

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

CMS Collaboration*

CERN, 1211 Geneva 23, Switzerland

Received: 9 October 2017 / Accepted: 5 March 2018 / Published online: 21 March 2018
© CERN for the benefit of the CMS collaboration 2018

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 η^{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 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 (η), 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 $\eta \sim \ln(1/x)$, 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 $e^\pm p$ 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

We dedicate this paper to the memory of our colleague and friend Sasha Proskuryakov, who started this analysis but passed away before it was completed. His contribution to the study of diffractive processes at CMS is invaluable.

*e-mail: cms-publication-committee-chair@cern.ch

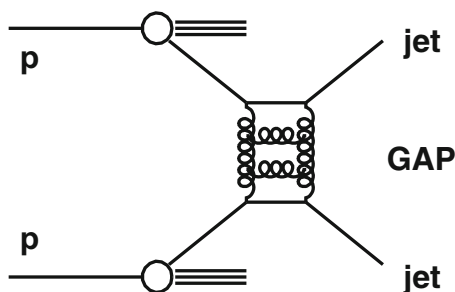


Fig. 1 Schematic diagram of a dijet event with a rapidity gap between the jets (jet-gap-jet event). The gap is defined as the absence of charged particle tracks above a certain p_T threshold

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 gaseous ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15,148 silicon strip detector modules. For nonisolated particles of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in transverse (longitudinal) impact parameter. The silicon tracker provides the primary vertex position with $\sim 15 \mu\text{m}$ resolution for jet events of the type considered in this analysis [33].

In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in both η and azimuth (φ , in radians). In the η - φ plane, and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 ECAL crystal arrays to form calorimeter towers projecting radially outwards from the nominal interaction point. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The forward component of the hadron calorimeter ($2.9 < |\eta| < 5.2$) consists of steel absorbers

with embedded radiation-hard quartz fibers, providing fast collection of Cherenkov light.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [34].

The first level of the CMS trigger system [35], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than $3.2 \mu\text{s}$. The high-level trigger processor farm further decreases the event rate from around 100 kHz to around 400 Hz, before data storage.

Tracks are reconstructed with the standard iterative algorithm of CMS, which is based on a combinatorial track finder that uses information from the silicon tracker. To reduce the misidentification rate, tracks are required to pass standard CMS quality criteria, usually referred to as 'high-purity' criteria [33]. These place requirements on the number of hits, the χ^2 of the track fit, and the degree of compatibility with the hypothesis that the track originates from a vertex reconstructed with the pixel detector. The requirements are functions of the track p_T and η , as well as the number of layers with a hit. A more detailed discussion on the combinatorial track finder algorithm and the high-purity track definition can be found in Ref. [33].

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 $p_T^{\text{jet}} = 40$ GeV (200 GeV) is about 12% (7%) for $|\eta^{\text{jet}}| < 0.5$ and about 10% for $4 < |\eta^{\text{jet}}| < 4.5$ [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, $\exp(b p_T^{\text{jet}2})$ 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_T^{jet} ranges, defined in terms of the p_T of the second leading jet in the dijet system, $p_T^{\text{jet}2}$: 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: $\eta^{\text{jet}1} \eta^{\text{jet}2} < 0$.

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 $p_T^{\text{jet}2} = 40\text{--}60$, $60\text{--}100$, and $100\text{--}200 \text{ GeV}$ jet samples, respectively.

5 Jet-gap-jet events

The charged-particle multiplicity (N_{tracks}) in the gap region between the two leading jets (the shaded area in Fig. 2) is

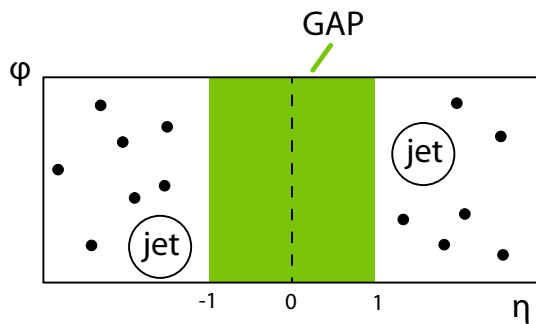


Fig. 2 Schematic picture of a jet-gap-jet event in the ϕ vs. η plane. The circles indicate the two jets reconstructed on each side of the detector, while the dots represent the remaining hadronic activity in the event. The shaded area corresponds to the region of the potential rapidity gap, in which the charged-particle multiplicity is measured (the so-called gap region)

used to discriminate between CSE and non-CSE events. The N_{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 η 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 η (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_{tracks} distribution in different p_T^{jet2} bins. In each p_T^{jet2} 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_T^{jet2} , 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_T , $p_T^{\text{jet2}}/p_T^{\text{jet1}}$ (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 $p_T^{\text{jet2}}/p_T^{\text{jet1}} = 1$ 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_{CSE} , defined as

$$f_{\text{CSE}} = \frac{N_{\text{events}}^{\text{F}} - N_{\text{non-CSE}}^{\text{F}}}{N_{\text{events}}}, \quad (1)$$

where $N_{\text{events}}^{\text{F}}$ 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), $N_{\text{non-CSE}}^{\text{F}}$ is the estimated number of events in these bins originating from non-CSE events, and N_{events} is the total number of events considered. The f_{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 $N_{\text{events}}^{\text{F}}$ and N_{events} is straightforward (event counting), the estimation of $N_{\text{non-CSE}}^{\text{F}}$ requires modeling of the non-CSE contributions, for which two data-driven approaches are considered.

In the first approach, the shape of the N_{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 $|\eta^{\text{jet}}| > 1.5$ 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_{tracks} distributions: whereas the shapes of the distributions are similar for the SS and OS samples, the mean N_{tracks} value in the SS sample is slightly lower. In order to minimize the difference between the average N_{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_{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

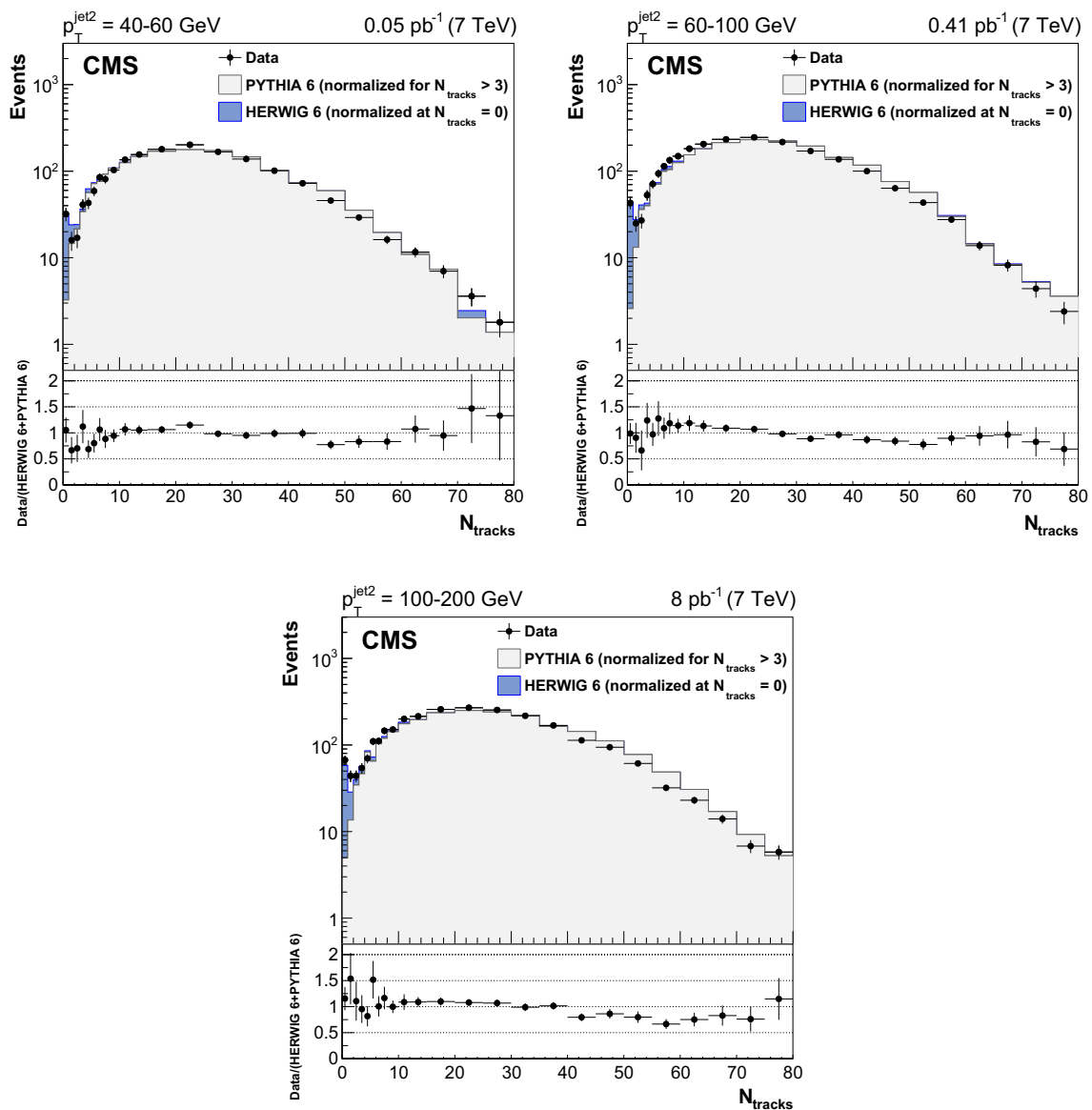


Fig. 3 Distribution, uncorrected for detector effects, of the number of central tracks between the two leading jets in events with $p_T^{\text{jet}2} = 40\text{--}60$ (top left), $60\text{--}100$ (top right), and $100\text{--}200$ (bottom) GeV, compared to the predictions of PYTHIA 6 (inclusive dijets) and HERWIG 6 (CSE jet-gap-jet events). The PYTHIA 6 and HERWIG 6 samples are normal-

