Correlations and Fluctuations, A Summary of Quark Matter 2002

Scott Pratta *

aDepartment of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

Results for correlations and fluctuations presented at Quark Matter 2002 are summarized. These results include Hanbury-Brown Twiss interferometry of a wide variety of species, large scale fluctuations and correlations in $p_t$ and multiplicity, and charge fluctuations and charge balance functions.

1. Introduction

A phenomenal number of new results have been presented at this meeting regarding fluctuations and correlations. With the analysis of SPS results for $\pi - \pi$ Hanbury-Brown Twiss (HBT) correlations as a function of energy, and with the maturing of the RHIC results, a consistent picture has developed of the evolving dynamics from AGS energies to RHIC. Additionally, several new probes have been analyzed and have been presented at this meeting, including $\gamma\gamma$ correlations. Fluctuations in $p_t$, multiplicity and isospin, derived from both the SPS and RHIC, hint at novel behaviors. Finally, charge correlations measured at RHIC suggest a delayed production of charge, and therefore a delayed hadronization. After being taken by surprise, the theory community has made significant progress toward understanding these measurements and reducing the list of possible interpretations.

Results on small relative momentum correlations are reviewed in the next section, with an emphasis on describing the HBT puzzle. The subsequent section reviews $p_t$ and multiplicity fluctuations, while isospin fluctuations, charge fluctuations and charge balance functions are reviewed in Sec. 4.

2. Two-Particle Correlations at Small Relative Momentum

A principal motivation for HBT analyses was the hope to view a long-lived source resulting from the low pressure associated with a first-order phase transition to the the quark-gluon plasma (QGP) [1–3]. The CERES collaboration presented results, shown in Fig. 1, of both their results at the SPS along with AGS and RHIC results [4,5]. A long-lived source would have emitted pions continuously over a time of the order of 10-20 fm/c, which would result in the outward size $R_{out}$ being larger than $R_{side}$ by an amount of the order of 10 fm. Figure 1 shows that such a long-lived source was not produced at any energy. In fact, the outward and sideways dimensions show little dependence with

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Figure 1. The three dimensions of the source are illustrated as a function of transverse momentum for several beam energies. Only $R_{\text{long}}$ changes significantly for higher beam energies.

Consistent measurements of the three source dimensions at RHIC were reported in this meeting by STAR, PHENIX and PHOBOS, with the ratio of $R_{\text{out}}/R_{\text{side}}$ varying from $\approx 0.85$ for PHENIX [6] to $\approx 1.15$ for PHOBOS [7]. Because of the inherent ambiguity between the temporal and spatial dimensions in $R_{\text{out}}$, one can only place an upper limit on the duration of the emission of $\Delta\tau < 10$ fm/c. Given the large transverse size, it appears that the breakup hypersurface is extremely space-like, i.e. emissions from the edge and the center occur within a few fm/c of one another.

The values reported for $R_{\text{long}}$ are as remarkable as the $R_{\text{out}}/R_{\text{side}}$ measurements. Whereas $R_{\text{out}}/R_{\text{side}}$ provides insight into the duration of emission, $R_{\text{long}}$ gives a measure of the emission time. HBT measures the spatial extent from which pions of a given rapidity might be emitted. Assuming that the emitting sources are well spread out in rapidity, the size
is determined by the temperature and the velocity gradient, \( R_{\text{long}} \sim v_{\text{th}} / (dv/dz) \), where \( v_{\text{th}} \) is the thermal velocity and \( dv/dz \) is the velocity gradient. In a Bjorken expansion, the matter does not accelerate along the \( z \) axis which means that the velocity gradient is determined by \( \tau \), \( dv/dz = 1/\tau \). Although the values for \( R_{\text{long}} \) reported by STAR, PHENIX and PHOBOS are very large compared to hadronic length scales, they still fall short of expectations, and suggest emission times of 10 fm/c, rather than the expected 15-20 fm/c. Unless the breakup temperatures are anomalously cold, or unless the matter accelerated in the longitudinal direction, explaining this result requires an extremely rapid transverse acceleration. Blast wave analyses [8] of \( \pi^- - \pi^+ \) HBT reveal sources which have expanded to an outer radius of 13 fm within this 10 fm/c, and with an outer velocity of \( \sim 0.7c \) as determined by comparing pion and proton spectra. Given that the original radius is near 6 fm, this implies an extremely rapid acceleration.

