Jet Correlations from PHENIX: Low-p_T to High-p_T

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PHENIX has measured many different two-particle azimuthal correlations in several different colliding systems, beam energies, p_T windows, etc. The initial striking results from the first full energy Au+Au run have been confirmed, *i.e.* the observation of away-side suppression at intermediate p_T and the shape modification at low p_T. With the new high-statistics data these results have been extended to further explore the physics resulting in these modified correlations. In this contribution we present a wide variety of correlation results at high-p_T (> 5 GeV/c) and at low p_T ($\sim$ 1-4 GeV/c). We discuss the implication of these data on energy loss models and on the possibilities of determining medium properties from these correlations.

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1. Introduction

With the advent of RHIC, study of hard-scattering physics in heavy-ion collisions has been possible. Hard-scattering physics touches both the hard and soft physics that is measured at RHIC. The jets that we are sensitive to, those with energies of a $\sim$5 to 20 GeV, typically fragment into relatively soft hadrons. As a result direct reconstruction of these jets is very difficult because it is virtually impossible to disentangle the jet fragmentation from those from bulk particle production. Jet quenching scenarios generally yield results that modify the bulk particle production, albeit at a small level. The radiated energy from the hard-scattered parton results in increased particle production, probably at low p_T. Also, v_2 as a function of p_T deviates from hydrodynamical calculations near 1-2 GeV/c [1]. Further, jet quenching at high-p_T was proposed as a probe of the soft medium produced in RHIC collisions.

Jet physics at RHIC has been accessed by single particle observables such as high-p_T spectra, but, more directly by two-particle correlations. In two-particle correlations one triggers on a hard-scattering process by selecting events with a high-p_T particle (the trigger) and measures the azimuthal (and longitudinal) distribution of other particles in the event (the associated particles) with respect to the trigger. Experimentally two-particle correlations are determined from a correlation function, $C(\Delta\phi)$ by measuring the *real* distribution of pairs within the triggered events and removing detector correlations by measuring the *mixed* distribution of pairs where a trigger is in one event and an associated particle is in a second event. The resulting correlation function is usually arbitrarily normalized since the shape of the distribution is most directly measurable. However, with the knowledge of the associated particle efficiency it is possible to determine the normalization such that the resulting distribution is the yield of pairs per trigger [2]. This is summarized as

$$\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} \propto C(\Delta\phi) \propto \frac{\mathrm{Real}(\Delta\phi)}{\mathrm{Mix}(\Delta\phi)} \tag{1.1}$$

In the two-component model of azimuthal correlations in A+A collisions, the shape is expected to be characterized by

$$\begin{aligned}
\frac{1}{N_{trig}}\frac{dN}{d\Delta\phi} &= \frac{N}{2\pi}\left(1 + 2v_2^{trigg}v_2^{assoc}\cos(2\Delta\phi)\right) + \\
&\quad \frac{Y_N}{\sqrt{2\pi}\sigma_N}\exp\left(\frac{-\Delta\phi^2}{2\sigma_N^2}\right) + \\
&\quad \frac{Y_F}{\sqrt{2\pi}\sigma_F}\exp\left(\frac{-(\Delta\phi-\pi)^2}{2\sigma_F^2}\right)
\end{aligned} \tag{1.2}$$

The first term is the correlation from the elliptic flow. The second term is the near-side correlation for two particles which fragment from a single jet. The last term is the away-side jet which results from the fragment of a second, recoil jet correlated with the trigger jet. Here we have explicitly assumed the hard scattering is the result of a 2→2 process.

Studies of these correlations began early at RHIC and there were some initial striking results. At intermediate p_T with a trigger hadrons of $\sim$ 4 GeV/c and associated hadrons $\sim$ 2 GeV/c, the recoil jet was almost completely suppressed [3]. This was not seen in p+p and d+Au collisions [4]

where a "normal", approximately Gaussian, away-side is present. The measurement of away-side suppression is complimentary to the single particle suppression results and indicated that the away-side is much more strongly affected by energy loss than the near-side. By triggering on a high-p_T particle, the measured correlations have a bias to jets produced near the surface of the interaction region. Therefore, the near-side jet has a short path length through the medium while the away-side potentially traverses a substantial distance across the whole of the interaction region. Measurements at lower p_T, near 2 GeV/c for the trigger and the associated particle, an away-side shape was measured but its shape was much broader and it was peaked away from $\Delta\phi = \pi$ [5]. This result stirred much theoretical interest into bending jets [6][7], mach cones [8][9], and Cerenkov radiation [10].

In the recent high-statistics data samples from RHIC of Au+Au and Cu+Cu, work has been done to extend these initial studies to further understand the physics that has been hinted at. In this contribution we review the recent work on two-particle correlations from the PHENIX experiment both at low-p_T and at high-p_T. At high-p_T it is interesting to look for the effects of jet quenching, *i.e.* measurements of the away-side jet broadening which should accompany the yield suppression from jet quenching. At low-p_T we would like to study the structure that was measured and attempt to rule out different scenarios which could provide an explanation for it, thereby possibly making contact with properties of the medium.

The organization is as follows. The first section deals with the high-p_T correlations and their results. We discuss the implications of these data on energy loss scenarios. In the next section lower-p_T correlations are discussed in some detail where we argue that existing data begin to distinguish between different models of the away-side jet structure. We end with a summary of the landscape of two-particle correlations as it exists at this point.

2. High-p_T Triggered Correlations

The high-statistics Au+Au and Cu+Cu data sets taken at RHIC in 2004 and 2005 are an improvement on the previous data in two respects. First, it is possible to extend the p_T reach of the initial two-particle results. Second, since the jet signal-to-background is only a few percent, with the higher statistics it is possible to observe a significant signal above the background where it was not possible with the initial data set. These two aspects of the data will be exploited in the next two sections.

In order to begin energy loss studies from two-particle correlations and because of the surface bias of these correlations, it is important to measure the away-side jet in the Au+Au environment. Fig. 1 shows trigger π^0 correlations with associated hadrons in 0-20% Au+Au collisions. The π^0 triggers are above 5 GeV/c and the associated hadrons are 2-4.5 GeV/c. These $C(\Delta\phi)$ are normalized such that the background around which the flow modulates is approximately unity. In this case the strength of the correlation signal is the signal-to-background of the jets. A clear near-side jet peak is seen above the background. What had not been seen before this data is the existence of excess yield above the v_2 correlation in the away-side. This is the away-side jet and we can measure a statistically significant yield for triggers of 5 GeV/c and associated hadrons of 2 GeV/c.

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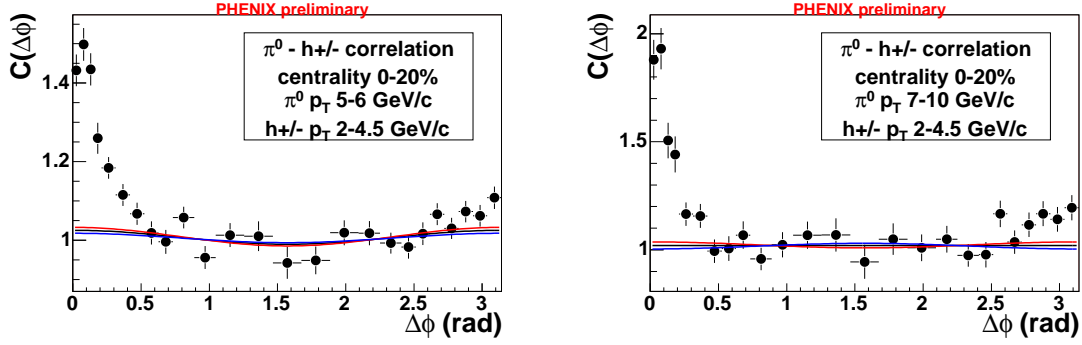
Figure 1: High-p_T π^0-h correlations in 0-20% central Au+Au collisions. The trigger π^0 has a p_T of 5-6 GeV/c (left) and 7-10 GeV/c (right) and the associated hadron has a p_T of 2.5-4.0 GeV/c. The lines indicated the contribution of the v_2 correlation.

Since the away-side is measurable with the high statistics in Au+Au, we can move to study the energy loss of the away-side. The expectation from radiative energy loss models is that the away-side jet should not only be suppressed but it also should be broadened. BDMPS showed that one component of the broadening is due to multiple scattering the parton undergoes as it radiates [11]. It was also recently shown that the radiated gluons have a broad angular spectrum and, when they subsequently hadronize and are measured as associated particles, they should significantly contribute to the expected broadening [12].

A measurement of the yields at high-p_T confirms the initial result that the away-side yield is suppressed. This is seen in Fig. 2 which plots several different h-h correlations in several Au+Au centrality classes and for a constant trigger and associated range. The near side yield changes very little as a function of centrality. This is contrasted by the away-side yield which visibly decreases from most peripheral to most central collisions. This away-side suppression is qualitatively consistent with the recent results from STAR [13].
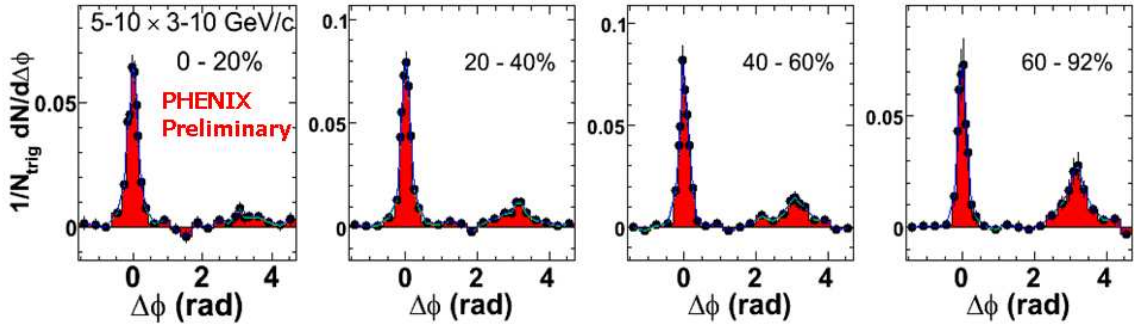
Figure 2: High-p_T h-h correlations for different Au+Au centrality classes, left to right, 0-20%, 20-40%, 40-60%, and 60-92%. The trigger hadron has a p_T of 5-10 GeV/c and the associated hadron has a p_T of 3-10 GeV/c. These are measured pair per trigger distributions after the v_2 correlation has been subtracted.

A corresponding broadening should accompany the suppressed yield that is measured. Such a measurement has been made by PHENIX in π^0-h correlations and is shown in Fig. 3. This figure plots the centrality dependence of the away-side Gaussian width for 5-10 GeV/c triggered π^0-h
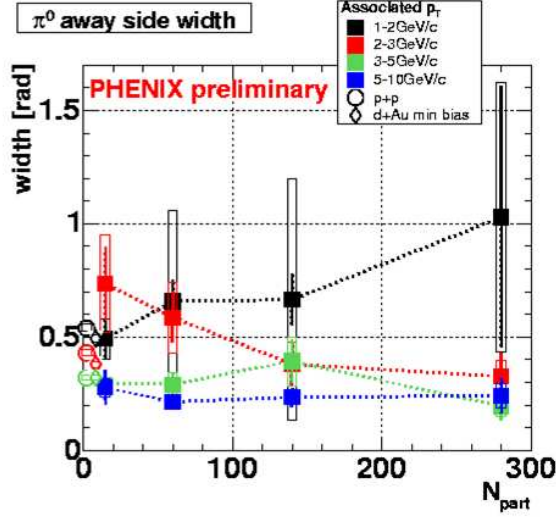
Figure 3: Away-side Gaussian widths from 5-10 GeV/c trigger π^0-h correlations as a function of centrality for different associated hadron p_T ranges. The lowest two curves correspond to the 3-5 GeV/c and 5-10 GeV/c hadron ranges where the away-side jet is most significant. The left most open points correspond to the p+p and d+Au results.

correlations. If one focuses on the lowest two curves corresponding to the 3-5 GeV/c and 5-10 GeV/c associated hadron ranges where the jet signal is most significant, the width is consistent with the p+p values and flat as a function of centrality. No significant broadening is measured. This is also in qualitative agreement with similar measurements from STAR [13].

The question from the data is how can the away-side jet be suppressed but not broadened by energy loss? It was argued before this data became available that the two-particle correlations result from tangentially emitted jets. That is, they are biased toward the surface and both near and away jets traverse little medium [14]. A suppression results from a surface-to-volume suppression of the jet cross-section. The lack of broadening results from the lack of interaction in the medium. This would imply that there is a black interior where jets which recoil into the center are absorbed and that the observed suppression is a geometrical effect. This unfortunately does little to aid in the understanding of the produced medium other than it is very opaque.

Another possibility is that the jets to which the two-particle correlations are measuring are those sensitive to $p_0\delta(\Delta E)$, the probability not to lose energy [15]. In their Monte Carlo, which includes expansion, the authors reproduce the suppression pattern of the published STAR data. Further, they find that although there is a surface bias, a non-negligible fraction of the di-jets are produced near the center of the collision zone. The suppression results again from the value of $p_0\delta(\Delta E)$. The lack of broadening results from lack of energy loss.

This $p_0\delta(\Delta E)$ term is implicit in the Gyulassy-Levai-Vitev (GLV) and explicit in the Armesto-Salgado-Wiedemann (ASW) energy loss models [16]. This term physically results from the Poisson fluctuations in the number of scattering centers. According to Ref. [16] $p_0\delta(\Delta E)$ could be around 30% from quark jets and 10% from gluon jets for multiple soft scattering. For single hard scattering this probability is only slightly smaller.

It seems that both explanations of suppression but lack of significant broadening result from a very opaque medium where the two-particle correlation carry little information from the interior. It is possible that the only information accessible by the high-p_T correlations is simply the probability not to interact.

3. Low-p_T Triggered Correlations

In contrast to high-p_T correlations, significant modification of low-p_T correlations has been observed. In the initial 200 GeV Au+Au collisions the away-side correlations are broadened such that there is significant correlations beyond $\Delta\phi = \pi \pm \pi/2$ and that the shape is peaked away from π. The high-statistics data set allows further study of this effect.

The left panel of Fig. 4 shows an example of a low-p_T correlation function prior to and after the v_2 background subtraction. The measured correlation function (points with the dashed line) is flat on the away-side. Therefore, any harmonic function subtracted from the correlation function will result in a minimum at $\Delta\phi = \pi$. This is what is observed after the background subtraction.
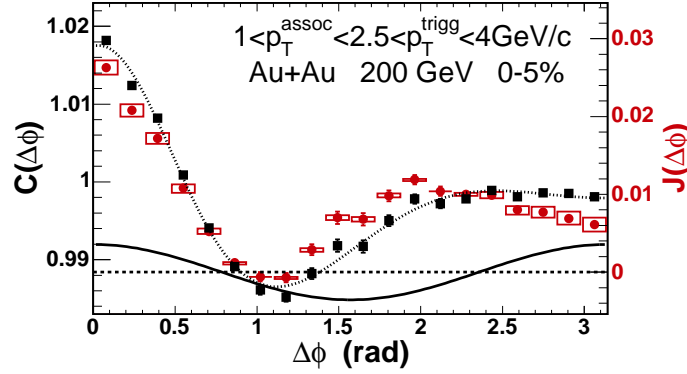

