Anomalous Evolution of the Near-Side Jet Peak Shape in Pb-Pb Collisions at √sNN = 2.76 TeV

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The measurement of two-particle angular correlations is a powerful tool to study jet quenching in a pT region inaccessible by direct jet identification. In these measurements pseudorapidity (Δη) and azimuthal (Δφ) differences are used to extract the shape of the near-side peak formed by particles associated with a higher pT trigger particle (1 < pT, trig < 8 GeV/c). A combined fit of the near-side peak and long-range correlations is applied to the data allowing the extraction of the centrality evolution of the peak shape in Pb-Pb collisions at √sNN = 2.76 TeV. A significant broadening of the peak in the Δη direction at low pT is found from peripheral to central collisions, which vanishes above 4 GeV/c, while in the Δφ direction the peak is almost independent of centrality. For the 10% most central collisions and 1 < pT, assoc < 2 GeV/c, 1 < pT, trig < 3 GeV/c a novel feature is observed: a depletion develops around the center of the peak. The results are compared to pp collisions at the same center of mass energy and AMPT model simulations. The comparison to the investigated models suggest that the broadening and the development of the depletion is connected to the strength of radial and longitudinal flow.

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In elementary interactions with large momentum transfer (Q2 ≫ Λ2 QCD), partons with high transverse momentum (pT) are produced. They evolve from high to low virtuality producing parton showers and eventually hadronizing into a spray of collimated hadrons called jets. In interactions between heavy ions, such high-pT partons are produced at the early stages of the collisions. They propagate through the dense and hot medium created in these collisions and are expected to lose energy due to medium-induced gluon radiation and elastic scatterings, a process commonly referred to as jet quenching. Correspondingly, an inclusive jet suppression has been observed at the LHC [1–3] together with a large dijet energy asymmetry [4,5], while studies of the momentum and angular distributions of jet fragments show only a small modification of the jet core [6–8], and an excess of soft particles radiated to large angles from the jet axis [9]. Semi-inclusive hadron-jet correlations show a suppression of recoil jet yield, with no in-medium modification of transverse jet structure observed [10].

Dihadron angular correlations represent a powerful complementary tool to study jet modifications on a statistical basis in an energy region where jets cannot be identified event by event over the fluctuating background. Such studies involve measuring the distributions of the relative azimuthal angle Δφ and pseudorapidity Δη between particle pairs consisting of a trigger particle in a certain transverse momentum pT, trig interval and an associated particle in a pT, assoc interval. In these correlations, jet production manifests itself as a peak centered around (Δφ = 0, Δη = 0) (near-side peak) and a structure elongated in Δη at Δφ = π (the away side or recoil region). At low pT, resonance decays as well as femtoscopic correlations also contribute to the near-side peak. The advantage of using dihadron correlations is that an event-averaged subtraction of the background from particles uncorrelated to the jet can be performed. This advantage is shared with the analysis of hadron-jet correlations recently reported in Refs. [9,10].

At RHIC, the near-side particle yield and peak shape of dihadron correlations have been studied for different systems and collision energies [11–13]. Small modifications of the yields with respect to a pp reference from PYTHIA are observed and there is remarkably little dependence on the collision system at the center-of-mass energies of √sNN = 62.4 and 200 GeV. An exception is the measurement in central Au-Au collisions at √sNN = 200 GeV where the jetlike correlation is substantially broader and the momentum spectrum softer than in peripheral collisions and than those in collisions of other systems in this kinematic regime. In Ref. [12], the broadening observed in central Au-Au collisions at √sNN = 200 GeV is seen as an indication of a modified jet fragmentation function. At the LHC, the measurement of the yield of particles associated with a high-pT trigger particle (8–15 GeV/c) in central Pb-Pb collisions relative

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to the $pp$ reference at $p_T^{assoc} > 3$ GeV/$c$ shows a suppression on the away side and a moderate enhancement on the near side, indicating that medium-induced modifications can also be expected on the near side [14]. Much stronger modification is observed for lower trigger and associated particle $p_T$ ($3 < p_T^{trig} < 3.5$ GeV/$c$ and $1 < p_T^{assoc} < 1.5$ GeV/$c$) [15,16]. In the most central Pb-Pb collisions, the near-side yield is enhanced by a factor of 1.7.

The present Letter expands these studies at the LHC to the characterization of the angular distribution of the associated particles with respect to the trigger particle. The angular distribution is sensitive to the broadening of the jet due to its energy loss and the distribution of radiated energy. Moreover, possible interactions of the parton shower with the collective longitudinal expansion [17–19] or with turbulent color fields [20] in the medium would result in near-side peak shapes that are broader in the $\Delta \eta$ than in the $\Delta \phi$ direction. Results from the study of the near-side peak shape of charged particles as a function of centrality and for different combinations of trigger and associated particle $p_T$ are discussed.

The data presented in this Letter were taken by the ALICE detector, of which a detailed description can be found in Ref. [21]. The main subsystems used in the present analysis are the Inner Tracking System (ITS), and the Time Projection Chamber (TPC). These have a common acceptance of $|\eta| < 0.9$. The ITS consists of six layers of silicon detectors for vertex finding, tracking, and triggering. The TPC is the main tracking detector measuring up to 159 space points per track. The V0 detector, two arrays of 32 scintillator tiles each, covering $2.8 < \eta < 5.1$ (V0-A) and $-3.7 < \eta < -1.7$ (V0-C), was used for triggering and centrality determination. All these detector systems have full azimuthal coverage.

Data from the 2010 and 2011 Pb-Pb runs of the LHC at $\sqrt{s_{NN}} = 2.76$ TeV are combined in the present analysis and compared with the 2011 $pp$ run at the same energy. In total, about 39 million Pb-Pb and 30 million $pp$ events are used. Details about the trigger and event selection in Pb-Pb ($pp$) collisions can be found in Ref. [22] (Ref. [23]), while the centrality determination is described in Ref. [24].

The collision-vertex position is determined with tracks reconstructed in the ITS and TPC [25], and its value in the beam direction ($z_{vtx}$) is required to be within 7 cm of the detector center. The Pb-Pb analysis is performed in the centrality classes 0%–10% (most central), 10%–20%, 20%–30%, 30%–50%, and 50%–80%. The analysis uses tracks reconstructed in the ITS and TPC with $1 < p_T < 8$ GeV/$c$ and in a fiducial region of $|\eta| < 0.8$. The track selection is described in Refs. [26,27]. The efficiency and purity of the primary charged-particle selection are estimated from a Monte Carlo (MC) simulation using the HIJING 1.383 event generator [28] (for Pb-Pb) and the PYTHIA 6.4 event generator [29] with the tune Perugia-0 [30] (for $pp$) with particle transport through the detector using GEANT3 [31]. The combined efficiency and acceptance for the track reconstruction in $|\eta| < 0.8$ is about 82%–85% at $p_T = 1$ GeV/$c$, and decreases to about 76%–80% at $p_T = 8$ GeV/$c$ depending on collision system, data sample, and event centrality. The contamination originating from secondary particles from weak decays and interactions in the detector material decreases from 2.5%–4.5% to 0.5%–1% in the $p_T$ range from 1 to 8 GeV/$c$. The contribution from fake tracks is negligible. From these quantities a correction factor is computed as a function of $\eta$, $p_T$, $z_{vtx}$, and event centrality, which is applied as a weight for each trigger particle and particle pair in the analysis.

