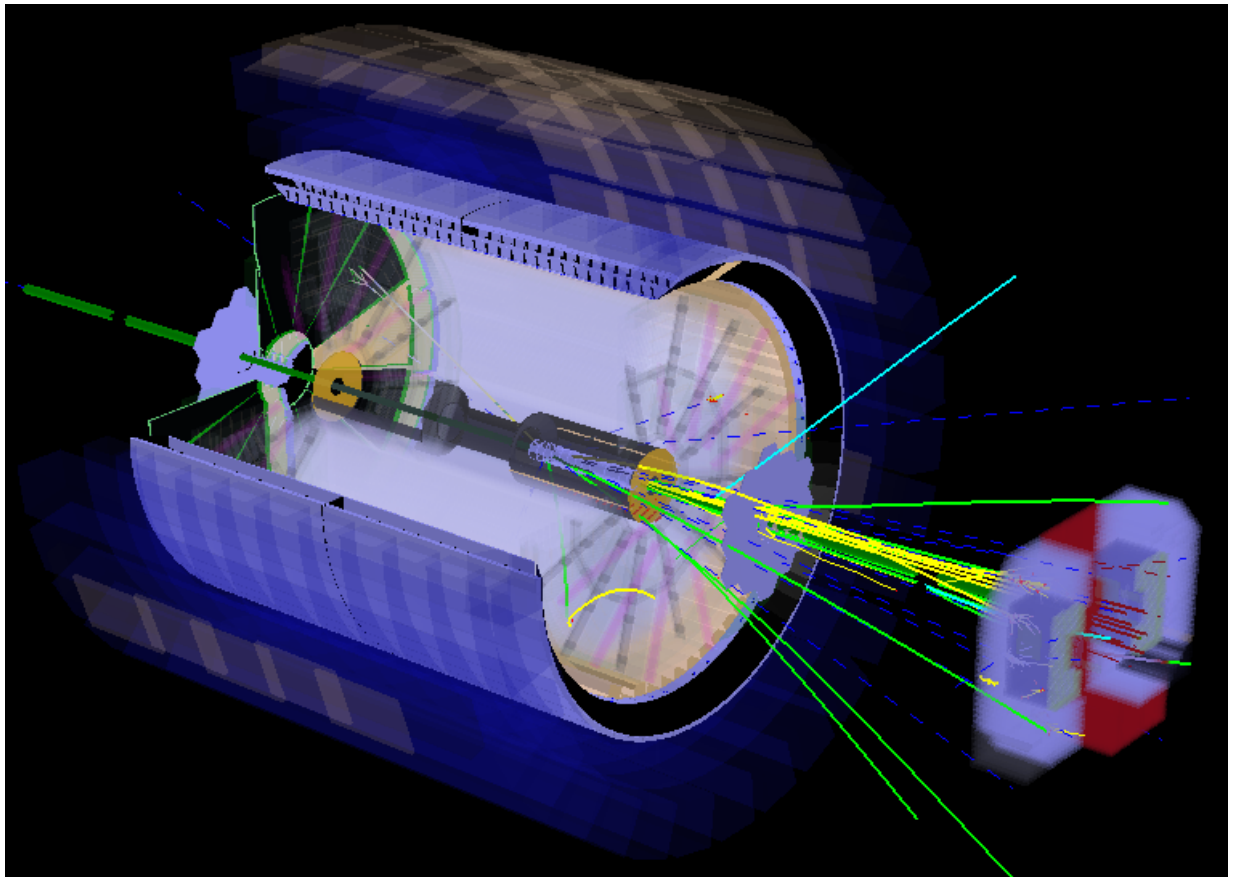


# The STAR Forward Calorimeter System and Forward Tracking System



**Proposal  
May 2017**



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# 1 Executive Summary

Quantum Chromodynamics (QCD), the theory of strong interactions, is a cornerstone of the Standard Model of modern physics. It explains all strongly interacting matter in terms of point-like quarks interacting via the exchange of gauge bosons, known as gluons. This strongly interacting matter is responsible for 99% of the visible mass in the universe. Over the past several decades, QCD has proven to be a remarkably rich theory. Enormous progress has been made in computational techniques in many topical areas of QCD and quite remarkable observations have been made in experiment.

The theoretical and experimental achievements of the current US QCD facilities JLab and RHIC as well as the next pressing questions to be answered by the existing and the newly proposed facility the Electron Ion Collider (EIC) are detailed in the 2015 Long Range Plan [1].

By precisely imaging gluons and sea quarks inside the proton and nuclei, some of the deepest issues regarding the emergence of nuclear properties from QCD will be addressed. These issues include:

- How are the gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of sea quark and gluon orbital motion in building the nucleon spin?
- What happens to the gluon density in nuclei at high energy? Does it saturate, giving rise to a gluonic matter component with universal properties in all nuclei, even the proton?
- How does the nuclear environment affect quark and gluon distributions and interactions inside nuclei? Do the abundant low-momentum gluons remain confined within nucleons inside nuclei?
- How does nuclear matter respond to a fast moving color charge passing through it? How do quarks of different flavor dress themselves in nuclear matter to emerge as colorless hadrons? What does this dressing process tell us about the mechanisms by which quarks are normally confined inside nucleons?

The outstanding p+p and p+A physics program as outlined in the 2016 RHIC Cold QCD Plan [2] and reviewed by the PAC in 2016 can address these questions in the next years preceding the EIC. This proposal gives a realization plan to address the 2016 PAC recommendation: “The PAC encourages the management and the collaborations to consider a potential (polarized) p+p and/or p+A program before 2023. In addition to the scientific benefits pointed out in the Cold QCD Report, this would help to keep the Cold QCD community active and engaged at RHIC, which might be important for the activities at BNL aiming at an EIC.”

The outlined measurements will be essential to fully realize the scientific promise of the EIC by providing a comprehensive set of measurements in hadronic collisions that, when combined with data from the EIC, will establish the validity and limits of factorization and universality. The outlined program will on the one hand lay the groundwork for the EIC, both scientifically and in terms of refining the experimental requirements for the physics program at the EIC, and thus be the natural next step on the path towards an electron-ion collider. On the other hand, while much of the physics in this program is unique to proton-proton and proton-nucleus collisions and offers discovery potential on its own, when combined with data from the EIC it will provide a broad foundation to a deeper understanding of fundamental QCD.

This proposal details **only** the part of p+p and p+A physics program outlined in the RHIC Cold QCD Plan [2], which requires an upgrade to the forward rapidity ( $2.5 < \eta < 4.5$ ) detection capabilities of STAR (for a summary see Table 2-1). A brief discussion of STAR’s ability concurrently to realize the mid-rapidity p+p and p+A physics program outlined in the RHIC Cold QCD Plan is given in a companion document [3].

The STAR forward upgrade is motivated mainly by exploration of cold QCD physics in the very high and low regions of Bjorken  $x$ . But it is specifically noted that the forward upgrade will also provide new detector capabilities at RHIC and STAR to explore the longitudinal structure of the initial state and the temperature dependent transport properties of matter in relativistic heavy ion collisions (for a summary of the A+A program see Table 2-2). A brief discussion of STAR's ability concurrently to realize a unique mid-rapidity A+A physics program is also outlined in the companion document [3].

Previous STAR efforts using the FPD and FMS detectors and the recently refurbished FMS and a new pre-shower and post-shower detector upgrade for Runs 2015-2017 have demonstrated that there are outstanding QCD physics opportunities in the forward region. In order to go beyond what STAR has already and will achieve with the currently existing forward detector system, a forward detector upgrade with superior detection capability for neutral pions, photons, electrons, jets and leading hadrons covering a pseudorapidity region of 2.5-4.5 in the years beyond 2020 is proposed. This is realized by combining tracking, an electromagnetic and a hadronic calorimeter.

The current design of the Forward Calorimeter System (FCS) is a follow up development of the original proposed FCS system and is driven by detector performance, integration into STAR and cost optimization. The FCS consist of the refurbished PHENIX sampling ECal. The hadronic calorimeter will be a sandwich iron scintillator plate sampling type, based on the extensive STAR Forward Upgrade and EIC Calorimeter Consortium R&D. Both calorimeters will share the same cost effective readout electronics, with SiPMs and/or APDs as photo-sensors. The proposed FCS system will have very good ( $\sim 8\%/\sqrt{E}$ ) electromagnetic and ( $\sim 70\%/\sqrt{E}$ ) hadronic energy resolutions. It can operate without shielding in a magnetic field and in a high radiation environment. In addition, the FCS will utilize the existing Forward Preshower Detector ( $2.5 < \eta < 4$ ) successfully operated in STAR since 2015. By design the system is scalable and easily re-configurable. Integration into STAR will require minimal modification of existing infrastructure.

In addition to the FCS, a Forward Tracking System (FTS) is also proposed. The FTS must be capable of discriminating hadron charge sign for transverse asymmetry studies and separating electrons and positrons for Drell-Yan measurements. In heavy ion collisions, it should be able to measure transverse momentum of charged particles in the range of  $0.2 < p_T < 2$  GeV/c with 20-30% momentum resolution. In order to keep multiple scattering and photon conversion background under control, the material budget of the FTS has to be small.

Based on STAR's considerable experience in Silicon technology from the Heavy-flavor tracker, a Silicon only detector option is considered for the FTS.

In the last years Silicon detectors have been widely used in high-energy experiments for tracking in the forward direction. We have evaluated a design based on Silicon mini-strip detectors that consists of maximum six disks at  $z$  locations from 60 to 180 cm. Each disk has wedges covering the full  $2\pi$  range in  $\phi$  and  $2.5 < \eta < 4$  with the read out from the larger radius of the sensors.

Alternatively we have investigated a FTS-system combining 3 Silicon disks as described before together with 4 Small-Strip Thin Gap Chamber (sTGC) wheels ala ATLAS [4,5]. The 4 sTGC wheels would be placed 30 cm apart starting from  $z=273$  cm. The sTGCs would also be extremely interesting as a cost effective alternative tracking detector technology to the planned GEM-trackers in the forward arms of the current EIC detector designs.

The total cost of the STAR forward upgrade consist of 0.57M\$ for the ECal, 1.25M\$ for the HCal, 0.1M\$ for refurbishing the existing preshower and the FCS trigger system and 4.1 M\$ for the Si only FTS. Realizing a FTS based on Silicon and sTGCs would result in a 1M\$ cost reduction for the tracking. These cost estimates include M&S, manpower and contingency.

**All projections and physics discussions are based on the following already planned data taking periods during the sPHENIX running periods in 2022 and 2023:**

- 1. 2022:** 20 weeks of Au+Au at  $\sqrt{s} = 200$  GeV
- 2. 2023:** 8 weeks transversely polarized p+p at  $\sqrt{s} = 200$  GeV
- 3. 2023:** 8 weeks each of transversely polarized p+Au and p+Al at  $\sqrt{s} = 200$  GeV

In addition, a 20 week  $\sqrt{s} = 500$  GeV polarized p+p run, split between transverse and longitudinal polarized running is proposed based on its merits for the overall physics program laid out in this document. This run could be scheduled in 2021, for which currently no dedicated physics program is assigned. It is especially noted none of the data taking periods proposed would result in any extra time delay to an eRHIC construction. **It is also noted that this high impact and cost-effective physics program can be executed even in challenging financial times.**

The Proposal is structured as following, in Section 2 we describe in detail how new data from (un)polarized p+p and p+A collisions at RHIC will serve as a gateway to the physics program at a future EIC (for further details please also see [6]). Section 0 details the simulation of the forward upgrade and its performance, and Section 0 and · describe the detailed design of the FCS and FTS.

The proposed program builds on the particular and unique strength of the RHIC accelerator facility compared to JLab, Compass and the LHC in terms of its versatility (i.e., the option of running with arbitrary nuclei), the availability of polarized proton beams, and wide kinematic coverage, further enhanced through an upgrade, consisting of electromagnetic and hadronic calorimetry as well as tracking, at forward rapidities at STAR. The program will bring to fruition the long-term campaign of STAR@RHIC on Cold QCD, with its recent achievements summarized in [7,2]. **It is especially stressed** that the final experimental accuracy achieved will enable quantitative tests of process dependence, factorization and universality by comparing lepton-proton with proton-proton collisions, providing critical checks of our understanding of QCD dynamics.

## 2 The Physics of the Forward Upgrade

### 2.1 Transverse Polarization Effects in the Proton: Twist-3 and TMDs

The study of spin phenomena in nuclear and particle physics has a long history of producing important and often surprising results. Attempts to understand such data have pushed the field forward, forcing the development of both new theoretical frameworks and new experimental techniques. The detector system proposed here, coupled with the versatility of RHIC, will allow us to gain new insights into long-standing puzzles, and to probe more deeply the complexities of emergent behavior in QCD.

Results from PHENIX and STAR have shown that large transverse single spin asymmetries (SSA) for inclusive hadron production,  $A_N$ , that were first seen in p+p collisions at fixed-target energies and modest  $p_T$  extend to the highest RHIC center-of-mass energies,  $\sqrt{s} = 500$  GeV, and surprisingly large  $p_T$ . Figure 2-1 summarizes the world data as a function of Feynman- $x$ . The asymmetries are nearly independent of  $\sqrt{s}$  over a very wide range ( $\sqrt{s}$ : 4.9 GeV to 500 GeV).

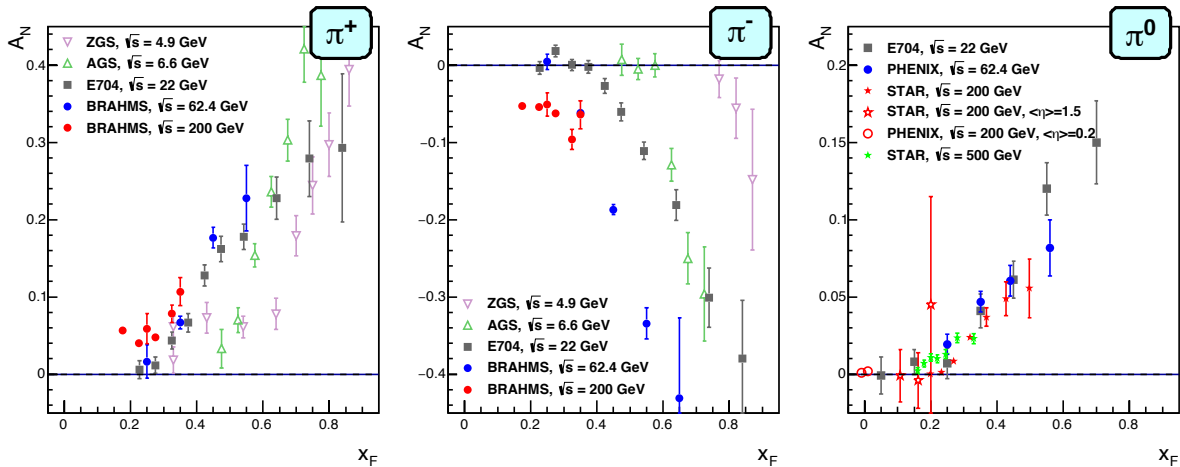


Figure 2-1: Transverse single spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as a function of Feynman- $x$ .

To understand the observed SSAs one has to go beyond the conventional leading twist collinear parton picture in the hard processes. Two theoretical formalisms have been proposed to explain sizable SSAs in the QCD framework: Transverse momentum dependent parton distributions and fragmentation functions, such as the Sivers and Collins functions, and transverse-momentum integrated (collinear) quark-gluon-quark correlations, which are twist-3 distributions in the initial state proton or in the fragmentation process. For many spin asymmetries, several of these functions can contribute and need to be disentangled to understand the experimental observations in detail, in particular the dependence on measured  $p_T$ . The functions express a spin dependence either in the initial state, for example the Sivers distribution and its Twist-3 analog, the Efremov-Teryaev-Qui-Sterman (ETQS) function [8], or in the final state via the fragmentation of polarized quarks, for example the Collins function.

The latest attempt to explain  $A_N$  for  $\pi^0$  production at RHIC incorporated the fragmentation term within the collinear twist-3 approach [9]. In that work, the relevant (non-pole) 3-parton collinear fragmentation function  $\widehat{H}_{FU}^S(z, z_z)$  was fit to the RHIC data. The so-called soft-gluon pole term, involving the ETQS function  $T_{q,F}(x_1, x_2)$ , was also included by fixing  $T_{q,F}$  through its well-known relation to the TMD Sivers function  $f_{1T}^\perp$ . The authors found a very good description of the data due to the inclusion of  $\widehat{H}_{FU}^S(z, z_z)$ . Based on this work, one is able to make predictions



for  $\pi^+$  and  $\pi^-$  production at forward rapidities covered by the forward upgrade. The results are shown in Figure 2-2 for  $\sqrt{s} = 200$  GeV and 500 GeV and rapidity ranges ( $2 < \eta < 3$  and  $3 < \eta < 4$ ).

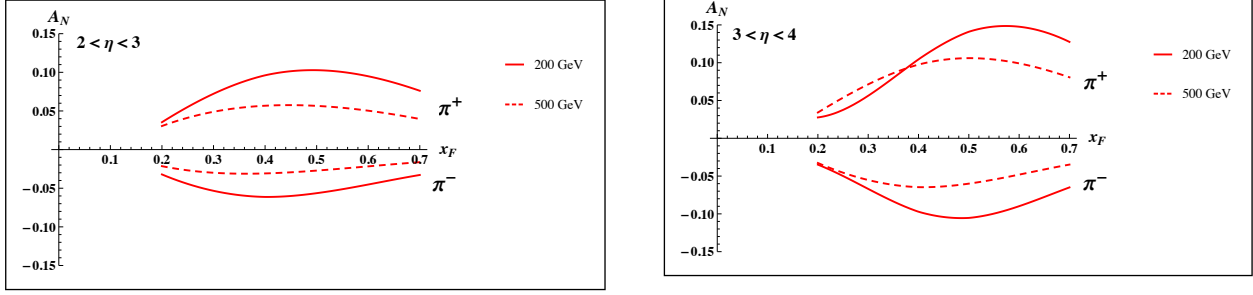


Figure 2-2:  $A_N$  predictions, based on the work in Ref. [9], for  $\pi^+$  and  $\pi^-$  production for  $2 < \eta < 3$  (left) and  $3 < \eta < 4$  (right) at  $\sqrt{s} = 200$  GeV (solid lines) and  $\sqrt{s} = 500$  GeV (dashed lines). The  $\sqrt{s} = 200$  GeV BRAHMS  $A_N$  data for charged pions cover up to  $x_F$  of 0.3.

The proposed forward upgrade, incorporating forward tracking, will enable us to access the previously measured charged hadron asymmetries [10] up to the highest center-of-mass energies at RHIC. It will be important to confirm that the charged hadron asymmetries are independent of center-of-mass energy. The measurement of  $A_N$  for charged hadrons together with the data from Run-2015 and 2017 on direct photons  $A_N$  and  $\pi^0$  should provide the best data set in the world to:

- Constrain the flavor dependence of the twist-3 ETQS distribution
- Constrain the evolution of the twist-3 ETQS distribution functions experimentally
- Determine if the 3-parton collinear fragmentation function  $\widehat{H}_{FU}^S(z, z_z)$  is the main driver for the large forward  $A_N$

Equally interesting is the opportunity to test the relation of the ETQS correlation functions and the Sivers function by measuring  $A_N$  for direct photon production and  $A_N$  for forward jet production. As discussed above, both the Sivers and the ETQS functions encapsulate partonic spin correlations inside the proton, but they are formally defined in different frameworks. The Sivers function is a TMD and the ETQS function is a twist three collinear distribution. Because both functions access essentially the same physics the Sivers function,  $f_{1T}^\perp$ , may be related to the ETQS functions,  $T_{q,F}$ , through an integral over transverse momentum:

$$T_{q,F}(x, x) = - \int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x, k_\perp^2)|_{SIDIS}$$

In contrast to the large pion asymmetries observed in the forward direction, inclusive jet asymmetries reported by the ANDY collaboration [11] in the same kinematic regime are small. An analysis by L. Gamberg et al. [12] argues these small asymmetries are due to cancellations between the  $u$  and  $d$  valence quark distributions. This idea is supported by the  $u$  and  $d$  Sivers functions extracted from SIDIS data have opposite sign but equal magnitude. Likewise, the twist-3 ETQS functions extracted from the Sivers functions using the integral relationship above, follow a similar pattern and fit the observed inclusive jet data well.

To better quantitatively test the relation between the two regimes, jet asymmetries which are *intentionally* biased towards either up or down quark jets with the help of a high- $z$  charged hadron should be studied. In higher twist calculations of the jet asymmetries based on the Sivers function [13], sizeable asymmetries for the enhanced jet samples are predicted. This is experimentally accessible in forward jet reconstruction by tagging an additional charged hadron in

the jet. Using realistic jet smearing in a forward calorimeter and tracking system and requiring a charged hadron with  $z > 0.5$ , the asymmetries can clearly be separated and compared to the predictions for the Siverson function based on the SIDIS data. The expected uncertainties, plotted at the predicted values can be seen in Figure 2-3. Dilutions by underlying event and beam remnants were taken into account. The simulations have assumed an integrated luminosity of only  $100 \text{ pb}^{-1}$  at  $\sqrt{s} = 200 \text{ GeV}$ , which is significantly lower than what is currently expected for a 200 GeV polarized p-p run in 2023. The same measurement is possible at 500 GeV.

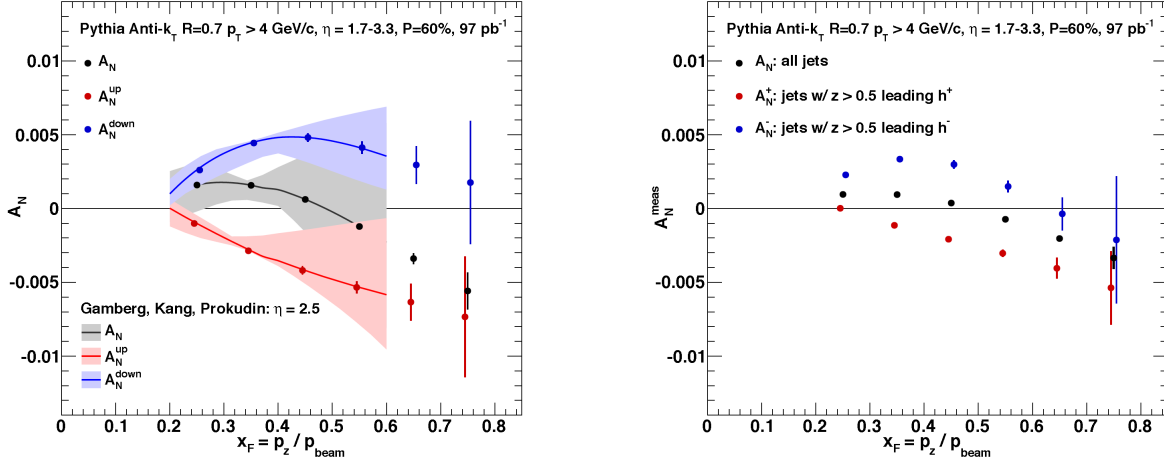


Figure 2-3: Left: up quark (red points), down quark (blue points) and all jet (black points) single spin asymmetries as a function of  $x_F$  as calculated by the ETQS based on the SIDIS Siverson functions. Right: Expected experimental sensitivities for jet asymmetries tagging in addition a positive hadron with  $z$  above 0.5 (red points), a negative hadron with  $z$  above 0.5 (blue points) or all jets (black) as a function of  $x_F$ . Note: these figures are currently for 200 GeV center-of-mass energy proton collisions – the 500 GeV results are expected to be qualitatively similar but with reduced uncertainties due to the larger luminosities expected.

## 2.2 Transversity, Collins and Interference Fragmentation Functions

A complete picture of nucleon spin structure at leading twist requires not only unpolarized and helicity distributions, but also those involving transverse polarization, such as the transversity distribution [14, 15, 16]. The transversity distribution can be interpreted as the net transverse polarization of quarks within a transversely polarized proton [15]. It is noted that the difference between the helicity distributions and the transversity distributions for quarks and antiquarks provides a direct,  $x$ -dependent, connection of nonzero orbital angular momentum components in the wave function of the proton [17]. Recently, the measurement of transversity has received renewed interest in an effort to access the so-called tensor charge of the nucleon, defined as the integral over the valence quark transversity:  $\delta q^a = \int_0^1 [\delta q^a(x) - \delta \bar{q}^a(x)] dx$  [15, 18]. Measuring the tensor charge is very important for two reasons: It can be calculated on the lattice with comparatively high precision, and due to the valence nature of transversity, it is one of the few quantities that allow us to compare experimental results on the spin structure of the nucleon to ab-initio QCD calculations. The second reason is that the tensor charge describes the sensitivity of observables in low energy hadronic reactions to beyond the standard model (BSM) physics processes with tensor couplings to hadrons. Examples are experiments with ultra-cold neutrons and nuclei [19].

Transversity is difficult to access due to its chiral-odd nature, requiring the coupling of this distribution to another chiral-odd distribution. SIDIS experiments have successfully probed transversity through two channels: asymmetric distributions of single pions, coupling transversity to the transverse-momentum-dependent (TMD) Collins fragmentation function [20], and

azimuthally asymmetric distributions of di-hadrons, coupling transversity to the so-called “interference fragmentation function” (IFF) [21] in the framework of collinear factorization. Taking advantage of universality and robust proofs of TMD factorization for SIDIS, recent results [22,23,24,reach 25] have been combined with  $e^+e^-$  measurements [26,27] isolating the Collins and IFFs for the first global analyses to extract simultaneously the transversity distribution and polarized FF [28, 29]. In spite of this wealth of data, the kinematic reach of existing SIDIS experiments, where the range of Bjorken- $x$  values does not extend above  $x \sim 0.3$ , limits the current extractions of transversity.

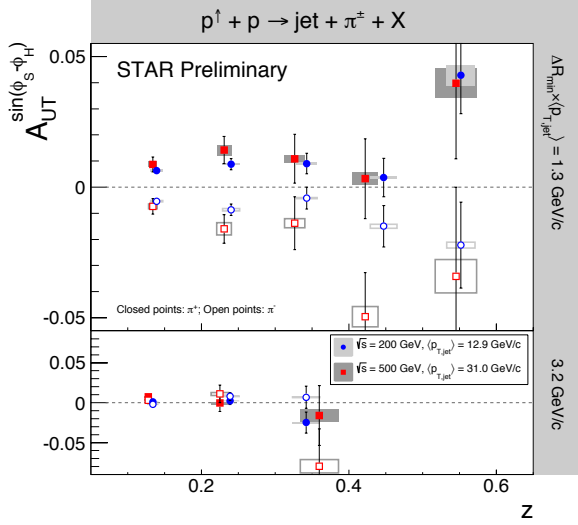


Figure 2-4:  $A_{UT}^{\sin(\phi_s - \phi_h)}$  vs.  $z$  for charged pions in jets at  $0 < \eta < 1$  from p+p collisions at  $\sqrt{s} = 200$  GeV and 500 GeV by STAR. The  $p_{T,jet}$  ranges have been chosen to sample the same parton  $x$  values for both beam energies. The angular cuts, characterized by the minimum distance of the charged pion from the jet thrust axis, have been chosen to sample the same  $j_T$ -values ( $j_T \sim z \times \Delta R \times p_{T,jet}$ ). These data show for the first time a nonzero asymmetry in p+p collisions sensitive to transversity x Collins FF.

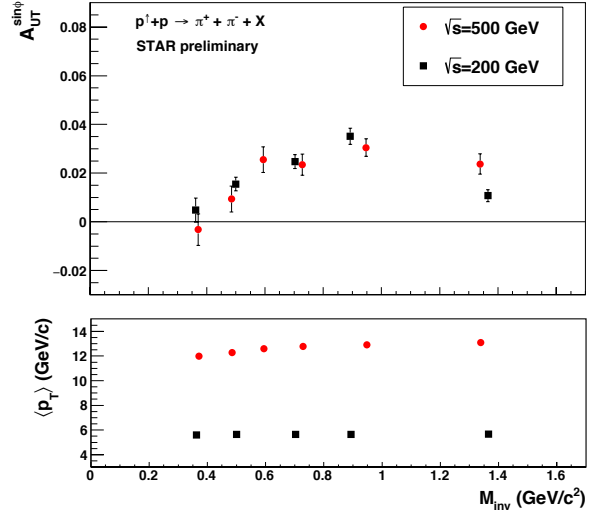


Figure 2-5:  $A_{UT}^{\sin(\phi)}$  as a function of  $M_{\pi^+\pi^-}$  (upper panel) and corresponding  $p_{T(\pi^+\pi^-)}$  (lower panel). A clear enhancement of the signal around the  $\rho$ -mass region is observed both at  $\sqrt{s} = 200$  GeV and 500 GeV by STAR for  $-1 < \eta < 1$ . The  $p_{T(\pi^+\pi^-)}$  was chosen to sample the same  $x_T$  for  $\sqrt{s} = 200$  GeV and 500 GeV.

Following the decomposition as described in [30,31,32] the Collins effect times the quark transversity distribution and the IFF times the quark transversity distribution may be accessed in polarized proton-proton collisions through single spin asymmetries of the azimuthal distributions of hadrons inside a high-energy jet and the azimuthal asymmetries of pion pairs with different charges, respectively. Figure 2-4 and Figure 2-5 show the sizeable asymmetries measured with the STAR detector for the mid-rapidity Collins and IFF channels. A comparison of the transversity signals extracted from the two observables will explore questions about universality and factorization breaking, while comparisons of the same channel at 200 and 500 GeV will provide experimental constraints on evolution effects. The first extraction of transversity from the STAR IFF data [33] has started (for details see Figure 14 in [34]).

By accessing the Collins asymmetry through the distribution of pions within a jet, one may also extract the  $k_T$  dependence of transversity, giving insight into the multidimensional dependence of the distribution. Following the decomposition described in Ref. [31], that shows how to correlate different angular modulations to different TMDs, STAR has extracted several other angular modulations [35]. One example is the Collins-like asymmetry  $A_{UT}^{\sin(\phi_s - 2\phi_h)}$ .

Currently all existing model predictions are unconstrained by measurements and suggest a maximum possible upper limit of  $\sim 2\%$ . The present data fall well below this maximum with the best precision at lower values of  $z$ , where models suggest the largest effects may occur. Thus, these data should allow for the first phenomenological constraint on model predictions utilizing linearly polarized gluons beyond the positivity bounds.

While the measurements of transversity through the Collins FF need TMD factorization to hold in p+p scattering, di-hadron asymmetries utilize collinear factorization. Thus, not only can more precise measurements of these effects in p+p improve our knowledge of transversity, such measurements are invaluable to test the longstanding theoretical questions, such as the magnitude of any existing TMD factorization breaking. Extractions at RHIC kinematics also allow the possibility for understanding the TMD evolution of the Collins FF (e.g. Ref. [36]) by comparing to those extractions from SIDIS and  $e^+e^-$  data. As noted earlier, extending measurements of di-hadron and Collins asymmetries in the forward direction will allow access to transversity in the region  $x > 0.3$ , which is not probed by current experiments. This valence quark region is essential for the determination of the tensor charge, which receives 70% of its contributions from  $0.1 < x < 1.0$ , for details on the current status of the tensor charge please see [37] In addition, probing transversity in p+p collision provides enhanced sensitivity to the d-quark transversity compared to SIDIS, due to the fact that there is no charge weighting in the hard scattering QCD  $2 \rightarrow 2$  process in p+p collisions. We note that this is a fundamental advantage of p+p collisions, as any SIDIS measurement of the d-quark transversity has to be on a bound system, i.e. He-3, which leads to nuclear corrections. The high scale we can reach in 500 GeV collisions at RHIC will also allow for the verification that previous SIDIS measurements at low scales are, in fact, accessing the nucleon at leading twist. Figure 2-6 shows the  $x-Q^2$  coverage spanned by the RHIC measurements compared to a future EIC, JLab-12, and the current SIDIS world data.

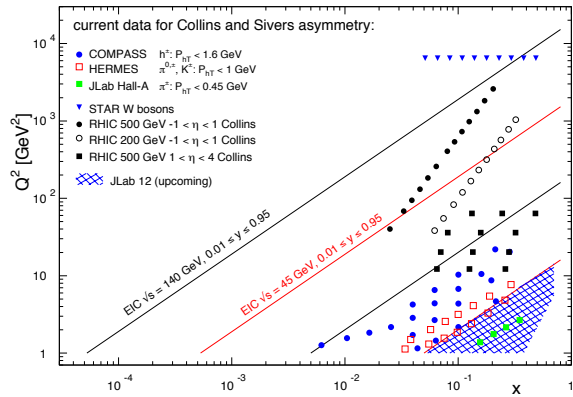


Figure 2-6: The  $x-Q^2$  plane for data from the future EIC and Jlab-12 GeV as well as the current SIDIS data and the W-boson data from RHIC. All data are sensitive to the Siverts function and transversity times the Collins FF in the TMD formalism.

Another fundamental advantage of p+p collisions is the ability to access gluons directly. While gluons cannot carry any transverse spin, there is a strong analogy between quark transversity and the linear polarization of gluons. Similarly, there exists an equivalent of the Collins fragmentation function for the fragmentation of linearly polarized gluons into unpolarized hadrons [38]. The linear polarization of gluons is a largely unexplored phenomenon, but it has been a focus of recent theoretical work, in particular due to the relevance of linearly polarized gluons in unpolarized hadrons for the  $p_T$  spectrum of the Higgs boson measured at the LHC. Polarized proton collisions at  $\sqrt{s} = 500$  GeV at RHIC are an ideal place to study the linearly polarized gluon distribution in polarized protons, especially for asymmetric partonic collisions in which the jets are detected in the backward direction. (Note: that the distributions of linearly polarized gluons inside an unpolarized and a polarized proton provide independent information). A first measurement of the ‘‘Collins-like’’ effect for linearly polarized gluons has been done by STAR with data from Run-2011, providing constraints on this function for the first time.

## 2.2.1 Opportunities with a Future Run at 500 GeV

In order to further advance our understanding of transverse momentum dependent effects it is critical to enhance the current kinematical reach to lower or higher  $x$ . This can only be realized by either going to substantially higher jet transverse momenta or by measuring jets at forward rapidities where more asymmetric collisions allow larger  $x$  and larger quark contributions in the hard process or to go to lower  $x$  and tag on gluon contributions in the hard scattering. The current RHIC plan does not include collisions above  $\sqrt{s} = 200$  GeV in the years after 2020. **If the timeline should change, making additional running in 2021 feasible**, proton-proton collisions at  $\sqrt{s} = 500$  GeV, combined with forward rapidity coverage between 2.5 and 4, would allow RHIC to extend the currently accessed coverage in  $x$  substantially above 0.3 for reasonably high scales, as well as quantitatively test universality in the  $x$  range below, which is overlapping the range accessed in SIDIS experiments. On the other end of the partonic momentum spectrum, which is important for the study of linearly polarized gluons,  $x$  values below  $2 \times 10^{-3}$  can be reached.

To estimate the physics impact of a possible run at  $\sqrt{s} = 500$  GeV, we have done careful simulations of the uncertainties one might expect for some of the transverse asymmetries discussed above. A realistic momentum smearing of final state hadrons as well as jets in this rapidity range was assumed and dilutions due to beam remnants (which become substantial at high rapidities) and underlying event contributions have been taken into account. As currently no dedicated particle identification at forward rapidities is feasible for these measurements, only charged hadrons were taken into account that mostly reduces the expected asymmetries due to dilution by protons (10-14%) and a moderate amount of kaons (12-13%). As antiprotons are suppressed compared to protons in the beam remnants, the negative hadrons in particular can be considered a good proxy for negative pions ( $\sim 78\%$  purity according to PYTHIA6). Given their sensitivity to the down quark transversity via favored fragmentation, they are of particular importance because SIDIS measurements are naturally dominated by up-quarks due to their electromagnetic interaction.

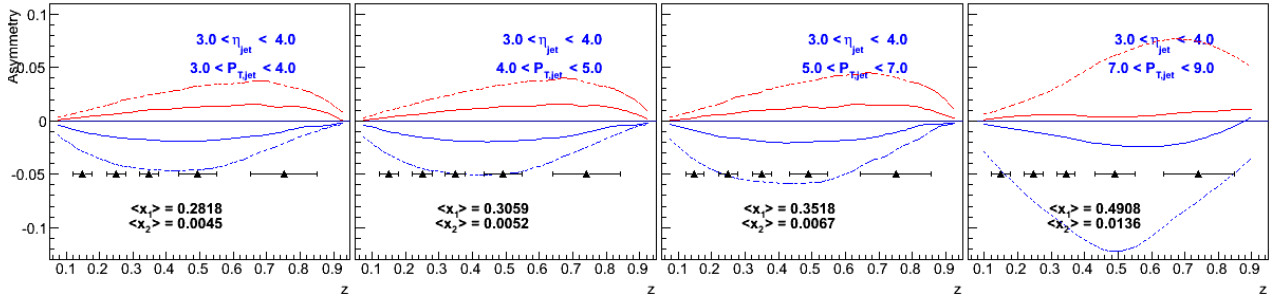


Figure 2-7: Expected  $h^\pm$  Collins asymmetry uncertainties (black points) from a sampled luminosity of  $268 \text{ pb}^{-1}$  compared to positive (red) and negative (blue) pion asymmetries based on the Torino extraction [39] (full lines) and the Soffer bound [40] (dashed lines) as a function of fractional energy  $z$  for various bins in jet rapidity and transverse momentum.

We have estimated our statistical uncertainties based on a sampled luminosity of  $268 \text{ pb}^{-1}$ , which leaves uncertainties nearly invisible after smearing. The uncertainties were evaluated in a very fine binning in jet transverse momentum, jet rapidity and the fractional energy  $z$  of the hadrons relative to the jet- $p_T$ . These expected uncertainties are compared in Figure 2-7 to the asymmetries obtained from the transversity extractions based on SIDIS and Belle data [28] as well as from using the Soffer positivity bound for the transversity PDF [41]. More recent global fits [42] have slightly different central up and down quark transversity distributions, but due to the lack of any data for  $x > 0.3$  the upper uncertainties are compatible with the Soffer bounds. As can

be seen from the average partonic  $x$  probed in the hard two-to-two process,  $x$  is increasing with increasing jet transverse momentum as well as rapidity. As discussed earlier it is this high- $x$  coverage that provides critical sensitivity into the tensor charge. It is important to emphasize that even though the studies presented here are for the Collins asymmetries, the resulting statistical uncertainties will be similar for other measurements using azimuthal correlations of hadrons in jets. One important example is the measurement of ‘‘Collins-like’’ asymmetries to access the distribution of linearly polarized gluons. As described earlier, the best kinematic region to access this distribution is at backward angles with respect to the polarized proton and at small jet  $p_T$ . With the instrumentation assumed for the forward Collins asymmetry studies, therefore a high precision measurement of the distribution of linearly polarized gluons can be performed as well.

