EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2015-309
2016/09/09

CMS-FSQ-12-002

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

The CMS Collaboration*

Abstract

The decorrelation in the azimuthal angle between the most forward and the most backward jets (Mueller–Navelet jets) is measured in data collected in pp collisions with the CMS detector at the LHC at $\sqrt{s} = 7\,\text{TeV}$. The measurement is presented in the form of distributions of azimuthal-angle differences, $\Delta\phi$, between the Mueller–Navelet jets, the average cosines of $(\pi - \Delta\phi)$, $2(\pi - \Delta\phi)$, and $3(\pi - \Delta\phi)$, and ratios of these cosines. The jets are required to have transverse momenta, p_{T}, in excess of 35 GeV and rapidities, $|y|$, of less than 4.7. The results are presented as a function of the rapidity separation, Δy, between the Mueller–Navelet jets, reaching Δy up to 9.4 for the first time. The results are compared to predictions of various Monte Carlo event generators and to analytical predictions based on the DGLAP and BFKL parton evolution schemes.

Published in the Journal of High Energy Physics as doi:10.1007/JHEP08(2016)139.

*See Appendix A for the list of collaboration members

1 Introduction

Quantum chromodynamics (QCD), the theory of strong interactions, has been successfully tested in hard processes in high-energy particle collisions. Perturbative QCD calculations performed within the framework of collinear factorisation using the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) parton evolution scheme [1–5] have been found to describe many measurements well.

An appropriate tool for QCD studies are hadronic jets—collimated bunches of hadrons, which are the visible manifestations of the energetic partons emerging from the underlying processes. At leading order in the strong coupling α_S, QCD predicts the production of two partons back-to-back in the azimuthal plane and consequently—even after parton showering and hadronisation—the appearance of two jets with a strong correlation in their azimuthal angle. A deviation from the back-to-back configuration and a weakening of the correlation, namely a decorrelation, occurs if higher-order processes are considered and more partons appear in the final state.

At high centre-of-mass energies, $\sqrt{s} \to \infty$, a kinematical domain can be reached where semi-hard parton interactions with transverse momenta $p_T \ll \sqrt{s}/2$ play a substantial role. This asymptotic domain is more appropriately described by the Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equation [6–8] than by the DGLAP approach. In pp collisions, such a regime can be experimentally approached by requiring two low-p_T jets that are widely separated in rapidity, y [9]—a scenario for which BFKL, in contrast to DGLAP, predicts a strong rise of the inclusive dijet cross section with increasing rapidity separation. In a kinematic region where semi-hard parton interactions are important, the azimuthal decorrelation will increase with increasing $\Delta y = |y_1 - y_2|$ between the jets [10, 11], where y_1 and y_2 are rapidities of the most forward and the most backward jets (Mueller-Navelet jets, MN) [9]. The large LHC centre-of-mass energy, and the large pseudorapidity coverage of the detectors, allows multijet production to be explored in a region of Δy that was previously kinematically inaccessible. The BFKL approach was derived in the infinite-energy limit using the leading-logarithm (LL) approximation. At finite energy, the BFKL approach can be significantly improved using the next-to-leading-logarithm (NLL) approximation [12–15], which incorporates further elements like energy-momentum conservation and correlations at small rapidities.

Earlier searches for BFKL signatures in hadron-hadron collisions using events with jets widely separated in rapidity were made at the Tevatron by D0 [16, 17]. The D0 measurements of azimuthal decorrelation were restricted to a pseudorapidity separation $\Delta\eta < 6$, where $\eta = -\log[\tan(\theta/2)]$ and θ is the polar angle relative to the beam direction. No significant indications of BFKL effects were found [16]. Studies [17] have revealed a strong dependence of the dijet production cross section at large rapidity separation on the collision energy. At the LHC, such measurements can be performed at much higher collision energies and with larger rapidity separation between the jets, thus enhancing the possibility to observe BFKL signatures in the data.

Both ATLAS [18] and CMS [19] have published measurements of dijet production in pp collisions at 7 TeV as a function of the rapidity separation between the two jets, and these measurements do not show evidence for BFKL signatures in events with jets with $p_T > 35$ GeV.

Although theoretical arguments support the idea that azimuthal decorrelation observables have greater sensitivity to BFKL effects [20], an earlier ATLAS measurement [21] between leading and subleading jets with $p_T > 60$ GeV and $p_T > 50$ GeV and $\Delta y < 8$ did not indicate any deviation from DGLAP predictions. However, the analysis of MN dijets with $p_T > 35$ GeV and

$\Delta y < 9.4$ presented in this paper should be more sensitive to BFKL effects, given the lower jet p_{T} thresholds and the wider dijet rapidity separation considered. Studies of jets with large rapidity separation require data collected at low instantaneous luminosity to avoid contamination from jets produced in different overlapping pp collisions [19]. In this paper, observables connected to the azimuthal decorrelation of MN dijets are presented that use a data sample corresponding to an integrated luminosity of $\approx$41 pb^{-1} collected during proton-proton running at $\sqrt{s} = 7$ TeV in the year 2010.

2 Physics motivation and Monte Carlo event generators

The normalised cross section as a function of the azimuthal-angle difference ($\Delta\phi$) between MN jets with $p_{\mathrm{T}} > p_{\mathrm{Tmin}}$ can be written as a Fourier series [10, 11]:

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

The Fourier coefficients C_n are equal to the average cosines of the decorrelation angle, $(\pi - \Delta\phi)$: $C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle\cos(n(\pi - \Delta\phi))\rangle$, where $\Delta\phi = \phi_1 - \phi_2$ is the difference between the azimuthal angles ϕ_1 and ϕ_2 of the MN jets.

If there are only two jets in the final state, they have to be approximately back-to-back in the azimuthal plane ($\Delta\phi = \pi$) and the average cosines equal unity: $\langle\cos(n(\pi - \Delta\phi))\rangle = 1$. Due to parton radiation, the $(\pi - \Delta\phi)$ distribution has a non-zero width that is determined by Fourier harmonics involving $\langle\cos(n(\pi - \Delta\phi))\rangle$. In the BFKL approach, an increasing rapidity interval between the MN jets leads to an increased number of emitted partons and thus to an increased azimuthal decorrelation: $\langle\cos(n(\pi - \Delta\phi))\rangle < 1$. In the DGLAP picture within the LL approximation, in contrast, the partons emitted between the MN jets have much lower p_{T} than the latter, and their emission does not depend on their rapidity separation. Hence, parton emissions from the parton cascade can change the azimuth of the parent partons to a much lesser extent than in the BFKL approach where the p_{T} of mother and daughter partons can be very similar. However, when the MN jets are not the jets with the highest p_{T}, then even in the DGLAP picture a significant decorrelation might be observed.

In this paper the average cosines of the azimuthal angle between MN jets, $(\pi - \Delta\phi)$, $2(\pi - \Delta\phi)$, and $3(\pi - \Delta\phi)$ (i.e. C_1, C_2, and C_3) are measured as functions of the rapidity separation, Δy, as suggested in Refs. [10, 11, 20, 22–25]. In addition, the ratios of the average cosines C_2/C_1 and C_3/C_2 are measured, as proposed in Refs. [20, 23–25]. To cover all available Δy space, $\Delta\phi$ distributions are measured in three bins of rapidity separation: $\Delta y < 3.0$, $3.0 < \Delta y < 6.0$, and $6.0 < \Delta y < 9.4$. The average cosines may be expressed explicitly using conformal symmetries of the BFKL evolution equation [14], which are absent in the DGLAP evolution equation. Moreover, since one expects a suppression of DGLAP contributions in the two ratios [23], they are particularly sensitive to manifestations of BFKL effects. In addition, uncertainties related to the factorisation and renormalisation scales are reduced in the ratios [26].

The measurements are performed with the CMS detector, using proton-proton collision data recorded at $\sqrt{s} = 7$ TeV for jets with $p_{\mathrm{T}} > 35$ GeV and $|y| < 4.7$, allowing a rapidity separation between the MN jets of up to $\Delta y = 9.4$. The jets are reconstructed with the anti-k_{T} algorithm [27, 28] with a distance parameter $R = 0.5$.

The measured jet observables, corrected to the stable-particle level (lifetime $c\tau > 1$ cm), are compared to predictions from various Monte Carlo (MC) event generators which extend the

DGLAP approach by including LL soft and collinear radiation in their parton-shower modelling: PYTHIA 6 (version 6.422) [29] tune Z2 [30], HERWIG++ (version 2.5.1) tune UE-7000-EE-3 [31], and PYTHIA 8 (version 8.145) [32] tune 4C [33]. In the mentioned generators, different models are used for the simulation of multiparton interactions and hadronisation. The parameters of multiparton interactions in these tunes are adjusted to best describe LHC data. The MC generator POWHEG [34–36]—using the CTEQ6M parton distribution function [37], and interfaced with PYTHIA 6 and 8—is used to investigate the sensitivity of the measured jet observables to the contribution of next-to-leading-order (NLO) terms. The measurements are also compared to the DGLAP-based MC generator SHERPA 1.4 [38], which uses tree-level matrix elements for $2 \to 2 + n$-jets (with $n = 0, 1, 2$ in this work) matched to LL parton showers. Finally, data-theory comparisons are also performed using the analytical NLL BFKL predictions as obtained in Ref. [39] at parton level, as well as with predictions obtained from the HEJ+ARIADNE generator package (version 0.99b) [40]. The latter consists of HEJ version 1.3.2 [41], which is based on LL BFKL matrix elements, and the hadronisation and parton-shower package of ARIADNE 4.12 [42].

