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How to make sense of the jet correlations results at RHIC?

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Abstract We review the di-hadron correlation results from RHIC. A consistent physical picture was constructed based on the correlation landscape in p_T, $\Delta\phi$, $\Delta\eta$ and particle species. We show that the data are consistent with competition between fragmentation of survived jets and response of the medium to quenched jets. At intermediate p_T where the medium response are important, a large fraction of trigger hadrons do not come from jet fragmentation. We argue that these hadrons can strongly influence the interpretation of the low p_T correlation data. We demonstrate this point through a simple geometrical jet absorption model simulation. The model shows that the correlation between medium response hadrons dominates the pair yield and mimics the double hump structure of the away-side $\Delta\phi$ distribution at low p_T. This correlation was also shown to lead to complications in interpreting the results on reaction plane dependence and three particle correlations. Finally, we briefly discuss several related experimental issues which are important for proper interpretations of the experimental data.

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1 Introduction

Single jets and back-to-back di-jet pairs are important tools for studying the properties of the dense matter created in relativistic heavy-ion collisions. Due to difficulties of full jet reconstruction at RHIC, they are accessed through leading hadron spectra and di-hadron correlation. The primary handle for spectra analysis is the hadron p_T, whereas multiple handles can be used in di-hadron correlation analysis: the momentum of trigger (p_T^A), momentum of partners (p_T^B), $\Delta\phi$ and $\Delta\eta$. The possibility of varying all these variables leads to large amount of experimental data.

A schematic illustration of the di-hadron correlation signal for unmodified jets (such as in $p + p$ collisions) is presented in left panel of Fig. 1.1. The signal appears as a narrow peak at $(\Delta\phi, \Delta\eta) \sim (0, 0)$ and a broad peak at $\Delta\phi \sim \pi$ which is flat in $\Delta\eta$ up to $|\Delta\eta| < 2$. The former corresponds to pairs from the same jet, while the latter corresponds to pairs from the away-side jet. The elongation of the away-side pairs in $\Delta\eta$ is due to longitudinal momentum imbalance between the two original partons that undergo hard-scatter process.

In Au + Au collisions, jets are modified by the dense medium. In addition to the jet fragmentation component coming mainly from those jets that do not interact with the medium (due to surface emission or punch-through) [1, 2], extensive experimental studies [3–6] have revealed additional medium response components as illustrated in the right panel of Fig. 1.1. These medium response components appear as three distributions that peaks at different $\Delta\phi$ locations: $\Delta\phi \sim 0, \pi \pm 1.1$, but are flat in $\Delta\eta$. The current focus of the field is to understand the interplay of the contributions from jet fragmentation and medium response.

Beyond this qualitative picture of the jet-medium interaction, the progress so far is limited in our understanding of the fundamental mechanisms in terms of the plasma properties. We do not yet fully understand the jet quenching, let alone the medium response mechanism. In a sense there are too much experimental information: new measurements are continuously being made, but the progress of integrating them into fundamental theoretical framework has been slow.

The reason for current impasse is two fold. Experimentally, there are assumptions made in the extraction of jet signal, such as the two-source model and ZYAM assumptions in background subtraction [3, 4]. There are also questions on how to deal with non-flow effects and event-by-event fluctuation in background subtraction. On the theory side, the medium response is intrinsically non-perturbative and difficult to model. Most calculations assume that there is a scale that separates jet energy loss and medium response [7, 8].
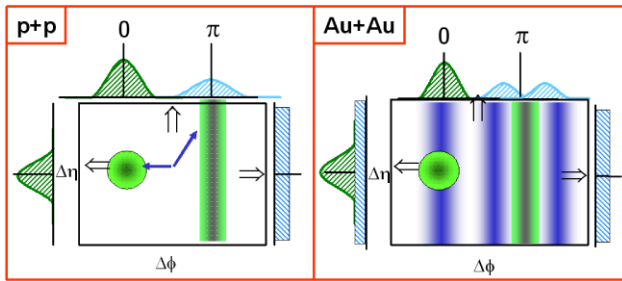
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Fig. 1.1 A schematic illustration of the jet-induced di-hadron correlation signal in $\Delta\phi$ and $\Delta\eta$ and associated projections in $\Delta\phi$ or $\Delta\eta$ for (*left*) $p + p$ and (*right*) central Au + Au collisions. The medium response components in Au + Au is illustrated by fuzzy *blue band*

The modeling of energy transport to medium response is done in an ad hoc fashion, which necessary introduce a scale dependence. The ADS/CFT based approaches can describe both jet energy loss and Mach-cone like medium response in a single framework [9–11]. However it is not clear that these results can be extrapolated to QCD. The next improvement is to combine the calculation of jet quenching and medium response with the 3-D hydrodynamics framework [12].

How can we as experimentalist help with current situation? Given the vast amount of data and the experimental difficulties mentioned earlier, we feel it is imperative to re-exam all the data and construct a global and self-consistent physical picture. A convincing picture should be able to connect results for high and low p_T, near- and away-side, and encompass different particle species and collision energies.

In the process of understanding underlying mechanisms for modification of jet correlation, we should not separate them from the mechanisms that are important for single particle spectra and flow measurements, such as hydrodynamic expansion and recombination. In fact, these bulk mechanisms should play a very important role in shaping the jet correlation pattern. The physical picture implied by correlation and bulk measurements should be consistent with each other. The second task of this manuscript is to exam the origin of triggers and the sources of correlated hadron pairs, such that we understand how the bulk production mechanism and medium response influence the interpretation of the correlation data.

In the end of the manuscript, we also discuss several experimental issues which are important for proper interpretations of the low p_T correlation data.

2 Correlation landscape

The primary goal of the correlation analysis is to understand the interactions between jet and medium, i.e. jet quenching and the medium response. We now know that the jet quenching is responsible for the large suppression of the jet pairs at

high p_T. The medium response is responsible for the enhancement of hadron pairs at low p_T. However most measurements typically focus on a particular momentum range or particular $\Delta\phi$ range. The methods and systematical errors associated with these measurements are not always the same, which makes the comparison of these results quite difficult. In a recent paper [6], PHENIX collaboration publish a detailed survey of the di-hadron correlation in broad ranges of trigger and partner p_T, which allows a systematic comparison of large amount data in a single analysis. Figure 2.1 shows the summary of the correlation landscape in p_T^A, p_T^B and $\Delta\phi$. Many features can be identified at both the near- and away-side. They reflect in detail how the jet quenching and medium response vary with momentum and $\Delta\phi$.

