Physics Letters B 789 (2019) 19–44

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s} = 8$ and 13 TeV

The CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 28 June 2018
Received in revised form 14 October 2018
Accepted 6 November 2018
Available online 9 November 2018
Editor: M. Doser

Keywords:
CMS
Physics
SM
ZZ
ZZjets
VBS

ABSTRACT

This Letter reports measurements of differential cross sections for the production of two Z bosons in association with jets in proton–proton collisions at $\sqrt{s} = 8$ and 13 TeV. The analysis is based on data samples collected at the LHC with the CMS detector, corresponding to integrated luminosities of 19.7 and 35.9 fb^{-1} at 8 and 13 TeV, respectively. The measurements are performed in the leptonic decay modes $\text{ZZ} \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = \text{e}, \mu$. The differential cross sections as a function of the jet multiplicity, the transverse momentum p_T, and pseudorapidity of the p_T-leading and subleading jets are presented. In addition, the differential cross sections as a function of variables sensitive to the vector boson scattering, such as the invariant mass of the two p_T-leading jets and their pseudorapidity separation, are reported. The results are compared to theoretical predictions and found in good agreement within the theoretical and experimental uncertainties.

© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

1. Introduction

The production of massive vector boson pairs is a key process for the understanding of both the non-Abelian gauge structure of the standard model (SM) and of the electroweak symmetry breaking mechanism. Thus, relevant information can be gathered measuring vector boson scattering [1] and triboson production processes that occur through the electroweak (EW) production of jets in association with bosons. Because of the very low cross sections for these processes compared to others leading to the same final state, a detailed understanding of the quantum chromodynamics (QCD) corrections to the associated production of vector boson pairs and jets is of paramount importance. The analysis presented in this Letter has been designed to provide such detailed understanding.

Both the ATLAS and CMS Collaborations have measured the inclusive production cross section of Z boson pairs and the differential cross sections as a function of Z boson pair observables [2–8]. In this Letter we present new measurements of differential cross sections for the production of two Z bosons in association with jets in proton–proton (pp) collisions at $\sqrt{s} = 8$ and 13 TeV that extend the analyses of Refs. [6,8] to jet variables. The most recent publication from the ATLAS Collaboration [4] includes jet variables as well. The decay modes of the Z boson to electron and muon ($\ell = \text{e}, \mu$) pairs have been exploited. Reconstructed distributions are corrected for event selection efficiency and detector resolution effects by means of an iterative unfolding technique, which makes use of a response matrix to map physics variables at generator level onto their reconstructed values.

This Letter presents the dependence of the cross section on the jet multiplicity and the kinematic properties of the two p_T-leading jets (where p_T is the transverse momentum). Comparison with theoretical predictions provides an important test of the QCD corrections to ZZ production. Normalized differential cross sections as a function of the p_T and pseudorapidity η of the two p_T-leading jets, as well as their invariant mass (m_jj) and pseudorapidity separation ($\Delta\eta_\text{jj}$), are presented. The study of m_jj establishes the basis for future multiboson final-state searches and for the investigation of phenomena involving interactions with four bosons at a single vertex, while the measurement of the $\Delta\eta_\text{jj}$ distribution is instrumental in the study of vector boson scattering. The analysis presented in this paper together with the analyses reported in [5–9] seeks a detailed understanding of the SM processes that generate four leptons in the final state through the production of two Z bosons. All measurements are compared to predictions from

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

https://doi.org/10.1016/j.physletb.2018.11.007
0370-2693/© 2018 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

recent Monte Carlo (MC) event generators. The data sets correspond to integrated luminosities of 19.7 and 35.9 fb^{-1}, collected by the CMS Collaboration at 8 and 13 TeV, respectively.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are silicon pixel and strip tracking detectors, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors up to $|\eta| = 5$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, using three different technologies: drift tubes for $|\eta| < 1.2$, cathode strip chambers for $0.9 < |\eta| < 2.4$, and resistive plate chambers for $|\eta| < 1.6$. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For nonisolated particles in the range $1 < p_{\mathrm{T}} < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [10].

The first level of the CMS trigger system [11], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events within a time interval of less than 4 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [12].

3. Signal and background simulation

Several MC event generators are used to simulate the signal and background contributions. The MC simulation samples are employed to optimize the event selection, evaluate the signal efficiency and acceptance, estimate part of the background, and extract the unfolding response matrices used to correct for detector effects in the measured distributions.

For the 8 TeV data analysis, MadGraph5 1.3.3 [13,14] is used to simulate the production of the four-lepton final state at leading order (LO) in QCD with up to 2 jets included in the matrix-element calculations. powheg 2.0 [15–18] is used for the simulation of the same process at next-to-leading-order (NLO). A sample of events generated with MadGraph5_aMC@NLO 2.3.3 (abbreviated as MG5_aMC@NLO in the following) [14,19], which simulates signal processes at NLO with zero and one jet included in the matrix-element calculations, is produced only at generator level and used for comparison purposes. For the 13 TeV data analysis, the four-lepton processes are simulated at NLO in QCD with 0 or 1 jet included in the matrix-element calculations with MG5_aMC@NLO and with powheg 2.0 at NLO. The latter is scaled by a factor of 1.1 to reproduce the total ZZ production cross section calculated at next-to-next-to-leading order (NNLO) [20] at 13 TeV. MG5_aMC@NLO and powheg 2.0, for both the 8 and 13 TeV analyses, include ZZ, $\mathrm{Z}\gamma^*$, Z, and $\gamma^*\gamma^*$ processes, with the generator level constraint $m_{\ell^+\ell^-} > 4$ GeV applied to all pairs of oppositely charged same-flavor leptons, to avoid infrared divergences.

The $\mathrm{gg} \to \mathrm{ZZ}$ processes, which occur via loop-induced diagrams, are generated at LO with mcfm 6.7 (7.0) [21] for the 8 (13) TeV analysis. The 13 TeV samples are scaled by a factor of 1.7 to match the cross section computed at NLO [22]. Electroweak production of four leptons and two jets is simulated at LO with Phantom [23]. This sample includes triboson processes, where the Z boson pair is accompanied by a third vector boson that decays into jets, as well as diagrams with quartic vertices.

Other diboson and triboson processes (WZ, $\mathrm{Z}\gamma$, WWZ) as well as $\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}}$, and Z+jets samples are generated at LO with MadGraph5 for the 8 TeV analysis, and at NLO with MG5_aMC@NLO, for the 13 TeV analysis.

For the 8 TeV analysis, the pythia 6.4.24 [24] package, with parameters set by the Z2* tune [25], is used for parton showering, hadronization, and the underlying event simulation for all MC samples except for MG5_aMC@NLO, for which pythia 8.205 [26] is employed. The default sets of parton distribution functions (PDFs) are CTEQ6L [27] for the LO generators, and CT10 [28], for the NLO ones. For the 13 TeV analysis, pythia 8.212 [26], with parameters set by the CUETP8M1 tune [29], is used for parton showering, hadronization, and the underlying event simulation. The NNPDF3.0 [30] PDF set is the default. For all simulated event samples, the PDFs used are evaluated at the same order in QCD as the process in the sample.

The detector response is simulated using a detailed description of the CMS detector implemented with the Geant4 package [31]. The simulated events are reconstructed with the same algorithms used for the data. The simulated samples include additional interactions per bunch crossing, referred to as pileup. Simulated events are weighted so that the pileup distribution reproduces that observed in the data, with an average of about 21 (27) interactions per bunch crossing for the 8 (13) TeV data set.

4. Particle reconstruction and event selection

The primary triggers for this analysis require the presence of two loosely isolated leptons of the same or of different flavor. The minimum p_{T} for the first lepton is 17 GeV, while it is 8 (12) GeV for the second lepton in the 8 (13) TeV analysis. Triggers requiring a triplet of low-p_{T} leptons with no isolation requirement and, for the 13 TeV analysis, isolated single-electron and single-muon triggers, with minimal p_{T}-thresholds of 27 and 22 GeV, respectively, help to increase the efficiency. The overall trigger efficiency for events that pass the ZZ selection is greater than 98%.

The offline event selection procedure is similar to that of the inclusive ZZ analyses [6–8] and is based on a global event description [32] that classifies particles into mutually exclusive categories: charged hadrons, neutral hadrons, photons, muons, and electrons. Events are required to have at least one vertex [10] within 24 cm of the geometric center of the detector along the beam direction, and within 2 cm in the transverse plane. Because of pileup the selected event can have several reconstructed vertices.

