Studying the Jet Medium Interaction by Two Particle $\Delta \eta - \Delta \phi$ Correlations

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Abstract. We present two dimensional $\Delta \eta - \Delta \phi$ inclusive photon-charged hadron correlations measured by the PHENIX experiment. Jet-like correlations are modified in central Au+Au compared to p+p, in both the trigger jet and opposing jet. The trigger jet is elongated in pseudo-rapidity (the “ridge”), while the opposing jet shows a double peak structure (“head” and “shoulder”). We decompose the structures by fitting the $\Delta \eta$ and $\Delta \phi$ correlations to disentangle contributions from the medium and the punch-through and trigger jets. The ridge exists for associated particle $p_T$ below 3 GeV/c; it is broad in rapidity and narrow in $\Delta \phi$. The away side correlated particle yield is enhanced in central collisions. The yield of the ridge closely resembles the shoulder in the centrality dependence of particle yield and spectra.

The hot dense QCD medium created in high energy heavy ion collisions at RHIC has been shown to suppress the production high $p_T$ hadrons which is indicative of parton energy loss in the medium [1, 2]. This phenomenon is known as “jet quenching”. The single particle nuclear modification factors provide quantitative constraints to the properties of the medium, such as the initial color-charge density, $dN^g/dy$, or the medium transport coefficient $\langle \hat q \rangle$ to $\pm 20 - 25\%$ level [3]. Two particle correlations are a powerful tool to study the jet-medium interactions and provide further information on the jet-energy loss mechanisms and the medium response to the jets. Correlations in azimuthal angle, $\Delta \phi$, and in pseudorapidity, $\Delta \eta$, are constructed with a trigger particle” from a specified $p_T$ range and all other particles in the event which fall in a given $p_T$ range (“associated particle”). When triggering on high $p_T$ particles, the away-side shape ($\Delta \phi \approx \pi$) depends on the $p_T$ of the associated particles. For high $p_T$ associated particles, the away-side shows a jet-like structure, that is suppressed compared to p+p collisions in which no hot medium in present [4] [5]. As the associated partner $p_T$ is lowered, instead of a jet-like structure peaked at $\Delta \phi = \pi$, a double peak structure is observed [6]. The shift of the away-side peak to $\Delta \phi \approx \pi \pm 1$ is independent from colliding species and energies, when number of participants, $N_{part}$, is larger than 100 [7].

The medium not only modifies the away-side but also modifies the near-side ($\Delta \phi \approx 0$). When measuring $\Delta \eta - \Delta \phi$ correlations, a significant enhancement along the $\Delta \eta$ direction has been observed on the near-side in central collisions and is known as “the ridge”. This feature has a strong associated $p_T$ dependence, which is most notable at low associated $p_T$ [8].

To investigate the medium response due to the jet-medium interaction, we are focusing on the low partner $p_T$ correlations. We measured the two particle $\Delta \eta - \Delta \phi$ correlation functions of Au+Au and p+p collisions at $\sqrt{s_{NN}} = 200$GeV in PHENIX at RHIC in Run 4 and Run 5. The trigger particles are inclusive photons with $p_T = 2 - 3$ GeV/c , and the associated particles
are inclusive charged hadrons with \( p_T = 1 - 5 \text{ GeV/c} \). The inclusive photons at this \( p_T \) range are mainly from meson decays. The underlying combinatorial events are removed by assuming there is zero yield at the minimum in the \( \Delta \phi \) correlation, which is known as the ZYAM method [6].

Fig. 1 shows the \( \Delta \eta - \Delta \phi \) correlation function in p+p collisions. A di-jet structure is visible. In the near-side, the correlation function is peaked at \( \Delta \phi = 0 \). In the away-side, it is peaked at \( \Delta \phi = \pi \) and extends along the \( \Delta \eta \) direction, due to \( k_T \) smearing. In central Au+Au collisions (0-20%), as shown in Fig. 2, we can still see a peak in the near-side at \( \Delta \phi = 0 \), but there also exists a significant enhancement along \( \Delta \eta \), which forms a “ridge”. In the away-side, instead of a jet-like structure as shown in Fig. 1, a double-peak structure is observed. The two peaks are located at \( \Delta \phi \approx \pi \pm 1 \), which is consistent previous measurements [7]. This double peak structure also extends along \( \Delta \eta \) direction.

\[ \Delta \eta - \Delta \phi \text{ correlation function for p+p collisions.} \]

\[ \Delta \eta - \Delta \phi \text{ correlation function for Au+Au collisions in 0-20% centralites.} \]

The near-side conditional yields are measured and plotted as a function of number of participants, \( N_{\text{part}} \), in four different \( |\Delta \eta| \) regions, from 0 - 0.1 up to 0.5 - 0.7, as shown in Fig. 3. The near-side yields in p+p collisions decrease with increasing \( \Delta \eta \), which is consistent with a jet-like structure. For Au+Au collisions, as \( N_{\text{part}} \) increases, up to \( N_{\text{part}} \approx 300 \), the yield in all four \( \Delta \eta \) regions increases. At the most central collisions, the near-side yield does not increase and may decrease. This is consistent with previous measurements [6, 9]. In the furthest \( \Delta \eta \) region, 0.5-0.7, the conditional yield in Au+Au collisions is significantly larger than in p+p. This is a clear sign of the existence of the long range rapidity correlations (“the ridge”), since there is very little jet-like yield in this \( \Delta \eta \) region in the p+p collisions. Hence in this analysis, we will use the near-side yield at 0.5 < |\( \Delta \eta \)| < 0.7 as the yield of the ridge, without removing the possible jet contamination.

In Fig. 3, the near side yield is significantly enhanced with increasing \( N_{\text{part}} \) due to the ridge. In heavy ion collisions, the multiplicity of the underlying event also increases with the number of participants, \( N_{\text{part}} \). This poses the question if the ridge comes from the underlying combinatoric background. In the case the ridge only relates to the underlying events, the yield of the ridge should scale with the underlying events. We measured the ratio between the ridge yield and the yield of the underlying event in the near-side and plotted it as a function of number of participants and partner \( p_T \) as shown in Fig. 4. The yield of the ridge is always a few percent of the underlying events. At \( N_{\text{part}} > 200 \), the ratios show a decreasing trend. This means that the ridge does not increase as fast as the underlying combinatoric background and therefore the ridge can not be due to the background. We also observe that as the partner \( p_T \) increases, the ratio also increases. This is evidence that the ridge is harder than the underlying background.

The double-peak structure appears in the away-side in central Au+Au collisions as seen in
Figure 3. Near-side yield of different $\Delta \eta$ regions as a function of number of participants, $N_{\text{part}}$. $N_{\text{part}}$s in different $\Delta \eta$ are shifted slightly to avoid overlap.

Figure 4. Ratio between the ridge yield and the underlying combinatorial background as function of $N_{\text{part}}$ and partner $p_T$. 
Fig. 2. We assume the away-side consists of two different components. The first component is the jet-like structure, the “head”, which is described by a Gaussian distribution peaked at $\Delta \phi = \pi$. The width of the head component is fixed to the away-side width of the p+p correlation function. The second component is referred to as “shoulder”. A double Gaussian which peaks at $\Delta \phi \approx \pi \pm 1$ is used to describe this structure. We use a fitting method to separate the head and shoulder. The yield of the shoulder is the sum of the two peaks.

After decomposing the away-side, which presumably separates out the jet and medium components, we can compare the medium modification on both sides: the ridge in near-side and the shoulder in away-side. The two yields are plotted as a function of the number of participants in Fig. 5. Both ridge and shoulder increase with $N_{\text{part}}$. Within errors, both yields are consistent up to $N_{\text{part}} \approx 300$. At the most central collisions where $N_{\text{part}} \approx 350$, the two yields do not agree. Here the yield of the shoulder is roughly constant while the yield of ridge is slightly decreasing.

The spectra of the ridge and shoulder are measured and are fitted with exponential function to extract the inverse slope. Fig. 6 shows the inverse slope of ridge and shoulder as a function of $N_{\text{part}}$. The inverse slope of ridge and shoulder are consistent in all centralities, which indicates that hadrons in both structures may come from a similar production mechanism. Both the ridge and shoulder are softer than p+p collisions. This suggests that the ridge and the shoulder do not come directly from hard processes. The spectra of the shoulder is consistent with the inclusive charged hadrons which come from the medium while the ridge is slightly harder. If the ridge and shoulder both come from the medium, there should be some mechanism to excite both features, which causes the spectra to be harder than the medium.

