**The eSTAR Letter of Intent**

**The STAR Collaboration**



# Introduction

During the 2007 Nuclear Physics Long Range Plan [1] the following overarching questions have been defined for the subfield of Quantum Chromodynamics (QCD):

1. What are the phases of strongly interacting matter, and what roles do they play in the cosmos?
2. What is the internal landscape of the nucleons?
3. What does QCD predict for the properties of strongly interacting matter?
4. What governs the transition of quarks and gluons into pions and nucleons?
5. What is the role of gluons and gluon self-interactions in nucleons and nuclei?
6. What determines the key features of QCD, and what is their relation to the nature of gravity and spacetime?

STAR is the one large acceptance detector at RHIC. Major advantages of the STAR experiment comprise large acceptance with full azimuthal angle coverage, TPC tracking within |eta|<1.0 with particle identification through Time-of-Flight. The central Barrel and End-cap ElectroMagnetic Calorimeters (BEMC and EEMC) provide coverage for electron, photon and neutral pion measurements, and jet measurements, when combined with charged particle tracking from the TPC. These unique capabilities have set the stage for the future research opportunities at RHIC. The STAR Collaboration has identified the following key questions [2] that will drive the RHIC science program during the current decade:

1. What are the properties of the strongly coupled system produced at RHIC, and how does it thermalize?
2. Are the interactions of energetic partons with QCD matter characterized by weak or strong coupling? What is the detailed mechanism for partonic energy loss?
3. Where is the QCD critical point and the associated first-order phase transition line?
4. Can we strengthen current evidence for novel symmetries in QCD matter and open new avenues?
5. What other exotic particles are created at RHIC?
6. What is the partonic spin structure of the proton?
7. How do we go beyond leading twist and collinear factorization in perturbative QCD?
8. What is the nature of the initial state in nuclear collisions?

The STAR experiment has addressed many of these questions over the last years with measurement in AA, dA and (un)-polarized pp collisions. Some of the most striking results during the past years are listed here. STAR has identified anti-hypertriton production in Au+Au collisions, the first ever observation of an anti-hypernucleus. Azimuthal charged-particle correlations have been observed in Au+Au collisions that may arise from local strong parity violation in the dense medium. Measurements of the correlations between non-photonic electrons and hadrons in *p*+*p* collisions have been combined with results for non-photonic electron *RAA* to provide indications that even hadrons containing *b*-quarks are suppressed in central Au+Au collisions. Jet-like correlations have identified several novel features in heavy-ion collisions relative to *p*+*p*, including the near-side “ridge” that may probe the early state of the collisions. Polarized *p*+*p* collisions have set the most precise constraints to date on the polarization of the gluons in the proton. New global analyses, which include results both from PHENIX (*0 ALL*) and STAR (jet *ALL*) indicate that the integrated contribution to the proton spin from gluons in the momentum range 0*.*05 *< x <* 0*.*2 is 20%. This should be compared to the 30% quark contribution in the quark momentum range 0*.*001 *< x <* 1.0. The STAR preliminary results ontaken during 2012 have been included in a pQCD-fit and show clear improvement on the determination of the polarization of the light sea quarks and their integral for  and  in the range  at *Q2*=10 GeV2. For a shift away from the current best mean value is observed, reflecting that the new STAR  data lie above the central value based on a fit to the world data. Already, with only the preliminary 2012 STAR data, the new global analysis shows a preference for  in the range *x* > 0.05.

The observation of a dramatic broadening of forward *0--0* correlations in *d*+Au collisions provides the clearest indication to date that the onset of gluon saturation is accessible at RHIC. Related theoretical developments point to a potential connection between gluon saturation and the “ridge”. Additional new research areas have been opened by the first reconstruction of full jets in relativistic heavy-ion collisions by STAR, and the beginning of the RHIC Beam Energy Scan, which revealed surprising levels of continuity in observables measured all the way from 2.76 TeV down to the lowest energy measured at RHIC so far, 7.7 GeV. Many of the observables related to the bulk of the particles show only gradual monotonic changes. Exceptions to these gradual trends include 1) the observation of large differences between positive and negative particles apparently related to mean field potentials, the effect of which is increased with increasing chemical potential at lower energies, and 2) a non-monotonic variation of the cos(phi) distribution for net protons that could indicate the presence of a minimum of the speed of sound in the QCD Equation of State.

Further upgrades as described in short in the following and in more detail in chapter 3 will position STAR well for these upcoming measurements. The Heavy Flavor Tracker (HFT)and Muon Telescope Detector (MTD) will be essential for these measurements. Upgrades to boththe trigger and data acquisition system will also be required to answer several of the heavy-ion questions. To enhance the STAR capabilities for the Phase-II RHIC beam energy scan an upgrade of the inner sectors of the STAR TPC (iTPC) is proposed. By increasing the segmentation on the inner pad plane better momentum resolution, better dE/dx resolution, and most importantly improved acceptance at high rapidity upto |eta|<1.7 compared to the current TPC configuration of |eta|<~1.0 will be achieved. Upgrades will also be necessary to take advantage of the opportunities presented by *p*+*p* and *p*+A collisions at RHIC. Upgrades to the Forward Meson Spectrometer to provide *e/h* and */0* discrimination, together with the addition of forward tracking and particle identification, will be critical to explore the origins of the large transverse spin asymmetries and the partonic structure of heavy nuclei. The addition of Forward Hadron Calorimetery will extend the STAR measurements of quark helicity distributions as well as help to unravel whether transversity combined with the Collins fragmentation function, or the Sivers distributions have a significant contribution to the large transverse single-spin asymmetries observed at large rapidities. An upgrade to the current Roman pot system will permit a high-sensitivity search for glueballs, the study of exclusive and diffractive reactions in *pp*, and (un)-polarized *pA*-collisions, which will allow one to study generalized parton distributions through exclusive *J/Ψ* -production.

The STAR envisioned physics programs as well as its current and future detector capabilities are well aligned with the science goals of the electron ion collider (EIC) as described in the recent EIC White Paper [3]. An Electron Ion Collider is being considered as the next generation national QCD facility in nuclear physics. The most intellectually pressing questions that an EIC will address that relate to our detailed and fundamental understanding of QCD in this frontier environment are:

1. How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?
2. Where does the saturation of gluon densities set in? Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
3. How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Answers to these questions are essential for understanding the nature of visible matter. An EIC is the ultimate machine to provide answers to these questions for the following reasons:

1. A collider is needed to provide kinematic reach well into the gluon-dominated regime;
2. Electron beams are needed to bring to bear the unmatched precision of the electromagnetic interaction as a probe;
3. Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin;
4. Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

Adding an electron beam to the RHIC hadron beams (eRHIC) will accomplish the machine requirements for an EIC as listed above.

The capabilities of a further upgraded STAR detector to explore the EIC scientific highlights at the initial stage of eRHIC will be discussed in the following chapters. It will be shown that further upgrades to STAR are needed to enhance capabilities to detect the scattered lepton for raditidites < -1. In the rapidity range -1 to -2 this includes adding a transition radiation detector and a time-of-flight detector to provide electron identification with high hadron rejection (~>103) over a wide momentum range (0.2 GeV/c <p< ~10 GeV/c). In the rapidity range < –2 a high resolution crystal calorimeter will be added to measure the scattered electron precisely.

# eSTAR Capabilities to Explore the EIC Scientific Highlights

## eRHIC Machine Design:

Simulations shown in the following chapters assume:

1. an eRHIC luminosity of 1033 cm-2s-1
2. a maximum electron beam energy of 10 GeV and hadron beam energies as currently available in RHIC
3. the interaction region (IR) design is assumed to follow the layout as described in Fig. 5.4 in the EIC Whitepaper. Due to the length of the STAR detector the first beam elements have to be moved from 4.5 m to ~9 m distance from the interaction point (IP), this will lead to a factor ~2 loss in luminosity compared to the EIC Whitepaper design.

