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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

The CMS Collaboration*

Abstract

A study of dijet production in proton-proton collisions was performed at $\sqrt{s} = 7$ TeV for jets with $p_{\mathrm{T}} > 35$ GeV and $|y| < 4.7$ using data collected with the CMS detector at the LHC in 2010. Events with at least one pair of jets are denoted as "inclusive". Events with exactly one pair of jets are called "exclusive". The ratio of the cross section of all pairwise combinations of jets to the exclusive dijet cross section as a function of the rapidity difference between jets $|\Delta y|$ is measured for the first time up to $|\Delta y| = 9.2$. The ratio of the cross section for the pair consisting of the most forward and the most backward jet from the inclusive sample to the exclusive dijet cross section is also presented. The predictions of the Monte Carlo event generators PYTHIA6 and PYTHIA8 agree with the measurements. In both ratios the HERWIG++ generator exhibits a more pronounced rise versus $|\Delta y|$ than observed in the data. The BFKL-motivated generators CASCADE and HEJ+ARIADNE predict for these ratios a significantly stronger rise than observed.

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The measurement of inclusive jet production in pp collisions provides an important testing ground for the Standard Model. Inclusive jet production is well described at LHC energies, over a wide range in jet transverse momentum and rapidity [1, 2], by calculations at next-to-leading-order (NLO) in perturbative quantum chromodynamics (QCD) using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) approach [3–7] and collinear factorization. The rapidity y is defined as $y = (1/2)\log[(E + p_z)/(E - p_z)]$, where E is the jet energy and p_z is the component of the jet momentum along the beam axis. Dijet production is also well described, when the rapidity difference between the jets is small [8]. For larger values of the rapidity separation, the description of the data becomes worse [2].

When the collision energy $\sqrt{s}$ is considerably larger than the hard scattering scale given by the jet transverse momentum, p_{T}, i.e. when the scaling variable $x \sim (p_{\mathrm{T}}/\sqrt{s})\mathrm{e}^{-y}$ becomes small, calculations in perturbative QCD require a resummation of large $\log(1/x)$ terms. This leads to the prediction of new dynamic effects, expected to be described by Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution [9–11] and k_{T} factorization [12–14]. An effective theory has been developed which describes strong interactions in this kinematic domain [15].

The ratio of the dijet production cross section in "inclusive" events to that in "exclusive" events, $R^{\mathrm{incl}} = \sigma^{\mathrm{incl}}/\sigma^{\mathrm{excl}}$, as a function of the rapidity separation $|\Delta y|$ between two jets, is a sensitive probe for effects beyond collinear factorization [16]. Only jets with transverse momenta above a minimal value of $p_{\mathrm{T}}^{\mathrm{min}}$ are considered. Events with at least one pair of jets are denoted as "inclusive". Events with exactly one pair of jets are called "exclusive". In the inclusive case, the rapidity separation is evaluated for each pairwise combination of jets above threshold [16]. Mueller-Navelet jet pairs [17] are a subset of the inclusive dijet class. In this case only the jet at highest rapidity (i.e. most forward) and that at lowest rapidity (most backward) are considered. At low $|\Delta y|$, the inclusive dijet ratio, R^{incl}, is enhanced in comparison to the corresponding Mueller-Navelet dijet ratio, $R^{\mathrm{MN}} = \sigma^{\mathrm{MN}}/\sigma^{\mathrm{excl}}$, by combinatorial factors due to the jets produced within the rapidity interval between the Mueller-Navelet jets.

From the theoretical point of view, an advantage of the ratios R^{incl} and R^{MN} with respect to the individual dijet production cross sections is that the influence of the uncertainty of the parton distribution functions is greatly reduced; in addition, the ratios are particularly sensitive to the parton radiation pattern [16]. At large enough energies, the parton subprocesses involve a large number of partons with comparable transverse energies. Such subprocesses, governed by BFKL evolution, lead to an increase of the ratios with increasing $|\Delta y|$ [16–18]. Experimentally, an additional advantage of the R^{incl} and R^{MN} ratios as defined above is the cancellation of most of the systematic uncertainties affecting both numerator and denominator.