ized to the number of events measured for $N_{\text{tracks}} > 3$ and $N_{\text{tracks}} = 0$, 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 $N_{\text{tracks}} = 3$, where the CSE signal to background ratio is expected to be negligible, and ends at $N_{\text{tracks}} = 35$, 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 $3 \leq N_{\text{tracks}} \leq 35$. The extrapolation of the fit to the $N_{\text{tracks}} < 3$ 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 $\Delta\eta_{jj}$

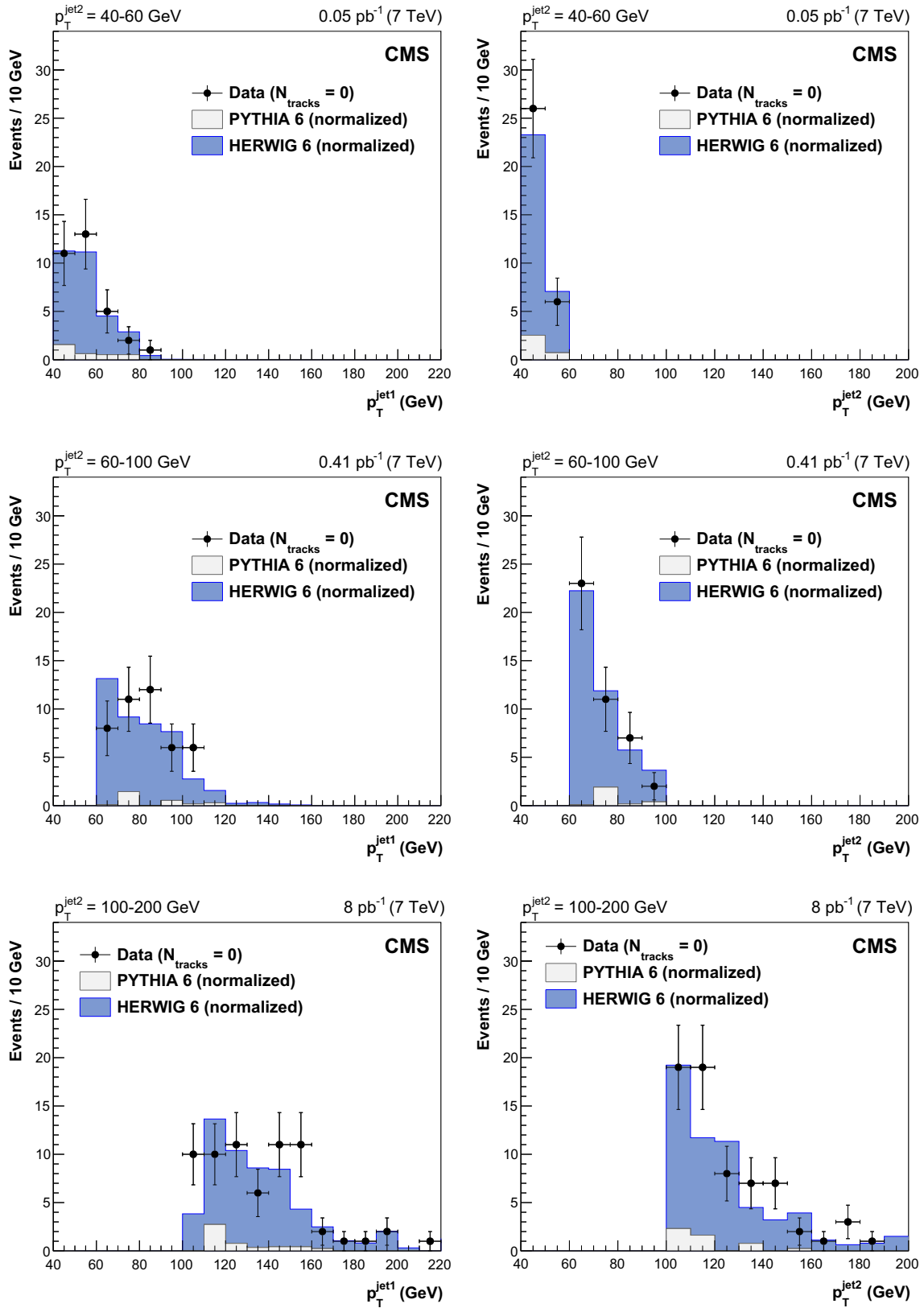


Fig. 4 Transverse momentum distributions, uncorrected for detector effects, of the leading jet (left) and the second-leading jet (right) in three dijet samples with $p_T^{\text{jet}2} = 40\text{--}60, 60\text{--}100,$ and $100\text{--}200$ GeV (from top to bottom) after all selections, for events with 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

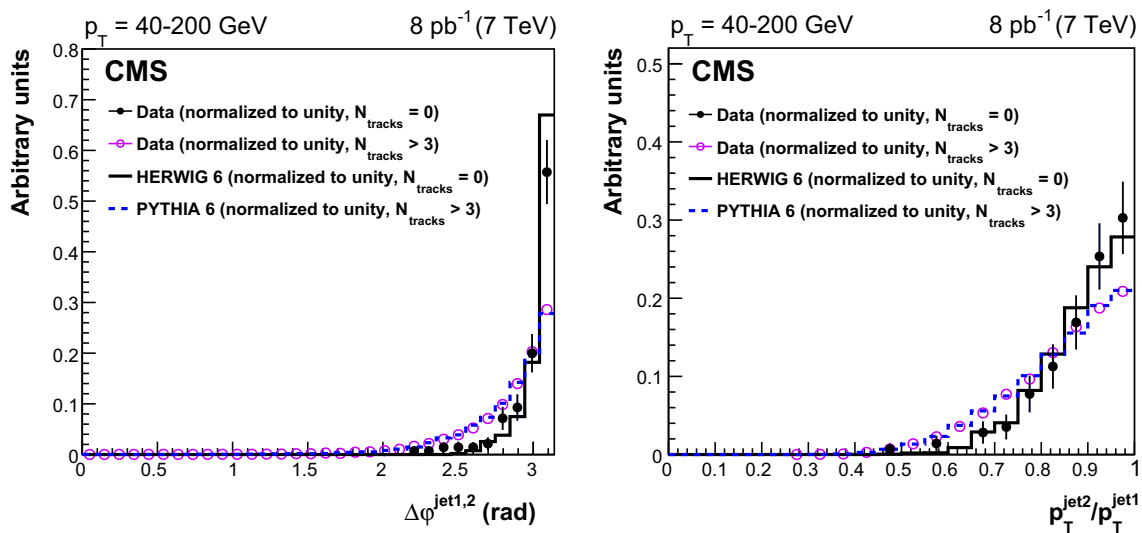


Fig. 5 Distributions, uncorrected for detector effects, of the azimuthal angle $\Delta\phi^{\text{jet}1,2}$ between the two leading jets (left) and the ratio $p_T^{\text{jet}2}/p_T^{\text{jet}1}$ of the second-leading jet p_T to the leading jet p_T (right) for events after all selections, with no tracks ($N_{\text{tracks}} = 0$, full circles) or more than three

tracks ($N_{\text{tracks}} > 3$, open circles) reconstructed in the $|\eta| < 1$ region, compared with the MC predictions. The distributions are summed over the three $p_T^{\text{jet}2}$ bins used in the analysis and normalized to unity for shape comparison

values than in the OS sample), the NBD fit is chosen as the main background determination method in this analysis. The method involving the SS sample is used as a systematic check, as discussed in the next section. The non-CSE background contributes about 10–15% of the events in the 0th bin of the multiplicity distribution, about 25–35% in the first two multiplicity bins, and about 40–60% when the signal is integrated over the first three multiplicity bins.