For the analysis at 8 TeV the vertex with the largest sum of the p_{T}^2 of the tracks associated to it is chosen as the primary pp interaction vertex, while at 13 TeV the reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary vertex. The physics objects are the objects returned by a jet finding algorithm [33,34] applied to all charged tracks associated with the vertex, and the associated missing p_{T}, taken as the negative vector sum of the p_{T} of those jets. Events with leptons are selected by requiring each lepton track to have a transverse impact parameter, with respect to the primary vertex, smaller than 0.5 cm and a longitudinal impact parameter smaller than 1.0 cm.

Electrons are measured in the range $|\eta| < 2.5$ by using both the tracking system and the ECAL. They are identified by means of a multivariate discriminant that includes observables sensitive to bremsstrahlung along the electron trajectory, the geometrical and momentum-energy agreement between the electron track and the associated energy cluster in the ECAL, the shape of the electromagnetic shower, and variables that discriminate against electrons

originating from photon conversions [35]. The momentum resolution for electrons with $p_T \approx 45$ GeV from $Z \to e^+e^-$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [35].

Muons are reconstructed in the range $|\eta| < 2.4$ by combining information from the silicon tracker and the muon system [36]. The matching between the inner and outer tracks proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track in the silicon tracker. The muons are selected among the reconstructed muon track candidates by applying minimal requirements on the track in both the muon system and the inner tracker system, and taking into account the compatibility with minimum-ionizing particle energy deposits in the calorimeters. In the intermediate range of $20 < p_T < 100$ GeV, matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1.3–2.0% in the barrel, and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [36].

Electrons (muons) are considered candidates for inclusion in the four-lepton final states if they have $p_T^\ell > 7\,(5)$ GeV and $|\eta_\ell| < 2.5\,(2.4)$. In order to suppress electrons from photon conversions and muons originating from in-flight decays of hadrons, we place a requirement on the impact parameter computed in three dimensions. We require that the ratio of the impact parameter for the track and its uncertainty to be less than 4. To discriminate between prompt leptons from Z boson decay and those arising from electroweak decays of hadrons within jets, an isolation requirement for leptons is imposed. The relative isolation is defined as

$$R_{\text{iso}} = \left[\sum_{\substack{\text{charged}\\ \text{hadrons}}} p_T + \max\left(0, \sum_{\substack{\text{neutral}\\ \text{hadrons}}} p_T + \sum_{\text{photons}} p_T - p_T^{\text{PU}}\right)\right] \Big/ p_T^\ell, \tag{1}$$

where the sums run over the charged and neutral hadrons, and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton trajectory. The radius ΔR is set to be 0.4 and 0.3 in the 8 and 13 TeV data analyses, respectively. To minimize the contribution of charged particles from pileup to the isolation calculation, charged hadrons are included only if they originate from the primary vertex. The contributions of neutral particles from pileup to the activity inside the cone around a lepton is referred to as p_T^{PU}, and is obtained with different methods for electrons and muons. For electrons, p_T^{PU} is evaluated with the jet area method described in Ref. [37]. For muons, it is taken to be half the sum of the p_T of all charged particles in the cone originating from pileup vertices. The factor of one-half accounts for the expected fraction of neutral to charged particles in hadronic interactions. A lepton is considered isolated if $R_{\text{iso}} < 0.4\,(0.35)$ in the 8 (13) TeV data analysis.

The lepton momentum scales are calibrated in bins of p_T^ℓ and η_ℓ using the decay products of known resonances decaying to lepton pairs. The measured lepton momentum scale is corrected with a $Z \to \ell^+\ell^-$ sample, by matching the peak of the reconstructed dilepton mass spectrum to the nominal value of m_Z [38]. Muon momenta are calibrated by using J/ψ decays as well. We account for final-state radiation of leptons by correcting their momenta with photons of $p_T > 2$ GeV and within a cone of $\Delta R = 0.5$ around the lepton momentum direction [39,40]. The photons selected by this algorithm are excluded from the lepton isolation computation. The efficiency of the lepton reconstruction and selection is measured with the tag-and-probe technique [41] in bins of p_T^ℓ and η_ℓ. This measurement is used to correct the simulation efficiency.

Jets are reconstructed from particle candidates by means of the anti-k_T clustering algorithm [33], as implemented in the FastJet package [34], with a distance parameter of 0.5 (0.4) in the 8 (13) TeV data analysis. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

Jet energy corrections are extracted from the data and the simulated events by combining several measurements and methods that account for the effects of pileup, non-uniform detector response, and residual data-simulation jet energy scale (JES) differences. The JES calibration [42,43] relies on corrections parametrized in terms of the uncorrected p_T and η of the jet, and are applied as multiplicative factors to the four-momentum vector of each jet.

In order to maximize the reconstruction efficiency while reducing the instrumental background and contamination from pileup jets, loose identification quality criteria [44] are imposed on jets, based on the energy fraction carried by charged and neutral hadrons, as well as charged leptons and photons. A minimum threshold of 30 GeV on the p_T of jets is required to ensure that they are well measured and to reduce the pileup contamination. Jets are required to have $|\eta| < 4.7$ and to be separated from all selected lepton candidates by at least $\Delta R = 0.5\,(0.4)$ in the 8 (13) TeV analysis.

A signal event must contain at least two Z/γ^* candidates, each reconstructed from a pair of isolated electrons or muons of opposite charges. The highest-p_T lepton must have $p_T > 20$ GeV, and the second-highest lepton $p_T^e > 10\,(12)$ GeV if it is an electron, or $p_T^\mu > 10$ GeV in case of a muon for the analysis at $\sqrt{s} = 8\,(13)$ TeV. All leptons are required to be separated by $\Delta R(\ell, \ell') > 0.02$, and electrons are required to be separated from muons by $\Delta R(e, \mu) > 0.05$.

Within each event, all permutations of oppositely charged leptons giving a valid pair of Z/γ^* candidates are considered separately. For each 4ℓ candidate, the lepton pair with the invariant mass closest to the nominal Z boson mass is denoted by Z_1 and the other dilepton candidate is denoted by Z_2. Both Z_1 and Z_2 are required to have a mass between 60 and 120 GeV. All pairs of oppositely charged leptons in the 4ℓ candidate are required to have $m_{\ell\ell'} > 4$ GeV regardless of their flavor to remove contributions from the decay of low-mass hadron resonances.

If multiple 4ℓ candidates within an event pass this selection, the candidate with m_{Z_1} closest to the nominal Z boson mass is chosen. In the rare cases (0.3%) of further ambiguity, which may arise in events with more than 4 leptons, the Z_2 candidate that maximizes the scalar p_T sum of the four leptons is chosen. The set of selection criteria just described is referred to as the ZZ selection, and gives a total of 288 (927) observed events at $\sqrt{s} = 8\,(13)$ TeV. The corresponding number of expected signal events from MC prediction is about 271 (850).

5. Background estimation

The largest source of background arises from processes in which heavy-flavor jets produce secondary leptons, and from processes in which jets are misidentified as leptons. The main contributing processes are Z+jets, $t\bar{t}$, and WZ+jets.

However, the lepton identification and isolation requirements reduce this background to a very small level compared to the signal. The residual contribution is estimated from data samples consisting of Z + $\ell\ell$ events that are required to pass the ZZ selection described in Section 4, except that either one or both leptons belonging to the Z_2 candidate fail the isolation or identification requirements. Two control samples are selected, with one and two misidentified leptons, respectively. The background yield in the signal region is estimated by weighting the number of

Table 1
The contributions to the uncertainty in the absolute and normalized differential cross section measurements in Fig. 2 and 3, upper panels. Uncertainties that depend on jet multiplicity are listed as a range.

Systematic source	8 TeV data		13 TeV data	
	Absolute (%)	Normalized (%)	Absolute (%)	Normalized (%)
Trigger	1.5	–	2.0	–
Lepton reconstruction and selection	0.9–4.4	≤0.1	3.7–4.5	0.1–0.8
Jet energy scale	1.5–9.2	1.5–9.1	4.6–17.5	4.6–17.5
Jet energy resolution	0.2–1.7	0.2–1.7	2.1–8.4	2.1–8.4
Background yields	0.7–7.2	0.7–5.4	0.5–2.8	0.4–2.0
Pileup	1.8	1.8	0.3–1.9	0.6–1.8
Luminosity	2.6	–	2.5	–
Choice of Monte Carlo generators	0.2–3.7	0.2–3.7	0.5–5.0	0.8–4.7
qq/gg cross section	0.1–0.8	0.1–0.8	<0.1–0.3	0.1–0.2
PDF	1.0	–	<0.1–0.2	<0.1–0.2
α_S	<0.1	<0.1	≤0.1	≤0.1

events in the control samples by the lepton misidentification rate measured in data in a dedicated control region. The procedure is identical to that of Refs. [7,8] and is described in more detail in Ref. [39].

Another source of background arises from processes that produce four genuine high-p_T isolated leptons, $pp \to t\bar{t}Z$ and $pp \to WWZ$. This contribution is small and is estimated by using the corresponding simulated samples.

