The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

19 December 2013 (v3, 08 January 2014)

Dijet Measurements in pPb collisions

Doga Can Gulhan for the CMS Collaboration

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Results on dijet production in pPb collisions at 5.02 TeV are discussed with a focus on dijet pseudorapidity, η_{dijet} , and centrality classification biases on it. The normalized η_{dijet} distributions from data and from calculations with CT10 proton parton distribution function (pPDF) and with EPS09 nuclear parton distribution function (nPDF) are compared. Despite the agreement between data and theoretical calculations for an inclusive centrality selection, as the raw transverse energy deposited in the forward calorimeter (forward activity) increases η_{dijet} distribution shifts towards lead beam direction an amount that is larger than what would be expected from the impact parameter dependence of nPDFs. To understand the driving mechanism of this shift an additional measurement of $\langle \eta_{\text{dijet}} \rangle$ as a function of forward activity on lead side is carried out in differential bins of forward activity on proton side. The shift is reduced by keeping proton side activity in a narrow interval.

Presented at *IS2013 International Conference on the Initial Stages in High-Energy Nuclear Collisions*

Dijet Measurements in pPb collisions

Doga C. Gulhan, on behalf of CMS collaboration

Massachusetts Institute of Technology, Cambridge, MA, USA

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Results on dijet production in pPb collisions at 5.02 TeV are discussed with a focus on dijet pseudorapidity, η_{dijet} , and centrality classification biases on it. The normalized η_{dijet} distributions from data and from calculations with CT10 proton parton distribution function (pPDF) and with EPS09 nuclear parton distribution function (nPDF) are compared. Despite the agreement between data and theoretical calculations for an inclusive centrality selection, as the raw transverse energy deposited in the forward calorimeter (forward activity) increases η_{dijet} distribution shifts towards lead beam direction an amount that is larger than what would be expected from the impact parameter dependence of nPDFs. To understand the driving mechanism of this shift an additional measurement of $\langle\eta_{\text{dijet}}\rangle$ as a function of forward activity in the lead direction is carried out in differential bins of forward activity in the proton direction. The shift is reduced by keeping forward activity in the proton direction in a narrow interval.

1. Introduction

Proton-lead (pPb) collisions at the LHC span a unique parameter space in $Q^2 - x$ plane for nPDFs, and jets can be used to probe regions that cannot be reached by hadrons alone [1]. To have sensitivity to initial state effects the modification of jets due to jet quenching in the final state should be insignificant. For this, one can rely on the measurement of the transverse momentum ratios, in which no jet quenching effect is observed. Any variation in $\langle p_{T,2}/p_{T,1} \rangle$, where the indices 1 and 2 refer to the leading and subleading jet respectively, with increasing forward activity is less than 2% [2]. Therefore, $\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2$ should be sensitive to initial state effects by nPDFs.

The PDFs in the lead nucleus are modified due to interactions between each nucleon and others surrounding it, meaning that nuclear modification depends on the position of the nucleon within the nucleus [3]. Centrality dependent measurement of $\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2$ distribution could be a way to measure the impact parameter nPDFs. However, as it will be discussed later, in pPb collisions centrality determination is problematic. Our effort in answering this question reveals other interesting physical phenomena.

2. Trigger, Jet Reconstruction and Data Sets

A total integrated luminosity of 31 nb^{-1} of pPb data collected with a high level trigger (HLT) that requires at least one jet with $p_T > 100 \text{ GeV}/c$ is used in the analysis. The lead nuclei and protons had beam energies of 1.58 TeV per nucleon and 4 TeV, respectively, corresponding to a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$. 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

Figure 1: The left panel shows the correlation between first layer of pixel hits and raw energy measured in the HF detector in the interval $|\eta| < 3$ in PbPb collisions. The middle and right panels show the correlation between the raw number of reconstructed primary tracks ($N_{\text{trk}}^{\text{offline}}$) with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c and raw transverse energy measured by the HF detector in the interval $|\eta| > 4$, $E_T^{\text{HF}[|\eta|>4]}$ in pPb collisions for minimum bias events (Middle Panel) and for dijet events (Right Panel).

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 massless particle emitted at $\eta_{\text{cm}} = 0$ in the nucleon-nucleon centre-of-mass frame will be detected at $\eta_{\text{lab}} = +0.465$ in the laboratory frame.

For the offline analysis, additional requirements for selection of hadronic collisions and beam background rejection are applied [4]. A set of selections are employed to remove the pile-up events that occur with 3% probability at each bunch crossing [5]. Offline jet reconstruction is performed using the CMS particle-flow (PF) algorithm [6] and FastJet anti- k_T recombination algorithm [7] with the iterative underlying event subtraction of CMS [8]. For dijet event selection leading and subleading jets are determined among all the jets in the range $|\eta| < 3$, and the event is required to have $p_{T,1} > 120$ GeV/c, $p_{T,2} > 30$ GeV/c with $\Delta\phi = |\phi_1 - \phi_2| > 2\pi/3$. For systematical uncertainty derivation and for comparison to the results from data, two fully simulated MC samples, PYTHIA (version 6.423, tune Z2) [9], and PYTHIA embedded HIJING [10], are used. They are boosted to have nucleon-nucleon center-of-mass at $\eta = -0.465$ as in

Figure 2: The mean η_{dijet} values are shown as a function of sum of the truth values of transverse momentum of particles in pp collisions generated by boosted PYTHIA generator at 5.02 TeV. The η of particles are restricted to be in the range of the HF detector only on the positive η side (left), only on the negative η end (middle), and on both sides (right).

Figure 3: The left panel shows the correlation between transverse energy deposited in HF detector in Pb going direction at $|\eta| > 4$, $E_T^{\text{HF,Pb}[|\eta|>4]}$, and transverse energy deposited in HF detector in p going direction at $|\eta| > 4$, $E_T^{\text{HF,p}[|\eta|>4]}$. The boundaries of event classes are shown with the dashed lines. The N_{part} distributions obtained from HIJING simulation for the same event classes are shown on the right panel.

pPb collisions at the LHC.

3. Centrality in pPb Collisions

Centrality determination in pPb collisions is very challenging due to the much looser correlation between experimental observables and the impact parameter, compared to PbPb collisions. In PbPb analysis the centrality classes are determined by grouping minimum bias events by the raw energy deposition in the Hadronic Forward (HF) calorimeter. In the left panel of Fig. 1 the correlation between this variable and multiplicity is shown. Since the width of the correlation is much smaller than the overall range of HF energy and multiplicity, even if the classification was done using multiplicity instead of HF energy most of the events would still fall in the same centrality class. To visualize this consider vertical and horizontal slices with same mean HF energy and multiplicity values. The events that stay in the same class in both cases are the ones in the intersection of the vertical and the horizontal slices. However, in pPb collisions the width of the correlation between multiplicity and raw transverse energy deposited in HF at large η , $E_T^{\text{HF}[|\eta|>4]}$, is comparable to the overall range of $E_T^{\text{HF}[|\eta|>4]}$, as shown in middle and right panels of Fig. 1 for minimum bias and dijet events respectively. Changing the direction of slicing moves around the majority of the events from one class to another.

Another complication is caused by the fact that energy (or multiplicity) carried by jets constitutes a significant portion of the overall energy (or multiplicity) available in the event, resulting in strong centrality biases on dijet observables. One such case is demonstrated using generator-level information from PYTHIA events in Fig. 2. The mean value of η_{dijet} is shown with respect to the total p_T carried by particles at large η . As it can be seen in the left and middle panels, requiring large total p_T in one direction shifts the hard scattering vertex to the opposite direction due to energy momentum to be conservation. Instead, if the total p_T on both sides is used, as shown in the right panel, the two shifts cancel out to a large extent. Therefore, for this analysis the events are classified with respect to the energy deposited on both sides of the HF. Further in-

Figure 4: (a) The η_{dijet} distribution is shown for 0 – 100% pPb collisions with red solid circles. The error bars represent the statistical uncertainties and the total systematic uncertainties are shown as yellow boxes. The results are compared to NLO calculations using CT10 (Blue solid line) and CT10+EPS09 (Black dashed curve) PDFs. (b) The difference of data and CT10 calculation. (c) The difference of data and EPS09 calculation. The curves in panels (b) and (c) denote the theoretical uncertainties.

formation on event classes are given in Ref. [2] and in Fig 3. For the study explained in Section 5.3 $\langle\eta_{dijet}\rangle$ is measured as a function of activity only on one side of the HF for which the bias explained above should be kept in mind.

4. Major systematic uncertainties

The major systematic uncertainties come from jet energy corrections (JEC) and forward activity binning. To reduce the JEC uncertainty, a data-driven jet energy correction step is applied using dijet balance technique[11], in addition to the corrections from MC simulations. This step is needed due to the calorimeter response difference in simulations and in data largest at large η , and it is crucial to extend the acceptance from $|\eta| < 2$ to $|\eta| < 3$. Forward activity binning uncertainty is calculated from PYTHIA+HIJING sample as the difference between the value in a given forward activity class compared to inclusive centrality events. For the highest forward activity class the systematic uncertainties from pile-up become comparable to the other dominant sources and they are determined by redoing the measurement without the pile-up filter.

Figure 5: (Left Panel) The η_{dijet} distributions normalized by the number of selected dijet events for the five HF activity classes are shown. (Right Panel) The mean values of the η_{dijet} distributions in data are shown together with the mean values from PYTHIA+HIJING simulation for the same HF activity classes as empty black circles, and with PYTHIA simulations without any HF selection as the grey band where the width of the band demonstrates the statistical uncertainty.

5. Results

5.1. Comparison to EPS09 calculations

Comparison of normalized η_{dijet} distributions from data[2] and from NLO calculations with CT10 pPDF and CT10+EPS09 nPDF [12] are shown in Fig. 4. The CT10 calculation lies outside of the theoretical and experimental systematic uncertainties compared to data (panel (b)), whereas CT10+EPS09 result is within systematic uncertainties (panel (c)). Using PYTHIA, η_{dijet} can be roughly mapped on Bjorken x of the parton from Pb nucleus. Approximately, $\eta_{\text{dijet}} > 0$ corresponds to EMC, $-2 < \eta_{\text{dijet}} < 0$ to anti-shadowing and $\eta_{\text{dijet}} < -2$ to the shadowing regions. The excess and deficit of dijet events in CT10 calculation corresponding to anti-shadowing and EMC regions respectively are significant, while it is hard to make a conclusive statement about shadowing region where the uncertainties are large.

5.2. Dijet pseudorapidity as a function of total forward activity

Fig. 5 shows η_{dijet} distributions in five $E_T^{\text{HF}[\eta > 4]}$ classes in the left panel, and the mean values of these in the right panel. The right panel also has the mean values from PYTHIA+HIJING sample for the same classes and from PYTHIA without any requirement on forward activity. In data the $\langle \eta_{\text{dijet}} \rangle$ shifts ~ 0.3 units in pseudorapidity, which cannot be due to impact parameter dependence of nPDFs alone. The $\langle \eta_{\text{dijet}} \rangle$ in the lowest activity bin does not agree with PYTHIA which has pPDF, instead it takes a lower value. By comparing the difference in η_{dijet} distribution between highest activity and lowest activity class on left panel of Fig 5 with the variation between the CT10 and CT10+EPS09 distributions in Fig. 4a. This means that the variation due to forward activity is larger than the overall nPDF effect.

Figure 6: (Left Panel) The same correlation as in the left panel of Fig. 3 is shown with lines that demonstrate the boundaries of event classes that are used for the measurement shown in right panel of this figure. (Right Panel) Mean η_{dijet} as a function of $E_T^{\text{HF,Pb}[|\eta|>4]}$ in bins of $E_T^{\text{HF,p}[|\eta|>4]}$. Lines indicate the systematic uncertainty and the error bars denote the statistical uncertainties. The results without the selection applied are also shown as a black line with statistical uncertainties denoted by the line width.

