Particle-Yield Modification in Jetlike Azimuthal Dihadron Correlations in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The yield of charged particles associated with high-p_t trigger particles ($8 < p_t < 15$ GeV/c) is measured with the ALICE detector in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV relative to proton-proton collisions at the same energy. The conditional per-trigger yields are extracted from the narrow jetlike correlation peaks in azimuthal dihadron correlations. In the 5% most central collisions, we observe that the yield of associated charged particles with transverse momenta $p_t > 3$ GeV/c on the away side drops to about 60% of that observed in pp collisions, while on the near side a moderate enhancement of 20%–30% is found.

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Ultrarelativistic heavy ion collisions produce the quark-gluon plasma (QGP), the deconfined state of quarks and gluons, and are used to explore its properties. In the last decade, important information about the dynamical behavior of the QGP has been obtained from the study of hadron jets, the fragmentation products of high transverse momentum (p_t) partons that are produced in initial hard scatterings of partons from the incoming nuclei [1,2]. It is generally accepted that prior to hadronization, partons lose energy in the high color-density medium due to gluon radiation and multiple collisions. These phenomena are broadly known as jet quenching [3].

The energy loss was first observed at the Relativistic Heavy Ion Collider (RHIC) in Au-Au collisions at $\sqrt{s_{NN}} = 130$ GeV as a suppression of hadron yields with respect to the reference from pp collisions at high p_t (3–6 GeV/c) [4,5]. At RHIC, distributions in relative azimuth $\Delta\varphi = \varphi_{trig} - \varphi_{assoc}$ between associated particles with transverse momenta $p_{t,assoc}$ and trigger particles with $p_{t,trig}$ have been measured. These studies indicate that the peak shapes from high-p_t ($p_{t,trig} > 4$ GeV/c and $2\,GeV/c < p_{t,assoc} < p_{t,trig}$) dihadron correlations in central Au-Au collisions are similar to those in small systems like pp and d-Au [6,7], where correlations are dominated by jet fragmentation. The near-side peak at $\Delta\varphi = 0$ is comparable in magnitude between all collision systems, while the away-side peak at $\Delta\varphi = \pi$ is strongly suppressed. In central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the suppression amounts to a factor of 3–5 in the range $0.35 < p_{t,assoc}/p_{t,trig} < 0.95$ for $8 < p_{t,trig} < 15$ GeV/c and $p_{t,assoc} > 3$ GeV/c [8].

At the LHC, the suppression of charged hadrons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV increases and the nuclear modification factor R_{AA} drops to 0.14 around 7 GeV/c [9]. Furthermore, a strong dijet energy asymmetry has been reported by the ATLAS and CMS collaborations [10,11]. A detailed study of the overall momentum balance in the dijet events shows evidence for sizable low-p_t radiation outside the cone of the subleading jet [11]. These analyses use full event-by-event reconstruction of di-jets for leading jet transverse momenta above 100 GeV/c. At lower transverse momenta ($p_{t,jet} <$ 50 GeV/c) background fluctuations due to the underlying event dominate [12] and event-by-event jet reconstruction becomes difficult. Hence, dihadron correlations are an interesting alternative probe. Measurements of dihadron correlations in central Pb-Pb collisions compared to PYTHIA 8 [13] pp simulations have been presented in [14].

The extraction of the particle yield associated with a jet requires the removal of correlated background primarily of collective origin (e.g., flow) at lower p_t. This is nontrivial and, therefore, we concentrate in this Letter on a regime where jetlike correlations dominate over collective effects: $8 < p_{t,trig} < 15$ GeV/c for the trigger particle and $p_{t,assoc} > 3$ GeV/c for the associated particle [15]. We present ratios of yields of central to peripheral collisions (I_{CP}) and, for different centralities, of Pb-Pb to pp collisions (I_{AA}). I_{AA} probes the interplay between the parton production spectrum, the relative importance of quark-quark, gluon-gluon and quark-gluon final states, and energy loss in the medium. On the near side, I_{AA} provides information about the fragmenting jet leaving the medium, while on the away side it additionally reflects the probability that the recoiling parton survives the passage through the medium. The sensitivity of I_{AA} and R_{AA} to different properties of the medium makes the combination particularly effective in constraining jet quenching models [16,17].

