STAR upgrade program and future physics

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Abstract. The STAR experiment at RHIC is dedicated for studying QCD matter to understand properties of QGP and nucleon spin structure. With Heavy Flavor Tracker (HFT) and Muon Telescope Detector (MTD) installed at the beginning of 2014, the STAR has been enhanced its capability for heavy flavor study in Au+Au collisions. The second phase of Beam Energy Scan (BES) program at STAR will be launched to study phase structure of the QCD matter with Inner TPC (iTPC) upgrade in 2017, which will extend pseudo-rapidity coverage and improve particle identification. The STAR transits to eSTAR phase on 2020-2025 timescale with major upgrade of capabilities in forward region. The STAR detector with these updates allows high precision study on partonic structures of nucleon, and nuclei in p+A and e+A collisions. STAR opens a door to explore QCD from the cold nuclear matter to the hot QGP. In this talk, we will present the STAR upgrade program and future physics in short, middle and long terms.

1. Introduction

The STAR experiment at RHIC is dedicated for studying QCD matter to understand properties of QGP and nucleon spin structure. With its large acceptance capabilities for tracking, calorimetry and particle identification, the STAR detector is ideally suited to answer the eight key questions [1] in the future. To answer these questions definitely will require upgrades on the existing STAR detectors.

Recent upgrades, including the Heavy Flavor Tracker (HFT) [2] and the Muon Telescope Detector (MTD) [3], have been fully commissioned since the beginning of 2014. Combined with the high luminosity heavy-ion beams, they will play key roles in exploring the properties of the strongly-coupled system, thermalization and the mechanism of partonic energy loss through the measurements of identified hadrons containing heavy quarks. To enhance the STAR capabilities for the Phase-II RHIC beam energy scan (BES), an upgrade of the inner sectors of the STAR TPC (iTPC) is proposed [4]. Toward the coming decade, STAR plans a major upgrade of its capabilities in the forward region with polarized p+p and p+A collisions to explore QCD in the high and low Bjorken x domain [5]. An additional suite of upgrades will enable STAR to make crucial measurements in e+p/e+A collisions, eSTAR, at the initial stage of eRHIC [6]. This paper will describe the STAR upgrade program and future physics in short, middle and long terms for addressing the eight questions.

2. Heavy flavor physics program

In high-energy collisions at RHIC, heavy quarks (c, b) are expected to be created from initial hard scatterings and change lightly with respected to their heavy mass by the strong interactions with the QCD matter [7]. Thus they are regarded as an ideal probe to investigate the properties of the strongly interacting QCD matter. The HFT and MTD will be essential to quantify the properties of the strongly-coupled Quark-Gluon Plasma (QGP) created in high energy heavy ion collisions through measurements of heavy quarks, both open (D^0 and Λ_c) and hidden (J/ψ and $\Upsilon(1s, 2s, 3s)$).

2.1. Heavy Flavor Tracker

The HFT is a state-of-art micro-vertex detector utilizing active pixel sensors and silicon strip technology. The HFT consists of 4 layers of silicon detectors grouped into three subsystems with different technologies, guaranteeing increasing resolution when tracking from TPC towards the vertex of the collisions. The Silicon Strip Detector (SSD) is an existing detector in double-sided strip technology but updating readout electronics, and it forms the outermost layer of the HFT. The Intermediate Silicon Tracker (IST), consisting of a layer of single-sided silicon-pad detectors, is located inside of the SSD. Two layers of thin monolithic pixel sensors (PXL) are installed inside the IST, amount to 360 million pixels. Table 1 shows technical details of the 3 sub-detectors of the HFT.

Table 1. HFT technical details

Sub-detector	**r (cm)**	**$\sigma_{r\text{-}\phi}$ / σ_Z (μm)**	**X/X_0 (%)**
SSD	22	20 / 740	1
IST	14	170 / 1800	1.5
PXL	8	12 / 12	0.6
	2.7	12 / 12	0.4

The HFT completed prior to RHIC Run 14, and has been fully commissioned at the beginning of 2014. Using alignment deduced from cosmic data, the PXL sector half pointing resolutions were observed at 20 microns and 40 microns for inner layer and outer layer, respectively.

The HFT will greatly enhance the capability of STAR for heavy flavor studies, allowing reconstruction of displaced decay vertices and topological identification of charm hadrons. It will provide unique access to very low p_T charmed mesons to explore whether charm flows hydrodynamically. Left panel of Figure 1 illustrates the sensitivity of the prospective elliptic flow measurements, estimated for 1 billion minimum-bias Au+Au collisions at 200 GeV using one-year RHIC delivered luminosity. The prediction from a transport model assumes charm quarks flow as that of the light quarks (red), as well as when charm quarks do not flow (green). A baryon to meson enhancement can be explained by a hadronization mechanism involving collective multi-parton coalescence rather than independent vacuum fragmentation. With the HFT, STAR will be able to identify baryons Λ_c and mesons D^0 to perform a measurement of R_{CP}. Right panel of Figure 1 shows the projected Λ_c/D^0 measurements with 2 billion minimum-bias events in the cases of zero enhancement (black) and the same enhancement as for Λ/K_s^0 (red).

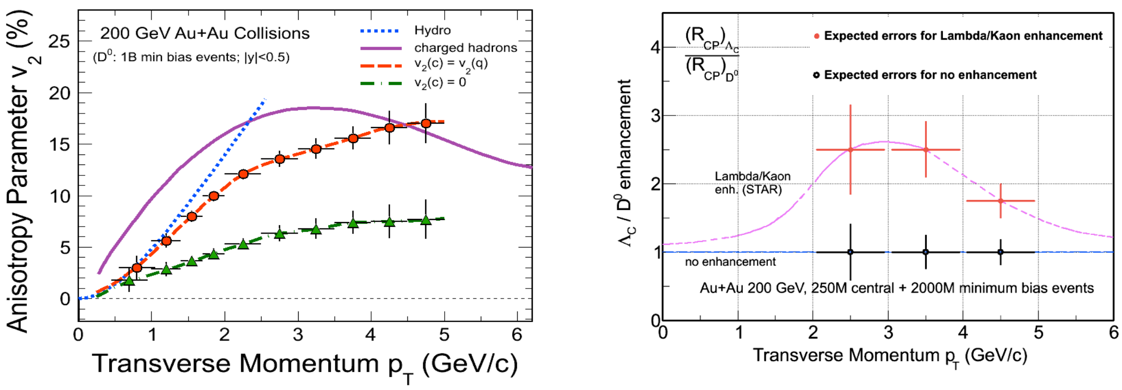

Figure 1. Left panel: The expected precision for D^0 flow after one RHIC year of Au+Au collisions studied with the HFT. The purple curve shows the measured v_2. Right panel: The expected statistical errors for the Λ_c/D^0 yield ratio for different assumptions about the production mechanism studied with the HFT.

Current measurements using non-photonic electrons of charm and bottom hadrons indicate the energy loss for heavy quarks is the same as the light quarks, which is inconsistent with our current understanding of pQCD models. With help of the HFT, the contributions from B and D decays could be determined due to their different lift times.

2.2. Muon Telescope Detector

The MTD, based on Multi-gap Resistive Plate Chamber with long read-out strips (LMRPC) in avalanche mode, covers 45% in azimuthal and $|\eta| < 0.5$ in pseudo-rapidity behind the return iron bars for the STAR magnet. It has 122 modules, 1664 readout strips, and 2928 readout channels. 10% modules were installed in 2012 and 63% modules were finished in 2013. The MTD has been commissioned with single muon, electron-muon (the electron was detected by barrel electromagnetic calorimeter) and di-muon triggers during the periods. In 2014, the MTD has been fully commissioned prior the RHIC Run 14.

The MTD enables the detection of and online triggering of both di-muons and single muon over a large phase space. Kinematics measurements of di-muons are used to study the properties of the QCD matter throughout its entire evolution, while single muon is a good means to study the semi-leptonic decayed heavy flavor hadrons. Measurements of the J/ψ flow to low p_T can be achieved in better precision via di-muon channel than di-electron channel as shown in left panel of Figure 2. Di-muon channel with the MTD is less affected by bremsstrahlung energy losses, and this enables separating different mass states of Υ family. Sequential suppression of different Υ states can be used as a QGP thermometer as shown in right panel of Figure 2.

