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Jet production in pp, p–Pb and Pb–Pb collisions measured by ALICE

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Abstract. Particle jets, formed when a hard scattered parton fragments into a jet of hadrons, are an ideal probe of the medium formed in heavy-ion collisions. The hard-scattered partons that produce them come from early in the collision, prior to the medium formation. These partons lose energy as they traverse the medium, and eventually fragment into jets of hadrons, which exhibit a modification when compared to jets produced in pp and p–Pb collisions. At LHC energies, the parton production cross-section is much larger than at RHIC, allowing jets to be reconstructed over a much wider kinematic range. Jet reconstruction allows for a more differential investigation of the parton energy loss than single hadrons, which have been used as jet proxies in the past, as the jets collect a larger percentage of the final state energy, which means their kinematics are more closely correlated to the kinematics of the initial parton.

Jets are reconstructed in ALICE either using information from the tracking systems, or by combining this with the ALICE electromagnetic calorimeter (EMCal). In these proceedings, jet spectra from 2.76 TeV Pb–Pb and pp collisions will be presented. In particular, the centrality and event-plane dependence of the measured spectra and the background will be discussed. Jets from different centrality classes and event-plane orientations provide additional information necessary for understanding the path-length and temperature dependence of energy loss mechanisms. The reconstruction and correction procedures for jets will be shown. Results from Pb–Pb events will be compared to the baseline pp and p–Pb results, which allows the initial state and cold nuclear matter effects to be disentangled from hot medium effects. The jet nuclear modification, which quantifies the suppression, will be compared to energy-loss models.

1. Introduction
In ultra-relativistic heavy-ion collisions, a new state of matter is formed which is called the Quark Gluon Plasma (QGP), where quarks and gluons are deconfined. One way to characterize the properties of the QGP is to use partons, quarks or gluons, from the hard scattering of the partonic constituents in the colliding nucleons as probes of the medium. Hard scattering occurs early in the collision evolution, prior to QGP formation. The high transverse momentum ($p_T$) partons produced in these scatters propagate through the expanding medium, and eventually fragment into jets of hadrons. The high-$p_T$ partons interact with the medium as they traverse through it, which will modify the fragmentation of the jets relative to proton-proton (pp) collisions. This modification is called jet quenching [1], and is the result of radiation or collisional energy loss of the high-$p_T$ parton.

At the LHC, there are three collisional systems that are available for analysis: pp, p–Pb and Pb–Pb. Jet measurements in pp collisions are an important baseline for the heavy-ion collisions, because while the production cross section of the initial hard scattered partons is calculable using perturbative Quantum Chromodynamics (pQCD), the measurements allow the
contribution from the non-perturbative hadronization processes to be calibrated. Measurements in p–Pb systems allow cold nuclear matter (CNM) effects to be quantified, which is key to understanding the modifications in Pb–Pb collisions.

2. Experimental Set-Up

The results reported in these proceedings are from data collected by the ALICE experiment in 2010 and 2011 at energies of 2.76 (pp and Pb–Pb), 5.02 (p–Pb), and 7 TeV (pp) per nucleon pair. Jets in ALICE are constructed from tracks measured in the ALICE tracking system and clusters measured by the Electromagnetic Calorimeter (EMCal). The tracks are from charged particles which are reconstructed with the Time Projection Chamber (TPC) and the Inner Tracking System (ITS), a six-layer silicon detector which provides precise measurement of the primary vertex location. The Silicon Pixel Detector (SPD), the two inner layers of the ITS, which has an acceptance in pseudorapidity of $|\eta_{lab}| < 1.4$, is also used in order to select high quality tracks which correspond to tracks from the primary collision. Tracks are reconstructed at mid-rapidity ($|\eta_{lab}| < 0.9$) and in full azimuth down to a transverse momentum ($p_T$) of 0.15 GeV/c. The EMCal is a Pb-scintillator sampling calorimeter, which measures energy from neutral particles that interact electromagnetically, which consist mainly of photons and $\pi^0$s. The clusters are reconstructed at mid-rapidity ($|\eta_{lab}| < 0.7$) and in azimuth with an acceptance of $\Delta \phi = 100^\circ$ down to a cluster energy of 0.30 GeV. The ALICE VZERO scintillator detectors, which cover $2.8 < \eta_{lab} < 5.1$ and $-3.7 < \eta_{lab} < -1.7$, measure the forward particle multiplicity so they are used to determine the event centrality in Pb–Pb and p–Pb events. The VZERO detectors are also used to define the minimum-bias interaction trigger and also to select central events in Pb–Pb collisions. For a complete description of the ALICE detector see [2].

