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Study of dijet events with large rapidity separation in proton-proton collisions at $\sqrt{s} = 2.76$ TeV

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Abstract

The cross sections for inclusive and Mueller–Navelet dijet production are measured as a function of the rapidity separation between the jets in proton-proton collisions at $\sqrt{s} = 2.76$ TeV for jets with transverse momentum $p_T > 35$ GeV and rapidity $|y| < 4.7$. Various dijet production cross section ratios are also measured. A veto on additional jets with $p_T > 20$ GeV is introduced to improve the sensitivity to the effects of the Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution. The measurement is compared with the predictions of various Monte Carlo models based on leading-order and next-to-leading-order calculations including the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi leading-logarithm (LL) parton shower as well as the LL BFKL resummation.

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1 Introduction

The hard scattering of hadrons with high transverse momentum p_T is well described within the perturbative quantum chromodynamics (QCD) formalism at large center-of-mass energies \sqrt{s} in the Bjorken limit. In this limit, $\sqrt{s} \rightarrow \infty$, while the scaling variable $x \sim p_T/\sqrt{s}$ is kept fixed near unity. In this framework $p_T^2 \approx Q^2$, where Q^2 is the square of the four-momentum transfer. Thus, since x is not small, Q^2 tends to infinity, requiring the terms with $[\alpha_S \ln Q^2]^n$ in the calculations to be resummed, where α_S is the strong coupling. This resummation can be carried out in the collinear factorization framework with the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) formalism [1–5].

Another important kinematic regime is the Regge–Gribov limit [6–8]: $x \rightarrow 0$, finite $p_T \gg \Lambda_{\text{QCD}}$, and $\sqrt{s} \rightarrow \infty$, where Λ_{QCD} is the QCD scale. This leads to large rapidity intervals between the scattered partons. The standard DGLAP approach fails at small x because of the necessity to sum the terms of the perturbation series enhanced by powers of $[\alpha_S \ln(1/x)]^n$. Resummation of the leading $[\alpha_S \ln(1/x)]$ terms is typically performed in the Balitsky–Fadin–Kuraev–Lipatov (BFKL) approach [6–8], which describes what is generally referred to as the perturbative pomeron. In the Regge–Gribov limit, the parton scattering subprocesses involve a large number of the partons emitted in a large rapidity interval with comparable p_T . Such subprocesses can be described by the BFKL evolution and lead to an increase of the dijet production cross section with increasing rapidity separation between the jets, $\Delta y = |y_1 - y_2|$, where y_1 and y_2 are the rapidities of the two jets constituting a dijet. In events that contain at least two jets with p_T above a $p_{T\text{min}}$ threshold, the most forward and the most backward ones are referred to as Mueller–Navelet (MN) jets [9]. The leading contribution to the dijet cross section in the BFKL approach comes from the MN jets production.

In Ref. [9], the BFKL approach was used to calculate the ratio of the MN dijet production cross section σ^{MN} to that calculated for the Born subprocess. It has been assumed that because of factorization, the corresponding hadronic dijet ratio is equal to the one at the subprocess parton level. This ratio is known as the MN dijet K factor. However, the cross section of the Born subprocess is not measurable, because it is not possible to neglect virtual contributions to the measured cross section. Nevertheless, one can measure the cross section for events with exactly two jets with $p_T > p_{T\text{min}}$. In the following, we will refer to such events as “exclusive”. The lower the value of $p_{T\text{min}}$, the better the “exclusive” process approximates the truly exclusive case, i.e., when there are only two jets and two protons in the final state. Therefore, the cross section of “exclusive” events can be an approximate measure of the Born subprocess cross section.

Each pairwise combination of jets with $p_T > p_{T\text{min}}$ in the event forms an inclusive dijet. Therefore, the MN jet pairs constitute a subset of the inclusive dijets. The inclusive cross section σ^{incl} may have an advantage with respect to the MN cross section σ^{MN} because some MN jets can fall outside of the detector acceptance [10]. For small Δy , the inclusive dijet cross section is larger than the corresponding MN one because all jets in the rapidity interval between the MN jets contribute to the inclusive cross section. For large Δy , the MN dijet cross section approaches that for inclusive dijets because of the kinematical limitations on additional jet production.

The present paper reports a measurement of inclusive and MN dijet differential cross sections as a function of Δy in proton-proton (pp) collisions at $\sqrt{s} = 2.76$ TeV, based on a sample corresponding to an integrated luminosity of 5.4 pb^{-1} collected by the CMS experiment at the CERN LHC in 2013:

$$\begin{aligned} d\sigma^{\text{incl}}/d\Delta y, \\ d\sigma^{\text{MN}}/d\Delta y, \end{aligned} \tag{1}$$

as well as the following cross section ratios:

$$\begin{aligned} R^{\text{incl}} &= (d\sigma^{\text{incl}}/d\Delta y)/(d\sigma^{\text{excl}}/d\Delta y), \\ R^{\text{MN}} &= (d\sigma^{\text{MN}}/d\Delta y)/(d\sigma^{\text{excl}}/d\Delta y), \\ R_{\text{veto}}^{\text{incl}} &= (d\sigma^{\text{incl}}/d\Delta y)/(d\sigma_{\text{veto}}^{\text{excl}}/d\Delta y), \\ R_{\text{veto}}^{\text{MN}} &= (d\sigma^{\text{MN}}/d\Delta y)/(d\sigma_{\text{veto}}^{\text{excl}}/d\Delta y). \end{aligned} \tag{2}$$

Here σ^{incl} is the inclusive dijet production cross section, i.e., the cross section for events with at least one pair of jets with $p_T > p_{T\text{min}} = 35$ GeV. In those events each pairwise combination of jets with $p_T > 35$ GeV contributes to the inclusive cross section. The “exclusive” dijet production cross section, σ^{excl} , corresponds to dijet events with exactly two jets with $p_T > 35$ GeV. The cross section of MN dijets is denoted as σ^{MN} ; here, for each event, only the dijet with the most forward and most backward jets with $p_T > 35$ GeV contribute. Finally, $\sigma_{\text{veto}}^{\text{excl}}$ corresponds to “exclusive” events in which there are no extra jets above $p_{T\text{veto}} = 20$ GeV [11].

Lowering the veto threshold $p_{T\text{veto}}$ makes the $R_{\text{veto}}^{\text{incl}}$ and $R_{\text{veto}}^{\text{MN}}$ ratios closer to the theoretical K factor and increases the sensitivity to BFKL evolution effects. The event definitions as well as the number of collected dijets are summarized in Table 1.

Table 1: Event definitions for cross section measurements.

Dijet types	Number of jets with $p_T > 35$ GeV in the event	Veto on extra jets with $p_T > 20$ GeV in the event	Dijet selection criteria	Number of dijets
Inclusive	≥ 2	no	each pairwise combination of jets	154 124
MN	≥ 2	no	pair of jets most separated in rapidity	138 908
“Exclusive”	$= 2$	no	just one jet pair	132 648
“Exclusive” with veto	$= 2$	yes	just one jet pair	107 770

Previous searches for BFKL evolution effects in jet production at hadron colliders were performed at the Tevatron by the D0 and CDF experiments. D0 observed a stronger dependence of the MN dijet production cross section on the collision energy than expected in the leading-logarithmic (LL) BFKL approach [12]. Conversely, no indications of BFKL effects in the MN dijet azimuthal decorrelations were observed [13]. The D0 results on dijet production via hard color-singlet exchange (jet-gap-jet events) [14] are consistent with next-to-LL (NLL) BFKL-based calculations [15, 16]. The CDF experiment observed that dijet production via color-singlet exchange is independent of the pseudorapidity interval between the jets [17]. The CDF results are in general agreement with BFKL-based calculations.

