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

The CMS Collaboration

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 $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e, \mu$. 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.

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 ($\ell = e, \mu$) 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 $\eta$ of the two $p_T$-leading jets, as well as their invariant mass ($m_{jj}$) and pseudorapidity separation ($\Delta \eta_{jj}$), 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 $\Delta \eta_{jj}$ 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 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 $\eta$ 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 $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in $p_T$ and 25–90 (45–150) $\mu$m 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, MadGraph 5 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, Zγ∗, Z, and γ∗γ∗ 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 gg → 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, Zγ, WWZ) as well as t̄Z, t̄t, 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 ZZ* 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 CUEP8M1 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 \( Z \rightarrow e^+e^- \) 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 $p_T > 7\,(5)\,\text{GeV}$ and $|\eta| < 2.5\,(2.4)$. 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

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

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 $\Delta R$ 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 $p_T^{\text{PU}}$, and is obtained with different methods for electrons and muons. For electrons, $p_T^{\text{PU}}$ 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 $p_T^\ell$ and $\eta_\ell$ using the decay products of known resonances decaying to lepton pairs. The measured lepton momentum scale is corrected with a $Z \rightarrow \ell^+ \ell^-$ 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 $J/\psi$ decays as well.

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 $\eta$ 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 $Z/\gamma^*$ candidates, each reconstructed from a pair of isolated electrons or muons of opposite charges. The highest-$p_T$ lepton must have $p_T > 20\text{GeV}$, and the second-highest lepton $p_T^{\ell'} > 10\,(12)\text{ GeV}$ if it is an electron, or $p_T^{\mu} > 10\text{GeV}$ in case of a muon for the analysis at $\sqrt{s} = 8\,(13)\text{ TeV}$. 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 $Z/\gamma^*$ candidates are considered separately. For each 4\ell 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 4\ell candidate are required to have $m_{\ell\ell'} > 4\text{ GeV}$ regardless of their flavor to remove contributions from the decay of low-mass hadron resonances.

If multiple 4\ell 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 $\sqrt{s} = 8\,(13)\text{ TeV}$. 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 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, $pp \rightarrow t\bar{t}Z$ and $pp \rightarrow WWZ$. This contribution is small and is estimated by using the corresponding simulated samples.

The total estimated background yields are $8 \pm 4\,(37 \pm 11)$ 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 4. 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 t̅t 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 q̅q → ZZ and gg → 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 → 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 $\alpha_S$ 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 2µ2e channels are shown in Fig. [1] together with the SM expectations, the estimated backgrounds, and the systematic uncertainty in the prediction.
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.

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>8 TeV data</th>
<th>13 TeV data</th>
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<tbody>
<tr>
<td></td>
<td>Absolute (%)</td>
<td>Normalized (%)</td>
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<td>Trigger</td>
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<tr>
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<td>0.7–5.4</td>
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<tr>
<td>Luminosity</td>
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<td>—</td>
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<tr>
<td>Choice of Monte Carlo generators</td>
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<td>0.2–3.7</td>
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<tr>
<td>qq/gg cross section</td>
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<tr>
<td>PDF</td>
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<td>—</td>
</tr>
<tr>
<td>$\alpha_S$</td>
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<td>&lt;0.1</td>
</tr>
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</table>

Figure 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 $t\bar{t}$ background is obtained from the data.

The differential $pp \rightarrow ZZ \rightarrow \ell\ell\ell'\ell'$ cross section is measured as a function of the jet multiplicity, the $p_T$-leading jet transverse momentum ($p_T^{j_1}$) and pseudorapidity ($\eta_{j_1}$) with the 8 and 13 TeV data. Because of the limited number of events with more than one jet at 8 TeV, the differential cross section as a function of the $p_T$-subleading jet transverse momentum ($p_T^{j_2}$) and pseudorapidity ($\eta_{j_2}$), as well as the invariant mass of the two $p_T$-leading jets ($m_{jj}$) and their pseudorapidity separation ($\Delta \eta_{jj}$) are studied at 13 TeV only. For all measurements we consider jets with $p_T^{j} > 30$ GeV and $|\eta| < 4.7$. For the jet multiplicity distribution we also present the measurements made with central jets ($|\eta| < 2.4$) only. The measurements are performed for the two slightly different phase space regions adopted for the 8 TeV and 13 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.

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

<table>
<thead>
<tr>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
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<tbody>
<tr>
<td>$p_T^\ell &gt; 7$ GeV, $</td>
<td>\eta^\ell</td>
</tr>
<tr>
<td>$p_T^\mu &gt; 5$ GeV, $</td>
<td>\eta^\mu</td>
</tr>
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</table>

Common definitions

- $p_T^\ell_1 > 20$ GeV, $p_T^\ell_2 > 10$ GeV
- $m_{\ell\ell'} > 4$ GeV (any opposite-sign same-flavor pair)
- $60 < (m_{Z_1}, m_{Z_2}) < 120$ GeV

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 (q$\bar{q}$ → ZZ), MCFM (gg → ZZ) and PHANTOM (q$\bar{q}$ → ZZ + 2 jets) for the 8 TeV data set and MG5_aMC@NLO (q$\bar{q}$ → ZZ), MCFM (gg → ZZ) and PHANTOM (q$\bar{q}$ → ZZ + 2 jets) for the 13 TeV data set. In the second one, the POWHEG sample is instead used for the q$\bar{q}$ → 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 pp → ZZ + N jets → $\ell\ell\ell'$ + N jets, for N = 0, 1, 2, and ≥3, are extracted.

