Project Description
Information about the Proposal

Instrument Location and Type

Instrument Location: STAR detector at the RHIC facility, Brookhaven National Laboratory
Instrument Code: MRI-61 Sub-atomic Particle Detector/Array – Calorimetry

Justification for submission as a Development Proposal

Funds are requested to design, construct, install, and commission a Forward Calorimeter System (FCS) for the STAR detector at RHIC. The FCS will extend the kinematic reach of STAR to far- forward pseudorapidities, and enable new physics measurements, as described below. The FCS will be a shared instrument for more than 350 researchers. The envisioned physics program places stringent requirements on the instrument's energy and angular resolutions, readout speed, triggering capabilities, ability to operate in a high rate environment, and overall geometry. It is not available for purchase from a vendor. The design of the FCS detectors and electronics draws extensively on similar subsystems currently operating successfully at STAR. Members of the consortium have many years of experience in collider experiments at high energy, and possess the skill and resources needed to bring the project to completion. We will also benefit from, and heavily rely on, the expertise of scientists, engineers, and technicians from Brookhaven National Laboratory (BNL).

Like most state-of-the-art detector systems for high-energy experiments, the devices needed cannot be bought 'off the shelf.' Hardware purchases are for raw stock items, or individual components, such as silicone photomultipliers (SiPM's). Substantial machine shop time will be required, and must be distributed over several university facilities. While smaller pieces will be assembled, tested, and QA'd at home institutes, final assembly will necessarily take place *in situ* at BNL. Significant effort is thus needed at all levels, from many undergraduate hourlies to highly specialized engineers. Several academic faculty have secured months of teaching release to devote large fractions of their time to supervise in-house construction and testing activities, final assembly at BNL and to oversee initial commissioning of the FCS with beam, along with ongoing simulation efforts.

Research Activities to be Enabled

Quantum Chromodynamics (QCD) is a building block in the Standard Model of particle physics. It describes strongly interacting matter in terms of point-like *quarks* interacting via the exchange of gauge bosons, the *gluons*. QCD has proven to be a remarkably rich theory; though it becomes 'simple' at very high energy, where perturbative approaches can be used, detailed understanding of low-energy phenomena—such as the structure of the hadrons that make up 99% of the visible mass of the universe—remains elusive theoretically, and must be explored through experiment.

Over the last decade or so, we have made enormous strides in our understanding of nucleon structure, and how the quarks and gluons of QCD give rise to observable properties of a proton, for example. This knowledge is due largely to the great success of the experimental programs at RHIC. We now have compelling evidence that *gluons contribute significantly to the proton's spin*, at a level comparable to that of the quarks. We have gained new insights into the *nature and origin of the quark-antiquark 'sea,'* through studies of $W^{\pm}$ production in *pp* collisions. Clear signatures of *transverse polarization effects*, sensitive to the relative alignment of the quark spins with that of a transversely polarized proton, have been revealed via studies of di-hadron and hadron-in-jet asymmetries. Details on these and many other key results can be found in ref. [1].

Despite these achievements, however, deep and critical questions remain unanswered. How are the quarks, gluons, and their spins distributed in space and momentum inside the nucleon? Does orbital motion contribute to the proton spin? In a large nucleus, how do quarks and gluons behave as they propagate through the ‘cold’ nuclear medium? Do some become unbound in this environment? Is there a predicted ‘saturated’ gluon state that is universal among all strongly-interacting systems, and if so, how would we know?

When the RHIC Beam Energy Scan is completed in 2021, STAR will be very well positioned with an excellent suite of detectors to address many of these questions – but over a limited range in *x*, the fraction of the proton momentum carried by the quark or gluon (collectively, parton) of interest. To advance our understanding of how known properties of hadrons and hadronic matter emerge from QCD, it is essential that one probes both the higher-*x* or valence region, and at low values of *x*, where gluons and sea quarks are abundant. These kinematic regions are accessed most directly in highly asymmetric partonic collisions, *i.e.*, when the *x* of one colliding quark or gluon greatly exceeds that of the other, *i.e.*, $x_1 \gg x_2$. For such events, the outgoing particles are emitted—and thus must be detected—at far forward angles. The FCS, in conjunction with new capabilities for charged particle tracking (not part of this request), meets this demand.

The physics program described below was strongly endorsed by the BNL Program Advisory Committee, which concluded in its 2018 final report: “STAR presented a rich program for future operation after BES II that addresses many important and innovative topics in *pp*, *p*A and AA physics. The most interesting of these is focused on forward physics that would be made possible by a forward upgrade covering rapidities up to 4.2.” Detail on the envisioned physics program can be found in [2].

Transverse polarization effects in the proton

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

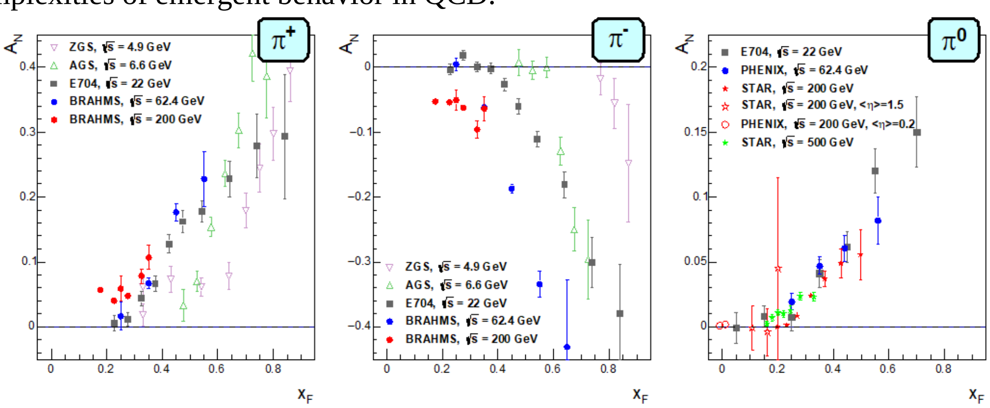

Figure 1: Transverse single spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as a function of Feynman-*x*.

Results from STAR and PHENIX have shown that transverse single spin asymmetries (SSA) for inclusive hadron production that were first seen in *pp* collisions at fixed-target energies and modest p_T remain large to the highest RHIC center-of-mass energies, $\sqrt{s}$ = 500 GeV, and surprisingly large p_T. Figure 1 summarizes the world data as a function of Feynman-*x*. The asymmetries are seen to be nearly independent of $\sqrt{s}$ over a range of roughly 5-500 GeV. This is particularly striking because, while the pion cross sections are consistent with NLO pQCD expectations at RHIC energies [3], they are up to an order of magnitude larger than NLO pQCD calculations at low $\sqrt{s}$ [4].