Finally, it is worthwhile to note that a transversely polarized 500 GeV p+p run with anticipated delivered luminosity of  $1 \text{ fb}^{-1}$  will reduce by a factor of two the statistical uncertainties of all the TMD and twist-3 observables that motivated the current RHIC Run 17, including  $A_N$  of  $W^{+/-}$ ,  $Z^0$ , direct  $\gamma$  and Drell-Yan pairs. This experimental accuracy will significantly enhance the quantitative reach of testing the limits of factorization and universality in lepton-proton and proton-proton collisions.

### 2.3 Using Dijets to access $\Delta G$ at $\sqrt{s} = 500 \text{ GeV}$

Additional longitudinally polarized proton-proton collisions at  $\sqrt{s} = 500 \text{ GeV}$  would allow RHIC to explore the low  $x$  region of the gluon helicity distribution  $\Delta g(x)$ . A future 500 GeV longitudinal polarized p+p run (8 weeks with a delivered integrated luminosity of  $1.1 \text{ fb}^{-1}$ ) would further reduce the statistical uncertainties of the two workhorses of the RHIC  $\Delta g$  program, inclusive mid-rapidity jets and neutral pions, by a factor of 1.25 compared to the existing data sets shown in Figure 2-8 and Figure 2-9.

The existing mid-rapidity analyses are sensitive to gluons in the range of  $0.01 < x < 1$ . While these measurements clearly point to a positive  $\Delta g(x)$  for moderate  $x$  values, they do little to constrain the functional form of the distribution at lower  $x$ . This lack of data translates directly into a large uncertainty on the total gluon contribution to the spin of the proton  $\Delta G = \int_0^1 \Delta g(x, Q^2) dx$ , as shown in Figure 2-10. Di-jet measurements provide a more direct connection to the probed values of momentum fractions  $x$ , and if extended to forward region, allow us to access  $x$  down to  $10^{-3}$ . Figure 2-11 shows the projected precision for the asymmetries  $A_{LL}$  as a function of the scaled invariant di-jet mass  $M_{inv}/\sqrt{s}$  for four topological di-jet configurations involving a generic forward calorimeter system (FCS) in combination with either  $-1.0 < \eta < 0.0$ ,  $0.0 < \eta < 1.0$ ,  $1.0 < \eta < 2.0$ , and the FCS ( $2.5 < \eta < 4.0$ ). In particular the  $1.0 < \eta < 2.0$  / FCS and FCS / FCS configurations would allow one to probe  $x$  values as low as a few times  $10^{-3}$ , as shown Figure 2-12. The systematic uncertainty, which is assumed to be driven by the relative luminosity uncertainty of  $\delta R = 5 \cdot 10^{-4}$ , is clearly dominating over the statistical uncertainties. Any future measurements in these topological configurations, including very forward measurements, would clearly benefit from an improved relative luminosity measurement.

Di-jet measurements would provide theoretically well-controlled insight into the nature of the proton spin compared to the current forward rapidity ( $2.8 < \eta < 4.0$ ) inclusive  $\pi^0$   $A_{LL}$ . Jet reconstruction in the region will require electromagnetic and hadronic calorimetry, as well as some nominal tracking to associate charged particles with a single vertex.

The STAR collaboration has already established di-jet double spin asymmetry  $A_{LL}$  measurements in the pseudorapidity range  $-1 < \eta < 2$ . Figure 2-13 shows the published results for p+p collisions at  $\sqrt{s} = 200 \text{ GeV}$  (blue) [43] and preliminary results for  $\sqrt{s} = 510 \text{ GeV}$  (red) [44], based on data that were recorded in 2009 and 2012, respectively. Figure 2-14 shows the most recent STAR preliminary result for di-jets at  $\sqrt{s} = 200 \text{ GeV}$  with both jets at more forward rapidities  $0.8 < \eta_{1,2} <$

1.8 [45]. The impact of the measurements from 2009+2015 ( $\sqrt{s} = 200$  GeV) and 2012 + 2013 ( $\sqrt{s} = 500$  GeV) on the helicity gluon distribution is currently being assessed by the DSSV collaboration in the context of a global QCD analysis at next-to-leading order accuracy, which matches the experimental cuts and jet parameters

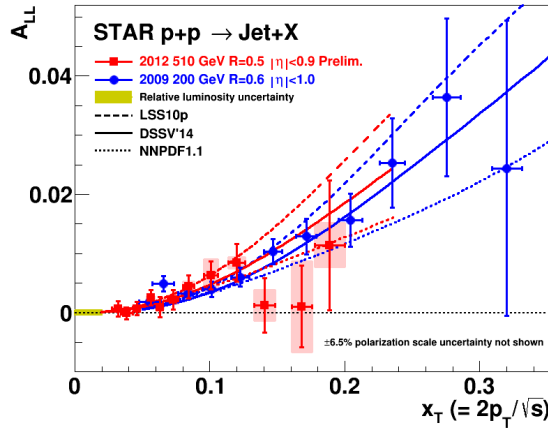


Figure 2-8:  $A_{LL}$  vs.  $x_T$  for inclusive jet production at mid-rapidity in 200 GeV (blue circles) [46] and 510 GeV (red squares) [47] p+p collisions, compared to NLO predictions [48,49] for three recent NLO global analyses [50,51,52] (blue curves for 200 GeV and red curves for 510 GeV).

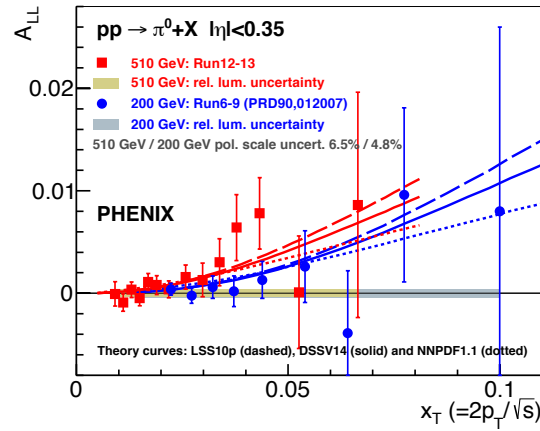


Figure 2-9:  $A_{LL}$  vs.  $x_T$  for  $\pi^0$ -meson production at mid-rapidity with the point-to-point uncertainties in 200 GeV (blue circles) [53] and 510 GeV (red squares) [54] p+p collisions, compared to NLO predictions [55] for three recent NLO global analyses [50,51,52] (blue curves for 200 GeV and red curves for 510 GeV). The gray/gold bands give the correlated systematic uncertainties.

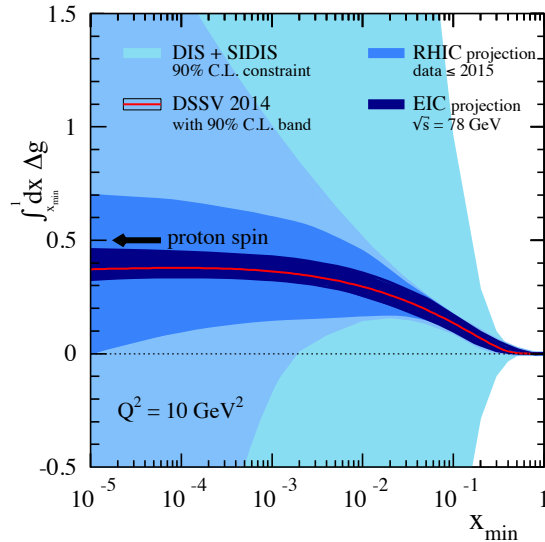


Figure 2-10: The running integral for  $\Delta g$  as a function of  $x_{min}$  at  $Q^2 = 10$  GeV<sup>2</sup> as obtained in the DSSV global analysis framework. The different uncertainty bands at 90% C.L. are estimated from the world DIS and SIDIS data, with and without including the combined set of projected pseudo-data for preliminary and RHIC measurements up to Run-2015, respectively as well as including EIC DIS pseudo data (taken from Ref. [56]).

An EIC is anticipated to resolve the individual contributions to the spin of the nucleon with unprecedented precision in the  $x$  range down to a few times  $10^{-5}$  [57,58]. Hence, RHIC mid- and forward-rapidity  $A_{LL}$  measurements would continue providing unique and compelling sensitivity to the gluon helicity distribution of the proton **only** if an EIC were not realized or be significantly delayed due to external constraints. By themselves, these measurements do not provide a sufficiently compelling reason for another longitudinally polarized p+p run at  $\sqrt{s} = 500$  GeV past 2020 and certainly do not justify delay in the planning or construction of an EIC in the 2025 timeframe.

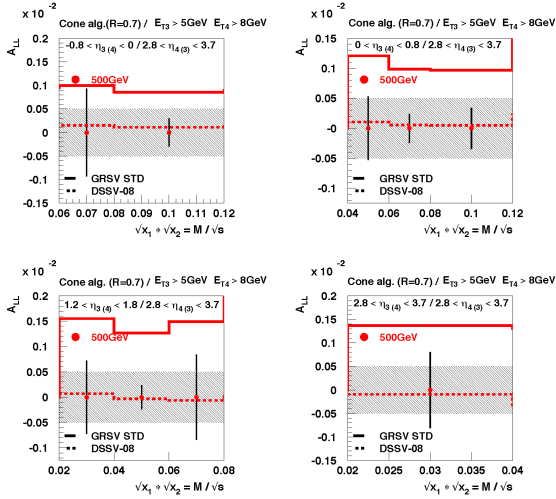


Figure 2-11:  $A_{LL}$  NLO calculations as a function of  $M_{inv}/\sqrt{s}$  for  $2.8 < \eta < 3.7$  together with projected statistical and systematic uncertainties. An uncertainty  $5 \cdot 10^{-4}$  has been assumed for the systematic uncertainty due to relative luminosity. A beam polarization of 60% and a total delivered luminosity of  $1 \text{ fb}^{-1}$  have been assumed with a ratio of 2/3 for the ratio of recorded to delivered luminosity.

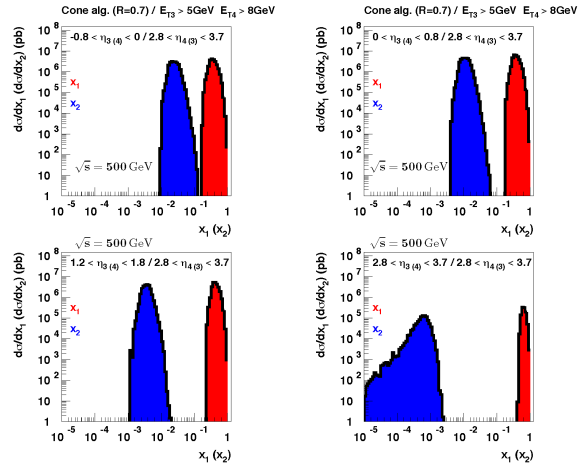


Figure 2-12:  $x_1/x_2$  range for the forward acceptance region of  $2.8 < \eta < 3.7$ .

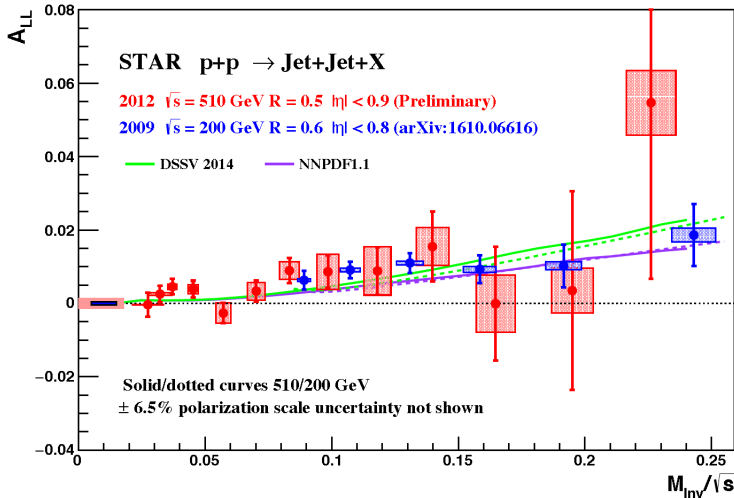


Figure 2-13: STAR measurements of the di-jet double spin asymmetry  $A_{LL}$  versus  $M_{inv}/\sqrt{s}$  of the pair for mid-rapidity p+p collisions at  $\sqrt{s} = 200 \text{ GeV}$  (blue) and  $\sqrt{s} = 510 \text{ GeV}$  (red), compared to model predictions based on DSSV14 and NNPDFp01.1. The uncertainties will be reduced by a factor of approximately 1.7 after additional data recorded during 2013 (510 GeV) and 2015 (200 GeV) are included.

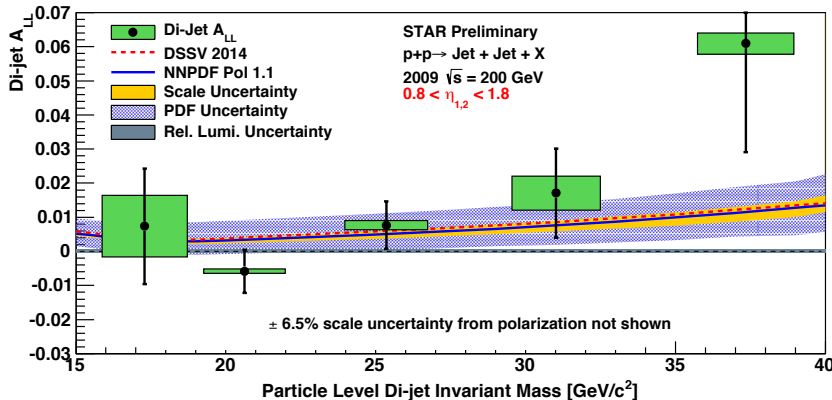


Figure 2-14: STAR measurements of the di-jet double spin asymmetry  $A_{LL}$  versus  $M_{inv}$  of the pair for mid-rapidity p+p collisions at  $\sqrt{s} = 200 \text{ GeV}$  with both jets in the rapidity range  $0.8 < \eta_{1,2} < 1.8$ , compared to model predictions based on DSSV14 and NNPDFp01.1.



## 2.4 Physics opportunities with (un)polarized proton-Nucleus collisions

Our quest to understand QCD processes in Cold Nuclear Matter (CNM) centers on the following fundamental questions:

- Can we experimentally find evidence of a novel universal regime of non-linear QCD dynamics in nuclei?
- What is the role of saturated strong gluon fields, and what are the degrees of freedom in this high gluon density regime?
- What is the fundamental quark-gluon structure of light and heavy nuclei?
- Can a nucleus, serving as a color filter, provide novel insight into the propagation, attenuation and hadronization of colored quarks and gluons?

Various aspects of these questions have been addressed by numerous experiments and facilities around the world, most of them at significantly lower center-of-mass energies and kinematic reach than RHIC. Deep inelastic scattering on nuclei addresses some of these questions with results from, for instance, HERMES at DESY [59], CLAS at JLab [60], and in the future at the JLab 12 GeV. This program is complemented by hadron-nucleus reactions in fixed target p+A at Fermilab (E772, E886, and E906) [61] and at the CERN-SPS.

In the following we propose a measurement program unique to RHIC to constrain the initial state effects in strong interactions in the nuclear environment. We also highlight the complementarity to the LHC p+Pb program and stress why RHIC data are essential and unique in the quest to further our understanding of nuclei. The uniqueness of the RHIC program is based on the flexibility of the RHIC accelerator to run collisions of different particle species at very different center-of-mass energies. This in combination with the existing and planned STAR detector capabilities allows to disentangle nuclear effects in the initial and final state as well as leading twist shadowing from saturation effects in a kinematic regime where all these effects are predicted to be large. The discussed measurements critically rely on the forward upgrade described in section 3.

### 2.4.1 The Initial State of Nuclear Collisions

#### *Nuclear Parton Distribution Functions*

A main emphasis of the 2015 and later p+A runs at RHIC is to determine the initial conditions of the heavy ion nucleus before the collision to support the theoretical understanding of the A+A program both at RHIC and the LHC. In the following, the current status of nPDFs will be discussed, including where the unique contribution of RHIC lie, in comparison to the LHC and a future EIC.

Our current understanding of nuclear parton distribution functions (nPDFs) is still very limited, in particular when compared with the rather precise knowledge of PDFs for free protons collected over the past 30 years. Figure 2-15 shows an extraction of nPDFs from available data, along with estimates of uncertainties. All results are shown in terms of the nuclear modification ratios, i.e., scaled by the respective PDF of the free proton. The yellow bands indicate regions in  $x$  where the fits are not constrained by data [62] and merely reflect the freedom in the functional form *assumed* in the different fits. Clearly, high precision data at small  $x$  and for various different values of  $Q^2$  are needed to better constrain the magnitude of suppression in the  $x$  region where non-linear effects in the scale evolution are expected. In addition, such data are needed for several different nuclei, as the A-dependence of nPDFs cannot be predicted from first principles in pQCD and, again,

currently relies on assumptions. Note that the difference between DSSZ [63] and EPS09 for the gluon modification arise from the different treatment of the PHENIX midrapidity  $\pi^0 R_{dAu}$  data [64], which in the EPS09 [65] fit are included with an extra weight of 20. The  $\pi^0 R_{dAu}$  data are the only data, which can probe the gluon in the nucleus directly, but these data also suffer from unknown nuclear effects in the final state (see Ref. [66]). Therefore, it is absolutely critical to have high precision data only sensitive to nuclear modification in the initial state over a wide range in  $x$  and intermediate values of  $Q^2$ , away from the saturation regime but where nuclear effects are still large, to establish the nuclear modification of gluons in this kinematic range.

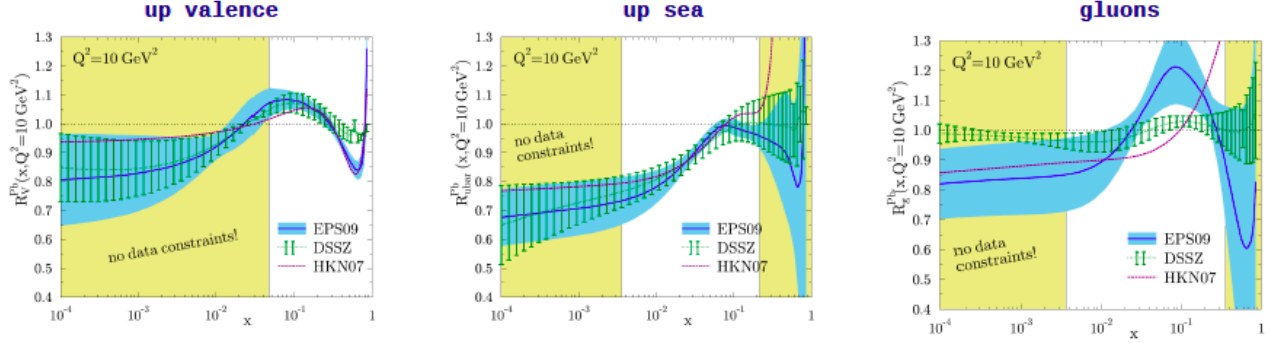


Figure 2-15: Summary of the most recent sets of nPDFs. The central values and their uncertainty estimates are given for the up valence quark, up sea quark, and the gluon. The yellow bands indicate regions in  $x$  where the fits are not constrained by any data (taken from Ref. [67]).

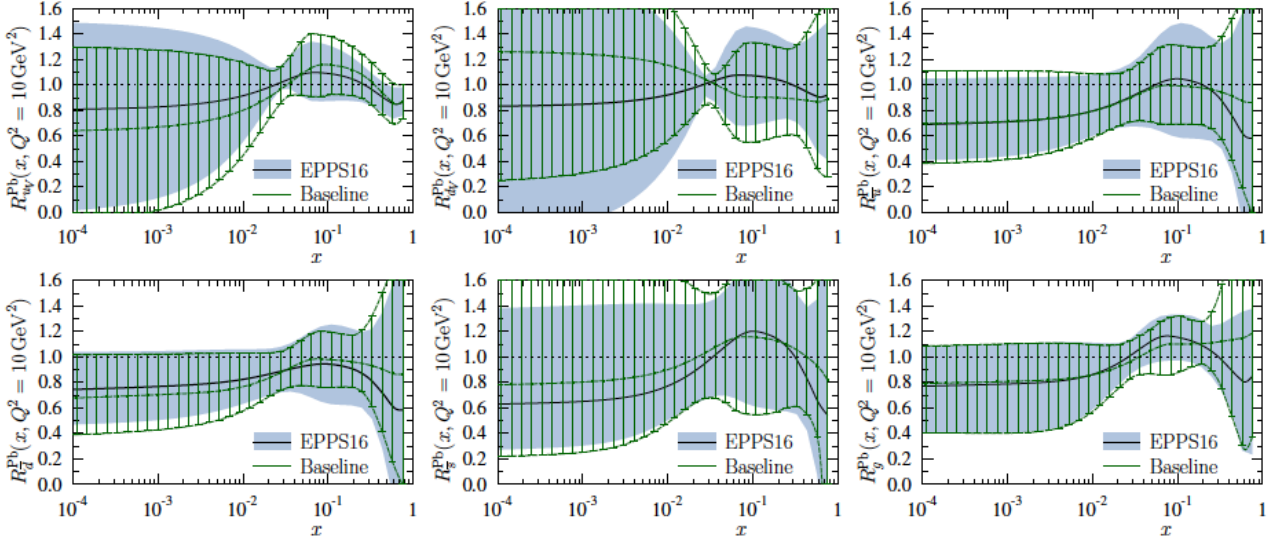


Figure 2-16: The nuclear modifications at  $Q^2=10 \text{ GeV}^2$  from the EPPS-16 fit (black central line and light-blue bands) compared with the Baseline fit (green curves with hatching) which uses only the data included in the EPS09 fit.

It is important to realize that the measurements from RHIC are compelling and essential even when compared to what can be achieved in p+Pb collisions at the LHC. Due to the higher center-of-mass system energy, most of the LHC data have very high  $Q^2$ , where the nuclear effects are already reduced significantly by evolution and are therefore very difficult to constrain. A recent article [68] assessed the impact of the available LHC Run-I p+Pb data on determinations of nPDFs. The rather moderate impact of these data is illustrated in Figure 2-16. Note that the extra weight factor of 20 for the PHENIX midrapidity  $\pi^0 R_{dAu}$  data [69] in the original EPS09 [70] fit was

removed in all of the new fits, leading to a much smaller nuclear modification factor for gluons, especially at medium to high  $x$ .

RHIC has the *unique* capability to provide data in a kinematic regime (moderate  $Q^2$  and medium-to-low  $x$ ) where the nuclear modification of the sea quark and the gluon is expected to be sizable and currently completely unconstrained. In addition, and unlike the LHC, RHIC can vary the nucleus in p+A collisions and as such also constrain the  $A$ -dependence of nPDFs.

Extraction of this information is less ambiguous if one uses processes in which strong (QCD) final-state interactions can be neglected or reduced. Such golden channels would include: a measurement of  $R_{pA}$  for Drell-Yan production at forward pseudo-rapidities with respect to the proton direction ( $2.5 < \eta_p < 4.$ ) to constrain the nuclear modifications of sea-quarks; and of  $R_{pA}$  for direct photon production in the same kinematic regime to constrain the nuclear gluon distribution. The first measurement of  $R_{pA}$  for direct photon production has been done already during the p+Au and p+Al runs in 2015, with recorded luminosities by STAR of  $L_{pAu} = 0.45 \text{ pb}^{-1}$  and  $L_{pAl} = 1 \text{ pb}^{-1}$ , respectively. The anticipated statistical precision for pA runs in 2015 and projections for a run in 2023 are shown in Figure 2-17. The planned forward upgrade with its tracking at forward rapidities will also provide the possibility to measure  $R_{pA}$  for positive and negatively charged hadrons.

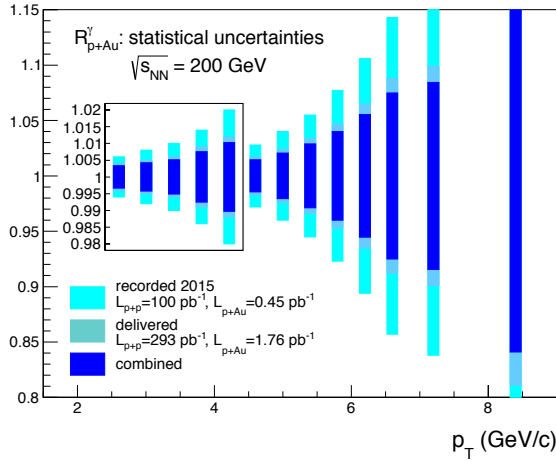


Figure 2-17: Projected statistical uncertainties for  $R_{pAu}$  for direct photons in Run-2015 (light blue) and a run in 2023 (blue) and the sum of both (dark blue). The recorded luminosity for Run-2015 was  $L_{pAu} = 450 \text{ nb}^{-1}$  and  $L_{pp} = 100 \text{ pb}^{-1}$ . The delivered luminosity for Run-2023 is assumed to be  $L_{pAu} = 1.8 \text{ pb}^{-1}$  and  $L_{pp} = 300 \text{ pb}^{-1}$ . A p+Al run of 8 weeks in 2023 would have matched parton luminosity resulting in an equal statistical precision.

Figure 2-18 shows the significant impact of the Run-2015  $R_{pA}$  for direct photon production plus a future run in the 2023, on the corresponding theoretical expectations and their uncertainties obtained with both the EPPS-16 and DSSZ sets of nPDFs. The uncertainty bands are obtained through a reweighting procedure [71] by using the projected data shown in Figure 2-17 and randomizing them according to their expected statistical uncertainties around the central values obtained with the current set of DSSZ and EPPS-16 nPDFs, respectively. Figure 2-19 shows how these measurements will help significantly in further constraining the nuclear gluon distribution in a broad range of  $x$  that is roughly correlated with accessible transverse momenta of the photon, i.e., few times  $10^{-3} < x < \text{few times } 10^{-2}$ . The relevant scale  $Q^2$  is set be  $\sim p_T^2$  and ranges from  $6 \text{ GeV}^2$  to about  $40 \text{ GeV}^2$ . Like all other inclusive probes in p+p and pA collisions, e.g., jets, no access to the exact parton kinematics can be provided event-by-event but global QCD analyses easily account for that. After the p+Au run in 2023, the statistical precision of the prompt photon data will be sufficient to contribute to a stringent test of the universality of nuclear PDFs when combined with the expected data from an EIC (see Figure 2.22 and 2.23 in Ref [72]).

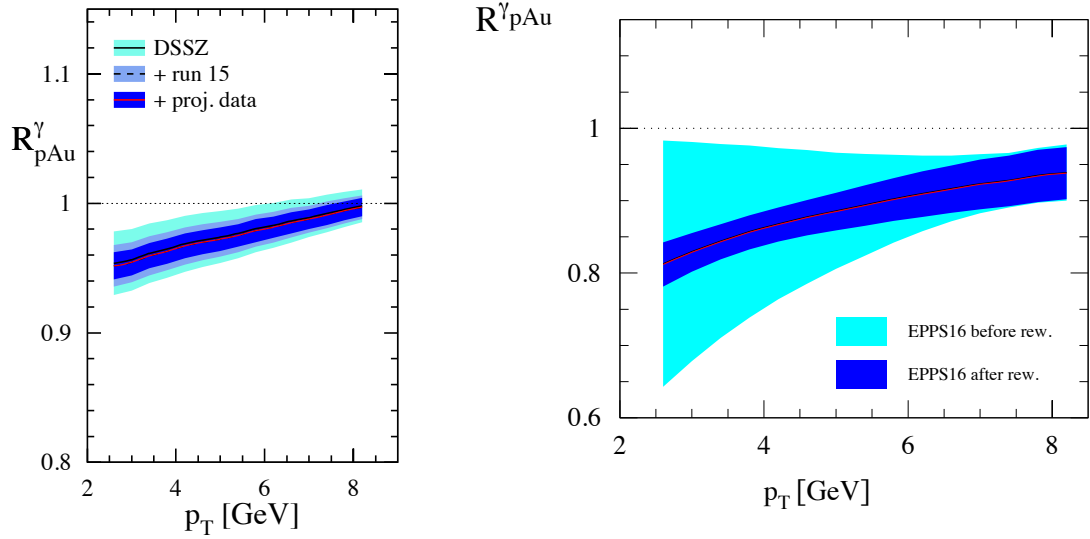


Figure 2-18: The impact of the direct photon  $R_{pA}$  data measured in Run-2015 (blue band) and for the anticipated statistics for a future p+Au run in 2023 (dark blue band) compared with the current uncertainties (cyan band) from DSSZ (left) and EPPS-16 (right).

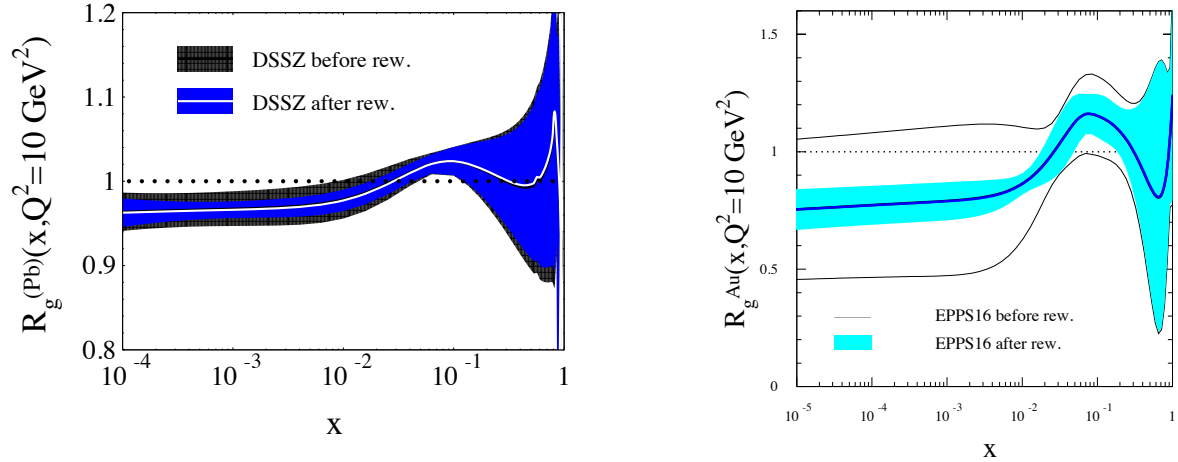


Figure 2-19: The impact of the direct photon  $R_{pA}$  data measured in Run-2015 and for the anticipated statistics for a future p+Au run in 2023 (blue band) on DSSZ (left) and (red band) EPPS-16 (right). The impact is shown on the nuclear suppression factor  $R_g$  of nPDF to the proton PDF, the grey bands represent the uncertainties before including the RHIC pseudo data.

Figure 2-20 shows the kinematic coverage in  $x-Q^2$  of past, present, and future experiments capable of constraining nuclear parton distribution functions. The experiments shown provide measurements that access the initial state parton kinematics on an event-by-event basis (in a leading order approximation) while remaining insensitive to any nuclear effects in the final state. Some of the LHC experiments cover the same  $x$ -range as DY at forward pseudo-rapidities at RHIC but at a much higher scale  $Q^2$ , where nuclear modifications are already significantly reduced [68,73]. At intermediate  $Q^2$ , DY at RHIC will extend the low- $x$  reach by nearly one decade compared to EIC.

The biggest challenge of a DY measurement is to suppress the overwhelming hadronic background: the total DY cross-section is about  $10^{-5}$  to  $10^{-6}$  smaller than the corresponding hadron production cross-sections. Therefore, the probability of misidentifying a hadron track as a lepton has to be suppressed to the order of 0.1% while maintaining reasonable electron detection efficiencies. To that end, we have studied the combined electron/hadron discriminating power of the proposed forward tracking and calorimeter systems. It was found that by applying multivariate

analysis techniques to the features of EM/hadronic shower development and momentum measurements we can achieve hadron rejection powers of 200 to 2000 for hadrons of 15 GeV to 50 GeV with 80% electron detection efficiency.

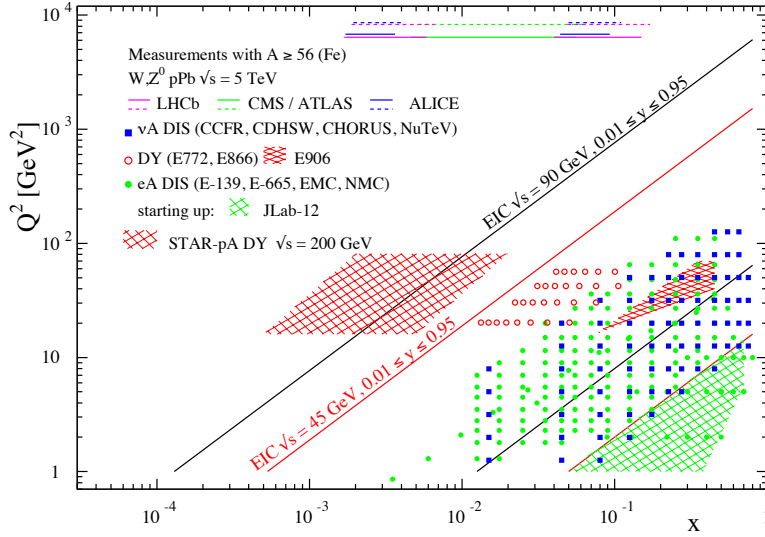


Figure 2-20: The kinematic coverage in  $x-Q^2$  of past, present and future experiments constraining nPDFs with access to the exact parton kinematics event-by-event and no fragmentation in the final state.

The left panel in Figure 2-21 shows the normalized background yields along with the expected DY production and their uncertainties for a delivered luminosity of  $2.3 \text{ pb}^{-1}$  and assuming the performance of the upgraded forward instrumentation as described in detail in Section 0 and . The green band represents the statistical uncertainties of the background yield and its shape. The right panel shows the DY signal to QCD background ratio as a function of the lepton pair mass.

The same procedure as for the direct photon  $R_{pA}$  was used to study the potential impact of the DY  $R_{pA}$  data. For the DSSZ and EPPS-16 sets of nPDFs both the predicted nuclear modifications and the current uncertainties are very similar. This is because both groups use the same DIS and DY data without any special weight factors in constraining sea-quarks. As can be inferred from Figure 2-21 we expect again a significant impact on the uncertainties of  $R_{pA}$  DY upon including the projected and properly randomized data (see Figure 2-22). Clearly, the DY data from RHIC will be instrumental in reducing present uncertainties in nuclear modifications of sea quarks (see Figure 2-23). Again, these data will prove to be essential in testing the fundamental universality property of nPDFs in the future when EIC data become available.

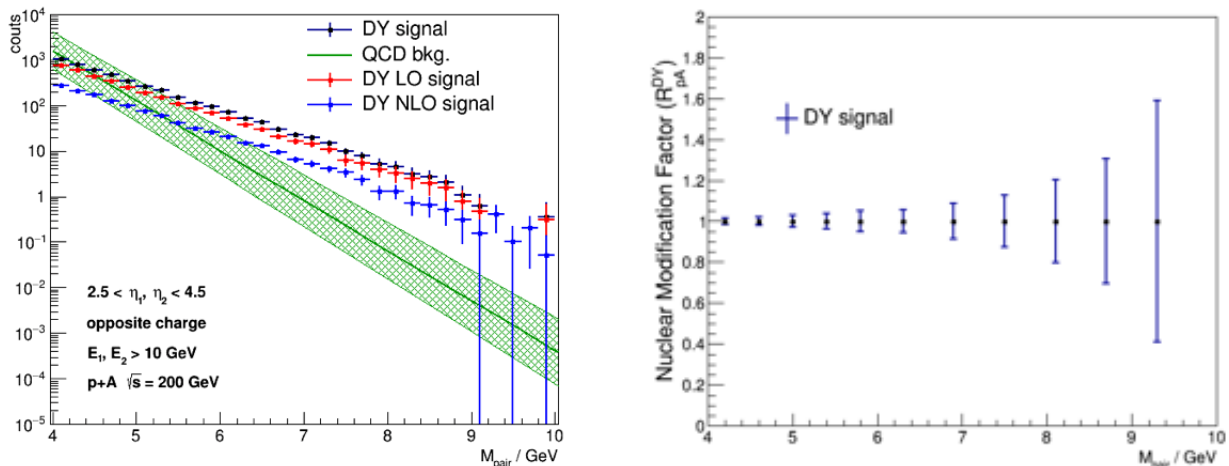


Figure 2-21: (left) DY signal and background yield from  $2.3 \text{ pb}^{-1}$  p+Au 200 GeV collisions. (right) The expected  $R_{pA}$  based on the  $2.3 \text{ pb}^{-1}$  p+Au and  $383 \text{ pb}^{-1}$  p+p reference data.

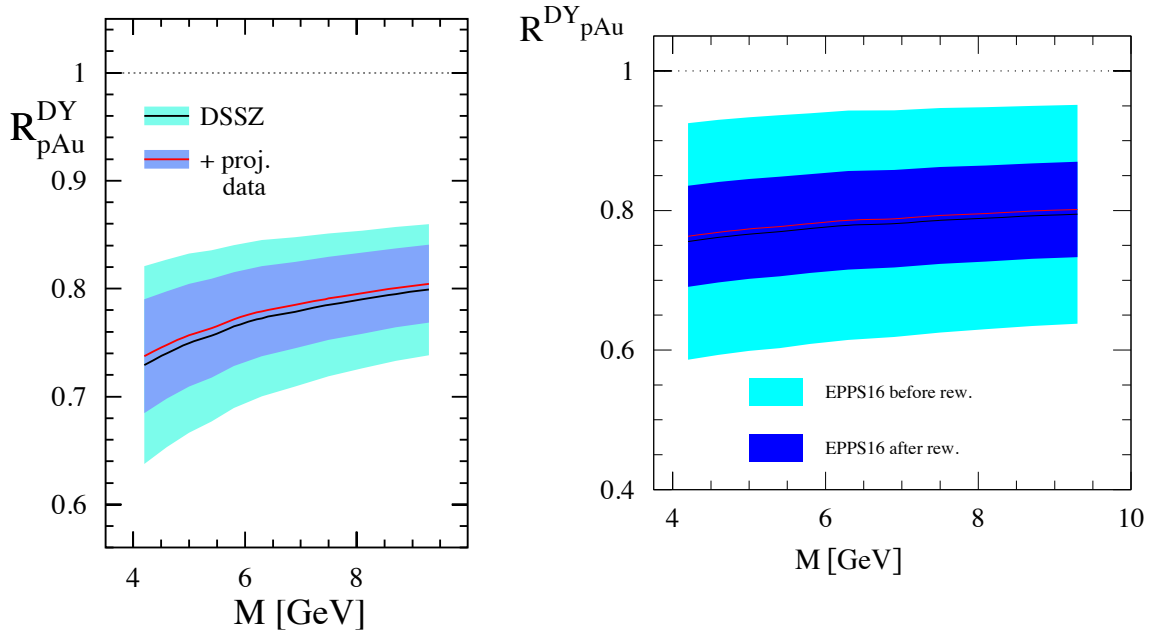


Figure 2-22: The impact of the DY  $R_{pA}$  data for the anticipated statistics for a p+Au run in 2023 (dark blue band) compared to the current uncertainties (cyan band) from DSSZ and EPPS-16.

