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Jet fragmentation Monte Carlo study in vacuum and in medium in the ALICE experiment at the LHC

M. Estienne for the ALICE Collaboration
Subatech/Ecole des mines - 4 rue Alfred Kastler, 44300 Nantes, France

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Summary. — The production of jets in proton+proton ($p + p$) and heavy ion collisions (HIC) is of great interest to study perturbative quantum chromodynamics (pQCD) in vacuum and in medium. In particular, jets yield information on the way partons radiate inside them (and how the radiation is modified in the medium) and then fragment into hadrons. For clear understanding of the in-medium modifications, it is first mandatory to have a good control of the measurements in $p + p$ collisions in the ALICE experiment. After a discussion on the expected jet reconstruction performances, the results of a MC-based analysis on intrajet radiations are shown. An attempt to estimate the background contamination from the collisions is presented.

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1. – Introduction

In Quantum Chromodynamics a jet can be defined as a cascade of partons emitted from an initial hard scattering and followed by fragmentation. The way the parton shower evolves is driven by color coherence effect which is responsible for an angular ordering of the sequential parton decays. This phenomenon is also called intrajet coherence. To understand its origin, a simple model of jet cascade, namely, the radiation of soft photons from an e^+e^- pair in a QED shower can be considered [1]. The typical formation time for a photon of momentum k to be emitted independently from one of the two legs is $t_{form} \approx 1/k\theta_{\gamma e}^2 = \lambda_\perp/\theta_{\gamma e}$, as the transverse wavelength of the photon $\lambda_\perp = (k\theta_{\gamma e})^{-1}$, $\theta_{\gamma e}$ being the angle between one of the lepton and the photon. During this time, the e^+e^- pair separates the distance $d_{e^+e^-} = t_{form}\theta_{e^+e^-} \approx \lambda_\perp\theta_{e^+e^-}/\theta_{\gamma e}$, with $\theta_{e^+e^-}$ the angle between the e^+ and e^- legs. We observe that for large emission angle $d_{e^+e^-} < \lambda_\perp$ so that γ does not resolve the pair and the emission is not permitted. On the contrary, as long as $\theta_{e^+e^-} > \theta_{\gamma e}$, the radiation is possible. It is the Chudakov effect in QED [2]. Because of the presence of the two charges, the emission angle of the photon is constrained.

Exactly the same phenomenon occurs in QCD, the role of the charge being played by the color charge carried by the partons. However, as the emitted soft gluon (g_1) from a quark leg also carries a color charge (by contrast to the photon which has no charge), a second soft-gluon (g_2) emission in the leg is thus constrained by the previous emitted gluon giving rise to the angular ordering $\theta_{q\bar{q}} > \theta_{g_1 q} > \theta_{g_2 q}$. Color coherence is said to suppress soft radiations at large angles [1]. However, this effect is counterbalanced by a conflicting phenomenon which "forces out" particles to be emitted at an angle always bigger than a lower bound $\theta_{min} = (kR)^{-1}$ where k is the momentum of the last emitted parton and R the typical hadronization scale ($1/R \sim$ hadron mass) [3]. These conflicting tendencies are responsible for the shape of the so-called Hump-Backed Plateau (HBP) which summarizes how hadrons are distributed inside jets as a function of the $\xi = \ln(p_T^{jet}/p_T^{hadron})$ variable and especially its depletion in the high ξ region [3].

The Modified Leading Logarithmic Approximation (MLLA) model predicts the shape of the HBP [1, 4]. It contains two free parameters: a QCD scale and a stopping scale (hadron mass dependent) to end up the evolution of the parton shower. MLLA is usually supplemented by the Local Parton Hadron Duality (LPHD) hypothesis to model the hadronization procedure at the end of the shower assuming a one-to-one correspondence between a last emitted parton and a hadron via one parameter, K_{LPHD} [5]. The HBP measurements have already been performed in e^+e^- and $p+\bar{p}$ collisions in TASSO, OPAL and CDF experiments, respectively, in good agreement with the modified Gaussian shape predicted by MLLA + LPHD in the vacuum [6]. Such measurement in $p+p$ collisions at LHC is challenging for the ALICE experiment but the jet p_T range that can be studied from 30 to 200 GeV/c will be of interest to test pQCD in a kinematic range whose lower bound approaches its limit of validity. The dependence of the HBP on the hadron mass also motivates the study of jet hadrochemistry in $p+p$ collisions to constrain the stopping scale parameter of the model and the hadronization procedure hypotheses.

