The inclusive transverse momentum \((p_T)\) distribution of hadrons inside jets produced in PbPb and pp collisions are simulated with the YAJEM and PYTHIA6 Monte Carlo (MC) event generators. The effects of jet quenching are studied via the ratios of PbPb over pp hadron \(p_T\) spectra, either by accounting for the induced virtuality \(\Delta Q^2\) transferred from the strongly-interacting medium to the parton shower or by modifying the soft sector of the parton-to-hadron fragmentation functions. The MC results are compared to experimental jet data measured by the CMS experiment at a center-of-mass energy of 2.76 TeV in four jet \(p_T^{\text{jet}}\) ranges above 100 GeV, accounting or not for the experimental jet reconstruction biases. The level of data-MC (dis)agreement provides valuable information on the mechanism of parton energy loss.
1 Introduction

High-energy heavy-ion collisions provide the means to study the properties of QCD matter in the quark-gluon plasma (QGP) state. Highly virtual partons produced in such collisions experience a strong energy degradation as they travel through the strongly-interacting medium, resulting in the suppression of high transverse momentum leading hadrons [1–4] and jets [5,6]. The study of such “jet quenching” phenomena provides information on the thermodynamical and transport properties of the QGP [7]. Since the start of the heavy-ion program at the LHC, with its plethora of new hard observables available, new theoretical approaches have been developed to study the interaction of energetic partons with the hot and dense medium [8]. In particular, realistic Monte Carlo (MC) codes for the simulation of in-medium parton shower evolution have been constructed from “QCD vacuum” event generators [9–14] such as PYTHIA [15,16] and HERWIG [17]. JEWEL (Jet Evolution With Energy Loss) [9] implements elastic and inelastic medium interactions which lead to distinctive modifications of the jet fragmentation pattern, including Landau-Pomeranchuk-Migdal destructive interference effects in a probabilistic framework [18]. In Q-Pythia [13,14], medium effects are introduced via an extra term in the QCD splitting functions arising from the multiple-soft scattering approximation. In PYQUEN [10], gluon radiation is associated with each parton scattering in the hot and dense medium and interference effects are included through the modified radiation spectrum as a function of the medium temperature (i.e. see [19] for the computation of fragmentation functions with the PYQUEN MC). The MC used in this work, YAJEM (Yet Another Jet Energy-loss Model) [11,12], assumes in its default setup that the virtuality of partons interacting with the medium increases according to the medium transport coefficient connected to the virtuality gain per unit pathlength. Other extensions of the YAJEM code such as YAJEM-DE and YAJEM-E [20] simulate a showering process evolved down to a hadronization scale which depends on the parton’s energy and medium pathlength.

In the present paper we compute the inclusive transverse momentum ($p_T$) distribution of hadrons inside jets $dN/dp_T$ with the YAJEM and PYTHIA6 [15,16] codes. We construct the ratios of PbPb over pp spectra and compare them to experimental jet data measured by the CMS experiment at a center-of-mass energy of 2.76 TeV. In the PbPb case, it is assumed that the cascade of branching partons traverses a medium characterized by a local transport coefficient $\hat{q}$ such that at the end the virtuality of the leading parton is increased by a total $\Delta Q^2$ factor which widens the phase space and leads to the jet quenching. We consider also an alternative scenario based on the Borghini-Wiedemann (BW) model [21], where the singular part of the branching probabilities in the medium is increased by a multiplicative factor $1 + f_{\text{med}}$, such that $P_{a\rightarrow bc} = (1 + f_{\text{med}})/z + O(1)$, where $a \rightarrow bc$ describes the QCD parton branchings, i.e. $q(\bar{q}) \rightarrow q(\bar{q})g$ and $g \rightarrow gg$ with $g \rightarrow q\bar{q}$ unchanged. In this case, the jet quenching is described by the extra amount of medium-induced soft gluons ($f_{\text{med}} > 0$) as compared to the vacuum ($f_{\text{med}} = 0$) which widens the transverse jet shape. In both cases, the final parton-to-hadron transition takes place in the vacuum, using the Lund model [22], for hadronization scales below $Q_0 \approx 1$ GeV.

Aiming at performing a realistic comparison of YAJEM with the CMS data requires following the CMS data analysis as closely as possible. For this purpose, jets are first reconstructed from all particles by using the anti-$k_t$ algorithm [23,25] with a resolution parameter $R = 0.3$. Secondly, charged particles with $p_T > 1$ GeV are selected and reclustered within the $p_T^{\text{jet}}$ ranges $100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 120$, $120 \leq p_T^{\text{jet}}(\text{GeV}) \leq 150$, $150 \leq p_T^{\text{jet}}(\text{GeV}) \leq 300$ and $100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 300$ reported by the CMS collaboration [6]. The condition...
$p_t > 1$ GeV removes a very large underlying-event background but may bias the jet study. In order to illustrate the role of the bias caused by the jet-finding procedure and, particularly, that required by the CMS trigger which takes jets above $p_T^{\text{jet}} \geq 100$ GeV, we compare the data-driven “biased” ratios with the “unbiased” ratios obtained by analyzing the jets at the MC-truth level. Note that we use different notations for the hadron’s transverse momentum $p_t$, the final reconstructed $p_T^{\text{jet}}$, which is potentially lower ($p_T^{\text{jet}} < p_T^{\text{parton}}$) than the initial parton $p_T^{\text{parton}}$ as a result of the main biases such as (i) reconstruction for the jet resolution $R = 0.3$, (ii) charged particle selection, (iii) soft background removal $p_t > 1$ GeV and (iv) the aforementioned $p_T^{\text{jet}}$ cuts.

2 Monte Carlo analysis for the medium-modified $p_t$ distribution of hadrons via the PbPb/pp ratios

In the YAJEM code, the hard-scattered partons evolving into a jet shower are embedded in a hydrodynamical medium whose transport coefficient is taken to be

$$
\hat{q}(\zeta) = K \cdot 2 \cdot e^{3/4}(\zeta) F(\rho(\zeta), \alpha(\zeta))
$$

(1)

with

$$
F(\rho(\zeta), \alpha(\zeta)) = \cosh \rho(\zeta) - \sinh \rho(\zeta) \cos \alpha(\zeta),
$$

where $\epsilon$ is the local energy density of the hydrodynamical medium, $F$ is a hydrodynamical flow correction factor accounting for the Lorentz contraction of the scattering centers density as seen by the hard parton for $\rho(\zeta)$, which is the local flow rapidity and $\alpha(\zeta)$, the angle between the hydrodynamical flow and the parton propagation direction. For a shower parton $a$, created at a time $\tau_a^0$ and evolving during $\tau_a$ before branching into a pair of offspring partons, the fully-integrated virtuality as propagated inside the shower code can be obtained from (1) and is given by

$$
\Delta Q^2 = \int_{\tau_a^0}^{\tau_a^{0+\tau_a}} d\zeta \hat{q}(\zeta),
$$

(2)

which widens the available phase space from $Q^2 \rightarrow Q^2 + \Delta Q^2$ and therefore, the probability for extra (medium-induced) radiation. The integration in Eq. (2) is taken over the eikonal trajectory of the parton-initiated shower from the production vertex to the exit from the medium. As explained in the introduction and also in [27], where more details are given on the YAJEM code description, the QCD splitting functions in the BW prescription are enhanced in the infrared sector by the medium parameter $f_{\text{med}}$ which is related to the hydrodynamical evolution sketched above [21]. The dimensionful parameter $K$ in Eq. (1) characterizes the strength of the coupling between partons and the medium which can be obtained by tuning the measured hadron suppression factor $R_{AA}(p_t)$ with the RHIC data in central 200 GeV AuAu collisions (see Ref. [12]).

Although this analysis is similar to the one used in [27] for the computation of fragmentation functions and its ratios, we explain the main steps in this section. The initial $p_T^{\text{parton}}$ distribution of gluon and quark jets produced in pp (PbPb) collisions are simulated by sampling the convolution product of the (nuclear) parton distribution functions (n)PDFs with the matrix elements of the partonic hard scattering cross-section at 2.76 TeV. The nPDFs and PDFs are provided by the EKS [28] and CTEQ [29] global-fits for heavy ions and hadron-hadron collisions in the medium and vacuum respectively. The starting random selection of 200000 dijets with center-of-mass energy $\sqrt{s} \sim 2p_T^{\text{parton}}$ on the intervals $100 \leq p_T^{\text{parton}}(\text{GeV}) \leq 120$, $120 \leq p_T^{\text{parton}}(\text{GeV}) \leq 150$, ...
150 \leq p_T^{\text{parton}}(\text{GeV}) \leq 300 \text{ and } 100 \leq p_T^{\text{parton}}(\text{GeV}) \leq 300 \text{ as input to YAJEM and PYTHIA6 is convenient for obtaining as small uncertainties and more accurate predictions as possible in the final comparison of the ratios with the CMS data. The next step involves the reconstruction of jets by using the anti-}k_t\text{ algorithm }[24,25]\text{ for each } p_T^{\text{parton}}\text{ range inside the jet cone of resolution } R = 0.3 \text{ with charged particles only, as in the CMS experiment.}

Reconstructed jets can be sorted by } p_T^{\text{jet}} (p_T^{\text{jet}} > p_T^{\text{jet}} > \ldots)\text{ for the analysis such that the most hardest one } (p_T^{\text{jet}}) \text{ can be randomly selected from its “almost” back-to-back pair } (p_T^{\text{jet}}) \text{ event-by-event. The final cuts applied to each } p_T^{\text{parton}}\text{ range, so as to match the experiment trigger selection, are } p_T^{\text{jet}} \geq 100 \text{ GeV, } p_T^{\text{jet}} \geq 120 \text{ GeV, } p_T^{\text{jet}} \geq 150 \text{ GeV and } p_T^{\text{jet}} \geq 100 \text{ GeV respectively. The theoretical fractions of gluon jets } “f_g” \text{ following directly from the initial distribution of partons were given in }[27]\text{ for each } p_T^{\text{parton}}\text{ range and found to be } \sim 30\% \text{ in average. However, after the trigger selection is applied, these fractions in each sample decrease dramatically, and especially for much narrower } p_T^{\text{parton}}\text{ ranges such as } 100 \leq p_T^{\text{parton}}(\text{GeV}) \leq 120 \text{ and } 120 \leq p_T^{\text{parton}}(\text{GeV}) \leq 150 \text{ where the resulting fraction due to the jet selection } p_T^{\text{jet}} \geq 100 \text{ GeV is biased to } 10^{-4} [27].}

For each sample, we construct the mixed inclusive transverse momentum (p_t) distribution of hadrons and the ratio given by,

$$
\left( \frac{dN_h}{dp_t} \right)_{\text{mixed}} = f_g \left( \frac{dN_h}{dp_t} \right)_{g} + (1 - f_g) \left( \frac{dN_h}{dp_t} \right)_{q}, \quad r = \frac{\left( \frac{dN_h}{dp_t} \right)_{\text{med}}}{\left( \frac{dN_h}{dp_t} \right)_{\text{vac}}} - 1.
$$

(3)

such that hadroproduction is enhanced for } r > 0 \text{ and suppressed for } r < 0. Experimentally, the ratios have been displayed as } (\text{PbPb/}pp - 1) \text{ by the CMS collaboration }[6]. \text{ In Figs. 1 and 2 we compare the final results of our MC simulations, for the mixed ratios } r \text{ obtained from YAJEM/PYTHIA6 for } \langle \Delta O^2 \rangle \sim 6 \text{ GeV}^2 \text{ and YAJEM+BW/PYTHIA6 for } \langle f_{\text{med}} \rangle \sim 0.4 \text{ in the BW model, with the CMS data in each } p_T^{\text{jet}}\text{ range after averaging over a large amount of events in the hydrodynamical medium. As for the fragmentation functions discussed in }[27], \text{ the YAJEM+BW/PYTHIA6 ratios fail at describing the shape and thereby, the physical features of the jet quenching phenomena in this framework. The biased and unbiased YAJEM/PYTHIA6 are displayed in the same panels together with the data. The unbiased ratios are softer at small } p_t \text{ (i.e. below 10 GeV) for all } p_T^{\text{jet}}\text{ ranges and much harder than the experimental ratios especially for } 100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 120 \text{ and } 120 \leq p_T^{\text{jet}}(\text{GeV}) \leq 150. \text{ In Fig. 2 the biased ratios YAJEM/PYTHIA6 are closer to the CMS data, but the difference between the biased and unbiased ratios is not as large as in the other cases.}

## 3 Summary

In this paper we compared the inclusive hadron } p_t\text{ distributions computed with the YAJEM and PYTHIA6 MC simulations with recent CMS PbPb and pp jet data in the } p_T^{\text{jet}}\text{ ranges } 100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 120, 120 \leq p_T^{\text{jet}}(\text{GeV}) \leq 150, 150 \leq p_T^{\text{jet}}(\text{GeV}) \leq 300 \text{ and } 100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 300 \text{ measured at 2.76 TeV. The physical scenario implemented in YAJEM describes qualitatively the data and reaches a much better agreement than the alternative YAJEM+BW approach in } 100 \leq p_T^{\text{jet}}(\text{GeV}) \leq 120, 120 \leq p_T^{\text{jet}}(\text{GeV}) \leq 150 \text{ despite uncertainties caused by the account of different biases on the jet fragmentation analysis. For } 150 \leq p_T(\text{GeV}) \leq 300 \text{ and } 100 \leq p_T(\text{GeV}) \leq 300, \text{ the ratios present an offset which makes the absolute medium-modified } p_t\text{ spectrum of hadrons softer at small } p_t \text{ and harder at large } p_t \text{ but even more pronounced for unbiased showers. As for fragmentation functions }[27], \text{ the analyses provide a mean medium transport coefficient } \hat{q} \sim 2.4 \text{ GeV}^2/\text{fm}^4.$
Figure 1: Comparison of hadron \( p_T^{\text{jet}} \) distribution ratios in PbPb over pp collisions for jets with \( 100 \leq p_T^{\text{jet}} \text{(GeV)} \leq 120 \) (left) and \( 120 \leq p_T^{\text{jet}} \text{(GeV)} \leq 150 \) measured by CMS [6] and obtained in two MC approaches (YAJEM and YAJEM+BW) as a function of the hadron’s \( p_t \).

Figure 2: Comparison of hadron \( p_T^{\text{jet}} \) distribution ratios in PbPb over pp collisions for jets with \( 150 \leq p_T^{\text{jet}} \text{(GeV)} \leq 300 \) (left) and \( 100 \leq p_T^{\text{jet}} \text{(GeV)} \leq 300 \) measured by CMS [6] and obtained in two MC approaches (YAJEM and YAJEM+BW) as a function of the hadron’s \( p_t \).
with the obtained $\Delta Q^2 \sim 6 \text{GeV}^2$ for a medium of length $L = 2.5 \text{ fm}$ in this hydrodynamical description of the QGP. Nevertheless, the comparison with other parton-energy-loss event generators such as JEWEL \cite{9}, PYQUEN \cite{10} and Q-PYTHIA \cite{14} should further constrain the medium parameters and shed more light on the intra-jet transverse momentum structure and its interaction with the QCD medium formed in heavy-ion collisions.

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