The Compact Muon Solenoid Experiment
Conference Report

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28 December 2018 (v4, 14 August 2020)

Dijets with large rapidity separation at CMS

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A search for asymptotic BFKL effects at CMS in dijet events with large rapidity separation between jets in proton-proton collisions at 7 TeV is presented. CMS data on cross-section ratios and azimuthal decorrelations for dijets with large rapidity separation between jets are compared with predictions by various Monte Carlo event generators based on DGLAP and BFKL evolutions. None of the DGLAP-based generators can describe all measured observables by CMS at 7 TeV. NLO BFKL predictions are consistent with CMS data on dijet azimuthal decorrelations at 7 TeV. More data at higher LHC energies are needed to reveal possible effects.

Presented at *HSQCD-2018 Hadron Structure and QCD from Low to High Energies 2018*

Dijets with large rapidity separation at CMS

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Abstract

A search for asymptotic Balitsky-Fadin-Kuraev-Lipatov (BFKL) effects at CMS in dijet events with large rapidity separation between jets in proton-proton collisions at 7 TeV is presented. CMS data on cross-section ratios and azimuthal decorrelations for dijets with large rapidity separation between jets are compared with predictions by various Monte Carlo (MC) event generators based on Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) and BFKL evolutions. None of the DGLAP-based generators can describe all measured observables by CMS at 7 TeV. NLL BFKL predictions are consistent with CMS data on dijet azimuthal decorrelations at 7 TeV. More data at higher LHC energies are needed to reveal possible effects.

Keywords: BFKL, DGLAP, CMS, jets

PACS: 01.30.Cc, 12.38.Aw, 12.38.-t, 13.87.-a

1 Introduction

Note that QCD is well tested in hard processes ($\sqrt{s} \geq p_T \gg \Lambda_{QCD}$) and the data are successfully described by perturbative QCD (pQCD) calculations within the framework of collinear factorization and DGLAP evolution equations [1, 2, 3, 4, 5]. Parton-parton scattering at leading order in the strong coupling α_S produces two outgoing partons which are back-to-back in the azimuthal plane. The partons manifest themselves as a collimated stream of hadrons, which are the observable jets. A deviation from the back-to-back configuration occurs if higher order parton contributions are considered, which can be described by the parton showers initiated by the initial and final partons in the scattering process. At high centre-of-mass energies a kinematical domain can be reached where semi-hard parton interactions ($\sqrt{s} \gg p_T \gg \Lambda_{QCD}$) play a substantial role. The asymptotic region, where $\sqrt{s} \rightarrow \infty$, is described by the BFKL equation [6, 7, 8].

2 Ratios of dijet production cross-sections as a function of the rapidity separation between jets in proton-proton collisions at $\sqrt{s} = 7$ TeV

In the paper of A. H. Mueller and H. Navelet [9], the ratio of the cross-section for dijet production the maximal rapidity separation (Mueller-Navelet (MN) pair) to the Born dijet production cross-section (MN K-factor) was calculated as a function of the rapidity separation $\Delta y = |y_1 - y_2|$. An exponential growth of the cross-section ratio with Δy was predicted in terms of the leading logarithm (LL) BFKL approach.

However, the Born dijet production cross-section is unmeasurable because one cannot kinematically exclude virtual corrections. The way to solve this problem was found by V. Kim and G. Pivovarov [10]: the Born cross-section should be replaced with the “exclusive” cross-section (exactly two jets with transverse momenta above a minimum value of p_{Tmin} should be considered). The inclusive (two and more jets with $p_T > p_{Tmin}$) dijet production cross-section and the corresponding “K-factor” were also calculated.

Measurements of dijet production in proton-proton collisions at $\sqrt{s} = 7$ TeV for jets with $p_T > 35$ GeV and $|y| < 4.7$ using data collected with the CMS detector at the LHC in 2010 are presented in Ref. [11]. Here the inclusive dijet production cross-section is taken from events with at least two jets with $p_T > 35$ GeV and $|y| < 4.7$, “exclusive” dijets are the subset of “inclusive” when there are exactly two jets in the event, and the MN cross-section is for jets with the maximal rapidity

separation. The measured ratios R_{incl} and R_{MN} are inclusive and Mueller-Navelet “K-factors” respectively.

The measured values of R_{incl} (Fig. 1, *left*) and R_{MN} (Fig. 1, *right*) are compared with predictions of various MC event generators: the LL DGLAP parton shower with various effects (color coherence, dipole approximation) with LL BFKL elements (PYTHIA6 tune Z2 [12, 13, 14], PYTHIA8 tune 4C [15, 16] and HERWIG++ tune UE-7000-EE-3 [17, 18]) and the LL BFKL-motivated generators CASCADE [19] and HEJ+ARIADNE [20, 21, 22].

PYTHIA6 and PYTHIA8 predictions are in agreement with the data. HERWIG++ predictions lie higher than data, especially for large Δy region. The LL BFKL-motivated MC generators predict a stronger rise of the ratios than in the data. A moderate rise of ratios indicates that BFKL-effects for jets with $p_T > 35$ GeV and $|y| < 4.7$ may be present for pp-collisions at 7 TeV.

Figure 1: Inclusive (R_{incl} , *left*) and Mueller-Navelet (R_{MN} , *right*) “K-factors” [11] as a function of the rapidity separation Δy between the two jets in comparison with predictions of the PYTHIA6, PYTHIA8, HERWIG++, CASCADE and HEJ+ARIADNE. The *shaded band* indicates the total systematic uncertainty of the data.

3 Azimuthal decorrelation of jets widely separated in the rapidity in pp-collisions at $\sqrt{s} = 7$ TeV

According to V. Del Duca, C. Schmidt and W. Stirling [23, 24], the normalised cross-section for MN jets with $p_T > p_{Tmin}$ can be written as a Fourier series:

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

where C_n , the Fourier coefficients, are the average cosines of the decorrelation angle, $(\pi - \Delta\phi)$, and $C_n = \langle \cos(n(\pi - \Delta\phi)) \rangle$, where $\Delta\phi = \phi_1 - \phi_2$ is the difference between the azimuthal angles ϕ_1 and ϕ_2 of MN jets.

The average cosines C_1 , C_2 and C_3 (Fig. 2) were measured in Ref. [25] for jets with $p_T > 35$ GeV and $|y| < 4.7$ for pp-collisions at $\sqrt{s} = 7$ TeV. The data and event selection are the same as in Ref. [11]. Also, in this paper the average cosine ratios C_2/C_1 and C_3/C_2 (Fig. 3) were measured as proposed in Ref. [26]. The measured observables were compared with predictions from

Figure 2: Measured average cosines C_1 (top row), C_2 (middle row) and C_3 (bottom row) [25] as a function of the rapidity separation Δy compared with the LL DGLAP MC generators and the NLO generator POWHEG (left column). Comparisons with the tree approximation MC generator SHERPA, the LL BFKL-motivated HEJ+ARIADNE and analytical NLL BFKL parton level calculations ($4.0 < \Delta y < 9.4$) (right column). The shaded band indicates the total systematic uncertainty of the data.

Figure 3: Measured average cosine ratios C_2/C_1 (*top*) and C_3/C_2 (*bottom*) [25] as a function of the rapidity separation Δy compared with the LL DGLAP MC generators and the NLO generator POWHEG (*left column*). Comparisons with the tree approximation MC generator SHERPA, the LL BFKL-motivated HEJ+ARIADNE and analytical NLL BFKL parton level calculations (*right column*). The *shaded band* indicates the total systematic uncertainty of the data.

the LL DGLAP MC generators (PYTHIA6 tune Z2 [12, 13, 14], PYTHIA8 tune 4C [15, 16] and HERWIG++ tune UE-7000-EE-3 [17, 18]), the tree approximation MC generator SHERPA [27], the next-to-leading-order (NLO) matrix element MC generator POWHEG [28, 29, 30] interfaced with the LL DGLAP-based PYTHIA6 and PYTHIA8 generators, LL BFKL-motivated HEJ+ARIADNE [20, 21, 22] and NLL BFKL parton level analytical calculations [31].

