Balance functions, correlations, charge fluctuations, and interferometry

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Connections between charge balance functions, charge fluctuations, and correlations are presented. It is shown that charge fluctuations can be directly expressed in terms of balance functions under certain assumptions. The distortion of charge balance functions due to experimental acceptance is discussed and the effects of identical boson interference is illustrated with a simple model.

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I. INTRODUCTION

Charge balance functions [1] and charge fluctuations [2–5] have been proposed as a means for gaining insight into the dynamics of hadronization in relativistic heavy ion collisions. Both observables are sensitive to the separation, in momentum space, of balancing charges. Such a pair is composed of a positive and negative particle whose charge derives from the same point in space-time. As a quark-gluon plasma (QGP) scenario entails a large production of new charges late in the reaction, a tight correlation between the balancing charge-anticharge pairs would provide evidence of the creation of a novel state of matter.

This tight correlation comes from the following two properties of the late stage QGP. First, since the quarks and gluons have been flowing for a long time (~ 10 fm/c), the momentum of each quark (gluon) is mostly determined by its location in space-time. Second, at this late stage, the system has been cooled down considerably so that the quarks and gluons do not have high energy in the rest frame of their fluid cell. Therefore, when the quarks and gluons hadronize, the space-time point of the hadronization and the momenta of the hadrons are highly correlated. Moreover, since quarks carry fractional charges and there are large number of gluons, the rapidities of unlike-sign hadrons must also be highly correlated.

For the charge fluctuations, these highly correlated unlike-sign pairs manifest themselves by making the charge fluctuation per degree of freedom unusually small [2,5]. For the balance function, the effect of the high correlation is to make the central peak unusually narrow [4]. Ideally, one would sweep either the centrality or the energy of the collisions and look for a sudden drop in the charge fluctuation and the width of the balance function. These would signal the production of a QGP. In reality, there are very few phenomena in heavy ion collisions for which a clean signal can be detected mainly due to the sheer complexity of the produced system. In this paper, we would like to address some of the issues in connecting these theoretical arguments with what is observed in actual experiments.

Both balance functions and charge fluctuations can be expressed in terms of one-particle and two-particle observables. In the following section we present expressions for both balance functions and charge fluctuations in terms of spectra and correlations, and show how the charge fluctuations can be simply expressed in terms of balance functions for nearly neutral systems.

Unfortunately, balance functions and charge fluctuations can both be rather sensitive to detector acceptance. In Sec. III we present a variant of balance functions which reduces acceptance effects for detectors with sharp cutoffs in rapidity. Identical pion correlations also affects both observables in a nontrivial manner. In a simple model utilizing parameters consistent with observed spectra and correlations from RHIC, we illustrate the distortion of the balance functions due to Bose-Einstein correlations in Sec. IV. The shape of the balance function is also influenced by the rapid cooling due to the transverse expansion of the system. We use a simple model in Sec. V to estimate such effect. The insights gained from these studies are summarized in Sec. VI. The effect of resonances on balance functions is also briefly discussed in Sec. VI

II. RELATING BALANCE FUNCTIONS, FLUCTUATIONS, AND CORRELATIONS

As mentioned in the Introduction, both balance-function and charge-fluctuation observables are generated from one-body and two-body observables which necessitates that they may be expressed in terms of spectra and two-particle correlation functions. In order to express the balance functions in terms of the elementary correlation functions, first define

$$\langle N(a,\Delta_1)\rangle = \int_{\Delta_1} d^3p \frac{dn_a}{d^3p} \tag{1}$$

and

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$$\langle N(b,\Delta_2;a,\Delta_1)\rangle$$

$$=\int_{\Delta_1} d^3p_a \int_{\Delta_2} d^3p_b \frac{d^2n_{ab}}{d^3p_a d^3p_b} \tag{2}$$

$$=\int_{\Delta_1} d^3p_a \int_{\Delta_2} d^3p_b \frac{dn_a}{d^3p_a}\frac{dn_b}{d^3p_b} C(b,\Delta_2;a,\Delta_1), \tag{3}$$

where $\Delta_{1,2}$ are phase space criteria such as rapidity intervals.