Both the ATLAS [18, 19] and CMS [20–22] Collaborations at the CERN LHC have measured forward dijet production in pp collisions at $\sqrt{s} = 7$ TeV. The CMS measurements extend up

to $\Delta y = 9.4$ between jets with $p_T > 35$ GeV, whereas the ATLAS measurements extend up to $\Delta y = 8$ for dijets with average transverse momentum $\bar{p}_T = (p_{T1} + p_{T2})/2 > 60$ GeV, where p_{T1} and p_{T2} are the transverse momenta of the jets in a dijet system. The ATLAS measurement of dijet production with no additional jets with $p_T > 20$ GeV between the jets [18] is in agreement [19] with the parton-level LL BFKL calculations of the HEJ Monte Carlo (MC) generator [23], combined with the dipole parton shower simulation of ARIADNE [24]. The ATLAS measurement of azimuthal decorrelations [19] in dijet events is also well described by the combination of HEJ and ARIADNE at large Δy and for $60 < \bar{p}_T < 200$ GeV. Conversely, in this region, the next-to-leading-order (NLO) parton matrix element prediction of the POWHEG generator [25], combined with the LL DGLAP-based parton shower simulated with PYTHIA8 [26] or HERWIG [27], fails to describe the data. The CMS measurement of the cross section for dijet production where one jet is at forward rapidities and one is central is described well by HEJ [20]. The CMS results for the dijet cross section ratios [21] are neither reproduced at large Δy by the LL BFKL-based HEJ+ARIADNE combination, nor by the LL DGLAP-based HERWIG++ [28] simulation; they are instead well described by the LL DGLAP-based PYTHIA8 [26] generator. Finally, the azimuthal decorrelations measured by CMS [22] are in agreement with NLL BFKL analytic calculations for large Δy [29], whereas the LL DGLAP-based MC generators PYTHIA8 and HERWIG cannot describe all the measured observables.

In summary, none of the DGLAP-based MC generators is able to reproduce all the observables; conversely, NLL BFKL calculations, when available, are consistent with the measurements. However, more data at different collision energies are necessary, since the energy dependence of the DGLAP and BFKL contribution is expected to be different.

The present analysis extends the 7 TeV results [21] by measuring R^{incl} , R^{MN} and, in addition, $R_{\text{veto}}^{\text{incl}}$, $R_{\text{veto}}^{\text{MN}}$ and $d\sigma^{\text{incl}}/d\Delta y$, $d\sigma^{\text{MN}}/d\Delta y$ at $\sqrt{s} = 2.76$ TeV. The event selection and jet definition are the same as in the previous measurement, which allows a direct comparison of the results. The integrated luminosity is approximately similar (5.4 pb^{-1} in the present analysis and 5 pb^{-1} at $\sqrt{s} = 7$ TeV). The number of events decreases because of the lower \sqrt{s} . However, the probability of additional pp interactions within the same or adjacent bunch crossings, i.e., ‘‘pileup’’ (PU), is lower in the present analysis, which reduces the systematic uncertainty. The data were taken in special runs with low PU. The average number of collisions per bunch crossing is estimated to be 0.35.

The CMS measurements of dijet events with a large rapidity gap at $\sqrt{s} = 7$ TeV [30] and at $\sqrt{s} = 13$ TeV [31] are complementary to the work presented here. The jet-gap-jet analysis excludes events with charged particles in the rapidity gap between the two leading jets, although allowing them outside the gap. In contrast, the present analysis allows the emission of jets with $p_T < p_{T\text{min}}$ or $p_{T\text{veto}}$, both inside and outside the rapidity interval between the two jets. The results in Refs. [30] and [31] are in partial agreement with NLL BFKL calculations.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity η coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The part of the CMS detector essential to the present analysis is the calorimeter system. The ECAL and HCAL extend to $|\eta| < 3.0$. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 in azimuth (ϕ). In the η - ϕ plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from close to the nominal interaction point. For $|\eta| > 1.74$, the coverage of the towers increases progressively to a maximum of 0.174 in $\Delta\eta$ and $\Delta\phi$. Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, which are subsequently used to provide the energies and directions of hadronic jets.

The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. They also serve as luminosity monitors. Each HF calorimeter consists of 432 readout towers, containing long and short quartz fibers running parallel to the beam. The long fibers run the entire depth of the HF calorimeter (165 cm, or approximately 10 interaction lengths), while the short fibers start at a depth of 22 cm from the front of the detector. By reading out the two sets of fibers separately, it is possible to distinguish showers generated by electrons and photons, which deposit a large fraction of their energy in the long-fiber calorimeter segment, from those generated by hadrons, which produce on average nearly equal signals in both calorimeter segments.

Events are selected online by means of a two-tiered trigger system [32]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of less than $4 \mu\text{s}$. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is reported in Ref. [33].

3 Event selection

The data sample used for the present analysis was collected with the CMS detector in 2013, when the LHC collided protons at $\sqrt{s} = 2.76 \text{ TeV}$. The sample corresponds to an integrated luminosity of 5.4 pb^{-1} .

Jets are clustered from particles reconstructed with the particle-flow (PF) algorithm [34]; this algorithm reconstructs and identifies each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The vertex with the largest value of the summed charged-particle track p_T is the primary pp interaction vertex (PV). The photon energy is obtained from the ECAL measurement. The electron energy is determined from a combination of the electron momentum at the PV as measured by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The muon energy is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. Therefore, jets with higher pseudorapidity are reconstructed using the calorimeter information only.

The clustering of jets is carried out with the anti- k_T algorithm [35] as implemented in the FAST-JET package [36] with a distance parameter 0.5. Jets in the analysis are required to have their charged tracks associated with the PV. Jet momentum is determined as the vector sum of all particle momenta in a jet, and is found from simulations to be within 5 to 10% of the true momentum over the entire p_T spectrum and detector acceptance.

Additional pp interactions (pileup) within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum [37]. To mitigate this effect, tracks identified as originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet and photon+jet, Z+jet, and multijet events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions.

The jet energy resolution (JER) typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [38].

Dijet events with moderate Δy were selected online by means of a single jet trigger that required the presence of at least one jet with $p_T > 20$ GeV and $|\eta| < 5.0$. Dedicated single and double forward jet triggers were used to select dijet events with large Δy . The single forward jet trigger required the presence of a jet with $p_T > 20$ GeV in the forward or backward η regions, i.e., $3.0 < \eta < 5.1$ or $-5.1 < \eta < -3.0$. Finally, the double forward jet trigger required at least one jet in the forward and at least one in the backward region with $p_T > 20$ GeV. To keep the rate of the triggers within the allocated bandwidth, prescale factors were used, which reduced the effective integrated luminosities to 47.3 nb^{-1} , 382 nb^{-1} , and 4.6 pb^{-1} for the single, single forward, and double forward jet triggers, respectively. The trigger efficiency for selecting events with at least one pair of jets with $p_T > 35$ GeV is higher than 98% for the single and single forward jet triggers, and is 100% for the double jet trigger.

The combination of the samples obtained with the triggers just discussed provides the coverage of the kinematic region relevant for the present analysis. The overlap regions are removed, and the samples are reweighted and merged. The weights are calculated as the ratios of the effective luminosities of the triggers. To exclude overlaps, appropriate offline selection conditions are imposed. Specifically, the events containing jets with $p_T > 35$ GeV in the forward or backward η regions are removed from the single-jet trigger sample. Events with at least one jet with $p_T > 35$ GeV in the forward or backward regions, but not in both, are kept in the sample selected by the single forward jet trigger. In addition, the events selected by the double forward jet trigger are required to have at least one jet with $p_T > 35$ GeV, both in the forward and backward regions. Control distributions are extracted from the single jet trigger sample without the exclusion of the forward-backward events described above. The event distributions from the combined sample coincide with the control distributions within statistical fluctuations.

Offline, events are required to have at least one reconstructed vertex. The PV must contain at least four tracks associated with it, should be within 2 cm of the beam axis in the transverse plane, and its z coordinate should be within the luminous collision region, $|z_{PV}| < 24$ cm. The efficiency for selecting events with at least one vertex is 98.9% for the single jet triggers and 99.5% for the double jet trigger. Background originating from the beam scraping some aperture limitation in the beamline is suppressed by requiring that events with more than ten tracks have a fraction of high-purity tracks of at least 25% [39].