A systematic approach to summarize these features can be done by dividing the $\Delta\phi$ distributions into three regions, an away-side head region ($|\Delta\phi - \pi| < \pi/6$), an away-side shoulder region ($\pi/6 < |\Delta\phi - \pi| < \pi/3$), and a near-side region ($\Delta\phi < \pi/3$), and then project them in the $\Delta\eta$ direction. The division of the away-side into the head and the shoulder regions facilitates the separation of the jet fragmentation contribution and medium response (the cone) at the away-side. The projection of near-side pairs in $\Delta\eta$ help us to separate the jet fragmentation contribution and medium response (the ridge) at the near-side. The $\Delta\eta$ projections for near-side pairs are shown in Fig. 2.2 for several representative $p_T^A \otimes p_T^B$ bins.

The information in Figs. 2.1 and 2.2 can be captured by a set of shape and yield variables. Jet shape variables include the ratio of head yield to shoulder yield R_{HS}, Mach cone location D or near-side width [2]. Jet yield variables include per-trigger yield (PTY) and I_{AA} in the three $\Delta\phi$ ranges. A careful analysis of these variables as functions of p_T^A and p_T^B shows that all the features in Figs. 2.1 and 2.2 can be explained by the combined p_T dependence of the jet fragmentation and medium response components at both the near- and away-side. The jet fragmentation contribution dominates at high p_T and the medium response dominates at low p_T. The transitional region where the two sources roughly equal to each other can be approximated by $p_T^A + p_T^B \sim 6$–8 GeV/c.

At the high p_T region where the jet fragmentation dominates, we normally use the I_{AA} to quantify the away-side suppression. It was observed that high p_T I_{AA} is similar to single particle suppression, R_{AA} [1, 6]. This observation is surprising at first sight, given that the away-side jets suffer on average more energy loss than that for inclusive jets. However, we should realize that the suppression level depends not only on the energy loss, but also on the jet spectral shape. As argued in [13], the away-side hadron spectra associated with a high p_T trigger is much flatter than that of the inclusive hadrons. A flatter spectrum needs more energy loss to achieve a given level of suppression. Even though
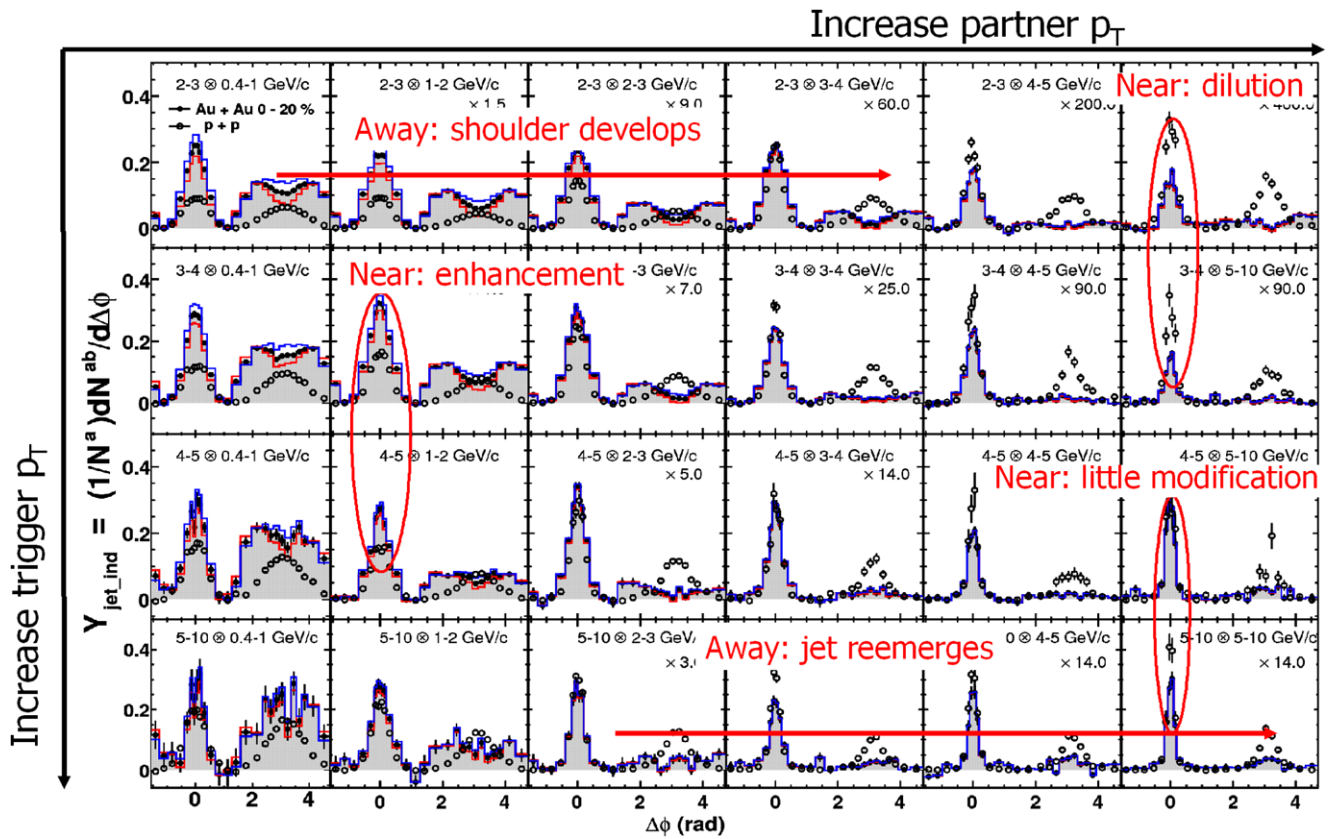
Fig. 2.1 The $\Delta\phi$ distribution in fine bin of trigger and partner p_T in $p + p$ (*open symbols*) 0–20% central Au + Au (*solid symbols*) collisions, and *thin lines* indicate the systematic uncertainties. Several important features are indicated by the *thick red lines* and *red circles*

