PROCEEDINGS OF SCIENCE

Measuring nuclear modification factors at high-p_T using jet triggers

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The suppression of hadron production at high transverse momenta is one of the most important observables to study medium induced parton energy loss in ultrarelativistic heavy ion collisions. In Pb+Pb collisions at the LHC, the transverse momentum reach of this measurement can be extended to about 300 GeV/c, due to the large hard scattering cross sections at the $\sqrt{s_{NN}} = 5500$ GeV collision energy, the high luminosity and the large acceptance of the CMS tracking system ($|\eta| < 2.5$). To reach this high transverse momentum range a trigger is neccessary to enhance particle yields at high p_T. In this proceedings, the benefits of a calorimeter based high jet trigger are studied with a simulation including parton energy loss and parametrized responses for the calorimeters and the resulting statistical reach of charged particle p_T spectra for the expected nominal 0.5 nb^{-1} integrated luminosity is estimated.

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1. Introduction

The abundance of high Q^2 processes at LHC energies will provide large samples of high E_T jets, large p_T hadrons, and jets produced opposite to gauge bosons (γ^*, Z) [1]. The strong interest in these observables in heavy-ion collisions stems from the concept that high E_T quark and gluon jets can be used to probe the hot and dense medium produced in the collision, because they are affected by the properties of the medium as they propagate through this dense environment. Partons with high transverse momentum are predicted to suffer radiative and collisional energy loss in the created medium, suppressing the yield of jets and particles found with high transverse energy in a heavy-ion collision, compared to the p+p collision case (see e.g. [2]).

Early results obtained at RHIC indeed showed suppression of the hadron yield at $p_T > 3$ GeV/c and the disappearance of back-to-back correlations of high-p_T particles [3]. These indirect measurements of jet properties suggest a significant in-medium energy loss of fast partons, which will be experimentally accessible at the LHC also by observing fully formed and reconstructed jets.

The performance of the CMS detector for Pb+Pb events was extensively studied in full simulations with realistic assumptions for particle multiplicity, jet and hadron spectra [4]. The charged particle reconstruction capabilities using the CMS Silicon Tracking System are evaluated using a full detector simulation, assuming a charged particle density in central Pb+Pb collisions of $dN_{ch}/dy = 3200$. In this high multiplicity environment, an algorithmic tracking efficiency of about 80% is achieved, with less than 5% fake track rate for $p_T > 1$ GeV/c and excellent momentum resolution, $\Delta p_T/p_T < 1.5\%$ (for $p_T < 100$ GeV/c) [5].

The High Level Trigger of the CMS data acquisition system is sufficiently powerful to allow the inspection of all minimum bias Pb+Pb events individually, where the full event information will be available for the trigger decision [4]. Jets are reconstructed in the calorimeters using an iterative cone algorithm, which is modified to subtract the underlying soft background, and can be included in the HLT. The lower limit of transverse energy needed for efficient and clean reconstruction is about 50 GeV. The energy resolution for jets with 100 GeV transverse energy at $\eta \approx 0$ is about 16% [6].

2. Nuclear Modification Factor

The nuclear modification factor (R_{AA}) and the central to peripheral ratio (R_{cp}) in nuclear collisions provide quantitative information on the amount and energy-dependence of the energy lost by hard scattered partons that traverse the extremely high energy density medium created in the heavy ion collision. The study of R_{AA}, R_{cp} for leading hadrons thus provide important information on the (thermo)dynamical properties of the created plasma (initial gluon rapidity density, dN_g/dy, transport coefficient $\langle \hat{q} \rangle$). The nuclear modification factors are defined as:

$$R_{AA} = \frac{\sigma_{pp}^{\text{inel}}}{\langle N_{\text{coll}} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

$$R_{cp} = \frac{\langle N_{\text{coll}}^{\text{periph}} \rangle}{\langle N_{\text{coll}}^{\text{central}} \rangle} \frac{d^2N_{AA}^{\text{central}}/dp_T d\eta}{d^2N_{AA}^{\text{periph}}/dp_T d\eta}$$

