Jet structure in pp and Pb-Pb collisions with the ALICE experiment

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Abstract.
We report results from the ALICE collaboration on jet production and jet properties in pp and Pb-Pb collisions at the LHC. The charged particle jet production cross-section and measurements of jet fragmentation and jet shape in pp collisions at $\sqrt{s}\ = 7$ TeV are presented. The results are confronted with simulations from Monte Carlo event generators. Measurements of charged particle jets in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with resolution parameter $R = 0.2$ and $R = 0.3$ show a strong momentum dependent suppression in central relative to peripheral collisions. The analysis of the semi-inclusive distribution of charged particle jets recoiling from a high-p_{T} trigger hadron allows an unbiased measurement of the jet structure for larger cone radii. No significant redistribution of the energy flow inside the jet cone is observed. Di-hadron correlations allow to assess jet structure at very low particle momenta. For $2 < p_{T,trig} < 3$ GeV/c and $1 < p_{T,assoc} < 2$ GeV/c, a strongly asymmetric near-side correlation, broader in $\Delta\eta$ than $\Delta\phi$, is observed.

1. Introduction

Jets are collimated sprays of particles associated with hard-scattered partons. The study of jet production and fragmentation allows us to test our understanding of perturbative and non-perturbative aspects of QCD. In heavy-ion collisions, jets produced in the initial stage probe the early hot and dense quark gluon plasma phase of the fireball evolution. Interactions with the medium result in collisional energy loss and give rise to additional induced radiation, which emitted at small angles inside the jet cone can lead to a broadening of the jet profile.

The coupling between partons and medium at a scale of the order of the initial parton energy may be weak, governed by perturbative dynamics. At a scale of the order of ~1 GeV, set by the medium temperature or the saturation scale, the coupling between the jet and the medium may be strong [1]. Empirical observations suggest that indeed the thermal scale is relevant for the parton energy loss [2]. It has been predicted, that the coupling of jet fragments to the longitudinally flowing medium [3] or to turbulent color fields [4] will lead to broadening that is larger in pseudorapidity η than azimuthal angle ϕ (excentric jets). Jet reconstruction and measurements of the jet properties aim to quantify the in-medium jet energy loss and determine the dynamics of jet quenching. At low particle momenta, where full jet reconstruction is difficult due to strong underlying event backgrounds, the jet structure can be assessed via di-hadron correlation measurements.

2. Results from pp collisions

Charged jets are reconstructed in the ALICE [5] central barrel from primary charged particle tracks measured in the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Tracks with transverse momentum $p_{\mathrm{T}} > 150$ MeV/c in the pseudo-rapidity interval $|\eta| < 0.9$ are clustered with the FastJet [6] anti-k_{T} algorithm with a resolution parameter $R = 0.4$ using the boost-invariant p_{T} recombination scheme. Jets which are fully contained within the detector acceptance are selected. The jet shape and jet constituents' transverse momentum spectra (jet fragmentation) are measured with charged particles in the leading (highest p_{T}) jet in each event. The jet spectra, shape, and fragmentation distributions are corrected for detector effects via unfolding or bin-by-bin corrections based on detector simulations.

In the top left panel of Fig. 1, the charged jet cross section [9] at $\sqrt{s} = 7$ TeV is shown. The top right panel presents the charged jet fragment distribution in scaled transverse momentum $\xi = \ln(p_{\mathrm{T}}^{jet,ch}/p_{\mathrm{T}}^{particle})$ [10]. The wide ALICE track momentum coverage down to $p_{\mathrm{T}} = 150$ MeV/c allows us to measure the distribution over more than 5 units in ξ.