The differential cross sections as a function of the jet multiplicity are shown in Fig. 2 for $|\eta| < 4.7$ (upper) and for $|\eta| < 2.4$ (lower). The ratios between the measured and expected distributions from the MadGraph5, MG5_aMC@NLO, and POWHEG set of samples for $\sqrt{s} = 8$ TeV, and POWHEG and MG5_aMC@NLO for $\sqrt{s} = 13$ 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 $\mu_R = \mu_F = m_4$ for POWHEG and $\mu_R = \mu_F = \frac{1}{2} \sum p_T + \sum p_T^\ell$ 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 $\alpha_S$. The measured and expected cross section values for $|\eta| < 4.7$ 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. Figure 3 (top panels) shows the normalized differential cross section as a function of the jet multiplicity, with $|\eta| < 4.7$. The observed fraction of events in the first bin with zero jets is larger than the predicted value, while for 1, 2, and ≥3 jets, the fraction is lower. Better agreement is observed for $|\eta| < 2.4$ (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
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 \( \geq 3 \) 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 ± 1.2 (stat)\(^{+0.9}_{-0.9}\) (syst) ± 0.4 (lumi) | 13.2 \(^{+0.9}_{-0.7}\) |
| 1                                    | 3.2 ± 0.6 (stat)\(^{+0.3}_{-0.3}\) (syst) ± 0.1 (lumi) | 4.0 \(^{+0.3}_{-0.3}\) |
| 2                                    | 0.7 ± 0.3 (stat)\(^{+0.1}_{-0.1}\) (syst) | 1.2 \(^{+0.2}_{-0.1}\) |
| \( \geq 3 \)                        | 0.14 ± 0.1 (stat)\(^{+0.01}_{-0.01}\) (syst) | 0.3 \(^{+0.1}_{-0.1}\) |

Table 4: The \( pp \to ZZ \to \ell\ell\ell' \ell' \) cross section at \( \sqrt{s} = 13 \) TeV as a function of the jet multiplicity. The integrated luminosity uncertainty for the number of jets \( \geq 3 \) 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 (\( |\eta_j| < 4.7 \)) | Cross section [fb] | Theoretical cross section [fb] |
|--------------------------------------|--------------------|-----------------------------|
| 0                                    | 28.3 ± 1.3 (stat)\(^{+1.5}_{-1.5}\) (syst) ± 0.7 (lumi) | 23.6 \(^{+0.8}_{-0.9}\) |
| 1                                    | 8.0 ± 0.8 (stat)\(^{+0.7}_{-0.7}\) (syst) ± 0.2 (lumi) | 9.7 \(^{+0.3}_{-0.3}\) |
| 2                                    | 3.0 ± 0.5 (stat)\(^{+0.3}_{-0.3}\) (syst) ± 0.1 (lumi) | 4.0 \(^{+0.3}_{-0.3}\) |
| \( \geq 3 \)                        | 1.3 ± 0.4 (stat)\(^{+0.2}_{-0.2}\) (syst) | 1.7 \(^{+0.1}_{-0.1}\) |

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 transverse 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.

Figure 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 \( N_{jets} \geq 1 \). Figures 5 and 6 show the cross section at 13 TeV as a function of several variables for events with \( N_{jets} \geq 2 \), 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. 6 displays the differential cross section as a function of \( m_{jj} \) and \( \Delta \eta_{jj} \).

Overall agreement is observed between data and theoretical predictions for all measurements related to the \( p_T \)-leading and subleading jets. The \( \Delta \eta_{jj} \) 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 func-
Figure 2: Differential cross sections of $pp \rightarrow ZZ \rightarrow 4\ell$ 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.
Figure 3: Differential cross sections normalized to the cross section of pp → ZZ → 4ℓ as a function of the multiplicity of jets with |η_j| < 4.7 (top panels) and |η_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.
Figure 4: Differential cross sections normalized to the cross section for $N_{\text{jets}} \geq 1$ of $pp \to ZZ \to 4\ell$ 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].
Figure 5: Differential cross sections normalized to the cross section for \( N_{\text{jets}} \geq 2 \) of \( pp \to ZZ \to 4\ell \) 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.

Figure 6: Differential cross sections normalized to the cross section for \( N_{\text{jets}} \geq 2 \) of \( pp \to ZZ \to 4\ell \) 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.
tion 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 $\geq 3$. 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.

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grama 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).

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A  The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, 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, SandraS. Padula a, D. Romero Abad b

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia,
Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang\textsuperscript{5}, X. Gao\textsuperscript{5}, L. Yuan

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov\textsuperscript{7}, T. Susa

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Finger\textsuperscript{8}, M. Finger Jr.\textsuperscript{8}

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A. Ellithi Kamel\textsuperscript{9}, M.A. Mahmoud\textsuperscript{10,11}, E. Salama\textsuperscript{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehattah, M. Kadastik, M. Raidal, C. Veelken
Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

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

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

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

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

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

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Tbilisi State University, Tbilisi, Georgia
I. Bagaturia

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

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

Deutsches Elektronen-Synchrotron, Hamburg, Germany

University of Hamburg, Hamburg, Germany

Karlsruher Institut fuer Technology

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

National and Kapodistrian University of Athens, Athens, Greece

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

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

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Tórcsanyi, B. Ujjvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

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

Panjab University, Chandigarh, India

University of Delhi, Delhi, 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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khazad, M. Mohammadi Najafabadi, M. Nasiri, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, A. Sharma\textsuperscript{a}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwilligen\textsuperscript{a}, G. Zito\textsuperscript{d}

\textbf{INFN Sezione di Bologna} \textsuperscript{a}, Università di Bologna \textsuperscript{b}, Bologna, Italy
G. Abbiendi\textsuperscript{a}, C. