STAR upgrade program and future physics

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Abstract. In this talk, we will present STAR's future plan in terms of both the detector upgrade and physics measurement to study matter with colour degrees of freedom. We will first discuss the status of the newly installed Heavy Flavor Tracker and Muon Telescope Detector, and their physics prospect in 2014-2016. We will then describe the proposed detector upgrades for the second phase of Beam Energy Scan program in 2018-2019 to study the QCD phase diagram. Finally we will present STAR's plan with detector upgrades in the forward directions for the anticipated pp/pA physics program in 2021-2022 and ep/eA in 2025+. The upgraded STAR experiment will be in an excellent position to perform precision measurements of the partonic structures of the nucleon and nuclei.

1. Introduction

The STAR Collaboration has identified eight key questions for understanding the QCD matter and strong force [1]. With the large acceptance tracking, calorimetry and particle identification detectors, STAR was able to make important measurements helping to answer these questions, such as the discovery of the strongly coupled Quark-Gluon Plasma (sQGP) at RHIC. In this proceedings, we present STAR's future plan to further improve our knowledge in order to address these fundamental questions, including the phase diagram of QCD and partonic structures of the nucleon and nuclei.

In section 2, we will discuss the most recent detector upgrades, including the Heavy Flavor Tracker (HFT) [2] and Muon Telescope Detector (MTD) [3] completed in the beginning of 2014. They will play key roles in studying interactions of heavy flavor particles with the sQGP and properties of the sQGP through measurements of heavy flavor hadrons. In section 3, we will describe upgrade proposals for the second phase of Beam Energy Scan (BES) program (BES-II) in 2018-2019. These upgrades, including the inner sectors of the Time Projection Chamber (iTPC) [4] and a new Event Plane and centrality Detector (EPD), will greatly enhance the STAR capability of studying the QCD phase diagram. In sections 4 and 5, we will present upgrade plans in the forward directions for the anticipated p+p and p+A physics program in 2021-2022 [5] and e+p and e+A physics program in 2025+ [6], respectively. These upgrades will allow high precision measurements to study the unexplored partonic structures of the nucleon and nuclei in low Bjorken x domain.

2. Heavy flavor physics program

Heavy flavor quarks (c, b) are dominantly created from initial hard scatterings at RHIC. They are regarded as an ideal probe to study the properties of the medium. The HFT and MTD were designed for measurements of open heavy flavor hadrons and quarkonia, respectively.

2.1. Heavy Flavor Tracker

The HFT [2] is a silicon vertex detector utilizing the state-of-the-art Monolithic Active Pixel Sensor (MAPS) and conventional silicon pad/strip detector technologies. It consists of 3 sub-detector systems, the Silicon Pixel (PXL) detector, Intermediate Silicon Tracker (IST) and Silicon Strip Detector (SSD). The PXL detector is made of two layers of thin MAPS installed close to the beam pipe at the radii of 2.8 and 8 cm, respectively. The excellent position resolution of the PXL detector (~12 μm) combined with its low material budget (0.4-0.6% radiation length per layer) allows precise measurements of track impact parameters even at low transverse momenta. The expected track impact parameter resolution is 60 (30) μm for Kaons with p_T=0.75 (>1.5) GeV/c. The IST (SSD) is made of one layer of single-sided Silicon Pad (double-sided Silicon Strip) sensors at the radius of 14 (22) cm. The IST and SSD not only provide the bridge between the PXL detector and TPC with a track pointing resolution ~1 mm, but also suppress contributions from pile-up tracks in offline reconstruction and data analyses, thanks to their fast readout electronics.

The HFT was installed and fully commissioned during cosmic rays and low energy Au+Au collisions in the beginning of 2014. Subsequently, it was included in the physics data taking. About 1.2 billion Minimum Bias (MB) events for Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV have been recorded with the HFT in 2014. In 2015 and 2016, we expect to collect p+p, p+Au and additional Au+Au data, allowing precise measurements of the nuclear modification factors R_{CP}, R_{pA} and R_{AA}, elliptic flow and particle correlations, for fully reconstructed open charm hadrons, as well as electrons or muons from semi-leptonic decays of open heavy flavor hadrons. Separate studies of charm and bottom contributions to the latter can be done using track impact parameters measured by the HFT.