3. Jet reconstruction in ALICE

The jets measured by ALICE detector are placed into two categories: charged jets and full jets. The former are jets that are reconstructed only from charged particles measured with the ALICE tracking system, and are not corrected for the missing neutral energy. These jets are corrected for effects such as the tracking efficiency and resolution based on simulations of jets with PYTHIA [3, 4], with the detector response simulated by GEANT3 [5]. Full jets, which will be referred to as jets for the rest of these proceedings, include the neutral energy component measured by the EMCal, and these are corrected for all detector effects similarly as done for charged jets.

The collection of tracks and EMCal clusters corrected for charged particle contamination, are clustered into jets using the anti-$k_T$ or the $k_T$ algorithms [6, 7, 8, 9] with a resolution parameter of $R = 0.2-0.6$ and with the boosted $p_T$ recombination scheme. In order to limit edge effects, only jets that are at least $R$ away from the acceptance boundaries of the TPC or EMCal are used in the analyses described here. The jets found by the anti-$k_T$ algorithm are used to determine the signal jets in the pp, p–Pb and Pb–Pb analyses, whereas the jets found by the $k_T$ algorithm are used to quantify the underlying event density in the p–Pb and Pb–Pb analyses.

4. Results from pp

Jet measurements in pp collisions are needed as baseline measurements in order to quantify the modification of the jet spectrum in heavy-ion collisions due to the presence of the QGP. Two important baseline measurements are the differential jet cross-section in $\sqrt{s} = 2.76$ TeV and the charged jet cross section at $\sqrt{s} = 7$ TeV. The measured jets were corrected back to the particle level utilizing a simulation based bin-by-bin technique [10]. Figures 1 and 2 show the inclusive differential jet cross section at $\sqrt{s} = 2.76$ TeV obtained with $R = 0.2$ and $R = 0.4$ compared to pQCD calculations at NLO with and without hadronization effects [11]. After the inclusion of hadronization and the parton shower, the calculations agree with the measured
Figure 1. The inclusive differential jet cross section at $\sqrt{s} = 2.76$ TeV obtained with $R = 0.2$ compared to NLO pQCD calculations with and without hadronization effects [10].

Figure 2. The inclusive differential jet cross section at $\sqrt{s} = 2.76$ TeV obtained with $R = 0.4$ compared to NLO pQCD calculations with and without hadronization effects [10].

Figure 3. Charged jet cross sections measured in the ALICE experiment in pp collisions at $\sqrt{s} = 7$ TeV compared to several MC generators: PYTHIA AMBT1, PYTHIA Perugia-0 tune, PYTHIA Perugia-2011 tune, HERWIG, and PHOJET. Bottom panels: Ratios MC/Data. Shaded bands show quadratic sum of statistical and systematic uncertainties on the data drawn at unity [12].

spectrum, which indicates that jet formation is well understood. This is especially important for jets with a small cone size, which are often used in heavy-ion analyses as small jets are less affected by the underlying event than larger jets. Additional analysis details can be found in [10]. Figure 3 shows the inclusive differential charged jet cross section at $\sqrt{s} = 7$ TeV obtained with $R = 0.2$, 0.4 and 0.6 compared to PYTHIA and HERWIG simulations [12]. There is good agreement between the measured spectra and the Perugia 2011 tune of PYTHIA and HERWIG. This analysis is used to construct the pp reference for the 5.02 TeV jet $R_{pp}$, as there is no
Figure 4. The solid circles show the $R_{p\text{Pb}}$ as a function of $p_{T,jet}$ for $R = 0.4$ charged jets in minimum-bias p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The reference used was the measured spectrum from pp collisions at $\sqrt{s_{NN}} = 7$ TeV scaled using PYTHIA. The solid boxes around the points are the systematic uncertainties from the detector effects, background fluctuations and unfolding. Uncertainties in the reference and the Glauber model are shown as a small box about $R_{p\text{Pb}} = 1$ [13, 14].

5. Results from p–Pb

Cold nuclear matter (CNM) effects such as shadowing or the nuclear modification of the parton distribution function (PDF) can cause the jets measured in p–Pb to be modified compared to pp collisions. These measurements are necessary in order to quantify how much of the jet modification measured in Pb–Pb collisions is a result of hot nuclear matter effects. The results in these proceedings uses the data from p–Pb collisions at an energy of $\sqrt{s_{NN}} = 5.02$ TeV taken in the first months of 2013. The underlying event in p–Pb collisions is much less than in Pb–Pb collisions, however, a similar procedure was used to remove the contribution from the measured jet spectra. The background energy density, $\rho$, is calculated event-by-event and subtracted jet-by-jet using the formula $p_{T,jet}^{\text{rec}} = p_{T,jet}^{\text{raw}} - \rho \times A_{jet}$. For the full jet measurement, in order to reduce the effect of the limited EMCal acceptance, the charged track background density is measured in full azimuth and scaled using a factor that includes the electromagnetic contributions. The distribution of the region-to-region fluctuations around the mean background density is evaluated using the Random Cone (RC) approach. The distribution of $\delta p_T$ is calculated by $\delta p_T = \Sigma p_T - \rho \pi R^2$ for each event by randomly placing a cone with the same radius as the resolution parameter used for the jet finding algorithm into the acceptance and adding the transverse momenta of its constituents. The measured spectrum is corrected for background fluctuations and detector effects using an unfolding technique with a response matrix based on
the measured $\delta p_T$ distributions, and detector response from PYTHIA+GEANT simulations. The difference in the unfolded spectra between different algorithm choices, such as Bayesian and SVD, is taken as a systematic uncertainty.

The cold nuclear matter effects can be quantified by the nuclear modification factor, $R_{p\text{Pb}}$, from minimum bias collisions. This can be calculated as: 

$$R_{p\text{Pb}}(p_T) = \frac{dN_{p\text{Pb}}/dp_T}{d\sigma_{\text{inelastic pp}}/dp_T}.$$ 

The nuclear overlap function, $T_{p\text{Pb}}$, is calculated by 

$$<T_{p\text{Pb}}> = <N_{\text{coll}}>/\sigma_{\text{inelastic pp}},$$

where the number of binary collisions was calculated using a Glauber model. The reference for the charged jet $R_{p\text{Pb}}$ shown in Fig. 4 was created by scaling the measured $R = 0.4$ charged jet spectrum from 7 TeV shown in Fig. 3 using a bin-by-bin factor calculated with POWHEG NLO plus PYTHIA8 [13]. The scaling systematics were determined using PYTHIA, and a power-law interpolation-based scaling factor. For comparison, the charged hadron $R_{p\text{Pb}}$ is also shown [14]. The full jet spectra are shown for $R = 0.2$ and $R = 0.4$ jets in Figures 5 and 6. Calculations of PYTHIA, and NLO POWHEG with PYTHIA fragmentation agree well with the data [15]. The ratio of the data over the Monte Carlo, like the charged particle $R_{p\text{Pb}}$, is consistent with unity, which indicates that there is no large CNM effect on the jet spectrum in p–Pb collisions.

6. Results from Pb–Pb

One of the main experimental challenges in heavy-ion collisions is removing the contribution from the underlying event from jet observables. As discussed in Section 5, this is done for the jet spectra by determining the average background energy density event-by-event and subtracting
Figure 7. The inclusive charged jet spectra from the 10% most central events for $R = 0.2$, normalized by $N_{\text{coll}}$ versus the choice of leading charged track $p_T$ [16].

Figure 8. The inclusive $R = 0.2$ jet spectra with a 5 GeV/c leading charged track bias in 0-10%, 10-30%, and in pp collisions normalized by $N_{\text{coll}}$[17].