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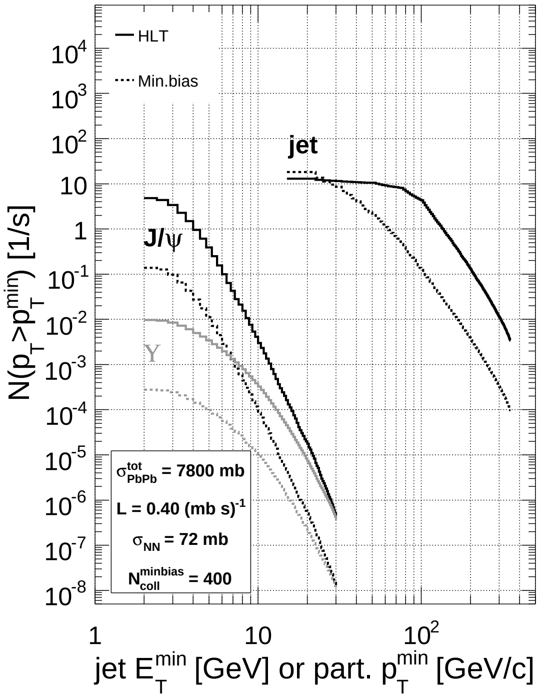

Figure 1: Event rate of various hard processes stored on tape above a certain E_T (p_T) at the design Pb+Pb luminosity. The minimum bias and the HLT data taking modes are compared.

where $\langle N_{\rm coll}\rangle$ is the average number of binary nucleon-nucleon collisions in a simple geometrical Glauber picture, over the events that belong to a certain centrality class of events.

R_{AA} quantifies the suppression (or enhancement) of hadron production with respect to p+p collisions, which are considered as a baseline. The charged particle yield (the invariant cross section) at high p_T is expected to scale with $\langle N_{\rm coll}\rangle$ if no nuclear effects take place. In that case the value of R_{AA} at high p_T would be unity.

At LHC, no p+p data will be available at $\sqrt{s_{NN}}$=5500 GeV collision energy at the time of the first Pb+Pb data taking and analysis. Thus, p_T spectra of charged particles in p+p collisions will be interpolated to this energy using next-to-leading-order (NLO) predictions constrained by the existing Tevatron data at 2 TeV and by the (future) results at top LHC (14 TeV) collision energies.

The R_{cp} ratio, on the other hand, does not require a p+p reference, as it compares central and peripheral heavy-ion collisions. It is not equivalent to R_{AA}, since even the most peripheral heavy-ion collisions are influenced by nuclear effects.

3. Triggering on Jets

For both R_{AA} and R_{cp}, triggering on jets will be essential to extend the measurable p_T range. Using the CMS calorimeter towers, it is possible to quickly reconstruct these energetic jets with a good energy resolution. The jet reconstruction algorithm can be included in the High Level Trigger, and will record events containing a high energy jet with high efficiency [4]. The increase in the number of recorded jets using the jet trigger is illustrated in Fig. 1.

