First results from Au+Au collisions at \( \sqrt{s_{NN}} = 9.2 \) GeV in STAR

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Abstract. One of the primary aims of heavy-ion collisions is to map the QCD phase diagram and search for different phases and phase boundaries. RHIC Energy Scan Program was launched to address this goal by studying heavy-ion collisions at different center of mass energies. The first test run with Au+Au collisions at \( \sqrt{s_{NN}} = 9.2 \) GeV took place in early 2008. The large acceptance STAR detector has collected few thousands minimum bias collisions at this beam energy. We present the first results for identified particle yields and particle ratios. The results for the azimuthal anisotropy parameters \( v_1 \) and \( v_2 \) and those from pion interferometry measurements are also discussed in this paper. These results are compared to data from the SPS at similar beam energies.

1. Introduction:

One of the main aims of heavy-ion collision experiments is to map the Quantum Chromodynamics (QCD) phase diagram [1]. The QCD phase diagram is described by the variation of temperature with respect to the baryon chemical potential (\( \mu_B \)). Efforts are being made to locate the QCD phase boundary (separates the matter dominated by quarks and gluons degrees of freedom from those dominated by hadronic degrees of freedom) and the QCD critical point (where the first order phase transition ends) in the QCD phase diagram. To locate these or to map the QCD phase diagram, one needs to find a way to vary temperature and \( \mu_B \), which can be achieved by varying the colliding beam energy. The freeze out temperature and \( \mu_B \) can be deduced from the spectra and ratios of produced particles by comparing with model calculations. Various signatures for locating different phases of matter and the QCD critical point will be studied.

Relativistic Heavy Ion Collider (RHIC) Energy Scan Program will be launched to address these issues and specifically, the STAR experiment (Solenoidal Tracker At RHIC) would also like to determine the beam energy at which the following interesting phenomena observed at top RHIC energy (200 GeV) start to appear in the data: Number of constituent quark (NCQ) scaling of elliptic flow parameter for produced
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hadrons at intermediate $p_t$, enhanced correlated yields at large $\Delta \eta$ and $\Delta \phi \sim 0$ (Ridge) and the suppression of high transverse momentum hadron production in heavy ion collisions [2, 3, 4]. To achieve these goals, STAR has proposed a beam energy scan program at RHIC spanning beam energies from 5 GeV to 50 GeV. As a first step of the energy scan program, a test run was organized in early 2008 with Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV.

2. Experiment and Analysis

The data presented here are from Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV using the Time Projection Chamber (TPC) [5] in the STAR experiment at RHIC. The events with a primary vertex within $\pm 75$ cm of the geometric center of TPC along the beam axis were accepted for this analysis and about $\sim 3000$ events were analyzed. The centrality selection for Au+Au 9.2 GeV was done by using the uncorrected charged particles, measured event-by-event within the pseudo-rapidity ($\eta$) region $\pm 0.5$. Those primary tracks which originate within 3 cm of the primary vertex (distance of closest approach or DCA) and have transverse momentum ($p_t$) $> 0.1$ GeV/c within the rapidity ($y$) interval $|y| < 0.5$ were selected for the analysis.

Particle identification is accomplished by measuring the ionization energy loss ($dE/dx$). For good momentum and $dE/dx$ resolution, tracks were required to have at least 20 number of fit points (Nfitpts) out of the maximum 45 hits in the TPC. Uncorrected particle yields are extracted from $dE/dx$ distributions for each $p_t$, $y$ and centrality bin [6].

The spectra were corrected for tracking inefficiency, detector acceptance and energy loss due to interactions. Total reconstruction efficiencies were obtained from embedding Monte-Carlo (MC) tracks into real events at the raw data level and subsequently reconstructing these events. Detailed description of STAR geometry and a realistic simulation of TPC are given in references [6]. The 0-10% centrality results presented here are not corrected for vertex inefficiency. Simulations suggest that this effect is small for collision centrality studied.

The systematic uncertainties on yield of particles were obtained by varying the analysis cuts like vertex-z position, Nfitpts, DCA and $y$. The systematic errors due to the type of function used to fit the spectra (error due to extrapolation), error on efficiency and error in extracting the yields of particles were also taken into account. The total systematic error for pions were found to be $\sim 10\%$, $\sim 12\%$ for kaons and greater than 15% for protons (results not shown in this paper).

3. Results

3.1. Hadron Yields, Average Transverse Mass and Ratios

Fig. 1 shows the particle yields at mid-rapidity $dN/dy$ for $\pi^\pm$ and $K^\pm$ plotted as a function of $\sqrt{s_{NN}}$ for central collisions at AGS, SPS and RHIC energies (as mentioned
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Figure 1. Left panel: $\pi^\pm$ yield per unit rapidity (dN/dy) as function of $\sqrt{s_{NN}}$ at mid-rapidity for central collisions. The errors are statistical and systematic added in quadrature. Right panel: Same as above, for $K^\pm$. Star symbols are the results for Au+Au 9.2 GeV, circles represent RHIC results from other energies, squares show the results from SPS and triangles represent those from AGS energies (This is same for all figures). RHIC: Results for $\sqrt{s_{NN}} = 9.2$ GeV and 19.6 - 200 GeV; SPS: Results for $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV; AGS: Results for $\sqrt{s_{NN}} < 6$ GeV.

Figure 2. Left panel: Average transverse mass for $\pi^\pm$ as function of colliding beam energy. Solid symbol are for the positively charged particles and open symbols for the negatively charged particles. Errors are statistical and systematic added in quadrature. Right panel: Same as above, for $K^\pm$.

in the caption) [7].

Fig. 2 shows the difference between average transverse mass ($< m_T >$) and hadron mass ($m$) plotted as a function of colliding beam energy ($\sqrt{s_{NN}}$) [7]. For a thermodynamical system, $< m_T > - m$ is related to temperature of the system and $\log(\sqrt{s_{NN}})$, which is proportional to yield of the particles, is related to entropy of the system.

The strangeness production in heavy-ion collision experiments can be observed from the kaon to pion ratio. Fig. 3 shows the $K^\pm/\pi^\pm$ ratio as a function of $\sqrt{s_{NN}}$. 
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Figure 3. Charged kaons to charged pions ratio as a function of colliding beam energy. Solid symbols represent $K^+/\pi^+$ ratio and the open symbols represent the $K^-/\pi^-$ ratio. Errors are statistical and systematic added in quadrature.

Figure 4. Left panel: $v_1$ as function of $\eta$ for charged hadrons. Results for Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV are compared with those from 200 and 62.4 GeV. Right panel: $v_2$ (0-60% for 9.2 GeV data) for charged hadrons as function of colliding beam energy. Errors are statistical only.

3.2. Azimuthal Anisotropy Measurements

Fig. 4 (left panel) shows the directed flow ($v_1$) as a function of $\eta$ for charged hadrons. Results for Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV are compared with those from 200 and 62.4 GeV [8]. It is observed that $v_1$ for 9.2 GeV shows different behavior as compared to 200 and 62.4 GeV. This could be due to the spectators effect, since the beam rapidity for 9.2 GeV is 2.3, which is within the Forward Time Projection Chamber (FTPC) acceptance in the STAR experiment. For 200 and 62.4 GeV, the beam rapidities are 5.4 and 4.2 respectively, which lie outside the FTPC acceptance region and hence flow due to spectators is not observed. Fig. 4 (right panel) shows the $v_2$ as a function of beam energy for charged hadrons [2, 9].
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3.3. Pion Interferometry Measurements

Fig. 5 shows the results for HBT (Hanbury Brown and Twiss) pion ($\pi^+$) interferometry measurements. In HBT measurement, we measure three radii - $R_{out}$, $R_{side}$ and $R_{\text{long}}$. $R_{out}$ measures the spatial and temporal extension of the source, $R_{side}$ measures the spatial extension of the source and the ratio $R_{out}/R_{side}$ gives the emission duration of the source. It is expected that for a first order phase transition, the ratio $R_{out}/R_{side}$ is very large compared to 1 \cite{10}. Fig. 5 shows that for the measured beam energies, the ratio $R_{out}/R_{side}$ is close to 1.

4. Conclusions and Summary

We observe that the hadronic yields, $<m_T>$ - m and ratios for Au+Au 9.2 GeV data presented are consistent with the observed beam energy dependence within the errors, which are dominated by statistics collected in this test run at RHIC. The results for azimuthal anisotropy measurements ($v_1$, $v_2$) are obtained in the Au+Au collisions at $\sqrt{s_{NN}} = 9.2$ GeV. The $v_2$ results are similar to those obtained at SPS from collisions at similar beam energies and follow the observed beam energy dependence. It is observed that results for pion interferometry measurements for Au+Au 9.2 GeV also follow the established beam energy dependence. These results are from only $\sim$3000 good events and the higher statistics will help doing a significant qualitative improvement. Apart from this, the Collider environment provides significant advantages over fixed target experiments. The $p_t$ vs. rapidity acceptance for produced particles are uniform over all beam energies. Particle density per unit area are much reasonable and slowly varying...
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with beam energy. In STAR there is added advantage of excellent particle identification, which will improve further with addition of Time-Of-Flight system in the year 2010.

In summary, we have obtained the results for identified hadron spectra, azimuthal anisotropy and pion interferometry measurements for Au+Au collisions at 9.2 GeV, the lowest beam energy injected at RHIC so far. The results from this small statistics data indicate that various observables follow the previously established beam energy dependence. Through this test run we have shown the readiness of STAR experiment for the future Beam Energy Scan program at RHIC. The higher statistics and good particle identification capability in the STAR experiment in a Collider set-up will help in locating the critical point and map the QCD phase diagram along with some new measurements that were not possible in SPS. It will also help locate the $\sqrt{s_{NN}}$ where the onset of several interesting observations (NCQ scaling of $v_2$ [2], high $p_t$ hadron suppression in A+A collisions relative to p+p collisions [4] and the ridge formation [3]) in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC.

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