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 the sizable SSAs in the QCD framework: Transverse momentum-dependent parton distribution and fragmentation functions, such as 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. The Sivers function and its twist-3 analog, the Efremov-Teryaev-Qui-Sterman (ETQS) function, encapsulate the probability for a quark or gluon preferentially to carry transverse momentum left or right in a proton that has spin up. Such a preference can arise, for example, from spin-orbit correlations. The Collins effect involves convolution of quark transversity with the Collins fragmentation function; the former characterizes the transverse polarization of a quark in a transversely polarized proton, while the latter describes azimuthal modulation of pions about the jet direction when a transversely polarized quark fragments. Transversity is a leading twist distribution in the proton: together with the unpolarized and helicity distributions, it is a fundamental proton property. However, it is chiral-odd, so much less is known about it, as it can't be probed with inclusive deep-inelastic lepton-proton scattering (DIS). Differences between the transversity and helicity distributions provide a direct, x-dependent connection to non-zero parton orbital angular momentum in the proton [5]. The integral of the transversity distribution gives the tensor charge of the nucleon, which can be calculated on the lattice for comparison with experiment, and plays a critical role in BSM physics [6].

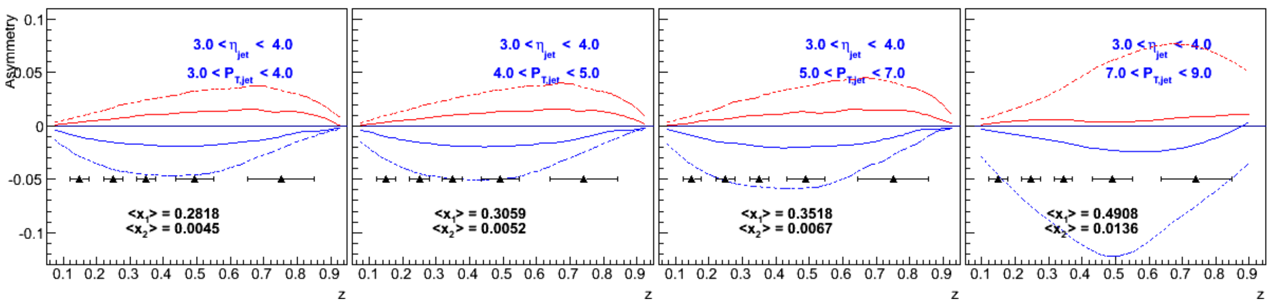

Figure 2: Expected h- Collins asymmetry uncertainties (black points) from a sampled luminosity of 268 pb^{-1} compared to positive (red) and negative (blue) pion asymmetries based on the Torino extraction [7] (full lines) and the Soffer bound [8] (dashed lines) as a function of fractional energy z for bins in jet η and p_T. Most uncertainties are smaller than the diamonds.

The STAR Forward Upgrade will enable unique measurements related to the Sivers and Collins effects. Contributions from finite momentum resolution, as well as beam remnants and underlying event, have been included in our statistical estimates for these two processes. By tagging a charged hadron in the jet, we will separate the inclusive jet asymmetry into contributions that arise primarily from up- *vs*. down-quark fragmentation, which have opposite sign Sivers effects in semi-inclusive DIS (SIDIS). At low jet p_T, Collins asymmetry measurements will overlap the high end of current SIDIS measurements, which only cover up to $x \sim 0.3$. At higher p_T, the Collins measurements made possible with the Forward Upgrade will extend our knowledge to $x \sim 0.5$. Mapping out this physics in the high-x region is essential in order to constrain the tensor charge.

The studies presented in 2 are for the Collins asymmetries, though statistical uncertainties should be similar for other measurements that use azimuthal correlations of hadrons in jets. One important example is the "Collins-like" asymmetry, to access the distribution of linearly polarized gluons, which play a critical role in recent calculations of the transverse momentum distribution of Higgs production at the LHC. The best kinematic region to access this distribution is at backward angles with respect to the polarized proton and at small jet p_T. The FCS will enable high precision measurements of gluon linear polarization down to $x \sim 0.005$

Longitudinal polarization studies and gluon helicity

Longitudinally polarized *pp* collisions at $\sqrt{s}$ = 500 GeV allow one to probe the very low *x* region of the gluon helicity distribution $\Delta g(x)$. A future 500 GeV *pp* run (integ. luminosity of 1.1 fb^{-1}) would reduce the statistical uncertainties of current STAR inclusive mid-rapidity jet results by a factor of 1.2. These data are sensitive to gluons in the range $0.01 < x < 1$, and while they suggest a positive $\Delta g(x)$ for moderate *x*, they do little to constrain the functional form of the distribution at low *x*. This translates into a large uncertainty in ΔG, the gluon contribution to the proton spin. Dijet experiments provide a more direct measure of the *x* values of the colliding partons; when extended to the FCS region, we can access *x* down to a few times 10^{-3}, with precision far beyond current uncertainties. The present status of STAR forward dijet studies is presented in the Prior Results section.

Physics opportunities with (un)-polarized proton-nucleus collisions

The FCS system, combined with forward tracking, will enable a *p*A physics program that is unique to RHIC, and will impose new and needed constraints on initial state effects in strong interactions with a finite nucleus. The uniqueness of the RHIC program stems from the flexibility of the RHIC accelerator to run collisions of different particle species at very different center-of-mass energies. This, in combination with existing and planned STAR detector capabilities, allows us to disentangle nuclear effects in the initial and final state, as well as shadowing from saturation effects, in regimes where all these effects are predicted to be large.

Our current understanding of nuclear parton distribution functions (nPDFs) is still very limited when compared with the rather precise knowledge of PDFs for free protons collected over the past 30 years. Extraction of the nPDFs from available data, performed by DSSZ [9] and EPS09 [10], are completely unconstrained in many regions of *x*, except for assumptions made in the functional form.

High precision data at small *x* and over several values of Q^2 are needed to constrain the magnitude of suppression in regions where non-linear effects in the scale evolution are expected. Such data are also needed for several different nuclei, as the A-dependence of nPDFs cannot be predicted from first principles in pQCD. We note that measurements from RHIC are essential even when compared to what can be achieved in p+Pb collisions at the LHC. Due to the higher center-of-mass energies, LHC data are at very high Q^2, where nuclear effects are already reduced significantly by evolution. As such, a recent article [11] that assessed the impact of the LHC Run-I p+Pb data on determinations of nPDFs showed modest improvement. In sum, 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 sea quarks and gluons is expected to be sizable, and yet is currently completely unconstrained.

Extraction of this information is less ambiguous if one uses *p*A processes in which strong QCD final-state interactions can be neglected or reduced. Such golden channels include a measurement of R_{pA} for Drell-Yan production at forward pseudorapidities (w.r.t. the proton), to constrain the nuclear modifications of sea-quarks, and R_{pA} for direct photon production, in the same kinematic regime, to constrain the nuclear gluon distribution. These form critical components of the nuclear initial-state studies that will become possible only with enhanced forward detector capabilities.

As a final comment, we note that Drell-Yan measurements are particularly challenging, as one must suppress an overwhelming hadronic background: the DY cross-section is 10^{-5} to 10^{-6} smaller than hadron production, so misidentifying a hadron as a lepton must be suppressed to about 0.1%, while maintaining reasonable electron detection efficiencies. We have therefore carried out detailed simulation studies of the combined electron/hadron discriminating power of the proposed forward upgrade [2]. By applying multivariate-analysis techniques to the EM/hadronic shower development and momentum measurements, we were able to achieve hadron rejection powers of 200 to 2000 for hadrons of 15 GeV to 50 GeV, while requiring 80% electron detection efficiencies.

Probing gluon saturation effects in nuclei

It is well known that PDFs increase at small x. If one imagines a large number of small-x partons in a highly Lorentz-contracted proton, the gluons and quarks become tightly packed in the transverse plane. The distance between partons decreases as parton density increases, and hence becomes large at low-x or for a heavy, contracted nucleus. One can define the saturation scale Q_s as the inverse of the mean transverse inter-parton distance, and expect it to grow with increasing A and decreasing x.

Our understanding of proton structure and nuclear interactions at high energy would advance significantly with the definitive discovery of this saturation regime [12]. Saturation physics would provide an infrared cutoff for perturbative calculations. If Q_s is large, it makes the strong coupling constant small, $\alpha_s(Q_s^2) << 1$, validating perturbative QCD calculations. The small-x evolution of TMDs in a longitudinally or transversely polarized proton can be derived in a saturation framework [13] under better theoretical control due to Q_s. Saturation physics may thus help us understand both the quark and gluon helicity PDFs, as well as the Sivers and Boer-Mulders functions. The actual calculations in saturation physics start with classical gluon fields (as gluons dominate quarks at small-x) [14], which are then evolved using the nonlinear BK/JIMWLK evolution equations [15]. These suggest that the saturation scale can be well-approximated by $Q_s^2 \sim (A/x)^{1/3}$.

While the EIC is expected to provide more definitive evidence for saturation physics [16], it is equally important, and complementary, to generate high-precision measurements in p+A collisions at RHIC. Such measurements would significantly enhance the discovery potential of the EIC, as they would provide a stringent test of universality for saturation. RHIC is capable of running p+A collisions for different nuclei, so one can check the expected $A^{1/3}$ dependence empirically, which avoids potential issues with dividing p+Pb collisions into N_{part} classes [17]. To access the kinematic regime sensitive to saturation, with $Q^2 > 1$ GeV^2, requires measurements at forward rapidity, where low-x nuclear gluons can be probed. The saturation scale here should be on the order of a few GeV^2.

To date, the golden channel at RHIC to search for saturation has been the angular dependence of two-particle correlations, an essential tool for testing the underlying QCD dynamics [18]. A proton headed towards the FCS provides a high-x parton—typically a valence quark—that probes the low-x partons—predominantly gluons—in the ion beam, with both outgoing partons, and hence particles, headed into the FCS. As noted earlier, for clean interpretation of the data it is highly advantageous to avoid strong interactions in the final state, so direct photon production will be one of primary tools. These events occur predominantly via QCD Compton scattering, $q + g \to q + \gamma$.

Through measurements of the azimuthal correlations in p+A collisions for direct γ+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 γ+jet production only accesses the dipole gluon density, which is better understood theoretically [19,20]. On the other hand, direct γ production is experimentally more challenging due to its small cross-section and large background from di-jet events in which photons from fragmentation or hadron decay are misidentified as direct photons. The feasibility to perform direct γ+jet measurements with the proposed forward upgrade at $\sqrt{s_{NN}}$ = 200 GeV has been studied. PYTHIA-8.189 [21] was used to produce direct γ+jet and di-jet events. To suppress di-jet backgrounds, the photon and jet were required have $\left|\phi^{\gamma} - \phi^{jet}\right| > 2\pi/3$ and $0.5 < p_T^{\gamma}/p_T^{jet} < 2$, with both $p_T > 3.2$ GeV/c. Detailed isolation cuts were imposed on the γ candidate. With these cuts, the signal-to-background ratio was ~ 3:1 [22]. The expected number of direct γ+jet events will be around 1.0M / 0.9M in p+Au / p+Al collisions for the proposed run in 2024, which is sensitive to the gluon density in $0.001 < x < 0.005$ in the Au nucleus.

Longitudinal dynamics in Au+Au collisions

The kinematics of RHIC A+A collisions provides a unique opportunity to make precise measurements of multiple flow harmonics and their correlations near the beam rapidity. In comparison to the LHC, one expects stronger breaking of boost-invariance, stronger variation of the initial temperature, and therefore greater sensitivity to temperature-dependent transport over a given window of rapidity at RHIC. The addition of new high-resolution calorimetry and charged-particle tracking at far-forward rapidity at STAR will allow scientists to fully exploit the unique and needed advantages offered at the RHIC facility. These detectors and these beams are essential ingredients, if one is to constrain the full 3D structure of the initial state and transport parameters such as η/s (T) and ζ/s (T). Hydrodynamic simulations indicate that RHIC collisions can better constrain η/s (T) near its minimum [23].

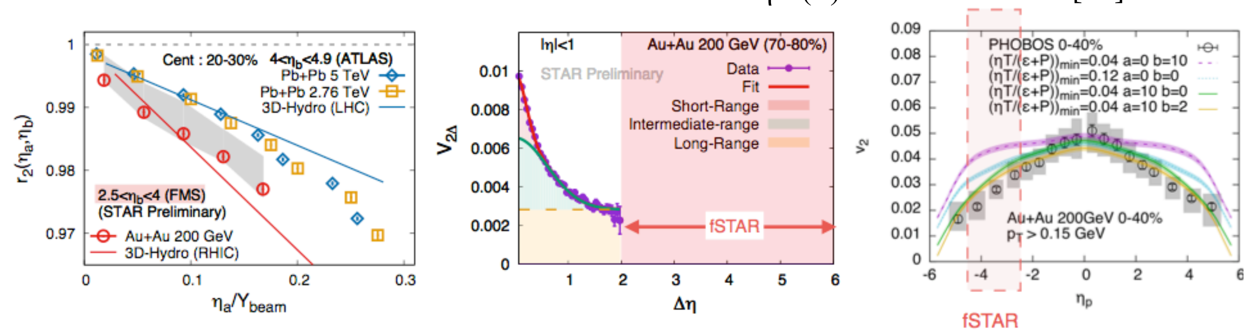

Figure 3: Left: Preliminary data from STAR demonstrating the measurement capabilities of longitudinal de-correlation of elliptic anisotropy (r_2) using the existing FMS detector (2.5<η<4). Current data show interesting trends but suffer from systematics (grey band); the forward upgrade (fSTAR) in this region will improve such measurements. Middle: The STAR measurement of the relative pseudorapidity dependence of the second-order Fourier harmonic coefficient $V_{2\Delta}$ of two-particle azimuthal correlations at mid-rapidity in 200 GeV Au+Au collisions. The measurement over the limited window of $|\eta|<1$ indicates contamination from short-range non-flow contributions. fSTAR will help disentangle the long-range component of $V_{2\Delta}$ that is sensitive to initial state physics. Right: Hydrodynamic simulations [23] demonstrating sensitivity of elliptic flow at forward rapidity to different parameterizations of η/s (T) (*a* and *b* are parameters that determine the growth of η/s in the hadronic and QGP phase respectively). Existing data from PHOBOS show large uncertainties; the fSTAR upgrade will improve these measurements & better constrain η/s (T).

Preliminary results from measurements of longitudinal de-correlation of elliptic flow (r_2) in Au+Au 200 GeV collisions, using the Forward Meson Spectrometer at forward rapidity (2.5<η<4), are shown in Figure 3(left). This demonstrates the capability of STAR to study the breaking of boost invariance in A+A collisions. The FCS will improve the systematics of such measurements. The need of increasing the acceptance of STAR to make more precise flow measurements is seen in Figure 3 (middle). The forward upgrade will help remove non-flow background contribution in such measurements. Precision flow measurements over a wide acceptance, particularly in the forward rapidity [23], will help constrain η/s (T) as shown in Figure 3 (right).

In 2017, STAR published in Nature [24] the discovery of Global Hyperon Polarization (GHP) in the most vortical fluid known. GHP is predicted to grow with rapidity due to the increase of QGP hydrodynamic viscosity. This discovery provides a new tool for studying viscosity and vorticity at RHIC, from top energies to the BES-II energies. Even with the multiple major upgrades in recent years, the STAR detector is only capable of tracking and particle identification of hyperons within pseudorapdity of |η|<1.5. Our simulations show that the proposed forward upgrade will allow us to reconstruct Λ's in both polarized p+p collisions at 500 GeV and non-central Au+Au collisions at different energies.

Selected Results from Prior Support

Many of the measurements to be carried out at forward η with the FCS have been studied at mid-rapidity (and at moderate x) with the current suite of STAR detectors. In addition to studies of the Collins asymmetry [25], one can also probe transversity via Interference Fragmentation Functions (IFF), the azimuthally asymmetric distribution of hadron pairs within a jet. Sizeable asymmetries have been measured at STAR 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 provide experimental constraints on evolution effects. The first extraction of transversity utilizing STAR 200 GeV IFF data from the 2006 RHIC run [26] has been performed recently [27]. In 2018 STAR published the first measurements of IFFs in 500 GeV *pp* data [28]. These 500 GeV results will be included in the next generation global analyses. Figure 4 shows the asymmetries as a function of η at 500 GeV.

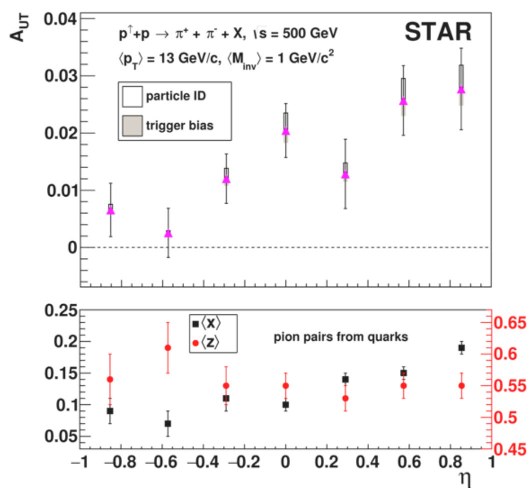

Figure 4: The upper panel shows the IFF asymmetry $A_{UT}^{sin(\phi)}$ as a function of di-pion pseudorapidity in 500 GeV *pp* collisions. The lower panel shows the mean values of x and z of the di-pion pairs for the points in the upper plot.

To probe gluon helicities, STAR has measured di-jet double spin asymmetries, A_{LL} in the pseudorapidity range $-1 < \eta < 2$ [29]. These build on our very successful mid-rapidity inclusive jet results. Figure 5 shows published results for p+p collisions at √s = 200 GeV (blue) [30] and preliminary data for √s = 510 GeV (red) [31] based on data from 2009 and 2012 respectively. The impact of measurements from 2009+2015 (√s = 200 GeV) and 2012 + 2013 (√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 NLO which matches the experimental cuts and jet parameters.

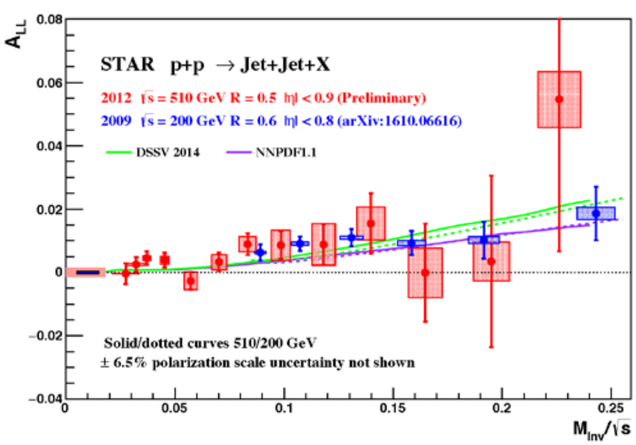

Figure 5: STAR measurements of di-jet double spin asymmetries A_{LL} versus scaled invariant mass $M_{inv}/\sqrt{s}$ for mid-rapidity p+p collisions at √s = 200 GeV (blue) and √s = 510 GeV (red), compared to model predictions based on the DSSV14 [32] and NNPDFpol1.1 [33]. The statistical uncertainties will be reduced by a factor of approximately 1.7 after data recorded during 2013 (510 GeV) and 2015 (200 GeV) are included.

Description of the proposed research instrument

The proposed FCS is a cost-effective design using low-risk technology. Substantial reduction in cost was achieved by replacing a proposed W/ScFi SPACAL EMCal with the refurbished PHENIX sampling EMCal [34]. In addition, the FCS will reuse the existing Forward Preshower Detector (2.5 < η < 4) that has operated successfully in STAR since 2015. The proposed system will have good electromagnetic (~8%/$\sqrt{E}$) and hadronic (~50%/$\sqrt{E}$+10%) energy resolutions. The FCS will consist of 1496 EMCal towers and 520 HCal towers, split into a pair of left/right symmetric modules, each covering a transverse area ~1.3 m wide × 2 m high. The hadronic calorimeter will be a sandwich iron-scintillator-plate sampling type, based on extensive STAR Forward Upgrade and EIC Calorimeter Consortium R&D. Both calorimeters will share the same cost-effective readout electronics, using SiPMs as photo-sensors. It can operate without shielding in a magnetic field and in high radiation environments. The system is scalable and easily re-configurable. Integration into STAR will require minimal modification of existing infrastructure. The method of construction for sandwich hadronic calorimeters was developed in the STAR R&D program and is considered a baseline design in the outgoing hadron region of a dedicated EIC detector.

