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Beyond-DGLAP searches with Mueller-Navelet jets, and measurements of low-p_T and forward jets at CMS

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We present searches for beyond-DGLAP resummation effects in the production of dijets with large rapidity separation in pp collisions at $\sqrt{s} = 7$ TeV. Ratios of inclusive to exclusive dijet production cross sections and dijet azimuthal decorrelations are presented as a function of the rapidity separation between jets. The measurements are compared to predictions of conventional LO+PS MC generators, as well as to MC generators incorporating elements of the BFKL approach and analytic NLL BFKL calculations. Measurements of inclusive low-p_T jet production in pp collisions at $\sqrt{s} = 8$ TeV are also presented.

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1. Introduction

Hard parton-parton interactions occurring during hadron collisions can be described in the theory of Quantum chromodynamics (QCD). Hadronic jets, collimated streams of particles carrying information about partons produced in the hard interaction, are particularly useful probes for studies of QCD. Perturbative QCD (pQCD) calculations at next-to-leading (NLO) order accuracy, using the collinear factorisation framework and Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations are well-tested tools describing inclusive jet or dijet production. Measurements of correlations of jets within the same event are sensitive to higher order pQCD radiation (or parton showers), which is taken into account in analytic calculations by the resummation procedure. The DGLAP equations account for such radiation to all orders of perturbation theory for hard parton collisions ($\sqrt{s} \sim p_{\mathrm{T}} \gg \Lambda_{QCD}$). At high centre-of-mass energies a kinematical domain can be reached where semi-hard parton interactions ($\sqrt{s} \gg p_{\mathrm{T}} \gg \Lambda_{QCD}$) play a substantial role. Perturbative QCD resummation in the asymptotic region, where $\sqrt{s} \to \infty$, is performed by the Balitsky-Fadin-Kuraev-Lipatov (BFKL) equation. In high-energy pp collisions, a promising final state for probing BFKL asymptotic consists of two jets of similar p_{T} that are widely separated in rapidity, y, often referred to as Mueller-Navelet jets [1]. In case of a significant contribution of semi-hard scattering in pp collisions at a given energy a strong rise of the inclusive dijet production cross section with increasing rapidity interval, Δy, is expected.

In this report a measurement of inclusive jet production at low p_{T} and forward rapidities is presented [2], and searches for beyond-DGLAP effects in Mueller-Navelet dijet production are discussed [3, 4].

2. The CMS detector

The calorimeter system of the CMS detector [5] covers pseudo-rapidity range $|\eta| < 5.0$, where $\eta = -\log[\tan(\theta/2)]$, and θ is the polar angle relative to the anticlockwise proton beam direction. The crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadronic calorimeter (HCAL) extend to pseudorapidities $|\eta| = 3.0$. The HCAL cells map to an array of ECAL crystals to form calorimeter towers projecting radially outwards from the nominal interaction point. The pseudorapidity region $3.0 < |\eta| < 5.0$ is covered by the hadronic forward (HF) calorimeter.

Several methods of jet reconstruction are used by the CMS collaboration. Calorimeter jets are clustered from energy deposits in calorimeter towers. Particle flow jets are formed by clustering particles as reconstructed by the particle plow algorithm using information from all subdetectors. The anti-k_{T} algorithm is used for jet clustering. The precision of the jet energy calibration varies for different jets types [6], and is within $7-8\%$ for forward jets(at $p_{\mathrm{T}} \simeq 35$ GeV and $3 < |\eta| < 4.7$).

3. Inclusive low-p_{T} jet cross section

The measurement of inclusive production of jets [2] was performed with 5.8 pb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV, recorded in special low pileup LHC runs during the summer of 2012. The production cross section was measured in bins of transverse momentum, p_{T}, in the rapidity range of $|y| < 4.7$.

To correct for the finite resolution of the jet p_T measurement, an unfolding procedure developed in [7] was used. A response matrix of the detector was obtained using Monte Carlo events passed through the full CMS detector simulation.