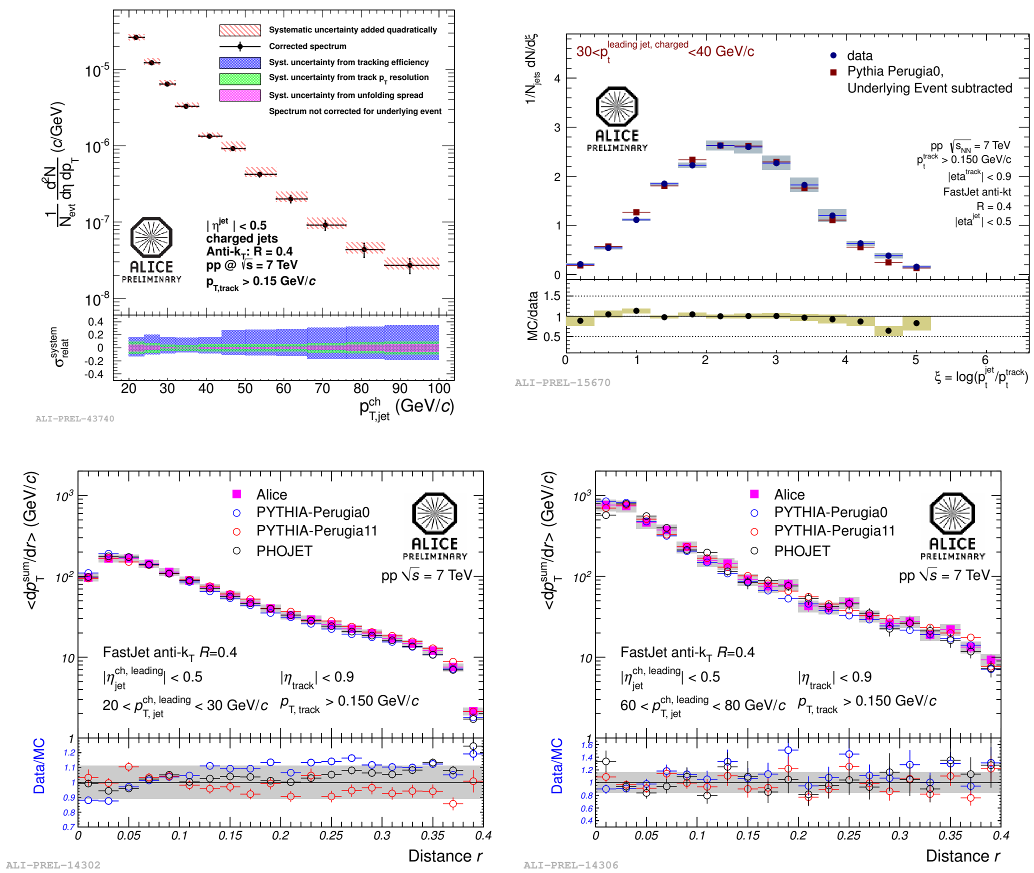

Figure 1. Results from pp collisions at $\sqrt{s} = 7$ TeV. Top left: charged jet cross section for $R = 0.4$. Systematic uncertainties are indicated by the boxes, the lower panel shows the contributions from detector effects and unfolding superimposed linearly. Top right: scaled transverse momentum distribution of jet fragments measured in leading charged jets with $30 < p_{\mathrm{T,jet}}^{\mathrm{ch}} < 40$ GeV/c. Bottom: radial distributions of transverse momentum density for $20 < p_{\mathrm{T,jet}}^{\mathrm{ch}} < 30$ GeV/c (left) and $60 < p_{\mathrm{T,jet}}^{\mathrm{ch}} < 80$ GeV/c (right). All results are corrected for detector effects and underlying event (see text). Jet shape and fragmentation distributions are compared to calculations from MC event generators.

The distribution exhibits the characteristic hump-backed plateau structure indicating QCD coherence [11]. The area of the distribution is equal to the charged particle multiplicity of the fragments. The bottom panels show the radial distributions of transverse momentum density around the jet axis [12]. The slope of the distribution measures the jet collimation. The increase in slope from $20 < p^{\mathrm{ch}}_{\mathrm{T,jet}} < 30$ GeV/c (bottom left) to $60 < p^{\mathrm{ch}}_{\mathrm{T,jet}} < 80$ GeV/c (bottom right) at small r indicates stronger collimation with increasing jet p_{T}.

The results are compared to Monte Carlo (MC) simulations from event generators: PYTHIA [13] tune Perugia0 [14] (fragmentation, jet shapes), PYTHIA tune Perugia2011 and PHOJET [15] (jet shapes). The underlying event contribution was measured inside perpendicular cones transverse to the jet axis and subtracted from the jet cross section, fragmentation and shape measurements, consistently in data and simulations. The data are reasonably well described by the simulations.