Figure 7 shows the track multiplicity distribution in the three bins of $p_T^{\text{jet}2}$ after subtracting the non-CSE background. A clear excess in the lowest bins is observed over a flat continuum, in agreement with the normalized predictions from a HERWIG 6 subsample with jet-gap-jet events only (no additional MPI); the jet-gap-jet events with additional MPI producing tracks in the rapidity gap are part of the background subtracted from the track multiplicity distributions, and are not included in the figure. In the region of the excess (CSE signal region), most events are in the 0th bin, with smaller contributions from events with one or two tracks reconstructed in the gap region. These tracks originate from the jets but are reconstructed outside of the jet cone, and their contribution is larger in the highest $p_T^{\text{jet}2}$ bin, for which jets tend to have a higher multiplicity and to be produced more centrally (closer to the gap). We use the $N_{\text{tracks}} < 2$ region to extract the CSE signal in the lowest and medium $p_T^{\text{jet}2}$ bins, and the $N_{\text{tracks}} < 3$ region to extract the CSE signal in the highest $p_T^{\text{jet}2}$ bin.

The CSE fractions are obtained from the data using Eq. (1), with the different terms in this formula uncorrected for detector effects. No unfolding of the data is necessary since the

effects of resolution and migration of the dijet variables cancel in the f_{CSE} ratio. In addition, the number of jet-gap-jet events extracted in the numerator of Eq. (1) does not depend on the track reconstruction efficiency; the latter only influences 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 τ such that $c\tau > 10$ mm) are used both for the jet reconstruction and for the extraction of the N_{tracks} variable.

6 Systematic uncertainties

The systematic uncertainties in the f_{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 $p_T^{\text{jet}, \text{new}} = p_T^{\text{jet}} \pm u(p_T^{\text{jet}}, \eta^{\text{jet}})$, where $u(p_T^{\text{jet}}, \eta^{\text{jet}})$ is the JES uncertainty, which increases at lower (higher) values of p_T^{jet} (η^{jet}) [49]. After changing the p_T of the jets, they are reordered in $p_T^{\text{jet}, \text{new}}$, and the analysis is repeated using the two highest $p_T^{\text{jet}, \text{new}}$ 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.

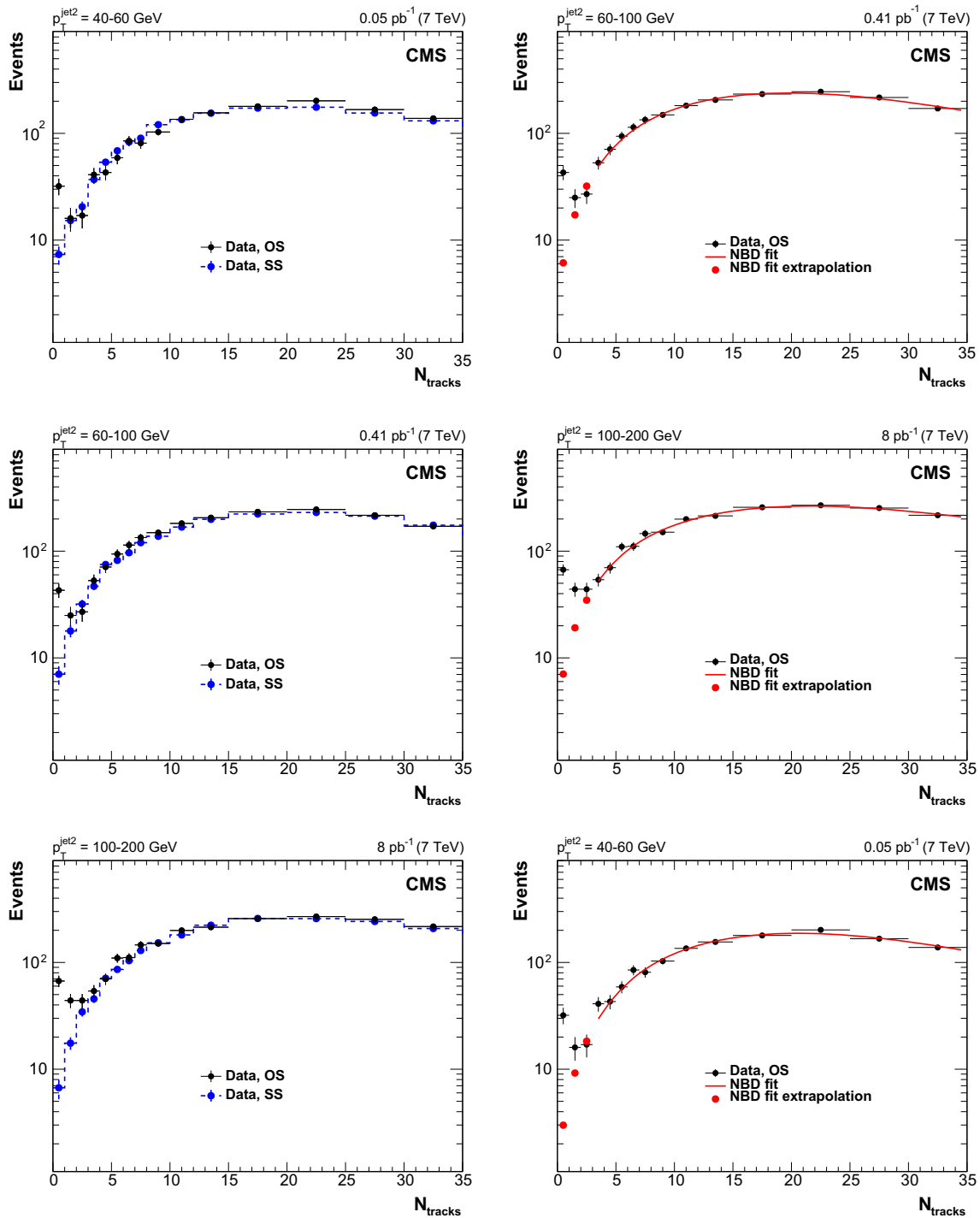


Fig. 6 Distribution, uncorrected for detector effects, of the number of central tracks in opposite-side (OS) dijet events (black circles) with $p_T^{\text{j}et2} = 40\text{--}60$ (top), $60\text{--}100$ (middle), and $100\text{--}200$ GeV (bottom), plotted

(left) together with the N_{tracks} distribution of same-side (SS) dijet events (blue circles), and fitted to a NBD function (right)

– *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_{tracks} distribution is estimated from data, based on the SS sample introduced in

