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Two-Particle Interferometry of 200 GeV Au+Au Collisions at PHENIX

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The PHENIX experiment has measured pion-pion, kaon-kaon, and proton-proton correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200GeV$. The correlations are fit to extract radii using both the Bowler[1] Coulomb correction and full calculation of the two-particle wave function. The resulting radii are similar for all three species and decrease with increasing k_t as expected for collective flow. The R_{out} and R_{side} radii are approximately equal indicating a short emission duration.

1. Introduction

Two-Particle interferometry (also known as HBT) has been used throughout the study of heavy ion collisions as the primary method to measure the size and lifetime of the nuclear collision. Predictions [2, 3] for a Quark Gluon Plasma (QGP) were long lifetimes due to the latent heat of the phase transition. In light of jet suppression results[4] indicating the formation of a QGP, it is interesting that interferometry measurements do not exhibit the corresponding long lifetime at RHIC starting with first reported measurement at QM2001 [5] for the $\sqrt{s_{NN}} = 130GeV$ Au+Au data, and continuing through to the $\sqrt{s_{NN}} = 200GeV$ data presented at QM2002 [6] and in this talk[7]. Improvements in the data quality have only sharpened the difference between the data and expectations while theoretical investigations continue.

The statistics of the run2 dataset ($\sqrt{s_{NN}} = 200GeV$ Au+Au) are sufficient to start looking at correlations of particles other than pions and perhaps provide more information about the mismatch between interferometry results and the jet suppression results. The kaon-kaon and proton-proton correlations measured by PHENIX are fit with a sophisticated fitter that properly calculates the correlation function through a direct calculation of the nonrelativistic two-particle wave function. This method [8] is required to fit complicated interactions like the proton, and could also be used for pions to replace the Coulomb correction which is still only an approximation to the full solution to the Schrödinger Equation.

‡ For the full PHENIX Collaboration author list and acknowledgments, see Appendix "Collaborations" of this volume.

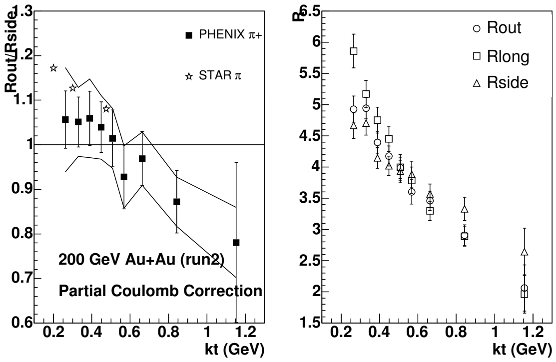

Figure 1. The Rout,Rside,Rlong and R_{out}/R_{side} ratio for positive pions. In the left plot open stars are measurements from STAR[9] and closed squares are PHENIX measurments[7]. The bands show the estimated systematic error for the PHENIX measurment. The right plot is Rout,Rside and Rlong as measured by PHENIX.

2. Coulomb Correction

Traditional Coulomb corrections that correct every pair by the full Coulomb effect have typically over corrected because the contribution from a diffuse halo does not undergo a significant Coulomb interaction. Some examples are misidentified particles and particles that did not originate from the collision but point back to it. This idea was pointed out a number of years ago [1] , but has recently become better recognized at the last Quark Matter[10].

A superior method[1] to Coulomb correction is to place the parameterized Coulomb correction function into the fit and weight the correction by λ (HBT chaoticity parameter). In the case where momentum resolution is good, as it is in PHENIX, and assuming perfect chaoticity, λ contains only the information about what fraction of the pairs should be corrected. This procedure has a small but significant effect on the resulting radii raising the R_{out}/R_{side} ratio to be consistent with 1.0 as shown in figure 1. This correction moved the experimental result slightly in the direction of the theoretical expectations for a QGP, but still does not explain the difference.

A further refinement involved considering daughters from the ω decay. Assuming that the unlike pion correlation has the same contamination effects as the like pion correlation, we fit the unlike correlation to extract the number of pions that are effected by the Coulomb. We would expect this fraction to be larger than λ in the like pion correlation because pions from the ω decay are too far apart to produce observable quantum statistics correlations, but could have significant Coulomb correlations because of the long range of the Coulomb force. Using the unlike pion fraction, we repeat the Bowler method with like pions adding a little more Coulomb as determined from the unlike pion correlations. The result of this was radii that differed by less than the systematic error of the data.

3. Correlation Calculations

A correlation of two particles is the result of three possible elements: strong potential, Coulomb, and quantum statistics. In the case of pions, the strong potential is negligible, and Coulomb is approximately removed by a Coulomb "correction" leaving only the quantum statistics effect between the pairs. The result of these simplifications is the familiar Fourier transform relationship between the source distribution and the observed correlation function. This simple relationship is only approximate because the Coulomb effects are not properly accounted for since the Coulomb can not be factored from the Schrödinger equation and applied to the correlation function separately. In addition, the Coulomb correction error grows with mass, and can not be accomplished at all in the case of protons where the strong potential is a significant effect.