3 The CMS detector

The most relevant component of the CMS detector [43] for this analysis is the calorimeter system, which covers the pseudorapidity range $|\eta| < 5.2$. The crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL) extend to $|\eta| = 3.0$. The HCAL cells map to an array of ECAL crystals to form calorimeter towers projecting radially outwards from the nominal interaction point. The pseudorapidity region $3.0 < |\eta| < 5.2$ is covered by the hadronic forward (HF) calorimeter, which consists of steel absorber wedges with embedded radiation-hard quartz fibres, oriented parallel to the beam direction. The calorimeter towers in the barrel region have a segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, becoming progressively larger in the endcap and forward regions ($\Delta\eta \times \Delta\phi = 0.175 \times 0.175$ at $\eta \approx 4.5$).

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 and is, like ECAL and HCAL, located in the 3.8 T field of the superconducting solenoid. It provides an impact parameter resolution of 50–175 μm [44], and thus, precise interaction vertex reconstruction using charged particle tracks within its acceptance.

The CMS trigger system consists of a hardware level-1 trigger and a software high-level trigger. Jets formed online by the trigger system use ECAL, HCAL, and HF inputs for energy clustering and are not corrected for the jet energy response.

4 Event selection

Dijet events with a large rapidity separation are rare. Therefore, in addition to the standard single-jet trigger that selects events containing at least one jet with raw $p_{\mathrm{T}} > 15\,\mathrm{GeV}$, a dedicated trigger for forward-backward dijets was implemented that selects events with two jets in opposite hemispheres, each with $|\eta| > 3.0$ and jet raw $p_{\mathrm{T}} > 15\,\mathrm{GeV}$. In order to keep the rate of the single-jet trigger within the allocated bandwidth, a prescale factor of $\approx 10^3$ was used, and an effective integrated luminosity of $\approx 33\,\mathrm{nb}^{-1}$ is recorded with it. The forward-backward trigger was operated with a moderate prescale factor of ≈ 8, recording an effective integrated luminosity of $\approx 5\,\mathrm{pb}^{-1}$, resulting in the collection of a sample of large Δy dijet events ($\Delta y > 6$), 100 times larger than that collected with the single-jet trigger alone.

The single-jet trigger efficiency is measured by means of a control sample selected with the minimum-bias trigger, which maximises the data collection efficiency while maintaining a low background level [45]. The single-jet trigger is measured to be 99.5% efficient for events containing dijets with $p_T > 35\,\text{GeV}$ and is used for the determination of the efficiency of the forward-backward dijet trigger. The latter is measured to be 100% efficient for dijets with $p_T > 35\,\text{GeV}$.

Jets are reconstructed offline using the energy depositions in the calorimeter towers. In the reconstruction process, the contribution from each tower is assigned a momentum. The magnitude and the direction of the momentum are given by the energy measured in the tower and the coordinates of the tower, respectively. The raw jet energy is obtained from the sum of the tower energies, while the raw jet momentum is calculated from the vectorial sum of the tower momenta. The raw jet energies are then corrected to establish a uniform relative response of the calorimeter in η and a calibrated absolute response in p_T [46]. The jet energy resolution (JER) for calorimeter jets with $p_T \approx 35\,\text{GeV}$ is about 22% for $|\eta| < 0.5$ and about 10% for $4 < |\eta| < 4.5$ [47]. The uncertainty on the jet energy calibration for jets with $p_T \approx 35\,\text{GeV}$ depends on η and is $\approx$7–8% [46].

In order to reduce the sensitivity to overlapping pp collisions within a single bunch crossing (so-called "pileup" events), only events with exactly one reconstructed pp primary vertex within the luminous region are used for the measurement. This selection leads to about 30% events lost, whereas without this selection the average number of pileup interactions over analysed data was $\approx$2.2 [48]. The primary vertex is required to be reconstructed within $\pm$24 cm of the nominal interaction point along the beamline [49].

Loose jet quality requirements [50] are applied to suppress the effect of calorimeter noise. Events with at least two jets with $p_T > 35\,\text{GeV}$ and $|y| < 4.7$ are selected, and only jets satisfying these criteria are used for the analysis.

Mueller–Navelet jet pairs are constructed from jets passing the above criteria. The azimuthal-angle difference $\Delta\phi$ between the two jets is measured in the range $0 < \Delta\phi < \pi$ for three bins of rapidity separation between the MN jets: $\Delta y < 3.0$, $3.0 < \Delta y < 6.0$, and $6.0 < \Delta y < 9.4$, normalised to unity integral. The average cosines C_1, C_2, and C_3 are measured in bins of Δy up to 9.4. The cosine ratios C_3/C_2 and C_2/C_1 are calculated as ratios of average cosines for each bin in Δy.

5 Corrections for detector effects

The finite jet p_T resolution results in jet p_T values at the detector level that deviate from those at stable-particle level. Due to the steep slope of the p_T spectrum, jets with smaller p_T may migrate to higher p_T and thus increase the number of jets in distributions at the detector level. The finite jet η resolution and measurement offset lead to a finite Δy resolution and offset, such that dijets may migrate from one Δy bin to another. Similarly, distributions in $\Delta\phi$ are affected by the finite ϕ resolution.

These effects are mitigated using corrections derived with a hybrid method. This method comprises both a multiplicative correction designed to compensate migrations in the jet p_T space and a full unfolding in the (Δy, $\Delta\phi$) space. The migration of jets into and out of the analysed phase space leads to the selection of different dijets at detector and stable-particle level, which is accounted for as a non-negligible background and a limited detection efficiency. Bin-wise multiplicative corrections for background and efficiency are derived from MC simulation and applied to the distributions before and after correction for inter-bin migrations, respectively. The associated purity is always larger than 91%. To account for inter-bin migrations, the $\Delta\phi$ distributions are unfolded with an iterative procedure [51] in each of the three analysed Δy bins. Probabilities for inter-bin migration were calculated for all $\Delta\phi$ bins in all three Δy ranges, and they were found to always be less than 20%. The same unfolding procedure is applied to the 2-dimensional (Δy, $\Delta\phi$) distributions for the calculation of $\langle\cos(n(\pi - \Delta\phi))\rangle$ at the stable-particle level. The correction factors associated with the hybrid method were found to be 0.6–1.1 for the $\Delta\phi$ distributions and 0.9–1.05 for $\langle\cos(n(\pi - \Delta\phi))\rangle$.

The corrections are calculated from the simulated events generated with PYTHIA 6 (version 6.422, Z2 tune) and HERWIG++ (version 2.4.1, default tune). These events are passed through the full CMS detector simulation based on GEANT4 [52]. The averages of the corrected values obtained using PYTHIA 6 and HERWIG++ are taken as the final, corrected values of the observables. The hybrid unfolding procedure is tested by comparing the MC prediction at the stable-particle level with the distribution corrected from detector level to stable-particle level. Closure tests, where distributions generated with PYTHIA 6 (HERWIG++) are unfolded with a response matrix obtained from PYTHIA 6 (HERWIG++), show differences of less than 1%. Cross-closure tests, i.e. unfolding PYTHIA 6 distributions with a response matrix from HERWIG++ and vice versa, show differences of less than 7%, which is much smaller than the differences between the stable-particle distributions predicted by both models.

In Ref. [46] it was shown that the jet energy resolution (JER) for calorimeter jets in the simulation is 6.5–14.9% better than the one found in data. To correct for this discrepancy, an additional smearing was applied to detector-level jets in the MC simulation.

6 Experimental uncertainties

The systematic uncertainties of the measurement are evaluated in the following way:

– To calculate the effect of the jet energy scale (JES) uncertainty, the p_T values of the jets are varied by p_T-dependent and η-dependent values [46]. Observables were then recalculated twice—with the p_T values varied up and down—and the difference between the results defines the uncertainty of the observable associated with JES.

– The JER obtained in MC simulations differs from that observed in data [46] (as discussed at the end of Section 5), while the uncertainty of the discrepancy varies between 7.6% and 23.7%, depending on η. The impact of this uncertainty is assessed by varying, in the MC simulation, the amount of p_T smearing on detector-level jets. The difference between the results again defines the uncertainty.

– The sensitivity of the measurement to pileup is investigated using collision data. In the analysis the number of primary vertices per event is required to be equal to 1. However, as the primary vertex reconstruction is not 100% efficient, a residual dependence of observables on pileup may be present. The available data are divided into two sets corresponding to different instantaneous bunch luminosities. In one set, the average number of pp interactions was restricted to be less than two, while in the other set more than two pp interactions in average were required. The observables obtained from each set are compared, and no dependence on the instantaneous bunch luminosity is found.

– The uncertainty of data correction to the stable-particle level (see Section 5) is determined from PYTHIA 6 and HERWIG++. The difference between the corrections obtained with the two different MC generators is taken as the systematic uncertainty for the model dependence, and it never exceeds 6.4% together with the uncertainty due to limited MC statistics being added in quadrature.

– In order to estimate the impact of the imprecise modelling of the angular resolution for jets in the MC simulation, an extra smearing is applied to the difference between the jets' azimuthal separation at the detector level and at the stable-particle level. This difference is varied by ±10% [47], which is a conservative estimation of the real smearing, and the same procedure is performed for the η difference. The resulting change in the measurements turns out to be negligible and is not included in the systematic uncertainty.

The total systematic uncertainty of the measurement is obtained by quadratically summing the individual experimental uncertainties listed above. The individual contributions to the total uncertainty are summarised in Table 1, together with the statistical uncertainties. The ranges correspond to the variation of the uncertainty with $\Delta\phi$ or with Δy, and for asymmetric uncertainties the upper and lower limits are shown.

Table 1: Systematic and statistical uncertainties (%) of the observables measured in this work.

Observable	JES	JER	Corrections	Total systematic	Statistical
$\Delta\phi(\lvert\Delta y\rvert < 3.0)$	$+(2.3-13.7)$ $-(3.0-10.2)$	$+(0.1-10.6)$ $-(0.4-7.6)$	0.1–2.0	$+(2.3-17.4)$ $-(3.0-12.7)$	0.3–5.1
$\Delta\phi(3.0 < \lvert\Delta y\rvert < 6.0)$	$+(2.5-16.4)$ $-(2.9-10.8)$	$+(0.7-6.2)$ $-(0.8-3.4)$	0.4–2.3	$+(3.0-17.5)$ $-(3.1-11.3)$	0.9–6.2
$\Delta\phi(6.0 < \lvert\Delta y\rvert < 9.4)$	$+(2.1-31.5)$ $-(1.9-17.3)$	$+(5.8-17.4)$ $-(2.1-9.7)$	0.4–4.5	$+(6.8-32.6)$ $-(3.6-19.5)$	5.3–22.0
C_1	1.0–5.5	0.6–4.6	0.1–3.2	1.1–6.5	0.2–9.7
C_2	1.8–16.9	1.0–4.0	0.1–4.9	2.3–17.4	0.5–17.7
C_3	2.7–23.8	1.5–15.1	0.1–6.4	3.2–24.6	0.7–23.7
C_2/C_1	0.8–12.5	0.4–5.6	0.1–2.6	1.0–13.1	0.5–19.7
C_3/C_2	0.7–7.1	0.2–7.0	0.03–4.3	0.7–10.6	0.8–28.1

7 Results

The $\Delta\phi$ distributions for MN dijets measured in the three rapidity intervals $\Delta y < 3.0$, $3.0 < \Delta y < 6.0$, and $6.0 < \Delta y < 9.4$ are shown in the left panes of Fig. 1. On the right-hand side of Fig. 1, the predictions are shown normalised to the data.

The systematic uncertainties are shown as a band around the data points. The measurement shows a high level of back-to-back correlation in the $\Delta y < 3.0$ bin (Fig. 1, top row), while the $\Delta\phi$ distributions become less peaked at $\Delta\phi \approx \pi$ when going to larger Δy separation (Fig. 1, centre and bottom rows). This demonstrates that higher-order corrections at larger Δy manifest themselves through additional hard-parton radiation.

In the central rapidity interval $\Delta y < 3.0$ (Fig. 1, top row), the LL DGLAP-based MC generators PYTHIA 6 and HERWIG++ describe the data well, showing some deviation only at low $\Delta\phi$ values. The LL DGLAP-based MC generators PYTHIA 8 and SHERPA, with parton matrix elements matched to LL DGLAP parton showers, exhibit significant deviations from the data beyond the experimental uncertainties at intermediate and large $\Delta\phi$. At intermediate ($3.0 < \Delta y < 6.0$) and large ($6.0 < \Delta y < 9.4$) rapidity separation, PYTHIA 6 and 8 show a significant deviation at small $\Delta\phi$ while the measurements are reasonably well described in the region $\Delta\phi > 1.5$. On the contrary, HERWIG++ and SHERPA show deviations to the measurements in the medium $\Delta\phi$ region, but are close to the data at very small $\Delta\phi$. The HEJ+ARIADNE package overestimates the azimuthal decorrelation at small $\Delta\phi$ at all Δy, though there are a lack of MC data for $6.0 < \Delta y < 9.4$. In Fig. 1 (bottom row) the $\Delta\phi$ distributions are also compared to analytical NLL BFKL calculations at the parton level [39], and this comparison is summarised at the end of Section 7, together with the discussion of the other measured observables.

The measured average cosines, $\langle \cos(n(\pi - \Delta\phi)) \rangle$, are less than unity at $\Delta y = 0$, due to the emission of jets with $p_{\mathrm{T}} < 35\,\mathrm{GeV}$. They decrease with increasing Δy, as shown in Fig. 2, indicating that the decorrelation of jets increases as the phase space opens up for emission of additional jets with $p_{\mathrm{T}} > 35\,\mathrm{GeV}$. At large values of the rapidity separation ($\Delta y \gtrsim 8$), additional emissions are becoming kinematically suppressed due to energy-momentum conservation near the phase space boundary ($\Delta y \approx 10$), resulting in an increase of the average cosines towards unity. In the bin $6 < \Delta y < 7$, a flattening of the average cosines is observed. Despite various checks, no systematic effect could be shown to be responsible for this flattening.

In Fig. 2 (left) the measured average cosines are compared to the predictions obtained from the LL parton shower MC generators PYTHIA 6, HERWIG++, and PYTHIA 8. Also shown are the predictions from the NLO POWHEG generator interfaced with the LL DGLAP generators PYTHIA 6 and PYTHIA 8. In Fig. 2 (right) the measurements are compared to the MC generator SHERPA, to the HEJ+ARIADNE package, and to analytical NLL BFKL calculations at the parton level [39]. The comparisons (Fig. 2) with the various MC predictions can be summarised as follows: PYTHIA 6 and PYTHIA 8 show a slightly stronger decorrelation for the average cosine at large Δy than observed in the data. For $\langle \cos(2(\pi - \Delta\phi)) \rangle$ and $\langle \cos(3(\pi - \Delta\phi)) \rangle$ PYTHIA 6 and PYTHIA 8 show a fair agreement with the data. HERWIG++ shows a satisfactory agreement with the data on the average cosine. For $\langle \cos(2(\pi - \Delta\phi)) \rangle$ and $\langle \cos(3(\pi - \Delta\phi)) \rangle$ HERWIG++ begins to show a stronger decorrelation at large Δy than observed in the data. The NLO generator POWHEG interfaced with the two LL DGLAP generators PYTHIA 6 and PYTHIA 8 does not improve the agreement with the data obtained with the standalone LL DGLAP generators, while SHERPA underestimates the azimuthal decorrelation at large Δy for the measured average cosines. The HEJ+ARIADNE package overestimates the azimuthal decorrelation at large Δy for the measured average cosines.

As mentioned in Section 2, the ratios of cosines are theoretically expected to be more sensitive to BFKL effects than the average cosines and $\Delta\phi$ distributions because of a cancellation of “pure” DGLAP contributions [23] (although the ratios are still sensitive to the detailed implementation of initial and final state parton radiation, parton showering, and colour coherence effects in each of the MCs). The measured ratios C_2/C_1 and C_3/C_2 as a function of Δy are shown in Fig. 3. PYTHIA 6 and PYTHIA 8 underestimate the azimuthal decorrelation for the average cosine ratio C_2/C_1 at large Δy but are consistent with the data for C_3/C_2 within the rather large experimental uncertainties. HERWIG++ overestimates the azimuthal decorrelation for the average cosine ratios C_2/C_1 and C_3/C_2 at large Δy. SHERPA underestimates the azimuthal decorrelation at large Δy for the average cosine ratio C_2/C_1 but is consistent with the data for C_3/C_2 within the experimental uncertainties. The HEJ+ARIADNE package overestimates the azimuthal decorrelation at large Δy for the average cosine ratios C_2/C_1 and C_3/C_2.

The analytical NLL BFKL calculations performed at the parton level [39] agree well with the data for all measured observables within the experimental and theoretical uncertainties. The predictions are based on a full NLL BFKL calculation [26, 53], which is improved by a generalised optimal choice of the renormalisation scale [14, 54], and available for the Δy range from 4.0 to 9.4.

The uncertainties on the NLL BFKL predictions in Fig. 1 (bottom row) and Fig. 2 (right) are obtained by variation of the parameters of the NLL BFKL approximation (renormalisation and

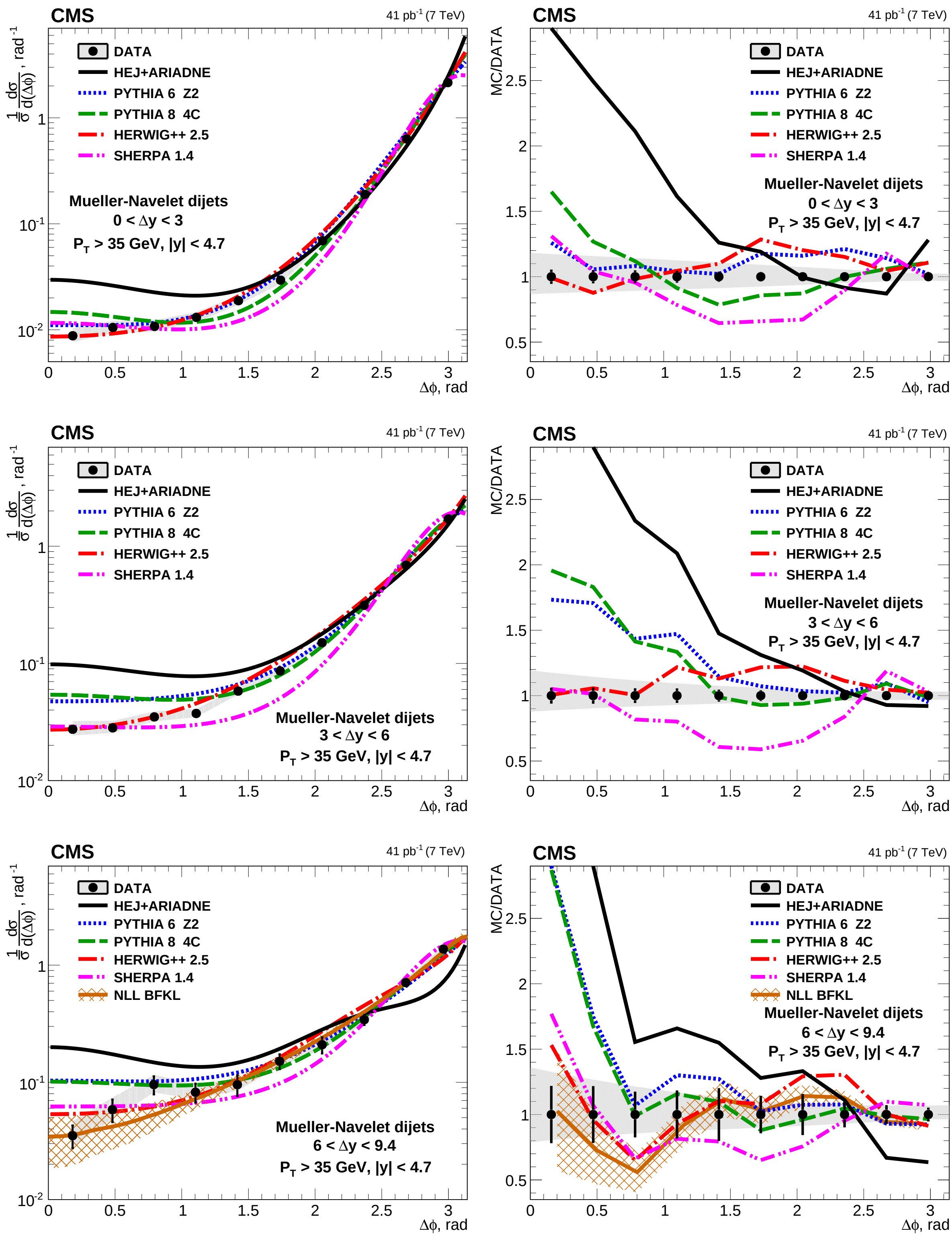

Figure 1: Left: Distributions of the azimuthal-angle difference, $\Delta\phi$, between MN jets in the rapidity intervals $\Delta y < 3.0$ (top row), $3.0 < \Delta y < 6.0$ (centre row), and $6.0 < \Delta y < 9.4$ (bottom row). Right: Ratios of predictions to the data in the corresponding rapidity intervals. The data (points) are plotted with experimental statistical (systematic) uncertainties indicated by the error bars (the shaded band), and compared to predictions from the LL DGLAP-based MC generators PYTHIA 6, PYTHIA 8, HERWIG++, and SHERPA, and to the LL BFKL-motivated MC generator HEJ with hadronisation performed with ARIADNE (solid line).

factorisation scales). Thus, theoretical uncertainties on the NLL BFKL predictions in Fig. 3 (right) consist just of those due to missing higher-order corrections. The NLL BFKL calculation performed by a different group of authors showed worse agreement with these data [55].

The measured data are also compared to predictions of the LL BFKL-motivated MC generator CASCADE 2 [56] (not shown), which is based on the CCFM evolution equation [57], and which shows an even stronger decorrelation than that predicted by the HEJ+ARIADNE package.

Multiparton interactions (MPI) are an additional source of azimuthal decorrelation since they can produce additional jets not correlated with those from the primary interaction. By default, MPI effects are included in the MC generators PYTHIA 6, PYTHIA 8 , HERWIG++, and SHERPA. In order to study the influence of the MPI on the azimuthal decorrelation, the corresponding options in the MC generators are used to disable the MPI modelling. The measurements are then compared with the PYTHIA 8 and HERWIG++ predictions with and without MPI in Figs. 4 and 5, where it can be seen that the average cosines are not sensitive to the details of MPI modelling in PYTHIA 8 and HERWIG++. Other generators show an even smaller spread of predictions with and without MPI.

Another potential source of azimuthal decorrelation is the hadronisation of the produced partons, which can potentially smear out their azimuthal angle. The size of this non-perturbative effect is estimated by a comparison of observables at the parton and stable-particle levels, as obtained with PYTHIA 6. The observed variations in the measured observables do not exceed 10%. It is found that, in general, the size of hadronisation and MPI effects does not significantly exceed the experimental uncertainties, justifying a direct comparison of the analytical NLL BFKL calculations [39] performed at the parton level with the measured observables.

It should be noted that all DGLAP MC generators used in this work incorporate colour-coherence effects (colour dipoles, polar-angle ordering, etc.), which are rapidity-dependent parton radiation effects that complement the DGLAP evolution. Taking these effects into account at small Δy, where $(\alpha_S\,\Delta y)^n$ terms are small (i.e. in the DGLAP domain), leads to an improvement of data description, while at large Δy they yield a worse description of the data. As a matter of fact, different implementations of colour-coherence effects in the DGLAP MC generators result in similar effects at small Δy, but in quite different predictions for the large Δy region for dijet ratios [19] and for the azimuthal decorrelation observables presented here. A better theoretical prediction might be obtained if these Δy dependent contributions are replaced by the complete BFKL calculation at large Δy, where $(\alpha_S\,\Delta y)^n$ terms are large and the BFKL approach is expected to be more reliable.

8 Conclusions

The first measurement of the azimuthal decorrelation of the most-forward and backward jets in the event (called Mueller–Navelet dijets), with rapidity separations up to $\Delta y = 9.4$, is presented for proton-proton collisions at $\sqrt{s} = 7$ TeV. The measured observables include azimuthal-angle distributions, moments of the average cosines of the decorrelation angle, $\langle \cos(n(\pi - \Delta\phi)) \rangle$ for $n = 1, 2, 3$, as well as ratios of the average cosines, as a function of the rapidity separation Δy between the MN jets.

The predictions of the DGLAP-based MC generator HERWIG++ 2.5, improved with leading-log (LL) parton showers and colour-coherence effects, exhibit satisfactory agreement with the data for all measured observables. Other MC generators of this type, such as PYTHIA 6 Z2, PYTHIA 8 4C, and SHERPA 1.4, provide a less accurate description of all measurements.