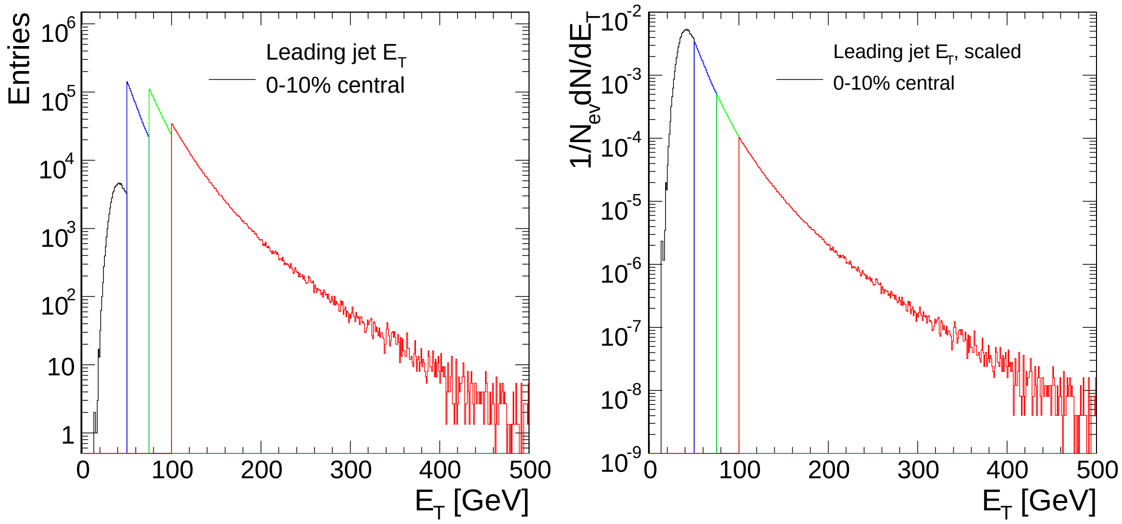

Figure 2: *Left*: leading jet E_T distributions for minimum bias (black), and triggered simulated data samples, with E_T thresholds of 50, 75 and 100 GeV. *Right*: the same distributions as on the left, sliced into the $0-50$, $50-75$, $75-100$ and $E_T > 100$ GeV intervals, and scaled by the appropriate factors to get back the non-triggered distribution, with significantly higher statistics.

Charged hadrons at $p_T > 20-30$ GeV/c originate from the fragmentation of high E_T jets: they are typically the leading hadrons of the energetic jets. The jet trigger is useful to collect sufficiently large jet statistics to study fragmentation functions, jet correlations, and other observables, among which we will present here the charged particle nuclear modification factors. To provide adequate and fast Monte Carlo tools to simulate jet quenching, the Monte Carlo event generator HYDJET (HYDrodynamics plus JETs) has been developed and is used to produce heavy-ion collisions at LHC energies [7] [8]. Final state particles in nuclear collisions from HYDJET are obtained as a superposition of soft hydro-type particle production and multiple hard parton-parton collisions.

4. Results

Within the 15% of the full bandwidth assigned to minimum bias events, 13.5 million events are expected to be taken in one month. The jet triggers with 50, 75 and 100 GeV E_T thresholds will be able to sample 0.35, 1.9 and 3.9 billion events, respectively. It is possible to generate the amount of minimum bias events with our generator-level tools. However, triggering enhances the number of jets at high E_T by more than two orders of magnitude. Thus, instead of generating one hundred times more minimum bias heavy-ion events to conduct our study, we have implemented a "trigger" at the generator level. This way, we only store simulated events which are likely to produce a large E_T jet when the jet finder is run on the calorimeter towers.

Figure 2 shows the distribution of the highest E_T jet within $|\eta| < 2$ per event, the "leading" jet, for minimum bias (black histogram), and for jet-triggered events with 50 (blue), 75 (green) and 100 (red) GeV thresholds. The scaling factors between consecutive data sets are determined by joining them with scaling factors determined by fitting the combined leading jet E_T spectrum with

