**The STAR Forward Upgrade**

**The Tale of the initial state:** **nucleon to nuclei**

**The STAR Collaboration**



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# Science Case for STAR’s Forward Upgrade:

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.

The theoretical and experimental achievements of the US QCD facilities, JLab and RHIC, as well as the as yet unanswered pressing questions, including those to be addressed at the proposed Electron Ion Collider (EIC) facility, are detailed in the 2015 NSAC Long Range Plan (LRP) [[[1]](#endnote-1)]. Precise imaging of gluons and sea quarks inside protons and nuclei will allow us to address some of the key issues regarding the emergence of nuclear properties from QCD. These subjects include:

* How are gluons and sea quarks, and their intrinsic spins, distributed in space and momentum inside the nucleon? What is the role of their orbital motion in building the nucleon spin?
* How does a dense nuclear environment affect quarks and gluons, their correlations, and their interactions? At high energy does the gluon density in nuclei saturate, giving rise to gluonic matter with universal properties in all nuclei, even the proton?
* How do color-charged quarks and gluons, and colorless jets, interact with the hot and dense deconfined nuclear medium known as the Quark-Gluon Plasma (QGP)? How do confined hadronic states emerge from these quarks and gluons?

The outstanding *pp* and *p*+A physics program as outlined in the 2016 RHIC Cold QCD Plan [[[2]](#endnote-2)] and reviewed by the 2016 RHIC Program Advisory Committee (PAC) can begin to address these questions prior to the EIC. This proposal lays out a plan to address the recommendation: “The PAC encourages the management and the collaborations to consider a potential (polarized) *pp* 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.”

Such a comprehensive set of measurements in hadronic collisions, when combined with data from the EIC, will establish the validity and limits of factorization and universality. Hence, they enable the full realization of the scientific promise of the EIC. This *p*+A and *pp* program is the natural next step on the path towards an electron-ion collider; laying both the scientific groundwork for the EIC and aiding the refinement of the experimental requirements. In addition, much of the program is unique to *pp* and *p*+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.

The STAR forward upgrade allows us to extend precision studies of the initial state of cold nuclear matter at very high and low Bjorken x regions, as well as the initial stages of A+A collisions that eventually leads to the formation of a medium of the QGP. These new forward detector capabilities will enable STAR and RHIC to:

* Study the 3D-structure of the hydrodynamic evolution constraining the initial state of A+A collisions that leads to large event-by-event fluctuation and breaks boost invariance.
* Map out the temperature dependent profile of transport parameters such as η/s(T), particularly near the region of perfect fluidity.
* Explore the rapidity dependence of vorticity via the newly discovered Global Hyperon Polarization.

Such measurements will be an important step towards an improved understanding of the emergence of the near-perfect fluidity of this QGP which is also a highlighted goal of the 2015 NSAC LRP1.

Recent STAR efforts using the FMS and a pre- and post-shower detector upgrade for Runs 2015-2017 have demonstrated the existence of outstanding QCD physics opportunities in the forward region. However, superior detection capability for neutral pions, photons, electrons, jets and leading hadrons covering a region of 2.5< η <4.5 are required.

 We propose such a forward detector system, realized by combining tracking with electromagnetic and hadronic calorimeters for the years beyond 2020. The design of the Forward Calorimeter System (FCS) is driven by consideration of detector performance, integration into STAR and cost optimization. The refurbished PHENIX sampling ECal is used and 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 and will utilize STAR’s existing Forward Preshower Detector. Both calorimeters share the same cost-effective readout electronics, with SiPMs as photo-sensors. This FCS system will have very good (~8%√E) electromagnetic and (~70%/√ E) hadronic energy resolutions. Integration into STAR requires minimal modification of existing infrastructure.

 In addition, a Forward Tracking System (FTS) is proposed. The FTS must be capable of discriminating hadron charge sign for transverse asymmetry and Drell-Yan measurements in *p*+A. In heavy ion collisions, measurements of charged particle transverse momenta of 0.2<pT<2 GeV/c with 20-30% momentum resolution are required. To keep multiple scattering and photon conversion background under control, the material budget of the FTS must be small. Hence, the FTS design is based on three Silicon mini-strip detectors that consists of disks with a wedge-shaped design to cover the full azimuth and 2.5<η<4.0; they are read out radially from the outside to minimize the material. The Si-disks are combined with four small-Strip Thin Gap Chamber (sTGC) wheels following the ATLAS design [[[3]](#endnote-3),[[4]](#endnote-4)]. These extremely cost effective sTGCs can also be studied as an alternative tracking detector technology to the planned GEM-trackers in the forward arms of current EIC detector designs.

The total cost of the forward upgrade is 5.02M$; 0.57M$ for the ECal, 1.25M$ for the HCal, 0.1M$ for refurbishing the existing preshower and the FCS trigger system and $3.1M$ for the FTS based on Silicon and sTGCs. These cost estimates include M&S, manpower and contingency.

**The outlined physics program based on the STAR forward upgrade is fully consistent with planned data taking during the sPHENIX running periods.**  In addition, a 20 week *√s* = 500 GeV polarized *pp* run, split between transverse and longitudinal polarized running is proposed. This run could be scheduled in 2021, for which currently no dedicated physics program is assigned. This high impact, cost-effective physics program can be executed even in challenging financial times.

In summary, the proposed program builds on the particular and unique strength of the RHIC accelerator compared to JLab, Compass and the LHC in terms of its versatility (i.e., the option of acccelerating 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 Cold QCD campaign of STAR@RHIC, with its recent achievements summarized in[2,[[5]](#endnote-5)]. It is especially stressedthat 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. This forward upgrade will also enhance the exploration the 3D structure of the initial state that leads to large event-by-event fluctuations and breaks boost invariance in heavy-ion collisions. It provides a crucial test for initial state models based on effective theories of high-energy QCD, explores the rapidity dependence of vorticity via the newly discovered Global Hyperon Polarization, and enables us to map the temperature-dependent transport properties of the QGP near the region of perfect fluidity.

Appendix:

In the following some exemplary measurements are given, which illustrate the scientific power of the STAR forward upgrade.

* **The polarized gluon distribution *g(x,Q2)*:**

Di-jet measurements provide a 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 *ALL* as a function of the scaled invariant di-jet mass *Minv/√s* (~√(*x1x2*)/√*s*) for four topological di-jet configurations involving a generic forward calorimeter system (FCS) in combination with either -1.0 < *η* < 0.0, 0.0 < *η* < 1.0, 1.0 < *η* < 2.0, and the FCS (2.5 < *η* < 4.0). In particular the 1.0 < *η* < 2.0 / FCS and FCS / FCS configurations would allow one to probe *x* values as low as a few times 10-3.

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| Figure 1: *ALL* NLO calculations as a function of *Minv/√s* for 2.8 < *η* < 3.7 together with projected statistical and systematic uncertainties. An uncertainty 5∙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 fb-1 have been assumed with a data taking efficiency of 2/3 for the ratio of recorded to delivered luminosity.**Plot is getting updated and beautified** |

* **The gluon distribution *g(x,Q2)* for nuclei:**

RHIC has the *unique* capability to provide data in a kinematic regime (moderate *Q2* 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 nuclear PDFs. *RpA*for direct photon production shows a significant impact on the theoretical expectations and their uncertainties obtained with the EPPS-16 set of nPDFs. These measurements will add significant constraints to the nuclear gluon distribution over a broad range of *x* that is roughly correlated with accessible transverse momenta of the photon, i.e., few times 10-3 < *x* < few times 10-2. The relevant scale *Q2* is set be ~ *pT2* and ranges from 6 GeV2 to about 40 GeV2.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 [[[6]](#endnote-6)]).

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| Figure 2: The impact of the anticipated direct photon data on *RpA* and on the nuclear suppression factor Rg of nPDF to the proton PDF, the cyan bands represent the uncertainties before including the STAR pseudo data and the dark blue bands after. The study is based on the EPPS-16 nPDFs. |

* **Longitudinal dynamics in Au+Au Collisions:**

The kinematics of RHIC A+A collisions provides us the unique opportunity to build detectors and make precise measurements of multiple flow harmonics and their correlations near the beam rapidity. In comparison to LHC, one expects stronger breaking of boost-invariance, stronger variation of initial temperature and therefore stronger sensitivity to temperature dependent transport, over a given widow of rapidity at RHIC. The forward upgrade of STAR (fSTAR) will utilize this uniqueness of RHIC collisions 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 minima [1].

