Study of dijet events with a large rapidity gap between the two leading jets in pp collisions at \( \sqrt{s} = 7\) TeV

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Abstract   Events with no charged particles produced between the two leading jets are studied in proton-proton collisions at \( \sqrt{s} = 7\) TeV. The jets were required to have transverse momentum \( p_T^{\text{jet}} > 40\) GeV and pseudorapidity \( 1.5 < |\eta^{\text{jet}}| < 4.7\), and to have values of \( \eta^{\text{jet}}\) with opposite signs. The data used for this study were collected with the CMS detector during low-luminosity running at the LHC, and correspond to an integrated luminosity of \( 8\) pb\(^{-1}\). Events with no charged particles with \( p_T > 0.2\) GeV in the interval \( -1 < \eta < 1\) between the jets are observed in excess of calculations that assume no color-singlet exchange. The fraction of events with such a rapidity gap, amounting to 0.5–1% of the selected dijet sample, is measured as a function of the \( p_T\) of the second-leading jet and of the rapidity separation between the jets. The data are compared to previous measurements at the Tevatron, and to perturbative quantum chromodynamics calculations based on the Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equations, including different models of the non-perturbative gap survival probability.

1 Introduction   In high-energy proton-proton collisions, an interaction with large momentum transfer between two partons may lead to the production of a pair of jets with large transverse momenta \( p_T\). Dijet production at the LHC [1–12] is generally well described by perturbative quantum chromodynamics (pQCD) calculations based on the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) evolution equations [13–15]. The DGLAP equations govern the emission of additional softer partons, ordered in transverse momentum \( k_T\) with respect to the jets axes. However, when the two jets are separated by a large interval in pseudorapidity \( (\eta)\), an alternative pQCD evolution based on the Balitsky–Fadin–Kuraev–Lipatov (BFKL) equations [16–18] is expected to describe the data better [19]. In the BFKL approach, the emission of additional partons is ordered in \( x \sim \ln(1/x)\), where \( x\) is the fractional momentum carried by the radiated parton.

The events considered in this study are pp collisions where two jets are produced with a large rapidity gap between them. The absence of particles between the jets is reminiscent of a diffractive process [20], in which a color-singlet exchange (CSE) takes place between the interacting partons. In diffractive processes, such an exchange is described in terms of the pomeron, a combination of gluons in a color-singlet state. However, the absolute value of the four-momentum squared exchanged in standard diffractive events (less than a few GeV\(^2\)) is much smaller than that in the events considered here. Such events can be understood in a BFKL-inspired approach in terms of the exchange of a color-singlet gluon ladder (Fig. 1), as first discussed by Mueller and Tang in Ref. [21] and further developed in Refs. [22–24]. Jet-gap-jet events in proton–proton collisions may be affected by additional scatterings among the spectator partons, which can destroy the original rapidity gap. Such a contribution is typically described by a non-perturbative quantity, the so-called gap survival probability, which quantifies the fraction of events where the rapidity gap is not destroyed by interactions between spectator partons [19].

Jet-gap-jet events were first observed in \( p\bar{p} \) collisions at the Tevatron by D0 [25–27] and CDF [28–30], and in e\(^+\)p collisions at HERA [31,32]. At the Tevatron, the fraction of dijet events produced through CSE was found to be \( \sim 1\% \) at \( \sqrt{s} = 1.8\) TeV, a factor of 2–3 less than at \( \sqrt{s} = 0.63\) TeV. This paper presents the first observation of jet-gap-jet events at the LHC, and the measurement of the CSE fraction at \( \sqrt{s} = 7\) TeV, using events with two leading jets of \( p_T^{\text{jet}} > 40\) GeV and \( 1.5 < |\eta^{\text{jet}}| < 4.7\), reconstructed in opposite ends of the CMS detector. The CSE signal is extracted from the distribution of the charged-particle multiplicity in the central region \( |\eta| < 1\) between the jets, for
particles with $p_T > 0.2$ GeV. The CSE fraction is studied as a function of the pseudorapidity separation $\Delta\eta_{jj}$ between the jets, and of the $p_T$ of the second-leading jet, as done by the D0 experiment [27].