Fig. 2.2 Per-trigger yield versus $\Delta\eta$ for $p + p$ (*open symbols*) and 0–20% central Au + Au (*filled symbols*) collisions. Results are shown for four $p_T^A \otimes p_T^B$ selections as indicated
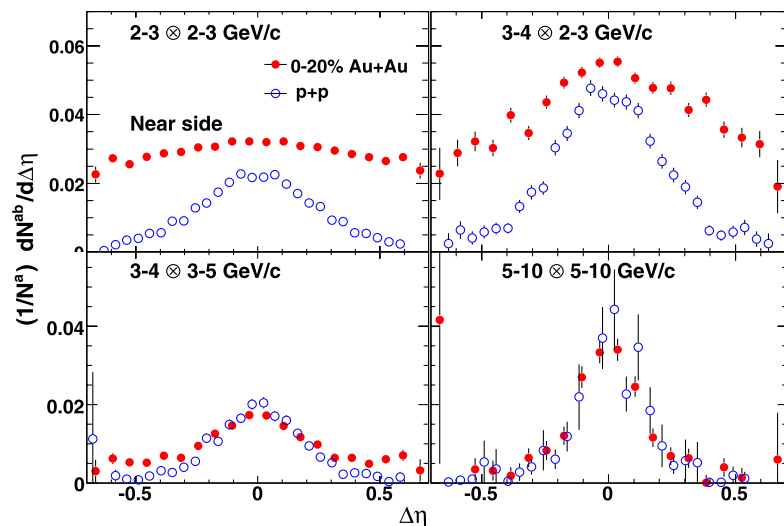

$I_{AA} \sim R_{AA}$, the away-side jets actually suffer on average 50% more energy loss than that for inclusive jets.

At the low p_T region, medium response contributions, i.e. *the cone* on the away-side and *the ridge* on the near-side, play an important role in shaping the $\Delta\phi$ and $\Delta\eta$ distribution. A careful comparison between the ridge and the cone,

after suppressing the jet fragmentation contribution, indicates that their properties are very similar. Both have similar spectral slopes, which are harder than inclusive hadrons but are softer than fragmentation hadrons [14]. Both have similar particle composition in terms of baryon to meson ratios [15, 16]: the ratios are bigger than that expected for

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Fig. 3.1 (*Left*) Inclusive charged hadron spectra from $p + p$ collisions compared with pQCD calculation down to 1.5 GeV/c [18]. (*Right*) Low p_T di-hadron correlation signal for charged hadrons in $p + p$. Both are for $\sqrt{s} = 200$ GeV
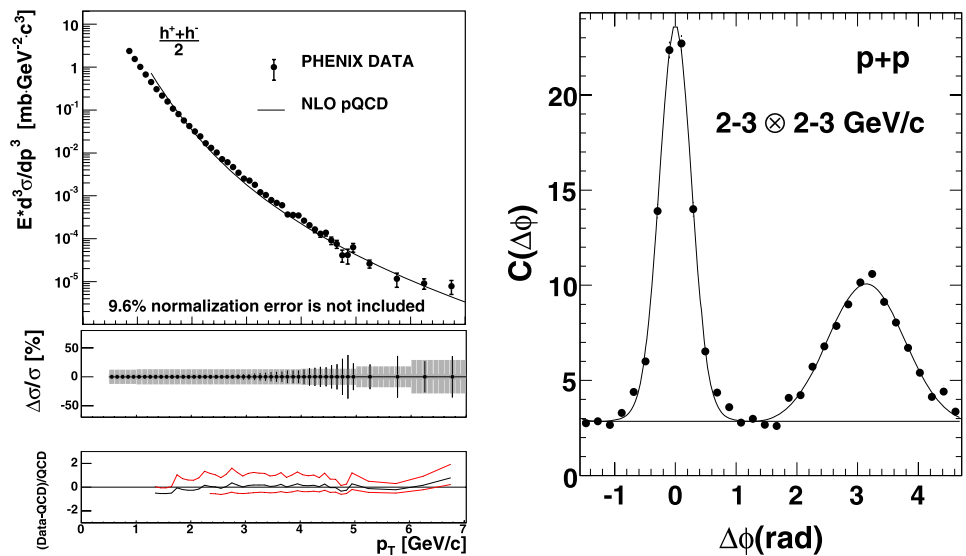
fragmentation and are close to that for the inclusive spectra (with large uncertainty). These similarities suggest that mechanisms for the ridge and the cone could be related. They also suggests that the bulk physics, hydrodynamical flow and parton recombination, should play an important role in this p_T region.

Most previous low p_T correlation analyses choose to use I_{AA}, the ratio of per-trigger yield in Au + Au collisions to that in $p + p$ collision, to characterize the medium response. The rationale being that since each trigger tags one jet, the per-trigger yield is a good approximation to the per-jet yield (similar to high p_T correlation analysis), thus I_{AA} measures the modification of a jet in Au + Au relative to that in $p + p$. As we shall show in the next section this assumption is not true at $p_T < 5$ GeV/c, and an alternative observable is needed for describing the medium response.

3 Origin of triggers: jet fragmentation? Bulk? Or medium response?

In $p + p$ collisions at RHIC energies, data from the single particle spectra and di-hadron correlation suggest that most hadrons above 2 GeV/c originate from jet fragmentation. This is attested by the fact the particle spectra are well described by the pQCD calculation [17, 18] and the correlation function show strong jet-like signals down to very low p_T [6, 19] as shown by Fig. 3.1.

The situation is very different in heavy ion collisions. At $p_T < 5$ GeV/c where medium response is important, the inclusive hadron yield is dominated by non-perturbative bulk production mechanisms such as hydrodynamic flow and recombination. The experimental evidences include: a particle composition that is strongly modified relative to

that in $p + p$ collisions [20], a R_{AA} that peaks around $p_T \sim 3$ GeV/c at a level much bigger than what is suggested by jet quenching [21], and a hadron elliptic flow that reaches maximum in this momentum region at a level much bigger than what one expect from the jet quenching [22]. These results imply that the origins of the hadrons at $p_T < 5$ GeV/c in Au + Au collisions are very different from those in $p + p$. Thus per-trigger yield and I_{AA} are not good observables for the medium response since the triggers are also modified. According to hydro + coalescence model, a large fraction of the triggers at $p_T < 5$ GeV/c may come from thermal-thermal or thermal-shower recombination. The former has no jet correlation, while the latter can retain some jet correlation which can be modified by the flow [23].

If most hadrons do not originated from jet fragmentation, and have either no correlation or reduced correlation strength, they should lead to a dilution of per-trigger yield in Au + Au collisions relative to $p + p$. In fact PHENIX data indicate the effect of the dilution on the per-trigger yield [24]. It is best illustrated with the near-side $\Delta\eta$ correlation as shown in Fig. 3.2.[1] We estimate dilution factor (~ 2) for 3–4 GeV/c triggers based on their correlations with 5–10 GeV/c hadrons as shown by the inserted panel: requiring 5–10 GeV/c hadrons ensures the pairs are dominated by the jet fragmentation (left panel of the insert), thus deviation of I_{AA} from one for soft triggers reflects the level of dilution (the red arrow). Once the dilution factor is corrected, we subtract out the jet fragmentation contribution and obtain the ridge distribution (black filled circles). The estimated ridge contribution is approximately flat, consistent with experimental data at large $\Delta\eta$ [5]. However, this dilution effect was not observed in some STAR analyses [5, 25],

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[1]The data are from Fig. 2.2.

Fig. 3.2 Per-trigger yield $\Delta\eta$ distribution for 3–4 GeV/c triggers and two parter p_T selections. The ridge distribution (*solid circles*) is estimated by subtracting the Au + Au distribution corrected by dilution effect (*open squares*) minus the $p + p$ (*open circles*). The dilution correction ($\times 2$) is indicated by the *red arrow* in the *insert* (see text for explanation)
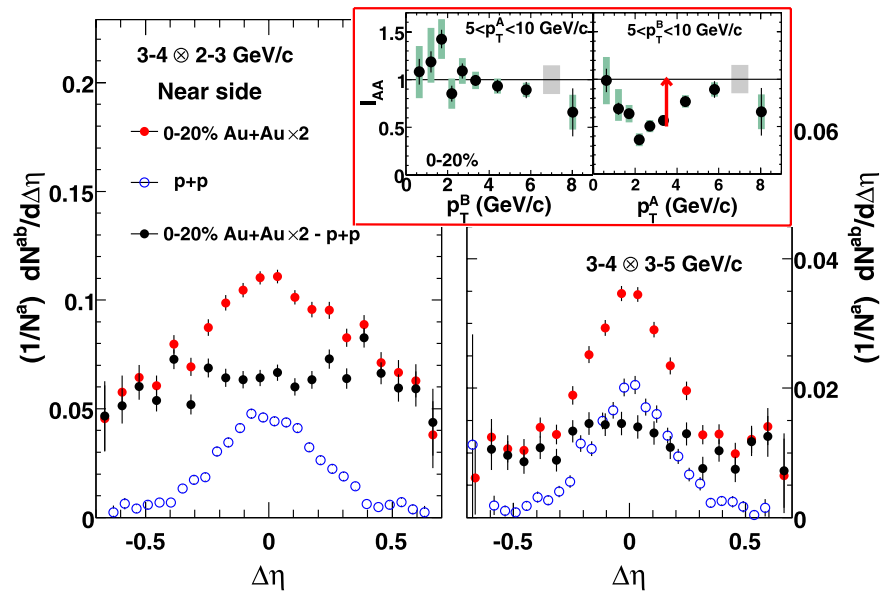
which showed that the PTY_{AA} subtracted by the estimated ridge equals PTY_{pp} before any correction for dilution effect.

Many previous analyses assume that most triggers originated from jet fragmentation. This naturally leads to different interpretations for the medium responses between the near- and away-side. The near-side pairs were thought to be surface biased and should have smaller modifications, while the away-side pairs traverse on average a longer path, thus should be strongly modified. However, this interpretation is not correct if most triggers come from the bulk or medium response. In this case, the triggers are not surfaced biased but are emitted from the whole volume of the overlap region. We shall elaborate on this point in the next section.

The interpretation of the PTY as a function of angle with respect to the reaction plane, $\phi - \Phi_{RP}$, should also be modified if non-jet triggers dominate. This is because the variation of trigger yield with $\phi - \Phi_{RP}$ (characterized by v_2) is much larger than what is expected from fragmentation of survived jets. Thus the dilution of PTY could also depend on $\phi - \Phi_{RP}$.

A physical observable better than PTY for describing the medium response is the hadron pair yield JPY, the total number of correlated pairs per-event, introduced in [6]. The modification of pair yield in Au + Au collision can be characterized by J_{AA}:

$$J_{AA}(p_T^a, p_T^b, \Delta\phi)$$
$$= \frac{JPY^{A+A}}{\langle N_{coll}\rangle JPY^{p+p}}$$
$$= \frac{1}{\sigma_{A+A}}\frac{d^3\sigma_{jet\_ind}^{A+A}}{dp_T^a dp_T^b d\Delta\phi} \bigg/ \frac{\langle N_{coll}\rangle}{\sigma_{p+p}}\frac{d^3\sigma_{jet\_ind}^{p+p}}{dp_T^a dp_T^b d\Delta\phi} \quad (3.1)$$
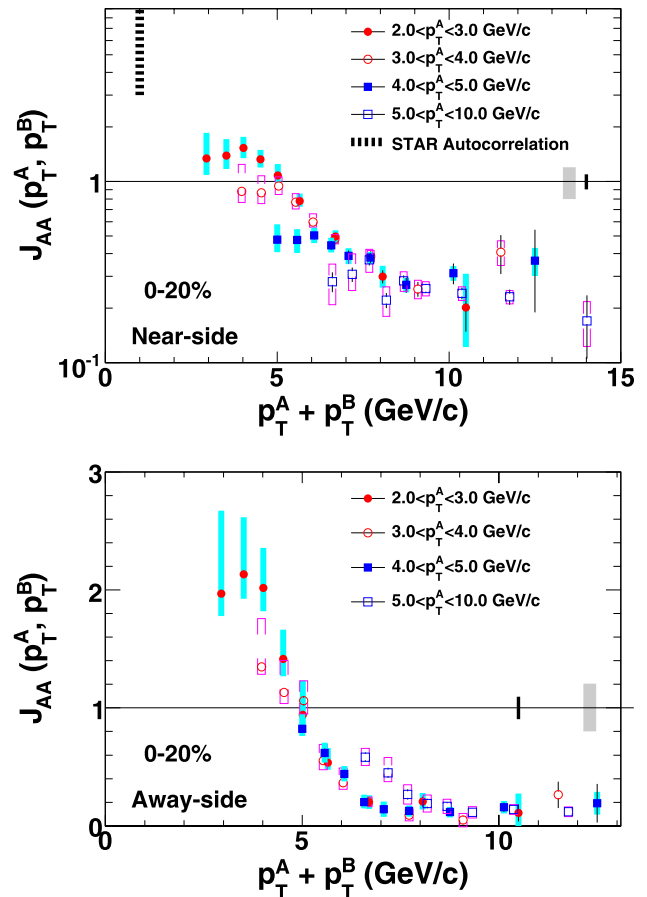