Figure 1 illustrates the expected measurement precision of open heavy flavor hadrons by the HFT. Left panel shows D^0 elliptic flow extracted from 1 billion min-bias (MB) events in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. A transport model is used for the projection in which charm quarks either flow as light quarks (red circles) or do not flow at all (green triangles). Right panel shows the ratio of the nuclear modification factors, R_{CP}, between Λ_c baryons and D^0 mesons extracted from 250 million central and 2 billion minimum-bias events in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. The black (red) points assume no baryon-over-meson enhancement (the same enhancement as that of Λ/K_s^0).

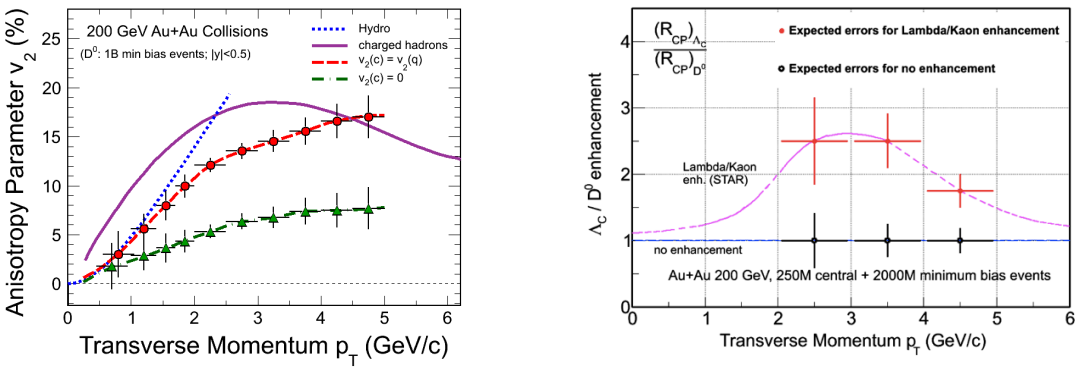

Figure 1. Projected open charm measurement precision with the Heavy Flavor Tracker in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV [2]. Left panel: D^0 elliptic flow extracted from 1 billion min-bias events. Right panel: ratio between Λ_c/D^0 R_{CP} extracted from 250 million central and 2 billion min-bias events. See text for details.

2.2. Muon Telescope Detector

The MTD is made of Multi-gap Resistive Plate Chambers (MRPC) operating in the avalanche mode [3]. It is installed outside the STAR Solenoid magnet, covering 45% of the 2π azimuthal angle in the pseudo-rapidity range -0.5<η<0.5. While 10% modules were installed in 2012 and 63% in 2013, the full MTD was commissioned in the beginning of 2014. Three MTD-related triggers, single muon, di-muon and electron-muon coincidence, were included in the physics data taking. 10 nb^{-1} of di-muon

data have been recorded for Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV in 2014. More data will be taken for p+p, p+Au and Au+Au collisions in 2015 and 2016.

The MTD enables identification and online triggering of high-p_T muons for the first time at STAR. It opens a door to many interesting physics studies. For example, quarkonium measurements have been traditionally performed in the di-electron channel at STAR. As muons are less affected by bremsstrahlung than electrons, separated measurements of different Υ states become possible with the MTD. Figure 2 illustrates the projected quarkonium measurements by the MTD. Measurements of $c\bar{c}$ correlations and its contribution to dilepton production can also be done through electron-muon pairs with small background contribution.

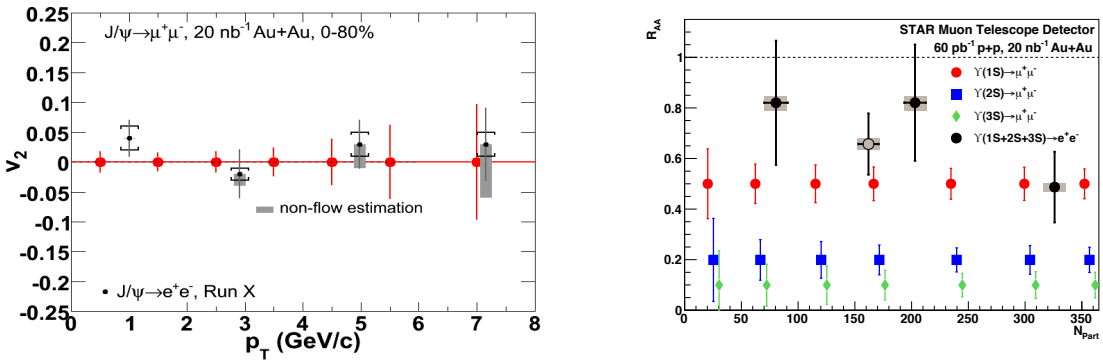

Figure 2. Projected quarkonium measurement precision with the Muon Telescope Detector in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV [3]. Recently STAR results are also shown as grey points. Left panel: J/ψ elliptic flow from 20 nb^{-1} data; Right panel: nuclear modification factors for different Υ states from 20 nb^{-1} data.

3. RHIC BES-II program

Understanding the QCD phase diagram is one of the major scientific goals for heavy-ion physics [4]. RHIC has completed the first phase of BES (BES-I) program to search for the critical point and first order phase transition boundary with Au+Au collisions at $\sqrt{s_{NN}}$=200, 62, 39, 27, 19.6, 14.5, 11.5 and 7.7 GeV. The results have narrowed the region of interest to collision energies between 7.7 and 20 GeV. However, better measurement precisions and theoretical interpretations will be needed for a definite conclusion. The former could be achieved in the second phase of the BES program (BES-II) in 2018-2019, with the following STAR detector upgrades:

(1) iTPC upgrade includes filling the inner sectors with active readout pads and renewing the wires. The iTPC upgrade will improve the track reconstruction efficiency, momentum and dE/dx resolutions for the mid-rapidity $-1<\eta<1$. But more importantly it can extend the TPC coverage from $-1<\eta<1$ to $-1.7<\eta<1.7$. Such improvements 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, plasma phase and freeze-out.

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

(3) End-cap Time-Of-Flight (ETOF) is proposed to provide particle identification capabilities at large rapidity, covering $1<|\eta|<2$. The ETOF, using similar hardware techniques of the current barrel STAR TOF detector, will be placed at the east and west surfaces of the TPC.

With these upgrades, STAR will make precise measurements to explore the QCD phase diagram (see Fig. 3). Note that these upgrades will not only be essential to the BES Phase-II program, but also benefit the future pp/pA and ep/eA programs, as described in sections 4 and 5.

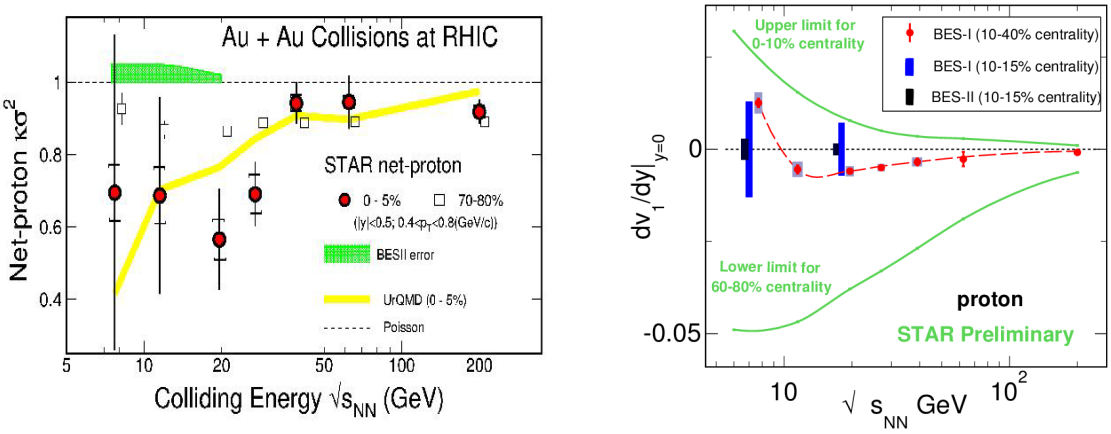

Figure 3. Left panel: Collision energy dependence of net-proton in 0-5% (filled-circles) and 70-80% (open-squares) Au+Au collisions from the BES-I. The vertical bars (parentheses) are statistical (systematic) uncertainties. The green band shows the expected statistical uncertainties from the BES-II. Right panel: Statistical uncertainties with narrow centrality bins for proton dv_1/dy near midrapidity at two sample beam energies for BES-I data sets (blue error bars) and with the proposed BES-II data sets (black error bars). The upper (lower) green curve shows the approximate upper (lower) bound of the measured dv_1/dy range for protons in central collisions (peripheral collisions). The red points show the BES-I measurement.

4. Polarized p+p and p+A program

For the anticipated p+p and p+A physics program in 2021-2022, STAR is considering to build a Forward electromagnetic and hadron Calorimetric System (FCS) and Forward Tracking System (FTS), as shown in Figure 4. FCS prototypes have been built and tested in test beams and the performance meets the expectation. The FTS design is still under study, using either Silicon or GEM technology. Note that the FTS and FCS will also be crucial for ep/eA physics program as described in section 5.

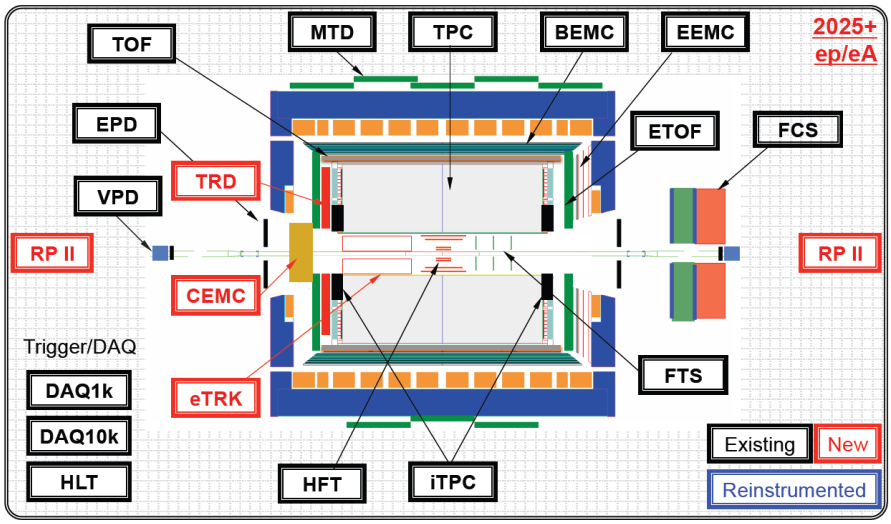

Figure 4. The planned STAR forward instrumentation upgrade, which is essential for detailed studies of polarized p+p/p+A and eSTAR programs. In polarized p+p/p+A program, the ion beams are from right to left (eastward) while proton beams from left to right (westward). In eSTAR program, the electron beams are from right to left (eastward) while hadron beams from left to right (westward).

The physics opportunities for polarized pp/pA collisions have been discussed in a Letter of Intent (LoI) by the STAR collaboration [5]. Through measurements of forward photons, J/ψ, Drell-Yan (DY), inclusive jets and di-jets, and forward-forward gamma/hadron/jet correlation, STAR will be able to study in great detail the partonic structure of the nucleon and nuclei. For example, by measuring transverse spin asymmetries of prompt photons, $W^{\pm}/Z$ bosons (see Fig. 5) and inclusive jets, one can understand the origin of the large transverse spin asymmetries at high x_F, and also constrain the transverse momentum dependent partron distribution and fragmentation functions. Through measuring double spin asymmetries in forward di-jet/hadron-jet/direct photon-jet productions, we can access the gluon helicity distribution at small x as shown in Figure 6.

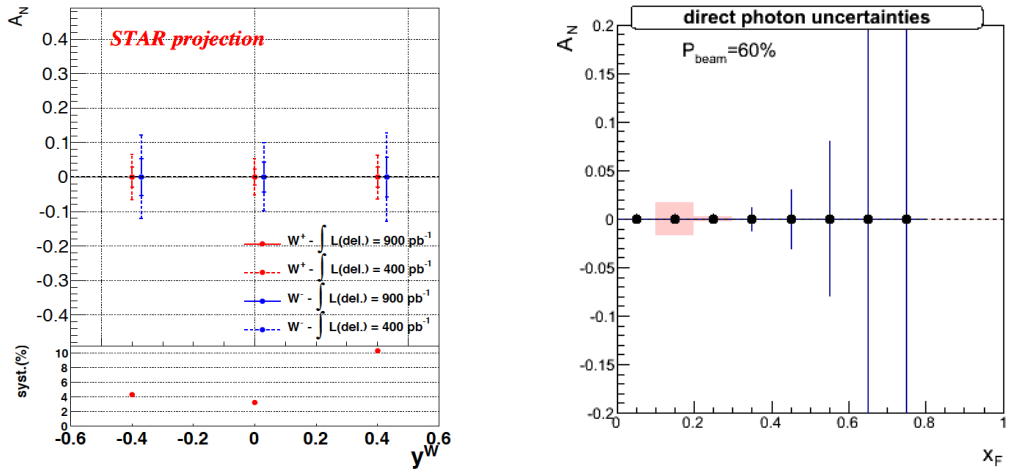

Figure 5. The projected uncertainties for transverse single spin asymmetries of $W^{\pm}$ (left panel) and direct photons after background subtraction (right panel).

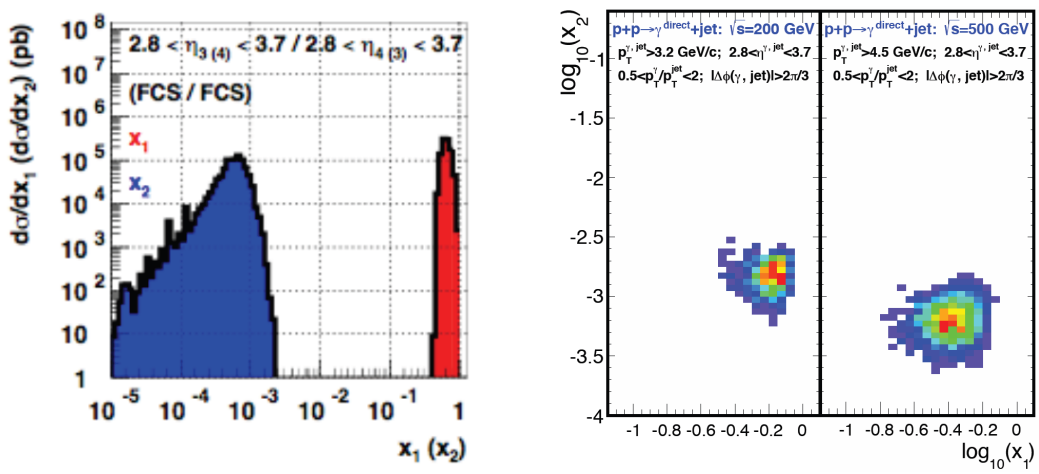

Figure 6. Left panel: The x_1/x_2 range for the forward STAR acceptance region in $2.8 < \eta < 3.7$ for di-jet measurement with FCS-FCS combinations. Right panel: Bjorken x distribution of hard scattering partons at small x via direct γ-jet coincidence channel.

5. eSTAR program

The nuclear physics community in the US is discussing the possibility of building a high-energy Electron Ion Collider (EIC) in the longer-term future. Such a machine will allow precise measurements of the gluon polarization contribution to the nucleon spin, 3D partonic structure of the

nucleon and nuclei, gluon saturation at small x, and parton energy loss in cold nuclear matter. One possibility of realizing such a machine is to convert RHIC into an EIC machine (eRHIC) by adding a new electron ring.

By adding a few more detectors in the electron going direction, the new STAR detector on eRHIC (eSTAR) will be well suited with the physics program [6]. The anticipated detector upgrades as shown in Figure 4 include a Crystal ElectroMagnetic Calorimeter (CEMC) with a pre-shower detector in front covering $-4<\eta<-2$, a Transition Radiation Detector (TRD) placed between the TPC and ETOF, covering $-2<\eta<-1$, and an upgraded Roman Pot detector (RP-II) with an additional silicon plane added to the existing RP detector. With the generic EIC R&D framework supported by BNL, the STAR collaboration is looking into the possibility of using BSO crystals for the CEMC and using a GEM detector in combination with a Xe+CO2 active volume for the TRD.

The physics potential of the eSTAR detector has been described in great details in [6]. Figure 7 shows two such examples, the projected measurement precisions for the polarized proton structure function $g_1(x,Q^2)$ and Deeply Virtual Compton Scattering (DVCS) cross-section at eSTAR. The former is extracted from inclusive electron measurements in longitudinally polarized electron-proton Deep Inelastic Scattering (DIS), from which one can extract the quark and gluon polarization contributions to the nucleon spin. The latter is sensitive to Generalized Parton Distributions (GPDs). By studying the GPD evolution, it will allow an access to gluon GPDs.

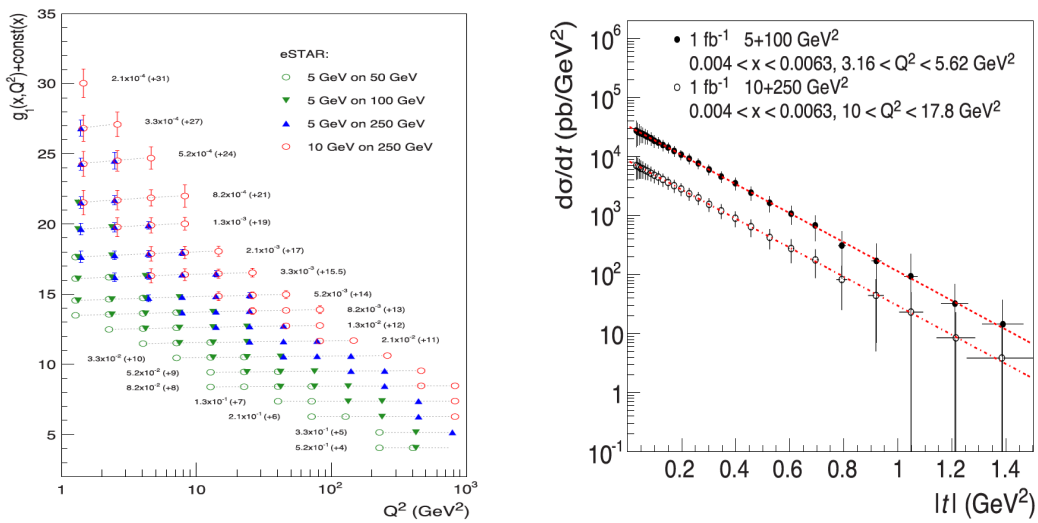

Figure 7. Left panel: projected $g_1(x,Q^2)$ measurement results at eSTAR. Right panel: projected measurement results for differential DVCS cross-sections at eSTAR.

6. Conclusion

The STAR experiment is a dedicated facility for studying matter with color degrees of freedom. Two recently completed detector upgrades, the Heavy Flavor Tracker and Muon Telescope Detector, will greatly help heavy flavor measurements. For the future, STAR has developed a compelling physics and detector upgrade plan to understand the dynamical evolution from the cold nuclear matter to the hot quark-gluon plasma.

References

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