Recent results on jet physics from ALICE at the LHC

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Abstract. An overview of recent results on jet physics from the ALICE collaboration is presented. We mainly discuss azimuthal correlations and nuclear modification factors for both hadrons and jets. The very low $p_T$ tracking (> 150 MeV/c) capabilities of the ALICE detector associated to its electromagnetic calorimetry, allow to reconstruct both charged jets and full jets, with minimum bias on the jet fragmentation. A detailed measurement of the underlying event fluctuations will be discussed, as well as, jet spectra measurements, in pp and Pb-Pb collisions, using low constituent $p_T$ cuts and hadron-recoil jet correlations, which give a controlled way to subtract the combinatorial background.

1. Physics motivations
Jets are produced in hard scatterings of high energy quarks and gluons in the early stage of heavy-ion collisions. This allows to probe the hot and dense matter formed in these collisions. Jets can be used to study in medium energy loss and its path length dependence thanks to their strong interaction with the medium, which leads to a modification of their structure and to a redistribution of their energy. Experimentally, this can be seen as a marked reduction of their energy measured in a given reconstruction cone. Their fragmentation pattern is also expected to be modified. This phenomenon is called ”jet quenching” [1].

Many experimental observations such as the suppression of back-to-back azimuthal correlations, the suppression of inclusive hadron – or even jet – spectra can all be used in order to learn about in-medium energy loss. Comparing those to theoretical calculations provides insight into the density of the system.

Moreover, measurements of jets in proton-proton collisions provide the baseline needed for heavy-ion studies, and at the same time allow to test pQCD.

In these proceedings, an overview of recent results on jet physics from the ALICE collaboration is presented. We mainly discuss azimuthal correlations and nuclear modification factors, for both hadrons and jets.

2. Experimental setup
In ALICE, high $p_T$ particles or jets are reconstructed at mid-rapidity using either two or three sub-systems:

Charged particles are measured using the central tracking system [2] which consists of the Time Projection Chamber (TPC) and of the Inner Tracking System (ITS). Photons (mainly from $\pi^0$ decay) and electrons are in turn measured by the ALICE Electromagnetic Calorimeter (EMCal) [3].
The ALICE TPC measures the momentum of charged particles down to $p_T = 150$ MeV/$c$ over a pseudo-rapidity range of $|\eta| < 0.9$ and has a full azimuthal acceptance ($0 < \phi < 2\pi$).

The electromagnetic component of the jet energy (which is on average about $1/3$ of the total energy of a given jet) is measured by the ALICE EMCal. This is a SHASHLIK [2, 3] (Pb-scintillator) sampling electromagnetic calorimeter which is read-out by APDs. It covers $|\eta| < 0.7$ and has an energy resolution of $11%/\sqrt{E} + 1.7\%$. It has been fully installed in 2011: its azimuthal acceptance was increased to $\Delta\phi = 107^\circ$ allowing it to be used for jet physics.

3. Hadron $R_{AA}$

The first observable that we will consider is the nuclear modification factor of charged hadrons. This quantity is defined as the ratio of charged particle yields in Pb-Pb (to study final state effects) or in p-Pb (to study initial state effects) over the corresponding yield in pp collisions, normalize by $1/N_{\text{coll}}$ calculated from the Glauber model [4]. In the absence of nuclear modifications, hard processes are expected to follow the $N_{\text{coll}}$ scaling. The corresponding nuclear modification factor would then be unity ($R_{AA} = 1$).

![Figure 1. Left: Comparison of the nuclear modification factor for different particle species. Right: The hadron $R_{AA}$ measured by ALICE and CMS.](image)

Initial state effects have been quantified in p-A collisions: Using data at $\sqrt{s_{NN}} = 5$ TeV taken during the LHC p-A pilot run from September 2012, ALICE made a first measurement of $R_{p-A}$ [5] (from $0.5$ GeV/$c < p_T < 20$ GeV/$c$) which is found to be consistent with binary scaling, indicating that the Cronin effect [6] at LHC is very small (if not null) compared to the one measured at RHIC [7, 8, 9, 10, 11].

In order to estimate final state effects in the medium, ALICE also measured the hadron $R_{AA}$ [12] in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV up to $p_T = 50$ GeV/$c$. In central collisions ($0 - 5\%$ centrality) hadrons are losing a large part of their energy in the medium and are suppressed by a factor 6 at 7 GeV/$c$. However, the amount of suppression slowly decreases with increasing $p_T$. Above 40 GeV/$c$, hadrons are suppressed by a factor 2 and $R_{AA} \simeq 0.4 - 0.5$.