The correlation between two charged particles (denoted trigger and associated particle) is measured as a function of $\Delta \phi$ (defined within $-\pi/2$ and $3\pi/2$) and $\Delta \eta$ [32]. The correlation is expressed in terms of the associated yield per trigger particle for intervals of $p_T^{trig}$ and $p_T^{assoc}$, measured as

$$\frac{1}{N_{trig}} \frac{d^2N_{assoc}}{d\Delta \eta d\Delta \phi} = \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)},$$

where $N_{trig}$ is the total number of trigger particles in the centrality class and the $p_T^{trig}$ interval, ranging from 0.18 to 36 per event. The signal distribution $S(\Delta \eta, \Delta \phi) = 1/N_{trig} d^2N_{same}/d\Delta \eta d\Delta \phi$ is the associated yield per trigger particle for particle pairs from the same event. The background distribution $B(\Delta \eta, \Delta \phi) = \alpha d^2N_{mixed}/d\Delta \eta d\Delta \phi$ accounts for the acceptance and efficiency of pair reconstruction. It is constructed by correlating the trigger particles in one event with the associated particles from other events. The background distribution is scaled by a factor $\alpha$ which is chosen such that $B(0,0)$ is unity for pairs where both particles travel in approximately the same direction (i.e., $\Delta \phi \approx 0$, $\Delta \eta \approx 0$), and thus the efficiency and acceptance for the two particles are identical by construction.

A selection on the opening angle of the particle pairs is applied to both signal and background to avoid a bias due to the reduced efficiency for pairs with small opening angles. Furthermore, correlations induced by secondary particles from long-lived neutral-particle decays ($K^0_s$ and $\Lambda$) and $\gamma$ conversions are suppressed by rejecting pairs in the corresponding invariant mass region. A correction is performed for a mild $\Delta \eta$ dependence of the structures in the two-particle correlation, which is due to a minor dependence of particle production and anisotropic flow on pseudorapidity. For further details on the analysis procedure, see Ref. [33].

In order to characterize the near-side peak shape, a simultaneous fit of the peak, the combinatorial background, and the long-range correlation background stemming from collective effects is performed. This exploits that in two-particle correlations the near-side peak is centered around $\Delta \phi = 0$, $\Delta \eta = 0$, while long-range correlation structures
are mostly independent of $\Delta \eta$ [34]. The away-side peak; however, is elongated in $\Delta \eta$; therefore, this strategy cannot be applied to studying the away side. The fit function used is a combination of a constant, a generalized two-dimensional Gaussian function and $\cos(n \Delta \phi)$ terms for $n = 2, 3, 4$.

$$F(\Delta \phi, \Delta \eta) = C_1 + \sum_{n=2}^{4} 2V_{n\Delta} \cos(n \Delta \phi) + C_2 G_{f_{\Delta \phi},w_{\Delta \phi}}(\Delta \phi) G_{f_{\Delta \eta},w_{\Delta \eta}}(\Delta \eta). \quad \text{(2)}$$

$$G_{r,\omega}(x) = \frac{\gamma_x}{2w_\Gamma(1/\gamma_x)} \exp \left[ - \left( \frac{|x|}{w_\Gamma} \right)^{\gamma_x} \right]. \quad \text{(3)}$$

Thus, in Pb-Pb collisions, the background is characterized by four parameters ($C_1, V_{n\Delta}$), where $V_{n\Delta}$ are the Fourier components of the long-range correlations [35], and it should be noted that the inclusion of orders higher than four does not significantly change the fit results. In $pp$ collisions, the background consists effectively only of the pedestal $C_1$. The peak magnitude is characterized by $C_2$, and the shape, which is the focus of the present analysis, by four parameters ($\gamma_{\Delta \phi}, w_{\Delta \phi}, \gamma_{\Delta \eta}, w_{\Delta \eta}$). The aim of using this fit function is to allow for a compact description of the data rather than attempting to give a physical meaning to each parameter. Therefore, the variance of $G$ is calculated, which reduces the description of the peak shape to two parameters ($\sigma_{\Delta \phi}$ and $\sigma_{\Delta \eta}$). To describe the evolution of the peak shape from peripheral to central collisions the ratios of the widths in the central bin ($0\%$–$10\%$) and the peripheral bin ($50\%$–$80\%$), denoted by $\sigma_{\Delta \phi}^C$ and $\sigma_{\Delta \eta}^C$, are also calculated.