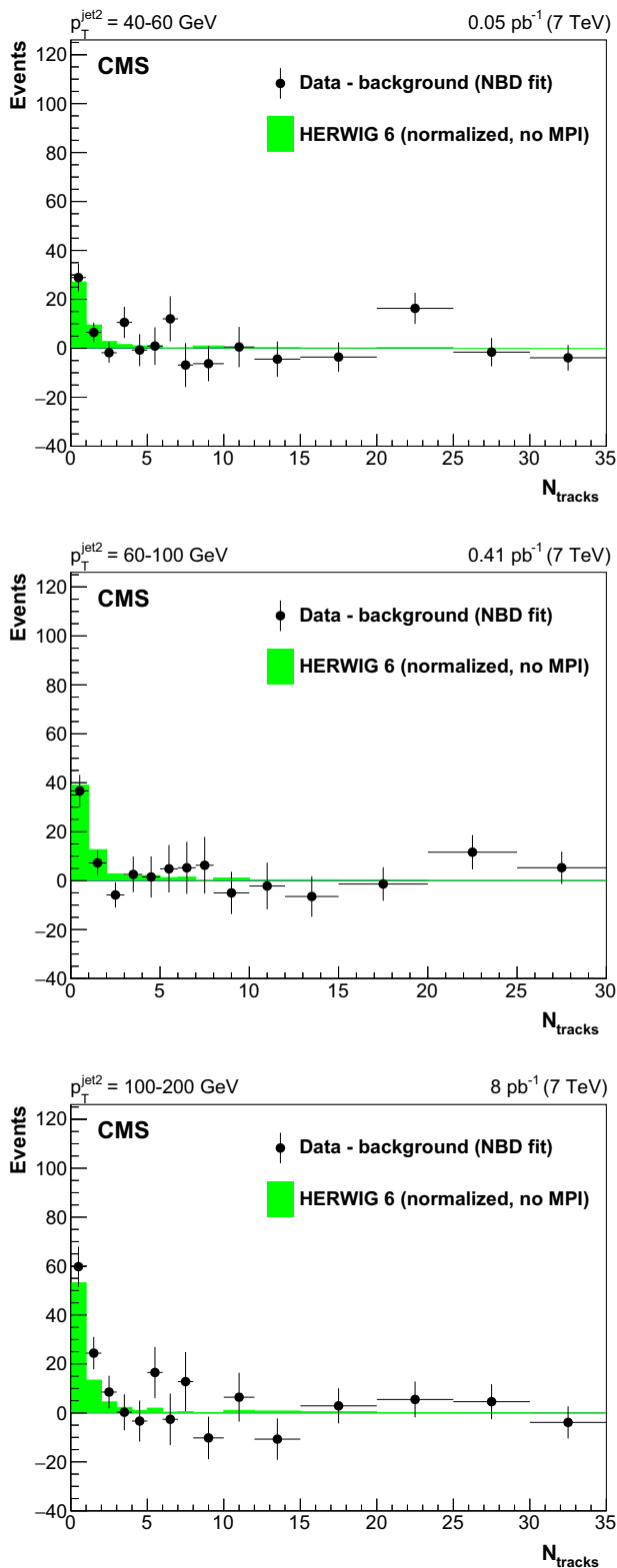


Fig. 7 Background-subtracted central track multiplicity distributions, uncorrected for detector effects, in the three bins of $p_T^{\text{jet}2}$, compared to the HERWIG 6 predictions without underlying event simulation (“no MPI”), normalized as in Fig. 3. The background is estimated from the NBD fit to the data in the $3 \leq N_{\text{tracks}} \leq 35$ 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 $p_T^{\text{jet}2}$

Source	40–60 GeV	60–100 GeV	100–200 GeV
Jet energy scale	± 5.1	± 6.7	± 2.1
Tracks quality	± 0.3	± 1.3	± 0.4
Background subtraction	± 14.1	± 0.9	± 1.9
Total systematic	± 15.0	± 6.9	± 2.8
Statistical	± 23	± 22	± 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 $\Delta\eta_{\text{jj}}$ in bins of $p_T^{\text{jet}2}$, the average uncertainty in the $p_T^{\text{jet}2}$ bin is used in each $\Delta\eta_{\text{jj}}$ 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 $p_T^{\text{jet}2}$ 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 $p_T^{\text{jet}2}$, are given in Table 2. Figure 8 presents the extracted f_{CSE} values as a function of $p_T^{\text{jet}2}$, 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-

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

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

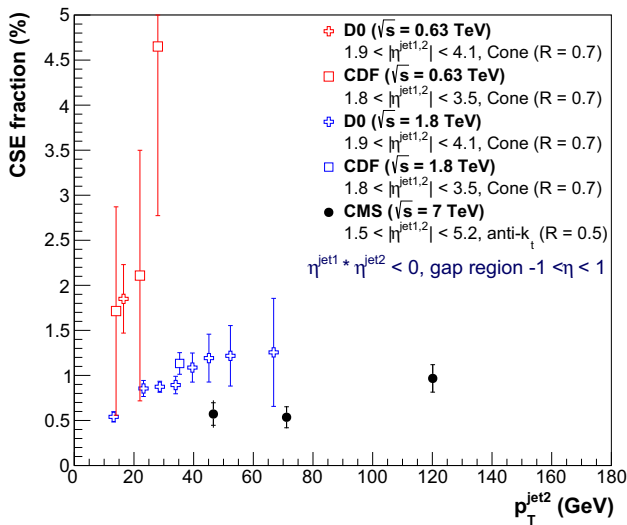


Fig. 8 Fraction of dijet events with a central gap (f_{CSE}) as a function of p_T^{jet2} at $\sqrt{s} = 7$ TeV, compared to the D0 [27] and CDF [29, 30] results at $\sqrt{s} = 0.63$ and 1.8 TeV. The details of the jet selections are given in the legend. The results are plotted at the mean value of p_T^{jet2} in the bin. The inner and outer error bars represent the statistical, and the statistical and systematic uncertainties added in quadrature, respectively

pidity range for the gap region, but differ in the selection of jets. D0 and CDF use the cone jet reconstruction algorithm with size parameter $R = 0.7$, and select jets in the regions $1.9 < |\eta^{jet1}| < 4.1$, and $1.8 < |\eta^{jet1}| < 3.5$, respectively. The latter difference only minimally affects the comparison with the CMS results, as the measured f_{CSE} fractions at 0.63 and 1.8 TeV depend only weakly on the gap size. At all the three collision energies f_{CSE} increases with p_T^{jet2} . This reflects the fact that the cross section for dijet events with a gap decreases with p_T^{jet2} less rapidly than the inclusive dijet cross section does. In addition, a decrease of the gap fraction with increasing \sqrt{s} is observed. The value of f_{CSE} measured for $40 < p_T^{jet2} < 60$ GeV at $\sqrt{s} = 7$ TeV is about a factor of two lower than those measured for the same p_T^{jet2} at $\sqrt{s} = 1.8$ TeV. This behavior is in agreement with observations by D0 and CDF, which reported that the jet-gap-jet fraction decreases by a factor of 2.5 ± 0.9 [27] and 3.4 ± 1.2 [30], respectively, when \sqrt{s} increases from 0.63 to 1.8 TeV. The decrease of f_{CSE} with increasing energy can

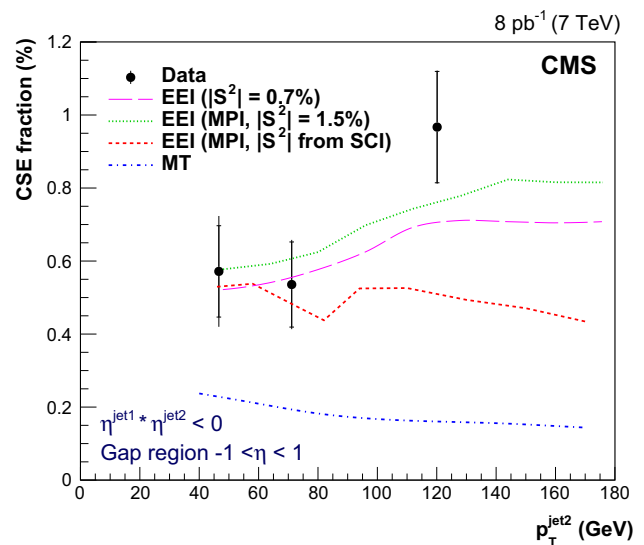


Fig. 9 Fraction of dijet events with a central gap (f_{CSE}) as a function of p_T^{jet2} at $\sqrt{s} = 7$ TeV, compared to the predictions of the Mueller and Tang (MT) model [21], and of the Ekstedt, Enberg, and Ingelman (EEI) model [22, 23] with three different treatments of the gap survival probability factor $|S|^2$, as described in the text. The results are plotted at the mean value of p_T^{jet2} in the bin. The inner and outer error bars represent the statistical, and the statistical and systematic uncertainties added in quadrature, respectively

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 of the p_T^{jet2} dependence) for pure jet-gap-jet events (no simulation of MPI). The MT prediction does not reproduce the increase of f_{CSE} with p_T^{jet2} , as already observed for the 1.8 TeV data [22]; it also underestimates the f_{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_{CSE}) as a function of the pseudorapidity separation between the jets ($\Delta\eta_{\text{jj}}$) in bins of $p_{\text{T}}^{\text{jet}2}$. The columns in the table correspond to $p_{\text{T}}^{\text{jet}2}$

$p_{\text{T}}^{\text{jet}2}$ (GeV)	40–60		60–100		100–200	
	$\langle\Delta\eta_{\text{jj}}\rangle$	f_{CSE} (%)	$\langle\Delta\eta_{\text{jj}}\rangle$	f_{CSE} (%)	$\langle\Delta\eta_{\text{jj}}\rangle$	f_{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	$1.95 \pm 0.69 \pm 0.44$

bins and the rows to $\Delta\eta_{\text{jj}}$ bins. The first and second errors correspond to the statistical and systematic uncertainties, respectively. The mean values of $\Delta\eta_{\text{jj}}$ in the bin are also given

approaches are considered, in which gap survival probability is either assumed to be a constant factor, or is partially or fully simulated using Monte Carlo models, to take into account its dependence on the variables $p_{\text{T}}^{\text{jet}2}$ and $\Delta\eta_{\text{jj}}$. In the first approach, the BFKL cross section is scaled by a constant factor corresponding to a gap survival probability value of $|S|^2 = 0.7\%$ (magenta long-dashed curve in Fig. 9), in order to match the data. Alternatively, the activity originating from perturbative gluons is modeled in terms of initial- and final-state parton showers, MPI and hadronization processes, as implemented in PYTHIA 6. The remaining nonperturbative interactions are simulated either by an additional gap survival probability factor of $|S|^2 = 1.5\%$ (green dotted line in Fig. 9), or by soft color interactions (SCI, red dashed line in Fig. 9) where a color exchange with negligible momentum transfer occurs between parton clusters [23].

As can be seen in Fig. 9, the EEI model with $|S|^2 = 0.7\%$, and that with MPI and $|S|^2 = 1.5\%$ reproduce the $p_{\text{T}}^{\text{jet}2}$ dependence of the f_{CSE} fraction in the data. The EEI model with MPI and SCI correctly predicts the amount of jet-gap-jet events in the first two $p_{\text{T}}^{\text{jet}2}$ bins, but tends to be lower than the data at higher $p_{\text{T}}^{\text{jet}2}$. The dip in the prediction around $p_{\text{T}}^{\text{jet}2} = 80$ GeV is a result of using the SCI model in conjunction with final state showering, and is a feature of the model rather than a statistical fluctuation.

The dependence of the f_{CSE} fraction on the size of $\Delta\eta_{\text{jj}}$ is studied for each $p_{\text{T}}^{\text{jet}2}$ sample in three bins of $\Delta\eta_{\text{jj}} = 3$ –4, 4–5, and 5–7. The measured values of the f_{CSE} fractions are listed in Table 3, and plotted in Fig. 10. The fraction of jet-gap-jet events increases with $\Delta\eta_{\text{jj}}$, and varies from 0.3 to 1.2%, and from 0.8 to 2%, in the lowest and the highest $p_{\text{T}}^{\text{jet}2}$ bins, respectively. Figure 10 also shows the comparison of the data with the predictions of the MT and EEI models. The MT model predicts a flat dependence of f_{CSE} with $\Delta\eta_{\text{jj}}$, and underestimates the measured jet-gap-jet fractions except for the lowest ($p_{\text{T}}^{\text{jet}2}$, $\Delta\eta_{\text{jj}}$) bin for which the agreement is good. The EEI model with the $|S|^2 = 0.7\%$ factor, as well as that with MPI plus $|S|^2 = 1.5\%$ predict a decrease of f_{CSE} with $\Delta\eta_{\text{jj}}$, and are at variance with the data. Conversely, the EEI model with MPI plus soft color interactions satisfactorily reproduces the rise of f_{CSE} with $\Delta\eta_{\text{jj}}$ in all $p_{\text{T}}^{\text{jet}2}$ bins.

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 $p_{\text{T}}^{\text{jet}} > 40$ GeV and pseudorapidity $1.5 < |\eta^{\text{jet}}| < 4.7$, reconstructed in opposite ends of the detector. The number of dijet events with no particles with $p_{\text{T}} > 0.2$ 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 ($p_{\text{T}}^{\text{jet}2}$) and as a function of the size of the pseudorapidity interval between the jets, $\Delta\eta_{\text{jj}}$. The f_{CSE} fraction rises with $p_{\text{T}}^{\text{jet}2}$ (from 0.6 to 1%) and with $\Delta\eta_{\text{jj}}$ (from 0.3 to 1.2% for $40 < p_{\text{T}}^{\text{jet}2} < 60$ GeV, from 0.5 to 0.9% for $60 < p_{\text{T}}^{\text{jet}2} < 100$ GeV, and from 0.8 to 2% for $100 < p_{\text{T}}^{\text{jet}2} < 200$ 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.

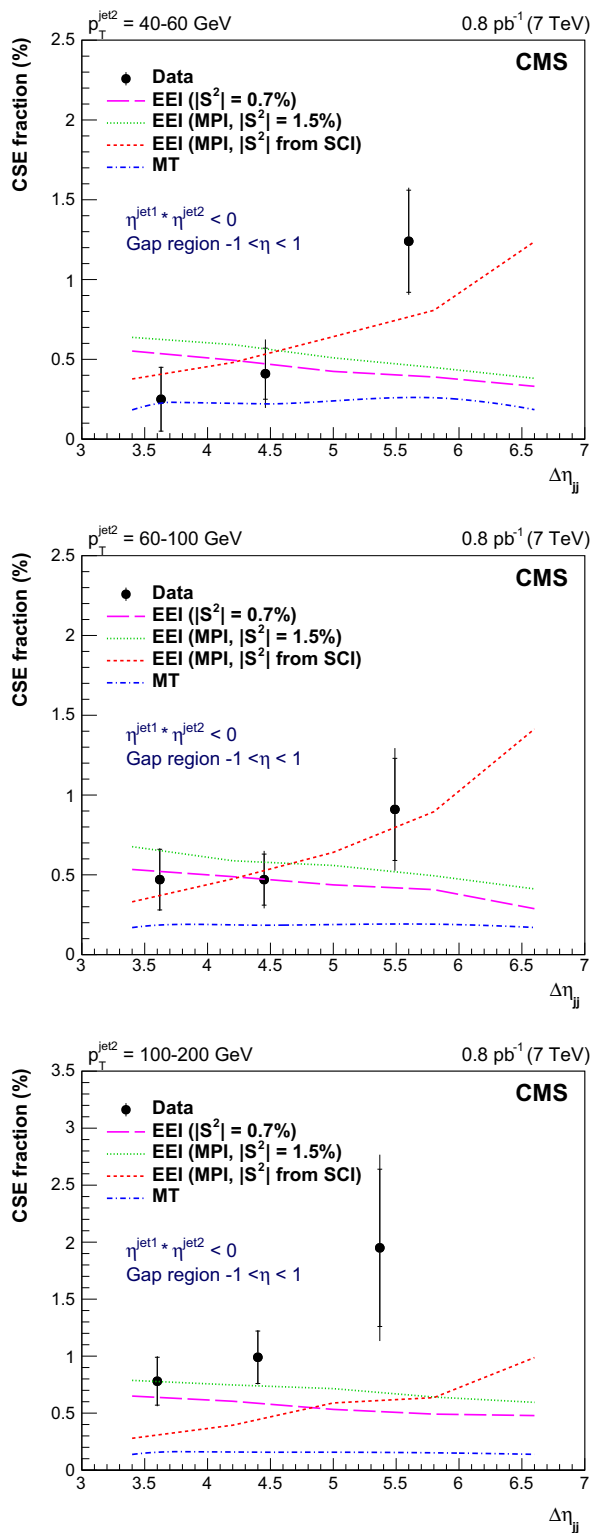


Fig. 10 Fraction of dijet events with a central gap (f_{CSE}) as a function of $\Delta\eta_{jj}$ at $\sqrt{s} = 7$ TeV in three different $p_T^{\text{jet}2}$ ranges, compared to the predictions of the Mueller and Tang (MT) model [21], and of the Ekstedt, Enberg, and Ingelman (EEI) model [22, 23] with 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 $\Delta\eta_{jj}$ in the bin. Inner and outer error bars correspond to the statistical, and the statistical and systematic uncertainties added in quadrature, respectively

Acknowledgements We would like to thank Andreas Ekstedt, Rikard Enberg, and Gunnar Ingelman for providing the next-to-LL BFKL analytical predictions of their model. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References

1. CMS Collaboration, Dijet azimuthal decorrelations in pp collisions at $\sqrt{s} = 7$ TeV. Phys. Rev. Lett. **106**, 122003 (2011). <https://doi.org/10.1103/PhysRevLett.106.122003>. arXiv:1101.5029

2. CMS Collaboration, Measurement of the differential dijet production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV. *Phys. Lett. B* **700**, 187 (2011). <https://doi.org/10.1016/j.physletb.2011.05.027>. arXiv:1104.1693
3. CMS Collaboration, Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP* **06**, 036 (2012). [https://doi.org/10.1007/JHEP06\(2012\)036](https://doi.org/10.1007/JHEP06(2012)036). arXiv:1202.0704
4. CMS Collaboration, Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in proton-proton collisions at $\sqrt{s} = 7$ TeV. *Eur. Phys. J. C* **72**, 2216 (2012). <https://doi.org/10.1140/epjc/s10052-012-2216-6>. arXiv:1204.0696
5. CMS Collaboration, Measurement of dijet azimuthal decorrelation in pp collisions at $\sqrt{s} = 8$ TeV. *Eur. Phys. J. C* **76**, 536 (2016). <https://doi.org/10.1140/epjc/s10052-016-4346-8>. arXiv:1602.04384
6. CMS Collaboration, Measurement of the triple-differential dijet cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV and constraints on parton distribution functions. *Eur. Phys. J. C* **77**, 746 (2017). <https://doi.org/10.1140/epjc/s10052-017-5286-7>. arXiv:1705.02628
7. ATLAS Collaboration, Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector. *Eur. Phys. J. C* **71**, 1512 (2011). <https://doi.org/10.1140/epjc/s10052-010-1512-2>. arXiv:1009.5908
8. ATLAS Collaboration, Measurement of dijet production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *JHEP* **09**, 053 (2011). [https://doi.org/10.1007/JHEP09\(2011\)053](https://doi.org/10.1007/JHEP09(2011)053). arXiv:1107.1641
9. ATLAS Collaboration, Measurement of inclusive jet and dijet production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Phys. Rev. D* **86**, 014022 (2012). <https://doi.org/10.1103/PhysRevD.86.014022>. arXiv:1112.6297
10. ATLAS Collaboration, Measurement of dijet cross sections in pp collisions at 7 TeV centre-of-mass energy using the ATLAS detector. *JHEP* **05**, 059 (2014). [https://doi.org/10.1007/JHEP05\(2014\)059](https://doi.org/10.1007/JHEP05(2014)059). arXiv:1312.3524
11. ATLAS Collaboration, Measurements of jet vetoes and azimuthal decorrelations in dijet events produced in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector. *Eur. Phys. J. C* **74**, 3117 (2014). <https://doi.org/10.1140/epjc/s10052-014-3117-7>. arXiv:1407.5756
12. ATLAS Collaboration, Dijet production in $\sqrt{s} = 7$ TeV pp collisions with large rapidity gaps at the ATLAS experiment. *Phys. Lett. B* **754**, 214 (2016). <https://doi.org/10.1016/j.physletb.2016.01.028>. arXiv:1511.00502
13. V.N. Gribov, L.N. Lipatov, Deep inelastic ep scattering in perturbation theory. *Sov. J. Nucl. Phys.* **15**, 438 (1972)
14. G. Altarelli, G. Parisi, Asymptotic freedom in parton language. *Nucl. Phys. B* **126**, 298 (1977). [https://doi.org/10.1016/0550-3213\(77\)90384-4](https://doi.org/10.1016/0550-3213(77)90384-4)
15. Y.L. Dokshitzer, Calculation of the structure functions for deep inelastic scattering and e^+e^- annihilation by perturbation theory in quantum chromodynamics. *Sov. Phys. JETP* **46**, 641 (1977)
16. E.E. Kuraev, L.N. Lipatov, V.S. Fadin, The Pomanchuk singularity in nonabelian gauge theories. *Sov. Phys. JETP* **45**, 199 (1977)
17. Y.Y. Balitsky, L.N. Lipatov, The Pomanchuk singularity in quantum chromodynamics. *Sov. J. Nucl. Phys.* **28**, 822 (1978)
18. L.N. Lipatov, The bare pomeron in quantum chromodynamics. *Sov. Phys. JETP* **63**, 904 (1986)
19. J.D. Bjorken, Rapidity gaps and jets as a new physics signature in very high-energy hadron hadron collisions. *Phys. Rev. D* **47**, 101 (1993). <https://doi.org/10.1103/PhysRevD.47.101>
20. V. Barone, E. Predazzi, High-energy particle diffraction. Texts and monographs in physics. Springer, Berlin (2002). <https://doi.org/10.1007/978-3-662-04724-8>
21. A.H. Mueller, W.-K. Tang, High-energy parton-parton elastic scattering in QCD. *Phys. Lett. B* **284**, 123 (1992). [https://doi.org/10.1016/0370-2693\(92\)91936-4](https://doi.org/10.1016/0370-2693(92)91936-4)
22. R. Enberg, G. Ingelman, L. Motyka, Hard color singlet exchange and gaps between jets at the Tevatron. *Phys. Lett. B* **524**, 273 (2002). [https://doi.org/10.1016/S0370-2693\(01\)01379-X](https://doi.org/10.1016/S0370-2693(01)01379-X). arXiv:hep-ph/0111090
23. A. Ekstedt, R. Enberg, G. Ingelman, Hard color singlet BFKL exchange and gaps between jets at the LHC. (2017). arXiv:1703.10919
24. O. Kepka, C. Marquet, C. Royon, Gaps between jets in hadronic collisions. *Phys. Rev. D* **83**, 034036 (2011). <https://doi.org/10.1103/PhysRevD.83.034036>. arXiv:1012.3849
25. D0 Collaboration, Rapidity gaps between jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. *Phys. Rev. Lett.* **72**, 2332 (1994). <https://doi.org/10.1103/PhysRevLett.72.2332>
26. D0 Collaboration, Jet production via strongly-interacting color-singlet exchange in $p\bar{p}$ collisions. *Phys. Rev. Lett.* **76**, 734 (1996). <https://doi.org/10.1103/PhysRevLett.76.734>. arXiv:hep-ex/9509013
27. D0 Collaboration, Probing hard color-singlet exchange in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV and 1800 GeV. *Phys. Lett. B* **440**, 189 (1998). [https://doi.org/10.1016/S0370-2693\(98\)01238-6](https://doi.org/10.1016/S0370-2693(98)01238-6). arXiv:hep-ex/9809016
28. CDF Collaboration, Observation of rapidity gaps in $p\bar{p}$ collisions at 1.8 TeV. *Phys. Rev. Lett.* **74**, 855 (1995). <https://doi.org/10.1103/PhysRevLett.74.855>
29. CDF Collaboration, Dijet production by color-singlet exchange at the Fermilab Tevatron. *Phys. Rev. Lett.* **80** (1998) 1156, <https://doi.org/10.1103/PhysRevLett.80.1156>
30. CDF Collaboration, Events with a rapidity gap between jets in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV. *Phys. Rev. Lett.* **81**, 5278 (1998). <https://doi.org/10.1103/PhysRevLett.81.5278>
31. ZEUS Collaboration, Rapidity gaps between jets in photoproduction at HERA. *Phys. Lett. B* **369**, 55 (1996). [https://doi.org/10.1016/0370-2693\(95\)01588-4](https://doi.org/10.1016/0370-2693(95)01588-4). arXiv:hep-ex/9510012
32. H1 Collaboration, Energy flow and rapidity gaps between jets in photoproduction at HERA. *Eur. Phys. J. C* **24**, 517 (2002). <https://doi.org/10.1007/s10052-002-0988-9>. arXiv:hep-ex/0203011
33. CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker. *JINST* **9**, P10009 (2014). <https://doi.org/10.1088/1748-0221/9/10/P10009>. arXiv:1405.6569
34. CMS Collaboration, The CMS experiment at the CERN LHC. *JINST* **3**, S08004 (2008). <https://doi.org/10.1088/1748-0221/3/08/S08004>
35. CMS Collaboration, The CMS trigger system. *JINST* **12**, P01020 (2017). <https://doi.org/10.1088/1748-0221/12/01/P01020>. arXiv:1609.02366
36. M. Cacciari, G.P. Salam, G. Soyez, The anti- k_r jet clustering algorithm. *JHEP* **04**, 063 (2008). <https://doi.org/10.1088/1126-6708/2008/04/063>. arXiv:0802.1189
37. M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual. *Eur. Phys. J. C* **72**, 1896 (2012). <https://doi.org/10.1140/epjc/s10052-012-1896-2>. arXiv:1111.6097
38. CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector. *JINST* **12**, P10003 (2017). <https://doi.org/10.1088/1748-0221/12/10/P10003>. arXiv:1706.04965
39. CMS Collaboration, Jet performance in pp collisions at 7 TeV. CMS Physics Analysis Summary CMS-PAS-JME-10-003 (2010)

40. CMS Collaboration, Determination of the jet energy scale in CMS with pp collisions at $\sqrt{s} = 7$ TeV. CMS Physics Analysis Summary CMS-PAS-JME-10-010 (2010)
41. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. JINST **6**, P11002 (2011). <https://doi.org/10.1088/1748-0221/6/11/P11002>. arXiv:1107.4277
42. T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual. JHEP **05**, 026 (2006). <https://doi.org/10.1088/1126-6708/2006/05/026>. arXiv:hep-ph/0603175
43. B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, Parton fragmentation and string dynamics. Phys. Rept. **97**, 31 (1983). [https://doi.org/10.1016/0370-1573\(83\)90080-7](https://doi.org/10.1016/0370-1573(83)90080-7)
44. CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV. JHEP **04**, 072 (2013). [https://doi.org/10.1007/JHEP04\(2013\)072](https://doi.org/10.1007/JHEP04(2013)072). arXiv:1302.2394
45. G. Corcella et al., HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes). JHEP **01**, 010 (2001). <https://doi.org/10.1088/1126-6708/2001/01/010>. arXiv:hep-ph/0011363
46. J.M. Butterworth, J.R. Forshaw, M.H. Seymour, Multiparton interactions in photoproduction at HERA. Z. Phys. C **72**, 637 (1996). <https://doi.org/10.1007/s002880050286>. arXiv:hep-ph/9601371
47. J. Pumplin et al., New generation of parton distributions with uncertainties from global QCD analysis. JHEP **07**, 012 (2002). <https://doi.org/10.1088/1126-6708/2002/07/012>. arXiv:hep-ph/0201195
48. GEANT4 Collaboration, GEANT4—a simulation toolkit. Nucl. Instrum. Meth. A **506**, 250 (2003). [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
49. CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS. J. Instrum. **6**, P11002 (2011). <https://doi.org/10.1088/1748-0221/6/11/P11002>. arXiv:1107.4277
50. CMS Collaboration, Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. JHEP **02**, 041 (2010). [https://doi.org/10.1007/JHEP02\(2010\)041](https://doi.org/10.1007/JHEP02(2010)041). arXiv:1002.0621
51. UA5 Collaboration, Multiplicity distributions in different pseudorapidity intervals at a CMS energy of 540 GeV. Phys. Lett. B **160**, 193 (1985). [https://doi.org/10.1016/0370-2693\(85\)91491-1](https://doi.org/10.1016/0370-2693(85)91491-1)
52. UA5 Collaboration, Charged particle multiplicity distributions at 200 GeV and 900 GeV c.m. energy. Z. Phys. C **43**, 357 (1989). <https://doi.org/10.1007/BF01506531>
53. ALICE Collaboration, Charged-particle multiplicity measurement in proton-proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC. Eur. Phys. J. C **68**, 345 (2010). <https://doi.org/10.1140/epjc/s10052-010-1350-2>. arXiv:1004.3514
54. E. Gotsman, E. Levin, U. Maor, Energy dependence of the survival probability of large rapidity gaps. Phys. Lett. B **438**, 229 (1998). [https://doi.org/10.1016/S0370-2693\(98\)00972-1](https://doi.org/10.1016/S0370-2693(98)00972-1). arXiv:hep-ph/9804404
55. V.A. Khoze, A.D. Martin, M.G. Ryskin, Diffraction at the LHC. Eur. Phys. J. C **73**, 2503 (2013). <https://doi.org/10.1140/epjc/s10052-013-2503-x>. arXiv:1306.2149
56. E. Gotsman, E. Levin, U. Maor, CGC/saturation approach for soft interactions at high energy: survival probability of central exclusive production. Eur. Phys. J. C **76**, 177 (2016). <https://doi.org/10.1140/epjc/s10052-016-4014-z>. arXiv:1510.07249

CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth¹, V. M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck¹, J. Strauss, W. Waltenberger, C.-E. Wulz¹

Institute for Nuclear Problems, Minsk, Belarus

O. Dvornikov, V. Makarenko, V. Mossolov, J. Suarez Gonzalez, V. Zykunov

National Centre for Particle and High Energy Physics, Minsk, Belarus

N. Shumeiko

Universiteit Antwerpen, Antwerp, Belgium

S. Alderweireldt, E. A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussels, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Brussels, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, C. Beluffi³, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Belyi

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W. L. Aldá Júnior, F. L. Alves, G. A. Alves, L. Brito, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato⁴, A. Custódio, E. M. Da Costa, G. G. Da Silveira⁵, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, A. Santoro, A. Sznajder, E. J. Tonelli Manganote⁴, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista^a, Universidade Federal do ABC^b, São Paulo, Brazil

S. Ahuja^a, C. A. Bernardes^a, S. Dogra^a, T. R. Fernandez Perez Tomei^a, E. M. Gregores^b, P. G. Mercadante^b, C. S. Moon^a, S. F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J. C. Ruiz Vargas^a

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁶

Institute of High Energy Physics, Beijing, China

M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, Y. Chen⁷, T. Cheng, C. H. Jiang, D. Leggat, Z. Liu, F. Romeo, M. Ruan, S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S. J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogotá, Colombia

C. Avila, A. Cabrera, L. F. Chaparro Sierra, C. Florez, J. P. Gomez, C. F. González Hernández, J. D. Ruiz Alvarez⁸, J. C. Sanabria

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia

N. Godinovic, D. Lelas, I. Puljak, P. M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa

University of Cyprus, Nicosia, Cyprus

M. W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁹, M. Finger Jr.⁹

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, EgyptS. Elgammal¹⁰, A. Ellithi Kamel¹¹, A. Mohamed¹²**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. DeJardin, D. Denegri, B. Fabbro, J. L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, A. G. Stahl Leitner, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS IPHC UMR 7178, 67000 Strasbourg, FranceJ.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E. C. Chabert, N. Chanon, C. Collard, E. Conte¹³, X. Coubez, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, C. Bernet, G. Boudoul, C. A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, A. Popov¹⁴, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret**Georgian Technical University, Tbilisi, Georgia**T. Toriashvili¹⁵**Tbilisi State University, Tbilisi, Georgia**Z. Tsamalaidze⁹**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

C. Autermann, S. Beranek, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Albert, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

V. Cherepanov, G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁶

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. A. Bin Anuar, K. Borras¹⁷, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J. M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁹, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M. Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, S. Spannagel, N. Stefaniuk, G. P. Van Onsem, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A. R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁶, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann¹⁶, S. M. Heindl, U. Husemann, F. Kassel¹⁶, I. Katkov¹⁴, S. Kudella, H. Mildner, M. U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H. J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, V. A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

N. Filipovic, G. Pasztor

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²⁰, F. Sikler, V. Veszpremi, G. Vesztergombi²¹, A. J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók²¹, P. Raics, Z. L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

J. R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²³, S. Bhowmik²⁴, S. Choudhury²⁵, P. Mal, K. Mandal, A. Nayak²⁶, D. K. Sahoo²³, N. Sahoo, S. K. Swain

Panjab University, Chandigarh, India

S. Bansal, S. B. Beri, V. Bhatnagar, U. Bhawandeep, R. Chawla, A. K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J. B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, A. Bhardwaj, B. C. Choudhary, R. B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P. K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A. K. Mohanty¹⁶, P. K. Netrakanti, L. M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G. B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, R. K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁴, G. Majumder, K. Mazumdar, T. Sarkar²⁴, N. Wickramage²⁷

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kotheekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani²⁸, E. Eskandari Tadavani, S. M. Etesami²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁹, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, C. Caputo^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b}, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,16}, R. Venditti^{a,b}, P. Verwilligen^a

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a, C. Battilana, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F. R. Cavallo^a, S. S. Chhibra^{a,b}, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G. M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F. L. Navarria^{a,b}, A. Perrotta^a, A. M. Rossi^{a,b}, T. Rovelli^{a,b}, G. P. Siroli^{a,b}, N. Tosi^{a,b,16}

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Albergo^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,31}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,16}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶

INFN Sezione di Genova^a, Università di Genova^b, Genoa, Italy

V. Calvelli^{a,b}, F. Ferro^a, M. R. Monge^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milan, Italy

L. Brianza^{a,b,16}, F. Brivio^{a,b}, V. Ciriolo, M. E. Dinardo^{a,b}, S. Fiorendi^{a,b,16}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R. A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy, Università della Basilicata^c, Potenza, Italy, Università G. Marconi^d, Rome, Italy

S. Buontempo^a, N. Cavallo^{a,c}, G. De Nardo, S. Di Guida^{a,d,16}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A. O. M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen^a

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy, Università di Trento^c, Trento, Italy

P. Azzi^{a,16}, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A. T. Meneguzzo^{a,b}, J. Pazzini^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

A. Braghieri^a, F. Fallavollita^{a,b}, A. Magnani^{a,b}, P. Montagna^{a,b}, S. P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

L. Alunni Solestizi^{a,b}, G. M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Saha^a, A. Santocchia^{a,b}

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy

K. Androsov^{a,31}, P. Azzurri^{a,16}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, R. Castaldi^a, M. A. Ciocci^{a,31}, R. Dell'Orso^a, S. Donato^{a,c}, G. Fedi, A. Giassi^a, M. T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,32}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P. G. Verdini^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Rome, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, D. Del Re^{a,b,16}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

INFN Sezione di Torino^a, Università di Torino^b, Turin, Italy, Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c,16}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b,16}, N. Demaria^a, L. Finco^{a,b}, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M. M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G. L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

Kyungpook National University, Taegu, Korea

D. H. Kim, G. N. Kim, M. S. Kim, S. Lee, S. W. Lee, Y. D. Oh, S. Sekmen, D. C. Son, Y. C. Yang

Chonbuk National University, Chonju, Korea

A. Lee

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim

Hanyang University, Seoul, Korea

J. A. Brochero Cifuentes, T. J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

Seoul National University, Seoul, Korea

J. Almond, J. Kim, H. Lee, S. B. Oh, B. C. Radburn-Smith, S. h. Seo, U. K. Yang, H. D. Yoo, G. B. Yu

University of Seoul, Seoul, Korea

M. Choi, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park, G. Ryu, M. S. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, MalaysiaI. Ahmed, Z. A. Ibrahim, M. A. B. Md Ali³³, F. Mohamad Idris³⁴, W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

S. Carpinteyro, I. Pedraza, H. A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P. H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, Q. Hassan, H. R. Hoorani, W. A. Khan, A. Saddique, M. A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, PolandK. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak**Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal**

P. Bargassa, C. Beirão Da Cruz E. Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M. V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucchio, J. Varela

Joint Institute for Nuclear Research, Dubna, RussiaS. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{37,38}, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin**Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg, Russia**L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, RussiaT. Aushev, A. Bylinkin³⁸

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, RussiaM. Danilov⁴¹, S. Polikarpov, E. Tarkovskii**P.N. Lebedev Physical Institute, Moscow, Russia**V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan, A. Leonidov³⁸, A. Terkulov**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, L. Khein, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, RussiaV. Blinov⁴², Y. Skovpen⁴², D. Shtol⁴²**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, SerbiaP. Adzic⁴³, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M. S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J. F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J. M. Vizán García

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I. J. Cabrillo, A. Calderon, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, SwitzerlandD. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A. H. Ball, D. Barney, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco⁴⁴, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁶, M. J. Kortelainen, K. Kousouris, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M. T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁵, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, H. Sakulin, J. B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas⁴⁷, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁸, G. I. Veres²¹, M. Verweij, N. Wardle, H. K. Wöhri, A. Zagozdinska³⁶, W. D. Zeuner**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

ETH Zurich-Institute for Particle Physics, and Astrophysics (IPA), Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M. T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzini, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov⁴⁹, V. R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland

T. K. Aarrestad, C. Amsler⁵⁰, L. Caminada, M. F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, T. H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C. M. Kuo, W. Lin, A. Pozdnyakov, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, P. Chang, Y. H. Chang, Y. Chao, K. F. Chen, P. H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y. F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J. f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Çukurova University Physics Department, Science and Art Faculty, Adana, Turkey

A. Adiguzel, S. Cerci⁵¹, S. Damarseckin, Z. S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵², E. E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁴, K. Ozdemir⁵⁵, D. Sunar Cerci⁵¹, H. Topakli⁵⁶, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, S. Bilmis, B. Isildak⁵⁷, G. Karapinar⁵⁸, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, E. A. Yetkin⁶¹, T. Yetkin⁶²

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen⁶³

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk, P. Sorokin

University of Bristol, Bristol, UK

R. Aggleton, F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G. P. Heath, H. F. Heath, J. Jacob, L. Kreczko, C. Lucas, D. M. Newbold⁶⁴, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V. J. Smith

Rutherford Appleton Laboratory, Didcot, UK

K. W. Bell, A. Belyaev⁶⁵, C. Brew, R. M. Brown, L. Calligaris, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams

Imperial College, London, UK

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas⁶⁴, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko⁴⁹, J. Pela, B. Penning, M. Pesaresi, D. M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁶, T. Virdee¹⁶, J. Wright, S. C. Zenz

Brunel University, Uxbridge, UK

J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, I. D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S. I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J. M. Hogan, O. Jesus, K. H. M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

University of California, Davis, Davis, USA

R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi

University of California, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O. R. Long, M. Olmedo Negrete, M. I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J. G. Branson, G. B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁷, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara-Department of Physics, Santa Barbara, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S. D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, J. Bendavid, A. Bornheim, J. Bunn, J. Duarte, J. M. Lawhorn, A. Mott, H. B. Newman, C. Pena, M. Spiropulu, J. R. Vlimant, S. Xie, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M. B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J. P. Cumalat, W. T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S. R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. McDermott, N. Mirman, G. Nicolas Kaufman, J. R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S. M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, G. Apollinari, A. Apresyan, S. Banerjee, L. A. T. Bauerdick, A. Beretvas, J. Berryhill, P. C. Bhat, G. Bolla, K. Burkett, J. N. Butler, H. W. K. Cheung, F. Chlebana, S. Cihangir[†], M. Cremonesi, V. D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre,

D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J. M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck, Y. Wu

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R. D. Field, I. K. Furic, J. Konigsberg, A. Korytov, J. F. Low, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutka, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

S. Linn, P. Markowitz, G. Martinez, J. L. Rodriguez

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Bein, S. Hagopian, V. Hagopian, K. F. Johnson, T. Kolberg, T. Perry, H. Prosper, A. Santra, R. Yohay

Florida Institute of Technology, Melbourne, USA

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, I. Bucinskaite, R. Cavanaugh, X. Chen, O. Evdokimov, L. Gauthier, C. E. Gerber, D. J. Hofman, K. Jung, I. D. Sandoval Gonzalez, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA

B. Bilki⁶⁸, W. Clarida, K. Dilsiz, S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁹, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, L. Forthomme, R. P. Kenny III, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J. D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L. K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S. C. Eno, C. Ferraioli, J. A. Gomez, N. J. Hadley, S. Jabeen, G. Y. Jeng, R. G. Kellogg, J. Kunkle, A. C. Mignerey, F. Ricci-Tam, Y. H. Shin, A. Skuja, M. B. Tonjes, S. C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, A. Apyan, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I. A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G. M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y. S. Lai, Y.-J. Lee, A. Levin, P. D. Luckey, B. Maier, A. C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G. S. F. Stephans, K. Tatar, D. Velicanu, J. Wang, T. W. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA

A. C. Benvenuti, R. M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, S. C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D. R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, J. Monroy, J. E. Siado, G. R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, D. Nguyen, A. Parker, S. Rappoccio, B. Roobahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D. M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K. A. Hahn, A. Kumar, N. Mucia, N. Odell, B. Pollack, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, N. Rupprecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B. L. Winer, H. W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik

Purdue University, West Lafayette, USA

A. Barker, V. E. Barnes, S. Folgueras, L. Gutay, M. K. Jha, M. Jones, A. W. Jung, A. Khatiwada, D. H. Miller, N. Neumeister, J. F. Schulte, X. Shi, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, B. Akgun, Z. Chen, K. M. Ecklund, F. J. M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B. P. Padley, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K. H. Lo, P. Tan, M. Verzetti

The Rockefeller University, New York, USA

R. Ciesielski

Rutgers, The State University of New Jersey, Piscataway, USA

A. Agapitos, J. P. Chou, Y. Gershtein, T. A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A. G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon⁷², R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K. A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, C. Dragoiu, P. R. Duderø, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S. W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

M. W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P. E. Karchin, J. Sturdy, S. Zaleski

University of Wisconsin-Madison, Madison, WI, USA

D. A. Belknap, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G. A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W. H. Smith, D. Taylor, N. Woods

† Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- 3: Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
- 4: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 8: Also at Universidad de Antioquia, Medellin, Colombia
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Now at British University in Egypt, Cairo, Egypt
- 11: Now at Cairo University, Cairo, Egypt
- 12: Also at Zewail City of Science and Technology, Zewail, Egypt
- 13: Also at Université de Haute Alsace, Mulhouse, France
- 14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 15: Also at Tbilisi State University, Tbilisi, Georgia
- 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 18: Also at University of Hamburg, Hamburg, Germany
- 19: Also at Brandenburg University of Technology, Cottbus, Germany
- 20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 24: Also at University of Visva-Bharati, Santiniketan, India
- 25: Also at Indian Institute of Science Education and Research, Bhopal, India
- 26: Also at Institute of Physics, Bhubaneswar, India
- 27: Also at University of Ruhuna, Matara, Sri Lanka
- 28: Also at Isfahan University of Technology, Isfahan, Iran
- 29: Also at Yazd University, Yazd, Iran
- 30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 31: Also at Università degli Studi di Siena, Siena, Italy

- 32: Also at Purdue University, West Lafayette, USA
- 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 44: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
- 45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 46: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 47: Also at National and Kapodistrian University of Athens, Athens, Greece
- 48: Also at Riga Technical University, Riga, Latvia
- 49: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 50: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 51: Also at Adiyaman University, Adiyaman, Turkey
- 52: Also at Istanbul Aydin University, Istanbul, Turkey
- 53: Also at Mersin University, Mersin, Turkey
- 54: Also at Cag University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Gaziosmanpasa University, Tokat, Turkey
- 57: Also at Ozyegin University, Istanbul, Turkey
- 58: Also at Izmir Institute of Technology, Izmir, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Yildiz Technical University, Istanbul, Turkey
- 63: Also at Hacettepe University, Ankara, Turkey
- 64: Also at Rutherford Appleton Laboratory, Didcot, UK
- 65: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
- 66: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 67: Also at Utah Valley University, Orem, USA
- 68: Also at Argonne National Laboratory, Argonne, USA
- 69: Also at Erzincan University, Erzincan, Turkey
- 70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 71: Also at Texas A&M University at Qatar, Doha, Qatar
- 72: Also at Kyungpook National University, Taegu, Korea