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# First jet and high-$p_\mathrm{T}$ measurements with the ALICE experiment at the LHC

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**Summary.** — The Large Hadron Collider at CERN currently provides $\mathrm{p+p}$ collisions at center-of-mass energies of $\sqrt{s} = 7\,\mathrm{TeV}$, which allow to study high-$p_\mathrm{T}$ particle production and jet properties in a new energy regime. For a clear interpretation and the quantification of the medium influence in heavy-ion collisions on high-$p_\mathrm{T}$ observables, a detailed understanding of these elementary reactions is essential. We present first results on the observation of jet-like properties with the ALICE experiment and discuss the performance of jet reconstruction in the first year of data taking.

PACS `13.85.-t` – Hadron-induced high- and super-high-energy interactions (energy $> 10\,\mathrm{GeV}$).
PACS `25.75.Dw` – Particle and resonance production.

## 1. – Introduction

The ALICE experiment is the only dedicated heavy-ion experiment at the Large Hadron Collider (LHC). Its major goal is to study the creation of a new state of strongly interacting matter, the Quark-Gluon Plasma (QGP), which is expected to form when sufficiently high initial energy densities are attained in collisions of heavy nuclei.

To study the full evolution of the produced medium the usage of so-called *hard probes* is of particular interest. Parton-parton scatterings with large momentum transfer $Q^2$ (*hard*) [1] occur in the early stages of the reaction, in heavy-ion collisions well before the formation of an equilibrated medium. While in $\mathrm{p+p}$ collisions the partons evolve in the QCD-vacuum and fragment directly into jets of observable hadrons, the evolution in heavy-ion collisions is influenced by the presence of a medium with large density of color charges. Thus, scattered partons can lose energy via medium-induced gluon radiation or elastic scattering, with the amount of energy loss depending on the color charge and mass of the parton, the traversed path length, and the medium density [2-5].

One of the earliest predicted consequences has been the suppression of hadrons with large transverse momentum ($p_\mathrm{T}$) compared to the expectation from scaled $\mathrm{p+p}$ reactions [2, 3]. This comparison is usually done in a ratio of cross-sections in $\mathrm{p+p}$ and

$A+A$, the nuclear modification factor $R_{AA}$:

$$R_{AA} = \frac{\mathrm{d}^2 N_{AA}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}}{T_{AA}\cdot \mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\,\mathrm{d}p_{\mathrm{T}}}\,, \tag{1}$$

where $T_{AA}$ accounts for the increased number of nucleons in the incoming $A$-nuclei and is related to the number of binary collisions $N_{\mathrm{coll}}$ by $T_{AA} \approx N_{\mathrm{coll}}/\sigma^{\mathrm{pp}}_{\mathrm{inel}}$. In the absence of any medium effects and at sufficiently high $p_{\mathrm{T}}$, where hard scattering is the dominant source of particle production, $R_{AA}$ should be unity, any deviation from unity indicating the influence of the medium.

Indeed, already the first hadron measurements in Au+Au reactions at RHIC showed a hadron yield suppressed up to a factor of five and a suppression of jet-like correlation in central collisions [6-9]. This suppression can be explained by the energy loss of hard scattered partons via induced gluon bremsstrahlung in a medium with high color density, which is also supported by the absence of suppression in the yield of direct photons [10].

Up to now, most measurements of the medium modification of hard scattered partons are based on single particle measurements, which have been used to deduce jet-like properties such as back-to-back correlations, spectral shape/yield and their changes in heavy-ion collisions. This has the disadvantage that the population of each single particle $p_{\mathrm{T}}$-bin is highly biased towards a hard fragmentation. The bias can be largely reduced by reconstruction of full jets, which also allows for a detailed investigation of the expected modification of the jet structure [11] by comparing momentum distributions of particles in jets created in $A+A$ and $\mathrm{p}+\mathrm{p}$ reactions. However, the measurement of jets in heavy-ion collision is hindered by the presence of a large background and its fluctuation. It recently succeeded for the first time at RHIC energies of $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ (see, *e.g.*, [12]), but the potential of full jet reconstruction in heavy-ion collisions for a more quantitative understanding of the medium properties will only be exploited at LHC energies where the increase in jet cross-section allows for a better separation of the jet signal from the background in a larger kinematical range.