In the data a depletion around $\Delta \phi = 0$, $\Delta \eta = 0$ is observed at low $p_T$, however, the fit function does not include such a depletion. To avoid a bias on the extracted peak width, some bins in the central region are excluded from the fit. The size of the excluded region varies with $p_T$ and collision centrality (from no exclusion to 0.3). Thus, by definition, the peak width describes the shape of the peak outside of the central region. The depletion in the central region is quantified below by computing the difference between the fit and the per-trigger yield within the exclusion region.

In Pb-Pb collisions, the obtained $\chi^2$/ndf values of the fits are in the range 1.0–2.5; most are around 1.5. In the highest two $p_T$ bins (i.e., in $3 < p_{T,\text{assoc}} < 8$ GeV/$c$ and $4 < p_{T,\text{trig}} < 8$ GeV/$c$) the values increase up to about 2.5 showing that at high $p_T$ the peak shape starts to depart from the generalized Gaussian description. In $pp$ collisions, the $\chi^2$/ndf values are in the range 1.3–2.0.

Systematic uncertainties connected to the measurement are determined by modifying the event and track selections. In addition, uncertainties related to the cut on pairs with small opening angles and neutral-particle decays, as well as the sensitivity to the pseudorapidity range are considered.

The difference in the extracted parameters is studied as a function of $p_T$, centrality, and collision system, but these dependencies are rather weak and in most cases one uncertainty value can be quoted for each type of systematic uncertainty. Finally, the different sources of systematic uncertainties are added in quadrature. The extracted peak widths are rather insensitive to changes in the selections (total uncertainty of about $2\%$–$4.5\%$), while the near-side depletion yield is more sensitive (about $24\%$–$45\%$ uncertainty). The contribution from resonance decays was studied by performing the analysis separately for like and unlike sign pairs, and a significant influence on the results presented below was not found.

Figure 1 shows the near-side peak in $1 < p_{T,\text{trig}} < 2$ GeV/$c$ and $1 < p_{T,\text{assoc}} < 2$ GeV/$c$ for the 10% most central collisions. In addition to the two-dimensional representation, projections are shown where the background estimated with Eq. (2) has been subtracted. The near-side peak is asymmetric, i.e., wider in $\Delta \eta$ than in $\Delta \phi$. It is also broader than in peripheral Pb-Pb and $pp$ collisions, where it is mostly symmetric in $\Delta \phi$ and $\Delta \eta$ (not shown, see Ref. [33]). Furthermore, a depletion around $\Delta \phi = 0$, $\Delta \eta = 0$ develops which will be discussed in more detail below. Also at higher $p_T$, the near-side peak is broader in central collisions than in peripheral or $pp$ collisions. This broadening is less pronounced at high $p_T$ than at low $p_T$, and the asymmetry between $\Delta \phi$ and $\Delta \eta$ disappears at the two highest $p_T$ bins; see Ref. [33].

The extracted shape parameters $\sigma_{\Delta \phi}$ and $\sigma_{\Delta \eta}$ are presented in Fig. 2. In $pp$ collisions, the $\sigma$ values range from about 0.14 to about 0.43 showing a $p_T$ dependence qualitatively expected due to the boost of the evolving parton shower; at larger $p_T$ the peak is narrower. In the $\Delta \phi$ direction (left panel) the values obtained in $pp$ collisions are consistent with those in peripheral Pb-Pb collisions. The peak width increases towards central events, which is most pronounced in the lowest $p_T$ bin ($20\%$ increase). In the higher $p_T$ bins no significant width increase can be observed. In the $\Delta \eta$ direction (right panel) a much larger broadening is found towards central collisions. Already in

FIG. 1. Left panel: associated yield per trigger particle as a function of $\Delta \phi$ and $\Delta \eta$. The background obtained from the fit function has been subtracted in order to emphasize the near-side peak. Right panel: projections to the $\Delta \phi$ and $\Delta \eta$ axes overlaid with the peak part of the fit function.
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200