3. Jets in Pb-Pb collisions

Jet reconstruction in heavy-ion collisions is faced with a large background from the underlying event uncorrelated to hard parton scattering. The background contribution is reduced using small values of the jet resolution parameter of $R = 0.2$ and $R = 0.3$. The average charged background energy density is calculated event by event as the median p_{T} density of FastJet k_{T} clusters and subtracted jet by jet. The spectra are corrected for detector effects and background

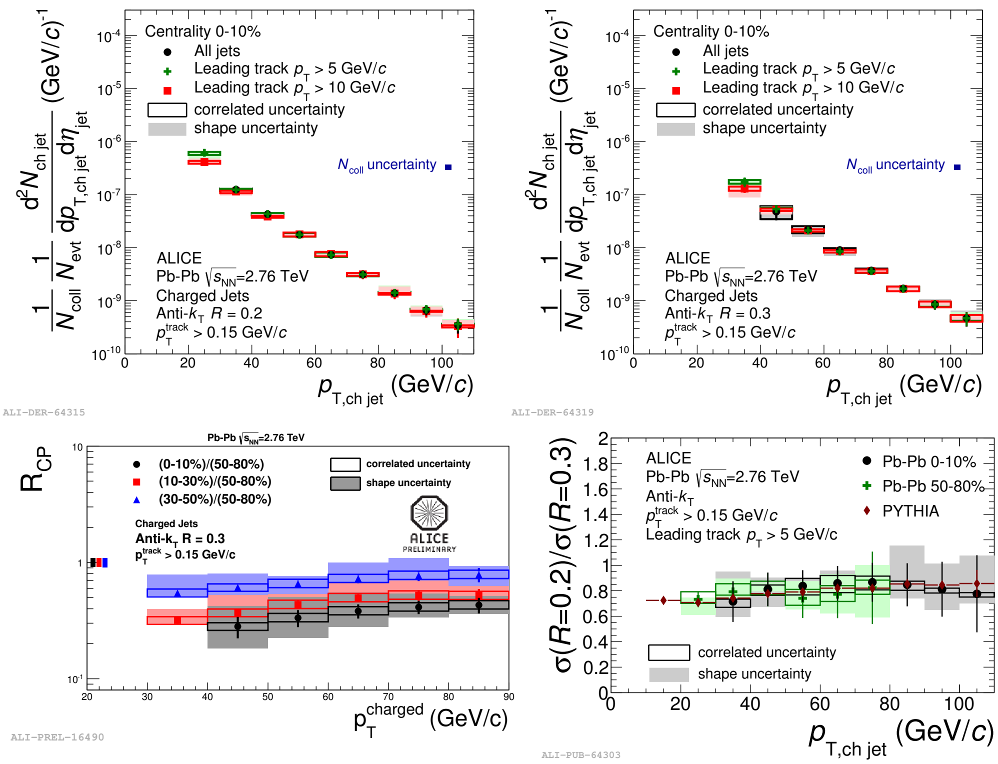

Figure 2. Single inclusive charged jet measurements for 10% most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Top: jet spectrum for $R = 0.2$ (left) and $R = 0.3$ (right) for different leading track selections, normalized to the number of binary collisions. Correlated (shape) systematic uncertainties are indicated by the boxes (shaded bands). Bottom left: jet nuclear modification factor R_{CP} for different centrality selections. Bottom right: spectral ratio for different R compared to PYTHIA calculations.

fluctuations via unfolding. Background fluctuations also give rise to low $p_{\rm T}$ 'combinatorial jets' composed of background particles. Their contribution can be suppressed, for example, by introducing a fragmentation bias requiring a high momentum jet constituent.

Fig. 2 shows single charged jet spectra in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $R = 0.2$ (top left) and $R = 0.3$ (top right) [16, 17, 18]. The spectra are normalized to the number of binary collisions. The inclusive jet spectra are compared to results requiring at least one jet constituent with $p_{\rm T} > 5$ or 10 GeV/c. Within uncertainties, no dependence on the momentum of the leading constituent is observed, which indicates that the longitudinal momentum distribution of high-$p_{\rm T}$ tracks of jets reconstructed in Pb-Pb collisions remains largely unmodified.