The correct method of calculating a correlation function for a given source is with the Koonin-Pratt equation,

$$C_2(q) = \int dr|\Psi(q,r)|^2 S(r) \tag{1}$$

where C_2 is the correlation function (the quantity measured), Ψ is the relative wave function and S is relative source function (the quantity of interest). The forces that create the correlation are described by the wave function Ψ. In most cases the system can be treated nonrelativistic so Ψ is simply the result of the Schrödinger equation,

$$H\Psi = \Psi E \tag{2}$$

where H is the Hamiltonian containing the description of the particle interactions. We use standard methods to solve this equation, first converting the problem from a 2 body to a 1 body and a potential, and then expanding the wave function into Legendre polynomials,

$$\Psi(r,\theta) = \sum_l (2l+1) i^l \frac{\phi(r)}{r} P_l(cos(\theta)) \tag{3}$$

where ϕ is the radial wave function and is determined by,

$$\left[\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2} - \frac{2m}{\hbar}[V(r)+E]\right]\phi(r) = 0 \tag{4}$$

The function $V(r)$ is where the Coulomb and strong potential enter the formulation. It is clear from this equation that two potentials summed to make $V(r)$ can not be simply factorized in the correlation, and this is why the Coulomb correction (even the Bowler method) is an approximation.

The correct method is to calculate the correlation using the Koonin-Pratt equation and fit that to the data. The quantum statistics enter the correlation through the symmetrization (antisymmetrization) of the wave function,

$$\Psi_{(anti)symm} = \frac{1}{\sqrt{2}}[\Psi(q,r) \pm \Psi(q,-r)] \tag{5}$$

where the sign depends on whether the particles are bosons or fermions. Also, the spin must also be carefully considered when calculating the wave function.

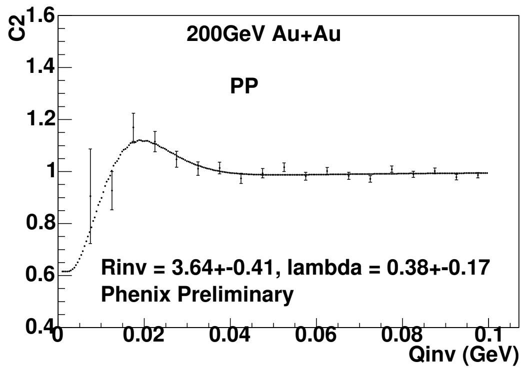

Figure 2. Proton correlation function fit to the Koonin-Pratt equation using a Gaussian source.

4. Results

The data analysis described in this article is based on data taken by the PHENIX detector during run2 of RHIC in 2001. After offline cuts the data sample is approximately 23 Million events. Tracking and momentum determination was accomplished with the central wire chambers in combination with the central magnet. Particle identification is through time of flight using the electromagnetic calorimeters.

The correlation function is generated by taking the ratio of all pairs of identified particles and a mixed background generated from pair of particles from different events. The pions were then projected into the Bertsch-Pratt coordinate system and fit using the Bowler method and a 3D Gaussian to extract the three radii $R_{out}, R_{side}, R_{long}$. Figure 1 shows the ratio of the R_{out} and R_{side} and it is clear that the ratio is consistent with 1.0. This implies a shorter emission time than current theoretical understanding can explain.

Correlation functions for the kaons and protons do not contain enough statistics to project in to 3D and therefore only 1D projections are generated in Q_{inv}. Figure 2 is an example of the proton correlation that shows the data points and the fit to the points using the Koonin-Pratt equation. Splitting the data into a few bins of m_t and fitting the 1D pion provides for the comparison shown in figure 3. Although the statistical errors are large, there is some indication that the radii scale with m_t.

5. Conclusion

PHENIX has measured pion-pion, kaon-kaon, and proton-proton correlations in Au+Au collision at $\sqrt{s_{NN}} = 200GeV$. The radii extracted from fits to the Q_{inv} correlations show all three correlation have consistent radii, and the radii fall as a function of m_t as expected for collective flow. This result places tighter constraints on models that must explain the interferometry results in light of the jet suppression measurements. The

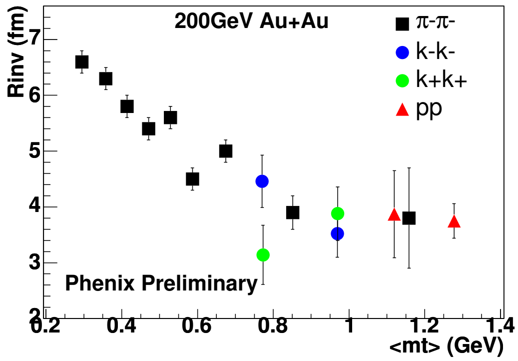

Figure 3. A summary the fitted radii for pion, kaon, and proton correlations.

current RHIC run of 2004 will provide more statistics substantially improving the kaon and proton correlation, providing for the extension to 3D, and increasing the k_t range of the measurements.

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