Earlier measurements of Mueller-Navelet jets with $|\Delta y|$ up to 5 were made at the Tevatron by the D0 experiment [19, 20]. D0 did not find indications of BFKL effects in the azimuthal decorrelation data [19]; however, a stronger than expected $\sqrt{s}$ dependence of the dijet production cross section was observed [20] when comparing the data at $\sqrt{s} = 630$ and 1800 GeV for dijets with large rapidity separation. The ATLAS Collaboration has recently studied various dijet production ratios at $\sqrt{s} = 7$ TeV in rapidity separation range $|\Delta y| < 6$ [21].

The component of the CMS detector [22] most relevant for this analysis is the calorimeter system extending to pseudorapidities $|\eta| = 5.2$, 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 $3.0 < |\eta| < 5.2$ is covered by the hadronic forward (HF) calorimeter, which consists of steel absorber wedges with embedded radiation-hard quartz fibers, oriented parallel to the beam direction. The calorimeter towers in the barrel region have segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, becoming progressively larger in the endcap and forward regions ($\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ at $\eta \sim 4.5$).

The CMS trigger system consists of a hardware Level-1 trigger and a software high-level trigger. Jets formed online by the trigger system use ECAL, HCAL and HF inputs for energy clustering and are not corrected for the jet energy response. The minimum-bias trigger was defined as the coincidence of a signal from one of the two beam scintillation counters covering the range $3.23 < |\eta| < 4.65$ and a signal from one of the beam pick-up timing devices.

The data were collected in 2010, when LHC collided protons at $\sqrt{s} = 7\,\text{TeV}$. Various triggers were used to cover the largest possible range in rapidity separation between jets. Dijets with moderate $|\Delta y|$ were selected by a single-jet trigger with a threshold on the raw (uncorrected) jet transverse momentum of 15 GeV. This trigger was significantly prescaled as the instantaneous luminosity increased and the effective integrated luminosity recorded with it is $\simeq 33\,\text{nb}^{-1}$.

Dijet events with large rapidity separation are rare. Therefore, a dedicated trigger for forward-backward dijets was developed. This forward-backward-dijet trigger selects events with two jets in opposite hemispheres and $|\eta| > 3.0$, and jet raw transverse momentum $p_{\text{T}} > 15\,\text{GeV}$. It was run with moderate prescaling and the effective integrated luminosity recorded with it is $\simeq 5\,\text{pb}^{-1}$, which allowed to increase the number of the dijet events at large $|\Delta y|$ by a factor of more than 100 with respect to the single-jet trigger.

The trigger efficiency was measured by means of a control sample selected with the minimum-bias trigger. The single-jet trigger was found to be 100% efficient for dijets with corrected $p_{\text{T}} > 35\,\text{GeV}$. The single-jet trigger was in addition used for the determination of the efficiency of the forward-backward-dijet trigger. The latter was also 100% efficient for dijets with $p_{\text{T}} > 35\,\text{GeV}$.

Jets were reconstructed offline from the energy depositions in the calorimeter towers, clustered by the anti-k_T algorithm [23, 24] with a distance parameter $R = 0.5$. In the reconstruction process, the contribution from each tower was assigned a momentum, the absolute value and the direction of which were given by the energy measured in the tower, and the coordinates of the tower, respectively. The raw jet energy was obtained from the sum of the tower energies, and the raw jet momentum from the vectorial sum of the tower momenta. The raw jet energies were then corrected to establish a uniform relative response of the calorimeter in η and a calibrated absolute response in transverse momentum p_{T} [25]. The jet energy resolution for calorimeter jets typically amounts to about 20% at 40 GeV, and 12% at 100 GeV [25].

In the offline analysis, at least one well-reconstructed primary vertex is required to be present within ± 24 cm from the nominal interaction point along the beamline [26]. In order to reduce the sensitivity to overlapping pp collisions (the so-called "pile-up" events), events with only one primary vertex reconstructed within the luminous region were used for the measurement.

Loose jet quality cuts were used to suppress the effect of calorimeter noise [27]. Events with at least two jets with $p_{\text{T}} > 35$ GeV and $|y| < 4.7$ were selected. Only jets satisfying these criteria were used for the analysis. All pairwise combinations of jets from the selected events entered the inclusive distribution. For studies of Mueller-Navelet jets, only the pair consisting of the most forward and the most backward jet was considered. The exclusive dijet sample is a subset of the inclusive and Mueller-Navelet samples, and is constructed from events where exactly one pair of jets is found. The measured observables, R^{incl} and R^{MN}, are defined as the ratios of the yield of inclusive or Mueller-Navelet dijets to the yield of exclusive dijets in a specific $|\Delta y|$ bin, respectively.