There are several factors which led us to adopt the above technologies for the proposed FCS. The electromagnetic and hadronic energy resolutions are sufficient to carry out the proposed measurements outlined previously. 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. In-beam tests have demonstrated that the required energy resolution can be reached by replacing lead with iron in the hadronic section, a cost-effective solution. The forward calorimeter system has to be very compact spatially, dictated by the configuration of the STAR beamline and other existing STAR detectors, another factor favoring SiPM's as photo-detectors for both the EM and hadronic sections. Finally, the FCS has to be designed so that the hadronic calorimeter can be assembled in place (the EMCal towers are simply stacked inside an enclosure). 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*, largely by undergraduate and graduate students, who provide important manpower resources within the STAR collaboration.

Much more detail on the technical design and prototyping of the FCS can be found in [2].

Electromagnetic and Hadronic calorimetry: technology and design

The Electromagnetic Calorimeter (EMCal) comprises 1496 individual Pb/Sc towers, each ~18 X_0 deep. These will be taken from the decommissioned PHENIX detector; the first SuperSector was recently (mid-January) moved to the STAR building for de-assembly. The existing PMT's will be removed and replaced with new light guides and a SiPM carrying board, optically connecting four SiPM's to each tower. The towers have penetrating (embedded) wavelength-shifting fibers to provide light collection. The refurbished towers will be checked for light-tightness, bundled into modules of four, and stacked in place at the west end of STAR, at which point the FEE boards will be connected utilizing Pogo pins in the existing holes of the modules. Structural support is provided by an enclosing box, to be designed and built by UCLA, for each half of the detector.

Mechanically, the Hadronic Calorimeter (HCal) is more complicated, yet still straightforward to assemble. Each 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 6.

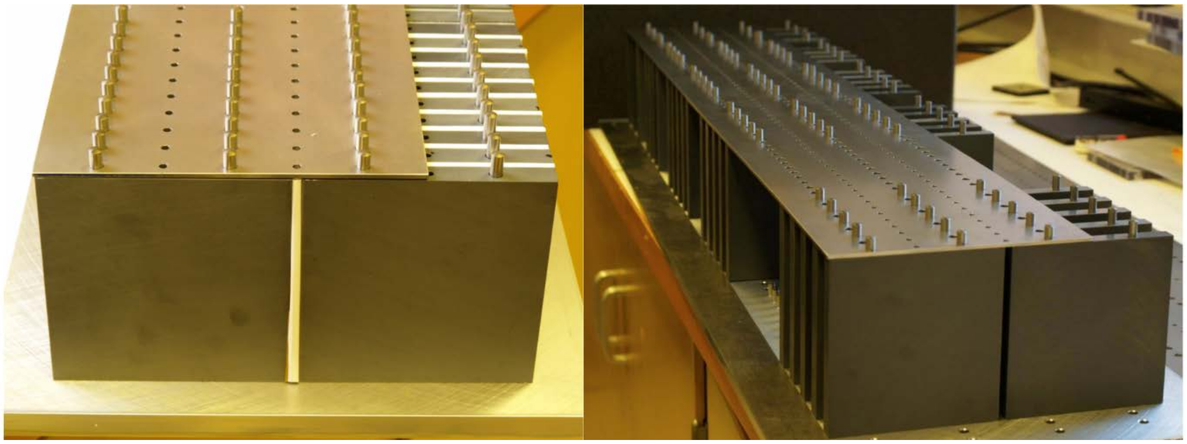

Figure 6: LEGO-type HCal mechanical structure. Absorber plates (gray) are positioned with the aid of dowel pins. Scintillation and WLS plates (white in color) are inserted in between absorber plates. Steel master plates work as a link between adjacent rows and front-and-back plates of the calorimeter.

Holes in the bottom base plate of the detector provide locations for the absorber plates. Each absorber plate has two holes for dowel pins at the bottom and two on top. 5-mm diameter steel dowel pins position each absorber plate with respect to the bottom base and top steel master plates. A single master plate covers one and a half rows of towers, providing interlinks between all absorber plates within one tower, between front and back steel plates of each section, and between adjacent rows of the HCal towers. The iron absorber plates are 20 mm thick, with a 3.1 mm gap between two adjacent plates. The 3-mm thick scintillation plates slide inside these gaps. There are 38 layers of Fe/Sc in the hadronic section, corresponding to ~4.5 interaction lengths. Scintillation light from each tower is collected with a 3-mm thick wavelength-shifting (WLS) plate (EJ-280) placed in the gap between two adjacent towers. All scintillation and WLS plates "float" within each layer (no mechanical load). Figure 7 shows an HCal prototype, which was assembled 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.

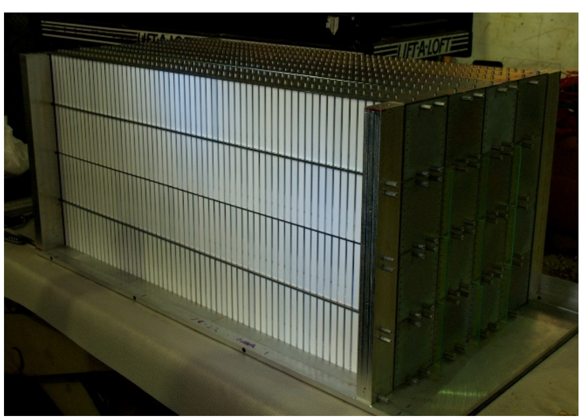

Figure 7*:* A full scale HCal prototype during assembly at the FNAL test run in 2014. The prototype consisted of sixteen individual towers. It was assembled from individual parts directly at the test beam site.

The light collection scheme of the HCal is 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 SiPM's to the WLS) were made through a narrow air gap. For the WLS plate, we found that 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 formed a good combination. The mylar film also serves as an optical isolator between the HCal towers. To achieve uniform light collection (within 10%) along the depth of the tower, we inserted a variable density filter printed on a clear mylar sheet between scintillation tiles and the WLS plate. Monte-Carlo calculations show that without such a filter the energy resolution degrades by a factor of two for energies above 20 GeV, compared to an ideal detector. Variation of light output from tile-to-tile in the tower within ±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 (mechanical tolerances required for assembly) has negligible effect on the detector energy resolution.

Photo-sensors and front-end electronics

A compact readout scheme has been developed for the FCS. For both the EMCal and HCal sections, we used silicon photo-multipliers (Hamamatsu Multi-Pixel Photon Counters, MPPC S10931-025p). They are small, fast, and insensitive to magnetic fields, and sufficiently radiation hard for readout in STAR [35]. SiPM's do not require HV for operation, which greatly simplifies the readout system. The cost of SiPM's continues to drop, while performance of these devices is becoming better and better for all manufacturers. In 2016 we tested a PHENIX Shashlyk module in the FNAL test beam, to verify energy resolutions and to measure the absolute light yields. The light yields (using PMTs) were approximately 1000 p.e./GeV, which is more than enough to proceed with SiPM readout.

The frontend electronics for the FCS builds on our extensive experience with SiPM readout in STAR, from the 2014 HCAL R&D, the FMS preshower and postshower detectors, the Event Plane Detector (EPD), and the 2017 test of PHENIX EMCal modules with SiPM readout and DEP at STAR. The common themes have been: to provide the SiPM's with accurate, high resolution, programmable, low noise bias voltage from a low source impedance, for a stable gain independent of the current drawn; to provide simple analog temperature monitoring and compensation (with programmable slope) of the bias voltage, again for a stable gain; to load the SiPM's with a low-input impedance signal chain, to keep the signal pulse fast and the bias voltage reasonably stable during the pulse; and to have a relatively simple, modular design which is easily integrated at low cost into a large system. This means low power, a multidrop control interface shared on power or signal cables, a robust signal output that can drive cleanly cables of 25 m or more to the digitizer boards, tolerance of input supply variations and noise, and so on.

The FCS EMCal frontend board provides readout for four towers of one calorimeter module. A precision NTC thermistor exists on each SiPM carrier board and is also connected through the pogo pins (thus 4 pins per tower). Signal processing on the frontend board consists of a 16 Ω load resistor, a passive pulse shaper, a programmable (CMOS switched) attenuator for gain control, and further a 50 Ω input amplifier, shaper, and cable driver circuit. We use relatively low cost, high density differential pair cables for the signal interface to the DEP boards. This innovation was extensively tested in the FMS postshower and EPD detectors. The programmable gain control in the FCS FEE board is a new feature, introduced in order to relate precisely the operating gain of the readout (with full scale 180 GeV) to an approximately 5× higher gain, to measure the response to cosmic ray muons for calibration purposes. It is expected to provide <1% uncertainty on relative gain, after calibration in the FEE board production test setup.

The SiPM bias voltage is regulated per channel with an on-board precision regulator with 14-bit control DAC with a voltage range of 0 to 70 V. Noise of the regulated bias voltage is <1 mV. Temperature compensation is provided per channel. The current to each SiPM board is monitored and multiplexed to a 16-bit ADC, with range of 0 to 410 μA. The absolute accuracy of the bias voltage and current monitor are each expected to be 1-2%. The slow controls interface to the FEE board utilizes I^2C, an industry standard. This has been tested in the 2017 EMCal FEE board and used successfully in the STAR EPD. Up to 16 FEE boards share a common control bus, using an addressable bridge chip on the FEE. The controls master is integrated into the DEP board. Each FEE board has a serial number chip which can be read and used for calibration lookup.

The FCS HCal frontend board is a two-tower board rather than four, and connects to its two SiPM carriers by short (~3 cm) cables. Other than this and the use of different absolute gains, the design is identical to the EMCal board. A photo of the EMCal FEE board is seen in Figure 8.

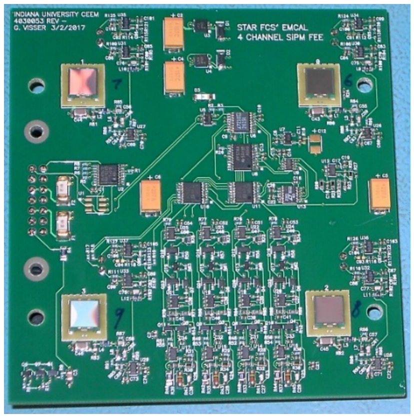

Figure 8: 2017 FEE board prototype, to be used on the refurbished PHENIX EMCal towers at STAR. The four SiPM’s are seen on small carrier boards that mount on this FEE.

Performance of the FCS in the FNAL test run

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 Cerenkov counter (standard equipment at the Muon Test Beam Facility, MTBF). Impact position was defined by a scintillator XY hodoscope. The HCal was oriented at a fixed angle of 2.5 degrees between the beam and the primary axis of the towers. The EMCal prototype was attached to the front steel plate of the HCal. All channels of the FCS were equipped with an LED monitoring system; 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 the gain stability for the 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%. No additional tower-by-tower calibration of the EMCal prototype with the beam was required.

The response of the FCS prototype module to hadrons is illustrated in Figure 4-6 in [2]. In a fully compensated calorimeter, the reconstructed energy of the incoming hadron is a simple sum of the energy deposited in the EMCal and HCal sections. To obtain the best energy resolution for hadrons in the FCS prototype module, we used an energy-dependent weighting factor for the EMCal, from about 2 at 3 GeV to 1.2 at 20 GeV and higher. With this weighting, we measured the e/h ratio for the FCS prototype module to be close to 0.95, and almost constant above 10 GeV. these results are quite consistent with results from detailed GEANT simulations of the detector response.

Mechanical Integration into STAR

Both the EMCal and HCal will reside on the West Platform (used previously for the FMS detector) and the West Alcove (on top of existing Concrete Structure) in the STAR Experimental Hall. The EMCal is about 10 tons in weight, whereas the HCal weighs ~40 tons. For the EMCal installation we will use the existing FMS rails and roller arrangement. The plate on top of the rollers will have to be shortened. The EMCal modules will be stacked on top of this plate.

The HCal will sit on top of the cavity in the west wall. Because the HCal detector will have to be moved to allow for maintenance of an ion pump and cryostat, a rail/roller arrangement similar to the one constructed for the FMS detector will be built. The preshower detector will be mounted in front of the EMCal using the existing structure of the FMS Preshower with small modifications.

FCS electronics digitizers and trigger processing

The FCS electronics system includes trigger, readout of SiPM's, a low-voltage system for SiPM's, low voltage power, slow control functions, calibration and monitoring controls, and interfaces to the STAR trigger, DAQ and slow controls systems. Essentially all of the front-end electronics functionality, including signal processing, digitization, buffering, and the formation of trigger primitives, will be carried out by the STAR DEP/ADC board.

The STAR BNL Electronics Group will design and produce a fairly 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. The basic board will consist of 32 12-bit ADCs running in sampling mode at 8× the RHIC clock. The ADC is 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. Up to 5 such boards (for a total of 160 channels) can be connected into a compact and cost-effective chassis. The data will be sent to a DAQ PC over a fast optical link. In a modification of the DEP board, the 32 ADC channels would be replaced with serial differential links. This board will form the core part of the FCS higher-level trigger.

Prototypes of the 16-channel digitizer DEP board, as well as the FCS FEE prototypes, were installed in STAR for the FY17 physics run at 500 GeV and connected to 8 SiPM's. The system was successfully commissioned and ran continuously in STAR, controlled via standard STAR Run Control, as well as the STAR Trigger System and Clock Distribution network.

Support from Brookhaven

It is important to note that Brookhaven National Laboratory will provide extensive resources to ensure the success of this project, including most of required manpower for electronics (other than frontend boards), and all costs associated with integration. They have secured all needed EMCal towers. Most importantly, given time constraints, they are making available funds to purchase ~10% of most critical components, so design and testing activities may begin soon. More details are provided in their support letter.

Broader Impacts

Advancing Discovery: Though QCD is commonly accepted as the correct theory of the strong nuclear interaction, there is much we need to learn and test experimentally regarding its implications, especially for low-energy, non-perturbative phenomena. As noted in earlier sections of this document, there are assumptions made regarding fundamental concepts, such as factorization and universality, that have not been subjected to experimental verification. These can be tested more carefully by comparing results from *pp* and *p*A measurements at RHIC with those obtained in (semi-inclusive) deep-inelastic lepton scattering at other facilities. The forward upgrade at STAR will increase the kinematic overlap between these measurements. The upgrade will also enable a more precise determination of the tensor charge, the integral over x of the valence quark transversity. This is important, as it is one of the few quantities related to the spin structure of the nucleon that can be compared between experiment and *ab initio* calculations in lattice QCD The tensor charge also sets the sensitivity of observables in low energy hadronic reactions to BSM physics processes involving tensor couplings to hadrons, *e.g.*, experiments with ultra-cold neutrons [36].

Impact on the Research Community: The addition of the proposed FCS, coupled with forward tracking, will significantly extend the physics reach and capabilities of the STAR detector. Upon completion of the Beam Energy Scan II in early 2021, STAR will continue as a premier facility for the cold QCD community at the national and international levels. The STAR collaboration, consisting of ~550 scientists from close to 60 universities and institutes, will remain open to participation from new institutes; indeed, 2-3 new groups join each year, as the scientific program evolves. A large fraction of the collaboration, especially many of our recent additions, are associated with institutes outside the United States.

Training and Mentoring Opportunities: To train the next generation of scientists, it is essential that students are given the opportunity to 'put into practice' the laboratory procedures and theoretical concepts they have encountered in their formal coursework. The instrument proposed here is very far from an off-the-shelf purchase: most of the hardware to be bought will be stock materials (sheets of scintillator and iron), electronic components, and miscellaneous supplies. Virtual armies of students, mostly undergrads, will work together with senior graduate students and technical personnel to turn the raw materials into the high-tech components that will need to be tested, characterized, QA'd, and eventually shipped to BNL, to become part of the assembly process.

The PI's have strong and established track records for student involvement in their research. Of the ten institutes in the coalition, two (Abilene Christian University and Valparaiso University) are RUIs. Each has requested support so that multiple students will be able to spend extended periods (during the summer) at Brookhaven Lab while the FCS detectors and electronics are stacked and cabled together. Many of the non-RUI institutes have similar requests. Equally important, several senior personnel within the coalition have asked for, and received, support from their home institute for teaching release, enabling them to spend time overseeing activities at their institute related to the project (QA/QC on machined parts, characterizing FEE boards, etc.) and, of particular importance, staying at Brookhaven throughout crucial periods, such as final assembly and system commissioning (internal monitoring systems, cosmic rays, and eventually beam).

We also note that three of the project PI's—Elke Achenauer (Brookhaven), Renee Fatemi (University of Kentucky), and Sevil Salur (Rutgers)—are women recognized as leaders in the field. Dr. Aschenauer is FCS Project Manager, and serves as the STAR Upgrade Coordinator. Their high visibility in a project of this scale makes it clear to students and others that it is meaningful and rewarding for women and other under-represented groups to pursue advanced degrees and careers in science.

Benefits to the National Interest: The students who will participate in this project will receive training and gain extensive experience in both hardware and software tasks. The skills they will develop in areas such as electronics, state-of-the-art particle detection, computer / Monte Carlo simulations, sophisticated analysis techniques appropriate for 'big data,' and physical interpretation of results, will serve them well, whether they continue with a career in physics or choose other directions. Many can be expected to work outside of academia; students thus trained will contribute significantly to the nation's technical work force.

Project Management Plan

PI Scott Wissink and Dr. Elke Aschenauer (BNL) will be responsible for managing all phases of the FCS Project. Prof Wissink and Dr. Aschenauer have extensive experience. Prof Wissink was a co-PI on the team from Indiana University that designed, built, installed, and commissioned the Endcap EM Calorimeter that has run successfully at STAR for almost two decades. Dr. Aschenauer is the STAR Upgrade Coordinator, and has extensive experience and training on project management, as Project Manager for the Hall-D part of the JLab 12 GeV Upgrade, and having just finished a one year program at the U.S. Department of Energy Project Leadership Institute (https://pli-slac.stanford.edu).

The FCS will be organizationally fully embedded in the STAR forward upgrade. This has several consequences, one being that the progress of the STAR forward upgrade is regularly reviewed by the sitting Review Panels of the BNL NPP directorate, *i.e.*, the RHIC physics advisory committee. To ensure the FCS and all other STAR forward upgrade components have a sound technical basis and will hold cost and schedule to be installed and commissioned without beam for a 500 GeV RHIC polarized proton-proton run starting mid of August 2021, the BNL Associate Laboratory director for NPP convened a cost and schedule review in November 2018. The outcome of the review can be summarized as:

"A five-member review panel (S. Boose, C. Miraval, G. van Nieuwenhuizen, A. Tricoli, and chaired by G. Young) conducted a review of the resource requirements for the proposed forward upgrades to the STAR detector on November 19, 2018. The panel noted good progress on the proposed concept for a cold-QCD experiment to run in late FY2021 at RHIC, with plausible plans for funding and conservative designs for all detector components, electronics, and support infrastructure. The panel opined that the major project risks are identified and that the experiment appears positioned to be ready for first operation in 2021."

The mechanical integration of the FCS into the STAR experiment will be coordinated by STAR's lead engineer Rahul Sharma with help from the STAR operations group, which has both a strong mechanical and electrical subgroup. Sharma has also let the integration effort for the STAR beam-energy-scan II upgrades, the inner TPC, the event plane detector and the forward rapidity Time-Of-Flight system.

As part of the STAR forward upgrade project structure the different FCS components are represented by experienced level 2 managers, who report progress to Prof. Wissink and the STAR forward upgrade manger. The Level-2 managers are Prof. Fatemi (Univ of Kentucky) for the ECal, Oleg Tsai (UCLA) for the HCal and G. Visser (Indiana) together with T. Ljubicic (BNL) for readout and data-acquisition. All of these level-2 managers have been members of the STAR collaboration for many years and have been deeply involved in earlier upgrades and the STAR operation.

The offline software effort for the FCS is supported by the STAR software team (10 people). Members of the university groups participating in the FCS are collaborating with the STAR offline software group to have all FCS software integrated into the STAR framework by the September 2021.

The FCS is an integral part of the STAR forward upgrade schedule, a high-level version of this schedule is shown in Figure 9. The FCS design and schedule obeys several overall requirements:

- RHIC operations schedule requires
    - Installation needs to be done without rolling STAR into assembly hall
- HCal and EMCal need to be movable transverse to the RHIC beam pipe to allow access to RHIC accelerator components.
- Calorimeter platform modifications and EMCal stacking needs to be done during the RHIC shutdown August 2019 to January 2020
- HCal, SiPMs and all readout electronics (FEE, DEP and Trigger) installation needs to be completed during the RHIC shutdown August 2020 to January 2021
- The FCS needs to be ready for physics data taking starting mid of August 2021

The costing of the FCS has also been reviewed during the November 2018. The level 2 managers together with subject matter experts prepared detailed cost estimates for M&S and labor. The contingency for each cost item was assigned following a standard DOE cost methodology, which links the maturity of the cost estimate with the to be assigned contingency. The average contingency for the estimate was in the order of 25%, which was considered fully adequate by the review team.

Great care is taken to keep the FCS project cost, schedule, and technical risk at a minimum. Therefore, a full system check of the Preshower, EMCal, HCal, and their final readout (FEEs + DEP) and Trigger system will be implemented during RHIC RUN-2019.

To mitigate schedule risks, BNL NP has agreed to pay for long lead items, *i.e.*, the EMCal light guides, the trigger electronics and 10% of all the material needed to build the HCal. The latter is critical to set up all production facilities before mass production has to start.

One of the PHENIX EMCal super modules has been already moved to the STAR experimental hall and work by the STAR operations group has started to prepare the EMCal towers for installing the light guides and stacking it at its new location in STAR, the former FMS platform during the 2019 summer shutdown.

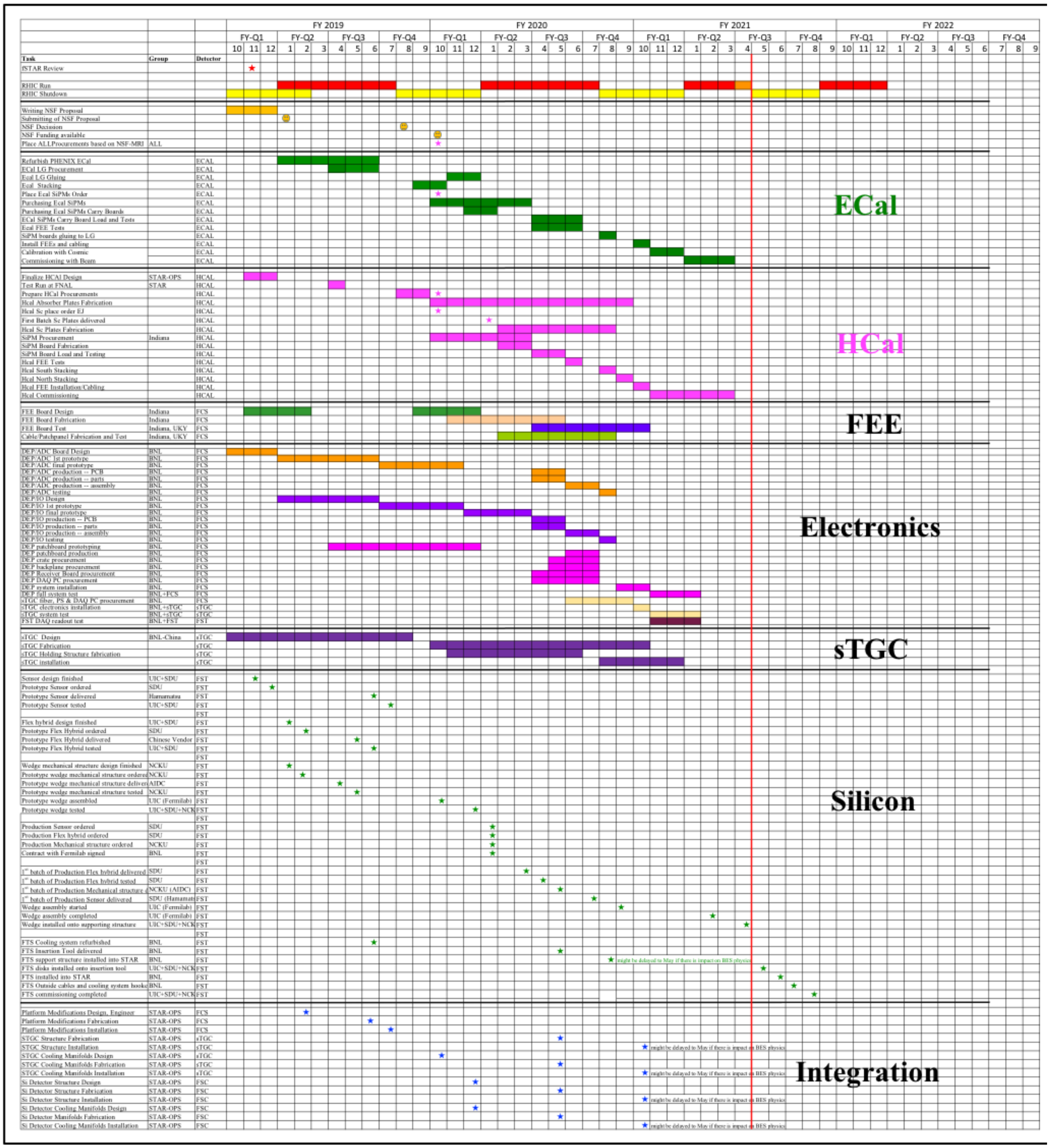

Figure 9: High level STAR forward upgrade schedule, integrating all schedule requirements.

The STAR ES&H practices exercised since many years will also be implemented for the FCS. The load calculations for the FCS system will be independently verified by engineers from the collider-accelerator department. The FCS system does not use any HV and the LV-systems will be integrated in the STAR monitoring and interlock system.

The STAR forward upgrade group has weekly meetings where the overall progress of all the subsystems are discussed. The individual subsystems have regular meetings at minimum bi-weekly to discuss and monitor every detail of the system.

In summary the FCS project will be managed the same way as many other successful STAR upgrade projects, *e.g.*, the iTPC, eTOF, EPD, and HFT, have been managed in the last 10 years.

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