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Detector, data sets and analysis.—The ALICE detector is described in detail in [18]. The inner tracking system (ITS) and the time projection chamber (TPC) are used for vertex finding and tracking. The collision centrality is determined with the forward scintillators (VZERO) as well as for the estimation of the systematic uncertainty with the first two layers of the ITS (silicon pixel detector, SPD) and the zero degree calorimeters (ZDCs). Details can be found in [19]. The main tracking detector is the TPC which allows reconstruction of good-quality tracks with a pseudorapidity coverage of $|\eta| < 1.0$ uniform in azimuth. The reconstructed vertex is used to select primary track candidates and to constrain the p_t of the track.

In this analysis 14×10^6 minimum-bias Pb-Pb events recorded in fall 2010 at $\sqrt{s_{\rm NN}} = 2.76$ TeV as well as 37×10^6 pp events from March 2011 ($\sqrt{s} = 2.76$ TeV) are used. These include only events where the TPC was fully efficient to ensure uniform azimuthal acceptance. Events are accepted which have a reconstructed vertex less than 7 cm from the nominal interaction point in beam direction. Tracks are selected by requiring at least 70 (out of up to 159) associated clusters in the TPC, and a χ^2 per space point of the momentum fit smaller than 4 (with 2 degrees of freedom per space point). In addition, tracks are required to originate from within 2.4 cm (3.2 cm) in transverse (longitudinal) distance from the primary vertex.

For the measurement of $I_{\rm AA}$ and $I_{\rm CP}$ the yield of associated particles per trigger particle is studied as a function of the azimuthal angle difference $\Delta\varphi$. This distribution is given by $1/N_{\rm trig} dN_{\rm assoc}/d\Delta\varphi$ where $N_{\rm trig}$ is the number of trigger particles and $N_{\rm assoc}$ is the number of associated particles. We measure this quantity for all pairs of particles where $p_{t,\rm assoc} < p_{t,\rm trig}$ within $|\eta| < 1.0$ as a function of $p_{\rm t,assoc}$. Pair acceptance corrections have been evaluated with a mixed-event technique but found to be negligible for the yield ratios due to the constant acceptance in φ and the same detector conditions for the different data sets.

Corrections for detector efficiency (17%–18% depending on collision system, p_t and centrality) and contamination (4%–8%) by secondary particles from particle-material interactions, γ conversions, and weak-decay products of long-lived particles are applied for trigger and associated particles, separately. Additional secondary particles correlated with the trigger particle are found close to $\Delta\varphi = 0$ in particular due to decays and γ conversions. We correct for this contribution (2%–4%). These corrections are evaluated with the HIJING 1.36 [20] Monte Carlo (MC) generator which was tuned to reproduce the measured multiplicity density [19] for Pb-Pb and the PYTHIA 6 [21] MC generator with tune PERUGIA-0 [22] for pp using in both cases a detector simulation based on GEANT3 [23]. MC simulations underestimate the number of secondary particles. Therefore, we study the distribution of the distance of closest approach between tracks and the event vertex. The tail of this distribution is dominantly populated by secondary particles and the comparison of data and MC calculations shows that the secondary yield in the MC events needs to be increased by about 10% (depending on p_t). An MC study shows that effects of the event selection and vertex reconstruction are negligible for the extracted observables. The correction procedure was validated by comparing corrected simulated events with the MC truth.