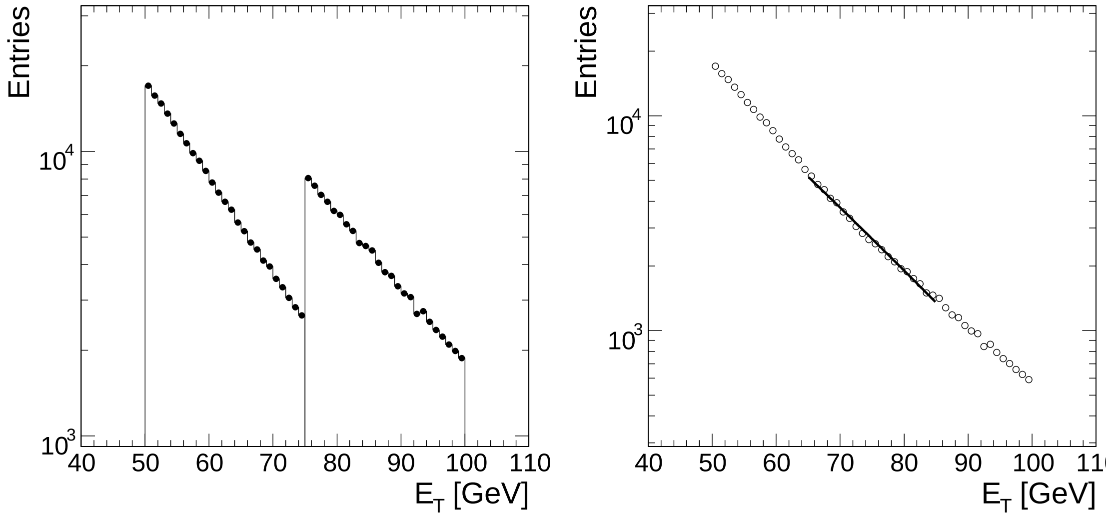

Figure 3: *Left*: leading jet E_T distributions for two consecutive triggered data samples. *Right:* The same distributions scaled with the factor obtained in the merging procedure.

a power law in the joining regions. This way, the optimal scaling factors can be determined from the data distribution, without any prior assumptions on the spectrum. This is illustrated in Fig. 3: the left panel shows the data sets before merging while the right hand side shows the same data sets after scaling, together with the power law fit. The minimum bias E_T spectrum is recovered with significantly increased statistics at high E_T.

Figure 4 shows the charged particle transverse momentum spectra in the four event classes: A) minimum bias events where the E_T of the leading jet is below 50 GeV; B) triggered events where $50 < E_T^{\text{leading}} < 75$ GeV; C) triggered events where $75 < E_T^{\text{leading}} < 100$ GeV; D) triggered events where $E_T^{\text{leading}} > 100$ GeV.

Each histogram is corrected by the appropriate trigger scaling factor. Since the four (scaled) sets of simulated data, together, give the minimum bias set (as was shown for the leading jet distributions), the sum of the four histograms (represented by the closed black circles) gives the minimum bias charged particle distribution. The shape of this merged charged particle pT spectrum is identical to the spectrum that would be obtained without the jet triggers from a data set of much larger statistics.

The procedure to match and merge data from different data streams is not sensitive to details of the physics model chosen for jet quenching. It is also insensitive to the precise knowledge of the jet energy resolution (the scale factors do not depend on the jet energy resolution by construction), as long as the jet energy resolution is not extremely poor. Other observables, like jet E_T spectra and jet fragmentation functions are much less robust against poor knowledge of the precise jet reconstruction performance.

Using this method to merge data sets with different thresholds, triggered data sets were generated with the number of jets with E_T above the thresholds expected from one month of Pb+Pb data taking at design luminosity. The statistical errors on the charged particle p_T spectrum in the

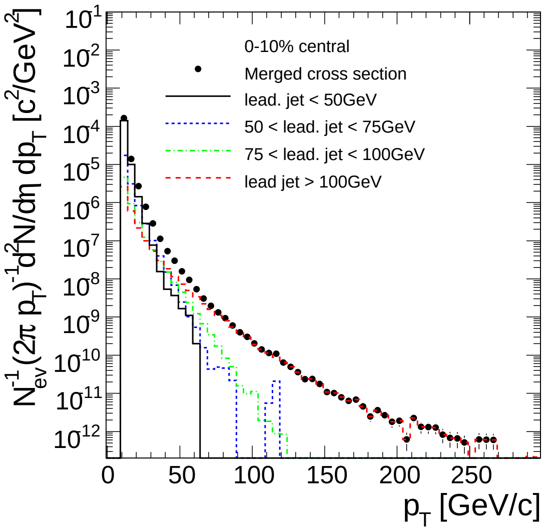

Figure 4: Charged particle transverse momentum distributions in the $|\eta| < 2.5$ window for the four trigger categories, selected according to the transverse energy of the highest E_T (leading) jet. The merged spectrum (closed black circles) has the same shape as the minimum bias spectrum but much larger statistics.

merged data set reflects, hence, the real experimental situation after one month of data taking, with the four different trigger thresholds.

