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Jet shapes in pp and Pb–Pb collisions at ALICE

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Abstract

The aim of this work is to explore possible medium modifications to the substructure of inclusive charged jets in Pb-Pb relative to proton-proton collisions by measuring a set of jet shapes. The set of shapes includes the radial moment, g, and the momentum dispersion $p_{\mathrm{T}}D$. They provide complementary information on the fragmentation and can help to discriminate between two different scenarios: intra-jet broadening or collimation as a result of jet quenching. The shapes are measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with a constituent cutoff of 0.15 GeV/c and jet resolution R = 0.2. New techniques for background subtraction are applied and a two-dimensional unfolding is performed to correct the shapes to particle level. The corrected jet shapes for jet p_{T} $40 \leq p_{\mathrm{T,jet}} \leq 60$ GeV/c are presented and discussed. The observed jet shape modifications suggest that the in-medium fragmentation is harder and more collimated than vacuum fragmentation as obtained by a PYTHIA calculation. The PYTHIA calculation is validated with proton-proton data at 7 TeV.

Keywords: jet quenching, jet shapes

1. Jet shapes

The hot and dense medium created in Heavy Ion Collisions is expected to modify the jet yield and fragmentation relative to pp collisions. The measurement of such modifications gives insight into the mechanisms of energy loss of partons in the medium and ultimately into the properties of the medium itself. The aim of this work is to characterize changes in the intrajet distribution using observables that are well-defined, preserving the infrared and collinear safety of the measurement and thus allowing for a direct connection to the theory. In this analysis we focus on two jet shape observables that probe complementary aspects of the jet fragmentation, namely the first radial moment g and the momentum dispersion $p_{\mathrm{T}}D$ [1].
The radial moment g is defined as:

$$g = \sum_{i \in jet} \frac{p_{\mathrm{T}}^{\mathrm{i}}}{p_{\mathrm{T,jet}}} |\Delta R_{\mathrm{i,jet}}| \tag{1}$$

where $p_{\mathrm{T}}^{\mathrm{i}}$ stands for the momentum of constituent i and $\Delta R_{\mathrm{i,jet}}$ is the distance in η, ϕ space between constituent i and the jet axis. This shape measures the radial energy profile of the jet. As an illustrative example, gluon jets fragment more and thus are broader and have higher radial moment than quark jets [2].
The momentum dispersion $p_{\mathrm{T}}D$ is defined as:

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$$p_T D = \frac{\sqrt{\sum_{i \in jet} p_{\mathrm{T,i}}^2}}{\sum_{i \in jet} p_{\mathrm{T,i}}}. \tag{2}$$

This shape measures the second moment of the constituent p_T distribution in the jet and tells how hard/soft the fragmentation is. For example, in the extreme case of few constituents carrying a large fraction of the jet momentum, $p_{\mathrm{T}}D \rightarrow 1$, while in the case of large number of constituents $p_{\mathrm{T}}D \rightarrow 0$. Contrary to the radial moment, gluon jets have a smaller $p_{\mathrm{T}}D$ than quark jets because their fragmentation is softer [2].
The use of these two shapes can help to discriminate between two different physics scenarios: intra-jet broadening or collimation as a result of jet quenching.

2. Jet reconstruction and corrections

Jets are reconstructed using the FastJet anti-k_T algorithm with resolution parameter $R = 0.2$, along with E-scheme recombination and using charged tracks reconstructed in the ALICE central barrel acceptance ($\eta < 0.9$, $p_T > 0.15$ GeV) assuming charged tracks to be pions. The 10% most central Pb–Pb collisions were selected. The effects of the large underlying event in central Pb–Pb collisions were addressed in two distinct steps, correcting separately for the median background level and for its fluctuations.