The second and main physics motivation to study the HBP in ALICE is to quantify the phenomenon of jet quenching [7] and to better understand hadronization in medium. In HIC, the medium should affect the fragmentation pattern of hard partons and has drastic effects on the jet structure itself. In particular, a softening of the fragmentation function (FF) is expected leading to the suppression of production of high-p_T particles (HBP depletion in the low-ξ region) as well as a numerous production of soft particles (HBP increase in the high ξ) [8]. Moreover, the interaction of a parent parton with a QCD medium should transfer color between projectile and target affecting the jet hadrochemistry. For instance, the chemical composition of a jet can be modified in the medium between the gluon projectile and the parton target or the flavor or baryon number can be exchanged between them modifying the final state hadrons [9].

In sect. **2**, we present the expected performances for jet reconstruction in ALICE. The feasibility of the FF measurement in MC $p+p$ collisions is discussed in sect. **3** emphasizing the experimental biases that have to be taken into account for a direct comparison with pQCD predictions. Some qualitative observations on intrajet observables are made and compared with color coherence effect expectations. Eventually, we present a study developed to get rid of the background contribution to the FF in sect. **4**.

2. – Jet reconstruction performances in $p+p$ and Pb + Pb collisions

ALICE is a multipurpose apparatus dedicated to particle measurements in the high-multiplicity environment of HIC at the LHC [10]. Its central barrel is mainly equipped with a Time Projection Chamber (TPC), a gas detector for charged track momentum measurement and particle identification coupled with the Inner Tracking System (ITS), a 6 layers silicon subsystem. ALICE has excellent tracking capabilities from low particle momenta ($p_T \sim 150\,\mathrm{MeV}/c$) to roughly $100\,\mathrm{GeV}/c$ with a $\delta p_T/p_T$ below 6% over the full range. It covers the full azimuthal range in the pseudorapidity window $|\eta| < 0.9$. During the first year of data taking, jets are reconstructed recombining only the charged particle momenta [11]. In 2011, when the EMCal calorimeter will be fully installed inside the L3 solenoidal magnet ($B = 0.5\,\mathrm{T}$), both track momenta and calorimeter cell energies will be combined to reconstruct the jet energy. In ALICE, a large variety of jet finders (based on cone or sequential algorithms [11]) with different sensitivities to the jet signal and event background is available. They have their advantages and drawbacks, nevertheless, as they are parameter dependent, they introduce biases in the reconstructed jet energy.

In $p+p$ collisions, the instrumental resolution for jet reconstruction using the tracking subsystems and calorimetry has been evaluated to 18–22% for jets of 50 to 200 GeV [12]. It accounts for the cumulative effect of experimental cuts, undetected neutral particles, tracking efficiency, and detector resolutions. Depending either on the physics observable studied or on the pQCD calculations available for direct comparison with the experiment, it might be required to quantify the bias introduced by the use of a limited cone size during jet finding as it leads to some out-of-cone (or splash-out) fluctuations of the signal. The use of a radius (R) of 0.4 implies a "global" energy resolution (including splash-out effect) of $\sim$ 30%. However, in the first year configuration, as only "charged" jets are reconstructed, the charged-to-neutral fluctuations add on top of the previous effects to shift the mean reconstructed energy relatively to the full jet energy by almost a factor of 0.6 and the resolution reaches $\sim$ 40% [13]. Depending on the experimental aims (observables, systems compared—$\mathrm{Pb}+\mathrm{Pb}$ relative to $p+p$—, to other experiments or to pQCD), it is possible to correct for these effects at different levels using unfolding techniques [11].

