Recent PHENIX Results from the RHIC Energy Scan

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Abstract

The PHENIX experiment has analyzed data produced in beam energy scans performed by the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, that cover an energy range of $\sqrt{s_{NN}}$ = 7.7 GeV to 200 GeV. Analyses search for signatures of the onset of sQGP formation and the QCD critical point by examining the evolution of event characteristics versus centrality as $\sqrt{s_{NN}}$ is varied. Results from excitation studies of global variables and their fluctuations, parton energy loss, J/ψ R_{AA} and anisotropic flow are presented.

1. Introduction

The Relativistic Heavy Ion Collider facility located at Brookhaven National Laboratory has collided ion beams over an energy range of $\sqrt{s_{NN}}$ = 7.7 GeV to 200 GeV with beam species varying from U+U to p+p collisions providing the RHIC physics program with approximately 20 unique, high statistics data sets [1]. The PHENIX and STAR experiments have used the flexibility of RHIC to map out the characteristics of the QCD phase diagram over a significant range of temperatures and baryon densities. The portion of the QCD phase diagram made accessible by RHIC is particularly well-situated because a state of hot partonic matter, the strongly-coupled Quark Gluon Plasma (sQGP) is created in the high temperatures produced by collisions at the RHIC top energies. PHENIX is exploiting the fortuitous location of the sQGP transition region within the operating range of RHIC to both characterize the evolution of partonic to hadronic matter through the QCD crossover region (the sQGP transition) and to search over the same general temperature-baryon density space for evidence of a QCD critical point.

2. Global Variables

PHENIX has recorded data sets covering ten different collision energies and six combinations of colliding species. Global event quantities such as the average particle multiplicity per unit rapidity, transverse energy and Bjorken energy density (dN/dη, dE_T/dη and ε_{Bj}) have been measured versus Au+Au collision centrality for a variety of collision energies. By plotting the excitation curves of the centrality-selected global variables one can look for non-monotonic behavior in the curves as an indication of a location where the underlying physics might change. The data in Figure 1 show that the dN/dη per participant increases by approximately a factor of

[1] A list of members of the PHENIX Collaboration and acknowledgements can be found at the end of this issue.

4 in the most central collisions as the collision energy is increased from 7.7 GeV to 200 GeV. The $dE_T/d\eta$ and ε_{Bj} increase by about a factor of 5 in central collisions over the same range in collision energies (Fig. 2)[2]. The increase in these quantities over the same energy range is less for the most peripheral collisions. No non-monotonic behavior is seen in the excitation curves of these particular global variables.

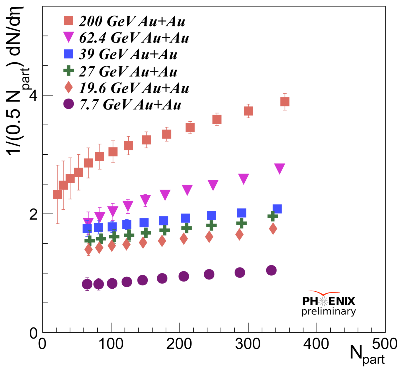

Figure 1: dN/dη vs N_{part} for Au+Au at different collision energies [2].

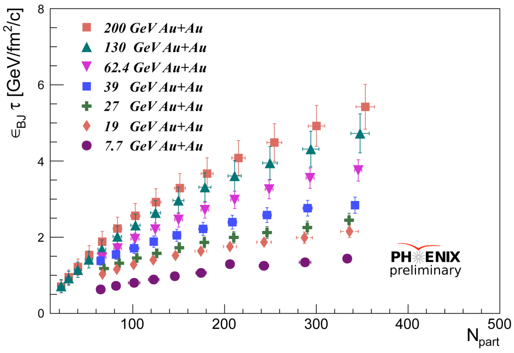

Figure 2: (Bjorken energy density)*τ vs N_{part} for Au+Au at different collision energies [2].