2.1. Event-by-event average background subtraction

The event-by-event estimate of the underlying event momentum and mass densities ρ and ρ_{m} is done using a Fastjet area based method[3]. This information is provided as input to two methods to subtract the background from the jet shapes:
-Area-derivatives method [4]: It involves a numerical determination of a given shape susceptibility to background and an extrapolation to zero background.
-Constituent subtraction method [5]: It operates particle-by-particle so that the four-momentum of the jet and its substructure are corrected simultaneously.
The first method is used as default while the second is used to study the systematic uncertainty due to method choice. To test the performance of the subtraction in Pb–Pb we embed PYTHIA[6] (Perugia11) jets at detector level into Pb–Pb events. The results for the radial moment are shown in Figure 1. We compare the detector level shapes (black symbols) to the subtracted hybrid shapes (red and green) where by hybrid we refer to detector-level PYTHIA jets that are embedded in Pb–Pb events, reconstructed and matched to the PYTHIA detector-level probe. Residual differences between background corrected and detector level jets are due to background fluctuations and need to be unfolded. Note that no background correction is performed in proton-proton collisions, where effects are negligible for R =0.2.

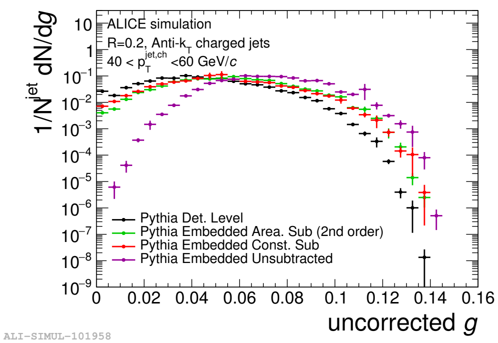

Fig. 1. Background subtraction performance

2.2. Unfolding in two dimensions

Residual background fluctuations and detector effects are unfolded. We use Bayesian unfolding in two dimensions as implemented in RooUnfold package [7] to obtain fully corrected jet shapes.
Since the unfolding procedure conserves counts, the raw input needs to be clean of combinatorial background for the sake of stability of the procedure. The background response of jets, δp_{T}, has a width of σ = 4 GeV/c for R = 0.2 [8]. The truncation of the raw yield at 30 GeV/c sets our working point at more than 7 σ away from zero and thus combinatorial background is negligible. To unfold, we use a 4D response matrix with axes (shape$^{\mathrm{part}}$,$\mathrm{p}_{\mathrm{T,jet}}^{\mathrm{part}}$,shape$^{\mathrm{rec}}$,$\mathrm{p}_{\mathrm{T,jet}}^{\mathrm{rec}}$). Upper index 'part' refers to particle level and 'rec' refers to reconstructed level. In pp, reconstructed level means detector level and the response is filled using PYTHIA at particle level and after full detector smearing. In Pb–Pb, reconstructed level means detector level after correction for the average background and smeared to account for fluctuations. To construct the response matrix, we embed PYTHIA detector-level jets into Pb-Pb events and we apply two successive matchings, between hybrid and detector-level jets and between detector and particle-level jets.

3. Jet shapes in pp

Figure 2 shows the fully corrected shapes in pp collisions at 7 TeV in the jet p_{T} range 40-60 GeV/c. The results are compared to PYTHIA Perugia 0 and 11, which show a reasonable agreement given that non-perturbative effects are expected for small R. The systematic uncertainty is dominated by single particle tracking efficiency uncertainty. Other sources of shape uncertainty are the regularization choice (we consider ±3 iterations around default), the truncation value (we consider truncating the yield at $p_{\mathrm{T,jet}}$ 10 GeV/c lower than nominal) or the prior choice (we smear by 20% the prior correlation based by default on PYTHIA Perugia 0).