The total estimated background yields are 8 ± 4 (37 ± 11) events in the 8 (13) TeV signal region.

6. Systematic uncertainties

The systematic uncertainties are estimated by varying the quantities that may affect the cross section and by propagating the changes to the analysis procedure. The systematic uncertainties from sources that may affect the differential cross section shapes have been estimated through the unfolding procedure by recomputing the response matrix, after varying each source of systematic uncertainty independently and in both directions, up and down. The systematic uncertainties in the differential cross section as a function of the jet multiplicity are summarized in Table 1. Those that depend on the number of jets in the event are listed as a range.

The systematic uncertainty in the trigger efficiency is evaluated by taking the difference between the value obtained from the data and that from the simulated events, and it leads to a 1.5 (2.0)% uncertainty in the differential cross sections measured with the 8 (13) TeV data. The uncertainties arising from lepton reconstruction and selection (identification, isolation, and impact parameter determination) depend on the jet multiplicity, are sensitive to statistical fluctuations, and range between 0.9 and 4.4%, in the 8 TeV analysis (3.7 and 4.5%, in the 13 TeV analysis). The largest contribution to the systematic uncertainty in the differential cross section measurements comes from the JES determination, which increases with the jet multiplicity and reaches 9.2 (17.5)% when the number of jets exceeds two in the 8 (13) TeV analysis. Likewise, the uncertainty due to the jet energy resolution (JER) increases from 0.2 to 1.7% (2.1 to 8.4%) for the 8 (13) TeV samples. The larger JES and JER uncertainties for the 13 TeV sample reflect the increase in the number of soft jets (with p_T close to the 30 GeV threshold) as a function of the center-of-mass energy.

The uncertainties in the Z+jets, WZ+jets, and $t\bar{t}$ background have two components, which are added in quadrature. The first relates to the different relative fraction of these background processes in the control sample where we measure the lepton misidentification rate and the sample to which this rate is applied. The second is the statistical uncertainty in the control sample. The effect of these uncertainties increases with the jet multiplicity and amounts to 0.7–6.9% (0.5–2.4%) in the 8 (13) TeV measurement. The contribution to the uncertainty from the modeling of genuine four lepton background is smaller and varies between 0.1 and 2.0% (<0.1 and 1.2%) for the 8 (13) TeV data. The pileup uncertainty is evaluated by varying the pileup modeling in the MC samples within its uncertainty. The uncertainty in the integrated luminosity is 2.6 [45] and 2.5% [46] for the 8 and 13 TeV data, respectively.

The contribution of the MC generator choice to the systematic uncertainty is obtained by comparing the results found with two different sets of MC samples: MadGraph5 + mcfm + Phantom (MG5_aMC@NLO + mcfm + Phantom) and powheg + mcfm + Phantom for the 8 (13) TeV measurement, and ranges from 0.2 to 3.7% (0.5 to 5.0%) at 8 (13) TeV. The impact of the relative contribution of the $q\bar{q} \to ZZ$ and $gg \to ZZ$ processes in the response matrix definition is less than 1% and is evaluated by varying the corresponding cross section within their renormalization and factorization scale uncertainties. For 8 TeV, where no LO to NLO factor is applied to the mcfm cross section, the $gg \to ZZ$ cross section is varied by 100% of its value. The statistical uncertainties of the MC samples result in negligible contributions to the response matrix uncertainty. The systematic uncertainty arising from the choice of the PDF and the strong coupling strength α_S has been evaluated using the PDF4LHC recommendations [47–49], using the CT10, MSTW08, and NNPDF2.3 [50] PDF sets, in the 8 TeV analysis, and the NNPDF3.0 set in the 13 TeV analysis.

The total systematic uncertainty is obtained by summing all the sources in quadrature, taking into account the correlations among the different channels.

For the normalized differential cross sections, only systematic uncertainties affecting the shape of the distributions are relevant. The uncertainties in the luminosity and trigger efficiency cancel out completely, as well as other contributions to the uncertainty in the total yield.

7. The ZZ+jets differential cross section measurements

The distributions of the jet multiplicity combining the 4μ, 4e, and $2\mu 2e$ channels are shown in Fig. 1, together with the SM expectations, the estimated backgrounds, and the systematic uncertainty in the prediction.

The differential $pp \to ZZ \to \ell\ell\ell'\ell'$ cross section is measured as a function of the jet multiplicity, the p_T-leading jet transverse momentum (p_T^{j1}) and pseudorapidity (η_{j1}) with the 8 and 13 TeV data. Because of the limited number of events with more than

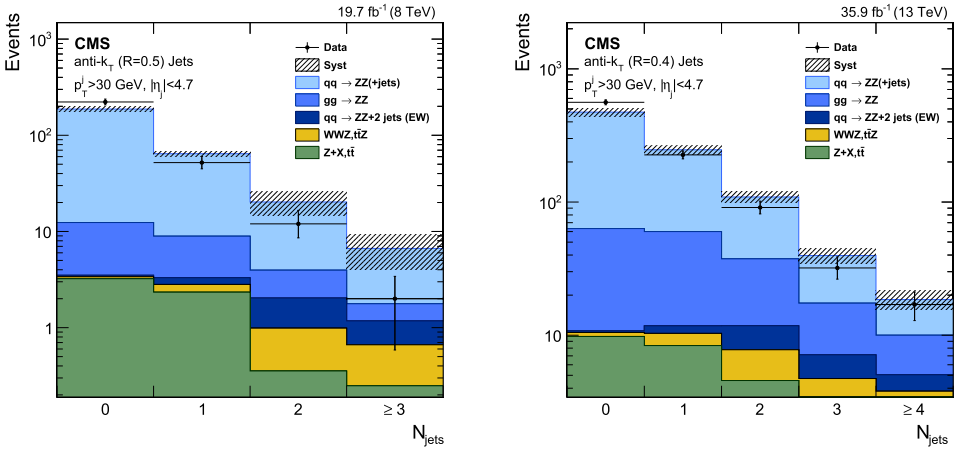

Fig. 1. Distribution of the reconstructed jet multiplicity in the 8 TeV (left) and 13 TeV (right) data. The points represent the data and the vertical bars correspond to the statistical uncertainty. The shaded histograms represent MC predictions and the background estimates, while the hatched band on their sum indicates the systematic uncertainty of the prediction. The Z+jets and $\mathrm{t\bar{t}}$ background is obtained from the data.

Table 2
Phase space definitions for cross section measurements at 8 TeV [6] and 13 TeV [8]. The common definitions apply to both measurements.

8 TeV	13 TeV
$p_{\mathrm{T}}^{\mathrm{e}} > 7\,\mathrm{GeV}$, $\lvert\eta^{\mathrm{e}}\rvert < 2.5$	$p_{\mathrm{T}}^{\mathrm{e}} > 5\,\mathrm{GeV}$, $\lvert\eta^{\mathrm{e}}\rvert < 2.5$
$p_{\mathrm{T}}^{\mu} > 5\,\mathrm{GeV}$, $\lvert\eta^{\mu}\rvert < 2.4$	$p_{\mathrm{T}}^{\mu} > 5\,\mathrm{GeV}$, $\lvert\eta^{\mu}\rvert < 2.5$
Common definitions	
$p_{\mathrm{T}}^{\ell_1} > 20\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell_2} > 10\,\mathrm{GeV}$	
$m_{\ell^+\ell^-} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair)	
$60 < (m_{\mathrm{Z}_1}, m_{\mathrm{Z}_2}) < 120\,\mathrm{GeV}$	

one jet at 8 TeV, the differential cross section as a function of the p_{T}-subleading jet transverse momentum ($p_{\mathrm{T}}^{\mathrm{j2}}$) and pseudorapidity ($\eta_{\mathrm{j2}}$), as well as the invariant mass of the two p_{T}-leading jets (m_{jj}) and their pseudorapidity separation ($\Delta\eta_{\mathrm{jj}}$) are studied at 13 TeV only. For all measurements we consider jets with $p_{\mathrm{T}}^{\mathrm{j}} > 30\,\mathrm{GeV}$ and $\lvert\eta_{\mathrm{j}}\rvert < 4.7$. For the jet multiplicity distribution we also present the measurements made with central jets ($\lvert\eta_{\mathrm{j}}\rvert < 2.4$) only. The measurements are performed for the two slightly different phase space regions adopted for the 8 [6] and 13 [8] TeV data, which are given in Table 2. The generator-level lepton momenta are corrected by adding the momenta of generator-level photons within $\Delta R\,(\ell, \gamma) < 0.1$. The Z bosons are then selected with the same method adopted to extract the signal at the reconstruction level. In order to define the jets at generator level, the generated particles are clustered using the anti-k_{T} algorithm, with a distance parameter identical to the corresponding one at reconstruction level.