When sQGP matter produced in heavy ion collisions passes close to the QCD critical point, one might have a measureable fluctuations in the correlation length of particular global variables. If a correlation length is ξ then moments of the global variable fluctuations can be related to higher powers of the correlation length. For example:

$$\begin{aligned} \text{Variance :} \quad & \sigma^2 = \langle(\Delta N)^2\rangle \sim \xi^2 \\ \text{Skewness :} \quad & S = \langle(\Delta N)^3\rangle/\sigma^3 \sim \xi^{4.5} \\ \text{Kurtosis :} \quad & \kappa = \langle(\Delta N)^4\rangle/\sigma^4 \sim \xi^7 \end{aligned}$$

This approach is similar to measurements of changes of the susceptibility of a substance that are typically performed when one is characterizing phase transitions in condensed matter. The scheme here is to choose a global variable that is expected to have a significant change in its correlation length due to a phase transition near the QCD critical point. One performs a moment analysis of that variable versus $\sqrt{s_{NN}}$ and looks for a sudden change in the correlation length. PHENIX has performed fluctuation analyses on net charge and charged particle multiplicity as a function of centrality and $\sqrt{s_{NN}}$ (Fig.3, 4, 5). Figure 3 shows the distributions of the Mean, Standard Deviation, Skewness and Kurtosis versus centrality for the four collision energies studied. The plots show that the data have excellent statistics and modest systematic errors. Figure 5 shows that neither the Skewness nor the Kurtosis vary with centrality. The Kurtosis is flat within errors over the range studied in $\sqrt{s_{NN}}$. Though the Skewness decreases with increasing $\sqrt{s_{NN}}$ it is consistent with predictions by UrQMD, which means no additional physics contributions due to proximity to a critical point.

One should note that there is a big gap between the 7.7 GeV and 39 GeV data. Additional data sets exist at 19 GeV and 27 GeV and are being analyzed by PHENIX. There is also an expectation that RHIC will collide Au+Au near $\sqrt{s_{NN}}$ = 15 GeV in the near future. A fluctuation analysis of the mean charged particle multiplicity was also performed using the same set of data. In Figure5, the mean multiplicity fluctuation of the most central events, $\omega = \langle N \rangle / var(N)$, is flat with respect to $\sqrt{s_{NN}}$. As with the net charge fluctuation analysis, there is a need to fill in the data gap between 7.7 and 39 GeV which we plan to do in the near future.