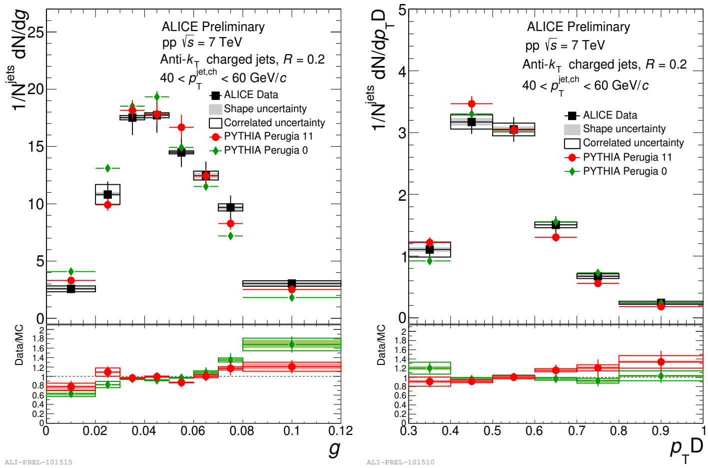

Fig. 2. Fully corrected shape distributions in pp for R = 0.2

4. Jet shapes in Pb–Pb

Upper plots in Figure 3 show the fully corrected shapes in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV compared to PYTHIA Perugia 11 in the same jet p_{T} range of 40-60 GeV/c. Note that in addition to the systematic uncertainties considered in pp, the background subtraction method choice contributes to the shape uncertainty. The radial moment (upper left plot) is shifted to lower values in data compared to PYTHIA. The $p_{\mathrm{T}}D$ (upper right plot) is shifted to higher values in data compared to PYTHIA. Our results indicate that the jet cores in Pb–Pb are more collimated and harder than the jet cores in PYTHIA at the same energy. Due to jet quenching, when we compare jet shapes in Pb–Pb and pp at the same measured energy, we might bias towards higher initial parton energy in Pb–Pb if a significant fraction of the radiated energy is outside the used jet cone. Then the question is how the energy was lost and how the radiation pattern of the jet was modified. JEWEL[9] medium-modified jets are narrower and are harder than vacuum jets at the same reconstructed energy [10], in qualitative agreement with Pb–Pb data as seen in Figure 3, lower plots. The underlying physics mechanism in JEWEL leads to a collimation of the jet, where soft modes are transported to large angle relative to jet axis. For illustrative purposes quark and gluon vacuum jets are added to the plot. One can think of gluon jets as an approximation to modified jets in the hypothetical case where quenching accelerates the shower just by increasing the number of splittings. This scenario would lead to a broadening/softening of the in-cone shower (see differences in the shape between inclusive jets and gluon jets in the plot) as opposed to data.

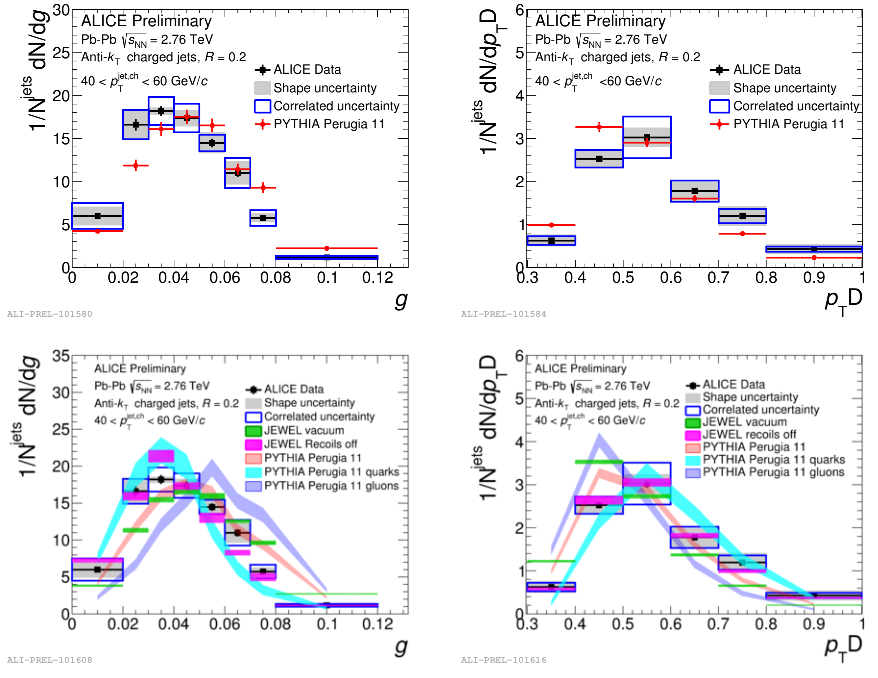

Fig. 3. Upper plots: Fully corrected shape distributions in Pb–Pb compared to PYTHIA Perugia 11. Lower plots: Fully corrected shape distributions in Pb–Pb compared to PYTHIA Perugia 11 inclusive, quark and gluon shapes and to JEWEL model

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