The STAR Detector Upgrades and Electromagnetic Probes in Beam Energy Scan Phase II

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Published 3 May 2018

The Beam Energy Scan Phase II at RHIC, BES-II, is scheduled from year 2019 to 2020 and will explore the high baryon density region of the QCD phase diagram with high precision. The program will focus on the interesting energy region determined from the results of BES-I. Some of the key measurements anticipated are the chiral symmetry restoration and QGP thermal radiation in the dilepton and direct photon channels. The measurements will be possible with an order of magnitude better statistics provided by the electron cooling upgrade of RHIC and with the detector upgrades planned to extend STAR experimental reach. The upgrades are: the inner Time Projection Chamber sectors (iTPC), the Event Plane Detector (EPD), and the end-cap Time of Flight (eTOF). We present the BES-II program details and the physics opportunities in the dilepton and direct photon channels enabled by the upgrades.

Keywords: Beam Energy Scan Phase II; Detector upgrade; Dilepton; Direct photon.

1. Introduction

The STAR Collaboration proposes a second phase of the Beam Energy Scan program at RHIC (BES-II) to explore the QCD phase structure ¹ in the years 2019 to 2020. The Beam Energy Scan Phase I program took place 2010 to 2014. From $\sqrt{s_{NN}} = 200$ to 7.7 GeV which are corresponding to baryon chemical potentials $\mu_B = 20$ to 420 MeV, 8 collision energies were scanned and many interesting results were achieved. At the top RHIC energy $\sqrt{s_{NN}} = 200$ GeV, the discovery of the quark-gluon plasma (QGP) is further confirmed. The results from BES-I identify the particular interesting energy range below $\sqrt{s_{NN}} = 20$ GeV. These results contain the studies related to the following topics: signature of the QGP turn-off ^{2,3}, the critical point ^{4,5}, the first-order phase transition ⁶ and chiral phase transition ^{7,8}.

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Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (MeV) in 0-5% central collisions	420	370	315	260	205
Fixed Target Energy (GeV)	3.0	3.2	3.5	3.9	4.5
Fixed Target μ_B (MeV)	721	699	666	633	589
Proposed Event Goals in BES-II	100	160	230	300	400
BES-I Events	4	N/A	12	20	36

The BES-II program requires low-energy running, requiring accelerator and detector upgrades. The program is focusing on precision measurements in the interesting energy region identified based on various BES-I results. The Au+Au collision data from $\sqrt{s_{NN}} = 19.6, 14.5, 11.5, 9.1$ and 7.7 GeV will be collected in year 2019 and 2020. The planned event statistics for various observables related to the topics mentioned above can be found in Table 1. Compared to BES-I, the statistics will be improved by more than a factor of ten. To achieve these statistics requirements and obtain conclusive messages on these topics, an accelerator upgrade at RHIC and detector upgrades at STAR are needed. At the same time, the Fixed-Target program (FXT) which uses only one beam allows us to reach higher μ_B with high luminosity. The planned collision energies and the corresponding FXT energies can also be found in Table 1.

2. Upgrades

To make high statistics measurements of the observables, the luminosities of RHIC need to be increased. The ongoing RHIC low energy electron cooling upgrade can raise the luminosity by a factor of $3 \sim 10$ in the range from $\sqrt{s_{NN}} = 5$ to 15 GeV.

At the same time, three detector upgrades are ongoing at STAR. They are the iTPC upgrade⁹, the EPD upgrade¹⁰ and the eTOF upgrade¹¹. The major goals of the iTPC upgrade are as follows: wider rapidity coverage, better momentum resolution, and better dE/dx resolution. By increasing the number of inner sector readout pad rows from 13 to 40 and increasing the pad size, we double the readout channels and get continuous coverage on η . This will increase the percentage of sampled track path length from 20% to 95% and extend the $|\eta|$ coverage from 1 to 1.5. The electronics will also be upgraded. In addition, the multi-wire proportional chambers (MWPCs) of the inner sectors will be renewed to reset the time for aging of the anode wires due to the increased integrated and instantaneous luminosity delivered by RHIC. Overall, the goal for the projects is to replace all 24 existing inner sectors in the STAR TPC with new, fully instrumented, sectors. The first new inner sector has been installed in STAR detector and will be commissioned in the coming RHIC run. For this sector, the local test on the MWPC showed qualified energy resolution (20% FWHM) in P10 gas as demonstrated in FIG. 1.