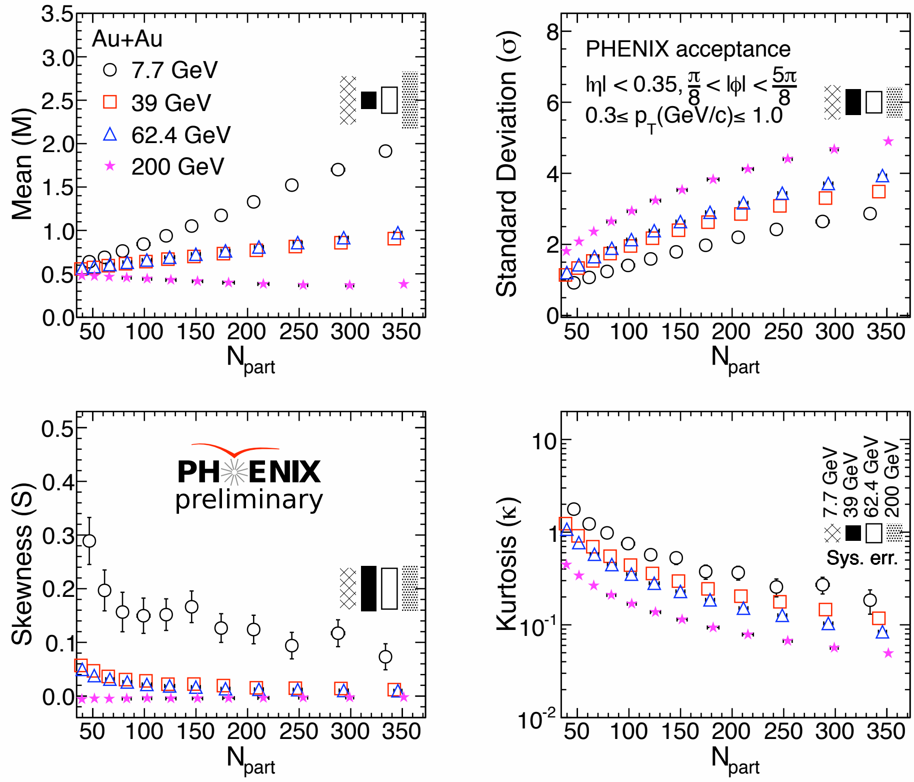

Figure 3: Net charge moments vs N_{part} for Au+Au at different collision energies. The bars near the legend represent the total systematic error for each data set.

3. Particle Production Suppression

Among the evidence that collectively established the formation of the sQGP in heavy ion collisions at RHIC [3] was the observation of partonic energy loss [4], the measurement of anisotropy (v2) in particle momentum distributions [5] and the determination of suppression patterns of the J/ψ [6, 7, 8]. Each of these signals has been measured using data from the RHIC energy scan to search for evidence of the onset of sQGP formation. The R_{AA} of π^0's measured by PHENIX in Au+Au collisions at 200, 62.4 and 39 GeV(fig 6) clearly shows that the energy loss mechanism is still operating in the most central collisions at 39 GeV. This should be contrasted

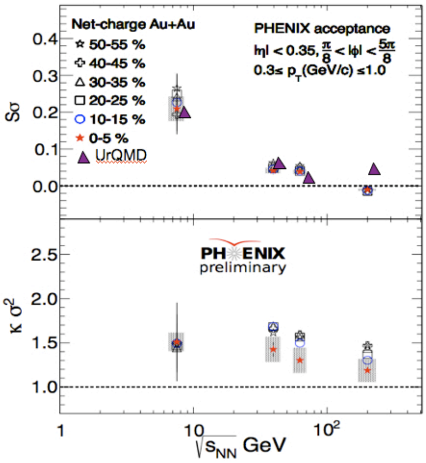

Figure 4: $\sqrt{s_{NN}}$ dependence of net charge fluctuations. Neither kurtosis nor skewness show variation vs centrality. The skewness is compared to an UrQMD calculation.

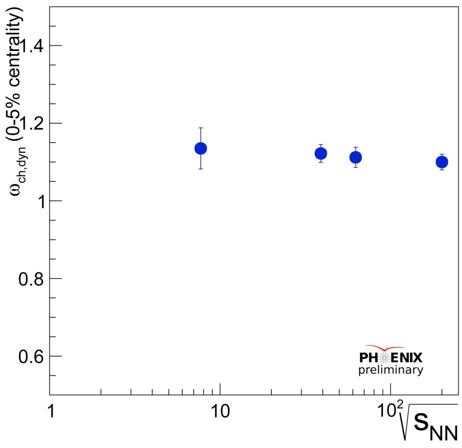

Figure 5: The mean multiplicity fluctuation is flat for the collision energies shown. ω_{dyn} is the scaled variance corrected for impact parameter fluctuations within each centrality bin

with PHENIX results of π^0 R_{AA} in Cu+Cu collisions at 22.4 GeV which has an $R_{AA} > 1.0$ [10]. It is important to point out that though the energy loss process dominates R_{AA} at large values of $\sqrt{s_{NN}}$, other factors contribute with different strengths as the collision energies change. These include changes to the inverse slope of the π^0 spectrum, differing contributions of soft and hard scattering and different strengths of the Cronin effect. All these effects must be carefully taken into account before one can conclude that the energy loss has gone away at a particular $\sqrt{s_{NN}}$.

Similarly, a number of factors contribute to differences in J/ψ production and suppression as the collision energy varies. These include suppression due to color screening, shadowing or break-up due to cold nuclear matter effects and regeneration. PHENIX has measured J/ψ R_{AA} vs centrality at $\sqrt{s_{NN}}$ = 39, 62.4 and 200 GeV[11] as shown in figure 7. The similarity of the suppression vs centrality at all three energies is notable. One could conclude that the amount of J/ψ suppression observed at 39 GeV means that color screening effects, and by extension deconfinement, are still in force at this low collision energy. The deconvolution of the physics processes contributing to the J/ψ R_{AA} will require the use of the data sets from the SPS, three RHIC energies, and the LHC, in addition to the control d(p)+A data sets from all three facilities.