5.3. Dijet pseudorapidity as a function of lead-going-side activity with fixed proton-going-side activity

It was suggested by Milhano and Armesto that the $\langle \eta_{\text{dijet}} \rangle$ shift might be driven by the initial state radiation from the proton [13]. Large initial state radiation (ISR) by the proton means large energy deposition in the HF on the proton-going-side, $E_T^{\text{HF,p}[|\eta|>4]}$, and vica versa for the lead. As can be seen from Fig. 3a by going from lowest forward activity class to the highest forward activity class there is a significant (on average ~ 10 GeV) increase in $E_T^{\text{HF,p}[|\eta|>4]}$. Since $E = \cosh(\eta)E_T$, an extra 10 GeV E_T at $\eta > 4$ that goes in ISR removes significant amount of the energy available for hard scattering. The parton of the lead that participates in hard scattering does not necessarily come from the nucleon that generates forward energy deposition, because there are more than one nucleons. On average, the longitudinal momentum of the parton from the proton is reduced, while the longitudinal momentum of the parton from the lead is unchanged. Therefore, the pseudorapidity of the hard scattering interaction shifts in the lead direction.

This hypothesis can be tested by measuring $\langle \eta_{\text{dijet}} \rangle$ in narrow bins of $E_T^{\text{HF,p}[|\eta|>4]}$ as a function of energy deposition in the lead direction $E_T^{\text{HF,Pb}[|\eta|>4]}$. The results are shown in Fig. 6. Comparing the results with no restriction on $E_T^{\text{HF,p}[|\eta|>4]}$ to the results for the differential $E_T^{\text{HF,p}[|\eta|>4]}$ requirements one can see that the shift in $\langle \eta_{\text{dijet}} \rangle$ is reduced. Especially for low $E_T^{\text{HF,p}[|\eta|>4]}$ $\langle \eta_{\text{dijet}} \rangle$ is consistent with flat.

6. Conclusions

The dijet transverse momentum ratio results presented in this paper confirm that any jet quenching effect in pPb collisions is small and jets are not modified significantly by final state effects, making it possible to study initial state effects with dijet pseudorapidity measurement. The

η_{dijet} distribution in inclusive pPb collisions are compared to NLO calculations using CT10 and CT10+EPS09 PDFs and provide constraints on the nuclear parton distribution functions. The dijet pseudorapidity distribution shifts in the Pb going direction with increasing forward activity. The observed magnitude of the modification of dijet pseudorapidity is larger than the predictions from the NLO calculations based on impact-parameter dependent nPDFs [14]. The origin of this shift is investigated further by fixing forward activity in the proton direction and looking at the evolution of $\langle\eta_{\text{dijet}}\rangle$ as forward activity in the lead direction increases. It is observed that the shift is reduced in this manner, suggesting the increase in the ISR from the proton in large forward activity events as the driving mechanism of the shift.

- [1] C. Salgado, J. Alvarez-Muniz, F. Arleo, N. Armesto, M. Botje, et al., J. Phys. G39 (2012) 015010.
- [2] CMS Collaboration, Study of dijet momentum balance and pseudorapidity distributions in pPb collisions at $\sqrt{s_{\text{nn}}} = 5.02$ TeV, CMS Physics Analysis Summary, CMS-PAS-HIN-13-001.
- [3] M. Hirai, S. Kumano, T.-H. Nagai, Phys. Rev. C70 (2004) 044905.
- [4] V. Khachatryan, et al., Eur. Phys. J. C70 (2010) 1165.
- [5] S. Chatrchyan, et al., Phys. Lett. B724 (2013) 213.
- [6] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary.
- [7] M. Cacciari, G. P. Salam, G. Soyez, JHEP 04 (2008) 063.
- [8] O. Kodolova, I. Vardanian, A. Nikitenko, A. Oulianov, Eur. Phys. J. C50 (2007) 117.
- [9] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 05 (2006) 026 (tune D6T with PDFs CTEQ6L1 used for 2.76 TeV, tune Z2 for pp 7 TeV).
- [10] X.-N. Wang, M. Gyulassy, Phys. Rev. D44 (1991) 3501.
- [11] CMS Collaboration, JINST 6 (2011) P11002.
- [12] K. Eskola, H. Paukkunen, C. Salgado, JHEP 1310 (2013) 213.
- [13] G. Milhano, N. Armesto, Jets and nPDFs, Talk in Jet Workshop, Paris (2013).
- [14] I. Helenius, K. J. Eskola, H. Honkanen, C. A. Salgado, JHEP 1207 (2012) 073.