The events of interest for the present analysis are those that contain at least two jets with $p_T >$

35 GeV and $|y| < 4.7$; jets with $p_T > p_{T\text{veto}} = 20$ GeV are considered for the “exclusive” with veto sample.

4 Simulated samples

The simulations are used to compare the results with theoretical models and to correct for detector effects. The following MC generators are used: PYTHIA8 (8.183) [26], tune 4C [40] and HERWIG++ (2.7.1) [28], tune EE3C [41]. These both implement leading-order (LO) matrix element predictions improved with LL DGLAP-based parton showering. POWHEG (2.0) [25] generates events according to NLO matrix element predictions; parton showering is carried out with PYTHIA8 (8.230), HERWIG7 (7.1.2) [42], and HERWIG++ (2.7.1). LL BFKL-based predictions are provided by HEJ (1.4.0) [23] at parton level; the hadronization is carried out with the ARIADNE (4.12J01) generator [24].

5 Corrections for detector effects

Trigger efficiencies are measured as functions of η and p_T using a minimum bias sample. The single jet trigger is 92% efficient in selecting events with p_T of the leading jet greater than 35 GeV. The single jet trigger is also used for the determination of the single forward jet trigger efficiency, which is at least as efficient as the single jet trigger. The double forward jet trigger is 100% efficient in selecting dijet events with the two leading jets on opposite sides. Therefore, only the single jet trigger inefficiency needs to be corrected. Dijet events have higher probability of being selected by the single jet trigger because each jet in the event can satisfy the trigger conditions. The total impact of the trigger inefficiency correction does not exceed 0.16% for the cross section ratios and 1.5% for the cross sections.

The finite resolution of the reconstructed values of the jet p_T and y leads to migration of the events across the p_T threshold and between y bins, resulting in distortions of the measured distributions. To study the impact of these effects and correct for them, MC simulations are employed.

Events at stable-particle level generated with PYTHIA8 and HERWIG++ are passed through the standard GEANT4 [43] simulation of the CMS detector and reconstructed in the same way as the collision data. The PU contribution is included by adding simulated pp interactions with a rate equal to that observed in data. A study in Ref. [44] has shown that the JER for PF jets in the MC simulation is 7.9–40.0% better than that in the data. To correct for this difference a further energy smearing is applied to the four-momentum of the simulated jets at the detector level.

To study the migrations of events in p_T and y , jets at stable-particle level are matched to jets at detector level. Matching requires a jet at stable-particle level to be within a 0.4 radius in (η, ϕ) space around the axis of the jet at detector level. The main distortion is caused by the migration across the p_T threshold. The migration from below to above the threshold causes background events to enter the sample. The background fraction increases from 40% at $\Delta y < 1$ to 85% at $\Delta y > 7$. The migration from above to below the threshold leads to the loss of up to 40% of the signal events. The migration between y bins affects less than 10% of the events. Since migration effects are correlated across dijet samples, their impact on the ratio of dijet cross sections is reduced.

The migration effects are corrected by unfolding the data with the Tikhonov regularisation scheme, as implemented in the TUnfold [45] package.

As a consistency check, we verified that unfolding the detector level distributions obtained with PYTHIA8 (HERWIG++) by using response matrices also determined with PYTHIA8 (HERWIG++) gives distributions consistent with the generated ones. Conversely, if the PYTHIA8 distributions are unfolded with HERWIG++, residual differences of up to 20% are found for the cross section measurement and 4.4% for the ratios; the residuals are approximately the same if the HERWIG++ distributions are unfolded with PYTHIA8. These residual differences do not change when both HERWIG++ and PYTHIA8 simulations are reweighted to match the data at the detector level. The bias produced by the change in shape of the reweighted simulation used for the unfolding is fully covered by the residual difference. The residual differences reflect the fact that the detector response to jets is simulated with different models. Therefore, the difference in the results obtained by unfolding the data with different models is an estimate of the model dependence of the unfolding procedure.

The average unfolding correction obtained with PYTHIA8 and HERWIG++ is used for the results. The unfolding corrections are in the range 0.92–0.20 for the differential cross section measurement, 0.97–1.01 for the ratios without veto, and 0.95–0.98 for the ratios with veto. The ranges correspond to the variation of the unfolding correction with increasing Δy .

6 Systematic uncertainties

The following sources of systematic uncertainty are considered.

1. *Jet energy scale (JES) uncertainty.* Its effect is estimated by scaling the four-momentum of the jets by the p_T and η dependent uncertainty of the jet energy correction factors, which are determined by using the multistep approach described in Ref. [44]. The magnitude of the uncertainty does not exceed 4.6 (3.2)% for jets with $p_T = 20$ (35) GeV. The difference between the nominal results and those obtained with the scaling is an estimate of the effect of the JES uncertainty in the results.
2. *Uncertainty in the JER correction factors.* The systematic uncertainty of the MC modeling of the JER depends on η of the jets [44], and varies between 2.6 and 19.0%. The contribution of this uncertainty is evaluated by smearing the four-momentum of the simulated jets at the detector level according to the JER correction uncertainty. The difference between the nominal results and those with the additional smearing is an estimate of the systematic uncertainty.
3. *Model dependent (MD) uncertainty of the unfolding.* The difference between the results obtained correcting the data with PYTHIA8 and HERWIG++ is an estimate of the model dependence of the unfolding. This uncertainty varies between 1.5 and 22.0% for the cross sections, whereas it is between 0.5 and 4.5% for the ratios.
4. *Uncertainty related to the parton distribution function (PDF) set.* The PYTHIA8 (tune 4C) and HERWIG++ (tune EE3C) samples used for the unfolding employ the LO CTEQ6L1 PDF set [46]. The PDF uncertainty is propagated as recommended by the PDF4LHC group [47]. The following PDF sets are used for the propagation: NNPDF31_lo_as_0130 [48], CT14lo [49], and MMHT2014lo68cl [50]. The PDF reweighting scheme is described in Ref. [51]. The reweighted MC distributions and response matrices obtained are used for the unfolding. The difference between the nominal results and the envelope of those obtained with the reweighted MC is an estimate of the uncertainty due to the PDFs.

5. *Renormalization and factorization scales uncertainty.* The uncertainty related to the renormalization and factorization scales, μ_r and μ_f , of the QCD renormalization group equation is estimated by modifying μ_r and μ_f independently by factors of 2 and 0.5 in PYTHIA8. The cases where one scale is simultaneously increased and the other is decreased by a factor 2 are not considered. The difference between the nominal results and the envelope of those obtained with the modified scales is a contribution to the systematic uncertainty.
6. *Uncertainty because of the limited MC statistics (MCS).* The propagation of the statistical uncertainty in the simulation is carried out with the statistical bootstrap method.
7. *The uncertainty in the integrated luminosity* is 3.7% [52]. It is treated as a normalization uncertainty for the cross section measurements. The luminosity uncertainty cancels in the cross section ratios.
8. *Uncertainty in the trigger efficiency corrections (TEC).* Trigger efficiencies are investigated as functions of η and p_T . The impact of the trigger inefficiency does not exceed 0.16% for the cross section ratios and 1.5% for the cross sections. The uncertainty in the correction is estimated as 100% of the correction itself.
9. *Uncertainty related to PU.* The sensitivity of the results to PU is investigated by subdividing the data sample into low- and high-PU subsamples depending on the instantaneous luminosity; no dependence of the results on PU is observed. As mentioned earlier, the MC samples are weighted to match the amount of PU observed in the data and the weighted samples are used for the unfolding. The difference between the results obtained with the weighted and unweighted samples is smaller than 0.05% for the ratios without veto, 0.96% for the ratios with the veto, and 3.2% for the cross section measurement. The systematic uncertainty related to the weighting procedure is estimated to be equal to these differences.

The contributions just discussed are shown in Fig. 1. The correlations between the uncertainty sources in the numerator and denominator of the ratios in Eq. (2) lead to significant improvements with respect to the individual cross section measurements. The dominant contributions to the systematic uncertainty in the cross section measurements are given by the JES and JER uncertainties. However, systematic uncertainties from different sources are approximately of the same order for the ratios, except the uncertainty in the trigger inefficiency and PU, which is much smaller than the other contributions. The total systematic uncertainty is the quadratic sum of all its components.

7 Results

Cross sections for inclusive and MN dijet production are presented, along with various cross section ratios for jets with $p_T > 35$ GeV and $|y| < 4.7$. The results are compared to DGLAP-based and LL BFKL-based MC models.

7.1 Differential cross sections $d\sigma^{\text{incl}}/d\Delta y$ and $d\sigma^{\text{MN}}/d\Delta y$

The differential cross section $d\sigma^{\text{incl}}/d\Delta y$ for inclusive dijet production is shown in Fig. 2, together with the predictions of various models. The LO+LL DGLAP-based PYTHIA8 simulation overestimates the data, whereas HERWIG++ underestimates them for $\Delta y < 4$ and overestimates them for $\Delta y > 6$. The predictions of the LL BFKL-based calculation of HEJ+ARIADNE systematically underestimate the data for $\Delta y < 7$ and overestimate them in the largest Δy bin.

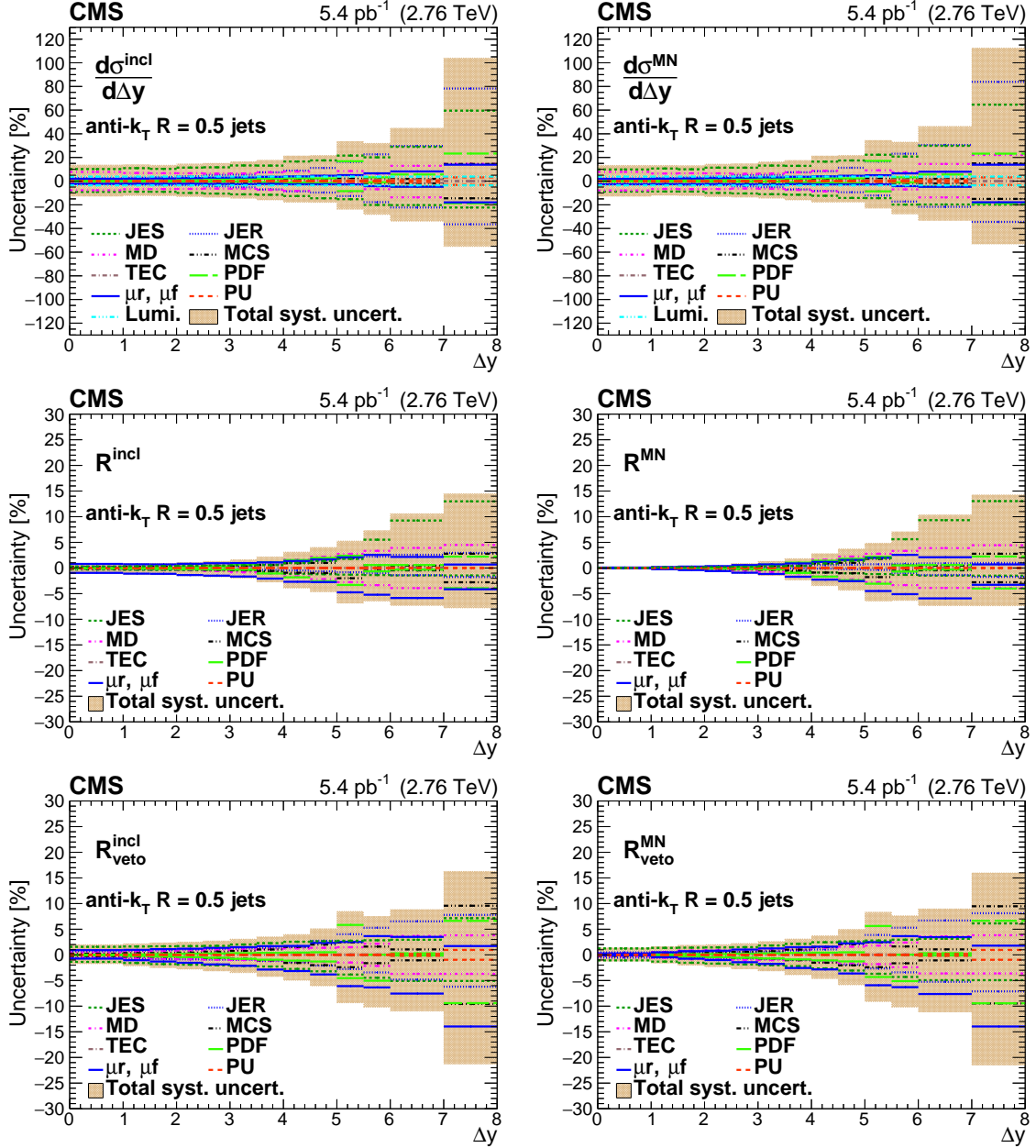


Figure 1: Summary of the systematic uncertainties on the cross sections $d\sigma^{\text{incl}}/d\Delta y$ (upper left) and $d\sigma^{\text{MN}}/d\Delta y$ (upper right), as well as the ratios R^{incl} (middle left), R^{MN} (middle right), $R_{\text{veto}}^{\text{incl}}$ (lower left), and $R_{\text{veto}}^{\text{MN}}$ (lower right). The various contributions are indicated by the lines and the total uncertainty is shown with a band.

The inclusion of the NLO corrections provided by POWHEG improves the DGLAP-based predictions in the $\Delta y < 4$ region. However, POWHEG+PYTHIA8 still overestimate the results. The predictions of POWHEG+HERWIG are consistent with the data for $\Delta y < 4$, but overestimate them for large values of Δy . The measured cross section decreases with Δy faster than the DGLAP-based MC predictions.

The differential cross section for the production of MN dijets, $d\sigma^{\text{MN}}/d\Delta y$, is presented in Fig. 3. The data are compared with the same models used in Fig. 2. The degree of agreement between data and the predictions is similar to that for the inclusive cross section discussed above.