In terms of these quantities, the balance function is expressed as

$$B(\Delta_2|\Delta_1)=\frac{1}{2}\{D(-,\Delta_2|+,\Delta_1)-D(+,\Delta_2|+,\Delta_1)+D(+,\Delta_2|-,\Delta_1)-D(-,\Delta_2|-,\Delta_1)\}, \tag{4}$$

where

$$D(b,\Delta_2|a,\Delta_1)=\frac{\langle N(b,\Delta_2;a,\Delta_1)\rangle}{\langle N(a,\Delta_1)\rangle}, \tag{5}$$

which can be considered as a conditional probability.

Thus correlation functions and spectra are sufficient to determine balance functions, although the required integration can be somewhat convoluted, depending on the binning, Δ_1 and Δ_2. The criteria Δ_1 is based solely on the momenta of the first particle, while the criteria Δ_2 might be any function of the momenta of both particles, e.g., it might be determined by the relative rapidity of the two particles.

To establish the correspondence between charge fluctuations and balance functions, consider a balance function binned as a function of the rapidity difference where both particles are required to reside within a fixed rapidity window of size Y. For this case Δ_1 constrains the first particle to be within the rapidity window, and Δ_2 constrains the second particle to have a relative rapidity $|y_b-y_a|=\Delta y$ while also existing inside the rapidity window. This binning was applied in preliminary results from STAR reported in Ref. [6]. Referring to this balance function as $B(\Delta y|Y)$, one can find the charge fluctuation within the rapidity window $0<y<Y$ by integrating $B(\Delta y|Y)$ in the interval $0<\Delta y<Y$. In this case,

$$B(Y|Y)=\int_0^Y d\Delta y\, B(\Delta y|Y)$$

$$=\frac{1}{2}\left\{\frac{\langle N_+N_-\rangle_\Delta}{\langle N_+\rangle_\Delta}+\frac{\langle N_+N_-\rangle_\Delta}{\langle N_-\rangle_\Delta}-\frac{\langle N_+(N_+-1)\rangle_\Delta}{\langle N_+\rangle_\Delta}-\frac{\langle N_-(N_--1)\rangle_\Delta}{\langle N_-\rangle_\Delta}\right\}, \tag{6}$$

where $\langle\cdots\rangle_\Delta$ denotes averages in the phase space region Δ. Writing $N_\pm=\langle N_\pm\rangle_\Delta+\delta N_\pm$, it is not hard to show

$$\frac{\langle(Q-\langle Q\rangle)^2\rangle}{\langle N_{\rm ch}\rangle}=1-\int_0^Y d\Delta y\, B(\Delta y|Y)+O\left(\frac{\langle Q\rangle}{\langle N_{\rm ch}\rangle}\right), \tag{7}$$

where $Q=N_+-N_-$ and $N_{\rm ch}=N_++N_-$. For electric charge, the size of the correction is usually less than 5% in relativistic heavy ion collisions where the number of produced charges is much greater than the net charge. However, for baryon number the additional term is not negligible even at RHIC.

In a boost-invariant system (independent of rapidity) the balance function $B(\Delta y|Y)$ can be related to the balance function for an infinite interval:

$$B(\Delta y|Y)=B(\Delta y|Y=\infty)(1-\Delta y/Y). \tag{8}$$

The factor $(1-\Delta y/Y)$ accounts for the probability that a particle's partner will fall within the rapidity window given that they are separated by Δy. Also, assuming boost invariance allows one to express the balance functions simply in terms of correlation functions as described in Eq. (4):

$$B(\Delta y|Y=\infty)=\frac{1}{2}\left\{\frac{dn_+}{dy}C_{++}(\Delta y)+\frac{dn_-}{dy}C_{--}(\Delta y)-\left(\frac{dn_+}{dy}+\frac{dn_-}{dy}\right)C_{+-}(\Delta y)\right\}. \tag{9}$$