However, for a clear interpretation of all high-$p_T$ observables in heavy-ion collision a detailed understanding of $\mathrm{p}+\mathrm{p}$ reactions is essential. The comparison to predictions for the new energy regime reached at the LHC in $\mathrm{p}+\mathrm{p}$ collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, provides an important test of our theoretical understanding of the underlying processes in these elementary collisions. The ALICE detector with its excellent tracking and PID capabilities provides a versatile tool for the studies of jet structure and composition over a large dynamic range from jet transverse momenta of about $100\,\mathrm{GeV}/c$ during the first LHC run, down to particle $p_T$ of $100\,\mathrm{MeV}/c$ [13].

## 2. – Trigger-particle correlations

Particle correlations provide access to jet properties on an inclusive basis and have been traditionally used in kinematical regions where full jet reconstruction is difficult (*i.e.* lower center-of-mass energy, low transverse momenta). In the large background environment of heavy-ion collisions they provide the means to study jet-like properties down to very low $p_{\mathrm{T}}$ but at the cost of a trigger bias towards hard fragmentation and jets with only little energy loss.

Particle correlation functions have been measured by ALICE in $\mathrm{p}+\mathrm{p}$ collisions at $\sqrt{s} = 900$ and $7000\,\mathrm{GeV}$. An example is shown in fig. 1a), where the average correlation with respect to a trigger particle in a given trigger $p_{\mathrm{Tt}}$ is shown. The associated particles