The predictions of the LL DGLAP MC generator HERWIG++ show reasonable agreement with the data for average cosines, while for their ratios it cannot describe the data for $\Delta y \geq 5$. On the contrary, the LL DGLAP MC generators PYTHIA6 and PYTHIA8 have a reasonable description for the average cosine ratios from $\Delta y \geq 5$, while it cannot describe the average cosines. The results of the NLO matrix element MC generator POWHEG interfaced with the LL DGLAP-based parton shower of PYTHIA6 and PYTHIA8 do not yield a better description of the measured observables than the standalone results of PYTHIA6 and PYTHIA8. The tree approximation MC generator SHERPA also provides the same level of MC data description as PYTHIA8. The LL BFKL-motivated MC generator HEJ+ARIADNE provides a stronger decorrelation than it is observed in the data. An analytical NLL

BFKL calculation provides reasonable agreement with data for $\Delta y \geq 4$.

All these facts (sensitivity to an implementation of color-coherence effects in different MC generators and reasonable data description by analytical NLL BFKL calculations) indicate that the given kinematic region (jets with $p_T > 35$ GeV and $\Delta y \geq 5$ at collision energy 7 TeV) may be beyond the domain described by the DGLAP approximation.

4 Summary

A moderate rise is observed in the ratios of dijet production cross sections (“K-factor”) as a function of the rapidity separation between jets Δy . This observed behaviour is described by the PYTHIA6 and PYTHIA8 MC generators. The other LL DGLAP-based MC generator HERWIG++ predictions for the dijet cross-section ratios lie significantly higher than the data. The LL BFKL-based MC predictions by the HEJ+ARIADNE have a stronger rise of the ratios than it is observed in the data.

As to dijet azimuthal decorrelations, there is we have a reasonable description of average cosines by for $\Delta y \geq 5$, while their ratios cannot be described with HERWIG++ LL DGLAP-based MC generators PYTHIA6 and PYTHIA8 have worse agreement in the description of all azimuthal decorrelation observables. The description does not become better even if we take the NLO matrix element MC generator POWHEG interfaced with LL parton shower with PYTHIA8. Tree multiparton approximation MC generator SHERPA also provides same level of MC/data disagreement as PYTHIA8. On the contrary, PYTHIA6 and PYTHIA8 have a reasonable description for the average cosine ratios at $\Delta y \geq 5$, while it cannot describe the average cosines. The data description does not become better even if one can take the NLO matrix element MC generator POWHEG interfaced with the LL DGLAP-based parton shower of PYTHIA8. The tree multiparton approximation MC generator SHERPA also provides the same level of MC data description as PYTHIA8.

The LL BFKL-based MC generator HEJ+ARIADNE predicts a stronger dijet azimuthal decorrelation than it is observed in the data, while an analytical NLL BFKL calculation shows reasonable agreement with the data.

Therefore, none of the DGLAP-based generators can describe all of the CMS measured observables for dijets with large rapidity separation at 7 TeV. The fact that there is reasonable agreement only for particular observables for dijets with large rapidity separation for different LL DGLAP-based MC generators, may be explained by implemented into the generators various effects beyond the DGLAP-evolution.

To conclude, the inability to describe the CMS measured observables for dijets with large rapidity separation between jets by DGLAP-based generators and at the same time good agreement of the NLO BFKL calculation with the dijet azimuthal decorrelations at 7 TeV mean that more pronounced signatures of BFKL effects can be expected at higher collision energies.

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