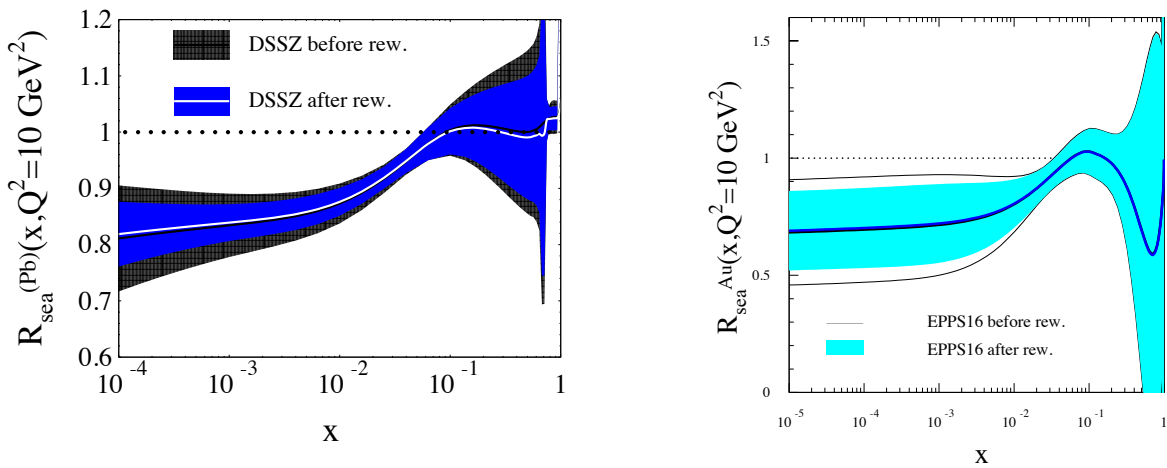


Figure 2-23: The impact for the anticipated statistics for the DY  $R_{pA}$  data for a future p+Au run in 2023 (blue band) on DSSZ (left) and (red band) EPPS-16 (right). The impact is shown on the nuclear suppression factor  $R_{\text{ubar}}$  of nPDF to the proton PDF, the grey bands represent the uncertainties before including the RHIC pseudo data.

## Gluon Saturation

Our understanding of the proton structure and of the nuclear interactions at high energy would be advanced significantly with the definitive discovery of the saturation regime [74]. Saturation physics would provide an infrared cutoff for perturbative calculations, the saturation scale  $Q_s$ , which grows with the atomic number of the nucleus  $A$  and with decreasing value of  $x$ . If  $Q_s$  is large it makes the strong coupling constant small,  $\alpha_s(Q_s^2) \ll 1$  allowing for perturbative QCD calculations to be under theoretical control.

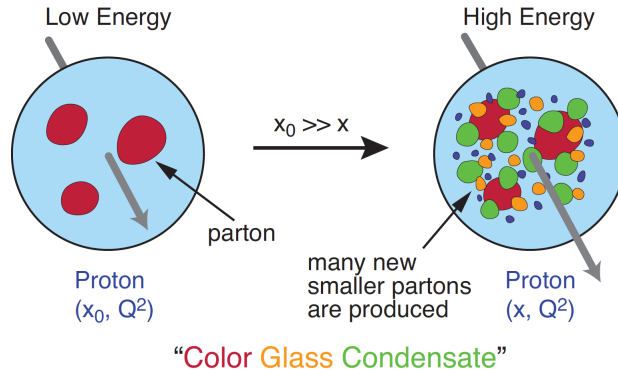


Figure 2-24: Proton wave function evolution towards small- $x$ .

It is well known that PDFs grow at small- $x$ . If one imagines how such a high number of small- $x$  partons would fit in the (almost) unchanged proton radius, one arrives at the picture presented in Figure 2-24: the gluons and quarks are packed very tightly in the transverse plane. The typical distance between the partons decreases as the number of partons increases, and can get small at low- $x$  (or for a large nucleus instead of the proton). One can define the saturation scale as the inverse of this typical transverse inter-parton distance. Hence  $Q_s$  indeed grows with  $A$  and decreasing  $x$ .

The actual calculations in saturation physics start with the classical gluon fields (as gluons dominate quarks at small- $x$ ) [75], which are then evolved using the nonlinear small- $x$  BK/JIMWLK evolution equations [76]. The saturation region is depicted in Figure 2-25 in the  $(x, Q^2)$  plane and can be well-approximated by  $Q_s^2 \sim (A/x)^{1/3}$ . Note again that at small enough  $x$  the saturation scale provides an IR cutoff, justifying the use of perturbative calculations. This is important beyond saturation physics, and may help us better understand small- $x$  evolution of the TMDs.

While evidence supporting saturation physics has been gleaned from the data collected at HERA, RHIC and the LHC, the case for saturation is not sealed and alternative explanations of these data exist. The EIC is slated to provide more definitive evidence for saturation physics [77]. To help the EIC complete the case for saturation, it is mandatory to generate higher-precision measurements in p+A collisions at RHIC. These higher-precision measurements would significantly enhance the discovery potential of the EIC as they would enable a stringent test of universality of saturation. We stress again that a lot of theoretical predictions and results in the earlier Sections of this document would greatly benefit from saturation physics: the small- $x$  evolution of TMDs in a longitudinally or transversely polarized proton, or in an unpolarized proton, can all be derived in the saturation framework [78] in a theoretically better-controlled way due to the presence of  $Q_s$ . Hence saturation physics may help us understand both the quark and gluon helicity PDFs as well as the Sivers and Boer-Mulders functions.

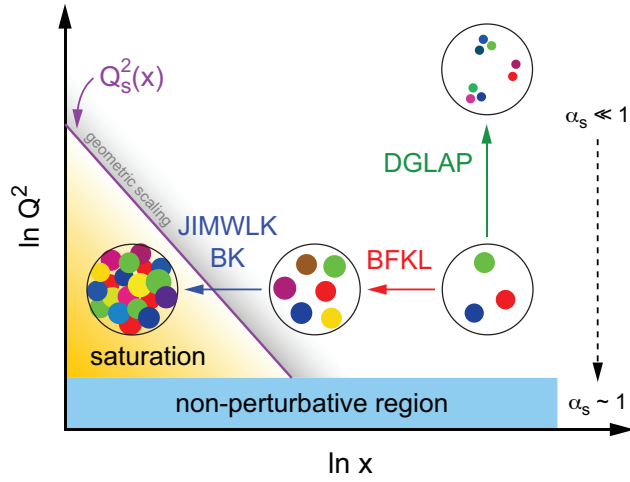


Figure 2-25: Saturation region in the  $(x, Q^2)$  plane.

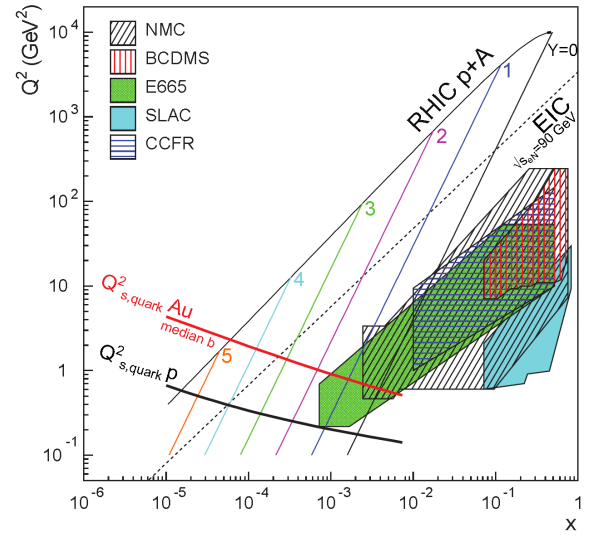


Figure 2-26: Kinematic coverage in the  $x-Q^2$  plane for p+A collisions at RHIC, along with previous e+A measurements, the kinematic reach of an electron-ion collider, and estimates for the saturation scale  $Q_s$  in Au nuclei and protons. Lines are illustrative of the range in  $x$  and  $Q^2$  covered with hadrons at various rapidities.

The saturation momentum is predicted to grow approximately like a power of energy,  $Q_s^2 \sim E^{\lambda/2}$  with  $\lambda \sim 0.2-0.3$ , as phase space for small- $x$  (quantum) evolution opens up. The saturation scale is also expected to grow in proportion to the valence charge density at the onset of small- $x$  quantum evolution. Hence, the saturation scale of a large nucleus should exceed that of a nucleon by a factor of  $A^{1/3} \sim 5$  (on average over impact parameters). RHIC is capable of running p+A collisions for different nuclei to check this dependence on the mass number. This avoids potential issues with dividing say p+Pb collisions in  $N_{part}$  classes [79]. Figure 2-26 shows the kinematic coverage in the  $x-Q^2$  plane for p+A collisions at RHIC, along with previous e+A measurements and the kinematic reach of an EIC. The saturation scale for an Au nucleus and the proton is also shown. To access at RHIC a kinematic regime sensitive to saturation with  $Q^2 > 1 \text{ GeV}^2$  requires measurements at forward rapidities. For this kinematics the saturation scale is moderate, on the order of a few  $\text{GeV}^2$ , so measurements sensitive to the saturation scale are by necessity limited to semi-hard processes.

To date the golden channel at RHIC to observe strong hints of saturation has been the angular dependence of two-particle correlations, because it is an essential tool for testing the underlying QCD dynamics [80]. In forward-forward correlations facing the  $p(d)$  beam direction one selects a large- $x$  parton in the  $p(d)$  interacting with a low- $x$  parton in the nucleus. For  $x < 0.01$  the low- $x$  parton will be back-scattered in the direction of the large- $x$  parton. Due to the abundance of gluons at small  $x$ , the backwards-scattered partons are dominantly gluons, while the large- $x$  partons from the  $p(d)$  are dominantly quarks. The measurements of di-hadron correlations by STAR and PHENIX [81,82] have been compared with theoretical expectations using the CGC framework based on a fixed saturation scale  $Q_s$  and considering valence quarks in the deuteron scattering off low- $x$  gluons in the nucleus with impact parameter  $b = 0$  [83,84]. Alternative calculations [85], that include both initial and final state multiple scattering (which determine the strength of this transverse momentum imbalance) and in which the suppression of the cross-section in d+Au collisions arises from cold nuclear matter energy loss and coherent power corrections, have also been very successful in describing the data.

The 2015 p+Au run at RHIC has provided unique opportunities to study this channel in more detail at STAR. The high delivered integrated luminosities ( $0.45 \text{ pb}^{-1}$ ) allow one to vary both



the trigger and associated particle  $p_T$  from 1 GeV to 4 GeV, thereby crossing the saturation boundary as shown in Figure 2-26 and reestablishing the correlations for central p+Au collisions for forward-forward  $\pi^0$ 's. In 2015 STAR took not only p+Au collisions for this channel, but also p+Al collisions with an integrated luminosity of  $1 \text{ pb}^{-1}$ . This provides for the first time the opportunity to test also the A-dependence of the saturations scale as predicted by models.

Studying di-hadron correlations in p+A collisions instead of d+A collisions has a further advantage. In reference [86], the authors point out that the contributions from double-parton interactions to the cross-sections for  $d+A \rightarrow \pi^0\pi^0X$  are not negligible. This mechanism is illustrated in Figure 2-27.

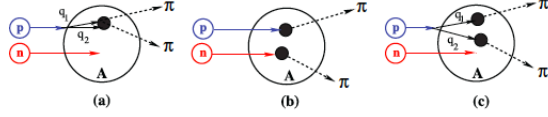


Figure 2-27: Contributions to two-pion production in d+A collisions through the double-interaction mechanism [86].

They find that such contributions become important at large forward rapidities, and especially in the case of d+A scattering. Whether or not this mechanism provides an alternative explanation of the suppression of the away-side peak in  $\pi^0$ - $\pi^0$  can be settled with the 2015 p+A data.

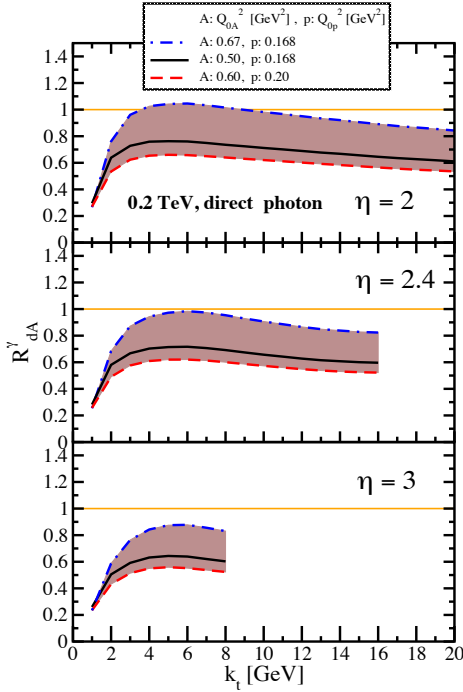


Figure 2-28: Nuclear modification factor for direct photon production in p(d)A collisions at various rapidities at RHIC  $\sqrt{s} = 0.2 \text{ TeV}$ . The curves are the results obtained from Eq. (12) in Ref. [87] and the solution to rcBK equation using different initial saturation scales for a proton  $Q_{op}$  and a nucleus  $Q_{oA}$ . The band shows our theoretical uncertainties arising from allowing a variation of the initial saturation scale of the nucleus in a range consistent with previous studies of DIS structure functions as well as particle production in minimum-bias p+p, p+A and A+A collisions in the CGC formalism, see Ref. [87] for details.

It is very important to note that for the measurements to date in p(d)+A collisions both initial and final states interact strongly, leading to severe complications in the theoretical treatment (see [88, 89] and references therein). As described in detail in the Section above in p+A collisions, removing the strong interaction from the final state, by using photons and Drell-Yan electrons, can ameliorate these complications. The Run-2015 p+A run will for the first time (see Figure 2-17) provide data on  $R_{pA}$  for direct photons and therefore allow one to test CGC based predictions on this observable as depicted in Figure 2-28 (taken from Ref. [87]). The higher delivered integrated luminosity for the upcoming p+Au and p+Al run in 2023 together with the proposed forward upgrade will enable one to study more luminosity hungry processes and/or complementary probes to the di-hadron correlations, i.e. photon-jet, photon-hadron and di-jet correlations.

We use direct photon plus jet (direct  $\gamma$ +jet) events as an example channel to indicate what can be done in 2023. These events are dominantly produced through the gluon Compton scattering process,  $g+q \rightarrow \gamma+q$ , and are sensitive to the gluon densities of the nucleon and nuclei in p+p and p+A collisions. Through measurements of the azimuthal correlations in p+A collisions for direct  $\gamma$ +jet production, one can study gluon saturation phenomena at small-x. Unlike di-jet production that is governed by both the Weizsäcker-Williams and dipole gluon densities, direct  $\gamma$ +jet production only accesses the dipole gluon density, which is better understood theoretically [87,90]. On the other hand, direct  $\gamma$ +jet production is experimentally more challenging due to its small cross-section and large background contribution from di-jet events in which photons from fragmentation or hadron decay could be misidentified as direct photons. The feasibility to perform direct  $\gamma$ +jet measurements with the proposed forward upgrade in unpolarized p+p and p+Au collisions at  $\sqrt{s_{NN}}=200$  GeV has been studied. PYTHIA-8.189 [91] was used to produce direct  $\gamma$ +jet and di-jet events. In order to suppress the di-jet background, the leading photon and jet are required to be balanced in transverse momentum,  $|\phi^\gamma - \phi^{jet}| > 2\pi/3$  and  $0.5 < p_T^\gamma/p_T^{jet} < 2$ . Both the photon and jet have to be in the forward acceptance  $1.3 < \eta < 4.0$  with  $p_T > 3.2$  GeV/c in 200 GeV p+p collisions. The photon needs to be isolated from other particle activities by requiring the fraction of electromagnetic energy deposition in the cone of  $\Delta R=0.1$  around the photon is more than 95% of that in the cone of  $\Delta R=0.5$ . Jets are reconstructed by an anti- $k_T$  algorithm with  $\Delta R=0.5$ . After applying these selection cuts, the signal-to-background ratio is around 3:1 [92]. The expected number of selected direct  $\gamma$ +jet events is around 1.0M/0.9M at  $\sqrt{s_{NN}}=200$  GeV in p+Au/p+Al collisions for the proposed run in 2023. We conclude that a measurement of direct photon-hadron correlation from p+A collisions is feasible, which is sensitive to the gluon density in  $0.001 < x < 0.005$  in the Au nucleus (see Figure 2-29) where parton saturation is expected.

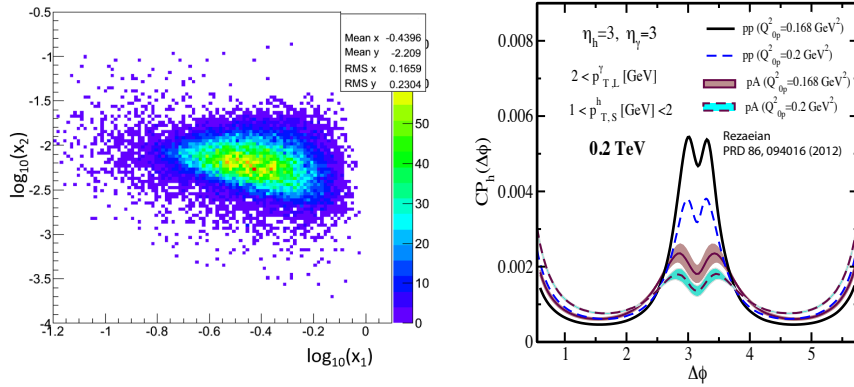


Figure 2-29: Left: Bjorken- $x$  distributions of hard scattering partons in direct  $\gamma$ +jet production after event selections described in the text in p+p collisions at  $\sqrt{s}=200$ . Right:  $\gamma$ -hadron azimuthal correlation in minimum bias p+p and p+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. The curves are obtained with two different initial saturation scale of proton  $Q_{0p}^2=0.168$  and  $0.2$  GeV<sup>2</sup> and the corresponding initial saturation scale in the nucleus within  $Q_{0A}^2 \sim 3-4Q_{0p}^2$  (c.f. [87,90]).

### Summary of the pp and pA measurements:

In Table 2-1 summarizes the pp and pA the scientific goals and measurements critical to reach these goals as discussed in the prior chapters. In addition the needed integrated luminosity as well as the detector components of the forward upgrade critical for the observable are listed.

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2023	p <sup>†</sup> p @ 200	300 pb <sup>-1</sup> 8 weeks	Subprocess driving the large $A_N$ at high $x_F$ and $\eta$	$A_N$ for charged hadrons and flavor enhanced jets	Forward instrum. ECal+HCal+Tracking
	2023	p <sup>†</sup> Au @ 200	1.8 pb <sup>-1</sup> 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions  Clear signatures for Saturation	$R_{pAu}$ direct photons and DY  Dihadrons, $\gamma$ -jet, h-jet, diffraction	Forward instrum. ECal+Hcal+Tracking
	2023	p <sup>†</sup> Al @ 200	12.6 pb <sup>-1</sup> 8 weeks	A-dependence of nPDF,  A-dependence for Saturation	$R_{pAl}$ : direct photons and DY  Dihadrons, $\gamma$ -jet, h-jet, diffraction	Forward instrum. ECal+HCal+Tracking
Potential future running	2021	p <sup>†</sup> p @ 510	1.1 fb <sup>-1</sup> 10 weeks	TMDs at low and high $x$	$A_{UT}$ for Collins observables, i.e. hadron in jet modulations at $\eta > 1$	Forward instrum. ECal+HCal+Tracking
	2021	$\vec{p}\vec{p}$ @ 510	1.1 fb <sup>-1</sup> 10 weeks	$\Delta g(x)$ at small $x$	$A_{LL}$ for jets, di-jets, h/ $\gamma$ -jets at $\eta > 1$	Forward instrum. ECal+HCal

Table 2-1: Summary of the pp and pA measurements as planned in the years 2021 and 2023. The most right column summarizes, which detector of the forward upgrade is essential for the measurement.

## 2.5 Ridge in p+p, p+A and A+A

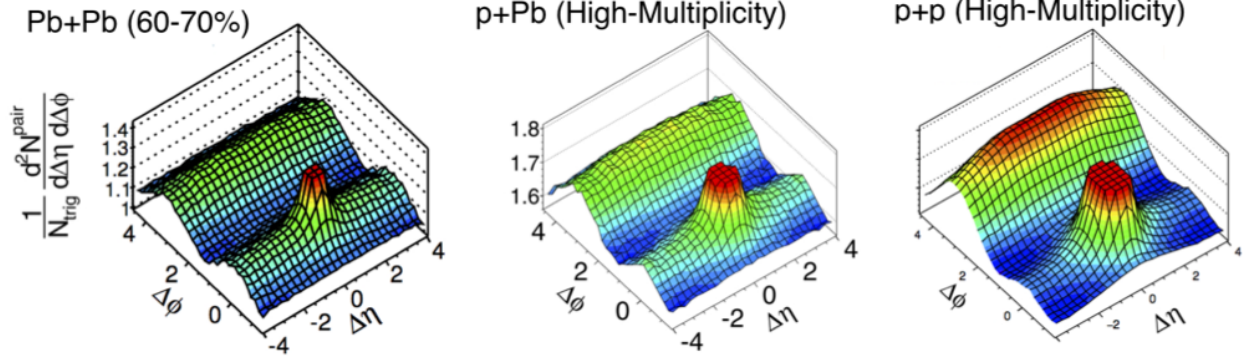


Figure 2-30: Long-range ridge structure observed in the di-hadron correlations measured in relative pseudorapidity and azimuthal angle in peripheral Pb+Pb and high multiplicity p+Pb and p+p collisions [93,94,95,96]

In heavy-ion (A+A) collisions the QCD matter formed immediately after the collisions undergoes a pre-equilibrium evolution and eventually evolves to a phase describable by viscous hydrodynamics. The most convincing evidence of such a scenario has been the long-range two-dimensional (2D) di-hadron correlation functions (per-trigger-particle associated yield distribution) expressed in terms of relative pseudorapidity ( $\Delta\eta$ ) and azimuthal angle ( $\Delta\phi$ ) of the emitted particles as shown in the left panel of Figure 2-30 (left). Such correlations include two major components, the di-jet and the ridge. The back-to-back di-jet correlations give rise to a narrow near-side peak at ( $\Delta\eta=0$ ,  $\Delta\phi=0$ ) but can extend over the entire  $\Delta\eta$  range on the away side  $\Delta\phi \sim \pi$  whereas the long-range ridge-like correlations can persist up to large  $\Delta\eta$  on both near and away sides. The ridge-like correlations are attributed to nearly boost-invariant (longitudinally invariant) hydrodynamic response of initial-state spatial anisotropy created at the early stages of collisions.

For years, collisions of small systems, such as hadronic (p+p) and light-heavy-ion (p/d/He<sup>3</sup>+A), have been providing baselines for measurements in A+A collisions. Such consensus has been strongly challenged by the recent striking observation of the long-range ridge like structure in the high multiplicity events in p+p and p+Pb collisions as shown in Figure 2-30 (middle and right).

An outstanding question is: does the same underlying mechanism drive these long-range correlations in all collision systems shown in Figure 2-30? The applicability of hydrodynamics is often debated in small collision systems particularly due to lack of evidences that can support the formation of a nearly equilibrated system. However, it has also been recently argued that criteria such as thermalization or isotropizations are not necessary for the applications of hydrodynamics [97]. Therefore, hydrodynamics can be a correct approach to describe small collision systems in principle down to the size of QCD matter of about 0.15 fm [97]. Several hydrodynamic calculations have successfully described many aspects of the experimental results in the small system collisions [98].

The alternative approaches are based on gluon saturation or Color Glass Condensate (CGC) that indicates intrinsic initial-state momentum space correlations of partons that survive the process of hadronization can lead to ridge-like structure of di-hadron correlations [99]. Many such predictions based on gluon saturation have been verified at LHC indicating small- $x$  dynamics playing an important role in the multi-particle production at high energies. In the CGC picture, the energy dependence of ridge-like correlations is determined by BK/JIMWLK evolution equations of non-linear QCD. In the saturation regime, CGC predicts an energy independent scaling of the

strength of ridge-like correlations when measurements are performed for events with fixed multiplicity [99]. Measurement of ridge correlations over a wide range of energy will be essential to test such predictions. A systematic breaking of such scaling will be essential to probe the regime of multi-particle production dominated by non-linear small- $x$  dynamics of QCD. Along with the existing LHC data, high multiplicity p+p and p+A collisions at RHIC provide unique opportunities in this context. Since RHIC kinematics are very different from those at the LHC, a measurement of the ridge-like correlations in p+A collisions at RHIC would provide direct access to the distribution of gluons inside hadrons at lower energies (large- $x$ ).

Measurements at RHIC can also provide a decisive test to distinguish whether the long-range correlations in small systems is due hydrodynamic response to the initial-state spatial correlations or due to the intrinsic momentum space correlations developed in the saturated wave functions of the colliding systems is still pending. An interesting approach taken so far at RHIC was to study various small collision systems such as p+Au, d+Au and  $^3\text{He}+\text{Au}$  [100]. Comparisons with hydrodynamic calculations have confirmed the expectations based on initial shapes of such collision systems [101]. It is however remain to be seen if initial-state models can also explain such data.

Earlier measurements of long-range ridge-like correlations at RHIC have previously been performed via di-hadron correlations, with an attempt to subtract the elliptic-flow and jet contributions from the region around  $\Delta\phi \sim 0$ , and designating the remaining yield as ridge [102]. However such measurements have been limited to light-heavy-ion collisions, low-statistics data sets and most importantly over a very narrow window of pseudorapidity  $|\Delta\eta| < 2$ . The planned forward upgrade of STAR will increase the capability of measurement of di-hadron correlations over a wide range of  $\Delta\eta$  and with high statistics (providing more high-multiplicity events). For example, a measurement of correlations between the detected particles in the forward rapidity with the charged particles from mid-rapidity, with a large  $\Delta\eta$  gap will be ideal for investigating the physics of the ridge at RHIC energies. Along with providing direct access to non-linear dynamics of QCD, in certain window of kinematics, such measurements might enable us to distinguish between final-state effects such as hydrodynamic response to initial geometry and intrinsic initial-state effects such as momentum-space correlations due to gluon saturation.

## 2.6 Correlation Measurements to Characterize Hot and Dense Nuclear Matter

One of the primary goals of the forward upgrade program of STAR is to explore the longitudinal structure of the initial-state and the temperature-dependent transport properties of the matter in relativistic heavy-ion collisions (HICs). The most conventional measurement in this context is the transverse momentum-dependent two-particle correlation function in relative azimuthal angle and pseudorapidity  $C(\Delta\eta, \Delta\phi)$ . The current acceptance of the STAR detector ( $-1 < \eta < 1$ ) limits the window of such a measurement to  $|\Delta\eta| < 2$  ( $|\Delta\eta| < 3.4$ , with the iTPC upgrade). The proposed forward upgrade of STAR with the FTS (FCS) detector, providing an additional with acceptance of  $-4.2 < \eta < -2.5$ ,  $p_T(E_T)$  information, and enhanced rate capabilities, will enable high-statistics measurements of long-range correlations  $C(\Delta\eta, \Delta\phi)$  up to  $\Delta\eta \sim 5.2$  ( $\Delta\eta \sim 5.9$  with the iTPC). Figure 2-31 demonstrates how the STAR forward upgrade with the FTS (FCS) will extend the two-particle phase space (in terms of  $\eta_1$  and  $\eta_2$ ) by about a factor of 6.5.

The importance of the measurements of long-range correlations can be understood as follows. As demonstrated in Figure 2-32 due to causality, correlations developed at different times over the evolution of a heavy-ion collision will spread to different ranges of space-time rapidities. In an approximately boost-invariant scenario, such correlations will appear at different values of the two-particle rapidity difference ( $\Delta\eta$  or  $\Delta y$ ). Correlations that span a wide range in rapidity are thus dominated by the early-time dynamics of the collision, although there is considerable “thermal

blurring” [103]. The goal of the forward upgrade is thus to measure such long-range correlations to explore the initial states of both A+A and light-ion+A collisions.

In the subsequent stages of evolution, fluid-dynamic response of the system converts the initial-state spatial correlations to long-range momentum-space correlations. Therefore, measurements of such long-range correlations can also provide ways to study the transport properties of such fluid-dynamical evolution. As we argue in the following section, the combination of STAR’s wide acceptance and the versatility of RHIC provides a unique opportunity to explore the rich dynamics that drives the early stages of collisions as well as the subsequent stages of evolution via measurements of long-range correlations over a wide range of energy and for varying collision systems.

In particular, the STAR forward upgrade will address the following two major topics:

- Constraining the longitudinal structure of the initial stages of HICs
- Constraining the temperature dependence of transport coefficients of the matter formed in HICs

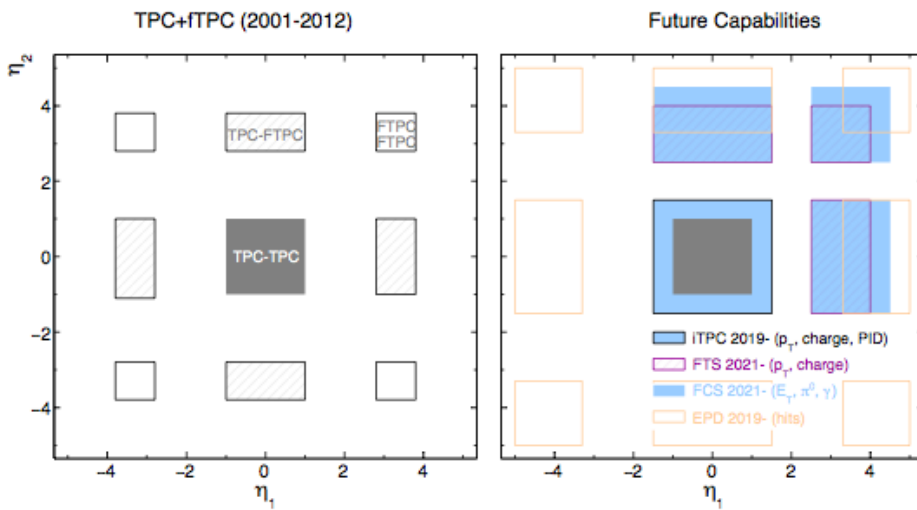


Figure 2-31: (left panel) The pseudorapidity coverage (area in the  $\eta_1 \times \eta_2$  space) of the STAR detector prior to the removal of FTPC in 2012. (right panel) The projected  $\eta_1 \times \eta_2$  acceptance after the iTPC and the forward upgrade shown can be quantified as  $|\Delta\eta|^2$ . One finds,  $|\Delta\eta|^2$  (past, before 2012) =  $(2+1.5 \times 2)^2 = 25$ ,  $|\Delta\eta|^2$  (current, 2012-17) =  $(2)^2 = 4$ ,  $|\Delta\eta|^2$  (with forward upgrade) =  $(2+1.7)^2 = 13.7$ ,  $|\Delta\eta|^2$  (with iTPC & forward upgrade) = 26.

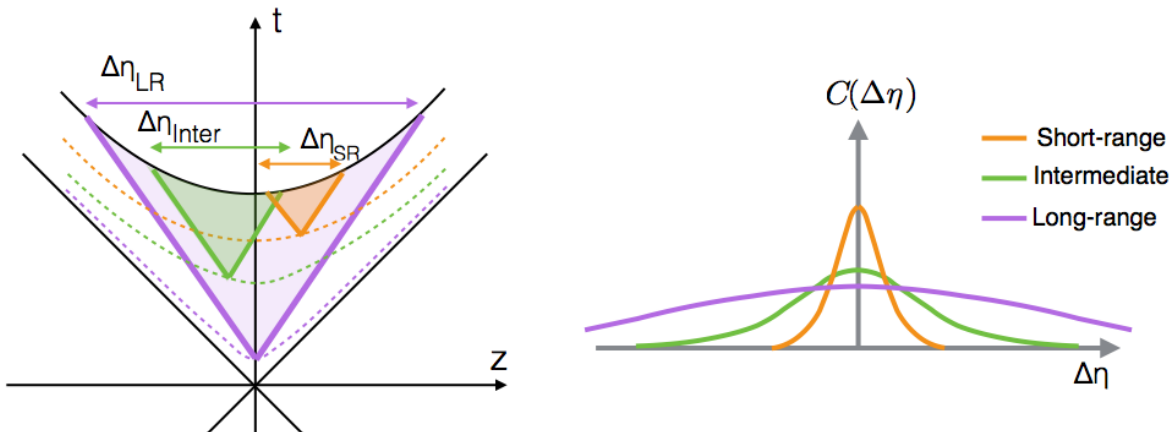


Figure 2-32: An illustration (inspired by Ref [104]) of the time evolution of correlations spreading over different windows of  $\Delta\eta$  in a heavy-ion collision (left). An illustration of correlations  $C(\Delta\eta)$  of various widths that are expected to be observed in experiment (right). Causality precludes correlations from later stages from growing as wide as those from earlier stages. This illustrates that a detector with a wide window

of acceptance can access physics throughout the entire window of evolution of HICs.

In addition, the forward upgrade will also enable studies of jets, underlying correlations, event-shape engineering [105], removal of the background for the chiral magnetic effect [106], etc. Also, in the case of light+heavy-ion collisions, the current upgrade will provide the opportunity to pin down the origin of initial-state and final-state interactions.

### 2.6.1 A more precise estimation of flow through measurements of long-range correlations

So far, long-range correlations at RHIC have been analyzed through the measurement of a ridge-like structure along  $\Delta\eta$  (at  $\Delta\phi\sim 0$ ) of the di-hadron correlation function  $C(\Delta\eta, \Delta\phi)$ . As we have discussed in the previous chapter, in HICs such correlations are a consequence of initial-state geometric fluctuations and nearly boost-invariant fluid-dynamic evolution. In particular for the transverse-momentum range of  $p_T < 3$  GeV, the long-range ridge-like correlations in HICs are dominantly driven by anisotropic flow. The strength of the long-range azimuthal ridge-like correlations are often characterized by the Fourier coefficients  $V_{n\Delta}$  (which can be related to the single-particle azimuthal anisotropy harmonics  $v_n$ ) obtained after the harmonic decomposition of the di-hadron correlation functions integrated over  $\Delta\eta$ . As shown in Figure 2-31 (right), since at small  $\Delta\eta$  different sources of short-range and intermediate-range correlations (e.g. HBT, Coulomb, Jet-Fragmentation, thermal fluctuations etc.) dominate the  $\Delta\eta$  dependence of the correlation function  $C(\Delta\eta)$ , a precise extraction of  $V_{n\Delta}$  can only be possible by measurements over a wider range of rapidity.

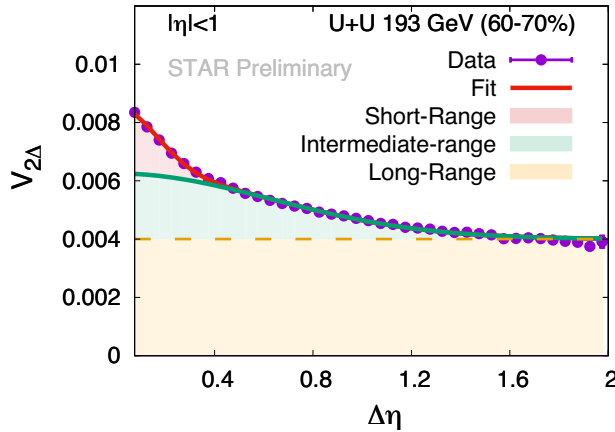


Figure 2-33: The STAR measurement of the relative pseudorapidity ( $\Delta\eta$ ) dependence of the second order Fourier harmonic coefficient  $V_{2\Delta}$  of two-particle azimuthal correlations at mid-rapidity in 193 GeV U+U collisions. The measurement over the limited window of  $|\eta| < 1$  indicates that the long-range flow driven component of  $V_{2\Delta}$  has contamination from short-range non-flow contributions. The proposed upgrade of STAR will extend the window of  $\Delta\eta$ , allowing for improved removal of non-flow correlations and thus a more precise estimation of the flow-driven component of  $V_{2\Delta}$ .

Figure 2-33 shows the STAR preliminary measurement of  $V_{2\Delta}$  in a window of  $|\Delta\eta| < 2$  at mid-rapidity using the Time Projection Chamber ( $|\eta| < 1$ ). Double Gaussian fits indicate the presence of both a short-range (red shading) and an intermediate-range (green shading) correlation. These contributions are effectively backgrounds to the long-range flow-driven components of  $V_{2\Delta}$  which are shown with the yellow shading below the dashed line in Figure 2-33. These backgrounds arise from non-flow contributions in the late stages of the collisions. It is only for the largest (presently accessible) values of  $\Delta\eta$  do these backgrounds disappear. This clearly demonstrates the importance of increasing the longitudinal acceptance of the STAR detector, so that short-range non-flow correlations can be efficiently removed for precise extraction of  $V_{n\Delta}$ . Thus, the precision measurement of  $V_{n\Delta}$  will lead to : 1) better constraints on the initial stages of HICs 2) more precise estimations of transport parameters such as  $\eta/s$  involved in the fluid-dynamic evolution of the subsequent phases of HICs [107,108,109]. Such measurements are of highest priority for the ongoing and the upcoming physics program at RHIC because the matter formed in HICs is expected

to have its smallest  $\eta/s$  value near the transition region ( $T=T_c$ ) from strongly correlated Quark Gluon Plasma (sQGP) to hadronic phase.

RHIC collisions spend relatively more time in that region of minimum  $\eta/s$  and are therefore best suited for studying the most perfect liquid known in nature as compared to collisions at LHC energies. Several recent theoretical estimates demonstrate that RHIC provides the best constraint on  $\eta/s$  at  $T_c$  [107,108,109]. The importance of the ‘‘Characterization of liquid QGP’’ through more precise measurements of its transport parameters (and its temperature dependence) has been mentioned as one of the future goals in the 2015 Long-range Plan for Nuclear Science (LRPNS) [110].

## 2.6.2 Constraining longitudinal structure of the Initial stages of Heavy Ion Collisions

Significant theoretical and experimental efforts have been made in recent times to understand the fluctuating structure of the initial stages of HICs. Although our knowledge of transverse (perpendicular to the collision axis) density fluctuations has improved over the years, the longitudinal structure of the initial-state has remained largely unexplored. One of the main challenges to model the longitudinal structure of HICs is the lack of experimental constraints. The goal of the STAR forward upgrade project is to provide precision measurements that will inspire studies of the breaking of longitudinal invariance (boost-invariance) and full 3D fluid-dynamic modeling of HICs. The proposed upgrade will teach us: 1) if the effective theories of QCD predict the correct rapidity dependence of the initial state, 2) about the mechanism of baryon stopping and, 3) potentially about the early-time non-equilibrium dynamics that lead to thermalization and formation of the sQGP. Understanding the longitudinal structure of the initial-state is also relevant for a better interpretation of the quantities like flow harmonics  $V_{n\Delta}$  that are sensitive to the transverse structure of the initial state.