Each distribution is corrected for the event selection efficiency and the detector resolution effects by means of a response matrix that translates the physics variables at generator level into their reconstructed values. The correction procedure is based on the iterative D'Agostini unfolding method technique [51], as implemented in the RooUnfold toolkit [52], and regularized by stopping after four iterations. The robustness of the result is tested against the singular value decomposition (SVD) [53] alternative unfolding method. For each measured distribution, a response matrix is evaluated using two different sets of generators: the first one includes MadGraph5 ($\mathrm{q\bar{q}} \to \mathrm{ZZ}$), mcfm ($\mathrm{gg} \to \mathrm{ZZ}$) and Phantom ($\mathrm{q\bar{q}} \to \mathrm{ZZ} + 2$ jets) for the 8 TeV data set and MG5_aMC@NLO ($\mathrm{q\bar{q}} \to \mathrm{ZZ}$), mcfm ($\mathrm{gg} \to \mathrm{ZZ}$) and Phantom ($\mathrm{q\bar{q}} \to \mathrm{ZZ} + 2$ jets) for the 13 TeV data set. In the second one, the powheg sample is instead used for the $\mathrm{q\bar{q}} \to \mathrm{ZZ}$ process in both the 8 and 13 TeV data analyses. The former set, where the leading-order MC generator can simulate up to two jets at matrix-element level, is taken as the reference, while the latter is used for comparison and to estimate the systematic uncertainty due to the MC generator choice. After the unfolding, the cross sections for $\mathrm{pp} \to \mathrm{ZZ} + N\,\mathrm{jets} \to \ell\ell\ell'\ell' + N\,\mathrm{jets}$, for $N = 0$, 1, 2, and $\geq$3, are extracted.

The differential cross sections as a function of the jet multiplicity are shown in Fig. 2 for $\lvert\eta_{\mathrm{j}}\rvert < 4.7$ (upper) and for $\lvert\eta_{\mathrm{j}}\rvert < 2.4$ (lower). The ratios between the measured and expected distributions from the MadGraph5, MG5_aMC@NLO, and powheg set of samples for $\sqrt{s} = 8\,\mathrm{TeV}$, and powheg and MG5_aMC@NLO for $\sqrt{s} = 13\,\mathrm{TeV}$ are also shown in the figures. Uncertainties in the MC predictions at the matrix-element level are evaluated by varying the renormalization and factorization scales independently, up and down, by a factor of two with respect to the default values of $\mu_R = \mu_F = m_{4\ell}$ for powheg and $\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \frac{1}{2}\sum p_{\mathrm{T}}^{\mathrm{j}} + \sum p_{\mathrm{T}}^{\ell}$ for MG5_aMC@NLO. In the mcfm predictions, the uncertainty in the LO to NLO cross section scaling factor includes the renormalization and factorization scales uncertainty. The theoretical uncertainties also include the uncertainties in the PDF and α_S. The measured and expected cross section values for $\lvert\eta_{\mathrm{j}}\rvert < 4.7$ are given in Tables 3 and 4.

The differential distributions, normalized to the cross sections, are presented in Figs. 3–6 together with the theoretical predictions. For the theoretical predictions, only the uncertainty in the shape is included, which yields a smaller uncertainty compared to the unnormalized case. Fig. 3 (top panels) shows the normalized differential cross section as a function of the jet multiplicity, with $\lvert\eta_{\mathrm{j}}\rvert < 4.7$. The observed fraction of events in the first bin with zero jets is larger than the predicted value, while for 1, 2, and $\geq$ 3 jets, the fraction is lower. Better agreement is observed for $\lvert\eta_{\mathrm{j}}\rvert < 2.4$ (Fig. 3, bottom panels). The measurements of the differential cross section as a function of the jet multiplicity are fairly well reproduced by the predictions both at 8 and 13 TeV when NLO matrix-element calculations are used in conjunction with pythia 8 for parton showering, hadronization, and underlying event simulation. In the data, jets tend to have a lower p_{T} value than in the simulations and therefore, on average, they are less likely to pass the 30 GeV threshold, thus increasing the number of events with no jets. The observation of fewer events than expected with at least one jet can be ascribed to a softer distribution of the trans-

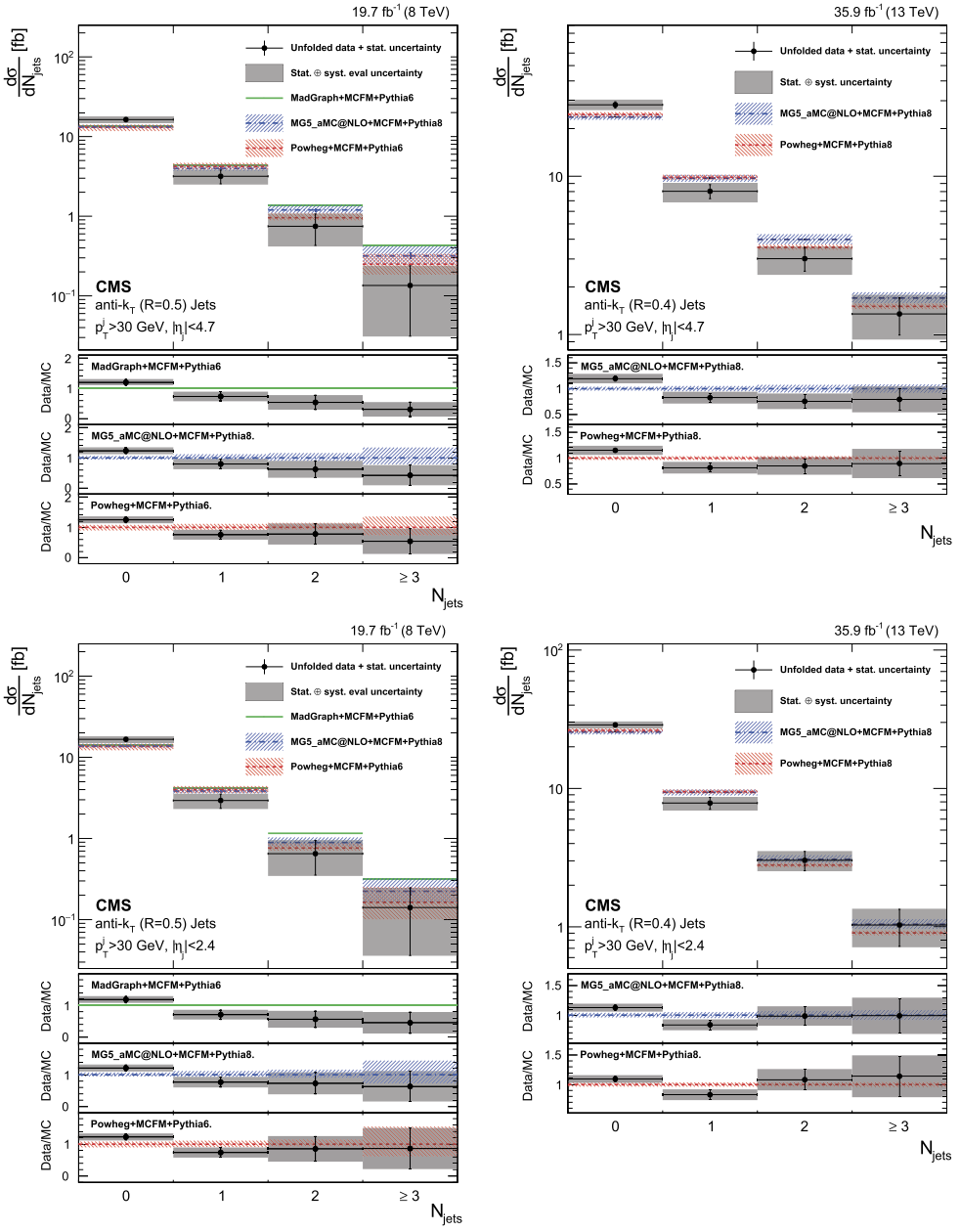

Fig. 2. Differential cross sections of $pp \to ZZ \to 4\ell$ as a function of the multiplicity of jets with $|\eta_j| < 4.7$ (top panels) and $|\eta_j| < 2.4$ (bottom panels), for the 8 (left) and 13 (right) TeV data. The measurements are compared to the predictions of MG5_aMC@NLO, POWHEG, and MADGRAPH5 (8 TeV only) sets of samples. Each MC set, along with the main MC generator, includes the MCFM and PHANTOM generators. PYTHIA 6 and PYTHIA 8 are used for parton showering, hadronization, and underlying event simulation, for the 8 and 13 TeV analysis, respectively, with the sole exception of MG5_aMC@NLO, which is always interfaced to PYTHIA 8. The total experimental uncertainties are shown as hatched regions, while the colored bands display the theoretical uncertainties in the matrix-element calculations.