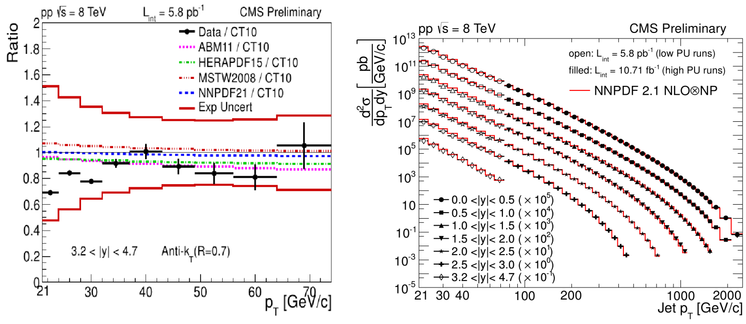

Figure 1: Ratio of inclusive jet cross section measurement to NLO calculation prediction with CT10 pdf set on the left. On the right inclusive jet cross-section measurement over the wide rapidity and p_T ranges is shown.

The total experimental uncertainty does not exceed 50%, with the leading contribution being due to the jet energy scale calibration.

The results of the measurement were compared to the predictions of fixed order NLO calculations performed in the NLOJET++ [8] framework. The theoretical uncertainty was evaluated by varying the factorisation and renormalisation scales by a factor of $\pm 1/2$. The total uncertainty of theoretical predictions was found to be up to 14%.

The results of the measurement for the very forward region of the detector are shown in Fig. 1, in addition to a combination of the described measurement with the inclusive jet production cross section measured over the full 8 TeV dataset [9] is presented. The theoretical predictions agree with the measurements within the wide range of p_T and rapidity.

4. Inclusive to exclusive dijet production ratio

An observable sensitive to higher order QCD radiation and the possible manifestation of BFKL effects is the inclusive to exclusive dijet production ratio [10]. Events with at least one pair of jets are denoted as “inclusive". Events with exactly one pair of jets are called “exclusive". Only jets with transverse momenta above a minimal value of $p_{T,\min} = 35$ GeV are considered. In the inclusive case, the rapidity separation is evaluated for each pairwise combination of jets above threshold. Dijet yields in bins of rapidity separation Δy are obtained, and the ratio for each bin is taken.

By constructing the observable in such a way many theoretical and experimental uncertainties are reduced. The total experimental uncertainty is at most 5%, with the most substantial sources being the jet energy scale calibration and the model dependence of the unfolding procedure.

The results of the measurement are presented in Fig. 2. The data points are compared to predictions of DGLAP-based Monte Carlo generators (PYTHIA6, PYTHIA8 and HERWIG++), and to generators incorporating elements of the BFKL approach in the leading-logarithmic approximation (HEJ and CASCADE).

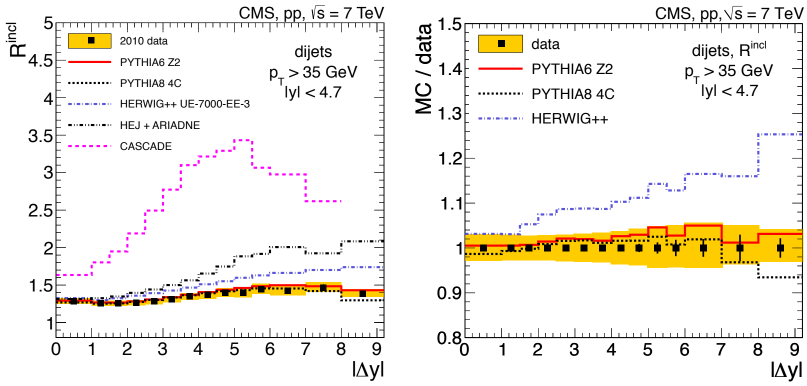

Figure 2: Inclusive to exclusive dijet production ratio compared to predictions of DGLAP-based MC PYTHIA6, PYTHIA8, HERWIG++ and MC with elements of LL BFKL - HEJ and CASCADE (left). Comparison to DGLAP-inspired MCs is presented as data/MC ratio on the right.

The PYTHIA8 and PYTHIA6 predictions agree with the data within the experimental uncertainties. HERWIG++ shows a stronger rise of the ratio with increasing rapidity separation, while HEJ and CASCADE predict too strong parton radiation.

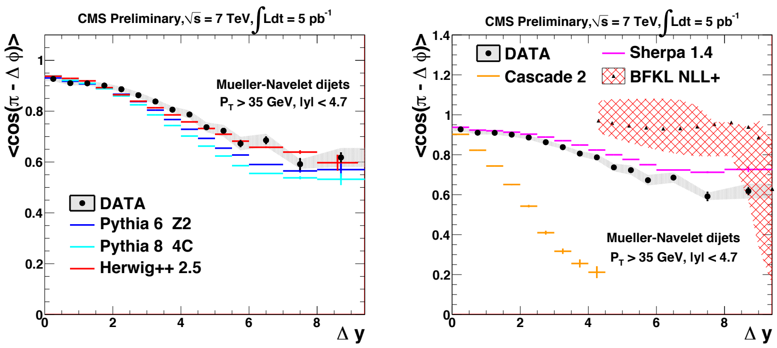

Figure 3: C_1 as a function of Δy compared to various theory predictions.

5. Azimuthal decorrelation of Mueller-Navelet jets

Perturbative QCD at the leading order predicts exactly two outgoing jets in parton-parton interactions. These jets are back-to-back in azimuthal angle, ϕ. If higher order pQCD radiation is added, jets become decorrelated. The BFKL equation predicts a strong rise of additional parton radiation with an increase of rapidity span of the event, while in DGLAP such a rise is only due to the increased phase space. Thus the study of azimuthal decorrelation of jets as a function of rapidity separation may reveal effects beyond the DGLAP description.

The dijet production cross section as a function of azimuthal angle difference can be written

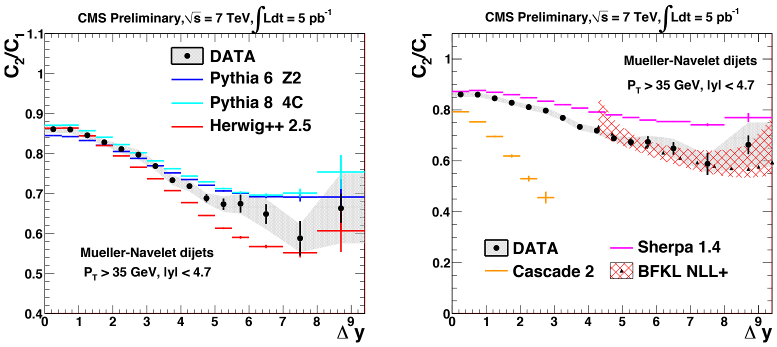

Figure 4: Ratio C_2/C_1 as a function of Δy compared to various theory predictions.

as a Fourier series:

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\text{Tmin}}) = \frac{1}{2\pi}\left[1+2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\text{Tmin}})\cdot cos(n(\pi-\Delta\phi))\right]. \tag{5.1}$$

The Fourier coefficients $C_n(\Delta y, p_{\text{Tmin}})$ are equal to the average cosines of the decorrelation angle: $C_n(\Delta y, p_{\text{Tmin}}) = \langle cos(n(\pi-\Delta\phi))\rangle$, where $\Delta\phi = \phi_1 - \phi_2$ is the difference between the azimuthal angles ϕ_1 and ϕ_2 of the jets most forward and backward in rapidity.

A measurement of C_1 was first performed by the D0 experiment at the Tevatron [11]. Later it was proposed that the ratios of coefficients C_2/C_1 and C_3/C_2 are observables more sensitive to BFKL contributions [12]. In this report a first measurement of cosine ratios is presented, in addition to C_n.

The present analysis was performed with pp collisions taken at $\sqrt{s} = 7$ TeV in 2010. Average cosines of the azimuthal angle difference were measured in bins of of rapidity separation between the jets, Δy. Jets with $p_T > 35$ GeV and $|y| < 4.7$ were considered.

The observables corrected for detector effects are compared to predictions of various MC and to analytic next-to-leading logarithmic approximation (NLL) BFKL calculations [13]. It should be noted that improved NLL BFKL calculations, including a comparison to the CMS data, were released after the present measurement was published [14].