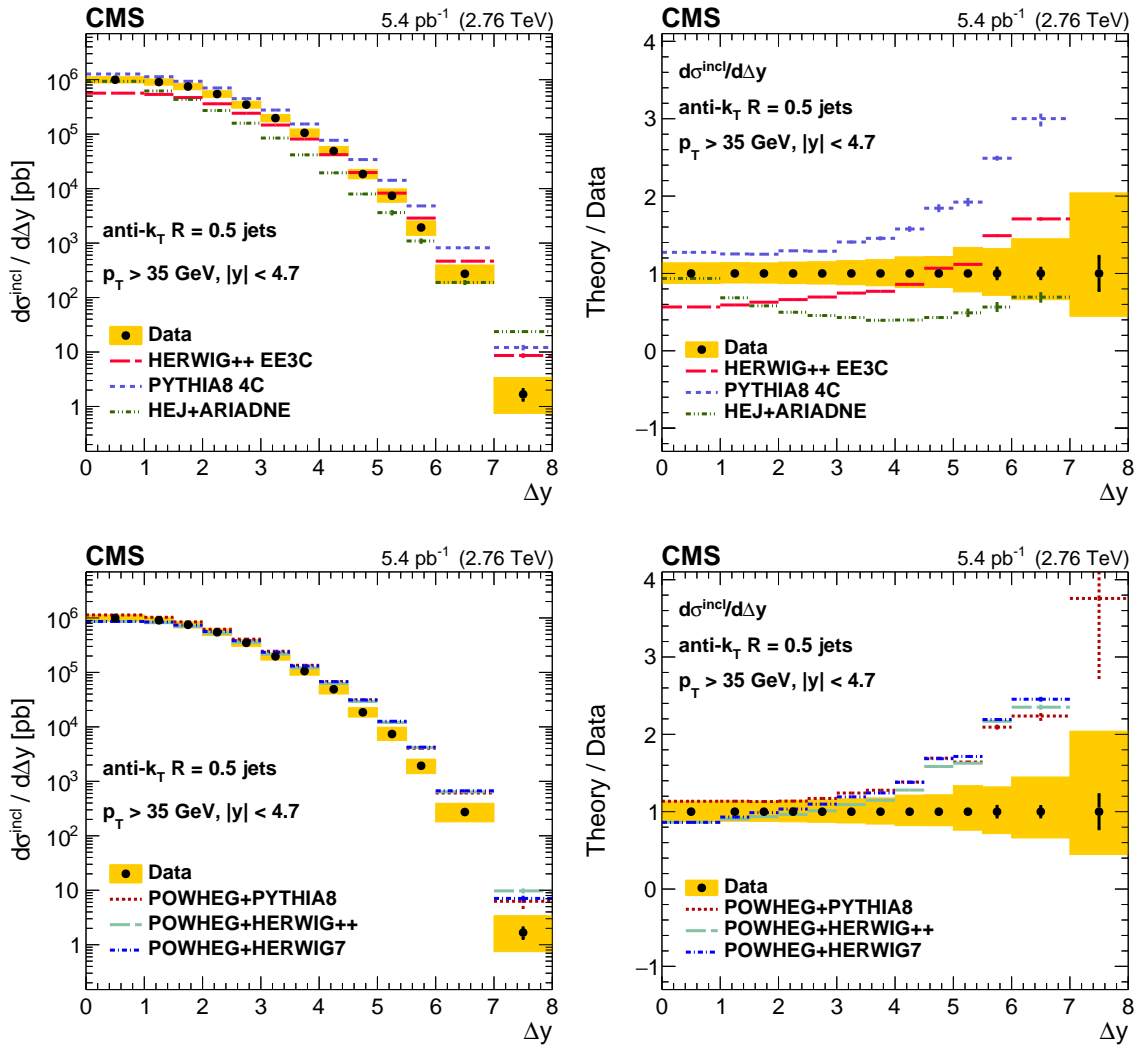


Figure 2: Differential cross section $d\sigma^{\text{incl}}/d\Delta y$ for inclusive dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the cross sections and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

7.2 Ratio R^{incl}

The ratio of the inclusive to the “exclusive” dijet production cross sections, R^{incl} , is presented in Fig. 4. The prediction of PYTHIA8 is in agreement with the data, whereas HERWIG++ and HEJ+ARIADNE overestimate the ratio. The addition of the NLO corrections via POWHEG to the

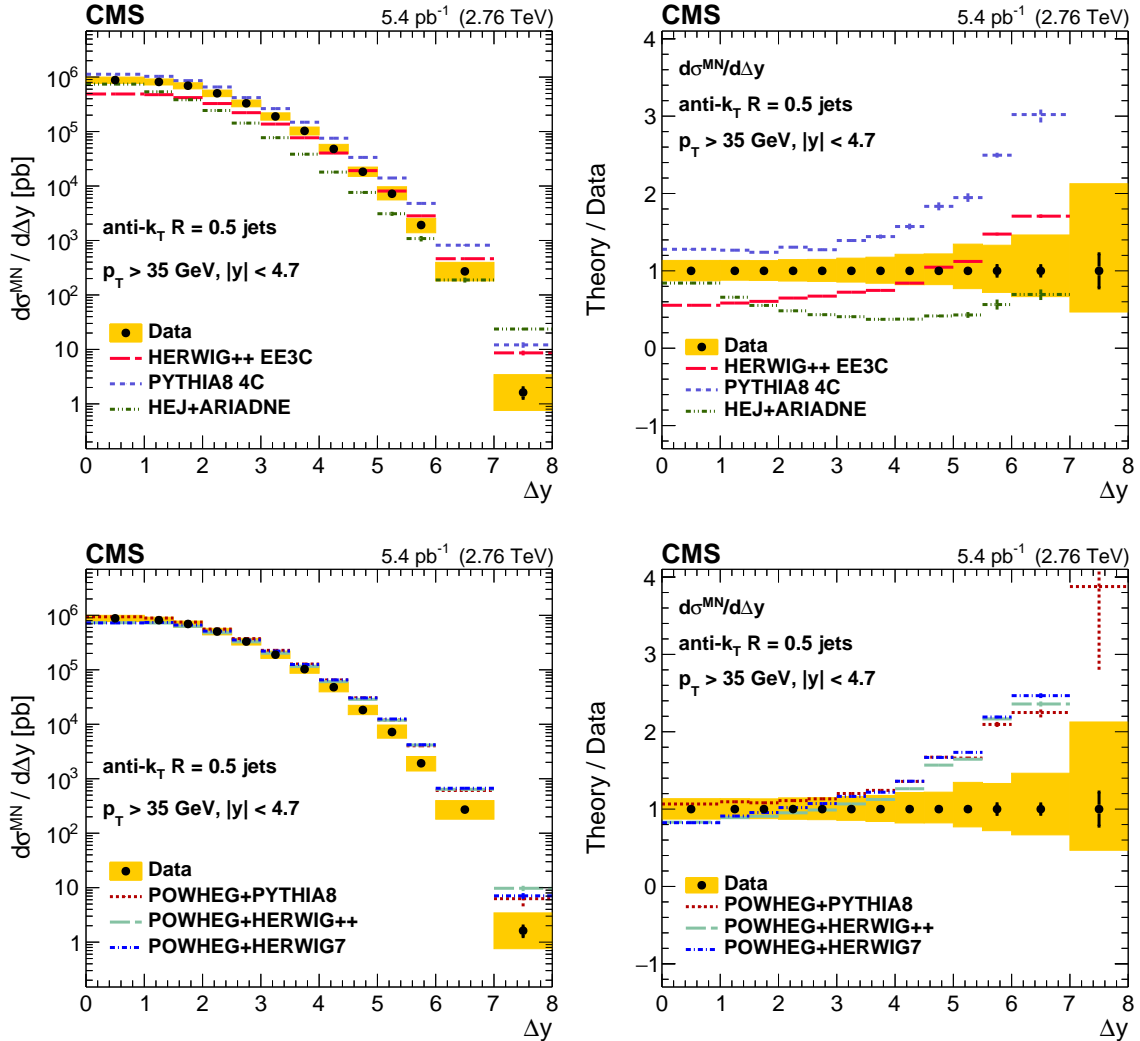


Figure 3: Differential cross section $d\sigma^{\text{MN}}/d\Delta y$ for MN dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the cross sections and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

LL DGLAP-based prediction of HERWIG degrades the quality of the description for $\Delta y < 2$ but improves it for large rapidity intervals. The inclusion of the NLO corrections to PYTHIA8 with POWHEG worsens the agreement significantly.

7.3 Ratio $R_{\text{veto}}^{\text{incl}}$

The ratio of the cross section for inclusive dijet production to that for “exclusive” with veto dijet production, $R_{\text{veto}}^{\text{incl}}$, is presented in Fig. 5. The event generators HERWIG++ and HEJ+ARIADNE overestimate the measurement. PYTHIA8 is in agreement with the data for $\Delta y < 1.5$ and for $\Delta y > 4$, but overestimates them for $2 < \Delta y < 4$. If POWHEG is used to add the NLO corrections to the LL DGLAP-based prediction of HERWIG, the description of the data becomes worse for $\Delta y < 2$ and improves at large rapidity intervals. In the case of POWHEG+PYTHIA8, adding the NLO corrections degrades the agreement significantly. In summary, none of the models considered reproduces all aspects of the data. Although PYTHIA8 with tune 4C offers the best description, it still fails to model the shape of the Δy dependence.

