EXPLORING JET MODIFICATION VIA γ–HADRON AND π^0–HADRON CORRELATIONS IN Au+Au COLLISIONS AT PHENIX*

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PHENIX has quantified the modification of jets in heavy-ion collisions due to partonic energy loss in the quark–gluon plasma (QGP) by measuring the distribution of hadrons relative to a trigger particle, such as a high-momentum photon or π^0. These two-particle correlations have revealed that high-momentum hadrons are suppressed, while the yield of low-momentum hadrons is enhanced. This enhancement is the most pronounced at relatively large angles away from the opposing jet axis. More recent analyses have further investigated and quantified these phenomena by studying the yield modification as a function of the azimuthal angle, $\Delta\phi$. The larger data sets collected by PHENIX in 2014 and 2016 enhance the statistical precision and enable more differential measurements, which provide insight into how the jet's substructure is modified by the QGP and crucial constraints on models of partonic energy loss and medium response. The latest analyses of π^0–hadron and direct photon–hadron correlations in Au+Au collisions measured by PHENIX are presented, and how these results impact our understanding of jet modification and partonic energy loss in the QGP and the medium response to jets is discussed.

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1. Introduction

Jets are an excellent probe of the quark–gluon plasma (QGP) produced in high-energy heavy-ion collisions. Jets refer to the collimated spray of particles resulting from the fragmentation of energetic partons produced by a hard scattering in the initial stage of the collision. When the produced parton traverses the QGP, it loses energy and the resulting jet is modified.

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This phenomenon, known as jet quenching, has been observed at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Comparisons with theoretical models provide insight into how partons lose energy in the QGP and are used to extract the transport properties of the QGP.

While jet-finding algorithms can be used to reconstruct the jets, two-particle correlations are a complementary way to study jets without introducing biases related to jet-finding algorithms. Jets are selected by triggering on a high-momentum photon or hadron and subtracting correlations associated with the underlying event. The PHENIX experiment at RHIC has measurements of π^0–hadron and direct photon–hadron correlations.

2. Analysis

Photons are measured using the PHENIX electromagnetic calorimeter. To extract direct photons from the inclusive sample of photons, the contribution of decay photons must be removed. The decay photon sample is determined by measuring π^0s which are identified as a pair of photons with an invariant mass in the range of 0.12–0.16 GeV/c.

After a trigger is identified, the azimuthal angle, $\Delta\phi$, between the trigger and each associated hadron in the event is measured. Hadrons are selected with the PHENIX tracking system which includes a drift chamber, pad chambers, and RICH detector. The rapdity acceptance of the PHENIX detectors is $|\eta| < 0.35$. Corrections for detector effects using mixed events and the hadron reconstruction efficiency calculated from Geant 3 simulations are applied. The flow shape and level are determined and subtracted following the procedure described in [1] which accounts for the $n = 2$, 3, and 4 flow harmonics. This finally gives the per-trigger yields as a function of $\Delta\phi$ which is referred to as a jet function.

The statistical subtraction used to extract direct photon–hadron correlations is described in detail in previous publications [2]. While direct photons have the added benefit of providing a handle on the initial energy of the awayside jet, π^0–hadron correlations allow us to study dijet events which are more abundant than direct photon-tagged jets.

3. Results

3.1. π^0–hadron correlations

This section focuses on the latest π^0–hadron correlation measurements using the 2014 PHENIX Au+Au dataset. To quantify the modification due to the QGP, measurements in Au + Au collisions are compared to those in $p + p$ collisions. The I_{AA}, the ratio of the awayside per-trigger yield in

Au+Au to that in p+p, is plotted as a function of the associated hadron $p_{\mathrm{T},h}$ for several π^0 trigger p_{T} bins in Fig. 1. An enhancement ($I_{AA} > 1$) at low hadron p_{T} (below 2 GeV/c) is observed for all trigger bins and in both the 0–20% and 20–40% centrality classes. The enhancement is the most pronounced for the lowest $p_{\mathrm{T},h}$ bin, 0.5–1 GeV/c. These results are consistent with previous PHENIX measurements using earlier datasets for both π^0–hadron [1] and direct photon–hadron correlations [2]. The goal of the present analysis is to explore where in $\Delta\phi$ space this enhancement is occurring. Figure 2 shows the awayside I_{AA} as a function of $\Delta\phi$ for all p_{T} bins. Across all trigger bins, the enhancement in the 0.5–1 GeV/c hadron bin is most pronounced at the widest angles relative to the awayside peak. However, it is interesting to note that for the lowest trigger bin, some level of enhancement is observed for all $\Delta\phi$ on the awayside for 0.5–1 GeV/c hadrons.

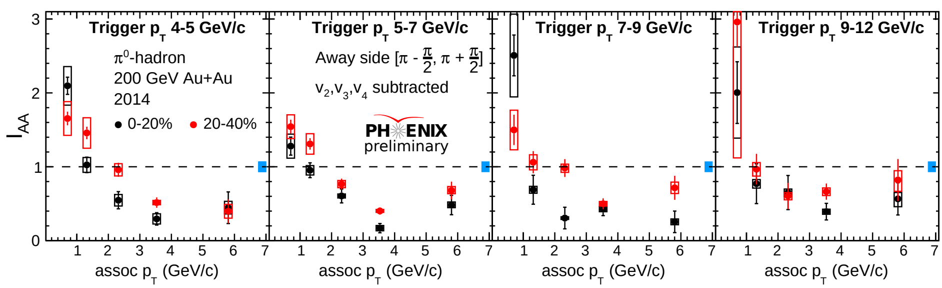

Fig. 1. (Color online) I_{AA} for π^0–hadron correlations as a function of the associated hadron p_{T} for four trigger p_{T} bins. Centrality bins 0–20% (black) and 20–40% (red/gray) are included.

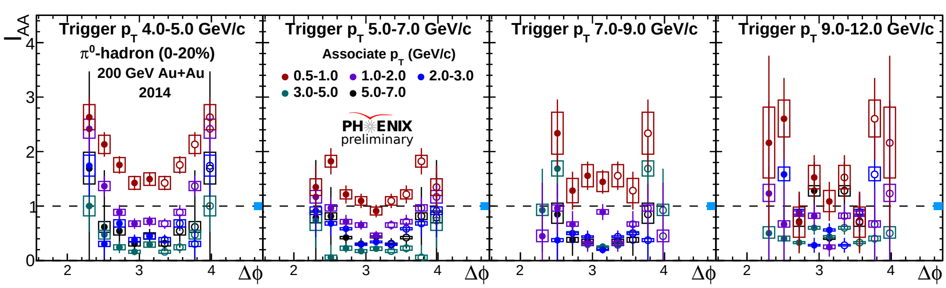

Fig. 2. (Color online) I_{AA} for π^0–hadron correlations in 0–20% central Au + Au collisions as a function of $\Delta\phi$. Each panel includes a different trigger p_{T} bin and the different hadron p_{T} bins shown as different colors as indicated in the legend.

Since ratios of small numbers can be inflated by dividing by numbers close to zero, a complimentary observable, D_{AA}, the difference between the yields in Au + Au and $p+p$, is extracted. Figure 3 shows the D_{AA} as a function of $\Delta\phi$ for hadrons with $0.5 < p_{\mathrm{T}} < 1$ GeV/c. The enhancement, which appears as values of $D_{AA} > 0$ is again observed over a wide range of angles and increases as one moves away from $\Delta\phi = \pi$ where the awayside jet sits. The enhancement seen at wider angles is also consistent with the phenomena of jet broadening. It is notable that the enhancement is even measured near the $\Delta\phi = \pi/2$ region between the two jet peaks. One key advantage of D_{AA} over I_{AA} is that the uncertainties in D_{AA} particularly near $\Delta\phi = \pi/2$ are reduced. Therefore, D_{AA} may provide stronger constraints on theoretical models than the I_{AA}. We can further explore the behavior of D_{AA} by observing how the distribution changes as a function of hadron p_{T}. Figure 4 shows the D_{AA} as a function of $\Delta\phi$ for different hadron p_{T} bins associated with 4–5 GeV/c pions and clearly demonstrates the transition from enhancement at low $p_{\mathrm{T},h}$ to suppression at high $p_{\mathrm{T},h}$.

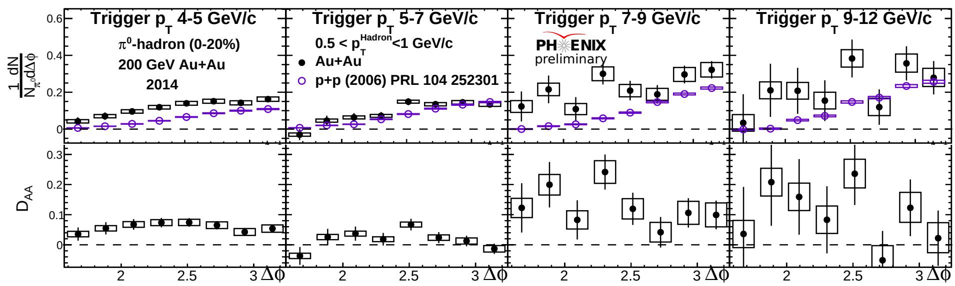

Fig. 3. The per trigger yield (top) and D_{AA} (bottom) for π^0–hadron correlations with $0.5 < p_{\mathrm{T},h} < 1$ GeV/c in 0–20% central Au + Au collisions as a function of $\Delta\phi$. Each panel includes a different trigger p_{T} bin as indicated.