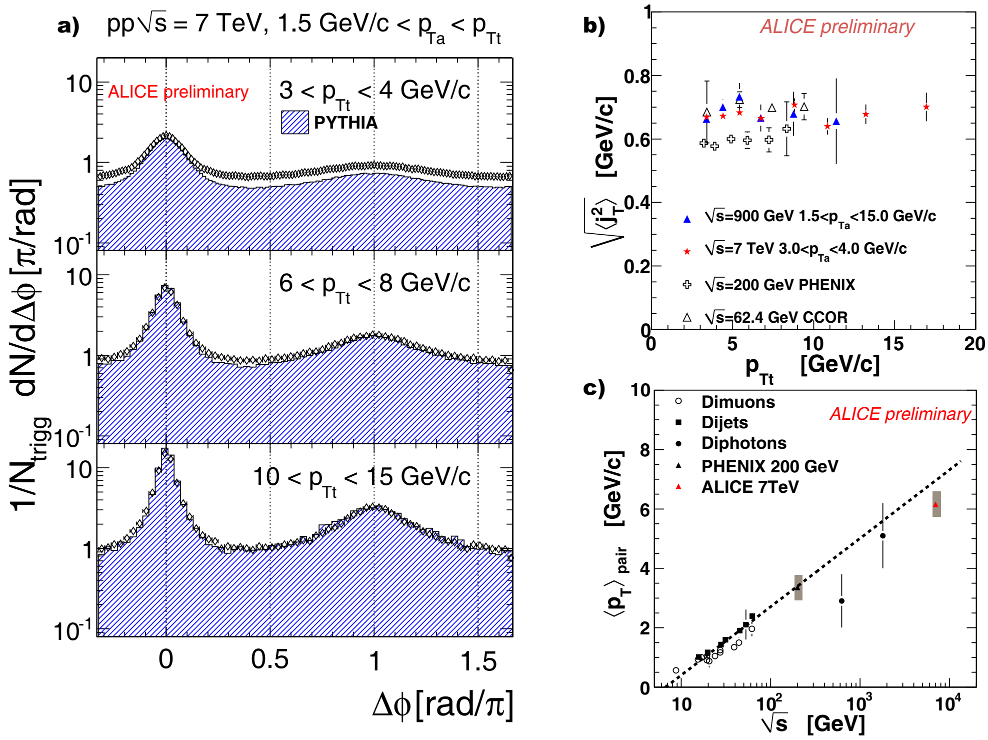

Fig. 1. – a) Correlation function for three different ranges of trigger $p_{\mathrm{T}}$ in $\mathrm{p}+\mathrm{p}$ collisions at $\sqrt{s_{\mathrm{NN}}} = 7\,\mathrm{TeV}$ compared to a PYTHIA simulation. b) $\sqrt{\langle j_{\mathrm{T}}^2\rangle}$ *vs.* the trigger $p_{\mathrm{T}}$ measured with the ALICE Experiment and compared to the values from CCOR and PHENIX [14, 15]. c) $\sqrt{\langle p_{\mathrm{T,pair}}^2\rangle}$ measured by ALICE at 7 TeV, compared to measurements at other $\sqrt{s}$.

are chosen in a $p_{\mathrm{T}}$ range from $1.5\,\mathrm{GeV}/c < p_{\mathrm{Ta}} < p_{\mathrm{Tt}}$. The expected back-to-back structure is clearly seen down to the lowest $p_{\mathrm{Tt}}$: a peak in direction of the trigger particle ($\Delta\phi = 0$, *near side*) and a peak at $\Delta\phi = \pi$ (*away side*).

The width of the distribution on the near side is only given by the non-perturbative fragmentation process, which leads to a transverse momentum component ($j_{\mathrm{T}}$) of the produced hadrons with respect to the direction of the original parton. Assuming a two-dimensional Gaussian distribution of the $x$ and $y$ components of the $j_{\mathrm{T}}$ vector, one can extract its mean value directly from the near-side width $\sigma_{\mathrm{N}}$ [15]:

$$\sqrt{\langle j_{\mathrm{T}}^2\rangle} = \sqrt{2\langle j_{\mathrm{T},y}^2\rangle} \approx \sqrt{2}\frac{p_{\mathrm{Tt}}p_{\mathrm{Ta}}}{\sqrt{p_{\mathrm{Tt}}^2 + p_{\mathrm{Ta}}^2}}\sigma_{\mathrm{N}}. \tag{2}$$

The results for different $p_{\mathrm{Tt}}$ and the two collision energies measured by ALICE are shown in fig. 1b) together with measurements from lower center-of-mass energies. Overall no change with either the trigger $p_{\mathrm{T}}$ or the center-of-mass energy is observed.

Due to the fact that the trigger particle direction fixes the near-side axis all effects of interjet-correlations are seen on the away-side. In particular deviations from the exact momentum balance of the outgoing partons lead to additional broadening of the away-side peak. It is expressed in terms of a net transverse momentum of the parton pair $\langle p_{\mathrm{T}}^2 \rangle_{\mathrm{pair}} = 2\langle k_{\mathrm{T}}^2 \rangle$. Here, $\langle k_{\mathrm{T}} \rangle$ denotes the effective magnitude of the apparent transverse momentum of each colliding parton caused mainly by a combination of the intrinsic transverse momentum of the incoming partons in the nucleons with initial and final state radiation. The momentum component of the away-side particle ($\vec{p}_{\mathrm{Ta}}$) with respect to the trigger particle ($\vec{p}_{\mathrm{Tt}}$) in the transverse plane is called $p_{\mathrm{out}}$. Its average value is related to the away-side width but can also be measured directly and is used to extract the magnitude of the momentum imbalance following [15]:

$$\frac{\langle z_{\mathrm{t}} \rangle}{\langle \hat{x}_{\mathrm{h}} \rangle} \sqrt{\langle k_{\mathrm{T}}^2 \rangle} = \frac{1}{x_{\mathrm{h}}} \sqrt{\langle p_{\mathrm{out}}^2 \rangle - \langle j_{\mathrm{T}y}^2 \rangle (1 + x_{\mathrm{h}}^2)}\,, \tag{3}$$

where $x_{\mathrm{h}} = p_{\mathrm{Ta}}/p_{\mathrm{Tt}}$ and all values on the right-hand side of the equation are measured. The mean momentum fraction from the original parton that is carried away by the trigger hadron $\langle z_{\mathrm{t}} \rangle$ can be calculated based only on the shape of the fragmentation function. $\langle \hat{x}_{\mathrm{h}} \rangle = \hat{p}_{\mathrm{Ta}}/\hat{p}_{\mathrm{Tt}}$ denotes the imbalance between near- and away-side momentum already at parton level. Since it depends on the magnitude of $k_{\mathrm{T}}$ it has to be determined iteratively. This procedure results in the average momentum imbalance of the parton pair at the highest $\sqrt{s}$ measured so far, it is shown in fig. 1c) and confirms the logarithmic increase of the net transverse momentum of the parton pair with the center-of-mass energy in nucleon-nucleon collisions.

