Studies of dijet pseudorapidity distributions and transverse momentum balance in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

Dijet production has been measured in pPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. A data sample corresponding to an integrated luminosity of 35 nb⁻¹ was collected using the Compact Muon Solenoid detector at the Large Hadron Collider. The dijet transverse momentum balance and pseudorapidity distributions are studied as a function of the transverse energy in the forward calorimeters ($E_T^{\text{HF}[|\eta|>4]}$). For pPb collisions, the dijet transverse momentum ratio is comparable to the same quantities obtained from a simulated pp reference and insensitive to $E_T^{\text{HF}[|\eta|>4]}$. In contrast, the distribution of the dijet pseudorapidity is changing with increasing $E_T^{\text{HF}[|\eta|>4]}$, indicating a correlation between the energy emitted at large pseudorapidity and the longitudinal motion of the dijet frame. The observed pseudorapidity distribution of the dijet system in minimum bias pPb collisions is consistent with next-to-leading-order perturbative QCD predictions from nuclear parton distribution functions.

1. Introduction

Relativistic heavy ion collisions allow to study the fundamental theory of strong interactions—Quantum Chromodynamics (QCD)—under extreme conditions of temperature and energy density. Lattice QCD calculations [1] predict a new chirally-symmetric form of matter that consists of an extended volume of deconfined quarks and gluons above the critical energy density

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of the phase transition, about 1 GeV/fm^3 [2, 3, 4, 5]. One of the most interesting experimental signatures of the formation of this novel matter, the quark-gluon plasma (QGP), is “jet-quenching” resulting from the energy loss of hard-scattered partons passing through the medium. Back-to-back dijets have long been proposed as a particularly useful tool for studying the QGP properties [6, 7]. In PbPb collisions at the Large Hadron Collider (LHC), the effects of this medium were observed in the first jet measurements as a dijet transverse momentum imbalance.

Recent data at the LHC for jets [8, 9, 10, 11, 12], correlations between jets and single particles [13, 14, 15], and charged-particle measurements [16, 17], provide unprecedented information about the jet-quenching phenomenon. For head-on collisions, a large broadening of the dijet transverse momentum ratio ($p_{T,2}/p_{T,1}$) and a decrease in its mean is observed where, as is the case for all the dijet observables in the following discussion, the subscripts 1 and 2 in the kinematical quantities refer to the leading and subleading jets (the two highest- p_T jets), respectively. This observation is consistent with theoretical calculations that involve differential energy loss of back-to-back hard-scattered partons as they traverse the medium [18, 19, 20].

Studies of dijet properties in pPb collisions are of great importance to establish a QCD baseline for hadronic interactions with cold nuclear matter [21, 22]. This is crucial for the interpretation of the PbPb results, which could include the effects of both cold nuclear matter and a hot partonic medium. The dijet production rates as a function of jet pseudorapidity (η) have also been proposed as a tool to probe the nuclear modifications of the parton distribution functions (PDFs) [23, 24, 25, 26, 27, 28]. Pseudorapidity η is defined as $-\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the proton beam direction.

In this proceedings, the first dijet transverse momentum balance and pseudorapidity distribution measurements in pPb collisions are presented as a function of the transverse energy in the forward calorimeters ($E_T^{\text{HF}[|\eta|>4]}$) [29]. This analysis uses pPb data recorded with the Compact Muon Solenoid (CMS) detector in 2013, corresponding to an integrated luminosity of $35 \pm 1 \text{ nb}^{-1}$. The lead nuclei and protons had beam energies of 1.58 TeV per nucleon and 4 TeV, respectively, corresponding to a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.

2. The CMS detector

A detailed description of the CMS experiment can be found in Ref. [30]. The detailed Monte Carlo (MC) simulation of the CMS detector response is
45 based on GEANT4 [31].

Because of the different energies of the two beams, the nucleon-nucleon center-of-mass frame in pPb collisions is not at rest in the detector frame. Results are presented in the laboratory frame, where the higher energy proton beam is defined to travel in the positive η direction ($\theta = 0$). Therefore, a
50 massless particle emitted at $\eta_{\text{cm}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta_{\text{lab}} = +0.465$ in the laboratory frame. During part of the data taking period, the directions of the proton and lead beams were reversed. For the dataset taken with the opposite direction proton beam, the standard CMS definition of η was flipped so that the proton always moves
55 towards positive η .

3. Jet reconstruction

Offline jet reconstruction is performed using the CMS “particle-flow” algorithm [32, 33]. By combining information from all sub-detector systems, the particle-flow algorithm attempts to identify all stable particles in an
60 event, classifying them as electrons, muons, photons, charged and neutral hadrons. These particle-flow objects are first grouped into “pseudo-towers” according to the CMS HCAL granularity. The transverse-energy of the pseudo-towers is calculated from the scalar sum of the transverse-energy of the particle-flow objects. Then, jets are reconstructed based on the pseudo-
65 towers, using the anti- k_T sequential recombination algorithm provided in the FASTJET framework [34, 35] with a distance parameter $R = 0.3$.

To subtract the underlying event (UE) background in pPb collisions, an iterative algorithm described in Ref. [36] is employed, using the same implementation as in the PbPb analysis [11].

70 4. The Monte Carlo simulation

In order to study the jet reconstruction performance in pPb collisions, di-jet events in pp collisions are first simulated with the PYTHIA MC generator (version 6.423, tune Z2) [37] and later embedded in the simulated pPb underlying events. A minimum hard-interaction scale ($\hat{p}_T$) selection of 30 GeV/ c is

75 used to increase the number of dijet events produced in the momentum range studied. To model the pPb underlying event, minimum bias pPb events are simulated with the HIJING event generator [38], version 1.383 [39].

The complete detector simulation and analysis chain is used to process PYTHIA dijet events and these events are then embedded into HIJING events
80 (denoted as PYTHIA + HIJING).

The CMS online event selection employs a hardware-based Level-1 trigger and a software-based high-level trigger (HLT). Events are selected using an inclusive single-jet trigger in the HLT, requiring a calorimeter-based jet with transverse momentum $p_T > 100$ GeV/ c . The trigger becomes fully efficient
85 for events with a leading jet with $p_T > 120$ GeV/ c . In addition to the jet data sample, a minimum-bias event sample is selected by requiring at least one track with $p_T > 0.4$ GeV/ c to be found in the pixel tracker coincident with the pPb bunch crossing.

In the offline analysis, an additional selection of hadronic collisions is
90 applied by requiring a coincidence of at least one of the HF calorimeter towers, with more than 3 GeV of total energy, from the HF detectors on both sides of the interaction point. Events are required to have at least one reconstructed primary vertex. The primary vertex is formed by two or more associated tracks and is required to have a distance from the nominal
95 interaction region of less than 15 cm along the beam axis and less than 0.15 cm in the transverse plane. If there are more than 10 tracks in the event, the fraction of good-quality tracks originating from the primary vertex is required to be larger than 20% in order to suppress beam backgrounds [40].

In addition to the selection of inelastic hadronic collisions, the analysis
100 has extra requirements on the leading and subleading jet, which are the jets with largest and second largest p_T in $|\eta| < 3$ interval, respectively. These requirements are $p_{T,1} > 120$ GeV/ c , $p_{T,2} > 30$ GeV/ c , and $\Delta\phi_{1,2} > 2\pi/3$. Only offline reconstructed jets within $|\eta| < 3$ in the lab frame are considered in this analysis. In order to remove events with residual HCAL noise that
105 are missed by the calorimeter noise rejection algorithms [41, 42], either the leading or subleading jet is required to have at least one track with $p_T > 4$ GeV/ c .

The selected minimum-bias and dijet events are divided into HF activity classes according to the raw transverse energy measured in the HF detectors
110 within the pseudorapidity interval $4.0 < |\eta| < 5.2$, denoted as $E_T^{|\eta|>4}$. This pseudorapidity interval is chosen in order to separate the transverse energy and dijet measurements by a pseudorapidity gap of at least one unit ($3.0 <$

$|\eta| < 4.0$).

The analysis is performed in five $E_T^{|\eta|>4}$ bins, separated by the boundaries
 115 20, 25, 30 and 40 GeV . The same analysis is also performed with inclusive
 data without $E_T^{|\eta|>4}$ selection.