In $\mathrm{Pb}+\mathrm{Pb}$ collisions, jet reconstruction is more complicated than in elementary systems as the underlying event (UE) dramatically changes. The reconstruction is dominated by the influence of the high multiplicity of the event [11, 13]. To optimize the jet identification efficiency, the signal energy has to be much larger than the background fluctuations. Both the energy of the UE and its fluctuations inside a given cone can be reduced by reducing its radius which in return, increases the splash-out fluctuations. In $\mathrm{Pb}+\mathrm{Pb}$, the "global" energy resolution is thus expected to degrade to $\sim$ 35% [13]. A correction of the inclusive jet measurement via an unfolding procedure to enable a direct comparison of the jet spectra in $p+p$ and $\mathrm{Pb}+\mathrm{Pb}$ collisions will be the first step to achieve before to be able to compare their FFs. The second step is the determination of a background FF to be subtracted event by event to the raw HBP (sect. **4**).

3. – Particle distribution inside jet: a qualitative look at intrajet radiations

Figure 1 (left) shows the charged hadron momentum distribution measured inside 10–20 (squares), 20–30 (stars), 30–40 (triangles) and 40–70 GeV/c (circles) jets in a cone of radius 0.4 from a full PYTHIA simulation of $p+p$ collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ in ALICE as a function of the non-corrected ξ variable. This distribution cannot yet be called HBP as it includes several experimental biases that would need to be taken into account for direct comparison with theoretical predictions. In the MLLA, the initial parton energy which enters the computation of ξ is required to derive the FF in $p+p$ collisions. The

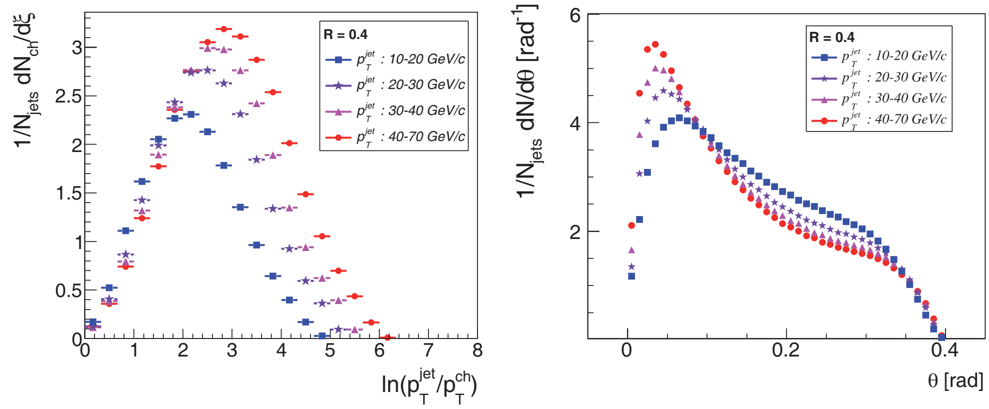

Fig. 1. – Left: charged hadron momentum distribution inside 10–20, 20–30, 30–40 and 40–70 GeV/c jets in PYTHIA p+p collisions at $\sqrt{s} = 7$ TeV. Right: θ angle distribution between the charged hadron momenta inside jet and its momentum (same experimental conditions).

same constraint should thus be applied to the experiment. A measurement of the jet energy corrected for the effects discussed in sect. **2** makes such measurement a challenge. On the one hand, a ξ shift towards the lower ξ values and a broadening of the HBP are expected due to these effects which underestimate and smear the reconstructed jet energy. On the other hand, the determination of the HBP in a limited angle ($R = 0.4$) biases its global shape in the high-ξ region by increasing the depletion in principle expected from the angular ordering only. Moreover, the bias may affect differently the distributions associated to different jet energy bins. In $p + p$ collisions, we can get rid of a great part of the splash-out fluctuations by increasing R to 0.7 [6] and only correct ξ for the instrumental resolution. In Pb + Pb, as a small radius is needed for the jet reconstruction, one has to deal with the signal and background fluctuation biases. They are still under study in ALICE. Despite the limitations quoted above, we observe the expected hierarchy of the non-corrected HBP with the jet p_T, namely, a shift of the maximum position in ξ towards the larger values. The more energetic the jet, the more phase space available for soft parton emissions in the shower. Real data are currently under analysis in order to extract the HBP over several bins of jet p_T.