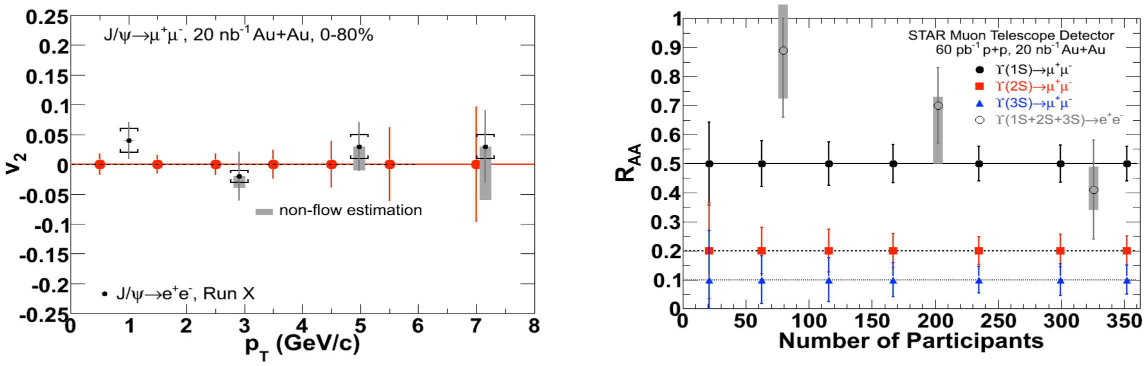

Figure 2. Left panel: The projected uncertainty of $J/\psi \rightarrow \mu^+\mu^-$ elliptic flow measurement with the MTD. Right panel: The projected uncertainty for the suppression of the different mass states of the upsilon family with the MTD.

Measurements of $c\bar{c}$ correlations will still be challenging, but can be approached through electron-muon correlations. These measurements are able to distinguish the contribution from heavy flavor correlations to the di-electron or di-muon continuum, which allow us to access the QGP thermal radiation contribution in the intermediate mass region (IMR) of di-lepton spectrum.

3. Phase-II RHIC BES program

Searching for the possible tri-critical point in the QCD phase diagram is one of the major scientific tasks in heavy-ion physics. The QCD critical point and first phase transition line would provide a landmark in the phase diagram. RHIC has completed the Phase I of the BES program with center of mass beam energies at 39, 27, 19.6, 11.5 and 7.7 GeV. The results of the search for the critical point and the first order phase boundary have narrowed the region of interest to collision energies between 7.7 and 20 GeV. In RHIC Run 14, Au+Au collisions at 15 GeV have been carried out for around three weeks. The BES Phase-II program is scheduled to launch in 2018-2019.

From the prospective of the Phase-II RHIC BES program, the following measurements need to be improved: better acceptance for the STAR TPC in pseudo-rapidity and p_T, centrality determination, event-plane determination and trigger performance. These improved measurements require upgrades including the increasing of the collider's luminosity for low energy running and detector upgrades to existing STAR detector system. The following detector upgrades are proposed as shown in Figure 5:

(1) iTPC upgrade mostly includes filling all inner sector with active pads and renewing the inner sector wires which are showing signs of ageing. The iTPC upgrade will provide better momentum resolution, better dE/dx resolution, higher track reconstruction efficiency, and mostly important it will provide improved acceptance at high rapidity from current $|\eta|<\sim1.0$ to $|\eta|<\sim1.7$. This increase in acceptance will enable STAR to better measure the longitudinal extent of "the ridge", which provides the best means to disentangle contributions to the correlations from various stages of the collisions, such as the initial state, the plasma phase

and freeze-out [6]. It's essential to BES Phase-II program, and will also benefit the STAR's future program with the polarized p+p/p+A and e+p/e+A collisions.

(2) Event-plane and centrality detector (EPD) is a new detector proposed to place in the forward rapidity region $1.5 < |\eta| < 5$. The EPD will provide the precise measurements of both the collision centrality and the event plane.

(3) End-cap Time-Of-Flight (ETOF) is proposed to provide particle identification capabilities at high rapidity. The ETOF, using similar hardware techniques of current barrel STAR TOF detector, will be positioned at the east and west end-planes of the STAR TPC.