From the above discussion it is clear that the charge fluctuation is the global measure of the charge correlation and the balance function is a differential measure of the charge correlation and therefore carries more information. The advantage of charge fluctuations is that they carry a clear physical meaning in terms of a grand canonical ensemble [3,5], and can therefore be easily connected to more ideal theoretical models, e.g., lattice QCD calculations. However, since there are no external sources of charge in heavy ion collisions to warrant a grand canonical treatment, both observables are effectively driven by the dynamics of how balancing charges are formed and separate.

We emphasize here that charge fluctuations were not intended to provide a derivative measure. As can be seen from Eq. (7) the charge fluctuation summarizes the balance functions in one number. It gives somewhat different information than the width of the balance function since it is also affected by the height. We do not recommend analyzing charge fluctuations as a function of the size of the rapidity window. If the different sized windows included the same pairs, the values would no longer be statistically independent when plotted against the window size. If the windows are used only once, the information from pairs which occupy adjacent windows is thrown away.

A similar set of issues surfaced in making the connection between fluctuations and correlations in the study of multiplicity distributions analyzed as a function of rapidity [7,8]. A more general connection between fluctuation and inclusive observables can be found in Ref. [9]. However, it should be noted that factorial moments and scaled factorial moments, which are measures of fluctuation [10,11], offer the opportunity to study n-body correlations for $n>2$ in a manner which, unlike correlations, can be easily collapsed into a single variable.

III. MINIMIZING ACCEPTANCE EFFECTS IN BALANCE FUNCTIONS

Balance functions analyzed by the STAR Collaboration [6] were constructed according to the prescription that p_1 would refer to any pion that is measured within a specified rapidity window while p_2 referred to the relative rapidity, again with the requirement that the second particle was within the rapidity window. In that case,

$$B(\Delta y|Y)=\frac{1}{2}\left\{\frac{\langle N_{+-}(\Delta y)\rangle-\langle N_{++}(\Delta y)\rangle}{\langle N_{+}\rangle}+\frac{\langle N_{-+}(\Delta y)\rangle-\langle N_{--}(\Delta y)\rangle}{\langle N_{-}\rangle}\right\}. \tag{10}$$

Here $N_{+-}(\Delta y)$ counts pairs with opposite charge that satisfy the criteria that their relative rapidity equals Δy, whereas N_+ is the number of positive particles in the same interval. Here the angular bracket represents averaging over the events and Y is the size of the detector rapidity window. From this example, one can readily understand how balance functions identify balancing charges. For any positive charge, there exists only one negative particle whose negative charge derived from the point at which the positive charge was created. By subtracting from the numerator the same object created with positive-positive pairs, one is effectively subtracting the uncorrelated negatives from the distribution and identifying the balancing charge on a statistical basis.

From the construction of Eq. (10), one can understand the sensitivity of $B(\Delta y|Y)$ to the acceptance size Y by considering a detector which covers a finite range in rapidity:

$$y_{\rm min}<y<y_{\rm max}. \tag{11}$$

with $y_{\rm max}-y_{\rm min}=Y$. For this example, the balance function must go to zero as Δy approaches Y. This occurs because the particle satisfying the condition p_1 must lie at the extreme boundary of the acceptance in order for the second particle to have a relative rapidity $\Delta y \sim Y$ while remaining in the acceptance. The balance function is thus forced to zero at the limits of the acceptance for trivial reasons.

Of course, the balance function corresponding to a perfect detector $B(\Delta y|\infty)$ is independent of any particular detector size Y. As described in Eq. (8), one can easily correct for the detector acceptance in the boost-invariant case by dividing the balance function by a factor $(1-\Delta y/Y)$.

These balance functions would not have more information than those created without the correction factor, but the information would more directly address the physics of charge separation rather than reflecting the experimental acceptance. We note that the statistical uncertainties of the corrected balance function will, however, be quite large as $\Delta y \sim Y$.

More generally, one can correct the balance functions for the acceptance by dividing the numerators in Eq. (4) $N(Q_2,p_2|Q_1,p_1)$ by acceptance factors $A(Q_1,p_2|Q_1,p_1)$:

$$B(p_2|p_1)=\frac{1}{2}\left\{\frac{N(-,p_2|+,p_1)}{A(-,p_2|+,p_1)N(+p_1)}-\frac{N(+,p_2|+,p_1)}{A(+,p_2|+,p_1)N(+,p_1)}+\frac{N(+,p_2|-,p_1)}{A(+,p_2|-,p_1)N(-,p_1)}-\frac{N(-,p_2|-,p_1)}{A(-,p_2|-,p_1)N(-,p_1)}\right\}. \tag{12}$$

The acceptance factor represents the probability that, given a particle i satisfied the criteria p_1, a second particle that satisfied p_2 would be detected. Since the criteria (Q_2,p_2) may depend on the individual particle that satisfied (Q_1,p_1), it may be simpler to calculate A in terms of $a_i(Q_2,p_2)$ which represents the acceptance into (Q_2,p_2) given the particular particle i:

$$A(Q_2,p_2|Q_1,p_1)=\frac{\sum_{i\in Q_1,p_1} a_i(Q_2,p_2)}{N(Q_1,p_1)}. \tag{13}$$

The acceptance probability $a_i(Q_2,p_2)$ would be between zero and unity. We note that the acceptance is effectively accounted for by performing a substitution for the denominators in Eq. (4)

$$N(Q_1,P_1)\rightarrow\sum_{i\in Q_1,p_1} a_i(Q_2,p_2). \tag{14}$$

For the boost-invariant case above where p_2 referred to the relative rapidity, and where the acceptance is represented by simple step functions in rapidity, the probabilities would become

$$a_i(p_2)=\begin{cases} 0, & y_{\rm max}-y_i<\Delta y \ \text{ and } \ y_i-y_{\rm min}<\Delta y,\\ 1/2, & y_{\rm max}-y_i<\Delta y \ \text{ and } \ y_i-y_{\rm min}>\Delta y,\\ 1/2, & y_{\rm max}-y_i>\Delta y \ \text{ and } \ y_i-y_{\rm min}<\Delta y,\\ 1, & y_{\rm max}-y_i>\Delta y \ \text{ and } \ y_i-y_{\rm min}>\Delta y. \end{cases} \tag{15}$$

Given that the bins p_2 would be of finite extent, the values might differ from 1/2, 0 or unity if the bin straddled the acceptance. For a boost invariant system, averaging over y_i results in the simple correction factor $(1-\Delta y/Y)$ mentioned previously.

In general, if the acceptance depends on where in the (Q_2,p_2) bin the second particle lies, one cannot calculate the acceptance correction exactly without knowledge of the charge correlation which is unavailable except by measuring the balance function in sufficiently small p_2 bins such that the acceptance is effectively uniform within the small bins. This may not be feasible due to statistics. It is our recommendation that such factors $a_i(Q_2,p_2)$ should be kept simple. One can always correct theoretical results for the detector response by applying whatever factor is applied to the experimental analysis. Although comparisons with models could have been made without any corrections, acceptance-corrected balance functions can allow for a more physical interpretation while not compromising the integrity of the analysis.

IV. BOSE-EINSTEIN CORRELATIONS AND BALANCE FUNCTIONS

Although Bose-Einstein correlations only affect identical particles at small relative momentum, they manifest themselves in balance functions despite the fact that the binning in balance functions typically covers a large volume in momentum space. In a related topic, Bose-Einstein correlations [also known as the Hanbury Brown–Twiss (HBT) effect] have been observed in rapidity correlations where all charged particles, both positive and negative, were used in the analysis [12,13,7]. The manifestations of HBT in balance function derives from the fact that it induces a correlation between a given charge and all other charges, not just those that were created to balance the given charge.

