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The STAR detector upgrades for the BES II and beyond physics program

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Abstract

The Beam Energy Scan program (BES) at the Relativistic Heavy Ion Collider (RHIC) is dedicated to explore the Quantum Chromodynamics (QCD) phase diagram and to search for the critical point of the QCD phase transition. The results from the BES phase I program show hints of a first-order phase transition in the QCD phase diagram and the turn-off of the characteristic signatures of the quark gluon plasma at low collision energies, $\sqrt{s_{\rm NN}} < 20$ GeV. Three upgrades of the STAR detector, the inner Time Projection Chamber, the Event Plane Detector, and the endcap Time Of Flight, provide unique opportunities to further investigate the nature of the QCD phase diagram during the BES phase II program (BES II), which covers the $\sqrt{s_{\rm NN}}$ from 7.7 to 19.6 GeV in the collider mode and from 3 to 7.7 GeV in the fixed-target mode. Beyond the BES II, the STAR Collaboration currently designs, constructs, and installs a suite of new detectors in the forward rapidity region ($2.5 < \eta < 4$) over the next two years, enabling a program of novel measurements in p+p, p+A and A+A collisions. This extension of STAR's kinematic reach will allow a detailed study of cold QCD physics at both very high and very low partonic momentum fraction. The new subdetectors to be installed comprise a Forward Calorimeter System, with electromagnetic and hadronic calorimetry. As well as a Forward Tracking System, which consists of 3 layers of silicon mini-strip detectors and 4 layers of small-strip Thin Gap Chambers. In this presentation, the detailed description on the STAR detector upgrades for the BES II and beyond, their performance, as well as the future physics opportunities, will be given.

Keywords: QCD phase diagram, Beam Energy Scan, BES-II, forward rapidity physics, and detector upgrades

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is the most versatile particle collider currently operated, the types of collisions provided include polarized p+p and p+Au, as well as Au+Au, d+Au, U+U, Zr+Zr, and so on. Its top collision energy for Au+Au collisions is $\sqrt{s_{\rm NN}}$ = 200 GeV. Therefore, RHIC is an ideal place to study the nature of Quantum Chromodynamics (QCD). The Beam Energy Scan program (BES) at RHIC is dedicated to study the properties of the QCD matter by varying the center-of-mass energy of the collisions [1]. The first phase of the BES (BES-I) in 2010 to 2011 and 2014 was performed with Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4, and 200 GeV, and the results show hints of a first-order phase transition in the QCD phase diagram and a disappearance of the characteristic signatures of the quark gluon plasma at low collision energies, namely $\sqrt{s_{NN}} < 20$ GeV [2]. The main subdetectors in STAR for BES-I have been the the Time Projection Chamber (TPC), the Time Of Flight (TOF), the Magnet, the Barrel Electromagnetic Calorimeter (BEMC), the Vertex Position Detectors (VPD), and the Beam-Beam Counters (BBC).

To further investigate the nature of the QCD phase diagram, the second phase of the BES program (BES-II) at RHIC started in 2019 with the upgraded *e*-cooling system (LEReC) to increase the luminosity for low energy beams [3] and it is expected to be completed in summer 2021. The STAR detector is running in the collider mode with the collision energies at 7.7, 9.1, 11.5, 14.6, 16.7, and 19.6 GeV, and in a special fixed-target configuration with center-of-mass energies of 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, and 7.7 GeV to access the higher baryon chemical potential regime in the QCD phase diagram [4]. Figure 1 illustrates the schematic of the STAR detector in the fixed-target mode for BES-II.

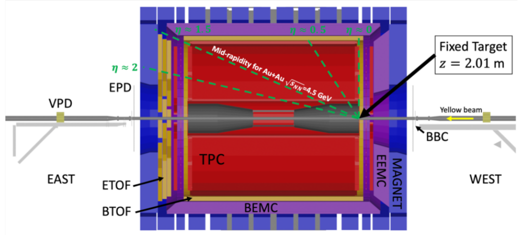
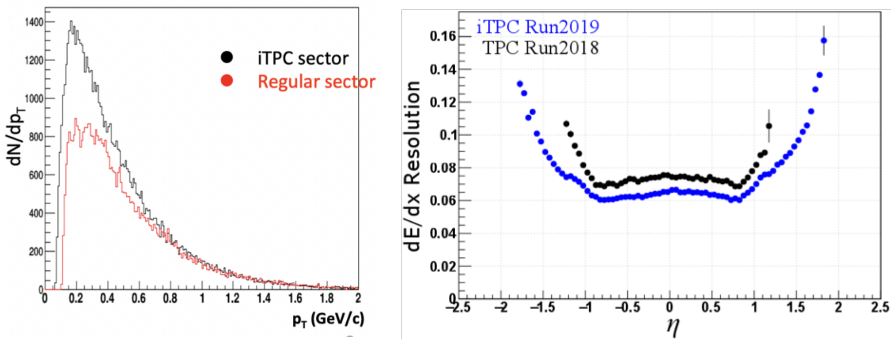


Fig. 1. The detector configuration of STAR for the fixed-target mode.

2. STAR Detector Upgrades for BES-II

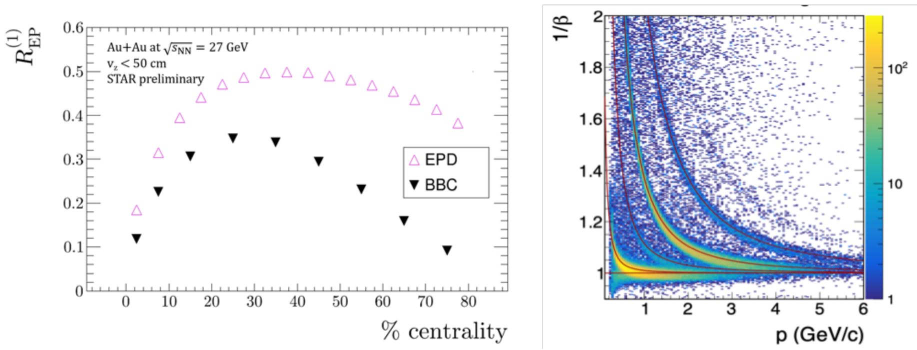
There are three major upgrades in STAR for the BES-II program, the inner TPC (iTPC) [5], the Event Plane Detector (EPD) [6], and the endcap TOF (eTOF) [7] providing larger acceptance coverage and better particle tracking for studying QCD matter. The iTPC upgrade is to rebuild the inner sectors of the TPC, and it provides continuous coverage, better energy loss (dE/dx) and transverse momentum (p_T) resolution, a lower p_T threshold from 125 MeV/c to 60 MeV/c, and wider pseudorapidity (η) coverage from 1.0 to 1.5. The iTPC detector is fully operational since the start of BES-II in 2019. Figure 2(a) and 2(b) show the reconstructed p_T and η distributions using the iTPC and regular TPC sectors, respectively. The improved iTPC performance will significantly impact the measurements of the net-proton Kurtosis to assess the sensitivity on the search of the QCD critical point [5].



(a) (b)

Fig. 2. (a) The reconstructed p_T distributions by the iTPC and regular TPC sectors are shown by black and red histograms, respectively. (b) The dE/dx resolutions as a function of η by the iTPC and regular TPC are shown by blue and black points, respectively.

The EPD is a scintillator based fast detector, which is designed for the event plane determination, centrality definition, and triggering. It has a large η coverage from 2.1 to 5.1 with an excellent timing resolution of about 1 ns. The EPD detector is fully operational since 2018 and Fig. 3(a) shows the significant improvement in resolution of the event plane reconstruction by using the EPD compared to that of using the BBC in STAR. The eTOF uses the multi-gap resistive plate chamber technology, it is installed on one side of the STAR detector as shown in Fig. 1 and will improve the particle identification (PID) coverage in η from 1.1 to 1.6 in the fixed-target mode. Figure 3(b) shows its $1/\beta$ response as a function of momentum, one sees excellent separation between different particle types. The eTOF detector was fully installed for the 2019 data-taking.



(a) (b)

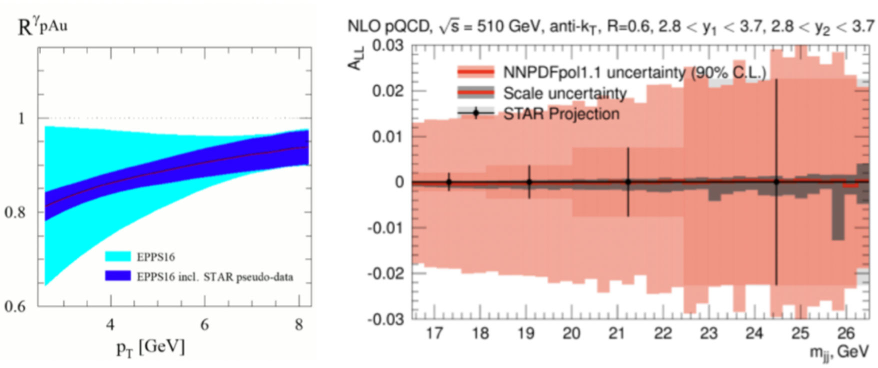
Fig. 3. (a) The resolution of the event plane reconstruction using the EPD (pink up-triangles) and the BBC (black down-triangles). (b) The $1/\beta$ as a function of momentum distribution using the eTOF.