With these upgrades, the BES Phase-II will allow for higher statistics and precise measurements to unfold the true phase structure of the QCD phase diagram as shown in Figure 3.

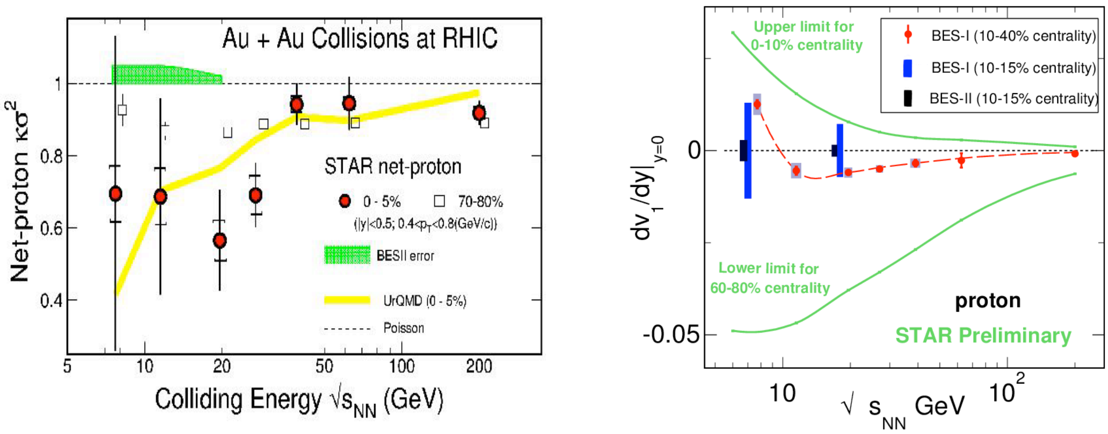

Figure 3. Left panel: Collision energy dependence of net-proton from 0-5% (filled-circles) and 70-80% (open-squares) Au+Au collisions at RHIC. The vertical error bars are statistical and the caps correspond to system errors. The green shaped band shows the estimated statistical errors for the BES Phase-II. Right panel: Statistical errors with narrow centrality bins for proton dv1/d*y* near mid-rapidity. The black error bars show the estimated BES Phase-II.

4. Polarized p+p and p+A program

The major scientific goal of the polarized p+p and p+A program is to explore QCD in the high and low Bjorken *x* domains. This program proposes measurements of forward photon, J/ψ, Drell-Yan, inclusive jet and di-jet, and forward-forward gamma/hadron/jet correlation probes at both energies, as well as *W* and *Z* probes at top energy.

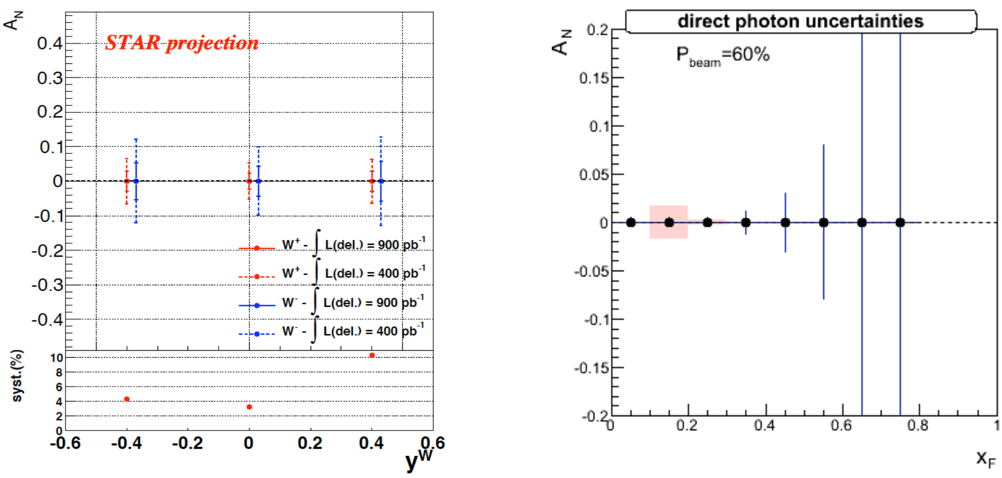

Figure 4. The projected uncertainties for transverse single spin asymmetries of $W^{\pm}$ (left panel) and direct photons after background subtraction (right panel).

While the required luminosities and background suppressions for a meaningful measurement of asymmetries in Drell-Yan (DY) production are challenging, other channels can be exploited in p+p collisions including prompt photons, $W^{\pm}$ and Z bosons, and inclusive jets [5]. They are sensitive to the predicted sign change. In Run 15 and Run 16, upgrades to the current Forward Meson Spectrometer (FMS) with Pre-shower detector equipped in front, are able to provide photon/charged-track separation and discriminate electron/photon from charged hadrons. The pre-shower detector will help to increase the signal/background fraction and extend the reach in x_F. Figure 4 shows the projected uncertainties for transverse single spin asymmetries of $W^{\pm}$ (left panel) and direct photons after background subtraction (right panel) for a delivered integrated luminosity of 400 pb^{-1}.

Further upgrades including the Forward electromagnetic and hadron Calorimetric System (FCS) and Forward GEM or silicon Tracking System (FTS) in pseudo-rapidity region of $2.5 < \eta < 4.0$, as shown in Figure 5, will be carried out since 2018.

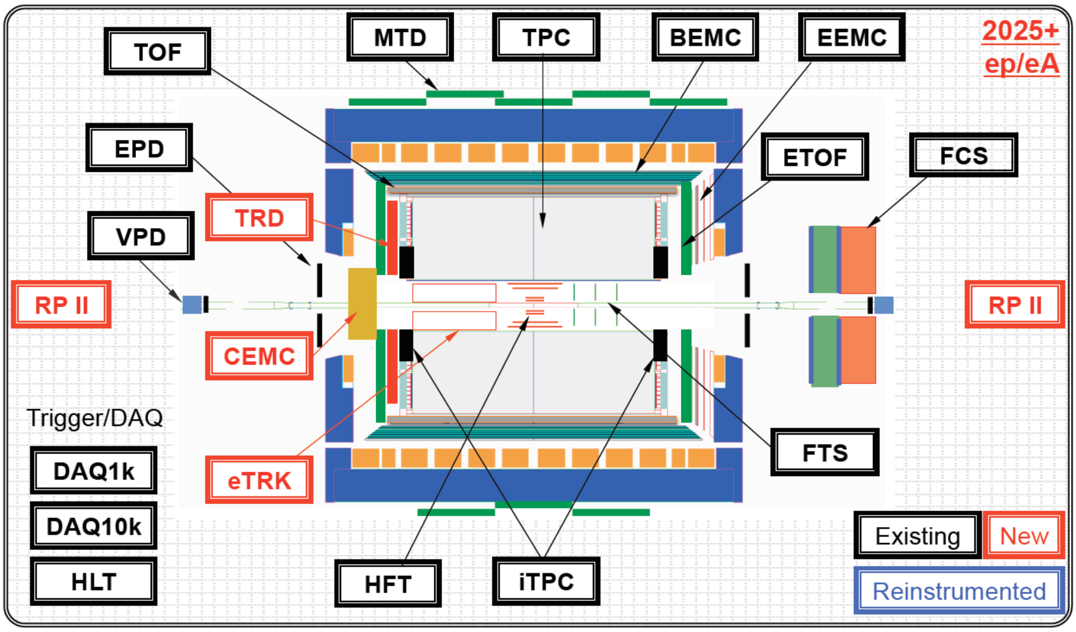

Figure 5. The planned STAR forward instrumentation upgrade, which is essential for detailed studies of polarized p+p/p+A and eSTAR programs. In polarized p+p/p+A program, the ion beams are from right to left (eastward) while proton beams from left to right (westward). In eSTAR program, the electron beams are from right to left (eastward) while hadron beams from left to right (westward).

The FCS and FTS will provide the needed background suppression to reach a signal to background of 0.5 to 100 as function of the DY di-lepton mass [5]. These upgrades are crucial to understand the origin of the large transverse spin asymmetries at high x_F. Additionally, these will constrain the shape and magnitude of the gluon helicity distribution at low parton momentum x through double spin asymmetries in forward di-jet/hadron-jet/direct photon-jet productions, as shown in Figure 6.

Existing d+Au measurements indicate the forward rapidities at the RHIC may provide access to the onset of gluon saturation. These upgrades of forward capabilities will enable detailed studies of the partonic structure of nuclei and the onset of gluon saturation with p+A collisions. Measuring these probes in p+A collisions give the unique opportunity to understand QCD processes in Cold Nuclear Matter (CNM) by studying the dynamics of partons at very small and large momentum fraction x in nuclei, and at high gluon-density to investigate the existence of nonlinear evolution effects.

The performance of the FCS prototype testing in March 2014 demonstrated that the proposed FCS detector met the STAR physics requirements. The FCS is scheduled to be ready for Run 17 at the earliest. The FTS are still under early stage of R&D, but are benefitted by the experiences on silicon mini-strip technology from STAR IST detector and GEM technology from STAR Forward GEM Tracker (FGT).

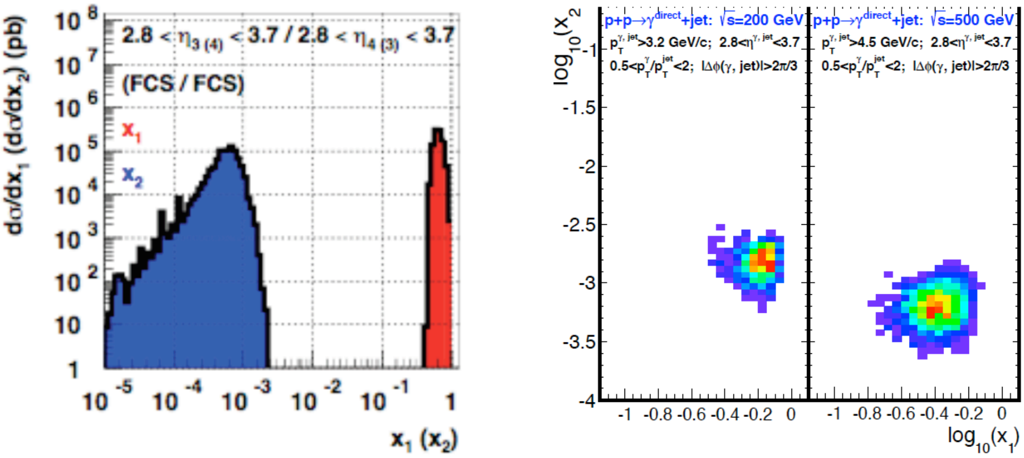

Figure 6. Left panel: The x1/x2 range for the forward STAR acceptance region in 2.8 < η < 3.7 for di-jet measurement with FCS-FCS combinations. Right panel: Bjorken x distribution of hard scattering partons at small x via direct γ-jet coincidence channel.

5. eSTAR program

The above existing mid-rapidity detectors and future upgrade programs will be well aligned with the scientific goal of eSTAR program, including precise measurements of nuclear parton distributions, direct measurements of nuclear gluon distributions and studies of parton energy loss in CNM [8]. These measurements require additional upgrades (marked in red color) to the existing STAR detector, as shown in the Figure 5.

Transition Radiation Detector (TRD) will be positioned between the TPC and the ETOF in the forward electron beams direction, covering -2 < η < -1. A generic R&D project is carried out to use GEM detectors in combination with a Xe+CO2 volume for the detection of transition radiation [6]. A BSO-based Crystal ElectroMagnetic Calorimeter (CEMC) with pre-shower detector in front is designed for very forward electron detection in rapidity region of -4 < η < -2. A generic R&D project has been conducted by the STAR Collaboration.