In balance functions the HBT effect should enhance the probability that same-charge particles have small relative momentum, thus providing a dip in the balance function at small relative rapidity. In order to model this effect, we consider pairs of pions with momenta p_a and p_b and opposite charge that are created according to a boost-invariant thermal distribution with a temperature of 190 MeV, thus roughly reproducing the pion spectra measured in Au + Au collisions at RHIC. In addition to the usual contribution to the balance function between p_a and p_b, a second component derives from the interaction with other pions from other pairs which in this case have momenta p_c and p_d. The thermal distribution describing the first two particles was centered at zero rapidity, while the thermal distribution responsible for emission of the second pair was randomly chosen within ± 4 units.

The particles p_a and p_c were assumed to have the same sign, as were the particles with momenta p_b and p_d. A contribution to the balance function was constructed using these particles, but with a weight,

$$w = C_{++}(p_a,p_c)C_{--}(p_b,p_d)C_{+-}(p_a,p_d)C_{-+}(p_b,p_c). \tag{16}$$

This accounts for the weight due to two-particle interactions. The correlation functions were simple functions of $Q_{\rm inv}(p_a,p_b) \equiv \sqrt{(p_a-p_b)^2}$, which were generated by calculating correlation functions for a spherically symmetric Gaussian source of radius, $R_{\rm inv}=7$ fm, again crudely in line with measurements at RHIC [14]. The weights were calculated by averaging the squared relative wave function for two particles, including the Coulomb interaction between the pions. The weight was multiplied by the number of such pairs which came from assuming that there were 200 pion pairs per unit rapidity. Only a fraction, $\lambda = 0.7$, of the pairs were assumed to interact due to the fact that some pions would be created in long-lived decays. The acceptance of the STAR detector, and the fact that only a fraction of the pions would truly be balanced by other pions (rather than by charged kaons or other particles) was roughly accounted for by accepting only 60% of the particles with transverse momenta between 100 and 700 MeV/c.

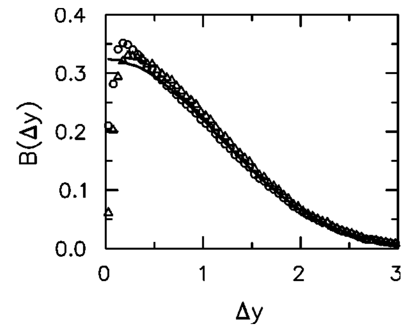

FIG. 1. The balance function from the simple thermal Bjorken model (line) has been parametrized and filtered to roughly provide rough consistency with measurements of STAR. The inclusion of HBT effects (triangles) gives a dip at small Δy, while the extra addition of Coulomb (circles) modifies the dip.

The resulting balance functions are displayed in Fig. 1. When the interaction between particles is neglected, the resulting balance function falls monotonically, and has a width consistent with the temperature. The inclusion of the HBT effect results in a large dip near $\Delta y = 0$, and an enhancement at somewhat larger Δy. The dip derives from the enhancement of same-sign pairs which results in a negative contribution to the balance function. Since the weight is assigned to the emission of the cd pair, the positive HBT weight contributes to opposite sign pairs with equal strength, but is spread out over a wider range of Δy. Hence, the balance function is slightly enhanced for $\Delta y \sim 1/2$ from HBT effects.

Also shown in Fig. 1 are calculations where the Coulomb interaction is included. Since Coulomb interactions result in attractions for opposite-sign pairs, and repulsions for same sign pairs, the dip due to HBT is mitigated.