The inability of numerical models of the dynamics to account for both the small values of the mean emission time, \( \langle \tau \rangle \), and the duration of the emission, \( \Delta \tau \), is referred to as the HBT puzzle. Several attempts have been made at reproducing the RHIC results using a variety of hydrodynamic, Boltzmann and hybrid treatments. All consistently overestimate \( R_{\text{long}} \) and \( R_{\text{out}}/R_{\text{side}} \) [9–12]. Figure 2 displays results from Kolb which come somewhat closer to the result than the other reference work cited above. It should be emphasized that the HBT puzzle is not particularly new to RHIC. As HBT statistics have increased from the SPS, it is clear that the emission duration was moderately over-predicted by RQMD at SPS energies, with measurements of \( R_{\text{out}}/R_{\text{side}} \) varying from near unity for CERES [4] to \( \sim 1.15 \) for NA49 [13].

Two-kaon correlations from PHENIX and from NA49 were also reported at this meeting [13,6]. It appears that the source size for kaons is somewhat larger than predicted by extrapolating from the pion source sizes assuming blast wave kinematics. However, it
should be pointed out that the NA49 measurement is somewhat larger than that previously reported by NA44 [14], and that the PHENIX measurement is preliminary.

Aside from the kaon measurements, the overall behavior of HBT measurements appears to follow the systematics of a blast wave, i.e. a sudden dissolution at a low temperature, \( \sim 110\,\text{MeV} \), after a rapid expansion to a high velocity, \( \sim 0.7c \). In addition to the \( R_{\text{out}}/R_{\text{side}} \) ratio and the small value of \( R_{\text{long}} \), the blast wave picture of sudden explosion and emission explains the \( p_t \) dependence of the source sizes \([6,13,4,15]\), and may also explain the results of STAR where two-pion HBT was performed relative to the reaction plane [16]. There, the source appears to be out-of-plane extended, i.e. the source appears to retain the shape of the original almond resulting from overlapping spheres at non-zero impact parameter. If the emission were long-lived, the differential expansion would have overcompensated for the initial deformation and resulted in an in-plane-extended shape.

One consequence of the smaller-than-expected values of \( R_{\text{long}} \) and \( R_{\text{out}} \) is that the phase space density must have been rather high at breakup. In fact, by combining the spectra and HBT measurements, one can extract the phase space density in a model-independent way [18]. This analysis was performed for STAR results [15], and the resulting phase space density suggests that pionic phase space is overpopulated by nearly a factor of two at low momentum as compared to a thermally equilibrated gas where the pion density is determined solely by the temperature. The phase space density increases markedly with centrality and is significantly higher than was extracted for central collisions at SPS energies [17]. It should be emphasized that the reported phase space values are averaged over coordinate space,

\[
\bar{f}(p) \equiv \frac{\int d^3x f(x,p)f(x,p)}{\int d^3x f(x,p)}, \tag{1}
\]

For a Gaussian source the peak phase space density is larger by \( 2\sqrt{2} \) at \( x = 0 \) than the average derived from the sum rule. This suggests that the break up density is a significant fraction of what is required for novel Bose coherence effects.

A high phase-space density necessitates a lower entropy. In a nearly model-independent fashion, the entropy carried by the pions was extracted from STAR results [19]. The entropy per pion appears to be in the neighborhood of three units which is significantly lower than that expected for a Bose gas as can be seen in Fig. 3. As hydrodynamic treatments over-predict the source sizes, while fitting the spectra [9], they thus over-predict the entropy. Since hydrodynamic treatments produce minimal entropy in their evolution, one must conclude that the initial entropy of the system in the hydrodynamic treatments was overestimated. This suggests that the initial state was not that of an equilibrated quark-gluon plasma, but might have instead involved energy in coherent forms, e.g. classical gluon fields, or may have excited fewer degrees of freedom, e.g. under-populating quark degrees of freedom.

The correlation functions presented at this conference for non-identical particles were shockingly superior to what had been previously measured. Following the ideas of Lednicky [20], correlations were compared for \( p_{a,\text{out}} - p_{b,\text{out}} > 0 \) to those with \( p_{a,\text{out}} - p_{b,\text{out}} < 0 \). Whereas the two correlations must be identical when the particles are indistinguishable, the difference offers insight into the relative positions of the emitted particles when the two particles are different. STAR presented results for \( \pi - K \) and \( \pi - p \) pairs [8] which
Figure 3. The entropy per pion as extracted from HBT and spectra. For the most central collisions, the entropy per pion appears low which puts doubt into assumptions about early equilibration.

showed that the heavier particles were emitted ahead of the lighter particles consistent with a blast wave interpretation. Results from NA49 for $\pi - p$ pairs demonstrated the same behavior [13].