The data used for this measurement correspond to an integrated luminosity of 8 pb$^{-1}$ and were recorded with the CMS detector in the year 2010, when the LHC operated at $\sqrt{s} = 7$ TeV with low probability of overlapping pp interactions (pileup).

2 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadronic calorimeter (HCAL). Muons are measured in gas-magnetic calorimeter (ECAL), and the brass and scintillator are the silicon pixel and strip tracker, the crystal electro-

The jets are reconstructed using the infrared- and collinear-safe anti-$k_T$ algorithm [36,37], with a distance parameter $R = 0.5$, starting from the particles identified with the particle-flow method [38]. The key feature of the anti-$k_T$ algorithm is the resilience of the jet boundary with respect to soft radiation. This leads to cone-shaped hard jets. Soft jets tend to have more complicated shapes. The jet momentum is determined as the vector sum of all particle momenta in the jet, and is found in the simulation to be within 5 to 10% of the true hadron-level momentum over the whole $p_T^{jet}$ spectrum and detector acceptance. When combining information from the entire detector, the jet energy resolution for jets with $p_T^{jet} = 40$ GeV (200 GeV) is about 12% (7%) for $|\eta^{jet}| < 0.5$ and about 10% for $4 < |\eta^{jet}| < 4.5$ [39]. Jet energy corrections are derived from the simulation, and are confirmed with in situ measurements of the energy balance in dijet and photon+jet events [40]. No jet energy corrections related to the removal of pileup contributions [41] are required for the jets studied in this analysis.

3 Monte Carlo simulation

The simulation of inclusive dijet events is performed using the PYTHIA 6.422 Monte Carlo (MC) event generator [42]. 

PYTHIA 6 is based on the leading order (LO) DGLAP evolution equations combined with a leading-logarithmic (LL) resummation of soft gluon emission in the parton shower, and uses the Lund string fragmentation model [43] for hadroniza-
tion. The underlying event in PYTHIA 6 includes particles produced in the fragmentation of minijets from multiple parton interactions (MPI), initial- and final-state radiation, as well as proton remnants. The events were simulated using the Z2* tune [44], which was developed to reproduce the CMS underlying event data at center-of-mass energies up to 7 TeV. PYTHIA 6 models the production of diffractive dijets (leading to a final state with a gap-jet-jet topology) and of central diffractive and exclusive dijets (leading to a gap-jet-jet-gap final-state). However, it does not directly generate the jet-gap-jet topology considered here unless a fluctuation in the radiation and hadronization of the parton showers in inclusive dijet production randomly leads to suppressed hadronic activity between the jets.

Jet-gap-jet events are simulated with the default tune of the HERWIG 6.520 generator [45] (switching on CSE production, and switching off all other processes). The HERWIG 6 generator simulates events with hard color-singlet exchange between two partons according to the model by Mueller and Tang [21], which is based on simplified (LL) BFKL calculations. The hadronization process in HERWIG is based on cluster fragmentation: at the end of the perturbative parton evolution, clusters are built and then decayed into the final-state hadrons. The HERWIG 6 generator does not include any modeling of MPI; they are instead simulated with the JIMMY package [46]. For simplicity, unless stated otherwise, by HERWIG 6 we hereafter refer to the combination of this MC generator with JIMMY. The HERWIG 6 generator predicts a decrease of the CSE fraction with increasing \( p_T \) of the jets, but the Tevatron data show instead the opposite trend [25,28]. In the present analysis, the events generated with HERWIG 6 are reweighted with an exponential function, \( \exp(b p^2_T) \) with \( b = 0.01 \text{ GeV}^{-1} \), to ensure that the CMS data are reproduced. In the following, this sample of reweighted HERWIG events will be referred to as the HERWIG 6 sample.

Both PYTHIA 6 and HERWIG 6 use the CTEQ6L1 parametrization of the proton parton distribution functions [47]. The simulated events are processed and reconstructed in the same manner as the collision data. A detailed MC simulation of the CMS detector response is performed with the GEANT4 toolkit [48].

4 Data samples and dijet event selection

Three non-overlapping samples of dijet events are used, corresponding to the following three \( p^2_T \) ranges, defined in terms of the \( p_T \) of the second leading jet in the dijet system, \( p^2_T \): 40–60, 60–100, and 100–200 GeV. The first two samples were selected online with dijet triggers with 15 and 30 GeV thresholds on the uncorrected jet \( p_T \), respectively, while the third sample was collected with a single jet trigger with uncorrected jet \( p_T \) threshold of 70 GeV. This selection maximizes the amount of dijet events for the analysis and ensures high dijet reconstruction efficiency. The triggers for the first two samples were heavily prescaled. The three samples correspond to integrated luminosities of 48, 410, and 8320 nb\(^{-1}\), respectively. The mean number of inelastic pp interactions per bunch crossing (pileup) in each of the three samples is 1.16, 1.17, and 1.60, respectively.

The following conditions are imposed offline on all samples:

- events are required to contain at least two jets that pass the standard CMS quality criteria [49];
- the number of primary vertices with more than zero degrees of freedom in the event, as defined in [33], is required to be 0 or 1;
- a primary vertex, if present, is required to be within a longitudinal distance \( |z| < 24 \text{ cm} \) from the nominal interaction point;
- events with long horizontal sections of the pixel tracker traversed by charged particles parallel to the beam (beam-scraping events) are rejected using a dedicated algorithm [50].

In order to allow for a sufficiently wide rapidity gap between the jets, the following conditions are further imposed on the jets:

- the two leading jets are required to be in the range \( 1.5 < |\eta^\text{jet}| < 4.7 \);
- the two leading jets are required to be in opposite hemispheres: \( \eta^\text{jet} \eta^\text{jet} < 0 \).

The single- or zero-vertex requirement rejects most of the events with pileup interactions, which can hide an existing rapidity gap. At the same time, it may reject dijet events in which one true primary vertex is wrongly reconstructed as two or more; however, the probability of such badly reconstructed vertices has been checked with the PYTHIA 6 Z2* and HERWIG 6 simulations and found to be negligible. Selecting events with no reconstructed vertices increases the acceptance for signal events in which the two jets are produced outside the tracker coverage. Such events are estimated from the data to contribute about 10% of all CSE events. According to the simulations the residual fraction of pileup events in the sample is negligible.

There are 6196, 8197, and 9591 events that satisfy the above selection criteria in the \( p^2_T = 40–60, 60–100, \) and 100–200 GeV jet samples, respectively.

5 Jet-gap-jet events

The charged-particle multiplicity (\( N_{\text{tracks}} \)) in the gap region between the two leading jets (the shaded area in Fig. 2) is
used to discriminate between CSE and non-CSE events. The \( N_{\text{tracks}} \) variable is defined as the number of reconstructed particles with \( p_T > 0.2 \) GeV in the interval \(|\eta| < 1\). Tracks are required to have a measured \( p_T \) with relative uncertainty smaller than 10% (\( \sigma_{p_T}/p_T < 10\% \)), which reduces the contribution of tracks from secondary interactions. The chosen \( \eta \) range ensures a high track reconstruction efficiency and, at the same time, is wide enough to suppress most of the background events with smaller gaps produced via non-CSE fluctuations.

The separation between the jet axes corresponds to at least three units of \( \eta \) (for jets with \( |\eta^{\text{jet}}| > 1.5 \) and \( \eta^{\text{jet1}} \eta^{\text{jet2}} < 0 \)), the minimum gap width typically used in studies of diffractive interactions. For the majority of the events the gap region is far from the edges of jets, which reduces the contamination of soft radiation from the jet shower evolution.