Figure 4: Example of a low-p_T h-h correlation in 0-5% central Au+Au collisions for trigger hadrons from 2.5-4.0 GeV/c and associated hadrons from 1-2.5 GeV/c. The points with the dashed line fit is the correlation function, the solid line indicates the v_2 correlation, and the (red) boxed points indicate the resulting jet shape after background subtraction.

To quantify this structure PHENIX has assumed the away-side shape is a double gaussian symmetrically distributed around $\Delta\phi = \pi$, that is

$$C_{away}(\Delta\phi) \propto \exp\left(\frac{-(\Delta\phi - \pi - D)^2}{2w^2}\right) + \exp\left(\frac{-(\Delta\phi - \pi + D)^2}{2w^2}\right) \tag{3.1}$$

with the parameter D quantifying the peak position of the away-side. This parameter is plotted in Fig. 5 as a function of centrality for Au+Au and Cu+Cu collisions both at 200 and 62.4 GeV. What is observed is that the data follow, within errors, a smooth trend as a function of N_{part}. This could indicate that the structure is determined by a property of the medium instead of, for example, the energy density. It is interesting to note recent studies from CERES indicate that there is a qualitatively similar structure at SPS energies [18].
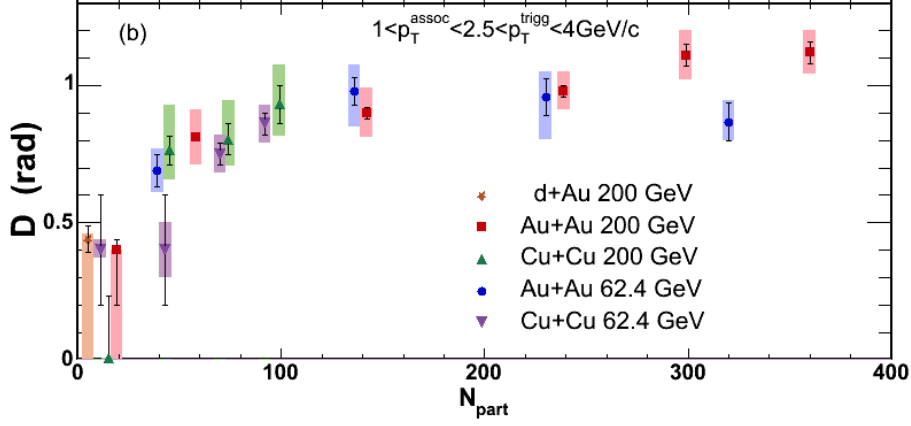
Figure 5: The *D* parameter (see text) from h-h correlations with triggers from 2.5-4.0 and associated hadrons from 1.0-2.5 GeV/c as a function of centrality for Au+Au and Cu+Cu collisions both at 200 GeV and 62.4 GeV.

There are many theoretical interpretations of the structure that was formed. It was pointed out initially, before the data were available, that jets could propagate through the medium with a velocity above the speed of sound and produce Mach shocks [8]. One prediction of these models is that the Mach angle is independent of the jet velocity, *i.e.* the particle p_T.

One competing model to Mach cones is conical emission due to Cerenkov radiation [10]. This model requires a set of bound states in the matter produced resulting in an index of refraction of the medium. The given index of refraction is determined by the bound state spectrum. Because it is Cerenkov radiation the cone angle will depend on the jet energy or particle p_T. The p_T dependence of the different models was proposed as one possible way to determine if the conical emission was due to Cerenkov radiation or Mach shocks.

The final set of models that are competing with the conical emission models are bent jet scenarios [6][7]. From the statistical nature of two-particle correlations, it is not clear that the two peak structure exists because of events having alternating bent jets or from a single event having conical emission. Two examples of bending jets are 1) longitudinal flow distorting the jet [6] and 2) partons multiple scattering away from the dense central medium [7].

Experimental measurements have been made in order to test these different scenarios. Since the workshop, data has appeared from PHENIX on the p_T dependence of the two-particle correlations shown in Fig. 4. These correlations indicate that there is little to no p_T dependence to the *D* parameter [17]. At the least this would indicate that the simple bound states spectrum from Ref. [10] is not correct. More strongly, this data disfavors the Cerenkov cone scenario. Still the bent jet scenarios cannot be explicitly ruled out.

Another interesting avenue of study is the reaction plane dependence of these low-p_T correlations. The reaction plane dependence gives another handle on the v_2 systematics. The reaction plane dependent correlations have a trigger in a particular bin in $|\phi_{trig} - \phi_{EP}|$ (EP for event plane). In this case the v_2^{trig} is not equal to the inclusive v_2^{trig} but varies between bins in a well defined way [19]. In fact, v_2^{trig} changes signs from positive when the trigger is along the reaction plane to negative when the trigger is perpendicular to the reaction plane. Depending on the reaction plane
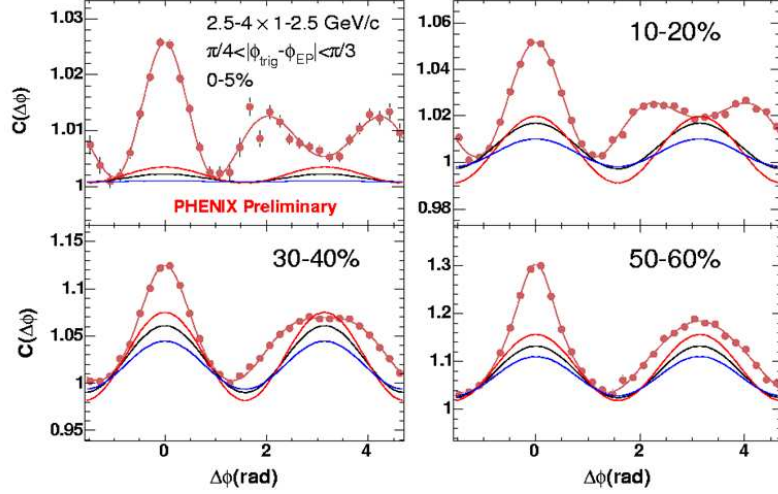
Figure 6: Centrality dependence of h-h correlation functions prior to v_2 subtraction where the trigger is fixed to be $\pi/4 < |\phi_{trig} - \phi_{RP}| < \pi/3$ with respect to the reaction plane (RP). The trigger range is 2.5-4.0 GeV/c and the associated range is 1.0-2.5 GeV/c. The lines indicate the v_2 correlation. In this reaction plane bin v_2^{trig} has its smallest absolute value.

resolution there is a bin in which the v_2^{trig} is nearly zero. Fig. 6 shows different h-h correlations for a fixed 2.5-4.0 GeV/c trigger and 1.0-2.5 GeV/c associated and a fixed $\pi/4 < |\phi_{trig} - \phi_{RP}| < \pi/3$ reaction plane bin. In this reaction plane bin v_2^{trig} has its smallest absolute value. What is observed in the most central two bins is that the double-peaked structure exists prior to the background subtraction.

The reaction plane dependence can be explored for which each have different v_2^{trig} systematics. These are shown in Fig. 7 where each of the six reaction plane bins in the 30-40% central Au+Au collisions for the same trigger and associated combination as in Fig. 6 are plotted. It is clear that the v_2^{trig} contribution changes quite dramatically between each of the reaction plane bins. The v_2-subtracted correlations are plotted together as the per trigger yields in Fig. 8. The observation is that the structure is, within errors, independent of the trigger orientation with respect to the reaction plane. It is important to stress that this result is after subtracting very different v_2 values for each of the different reaction plane bins. Such a measurement requires good control over the v_2 systematics. The physics implication of this may be an indication that the data does not support bent jets from a flowing medium since the peak angle would be dependent on the trigger's orientation with respect to the reaction plane. Still, other bent jet scenarios cannot be explicitly ruled out.

4. Summary and Conclusions

Two-particle correlations are still a developing field with many results but no clear, consistent picture. At high-p_T the data from both STAR and PHENIX indicate a strongly suppressed yield on the away-side. However, the required corresponding strong broadening of the away-side based on radiative energy loss models is not observed. The implications of this is under investigation.
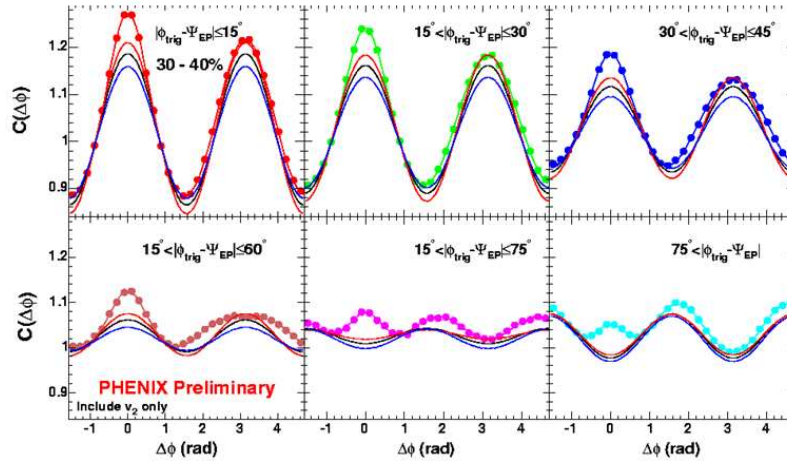
Figure 7: Reaction plane dependence of 2.5-4.0 GeV/c trigger and 1.0-2.5 GeV/c associated h-h correlations in 30-40% central Au+Au collisions. The lines indicate the v_2 correlation.
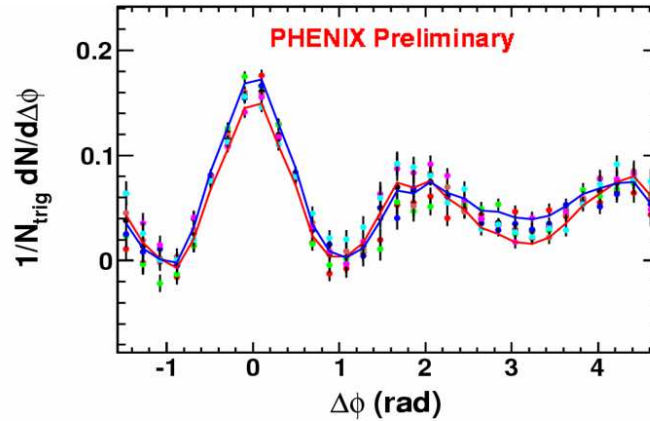
Figure 8: Compilation of the v_2-subtracted pair per trigger distribution for all reaction-plane dependent correlations.

The possibilities could be that, if the central core is true "black", the correlations are only possibly sensitive to tangential jets or to the non-interacting jets.

At lower trigger p_T, the away-side is strongly modified both in the yield and in the shape. This shape seems to be independent of the system size and collision species and with the trigger orientation with respect to the reaction plane. The lack of p_T dependence of the peak position of the away-side disfavors models of Cerenkov radiation. The independence of the peak position on the trigger orientation with respect to the reaction plane also disfavors bent jets due to a flowing medium. However, other bent jet scenarios have not be explicitly ruled out.

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