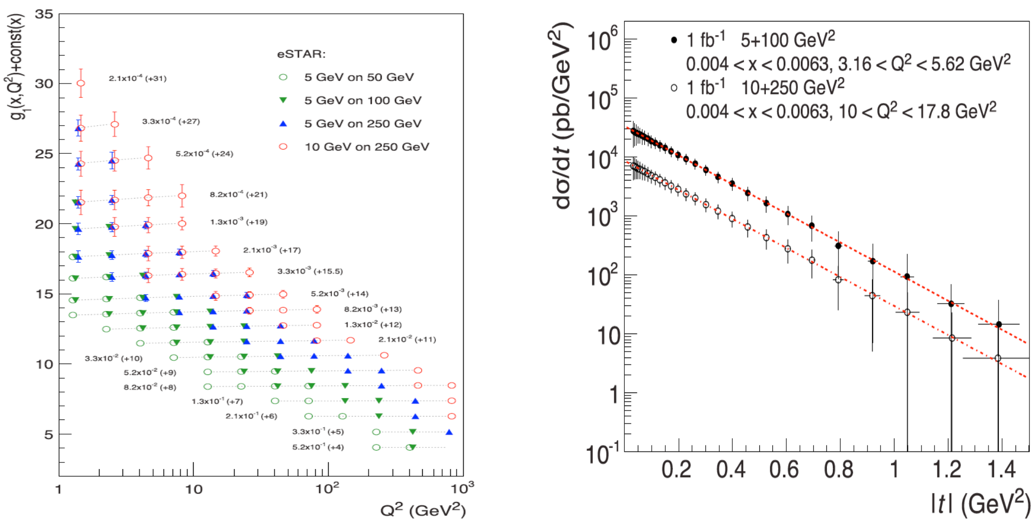

Figure 7. Left panel: The projected eSTAR measurement capabilities for $g_1(x,Q^2)$ for integrated of 1 fb^{-1} at each of energies and 70% beam polarizations. Right panel: The projections for the measurement of the differential DVCS cross-sections for 1 fb^{-1} of data collected within the eSTAR acceptance.

The pQCD analysis of $g_1(x,Q^2)$ is anticipated to give definitive insight into the size and distribution of the quark and gluon spin contributions to the nucleon spin. The left panel of Figure 7 shows the distribution of inclusive spin structure function $g_1(x,Q^2)$ as function of Q^2 at constant x for 5 and 10 GeV longitudinal polarized electron beams colliding with 50, 100, and 250 GeV longitudinal polarized proton beams at eRHIC.

By detecting the scattered protons in Roman Pots (RP), one can reconstruct its momentum from the measured positional and directional information of the protons in the given beam optics. This is the first access to gluon generalized parton distributions (GPDs). The Deeply Virtual Compton Scattering (DVCS) channels are described in terms of GPDs. With help of tracking detectors or calorimeters for electron detection and instrumented RP stations (RP II) for scattered proton detection, eSTAR is able to provide good opportunities to study the evolution effects predicted by pQCD and extract gluon GPDs. The right panel of Figure 7 shows projected measurements of the differential DVCS cross-sections for 1 fb^{-1} of data collected within the eSTAR acceptance.

6. Conclusion

The STAR is a dedicated facility for studying matter with QCD degrees of freedom. The STAR Collaboration has conducted and finished two major upgrades aimed at heavy flavor physics: HFT and MTD. Both HFT and MTD detectors have joined data taking for Au+Au collisions at 200 GeV in 2014. Regarding the future physics, the STAR Collaboration has identified several compelling physics goals and the detector upgrades will be required to address these scientific goals in the middle and long term. We will be able to understand the dynamical evolution from the cold nuclear matter to the hot QGP created at RHIC.

References

[1] STAR Decadal Plan, 2010, *http://www.bnl.gov/npp/docs/STAR_Decadal_Plan_Final[1].pdf*

[2] Technical Design Report: The STAR Heavy Flavor Tracker, 2011, *https://drupal.star.bnl.gov/STAR/system/files/HFT_TDR_Final.doc*

[3] L. Ruan et al., J. Phys. G: Nucl. Part. Phys. **36** (2009) 095001

[4] Beam Energy Scan White Paper: Studying the Phase Diagram of QCD Matter at RHIC, 2014, *https://drupal.star.bnl.gov/STAR/system/files/BES_WPII_ver6.9_Cover.pdf*

[5] Letter of Intent: A polarized p+p and p+A program for the next years, 2014, *https://drupal.star.bnl.gov/STAR/system/files/pp.pA_.LoI_.pp_.pA_.v7.pdf*

[6] eSTAR: A Letter of Intent, 2014, *https://drupal.star.bnl.gov/STAR/system/files/eSTAR-LoI_v30_0.pdf*

[7] F. Videbaek, J. Phys.: Conf. Serious 420 (2013) 012024

[8] C. A. Gagliardi, J. Phys. G: Nucl. Part. Phys. 38 (2011) 124130