Identified Light and Strange Hadron Spectra at $\sqrt{s_{NN}} = 14.5$ GeV with STAR at RHIC BES I

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Abstract. With the recently measured Au+Au collisions at $\sqrt{s_{NN}}=14.5$ GeV, RHIC completed its first phase of the Beam Energy Scan (BES) program. The main motivation of the BES program is the search for a conjectured critical point and possible first order phase transition. Amongst the various collision energies of 7.7, 11.5, 19.6, 27, and 39 GeV, that have been previously presented by STAR, collisions at 14.5 GeV will provide data set in the relatively large chemical potential gap between the 11.5 and 19.6 GeV center-of-mass energies. In this contribution, we report new STAR measurements of Au+Au at $\sqrt{s_{NN}}=14.5$ GeV that include identified light particle $R_{CP}$ and spectra, as well as measurements of the strange hadrons ($K^0_s$, $\Lambda$, $\Xi$, and $\Omega$). The spectra from both light and strange particles cover a significant range of the intermediate transverse momentum ($2 < p_T < 5$ GeV/$c$) in all beam energies. We will discuss the physics implications of these observables and whether hadronic or partonic interactions dominate the collision dynamics at a given center-of-mass energy.

1. Introduction

The Relativistic Heavy Ion Collider’s (RHIC) Beam Energy Scan (BES) is a program designed to scan the QCD phase diagram. One of the 3 primary goals of the BES program is to search for the onset of signatures attributed to the formation of a Quark Gluon Plasma (QGP)[1]. As part of the Beam Energy Scan Phase I (BES I) program Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27$, and 39 GeV were collected in 2010 and 2011. The BES I program was then completed with the recently collected Au+Au collisions at $\sqrt{s_{NN}} = 14.5$ GeV in 2014. Collisions at these energies cover a significant range in the temperature vs. baryon chemical potential ($\mu_B$) phase space and provide a unique dataset for studying the QCD phase diagram. The final set of Au+Au collisions collected at $\sqrt{s_{NN}} = 14.5$ GeV is of particular interest because it provides data in the relatively large $\mu_B$ gap between $\sqrt{s_{NN}} = 11.5$ and 19.6 GeV [2]. Particle yields for the light hadrons ($\pi^\pm$, $p$, and $\bar{p}$) and the strange hadrons ($K^0_s$, $\Lambda$, $\Xi$, and $\Omega$) are obtained by employing the particle identification techniques discussed in Sec. 2. The identified particle yields can be used to construct several experimental observables. In this contribution we report a systematic study of the nuclear modification factor and baryon-to-meson ratio for the BES I energies and discuss their physics implications.

The nuclear modification factor, or $R_{AA}$, is the ratio of particle yields in central heavy ion collisions to the appropriately scaled particle yields in proton-proton ($pp$) collisions. When $pp$ data at the corresponding collision energy and conditions are not available, as was the case in the BES I, it is common to measure the nuclear modification factor via the proxy $R_{CP}$. The $R_{CP}$ is the ratio of particle yields in central heavy ion collisions to the appropriately scaled particle...
Figure 1. The charged hadron $R_{CP}$ for events with a centrality of 0-5% over those with a centrality of 60-80% for the BES I energies and $\sqrt{s_{NN}} = 62.4$ GeV. The colored error bars on the right side of each plot are the correlated uncertainty due to the $N_{coll}$ scaling for each $\sqrt{s_{NN}}$ energy calculated from MC Glauber. Horizontal bars represent the $p_T$ range used for measuring each point in the spectra. Vertical bars are used to show statistical uncertainty only.

Yields in peripheral heavy ion collisions. $R_{CP}$ can be calculated from a single minimum bias dataset and is less sensitive to cold nuclear matter effects than $R_{AA}$. However, $R_{CP}$ generally comes with large correlated systematic uncertainties due to the determination, using Monte Carlo (MC) Glauber, of the number of binary collisions ($N_{coll}$) in peripheral events [3, 4].

Measurements of the nuclear modification factor ($R_{CP}$) for inclusive charged particles in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have shown significantly suppression ($R_{CP} << 1$) at high $p_T$ ($p_T > 5$ GeV/c) [5]. The observation of strong suppression at high $p_T$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is attributed to partonic energy loss due to interactions in a hot and dense medium such as the QGP. For this reason strong suppression is considered to be a key signature of QGP formation. In Fig. 1 the $R_{CP}$ of charged hadrons is shown for Au+Au collisions at each BES I energy and for $\sqrt{s_{NN}} = 62.4$ GeV. The $R_{CP}$ of charged hadrons shows a smooth transition from enhancement ($R_{CP}>1$) at the lower $\sqrt{s_{NN}}$ energies to suppression ($R_{CP}<1$) at $\sqrt{s_{NN}} = 62.4$ GeV. This observation in the charged hadrons motivates a systematic study of the identified particle $R_{CP}$. Specifically measurement of the $R_{CP}$ of identified particles will help provide more stringent limits on models and help distinguish competing physics effects.