The instantaneous luminosity of the pPb run in 2013 resulted in a 3%
 probability of at least one additional interaction occurring in the same bunch
 crossing. Events with more than one interaction are referred to as “pileup
 120 events”. Since the event classes are typically determined from the forward
 calorimeter information, the energy deposits from each collision in a given
 pileup event cannot be separated. Therefore, a pileup rejection algorithm
 developed in Ref. [43] is employed to select a clean single-collision sample.
 The fraction of pileup events after pileup rejection is increasing as a function
 125 of $E_T^{|\eta|>4}$. This fraction is found to be smaller than 2% in the highest $E_T^{|\eta|>4}$
 bins.

5. Results and discussion

5.1. Dijet transverse momentum balance

As a function of collision centrality (i.e. the degree of overlap of the two
 130 colliding nuclei), dijet events in PbPb collisions were found to have an in-
 creasing transverse momentum imbalance for more central events compared
 to a pp reference [8, 11, 12]. The same analysis is performed in pPb collisions.
 To characterize the dijet transverse momentum balance (or imbalance) quan-
 titatively, the dijet transverse momentum ratio $p_{T,2}/p_{T,1}$ is used. As shown in
 135 Fig. 1, $p_{T,2}/p_{T,1}$ distributions measured in pPb data and PYTHIA agree within
 the systematic uncertainty in different $E_T^{|\eta|>4}$ intervals, including the event
 class with the largest forward calorimeter activity. The residual difference in
 the dijet transverse momentum ratio between data and PYTHIA+HIJING sim-
 ulation can be attributed to a difference in the jet energy resolution, which
 140 is better in the MC simulation by about ~ 1 –2% compared to the data [44].

5.2. Dijet pseudorapidity

The normalized distributions of dijet pseudorapidity η_{dijet} , defined as
 $(\eta_1 + \eta_2)/2$, are studied in bins of $E_T^{|\eta|>4}$. Since η_{dijet} and the longitudinal-
 momentum fraction x of the hard-scattered parton from the Pb ion are highly
 145 correlated, these distributions are sensitive to possible modifications of the
 PDF for nucleons in the lead nucleus when comparing η_{dijet} distributions in

Figure 1: Dijet transverse momentum ratio ($p_{T,2}/p_{T,1}$) distributions for leading jets with $p_{T,1} > 120$ GeV/c, subleading jets with $p_{T,2} > 30$ GeV/c, and $\Delta\phi_{1,2} > 2\pi/3$ are shown (a) without any selection on the HF transverse energy $E_T^{|\eta|>4}$, and (b)–(f) for different $E_T^{\text{HF}[|\eta|>4]}$ classes. Results for pPb events are shown as the red solid circles, while the crosses show the results for PYTHIA + HIJING simulated events. Results for the simulated PYTHIA events are shown as the grey histogram which is replicated in all the panels. The error bars for the statistical uncertainties are smaller than the marker size and the total systematic uncertainties are shown as yellow boxes.

pp and pPb collisions. As discussed previously, the asymmetry in energy of the pPb collisions at the LHC causes the mean of the *unmodified* dijet pseudorapidity distribution to be centered around a positive value. However, due to the limited jet acceptance (jet $|\eta| < 3$) it is not centered around $\eta = 0.465$, but at $\eta \sim 0.4$.

The normalized η_{dijet} distribution measured in inclusive pPb collisions, which is compared to next-to-leading-order (NLO) perturbative QCD predictions [45] using the CT10 [46] and EPS09 [24] PDFs, is shown in Fig. 2. The measurement and the NLO calculation based on CT10 + EPS09 PDFs are consistent within the quoted experimental and theoretical uncertainties in the whole η_{dijet} range. On the other hand, the calculation using CT10 alone, which did not account for possible nuclear modifications of the PDFs, gives a poorer description of the observed distribution. This also shows that η_{dijet}

Figure 2: (a) Distribution of dijet pseudorapidity ($\eta_{\text{dijet}} = [\eta_1 + \eta_2]/2$) is shown for pPb dijet events with $p_{T,1} > 120$ GeV/c, $p_{T,2} > 30$ GeV/c, and $\Delta\phi_{1,2} > 2\pi/3$ as the red solid circles. The results are compared to NLO calculations using CT10 (black dashed curve) and CT10 + EPS09 (blue solid curve) PDFs. (b) The difference between η_{dijet} in data and the one calculated with CT10 proton PDF. The black squares represent the data points, and the theoretical uncertainty is shown with the black dashed line. (c) The difference between η_{dijet} in data and the one calculated with CT10+EPS09 nPDF. The blue solid circles show the data points and blue solid curve the theoretical uncertainty. The yellow bands in (b) and (c) represent experimental uncertainties. The experimental and theoretical uncertainties at different η_{dijet} values are correlated due to normalization to unit area.

160 in pPb collisions could be used to better constrain the nPDFs by including the measurement in standard global fits of parton densities.

The η_{dijet} distributions are also studied in different HF activity classes, as shown in Fig. 3. The pPb data are compared to PYTHIA and PYTHIA + HIJING simulations. Deviations of the η_{dijet} distributions in each class are

Figure 3: Distributions of the dijet pseudorapidity (η_{dijet}) for leading jets with $p_{T,1} > 120$ GeV/c and subleading jets with $p_{T,2} > 30$ GeV/c are shown (a) without any selection on the HF transverse energy $E_T^{|\eta|>4}$, and (b)–(f) for different $E_T^{|\eta|>4}$ classes. Results for pPb events are shown as the red solid circles, while the crosses show the results for PYTHIA + HIJING simulated events. Results for the simulated PYTHIA events are shown as the grey histogram which is replicated in all the panels. The error bars for the statistical uncertainties are smaller than the marker size and the total systematic uncertainties are shown as yellow boxes.

165 observed with respect to the PYTHIA reference without HF activity selection. The analysis was also performed using the PYTHIA + HIJING simulation in the same HF activity classes and no sizable deviation was observed with respect to the PYTHIA reference. This shows that the PYTHIA + HIJING embedded sample, which assumes that hard and soft scatterings are independent, does not describe the correlation between the dijet pseudorapidity distribution and forward calorimeter energy. The magnitude of the observed modification is much larger than the predictions from the NLO calculations based on impact-parameter dependent nPDFs [47]. Note that theory calculations are based on impact parameter, which can take a large range of values in each HF activity class.

175 The pPb distributions for different HF activity classes, from panels (b)–(f) of Fig. 3, are overlaid in Fig. 4. As shown in Fig. 4a, a systematic monotonic

Figure 4: Dijet pseudorapidity distributions in the five HF activity classes. (a) The distributions are normalized by the number of selected dijet events. (b) The distributions are normalized by the number of dijet events with $\eta_{\text{dijet}} < 0$.

decrease of the average η_{dijet} as a function of the HF transverse energy $E_T^{|\eta|>4}$ is observed. A decrease in the longitudinal momentum carried by partons that participate in hard scattering coming from the proton, or an increase in the longitudinal momentum of partons from the lead nucleus, with increasing HF transverse energy $E_T^{|\eta|>4}$ would result in a shift in this direction. In order to compare the shape of the η_{dijet} distributions in the interval $\eta_{\text{dijet}} < 0$ the spectra from pPb data are normalized by the number of dijet events with $\eta_{\text{dijet}} < 0$ in the corresponding HF activity class. In inclusive pPb collisions, this interval roughly corresponds to $x > 0.1$ for partons in lead, a region where the measurement is sensitive to the nuclear EMC effect [48]. Using this normalization, the shapes of the η_{dijet} distributions in the region $\eta_{\text{dijet}} < 0$ are found to be similar, as is shown in Fig. 4(b).

6. Summary

The CMS detector has been used to study dijet production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The anti- k_T algorithm with a distance parameter of 0.3 was used to reconstruct jets based on the combined tracker and calorimeter information. Events containing a leading jet with $p_{T,1} > 120$ GeV/c and a subleading jet with $p_{T,2} > 30$ GeV/c in the pseudorapidity range $|\eta| < 3$ were analyzed. Data were compared to PYTHIA as well as PYTHIA + HIJING dijet simulations. In contrast to what is seen in head-on

PbPb collisions, no significant dijet transverse momentum imbalance is observed in pPb data with respect to the simulated distributions. These pPb dijet transverse momentum ratios confirm that the observed dijet transverse momentum imbalance in PbPb collisions is not originating from initial-state effects.

The dijet pseudorapidity distributions in inclusive pPb collisions are compared to NLO calculations using CT10 and CT10 + EPS09 PDFs, and the data more closely match the latter. A strong modification of the dijet pseudorapidity distribution is observed as a function of forward activity. The mean of the distribution shifts monotonically as a function of $E_T^{|\eta|>4}$. This indicates a strong correlation between the energy emitted at large pseudorapidity and the longitudinal motion of the dijet frame.

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