Figure 3 shows the measured \( N_{\text{tracks}} \) distribution in different \( p^\text{jet2}_T \) bins. In each \( p^\text{jet2}_T \) bin, the PYTHIA 6 distribution is normalized to the integral of the number of events measured for \( N_{\text{tracks}} > 3 \), and the HERWIG 6 predictions are normalized to the number of events with \( N_{\text{tracks}} = 0 \) measured in the data. The data are satisfactorily described by the PYTHIA 6 simulation, with the exception of the lowest multiplicity bins, in which a large excess of events is observed, consistent with a contribution from CSE events. This excess is well described by the reweighted HERWIG 6 generator, as seen in the data/MC ratio plots.

The leading and the second-leading jet \( p_T \) spectra for events with no tracks reconstructed in the gap region \(|\eta| < 1\) are presented in Fig. 4. The data, plotted in bins of \( p^\text{jet2}_T \), are reproduced by the normalized HERWIG 6 CSE events. A very small contribution from PYTHIA 6 events can be explained by fluctuations in the hadronization of (non-CSE) inclusive dijet events, with no particles or only neutral particles produced inside the gap region. Figure 5 shows the distributions of the azimuthal angle \( \Delta \phi^{\text{jet1},2} \) between the jets (left), and of the ratio of the second-leading jet \( p_T \) to the leading jet \( p^\text{jet1}_T \), \( p^\text{jet2}_T / p^\text{jet1}_T \) (right). The data, shown separately for events with no tracks and with more than three tracks reconstructed in the \(|\eta| < 1\) region, are well described by the normalized simulations, which are dominated by CSE (HERWIG 6) and non-CSE (PYTHIA 6) events, respectively. The peaks in the distributions at \( \Delta \phi^{\text{jet1},2} = \pi \) and \( p^\text{jet2}_T / p^\text{jet1}_T = 1 \) are narrower for events with no tracks, reflecting the fact that the CSE dijets are more balanced in azimuthal angle and momentum than the non-CSE ones, because of the extra radiation in the latter.

In order to quantify the contribution from CSE events, we measure the CSE fraction, \( f_{\text{CSE}} \), defined as

\[
 f_{\text{CSE}} = \frac{N^F_{\text{events}} - N^F_{\text{non-CSE}}}{N_{\text{events}}},
\]

where \( N^F_{\text{events}} \) is the number of events in the first bins of the multiplicity distribution (\( N_{\text{tracks}} < 2 \) or 3, as explained later in this section), \( N^F_{\text{non-CSE}} \) is the estimated number of events in these bins originating from non-CSE events, and \( N_{\text{events}} \) is the total number of events considered. The \( f_{\text{CSE}} \) fraction defined in this way is not sensitive to the trigger efficiencies and jet reconstruction uncertainties as they cancel in the ratio. While the extraction of \( N^F_{\text{events}} \) and \( N_{\text{events}} \) is straightforward (event counting), the estimation of \( N^F_{\text{non-CSE}} \) requires modeling of the non-CSE contributions, for which two data-driven approaches are considered.

In the first approach, the shape of the \( N_{\text{tracks}} \) distribution for background events is obtained from a sample in which the two leading jets are produced on the same side of the CMS detector (same side, or SS, sample, with jets satisfying the selection \(|\eta^{\text{jet1}} > 1.5 \) and \( \eta^{\text{jet1}} \eta^{\text{jet2}} > 0 \)). For the nominal sample defined in Sect. 4 (opposite side, or OS, sample, with two jets produced on opposite sides of the CMS detector), the gap region \(|\eta| < 1\) mainly contains particles originating from the hard scattering, while for the SS sample it is dominated by particles originating from the underlying event. This difference is reflected in the \( N_{\text{tracks}} \) distributions: whereas the shapes of the distributions are similar for the SS and OS samples, the mean \( N_{\text{tracks}} \) value in the SS sample is slightly lower. In order to minimize the difference between the average \( N_{\text{tracks}} \) values of the two samples, the gap region for the SS sample is enlarged to \(|\eta| < 1.2\), in agreement with the range reported by the CDF Collaboration [30]. The adjusted multiplicity distribution in the SS sample (Fig. 6 left) is normalized to the one in the OS sample for \( N_{\text{tracks}} > 3 \), and the number of events in the first bins is taken as an estimate of the background.