The two observables discussed in this contribution are constructed from the various identified particle spectra. For this reason the procedures used to conduct particle identification will be briefly discussed. First, the detectors used for particle identification will be introduced. Second, the particle identification techniques used for these results will be presented. Finally, the $R_{CP}$ and baryon-to-meson ratios will be presented and their physics implications will be discussed.
2. Particle Identification with the STAR Detector

The Solenoidal Tracker at RHIC (STAR) [6] is used for the analyses in this paper. The Time Projection Chamber (TPC) [7] is the central detector in STAR and provides charged particle tracking, momentum reconstruction, and particle identification information as dE/dx. The TPC has nominal acceptance in the region |ζ| < 1.0. In addition to the TPC, the Time of Flight (TOF) [8] detector is also used for identification of the π±, p, and ¯p. The TOF detector provides particle identification information through its measurement of 1/β. The nominal acceptance of the TOF detector is in the region |ζ| < 0.9. Both the TPC and the TOF detectors provide full azimuthal coverage of 2π.

The measurement of the π±, p, and ¯p identified yields is conducted using a method that combines the dE/dx information from the TPC and the 1/β information from the TOF. In this method the full 2D distribution of the tracks’ dE/dx vs. 1/β is reduced into eight complimentary 1D distributions. Two of these distributions are the 1D projections of all tracks onto the dE/dx and 1/β axes. The remaining six distributions are subsets of the first two with a relative enhancement for the particle of interest, either π, K, or p. The first three distributions are formed by cutting around the dE/dx peak for each of the π, K, and p and then projecting onto the 1/β axis. The final three distributions are formed by cutting around the 1/β peak for each of the π, K, and p and then projecting onto the dE/dx axis. These eight 1D distributions, two “unenhanced” and six “enhanced”, capture the vast majority of the information contained in the full 2D distribution while reducing the dataset’s overall complexity. These eight distributions are then fit simultaneously to extract the yields for each particle species. In the simultaneous fit, the enhanced distributions are primarily used to constrain shape parameters, while the two unenhanced distributions are used to determine the particle yields.

The strange hadrons, K0, Λ, Ξ, and Ω, are identified using tracks reconstructed in the TPC from each particle’s charged decay products to identify the secondary decay vertex. Topological cuts are then applied to these charged daughter tracks to reduce the combinatorial background and to optimize the acceptance of the signal. The particle yields are then extracted by fitting the invariant mass distribution from the daughter particles with combinatorial background subtracted. This topological method of particle identification provides a robust method of extracting K0, Λ, Ξ, and Ω yields over a significant portion of the pT range for the BES I energies.

The spectra for the light hadrons, π±, p, and ¯p, and the strange hadrons, K0, Λ, Ξ, and Ω are corrected for the TPC’s detection efficiency and acceptance using simulated events embedded into real data events. The simulated events are produced using STARSIM; a GEANT3 based simulation of the STAR detector geometries [9]. The π±, p, and ¯p are further corrected for the detection efficiency and acceptance of the TOF detector using a data-driven method. Finally the π±, p, ¯p, and Λ are corrected for weak-decay feeddown contributions and the π±, p, and ¯p are corrected for knock-out contributions.

3. Results

With the recent addition of the identified light and strange hadron spectra from Au+Au collisions at √sNN = 14.5 GeV, we now have a complete set of identified particle spectra from the BES I energies. These spectra provide a wealth of data from which we can extract observables sensitive to the collision dynamics. In this contribution, we are specifically interested in the RCP and baryon-to-meson ratios; two observables identified as key QGP signatures. With the complete set of identified particle spectra it is possible to systematically study the √sNN dependence of RCP and the baryon-to-meson ratios for the BES I energies.

In Fig. 2 the RCP calculated from 0-5% central events over 60-80% central events for π±, p, and ¯p is shown. In this figure, each plot shows the RCP for a single particle species for all six BES I energies to highlight the √sNN dependence. The RCP for π±, p, and ¯p are all below
Figure 2. The $R_{CP}$ for Au+Au collisions at the BES I energies constructed from events with a centrality of 0-5% over those with a centrality of 60-80%. The colored error bars on the right side of each plot are the correlated uncertainty due to the $N_{coll}$ scaling for each $\sqrt{s_{NN}}$ energy calculated from MC Glauber. Horizontal bars represent the $p_T$ range used for measuring each point in the spectra. Vertical bars are used to show statistical uncertainty while shaded boxes are used to show systematic uncertainties.

Figure 3. The $R_{CP}$ for Au+Au collisions at the BES I energies for events with a centrality of 0-5% over those with a centrality of 40-60%. The gray error bar on the right side of each plot is the correlated uncertainty due to the $N_{coll}$ scaling for each $\sqrt{s_{NN}}$ energy calculated from MC Glauber. Vertical bars are used to show statistical uncertainty only.

unity at low $p_T$ ($< 1.0$ GeV/c). In this region number of binary collision scaling ($N_{coll}$) is not expected to hold. Instead number-of-participant scaling ($N_{part}$) is expected to better describe...
the production at low $p_T$ where soft processes dominate.