Fig. 3.3 The modification factor for hadron pair yield as function of $p_T^{sum} = p_T^A + p_T^B$ for the near-side (*top*) and away-side (*bottom*). p_T^{sum} condenses the 2-D correlation data in p_T^A and p_T^B space into a one dimensional plot. The STAR auto-correlation result [26] is divided by 3 (the lower end) to normalize the η acceptance relative to PHENIX

J_{AA} quantify the medium modification of hadron pair yield from the expected yield, in a way similar to R_{AA} for describing the modification of single hadron yield. The hadron pair yield is proportional to the di-jet yield, and in the absence of nuclear effects, it should scale with N_{coll}, and $J_{AA} = 1$. Figure 3.3 shows J_{AA} as a function of pair proxy energy ($p_T^{sum} = p_T^A + p_T^B$) for the near- (top panel) and away-side (bottom panel). In contrast to a constant suppression at large p_T^{sum}, the pair yields are less suppressed at $p_T^{sum} < 6$–8 GeV/c. This reflects directly the energy transport that redistributes energy of the quenched jets to low p_T hadrons (i.e. medium response). We would like to point out that p_T^{sum} is a natural variable for the near-side correlation since it approximates the original jet energy. In fact the data show an approximate scaling in p_T^{sum}. Even the away-side data tend to group together, because the medium response increases with away-side jet energy which in turn increases with both p_T^A and p_T^B.

4 Consequence of triggering on medium response

As argued above, the soft triggers (at $p_T < 5$ GeV/c) have three possible origins: jet fragmentation, hadrons that have no correlation which leads to dilution of per-trigger yield, or triggers come directly from medium response (e.g. the cone and the ridge). In many theoretical models, the energy loss processes lead to heating of the partons in the local medium. This local heating effectively boosts bulk partons to higher energy, which then hadronize into particles that are correlated with the quenched jets. Since this type of mechanisms does not require new particle production, they are more effective in generating large yield of correlated pairs than those involving gluon radiation. However, this contribution has a steeper slope in p_T than the jet fragmentation contribution. Thus it is important at $p_T < 5$ GeV/c, but become less important at higher p_T. In a simple jet absorption picture, the yield of fragmentation hadrons from survived jets scales with $R_{AA,o}$ (the constant suppression factor at high p_T). The yield of medium response hadrons should scale with the number of quenched jets, i.e. $1 - R_{AA,o}$.

In general, hadrons in correlated pairs can be chosen from either survived jets or quenched jets. Therefore, jet-induced pairs can be divided into three groups. **Jet-jet pair**: both hadrons come from fragmentation of survived jets. **Jet-medium pair**: one hadron comes from fragmentation of survived jet, the second hadron comes from medium feedback of quenched jet. **Medium-medium pair**: both hadrons come from medium feedback of quenched jets. The rates of their contributions to inter-jet pairs scale approximately as $R_{AA,o}^2$, $R_{AA,o}(1 - R_{AA,o})$ and $(1 - R_{AA,o})^2$. Clearly, in this simple picture, the stronger the suppression is, the larger the contribution from medium-medium pairs is. In

the limit $R_{AA,o} \to 0$, the medium-medium contribution naturally dominates.

We performed a simple simulation based on jet absorption picture [27] to investigate contributions from the three sources, focusing on the medium-medium pairs which were not considered in many previous models. The details of the simulation can be found in [28]. The idea is to generate di-jets according to collision density distribution in the overlap plane ($\rho_{ncoll}(x, y)$), and attenuate them as they traverse a medium whose density is proportional to the participant nucleon density ($\rho_{npart}(x, y)$) [27]. Both ρ_{ncoll} and ρ_{part} were generated via a Monte-Carlo Glauber model code. If a jet survives the medium, it is converted into N_{jet} hadron via fragmentation, otherwise it is converted into N_{med} medium response hadrons. N_{jet} and N_{med} are assumed to have a Poisson distribution with a mean of 1 and 2 respectively. The former corresponds to multiplicity of hadron in 1–4 GeV/c from a 6 GeV/c jet. The latter is chosen to take into account the observed enhancement in 1–4 GeV/c seen in the data. Figure 4.1 compares the yields for jet-jet, jet-medium and medium-medium pairs as a function of centrality. The medium-medium contribution increases with N_{part} and dominates the yield in central collisions.

To describe the $\Delta\phi$ distribution, we adjust the jet fragmentation kinematics to match the $p + p$ correlation data [19]. We also assume that only 30% of the inter-jet pairs are detected, so as to account for finite detector acceptance and the swing of the away-side jet in pseudo-rapidity. The medium response hadrons are assumed to be emitted equally at $\pi \pm D$ ($D = 1.1$). This step makes sure that the shape of jet-jet and jet-medium pairs, those included in traditional models, matches the measured away-side distribution, so we can study the impact of medium-medium pairs to the $\Delta\phi$ distribution.