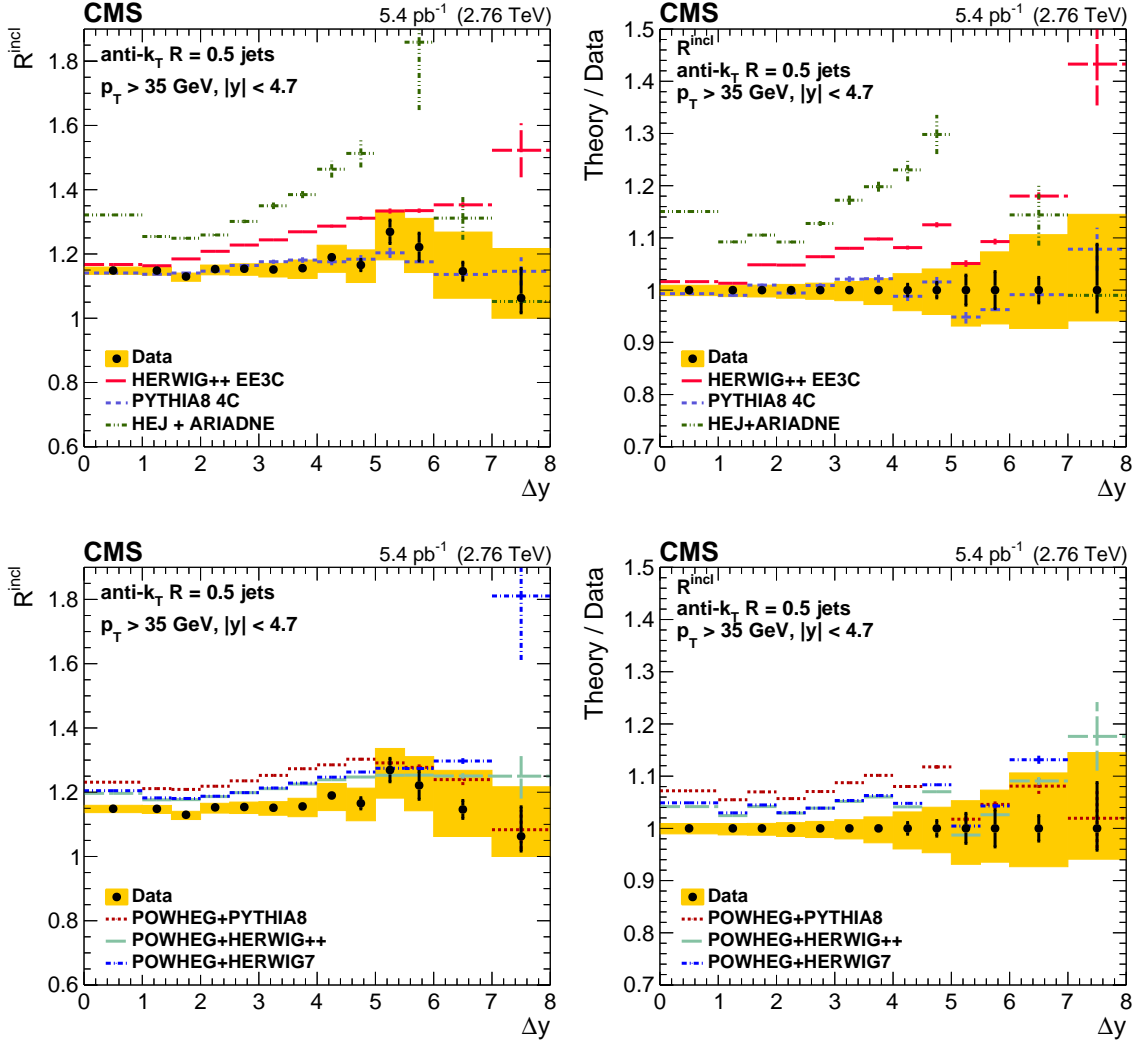


Figure 4: Ratio R^{incl} of the cross sections for inclusive to “exclusive” dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the ratio R^{incl} and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

7.4 Ratios R^{MN} and $R_{\text{veto}}^{\text{MN}}$

The ratios of the cross section for MN dijet production and those for σ^{excl} as well as $\sigma_{\text{veto}}^{\text{excl}}$, R^{MN} , and $R_{\text{veto}}^{\text{MN}}$ are presented in Figs. 6 and 7. By definition the MN ratio R^{MN} begins from unity at $\Delta y = 0$, because there is no phase space for additional emission between the jets of the MN dijet. The MN ratio with veto $R_{\text{veto}}^{\text{MN}}$ is higher than unity at $\Delta y = 0$, because of the veto condition. At large Δy both R^{MN} , and $R_{\text{veto}}^{\text{MN}}$ approach R^{incl} and $R_{\text{veto}}^{\text{incl}}$, respectively, because there is insufficient energy to produce many jets with transverse momentum above 35 GeV within the rapidity interval of the MN dijet. The results of the comparison of the MN dijet ratios with simulations are similar to those just discussed for R^{incl} and $R_{\text{veto}}^{\text{incl}}$.

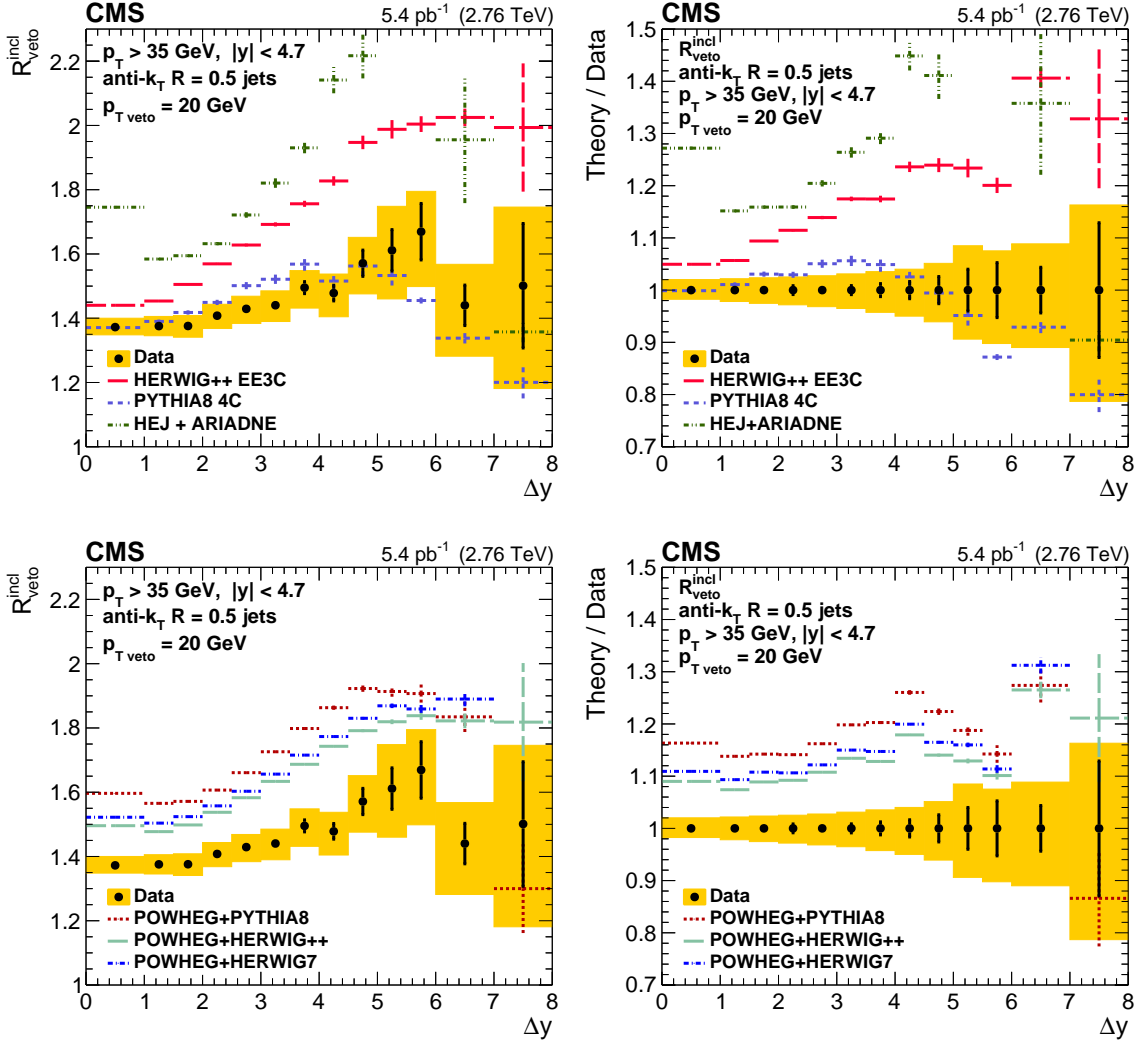


Figure 5: Ratio $R_{\text{veto}}^{\text{incl}}$ of the cross sections for inclusive to “exclusive” with veto dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the ratio $R_{\text{veto}}^{\text{incl}}$ and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