From Fig. 2 we can observe that the $R_{CP}$ for $\bar{p}$ shows very little $\sqrt{s_{NN}}$ dependence, while the $R_{CP}$ of $p$ shows some non-trivial splitting at intermediate $p_T$ as a function of $\sqrt{s_{NN}}$. The $R_{CP}$ of both $p$ and $\bar{p}$ show enhancement at the highest measured $p_T$ for each energy. Unlike $p$ and $\bar{p}$, the $R_{CP}$ of $\pi^+$ and $\pi^-$ show significant dependence on $\sqrt{s_{NN}}$ for $p_T > 1.0$ GeV/c.

While high $p_T$ suppression is attributed to partonic energy loss, other effects such as coalescence, radial flow and cold nuclear matter effects, similar to the Cronin effect, can lead to enhancement in the $R_{CP}$ [10]. Previous measurements have shown that there is significant radial flow even at the BES I energies [11]. The presence of radial flow will contribute to the enhancement observed in the $R_{CP}$ of $p$ and $\bar{p}$ at intermediate $p_T$. The pions are less affected by radial flow and coalescence and, therefore, the pion $R_{CP}$ should be a more sensitive probe for observing suppression due to partonic energy loss.

The uncertainty on the $N_{coll}$ scaling calculated with MC Glauber is shown on the right side of each plot. The scaling uncertainty makes it difficult to determine at exactly which energy the $\pi^+$ and $\pi^-$ $R_{CP}$ transitions from suppression to unity to enhancement. However, since the scaling uncertainty is correlated from one energy to the next, it is clear that the relative amount of suppression increases as a function of $\sqrt{s_{NN}}$.

![Figure 4](image-url)

**Figure 4.** The $p / \pi^+$ ratio for Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 14.5, 19.6, 27.0, and 39.0 GeV. Horizontal bars represent the $p_T$ range used for measuring each point in the spectra. Vertical bars are used to show statistical uncertainty while shaded boxes are used to show systematic uncertainties.

In Fig. 3 the $R_{CP}$ calculated from 0-5% central events over 40-60% central events for $K^0$, $\Lambda$, $\Xi$, and $\Omega$ is shown. In this figure, each plot shows the $R_{CP}$ for a single $\sqrt{s_{NN}}$ energy for all particle to highlight the particle species dependence at each energy. At $\sqrt{s_{NN}} = 14.5$ GeV
and above the $R_{CP}$ shows significant dependence on the particle species. However, for the two lowest $\sqrt{s_{NN}}$ energies, the $R_{CP}$ for $K^0_s$, $\Lambda$, and $\Xi$ are roughly consistent. This is evidence that hadronic degrees of freedom are dominant at the lowest $\sqrt{s_{NN}}$ energies, while partonic degrees of freedom may play a larger role as the $\sqrt{s_{NN}}$ energy is increased.

Previous STAR measurements in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV observed that the baryon-to-meson ratio (e.g. $\Lambda/K^0_s$) in central events at intermediate $p_T$ is significantly larger than the same ratio measured in $pp$ collisions[12, 13, 14]. The models capable of reproducing this effect generally include coalescence and recombination when simulating the momentum distribution of the particles[15]. Since modeling the baryon-to-meson ratios require the use of coalescence and recombination, the baryon-to-meson ratio is an observable that is considered sensitive to the formation of a QGP.

Measurements of the $p/\pi^+$ ratios are shown in Fig. 4 for several centralities for each BES I energy. The $\Lambda/K^0_s$ ratios are shown in Fig. 5 (previously shown in [16]) for several centralities for each BES I energy. In both the $p/\pi^+$ and $\Lambda/K^0_s$ ratios we observe a significant centrality dependence at intermediate to high $p_T$ for $\sqrt{s_{NN}}$ energies of 14.5 GeV and above. However, no significant centrality dependence is observed for $\sqrt{s_{NN}} = 11.5$ GeV and below. This may be evidence that recombination and coalescence are more dominant production mechanisms at higher $\sqrt{s_{NN}}$ energies, while fragmentation is a more dominant production mechanism at lower $\sqrt{s_{NN}}$.

**Figure 5.** The $\Lambda/K^0_s$ ratio for Au+Au collisions at the BES I energy. Vertical bars are used to show statistical uncertainty only.
4. Summary
In this contribution a systematic study of the particle-identified $R_{CP}$ and baryon-to-meson ratio is presented for Au+Au collisions at the BES I energies of $\sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 27.0,$ and 39.0 GeV. The measurements presented here would benefit from an increased $p_T$ reach, especially for the lowest collision energies. The Beam Energy Scan Phase II (BES II) program at RHIC will provide significantly more data at these energies and will allow these results to be improved in the future.

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