The emission directions for hadrons contributing to medium-medium pairs are illustrated by left panel of Fig. 4.2. In this picture, both jets are quenched and converted into
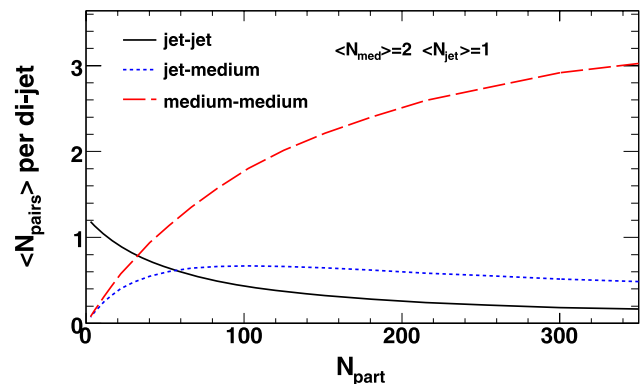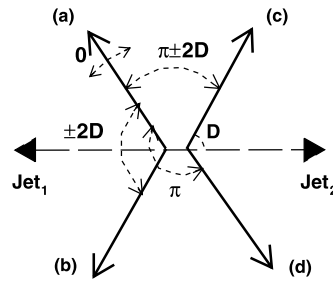

Fig. 4.1 The centrality dependence of pair yield normalized by number of dijets from jet-jet, jet-medium and medium-medium sources

Fig. 4.2 $\Delta\phi$ distributions in 0–5% central Au + Au collisions for medium-medium pairs. The diagram at the *left* illustrates the typical emission directions (*solid arrows*) and $\Delta\phi$ values (numbers)

hadrons at angle $\pm D$ radians relative to the original jet direction. The pairs constructed from these hadrons, when plotted in $\Delta\phi$, should concentrate at $\Delta\phi \sim 0, \pi, \pm 2D$ and $\pi \pm 2D$. The intra-jet pairs split up into three branches at $\Delta\phi \sim 0, 2D$ and $-2D$, while the inter-jet pairs have a sizeable peak at $\Delta\phi \sim \pi$ and two small satellite peaks around $\Delta\phi \sim \pi \pm 2D$. Since the value of $D = 1.1$ implies $2D \approx \pi - D$, the pairs from the same jets (at $\pm 2D$) coincide with the location of jet-medium pairs (at $\pi \pm D$). Thus in our simulation, the medium-medium contribution alone already accounts for the double-humped structure on the away-side. Note that most of the pairs originate from the same jets. If there are some mechanisms which broaden the hadrons from the same jet in pseudo-rapidity, then both the near-side peak and away-side shoulders should be elongated in $\Delta\eta$. Thus our model provides a natural explanation for the similarities between the ridge and the cone.

Due to the path length difference of their parent partons, jet absorption also leads to a positive anisotropy for the survived jets, characterized by a positive v_2, $v_{2,sur}$. Since the originally generated jets are isotropic, the v_2 of the quenched jets should have an opposite sign relative to survived jets: $v_{2,quen} = -v_{2,sur}$. However, the medium response hadrons are emitted at a large angle ($D = 1.1$ radian) relative to the original jet direction, which significantly dilutes the observed v_2 values for the medium response hadrons as shown by Fig. 4.3. So if we indeed are triggering on the medium response hadrons, the pair v_2 should be smaller than that for inclusive hadrons.

We note that the anisotropy studied in this model originates purely from jet-quenching, other mechanisms could introduce new sources of v_2 for hadron pairs, which can change the values presented in Fig. 4.3. A measurement of the reaction plane dependence of the hadron pair yield (instead of the per-trigger yield), and the corresponding v_2 pa-
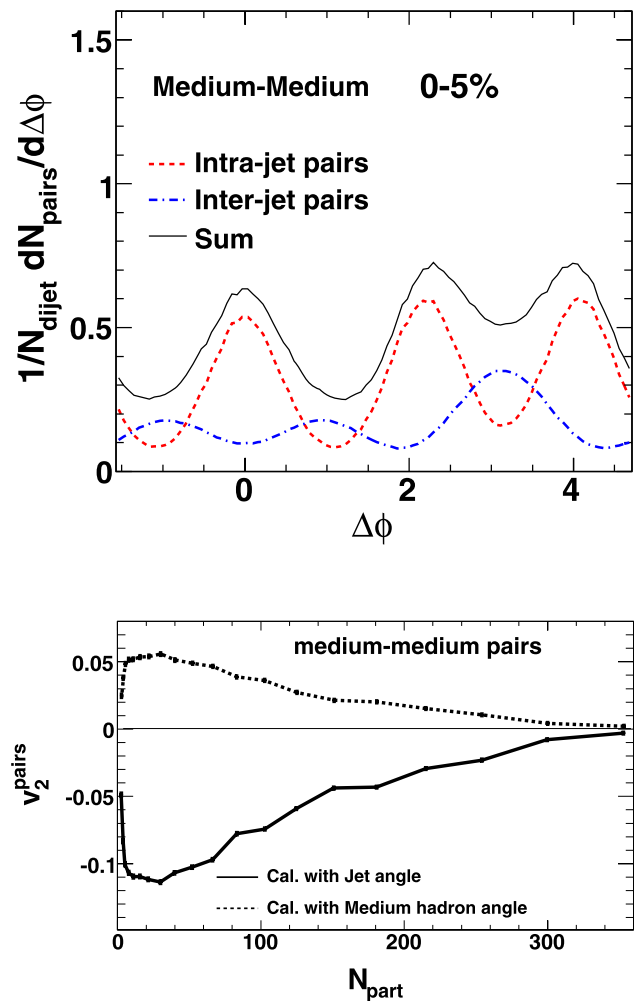

Fig. 4.3 The v_2 for and medium-medium pairs calculated as $\langle \cos 2(\phi - \Psi_{RP}) \rangle$, where ϕ is the azimuthal angle of jets (*solid lines*) or medium response hadrons (*dotted lines*)

rameter, should be useful in helping us to constrain the underlying mechanisms of the medium response.