3. STAR Forward Physics Program

To enable a unique program in cold [8] and hot QCD, the STAR Collaboration designs, constructs, and installs a suite of new detectors in the forward rapidity region ($2.5 < \eta < 4$) over the next two years, enabling a program of novel measurements in p+p, p+A and A+A collisions. This extension of STARs kinematic reach will allow detailed study of cold QCD physics at both very high and very low partonic momentum fraction, i.e., when the colliding quarks and gluons carry significant amounts, or very little, of the nucleon energy. Previous STAR efforts using the FPD and FMS detectors have demonstrated that there are outstanding QCD physics opportunities in the forward region. To fully explore this physics, a forward upgrade [9], with superior detection capability for neutral pions, photons, electrons, jets and leading hadrons is proposed, adding charged-particle tracking and electromagnetic and hadronic calorimetry to STARs capabilities at high pseudorapidity. The upgrade will greatly expand the kinematic range of ongoing measurements on the spin and flavor structure of the nucleon, and will enable studies of the longitudinal structure of the nuclear initial state that leads to breaking of boost invariance in heavy-ion collisions. Transport properties of the hot and dense matter formed in collisions. This program is planned to be carried out in starting 2022 to 2025 starting with a polarized 500 GeV p+p run and polarized p+p, p+A and A+A collisions at 200 GeV center-of-mass energy during the RHIC sPHENIX data taking campaign.

The Forward Tracking System consists of 3 layers of silicon tracker and 4 layers of small-strip Thin Gap Chamber (sTGC). The silicon tracker is using the single-sided double metal AC-coupled architecture. Each silicon disk has 12 modules and each modules has 8×128 mini-strips in the $r\phi$ plane. Therefore, the silicon tracker has finer and coarser granularities in ϕ and r direction, respectively. The sTGC is a gaseous detector based on the technology developed by the ATLAS collaboration [10] and each layer is double-sided to provide the measurements in x-y coordinate with a position resolution $\sim$100 μm. The first sTGC prototype has a size of 60 cm $\times$ 60 cm with a strip length of 30 cm and the efficiency tested in lab achieved $> 98\%$. The Forward Calorimeter system is a combination of an electromagnetic calorimeter (ECAL) and hadronic calorimeter (HCAL). The ECAL reuses the lead-scintillator calorimeter from the PHENIX collaboration with new silicon photonmultiplier (SiPM) based readout system. There are total 12 sectors in the ECAL, each sector has 6×6 EM modules, and each EM module has 4 independent towers with penetrating wavelength-shifting fibers for light collection. The HCAL in the first hadronic calorimeter in STAR which is a iron-scintillator sandwich sampling calorimeter. The prototypes including the HCAL, the ECAL, preshower, and the sTGC were installed for the 2019 data-taking in STAR.

As indicated earlier many important physics topics can be studied with high precission, for example, the constraints on the longitudinal structure of initial conditions through correlations in different rapidity [11], distinguishing the model predictions for the global hyperon polarization in Au+Au collisions [12, 13, 14]. On the other hand, in p+p and p+A collisions, for instance, the measurements with the STAR forward upgrade will provide tight constraint on the nPDFs with unique kinematic coverage as shown in Fig. 4(a), and the constraint on the gluon helicity $\Delta g(x)$ at very low x through the di-jets final states as shown in Fig. 4(b) [9].



(a) (b)

Fig. 4. (a) The improved constraint on the gluon PDF in nuclei using direct photons nuclear modification factor (R^{γ}_{pAu}). (b)A_{LL} as a function of di-jets mass with the projected uncertainty.

4. Summary

The STAR experiment plays a crucial role in understanding the QCD phase diagram and in expanding our understanding of cold QCD physics. The STAR BES-II upgrades, including the iTPC, the EPD, and the eTOF subdetectors, provide excellent particle PID with wider η coverage, and significantly better resolution in dE/dx, p_T, and the event plane determination. Beyond 2021, the STAR experiment will install a forward upgrade, which consists of tracking (silicon and sTGC) and calorimetry (ECAL and HCAL) with a coverage of $2.5 < \eta < 4.0$ to further investigate the nature of QCD, especially the cold QCD physics at both very high and very low partonic momentum fraction.

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