The centrality dependence of the jet quenching can be quantified using $R_{\rm CP}(p_{\rm T}) = \frac{\langle N^P_{\rm coll}\rangle}{\langle N^C_{\rm coll}\rangle}\frac{{\rm d}^2N^C_{\rm jet}/{\rm d}p_{\rm T,jet}\,{\rm d}\eta}{{\rm d}^2N^{\rm P}_{\rm jet}/{\rm d}p_{\rm T,jet}\,{\rm d}\eta}$, where C stands for central and P for peripheral. The measured R_{CP} (bottom left) is significantly smaller than unity. The suppression is strongest at low jet momentum, and at high momentum $R_{\rm CP}$ rises to values of approximately 0.4. In the bottom right panel, the ratio of the charged jet spectra obtained for $R = 0.2$ and $R = 0.3$ is shown for two centrality classes. This ratio is sensitive to the jet structure. The data are consistent with the PYTHIA values for peripheral and central events: no broadening of the hard core of the reconstructed jets is observed within the present systematic uncertainties.

4. Hadron triggered recoil jets in Pb-Pb collisions

The analysis of hadron triggered recoil jets allows us to extend the study of jet quenching to larger values of R. The semi-inclusive distribution of charged jets recoiling back-to-back from a high-$p_{\rm T}$ charged hadron in Pb-Pb collisions [19] is measured. Model studies [20] show that a high $p_{\rm T}$ hadron trigger introduces a geometrical bias, towards jets generated on the surface of the fireball and directed outward. Jets recoiling from such a trigger tend to have a larger in-medium path length. The recoil jet $p_{\rm T}$ distribution normalized per trigger is shown in the upper left panel of Fig. 3 for different hadron trigger intervals. After subtraction of the average background, a large fraction of the jet population is assigned a negative energy. This part of the spectrum is dominated by combinatorial jets, and is uncorrelated with the trigger $p_{\rm T}$. For high $p_{\rm T,jet}$, the recoil jet distribution is seen to depend strongly on p_T^{trig}, since a harder hadron trigger selects on average a larger Q^2.

In the difference of the spectra for different intervals of trigger hadron $p_{\rm T}$, the contribution of combinatorial jets uncorrelated to the hadron trigger cancels:

$$\Delta_{recoil}((p_{\rm T}^{\rm trig,1}-p_{\rm T}^{\rm trig,2})-(p_{\rm T}^{\rm trig,3}-p_{\rm T}^{\rm trig,4}))=\frac{1}{N_{\rm trig}}\frac{{\rm d}N}{{\rm d}p^{\rm ch}_{\rm T,jet}}(p_{\rm T}^{\rm trig,1}<p_{\rm T}^{\rm trig}<p_{\rm T}^{\rm trig,2})-c\frac{1}{N_{\rm trig}}\frac{{\rm d}N}{{\rm d}p^{\rm ch}_{\rm T,jet}}(p_{\rm T}^{\rm trig,3}<p_{\rm T}^{\rm trig}<p_{\rm T}^{\rm trig,4}) \quad (1)$$

The $\Delta_{\rm recoil}$ spectrum for $R = 0.4$ is shown in the upper right panel of Fig. 3 for hadron trigger intervals from 20-50 GeV/c and 15-20 GeV/c, using a scale factor $c = 0.956$. This novel variable allows us to study an unbiased sample of jets reconstructed with a large radius, maintaining a jet constituent cutoff as low as $p_{\rm T}^{\rm const} > 0.15$ GeV/c.

To explore the energy redistribution within recoil jets, we consider the ratio for the measured Δ_{recoil} distribution over PYTHIA (tune Perugia2010) simulations ΔI_{AA}^{PYTHIA}, presented in the bottom panels of Fig. 3. We find similar values of ΔI_{AA}^{PYTHIA} for $R = 0.2$ (left) and $R = 0.4$ (right) and constituent $p_{\rm T}$ threshold [19] (not shown). Within present experimental uncertainties, we do not observe significant redistribution of the jet energy.