## Physics Performance:

### Inclusive Measurements:

|  |
| --- |
| **Inclusive** DIS refers to measurements that involve only the scattered lepton. The requirements for detecting the scattered lepton are critical, and remain the same for semi-inclusive, exclusive and diffractive reactions, as the scattered lepton defines the parton kinematics (through *x* and *Q2*) for all reaction types.**Key Physics Measurements based on inclusive observables are:**1. The measurement of the polarised spin structure function g1 in polarized ep scattering.
2. The measurement of the unpolarised structure functions F2 and FL in eA scattering to study nuclear parton distributions and their saturation at low *x*.
 |

### Semi-Inclusive Measurements

|  |
| --- |
| **Semi-inclusive** DIS (SIDIS) involves measuring one or more (in the case of correlation measurements) final-state particles in addition to the detection of the scattered lepton. All the requirements for detection of the scattered lepton apply in SIDIS as for inclusive reactions. However further requirements are posed by the need to detect the final state hadron(s). A measured hadron is typically characterized by its transverse momentum, *pT*, with respect to the virtual photon (not the incident beams) and its energy fraction, *z*.**Key Physics Measurements based on semi-inclusive observables are:**The following is a list of measurements that rely on the measurement of a hadron or hadrons in addition to the scattered lepton. ep:1. Flavour-separated polarized (anti-)quark parton distributions.
2. Transverse-momentum-dependent parton distributions.
3. Investigate SU(3) flavor symmetry breaking, via (anti-)strange distributions.

eA:1. Transverse-momentum-dependent gluon distributions and gluon saturation in nuclei, via di-hadron correlations.
2. Hadronisation and energy loss during the propagation of a fast-moving color charge in QCD matter.
 |

### Exclusive and diffractive Measurements

|  |
| --- |
|  |
| **Exclusive** DIS describes measurements that involve the measurement of the scattered lepton, the scattered proton (either intact or dissociated into a hadronic final state) and the reconstruction of the final particle produced in the interaction. For low-x events the proton scatters at such a small angle that very often it escapes the main detector through the beam pipe hole, and its measurement requires forward detectors ("Roman Pots") installed along the beam pipe. The reconstruction of the produced particle, such as a photon or a vector meson decaying into leptons, imposes extra detector requirements, mainly on tracking and calorimetry.**Key Physics Measurements based on exclusive observables are:**Below is a list of measurements from the EIC WP are that rely only on the reconstruction of the entire final state.ep:1. Spatial Imaging of Quarks and Gluons
	1. Deeply Virtual Compton Scattering (DVCS): e+p 🡪 e’+p’+
	2. Production of J/Ψ-mesons: e+p 🡪 e’+p’+ J/Ψ

**Diffractive** events, e + A(p) → e′ + A’(p′) + X, are events where the proton/nucleus remains intact and the highly virtual photon fragments into a final state, X, that is separated from the scattered proton/nucleus by a large rapidity gap without any particles. These events are indicative of a color neutral exchange in the t-channel between the virtual photon and the proton over several units in rapidity.**Key Physics Measurements based on exclusive observables are:**Below is a list of measurements from the EIC WP are that rely only on diffractive events.eA:1. Gluon Saturation: a New Regime of QCD
 |

# Detector Configuration and Components

# Simulations

# R&D

# Collaboration Evolution

**References:**

[1] NSAC Long Range Plan (2007), http://science.energy.gov/np/nsac/.

[2] STAR Decadal Plan, see: [http://www.bnl.gov/npp/docs/STAR\_Decadal\_Plan\_Final[1].pdf](http://www.bnl.gov/npp/docs/STAR_Decadal_Plan_Final%5B1%5D.pdf)

[3] The EIC White Paper “The Next QCD Frontier-Understanding the glue that binds us all” arXiv:1212.1701 (nucl-ex)