Dijet pseudorapidity in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector

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Abstract

We report on measurements of the dijet pseudorapidity distributions in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the CMS detector. These measurements are sensitive to nuclear modifications of parton distribution functions (PDF). Recent theoretical studies based on NLO calculations show that the constraining power of pPb data on nuclear PDF fits can be improved by the knowledge of the corresponding measurement in pp collisions. Moreover, measurements of dijet average transverse momentum provide a good handle on $Q^2$. In this physics analysis summary, the dijet pseudorapidity spectra are studied in different dijet average transverse momentum intervals. These measurements can provide constraints on the nuclear PDF over a wide phase space of $x$ and $Q^2$. 
1 Introduction

The Large Hadron Collider (LHC) has opened a new era for precision jet measurements for the study of the strongly interacting medium produced in the relativistic heavy ion collisions [1–4]. 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 traversing the medium [5–7]. Jet production in PbPb collisions was proposed as a particularly useful tool to study the properties of the QGP.

Dijet production has also been measured in pPb collisions [8, 9]. In contrast to what is observed in head-on PbPb collisions [10–12], no significant dijet transverse momentum imbalance is observed in pPb data with respect to the simulated pp distributions. Moreover, the jet spectra measurements [13, 14] also show no sign of jet quenching. The relative small or negligible final state effects on jets in pPb collisions support the idea of using jets as important hard probes for the understanding of the nuclear parton distribution functions (nPDFs). 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 [15, 16]. Recent theoretical calculations suggest that the dijet pseudorapidity distribution provides strong constraints on the nPDF [17] due to the achievable small experimental and theoretical uncertainties.

In order to constrain the baseline pp PDF and to compare with pPb dijet pseudorapidity distributions, measurements with pp data at nucleon-nucleon centre-of-mass energy √s_{NN} = 5.02 TeV are reported in this physics analysis summary. In order to provide important constraints on the nPDF over a wide x and Q^2 phase space, measurements of dijet pseudorapidity spectra in bins of dijet average transverse momentum in pp and pPb collisions are also reported.

2 The CMS detector

A detailed description of the CMS experiment can be found in Ref. [18]. The silicon tracker, located in the 3.8 T magnetic field of the superconducting solenoid, is used to measure charged particles within the pseudorapidity range |η| < 2.5. It provides an impact parameter resolution of ≈ 15 µm and a p_T resolution of about 1.5% for particles with p_T = 100 GeV/c. Also located inside the solenoid are an electromagnetic calorimeter (ECAL) and a hadron calorimeter (HCAL). The ECAL consists of more than 75 000 lead tungstate crystals, arranged in a quasi-projective geometry, and distributed in a barrel region (|η| < 1.48) and in two endcaps that extend up to |η| = 3.0. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates, covering |η| < 3.0. Iron hadron-forward (HF) calorimeters, with quartz fibers read out by photomultipliers, extend the calorimeter coverage up to |η| = 5.2 and are used to differentiate between central and peripheral pPb collisions. Calorimeter cells are grouped in projective towers of granularity in pseudorapidity and azimuthal angle given by Δη × Δφ = 0.087 × 0.087 close to midrapidity, having a coarser segmentation at large rapidities. An efficient muon system is deployed for the reconstruction and identification of muons up to |η| = 2.4. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on Geant4 [19].

Because of the different energies of the two beams, the nucleon-nucleon centre-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 (θ = 0). Therefore, a massless particle emitted at η_{cm} = 0 in the nucleon-nucleon centre-of-mass frame will be detected at η_{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 $\eta$ was flipped so that the proton always moves towards positive $\eta$.

3 Datasets and Event Selection

This analysis uses pPb and pp data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV recorded with the CMS detector, corresponding to an integrated luminosity of $35 \pm 1 \text{ nb}^{-1}$ and $28 \text{ pb}^{-1}$, respectively. In addition to minimum-bias events, high $p_T$ jet events are selected using jet triggers with online thresholds of 40, 60 and 80 GeV. Those triggers are more than 99% efficient in the kinematics range studied in this analysis.