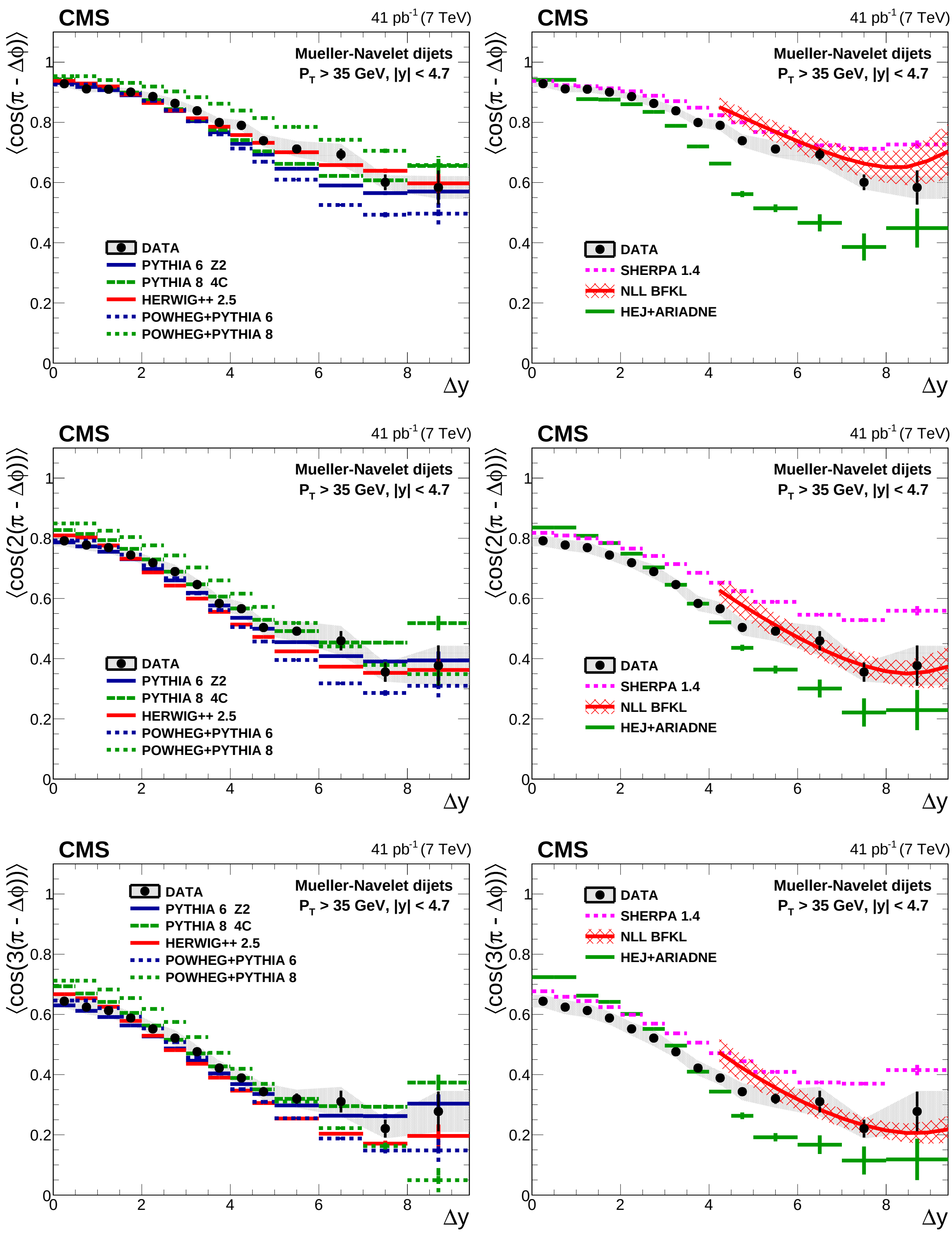

Figure 2: Left: Average $\langle \cos(n(\pi - \Delta\phi)) \rangle (n = 1, 2, 3)$ as a function of Δy compared to LL DGLAP MC generators. In addition, the predictions of the NLO generator POWHEG interfaced with the LL DGLAP generators PYTHIA 6 and PYTHIA 8 are shown. Right: Comparison of the data to the MC generator SHERPA with parton matrix elements matched to a LL DGLAP parton shower, to the LL BFKL inspired generator HEJ with hadronisation by ARIADNE, and to analytical NLL BFKL calculations at the parton level ($4.0 < \Delta y < 9.4$).

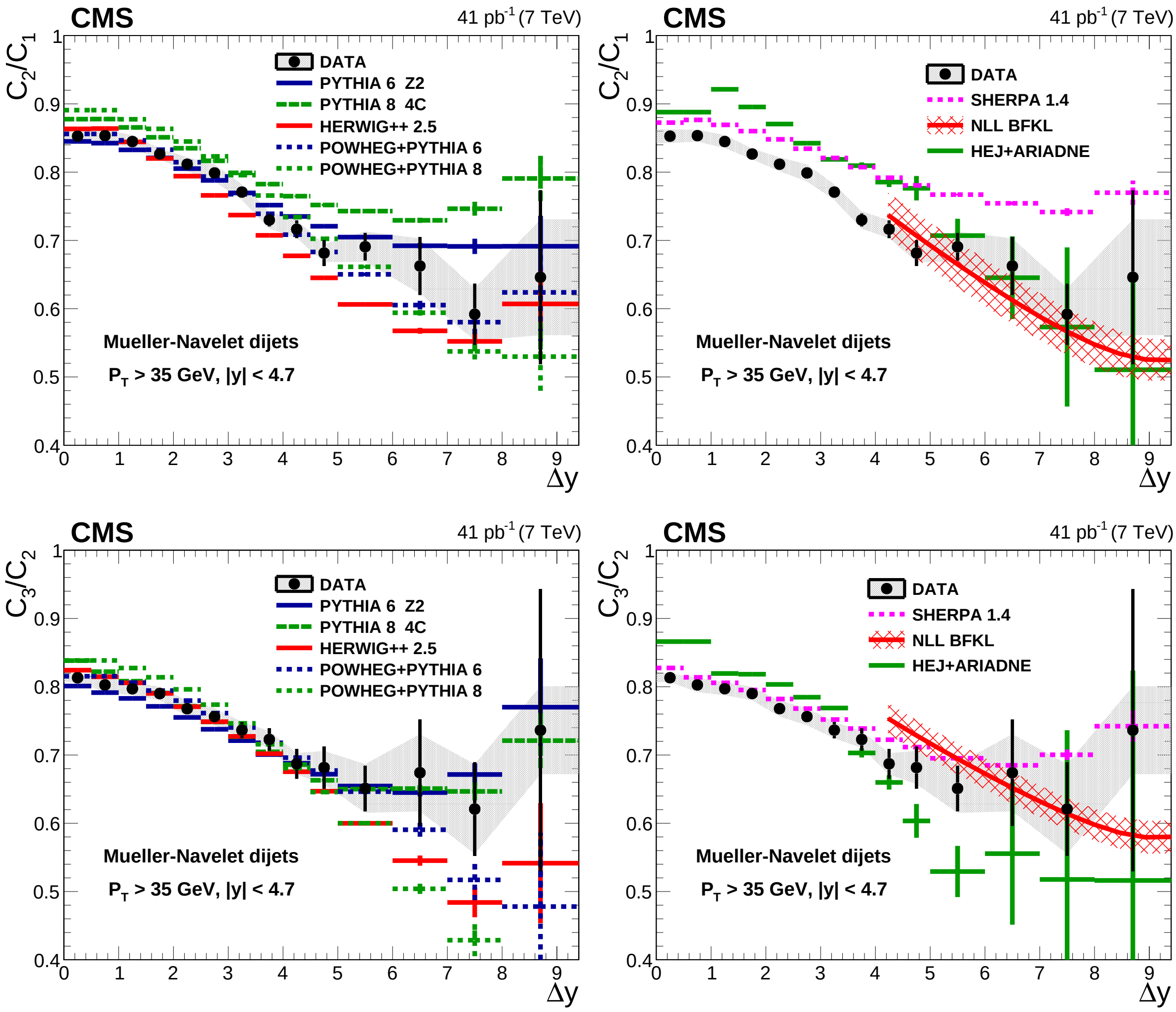

Figure 3: Left: The measured ratios C_2/C_1 (top row) and C_3/C_2 (bottom row) as a function of rapidity difference Δy are compared to LL DGLAP parton shower generators and to the NLO generator POWHEG interfaced with PYTHIA 6 and PYTHIA 8. Right: Comparison of the ratios to the MC generator SHERPA with parton matrix element matched to a LL DGLAP parton shower, to the LL BFKL-inspired generator HEJ with hadronisation by ARIADNE, and to analytical NLL BFKL calculations at the parton level.