Figure 5 shows the expected charged particle p_T spectra for the minimum bias (left) and merged triggered (right) data samples, in several centrality bins. Using the jet-triggered data samples, CMS can measure with good efficiency the inclusive charged spectra up to $p_T \approx 300$ GeV/c in $R_{AA}(p_T)$, in central Pb+Pb collisions.

The obtained R_{AA} is shown in Fig. 6. In the present study, the PYTHIA event generator was used to simulate the p+p reference for R_{AA}. The R_{cp} ratio, which uses peripheral Pb+Pb collisions as reference, instead of p+p collisions, is shown in Fig. 7, for one month of data taking at nominal luminosity. The actual R_{AA} and R_{cp} values only reflect the specific implementation of the jet energy loss model in our HYDJET event generator.

Comparing the results for the minimum bias data to the results for the jet triggered data, we see that triggering on jets significantly extends the p_T range of R_{AA} and R_{cp}, from ~ 100 to ~ 300 GeV/c in $R_{AA}(p_T)$ and from ~ 50 to ~ 150 GeV/c in $R_{cp}(p_T)$.

Acknowledgments

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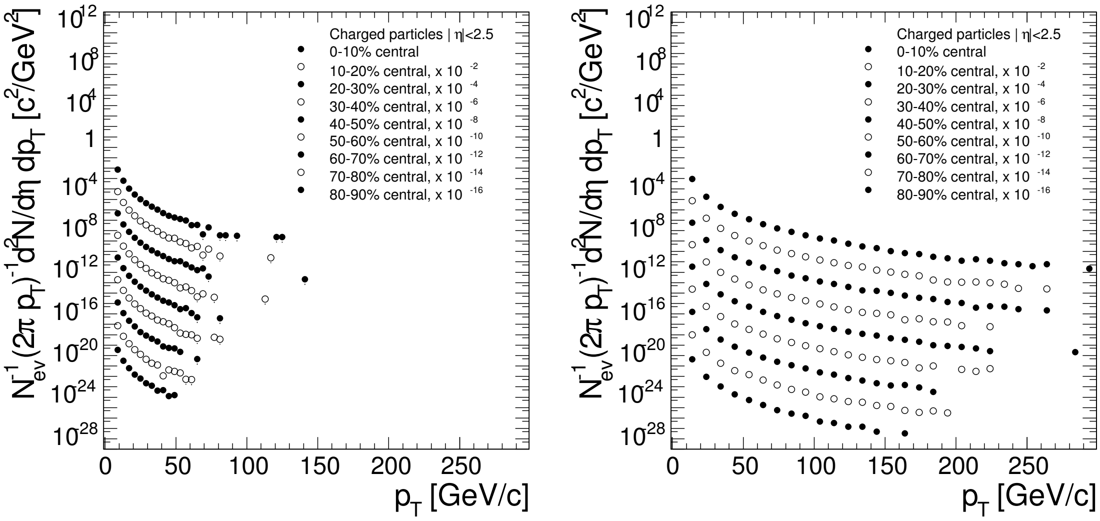

Figure 5: *Left*: charged particle p_T spectra only using minimum bias triggered sample, offset by factors of 100 for illustration purposes. *Right:* same spectra using the jet-triggered data sets merged following the procedure described in the text.