Figure 9. The $R = 0.2$ nuclear modification factor, $R_{AA}$, for 0-10% and 10-30% central events compared to YaJEM and JEWEL [17]. The spectra used to determine the $R_{AA}$ are shown in Figure 8.

it jet-by-jet. The geometric background fluctuations are also quantified by $\delta p_T$, which is larger in central Pb–Pb collisions than it is in p–Pb and thus will smear the resulting $p_T$, jet spectrum more than for the same jet resolution parameter in p–Pb. The smearing of the jet $p_T$ spectrum due to background fluctuations, as well as the smearing due to detector effects, is corrected on an ensemble basis in an unfolding procedure that is very similar to what was used in Section 5.
In order to remove combinatorial jets and achieve a stable result with the unfolding method for full jets, it was necessary to require that all jets have a track with $p_T > 5$ GeV/c. This selection does not introduce a large fragmentation bias above $p_T, \text{jet} = 30$ GeV/c, and is effective at removing the combinatorial jets from the sample. The unfolded $R = 0.2$ charged jet spectra from the 10% most central events versus the choice of leading track bias is shown in Fig. 7. Above 30 GeV/c the effect is small. The $R = 0.2$ full jet spectra for 0-10% and 10-30% are shown in Fig. 8. Additionally, the biased pp spectrum is also shown, the analysis details are described in Section 4, other than the inclusion of the bias.

The nuclear modification factor, $R_{AA}$, for $R = 0.2$ full jets in 0-10% and 10-30% is shown in Fig. 9. Jets are suppressed with an $R_{AA}$ of 0.28 ± 0.04 in 0–10% and 0.35 ± 0.04 in 10–30% collisions, independent of $p_T, \text{jet}$ within both the statistical and systematic measurement uncertainties [17]. Also shown are the results from two different models, YaJEM [18] and JEWEL [19]. For a brief summary of the models, see [17]. Both calculations are found to reproduce the jet suppression measured in these events with calculated $\chi^2$ of 1.690 for YaJEM and 0.368 for JEWEL, even though they take a very different approach to the inclusion of $\hat{q}$ into their calculations. In order to gain a better understanding of jet quenching, $R = 0.2$ charged jet spectra with a 3 GeV/c charged track bias relative to the reaction plane is measured, allowing for a determination of jet $v_2$. For this measurement, the average background and fluctuations are subtracted differentially with respect to the angle of the reaction plane, which decreases the $p_T$ smearing of the resulting jets. The $v_2$ was corrected for the finite $v_2$ resolution using a three sub-event method [20]. The result in the 5% most central events can be seen in Fig. 10, where the expectation is that $v_2$ should be minimal given the geometry in these most central collisions. The result in 30-50% central events is shown in Fig. 11, where the path-length dependence should be maximal [20]. We do not see a significant indication of a non-zero jet $v_2$ in the most central events, but the semi-central events hint at a non-zero $v_2$, though are compatible with zero given the large uncertainties.

**Figure 10.** Charged jet $v_2$ in 5% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at mid-rapidity. The jets are required to have a leading charged hadron with $p_T$ larger than 3 GeV/c [20].

**Figure 11.** Charged jet $v_2$ in 30-50% central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at mid-rapidity. The jets are required to have a leading charged hadron with $p_T$ larger than 3 GeV/c [20].
7. Conclusions
The jet spectra measurements from pp collisions at $\sqrt{s_{NN}} = 2.76$ and 7 TeV by ALICE were shown. These results are important in establishing a baseline for cold nuclear and hot nuclear effects. In p–Pb collisions, we see no evidence of large cold nuclear matter effects at high $p_T$, either compared to a pp reference scaled from $\sqrt{s} =$7 TeV, or using PYTHIA and a NLO POWHEG and PYTHIA calculations. In Pb–Pb collisions jets are suppressed, with $R_{AA} < 1$, with the largest suppression occurring in the most central events. Two models, YaJEM and JEWEL, give a fair comparison with the data. A jet $v_2$ measurement, which should allow a more differential understanding of jet quenching, is also shown, though drawing a significant conclusion is difficult with the current statistical and systematic precisions.

References