Jet and Dijet Rates in AB Collisions

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Jet studies will play a central role as a proposed signature of the formation of QGP in AB collisions. Energy loss of energetic partons inside a medium where colour charges are present, the so-called jet quenching \cite{1}, has been suggested to behave very differently in cold nuclear matter and in QGP, and postulated as a tool to probe the properties of this new state of matter \cite{2}.

On the other hand, jet calculations at NLO have been successfully confronted with experimental data in hadron-hadron collisions \cite{3}. Monte Carlo codes have become available: among them, we will use that of \cite{4, 5} adapted to include isospin effects and modifications of nucleon pdf inside nuclei, see the Section on Jet and Dijet Rates in pA Collisions \cite{6} for more information. Here we will present the results of ’initial’ state effects, i.e. no energy loss of any kind will be considered. These results can be considered as the reference, hopefully to be tested in pA, whose failure should indicate the presence of new physics. As in pA collisions, we will work in the LHC lab frame, which for symmetric AB collisions coincide with the center-of-mass one, and the accuracy of our computations, limited by CPU time, is the same as in the pA case.

Unless explicitly stated and as in the pA case, we will use as nucleon pdf MRST98 central gluon \cite{7} modified inside nuclei using the EKS98 parameterizations \cite{8}, a factorization scale equal to the renormalization scale \( \mu = \mu_F = \mu_R = E_T/2 \), with \( E_T \) the total transverse energy of all the jets in the generated event, and for jet reconstruction we will employ the \( k_T \)-clustering algorithm \cite{9} with \( D = 1 \).

The kinematical regions we are going to consider are the same as in the pA case:

- \( |\eta_i| < 2.5 \), with \( \eta_i \) the pseudorapidity of the jet; this corresponds to the acceptance of the central part of the CMS detector.
- \( E_{T1} > 20 \) GeV in the pseudorapidity distributions, with \( E_{T1} \) the transverse energy of the jet; this will ensure the validity of perturbative QCD.
- \( E_{T1} > 20 \) GeV and \( E_{T2} > 15 \) GeV for the \( \phi \)-distributions, with \( E_{T1} \) (\( E_{T2} \)) the transverse energy of the hardest (next-to-hardest) jet entering the CMS acceptance, and \( \phi \) the angle between these two jets.

Please have a look to the mentioned Section on pA to obtain more information. As we did there, no centrality dependence is studied in this article.

The words of caution about our results which were given in the pA Section are even more relevant in AB collisions, as our ignorance on soft multiparticle production in this case is even larger than in pA collisions. For example, the number of particles produced at midrapidity in a central PbPb collision at the LHC may vary as much as a factor 3 \cite{10} among different models which, in principle, are able to reproduce the available experimental data on multiplicities at SPS, RHIC and TeVatron. Therefore, these issues of the underlying event \cite{11} and multiple hard parton scattering \cite{12, 13} demand extensive Monte Carlo studies including full detector simulation. Preliminary analysis, based on the developed sliding window-type jet finding algorithm (which subtracts the large background from the underlying event) and full GEANT-based simulation of the CMS calorimetry, shows that even in the worst case of central PbPb collisions with maximal estimated charged particle density at mid-rapidity \( dN^+/dy|_{y=0} = 8000 \), jets can be reconstructed with almost 100 % efficiency, low noise and satisfactory energy and spatial resolution starting from \( E_{T1} \sim 100 \) GeV (see the Section on Jet Detection at CMS). In the case of more realistic, lower multiplicities, the minimal threshold for adequate jet reconstruction could even decrease.

As in the pA case, see the previously mentioned Section on pA collisions \cite{6}, the influence of disconnected collisions on jet production in AB collisions may be studied using simple estimates in
AB collisions on the number $\langle n \rangle$ of nucleon-nucleon collisions involved in the production of jets with $E_{T_i}$ greater than a given $E_{T0}$, which can be obtained in the Glauber model [14] in the optical approximation: $\langle n \rangle(b, E_{T0}) = AB T_{AB}(b) \sigma(E_{T0})/\sigma_{AB}(b, E_{T0})$, with $b$ the impact parameter, $T_{AB}(b) = \int d^2 s T_A(s) T_B(b - s)$ the convolution of the nuclear profile functions of projectile and target normalized to unity, $\sigma(E_{T0})$ the cross section for production of jets with $E_{T_i}$ greater than $E_{T0}$ in pp collisions, and $\sigma_{AB}(b, E_{T0}) = 1 - [1 - T_{AB}(b)\sigma(E_{T0})]^{AB}$. Taking $\sigma(E_{T0}) = 70, 0.1$ and 0.006 $\mu b$ as representative values in PbPb collisions at 5.5 TeV for $E_{T0} = 20, 100$ and 200 GeV respectively (see results in Fig. 2 below), the number of nucleon-nucleon collisions involved turns out to be respectively 1.6, 1.0 and 1.0 for minimum bias collisions (i.e. integrating numerator and denominator in $\sigma_{pA}(b, E_{T0})$ between $b = 0$ and $\infty$), while for central collisions (integrating between $b = 0$ and 1 fm) the numbers are 2.4, 1.0 and 1.0 respectively. So, in AB collisions at LHC energies the contribution of multiple hard scattering coming from different nucleon-nucleon collisions seems to be negligible for transverse energies of the jets greater than $\sim 100$ GeV, while for $E_{T_i}$ smaller than $\sim 50$ GeV this effect, not taken into account in our computations, may be of importance.