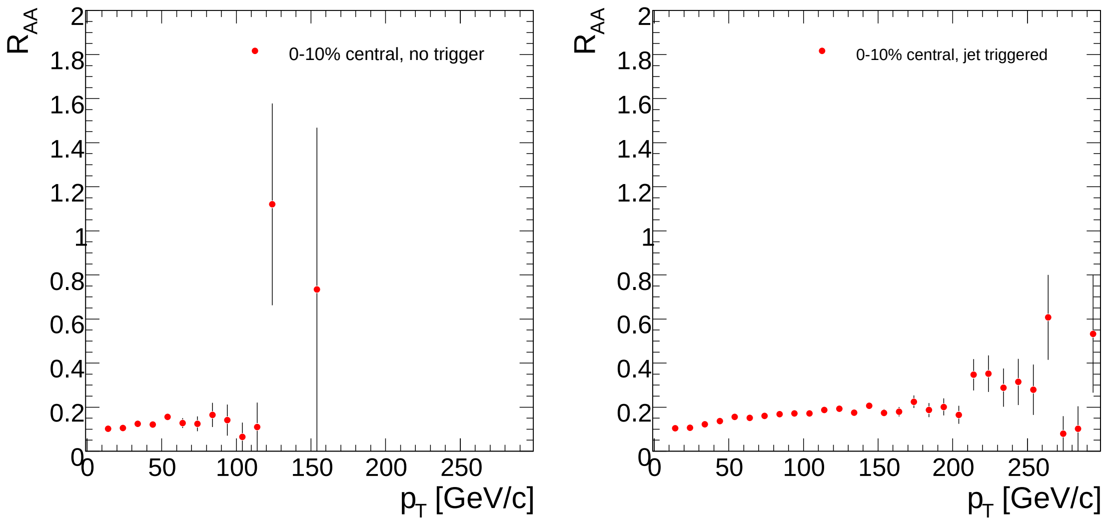

Figure 6: *Left*: the nuclear modification factor R_{AA} as a function of p_T for charged particles, for minimum bias data, for one month of data taking. *Right*: The nuclear modification factor R_{AA} as a function of p_T for charged particles, for data triggered on high-E_T jets, for one month of data taking.

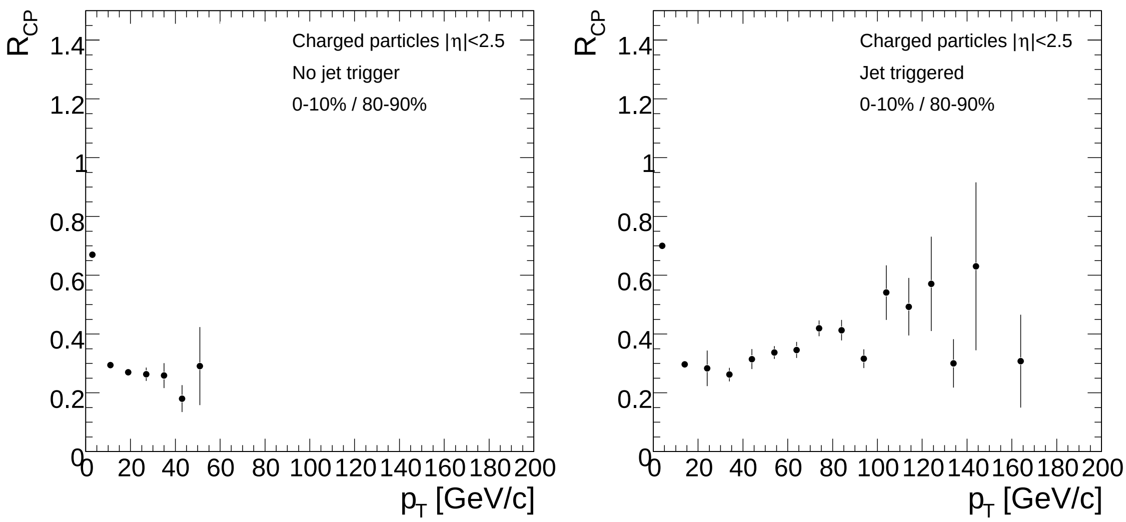

Figure 7: *Left*: the central-to-peripheral ratio, R_{cp}, as a function of p_T, for charged particles, for minimum bias data, for one month of data taking. *Right*: the central-to-peripheral ratio, R_{cp}, as a function of p_T, for charged particles, for data triggered on high-E_T jets, for one month of data taking.

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