## 3. – Fully reconstructed jets

Jets in ALICE are reconstructed using a variety of different algorithms: *e.g.*, sequential recombination algorithms (anti-$k_{\mathrm{T}}$ and $k_{\mathrm{T}}$), simple cone algorithms as well as the modern seedless and infrared safe cone (SISCone) algorithm. The variety is motivated by the different sensitivity to the background and different background subtraction schemes enabled by the various algorithms [16, 17].

The definitive procedure for measuring jets in ALICE will be via the combination of the central tracking system and the calorimetric information from the EMCAL [16]. Since the EMCAL represents an upgrade to the original ALICE setup, it has not been fully installed for the first period of data taking and currently only covers a limited acceptance. Thus the jet reconstruction in ALICE at present is based on the information from reconstructed tracks, *i.e.* only charged particles. When comparing these reconstructed jets to full particle jets the momentum scale is shifted to lower values by roughly a factor of 0.6 due to the missing neutral energy and the jet resolution is dominated by charged-to-neutral fluctuations in addition to the instrumental momentum resolution. The raw jet spectrum (not corrected for the aforementioned effects) from reconstructed tracks is shown in fig. 2 for different algorithms with a resolution parameter or cone size of $R = 0.4$ within $|\eta| < 0.5$, the input tracks are taken in the acceptance of $|\eta| < 0.9$. The results from all jet finders agree well in the region above $p_{\mathrm{T}} = 20\,\mathrm{GeV}/c$, where the effects of seed particles (UA1 cone algorithm) and split-merge algorithm (SISCone) become negligible, illustrating that in p + p collisions all jet definitions lead to a uniform picture. This will be tested again in Pb + Pb collisions, where the different susceptibility to background is more important.

The final measurement of the jet spectrum with charged particles will employ an unfolding method to fully account for the jet response of the ALICE detector. The

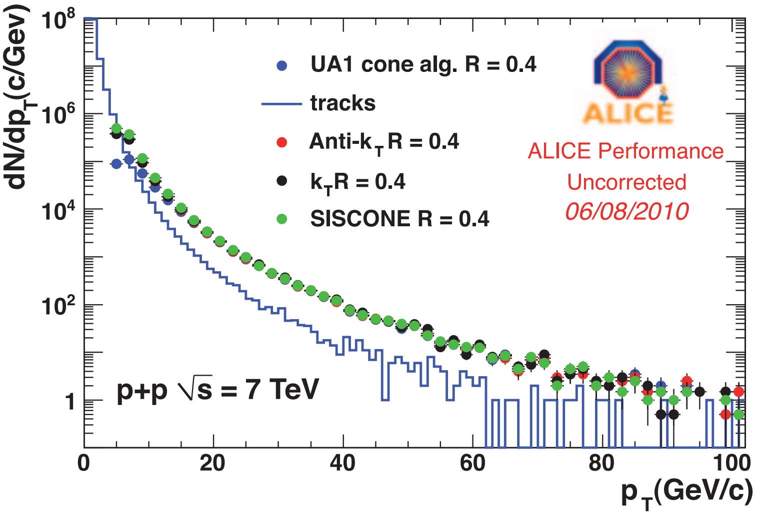

Fig. 2. – The raw number of jets reconstructed in $|\eta| < 0.5$ with different algorithms and $R = 0.4$, using 128 M minimum bias p + p collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. As comparison the input raw track momentum spectrum ($|\eta| < 0.9$) is also shown. Neither the jet energy-scale has been corrected, nor any other acceptance and efficiency corrections have been applied.

corrections will be done up to the level of charged particles accounting mainly for instrumental resolution, acceptance and efficiency, which can be compared to the same measurement in Pb + Pb. The correction up to the level of jets from all particles introduces a larger uncertainty due to the magnitude of the charged-to-neutral fluctuations, but it will allow to compare more directly to pQCD calculations and jet measurements by other experiments. The limitation in the response due to the missing neutral energy will be overcome with the addition of the EMCAL information after its completion to full acceptance.