Table 3
The $pp \to ZZ \to \ell\ell\ell'\ell'$ cross section at $\sqrt{s} = 8$ TeV as a function of the jet multiplicity. The integrated luminosity uncertainty for number of jets = 2 and ≥3 is negligible and not quoted. The cross sections are compared to the theoretical predictions (last column) from MG5_aMC@NLO + MCFM + PHANTOM.

Number of jets ($\|\eta_j\| < 4.7$)	Cross section [fb]	Theoretical cross section [fb]
0	$16.3 \pm 1.2\,(\text{stat})^{+1.0}_{-0.9}\,(\text{syst}) \pm 0.4\,(\text{lumi})$	$13.2^{+0.9}_{-0.7}$
1	$3.2 \pm 0.6\,(\text{stat})^{+0.3}_{-0.3}\,(\text{syst}) \pm 0.1\,(\text{lumi})$	$4.0^{+0.5}_{-0.3}$
2	$0.7 \pm 0.3\,(\text{stat})^{+0.1}_{-0.1}\,(\text{syst})$	$1.2^{+0.2}_{-0.1}$
≥3	$0.14 \pm 0.1\,(\text{stat})^{+0.01}_{-0.01}\,(\text{syst})$	$0.3^{+0.1}_{-0.1}$

verse momentum of the hadronic particles recoiling against the diboson system. This explanation is supported by the measurement of a softer-than-expected p_T distribution of the ZZ system [6,8]. The observed discrepancy may be due to higher-order corrections to ZZ production, not included in MC samples used in this analysis, or to the parton shower modeling.

Table 4
The $pp \to ZZ \to \ell\ell\ell'\ell'$ cross section at $\sqrt{s} = 13\,\text{TeV}$ as a function of the jet multiplicity. The integrated luminosity uncertainty for the number of jets ≥ 3 is smaller than 0.1 fb and is not quoted. The cross sections are compared to the theoretical predictions (last column) from MG5_aMC@NLO + MCFM + PHANTOM.

Number of jets ($\lvert\eta_j\rvert < 4.7$)	Cross section [fb]	Theoretical cross section [fb]
0	$28.3 \pm 1.3\,(\text{stat})^{+1.7}_{-1.5}\,(\text{syst}) \pm 0.7\,(\text{lumi})$	$23.6^{+0.8}_{-0.9}$
1	$8.0 \pm 0.8\,(\text{stat})^{+0.7}_{-0.8}\,(\text{syst}) \pm 0.2\,(\text{lumi})$	$9.7^{+0.5}_{-0.5}$
2	$3.0 \pm 0.5\,(\text{stat})^{+0.3}_{-0.4}\,(\text{syst}) \pm 0.1\,(\text{lumi})$	$4.0^{+0.3}_{-0.3}$
≥ 3	$1.3 \pm 0.4\,(\text{stat})^{+0.2}_{-0.2}\,(\text{syst})$	$1.7^{+0.1}_{-0.1}$

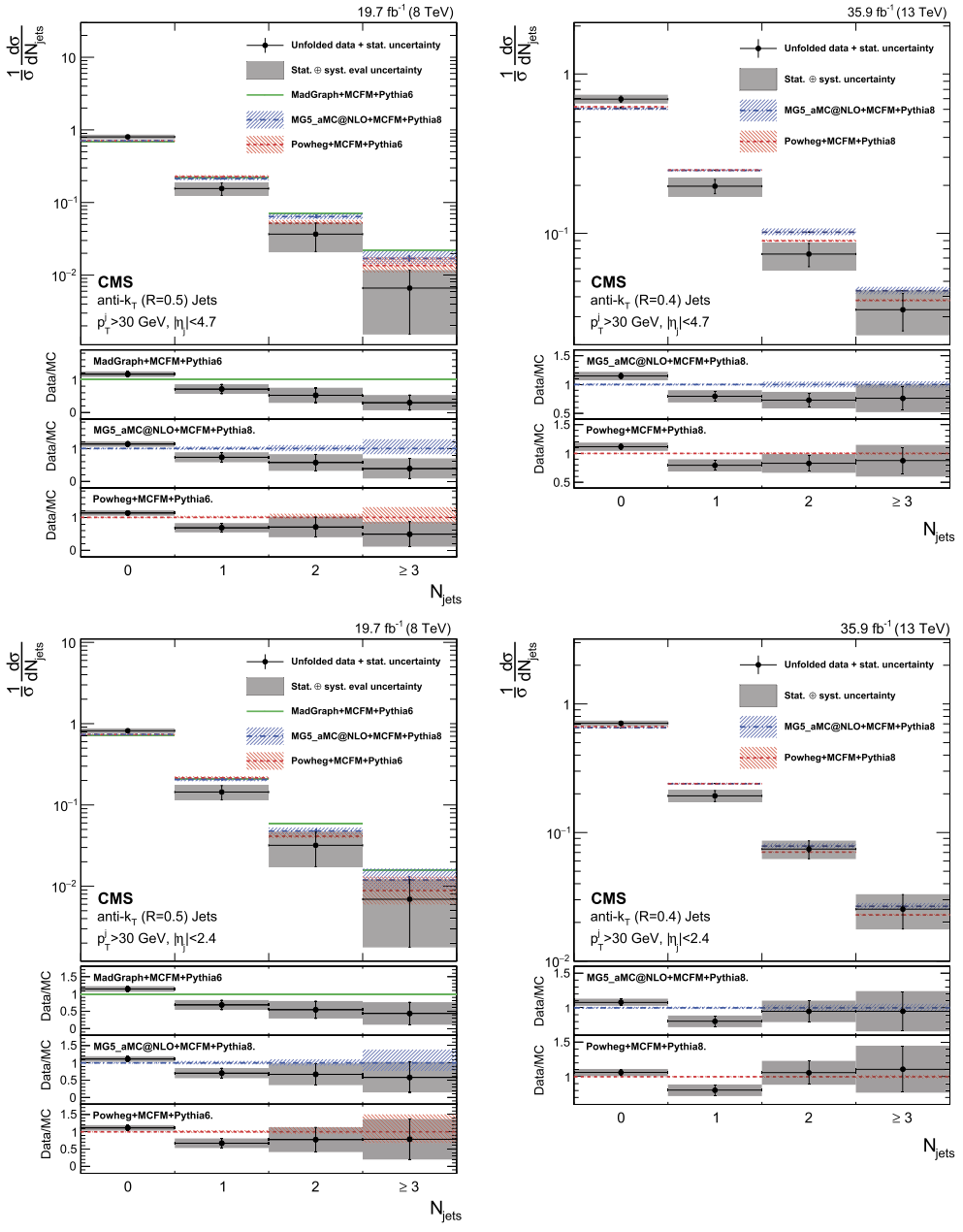

Fig. 3. Differential cross sections normalized to the cross section of $pp \to ZZ \to 4\ell$ as a function of the multiplicity of jets with $|\eta_j| < 4.7$ (top panels) and $|\eta_j| < 2.4$ (bottom panels), for the 8 (left) and 13 (right) TeV data. Other details are as described in the caption of Fig. 2.

Fig. 4 shows the differential cross sections at 8 and 13 TeV as functions of the transverse momentum and pseudorapidity of the p_T-leading jet, normalized to the cross section for $N_{\text{jets}} \geq 1$. Figs. 5 and 6 show the cross section at 13 TeV as a function of several variables for events with $N_{\text{jets}} \geq 2$, normalized to the corresponding cross section. More specifically, Fig. 5 presents the normalized differential cross sections as functions of the transverse momentum and pseudorapidity of the p_T-subleading jet, while