Figure 1(a) shows a typical distribution of the corrected per-trigger pair yield before background subtraction. The fact that the $\Delta\varphi$ distribution is flat outside the near- and away-side regions gives us confidence that the background can be estimated with the zero yield at minimum (ZYAM) assumption [24]. This procedure estimates the pedestal value by fitting the flat region close to the minimum of the $\Delta\varphi$ distribution ($|\Delta\varphi - \pi/2| < 0.4$) with a constant. The validity of the ZYAM assumption has been questioned in cases where collective effects dominate [25,26]; however, for the high-p_t correlations of this analysis, the narrow width and large amplitude of the correlated signal

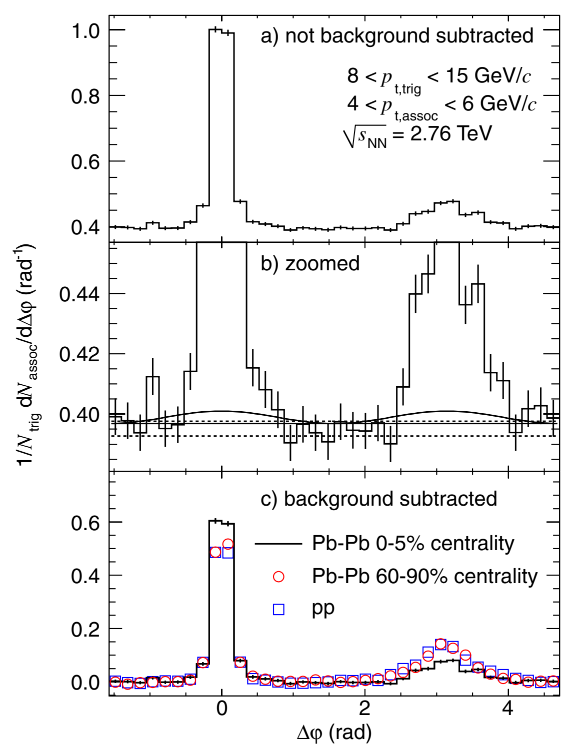

FIG. 1 (color online). Corrected per-trigger pair yield for $4 < p_{t,\rm assoc} < 6$ GeV/c for central Pb-Pb events (histogram), peripheral Pb-Pb events (red circles) and pp events (blue squares). (a) Azimuthal correlation; (b) zoom on the region where the pedestal values (horizontal lines) and the v_2 component ($\cos 2\Delta\varphi$) are indicated. Solid lines are used in the yield extraction while the dashed lines are used for the estimation of the uncertainty of the pedestal calculation; (c) background-subtracted distributions using the flat pedestal. Error bars indicate statistical uncertainties only.

compared to the flow modulation drastically reduce the ZYAM bias. Therefore, we define the integrated associated yield as the signal over a flat background. Figure 1(b) illustrates the background determination. Also indicated is a background shape accounting for elliptic flow v_2, the second coefficient of the particle azimuthal distribution measured with respect to the reaction plane. It is given by $2v_{2,\text{trig}}v_{2,\text{assoc}}\cos 2\Delta\varphi$ where $v_{2,\text{trig}}$ ($v_{2,\text{assoc}}$) is the elliptic flow of the trigger (associated) particles. The v_2 values are taken from an independent measurement [27] of v_2 up to $p_t = 5$ GeV/c. As an upper limit we use the v_2 measured for $p_t = 5$ GeV/c for higher p_t where v_2 is expected to decrease. For the centrality class 60%–90% no v_2 measurement is available; therefore, as an upper limit, v_2 is taken from the 40%–50% centrality class. Since v_2 decreases from midcentral to peripheral collisions and the flat pedestal assumes $v_2 = 0$, this includes all reasonable values of v_2.

Contributions from $\Delta\eta$-independent correlations (e.g., due to flow harmonics at all orders) can also be removed on the near side (where the jet peak is centered around $\Delta\eta \approx 0$) by calculating the per-trigger pair yield in the region $|\Delta\eta| < 1$ and subtracting the contribution from $1 < |\Delta\eta| < 2$ normalized for the acceptance. This prescription, which we call the η-gap method, provides a measurement independent of the flow strength.

In Fig. 1(c) the flat-pedestal subtracted distributions of central and peripheral Pb-Pb collisions are compared to that of pp collisions. The integral over those distributions in the region where the signal is significantly above the background, i.e., within $\Delta\varphi$ of ± 0.7 and $\pi \pm 0.7$, results in the near- and away-side yields per trigger particle (Y), respectively. This procedure samples the same fraction of the signal in Pb-Pb and pp collisions, since in the p_t range used for this study the width of the peaks is similar for both systems. The yields are used to compute the ratio $I_{AA} = Y_{\text{Pb-Pb}}/Y_{pp}$ where $Y_{\text{Pb-Pb}}$ (Y_{pp}) is the yield in Pb-Pb (pp) collisions and the ratio $I_{CP} = Y_{0\text{–}5\%}/Y_{60\text{–}90\%}$ where $Y_{0\text{–}5\%}$ ($Y_{60\text{–}90\%}$) is the yield in central (peripheral) Pb-Pb collisions.

Systematic uncertainties.—The uncertainty from the pedestal determination has been estimated by comparing different pedestal evaluation strategies [see Fig. 1(b)]. The constant-fit region has been shifted and an average of the 8 (out of 36) lowest $\Delta\varphi$ points has been used. The integration window for the near and away side has been varied between ± 0.5 and ± 0.9. The effect of detector efficiency and track selection has been studied by systematically varying the track cuts. Track splitting and merging effects were assessed by studying the tracking performance as a function of the distance of closest approach of the track pairs in the detector volume. A bias due to the p_t resolution on the extracted yields was evaluated by folding the detector resolution with the extracted associated spectrum and found to be negligible. The sensitivity of the corrections to details of the MC simulations has been studied by varying the particle composition, the material budget and the MC generator (using AMPT [28] for Pb-Pb and PHOJET [29] for pp). Uncertainties in the centrality determination were evaluated by comparing results obtained with the different centrality estimates from the VZERO, the SPD, and ZDCs. Table I lists the size of the different contributions to the systematic uncertainties for I_{AA} and I_{CP} as well as their sum in quadrature.

Results.—Figure 2(a) shows the yield ratio I_{AA} for central (0%–5% Pb-Pb/pp) and peripheral (60%–90% Pb-Pb/pp) collisions using the three background subtraction schemes discussed. The fact that the only significant difference between the different background subtraction schemes is in the lowest bin of $p_{t,\text{assoc}}$ confirms the assumption of only a small bias due to flow anisotropies in this p_t region. The influence of higher flow harmonics [27] on the background shape can be explicitly estimated: including v_3, v_4, and v_5 from [27] changes the extracted jet yield by less than 1%, except for the first bin in $p_{t,\text{assoc}}$ in the most central collisions where it is about 8%. This is consistent with the difference between the data points labeled v_2 bkg and η gap where the latter includes flow at all orders. In central collisions, an away-side suppression ($I_{AA} \approx 0.6$) is observed which is evidence for in-medium energy loss. Moreover, there is an enhancement above unity of 20%–30% on the near side which has not been observed with any significance at lower collision energies at these momenta [8]. In peripheral collisions, both the near- and away-side I_{AA} measurements approach unity, as expected in the absence of significant medium effects.

Figure 2(b) shows the yield ratio I_{CP}. As for I_{AA}, the influence of the flow modulation is small and only significant in the lowest $p_{t,\text{assoc}}$ bin. I_{CP} is consistent with I_{AA} in central collisions with respect to the near-side enhancement and the away-side suppression.

Comparing this measurement and R_{AA} to models simultaneously will constrain energy-loss mechanisms and model parameters. Robust conclusions can only be drawn with a systematic comparison of multiple observables with

TABLE I. Systematic uncertainties evaluated separately for near side and away side. Ranges indicate different values for different centrality ranges: the smaller (larger) number is for peripheral (central) events.