One can qualitatively observe how particles are geometrically distributed in angle inside the jet with respect to its momentum direction by looking at their θ ($\vec{p}^{had} \cdot \vec{p}^{jet} = p^{had} \times p^{jet} \times \cos(\theta)$) distribution (fig. 1 (right)). Whatever the jet energy is, the number of particles increases while approaching the jet axis. The trend becomes more pronounced with more energetic jets in agreement with the idea of collimation. The distributions exhibit however quite a flat behaviour above $\theta = 0.2$ which suggests the presence of a non-negligible background of the $p + p$ collisions that will need to be subtracted. The 2-dimensional histograms presented in fig. 2 (left) show how the average θ of hadrons correlates with the fraction z ($= p_T^{had}/p_T^{jet}$) of jet p_T they carry. Both curves for 10–20 (squares) and 30–40 (circles) GeV/c jets follow a hyperbolic shape. We first observe that we have softer emissions at larger angles as expected from angular ordering. Second, the average θ of 30–40 GeV/c jets is always below the same distribution for lower p_T jets. It supports the collimation picture: on average, more particles are found at smaller angles over the full z range for higher p_T jets. The correlation of the hadron θ and p_T in

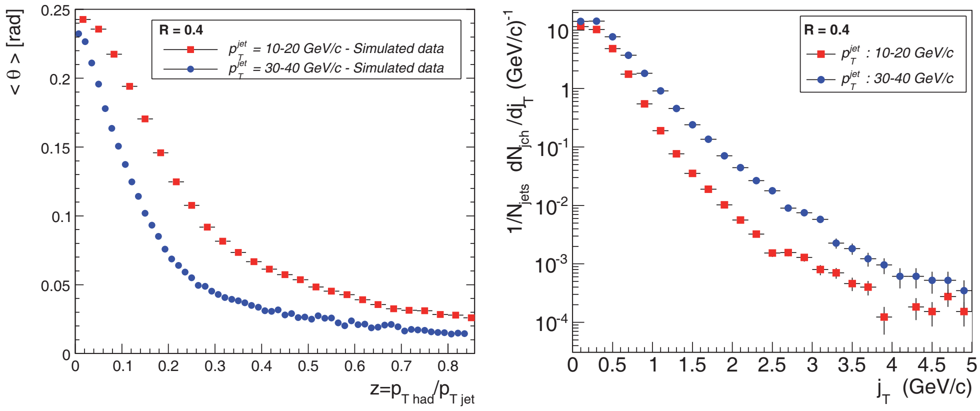

Fig. 2. – Left: average θ angle between the charged hadrons and the jet momenta for 10–20 and 30–40 GeV/c jets *vs.* their p_T fraction inside jet (z) in MC $p + p$ collisions at $\sqrt{s} = 7$ TeV. Right: j_T distribution of the hadrons in jets in the same experimental conditions as left.

jets is contained in the transverse momentum component ($j_T = p^{had} \sin(\theta)$) distribution of the produced hadrons with respect to the jet direction whose mean value should be approximately constant with the jet energy. The resulting distributions for 10–20 (squares) and 30–40 GeV/c (circles) jets reconstructed with $R = 0.4$ are addressed in fig. 2 (right). More hadrons are found in high-energy jets as the splitting probability is bigger. In both cases, high values of j_T are reached. For lower p_T jets it might come from the fact that this region is dominated by emissions at large angles whereas in higher-energy jets, it might be dominated by larger momentum hadron emissions.

The qualitative observations made in fig. 1 and 2 as manifestations of the color coherence effects suffer from some experimental limitations already partially discussed. They are threefold. First, the reconstructed jet energy has to be corrected as discussed in sect. **2**. Then, the presented distributions should be corrected for the track reconstruction efficiency. Eventually, the background from the UE of both $p + p$ and Pb + Pb collisions has to be subtracted before drawing any final physical conclusion. These analyses are currently under study on the $\sqrt{s} = 900$ GeV and 7 TeV $p+p$ real data but not yet presented as too preliminary. A first attempt to estimate the background contribution to the HBP in $p + p$ collisions is introduced in the next section.