A comparison of the hadron nuclear modification factors (presented in the left panel of Fig. 1) for different particle species (unidentified particles, pions, Kaons and Lambdas) has also been made at the same center of mass energy of 2.76 TeV. Those measurements show a different behaviour at low $p_T$ (corresponding to the soft regime): the $\Lambda R_{AA}$ is close to unity at $p_T = 3$ GeV/$c$, whereas the Kaon and pion $R_{AA}$ are smaller. The $\Lambda/K$ ratio is found to be enhanced at intermediate $p_T$ but starting at $p_T \sim 8$ GeV/$c$ and above an agreement is found for all particles: the magnitude of the suppression is measured to be $R_{AA} = 0.2 - 0.3$ independent of the particle type.
The hadron $R_{AA}$ measured by ALICE and CMS (see right panel of Fig. 1) [12, 13] are in good agreement and the trend of those measurements is reproduced by a large number of theoretical predictions. Many of the theory extrapolations from RHIC, however, predict too strong suppression at the LHC [14]. It has been suggested that taking into account the running of $\alpha_s$ reduces the suppression [15]. Overall, a full quantitative understanding of energy loss and the medium density requires further theoretical work [16].

4. Di-hadron azimuthal correlations

The second observable that we will consider are di-hadron azimuthal correlations. To build such correlations, a high $p_T$ particle, called ”trigger particle” is selected and associated with all other particle in the event.

One of the first experimental measurement of jet quenching was performed by the STAR collaboration at RHIC [9]. In Au-Au collisions, the disappearance of the away side peak of a di-hadron $\Delta\phi$ correlations was observed first by STAR. This indicated substantial interactions as the hard-scattered partons traverse the medium. The near side peak, on the other hand, was found to be very similar in pp and Au-Au collisions, one interpretation of these observations is that there is a strong “surface bias” effect, i.e. that the trigger particle selects jets with a short in-medium path length and/or little energy loss.

The ALICE collaboration measured long range di-hadron $\Delta\eta$ – $\Delta\phi$ azimuthal correlations in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV (see Fig. 2) [17]. A different behaviour is found for low and high $p_T$ regimes: At low $p_T$ (3 GeV/c < $p_T^T$ < 4 GeV/c and 2 GeV/c < $p_T^A$ < 2.5 GeV/c), a clear near side ridge structure is seen and the away side is broad. A Fourier decomposition was made and the measured distribution is well reproduced by summing $v_n$ harmonics with $n = 1$ to $n = 4$. This suggests that in this $p_T$ range, the underlying physics is well described by hydrodynamics. At higher $p_T$ (8 GeV/c < $p_T^T$ < 15 GeV/c and 6 GeV/c < $p_T^A$ < 8 GeV/c) a different scenario is observed: the near side ridge is replaced by a ”jet” peak and in the away side a small recoiling jet distribution can be seen. In addition, the previous global fit fails indicating that the physics is different in this higher $p_T$ regime.

![Figure 2. Di-hadron $\Delta\eta$ – $\Delta\phi$ azimuthal correlations in Pb-Pb for two different $p_T$ regime (see text).](image)

However, those measurements do not give access to the full jet energy: they are limited by the fact that a high $p_T$ leading particle at LHC energies only carries about 50% of the energy of the corresponding jet. To overcome this limitation, we have to measure full jets.

5. Full Jets measurements

A jet can be defined at several levels: A hard scattering process will lead into a partonic shower (which can be seen as a parton jet) which after hadronization will generate a hadronic shower
(corresponding to a hadron jet). The charged tracks (particle jet) and the neutral energy of those hadrons will then be detected in the ALICE TPC and EMCal (see section 2). Experimentally, the jet energy has to be reconstructed. To do that, a simple algorithm consists in opening a cone, of a given radius $R$, around the jet axis and to sum the energy of all particles inside the cone. Sequential recombination algorithms, which have the advantage of collinear and infrared safety, can also be used. The $k_T$ (for background clusters) and anti-$k_T$ (for signal jets) algorithms [18, 19] from the FastJet package (with $0.2 \leq R \leq 0.4$) were used in the following analyses.

Analyses with charged jets using only tracking information (tracks with $p_T > 150$ MeV/c) and fully reconstructed jets including EMCal information (cluster energy with $E_T > 150$ MeV/c) have been performed.