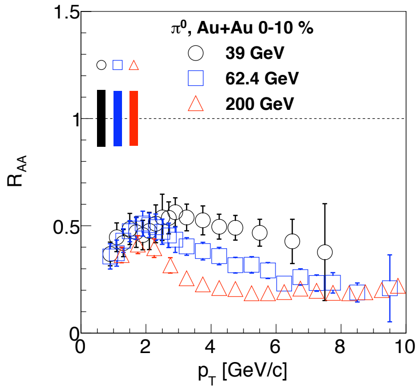

Figure 6: π^0 R_{AA} vs p_T for Au+Au at 39, 62.4 and 200 GeV[9].

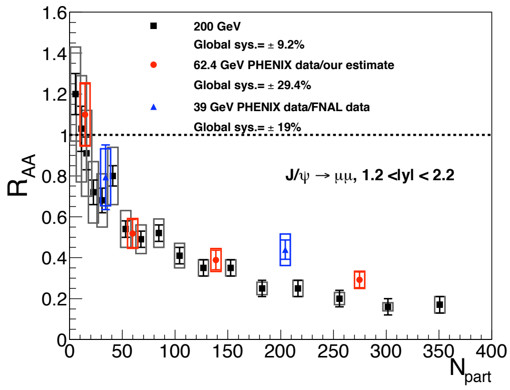

Figure 7: J/ψ R_{AA} vs p_T for Au+Au at 39, 62.4 and 200 GeV at forward rapidities[11].

4. Anisotropic Flow

The significant elliptic flow observed at RHIC together with the fact that flow apparently scales with quark number, not hadron mass, prompted the conclusion that full energy RHIC collisions produce strongly coupled partonic matter. To determine if an sQGP is produced in RHIC collisions at lower $\sqrt{s_{NN}}$, then a study of the behavior of the anisotrpic flow is important. Figure 8 shows that the strength of both v2 and v3 remain the same at 39, 62.4 and 200 GeV. In addition, Figure 9 shows that constituent quark scaling continues to hold at $\sqrt{s_{NN}}$ = 62.4 and 39 GeV. The flow data from the lower energy data sets support the conclusion that a strongly-coupled partonic plasma, the sQGP, is produced at RHIC at these lower collision energies [12].