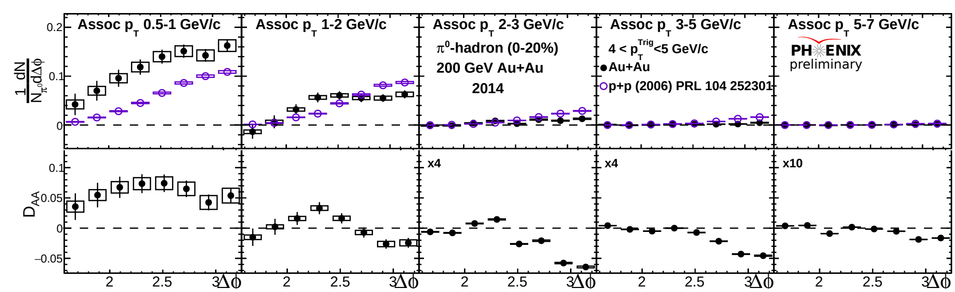

Fig. 4. The per trigger yield (top) and D_{AA} (bottom) for π^0–hadron correlations in 0–20% central Au + Au collisions as a function of $\Delta\phi$. From left to right: the hadron p_{T} bin increases while the trigger has $4 < p_{\mathrm{T}} < 5$ GeV/c.

3.2. Direct photon–hadron correlations

Direct photons are considered a "golden channel" to study energy loss in the QGP, since the unmodified direct photon approximately balances the initial energy of the opposing jet. PHENIX has published the jet functions for direct photon–hadron correlations using Au + Au data collected in 2007, 2010, and 2011 [2]. The D_{AA} described above can be directly calculated from the published results. The D_{AA} for the $\xi = \ln(\frac{p_{\mathrm{T},\gamma}}{p_{\mathrm{T},h}})$ bins published are shown in Fig. 5. A similar trend to that observed for the π^0–hadron correlations is seen but with larger uncertainties. The more statistically starved direct photon–hadron correlations will benefit from future analysis of the 2014 and 2016 Au + Au datasets.

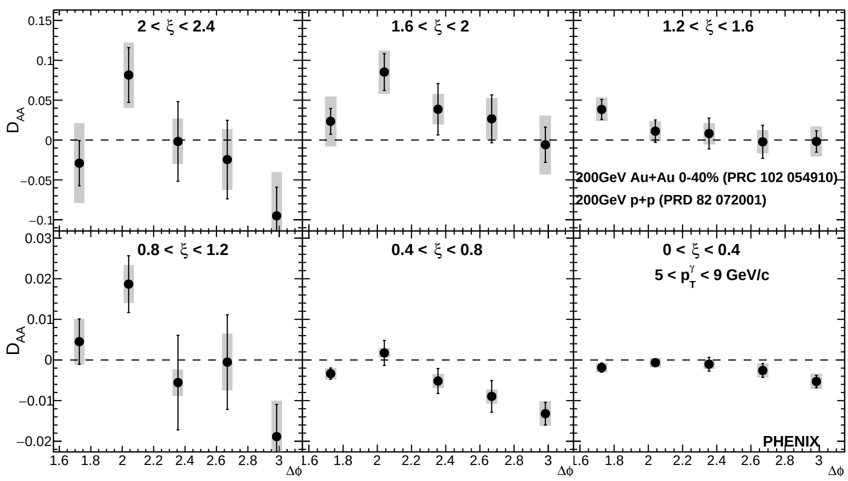

Fig. 5. The D_{AA} for direct photon–hadron correlations in 0–40% central *vs.* collisions as a function of $\Delta\phi$. Each panel includes a different ξ as indicated.

4. Discussion

The correlation results described above indicate a modification of the hadron yields associated with dijets and direct photon-tagged jets. This modification is attributed to energy loss effects in the medium that cause suppression of high momentum particles along the axis of the jet and an enhancement of lower momentum particles at wide angles relative to the jet axis. A similar story is unfolding at the LHC for measurements of hadron yield associated with Z bosons, which are also not modified by the QGP. The CMS measurements [3] are compared to theoretical models including the hybrid model [4]. One hybrid curve includes the effect of the "wake" which is the result of the medium response as the jet passes through it, while the "no wake" case does not account for the medium response. The two curves are similar at high $p_{\mathrm{T},h}$ but the curve including the wake reproduces the enhancement seen at low $p_{\mathrm{T},h}$, while the no wake curve is below the data. The wake calculation also reproduces the shape of the enhancement on the awayside observed in the D_{AA} *vs.* $\Delta\phi$ distributions. Another model, CoLBT [5], which includes medium response propagated through a hydrodynamical evolution, also describes the CMS data. These models are also consistent with the ATLAS I_{AA} measurements for Z-tagged charged hadron yields [6]. The features observed at the LHC for Z-hadron correlations are consistent with those in the PHENIX correlation results, implying the significance of the medium response at low $p_{\mathrm{T},h}$ for the PHENIX data as well. However, comparisons with these models for RHIC kinematics are warranted.

Direct photon–hadron and π^0–hadron correlations probe energy loss effects including the medium response. The latest π^0–hadron measurements from the 2014 Au + Au dataset collected at PHENIX are presented. I_{AA} *vs.* $\Delta\phi$ indicates a redistribution of low momentum hadrons to wide angles. Drawing from comparisons between theoretical models and similar features in the LHC data, the D_{AA} *vs.* $\Delta\phi$ measured at PHENIX shows a dependence on associate p_{T} that may be related to the medium response. However, direct comparisons to theoretical models are needed to draw more detailed conclusions. In addition, PHENIX plans to extract direct photon–hadron and π^0–hadron correlations using the larger 2016 Au + Au dataset.

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