Jet-by-jet, to avoid double counting, we correct for the energy contribution from charged particles to the energy measured with EMCal (hadronic correction). The contribution from the underlying event is also subtracted (see section 5.2). Background fluctuations have a large impact on the measured jet spectrum in Pb-Pb. A response matrix $R_{M_{pp}}$ containing the $p_T$ smearing due to background fluctuations is constructed from the measured $p_T$ distribution. The detector effects (efficiency, detector resolution) are corrected using a second response matrix $RM_{det}$. The two response matrices are combined to obtain the response matrix which will be needed for correcting the data using the unfolding procedure in order to obtain the results that will follow.

5.1. Inclusive differential jet cross-section in pp collisions

As a baseline (and as a reference for Pb-Pb analyses), in pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV, the inclusive differential jet cross-section was measured [20] at mid-rapidity (with an integrated luminosity of 13.6 nb$^{-1}$). Jets are measured over the transverse momentum range 20 to 125 GeV/c and are corrected using a bin-by-bin technique. Calculations based on Next-to-Leading Order perturbative QCD and PYTHIA 8 are in good agreement with the measurements (see Fig. 3). The ratio of inclusive jet cross-sections for jet radii $R = 0.2$ and $R = 0.4$ (see Fig. 4) is well reproduced by a Next-to-Leading Order perturbative QCD calculation when hadronization effects are included.

![Figure 3](image-url) **Figure 3.** Upper panel: inclusive differential jet cross section for $R = 0.4$. The bands show the NLO pQCD calculations. Lower panels: ratio of NLO pQCD calculations to data.

![Figure 4](image-url) **Figure 4.** Ratio of inclusive differential jet cross sections for $R = 0.2$ and $R = 0.4$, with pQCD calculations.
5.2. Background estimation and fluctuations in Pb-Pb
One of the main experimental difficulties of measuring jets in heavy-ion collisions is the estimation and the subtraction of the fluctuating background (contribution from the underlying event).

In ALICE, the background energy density is estimated by clustering the whole event with the $k_T$-algorithm and calculating the density $\rho = \text{median}(\rho_{\text{jet}})$ (where $A$ is the area of a given jet $i$) for every jet except the two leading ones as proposed in [21]. The average background density is then subtracted from the $p_T$ of signal jets (found using anti-$k_T$) as $p_{T,\text{sub}} = p_T - \rho \times A$. $\rho$ which was estimated for charged only (using 2010 data [22]) and full (charged + neutral) jets (using 2011 data [23]), scales with the event multiplicity [22]: $\rho \sim N \times <p_T>$.

In addition, point-to-point background fluctuations $\delta p_T$ were estimated [22] by placing random cones in the measured events, or by embedding a known (high $p_T$) probe in the event and then looking at the collection of jets found by the anti-$k_T$ algorithm and matched to the embedded probe, in this event, the corresponding $\delta p_T = p_{T,jet} - \rho \times A - p_{T,\text{probe}}$. The $\delta p_T$ distribution is then fitted with a Gaussian and the width ($\sigma$) of the distribution is extracted. The corresponding $\sigma_{\text{ch}}$ and $\sigma_{\text{ch}+\text{em}}$ were estimated for a given jet radius from $R = 0.2$ to $R = 0.4$. For smaller reconstructed jets radii, the total energy inside the cone is smaller and consequently, the corresponding background fluctuations are also reduced. $\sigma_{\text{ch}} \approx 10 \text{ GeV}/c$ was measured for $R = 0.4$ compared to $\sigma_{\text{ch}} \approx 4.5 \text{ GeV}/c$ for $R = 0.2$. When neutral particles are included, the jet energy resolution increases, but the background fluctuations also become larger: $\sigma_{\text{ch}+\text{em}} > \sigma_{\text{ch}}$.

For instance, for $R = 0.3$, $\sigma_{\text{ch}+\text{em}} \approx 9 \text{ GeV}/c$ and $\sigma_{\text{ch}} \approx 7 \text{ GeV}/c$.

5.3. Jet spectrum in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV
Two analyses have been performed:

The first one [24] uses data from 2010 and is only using jets from charged particles. For this analysis jet radii of $R = 0.2$ and 0.3 were used. The minimum $p_T$ of the jet constituents is $p_{T,\text{const}} = 0.15 \text{ GeV}/c$. All jets with a jet axis within $|\eta| < 0.5$ were considered.