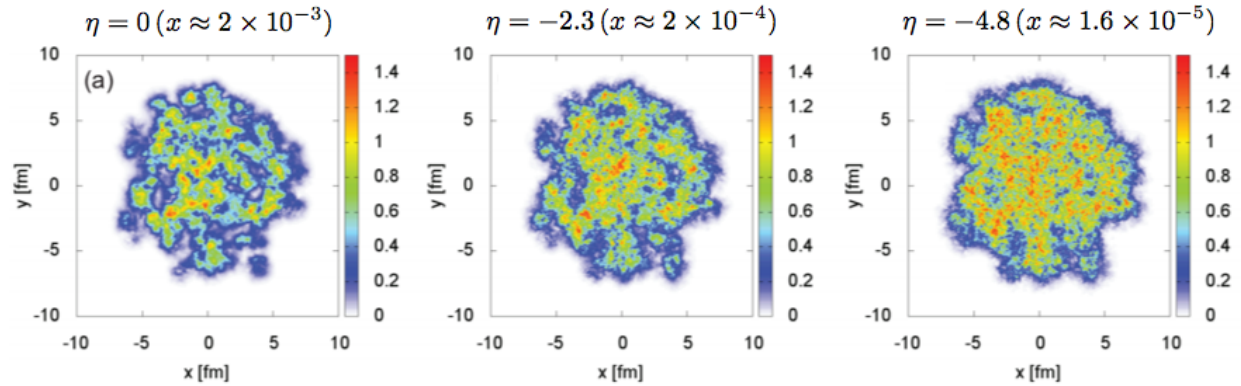


Figure 2-34: Obtained from Ref [111] showing rapidity (Bjorken  $x \sim \langle p_T \rangle \exp(-y)/\sqrt{s}$ ,  $y \sim \eta$ ) evolution of the gluon fields in the transverse plane (perpendicular to the beam axis) inside colliding nuclei obtained by 3D-Glasma model calculations. The three frames show how the length scale of fluctuations vary due to rapidity evolution of the parton densities when going from mid-rapidity to forward rapidity at RHIC. This will lead to the breaking of boost-invariance of the initial conditions, which, can only be probed by measurements at forward rapidities. While 3D-Glasma has been constrained at the LHC, future measurements at RHIC will provide crucial tests for the underlying QCD evolution equation that predicts the rapidity evolution of gluon densities inside the colliding nuclei.

Figure 2-34 shows the theoretical calculation from the 3D-Glasma model of the initial conditions [111], indicating, that the characteristic transverse length scale over which gluon distributions are correlated inside a nucleus changes with the evolution in Bjorken- $x$ . The



corresponding (pseudo) rapidity values at RHIC are also shown. Such an evolution of the gluon density will determine the structure of the transverse energy-density at different pseudorapidities, eventually leading to the breaking of longitudinal invariance. This can only be probed by measurements over a wider range of pseudorapidity. In that context, a large number of observables have been identified that go beyond the conventional measurements of flow harmonics  $V_{n\Delta}$  to better quantify the 3D structure of HICs [112,113,114,115,116,117,118,119,120].

For example, the  $a_{mn}$  coefficients of the Legendre polynomial decomposition of the two-particle rapidity correlation function, the three particle correlator  $C_{m,n,m+n}(\eta_a, \eta_b)$ , the  $r_n(\eta_a, \eta_b)$  variables etc., which we discuss in the following section, are ideal observables for studying the longitudinal structure of the HICs. Current measurements of some of these observables at RHIC are available for a narrow window of  $\Delta\eta$  from STAR. The forward upgrade will allow us to perform measurements over wider  $\Delta\eta$  and with greater precision. This will be necessary to confirm predictions from saturation models such as the 3D-Glasma. This model has been constrained at the LHC, but measurements at RHIC will provide crucial tests for the underlying QCD evolution equation that predicts rapidity dependence of the initial state. It must be noted that, even with the measurements of these observables, in HICs it is challenging to directly constrain the longitudinal structure of the initial-state though data-model comparisons without sophisticated modeling of the subsequent sQGP and hadronic phase.

It is worth noting the uniqueness of RHIC for explorations of the longitudinal structure of HICs. Since the beam rapidity at RHIC is smaller than that at the LHC, one expects stronger variations of the initial geometry, fluctuations, energy density, temperature, baryon density, etc., over a relatively smaller window of acceptance. In principle, at RHIC it is possible to build upgrades that reach near-beam rapidity; or even beyond for lower energies (as in the Beam-Energy-Scan program). In addition, the structure of the initial-state and its fluctuations at lower energies have not been well constrained. The proposed upgrade of STAR will help constrain models of initial conditions at lower energies [118], which is absolutely necessary for a successful dynamical modeling of heavy-ion collisions in the Beam-Energy-Scan program.

Along with a state-of-the-art modeling of initial-state geometry and fluctuations by including longitudinal dynamics, a complete modeling of HICs must also include a full treatment of 3+1 dimensional viscous hydrodynamics evolution, and, (ideally) transport of the hadronic phase. Due to the large number of unknown parameters involved in such simulations, uncertainties remain in full 3+1 dimensional modeling of HICs. It turns out that one needs to go beyond the conventional measurement of flow harmonics and find new observables to constrain such models. As mentioned previously, recent combined explorations from both theory and experiment have produced several promising tools for studying longitudinal correlations in HICs [112-120].

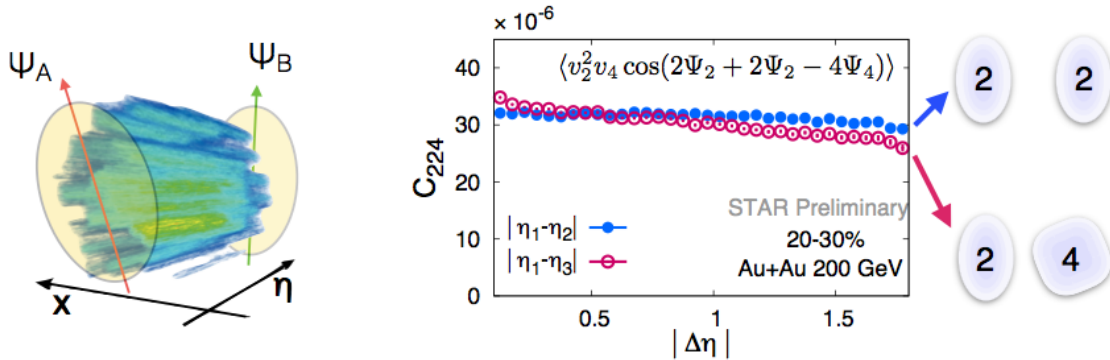


Figure 2-35: (left) A cartoon inspired by Ref [111] showing the deceleration of the transverse geometry characterized by event-plane angles  $\Psi$  along the longitudinal (pseudorapidity) direction. (Right) Figure from Ref [112] showing the STAR measurement of such effects through relative pseudorapidity variation of the three-particle azimuthal correlator  $C_{2,2,4}(\eta_a, \eta_b)$ . Measurements for different harmonics are highlighted to the

right of the plot by cartoons of corresponding initial-state anisotropies.

The cartoon in Figure 2-35 demonstrates how the initial-state longitudinal fluctuations and fluid dynamical response of the medium formed in HICs can lead to decorrelations of the reaction planes  $\Psi_n(\eta)$  (which determines the orientation of the harmonic anisotropies) in different pseudorapidity regions. Such effects are often referred to as torque or twist of the event shape [113] and can be probed by measurements of mixed harmonic correlations of reaction planes as shown in the right frame of Figure 2-35. Such correlations have been measured in STAR [112] using the relative pseudorapidity dependence of the three-particle correlator  $C_{m,n,m+n}(\eta_a, \eta_b) = \langle \cos(m\varphi_1(\eta_a) + n\varphi_2(\eta_b) - (m+n)\varphi_3) \rangle$ . In the limited (currently available) acceptance at STAR, a small but significant decorrelation of the event planes is observed [112]. At lower energies such decorrelations are found to be stronger than at higher energies<sup>121</sup>. One also expects the effect of such a decorrelation to be more pronounced over a wider range of relative pseudorapidity. The proposed forward upgrade of STAR will explore the origin of such decorrelations in detail.

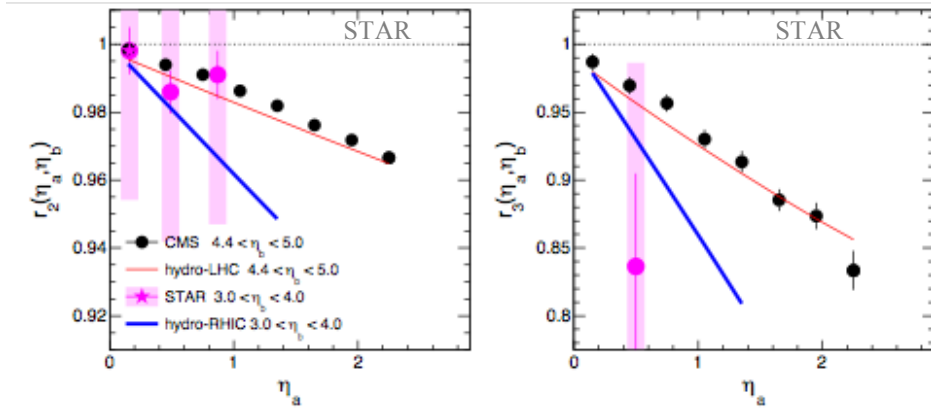


Figure 2-36: The decorrelation of the second  $v_2$  (left panel) and third  $v_3$  (right panel) harmonic anisotropies between  $\eta_a$  and  $\eta_a$  with the reference detector chosen at certain  $\eta_b$  ranges, measured by CMS (black circles) and STAR (magenta circles), and calculated with a hydrodynamic model for LHC (thin lines) and RHIC (thick lines) energies. The correlator  $r_n$  is calculated from the two-particle flow coefficients  $V_{n\Delta}$  as:  $r_n(\eta_a, \eta_b)$ . The model describes the CMS data and predicts a much stronger effect at RHIC even in the smaller  $\eta_a$  range. The large uncertainty of the STAR measurement is due to limitations in the available statistics and detector performance. The proposed forward upgrade of STAR is essential toward a precise measurement of  $r_n$ .

Another promising observable which measures the decorrelation of azimuthal anisotropies along pseudorapidity is the observable  $r_n(\eta_a, \eta_b) = V_{n\Delta}(-\eta_a, \eta_b) / V_{n\Delta}(\eta_a, \eta_b)$ , where  $V_{n\Delta}(\eta_a, \eta_b)$  is the Fourier coefficient calculated with pairs of particles taken from different pseudorapidity regions, as introduced in Ref [114]. Figure 2-36 shows the experimental measurement of this observable for two harmonics  $r_2(\eta_a, \eta_b)$  and  $r_3(\eta_a, \eta_b)$  by the CMS collaboration [114] and preliminary results from STAR with the existing data from the Forward Time Projection Chamber (a previously operational but presently dismantled subsystem). The results are compared to estimates from a 3+1D hydrodynamic simulation, which predicts a much stronger variation of  $r_n(\eta_a, \eta_b)$  with  $\eta$  at RHIC than at the LHC. The current precision of the STAR measurement cannot constrain the model due to large uncertainties. A similar, stronger longitudinal decorrelation effect was also demonstrated using the AMPT model (see Figure 2-37) [122], where the variation of the observable  $C_n(\Delta\eta) \sim \cos(n(\varphi(\eta_a) - \varphi(\eta_b)))$  with  $\Delta\eta = |\eta_a - \eta_b|$  was studied. Precise high-statistics measurements of the  $r_n(\eta_a, \eta_b)$  and the  $C_n(\Delta\eta)$  observables will be possible with the forward upgrade that will provide important insights about the longitudinal dynamics of HICs and help constrain 3D fluid dynamical modeling of HICs.

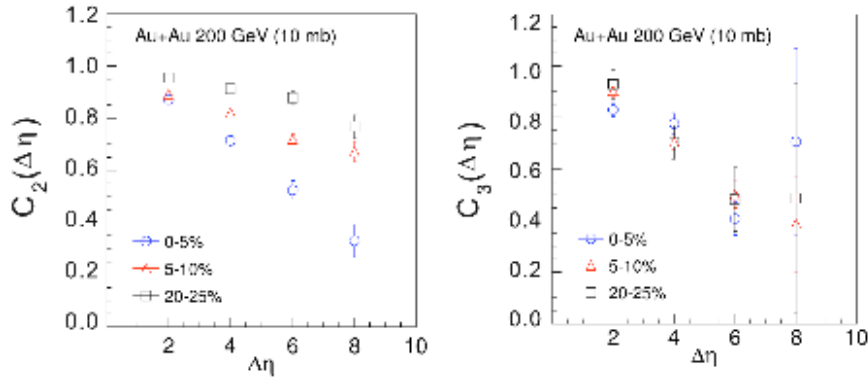


Figure 2-37: AMPT predictions of  $v_2$  and  $v_3$  de-correlation estimated in terms of the observable  $C_n(\Delta\eta)$  versus the pseudorapidity at RHIC with given parton cross-sections [122].  $C_n(\Delta\eta)$  directly probes the longitudinal structure of the HICs. The STAR forward upgrade will enable precise measurements of such observables and help constrain 3D modeling of HICs.

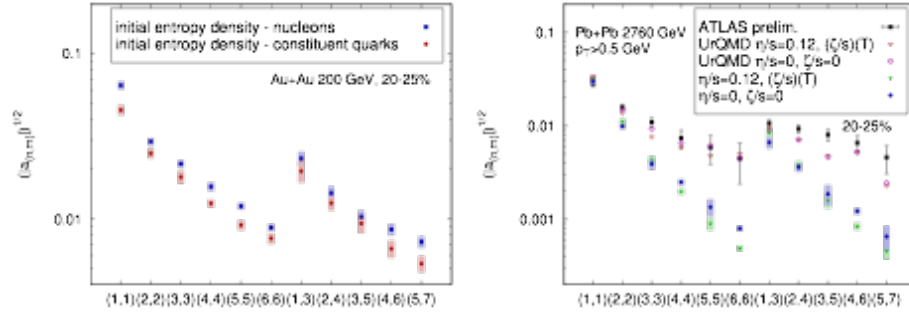


Figure 2-38: The  $amn$  coefficients obtained from the two-particle pseudorapidity correlation functions projected onto a basis set of Legendre polynomials [115,116,117] for different combinations of orders  $m$  and  $n$ . Model calculations [118] are done with a 3+1D viscous hydrodynamic simulation for RHIC (left panel) and the LHC (right panel). The model calculations shown in the right panel are compared to the LHC data, whereas the proposed forward upgrade will constrain the prediction shown in the left panel.

Observables like  $C_{m,n,m+n}(\eta_a, \eta_b)$  and  $r_n(\eta_a, \eta_b)$  are designed to study the longitudinal dependence of two-particle correlations decomposed in terms of Fourier coefficients. Recent studies have proposed a similar decomposition of the two-particle pseudorapidity correlations in the basis of Legendre polynomials [115,116]. Based on such decomposition, a new observable has been recently introduced by the ATLAS collaboration [117] to characterize the structure of the longitudinal fluctuation which is referred to as  $amn$  coefficients, for which the indices “ $m$ ” and “ $n$ ” correspond to different orders of Legendre polynomials. STAR results for these observables were reported at Quark Matter 2017 [123]. So far, measurements of  $amn$  done at the LHC have been compared to a recent 3+1D viscous hydrodynamic simulation in Ref [107, 118] as shown in Figure 2-38. The study has shown that the coefficients  $amn$  are not very sensitive to the transport properties of the sQGP. They are however sensitive to the initial-state longitudinal fluctuations and the hadronic re-scattering and decays at the final stages of the collisions. With the future forward upgrade, measurements of this observable at RHIC over a wider range of rapidity will provide insight about energy dependence of the longitudinal fluctuations, further constraining the initial-state models of HICs. Also since the effect of the hadronic phase is different at lower collision energies, the measurements at RHIC will allow ways to constrain the hadronic transport models (“afterburners”) used along with the 3D hydrodynamic models. Full 3D fluid-dynamical modeling is crucial for data-model comparisons and interpretations of several experimental results at RHIC. In particular, at the lower energies of the RHIC BES program, baseline predictions from 3D fluid-dynamical models are important in the search for the QCD critical point.

## Constraining the temperature dependence of the transport parameter $\eta/s(T)$

The QCD matter formed at RHIC shows nearly perfect fluidity characterized by the smallest viscosity to entropy ratio  $\eta/s$  known in nature. Although significant efforts from both theory and experiment have been dedicated towards the precise extraction of  $\eta/s$ , the temperature dependence of this transport parameter has not been fully constrained. A major goal of the STAR forward upgrade is to provide precision measurements to contain the temperature dependence of the transport parameters  $\eta/s(T)$  (and  $\zeta/s(T)$ ) of the matter formed in HICs.

Recently, hydrodynamic simulations have demonstrated that since the temperature of the produced fireball in HICs vary with the rapidity, the measurement of the rapidity dependence of flow harmonics has the potential to constrain  $\eta/s(T)$  and  $\zeta/s(T)$  [107]. The advantage of performing such measurements at RHIC over LHC is 1) the measurement can be more precise because, even at a single energy, the smaller beam rapidity at RHIC provides stronger variations of the temperature with rapidity, 2) measurements at RHIC can be done over a wide range of energy which, in addition to rapidity, provide an additional handle on temperature to map  $\eta/s(T)$ , and  $\zeta/s(T)$  over a wide range of temperature. In particular, the hydrodynamic simulation of Ref [109] indicates that  $\eta/s(T)$  at lower temperatures, near its possible minimum ( $T=T_c$ ), can be better constrained at RHIC.

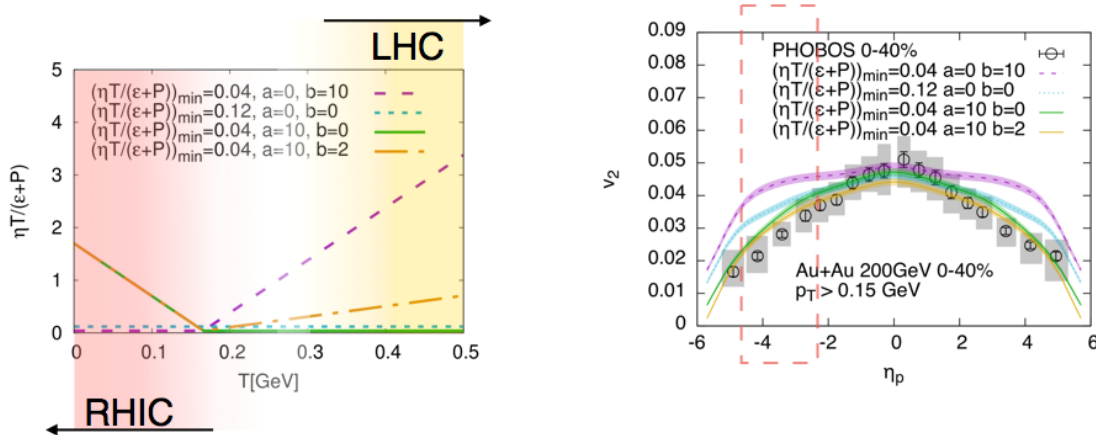


Figure 2-39: (left) Different parameterizations of temperature dependence of shear viscosity to entropy  $\eta/s$  (at zero chemical potential) used in the hydrodynamical simulation of Ref [107]. Interestingly, it has been demonstrated in Ref [109] that the region of lowest  $\eta/s$  is the one that can be probed at RHIC. (Right) Effects on the elliptic flow co-efficient  $v_2$  due to the different parameterizations of the viscosity parameter indicating better constraints on  $\eta/s(T)$  can only be performed by measurements at forward rapidities at RHIC. The red box shows the region of the proposed STAR upgrade. The interpretation of the PHOBOS results is limited by the large uncertainties.

Figure 2-39 shows the results of a very recent theoretical calculation using event-by-event 3+1D viscous relativistic hydrodynamic simulations from Ref [107]. In this simulation, a number of QCD-motivated parameterizations of the temperature dependence of the shear viscosity was assumed, as shown in Figure 2-39 (left). It was shown that a precise measurement of the pseudorapidity dependence of the flow harmonics is instrumental in discriminating such parameterizations. A comparison to the predictions from this study with the existing elliptic flow as a function of pseudorapidity,  $v_2(\eta)$ , data from RHIC is shown in Figure 2-39 (right). However, due to the large uncertainties and limited acceptance of the currently available measurements, only limited conclusions can be drawn on the temperature dependence of the transport parameters. The forward upgrade of STAR will provide precise estimation of  $v_2(\eta)$  and other higher-order flow coefficients  $v_n(\eta)$  that are essential in terms of constraining  $\eta/s(T)$  near its possible minimum.

### Additional studies using the proposed forward upgrade

The forward upgrade of STAR, with its wide acceptance and enhanced-rate capabilities, will be useful for many other measurements that are important towards understanding the properties of the hot and dense matter formed at RHIC. Along with the previously mentioned main interests, the forward upgrade program of STAR will also enable us to perform many more interesting studies such as:

- Event-shape engineering [124,125] and correlation between flow harmonics to test the non-linear hydrodynamic response.
- Data-driven subtraction of anisotropic-flow backgrounds in jet-correlations measurements.
- Background estimation to improve the presently observed signals of charge separation in the search for the Chiral Magnetic Effect [106].
- Independent estimation of centrality to remove auto-correlations in the study of higher moments of conserved-charge fluctuations in the search for the QCD critical point.

Physics Measurements		Longitudinal de-correlation $C_n(\Delta\eta)$ $r_n(\eta_a\eta_b)$	$\eta/s(T)$ , $\zeta/s(T)$	Mixed flow Harmonics $C_{m,n,m+n}$	Ridge	Event Shape and Jet-studies
Detectors	Acceptance					
Forward Calorimeter (FCS)	$-2.5 > \eta > -4.2 E_T$ (photons, hadrons)	One of these detectors necessary		One of these detectors necessary	Good to have	One of these detectors needed
Forward Tracking System (FTS)	$-2.5 > \eta > -4.2$ (charged particles)		Important		Important	

Table 2-2: Physics measurements in A+A collisions with the proposed forward upgrade and with other STAR upgrades that are relevant to those measurements.

In summary, the forward upgrade program of STAR will enable us to study the longitudinal structure of the initial-state that leads to the breaking of boost invariance in heavy-ion collisions and to explore of the transport properties of the hot and dense matter formed in heavy-ion collisions near the region of perfect fluidity. The measurements at forward rapidity at RHIC will provide crucial tests for the effective theories of high-energy QCD and its evolution equation, such as BK or JIMWLK [111], that predicts the rapidity dependence of the parton densities inside the colliding nuclei that leads to the fluctuating structure of the initial states in heavy-ion collisions.

Such studies will be essential for a smooth transition toward the physics program in e+A collisions at a future Electron Ion Collider (EIC). Understanding the longitudinal structure of the initial-state will lead to a better understanding of the early time non-equilibrium dynamics that leads to thermalization and the formation of the sQGP. Measurements at forward rapidities will also provide more insights about baryon stopping. In particular, the proposed upgrade program will help constrain full three-dimensional fluid-dynamical modeling of heavy-ion collisions. Such modeling will be essential to provide baseline predictions for the search for the QCD critical point. In addition, increasing the rapidity acceptance of STAR will allow for more precise measurements of anisotropic flow and its rapidity dependence. Building on the discovery of the perfect liquid, such measurements at RHIC will be crucial for mapping out the temperature-dependent transport properties that characterize such an extreme state of matter. A brief summary of the different heavy-ion physics topics, and the corresponding detector requirements for each, are listed in Table 2-2.

### 3 Forward Upgrade Overview and Simulation

#### 3.1 Forward Calorimeter System

The STAR forward upgrade is motivated to a large extent to explore QCD physics in the very high and low regions of Bjorken  $x$ . Previous STAR efforts using the FPD and FMS detectors, and the recently refurbished FMS and a new pre-shower and post-shower detector upgrade for Runs 2015-2017, have demonstrated that there are outstanding QCD physics opportunities in the forward region. In order to go beyond what STAR has/will achieve with the currently existing forward detector system, a forward detector upgrade with superior detection capability for neutral pions, photons, electrons, jets and leading hadrons covering a pseudo-rapidity region of 2.5-4 in the years beyond 2020 is proposed. The forward upgrade program of STAR will also enable to study the longitudinal structure of the initial state that leads to breaking of boost invariance in heavy ion collisions and explore of the transport properties of the hot and dense matter formed in heavy ion collisions near the region of perfect fluidity. Table 3-1 gives a summary of the detector requirements of the different components of the forward upgrade based on the discussed pp, pA and AA physics programs.

Detector	pp and pA	AA
ECal	$\sim 10\%/\sqrt{E}$	$\sim 20\%/\sqrt{E}$
HCal	$\sim 60\%/\sqrt{E}$	---
Tracking	charge separation photon suppression	$0.2 < p_T < 2 \text{ GeV}/c$ with 20-30% $1/p_T$

Table 3-1: Requirements of the different forward upgrade detector parts for the different physics programs summarized in Table 2-1 and Table 2-2.

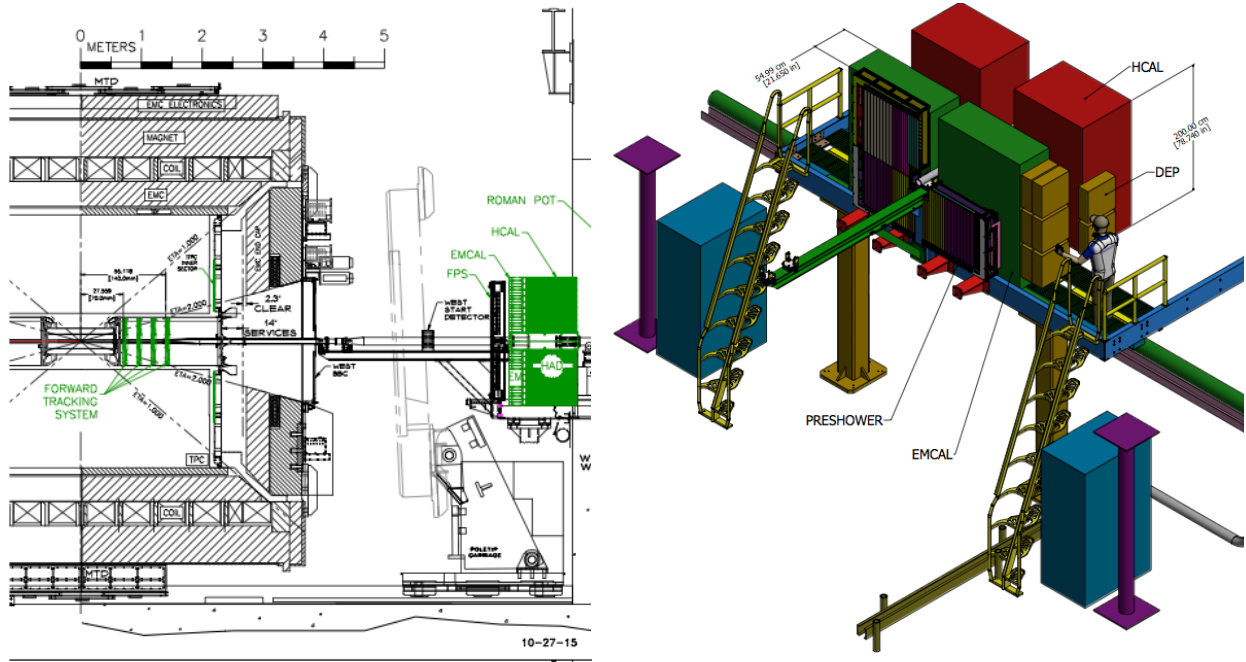


Figure 3-1: Location of the FCS at the West side of the STAR Detector system and a three-dimensional CAD model of the FCS in the STAR detector model.

The design of the FCS is a modification of the original proposed Forward Calorimeter System and is driven by required detector performance, integration into STAR and cost optimization.

Figure 3-1 shows the location of the proposed FCS at the West side of the STAR detector system and a schematic description of the FCS in the STAR three-dimensional CAD model. The original design of the FCS consisted of a Spaghetti ElectroMagnetic Calorimeter (SPACal) followed by a Lead and Scintillating Plate sampling Hadronic Calorimeter (HCal) with a tower size of  $10 \times 10 \times 81 \text{ cm}^3$  corresponding to 4-interaction length. The SPACal is made of Tungsten powder and scintillating fibers as such it has achieved one of the highest densities and among the most compact calorimeters [126]. The goal was to have a fully compensated calorimeter system. With the end of the PHENIX data-taking in 2016, the PHENIX ECal [127] became available. The PHENIX ECal has the required energy resolution and constitutes therefore a very cost-effective alternative. The only drawback is that the calorimeter system will not be fully compensated anymore. The read-out for the refurbished PHENIX ECal will be placed in the front so that there will be no significant dead gaps between the ECal and the HCal. Wavelength-shifting slats are used to collect light from the HCal scintillating plates to be detected by photon sensors at the end of the HCal. Both calorimeters will share the same cost-effective readout electronics and SiPMs and/or APDs as photo-sensors.

## 3.2 Forward Tracking System

In addition to the Forward Calorimeter System, a Forward Tracking System (FTS) is required for the STAR forward upgrade project. The FTS, aided by the STAR 0.5 T magnetic field, must discriminate the charge sign of tracks for transverse asymmetry studies, and those of dielectron pairs for Drell-Yan measurements. It needs to find primary vertices for tracks and point them towards the calorimeters in order to suppress pile-up events in the anticipated high luminosity collisions, or to select particles from Lambda decays. It should also help with electron and photon identification by providing momentum and track veto information. In studies of heavy ion collisions, it should be able to measure transverse momenta of charged particles in the range of  $0.2 < p_T < 2 \text{ GeV}/c$  with 20-30% momentum resolution. In order to keep multiple scattering and photon conversion background under control, the material budget of the FTS has to be small. These requirements present challenges for detector design in terms of position resolution, fast readout, high efficiency, and low material budget.

An obvious candidate is to use Silicon detectors. STAR has gained considerable experience in the technology from the Intermediate Silicon Tracker (IST) construction in recent years. Silicon detectors have also been widely used in other high-energy experiments for tracking in the forward direction. For example, Silicon strip detectors have been successfully used at the D0 experiment at the Tevatron, CMS and LHCb at the LHC, and PHENIX at RHIC. More recent designs incorporate hybrid Silicon pixel detectors, which resulted in the improvement of position resolutions and removal of ghost hits, but unfortunately also significantly increased the cost and material budget. According to detailed Monte Carlo simulations, charge sign discrimination and momentum resolution for the FTS in the STAR Solenoid magnet depends mostly on the phi resolution, and is insensitive to the radial position resolution. Therefore a Silicon mini-strip detector design would be more appropriate than a pixel design. We are evaluating a design that consists of four to six disks at  $z$  locations from about 60 to 180 cm. Each disk has wedges covering the full  $2\pi$  range in  $\phi$  and 2.5-4 in  $\eta$ . Each wedge will use Silicon mini-strip sensors to be read out from the outer radius of the sensors. Compared to the configuration of reading out from the edges along the radial direction, the material budget in the detector acceptance will be smaller since the frontend readout chips, power and signal buses and cooling lines can be placed outside of the detector acceptance.

STAR will continue to evaluate these technology options for the FTS design. Continued R&D efforts are pursued to demonstrate the technical feasibility of these options through detector prototyping and Monte Carlo simulations.

To reduce costs further STAR has also investigated a system combining 3 Silicon disks as described above combined with Small-strip Thin Gap Chamber (sTGC) wheels ala ATLAS [128,129]. The sTGC wheels would be placed 30 cm apart starting from  $z = 273$  cm. The first simulation results are shown in section 3.3.2.

### 3.3 Detector Simulations

The sections below report on a number of simulations, both standalone and in the STAR simulation framework, that have been performed for the proposed FCS and FTS.

#### 3.3.1 Silicon-based FTS detector simulations

Below we evaluate the FTS design with 4-6 disks with realistic MC geant simulations in the STAR framework. An FTS layout is shown in Figure 3-2, in which six FTS disks are placed 23.3 cm apart, with the first disk at  $z = 70$  cm. In the simulations, each FTS plane has 12 wedges covering  $2\pi$  in azimuthal angle  $\phi$  and 2.5-4 in pseudo-rapidity  $\eta$ . Each wedge has 128  $\phi$  times 8  $\eta$  Silicon Mini-strips.

The material budget per FTS disk is assumed to be 0.4-0.6%  $X_0$  with a thickness of about 300  $\mu\text{m}$ . With the HIJING simulation, the occupancy in the most central (head-on) Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV is estimated to be 5% (9%) at  $\eta = 2.5$  (4) for the first disk. For the fourth disk, the occupancy is 7% (13%) at  $\eta = 2.5$  (4). The higher occupancy for the disk further from the collision center is due to multiple scattering.

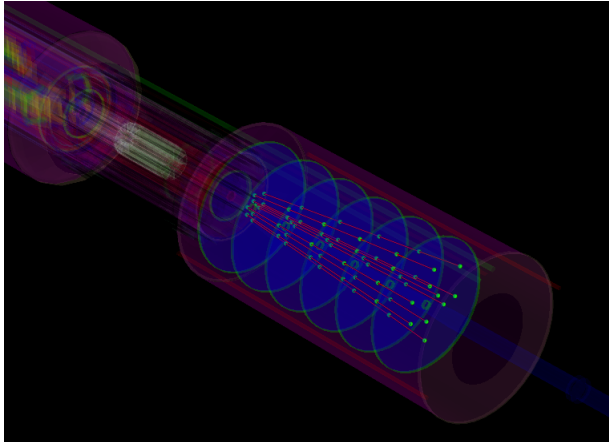


Figure 3-2: Layout of a Forward Tracking System consisting of six radially oriented Silicon Mini-strip planes located at  $z = 70, 93.33, 116.66, 140, 163.33,$  and  $186.66$  cm, respectively. Each of the planes includes 12 wedges, each with 128 strips in  $\phi$  at a fixed radius and 8 strips in the radial direction at a fixed  $\phi$  value

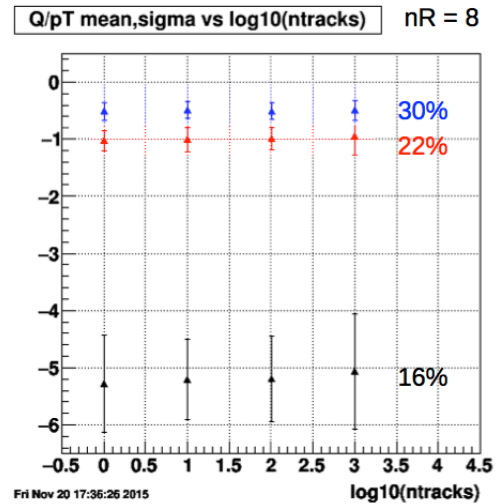


Figure 3-3: The reconstructed transverse momentum (the nominal value) and its standard deviation (the bar) for charged pions at  $p_T=0.2$  (black), 1 (red), and 2 GeV/c (blue) for 4 different track densities of 1, 10, 100, and 1000 per event.



The FTS geometry described above has been fully integrated into the STAR production simulation and reconstruction chains. A fast simulator digitizes the GEANT hits, segmenting the detector in radius and azimuth as described above. Hits are placed at the geometric center of the detector segment, and multiple hits on a segment are merged. The digitized hits are made available in the STAR event data model to the Stv forward tracking code. Track finding in the Stv tracker is based on the follow-your-nose seed finder utilized in STAR production tracking for over a decade. After seeds consisting of at least four hits are found, a Kalman filter is used to extend tracks to include the vertex, which we presume we will know with 50  $\mu\text{m}$  uncertainty, and through the rest of the detector to pick up remaining hits. A Kalman smoother is then used to extract the final fit parameters. In the following, we examine the tracker performance over a range of  $p_T$  and under different track densities required for physics cases. We input negatively charged pions in the simulation with uniform azimuthal angle and pseudo-rapidity distributions in the range  $2.5 < \eta < 4.0$ . Three transverse momenta (0.2, 1 and 2 GeV/c) and four track densities (1, 10, 100, and 1000 per event) have been investigated.

Figure 3-3 shows the reconstructed transverse momentum (nominal value) and its standard deviation (the bar) for charged pions at  $p_T = 0.2, 1, \text{ and } 2 \text{ GeV}/c$  for four track densities: 1, 10, 100, and 1000. The  $1/p_T$  resolution has no strong track density dependence and is 16%, 22%, and 30% for  $p_T = 0.2, 1, \text{ and } 2 \text{ GeV}/c$ , respectively.

We also find that the track-finding efficiency for the primary tracks (the tracks generated at the collision point) is about 80-90% when the track density is below 100 per event, but drops significantly for high density events. In addition, we increased the radial segmentation from 8 to 16, 32, and 64 and found no significant improvement on the momentum resolution or tracking efficiency.

Decreasing the number of disks would reduce the cost of the tracker significantly. We have therefore evaluated two other configurations, one with four disks and the other with five. For each configuration, instead of positioning each disk center at (0,0) in the transverse plane, we add additional offsets to the disk centers as shown in Figure 3-4, and rotate the disk by  $360/n_{\text{disk}}$  degrees, where  $n_{\text{disk}}$  is 4, 5, or 6 for the three cases.

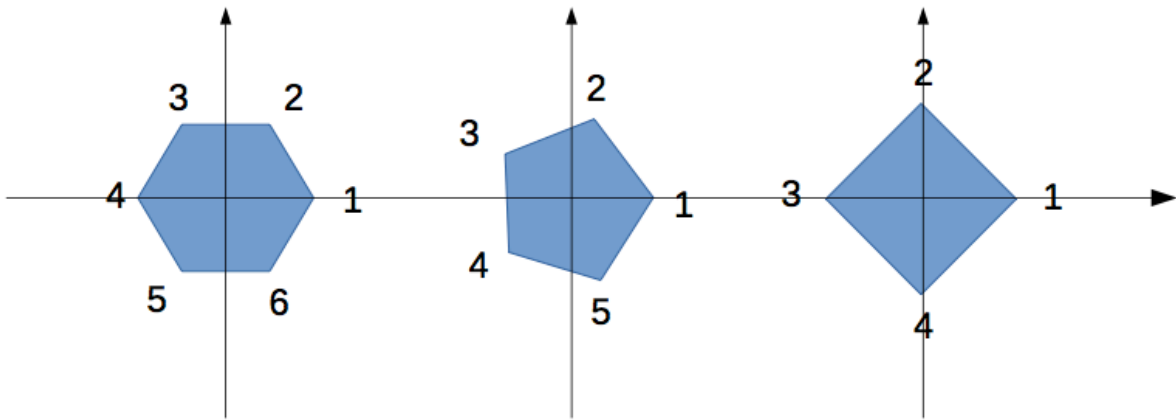


Figure 3-4: The offsets for each disk center in the transverse plane for 6-disk, 5-disk, and 4-disk configuration cases. For each configuration, every disk center is offset differently by 1 mm radially.

Figure 3-5 shows the performances of the 4-disk and 5-disk cases compared to the 6-disk case. We find that the momentum resolution does not change when we reduce the disk number from 6 to 4. However, the efficiency is reduced from 95% to 80%, even for events in which the track density is below 100.

We also find that adding 1 mm radial offsets (see Fig. 3-4) to each disk center significantly improves the tracking, by removing degeneracies in the fits. It also enables us to reconstruct tracks with  $p_T$  as large as 3 GeV/c with 1 sigma charge sign separation. We note that the sagittas for tracks of  $p_T = 2$  GeV/c at  $\eta = 2.5$  are 125  $\mu\text{m}$ , 500  $\mu\text{m}$ , and 889  $\mu\text{m}$  at disks 1, 4, and 6, respectively, while the sagittas for tracks of  $p_T = 2$  GeV/c at  $\eta = 4$  are 6  $\mu\text{m}$ , 25  $\mu\text{m}$ , and 44  $\mu\text{m}$  at disks 1, 4, and 6, respectively. For the latter set, the sagittas to be measure are less than the azimuthal width of the proposed detector elements. With ideal alignment, one would get either all hits at the same phi location, in which case the circle (helix) model fails; or else discs 1 through N see one phi location, and discs N+1 through 6 see the next phi location, causing an overestimate of the curvature, and an underestimate of  $p_T$ . Intentionally misaligning the disks slightly (Fig. 3-4) obscures this effect.

**To summarize**, we have evaluated the silicon-based forward tracking system performance. We find that with 4 to 6 disks, the forward tracking system can provide momentum measurements for charged particles in the range of  $0.2 < p_T < 2$  GeV/c with 20-30%  $1/p_T$  resolution. We note that the 4-disk configuration will reduce the tracking efficiency quite significantly, from 95% to 80%. We also find that the tracking efficiency will decrease in a high-density event, where further optimizations are clearly needed. Considering that 4 hits is the minimum required for the tracking, and that an imperfect detector acceptance is always the case in reality, a 5-to-6-disk configuration is at least needed to meet the requirements for the physics proposed here.

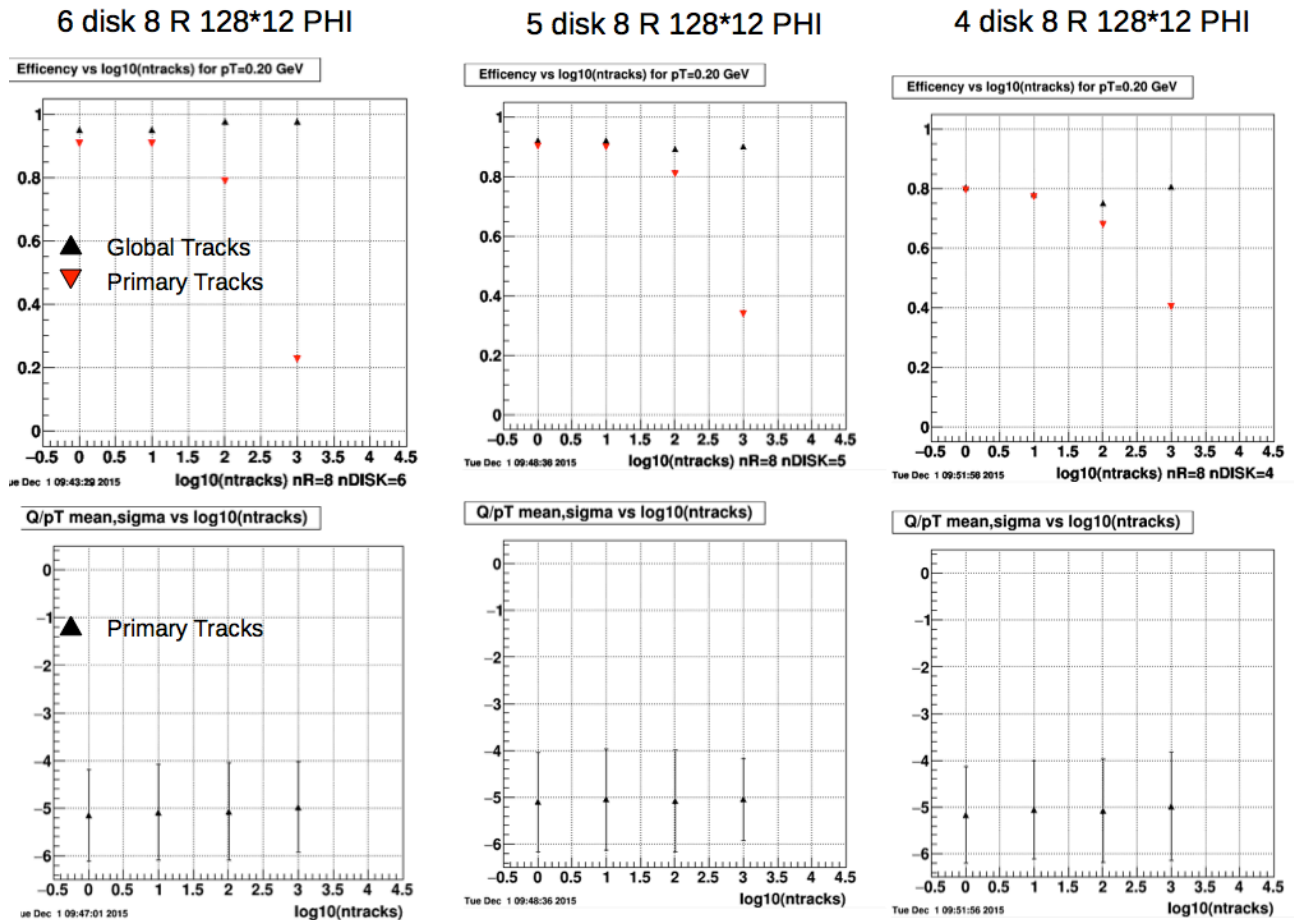


Figure 3-5: The track finding efficiency for primary and global tracks (top panels), and the momentum resolution (bar of the data points in bottom panels) for negatively charged pions at  $p_T = 0.2$  GeV/c as a function of track density per event.

An alternate simulation study, based on the EICROOT framework, has also been performed to investigate the performance of the proposed FTS. The study uses a full geometrical modeling of the existing STAR detector, as well as the FTS, in GEANT4. Tracks are generated either with flat distributions in  $p_T$ ,  $\eta$  and  $\phi$ , or according to the distribution from the Hijing generator. The track finder and fitter are based on offline reconstruction codes developed by the HERMES and OLYMPUS experiments. Technical details are provided in the following:

Track finder: global “tree search” in  $\{q, \phi, 1/p\}$  parameter space (assuming vertex is  $\sim$ known); individual-hit-to-parameter-space Hough transform; embedded Kalman-filter-based ambiguity resolution logic. Track fitter: Kalman filter node chain of variable length (multiple hits per plane possible, etc); material effects included (multiple scattering for hadrons as a process noise model); fixed-location linearized Runge-Kutta track propagation in the magnetic field; automatic iterative outlier hit rejection based on the smoother  $c^2$  (optional); specifically tuned for forward spectrometer geometries. Configurations with 6 disks have been studied extensively with the disks located at  $z = 62.0, 83.3, 106.7, 140.0, 163.3,$  and  $186.6$  cm (see Figure 3-6).

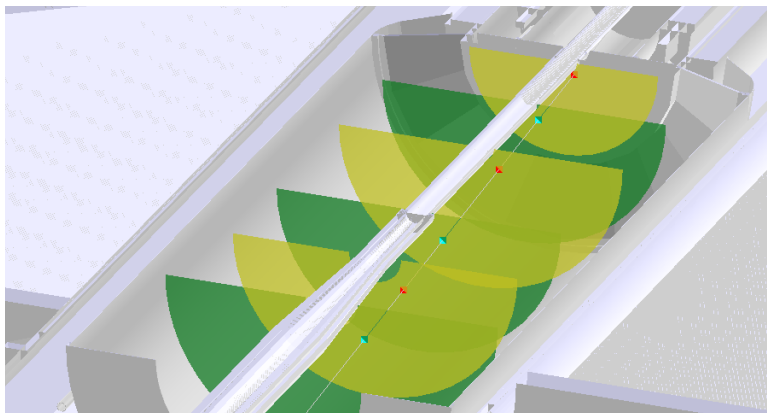


Figure 3-6: Forward Tracking System and other components of the STAR experiment in the forward direction. Also shown is the trajectory of a charge pion and the associated hits on the FTS disks.

The configurations include:

- A. Disks of Silicon pixel sensors with a thickness of 0.2 mm and pitch size of 20\*20 microns;
- B. Disks of Silicon ministrip sensors with a thickness of 0.4 mm and 128\*12 strips in phi at any given radius, and each strip has a 1 cm<sup>1</sup> length along the radius direction;
- C. Same as B, but the number of strips is 128\*12\*2 in phi at any given radius.

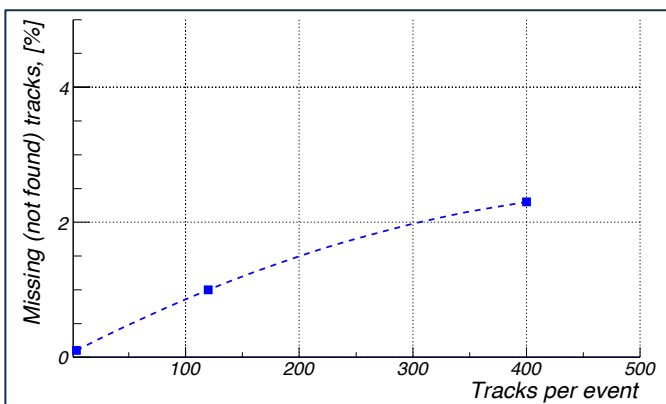


Figure 3-7: Track finding inefficiency as a function of number of tracks per event in  $2.5 < \eta < 4$ . The track kinematic distributions are based on Hijing simulation.

<sup>1</sup> Due to a limitation in the version of EICROOT that was used in this study, only strips with

The results of the simulation can be summarized as the following:

- Track finding efficiency is well above 90% (see Figure 3-7).
- Transverse momentum resolution for  $p_T < 2$  GeV/c is better than 20%, 10% and 5% for  $\theta = 3, 5,$  and  $8$  degrees<sup>2</sup>, respectively, for configuration A. There is no strong bias in the reconstructed  $p_T$  (see Figure 3-8).
- Transverse momentum resolution for  $p_T < 2$  GeV/c is better than 50%, 40% and 25% for  $\theta = 3, 5,$  and  $8$  degrees, respectively, for configurations B and C. The bias is as large as 20% at 3 degrees, and is less than 5% at 5 and 8 degree (see Figure 3-9).
- There is no obvious improvement in configuration C compared to B (see Figure 3-10).

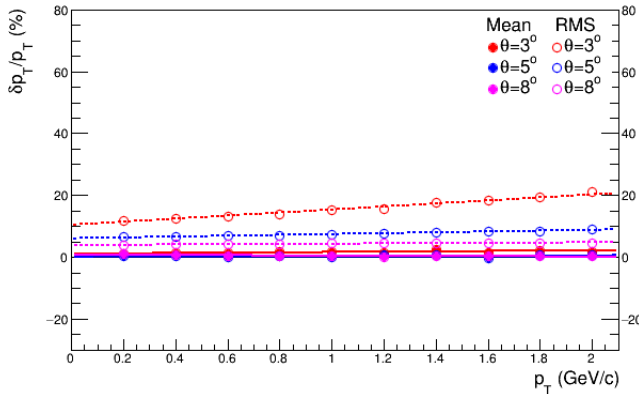


Figure 3-8: Mean and RMS of reconstructed transverse momentum distribution as a function of generated transverse momentum for configuration A.

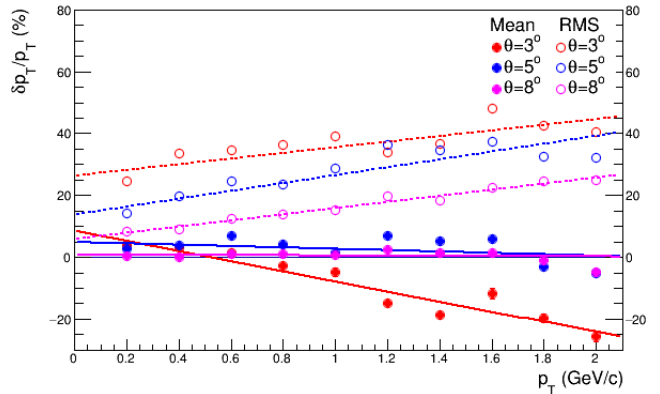


Figure 3-9: Mean and RMS of reconstructed transverse momentum distribution as a function of generated transverse momentum for configuration B.

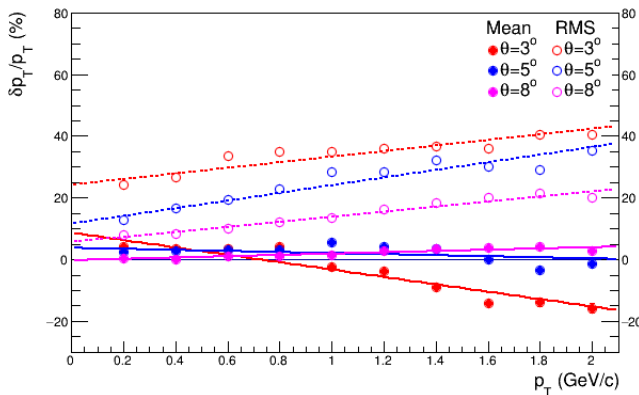


Figure 3-10: Mean and RMS of reconstructed transverse momentum distribution as a function of generated transverse momentum for configuration C.

### 3.3.2 Silicon-based and Small-Strip Thin Gap Chamber FTS detector simulations

Simulations of a FTS comprised of three Si disks and four small-strip thin gap chambers (sTGC) were performed in the STAR software framework. The overall simulation followed closely the silicon only simulation described before. Particles were thrown uniformly over the acceptance of the detector, in order to estimate the detector performance for various hit densities and various levels of segmentation. For this study, the Si disks were segmented into 12 sectors, each containing 128 divisions in phi and 8 divisions in radius. The sTGC wheels were divided into 8 octants, 54 cm tall. Each octant was subdivided into three phi-columns, with 6 cm tall pads. Each pad was further subdivided into strips, which measure the local-x ( $\sim$ radial) and local-y ( $\sim$ phi) coordinates. The width of the strips was tuned to approximate the resolution anticipated from the ATLAS test-beam

<sup>2</sup>  $\theta = 3, 5,$  or  $8$  degrees corresponds to  $\eta = 2.660, 3.131,$  or  $3.643,$  respectively.

measurements. The Si disks were placed at  $z = 93.33, 140, \text{ and } 186.66$  cm. The sTGC wheels were placed at  $z = 273, 303, 333 \text{ and } 363$  cm. Figure 3-11 shows the layout of the 7 detector planes, and the resulting hit densities at 1000 tracks/event (which is significantly higher than what we expect in central AuAu collisions at RHIC).

The simulated events were reconstructed by the Stv tracker – a Kalman-filter tracker using a follow-your-nose seed finder. The tracker is permitted to reuse hits during track finding, but must uniquely assign hits to tracks before track fitting. Shared hits are assigned to the best track, based on length and chi-squared. Tracks with fewer than 4 hits are eliminated. We will present results from these initial tracking studies. **In summary**, it can be said that the performance of this configuration with 3 Si disks and 4 sTGC wheels, in terms of efficiency and charge-sign discrimination, equals the performance of the Si-only configuration up to 1000 tracks/event.

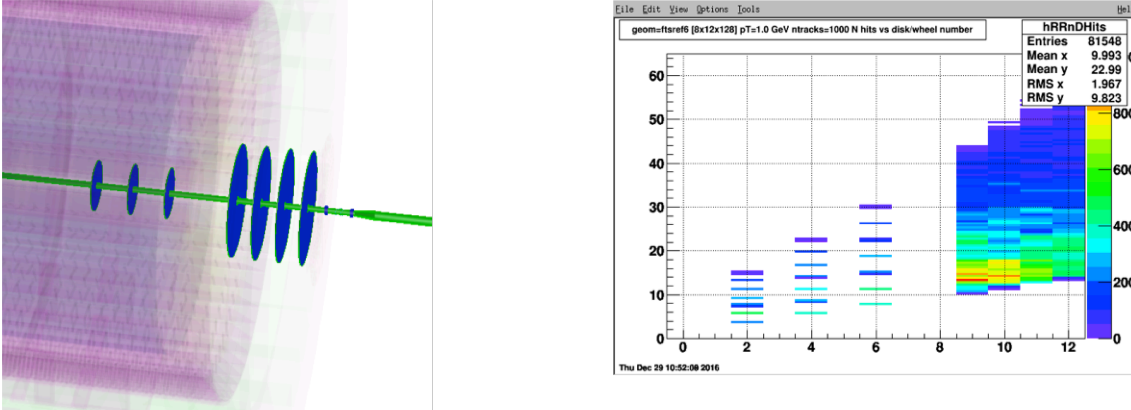


Figure 3-11: The implementation of the different tracking layers along  $z$  into STAR (left) and the hit density per tracking layer for tracks with  $p_T = 1$  GeV/c and a total track density of 1000 tracks.

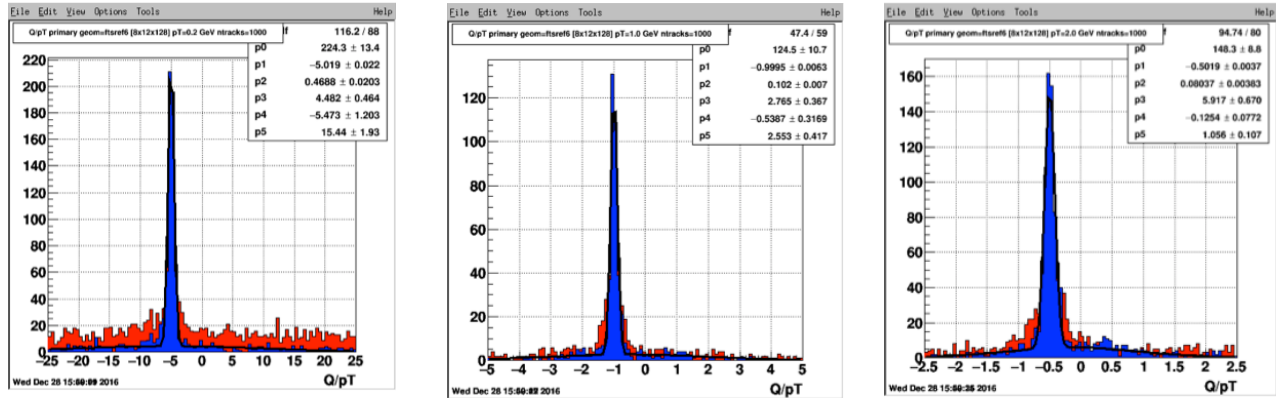


Figure 3-12: The ratio of  $Q/p_T$  for a track density of 1000 tracks in the rapidity range  $2.5 < \eta < 4$  with a  $p_T$  of 0.2, 1.0, and 2.0 GeV/c. The fake global tracks are represented by the red histogram and correctly reconstructed primary tracks by the blue histogram.

Figure 3-12 shows the reconstructed  $Q/p_T$  distributions for global tracks (red histogram) and primary tracks (blue histogram) for 0.2, 1.0 and 2.0 GeV muons, for 1000 muons/event. The charge of both global and primary tracks can be cleanly identified, although at low  $p_T$  inclusion of the primary vertex in the fit becomes important. The dependence of the tracking performance on the track density (logarithm of the number of tracks/event) is shown in Figure 3-13, with the dashed lines in the efficiency plot indicating an estimate of the wrong-sign contamination. For up to 100 tracks/event, the tracking efficiency is good (>80%), with adequate tracking efficiency out to  $\sim 300$  tracks/event. Optimizing the positions of the detector planes can increase efficiency further, albeit

at a trade-off for charge-sign discrimination. Figure 3-14 shows comparable performance for both electrons and pions, instead of muons.

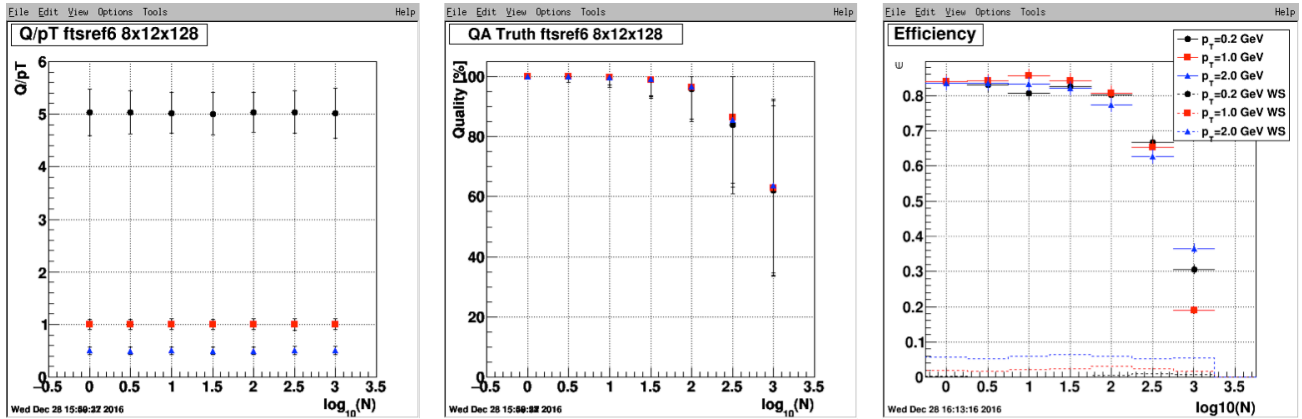


Figure 3-13:  $Q/p_T$ , the track reconstruction quality, and the tracking efficiency as function of the track density in the rapidity range  $2.5 < \eta < 4$  for muons with  $p_T$  of 0.2 GeV/c (black), 1 GeV/c (red) and 2 GeV/c (blue). The dashed histograms in the tracking efficiency plot represent the wrong sign yield.

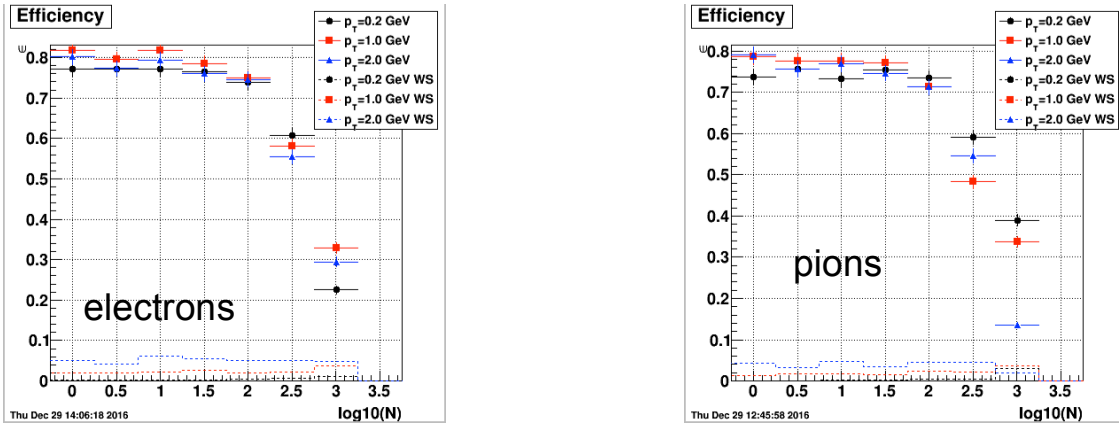


Figure 3-14: The tracking efficiency as function of the track density in the rapidity range  $2.5 < \eta < 4$  for electrons and pions with  $p_T$  of 0.2 GeV/c (black), 1 GeV/c (red) and 2 GeV/c (blue). The dashed histograms in the tracking efficiency plot represent the wrong sign yield.

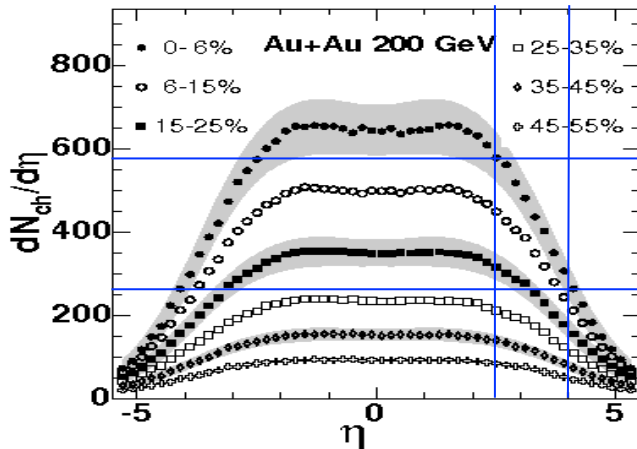


Figure 3-15: The track density / event measured by PHOBOS. The density drops quickly from 600 to 250 tracks for the most central events in the rapidity range  $2.5 < \eta < 4$ .

We have demonstrated that the tracking performance of the Silicon and sTGC combined setup is comparable to the all-Si design, and can achieve efficiencies of 80% out to 100 tracks/event and above 65% at 300 tracks/event. This level of performance easily satisfies the requirements from both the proton and HIC physics. Figure 3-15 shows the track density measured by PHOBOS. In the most central collisions, it falls rapidly from 600 tracks/event at  $\eta = 2.5$  to 250 tracks/event at  $\eta = 4.0$ .

## 3.4 Physics Simulations

The measurements of jets and of Drell-Yan production processes are of key importance to the science of the proposed FCS and FTS. These topics are discussed below in sections 3.4.1 and 3.4.2. Section 3.4.3 describes two of the key measurements that are enabled by the FCS and FTS, and quantifies the anticipated measurement precision.

### 3.4.1 Jet measurements

We have studied how in single- and di-jet events, the jet pseudorapidity  $\eta$  and  $p_T$  are related to the underlying partonic variables  $x_1$  and  $x_2$ . We also studied the matching between reconstructed jets and scattered partons, and the resolutions with which the parton axis can be reconstructed from the reconstructed detector jets. The latter is important to understand, in order to evaluate how well azimuthal asymmetries around the outgoing parton axis will be reconstructed by looking at asymmetries of reconstructed particles around the reconstructed jet axis.

For this study we used 500k events simulated with Pythia Tune A at  $\sqrt{s} = 500$  GeV and a minimum partonic  $p_T$  (CKIN3) of 3 GeV. We then used a fast simulation of the detector resolutions of the STAR barrel and the forward upgrade. For the purpose of this study we assumed a tracking detector with three planes at distances from the interaction point of 70 cm, 105 cm and 140 cm. Each plane is comprised of 1.2% radiation lengths of material with resolutions in the azimuthal direction between 0.11 and 0.85 mm/ $\sqrt{12}$ . Furthermore, we simulated a detector subsystem combining hadronic and electromagnetic calorimeters (FCS) with  $0.58/\sqrt{E}$  hadronic resolution and an electromagnetic resolution of  $0.11/\sqrt{E}$ . In this setup, except for those tracks with very low energy, the track momentum is reconstructed in the FCS and the tracking is used mainly for charge discrimination. Jets were reconstructed with an anti- $k_T$  algorithm with a radius  $R$  of 0.7. An association between reconstructed jets and scattered partons is defined to be a distance in  $\eta$ - $\phi$  space of less than 0.5. In the following, we refer to reconstructed jets as “detector jets” and jets found using stable, final state particles as “particle jets.” The outgoing partons in the event are determined by using the corresponding entries in the Pythia record, so there is no partonic jet finding.

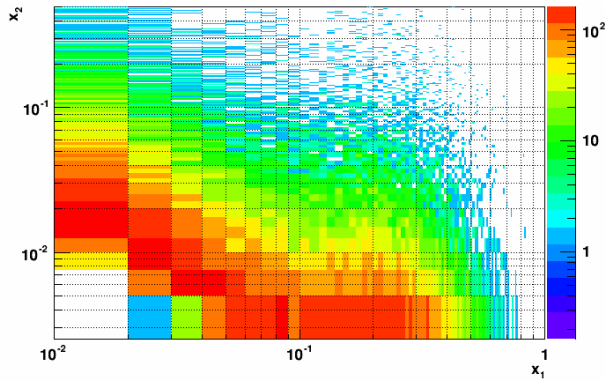


Figure 3-16: Distribution of the partonic variables  $x_1$  and  $x_2$  for events with a jet with  $p_T > 3$  GeV/ $c$  and  $2.8 < \eta < 3.5$ .  $x_1$  values of around 0.6 can be reached whereas  $x_2$  goes as low as  $7 \times 10^{-3}$ .

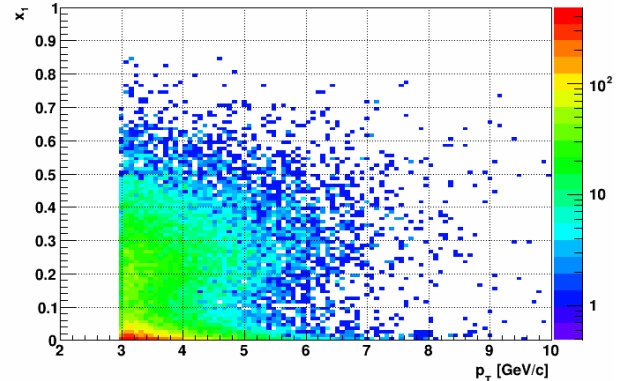


Figure 3-17:  $x_1$  versus jet  $p_T$ . As expected, there is a correlation between the  $x$  accessed and the  $p_T$  of the jet. However, there is an underlying band of low  $x_1$  values. This can be improved by further restricting the  $\eta$  range of the jet. Here,  $2.8 < \eta < 3.8$ .



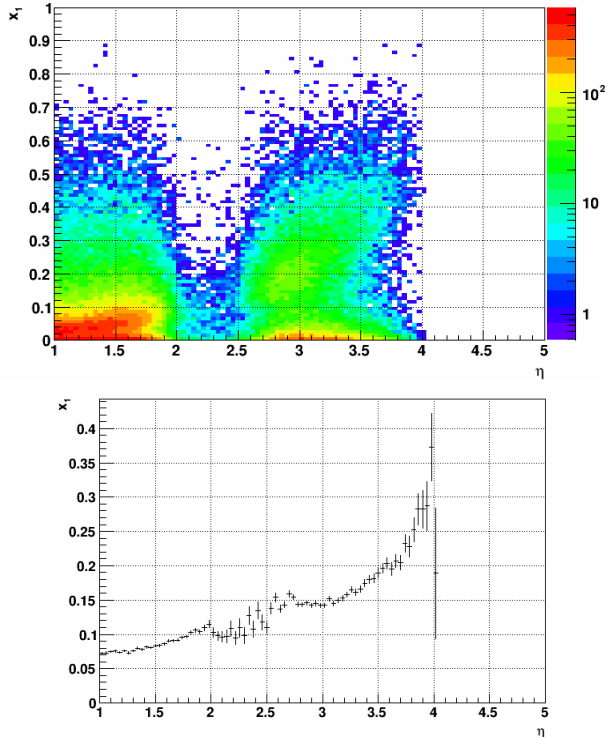


Figure 3-18:  $x_1$  vs jet  $\eta$ . The upper figure shows a 2D histogram and the lower figure the profile plot. A minimum jet  $p_T$  of 3 GeV/c was required. One can see that the events are split into two bands. One exhibits a strong correlation with  $\eta$ , whereas the other is flat at low  $x_1$ . With the forward upgrade  $x_1$ -values between 0.15 and 0.3 are accessible.

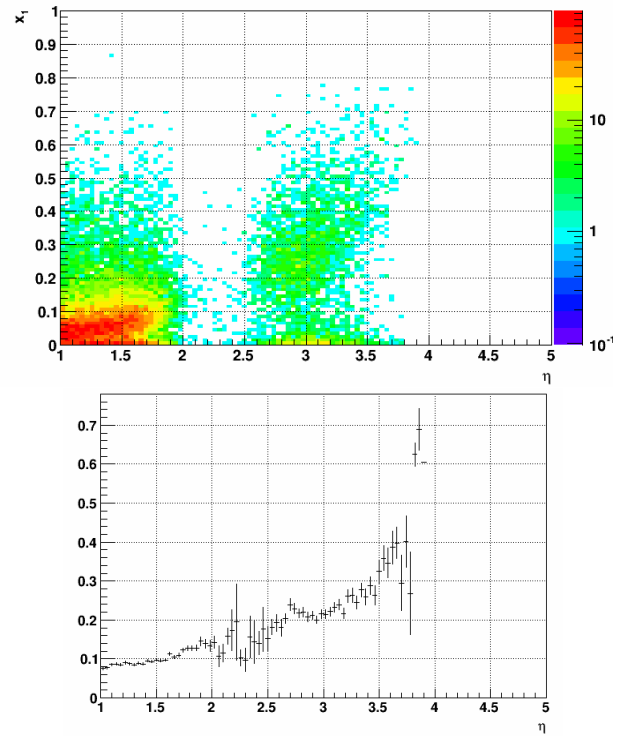


Figure 3-19: Same as Fig. 3-18, but with a minimum jet  $p_T$  of 5 GeV/c. This shows that additional  $p_T$  cuts allow one to push the accessible mean  $x$  to higher values. In this case,  $x_1$  values between 0.2 and 0.4 are achievable.

Figure 3-16 shows the regions of  $x$  that can be accessed by jets in the forward region. A minimum jet  $p_T$  of 3 GeV/c was chosen to ensure that the momentum transfer is sufficiently high for pQCD calculations to be valid. At high  $x$ , values of  $x \sim 0.6$  should be reachable. This compares well with the current limit of SIDIS measurements,  $x \sim 0.3$ , and encompasses the region in  $x$  that dominates the tensor charge. To investigate the possibility of selecting specific  $x$  regions, in particular high  $x$ , the dependence of  $x$  on the jet  $p_T$  and pseudorapidity was studied.

Figure 3-17 shows  $x_1$  as a function of jet  $p_T$ , and Figure 3-18 and Figure 3-19 show the  $\eta$  dependence for two  $p_T$  bins. For both the  $\eta$  and  $p_T$  dependences, one can observe two bands: one that exhibits an  $\eta$  or  $p_T$  dependence, and one that remains at low  $x$ . Based on the profile plots in Figure 3-18 and Figure 3-19, high  $x$  can be reached with small dilution for high  $\eta$  and  $p_T$ .

For measurements of azimuthal asymmetries of jets or hadrons within a jet, to probe the transverse spin structure of the nucleon, it is important to reconstruct reliably the outgoing parton direction. Therefore, the matching of reconstructed jets to scattered partons was studied (Figure 3-20). Figure 3-21 and Figure 3-22 show the mean distance of partons to associated detector jets and detector jets to associated particle jets. In general, matching and parton axis smearing improves with  $p_T$ , which may be connected to the jet multiplicity that rises with transverse momentum. Figure 3-23 and Figure 3-24 give the  $p_T$  and resulting  $z$  smearing for the reconstructed jets. Here,  $z$  is defined as the fractional energy carried by the fragmenting hadron. The reconstruction of the transverse momentum is poor, but  $z$  exhibits a more favorable correlation. Possible explanations include compensation between jet and hadron momentum smearing, and the domination of the  $z$  correlation by high multiplicity jets where the jet  $p_T$  reconstruction is more reliable.

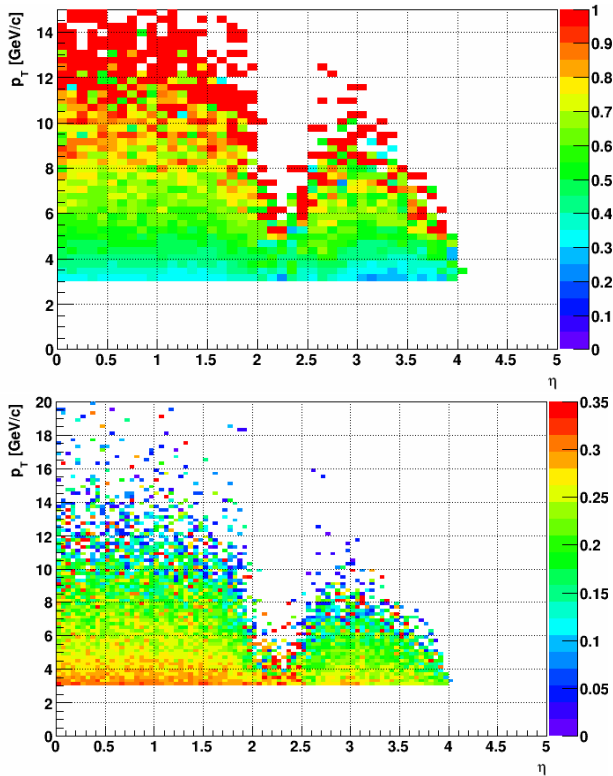


Figure 3-20: Matching Fraction between detector jets and partons. The matching fraction at low  $p_T$  is only around 50%, but grows to over 90% for high  $p_T$ . Unfortunately, the statistics at high  $p_T$  in the forward region is small.

Figure 3-21: Mean distance between matching parton and detector jets. For most jets the mean distance in  $\eta$ - $\phi$  space is around 0.2, but depends strongly on the jet  $p_T$ .

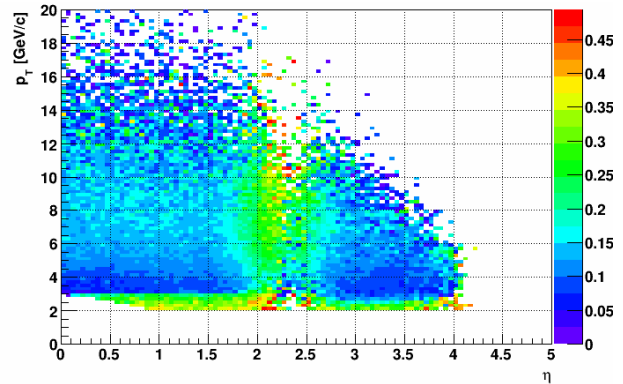


Figure 3-22: Mean distance between detector and particle jets. Detector and particle jets are closer to each other than the detector jets to the parton. The regions of large distance are due to lack of coverage between barrel+endcap and forward instrumentation and the lower minimum  $p_T$  cut for the particle jets.

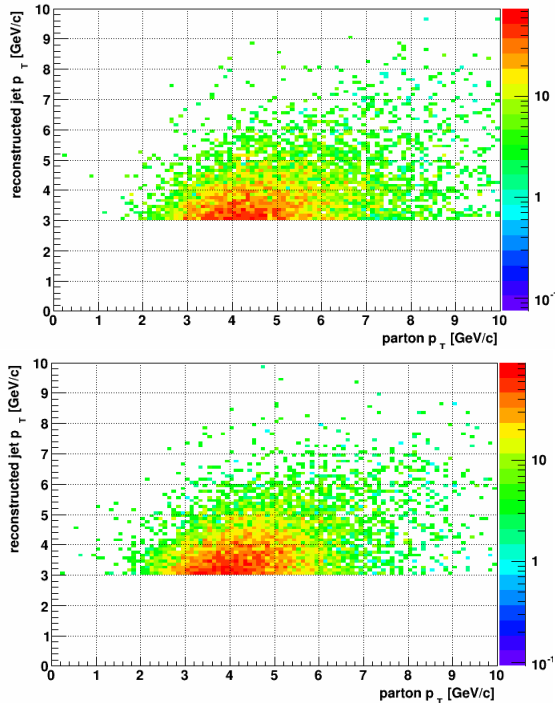


Figure 3-23: Transverse momentum smearing for reconstructed jets compared to that of the associated parton. The upper figure shows the smearing for jets with  $2 < \eta < 3$  and the lower for those with  $3 < \eta < 4$ .

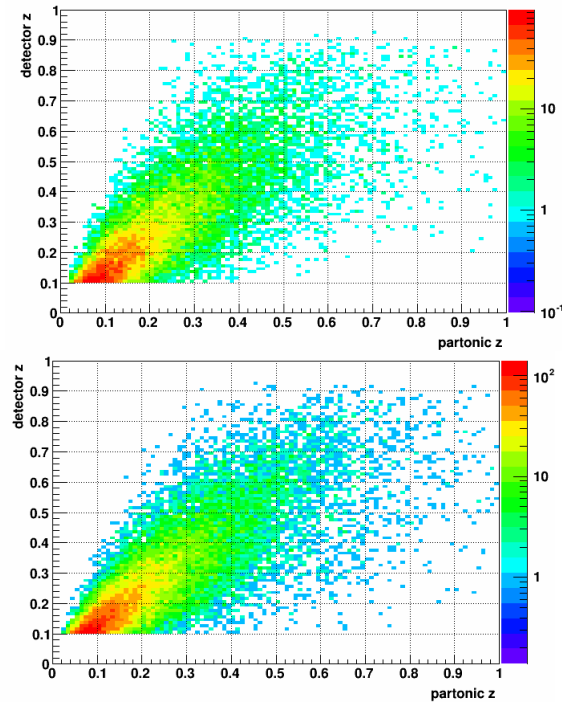


Figure 3-24: Smearing of  $z$ , the fractional momentum of the outgoing parton/jet carried by the outgoing hadron. The upper figure shows the smearing for jets with  $2 < \eta < 3$  and the lower figure for jets with  $3 < \eta < 4$ .

### 3.4.2 Drell-Yan capability

The most formidable challenge of DY measurements is to suppress the overwhelming hadronic background. The total DY cross-section is on the order of  $10^{-5}$ - $10^{-6}$  of the hadron production cross-sections; therefore the probability of mis-identifying a hadron track as  $e^+e^-$  has to be suppressed down to the order of 0.1% while maintaining reasonable electron detection efficiencies. To that end, we have studied the combined electron/hadron discriminating power of the proposed forward tracking and calorimeter systems. We found that by applying multivariate analysis techniques to the features of EM/hadronic shower development and momentum measurements we can achieve hadron rejection powers of 200 to 2000 for hadrons of 15 GeV to 50 GeV with 80% electron detection efficiency. The hadron rejection power has been parameterized as a function of hadron energy and pseudo-rapidity, and has been used in a fast simulation to estimate DY signal-to-background ratios. In the subsection we will describe the procedures of our simulation and discuss some of the results.

We have implemented the exact geometry of the proposed forward calorimeter system in section 2.1 into the STAR simulation framework. With the EM and hadronic sections, as well as the high-granularity of the EMCal, we will be able to measure the shower development in both longitudinal and transverse directions. We have simulated the response of the FCS to single electrons and  $\pi^-$ .

To discriminate EM shower against hadronic shower we have used three observables:

- 1. Eratio:**  
the ratio of a 5x5 EMCal cluster energy to the sum of the energies of the same 5x5 EMCal cluster and the projected 5x5 HCal cluster.
- 2. Swidth:**  
The effective EMCal shower width defined as  $R_p = \sum_i r_i E_i^{0.4} / \sum_i E_i^{0.4}$  where  $r_i$  is the distance of the  $i$ th tower to the centroid of a 5x5 EMCal cluster, and  $E_i$  is the energy of that tower. The summation is over the 25 towers in the 5x5 EMCal cluster around the highest tower.
- 3. NTratio:**  
the number of EM towers with energies above 100 MeV divided by the total number of EMCal and HCal towers above the same threshold. All the towers come from a pre-defined 5x5 EMCal cluster around the highest tower and the corresponding 5x5 HCal cluster.

Figure 3-25 shows the distribution of these three variables for 30 GeV electrons and  $\pi^-$ , respectively. The FTS helps reject hadrons by measuring the total track momentum. The ratio of energy deposition in the EMCal to track momentum ( $E/p$  ratio) could serve as additional information in separating  $e^{+/-}$  from charged hadrons. The momentum resolution was evaluated from a standalone simulation of the forward tracking system, with typical expected performance for the technology choice and parameterized as a function of energy and pseudo-rapidity. Figure 3-26 shows the parameterized momentum resolution at  $\eta = 2.5$  and 4.0. Figure 3-27 shows the energy to momentum ratio,  $E/p$ , for 30 GeV electrons and  $\pi^-$ .

These observables from the FTS and FCS have been used as inputs to a Boosted Decision Trees (BDT) algorithm. The BDT contains 1000 binary decision trees: each has a depth of 4 and corresponds to a particular partition of the 4-dimensional feature space into signal (electron) and background (hadron) regions. They are trained sequentially using half of the electron/ $\pi^-$  samples generated. Mis-identified tracks from the previous decision trees were given a higher weight in training the subsequent trees. In the end, each decision tree was given an index representing its performance during the training. In the validation stage, the decision of each track identification was made based on the collective response of all of the decision trees, with each of their responses

weighted by the performance index. The boosting algorithm takes advantage of using not only the discriminating power of each single observable, but also the correlations among them.

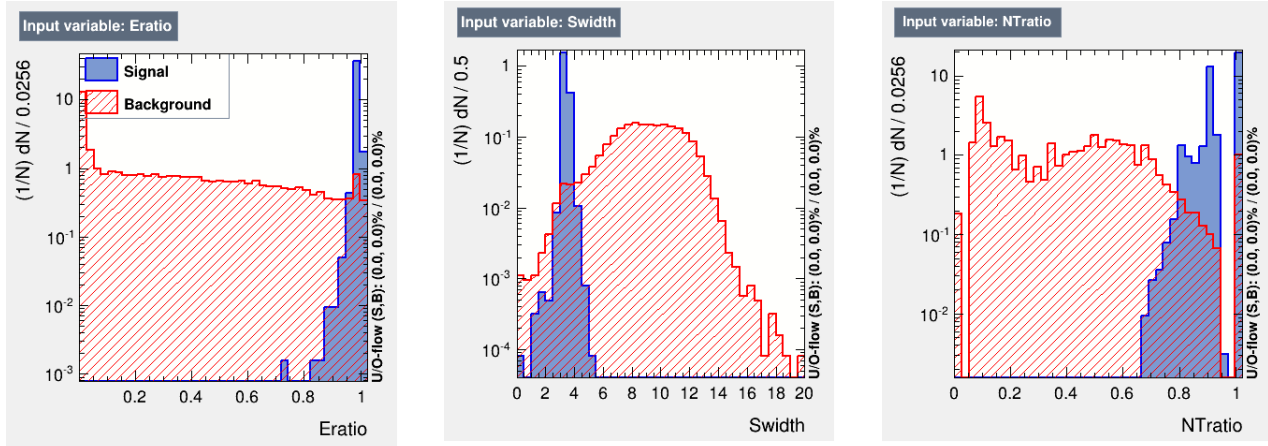


Figure 3-25: Eratio, Swidth & NTratio distribution for 30 GeV electrons (Signal) and  $\pi^-$  (Background). See text for explanation.

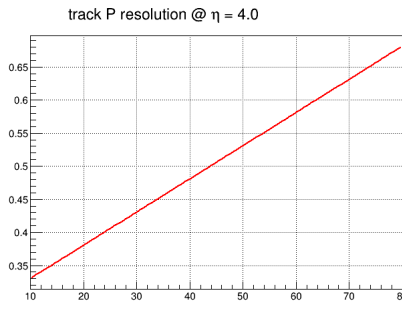
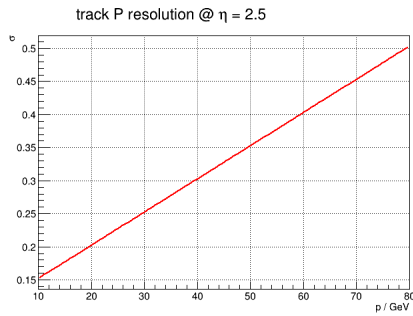


Figure 3-26: Expected track momentum resolution of the forward tracking system from simulations.

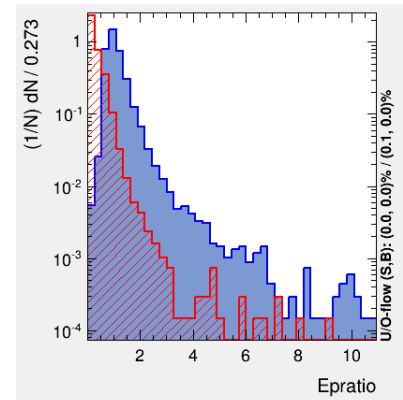


Figure 3-27:  $E/p$  ratio of 30 GeV electrons (blue) and  $\pi^-$  (red).

To estimate the DY signal to background ratio the  $e/h$  discriminating power has been parameterized as a function of the track energy and the pseudo-rapidity, as is shown in Figure 3-28. We have generated 4 billion PYTHIA  $p+p$  events at 200 GeV with CKIN(3) = 3 GeV and a forward filter requiring a total  $p_T > 3$  GeV in any of the four jet-patch-like regions in  $2.5 < \eta < 4.0$ . All basic QCD  $2 \rightarrow 2$  scatterings, as well as heavy flavor channels, were enabled. As a reference we note that  $2.5 \text{ pb}^{-1} p+\text{Au}$  luminosity is equivalent to  $500 \text{ pb}^{-1} p+p$  luminosity, which corresponds to 240.5 billion  $p+p$  events with the above setting. The DY productions through  $q\bar{q}$  annihilation and  $qg$  scattering processes were separately generated and scaled to  $500 \text{ pb}^{-1}$ .

Figure 3-29 (left panel) shows the yield of track pairs from a QCD background sample with the proposed cuts applied accumulatively to illustrate the background reduction process from each step. The final background yields from the 4 billion event sample after gamma/neutron removal + track energy cuts + charge sign requirement and  $e/h$  discrimination are shown by the green points. The right panel of Figure 3-29 shows the accumulative background reduction factor after each step of applying the cuts.

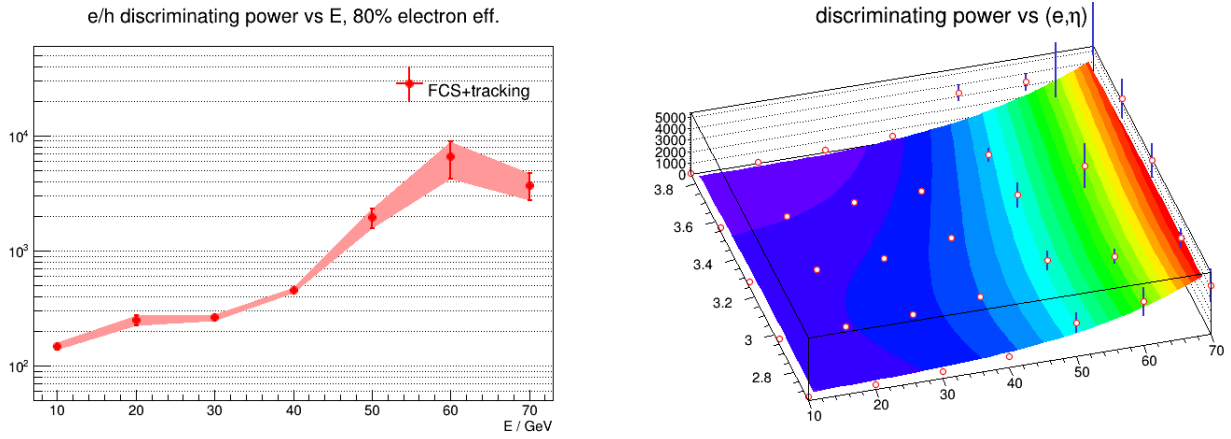


Figure 3-28:  $e/h$  discriminating power as a function of the track energy (left panel) and the variation over the pseudo-rapidity (right panel) from combined forward tracking and calorimeter systems

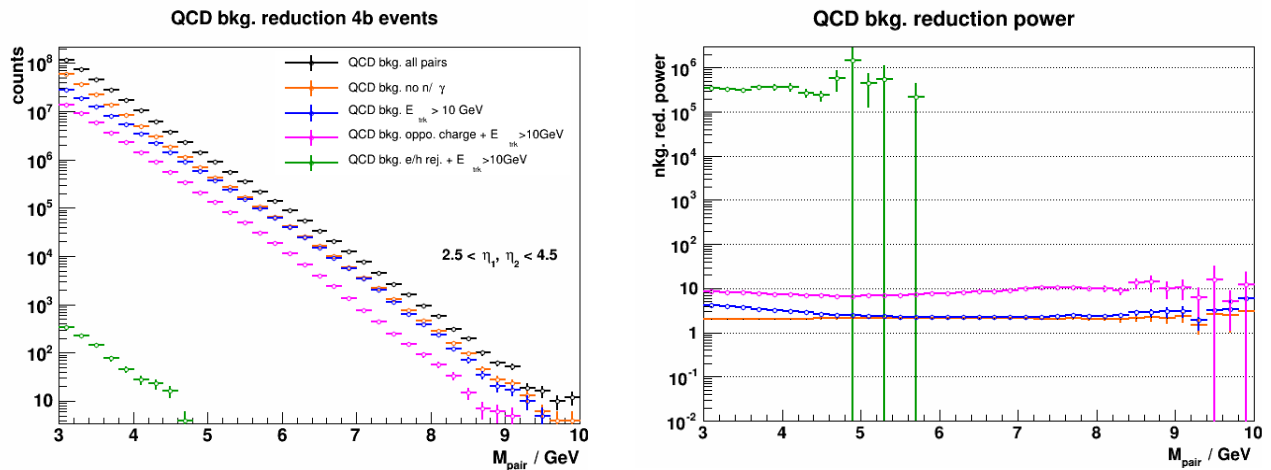


Figure 3-29: QCD background reduction with kinematics cuts and  $e/h$  rejections

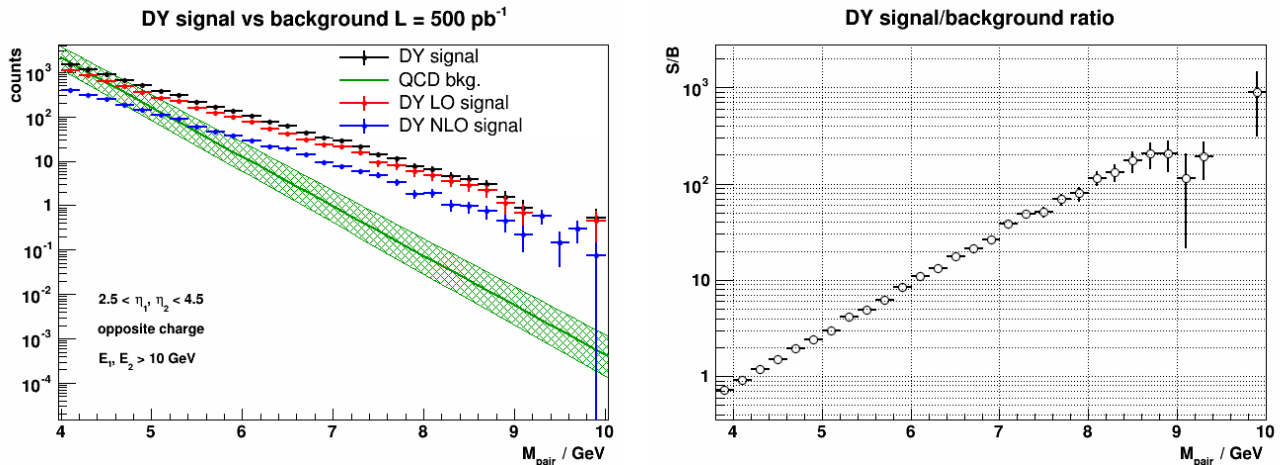


Figure 3-30: DY signal and background yield from 500 pb<sup>-1</sup>  $p+p$  200 GeV collisions

The final background yields as a function of pair mass were then fit by an exponential function and rescaled to a total luminosity of 500 pb<sup>-1</sup>. The left panel of Figure 3-30 shows the normalized background yield, along with the expected DY productions. The green band represents

the statistical uncertainties of the background yield and its shape. The right panel shows the DY signal to the QCD background ratio as a function of pair mass.

Finally we note that we have only considered the QCD background in the DY signal-to-background ratio presented in this subsection. We expect additional backgrounds from photon conversion from materials. Without a detailed design of the beam pipe and the FTS and its supporting structure, we do not have a reliable GEANT model to simulate the photon conversion background yet. Rough estimates indicate that these additional backgrounds may be on the same order as the QCD background, if care is taken to minimize the materials in the fiducial acceptance of the forward detectors.

### 3.4.3 Physics observables

Section 2 describes the envisioned science program with the FCS and FTS. Jets are among the experimentally more elaborate probes in this program. The remainder of this section focuses on two of the proposed jet measurements, and quantifies the anticipated precision from simulation.

#### *Longitudinal Spin Physics*

Figure 3-31 shows the correlation of the particle and detector di-jet mass based on the fast simulation framework discussed earlier. Good correlation is found for all four topological di-jet configurations. This study assumes only a forward calorimeter system. The impact of a tracking system based on silicon disks would have a marginal effect on the  $p_T$  reconstruction, considering the STAR magnetic field configuration. However, a tracking system is expected to improve the actual localization and separation of jets, in particular for the FCS+FCS di-jet topology that gives access to the lowest possible values of Bjorken- $x$ . High rate capability and efficiency are essential performance measures in particular for background rejection. The FCS and FTS upgrade is required for these measurements. In addition to di-jet correlation measurements, we will make measurements of  $\pi^0$ -jet correlations, with the neutral pion reconstructed at forward rapidity as a systematic cross-check [130]. The NLO framework for hadron / hadron jet measurements exists [131].

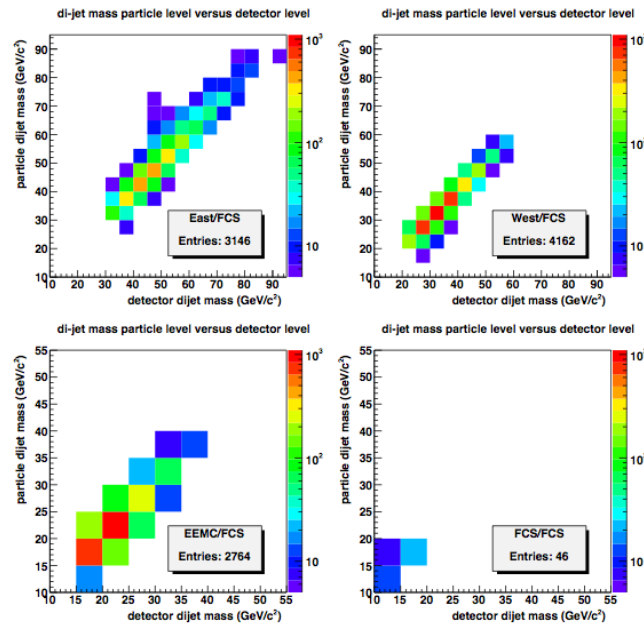


Figure 3-31: Correlation of the particle and detector di-jet mass, including effects for the forward STAR acceptance region.

The proposed forward di-jet production measurements, shown in Figure 2-12, in combination with measurements of the current STAR acceptance region, would allow STAR to probe spin phenomena of gluons well below the region of  $0.05 < x$  that is currently accessible.

### *Transverse Spin Physics*

As was discussed in Section 2.2, the spin-dependent azimuthal distribution of charged particles within jets is sensitive to quark transversity  $\times$  Collins fragmentation. The asymmetries are known as Collins asymmetries. RHIC measurements are complementary to those that will be made at Jefferson Laboratory, with unique sensitivity at forward rapidity. In Figure 3-32 we show the expected Collins asymmetries for  $p^\uparrow + p \rightarrow \text{jet} + \pi^\pm + X$  at  $2.8 < \eta < 3.7$  and  $\sqrt{s} = 500$  GeV. Jets are required to have a minimum  $p_T$  of 3 GeV/ $c$ . The 2008 transversity and Collins fragmentation function parameterization by the Torino group [28] has been inserted into a leading-order PYTHIA simulation using CDF Tune A. Jets are reconstructed utilizing an anti- $k_T$  algorithm, and the asymmetries are calculated relative to the associated hard-scattered parton. The projections assumed  $1 \text{ fb}^{-1}$  of luminosity with 60% beam polarization. Particle kinematics are reconstructed assuming a fast simulation for detector smearing based on a silicon forward tracking system and electromagnetic and hadronic calorimetry. Asymmetries of nearly 2% are expected for both flavors of pions. In Figure 3-33 we show a comparison of di-hadron asymmetries at the detector level, with the fast simulation detector smearing, to those at the particle level, before simulated detector smearing. Based on these simulations, the effects of kinematic smearing on the asymmetries are expected to be quite small. This suggests that within the same subsystem, one can simultaneously measure in a robust fashion the Collins asymmetry (within the TMD framework) and the di-hadron asymmetry (within the collinear framework). These measurements are critical for extending current understanding of transversity and questions concerning TMD evolution, factorization breaking, and universality, as well as longstanding questions about the nature of large inclusive asymmetries seen in  $p+p$  collisions.

In Figure 3-34 we show the expected Sivers asymmetries [132] for  $p^\uparrow + p \rightarrow \text{jet} + X$  at  $2.8 < \eta < 3.7$  and  $\sqrt{s} = 500$  GeV. Jets are reconstructed in the same manner as discussed above for the Collins asymmetries, and the Torino parameterization is assumed for the Sivers function [28]. Since the inclusive jet asymmetry provides only a single hard scale, namely, jet  $p_T$ , the twist-3 framework is most naturally suited for theoretical interpretation. However, the current estimates give a sense for the expected size of such effects. One can see that  $1 \text{ fb}^{-1}$  statistics may be sufficient to observe a nonzero asymmetry. However, the effects are expected to be quite small, of order less than 1%. The magnitude of this projection is qualitatively similar to existing inclusive jet asymmetries at forward pseudorapidity [133].

Recent theoretical work [134] has found that by taking into account initial-state and final-state interactions between the hard scattered parton and the polarized remnant, extractions of the Sivers function from SIDIS data [22,23] are consistent with existing inclusive jet data from  $p+p$  scattering [133]. The extracted Sivers functions were used to derive the twist-3 function  $T_{q,F}(x, x)$  [135] that was then used to compute the corresponding inclusive jet asymmetry for  $p+p$  scattering. The prediction compares favorably to the measured asymmetry, indicating a process dependence to the Sivers effect. Due to the small size of the apparent inclusive jet asymmetries, more precise measurements are clearly needed.

In addition to the inclusive jet measurements outlined above, di-jet measurements allow further probes of the transverse momentum-dependent structure of the nucleon. Here the relative transverse momentum between the jets,  $k_T$ , gives the additional soft scale needed for the TMD framework. In addition, accessing functions like Sivers [132] and Boer-Mulders [136] in  $p+p$

collisions allows one to explore additional asymmetries that may result from the “color-entanglement” in  $p+p$ , which also leads to the breakdown of factorization theorems [137].

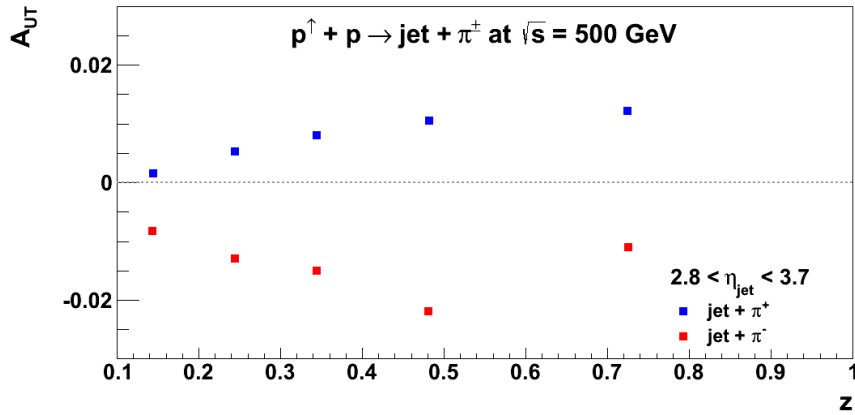


Figure 3-32: Expected Collins asymmetries assuming the Torino parameterization [28] within a leading-order PYTHIA Monte Carlo for charged pions within jets produced with  $2.8 < \eta < 3.7$  and  $p_T > 3$  GeV/c.

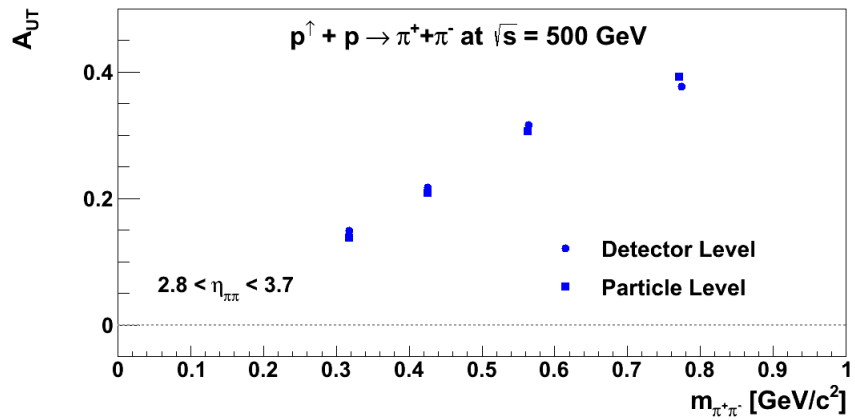


Figure 3-33: Comparison of IFF asymmetries at the detector level and at the particle level for charged pions produced within  $2.8 < \eta < 3.7$ . Asymmetries are shown as a function of di-hadron invariant mass, and assuming a parameterization inspired from fragmentation function measurements at Belle [27]. Statistical uncertainties are smaller than the size of the points.

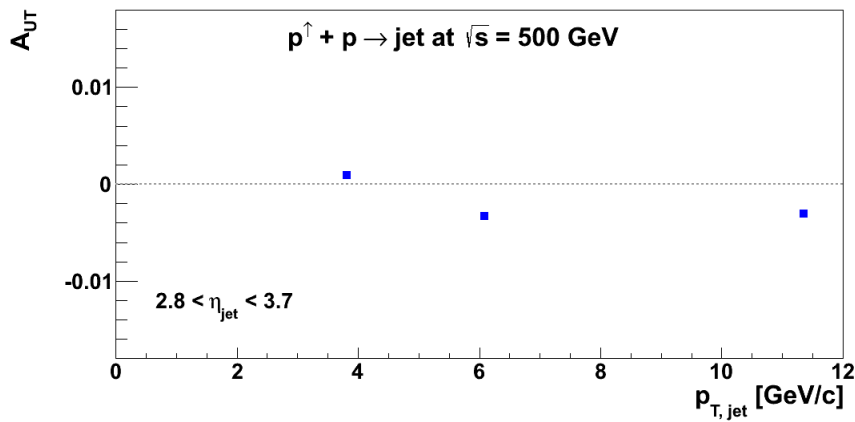


Figure 3-34: Expected Siverts asymmetries based on the Torino parameterization [28] within a leading-order PYTHIA Monte Carlo for jets produced with  $2.8 < \eta < 3.7$  and  $p_T > 3$  GeV/c..



## 4 The Forward Calorimeter System

### 4.1 Introduction

The original design of the Forward Calorimeter System (FCS) was driven by detector performance, integration into the STAR system and cost optimization. The previous FCS combined the strength of the ZEUS calorimeter [138], with its excellent hadronic energy resolution, and the H1 calorimeter [139], with its excellent electromagnetic energy resolution; arguably, both of these are among the best sampling calorimeter systems operated in the past. The proposed system has very good electromagnetic and hadronic energy resolutions. It is probably the most compact calorimeter system (for given energy resolution) tested to date.

The current proposed design of the FCS is a follow-up development of the original FCS system, and is driven by cost optimization. The big reduction in cost is achieved by replacing the originally proposed W/ScFi SPACAL ECal with the refurbished PHENIX sampling ECal [127]. In addition, the FCS will utilize the existing Forward Preshower Detector ( $2.5 < \eta < 4$ ) operated in STAR since 2015. The proposed FCS system will have very good electromagnetic ( $\sim 8\%/\sqrt{E}$ ) and hadronic ( $\sim 70\%/\sqrt{E}$ ) energy resolutions. The FCS consists of 2400 of the 15552 existing PHENIX EMCal towers and 480 HCal towers, covering an area of approximately  $3 \text{ m} \times 2 \text{ m}$ . The hadronic calorimeter will be a sandwich iron-scintillator plate sampling type, based on the extensive STAR Forward Upgrade and EIC Calorimeter Consortium R&D. Both calorimeters will share the same cost effective readout electronics, and SiPMs and/or APDs as photo-sensors. It can operate without shielding in a magnetic field and in a high radiation environment. By design the system is scalable and easily re-configurable. Integration into STAR will require minimal modification of existing infrastructure.

A new method of construction for sandwich hadronic calorimeters was developed during the STAR R&D program. A calorimeter system similar to the FCS is considered as a baseline design in the outgoing hadron region of a dedicated EIC detector.

### 4.2 Choice of Technology

There are several factors which led us to adopt the technology choice for the proposed FCS. The electromagnetic energy resolution at the level of about  $10\%/\sqrt{E}$  and hadronic energy resolution at about  $60\%/\sqrt{E}$  are sufficient to carry out the proposed measurements outlined in previous chapters. The same levels of energy resolution are desired for a future EIC detector as was carefully studied in Ref. 5. For comparison, the best hadronic energy resolution of  $44\%/\sqrt{E}$  was achieved by the ZEUS collaboration in their compensated uranium sampling calorimeter. Calorimeters in ATLAS and CMS at LHC have hadronic energy resolution  $> 100\%/\sqrt{E}$ . To achieve the best hadronic energy resolution (for single hadrons) usually requires a compensated calorimeter system, which was realized in the original FCS design. By constructing the EM section from existing PHENIX EM modules, there is no reason to make the hadronic section from lead, as the whole system is no longer compensated. Targeted energy resolution can be reached by replacing lead with iron in the hadronic section. This solution is cost-effective, but will require more complicated procedures for energy reconstruction.

The forward calorimeter system has to be very compact for the STAR forward upgrade. This is required by the configuration of the STAR IP and existing STAR detector. We chose SiPMs as photo-detectors for the EM section, and SiPMs or APDs as a base sensor for HAD sections of the redesigned FCS. The choice of readout sensors will be explained in detail later.

The FCS has to be designed so that the hadronic calorimeter can be assembled in place. The access at the FCS location is limited, with no overhead crane available. Thus it will be preferable to have the whole detector assembled from relatively light parts *in situ*, preferably by undergraduate and graduate students, who provide important manpower resources in the STAR collaboration.

### 4.3 Hadronic Section -- Technology and Design

The design of the sampling structure of the HCal is modeled after the ZEUS Pb/Sc compensated prototype, which was the first compensated calorimeter. Mechanically, the HCal section is a stack of layers of absorber and scintillation plates. The easiest way to describe the assembly process is to imagine building an entire HCal block from LEGO-style parts layer-by-layer. The basic structure of the HCal mechanical prototype is shown in Figure 4-1.

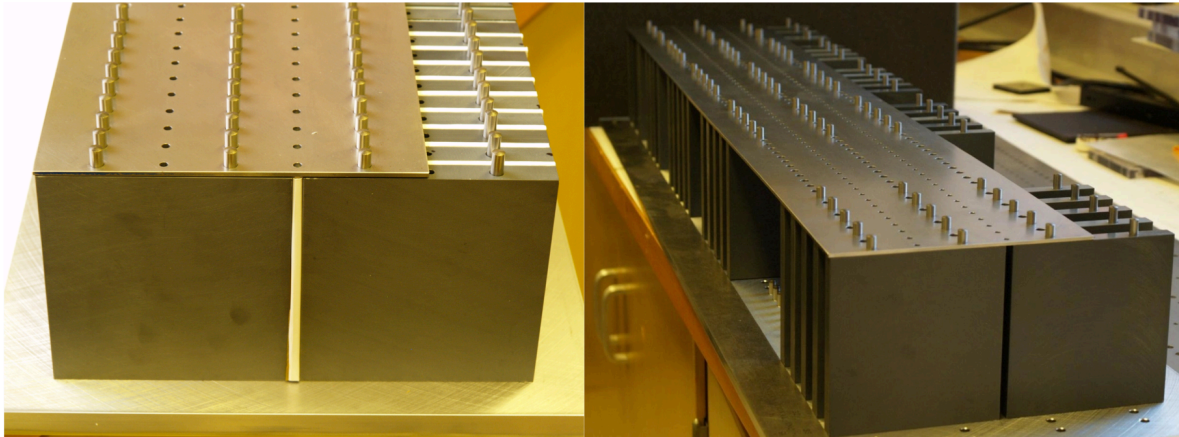


Figure 4-1: LEGO-type HCal mechanical structure. Absorber plates (gray in color) are positioned with the aid of dowel pins. Scintillation and WLS plates (white in color) are inserted in between absorber plates. Steel master plates work as a link between adjacent rows and front-and-back plates of the calorimeter.

Holes in the bottom base plate of the detector provide locations for the absorber plates. Each absorber plate has four holes for dowel pins, two at the bottom and two at the top. Steel dowel pins (5 mm in diameter) position absorber plates with respect to the bottom base and top steel master plates. A single master plate covers one and a half rows of HAD towers, providing interlinks between all absorber plates within one tower, between front and back steel plates of the HAD section, and between adjacent rows of the HAD towers. The iron absorber plates are 20 mm thick, and the gap between two adjacent absorber plates is 3.1 mm. Scintillation plates of thickness 3 mm are placed inside these gaps. There are 38 layers of Fe/Sc in the hadronic section, which is approximately 4.5 interaction lengths. Scintillation light from each tower is collected with a 3 mm thick wavelength shifting (WLS) plate (EJ-280), which is placed in the gap between two adjacent HCal towers. All scintillation and WLS plates are “floating” within each layer (there are no mechanical loads on these elements). Figure 4-2 shows an assembled HCal prototype. We assembled this prototype in place at the FNAL test beam facility in order to validate the construction technique. It took about eight hours for four people to build the sixteen-channel HCal prototype from the individual components at the test beam site. With a reduced number of layers in the proposed FCS, the assembly process will be faster.

The light collection scheme of the original HCal was optimized to provide uniform and efficient light collection from all scintillation tiles along the depth of the HCal tower. All optical connections in the HCal (except for coupling of the silicon photo-multipliers to the WLS) were made through a narrow air gap. We found that a good combination of reflective materials for the

WLS plate was a white diffusive reflector (Bicron BC-620) at the far end (from the photo-detector) and aluminized mylar at the back side of the WLS (opposite to the edge of the scintillation tiles). The mylar film also serves as an optical isolator between HCal towers within one layer of the HCal. To achieve uniform light collection (within 10%) along the depth of the HCal tower, we placed a variable density filter printed on a clear mylar sheet inserted between scintillation tiles and the WLS plate. Monte-Carlo calculations show that without such a filter, the energy resolution of the HCal degrades by about factor of two for the energy range above 20 GeV compared to an ideal detector. Variation of light from tile-to-tile in the tower within  $\pm 10\%$  has a negligible effect on energy resolution. Bench test measurements also show that variation of the thin air gap between the scintillation tiles and WLS plate (due to mechanical tolerances required for HCal assembly) has a negligible effect on the energy resolution of the detector. We found no degradation in light collection efficiency for unwrapped scintillation tiles placed between painted absorber plates compared to that for scintillation tiles wrapped with Tyvek.

We will slightly modify the light collection scheme for the HCal once we make a final decision on readout sensors for it, which will be discussed below.

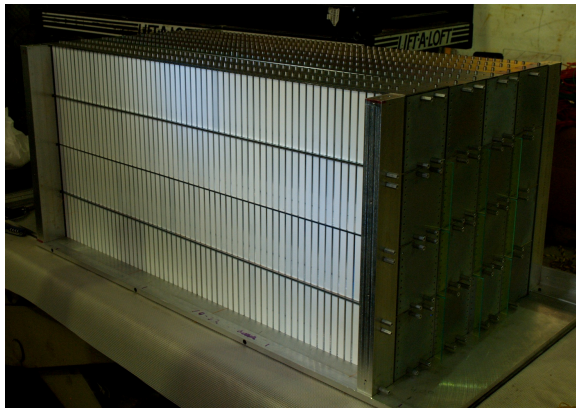


Figure 4-2: A full scale HCal prototype during assembly at the FNAL test run in 2014. The prototype consisted of sixteen individual towers. It was assembled from individual parts directly at the test beam site.

#### 4.4 Photo-sensors and Front-End Electronics

We have developed a new compact readout scheme for the FCS. For both the EMCAL and HCal sections, we used silicon photo-multipliers (Hamamatsu Multi-Pixel Photon Counters (MPPC) S10931-025p were used in the FNAL test run in 2014). They are very compact, fast and insensitive to magnetic fields, and sufficiently radiation hard for FCS readout in STAR [140]. SiPMs do not require HV for operation, which can significantly simplify the readout system. The cost of SiPMs continues to drop, while performance of these devices is becoming better and better for all manufacturers. We are making a second iteration of readout electronics for the re-designed FCS, which will be tested during RHIC Run17 at the STAR IP.

In 2016 we tested a PHENIX Shashlyk module in the FNAL test beam. The purpose of this test was to verify energy resolution and to measure the absolute light yield. The measured light yield (with PMTs) was approximately 1000 p.e./GeV, which is more than enough to proceed with SiPM readout.

In 2014 we used 8 MPPCs per tower for the HCal section to collect enough light to keep the contribution from photo-statistics to the energy resolution of the detector at a negligibly small level.

The front-end electronics for the HCal section is shown in Figure 4-3 and Figure 4-4. The HCal front-end board is designed for low power and reliable, low-cost integration into a large detector system. The unregulated 90 VDC input is regulated to the required SiPM bias voltage set by two DAC channels, one incorporating a thermistor. In this way, both the voltage and temperature

compensation slope (to maintain a constant gain for the SiPMs) are programmable. Signals from four SiPM's are directly summed at the input of a single preamplifier, which is a regulated common-base stage using BFR92A transistors. The amplifier input impedance is very low, a few Ohms; as a result, the high capacitance (1.3nF) of the four parallel SiPM's does not limit the charge collection time as it would with a 50 Ohm input. The preamplifier is followed by a differential output driver providing a 4V peak-to-peak signal to be used with low-cost, low-mass twisted pair cables to an external ADC system. The large signal swing and differential interface ensure satisfactory performance with a robust high dynamic range even when there is external EMI or ground noise in the system. The read-out scheme for the HCal will be further optimized in the coming months as we work towards the final electronics design.

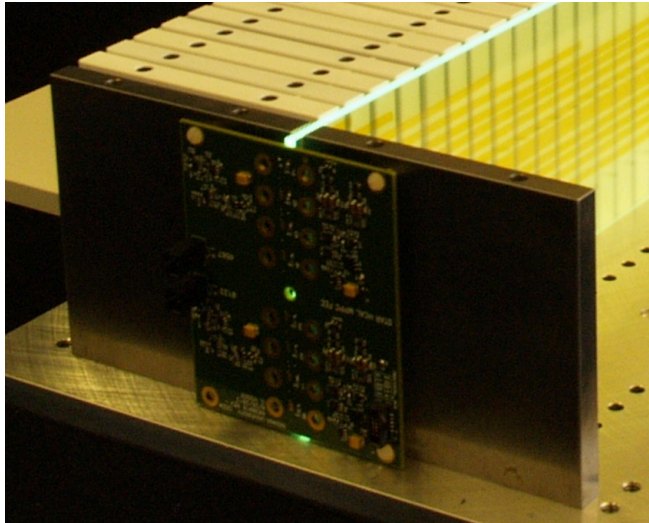


Figure 4-3: HAD FEE attached to a WLS plate during bench tests.

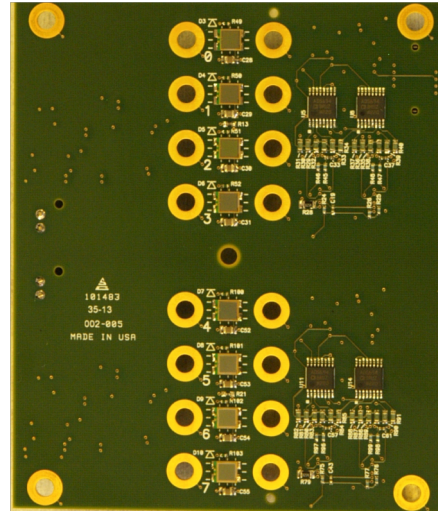


Figure 4-4: HAD FEE Board with 8 SiPMs installed.

In 2016 we performed a series of tests at the STAR IP to investigate the behavior of SiPM and APD sensors under realistic collider conditions, funded by EIC calorimetry R&D. An EMCAL prototype developed for the EIC forward calorimeter system was equipped with dual readout and placed near the beam pipe on the East side of the STAR detector. Scintillation light from fibers in this prototype was detected by a PMT at one end of the detector and by silicon sensors at the other end. We found that the SiPM was immune to the nuclear counting effect (NCE), as was expected, while APDs were not. However, we also observed that there is an additional contribution to the SiPM signals due to ‘primary’ ionization in the silicon. The magnitude of this additional pickup depends on the configuration of the detector, such as the presence of a pre-shower detector in front of the prototype. We estimate that about 90 extra pixels per GeV are potentially fired by ‘primary ionization’ in SiPMs. This should not be a problem for the EM section of the FCS, where the light yield will be above 1000 p.e./GeV. However, in the case of the HCal readout, shown in Figure 4-4, this additional pickup may be a problem due to the much smaller light yield from the HCal (140 pixels per GeV, as measured in the 2014 test run at FNAL).

We modified the forward EIC EM prototype and equipped it with a triple readout, which included a PMT on one side, 64 SiPMs collecting light at the other end of the detector, and 64 blind SiPMs next to the normal SiPMs to detect ‘primary ionization’ signals. This prototype has been installed near the beam pipe on the East side of the STAR detector, and we plan to take data with this setup during all of Run17 at RHIC. This measurement will allow us to make a final decision on the readout sensor for the HCal by the summer of 2017.

## 4.5 Performance of the FCS in the Test Run at FNAL in 2014

We tested the response of the FCS prototype to hadrons, electrons, and muons in the energy range 3-32 GeV at FNAL. Electrons were identified with a differential Cherenkov counter (standard equipment at the Muon Test Beam Facility, MTBF). Impact position was defined by a scintillator XY hodoscope (4.9 mm wide scintillator square rods with readout by SENSL SiPMTs). We minimized the amount of material upstream of the calorimeters in the beam line to about 4 cm of scintillation counters. Additionally, MTBF personnel installed He-filled beam pipes between our apparatus and the upstream Cherenkov counter. The initial setup of our apparatus in the beam line is shown in Figure 4-5. Two MTBF MWPCs (one is seen in Figure 4-5) were used as additional monitoring devices during the beam energy scans to track reproducibility of the beam settings at different energies. The HCal was oriented with a fixed angle of 2.5 degrees between the beam and the primary axis of the HCal towers. The EMCal prototype was attached to the front steel plate of the HCal. The angle between the axis of the EMCal towers and beam was kept at 4 degrees. All channels of the FCS were equipped with an LED monitoring system. Events for LED monitoring signals and pedestals were continuously recorded at a rate of about 1 Hz during most of the test run. Preliminary analysis of these data showed that stability of the gain for HCal and EMCal front-end electronics was better than 1% during a typical twelve-hour shift of data-taking. All SiPM's were tested and calibrated with a laser system prior to the test run. With this system, we verified that the response of the MPPC assemblies for both the HCal and EMCal prototypes were set equal to within 1%. We found that no additional tower-by-tower calibration of the EMCal prototype with the beam was required. This was expected based on our previous beam test results in 2012, when we measured excellent internal homogeneity for the EMCal modules built with our construction technique.

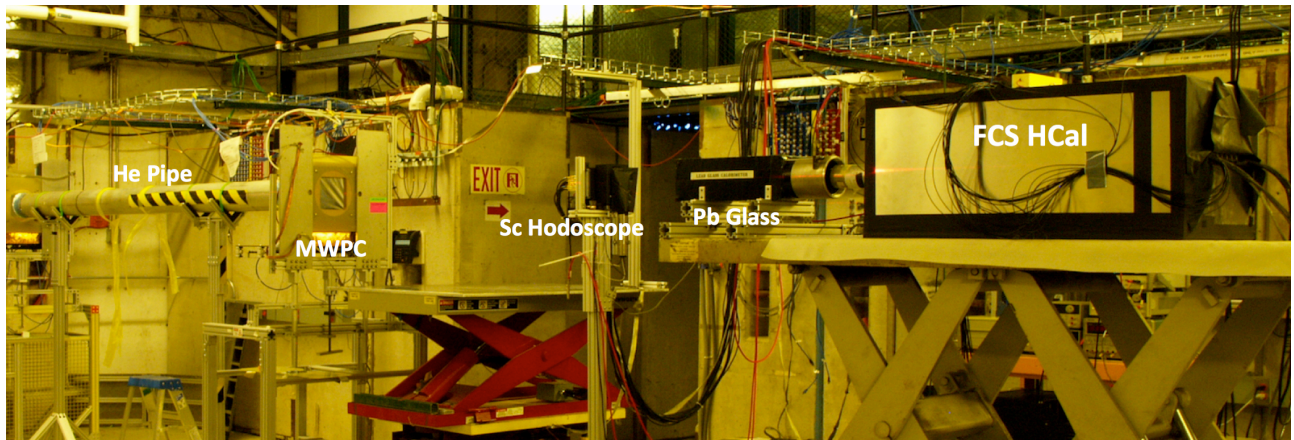


Figure 4-5: FCS prototype at the beam line. The Pb-glass calorimeter in front of the HCal section was used for initial beam studies.

The HCal required additional tower-by-tower calibrations with MIPs. For that, an absorber was inserted into the beam line (8 GeV muon mode for the MT6 test line). A MIP peak was selected in each HCal tower using an isolation requirement: a single muon hit in a tower, with no other energy deposition in the rest of the HCal. For calibrations with MIPs, the EMCal prototype was removed from the beam line. We found that large corrections ( $\sim 20\%$ ) were needed in addition to the calibrations made prior to the test run. About 10% of this shift can be explained by the alignment of the WLS plate and the MPPCs: both have a 3 mm active area, and about 250 microns misalignment is possible due to positioning of the MPPCs on the FEE board). The rest can be attributed to the quality of optical components. One possible source is variations in the response of the WLS tiles

used in different HCal towers. The concentration of dopants and attenuation length have not been measured for every WLS tile used in the HCal, and they were all assumed to be identical.

The response of the FCS prototype module to hadrons is illustrated in Figure 4-6. In an ideal, fully compensated calorimeter detector, the reconstructed energy of the incoming hadron is a simple sum of the energy deposited in the EMCal and HCal sections (assuming that the responses in both sections are equalized and energy-independent). To obtain the best energy resolution for hadrons in the FCS prototype module, we found that the weighting factor for the EMCal section should be energy-dependent. The factor changes from about 2 at a beam energy of 3 GeV, to 1.2 at 20 GeV, then stays approximately flat above 20 GeV. With this energy-dependent weighting of the EMCal energy, we measured the  $e/h$  ratio for the FCS prototype module to be close to 0.95, and almost constant above 10 GeV.

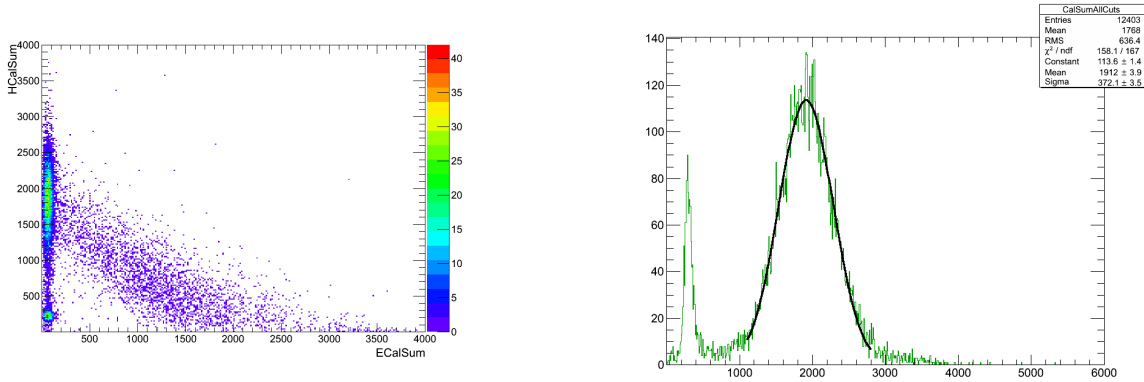


Figure 4-6: Response of the FCS prototype module to hadrons. (left) Energy deposition in an HCal section (Y-axis) versus energy deposition in EMCal section (X-axis) for 12 GeV hadrons. (right) A weighted sum of the energy deposited in EMCal and HCal section for 12 GeV hadrons.

We did not perform any corrections due to leakages in the transverse and longitudinal directions in the FCS prototype module. Qualitatively, this result is close to MC predictions; however, in our MC model we did not include some of the structural elements between the EMCal and HCal sections, or account for the limited size of the prototype tested at FNAL. The questions of optimal weighting factor and the final expected  $e/h$  ratio in the FCS prototype module, will need to be clarified with a MC model of the exact geometry of the detector that was used in the test run.

The response of the FCS prototype module to electrons is illustrated in Figure 4-7. Due to non-uniform light collection with MPPCs, the response of the EMCal section depends on the impact position. We corrected the energy deposition in the EMCal section according to impact position and restricted the impact area only to the circle with a diameter of 1.4 cm at the center of the EMCal tower.

Local coordinates of the impact positions were determined using calorimeter information only. We used a logarithmic weighting method with the cut-off parameter set at 3.8. The difference in the shapes of the responses of the EMCal section in the X and Y directions is due to a tilt of the EMCal prototype of 4 degrees around the Y-axis.

The performance of the FCS prototype module during the beam test in 2014 is summarized in Figure 4-8. The response to electrons is approximately linear, while the response to hadrons shows clear deviations from linearity above 15 GeV. The most likely reasons for this deviation are the weighting procedure of the fraction of energy deposited in the EMCal section and leakages from the FCS prototype module. We tested the HCal section alone (with EMCal section removed from the beam line) and did not observe a similar deviation from linearity in this energy range. The energy resolution of the FCS prototype module for hadrons, shown in Figure 4-8, is about 15% worse compared to MC predictions for the FCS module at 10 GeV. One of the reasons is likely the

transverse leakage from the FCS prototype module, which was not taken into account for the test beam results. We also note that the energy resolution of the FCS in the MC simulation depends on the physics list used in GEANT4. We used a LHEP physics list, which, in our studies, provides the most accurate description of the FCS performance. The electromagnetic energy resolution of the FCS prototype module is close to MC predictions. There are two fits to our experimental results shown in Figure 4-8. One assumed that the momentum spread of the beam is zero. In this case the stochastic term is close to 10% and the constant term is 1.7%. If we use our earlier (2012) estimates for the momentum spread of the beam to be 2.7 % below 4 GeV and 2.3% above 4 GeV, then the stochastic term becomes 11% and constant term is close to zero.

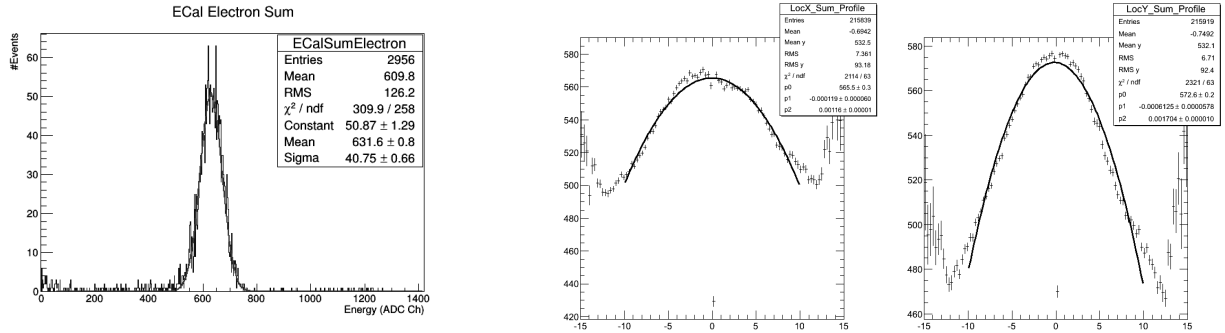


Figure 4-7: Response of the FCS EMCAL prototype module to electrons. (left) Energy deposition in the EMCAL section for 4 GeV electrons, with the impact point restricted by the scintillation hodoscope to an area of 5 mm x 5 mm. The energies deposited in the EMCAL section are shown as a function of impact positions in the local X coordinate (center) and local Y coordinate (right).

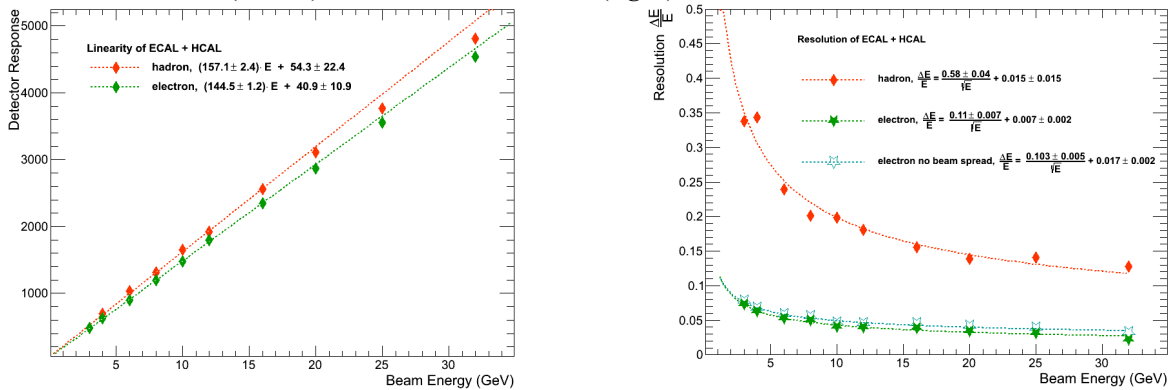


Figure 4-8: (left) Responses of the FCS prototype module to electrons and hadrons versus energy. (right) Energy resolution of the FCS prototype module for hadrons and electrons versus energy.

The absolute light yield measured in the EMCAL section is about 400 pixels/GeV, with the front face of the EMCAL prototype painted with the white diffusive paint BC-620. The measured absolute light yield for the HCal section is about 130 pixels/GeV. MPPCs for both EMCAL and HCal sections should behave almost linearly with these light yields for the energy range used in the test run. The light yield measured for the EMCAL prototype is sufficiently large that we can introduce a mask between the scintillation fibers and the light guide to improve the light collection uniformity in the future. Given that the most recent generation of MPPCs have much better PDE, compared to the MPPCs used in the test run, and anticipating future improvements in SiPMs, we believe that there is no need for any type of reflectors at the end of the scintillation fibers. This will significantly simplify the construction of the EMCAL section. According to our measurements in 2012, with the EMCAL prototypes equipped with a good mirror (versus black tape) at the end of the fibers, all degradation in the energy resolution can be explained by photo-statistics alone, *i.e.*, degradation due to light attenuation length in the scintillation fibers is not critical in this case.

## 4.6 Summary of Technology Development for FCS

We have developed a new construction technique for a high-resolution lead scintillation tile hadronic calorimeter. The original FCS system with EMCAL and HCal sections was designed for the STAR forward upgrade and for the Backward calorimeter system for EIC. The performance of the FCS system from the test run data met both STAR and EIC expectations. The novel compact readout scheme based on SiPM readout works well for the FCS prototype. The re-designed FCS based on extensive R&D we performed for the STAR forward upgrade and continuing efforts for EIC calorimetry R&D was described above.

## 4.7 Mechanical Integration into STAR

The FCS in STAR will be located in the space presently occupied by the FMS. Mechanical integration will require reinforcement of the existing FMS platform. Preliminary discussions with the engineers involved in the design of this platform indicate there is no problem with reinforcing the existing FMS platform. Preliminary FEA calculations of seismic loads and long-term stability of the FCS at the BNL location were performed. No problems were found in preliminary analysis of seismic stability performed by a mechanical engineer at UCLA.

## 4.8 FCS Electronics Overview

The FCS electronics system includes trigger, readout of SiPMs, a low-voltage system for SiPMs, low voltage power, slow control functions, calibration and monitoring controls, and interfaces to the STAR trigger, DAQ and slow controls systems. The bulk of the front-end electronics functionality, including signal processing, digitization, buffering, and the formation of trigger primitives, will be carried out by STAR DEP and/or QT boards.

The STAR BNL Electronics Group proposed to design and build a generic digitizer system (“Detector Electronics Platform” or DEP) which would be cheap, fast and modular, and could be used for many different applications within STAR and its upgrades. It may also serve as a platform for future readout systems at EIC. The basic board would consist of 32 12-bit ADCs running in sampling mode at 8x the RHIC clock. The ADC would be followed by a fast FPGA capable of running various digital filters and other typical trigger algorithms, such as pedestal subtraction, zero suppression, charge integration, moderate timing information ( $< 1$  ns), highest-tower, tower sums, etc. The system will be capable of connecting up to 5 such boards (for a total of 160 channels) into a compact and cost-effective chassis. The data will be sent to a DAQ PC over a fast optical link, and will have sufficient bandwidth to work in full streaming mode for typical occupancies, if so desired. It would also house the STAR TCD interface for the RHIC clock and Trigger command, which could also act as a Slow Controls Interface if needed. An interface to current or future STAR DSM boards will also be provided. Readout of FCS will be based on DEP, with a backup option based on extending the QT readout system that is currently used in the FMS and FPS. The two FCS readout schemes are comparable in cost.

The front-end electronics developed for the HAD section during R&D will need minor modifications for interfacing with the DEP in case readout sensors based on SiPMs are used. If the final choice for readout is APDs, then we will need to redesign the FEEs completely (the first version of FEEs for APDs were made and tested at STAR in 2016). Cost-wise, both versions of the FEEs/sensors will be the same.

The front-end electronics for the EMCAL section will be a simpler version of what we used in 2014: instead of four SiPMs per EM tower, we are using one based on all developments for the STAR FEEs for the pre-shower detector (successfully operated during Run 15) and post-shower



detector (constructed for STAR FMS Run 17). The first version of FEEs for tests with Shashlyk modules and DEP readout are tested right now during Run 17.

In the last test run at FNAL in 2014, both EMCal and HCal sections used a monitoring system with optical fibers to distribute light to individual towers. For the HCal section, this scheme will work well in the final detector configuration. For the EMCal section, such implementation is not practical, due to the high density of readout channels. At present we envision two different monitoring/calibration schemes for the EMCal and HCal sections of the FCS.

## 4.9 Production Plan

The design of the HAD section of the FCS has relied on existing standard technological processes to produce components of the detector in industry. For the full-scale prototype, all components were produced in a way that we envisioned for the final detector, with the exception of the scintillation tiles. In the prototype detector, we used scintillation tiles produced by Eljen (the tiles were cut to the desired size and were polished at UCLA). For the scintillation tiles to be used for the proposed FCS, we plan to use an injection molding technique to produce these tiles, similar to the construction techniques used for the ATLAS and LHCb calorimeters. The same technique is planned for the proposed sPHENIX HCal. One possibility is to use existing capabilities at IHEP (Protvino, Russia) which is a member institution of the STAR collaboration. Another option is to work with the same company that sPHENIX is working with at present for their HCal. The design of the HCal tiles is straightforward, and any technical risk in producing them is very low. University groups involved in this project will carry out QA for HCal components, tests and calibration of the FEEs and SiPMs. The project team will perform the final assembly of the detector in place at BNL, with help from the STAR technical support group. The STAR technical support group will be responsible for modification of the existing FMS platform.

## 4.10 Additional R&D

Additional R&D will be required to develop DEP, finalize the choice of readout sensors for HCal, investigate potential radiation damages of Shashlyk modules near the beam pipe, and perform a final calibration of the FCS system at the FNAL test beam. Some of these R&D projects are already in progress. The first prototype of the DEP board, shown in Figure 4-9, was designed, assembled, and is currently being tested in the lab.

Prototypes of the 16-channel digitizer DEP board as well as 2 FCS FEE prototypes (each with 4 channels) were installed in STAR for the FY17 physics proton-proton at 500 GeV/c run and connected to 8 SiPMs. The system was successfully commissioned and is running continuously in STAR controlled by STAR's Run Control as well as STAR's Trigger system & Clock Distribution network. Figure 4-9 shows 4 example events for 4 different channels showing the digitized output from the SiPM and FEE cards. The Gaussian fits to the shaped digitized FEE outputs show excellent agreement with the expected response. The abscissa shows the ADC clock (which is 8x the RHIC clock or 13.3 ns). The width of the pulse from the shaper is thus 50ns, as expected. Note also pulses from other collision crossings.

At the same time the timing information for each event was extracted relative to the RHIC clock edge and is shown in Figure 4-10 below. The resulting width of 3ns is a convolution of the RHIC collision ("diamond") width in time as well as time-of-flight of particles hitting the FCS prototype and is as expected.

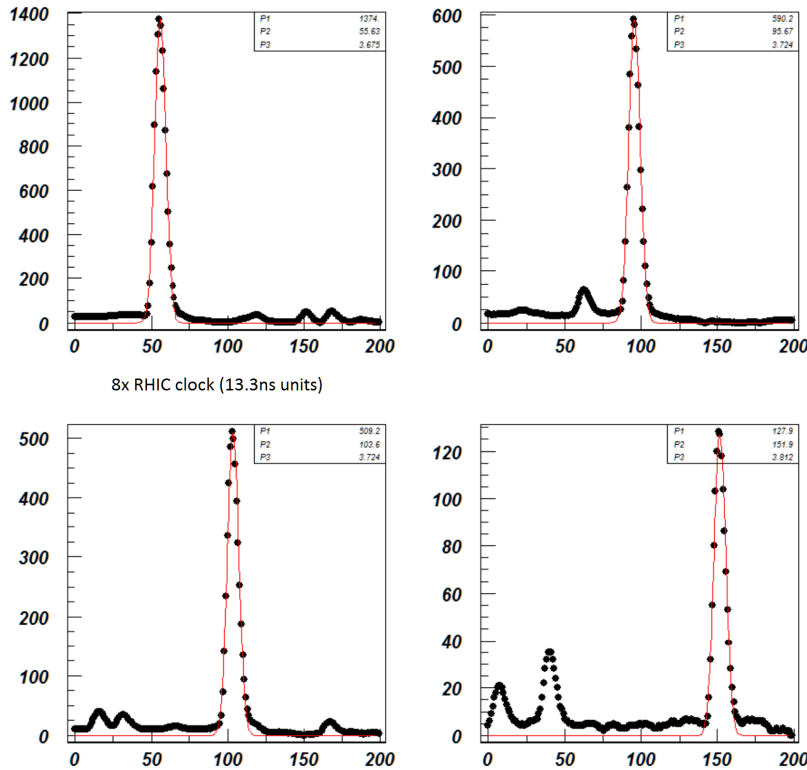


Figure 4-9: ADC output for 4 different DEP channels

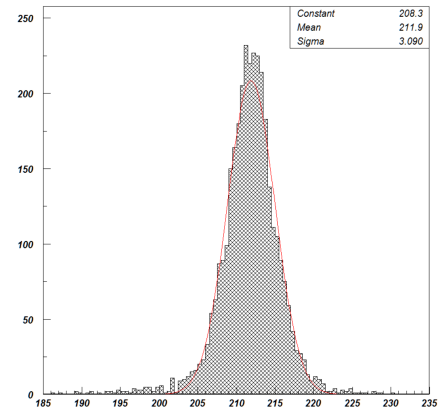


Figure 4-10: Distribution of arrival times of particles relative to the RHIC clock (in ns)

To investigate potential degradation of Shashlyk scintillator, we assembled a passive stack of EM modules at the East side of STAR near the beam pipe. All of these modules will get full exposure during Run17: then the light yield from these modules will be compared with unexposed blocks. The smaller stack of modules seen on the right in Figure 4-12 will be instrumented with the new version of FEEs and readout with the prototype DEP board shown in Figure 4-11.

The study of effects of radiation damage on SiPMs will continue. In 2014 we reported measurements of thermal neutron fluxes at different locations in the STAR experimental hall during RHIC Run 13 with proton–proton collisions at  $\sqrt{s} = 510$  GeV. We compared these measurements to calculations based on PYTHIA as a minimum-bias event generator, using a detailed GEANT3 simulation of the STAR detector and experimental hall, and with GCALOR as the neutron transport code. Fairly good agreement (factor of two) was found between simulation and measurements [139]. Thus we demonstrated that it is possible to do a reliable estimate of the neutron fluxes in the STAR detector. Additional insight into SiPM damage was gained during operation of the Forward Preshower detector (FPS) at STAR in 2015-2016. We observed no degradation of gain, and an increase in leakage current in accordance with calculated neutron fluences at the location of the FPS (same location as the proposed FCS). The increase in leakage current due to neutron damage will have minimal impact on the energy resolution of the FCS.

Additional studies of SiPM behavior in the STAR experiment will be performed during Run 17. The main goal for these studies is to quantify the fraction of signal in SiPMs due to ‘primary ionization’. These studies are funded by EIC R&D and are needed to make a final choice of sensors for the HCal.

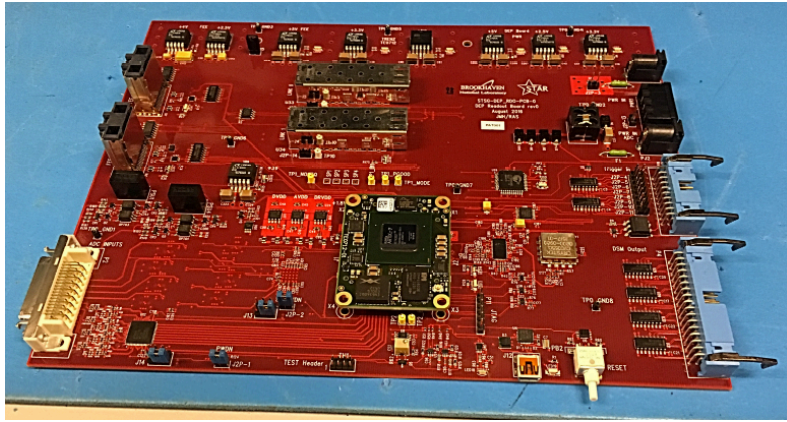


Figure 4-11: First prototype of the DEP board.

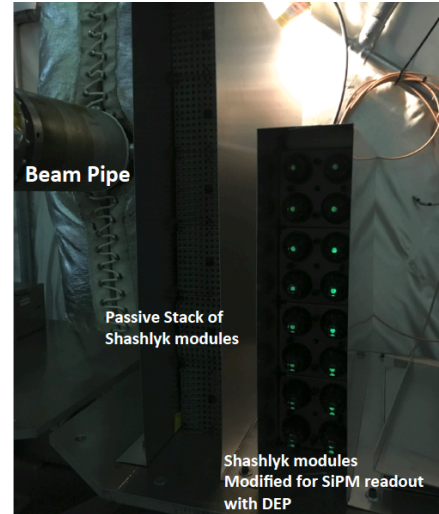


Figure 4-12: Stacks of Shashlyk blocks at the East side of STAR.

Based on studies performed in 2014-2016 in the STAR experimental area, we are confident in our predictions of the radiation and neutron fields at the proposed FCS location and in the whole STAR area. As an example, MC-generated neutron fluxes at STAR for the Run 14 Au-Au configuration are shown in Figure 4-13, normalized to 1 MHz minimum bias collision rate. During the 2014 run, we integrated the flux of neutron over 93 days of running with  $E_{kin} > 100$  keV at the location of the FCS. According to these simulations, the expected neutron fluxes are  $3.4 \times 10^9$  and  $5.1 \times 10^9$  n/cm<sup>2</sup> at pseudo-rapidities of 2.5 and 4, respectively.

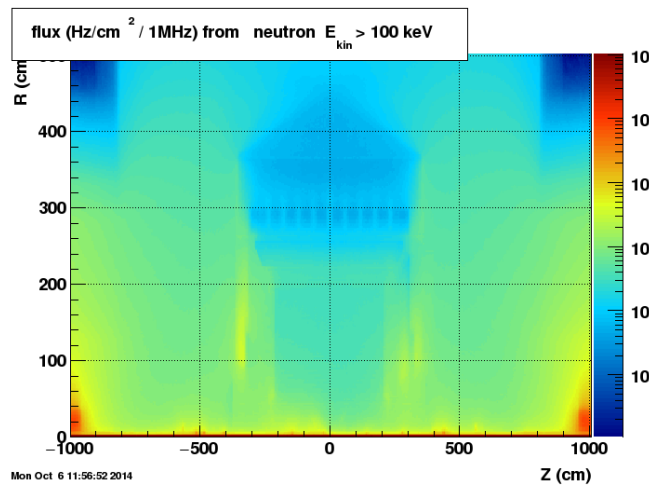


Figure 4-13: A normalized neutron flux in the STAR experiment during Au-Au Run 14.

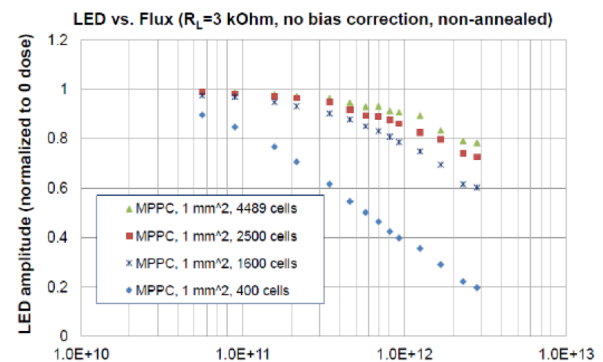


Figure 4-14: Degradation of performance of different SiPMs versus irradiation [n/cm<sup>2</sup>].

In addition, the EIC calorimeter consortium carried out a series of tests to quantify the effects of radiation damage on SiPMs. Sensors were irradiated at BNL and at the LANSCE Facility at Los Alamos at up to  $7 \times 10^{10}$  n/cm<sup>2</sup>. With irradiations up to  $10^9$  n/cm<sup>2</sup>, response of the SiPMs to light pulses is largely unaffected, apart from loss in single pixel resolution and increased dark and leakage currents. With higher doses of irradiations, some losses in photon detection efficiency and, as a consequence, changes in the response to different levels of light were observed. The degradation effects measured by the CMS collaboration are shown Figure 4-14.

A very good understanding of degradation effects in SiPMs has been gained in the past few years due to extensive R&D efforts by many groups, including our own measurements at the STAR

IP, which is necessary for proper design of the front-end electronics and monitoring systems. At very close proximity to the beam pipe, accidental losses of the beam may still lead to catastrophic failures. The current optical and mechanical integration of the readout allows for quick replacement of failed FEEs in such cases. This was demonstrated during the latest test run at FNAL, when two different prototypes of the EM calorimeters were sequentially tested successfully with the same sets of readout boards.

We plan to carry out at least one additional beam test run at FNAL with a full-scale pre-production prototype equipped with final version of readout electronics.

## 4.11 Trigger System

The trigger system for the Forward Calorimeter System will identify energetic clusters in the electromagnetic calorimeter to trigger on photons and  $\pi^0$ . Appropriately separated clusters will be used to trigger on  $e^+e^-$  pairs from Drell-Yan and  $J/\psi$ . Eight overlapping large-area transverse energy sums, each spanning approximately  $\frac{1}{4}$  of the detector and including contributions from both the electromagnetic and hadronic calorimeters, will be used to trigger on jets. Pairs of non-overlapping large-area sums will be used to trigger on di-jets.

The trigger will be architecturally similar to the current trigger for the FMS. The FMS trigger consists of initial logic performed in the QT boards that digitize the analog signals for every bunch crossing. The QT boards are followed by a three-layer tree of Data Storage and Manipulation (DSM) boards, each of which receives 128 input bits every bunch crossing, processes them through an FPGA, then outputs the 32-bit result. For the Forward Calorimeter System, DEP boards will implement the functions currently performed in the QT boards. The existing FMS DSM boards could, in principle, handle the trigger processing for the electromagnetic calorimeter. However, there are several problems with that approach. The DSM boards were designed and built in the mid-1990's. Critical components are no longer commercially available. The vintage-1990's FPGAs are barely capable of performing the current logic in the time available. Likely, they are incapable of performing the more complex logic required to merge the EMcal and Hcal information together. Furthermore, there aren't enough DSM boards available to instrument the full EMcal+Hcal system. For these reasons, we plan to replace the DSM boards with a new logic board that will provide more input bits and includes a modern, faster, more capable FPGA. The full trigger system is expected to require 20 new boards, plus 4 spares. The estimated cost, including NRE and 25% contingency, is \$57K.

## 4.12 Milestones and Schedule

Major milestones to realize the FCS for Run 21 are listed below:

- 09/2018 Technical Design Report.
- 01/2019 Final Design Report and Review.
- 06/2019 Production Readiness Review.
- 08/2019 Start Procurements (absorber and scintillation plates, electronics components, etc.).
- 08/2020 Start Assembly of FCS at WAH.
- 01/2021 Start Commissioning of FCS.

Time prior to the TDR will be used to develop, test and optimize front-end electronics, the digitizing and triggering scheme for the FCS, optimization of the HCal configuration, and integration into STAR. We plan to use every RHIC Run in the years 2017-2019 to continue optimization and testing of the FCS. Major milestones are listed below:

- Test of small scale, sixteen channel EM prototype equipped with first iteration of FEE and DEP at STAR during RHIC Run17 (06/2017).
- Investigate potential degradation of Shashlyk EM modules near the Beam Pipe, exposure of passive EM stack at STAR during Run17 (06/2017).
- Finalize choice of readout sensors for HCAL by 03/2017.
- Optimize Light collection for HCAL by 08/2017.
- Produce final design of FEEs for EM section by 06/2017.
- Produce next iteration of DEP by 12/2017.
- Produce 64 channel readout electronics for EM by 12/2017.
- Assemble 64 channels EM prototype for Run 18 by 01/2018.
- Test of 64 channels EM prototype during Run 18 including HT functionality integrated with STAR DAQ and Trigger (06/2018).
- Design and produce prototype of HCAL FEE by 02/2018.
- Start production of final FCS prototype (64 ch. EMcal + 16 Ch. HCAL) by 03/2018
- Test one HCAL tower in final configuration with the first version of FEEs and DEP at STAR during Run 18 (06/2018).
- Final design and production of sixteen HCAL FEEs by 06/2018.
- Beam test and calibration of full scale FCS prototype at FNAL by 12/2018.
- Operate full scale FCS prototype at STAR during Run 19, fully integrated with STAR DAQ and Trigger.

## 5 The Forward Tracking System

### 5.1 Overview

The physics case for the STAR forward FCS and Forward Tracking System (FTS) upgrade is described in section 2 of this document. For transverse spin asymmetry measurements of charged pions in the forward direction in p+p and p+A collisions, it is necessary to distinguish positively charged pions from negatively charged ones with momentum up to 80 GeV/c. For Drell-Yan and  $J/\psi$  (direct photon and photon+jets) measurements in the forward direction, excellent electron (photon) identification capability is demanded in order to suppress the large hadron backgrounds by 3-4 orders of magnitude. Adding a forward tracking system becomes essential to achieve such goals. The FTS can separate particles with different charge signs, based on the different bending directions in the 0.5 T STAR solenoid magnet field. The FTS can improve electron identification by measuring charged particle momenta and comparing these to the associated energy depositions in the FCS. The FTS can also aid photon identification by vetoing on hits from charged particles. In order to achieve these goals, the FTS needs to have good position resolution and a low material budget. The FTS will provide essential information to study the longitudinal structure of the initial state that leads to breaking of boost invariance in heavy-ion collisions, and to explore the transport properties of the hot and dense matter formed in heavy-ion collisions near the region of perfect fluidity.

### 5.2 Proposed Configurations

STAR is currently looking into two different tracking detector schemes. One option is based on using only silicon-strip sensors for the FTS. The other combines 3 silicon-strip sensor disks with 4 small-strip Thin Gap Chamber (sTGC). These two designs for the FTS are discussed below.

