**Science Case for STAR’s Forward Upgrade - February 2018**

 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]](#footnote-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]](#footnote-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]](#footnote-3),[[4]](#footnote-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]](#footnote-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.

1. The 2015 Long Range Plan for Nuclear Science “Reaching for the Horizon” http://science.energy.gov/~/media/np/nsac/pdf/2015LRP/2015\_LRPNS\_091815.pdf. [↑](#footnote-ref-1)
2. The RHIC Cold QCD Plan for 2017 to 2023 – A Portal to the EIC, E.C. Aschenauer et al., arXiv:1602.03922 [↑](#footnote-ref-2)
3. A. Abusleme et al., Nucl.Instr. & Meth. A817 (2016) 85. [↑](#footnote-ref-3)
4. V. Smakhtin et al., Nucl.Instr. & Meth. A598 (2009) 196. [↑](#footnote-ref-4)
5. [The RHIC Spin Program: Achievements and Future Opportunities](http://inspirehep.net/record/1225974), E.C. Aschenauer et al., arXiv:1501.01220 [↑](#footnote-ref-5)