## 4. – Jet finding in Pb + Pb

The first essential measurement in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.75\,\mathrm{TeV}$, which will be recorded in November 2010, is the determination of the overall multiplicity and thereby the level of background for the jet reconstruction and its fluctuation. In simulations for central Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$ the total amount of background energy is about 200 GeV in an area corresponding to $R \approx 0.4$, this can be determined and subtracted on a event-by-event basis. The fluctuations in the background within one event have been estimated to have a width of $B_i^A = 12\,\mathrm{GeV}$ when using the same area as above [16]. These can be corrected for in the inclusive jet measurement via an unfolding procedure, enabling the comparison of the jet spectra in p + p and Pb + Pb. The expected magnitude and precision of the nuclear modification factor for jets in one nominal year of data taking and including the EMCAL, is shown in fig. 3 for different values of the medium transport coefficient $\hat{q}$ [16]. It is clearly seen that jet measurements in ALICE will be sensitive to the change of $R_{AA}^{\mathrm{jet}}$ with increasing energy loss. A more discriminative measure, which will help to verify the effect of jet broadening is the ratio of the jet yields obtained with different resolution parameters $R$. It is also shown in fig. 3

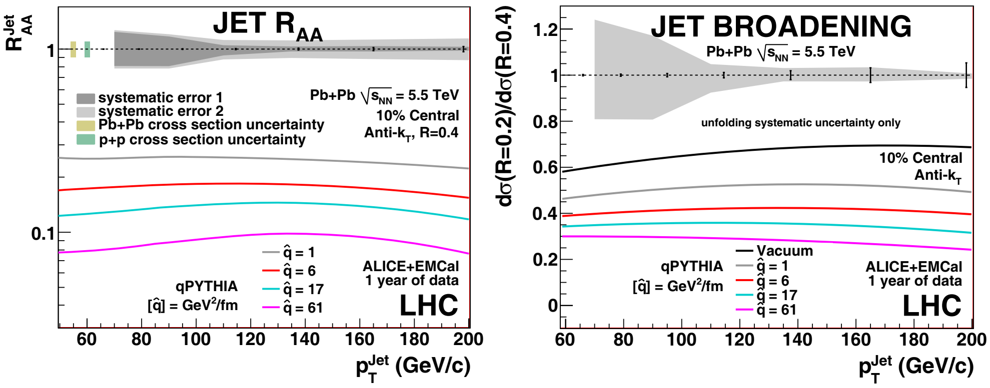

Fig. 3. – Expected performance of ALICE jet measurements in one year of nominal Pb + Pb data taking, jets measured with the anti-$k_\mathrm{T}$ algorithm and $R = 0.4$. Left: jet $R^{\mathrm{jet}}_{AA}$ simulated for different $\hat{q}$ with Q-PYTHIA at $\sqrt{s_{\mathrm{NN}}} = 5.5\,\mathrm{TeV}$. Right: ratio of inclusive differential jet cross-sections at different $R$ simulated for various $\hat{q}$ with Q-PYTHIA [16].

and illustrates how the energy within the jet is redistributed to larger distances from the jet axis, in this particular model due to modified splitting functions for the parton shower evolution in the medium [18]. These measurements will be complemented by a detailed comparison of momentum distributions within jets.

## 5. – Conclusions

We have presented the first results on particle correlations measured by the ALICE experiment in p + p collisions at the LHC, they give access to jet properties in a kinematical region which is difficult to access with full jet finding and provide the first measurement of the momentum imbalance of parton pairs in this energy regime. The detailed characterisation of reconstructed jets in p + p events at 7 TeV is currently going on and we await the first reconstruction of jets in heavy-ion collisions at the LHC in the fall of 2010.

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