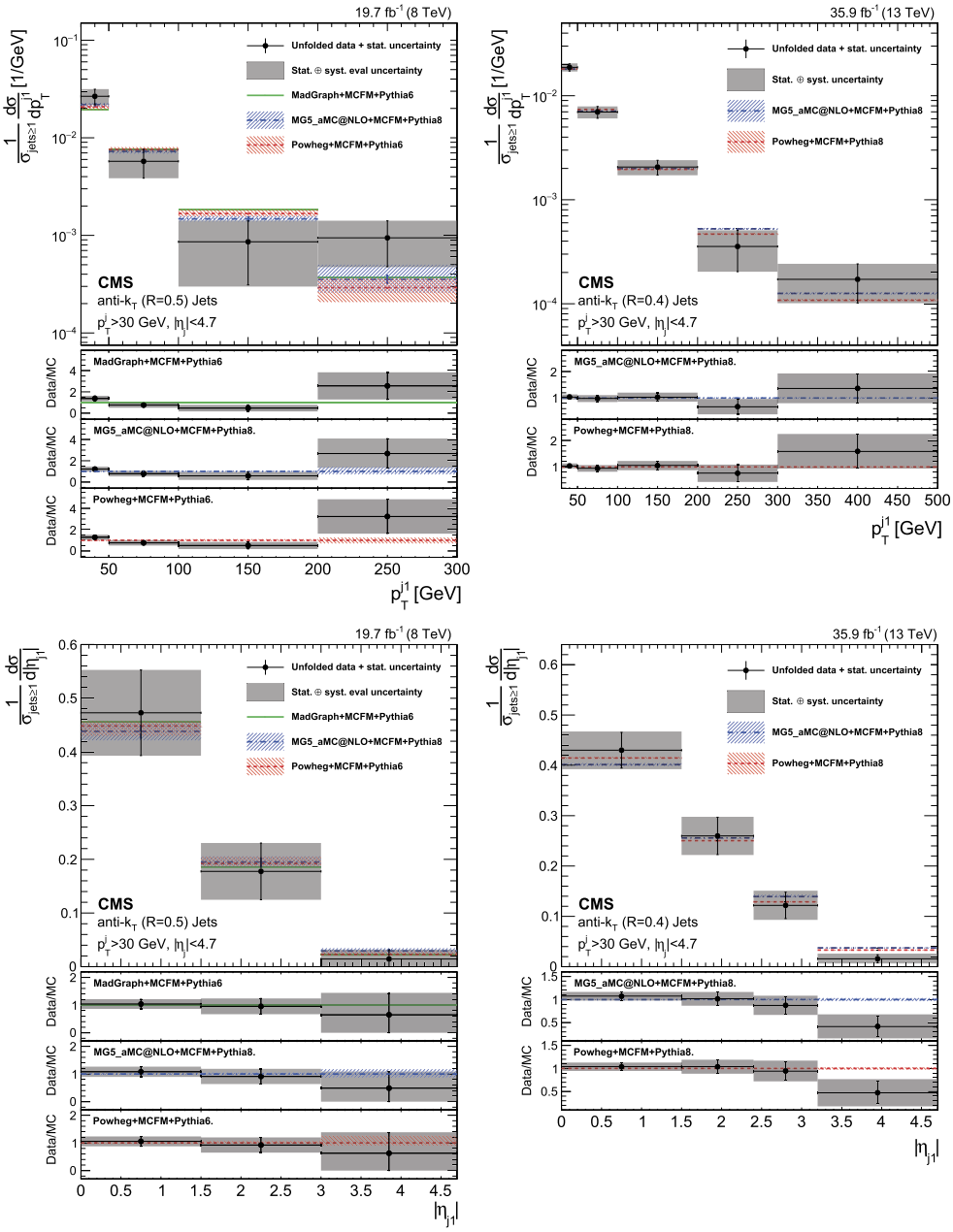

Fig. 4. Differential cross sections normalized to the cross section for $N_{\text{jets}} \geq 1$ of $\text{pp} \to \text{ZZ} \to 4\ell$ as a function of the p_{T}-leading jet transverse momentum (top panels) and the absolute value of the pseudorapidity (bottom panels), for the 8 (left) and 13 (right) TeV data. Other details are as described in the caption of Fig. 2.

Fig. 6 displays the differential cross section as a function of m_{jj} and $\Delta\eta_{\text{jj}}$.

Overall agreement is observed between data and theoretical predictions for all measurements related to the p_{T}-leading and subleading jets. The $\Delta\eta_{\text{jj}}$ distribution (Fig. 6, right) measured with 13 TeV data tends to be steeper than the MC predictions, but the differences are not statistically significant.

8. Summary

The differential cross sections for the production of Z pairs in the four-lepton final state in association with jets in proton–proton collisions at $\sqrt{s} = 8$ and 13 TeV have been measured. The data correspond to an integrated luminosity of 19.7 (35.9) fb^{-1} for a center-of-mass energy of 8 (13) TeV. Cross sections are presented for the production of a pair of Z bosons as a function of the number of jets, the transverse momentum p_{T}, and pseudorapidity of the p_{T}-leading and subleading jets. Distributions of the invariant mass of the two p_{T}-leading jets and their separation in pseudorapidity are also presented. Good agreement is observed between the measurements and the theoretical predictions when next-to-leading order matrix-element calculations are used together with the PYTHIA parton shower simulation. Cross sections for ZZ production in association with jet have been measured with a precision ranging from 10 to 72% (8 to 38%) at 8 (13) TeV, for jet multiplicities ranging from 0 to ≥ 3. The systematic uncertainty is of the same size, or smaller, than the statistical one. Analyses using future, larger data sets, with smaller statistical uncertainties, will allow the theoretical prediction of ZZ+jets to undergo more stringent tests.

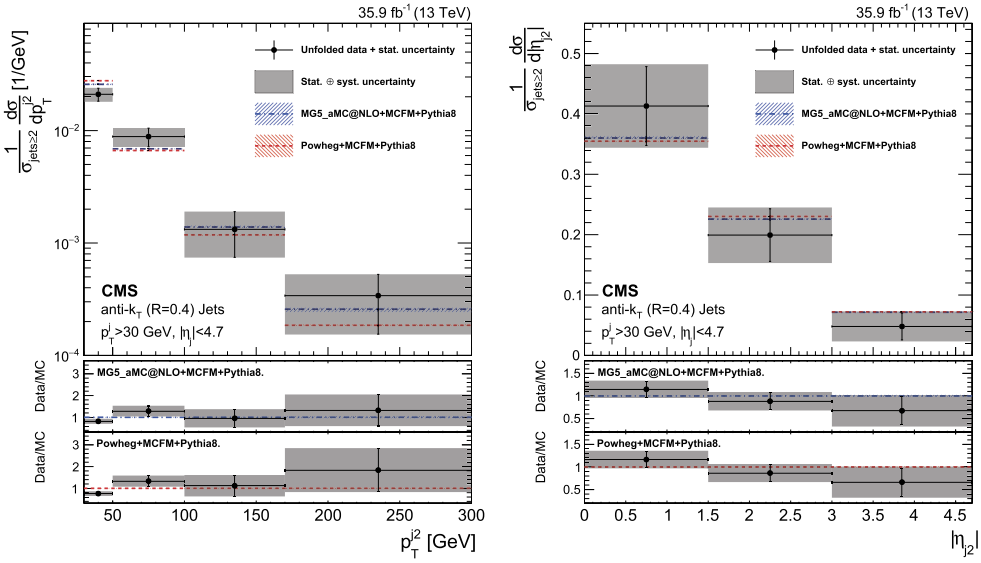

Fig. 5. Differential cross sections normalized to the cross section for $N_{\text{jets}} \geq 2$ of $\text{pp} \to \text{ZZ} \to 4\ell$ at $\sqrt{s} = 13\,\text{TeV}$ as a function of the p_{T}-subleading jet transverse momentum (left) and the absolute value of the pseudorapidity (right). Other details are as described in the caption of Fig. 2.

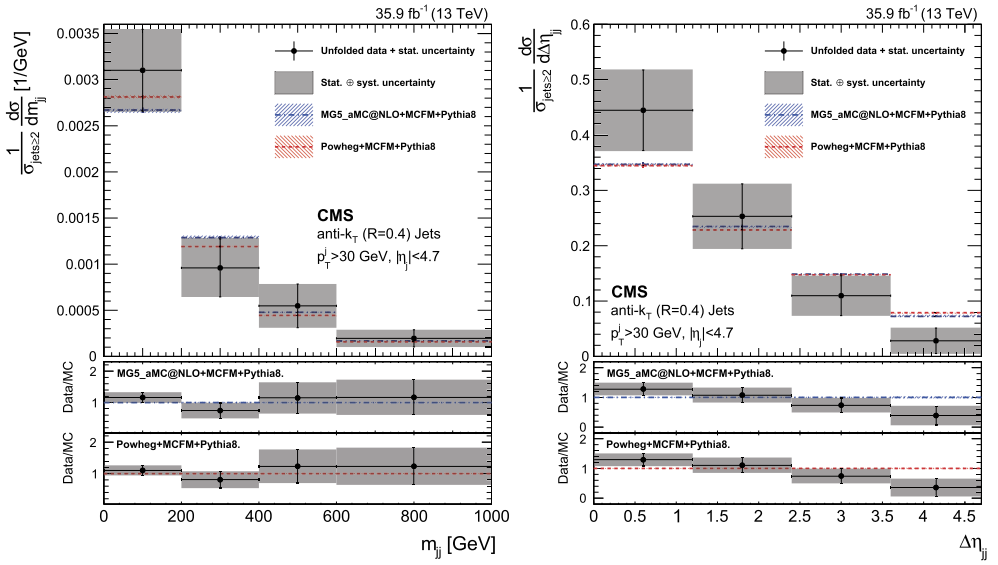

Fig. 6. Differential cross sections normalized to the cross section for $N_{\text{jets}} \geq 2$ of $\text{pp} \to \text{ZZ} \to 4\ell$ at $\sqrt{s} = 13\,\text{TeV}$ as a function of the invariant mass of the two p_{T}-leading jets (left) and their pseudorapidity separation (right). Other details are as described in the caption of Fig. 2.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS and RFBR (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TÜBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the Alfred 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 F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h

project No. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Centre (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] M. Lemoine, M.J.G. Veltman, Radiative corrections to $e^+e^- \to W^+W^-$ in the Weinberg model, Nucl. Phys. B 164 (1980) 445, https://doi.org/10.1016/0550-3213(80)90521-0.