The second method is based on the fit of the \( N_{\text{tracks}} \) distribution with a negative binomial distribution (NBD), which was first used to describe charged-particle multiplicity distributions by the UA5 Collaboration [51] at energies up to
Fig. 3 Distribution, uncorrected for detector effects, of the number of central tracks between the two leading jets in events with $p_T^{jet_2} = 40–60$ (top left), 60–100 (top right), and 100–200 (bottom) GeV, compared to the predictions of pythia 6 (inclusive dijets) and herwig 6 (CSE jet-gap-jet events). The pythia 6 and herwig 6 samples are normalized to the number of events measured for $N_{tracks} > 3$ and $N_{tracks} = 0$, respectively. Beneath each plot the ratio of the data yield to the sum of the normalized herwig 6 and pythia 6 predictions is shown. The vertical error bars indicate the statistical uncertainties.

$\sqrt{s} = 546$ GeV. Later, it was observed that the NBD fit reproduces less well the tails of the particle multiplicity at higher center-of-mass energies (deviations were reported at $\sqrt{s} = 900$ GeV by UA5, and later at Tevatron and LHC energies [26,52,53]). This issue is largely avoided when one restricts the NBD fit to the region around the mean of the distribution. The fit used in this analysis starts at $N_{tracks} = 3$, where the CSE signal to background ratio is expected to be negligible, and ends at $N_{tracks} = 35$, slightly above the maximum of the distribution. The extrapolation of the fit to the first multiplicity bins provides an estimate of the non-CSE background. The results of the NBD fits are shown in Fig. 6 (right). To check the performance of the method, the fit is repeated on the SS sample in the range $3 \leq N_{tracks} \leq 35$. The extrapolation of the fit to the $N_{tracks} < 3$ region agrees with the number of events observed in the SS sample data, which confirms the validity of this approach.

The numbers of background events obtained with the two methods described above agree within statistical uncertainties, with the results of the NBD fit being slightly lower. Since the SS method cannot be used to estimate the background in bins of $\Delta \eta_{jj}$ between the jets (because of the smaller $\Delta \eta_{jj}$
Fig. 4 Transverse momentum distributions, uncorrected for detector effects, of the leading jet (left) and the second-leading jet (right) in three dijet samples with $p_{T}^{jet1} = 40–60$, 60–100, and 100–200 GeV (from top to bottom) after all selections, for events with no tracks reconstructed in the gap region $|\eta| < 1$, compared to predictions of PYTHIA 6 (inclusive dijets) and HERWIG 6 (CSE jet-gap-jet events), normalized as in Fig. 3. The error bars indicate the statistical uncertainties.
integrated over the first three multiplicity bins. Two multiplicity bins, and about 40–60% when the signal is present in the second-leading jet of the multiplicity distribution, about 25–35% in the first bin of the multiplicity distribution, about 10–15% in the 0th bin, full circles) or more than three events the non-CSE background count, which is subtracted from the data. Studies with simulated events show that the results do not change, within uncertainties, if the hadron-level variables are used. For the latter, stable particles (with lifetime $\tau$ such that $\tau > 10$ mm) are used both for the jet reconstruction and for the extraction of the $N_{\text{tracks}}$ variable.

6 Systematic uncertainties

The systematic uncertainties in the $f_{\text{CSE}}$ extraction are estimated by modifying the selection criteria and the analysis procedure. The following sources of systematic uncertainty are taken into account:

Jet energy scale (JES) The $p_T$ of each jet in an event is varied up and down according to the formula $p_{T,\text{new}}^{\text{jet}} = p_{T,\text{jet}}^{\text{jet}} \pm u(p_{T,\text{jet}}, \eta)^{\text{jet}}$, where $u(p_{T,\text{jet}}, \eta)^{\text{jet}}$ is the JES uncertainty, which increases at lower (higher) values of jet $p_T$ ($\eta$) [49]. After changing the $p_T$ of the jets, they are reordered in $p_{T,\text{jet}}^{\text{jet, new}}$, and the analysis is repeated using the two highest $p_{T,\text{jet}}^{\text{jet, new}}$ jets. The average difference of the results obtained for the positive and negative variations relative to the nominal result is taken as an estimate of the uncertainty associated with the JES.
Track quality  The track multiplicity distributions are redetermined after relaxing the track quality criteria [33], in order to study the effect of variations in the track finding algorithm. The symmetrized difference between the results obtained with the relaxed and nominal conditions is taken as an estimate of the uncertainty.

Background subtraction  The number of background events in the first bins of the $N_{\text{tracks}}$ distribution is estimated from data, based on the SS sample introduced in
Fig. 7 Background-subtracted central track multiplicity distributions, uncorrected for detector effects, in the three bins of $p_T^{jet2}$, compared to the HERWIG 6 predictions without underlying event simulation (“no MPI”), normalized as in Fig. 3. The background is estimated from the NBD fit to the data in the $3 \leq N_{tracks} \leq 35$ range, extrapolated to the lowest multiplicity bins.

### Table 1 Percent systematic (individual, and total) and statistical uncertainties of the CSE fraction in the three bins of $p_T^{jet2}$

| Source | 40–60 GeV | 60–100 GeV | 100–200 GeV |
|--------|------------|------------|-------------|
| Jet energy scale | $\pm 5.1$ | $\pm 6.7$ | $\pm 2.1$ |
| Tracks quality | $\pm 0.3$ | $\pm 1.3$ | $\pm 0.4$ |
| Background subtraction | $\pm 14.1$ | $\pm 0.9$ | $\pm 1.9$ |
| Total systematic | $\pm 15.0$ | $\pm 6.9$ | $\pm 2.8$ |
| Statistical | $\pm 23$ | $\pm 22$ | $\pm 15$ |

Sect. 5. The symmetrized difference of the results with respect to those found with the nominal method, based on the NBD fit, is taken as an estimate of the corresponding uncertainty. For the measurement of $f_{CSE}$ as a function of $\Delta\eta_{jj}$ in bins of $p_T^{jet2}$, the average uncertainty in the $p_T^{jet2}$ bin is used in each $\Delta\eta_{jj}$ bin.

The total systematic uncertainty is calculated as the quadratic sum of the individual contributions. The effect of each systematic source and the total systematic uncertainty are also given in Table 1, for each of the $p_T^{jet2}$ bins. In this analysis, the systematic uncertainties are smaller than the statistical ones.

As a check of the sensitivity of the results to the definition of the hadronic activity in the gap region, the track multiplicity distributions are redetermined after increasing the lower limit of the track $p_T$ from 0.2 to 0.25 GeV. The results agree within a few percent with the nominal ones, implying no strong dependence on the hadronic activity definition. This observation is in accordance with the results of the D0 experiment [27] using calorimeter towers, in which consistent values of the $f_{CSE}$ fraction were obtained for tower transverse energy thresholds of 0.15, 0.2 and 0.25 GeV. Likewise, in the CDF analysis [29] consistent results were obtained based on track multiplicities ($p_T > 0.3$ GeV) and calorimeter tower multiplicities ($E_T > 0.2$ GeV). In the present analysis, neutral particles are not included in the multiplicity calculation because of the relatively high transverse energy thresholds required above calorimeter noise, about 0.5 GeV for photons and 2 GeV for neutral hadrons, compared to the much lower 0.2 GeV value for charged tracks.

### 7 Results

The values of the $f_{CSE}$ fraction, measured as explained in Sect. 5 in three bins of $p_T^{jet2}$, are given in Table 2. Figure 8 presents the extracted $f_{CSE}$ values as a function of $p_T^{jet2}$, compared to the results of the D0 [27] and CDF [29,30] experiments obtained in similar p$\bar{p}$ analyses at $\sqrt{s} = 0.63$ and 1.8 TeV. All the measurements are based on the same pseudora-
Figs. 8, 9 Fraction of dijet events with a central gap $(f_{\text{CSE}})$ as a function of $p_T^{\text{jet2}}$ at $\sqrt{s} = 7$ TeV, compared to the predictions of the Mueller and Tang (MT) model [21], and of the Ekstedt, Enberg, and Ingelman (EEI) model [22,23] with three different treatments of the gap survival probability factor $|S|^2$, as described in the text. The results are plotted at the mean value of $p_T^{\text{jet1}}$ in the bin. The inner and outer error bars represent the statistical, and the statistical and systematic uncertainties added in quadrature, respectively.

Table 2 Measured values of $f_{\text{CSE}}$ as a function of $p_T^{\text{jet2}}$. The first and second uncertainties correspond to the statistical and systematic components, respectively. The mean values of $p_T^{\text{jet2}}$ in the bin are also given.

| $p_T^{\text{jet2}}$ range (GeV) | $\langle p_T^{\text{jet2}} \rangle$ (GeV) | $f_{\text{CSE}}$ (%) |
|-----------------------------|----------------|----------------|
| 40–60                       | 46.6           | 0.57 ± 0.13 ± 0.09 |
| 60–100                      | 71.2           | 0.54 ± 0.12 ± 0.04 |
| 100–200                     | 120.1          | 0.97 ± 0.15 ± 0.03 |

be ascribed to a stronger contribution from rescattering processes, in which the interactions between spectator partons destroy the rapidity gap [19,54]. As a consequence, the gap survival probability factor $|S|^2$ is expected to decrease with collision energy. Although no explicit predictions for $|S|^2$ currently exist for jet-gap-jet production at $\sqrt{s} = 7$ TeV, a suppression factor of about 2, for $\sqrt{s}$ increasing from 1.8 to 7 TeV, is predicted for central exclusive production [55,56].

Figure 9 shows the comparison of the present results with the BFKL-based theoretical calculations of the Mueller and Tang (MT), and Ekstedt, Enberg and Ingelman (EEI) models. The gap fractions are plotted relative to the standard LO QCD dijet production rates, calculated with PYTHIA 6 (using tune Z2* for MT, and the default settings with color reconnection features turned off for EEI). The MT model [21] prediction is based on the LL BFKL evolution in the asymptotic limit of large rapidity separations between the jets, and is obtained with HERWIG 6 (as described in Sect. 3, without reweighting the $p_T^{\text{jet2}}$ dependence) for pure jet-gap-jet events (no simulation of MPI). The MT prediction does not reproduce the increase of $f_{\text{CSE}}$ with $p_T^{\text{jet2}}$, as already observed for the 1.8 TeV data [22]; it also underestimates the $f_{\text{CSE}}$ fractions measured at 7 TeV. The EEI predictions [23] are based on the model of Ref. [22] extended to the present energy. The model includes the dominant next-to-LL corrections to the BFKL evolution of the parton-level cross section, as well as the effect of rescattering processes. For the latter, three
Table 3 Measured values of the fraction of dijet events with a central gap ($f_{\text{CSE}}$) as a function of the pseudorapidity separation between the jets ($\Delta\eta_{jj}$) in bins of $p_T^{\text{jet}2}$. The columns in the table correspond to $p_T^{\text{jet}2}$ bins and the rows to $\Delta\eta_{jj}$ bins. The first and second errors correspond to the statistical and systematic uncertainties, respectively. The mean values of $\Delta\eta_{jj}$ in the bin are also given.

| $p_T^{\text{jet}2}$ (GeV) | 40–60 | 60–100 | 100–200 |
|--------------------------|-------|--------|--------|
| $\Delta\eta_{jj}$ range | $\langle\Delta\eta_{jj}\rangle$ | $f_{\text{CSE}}$ (%) | $\langle\Delta\eta_{jj}\rangle$ | $f_{\text{CSE}}$ (%) | $\langle\Delta\eta_{jj}\rangle$ | $f_{\text{CSE}}$ (%) |
| 3–4 | 3.63 | 0.25 $\pm$ 0.20 $\pm$ 0.04 | 3.62 | 0.47 $\pm$ 0.19 $\pm$ 0.05 | 3.61 | 0.78 $\pm$ 0.21 $\pm$ 0.06 |
| 4–5 | 4.46 | 0.41 $\pm$ 0.16 $\pm$ 0.14 | 4.45 | 0.47 $\pm$ 0.16 $\pm$ 0.08 | 4.41 | 0.99 $\pm$ 0.23 $\pm$ 0.06 |
| 5–7 | 5.60 | 1.24 $\pm$ 0.32 $\pm$ 0.10 | 5.49 | 0.91 $\pm$ 0.32 $\pm$ 0.21 | 5.37 | 1.95 $\pm$ 0.69 $\pm$ 0.44 |

8 Summary

Events with a large rapidity gap between the two leading jets have been measured for the first time at the LHC, for jets with transverse momentum $p_T > 40$ GeV and pseudorapidity $1.5 < |\eta| < 4.7$, reconstructed in opposite ends of the detector. The number of dijet events with no particles with $p_T > 0.2$ GeV in the region $|\eta| < 1$ is severely underestimated by PYTHIA 6 (tune Z2*). HERWIG 6 predictions, which include a contribution from color singlet exchange (CSE), based on the leading logarithmic Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equations, are needed to reproduce the type of dijet topologies selected in our analysis. The fraction of selected dijet events with such a rapidity gap has been measured as a function of the second-leading jet transverse momentum ($p_T^{\text{jet}2}$) and as a function of the size of the pseudorapidity interval between the jets, $\Delta\eta_{jj}$. The $f_{\text{CSE}}$ fraction rises with $p_T^{\text{jet}2}$ (from 0.6 to 1%) and with $\Delta\eta_{jj}$ (from 0.3 to 1.2% for $40 < p_T^{\text{jet}2} < 60$ GeV, from 0.5 to 0.9% for $60 < p_T^{\text{jet}2} < 100$ GeV, and from 0.8 to 2% for $100 < p_T^{\text{jet}2} < 200$ GeV).

The measured CSE fractions have been compared to the results of the D0 and CDF experiments at a center-of-mass energies of 0.63 and 1.8 TeV. A factor of two decrease of the CSE fraction measured at $\sqrt{s} = 7$ TeV with respect to that at $\sqrt{s} = 1.8$ TeV is observed. Such a behavior is consistent with the decrease seen in the Tevatron data when $\sqrt{s}$ rises from 0.63 to 1.8 TeV, and with theoretical expectations for the $\sqrt{s}$ dependence of the rapidity gap survival probability.

The data are also compared to theoretical perturbative quantum chromodynamics calculations based on the BFKL evolution equations complemented with different estimates of the non-perturbative gap survival probability. The next-to-leading-logarithmic BFKL calculations of Ekstedt, Enberg and Ingelman, with three different implementations of the soft rescattering processes, describe many features of the data, but none of the implementations is able to simultaneously describe all the features of the measurement.
Fraction of dijet events with a central gap ($f_{\text{CSE}}$) as a function of $\Delta_\eta$ at $\sqrt{s} = 7$ TeV in three different $p_T^{cjj}$ ranges, compared to the predictions of the Mueller and Tang (MT) model [21], and of the Ekstedt, Enberg, and Ingelman (EEI) model [22,23] with three different treatments of the gap survival probability factor $|S|^2$, as described in the text. The results are plotted at the mean value of $\Delta_\eta$ in the bin. Inner and outer error bars correspond to the statistical, and the statistical and systematic uncertainties added in quadrature, respectively.

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