1. Uncertainties

Uncertainties on the renormalization/factorization scale, on the jet reconstruction algorithm and on nucleon pdf, have been discussed in the mentioned Section on pA collisions and show very similar features in the AB case, so we will discuss them no longer. Here we will focus, see Fig. 1, on isospin effects (obtained from the comparison of pp and PbPb without any modifications of nucleon pdf inside nuclei at the same energy per nucleon, 5.5 TeV) and on the effect of modifications of nucleon pdf inside nuclei, estimated by using EKS98 [8] nuclear corrections.

On the transverse momentum distributions isospin effects are negligible, while effects of EKS98 result in a $\sim 3\%$ increase. On the pseudorapidity distributions, isospin effects apparently tend to fill a small dip at $\eta \simeq 0$ present in the pp distribution, while EKS98 results in some increase, but nevertheless effects never go beyond 5% and are not very significant when statistical errors are considered. On the dijet angular distributions, isospin effects are negligible while EKS98 produces an increase of order 10% at maximum.

2. Results

In Table 1 the number of expected events with at least one jet with a given $E_{T_i} > 20$ GeV and $|\eta_i| < 2.5$ (or with two jets $1, 2$ with $E_{T1} > 20$ GeV, $E_{T2} > 15$ GeV and $|\eta_{1,2}| < 2.5$ for the dijet $\phi$-distributions), per $\mu b$ and pair of colliding nucleons, is shown for different collisions and possible luminosities. From this Table and using the Figures it is possible to know the number of expected events with a given kinematical variable. For example, examining the solid line in Fig. 3 (upper-left) one can expect, within the pseudorapidity region we have considered, the following number of jets per month in PbPb collisions at 5.5 TeV with a luminosity of $5 \cdot 10^{26}$ cm$^{-2}$s$^{-1}$: 2.2 $\cdot 10^7$ jets with $E_{T_i} \sim 50$ GeV (corresponding to a cross section of $1 \mu b/AB$), and 2.2 $\cdot 10^3$ jets with $E_{T_i} \sim 250$ GeV (corresponding to a cross section of $10^{-4}$ $\mu b/AB$).

A detailed study of jet quenching [1, 2] and of associated characteristics as jet profiles, which should be sensitive to radiation from the jet [15], should be feasible with samples of $\sim 10^3$ jets. Looking at the results given in Fig. 3 it becomes evident that, from a theoretical point of view, the study of such samples should be possible up to a transverse energy $E_{T_i} \sim 275$ GeV with a run of 1 month at the considered luminosity: indeed, from Table 1, $10^3$ jets for PbPb would correspond to a cross section of $4.5 \cdot 10^{-5}$ $\mu b/AB$, which in Fig. 3 (upper-left) cuts the curve at $E_{T_i} \sim 275$ GeV.

The centrality dependence of the observables has not been examined due to our poor knowledge of the centrality behaviour of the modification of nucleon pdf inside nuclei; if this behaviour becomes clear in future experiments at eA colliders [16], such study would become very useful [17]. In any case,
Fig. 1: Isospin and nuclear pdf dependence of jet cross sections (pp results: solid lines; PbPb results without modification of nucleon pdf inside nuclei: dashed lines; PbPb results with EKS98 modification of nucleon pdf inside nuclei: dotted lines) versus transverse energy of the jet (for $|\eta| < 2.5$, upper plot) and pseudorapidity of the jet (for $E_T > 20$ GeV, middle plot), and dijet cross sections (lower plot) versus angle between the two hardest jets for $E_{T1} > 20$ GeV, $E_{T2} > 15$ GeV and $|\eta_1|, |\eta_2| < 2.5$, for collisions at 5.5 TeV. Unless otherwise stated default options are used, see text.
Table 1: Luminosities and expected number of events with at least one jet with a given $E_{T1} > 20$ GeV and $|\eta_1| < 2.5$ (or with two jets (1, 2) with $E_{T1} > 20$ GeV, $E_{T2} > 15$ GeV and $|\eta_{1,2}| < 2.5$ for the dijet $\phi$-distributions), per $\mu b/(AB)$ in one month ($10^6$ s), for different collisions.

| Collision | $E_{cm}$ per nucleon (TeV) | $\mathcal{L}$ (cm$^{-2}$s$^{-1}$) | Number of events per month per $\mu b/(AB)$ |
|-----------|-----------------------------|----------------------------------|--------------------------------------------|
| ArAr      | 6.3                         | $10^{20}$                        | $1.6 \cdot 10^8$                          |
| ArAr      | 6.3                         | $3 \cdot 10^{21}$               | $4.8 \cdot 10^6$                          |
| PbPb      | 5.5                         | $5 \cdot 10^{23}$               | $2.2 \cdot 10^7$                          |

A variation of nuclear sizes should allow a systematic study of the dependence of jet spectra on the size and energy density of the produced plasma.

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Fig. 2: Jet cross sections versus transverse energy of the jet (for $|\eta_i| < 2.5$, plots on the left) and pseudorapidity of the jet (for $E_{T_i} > 20$ GeV, plots in the middle), and dijet cross sections versus angle between the two hardest jets for $E_{T_1} > 20$ GeV, $E_{T_2} > 15$ GeV and $|\eta_1|, |\eta_2| < 2.5$ (plots on the right), for PbPb collisions at 5.5 TeV (upper plots) and ArAr collisions at 6.3 TeV (lower plots). Default options are used, see text.
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