The EPD is a dedicated event-plane and centrality detector placed in the forward rapidity region $2.1 < |\eta| < 5.1$. With 16 radial segments and 24 azimuthal segments,

Fig. 1. The spectrum of ^{55}Fe for the new inner TPC MWPC sector measured by MCA. The X axis represents the channel number, while Y axis represents the counts. A function which is consist with two gaussian functions and an exponential function is used to fit the data and get the energy resolution.

the detector will provide precise measurements of both the collision centrality and the event plane. Additionally, the EPD will be a good trigger detector for collisions at lower beam energies with good time resolution ($\sim 1\text{ns}$). For the eTOF upgrade, the CBM and STAR joined collaboration will install 10% of the full CBM TOF system at STAR as part of the FAIR Phase 0 program. The eTOF will cover the rapidity range from -1.1 to -1.6. Combined with the iTPC upgrade, the eTOF upgrade will provide particle identification capability in forward direction at STAR which is crucial to the Fixed Target program at BES-II.

3. Dilepton and direct photon analyses in BES-II

With the performance improvements provided by the collider and detector upgrades, many physics opportunities will be opened in BES-II. The significant improved statistics will benefit many analyses.

For direct photon analysis, p_T dependent direct photon yield are only extracted at top RHIC energy due to statistical limitation ¹². In BES-II, this study can be extended to the lower energy region. The direct photon p_T spectra in the lower energy region compared with theoretical calculations will help us to get an in-depth view of the hot and dense medium and give an important cross check to model calculations that same model should simultaneously describe both thermal photons from direct photon analysis and the vector meson in-medium modification from dilepton analysis. As shown in FIG. 2, model predictions from Rapp et al. ^{13,14} and Paquet et al. ¹⁵ describe the direct photon spectra in the thermal region ($< 3\text{ GeV}/c$) well within uncertainties.

For dilepton measurements, the vector meson in-medium modification study can be used to study the fundamental properties of the hot and dense medium. In STAR BES-I, clear enhancements in the ρ -like region have been observed from RHIC top energy down to 19.6 GeV. As one can see from FIG. 3, these excesses are

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Fig. 2. The direct photon invariant yields as a function of p_T in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to model predictions. The statistical and systematic uncertainties are shown by the bars and boxes, respectively.

Fig. 3. The acceptance-corrected dielectron mass spectra normalized to the charged particle multiplicity at mid-rapidity dN_{ch}/dy , in Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ (solid circles) and $\sqrt{s_{NN}} = 200$ GeV (diamonds).

consistent with the ρ broadening scenario within uncertainties which is based on partial chiral symmetry restoration in hot and dense medium^{7,8}. The same model can describe the thermal photon spectra as discussed above. As shown in this figure, both statistical and systematic uncertainties are relative large. In BES-I, 19.6 GeV is the lowest energy where we made a valuable measurement.

Because of the iTPC upgrade, in BES-II, the measurements on dilepton will be significantly improved. Better dE/dx resolution will give pure electron identification at higher p_T . FIG. 4 shows the projected improvements from both statistical and systematic sides. The systematic and statistical uncertainties will be reduced by

Fig. 4. Dilepton uncertainty projection in the ρ -like region compared to the measurement in BES-I. The bars and boxes represent the statistical and systematic uncertainties, respectively. The projection mean values shown in red are set as same as current data.

Fig. 5. Normalized dilepton low mass excess as a function of collision energies. The blue markers represent the projection in BES-II with the iTPC upgrade. The projection mean values are set as same as current data at 19.6 GeV.

a factor of 2 and 3, respectively. In FIG. 5, from 200 down to 20 GeV, BES-I measurements are consistent with the theoretical calculations and show a “flat” distribution within uncertainties. Since in this range the total baryon density does not change much, it is important to extend this analysis to an energy region below 20 GeV where the total baryon density increases significantly as the collision energy decreases. The blue markers give the projected precision below 20 GeV in BES-II and the mean values of this projection are fixed to the measured 19.6 GeV mean

value. Combining with eTOF, in BES-II, STAR can provide forward PID capability. The dilepton analysis can be extended to more forward directions in BES-II.

4. Summary

The STAR beam energy scan phase II in year 2019 and 2020 will explore the QCD phase diagram in high baryon density region. The electromagnetic probes such as dileptons and direct photons will be measured. The upgrades at both RHIC (electron cooling system) and STAR (iTPC, EPD, eTOF) are ongoing and will be ready for BES-II data taking. With these upgrades, there will be significant improvements for the electromagnetic probes at STAR: better statistics, lower systematic uncertainties, wider p_T and rapidity coverage, and extended PID capability. The Fixed Target program enables high statistics studies below 7.7 GeV.

Acknowledgments

Supported by the National Natural Science Foundation of China (Grant Number: 11505181, 11520101004 and 11720101001).

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