In order to reject beam-gas and beam background events, the same strategy as previous dijet analysis in pPb is employed. In the offline analysis, an additional selection of hardonic collision is applied. It requires at least one HF calorimeter tower, on both sides of the interaction point, to have more than 3 GeV of total energy. In pp collisions this coincidence requirement is not present, as the pp events do not suffer as much from the electromagnetic interactions which contaminate inelastic pPb collision cross-section.

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 interaction point of less than 15 cm along the beam axis and less than 0.15 cm in the transverse plane. Finally, to remove beam-scraping events, 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 pPb collisions a pileup filter is employed. The pileup rejection efficiency of this filter is greater than 90% in minimum bias events and it removes a very small fraction (0.01%) of the events without pileup. In pp collisions no filter is applied, but the same filter is used to check the effect of pileup on results and the change is included in the systematic uncertainties.

This analysis is performed using events required to have a dijet with a leading jet of $p_{T,1} > 30$ GeV/$c$, a subleading jet of $p_{T,2} > 20$ GeV/$c$, and $\Delta \phi_{1,2} = |\Delta \phi_1 - \Delta \phi_2| > 2\pi/3$. Further selections are applied on the average $p_T$, $p_{T,\text{ave}} = (p_{T,1} + p_{T,2})/2$ to select different $Q^2$ ranges. The $p_{T,\text{ave}}$ ranges used in the analysis are 25-55, 55-75, 75-95, 95-115, 115-150 and 150-400 GeV. For each $p_{T,\text{ave}}$ range a single trigger, minimum-bias, single jet trigger 40 GeV threshold (jet40), jet60, jet80, jet100 and jet100, respectively, is used.

According to the convention used in this analysis the Pb beam is going in the $-z$ direction. The beam energies of Pb and proton are different, as a result, the pseudorapidity of center-of-mass is at $\eta_{CM} = +0.465$. On the other hand, in pp collisions the nucleon-nucleon center-of-mass is same as the lab frame. To compare the two collisions pp reference was boosted by selecting jets in an interval of $-3.465 < \eta < 2.535$ and later shifting leading and subleading jet $\eta$ values by $\eta_{1(2)} \rightarrow \eta_{1(2)} + 0.465$. In the results section this change of variables is not explicitly stated, but from now on the changed coordinate system is used. It should be noted that $\eta_{dijet}$ for pp collisions is not defined in the lab frame, while it is in the lab frame for pPb collisions.

4 Jet Reconstruction

Offline jet reconstruction is performed using the CMS “particle-flow” algorithm [20, 21]. By combining information from all sub-detector systems, the particle-flow algorithm attempts to identify all stable particles in an event, classifying them as electrons, muons, photons, charged and neutral hadrons. Then jets are reconstructed based on the particles, using the anti-$k_T$ sequential recombination algorithm provided in the FASTJET framework [22], with a distance
parameter of $R = 0.3$.

5 Average dijet pseudorapidity and momentum

Compared to inclusive jets, the dijet system is more sensitive to the $x$ and $Q$ values that determine the hard scattering process between two incoming partons, because in the case of dijets information from both of the outgoing partons are used instead of only one. This analysis aims to make a $x$ and $Q$ dependent measurement of PDFs by making use of the sensitivity of the dijet system, where the $x$ values are controlled by $\eta_{dijet} = (\eta_1 + \eta_2)/2$ and $Q$ by $p_T^{ave} = (p_{T1} + p_{T2})/2$.