In order to reduce the number of combinatorial background jets, which helps to stabilize the unfolding procedure, the transverse momentum of the leading track of a given jet was required to be $p_{T,\text{leading}} > 5 \text{ GeV}/c$. The effect of this selection on the corrected spectra was found to be small in the case of this analysis. To quantify it, the inclusive spectrum was compared to the ones obtained using $p_{T,\text{leading}} > 5 \text{ GeV}/c$ and $p_{T,\text{leading}} > 10 \text{ GeV}/c$. The corrected spectra (using $R = 0.3$ jets) is shown in Fig. 5 (left panel). A centrality evolution (using 4 centrality classes from $0 - 10$ to $50 - 80\%$) of the yield of jets, is observed. In addition, a ratio of the spectrum using $R = 0.2$ devided by the spectrum using $R = 0.3$ jets shows that there is no significant jet broadening (from $R = 0.2$ to $R = 0.3$).

A second analysis was made [25], following the same strategy but using fully reconstructed (including both charged and neutral particles) $R = 0.2$ jets from 2011 Pb-Pb data. This full jet spectrum (shown Fig. 6 on the left panel) was obtained using the 10% most central events. As for the charged jet analysis (see above), the effect of the leading constituent track transverse momentum cut was studied using both $p_{T,\text{leading}} > 5 \text{ GeV}/c$ and $p_{T,\text{leading}} > 10 \text{ GeV}/c$.

6. Jet nuclear modification factors
Using the charged jet spectrum measured in 4 centrality classes [24] from 2010 Pb-Pb data, a jet $R_{CP}$ was obtained in 3 centrality classes (from $0 - 10\%$ to $30 - 50\%$), using the spectrum measured in $50 - 80\%$ centrality as a reference (see Fig. 5 central panel).

A strong jet suppression, similar to the hadron $R_{AA}$, is observed for central events. For more peripheral events the suppression decreases. This implies that the full jet energy is not captured by jets with $R = 0.2$ and $R = 0.3$ in Pb-Pb collisions.
If we compare those measurements to other measurements from LHC (see Fig. 5 right panel), the jet $R_{CP}^{jet}$ from ALICE, CMS and ATLAS [26] are consistent within systematic errors.

Using the full jet spectra [25] from 2011 data, combined with the differential cross-section measured in pp collisions (see section 5.1), a full jet nuclear modification factor $R_{AA}^{jet}$ was built.

A strong suppression is observed (see Fig. 6 central panel) for $R = 0.2$ jets (in the 0 – 10% centrality class). At low jet $p_T$ this suppression decreases with $p_T$. At high $p_T$ the jet $R_{AA} = 0.3-0.4$. These results are consistent with the CMS $R = 0.2$ results from the 5% most central events (see Fig. 6 right panel) [27], despite the differences in the detector configurations as well as in jet finding and background subtraction procedures. As explained in section 2, in ALICE, jets can be found using tracking and electromagnetic calorimetry, whereas CMS uses particle-flow jets, which combine information from three detectors (tracker, electromagnetic and hadronic calorimeters).

In order to fully quantify the measured jet quenching, additional measurements are ongoing in order to study the radius and the centrality dependence of $R_{AA}^{jet}$.

**Figure 5.** Left: Corrected jet spectrum and $R_{CP}^{jet}$ (central panel) with charged tracks for jet radius $R = 0.3$. Right: Jet $R_{CP}^{jet}$ from ALICE compared to CMS and ATLAS results.

**Figure 6.** Corrected spectrum (left panel) and $R_{AA}^{jet}$ (central panel) of fully reconstructed jets (reconstructed using $R = 0.2$ and requiring a high $p_T$ leading track $p_T > 5$ GeV/c) in the 0–10% centrality bin. Right: ALICE $R_{AA}^{jet}$ compared to CMS $R = 0.2$ results from the 5% centrality bin.

**7. Hadron-jet correlations**

Both di-hadron and hadron-jet correlations are sensitive to the di-jet structure expected from hard scattering.

Model calculations show that a high $p_T$ hadron trigger induces a geometrical bias [28], towards jets generated close to the surface of the fireball. The jet population recoiling from such a trigger is biased towards larger in-medium path length.
To exploit that effect, a jet-hadron measurement was made [29], using 2010 Pb-Pb data, based on the semi-inclusive distribution of reconstructed charged particle jets (using anti-$k_T$ with $R = 0.2$ and 0.4) recoiling from a high $p_T$ trigger hadron.