Although the shape of the balance function is visibly altered by the inclusion of two-particle interactions, the mean width changed by only a few percent. The strength of the distortion was proportional to the multiplicity, but the effect is not necessarily weaker for peripheral events. This follows because the HBT correction contributes with a strength proportional to R^{-3}. Since the product of dn/dy and R^{-3} stays roughly constant over a wide range of centralities in heavy ion collisions, the distortion due to interactions should not appreciably affect the centrality dependence of the balance function's width.

V. COOLING AND TRANSVERSE EXPANSION

Balancing particles, when emitted in close proximity to one another, are separated in momentum space according to the thermal properties of the breakup stage. Cooler breakup temperatures result in smaller thermal velocities and narrower balance functions. Since the characteristic volume of a heavy ion collision is much larger than the characteristic volume of a pp collision, breakup temperatures tend to be much lower, perhaps near 100 MeV as opposed to the $\sim$160 MeV temperatures which describe spectra from pp collisions.

Thermal velocities are determined by the local temperature and particle mass. For relativistic particles, the thermal velocity along the beam axis is a function of the particle's transverse mass, and is therefore affected by transverse expansion. Thus, for a delayed-hadronization scenario, one expects the balance function to become narrower for two reasons: cooler temperatures and transverse expansion.

In order to illustrate the sensitivity of balance functions to the temperature and transverse collective flow we consider a simple thermal model where the collective velocities of the thermal sources are determined by a simple thermal Bjorken model which incorporates transverse expansion. The collective transverse rapidities are chosen according to the distribution

$$\frac{dN}{y_t dy_t} = \begin{cases} \text{const}, & v_t < v_{\max}, \\ 0, & v_t > v_{\max}. \end{cases} \tag{17}$$

Due to boost invariance, the longitudinal source rapidities were chosen to be zero, which means that the transverse source rapidities are defined by

$$y_t = \frac{1}{2}\ln\left(\frac{1+v_t}{1-v_t}\right), \tag{18}$$

where v_t is the transverse velocity of the source as measured in a frame boosted along the beam axis such that the longitudinal rapidity of the source is zero.

Figure 2 displays $\pi^+\pi^-$ balance functions for three parameter sets. The lower panel presents results assuming a temperature of 160 MeV and no transverse expansion. The balance functions shown in the middle panel were calculated assuming no transverse expansion but assuming a temperature of 105 MeV which is consistent with analyses from RHIC where the breakup temperature was determined by comparing pion and proton spectra. As expected, these balance functions are narrower due to the reduced thermal velocities. The results of the upper panel also assume a temperature of 105 MeV, but incorporate a transverse expansion velocity $v_{\max} = 0.77c$. This velocity was chosen such that the mean p_t of the pions would equal that of the 160 MeV source where transverse expansion was neglected. It is apparent that the transverse expansion indeed results in a further narrowing of the balance function.

All three panels of Fig. 2 also illustrate the dependence of the balance functions with respect to the transverse of the pions. In addition to the calculations which assumed a perfect detector finding all pions, balance functions were calculated where the criteria Δ_1 for gating on the first pion restricts the first pion to be within a specific range of transverse momentum. For each parameter set, restricting the pion to higher p_t results in narrower balance functions as expected given the higher transverse mass of the higher p_t particles.

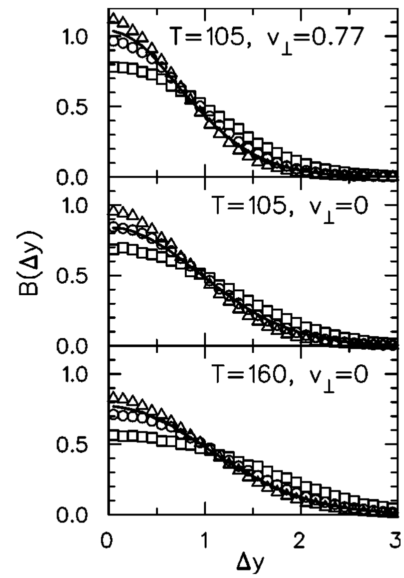

FIG. 2. Two-pion balance functions are shown for thermal models with three parameter sets illustrating the narrowing of the balance function due to cooling and expansion. For each case calculations were performed with no gates on the conditional pion (line), a condition that $p_t < 100$ MeV (squares), 200 MeV/c $< p_t < 300$ MeV/c (circles), and 400 MeV/c $< p_t < 500$ MeV/c (triangles).

Balance functions are primarily determined by two factors, the conditions at breakup (temperature and collective flow) and the relative diffusion of the balancing charges that takes place between the time of their creation and their emission. The discussion of this section has ignored the latter, although it should be emphasized that the principal motivation for analyzing balance functions derives from the quest to observe the correlation in coordinate space between balancing charges. Finally, we point out that collective transverse flow should result in a correlation of the balancing pairs in relative p_t and relative ϕ in addition to the correlation in rapidity. Thus, a multidimensional analysis of balance functions should provide an additional means for either disproving or corroborating models of hadronization and diffusion.

VI. SUMMARY AND DISCUSSION

This paper covered several technical issues related to balance functions. The conclusion of Sec. II is that charge fluctuations can be related to balance functions in a straightforward manner unless the average net charge is large. In fact, the charge fluctuation can be thought of as a measure of the integrated balance function $B(\Delta y|Y)$ from zero to Y. In that sense, it represents a one-component measure of the balance function, just like the mean width.

Section III provided an illustration of how balance functions can be created in such a way as to minimize sensitivity to experimental acceptance. Although the example addressed only problems with finite acceptance in rapidity where the balance function was binned according to relative rapidity, the principles could be applied to balance functions in any variables.

Section IV considered the inclusion of two-particle interactions into balance functions. The effects were shown to be quite visible at small relative rapidity. However, the width of the balance function was not significantly affected by the two-particle interactions. This is encouraging, as it justifies interpreting balance functions as objects that statistically identify balancing partners, while subtracting out contributions from other pairs.

In the last section, the effect of cooling and transverse expansion on the balance function was studied. Cooler temperature, with or without transverse expansion, resulted in a narrower balance function by simply reducing the thermal velocity. In addition to the effect of cooler temperature, the collective flow should provide additional correlations in p_t and ϕ. To disentangle such effects from the effect of QGP requires more detailed study of multidimensional balance functions.

So far in our analysis, we neglected in most part the effect of resonances. Resonances affect the balance function in two ways. First, two balancing charges might be emitted from the same resonance and not interact with other hadrons before detection. Examples of such decays are $\phi \rightarrow K^+K^-$, $\rho_0 \rightarrow \pi^+\pi^-$, and ω or $\eta \rightarrow \pi^+\pi^-\pi^0$. Such particles are typically closer to one another in momentum space than balancing pariticles emitted from uncorrelated sources. However, one should stress that such effects also exist in pp collisions and the expectation is that the resonance fraction is lower in heavy ion collisions since the breakup temperature is significantly lowered. Of course one can imagine scenarios for which this fraction actually increases for HI collisions, e.g., surplus η mesons or the decay of a collective coherent state as described in a disoriented chiral condensate scenario.

The second way in which resonances would affect the balance function is when the balancing particles have interactions with other particles through resonant interactions. The distortion of the single particle spectra clearly affects the balance function, but this can be accounted for in a thermal model by assigning a temperature to effectively provide a singles spectra consistent with experiment. More importantly, resonances provide the predominant means for inelastic reactions, e.g., $K^+\pi^0 \rightarrow K^* \rightarrow K^0 + \pi^+$. This reaction could reduce the normalization of the K^+K^- balance function by shifting the balancing strangeness to a neutral kaon. Incorporating such effects into a statistical model is not trivial as absolute conservation of charge, strangeness, and isospin must be obeyed.

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