The leading source of experimental uncertainty in the measurement is the jet energy scale calibration, which constitutes up to 24% depending on observable and rapidity separation range. The total experimental uncertainty does not exceed 25%.

The measured average cosines are shown in Fig. 3. The cosine ratios are presented at Fig. 4. DGLAP-based MC generators (PYTHIA6, HERWIG++ and SHERPA) do not describe all observables within the experimental uncertainty. The NLL BFKL calculations describe well the cosine ratios but fail for the average cosines. It should be noted that the NLL BFKL calculations performed in [14] agree with the data for all observables.

6. Conclusions

The experimental data on inclusive jet production in a wide range of p_T and rapidity is described by the pQCD NLO predictions within the experimental and theoretical uncertainties. Dijet production ratios and azimuthal decorrelations probe higher order pQCD radiation, with the theory predictions for measured observables demonstrating a significant spread. Dijet production ratios are described by PYTHIA6 and PYTHIA8 within the experimental uncertainties, while the HERWIG++, HEJ and CASCADE MC generators predict more intensive pQCD radiation than observed. The MC predictions show different levels of agreement with the data for different decorrelation observables, with the best overall agreement demonstrated by HERWIG++. NLL BFKL calculations provide a good description of the average cosine ratios.

7. Acknowledgements

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References

[1] A.H. Mueller, H. Navelet, *An Inclusive Minijet Cross-Section and the Bare Pomeron in QCD*, Nucl. Phys. B **282**, 1987

[2] CMS Collaboration, *Measurement of Low-p_{T} Jet Cross Section in proton-proton Collisions at $\sqrt{s} = 8$ TeV*, CMS Physics Analysis Summary **FSQ-12-031**, 2013

[3] CMS Collaboration, *Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton-proton collisions at $\sqrt{s} = 7$ TeV*, Eur. Phys. J. C **72**, 2012 [arXiv:1204.0696 [hep-ex]].

[4] CMS Collaboration, *Azimuthal angle decorrelations of jets widely separated in rapidity at $\sqrt{s} = 7$ TeV*, CMS Physics Analysis Summary **FSQ-12-002**, 2013

[5] CMS Collaboration, *The CMS experiment at the CERN LHC* , JINST **0803:S08004**, 2008

[6] CMS Collaboration, *Determination of Jet Energy Calibration and Transverse Momentum Resolution in CMS*, JINST **6**, 2011 [arXiv:1107.4277 [physics.ins-det]] .

[7] G. D'Agostini, *A Multidimensional unfolding method based on Bayes' theorem*, Nucl.Instrum.Meth. **A362**, 1995

[8] Z. Nagy, *Next-to-leading order calculation of three-jet observables in hadron hadron collision*, Phys. Rev. **D68**, 2003 [arXiv:hep-ph/0307268]

[9] CMS Collaboration, *Measurement of the double-differential inclusive jet cross section at $\sqrt{s} = 8$ TeV with the CMS Detector*, CMS Physics Analysis Summary **SMP-12-012**, 2013

[10] V. T. Kim and G. B. Pivovarov, *BFKL QCD pomeron in high-energy hadron collisions: Inclusive dijet production*, Phys. Rev. D **53**, 1996 [arXiv:hep-ph/9506381]

[11] S. Abachi *et al.* [D0 Collaboration], *The Azimuthal decorrelation of jets widely separated in rapidity*, Phys. Rev. Lett. **77**, 1996 [arXiv:hep-ex/9603010]

[12] A. Sabio Vera and F. Schwennsen, *The Azimuthal decorrelation of jets widely separated in rapidity as a test of the BFKL kernel*, Nucl. Phys. B **776**, 2007 [arXiv:hep-ph/0702158]

[13] B. Ducloué, L. Szymanowski and S. Wallon, *Confronting Mueller-Navelet jets in NLL BFKL with LHC experiments at 7 TeV*, JHEP **1305**, 2013 [arXiv:1302.7012 [hep-ph]]

[14] B. Ducloué, L. Szymanowski and S. Wallon, *Evidence for high-energy resummation effects in Mueller-Navelet jets at the LHC*, 2013 [arXiv:1309.3229 [hep-ph]]