7.5 Comparison of R^{incl} and R^{MN} at $\sqrt{s} = 2.76$ and 7 TeV

The comparison of the ratios R^{incl} and R^{MN} measured at different energies, $\sqrt{s} = 7$ TeV [21] and 2.76 TeV, is presented in Fig. 8. The ratios rise faster with Δy at higher energy, which may reflect both the increasing available phase space and BFKL dynamics. Large Δy can be more easily reached at higher energy. The qualitative features of the ratios can be understood as follows. The ratios rise with Δy because of the increasing phase space volume for hard parton radiation. At very large Δy , the ratios decrease because of the kinematic limitations on the production of events with more than two jets, each with $p_T > 35$ GeV (for $p_T = 35$ GeV: $\Delta y_{\text{max}} = 8.7$ and 10.6 at 2.76 TeV and 7 TeV, respectively). These trends are qualitatively reproduced by the MC predictions shown in Figs. 4-7 as well as the corresponding MC predictions in Ref. [21]. No events are observed for $\Delta y > 8$ at 2.76 TeV because this region is too close to the edge of the available phase space. The comparison of the measurement with the MC models in Ref. [21] shows that PYTHIA8 gives the best description of R^{incl} and R^{MN} whereas

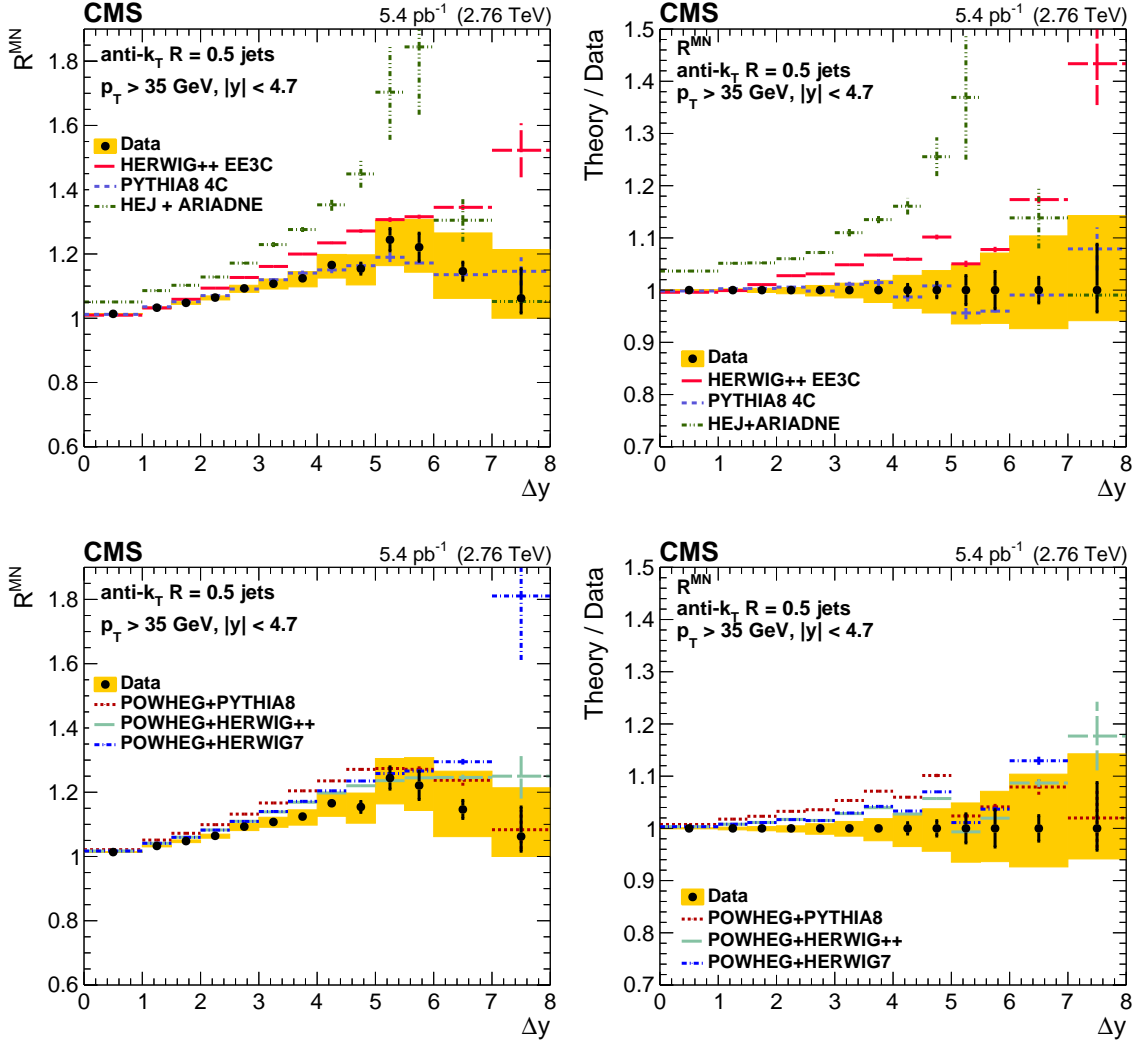


Figure 6: Ratio R^{MN} of the cross sections for MN to “exclusive” dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the ratio R^{MN} and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

HERWIG++ and HEJ+ARIADNE significantly overestimate the rise of the ratios with Δy , which is also consistent with the results from this analysis.

7.6 Overall results at $\sqrt{s} = 2.76$ TeV and discussion

In general, the measured cross sections decrease with Δy between the jets faster than all LO DGLAP-based MC predictions. PYTHIA8 overestimates the data, whereas HERWIG++ underestimates them at small Δy and overestimates them at large Δy . The inclusion of the NLO corrections via POWHEG for the LO DGLAP-based models improves the description of the inclusive (MN) cross sections at small Δy only. The LL BFKL-based HEJ+ARIADNE generator underestimates the results.

The ratios R^{MN} and R^{incl} are well described only by the LO DGLAP-based generator PYTHIA8. The HERWIG++ generator calculation in the same approximation overestimates these ratios. This emphasizes the importance of corrections beyond the main approximation, such as color