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FIG. 2. Shape parameters $\sigma_{\Delta \eta}$ (left panel) and $\sigma_{\Delta \phi}$ (right panel) as a function of centrality in different $p_T$ ranges. Lines indicate statistical uncertainties (mostly smaller than the marker size), while boxes denote systematic uncertainties. The markers are placed at the center of the centrality bins.

peripheral collisions the width is larger than in $pp$
collisions. From peripheral to central collisions the width
increases further up to $\sigma_{\Delta \eta} = 0.67$ in the lowest $p_T$ bin and
the largest relative increase of about 85% is observed for
$2 < p_{T,\text{trig}} < 3$ GeV/$c$ and $2 < p_{T,\text{assoc}} < 3$ GeV/$c$. For
all but the two largest $p_T$ bins a significant broadening
can be observed. This increase is quantified for all $p_T$ bins in
Fig. 3 by $\sigma_{\Delta \phi}^{\text{CP}}$ and $\sigma_{\Delta \phi}^{\text{CP}}$. The increase is quantified with
respect to peripheral Pb-Pb instead of $pp$ collisions to facilitate the MC comparisons discussed below.

In $pp$ collisions, the peak shows circular symmetry in the
$\Delta \eta$–$\Delta \phi$ plane for all $p_T$ values. In Pb-Pb collisions, the
peak becomes asymmetric towards central collisions for all
but the two highest $p_T$ bins. The magnitude of this
asymmetry depends on $p_T$ and is largest with about
70% ($\sigma_{\Delta \eta} > \sigma_{\Delta \phi}$) in the range $2 < p_{T,\text{assoc}} < 3$ GeV/$c$
and $2 < p_{T,\text{trig}} < 3$ GeV/$c$. These results are compatible
with a similar study by the STAR Collaboration at $\sqrt{s_{NN}} =
200$ GeV [12], which is detailed in the companion
paper [33].

In Ref. [17] it was suggested that the interplay of
longitudinal flow with a fragmenting high $p_T$ parton can
lead to the observed asymmetric peak shape. The authors
argue that hard partons interact with a medium which
shows collective behavior, contrary to the simpler picture
where the parton propagates through an isotropic medium
with respect to the parton direction. In their calculation the
scattering centers are Lorentz boosted by applying a
momentum shift depending on the collective component
of the yield is missing in the lowest \( p_T \) bin and in the 10% most central events. This value decreases gradually with centrality and with \( p_T \). No significant depletion yield is observed for 50%–80% (30%–80%) centrality or \( pp \) collisions for the lowest (second lowest) \( p_T \) range. The depletion observed in the AMPT events is present only in the lowest \( p_T \) bin, where its value is compatible with the data for both settings where hadronic rescattering is switched off. For larger \( p_T \) bins and for the configuration without hadronic rescattering the depletion yield is consistent with 0 in AMPT.

The reported results can be interpreted in the context of radial and anisotropic flow by calculating the radial-flow expansion velocity \( \beta_T \) and the elliptic flow coefficient \( v_2 \) from the 10% most central events from data and from the AMPT samples. The expansion velocity \( \beta_T \) is extracted from a blast-wave fit to the \( p_T \) spectra of \( \pi, K \), and \( p \) in the rapidity range of \( |y| < 0.5 \). The \( v_2 \) is extracted from two-particle correlations within \( |\eta| < 0.8 \) and 0.2 < \( p_T \) < 5 GeV/c.

The depletion (Fig. 4) occurs in the two AMPT configurations (b) and (c) where the \( \beta_T \) is large, while the configuration (a) without the depletion has the smallest \( \beta_T \). The coefficient \( v_2 \) has significantly different values in the two configurations (b) and (c) with depletion, and the relative increase of the peak width (Fig. 3) is best described by the AMPT configuration with the largest \( \beta_T \) (b). Based on these studies, it seems that the depletion and the broadening observed in the data are more likely accompanied by radial flow than elliptic flow.
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