[2] ATLAS Collaboration, Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and ZZγ couplings with the ATLAS detector, J. High Energy Phys. 03 (2013) 128, https://doi.org/10.1007/JHEP03(2013)128, arXiv:1211.6096.

[3] ATLAS Collaboration, Measurement of the ZZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. 116 (2016) 101801, https://doi.org/10.1103/PhysRevLett.116.101801, arXiv:1512.05314.

[4] ATLAS Collaboration, $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ cross-section measurements and search for anomalous triple gauge couplings in 13 TeV pp collisions with the ATLAS detector, Phys. Rev. D 97 (2018) 032005, https://doi.org/10.1103/PhysRevD.97.032005, arXiv:1709.07703.

[5] CMS Collaboration, Measurement of the ZZ production cross section and search for anomalous couplings in $2\ell 2\ell'$ final states in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2013) 063, https://doi.org/10.1007/JHEP01(2013)063, arXiv:1211.4890.

[6] CMS Collaboration, Measurement of the pp $\to$ ZZ production cross section and constraints on anomalous triple gauge couplings in four-lepton final states at $\sqrt{s} = 8$ TeV, Phys. Lett. B 740 (2015) 250, https://doi.org/10.1016/j.physletb.2014.11.059, arXiv:1406.0113, Erratum: https://doi.org/10.1016/j.physletb.2016.04.010.

[7] CMS Collaboration, Measurement of the ZZ production cross section and $Z \to \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B 763 (2016) 280, https://doi.org/10.1016/j.physletb.2016.10.054, arXiv:1607.08834.

[8] CMS Collaboration, Measurements of the pp $\to$ ZZ production cross section and the $Z \to 4\ell$ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 78 (2018) 165, https://doi.org/10.1140/epjc/s10052-018-5567-9, arXiv:1709.08601.

[9] CMS Collaboration, Measurement of vector boson scattering and constraints on anomalous quartic couplings from events with four leptons and two jets in proton–proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B 774 (2017) 682, https://doi.org/10.1016/j.physletb.2017.10.020, arXiv:1708.02812.

[10] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[11] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[12] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[13] J. Alwall, et al., Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, Eur. Phys. J. C 53 (2008) 473, https://doi.org/10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[14] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[15] T. Melia, P. Nason, R. Röntsch, G. Zanderighi, W^+W^-, WZ and ZZ production in the POWHEG BOX, J. High Energy Phys. 11 (2011) 078, https://doi.org/10.1007/JHEP11(2011)078, arXiv:1107.5051.

[16] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[17] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[18] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[19] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061, https://doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.

[20] F. Cascioli, T. Gehrmann, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S. Pozzorini, D. Rathlev, L. Tancredi, E. Weihs, ZZ production at hadron colliders in NNLO QCD, Phys. Lett. B 735 (2014) 311, https://doi.org/10.1016/j.physletb.2014.06.056, arXiv:1405.2219.

[21] J.M. Campbell, R.K. Ellis, MCFM for the Tevatron and the LHC, Nucl. Phys. B, Proc. Suppl. 10 (2010) 205, https://doi.org/10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.

[22] F. Caola, K. Melnikov, R. Röntsch, L. Tancredi, QCD corrections to ZZ production in gluon fusion at the LHC, Phys. Rev. D 92 (2015) 094028, https://doi.org/10.1103/PhysRevD.92.094028, arXiv:1509.06734.

[23] A. Ballestrero, A. Belhouari, G. Bevilacqua, V. Kashkan, E. Maina, PHANTOM: a Monte Carlo event generator for six parton final states at high energy colliders, Comput. Phys. Commun. 180 (2009) 401, https://doi.org/10.1016/j.cpc.2008.10.005, arXiv:0801.3359.

[24] T. Sjöstrand, S. Mrenna, P. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, https://doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[25] CMS Collaboration, Study of the underlying event at forward rapidity in pp collisions at $\sqrt{s} = 0.9$, 2.76, and 7 TeV, J. High Energy Phys. 04 (2013) 072, https://doi.org/10.1007/JHEP04(2013)072, arXiv:1302.2394.

[26] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[27] H.-L. Lai, J. Huston, Z. Li, P. Nadolsky, J. Pumplin, D. Stump, C.P. Yuan, Uncertainty induced by QCD coupling in the CTEQ global analysis of parton distributions, Phys. Rev. D 82 (2010) 054021, https://doi.org/10.1103/PhysRevD.82.054021, arXiv:1004.4624.

[28] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, C.P. Yuan, New parton distributions for collider physics, Phys. Rev. D 82 (2010) 074024, https://doi.org/10.1103/PhysRevD.82.074024, arXiv:1007.2241.

[29] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016) 155, https://doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[30] R.D. Ball, et al., NNPDF Collaboration, Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.

[31] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4 – a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[32] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[33] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[34] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[35] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, https://doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[36] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, https://doi.org/10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[37] M. Cacciari, G.P. Salam, Pileup subtraction using jet areas, Phys. Lett. B 659 (2008) 119, https://doi.org/10.1016/j.physletb.2007.09.077, arXiv:0707.1378.

[38] The ALEPH Collaboration, the DELPHI Collaboration, the L3 Collaboration, the OPAL Collaboration, the SLD Collaboration, the LEP Electoweak Working Group, the SLD Electroweak and Heavy Flavour Groups, Precision electroweak measurements on the Z resonance, Phys. Rep. 427 (2006) 257, https://doi.org/10.1016/j.physrep.2005.12.006.

[39] CMS Collaboration, Measurement of the properties of a Higgs boson in the four-lepton final state, Phys. Rev. D 89 (2014) 092007, https://doi.org/10.1103/PhysRevD.89.092007, arXiv:1312.5353.
[40] CMS Collaboration, Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} =$ 13 TeV, J. High Energy Phys. 11 (2017) 047, https://doi.org/10.1007/JHEP11(2017)047, arXiv:1706.09936.
[41] CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 10 (2011) 132, https://doi.org/10.1007/JHEP10(2011)132, arXiv:1107.4789.
[42] CMS Collaboration, Jet Energy Scale and Resolution Performances with 13 TeV Data, CMS Detector Performance Summary CMS-DP-2016-020, 2016, https://cds.cern.ch/record/2160347.
[43] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
[44] CMS Collaboration, Jet Algorithms Performance in 13 TeV Data, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017, https://cds.cern.ch/record/2256875.
[45] CMS Collaboration, CMS Luminosity Based on Pixel Cluster Counting – Summer 2013 Update, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013, https://cds.cern.ch/record/1598864.
[46] CMS Collaboration, CMS Luminosity Measurements for the 2016 Data Taking Period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017, https://cds.cern.ch/record/2257069.
[47] M. Botje, et al., The PDF4LHC working group interim recommendations, arXiv:1101.0538, 2011.
[48] S. Alekhin, et al., The PDF4LHC working group interim report, arXiv:1101.0536, 2011.
[49] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, https://doi.org/10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
[50] R.D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Impact of heavy quark masses on parton distributions and LHC phenomenology, Nucl. Phys. B 849 (2011) 296, https://doi.org/10.1016/j.nuclphysb.2011.03.021, arXiv:1101.1300.
[51] G. D'Agostini, A multidimensional unfolding method based on Bayes' theorem, Nucl. Instrum. Meth. A 362 (1995) 487, https://doi.org/10.1016/0168-9002(95)00274-X.
[52] T. Adye, Unfolding algorithms and tests using RooUnfold, in: Proceedings, PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, CERN, Geneva, Switzerland, 17–20 January 2011, 2011, p. 313, arXiv:1105.1160.
[53] A. Höcker, V. Kartvelishvili, SVD approach to data unfolding, Nucl. Instrum. Meth. A 372 (1996) 469, https://doi.org/10.1016/0168-9002(95)01478-0, arXiv:hep-ph/9509307.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth [1], V.M. Ghete, J. Hrubec, M. Jeitler [1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck [1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz [1], M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov [2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

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

F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], E. Coelho, E.M. Da Costa, G.G. Da Silveira [4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote [3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja [a], C.A. Bernardes [a], L. Calligaris [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad [b]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

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

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

University of Sofia, Sofia, Bulgaria

W. Fang [5], X. Gao [5], L. Yuan

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen [6], A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

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

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

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov [7], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger [8], M. Finger Jr. [8]

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A. Ellithi Kamel [9], M.A. Mahmoud [10,11], E. Salama [11,12]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam [13], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

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

J.-L. Agram [14], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte [14], J.-C. Fontaine [14], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [15], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili [16]

Georgian Technical University, Tbilisi, Georgia

I. Bagaturia [17]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov [15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier

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

G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl [18]

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras [19], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo [20], A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann [21], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann [18], S.M. Heindl, U. Husemann, F. Kassel [18], I. Katkov [15], S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technology, Germany

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

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

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók [22], M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath [23], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi [†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [24], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [25], C. Kar, P. Mal, K. Mandal, A. Nayak [26], D.K. Sahoo [25], S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj [27], M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep [27], D. Bhowmik, S. Dey, S. Dutt [27], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur [27]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

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

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity [28], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar [28]

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

S. Chenarani [29], E. Eskandari Tadavani, S.M. Etesami [29], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh [30], M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], F. Errico [a,b], L. Fiore [a], A. Gelmi [a,b], G. Iaselli [a,c], M. Ince [a,b], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a], A. Ranieri [a], G. Selvaggi [a,b], A. Sharma [a], L. Silvestris [a], R. Venditti [a], P. Verwilligen [a], G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a,b], S. Braibant-Giacomelli [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], C. Ciocca [a], G. Codispoti [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], F. Iemmi [a,b], S. Marcellini [a], G. Masetti [a], A. Montanari [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b,18], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], K. Chatterjee [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], G. Latino, P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], L. Russo [a,31], G. Sguazzoni [a], D. Strom [a], L. Viliani [a]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro [a], F. Ravera [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia [a], A. Beschi [b], L. Brianza [a,b], F. Brivio [a,b], V. Ciriolo [a,b,18], S. Di Guida [a,b,18], M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M. Malberti [a,b], S. Malvezzi [a], A. Massironi [a,b], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b], D. Zuolo

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], A. Di Crescenzo [a,b], F. Fabozzi [a,c], F. Fienga [a], G. Galati [a], A.O.M. Iorio [a,b], W.A. Khan [a], L. Lista [a], S. Meola [a,d,18], P. Paolucci [a,18], C. Sciacca [a,b], E. Voevodina [a,b]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata, Potenza, Italy*
[d] *Università G. Marconi, Roma, Italy*

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], A. Boletti [a,b], A. Bragagnolo, R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S.Y. Hoh, S. Lacaprara [a], P. Lujan, M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], A. Tiko, E. Torassa [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, Italy*

A. Braghieri [a], A. Magnani [a], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti [a,b], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

L. Alunni Solestizi [a,b], M. Biasini [a,b], G.M. Bilei [a], C. Cecchi [a,b], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], E. Manoni [a], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a], P. Azzurri [a], G. Bagliesi [a], L. Bianchini [a], T. Boccali [a], L. Borrello, R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], G. Fedi [a], F. Fiori [a,c], L. Giannini [a,c], A. Giassi [a], M.T. Grippo [a], F. Ligabue [a,c], E. Manca [a,c], G. Mandorli [a,c], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], N. Daci [a], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] *INFN Sezione di Roma, Rome, Italy*
[b] *Sapienza Università di Roma, Rome, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], F. Cenna [a,b], S. Cometti [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], R. Gomez Ambrosio, B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], F. Vazzoler [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

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

Kyungpook National University, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

J. Goh [32], T.J. Kim

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali [33], F. Mohamad Idris [34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz [35], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

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

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

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

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

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

A. Baginyan, A. Golunov, I. Golutvin, V. Karjavin, I. Kashunin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev [37,38], V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, B.S. Yuldashev [39], A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [40], E. Kuznetsova [41], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva [42], P. Parygin, D. Philippov, S. Polikarpov [42], E. Popova, V. Rusinov

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

V. Andreev, M. Azarkin [38], I. Dremin [38], M. Kirakosyan [38], S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin [43], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov [44], T. Dimova [44], L. Kardapoltsev [44], D. Shtol [44], Y. Skovpen [44]

Novosibirsk State University (NSU), Novosibirsk, Russia

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

State Research Center of Russian Federation, Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino, Russia

A. Babaev, S. Baidali, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic [45], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita [46], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban [21], J. Kieseler, A. Kornmayer, M. Krammer [1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic [47], F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo [18], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi [48], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas [49], A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns [50], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [51], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

T.K. Aarrestad, C. Amsler [52], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.y. Li, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

M.N. Bakirci [53], A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos [54], C. Isik, E.E. Kangal [55], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir [56], S. Ozturk [53], D. Sunar Cerci [57], B. Tali [57], U.G. Tok, H. Topakli [53], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak [58], G. Karapinar [59], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya [60], O. Kaya [61], S. Tekten, E.A. Yetkin [62]

Bogazici University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen [63]

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold [64], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [65], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash [66], A. Nikitenko [7], V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee [18], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

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

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan [67], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Piperov, S. Sagir [68], R. Syarif, E. Usai, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [69], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

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

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

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla [†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro [70], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, V. Sharma, R. Yohay

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

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

M. Alhusseini, B. Bilki [71], W. Clarida, K. Dilsiz [72], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul [73], Y. Onel, F. Ozok [74], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

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

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

University of Tennessee, Knoxville, USA

O. Bouhali [75], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [76], S. Luo, R. Mueller, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[4] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at University of Chinese Academy of Sciences, Beijing, China.
[7] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[8] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[9] Now at Cairo University, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.

[11] Now at British University in Egypt, Cairo, Egypt.
[12] Now at Ain Shams University, Cairo, Egypt.
[13] Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.
[14] Also at Université de Haute Alsace, Mulhouse, France.
[15] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[16] Also at Tbilisi State University, Tbilisi, Georgia.
[17] Also at Ilia State University, Tbilisi, Georgia.
[18] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[19] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[20] Also at University of Hamburg, Hamburg, Germany.
[21] Also at Brandenburg University of Technology, Cottbus, Germany.
[22] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[23] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[24] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[25] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[26] Also at Institute of Physics, Bhubaneswar, India.
[27] Also at Shoolini University, Solan, India.
[28] Also at University of Visva-Bharati, Santiniketan, India.
[29] Also at Isfahan University of Technology, Isfahan, Iran.
[30] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[31] Also at Università degli Studi di Siena, Siena, Italy.
[32] Also at Kyunghee University, Seoul, Republic of Korea.
[33] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[34] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[35] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[36] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[37] Also at Institute for Nuclear Research, Moscow, Russia.
[38] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[39] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[40] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[41] Also at University of Florida, Gainesville, USA.
[42] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[43] Also at California Institute of Technology, Pasadena, USA.
[44] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[45] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[46] Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy.
[47] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[48] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[49] Also at National and Kapodistrian University of Athens, Athens, Greece.
[50] Also at Riga Technical University, Riga, Latvia.
[51] Also at Universität Zürich, Zurich, Switzerland.
[52] Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[53] Also at Gaziosmanpasa University, Tokat, Turkey.
[54] Also at Istanbul Aydin University, Istanbul, Turkey.
[55] Also at Mersin University, Mersin, Turkey.
[56] Also at Piri Reis University, Istanbul, Turkey.
[57] Also at Adiyaman University, Adiyaman, Turkey.
[58] Also at Ozyegin University, Istanbul, Turkey.
[59] Also at Izmir Institute of Technology, Izmir, Turkey.
[60] Also at Marmara University, Istanbul, Turkey.
[61] Also at Kafkas University, Kars, Turkey.
[62] Also at Istanbul Bilgi University, Istanbul, Turkey.
[63] Also at Hacettepe University, Ankara, Turkey.
[64] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[65] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[66] Also at Monash University, Faculty of Science, Clayton, Australia.
[67] Also at Bethel University, St. Paul, USA.
[68] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[69] Also at Utah Valley University, Orem, USA.
[70] Also at Purdue University, West Lafayette, USA.
[71] Also at Beykent University, Istanbul, Turkey.
[72] Also at Bingol University, Bingol, Turkey.
[73] Also at Sinop University, Sinop, Turkey.
[74] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[75] Also at Texas A&M University at Qatar, Doha, Qatar.
[76] Also at Kyungpook National University, Daegu, Republic of Korea.