If the away-side jet is quenched in the medium, conservation of transverse momentum requires that the momentum lost by the jet must come out somewhere. On the other hand, the existence of the ridge means that some momentum is carried out along with the jet. In order to understand
how the transverse momentum is distributed, the conditional yields in both near and away side are weighted with the transverse momentum with respect to the direction of the trigger particle. The momentum of the trigger particle is not included.

We take the ratio of the away to near side $p_T$ weighted yields as a function of $N_{\text{part}}$ in different $\Delta \eta$ regions and plot this in Fig. 7. In right hand side of Fig. 7, at $0.0 < |\Delta \eta| < 0.1$, the near-side is predominantly from jet origin. The yields in both near and away side in Au+Au collisions increase with $N_{\text{part}}$. After weighting with $p_T$ and taking the ratio between different away side components, such as head and shoulder, and the near side, we see a different trend for the head and shoulder as a function of $N_{\text{part}}$. As $N_{\text{part}}$ increases, the ratio between head and near side decreases. This is consistent with the jet quenching scenario, where more medium medium is present, the more quenched are the jets. On the other hand, the ratio of shoulder to near side increases with $N_{\text{part}}$. This is consistent with Fig. 5, where the yield of the shoulder increases with $N_{\text{part}}$.

When the ratio is taken by the total away side over the near side, where the away side is the head + shoulder, we find that the ratios in Au+Au are consistent with p+p, where the ratio is about 0.55. This means that at this $\Delta \eta$ range, this ratio scales with $N_{\text{part}}$, and the $p_T$ carried in the near and away side increase together by the same ratio with $N_{\text{part}}$. In addition, this indicates that the $p_T$ lost in the medium from the scattered parton, which forms the head component is recovered in the shoulder.

The same method is also applied to $0.5 < |\Delta \eta| < 0.7$ and is shown in right hand side of Fig. 7. At this $\Delta \eta$ region, the near-side is mostly from the ridge. The ratio of the total away-side over near-side components increases when moving from central to peripheral collisions due to fewer near-side particles in peripheral Au+Au and p+p collisions. When looking only at the ratio of shoulder to the near-side, the ratio is about 0.6 and is independent of $N_{\text{part}}$. This tells us
two things. First, the transverse momentum carried by ridge scales with the yield in shoulder, which is possibly populated by hadrons produced in a similar mechanism. Second, the ratio is less than one which means that there is more momentum carried by the ridge or the near-side than in shoulder.

![Figure 7](image)

**Figure 7.** Ratio of away-side $p_T$ over near-side $p_T$ vs $N_{part}$ at 0.0 < $|\Delta \eta|$ < 0.1 and 0.5 < $|\Delta \eta|$ < 0.7

In order to further investigate the relation between the ridge and the shoulder, more studies are needed. The conditional yields of near-side and the shoulder as a function of angle between reaction plane and the trigger particle, $\Phi_s$, have been measured recently [10]. The results show that for the near-side, the yield increases when moving from in-plane ($\Phi_s \approx 0$), where the direction of the trigger particle is closer to the reaction plane, to out-of-plane, where the trigger is more perpendicular to the reaction plane or $\Phi_s \approx \pi/2$. On the other hand, the shoulder yield does not follow the same trend and the yield is at its strongest at $\Phi_s \approx \pi/4$. Such studies may allow to distinguish the production mechanism of these two structures.

In summary, in central Au+Au collisions, strong modification in the shape of two particle $\Delta \eta$-$\Delta \phi$ correlations has been observed in comparison to the correlations measured in p+p collisions. The modification in both sides, which is the ridge in the near side and the shoulder in the away side, are compared. The ridge and shoulder are similar in conditional yields. Both have similar inverse slopes, which may indicate that both have the same origin. The inverse slope of the ridge and shoulder indicates both are not produced directly from hard scattering. The ratio of the $p_T$ carried by the near-side and away-side associated particles at $\Delta \eta \approx 0$ indicates that the $p_T$ loss in the medium comes out in the shoulder. The new high-statistics data sets taken in Run 7 and Run 10 will allow us to perform a more detailed analysis.

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