5. Jet-like near-side peak shapes in Pb-Pb collisions

In the analysis of di-hadron correlations, the angular differences $\Delta\eta$ and $\Delta\phi$ between trigger particles and all associated particles satisfying pairs of cuts on $(p_{\rm T,trig}, p_{\rm T,assoc})$ are studied. We use tracks reconstructed in the TPC within $|\Delta\eta| < 0.9$ constrained to the primary vertex. The

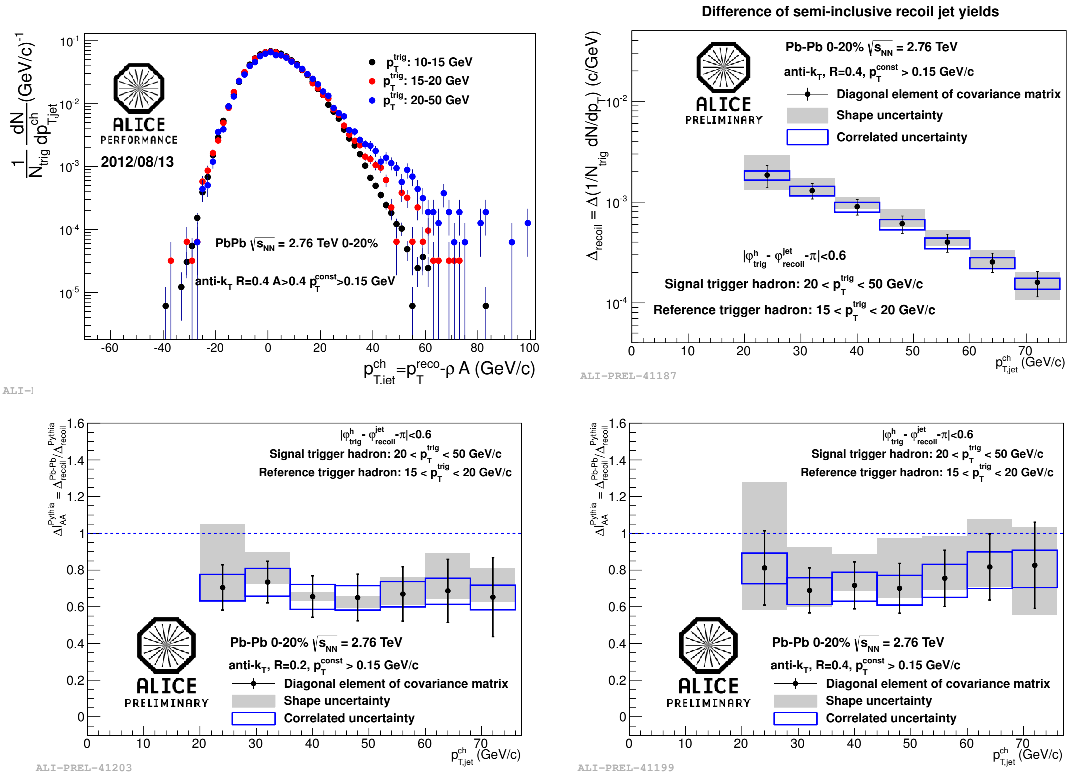

Figure 3. Upper left: Semi-inclusive recoil jet spectrum for 0-20% central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, for different trigger $p_{\rm T}$ classes. Jets reconstructed with the anti-$k_{\rm T}$ algorithm for $R = 0.4$, $p_{\rm T}^{const} > 0.15$ GeV/c. Upper right: Semi-inclusive recoil jet spectrum difference Δ_{recoil}. Lower panels: ΔI_{AA} for recoil jets using PYTHIA as a reference, for $R = 0.2$ (left) and $R = 0.4$ (right).

angular correlations are quantified by the per trigger associated yield $1/N_{trig}\ {\rm d}^2N/{\rm d}\Delta\phi{\rm d}\Delta\eta$. The uncorrected distributions at the near-side ($\Delta\phi = \Delta\eta = 0$) represent the sum of a jet-like correlation 'signal' and a 'background' induced by $\Delta\eta$ independent long-range correlations (mostly due to hydrodynamic flow [7] related to the initial spatial anisotropy of the overlap zone of the two colliding nuclei). This background is estimated by introducing a gap in pseudo-rapidity $1 < |\Delta\eta| < 1.6$, and subtracted. The associated yield is corrected for acceptance, detector effects and secondary particle contamination [8].

The near-side di-hadron correlations are studied for different ($p_{\rm T,trig}, p_{\rm T,assoc}$) ranges. In the top left panel of Fig. 4, the per trigger associated yield for the lowest $p_{\rm T}$ bin ($2 < p_{\rm T,trig} < 3$ GeV/c, $1 < p_{\rm T,assoc} < 2$ GeV/c) for the 10% most central collisions is shown. The distribution is asymmetric, and a strong broadening in $\Delta\eta$ is observed. The projections on $\Delta\eta$ and $\Delta\phi$ (upper right) indicate a flattening in the region $|\Delta\eta| <0.4$. The centrality and $p_{\rm T}$ dependence of the rms $\sigma_{\Delta\phi}$, $\sigma_{\Delta\eta}$ of the distributions is presented in the bottom panels of Fig. 4. The near-side peak width decreases with increasing ($p_{\rm T,trig}, p_{\rm T,assoc}$), reflecting the stronger collimation of higher $p_{\rm T}$ jets. Within uncertainties, no centrality dependence of $\sigma_{\Delta\phi}$ is observed, whereas $\sigma_{\Delta\eta}$ increases from the pp reference (centrality 100% data points) to the most central Pb-Pb collisions.

The data points are compared with the result of an AMPT 2.25 (with string melting) MC simulation [21] shown as lines. The pp values have been simulated with PYTHIA (tune Perugia0 [14]). AMPT simulates the initial conditions using HIJING [22]. It includes re-scattering of

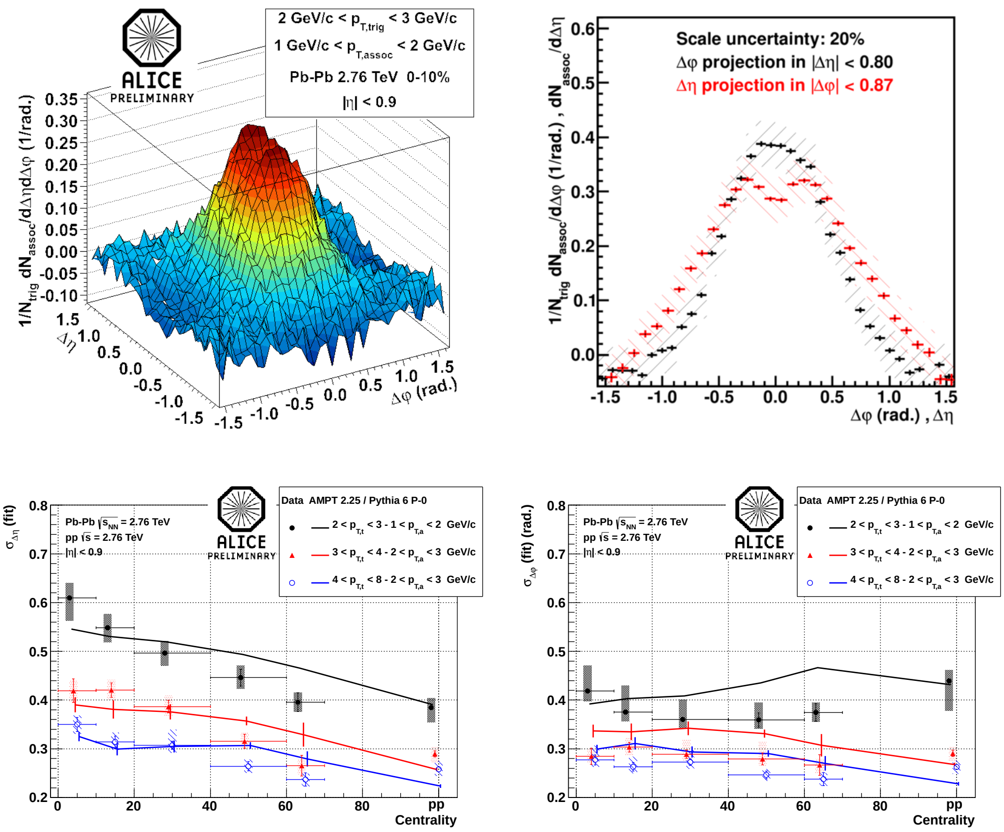

Figure 4. Upper left: Per trigger associated yield differential in $\Delta\eta$ and $\Delta\phi$ for the 10% most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, and the lowest $p_{\rm T}$ bin studied. Upper right: Corresponding projections. Bottom: centrality dependence of $\sigma_{\Delta\eta}$ (left) and $\sigma_{\Delta\phi}$ (right) for three different bins of $p_{\rm T,trig}$ and $p_{\rm T,assoc}$. The lines indicate results of AMPT and PYTHIA calculations.

partons and hadrons. Hadronization is simulated using the Lund model and coalescence. The AMPT simulations are in good agreement with our measurements.

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