Uncertainty	I_{AA} Near side	I_{AA} Away side	I_{CP} Near side	I_{CP} Away side
Pedestal calculation	5%	5%–20%	5%	20%
Integration window	0	3%	0	3%
Tracking efficiency		4%		
Two-track effects		<1%		
Corrections		2%		1%
Centrality selection		2%		3%
Total	7%	8%–21%	7%	21%

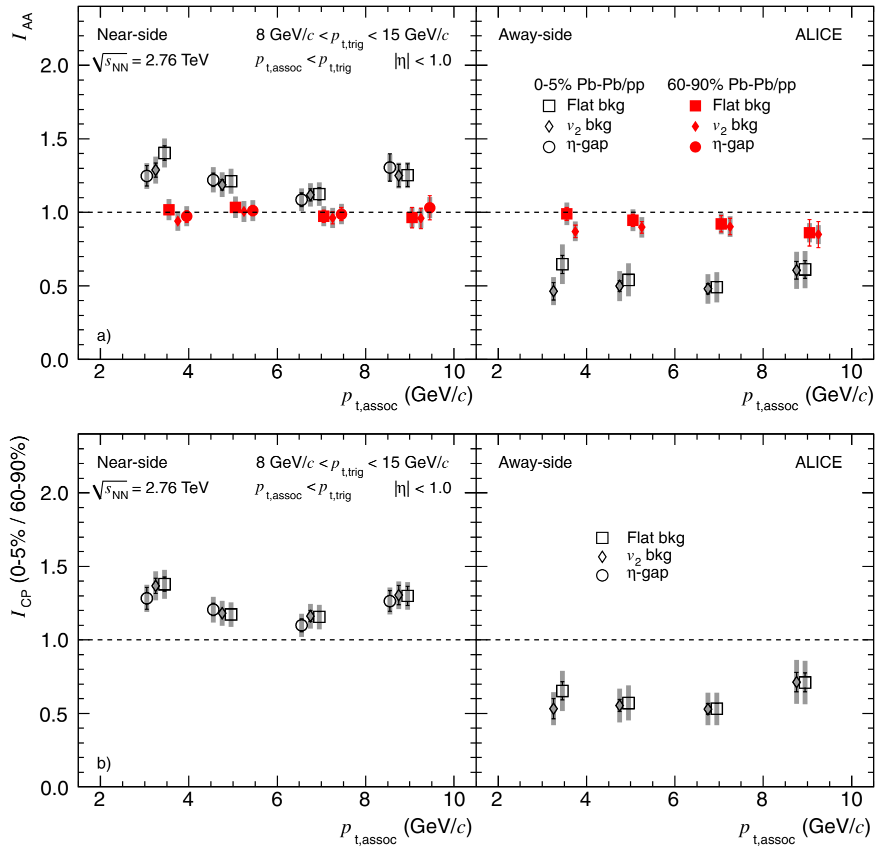

FIG. 2 (color online). (a) I_{AA} for central (0%–5% Pb-Pb/pp, open black symbols) and peripheral (60%–90% Pb–Pb/pp, filled red symbols) collisions and (b) I_{CP}. Results using different background subtraction schemes are presented: using a flat pedestal (squares), using v_2 subtraction (diamonds) and subtracting the large $|\Delta\eta|$ region (circles, only on the near side). For details see text. For clarity, the data points are slightly displaced on the $p_{t,\mathrm{assoc}}$ axis. The shaded bands denote systematic uncertainties.

calculations spanning the parameter space and cannot be done with current calculations (e.g., [30]). Such a study is beyond the scope of this Letter.