We also studied the consequence of triggering on medium response for three particle correlation. There are three types of triplets: jet-jet-jet (j-j-j) triplets, jet-medium-medium (j-m-m), jet-jet-medium (j-j-m) triplets and medium-medium-medium (m-m-m) triplets. The standard coordinate system [29, 30] is adopted, i.e, we plot the azimuth angle difference between particle 1 and 2 ($\Delta\phi_{12}$) vs azimuth angle difference between particle 1 and 3 ($\Delta\phi_{13}$) as shown in Fig. 4.4. The j-j-m and j-m-m contributions lead to the conventional off-diagonal terms which were used to identify the Mach-cone pattern in the data [30, 31]. The dominating contribution comes from m-m-m term, which has a more complicated shape due to the large deflection angle *w.r.t* the original jet direction. The m-m-m term appears as several broad peaks in the $\Delta\phi_{1,2}$ and $\Delta\phi_{1,3}$ plane. It's away-side peak is so spread out that it shadows the mod-

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Fig. 4.4 Azimuthal distributions for triplets from various sources in 0–5% Au + Au collisions
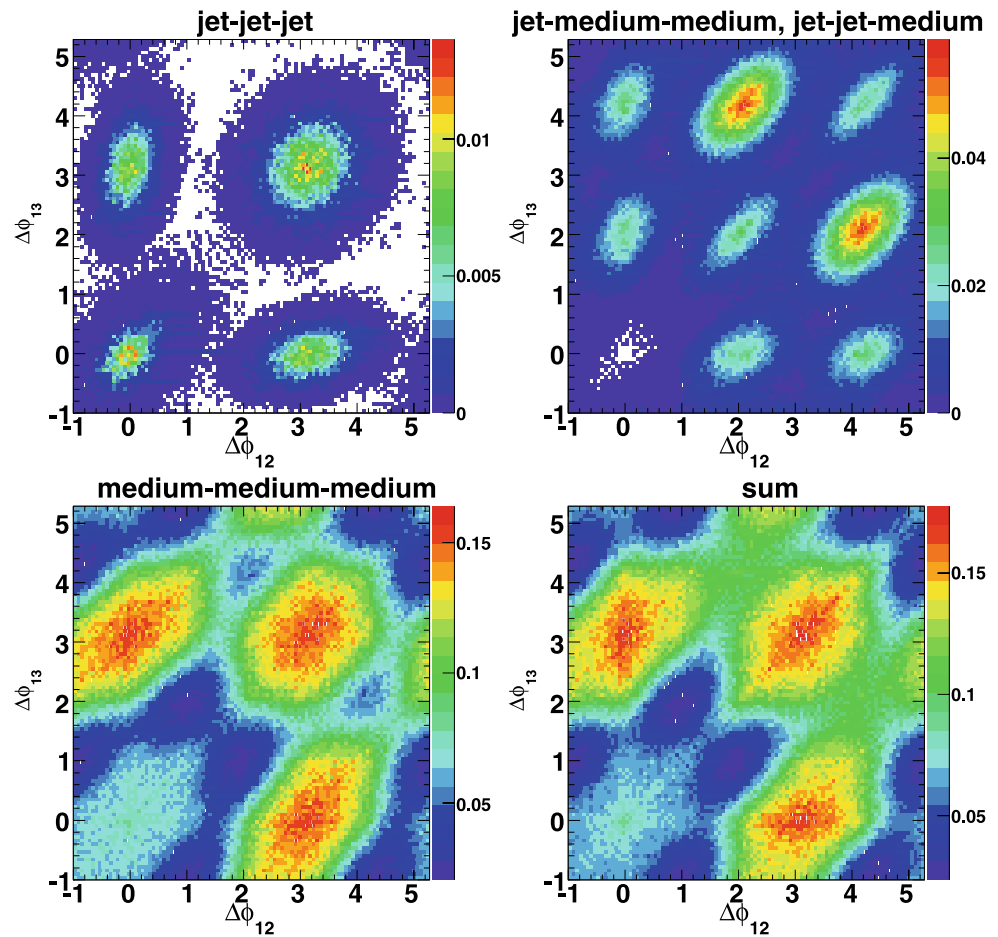
est off-diagonal contribution from j-m-m and j-j-m terms. Clearly, the shape of the three-particle correlation signal depends strongly on whether we trigger on jet fragmentation (j-m-m, j-j-m) or medium response (m-m-m), even though the correlation shape from medium-medium and jet-medium can be similar. Our study shows that the interpretation of the three particle correlation results are complicated if the triggers come from the medium response.

5 Additional thoughts

Most di-hadron correlation analyses rely on the following two-source model formula to obtain the jet signal by subtracting the background term [4, 6]:

$$C(\Delta\phi) = J(\Delta\phi) + \xi(1 + 2v_2^A v_2^B \cos 2\Delta\phi) \qquad (5.1)$$

where ξ is the background level, which is a number close to one in central collisions. This approach implicitly assumes that either there is no jet-flow cross-term, or the cross-term is included in the definition of the jet function $J(\Delta\phi)$. Currently, the main debate over (5.1) centers on what v_2

values to use for triggers (v_2^A) and partners (v_2^B). This debate is caused by a proliferation of different flow measurements, designed to remove non-flow bias and/or event-by-event fluctuation effects. In our opinion, these additional sources contribute to $C(\Delta\phi)$, but they should not be included in the jet function $J(\Delta\phi)$. Instead, they should be included in the flow background, i.e. the v_2^A, v_2^B used in the background subtraction should include various non-flow effects (other than jet) and event by event fluctuations. If we do not include them in the flow background, then we would need to subtract their contributions later from the jet yield.[2]

The v_2 values used in the background subtraction are different between STAR and PHENIX. PHENIX collaboration uses reaction plane v_2 based on forward detectors. STAR collaboration use the average of reaction plane v_2 and four particle culminant v_2 [3]. The latter is about 20% smaller than the former, and the difference between the two is quote as the systematic error. As a result, the v_2 used by STAR is about 10% smaller than that for PHENIX, but their dif-

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[2]The only caveat is that the non-flow and event by event contributions are assumed to have $\cos 2\Delta\phi$ shape. Based on how the $C(\Delta\phi)$ varies with angle *w.r.t* reaction plane [32], it is a fairly good assumption.