Detector effects were accounted for by applying bin-by-bin corrections derived from Monte Carlo (MC) simulations. Simulated events produced with the generators PYTHIA6 (version 6.422) tune Z2 [28–30] and HERWIG++ (version 2.4.2) tune 23 [31] were passed through the full CMS detector simulation based on the GEANT4 package [32], and were input to the same event reconstruction program as used for collision data. To quantify detector effects, the distributions obtained from detector-level quantities were compared to the distributions obtained at the level of stable particles (lifetime τ such that $c\tau > 10\,\mathrm{mm}$). The ratios of the stable-particle level and detector-level quantities in a given bin were used to correct the data.

Because of the finite p_{T} and y resolutions, the distributions at detector-level deviate from the corresponding ones at stable-particle level. Events can migrate to and from the exclusive or the inclusive samples due to fluctuations of the measured transverse jet momentum around the $p_{\mathrm{T}}^{\mathrm{min}}$ threshold. The amount of these migrations was estimated not to exceed 20%. Similarly, events can migrate to different $|\Delta y|$ bins; this effect, for the present data, is typically around 5-10% and reaches 15-25% at most. The influence of these migrations on the measured ratios R^{incl} and R^{MN} is minimal as the effects for numerator and denominator are similar. The uncorrected distributions in the data are reasonably well reproduced by the PYTHIA6 events passed through the detector simulation, whereas the detector-level distributions for HERWIG++ show some deviations from the measurement. The correction factors were therefore obtained with PYTHIA6, while the model dependence of the corrections was estimated from the difference between the PYTHIA6- and HERWIG++-driven correction factors.

The following sources of systematic effects were considered:

1. Uncertainty of the jet energy calibration. The uncertainty of the measurement was estimated by shifting the jet energy scale (JES) by p_{T}- and η-dependent uncertainties derived in [25]. The resulting variation of the measurements does not exceed 4.2% for R^{incl} and 3.8% for R^{MN}.

2. Uncertainty of the corrections for detector effects.

   (a) Uncertainty due to model dependence of the correction factors. As discussed above, correction factors were determined by using HERWIG++ and PYTHIA6, and corrected measurements were obtained for each case. The difference in the results was taken as a measure of the model dependence of the correction factors; it does not exceed 3.4% for R^{incl} and 3.3% for R^{MN}.

   (b) Uncertainty related to the quality of the MC description of the jet p_{T} and y resolutions. These resolutions were modified by $\pm10\%$ in the simulation as suggested in [33]. A conservative estimate of the uncertainty associated to this effect does not exceed $\pm1.0\%$.

3. An additional systematic effect may originate from the extra energy and jets due to pile-up collisions. As noted earlier, the measurement was restricted to events with only one reconstructed primary vertex to reduce the impact of pile-up. A contribution from interactions undetected because of vertex reconstruction inefficiency may still be present. Comparing data taken at different instantaneous luminosities an upper limit of 1.3% was estimated for this effect. The value was obtained for pairs of jets from the forward region, where the impact of pile-up on jet reconstruction is more significant [25]; the effect is thus expected to be smaller for jets at central rapidities.

The total systematic uncertainty was calculated as the quadratic sum of the individual uncertainties. The total uncertainty is $|\Delta y|$ dependent but always smaller than 5.6% for R^{incl} and

4.8% for R^{MN} (Table 1).

Table 1: Sources of systematic effects and associated uncertainties. Ranges correspond to variation of uncertainty with $|\Delta y|$. For asymmetric uncertainties the upper and lower ranges are shown.

source	R^{incl} uncertainty (%)	R^{MN} uncertainty (%)
jet energy scale	$+(2.2-4.2)$ $-(1.0-3.0)$	$+(0.2-3.8)$ $-(0.2-2.3)$
uncertainty of detector corrections	$\pm(1.5-3.5)$	$\pm(0.1-3.4)$
pile-up	< 1.3	< 1.3
total	$+(2.8-5.6)$ $-(2.7-4.5)$	$+(0.2-4.8)$ $-(0.2-3.7)$

The measured ratios, corrected for detector effects, were compared to the predictions of several MC generators at the stable-particle level. A DGLAP-based approach to generation of hard-parton radiation is used in PYTHIA6 (version 6.422) tune Z2, PYTHIA8 (version 8.145) [34] tune 4C [35] and HERWIG++ (version 2.5.1) tune UE-7000-EE-3 [31, 36]. The tunes mentioned include multiple parton interactions (MPI) as a part of the underlying event (UE) modeling. The dijet observables might be affected by the MPI effect through jets which do not originate from the same hard interaction. The effect was estimated by switching off the MPI options in PYTHIA6 and HERWIG++. No significant change in the predictions was observed.