In this meeting correlations were reported for several new pairs which had not previously been measured in heavy ion collisions. NA49 displayed results for both $\Lambda\Lambda$ and $\Lambda p$ correlations [13]. The $\Lambda\Lambda$ results showed a flat correlation, which means that they are not useful for source-size determination, but can put limits on the $\Lambda\Lambda$ scattering length. This is important as it sheds light on whether there is a low-energy resonance associated with the $H_0$ di-baryon. The $\Lambda - p$ correlation function exhibited a peak near zero momentum which was consistent with expectations for a three to four Fermi source, though the size was difficult to ascertain without knowing the $\lambda$ parameter which depends on the fraction of $\Lambda$s from decays of heavier hyperons. With greater statistics, this measurement offers the possibility of determining whether $\Lambda$s are emitted ahead or behind the protons.

The Coulomb interaction between the residual source and the pairs used for HBT has always clouded the interpretation of experiments. However, $K_s - K_s$ interferometry sidesteps the issue since the $K_s$ is neutral. A first measurement of the $K_s - K_s$ correlation function was presented by STAR [16]. Although the statistics were insufficient for a detailed analysis, this preliminary result was extremely encouraging.

The most surprising result of the conference was the presentation of two-photon HBT by WA98 [21,22]. The height of the correlation function shown in Fig. 4 has a height which requires that 10% of the photons must be direct photons, i.e. not from $\pi_0$ decay or dalitz decays from long-lived particles such as the $\eta$. In fact, by measuring the inclusive
Figure 4. The two-photon correlation function from WA98 is shown with and without cuts for cluster splitting in the calorimeter.

For the direct photon spectrum, one can use the intercept of the correlation function, $1 + \lambda$, to infer the direct photon spectrum,

$$
\frac{dN_{\text{direct}}}{d^3p} = \sqrt{\lambda \gamma(p_t)} \frac{dN_{\text{inclusive}}}{d^3p}.
$$

This result was surprising because the $\lambda$ parameter was expected to be much smaller. If the fraction of direct photons to inclusive photons were 1% rather than 10% the height of the correlation function would have been smaller by a factor of 100, and the statistical requirement for events would have increased by a factor of $10^4$.

I conclude this section with a brief summary of theoretical attempts at solving the HBT puzzle. Most importantly, it should be emphasized that there is consensus that hydrodynamics with a Boltzmann or cascade afterburner will over-predict source sizes [9,11,12,10,23,24]. However, it is not yet clear that fitting the data would not be possible if an extreme equation of state were used, e.g. one with a speed of sound greater than $1/\sqrt{3}$. Several careful studies have been performed to ensure that experimental resolution and Coulomb corrections have been properly treated [4,25,26]. The effects of viscosity have just begun to be included, and it seems that they will provide only a modest correction in order to be consistent with elliptic flow results which preclude large viscosities [27,28]. The effect of modifying chemical rates and cross sections has also been investigated with only modest changes in HBT results [23,11]. Finally, the efforts at comparing theory to experiment have become more meaningful as theoretical models have generated
correlation functions which are then fit for Gaussian parameters, rather than comparing radii generated from looking at source functions. It appears that the HBT puzzle indeed derives from comparing “apples to apples”.

In addition to listing all the investigations presented in this conference, it is worthwhile to list the issues not yet addressed which might shed light on the HBT puzzle. First, it should be pointed out that the hydrodynamic treatments all assume a Bjorken space-time geometry, i.e. the matter coasts along the beam axis. If the matter accelerates significantly due to the finite size in the beam direction, the extrapolations for $\langle \tau \rangle$ at breakup might be too small. This issue could be settled by three-dimensional hydrodynamic studies. Secondly, three-body interactions such as the residual Coulomb interaction have not been totally ruled out as being unimportant, although schematic calculations suggest they are indeed unimportant, and the equivalence of $\pi^+\pi^+$ and $\pi^-\pi^-$ results also points to their insignificance. The most interesting possible explanation of the $R_{\text{out}}/R_{\text{side}}$ puzzle might lay in a reduced emissivity of the surface, which would allow the matter to fall apart suddenly. The emissivity might be reduced in the case of a super-cooled phase. The problem of how quarks might escape microscopically from a QGP region and form mesons has been considered from the point of fissioning flux tubes [30]. Effects of an increased emissivity were reported on at this conference [29]. As a final possibility, it may be that the picture of the dynamics assumed in cascade or Boltzmann algorithms is fundamentally flawed due to the neglect of quantum effects. Again, this seems unlikely, but it should not be forgotten that the thermal wavelengths at breakup correspond to volumes with several particles. In order to explain the HBT puzzle, these issues must somehow account for corrections of the order of 30%.

3. Multiplicity correlations and $p_t$ fluctuations

Fluctuations in multiplicity or transverse momentum have been proposed as signatures for phase separation [31,32] or critical fluctuations [33]. Of course, such fluctuations are also affected by jets and jet quenching. In this conference we have seen new results for $p_t$ fluctuations from NA49 [13], PHENIX [34] and STAR [15]. The results from NA49, shown in Fig. 5, illustrate that the fluctuation is smaller for same-sign particles. This may be due to the positive correlation between opposite sign particles from resonance decays. HBT effects, jets and the distorted shapes of the nuclei are other potential correlations which would give $p_t$ fluctuations.

The value of $\Phi_{p_t}$ increases if there is an increased correlation in $p_t$ between given particles or if the number of particles with which one is correlated increases. By measuring the kinematic range of the correlation, one should gain insight into the source of the non-zero $\Phi_{p_t}$. The fluctuations measured by PHENIX were even smaller than those reported by NA49, while the fluctuations measured by STAR were significantly larger. There seems to be a trend that the fluctuations are larger for larger acceptances, which suggests that the correlation may span more than a unit of rapidity.

A wavelet analysis, which can measure the same class of correlations as $p_t$ fluctuations, was presented by the STAR collaboration in this meeting [35]. For low multiplicities, the correlations were consistent with HIJING with jets, while at high multiplicities, the results were smaller and were consistent with HIJING without jets. This emphasizes the
point that jet quenching should be manifest in low $p_t$ observables. Perhaps, experiment could decide not only the existence but the nature of jet quenching, i.e. determining whether the jet energy is transformed into more particles through radiation or whether it is shared among the collision partners.

4. **Isospin fluctuations and correlations arising from charge conservation**

Large fluctuations in the fraction of neutral pions to total pions has been suggested as a signal for coherent emission of pions which might result from a disoriented chiral condensate [36]. Unfortunately, this is a tremendously difficult measurement due to the fact that neutral pions decay into two photons, making the exact counting of soft pions extremely difficult, especially in a central collision. WA98 presented an analysis showing no evidence for large fluctuations [21]. However, one should not jump to the conclusion that the observations were entirely consistent with random emissions until a more detailed theoretical investigation is performed. In this conference, new ideas were also presented for investigating fluctuations of a different flavor, i.e. fluctuations in flavor [37] and baryon number [38].

Charge fluctuations, charge correlations and balance functions represent another class of observables, which are sensitive to the dynamics of separating conserved charges. Since charge conservation is local in space-time, each positive charge is accompanied by a negative charge. If these balancing charges remain close to one another in coordinate space at the time of their emission, they will be correlated in momentum space. This means that

![Figure 5](image_url)

Figure 5. Fluctuations in $p_t$ from the SPS are shown as a function of centrality for all charges or for same-sign particles.
Figure 6. Charge balance functions (left panel) measured by STAR show that balancing charges are more correlated in central collisions than in peripheral collisions. The widths are plotted as a function of centrality in the right panel. This behavior is consistent with a delayed hadronization.

The net charge measured into a large volume of phase space, e.g. the STAR acceptance, would tend more toward zero since each charge would be canceled by a balancing partner. A delayed hadronization would lead to more highly correlated balancing charges since the charges would have less time to separate and would also be produced after the early stage of the collision where there is a high velocity gradient pulling particles apart. Since most charge is created at hadronization, a tighter correlation of balancing charges could serve as a signal of QGP formation [39,40].

Several analyses were presented at this meeting which measured this correlation. Charge fluctuations were measured by NA49 [13], and charge fluctuations and balance functions were presented by STAR [15]. The balance functions from STAR are shown in Fig. 6. The balance function statistically measures the distribution of relative rapidities of balancing π⁺ − π⁻ pairs. The narrowing of the balance function as a function of centrality is highly suggestive of a delayed hadronization.

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