Fig. 5.1 Correlation for 4–6 ⊗ 0.15–4 GeV/c from STAR collaboration in d + Au and 0–5% Au + Au collisions [33]: (**a**) the per-trigger yield distribution in Δφ, (**b**) the mean p_T of partners as function of Δφ
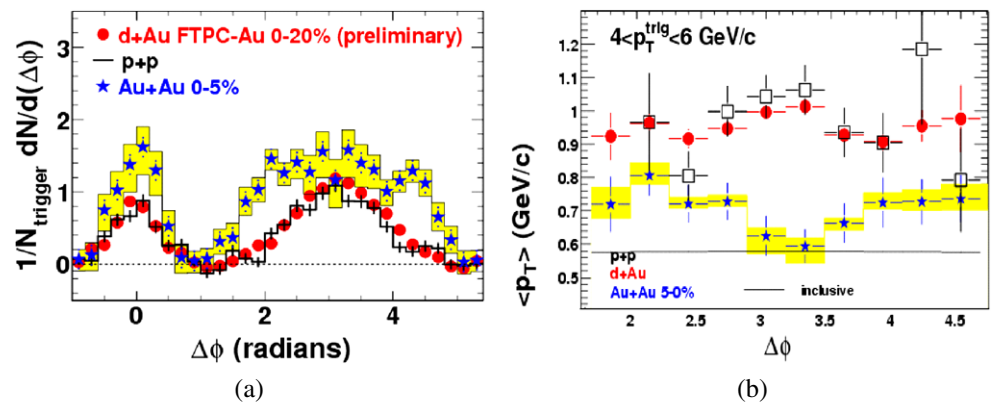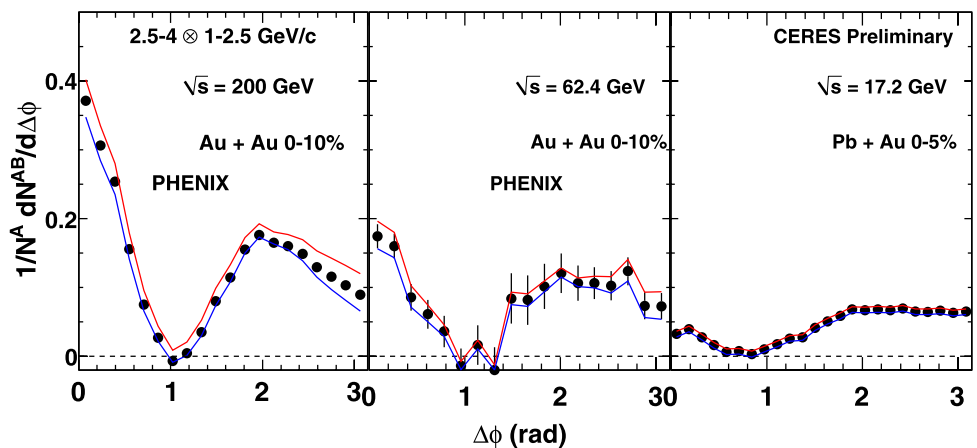

(a)   (b)

Fig. 5.2 The Δφ distribution in central collisions for three collision energies in central collisions

ferences is covered by the large v_2 error quoted by STAR. But because of this difference, STAR collaboration does not see a very pronounced dip in the $dN/\Delta\phi$ distribution as in PHENIX (Fig. 5.1a). However, they show that if one chose a different quantity, such as the mean p_T which characterizes the energy flow, one observes a clear dip at $\Delta\phi \sim \pi$ (Fig. 5.1b). This shows that away-side shape also depends on the physical observable. Existence of a dip in multiplicity distribution is not a sufficient condition for Mach cone, because it could be filled up by the punch-through jet, or the jet wake.

Important insights on the origin of the cone and the ridge have been provided by a energy scan from SPS to RHIC. A strong modification of the away-side correlation was observed at the top SPS energy ($\sqrt{s_{NN}} = 17.2$ GeV) [34]. There, the strong away-side broadening has been used to argue for a similar interpretation (such as Mach cone) as for results at RHIC. However a quantitative analysis of the energy dependence of the modification patterns (see Fig. 5.2) shows that the yield of medium response are quite different between RHIC and SPS energies. The near-side yield drop by almost factor of 8 going from 200 to 17 GeV, the away-side shoulder yield drops by a factor of 2 in the same energy range, while little dependence of the yield on

$\sqrt{s}$ is observed for the away-side head region, where the jet fragmentation is expected to be important. This suggests a much weaker medium response at SPS energy (the ridge almost disappeared and cone strongly suppressed) than that at RHIC, which probably implies different mechanisms are in play at SPS energy, such as a stronger Cronin effect combined with a weaker energy loss at lower energy [35].

6 Conclusion

First several years of RHIC data on jet-induced particle correlations have revealed a fascinating and rich set of insights on the mechanisms for jet medium interactions. The p_T, PID and centrality dependence of the correlation patterns are observed to be consistent with competition between jet fragmentation and medium response. Fragmentation of survived jets dominates the correlation signal at high p_T, while the medium response to quenched jets dominates the correlation signal at low p_T. It is also observed that the medium response at the near-side (the ridge) and the away-side (the cone) share similar properties.

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Understanding the medium response requires knowledge of the origins of the hadrons in the pairs at $p_T < 5$ GeV/c. Both the spectra and correlation results suggest we may be triggering on medium response at intermediate p_T. A simple jet absorption model is employed to investigate the roles of pairs from medium response (medium-medium pair) on the pair shape and pair yield. The correlations among medium response particles were shown to dominate the pair yield at intermediate p_T, while preserving the di-hadron correlation patterns in $\Delta\phi$. These medium-medium pairs are expected to have significantly reduced anisotropy due to the smearing caused by the large emission angle *w.r.t* the original jet direction. The model suggests a common mechanistic origin for the ridge and the cone, and provides a natural explanation for their similarities.

We also touched on the flow background subtraction in the two-source model framework. We argue that the non-flow effects and event by event fluctuation effects should not be taken out of the v_2 used in the subtraction. We also show that the shape of the away-side $\Delta\phi$ distribution shows a more significant dip in mean p_T than in multiplicity. Finally the energy scan data suggests that the medium response mechanisms might be different at SPS from those at RHIC energies.

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