Comparison to RHIC.—Similar measurements have been performed at RHIC. Although the same range in $p_{t,\mathrm{trig}}$ does not necessarily probe the same parton p_t region at different $\sqrt{s}$, we assess changes from RHIC to LHC in the following. The STAR measurement [8] (which includes only statistical uncertainties) of the near-side I_{AA} is consistent with unity, albeit with a large uncertainty (18%–40%). On the away side the result from STAR is about 50% lower than the results shown in Fig. 2. We also calculated I_{AA} for the 20% most central events to compare to PHENIX [7] (only v_2-subtracted data on the away side available). For $p_{t,\mathrm{assoc}} < 4$ GeV/c, the flow influence in this centrality interval is about 75%, too large to provide a reliable measurement. For $4 < p_{t,\mathrm{assoc}} < 10$ GeV/c, the v_2-subtracted I_{AA} is $0.5 - 0.6 \pm 0.08$. This result is slightly larger than results from PHENIX in a similar $p_{t,\mathrm{trig}}$ region of $7 < p_{t,\mathrm{trig}} < 9$ GeV/c: 0.31 ± 0.07 and 0.38 ± 0.11 for $p_{t,\mathrm{assoc}} \approx 3.5$ GeV/c and 5.8 GeV/c, respectively. Based on an analysis in a lower p_t region, where collective effects are significantly larger than in the measurement presented here, the STAR collaboration mentions a slightly enhanced jetlike yield in Au-Au compared to d-Au collisions, but does not assess the effect quantitatively [31]. In conclusion, the observed away-side suppression at the LHC is less than at RHIC (I_{AA} is larger), while the single-hadron suppression R_{AA} is found to be slightly larger (R_{AA} is smaller) than at RHIC [9].

Near-side enhancement.—These measurements represent the first observation of a significant near-side enhancement of I_{AA} and I_{CP} in the p_t region studied. This enhancement suggests that the near-side parton is also subject to medium effects.

I_{AA} is sensitive to (i) a change of the fragmentation function, (ii) a possible change of the quark/gluon jet ratio in the final state due to the different coupling to the medium, and (iii) a bias on the parton p_t spectrum after energy loss due to the trigger particle selection. If the fragmentation function (FF) is softened in the medium, hadrons carry a smaller fraction of the initial parton momentum in Pb-Pb collisions as compared to pp collisions. Therefore, hadrons with a given p_t originate from a larger average parton momentum which may lead to more associated particles and $I_{\mathrm{AA}} > 1$. An increased fraction of gluon (quark) jets has an effect similar to softening (hardening) of the FF and leads to $I_{AA} > 1$ (< 1).

A different parton distribution in pp and Pb-Pb collisions can modify I_{AA} even if fragmentation of a given parton after energy loss is unmodified. In particular, in the same transverse momentum region, we see a strong suppression of the trigger particles ($R_{AA} \approx 0.2$) and the rising slope of $R_{AA}(p_t)$ [9]. A similar suppression should apply to partons, leading to a parton distribution after energy loss which is biased towards higher parton p_t. Therefore, for a fixed trigger p_t, the mean parton p_t would be larger in Pb-Pb than in pp, leading to an increase in I_{AA}. This argument can be quantified with the hadron-pair suppression factor J_{AA} [32]. $J_{AA}(p_{t,\mathrm{trig}}, p_{t,\mathrm{assoc}}) = R_{AA}(p_{t,\mathrm{trig}}) I_{AA}(p_{t,\mathrm{trig}}, p_{t,\mathrm{assoc}})$ is approximately $R_{AA}(p_{t,\mathrm{trig}} + p_{t,\mathrm{assoc}})$ in this case, and with a rising R_{AA} leads to $I_{AA} > 1$.

It is likely that all three effects play a role, and following the above arguments, we note that the combined measurement of R_{AA} and I_{AA} is sensitive to the interplay of energy loss and the change of the fragmentation pattern in the medium.

In summary, the modification of the per-trigger yield of associated particles, I_{AA} and I_{CP}, has been extracted from dihadron correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In central collisions, on the away side, suppression ($I_{AA} \approx 0.6$) is observed as expected from strong in-medium energy loss. On the near side, a significant enhancement ($I_{AA} \approx 1.2$) has been reported for the first time. Along with the measurement of R_{AA}, I_{AA} provides strong constraints on the quenching mechanism in the hot and dense matter produced.

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