The Monte Carlo generators CASCADE (version 2.2.03) [37] and HEJ (version 1.3.2) [38] are motivated by the leading-logarithmic BFKL approach and incorporate parts of a next-to-leading logarithmic approximation. The HEJ generator produces parton-level jets which are then showered with the ARIADNE [39] program. The HEJ+ARIADNE package version 0.99b consisting of HEJ 1.3.2 and ARIADNE 4.12 was used.

The ratio R^{incl} of inclusive to exclusive dijet production as a function of the rapidity separation $|\Delta y|$ between the jets with $p_{\mathrm{T}} > 35$ GeV and $|y| < 4.7$ is presented in Fig. 1 (left panel). On average the inclusive cross section is 1.2 – 1.5 times larger than the exclusive cross section. The ratio R^{incl} rises with increasing $|\Delta y|$, as expected due to the increased phase space for hard parton radiation. At the highest $|\Delta y|$, R^{incl} decreases because the emission of an extra jet is suppressed due to energy-momentum conservation.

The predictions from PYTHIA6 and PYTHIA8 agree well with the measurement. HERWIG++ overestimates the ratio R^{incl} at medium and large rapidity intervals. A detailed comparison between the data and the predictions of the DGLAP-based MC generators is presented as a ratio in Fig. 2 (left panel).

The R^{MN} and the corresponding MC to data ratio are presented in the right panels of Figs. 1–2. At large $|\Delta y|$, R^{MN} approaches R^{incl} as extra jet radiation contributing to R^{incl} tends to concentrate at moderate rapidities. The quality of the predictions of the DGLAP-based MC generators for R^{MN} is similar to those for R^{incl}. The MC generators CASCADE and HEJ+ARIADNE considerably overestimate the measurements of both R^{incl} and R^{MN}. ATLAS data [21] on Mueller-Navelet dijet cross section ratio with the mean transverse momentum of jets $70 < p_{\mathrm{T}}^{\mathrm{mean}} < 90\,\mathrm{GeV}$ at $|\Delta y| < 6$ cannot be directly compared with the R^{MN}, however there is a qualitative agreement between the observations made by ATLAS and the presented result.