### 5.3 Silicon-Based FTS Option

Silicon detectors have been widely used in high-energy physics experiments. STAR recently built a silicon micro-vertex detector, the Heavy Flavor Tracker (HFT), to study heavy flavor production at mid-rapidity ( $|\eta| < 1$ ) in high-energy nuclear collisions. The HFT includes 3 sub-systems: the Silicon Pixel detector (PXL), made of Monolithic Active Pixel Sensors (MAPS); the Intermediate Silicon Tracker (IST), made of single-sided double-metal Silicon Ministrip sensors; and the Silicon Strip Detector (SSD), made of double-sided Silicon Strip sensors.

In order to achieve good charge separation and momentum resolution, the silicon sensors for the FTS need to have precise position resolution in the azimuthal direction (*c.f.* section 3.3.1). The requirement on resolution in the radial direction is not very demanding. As it is mandatory to keep the ghost hit rate and occupancy under control, especially for A+A collisions, it is proposed to use single-sided double-metal Silicon Ministrip sensors with fine granularity in  $\phi$  and coarse granularity in  $r$ . These sensors will be read out from their edges at large radii, so that the frontend readout chips, cabling, and cooling pipes and liquid can be placed outside of the  $2.5 \leq \eta \leq 4$  region to minimize the amount of materials in the FTS acceptance.

An FTS using Silicon Ministrip sensors can take advantage of the successful experience of the STAR IST detector. The latter has good S/N ratio (25:1), high hit efficiency ( $\sim 99\%$ ), and small readout dead time (4%@1kHz, with potential improvement). The FTS would consist of three or more planes of Silicon sensors mounted transverse to the beam axis. In order to have the longest possible lever arm for momentum measurements, the FTS plane nearest (farthest) to the center of

STAR will be placed at  $Z \sim 70$  (140-180) cm. These locations are constrained by the requirement to have  $\eta$  coverage between 2.5 and 4, and by the outer (inner) radius of the beam pipe. As shown below, such a design can provide optimal charge-sign separation and momentum resolution in p+p and p+A collisions, with minimal materials (0.4-0.6%  $X_0$ , Silicon sensors with a thickness of about 300  $\mu\text{m}$ ) in the acceptance. We estimate that the average occupancy in the silicon-based FTS option is 3.2% (10%) at  $\eta = 4$  (2.5) in the 0-3% most central Au+Au collisions at  $\sqrt{s_{\text{NN}}} = 200$  GeV. This estimate is based on the charged particle multiplicities measured with the PHOBOS experiment [141], taking into account that the number of primary tracks is roughly 50-60% of the total number of tracks.

### 5.3.1 Silicon Ministrip Sensors

This FTS design option uses single-sided double-metal Silicon Ministrip sensors, in which a second Al layer is needed to bring the signals from the inner radii to the outer radius of the sensors. It is important to perform R&D studies to validate and optimize the sensor design. STAR has started an R&D project for this purpose. Shown in Figure 5-1 are sensor masks currently under development. Shown in Figure 5-2 are finite element simulation results for the sensor electrical properties and its response to charged particles passing through. It is crucial that the R&D and PED for the Silicon Ministrip sensors continues, so that a full design of the FTS can be available by the beginning of 2019.

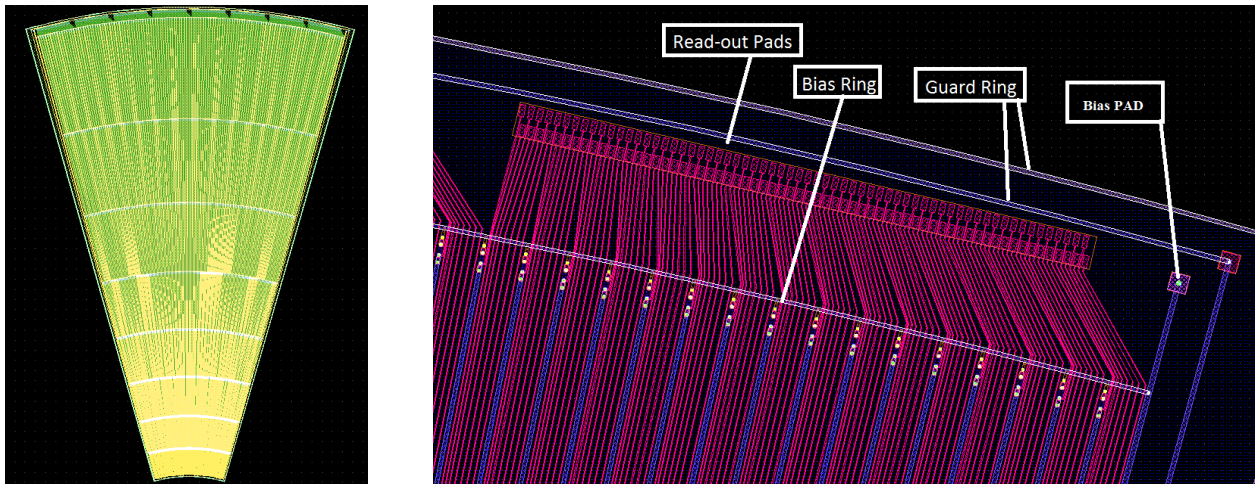
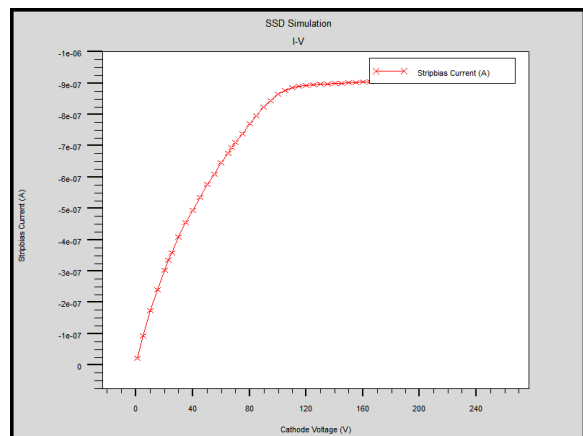
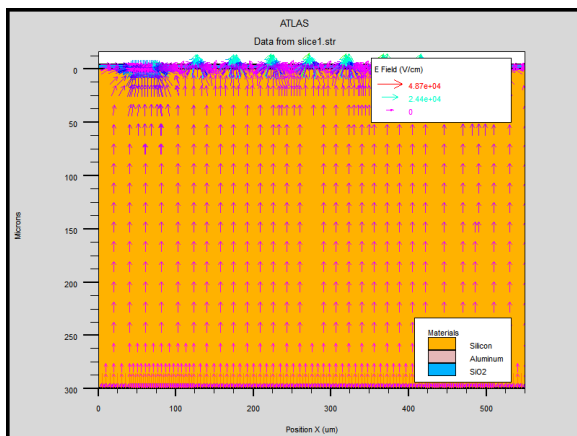


Figure 5-1: (Left) Full view of a FTS Silicon sensor mask. (Right) Zoomed-in view of the sensor mask.



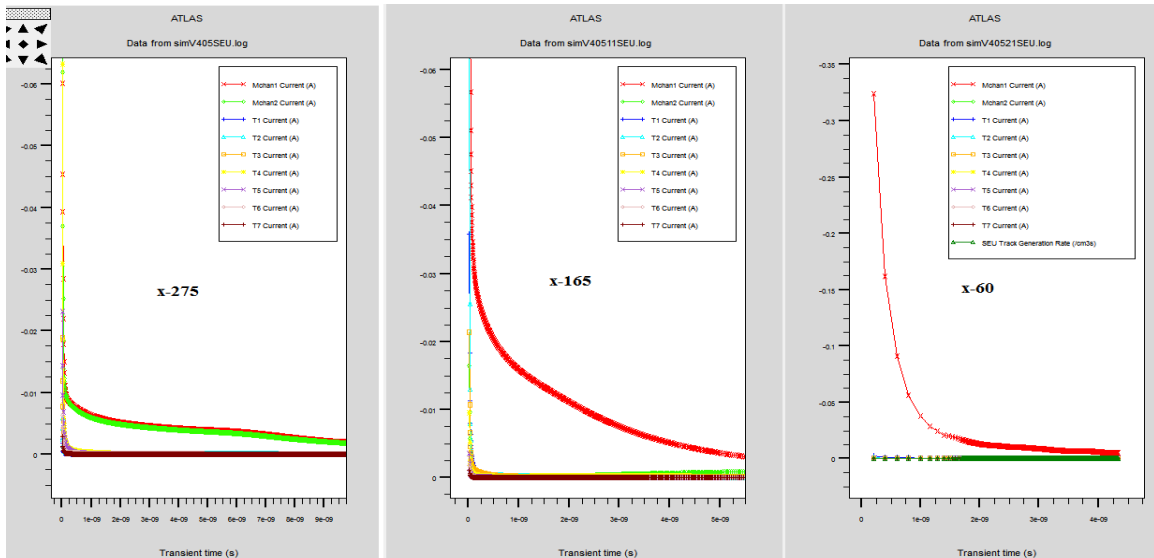


Figure 5-2: Finite-element simulation results of a FTS Silicon Ministrrip sensor. Top-left: electrical field lines in the sensor cross-section view. Top-right: sensor leakage current vs bias voltage. Bottom: transient electrical signals from the top layer Al strips when a charged particle hit is in the middle (left), at one quarter of the distance between (middle), or on top of (right) one of the two azimuthally neighboring Silicon P+ implant strips. The red and green curves correspond to the top layer Al strips on top of the Silicon P+ implant strips, while the others are the top layer Al strips to bring signals from smaller radius P+ implant strips to the sensor outer radius edge.

### 5.3.2 Frontend Readout Chips

Several different frontend chips are available to read out the Silicon Ministrrip sensors. The APV25-S1 chip has been used in the IST. It has 128 channels each, with a charge sensitive pre-amplifier, shaper, and 4  $\mu\text{s}$  long pipeline (see Figure 5-3). Events are read into the pipeline at 40MHz. Events in the pipeline are selected by triggers and marked for readout. A single differential pair per chip reads out each of the 128 channels in series for a selected event. The APV25-S1 chip can also be used to read out FTS sensors, in which case the same DAQ system as that of the IST can be used to minimize electronics engineering work. While a final decision has not been made on this issue, a sufficient number of APV chips have been obtained to keep such an option viable.

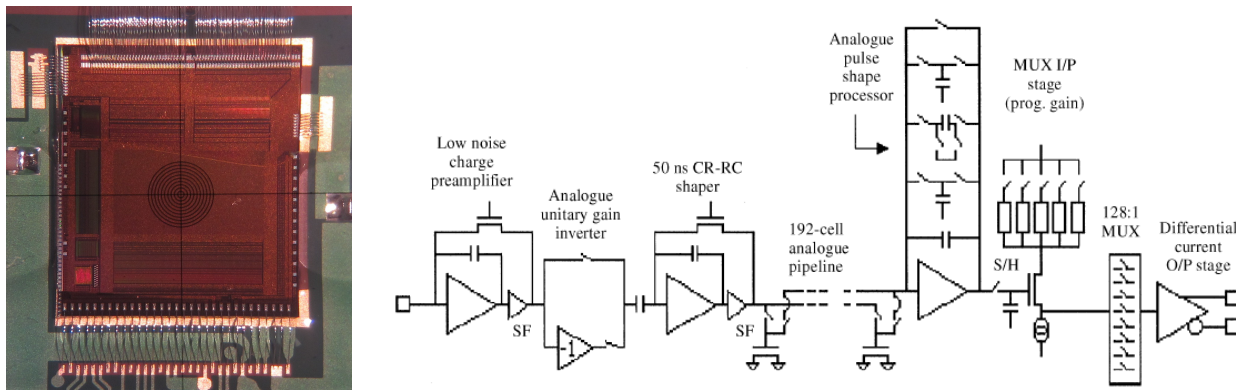


Figure 5-3: Left: Picture of an APV25-S1 chip. Right: block diagram of one channel of the APV25



### 5.3.3 FTS Wedge

A complete layout design for the FTS wedge has not been developed. However, based on previous experience, one possibility is that a FTS wedge will be made of low mass materials such as carbon fiber or beryllium frames as supporting structures, with Silicon Ministrip sensors and frontend readout chips mounted on a thin, flexible, printed circuit hybrid. The Silicon sensors will be wire-bonded to frontend readout chips at the outermost radius edge (see Figure 5-4).

Cooling pipes will run beneath the readout chips to keep the chips and sensors at low temperature. Compared to a configuration in which the sensors are read out from their edges along the radial direction, the material budget in the FTS acceptance will be much smaller (0.4–0.6%  $X_0$  per plane) since the frontend readout chips, power and signal buses, and cooling lines will all be located outside of the detector acceptance.

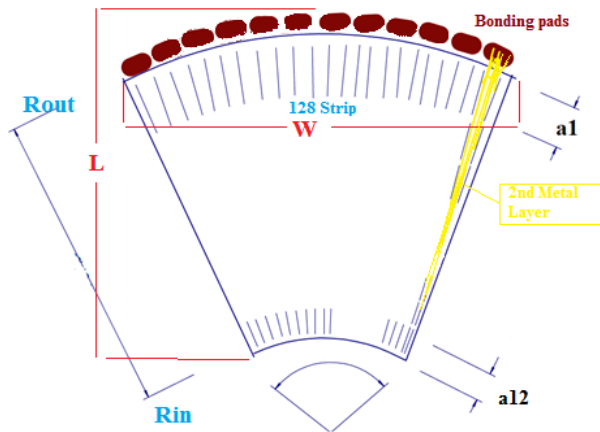


Figure 5-4: Schematic view of a FTS wedge. A Silicon Ministrip sensor with 128\*12 strips and 12 frontend readout chips is shown.

### 5.3.4 DAQ System

If STAR decides to use APV chips to read out the Silicon-based FTS, the DAQ system used for the IST can be used for the FTS. The DAQ system has a modular design, which is based on a passive compact PCI backplane running a custom protocol, connecting 6 readout modules to a readout controller module. The readout modules provide all necessary functions, including isolated power supplies, to operate up to 24 APV25 chips per module with high-impedance ground isolation. The frontend boards contain a minimal set of components as they are located inside the STAR TPC inner field cage and are inaccessible except during long shutdown periods. The frontend boards connect to the readout modules with cables up to 24 m in length, carrying unbuffered analog readout signals from the APV25 as well as power, trigger, clock and control signals. The readout module digitizes the APV analog samples to 12-bits at 37.532 MHz, and buffers the data. The readout controller distributes trigger and clock from the central trigger system, gathers the data over the backplane, and ships it to a linux PC via a 2.125 Gbps optical data link (Detector Data Link (DDL) from ALICE). The PC gathers data from multiple readout controllers and dispatches it to the STAR event builders. The readout modules, controllers, and backplanes are housed in a common crate together with the Silicon sensor HV bias power supplies. The DAQ system described above is shown in Figure 5-5.

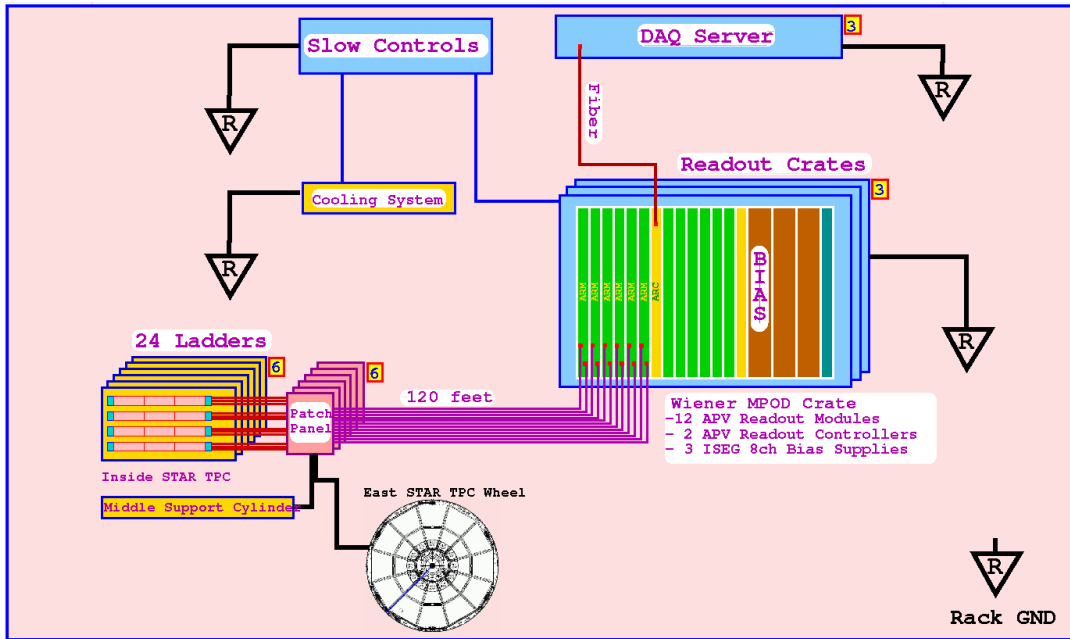


Figure 5-5: DAQ System for the FTS based on APV-chip readout.

### 5.3.5 Cooling System

The amount of heat generated by an APV chip is around 0.3 W. In order to keep the APV chips and Silicon sensors at low temperature, the APV chips need to be cooled. By replicating the cooling system of the STAR IST, a cooling system for the FTS can be easily fabricated, as in Figure 5-6.

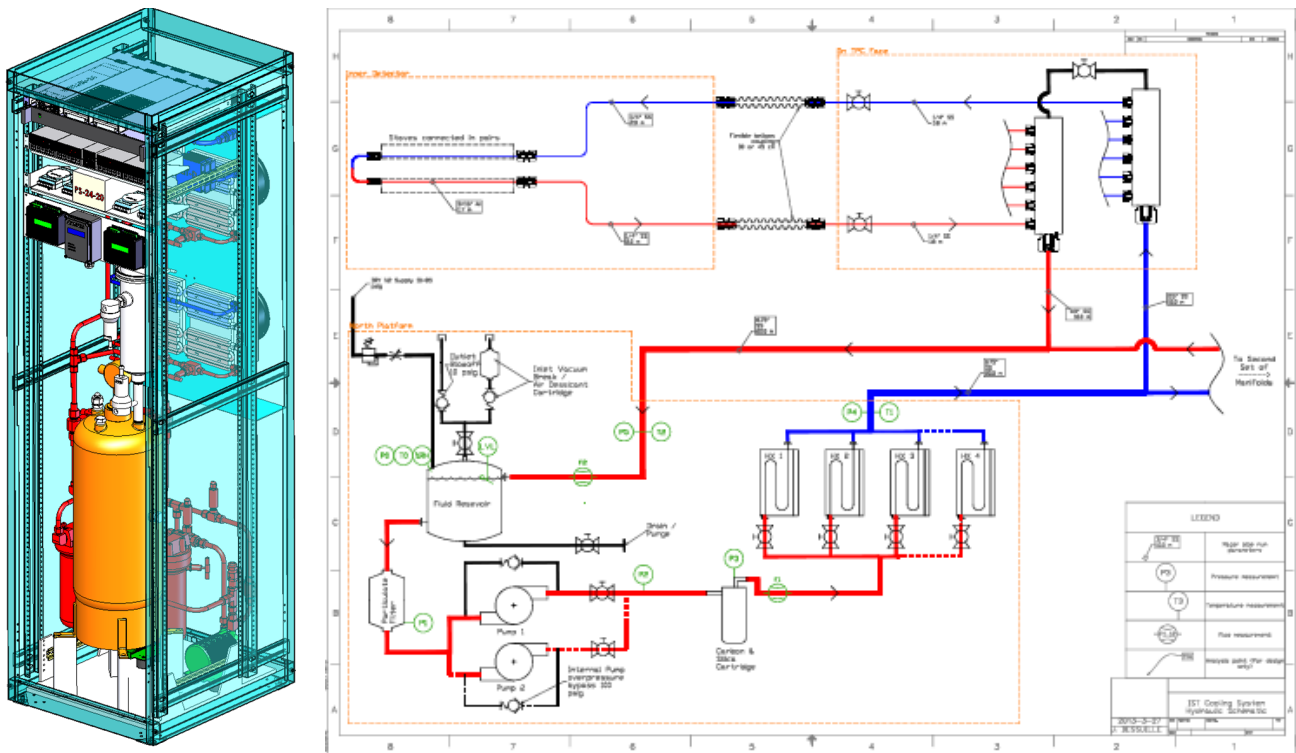


Figure 5-6: FTS cooling system. (Left) CAD drawing of the cooling system rack. (Right) Connections and flows.

### 5.3.6 Slow Control System

The slow controls system will serve as the primary means for controlling and monitoring the working parameters of the FTS. These parameters, such as temperatures, component currents and voltages will be interfaced with the standard STAR alarm system. The alarm system logs the parameter history and alerts the shift crews if operating limits are exceeded. The slow controls for the FTS and readout crates will be handled exclusively by Ethernet traffic to the FTS Linux box, through the ALICE DDL link to the readout crates, and then finally through the RDOs to the APV's via the local I<sup>2</sup>C link. There will be no other hardware needed for slow controls. All power supplies will be fitted with an Ethernet controls interface.

### 5.3.7 Radiation Exposure

The primary concerns in radiation damage to Silicon Ministrip detectors include possible damage to frontend readout chips by ionizing energy losses of charged particles, and to the Silicon sensors by non-ionizing energy losses of hadrons. The former will not be a concern if APV chips are used for the FTS. The APV chip was designed for the much higher radiation environment at the LHC. It is manufactured using an IBM 0.25  $\mu\text{m}$  radiation hard process and can tolerate 20+ Mrad radiation dose. The expected ionizing radiation exposure at STAR is orders of magnitude smaller, as shown in Table 5-1. From the running experience of the STAR IST at a radius of 14 cm from the beam, the non-ionizing radiation at RHIC is also small. After 14 weeks of Au+Au collisions at  $\sqrt{s}=200$  GeV in 2014, the bias current increased by 1-2  $\mu\text{A}$  per IST sensor, which has a volume of  $0.03 \times 4 \times 7.7 \text{ cm}^3$ . This suggests that 1-MeV neutron equivalent fluence in Run14 was less than  $5 \times 10^{10} \text{ cm}^{-2}$ . As the closest distance of the FTS sensor to the beam would be around 2.6 cm, the 1-MeV neutron equivalent fluence received in the proposed p+p and p+A running should be less than  $1 \times 10^{13} \text{ cm}^{-3}$ , which would not have a significant impact on the sensor performance. Therefore it can be safely assumed that radiation damage to the APV chips and Silicon sensors would not be a concern during normal data taking. Caution will be taken during beam injections and machine studies by turning off the power to the APV chips and Silicon sensors.

Radius [cm]	200 GeV Au+Au [krad]	500 GeV p+p [krad]
2.5	5.3-28	29-133
14	0.2-1	1-4
22	0.1-0.4	0.4-2

Table 5-1: Radiation field in krad from physics collisions in the center of STAR extrapolated to RHIC II luminosities for different radial positions for 12 weeks of run time.

### 5.3.8 Additional R&D

To validate and optimize the FTS design based on the Silicon Microstrip detector technology, R&D is needed in order to develop appropriate Silicon Ministrip sensors to meet the requirements. STAR has started an R&D program, which is crucial, so that a full design of the Silicon Ministrip sensors can be available by the beginning of 2019.

It is also important to reach a decision on the front-end readout chips. While the APV chip is attractive, as the full designs of backend readout and DAQ systems are available from the STAR IST detector, a survey of the chips available on the market will be performed before the final

decision. In order to have a full system design for the FTS, mechanical designs for the FTS disk and support structure are also needed. These will be investigated in the near future.

## 5.4 Support Structure

The STAR collaboration has successfully designed and installed a support cylinder supporting the HFT system and the West Support Cylinder (WSC) with an internal support mechanism for GEM disks as part of the existing STAR Forward Gem Tracker (FGT). Figure 5-7 shows a photograph of the WSC (left) along with a photograph of the inside of the WSC showing a FGT-type disk supported in the horizontal direction by carbon fiber rail using rail supports allowing to slide each disk on the actual rail. This is an important feature for installation and extraction and will be discussed in more detail below including the need for an in-situ installation. The forward tracking upgrade options discussed here will re-use this lightweight support system.

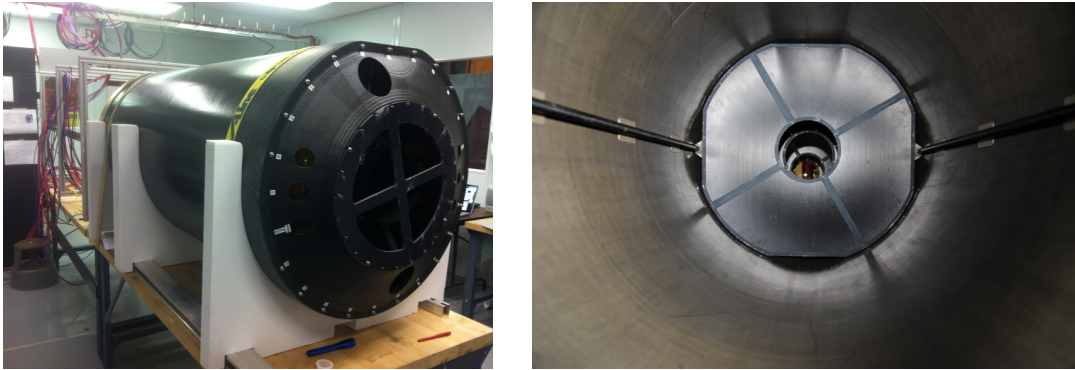


Figure 5-7: Photographs of the WSC prior to installation (left) and (right) of the inside of the WSC with two carbon rails supporting one FGT disk.

## 5.5 Survey and Alignment

The FTS planes will have to be aligned, both with respect to each other and with respect to the STAR reference frame. This will be achieved by survey measurements and ultimately by using tracks in p+p, p+A, and A+A collisions. In a silicon-based FTS, the internal structure of the silicon sensors will be known with an accuracy of better than 10  $\mu\text{m}$ , far beyond the physics requirements. This information is obtained through the production mask drawings of the silicon sensors, and accessed through alignment marks on these sensors. The FTS planes and mechanic mounting structures will again be surveyed after their assembly and before the installation into STAR. Once the FTS is installed in STAR, tracks produced in p+p, p+A, and A+A collisions will travel through the FTS planes. The relative positions and rotations among the FTS planes, and between the FTS planes and other mid-rapidity detectors, will be determined using an iterative residual method for the reconstructed tracks.

## 5.6 Installation Procedure

Following cosmic-ray, source, and beam tests, the FTS will be transported from UIC, the facilities where the wedges are assembled to Brookhaven National Laboratory for final assembly and integration. It is planned to design and use a suitable extension of the existing West-Support-

Cone internal rail structure on the West side of the STAR experiment, similar to the insertion mechanism of the FGT shown in Figure 5-8. Besides installation, this support will allow systematic in-situ tests of the FTS with STAR services as well as maintenance repair between RHIC runs without having to move the main detector to the assembly hall.

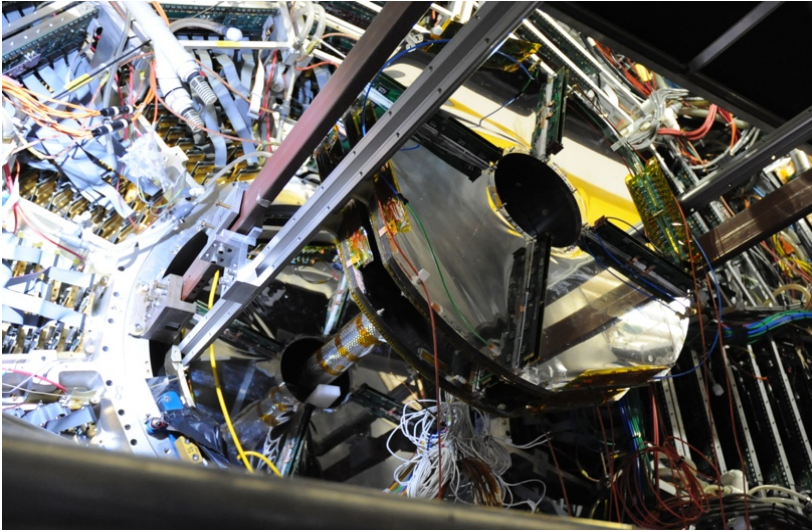


Figure 5-8: Rail setup for the STAR in-situ installation of the FGT subsystem. A similar concept is proposed for the FTS.

## 5.7 sTGC option for FTS system

Using Small-strip Thin Gap Chambers (sTGC), designed by the ATLAS experiment, is considered a practical alternative for the FTS forward tracking, when combined with inner silicon-strip sensors. One key advantage is a significant reduction of the project cost, while maintaining the excellent momentum resolution required.

### 5.7.1 sTGC Detector technology

The basic structure of a Small-strip Thin Gap Chamber (sTGC) is shown in Figure 5-9; more details can be found in Ref. [142]. It consists of a grid of 50  $\mu\text{m}$  diameter gold-plated tungsten wires, with a 1.8 mm pitch, sandwiched between two cathode planes located at a distance of 1.4 mm from the wire plane. The operating voltage is 2900 V for the wires. The cathode planes are made of a graphite-epoxy mixture with a typical surface resistivity of 100 k $\Omega$  sprayed on a 100  $\mu\text{m}$  thick G-10 plane. Behind the cathode planes, on one side of the anode plane there are copper strips for precise coordinate measurements that run perpendicular to the wires, and on the other side of the anode plane are copper pads used for fast triggering. The copper strips and pads act as readout electrodes. The pads cover large rectangular surfaces on a 1.5 mm thick printed circuit board (PCB), with the shielding ground on the opposite side. The latter will probably not be used at STAR.

The strips have a 3.2 mm pitch, much smaller than that of the ATLAS TGC; hence, they are named ‘small-strip TGC’. This strip pitch was optimized for good position resolution ( $< 100 \mu\text{m}$ ) using charge division between strips while maintaining a minimal number of read-out channels [143]. In practice, single strip-layer position resolutions of better than 50  $\mu\text{m}$  have been obtained, uniform along the sTGC strip and perpendicular wire directions, in recent prototype tests [144]. The operational gas is a mixture of 55%  $\text{CO}_2$  and 45% n-pentane. For the FTS setup, two layers of sTGC modules, with their strips perpendicular to each other, will be combined into one sTGC disk, which will provide  $x$ - $y$  (2-d) position reconstruction from strip charge read out.

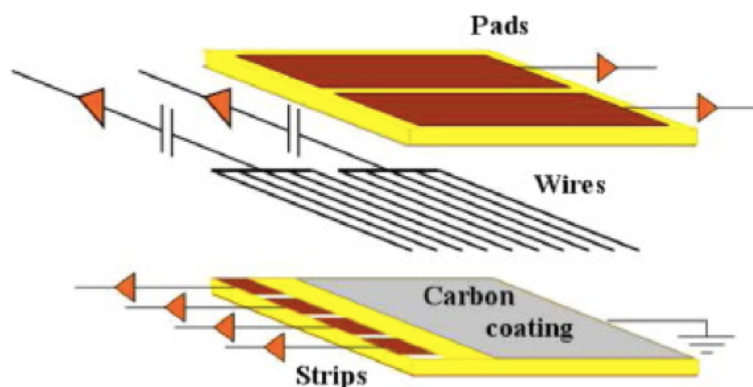


Figure 5-9: The sTGC internal structure.

### 5.7.2 Readout electronics of the sTGC

The detector is basically an MWPC with pad readout – similar to the STAR TPC – so this offers the possibility for large savings in cost and effort by re-using the STAR TPC electronics for its readout.

The simplest possibility (“Option A”) is *literally* reusing the current STAR TPC electronics as-is (based on the ALTRO ASIC). A sufficient amount of this electronics will become available after 2019 when STAR will replace it with new electronics for the STAR Inner TPC (iTTPC) Project. The obvious advantage is little or no cost in the design & production of the readout system. The whole section of the TPC readout chain can thus be repurposed, including the frontend (FEE) cards, the multiplexer cards (RDO), power-supplies, optical fibers, the readout cards, readout PCs, all the DAQ readout and control software, leading to a dramatic decrease in cost, effort, risk & integration.

Another possibility (“Option B”) is using the new electronics that is being developed for the STAR iTTPC Project based on the SAMPA ASIC. STAR is currently designing and testing the electronics readout for the iTTPC and could re-use those efforts for the electronics of the sTGC with small modifications. The cost of the readout in the next subsection is based on this assumption.

Lastly (“Option C”), we could use the original ATLAS electronics, which was already designed for this detector. The cost for this option would be \$225K for 19200 channels for 4 sTGC double-layer disks excluding VMM, TDS, ROCs. The disadvantage is in the effort to integrate in the existing DAQ. The clear advantage is that this electronics works well for this specific sTGC.

At this stage of the Proposal, it is too early to make a decision as to which of these options will be considered the best. An R&D effort will be necessary, and investigation of “Option A” has already been started using the ATLAS prototypes. This will continue into the next year.

### 5.7.3 Construction & cost estimation sTGC

The high-energy physics group at Shandong University is responsible for building 40 modules (each consisting of four layers) of new small-wheel sTGC’s. Because of the minimal re-design of the sTGC for the STAR forward tracking option – for example, using a square shape of 120 cm x 120 cm, with 3.2 mm strip pitch perpendicular to wire direction – it will be straightforward for the Shandong University group to produce 4 sTGC disks (each consisting of two layers) for STAR. The construction cost is estimated to be about \$300K, based on ATLAS experience, which can possibly be financed by the STAR Chinese groups.

The main cost will likely come from the electronics. For each 120 cm x 120 cm sTGC module, assuming 3 mm strip pitch, with each strip segmented into 6 pieces (20 cm long), and four

two-layer disks,  $2400 \times 8 = 19200$  channels will be required. Segmented strips are important for multiple readout of each line perpendicular to the wire, for high-multiplicity events such as heavy ion collisions. The cost will be about \$300K, assuming the iTPC option (see previous subsection), and could be reduced substantially by simply re-using the current TPX electronics (Option A).

## **5.8 Milestones and Schedule**

In order to realize the FTS for 2021 following the milestones below, it is critical to realize an approval process of the forward upgrade in a timely fashion.

- 05/2019 Technical Design Report
- 07/2019 Production Readiness Review
- 09/2019 Start Procurements and Assembly
- 09/2020 Install FTS into STAR
- 01/2021 Start Commissioning of FTS

## 6 Project Cost, Schedule, and Management

Please note none of the cost presented below includes the 20% overhead needs to be paid as a BNL handling tax.

Below is the cost information for FCS.

### FCS WBS Level 3.

WBS Number	WBS Description <b>Electromagnetic Calorimeter</b>	Base Cost (direct + indirect)	Contingency
y.1.1	SiPMs	\$120,000	\$18,000 (15%)
y.1.2	Monitoring System	\$5,000	\$1,500 (35%)
y.1.3	Readout Electronics (FEE/Digitizers)	\$272,700	\$95,000 (35%)
y.1.4	Light Guides	\$20,000	\$7,000 (35%)
y.1.5	Calibration of FEEs (students labor)	\$20,000	\$7,000 (35%)
Base Cost		\$437,000	
Contingency		\$128,500	
Total Cost		\$566,200	

The base line scenario of using SiPM as readout sensors for EM section may change in favor of APDs once we'll finish ongoing R&D on radiation hardness of both type of sensors at STAR IP. In this case the cost of readout sensors will be approximately \$240k.

WBS Number	WBS Description <b>Hadronic Calorimeter</b>	Base Cost (direct + indirect)	Contingency
x.1.1	HAD Absorber Plates	\$316,000	\$80,000 (25%)
x.1.2	HAD Scintillator and WLS	\$224,640	\$48,000 (25%)
x.1.3	HAD Structural elements	\$89,000	\$32,000 (35%)
x.1.4	Mechanical Integration into STAR	\$100,000	\$35,000 (35%)
x.1.5	HAD Final Assembly Labor (stacking)	\$40,000	\$14,000 (35%)
x.1.6	APDs (exclusive of electronics)	\$135,000	\$20,000 (15%)
x.1.7	Monitoring System	\$5,000	\$1,500 (35%)
x.1.8	Readout Electronics (FEE/Digitizers)	\$92,000	\$20,000 (35%)
Base Cost		\$1,001,640	
Contingency		\$250,500	
Total Cost		\$1,252,140	

WBS Number	WBS Description <b>Preshower-Detector</b>	Base Cost	Contingency
x.1.1	Refurbished SiPM readout boards	\$20,000	\$5,000 (25%)
x.1.2	DEP readout electronics (Digitizers)	\$25,000	\$9,000 (35%)
Base Cost		\$45,000	
Contingency		\$14,000	
Total Cost		\$59,000	



The full trigger system for the FCS is estimated to cost, including NRE and 25% contingency, \$57K.

### FTS WBS Level 3.

WBS Number	WBS Description	Base Cost	Contingency
	<b>FTS (6-disk)</b>		
y.1.1	Electronics	\$900,000	\$270,000 (30%)
y.1.2	Mechanics	\$1,000,000	\$450,000 (45%)
y.1.3	Assembly and Testing	\$560,000	\$196,000 (35%)
y.1.4	Integration	\$450,000	\$225,000 (50%)
Base Cost		\$2,910,000	
Contingency		\$1,141,000	
Total Cost		\$4,051,000	

This table details the cost for the FTS if a pure Silicon solution is chosen with APV chips, and reusing the IST readout and cooling systems.

### FTS WBS Level 3.

WBS Number	WBS Description	Base Cost	Contingency
	<b>FTS (3-disk)</b>		
y.1.1	Electronics	\$600,000	\$180,000 (30%)
y.1.2	Mechanics	\$640,000	\$288,000 (45%)
y.1.3	Assembly and Testing	\$400,000	\$140,000 (35%)
y.1.4	Integration	\$450,000	\$225,000 (50%)
Base Cost		\$2,090,000	
Contingency		\$833,000	
Total Cost		\$2,923,000	

This table details the cost of the Si for the FTS with APV chips, and reusing the IST readout and cooling systems if the solution chosen is a combination of Silicon disks and sTGCs.

Assuming using APV chips for the readout but the FTS cannot reuse the IST readout and cooling systems, it will bring the total cost up to \$4,456,000 (\$3,198,000) for 6 (3) disks, respectively.

The cost of 4-disks (8 layers) of sTGC (120cmx120cm) estimated from the ATLAS experience.

WBS Number	WBS Description	Base Cost (RMB)	Contingency
	<b>sTGC (4-disks)</b>		
y.1.1	Ground Plane Board	320k	110k (50%)
y.1.2	Anode Wire	80k	40k (50%)
y.1.3	FR4 side mounts	40k	20k (50%)
y.1.4	Assembly	60k	30k (50%)
Base Cost		500k (RMB) (\$72k)	
Contingency		250k (RMB) (\$36k)	
Total Cost		750k (RMB) (\$110k)	

To this cost the cost for the readout system (see section 5.7.2) and infrastructure should be added.

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