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A PHENIX perspective on soft observables in Heavy Ion Collisions

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We present an overview of measurements from the PHENIX experiment focusing on soft observables in nucleus-nucleus collisions. The excellent particle identification of the PHENIX detector at low and intermediate transverse momentum provide an extensive set of measurements in nucleus-nucleus collisions and baseline measurements in p+p and d+Au collisions. Thermalized particle spectra, strong elliptic and radial flow, and HBT measurements reveal the global features of the hot QCD medium produced at RHIC energies while fluctuation measurements probe critical behavior near a phase transition. Collectively these measurements reveal a hot, dense medium with partonic degrees of freedom undergoing a locally-thermalized hydrodynamic expansion.

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1. Introduction

Relativistic heavy-ion collisions allow us to study quantum chromodynamcs (QCD) from a very different perspective than high energy particle physics. By colliding heavy ions at high energy we study bulk properties of the medium over an extended volume with a finite time evolution. This enables us to explore a narrow region of the QCD phase diagram at low baryon density and sufficiently high temperature to observe a new QCD phase, the quark-gluon plasma (QGP). In the five years of RHIC operations, the PHENIX experiment has made a comprehensive set of measurements across a broad range of observables which indicate the creation of a medium qualitatively very different from normal nuclear matter and has begun to make a quantitative description of this new phase.

2. Identified Spectra

PHENIX has measured the charged particle multiplicity and transverse energy at mid-rapidity in Au+Au collisions at full RHIC energy which indicate a peak energy density of at least 15 GeV/fm^3 at the time of particle formation [1]. A picture of the system evolution begins to emerge from measurements of the centrality dependence of the charged particle p_T spectra and the azimuthal dependence of charged particle production in non-central collisions. The mean transverse momentum of pions, kaons, and protons increases with collision centrality and more dramatically for the heavier particles [2]. This is consistent with the collective expansion of the medium with a mean radial velocity of $\sim 0.5c$.

In non-central Au+Au collisions, there is an initial azimuthal anisotropy in the geometry of the system which results in an azimuthal anisotropy in the momentum distribution of particles. The second Fourier coefficient, $v_2(p_T)$, is extracted from the differential particle multiplicity and provides some indication of the time when the collective expansion is established; a larger thermalization time results in a smaller azimuthal asymmetry. The measured p_T dependence of the asymmetry shown in the left panel of Figure 1 demonstrates an increase in the slope of the p_T dependence by about 50% over that measured at the SPS [1]. If a locally thermalized hydrodynamic expansion is responsible for both the radial and elliptic flow, then calculations must simultaneously reproduce both the transverse momentum spectra and the v_2. Several hydrodynamic calculations were compared in ability to reproduce these measurements in [1] and favored a model which included a strong expansion in a QGP phase. The species dependence of the v_2 has been measured with the PHENIX detector [4]. The observed scaling of elliptic flow with the number of constituent quarks suggests that the flow develops at a time when quarks (not hadrons) are the relevant degrees of freedom.

Further evidence of this scenario is the observed enhancement of baryon production (Figure 2 left) at mid-p_T in central Au+Au collisions which is absent in all other measured systems. If quarks are the relevant degrees of freedom, baryons with three quarks will receive a larger p_T boost than mesons of two quarks. This interpretation is also consistent with the observation that the production of the ϕ meson in central collisions as compared to peripheral collisions follows the trend of the pions with the same number of constituent quarks rather than the protons which have similar mass [6].

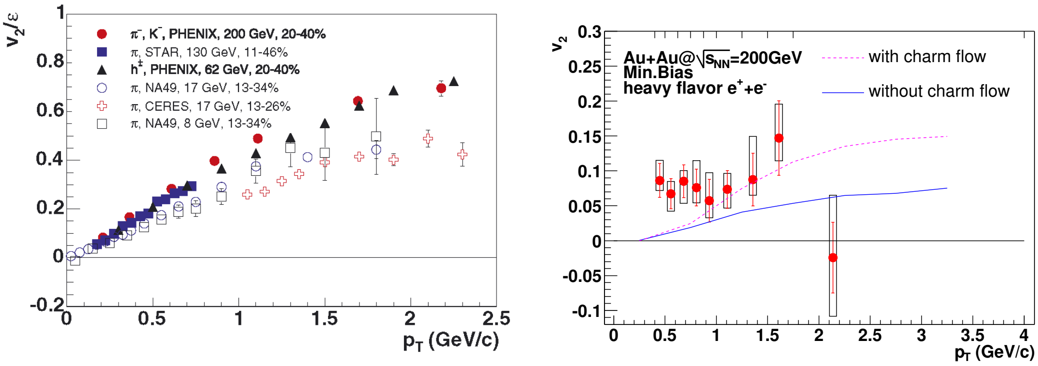

Figure 1: PHENIX has measured the second Fourier coefficient in the azimuthal dependence of charged particle production for hadrons of light quarks(left) [1] and charmed hadrons(right) [3] in non-central collisions Au+Au.