4. – First subtraction attempt of the underlying event

The techniques developed below for background estimation in $p + p$ collisions will be of major importance and immediately applicable during the analysis of the Pb + Pb data which will be recorded from November 2010. 3500 PYTHIA $p+p$ events containing 100 ± 5 GeV jets (generated energy) have been produced to perform this preliminary study. All reconstructed jets were considered in order to test the method. In real data where the full jet p_T spectrum will be reconstructed, the method will be applied per bin of jet p_T.

A background FF to be subtracted to the raw HBP has been determined in two different ways. It has been first built event-by-event with $N_{out} \times A_{jet}/A_{bckg}$ charged hadrons taken randomly outside the leading jet (*out lead.* case), namely, outside a cone

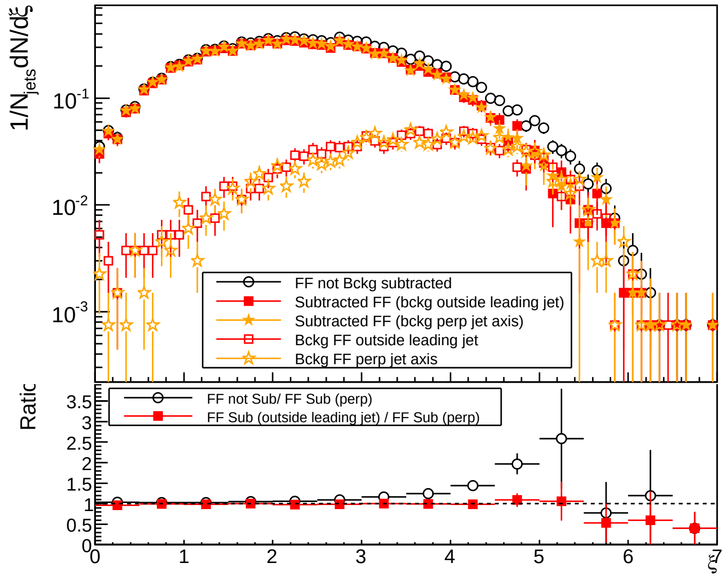

Fig. 3. – Top: comparison of the HBP before and after background subtraction and the background HBP using 2 methods for background estimation (see details in the text). Bottom: ratios of the non–background-subtracted HBP and the *outside leading jet* background-subtracted HBP to the *perpendicular* background-subtracted HBP.

of radius $R' > R$ centered around the jet axis, A_{jet} and A_{bckg} being the jet and background areas, respectively. The second method takes the charged hadrons inside a cone of radius R centered around the perpendicular direction in azimuth to the jet axis (*perp.* case). In both cases the FF distribution as a function of the $\xi^{bckg} = \ln(p_T^{jet}/p_T^{had\ backg})$ has been built. They are presented in fig. 3 (open squares = background *out lead.* and open stars = background *perp.*) together with the non-background–subtracted FF (open circles) and the FFs after subtraction (full squares = *out lead.* subtracted and full stars = *perp.* subtracted). As expected, the dominant contribution to the background coming from low-p_T hadrons, the background FF is peaked in the high-ξ region. We obtain quite good agreement between the two background estimates with some small deviations in the low ξ part. The *out lead.* techniques might contain contributions from high-p_T hadrons coming from a second jet present for instance in a di-jet event. The statistics being small in such ξ domain, the subtracted FFs exhibit no significant differencies as can be seen in the ratio *out lead.* over *perp.* (bottom figure, full squares). The contribution from the UE in contrast is clearly visible starting from $\xi = 2.5$ and above looking at the ratio *FF not subtracted* over *perp.* (bottom figure, open circles). The techniques will be applied to the distributions presented in the previous section and on real data.

5. – Conclusion

The FF measurement capabilities at the MC level in ALICE have been addressed. The real $p+p$ data at $\sqrt{s} = 7$ TeV are currently being analysed to extract the FF which will be background subtracted and corrected for jet and track reconstruction efficiencies.

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