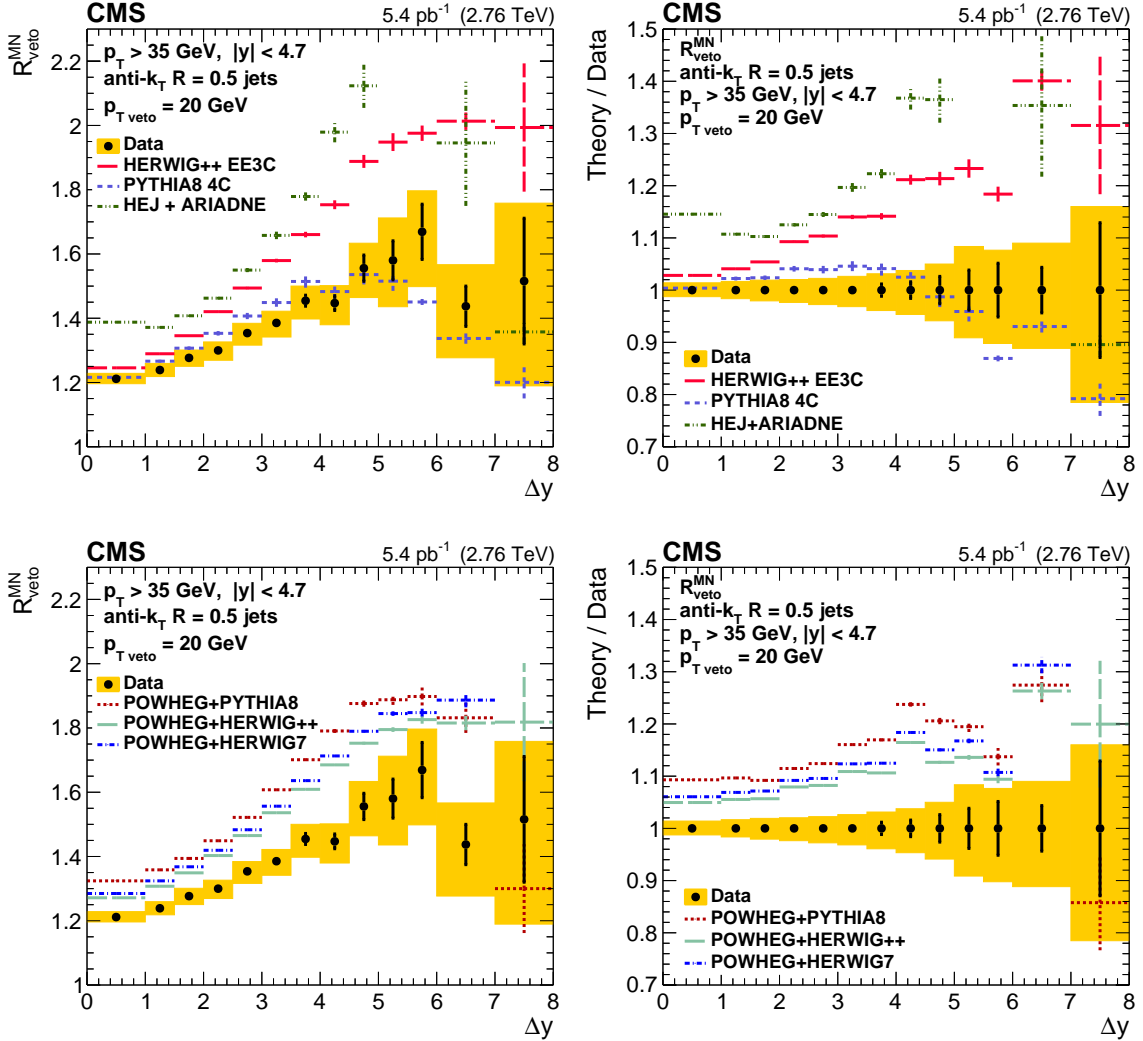


Figure 7: Ratio $R_{\text{veto}}^{\text{MN}}$ of the cross sections for MN to “exclusive” with veto dijet production. The upper and lower rows present the comparison with different MC models. The plots on the left present the ratio $R_{\text{veto}}^{\text{MN}}$ and those on the right the ratio of theory to data. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

coherence, which can produce Δy dependence. However, it is the BFKL resummation that consistently accounts for the principal contributions at large Δy . The ratios $R_{\text{veto}}^{\text{MN}}$ and $R_{\text{veto}}^{\text{incl}}$ cannot be perfectly reproduced by any LO DGLAP-based generator in the interval $2 < \Delta y < 5$. This may be an indication of BFKL effects, although the LL BFKL-based generator does not describe the data well either. The LL BFKL-based generator overestimates significantly the rise of the ratios. This can be understood because the LL BFKL calculation overestimates the intercept of the pomeron, which leads to a stronger rise of cross sections with Δy . The analysis for the NLL BFKL contributions, with a lower pomeron intercept, is important [53]. Since an analytic NLL BFKL evolution calculation [29] provides a good description of the decorrelations of MN dijets [22], we also need an analogous prediction (based on the NLL BFKL evolution) to draw a more firm conclusion from our measurement.

In conclusion, none of the LO or NLO DGLAP-based generators can provide a reasonable description of the measured cross sections and their ratios simultaneously. The dijet ratio with

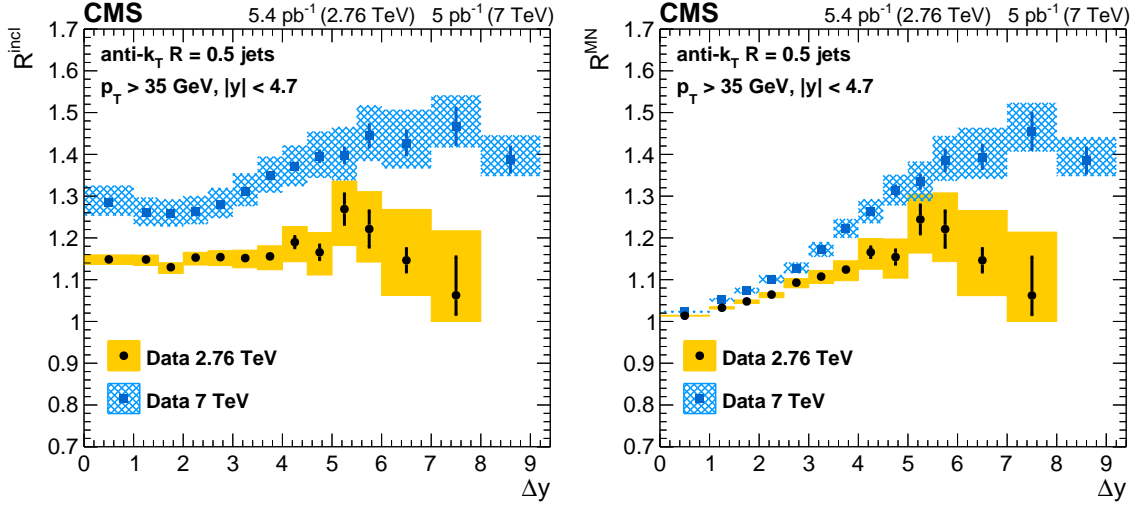


Figure 8: Ratios R^{incl} (left) and R^{MN} (right) of the cross sections for inclusive (left) and MN (right) and “exclusive” dijet production, measured at 2.76 TeV and 7 TeV [21] collision energies. The systematic uncertainties are indicated by the shaded bands and the statistical uncertainties by the vertical bars.

extra jet veto cannot be described by DGLAP-based generators either at LO or at NLO. For a useful comparison of the present data with the BFKL approach, calculations at NLL are needed.

8 Summary

A study of dijet events with large rapidity separation Δy between the jets has been performed using proton-proton collision data at $\sqrt{s} = 2.76$ TeV, collected by the CMS experiment in 2013 with an integrated luminosity of 5.4 pb^{-1} . The cross sections for Mueller–Navelet and inclusive dijet event production, as well as their ratios to “exclusive”, and “exclusive” with veto, dijet event production, are measured up to $\Delta y \leq 8.0$ between the jets.

None of the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP)-based Monte Carlo generators using leading-order (LO) or next-to-LO (NLO) calculations can provide a complete description of all measured cross sections and their ratios. The dijet ratio with extra jet veto cannot be described by the LO or NLO DGLAP-based generators. To compare the present results with the Balitsky–Fadin–Kuraev–Lipatov approach, calculations at the next-to-leading-logarithm level are needed.

The present results at $\sqrt{s} = 2.76$ TeV can be used along with data at higher energies to reveal possible effects beyond the DGLAP approach to make more definite conclusions. Tabulated results are provided in the HEPData record for this analysis [54].

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
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










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







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

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

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


































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












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






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
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


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



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


















































































































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

















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

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



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

























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












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

































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




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


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K. Bunkowski, K. Doroba, A. Kalinowski , M. Konecki , J. Krolikowski , M. Walczak 




Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

M. Araujo, P. Bargassa , D. Bastos, A. Boletti , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad, M. Pisano, J. Seixas , O. Toldaiev , J. Varela 

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












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















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














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



























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















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











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
National Central University, Chung-Li, Taiwan

C. Adloff⁶⁴, C.M. Kuo, W. Lin, A. Roy , T. Sarkar³⁷ , S.S. Yu











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

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



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







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



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











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












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








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








































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







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













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









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





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













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









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