The preliminary measurements of longitudinal de-correlation of elliptic flow (r2) in Au+Au 200 GeV collisions, using the Forward Meson Spectrometer at forward rapidity (2.5<η<4), is shown in Figure 3 (left). This demonstrates the capability of STAR to study the breaking of boost invariance in A+A collisions. fSTAR will improve the systematics of such measurements. The need of increasing the acceptance of STAR to make more precise flow measurements is demonstrated in Figure 3 (middle). fSTAR will help remove non-flow background contribution in such measurements. Precision flow measurements over a wide acceptance, particularly in the forward rapidity [[[7]](#endnote-7)], will help constrain η/s (T) as shown in Figure 3 (right).

In 2017, the STAR Collaboration has published in NATURE [[[8]](#endnote-8)] 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 ||<1.5. Our simulations show that the proposed forward upgrade allow us to reconstruct Lambdas in both polarized p+p collisions at 500 GeV and non-central Au+Au collisions at different energies.

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| Figure 3: Left: Preliminary data from STAR demonstrating the measurement capabilities of longitudinal de-correlation of elliptic anisotropy (r2) using the existing FMS detector (2.5<η<4). Current data show interesting trend 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 (*Δη*) dependence of the second order Fourier harmonic coefficient *V2∆* of two-particle azimuthal correlations at mid-rapidity in 200 GeV Au+Au collisions. The measurement over the limited window of |*η*|<1 indicates contamination from short-range non-flow contributions. fSTAR will help disentangle the long-range component of *V2∆* that is sensitive to initial state physics. Right: Hydrodynamic simulations [7] demonstrating the sensitivity of elliptic flow at forward rapidity to different parameterizations of η/s (T) (a, b are parameters the 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). |

#### Summary of the pp, pA, AA measurements:

 Table 1‑1 summarizes the pp, pA and AA scientific goals and measurements critical to reach these goals as discussed prior. In addition, the needed integrated luminosity as well as the detector components of the forward upgrade critical for the observable are listed. It is noted that a brief discussion of STAR’s ability concurrently to realize a unique mid-rapidity p+p. p+A and A+A physics program is also outlined in a companion document [3].

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|  | **Year** | ***√s* (GeV)** | **Delivered****Luminosity** | **Scientific Goals** | **Observable** | **Required****Upgrade**  |
| **Scheduled RHIC running**  | **2023****to****2025** | p↑p @ 200 | 300 pb-18 weeks | Subprocess driving the large *AN* at high *xF* and ** | *AN* for charged hadrons and flavor enhanced jets | Forward instrum.ECal+HCal+Tracking |
| p↑Au @ 200 | 1.8 pb-18 weeks | What is the nature of the initial state and hadronization in nuclear collisionsClear signatures for Saturation | *RpAu* direct photons and DYDihadrons, -jet, h-jet, diffraction | Forward instrum.ECal+Hcal+Tracking |
| p↑Al @ 200 | 12.6 pb-1 8 weeks | A-dependence of nPDF, A-dependence for Saturation | *RpAl*: direct photons and DYDihadrons, -jet, h-jet, diffraction | Forward instrum.ECal+HCal+Tracking |
| AuAu @ 200 | 1 Billion MinbiasEvents | Longitudinal de-correlation | *Cn*(*Δη*) and *rn* (*ηa,ηb*) | Forward instrum.ECal+HCal or Tracking |
| η/s(T) and ζ/s(T) | *VnΔ (η)* | Forward instrum.Tracking |
| Mixed flow Harmonics | *Cm,n,m+n* | Forward instrum.ECal+HCal or Tracking |
| Rapidity dependence of Hyperon Polarization  | *PH (η)* | Forward instrum.Tracking |
| Ridge | *dN/d(Δη)d(Δφ) & VnΔ* | Forward instrum.ECal+HCal or Tracking |
| **Potential****future running** | 2021 | p↑p @ 510 | 1.1 fb-110 weeks | TMDs at low and high *x* | *AUT*for Collins observables, i.e. hadron in jet modulations at ** > 1 | Forward instrum.ECal+HCal+Tracking |
| 2021 | $\vec{p }\vec{p}$@ 510 | * 1. fb-1

10 weeks | *g(x)* at small *x* | *ALL*for jets, di-jets, h/-jets at ** > 1 | Forward instrum.ECal+HCal |

Table 1: Summary of the pp, pA and AA measurements as planed in the years 2021 and 2023 to 2025 in parallel to the sPHENIX running. The most right coloumn summarizes, which detector of the forward upgrade is essential for the measurement.

# Bibliography

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