If partons are indeed the relevant degree of freedom in the strong initial expansion, charm quarks produced in the early stage of the collision may thermalize with the medium and participate in the collective expansion of the system. PHENIX has extracted the azimuthal dependence of the charm contribution to the measured electron spectra [3]. There right panel of Figure 1 shows the v_2 of the extracted charm production as a function of transverse momentum. A non-zero v_2 is indeed observed with a 90% confidence level, but the uncertainties of the current measurement limit the discrimination of scenarios with and without charm thermalization.

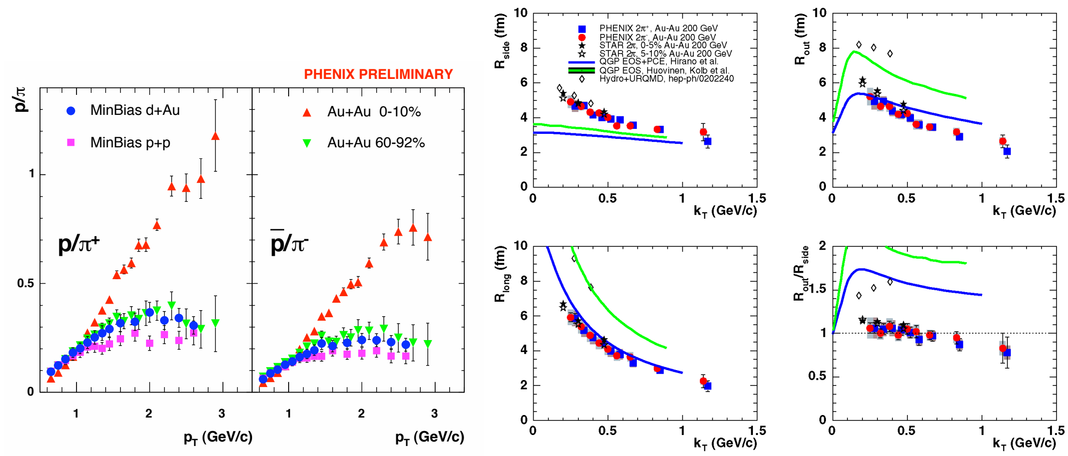

Figure 2: PHENIX has measured the (anti-)proton to pion ratio in p+p, d+Au, and Au+Au collisions (left) [5]. The 3D HBT radii are extracted for identical two-pion correlations by PHENIX [9] and STAR [10](right) and compared with several hydrodynamic calculations [11][12][13].

3. Fluctuations

PHENIX has measured event-by-event fluctuations in net-charge [7] and in the average transverse momentum [8] near mid rapidity which might be sensitive to critical behavior near the QCD phase transition. Small deviations from stochastic fluctuations were observed, but may be attributed entirely to the effects of hadronic decays. The absence of nonrandom fluctuations beyond that expected from the contribution of jets are consistent with a smooth crossover in the phase transition.

4. Interferometry

The space-time evolution of heavy-ion collisions is probed through the Bose-Einstin correlations of identical particles. Although two-particle correlations are formed from the measured final state particles, they are sensitive to the integrated expansion dynamics of the system through space-time correlations. PHENIX has measured the pair transverse momentum dependence, k_T, of the 3D Bertsch-Pratt parameters for charged pions correlations [9]. The extracted radii (Figure 2 right) fall with increasing k_T as expected from the space-momentum correlations of a rapidly expanding source. However, a quantitative reproduction of the radii constrained by the measured spectra and elliptic flow remains a challenge for full hydrodynamic calcualtions.

5. Conclusions

The PHENIX collaboration has made an extensive set of measurements of heavy-ion collisions to explore the properties of the medium created at RHIC. The measured particle transverse momentum spectra and the measured elliptic flow indicate the collective behavior of a rapidly expanding source. The excess baryon production at mid-p_T and species dependence of the elliptic flow are strong evidence that collective expansion develops during a stage of system evolution when partons and not hadrons are the relevant degrees of freedom. While the quantitative agreement of hydrodynamic calculations with these measurements has been important in developing a picture of the system evolution, remaining inconsistencies with the HBT measurements demonstrate that our understanding is incomplete.

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