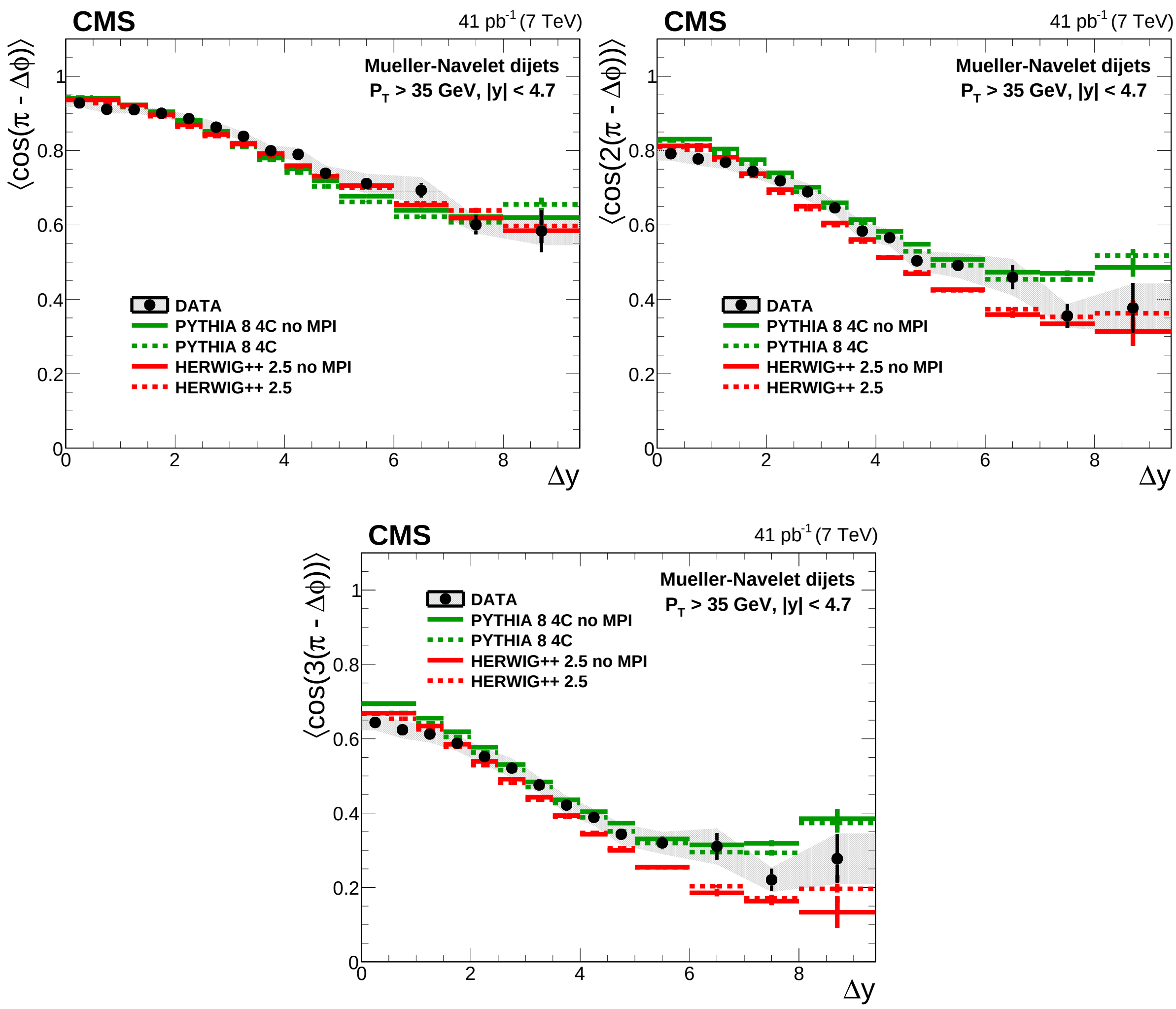

Figure 4: Average $\langle \cos(\pi - \Delta\phi) \rangle$, $\langle \cos 2(\pi - \Delta\phi) \rangle$ and $\langle \cos 3(\pi - \Delta\phi) \rangle$ compared to PYTHIA 6 with and without MPI.

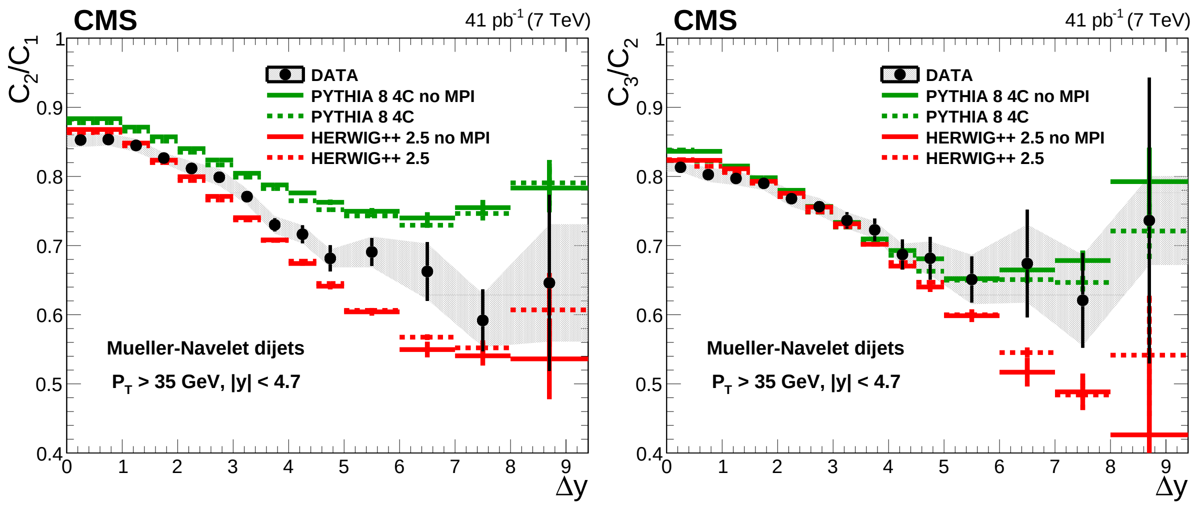

Figure 5: Measured ratios C_2/C_1 (left) and C_3/C_2 (right) compared to PYTHIA 8 with and without MPI.

The MC generator POWHEG, with NLO matrix elements interfaced with the LL parton shower of PYTHIA 6 and PYTHIA 8, does not improve the overall agreement with the data compared to the description provided by PYTHIA 6 and 8 alone.

The MC generator HEJ, based on LL BFKL matrix elements combined with ARIADNE for parton shower and hadronisation, predicts a stronger decorrelation than observed in the data.

An analytical BFKL calculation at next-to-leading logarithmic (NLL) accuracy with an optimised renormalisation scheme and scale, provides a satisfactory description of the data for the measured jet observables at $\Delta y > 4$.

The observed sensitivity to the implementation of the colour-coherence effects in the DGLAP MC generators and the reasonable data-theory agreement shown by the NLL BFKL analytical calculations at large Δy, may be considered as indications that the kinematical domain of the present study lies in between the regions described by the DGLAP and BFKL approaches. Possible manifestations of BFKL signatures are expected to be more pronounced at increasing collision energies.

Acknowledgements

We would like to thank Bertrand Ducloué, Lech Szymanowski, and Samuel Wallon for providing the full NLL BFKL analytical predictions. We also thank Lev Lipatov for useful discussions.

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 centres 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: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and

Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (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 programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

References

[1] V. N. Gribov and L. N. Lipatov, "Deep inelastic ep scattering in perturbation theory", *Sov. J. Nucl. Phys.* **15** (1972) 438.

[2] V. N. Gribov and L. N. Lipatov, "e^+e^- pair annihilation and deep inelastic ep scattering in perturbation theory", *Sov. J. Nucl. Phys.* **15** (1972) 675.

[3] L. N. Lipatov, "The parton model and perturbation theory", *Sov. J. Nucl. Phys.* **20** (1975) 94.

[4] G. Altarelli and G. Parisi, "Asymptotic freedom in parton language", *Nucl. Phys. B* **126** (1977) 298, doi:10.1016/0550-3213(77)90384-4.

[5] 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** (1977) 641.

[6] E. A. Kuraev, L. N. Lipatov and V. S. Fadin, "Multi-reggeon processes in the Yang-Mills theory", *Sov. Phys. JETP* **44** (1976) 443.

[7] E. A. Kuraev, L. N. Lipatov and V. S. Fadin, "The Pomeranchuk singularity in nonabelian gauge theories", *Sov. Phys. JETP* **45** (1977) 199.

[8] I. I. Balitsky and L. N. Lipatov, "The Pomeranchuk singularity in quantum chromodynamics", *Sov. J. Nucl. Phys.* **28** (1978) 822.

[9] A. H. Mueller and H. Navelet, "An inclusive minijet cross-section and the bare pomeron in QCD", *Nucl. Phys. B* **282** (1987) 727, doi:10.1016/0550-3213(87)90705-X.

[10] V. Del Duca and C. R. Schmidt, "Mini-jet corrections to Higgs production", *Phys. Rev. D* **49** (1994) 177, doi:10.1103/PhysRevD.49.177, arXiv:hep-ph/9305346.

[11] W. J. Stirling, "Production of jet pairs at large relative rapidity in hadron hadron collisions as a probe of the perturbative pomeron", *Nucl. Phys. B* **423** (1994) 56, doi:10.1016/0550-3213(94)90565-7, arXiv:hep-ph/9401266.

[12] V. S. Fadin and L. N. Lipatov, "BFKL pomeron in the next-to-leading approximation", *Phys. Lett. B* **429** (1998) 127, doi:10.1016/S0370-2693(98)00473-0, arXiv:hep-ph/9802290.

[13] M. Ciafaloni and G. Camici, "Energy scale(s) and next-to-leading BFKL equation", *Phys. Lett. B* **430** (1998) 349, doi:10.1016/S0370-2693(98)00551-6, arXiv:hep-ph/9803389.

[14] S. J. Brodsky et al., "The QCD pomeron with optimal renormalization", *JETP Lett.* **70** (1999) 155, doi:10.1134/1.568145, arXiv:hep-ph/9901229.

[15] M. Ciafaloni, D. Colferai, and G. P. Salam, "Renormalization group improved small-x equation", *Phys. Rev. D* **60** (1999) 114036, doi:10.1103/PhysRevD.60.114036, arXiv:hep-ph/9905566.

[16] D0 Collaboration, "The azimuthal decorrelation of jets widely separated in rapidity", *Phys. Rev. Lett.* **77** (1996) 595, doi:10.1103/PhysRevLett.77.595, arXiv:hep-ex/9603010.

[17] D0 Collaboration, "Probing BFKL dynamics in the dijet cross section at large rapidity intervals in $p\bar{p}$ collisions at $\sqrt{s} = 1800\,\text{GeV}$ and $630\,\text{GeV}$", *Phys. Rev. Lett.* **84** (2000) 5722, doi:10.1103/PhysRevLett.84.5722, arXiv:hep-ex/9912032.

[18] ATLAS Collaboration, "Measurement of dijet production with a veto on additional central jet activity in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ using the ATLAS detector", *JHEP* **09** (2011) 053, doi:10.1007/JHEP09(2011)053, arXiv:1107.1641.

[19] CMS Collaboration, "Ratios of dijet production cross sections as a function of the absolute difference in rapidity between jets in pp collisions at $\sqrt{s} = 7\,\text{TeV}$", *Eur. Phys. J. C* **72** (2012) 2216, doi:10.1140/epjc/s10052-012-2216-6, arXiv:1204.0696.

[20] A. Sabio Vera and F. Schwennsen, "The azimuthal decorrelation of jets widely separated in rapidity as a test of the BFKL kernel", *Nucl. Phys. B* **776** (2007) 170, doi:10.1016/j.nuclphysb.2007.03.050, arXiv:hep-ph/0702158.

[21] ATLAS Collaboration, "Measurements of jet vetoes and azimuthal decorrelations in dijet events produced in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ using the ATLAS detector", *Eur. Phys. J. C* **74** (2014), no. 11, 3117, doi:10.1140/epjc/s10052-014-3117-7, arXiv:1407.5756.

[22] V. T. Kim and G. B. Pivovarov, "Balitskiĭ-Fadin-Kuraev-Lipatov QCD Pomeron in high energy hadron collisions: Inclusive dijet production", *Phys. Rev. D* **53** (1996) 6, doi:10.1103/PhysRevD.53.R6, arXiv:hep-ph/9506381.

[23] M. Angioni, G. Chachamis, J. D. Madrigal, and A. Sabio Vera, "Dijet production at large rapidity separation in $N = 4$ SYM", *Phys. Rev. Lett.* **107** (2011) 191601, doi:10.1103/PhysRevLett.107.191601, arXiv:hep-th/1106.6172.

[24] D. Colferai, F. Schwennsen, L. Szymanowski, and S. Wallon, "Mueller-Navelet jets at LHC: complete NLL BFKL calculation", *JHEP* **12** (2010) 026, doi:10.1007/JHEP12(2010)026, arXiv:1002.1365.

[25] B. Ducloué, L. Szymanowski, and S. Wallon, "Mueller-Navelet jets at LHC: the first complete NLL BFKL study", in *Sixth International Conference on Quarks and Nuclear Physics*. 2012. arXiv:1208.6111. PoS QNP2012 165.

[26] B. Ducloué, L. Szymanowski, and S. Wallon, "Confronting Mueller–Navelet jets in NLL BFKL with LHC experiments at 7 TeV", *JHEP* **05** (2013) 096, doi:10.1007/JHEP05(2013)096, arXiv:1302.7012.

[27] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[28] M. Cacciari and G. P. Salam, "Dispelling the N^3 myth for the k_t jet-finder", *Phys. Lett. B* **641** (2006) 57, doi:10.1016/j.physletb.2006.08.037, arXiv:hep-ph/0512210.

[29] T. Sjöstrand, S. Mrenna and P. Skands, "PYTHIA 6.4 physics and manual", *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[30] R. Field, "Min-bias and the underlying event at the LHC", in *51st Cracow School of Theoretical Physics*. 2011. arXiv:1110.5530. Acta Phys. Polon. B 42 (2011) 2631.

[31] M. Bähr et al., "Herwig++ physics and manual", *Eur. Phys. J. C* **58** (2008) 639, doi:10.1140/epjc/s10052-008-0798-9, arXiv:0803.0883.

[32] T. Sjöstrand, S. Mrenna, and P. Skands, "A brief introduction to PYTHIA 8.1", *Comput. Phys. Commun.* **178** (2008) 852, `doi:10.1016/j.cpc.2008.01.036`, `arXiv:0710.3820`.

[33] R. Corke and T. Sjöstrand, "Interleaved parton showers and tuning prospects", *JHEP* **03** (2011) 32, `doi:10.1007/JHEP03(2011)032`, `arXiv:1011.1759`.

[34] P. Nason, "A New method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, `doi:10.1088/1126-6708/2004/11/040`, `arXiv:hep-ph/0409146`.

[35] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with Parton Shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, `doi:10.1088/1126-6708/2007/11/070`, `arXiv:0709.2092`.

[36] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", *JHEP* **06** (2010) 043, `doi:10.1007/JHEP06(2010)043`, `arXiv:1002.2581`.

[37] J. Pumplin et al., "New generation of parton distributions with uncertainties from global QCD analysis", *JHEP* **07** (2002) 012, `doi:10.1088/1126-6708/2002/07/012`, `arXiv:hep-ph/0201195`.

[38] T. Gleisberg et al., "Event generation with SHERPA 1.1", *JHEP* **02** (2009) 007, `doi:10.1088/1126-6708/2009/02/007`, `arXiv:0811.4622`.

[39] B. Ducloué, L. Szymanowski, and S. Wallon, "Evidence for high-energy resummation effects in Mueller-Navelet jets at the LHC", *Phys. Rev. Lett.* **112** (2013) 082003, `doi:10.1103/PhysRevLett.112.082003`, `arXiv:1309.3229`.

[40] J. Andersen, L. Lonnblad, and J. Smillie, "A parton shower for high energy jets", *JHEP* **07** (2011) 110, `doi:{10.1007/JHEP07(2011)110}`, `arXiv:1104.1316`.

[41] J. R. Andersen and J. M. Smillie, "Multiple jets at the LHC with high energy jets", *JHEP* **06** (2011) 010, `doi:10.1007/JHEP06(2011)010`, `arXiv:1101.5394`.

[42] L. Lönnblad, "Ariadne version 4: A program for simulation of QCD cascades implementing the colour dipole model", *Comput. Phys. Commun.* **71** (1992) 15, `doi:10.1016/0010-4655(92)90068-A`.

[43] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, `doi:10.1088/1748-0221/3/08/S08004`.

[44] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, `doi:10.1088/1748-0221/9/10/P10009`, `arXiv:1405.6569`.

[45] CMS Collaboration, "Zero bias and HF-based minimum bias triggering for pp collisions at 14 TeV in CMS", CMS Physics Analysis Summary CMS-PAS-QCD-07-002, CERN, 2007.

[46] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *JINST* **6** (2011) P11002, `doi:10.1088/1748-0221/6/11/P11002`, `arXiv:1107.4277`.

[47] CMS Collaboration, "Jet performance in pp collisions at $\sqrt{s} = 7$ TeV", CMS Physics Analysis Summary CMS-PAS-JME-10-003, CERN, 2010.

[48] 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** (2012) 036, doi:10.1007/JHEP06(2012)036, arXiv:1202.0704.

[49] CMS Collaboration, "Alignment of the CMS tracker with LHC and cosmic ray data", *JINST* **9** (2014) P06009, doi:10.1088/1748-0221/9/06/P06009, arXiv:1403.2286.

[50] CMS Collaboration, "Calorimeter jet quality criteria for the first CMS collision data", CMS Physics Analysis Summary CMS-PAS-JME-09-008, CERN, 2010.

[51] G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem", *Nucl. Instrum. Meth. A* **362** (1995) 487, doi:10.1016/0168-9002(95)00274-X.

[52] GEANT4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[53] F. Caporale, D. Y. Ivanov, B. Murdaca, and A. Papa, "Mueller-Navelet small-cone jets at LHC in next-to-leading BFKL", *Nucl. Phys. B* **877** (2013) 73, doi:10.1016/j.nuclphysb.2013.09.013, arXiv:1211.7225.

[54] S. J. Brodsky, G. P. Lepage, and P. B. Mackenzie, "On the elimination of scale ambiguities in perturbative quantum chromodynamics", *Phys. Rev. D* **28** (1983) 228, doi:10.1103/PhysRevD.28.228.

[55] F. Caporale, D. Y. Ivanov, B. Murdaca, and A. Papa, "Mueller-Navelet jets in next-to-leading order BFKL: theory versus experiment", *Eur. Phys. J. C* **74** (2014) 3084, doi:10.1140/epjc/s10052-014-3084-z, arXiv:1407.8431.

[56] H. Jung et al., "The CCFM Monte Carlo generator CASCADE version 2.2.03", *Eur. Phys. J. C* **70** (2010) 1237, doi:10.1140/epjc/s10052-010-1507-z, arXiv:1008.0152.

[57] H. Jung and G. P. Salam, "Hadronic final state predictions from CCFM: The hadron level Monte Carlo generator CASCADE", *Eur. Phys. J. C* **19** (2001) 351, doi:10.1007/s100520100604, arXiv:hep-ph/0012143.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler[1], V. Knünz, A. König, M. Krammer[1], I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady[2], B. Rahbaran, H. Rohringer, J. Schieck[1], R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang[3]

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi[4], O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco[5], J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov[6], L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, C. Mora Herrera, 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. Chinellato[7], A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote[7], A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
S. Ahuja[a], C.A. Bernardes[b], A. De Souza Santos[b], S. Dogra[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], C.S. Moon[a,8], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, 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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina[9], F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger[10], M. Finger Jr.[10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
E. El-khateeb[11], T. Elkafrawy[11], A. Mohamed[12], A. Radi[13,11], E. Salama[11,13]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, 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, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri,

S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte[14], X. Coubez, J.-C. Fontaine[14], D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin[2], K. Skovpen, 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, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[15]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[10]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov[6]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, 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, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann[2], A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo[16], J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel[17], H. Jung,

A. Kalogeropoulos, O. Karacheban[17], M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann[17], R. Mankel, I. Marfin[17], I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo[2], T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann[2], S.M. Heindl, U. Husemann, I. Katkov[6], A. Kornmayer[2], P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, 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, A. Psallidas, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, 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, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath[18], F. Sikler, V. Veszpremi, G. Vesztergombi[19], A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[20], J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary
M. Bartók[21], A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik[22], R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu[23], G. Kole, S. Kumar, B. Mahakud, M. Maity[22], G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar[22], K. Sudhakar, N. Sur, B. Sutar, N. Wickramage[24]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami[25], A. Fahim[26], R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh[27], 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,c], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a,b], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a,2], R. Venditti[a,b], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[2], A.C. Benvenuti[a], 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], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
G. Cappello[a], M. Chiorboli[a,b], S. Costa[a,b], 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], S. Gonzi[a,b], V. Gori[a,b], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b], L. Viliani[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
V. Calvelli[a,b], F. Ferro[a], M. Lo Vetere[a,b], M.R. Monge[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
L. Brianza, M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b],

S. Malvezzi[a], R.A. Manzoni[a,b], B. Marzocchi[a,b,2], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], 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], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,2], M. Esposito[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], G. Lanza[a], L. Lista[a], S. Meola[a,d,2], M. Merola[a], P. Paolucci[a,2], C. Sciacca[a,b], F. Thyssen

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a,2], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b,2], T. Dorigo[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], M. Margoni[a,b], G. Maron[a,28], A.T. Meneguzzo[a,b], F. Montecassiano[a], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Ventura[a], M. Zanetti, P. Zotto[a,b], A. Zucchetta[a,b,2], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b,2], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a,29], P. Azzurri[a], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], M.A. Ciocci[a,29], R. Dell'Orso[a], S. Donato[a,c,2], G. Fedi, L. Foà[a,c†], A. Giassi[a], M.T. Grippo[a,29], 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,30], A.T. Serban[a], P. Spagnolo[a], P. Squillacioti[a,29], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], G. D'imperio[a,b,2], D. Del Re[a,b], M. Diemoz[a], S. Gelli[a,b], C. Jorda[a], E. Longo[a,b], F. Margaroli[a,b], P. Meridiani[a], G. Organtini[a,b], R. Paramatti[a], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], P. Traczyk[a,b,2]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c,2], S. Argiro[a,b], M. Arneodo[a,c], R. Bellan[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], A. Degano[a,b], N. Demaria[a], L. Finco[a,b,2], C. Mariotti[a], S. Maselli[a], G. Mazza[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Musich[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], A. Solano[a,b], A. Staiano[a], U. Tamponi[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b,2], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], C. La Licata[a,b], M. Marone[a,b], A. Schizzi[a,b], A. Zanetti[a]

Kangwon National University, Chunchon, Korea
A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

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

Korea University, Seoul, Korea
S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali[31], F. Mohamad Idris[32], W.A.T. Wan Abdullah, M.N. Yusli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz[33], A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen

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, T. Khurshid, M. Shoaib

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, Poland
G. Brona, K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, N. Leonardo, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, A. Lanev, A. Malakhov, V. Matveev[34], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[35], E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, 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, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
A. Bylinkin

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin[36], I. Dremin[36], M. Kirakosyan, A. Leonidov[36], G. Mesyats, S.V. Rusakov, A. Vinogradov

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. Myagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[37], M. Ekmedzic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, 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
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, J. Duarte Campderros, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi[38], M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli[39], L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi[40], M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Sphicas[41], D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres[19], N. Wardle, H.K. Wöhri, A. Zagozdzinska[42], 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, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, A. Starodumov[43], M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[44], L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, Y. Yang

National Central University, Chung-Li, Taiwan
M. Cardaci, K.H. Chen, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tzeng

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci[45], Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal[46], A. Kayis Topaksu, G. Onengut[47], K. Ozdemir[48], S. Ozturk[49], D. Sunar Cerci[45], H. Topakli[49], M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, B. Isildak[50], G. Karapinar[51], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E.A. Albayrak[52], E. Gülmez, M. Kaya[53], O. Kaya[54], T. Yetkin[55]

Istanbul Technical University, Istanbul, Turkey
K. Cankocak, S. Sen[56], F.I. Vardarlı

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, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold[57], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[58], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, L. Thomas, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, N. Cripps, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Kenzie, R. Lane, R. Lucas[57], L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko[43], J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta[59], T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, D. Gastler, P. Lawson, D. Rankin, C. Richardson, J. Rohlf, J. St. John, L. Sulak, D. Zou

Brown University, Providence, USA
J. Alimena, E. Berry, S. Bhattacharya, D. Cutts, N. Dhingra, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, T. Sinthuprasith, R. Syarif

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny

University of California, San Diego, La Jolla, USA
J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[60], C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, 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, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klima, B. Kreis, S. Kwan[†], S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn,

S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, H.A. Weber, A. Whitbeck, F. Yang

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic[61], G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, M. Hohlmann, H. Kalakhety, 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, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, USA
B. Bilki[62], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[63], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[52], A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
D. Lange, 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, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. Mcginn,

C. Mironov, X. Niu, C. Paus, D. Ralph, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
B. Dahmes, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, 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, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA
K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
A. Brinkerhoff, N. Dev, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[34], T. Pearson, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
S. Malik

Purdue University, West Lafayette, USA
V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, 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, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

The Rockefeller University, New York, USA
L. Demortier

Rutgers, The State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA
O. Bouhali[64], A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[65], V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer[2]

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Now at Ain Shams University, Cairo, Egypt
12: Also at Zewail City of Science and Technology, Zewail, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at University of Hamburg, Hamburg, Germany
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Eötvös Loránd University, Budapest, Hungary
20: Also at University of Debrecen, Debrecen, Hungary
21: Also at Wigner Research Centre for Physics, Budapest, Hungary
22: Also at University of Visva-Bharati, Santiniketan, India
23: Now at King Abdulaziz University, Jeddah, Saudi Arabia
24: Also at University of Ruhuna, Matara, Sri Lanka
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Purdue University, West Lafayette, USA
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Institute for Nuclear Research, Moscow, Russia
35: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
36: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
37: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
38: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
39: Also at National Technical University of Athens, Athens, Greece
40: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
41: Also at National and Kapodistrian University of Athens, Athens, Greece
42: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
43: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
44: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
45: Also at Adiyaman University, Adiyaman, Turkey
46: Also at Mersin University, Mersin, Turkey
47: Also at Cag University, Mersin, Turkey
48: Also at Piri Reis University, Istanbul, Turkey
49: Also at Gaziosmanpasa University, Tokat, Turkey
50: Also at Ozyegin University, Istanbul, Turkey

51: Also at Izmir Institute of Technology, Izmir, Turkey
52: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
53: Also at Marmara University, Istanbul, Turkey
54: Also at Kafkas University, Kars, Turkey
55: Also at Yildiz Technical University, Istanbul, Turkey
56: Also at Hacettepe University, Ankara, Turkey
57: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
58: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
59: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
60: Also at Utah Valley University, Orem, USA
61: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
62: Also at Argonne National Laboratory, Argonne, USA
63: Also at Erzincan University, Erzincan, Turkey
64: Also at Texas A&M University at Qatar, Doha, Qatar
65: Also at Kyungpook National University, Daegu, Korea