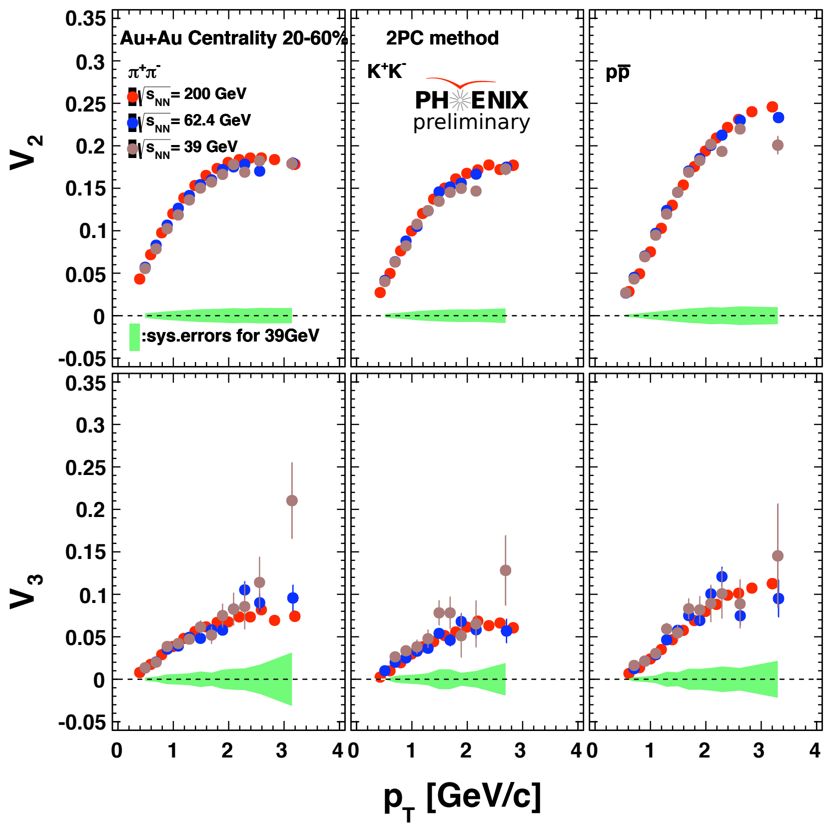

Figure 8: Anisotropic flow v2, v3 of π, K, p measured in Au+Au collisions at 39, 62,4 and 200 GeV[12].

5. Summary

The RHIC facility has collided a variety of ion species covering an energy range from $\sqrt{s_{NN}}$ = 7.7 GeV to 200 GeV. PHENIX has analyzed this data to search for evidence of the onset of

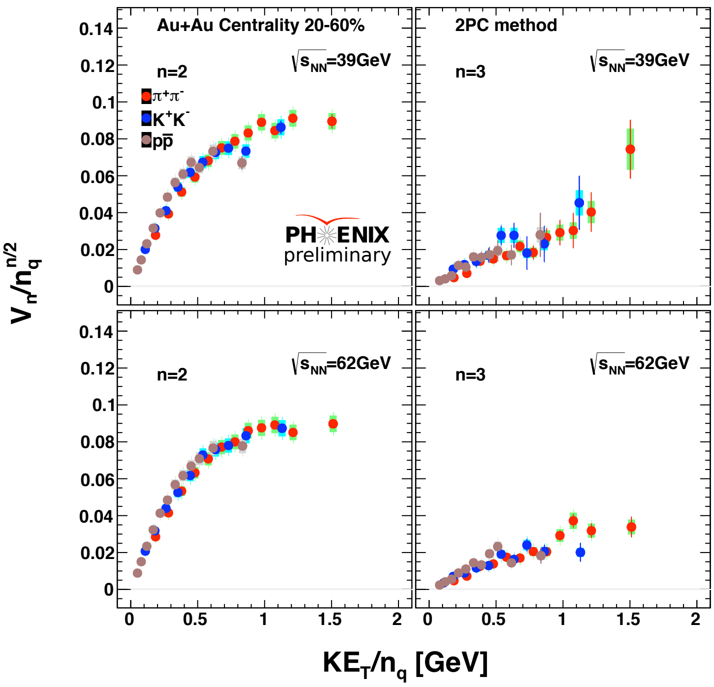

Figure 9: Constituent quark scaling of v2 and v3 for π, K, p measured in Au+Au collisions at 39, 62,4 and 200 GeV[12].

sQGP production and a QCD critical point. Global variables such a dN/dη, dE_T/dη and ε_{Bj} were measured as a function of centrality and a fluctuation analysis of net charge and mean charged particle multiplicity were performed in a search for a signal of a critical point. No non-monotonic behavior was observed in these results, however the quantities analyzed may not be sensitive to proximity to the QCD critical point. There exists a gap in data sets between 7.7 GeV and 39 GeV that will be addressed in the near future. The R_{AA} of π^0 and J/ψ's were measured at 39, 62.4 and 200 GeV. Evidence of partonic energy loss in the π^0 data and color screening in the J/ψ R_{AA} were seen in the 62.4 and 39 GeV data. This implies that sQGP effects dominate in data as low as $\sqrt{s_{NN}}$= 39 GeV in central Au+Au collisions. Likewise the anisotropic flow measured at 39 and 62.4 GeV is as strong as that produced in Au+Au collisions at 200 GeV, and continues to have a flow pattern consistent with partonic scaling. Both the R_{AA} and flow data support the conclusion that the sQGP is produced at these lower collision energies.

References

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