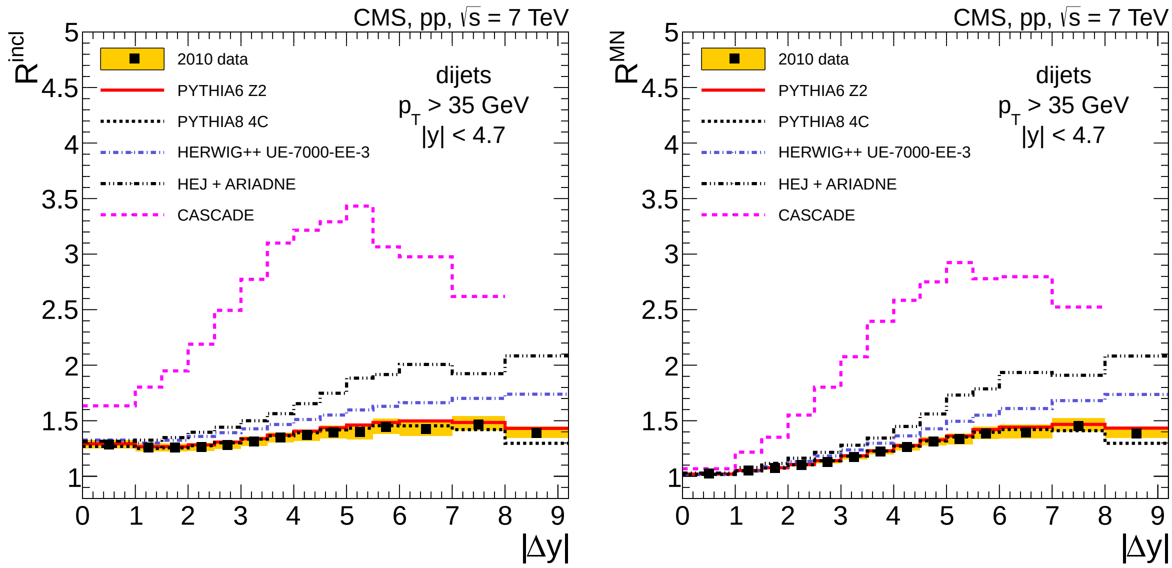

Figure 1: Ratios of the inclusive to exclusive dijet cross sections as a function of the rapidity separation $|\Delta y|$ between the two jets, R^{incl} (left panel) and R^{MN} (right panel), compared to the predictions of the DGLAP-based MC generators PYTHIA6, PYTHIA8 and HERWIG++, as well as of CASCADE and HEJ+ARIADNE which incorporate elements of the BFKL approach. The shaded band indicates the size of the total systematic uncertainty of the data. Statistical uncertainties are smaller than the symbol sizes. Because of limitations in the CASCADE generator it was not possible to obtain a reliable prediction for $|\Delta y| > 8$.

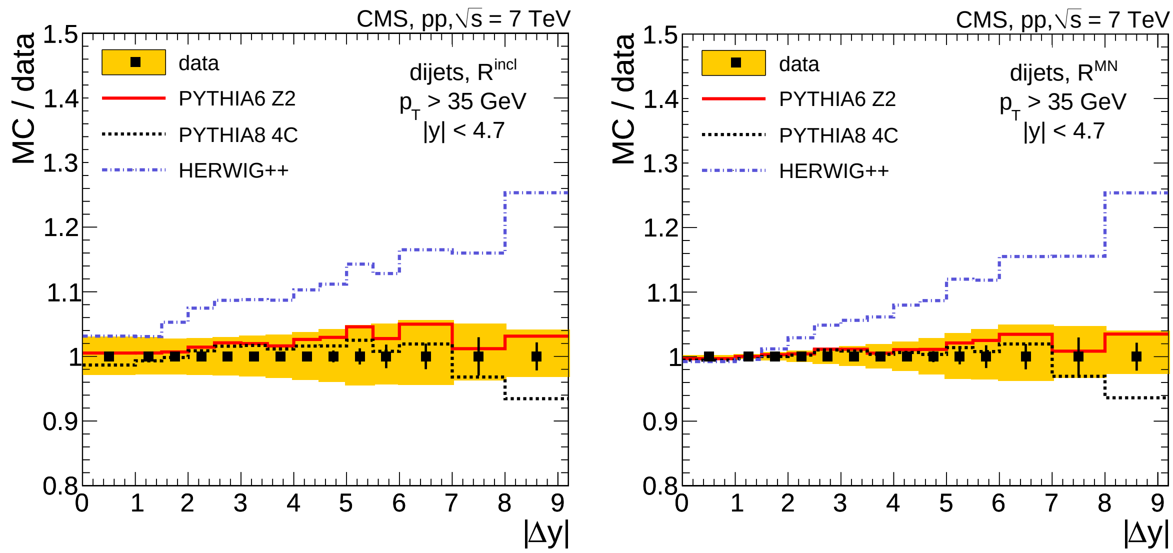

Figure 2: Predictions for R^{incl} (left) and R^{MN} (right) from DGLAP-based MC generators presented as ratio to data corrected for detector effects. Both BFKL-motivated generators CASCADE and HEJ+ARIADNE (not shown) lead to a MC/data ratio well above unity. The shaded band indicates the size of the total systematic uncertainty of the data while statistical uncertainties are shown as bars.

To conclude, the first measurement of the ratios R^{incl} and R^{MN} in a wide range of rapidity separation, up to $|\Delta y| = 9.2$, in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$ was presented. A moderate rise of the ratio of the inclusive to exclusive dijet production cross sections as a function of $|\Delta y|$ is observed. The predictions of the PYTHIA6 and PYTHIA8 generators agree with the measurements. The predictions of the HERWIG++ generator are larger than the measurement especially at large $|\Delta y|$. The BFKL-motivated generators CASCADE and HEJ+ARIADNE predict for these ratios a significantly stronger rise than observed. The moderate rise of the measured dijet ratios indicates that the BFKL effects are not dominant for jets with $p_{\text{T}} > 35\,\text{GeV}$ at the present collision energy of 7 TeV.

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