Jet-hadron correlations relative to the event plane at the LHC with ALICE

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Abstract. Jet quenching is observed at both RHIC and LHC energies. This suggests that partons lose energy as they traverse the medium. When the trigger jet is studied relative to the event plane, the path length dependence of medium modifications can be studied. We present measurements of the angular correlations relative to the event plane between reconstructed jets and charged hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in ALICE. A newly implemented, robust background subtraction method to remove the complex, flow dominated, combinatorial background is used in this analysis.

1. Introduction
Jets are ideal probes of the Quark Gluon Plasma (QGP) because they originate from hard-scattered partons created early in the collision, prior to the formation of the medium. These partons are modified in the presence of a medium through collisional energy loss and induced gluon radiation. This modification is observed at both LHC and RHIC energies via the suppression of high-momentum particles [1–4]. A suppression is also seen for high $p_T$ di-hadron correlations [5–8].

By reconstructing jets, ideally, a more complete picture of how lost energy is redistributed and how the effects of jet quenching emerge can be obtained. This article will discuss the status of azimuthal correlations of reconstructed jets binned relative to the event plane with charged hadrons in ALICE.

2. Experiment
Clusters measured in the Electromagnetic Calorimeter (EMCal) and charged hadrons measured with the central tracking system allow ALICE to study fully reconstructed jets [4]. Charged hadrons are reconstructed from their tracks using information from the Time Projection Chamber (TPC) and the Inner Tracking System (ITS).

Tracks are reconstructed over the full azimuthal range and come from mid-rapidity in a range of $|\eta_{lab}| < 0.7$ when reconstructed in a jet, and $|\eta_{lab}| < 0.9$ for the associated charged hadrons. The EMCal has an acceptance window of $|\eta_{lab}| < 0.7$ and $|\Delta\phi| = 107^\circ$. For a complete description of the ALICE detector, see [9–12].
3. Jet-hadron correlations

3.1. Data sample
The data used for the correlation analysis was collected by the ALICE Experiment in 2011 during the 2.76 TeV Pb–Pb collision data taking. This work uses events which fired the gamma trigger used by the ALICE EMCal [10]. In addition, a cluster constituent of the trigger jet was required to be matched to the fired trigger patch of the event.

3.2. Jet Reconstruction
Jets are reconstructed with a resolution parameter of R=0.2 using the anti-\(k_T\) jet-finding algorithm from the FastJet package [13]. Jets reconstructed in this analysis require a leading cluster to have \(E_T > 6.0\) GeV, which exceeds the trigger threshold. The jets are reconstructed with constituent tracks of \(p_T > 3.0\) GeV/c and clusters of \(E_T > 3.0\) GeV. Since the primary goal of jet finding is to reconstruct the jet axis accurately, this high constituent cut limits the influence of background on jet finding.

3.3. Measurement
We define the jet-hadron correlation function in heavy-ion collisions by Eq. 1.

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc,jet}}}{d\Delta \phi d\Delta \eta} = \frac{1}{\epsilon \alpha N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d\Delta \phi d\Delta \eta} - b_0(1 + \sum v_n^{\text{trig}} v_n^{\text{assoc}} \cos(n\Delta \phi))
\]

Here the first term represents the same event pairs which are divided by an acceptance correction, \(\alpha\), provided by mixed events. Mixed events are used to correct for the limited detector efficiency and acceptance for track pairs. The single track reconstruction efficiency of associated particles is denoted by \(\epsilon\). The second term of Eq. 1 is the combinatorial heavy-ion background where \(b_0\) is the background level and the \(v_n\) terms are the Fourier coefficients of the trigger jet and associated particles.

The trigger jets in this analysis are binned in angle relative to the event plane to explore the path length dependence of medium modifications. The orientations are defined such that in-plane is \(0 < |\Delta \phi| < \frac{\pi}{6}\), mid-plane is \(\frac{\pi}{6} < |\Delta \phi| < \frac{\pi}{3}\), and out-of-plane is \(\frac{\pi}{3} < |\Delta \phi| < \frac{\pi}{2}\), where \(\Delta \phi\) denotes the angular difference between the trigger jet and the reconstructed event plane.

3.4. Background subtraction
When the trigger jet is restricted relative to the event plane, both the background level and \(v_n\) are modified and will contain a dependence on the reaction plane resolution \(\mathscr{R}\). The derivation of the event plane dependent background equations are given in [14]. The reaction plane resolution corrects for the difference between the reconstructed event plane and the underlying symmetry plane, \(\Psi_n\).

Various background subtraction methods were developed in [15] and applied to the azimuthal correlation functions. The primary method is the reaction plane fit (RPF). The RPF method works under the assumption that the signal is negligible in the large \(\Delta \eta\) and small \(\Delta \phi\) region. The 2D correlations are projected over \(0.8 < |\Delta \eta| < 1.2\) to define the background dominated region, while the signal+background region is defined to be \(|\Delta \eta| < 0.6\). To ensure as much information as possible is going into the fit by constraining the shape and level of the background, the in-plane, mid-plane, and out-of-plane orientations are simultaneously fit up to fourth order in \(v_n\) and required to have the same fit parameters.

The background dominated region is fit over the region \(|\Delta \phi| < \pi/2\), shown in Fig. 1. We see from the blue band that the RPF fit models the data quite well, even at low \(p_T\) where the background is large. The higher order Fourier coefficients clearly matter, as the background for trigger jets mid-plane has four peaks, consistent with a \(v_4\) dependence. This method does
not require independent measurements of $v_n$ and is able to extract the signal with smaller errors while requiring fewer assumptions and less bias than prior subtraction methods. This is especially useful since there are currently no $v_3^{jet}$ or $v_4^{jet}$ measurements.

$$\text{Figure 1.} \text{ Signal+background region, background dominated region and RPF fit to background are shown for the 1.5-2.0 GeV/c associated } p_T \text{ bin for full jets in Pb–Pb collisions at } \sqrt{s_{NN}} = 2.76 \text{ TeV for the 30-50% most central events. The blue band shows the uncertainty of the background fit, which is non-trivially correlated point-to-point [15,16].}$$

3.5. Results

We extract the signal by subtracting the large correlated background from the correlation function. Figure 2 shows the signal for associated particles of 2.0-3.0 GeV/c. The uncertainties are dominated by statistics. With higher statistics, the uncertainties could be vastly reduced to allow for a more precise measurement.

$$\text{Figure 2.} \text{ Corrected } \Delta \phi \text{ correlation function for } 2.0 < p_T < 3.0 \text{ GeV/c associated hadrons for full jets in Pb–Pb collisions at } \sqrt{s_{NN}} = 2.76 \text{ TeV for the 30-50% most central events. The blue band corresponds to the correlated uncertainty and the grey band corresponds to the background uncertainty which is non-trivially correlated point-to-point [15,16]. There is an additional 6% global scale uncertainty.}$$

We define the yields by Eq. 2.

$$Y = \frac{1}{N_{\text{trig}}} \int_{a}^{b} \int_{\phi_{a}}^{\phi_{b}} \frac{d(N_{\text{meas}} - N_{\text{bkgd}})}{d\Delta \phi} d\Delta \phi d\eta$$

Where the integration limits a and b correspond to $\Delta \phi$ values of -1.047 and +1.047 on the
near-side and +2.094 and +4.189 on the away-side respectively. In addition, the integration limits $c$ and $d$ correspond to $\Delta \eta$ values of -0.6 and 0.6 for both the near-side and away-side. The near-side (left) and away-side (right) jet yields for $1.0 < p_{T}^{assoc} < 10.0$ GeV/c are shown in Fig. 3. The near-side yield is consistent with little or no modification. There is no clear dependence of the away-side peaks on orientation relative to the event plane. There are competing effects across different $p_{T}$ ranges. Jet quenching could cause a decrease in yield going from in-plane to out-of-plane, while gluon radiation could cause an increase.

Figure 3. The near-side yield (left) and away-side yield (right) for full jets in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for the 30-50% most central events. The colored bands correspond to the correlated uncertainties and the grey band corresponds to the background uncertainty which is non-trivially correlated point-to-point [15,16]. There is an additional 6% global scale uncertainty.

4. Summary and Outlook

The jet-hadron correlation results were seen to have their uncertainties dominated by statistics. No significant event plane dependence was seen to within the current uncertainties on the extracted jet yield. The RPF background subtraction method applied to data was seen to have various advantages in that it does not require independent $v_n$ measurements, has less bias and fewer assumptions than prior background subtraction methods, and can extract the signal with great precision. The current results are consistent with the re-analysis of STAR data seen in [16].

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