The distribution of recoil jets is measured by counting the number of jets in the event within $\phi$ (trigger) $\leq \phi$ (jet) $\leq \pi - 0.6$ and normalized to the corresponding number of triggers. Hadron triggers are selected with $p_T > 10$ GeV/c in order to select a single hard process in the collision.

The recoil jet distribution (measured in $0 - 20\%$ central Pb-Pb collisions), plotted as function of the jet $p_T^{ch} = p_T^{reco} - \rho \times A$, is shown Fig. 7 (left panel). For jet $p_T < 20$ GeV/c the shape of the distribution is identical for all choices of trigger $p_T$. This $p_T$ region corresponds to combinatorial background jets. For jet $p_T > 20$ GeV/c a clear evolution with the trigger $p_T$ can be seen. This region, dominated by high $Q^2$, corresponds to the “signal” part of the recoil jet spectrum which depends strongly on the trigger $p_T$ (as a consequence of the trigger bias effect: the $p_T$ of selected partons increases while increasing the trigger $p_T$).

To get rid of the combinatorial jets (in a purely data driven way [30]), the difference (called $\Delta_{recoil}$) of two measured jet distributions (with hadron triggers in different $p_T$ intervals) is used:

$$\Delta_{recoil}(p_T, jet) = Y(p_T^{max}; p_T^{min}, p_T^{max}) - Y(p_T^{max}; p_T^{min}, p_T^{max})$$

with

$$Y(p_T^{max}; p_T^{min}, p_T^{max}) = \frac{1}{N_{tr}} \int \frac{dN}{dp_T^{ch}}$$

In addition, this method does not impose any bias on the fragmentation of the recoil jets.

The resulting $\Delta_{recoil}$ distribution (which is free of combinatorial jets) is then unfolded using both $\chi^2$ minimization and the Bayes theorem. The difference between the two methods contributes to the anti-correlated shape uncertainty shown in Fig. 7 (right panel).

The ratio $\Delta_{IAA} = \Delta_{Pb-Pb} / \Delta_{PYTHIA}$ of the measured recoil distribution over the same distribution from PYTHIA is shown Fig. 7 (right panel).

This measurement was made for $R = 0.2$ and $R = 0.4$ jets with $p_T^{const} > 0.15$ GeV/c and $p_T^{const} > 2$ GeV/c. Overall, $\Delta_{IAA} \simeq 0.6 - 0.7$ with no visible broadening of recoil jets from $R = 0.2$ to $R = 0.4$. In addition, the comparison of these distributions (relative to PYTHIA) does not indicate a large energy redistribution towards lower $p_T$ constituents.

ALICE has also measured [31] the hadron $I_{AA} = Y_{PbPb} / Y_{pp}$ (where $Y$ is the yield measured as the integral of a given $\Delta \phi$ correlation peak) from di-hadrons azimuthal correlations. On the away side a suppression by a factor two is seen (redistribution of the energy of the high
$p_T$ particle in the medium) which can be compared to $\Delta I_{AA}^{jet}$ from hadron-jet measurements: $\Delta I_{AA}^{jet} \geq$ hadron $I_{AA}$. We can also note that on the near side a $\sim 20\%$ yield enhancement was measured (effect of fragmentation after energy loss).

8. Summary

The inclusive differential jet cross-section measured in pp collisions is in good agreement with NLO pQCD calculations and provides an important reference for Pb-Pb studies. In heavy-ion collisions, the background contribution and its fluctuations have been studied in details. Jets are strongly suppressed in Pb-Pb collisions. This suggests significant out-of-cone radiation. Overall, hadron and jet observables tend to be in agreement ($R_{AA}^{jet} \sim$ hadron $R_{AA}$ and $\Delta I_{AA}^{jet} \geq$ hadron $I_{AA}$). Recoil jets are found to be significantly less suppressed than inclusive jets (a similar behavior exists for single particle i.e. $R_{AA}$ vs $I_{AA}$).

A qualitative agreement between experiments exists. However, the measurements are not directly comparable as they use different jet reconstruction techniques, background estimation, etc. An apple to apple comparison would help to build a coherent picture of jet quenching at LHC.

Comparing jet measurements to theory predictions is essential to learn about the medium properties but it is also a very challenging task, which requires close collaboration between theorists and experimentalists in order to find good observables or even to define a common framework. In the near future, more differential measurements using larger cone radii as well as the recent p-A run at LHC will provide some additional constraints.

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