Let us define $x_1$ ($x$ from proton, $x_p$, in pPb collisions) as the $x$ of the parton from the nucleon going in the $+z$ direction and $x_2$ ($x$ from Pb, $x_{Pb}$, in pPb collisions) as the $x$ of the praton from the nucleon going in $-z$ direction. Different configurations of $x_1$ and $x_2$ can be chosen by selecting on ranges of the dijet pseudorapidity defined as $\eta_{dijet} = (\eta_1 + \eta_2)/2$. In the simple case of two partons colliding without initial state radiation (ISR) or final state radiation (FSR) $\eta_{dijet}$ would be proportional to $\log(x_1/x_2)$. The effect of ISR and FSR on this correlation was checked using particle-level PYTHIA and was found to be small. The correlation is shown in Fig. 1 for a particular $p_T^{ave}$ selection, but the conclusion holds for other intervals as well. This tight correlation shows that $\eta_{dijet}$ is an observable, which is sensitive to PDFs.

The dependence of $x_1/x_2$ on $\eta_{dijet}$ does not vary significantly as a function of $p_T^{ave}$, because when $p_T^{ave}$ gets larger both $x_1$ and $x_2$ increases and this change cancels in their ratio. However, we are mainly interested in studying the modification of $\eta_{dijet}$ distributions as a function of $x_{Pb}$ to study nuclear PDFs. The change in the dependence of $x_{Pb}$ on $\eta_{dijet}$ at different $p_T^{ave}$ can roughly be estimated using particle-level boosted pp PYTHIA where $x_2 \approx x_{Pb}$. As shown in Fig. 1, mean $x_{Pb}$ as a function of $\eta_{dijet}$ get larger by increasing $p_T^{ave}$. Therefore, to study the $Q$ variation of PDFs and nPDFs slightly different regions of $\eta_{dijet}$ needs to be compared among the $p_T^{ave}$ bins. In this study $x_{Pb}$ distributions in narrow intervals of $\eta_{dijet}$ and $p_T^{ave}$ are parametrized with a Gaussian fit and the $\mu$ parameter of the Gaussian fit taken as a proxy to mean $x_{Pb}$.

Figure 1: (Left) Correlation between the ratio of $x_{Pb}$ and $x_p$ and $\eta_{dijet}$. (Right) Mean $x$ values obtained from particle-level PYTHIA are shown as a function of $\eta_{dijet}$ in bins of dijet $p_T^{ave}$.
6 Systematic Uncertainties

The shape of $\eta_{\text{dijet}}$ distributions can be affected by reconstruction biases mainly in two ways: Through the reconstruction effects on the $p_T$ and on the $\eta$ of the leading and subleading jets.

The reconstruction effects on $p_T$ are important as a result of the dependence of the shape of the $\eta_{\text{dijet}}$ distributions on $p_{\text{ave}}^T$. For large $p_{\text{ave}}^T$, $\eta_{\text{dijet}}$ is narrower, and for small $p_{\text{ave}}^T$, $\eta_{\text{dijet}}$ is wider. As a result, the under-estimate of jet transverse momentum can cause $\eta_{\text{dijet}}$ shape to be biased towards wider values and an similarly, over-estimate can make it narrower. Therefore, a precise measurement of $\eta_{\text{dijet}}$ is only possible after going through several steps of calibration of jet $p_T$. These steps are well established by CMS and described in Refs. [23, 24].

The first step of jet energy corrections are based on simulations and are derived as a function of $p_T$ and $\eta$ of the jet. In pPb collisions the jet energy scale, defined as agreement between the reconstructed jet $p_T$ and the particle-level jet $p_T$, is found to be better than 1% at low $p_T$ and less than 0.5% at high $p_T$ for pPb collisions within $|\eta| < 3$. For the pp reference, due to usage of HF the deviation from unity can reach values as high as 5% for jets at $|\eta| > 3$ at high $p_T$. Due to the precision reached on the jet energy scale these deviations are not the most dominant sources of systematic uncertainties except in the HF region.

After calibration of jets using simulations, jet energy response in data and MC are compared by employing several methods that mainly depend on transverse momentum balance in the event either among dijet and $\gamma - \text{jet}$ pairs or the total transverse energy balance. The jets outside of barrel calorimeter are calibrated relative to the jets in the barrel calorimeter, $|\eta| < 1.3$, as the response in the barrel is more reliably modelled by simulations. These corrections change as a function of $\eta$ significantly, take on values $> 50\%$ in the HF, and are therefore essential measurement of $\eta_{\text{dijet}}$ distributions.

After the correcting data and MC discrepancies relative to the barrel region, a possible offset in jet response in the barrel is quantified by $\gamma$-jet events as $\gamma$ energy is calculated to high accuracy using ECAL information. Due to the available statistics with 25.8 $pb^{-1}$ pp collisions and 35 $nb^{-1}$ pPb collisions this step of calibration cannot be applied. However, an upper bound of 2% on possible deviations is obtained. The 2% uncertainty on jet energy scale over the whole range of $\eta$ due to the possible discrepancies between data and simulations is quoted and this represents one of the dominant sources of uncertainty.

In addition to jet energy scale the resolution of jet energy can also modify the $\eta_{\text{dijet}}$ distributions. Although, on average the jet energy is calculated within few percent accuracy, there are jet by jet variations with respect to this average behaviour. Due to the falling shape of jet $p_T$ spectrum, the resolution of jet transverse momentum is more likely to results in jets with lower $p_T$ to pass a give threshold due to reconstruction biases than the jets feeding down from higher $p_T$ values. The jet energy resolution causes $\eta_{\text{dijet}}$ shapes to get wider and it constitutes another dominant source of systematic uncertainty.

There are competing effects to the widening of $\eta_{\text{dijet}}$, which makes the shapes narrower, coming from reconstruction effects on $\eta$ of the jets. The direction of jets are determined before the detector response is corrected with the steps described above, as these steps apply on a jet-by-jet basis and not on the constituents of the jet. A larger fraction of jet energy is captured in the central part of the detector due to sub-detectors that perform better in the barrel and due to the existence of tracker. As a results, jet directions are tilted towards the centre of the detector after reconstruction. The offset in reconstructed $\eta$ values with respect to the particle-level $\eta$ values is always less than $\approx 0.01$, it still causes the $\eta_{\text{dijet}}$ distributions to get narrower, because of the steep shape of $\eta_{\text{dijet}}$ in the forward region. Resolution of $\eta$, defined as the width
of the distribution of the difference of reconstructed jet $\eta$ and particle-level jet $\eta$, plays a less significant role than the offset in the $\eta$ values and is not a significant source of uncertainty.

The competing effects of jet energy resolution and tilt in jet $\eta$ values cancel to a large extent. The cancellation of these two sources can be checked using PYTHIA and PYTHIA+HIJING simulations by comparing distributions obtained with fully particle-level jets to fully reconstructed jets. The discrepancy between reconstructed and particle-level event fractions is less than 5% for $|\eta_{\text{dijet}}| < 2.5$, and less than 20% for more forward jets in both pp and pPb collisions. This discrepancy is easily covered by the total systematic uncertainty obtained by adding each source of systematic uncertainty in quadrature.

Other sources of uncertainties that are not dominant, but nevertheless included in the total uncertainty, are the combinatorial jets in the pPb collisions coming from nucleon-nucleon collisions that happen simultaneously with the hard-scattering collision of interest. The effect of remaining pileup events in pPb collisions is found to be less than 2%, in pp collisions the effect of pileup is found to be negligible.

7 Results

The $\eta_{\text{dijet}}$ distributions are measured in pp and pPb collisions for various $p_T^{\text{ave}}$ values in order to constrain proton and nuclear PDFs. This detailed study is motivated by the previous pPb dijet measurement which was done without a pp reference because of the lack of available data at same $\sqrt{s_{\text{NN}}}$. In Ref. [17] jet measurements from LHC pPb run are used to test the performance of different sets of nPDFs and proton PDFs, the results show that the measurement of normalized $\eta_{\text{dijet}}$ distributions result in cancellation of part of theoretical uncertainties and are therefore optimal for nPDF studies. The results show good agreement with EPS09 nPDF, and disfavor the DSSZ nPDF set. However, it was also shown that the different sets of proton PDFs effect the $\xi_2^2$ between measurements and NLO nPDFs by a factor of two. Therefore, the pp data are first compared to NLO calculations with proton PDF, which is shown in Subsection 7.1. The same comparison between pPb data and the NLO calculation with nPDF sets, which is shown in Subsection 7.2. Finally the ratio and the difference between pp and pPb data are shown in Subsection 7.3 to extract nuclear modification effects.

7.1 Dijet pseudorapidity distribution in pp collisions

A comparison of pp collisions to NLO calculations is done in the boosted frame. These distributions will be used as a baseline in Section 7.3. The two sets of NLO PDFs that are used are: CT14nlo, with number 13100-13156 in LHAPDF, and MMHT2014nlo68cl, with 25100-25150 in LHAPDF. The distribution in pp collisions is overlaid with NLO calculations in Fig. 2. MMHT14 is in slightly better agreement with data and produces a narrower distribution. However, distributions from both NLO PDFs predictions are significantly wider than in data.

7.2 Dijet pseudorapidity distributions in pPb collisions

The dijet pseudorapidity distributions are also measured in pPb and compared to NLO predictions from nPDF sets of DSSZ, EPS09, and nCTEQ15. For all three nPDF sets the baseline proton PDF is varied between, CT14 and MMHT14. The $\eta_{\text{dijet}}$ distributions in bins of $p_T^{\text{ave}}$ are compared to nPDF sets for the CT14 proton PDF option in Fig. 3 and for MMHT14 proton PDF option in Fig. 4. Similar to the comparison between pp and NLO calculations, the predicted $\eta_{\text{dijet}}$ distributions from NLO calculations using different nPDF sets are significantly wider than the pPb data.
7.3 Comparison of pPb and pp ratios to NLO

As discussed in Section 7.1 the NLO calculations are wider than the pp measurement. However these are used as baseline nucleon PDF in the nPDF calculations. In order to reduce the dependence on the nucleon PDF, ratios and differences of pPb and pp are compared to ratios of
NLO predictions with and without nuclear modification of baseline nucleon PDF. As shown in Figure 5 and 6, the ratios of pPb and pp data agree with NLO calculation with EPS09 nPDF in the $\eta_{\text{dijet}} > -1$ region. In the region $\eta_{\text{dijet}} < -1$, the data is higher than predictions with EPS09 and nCTEQ15 nPDFs.

Figure 4: The measured pPb dijet pseudorapidity spectra in bins of dijet average transverse momentum overlaid with NLO calculations with nPDF sets of DSSZ, EPS09 and CTEQ15 for proton PDF baseline of MMHT14.

Figure 5: The ratio between pPb and pp dijet pseudorapidity is compared to NLO calculations. Calculations are with nPDF sets DSSZ, EPS09 and nCTEQ15 and proton PDF MMHT14.
Figure 6: The ratio between pPb and pp dijet pseudorapidity is compared to NLO calculations. Calculations are with nPDF sets DSSZ, EPS09 and nCTEQ15 and proton PDF CT14.

The difference between pPb and pp data are shown in Figure 8 and 7. The data are closer to nPDF calculations using EPS09 nPDF and disagree with predictions using nCTEQ15 and DSSZ nPDF sets.

Figure 7: The difference between pPb and pp dijet pseudorapidity is compared to NLO calculations. Calculations are with nPDF sets DSSZ, EPS09 and nCTEQ15 and proton PDF MMHT14.
8 Summary

Measurements of the dijet pseudorapidity in different dijet average $p_T$ intervals in pp and pPb collisions at nucleon-nucleon centre-of-mass energy of 5.02 TeV are reported. The measured dijet pseudorapidity distributions are compared to NLO calculations using nuclear and proton parton distribution functions. Significant modifications of the dijet pseudorapidity are observed in pPb data compared to pp references. Those measurements are compared with NLO calculation with EPS09, DSSZ and nCTEQ15 which provide strong constrain to the nPDF.

References


Temporary entry *.

Momentum Resolution in CMS”, JINST 6 (2011) P11002,

[24] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp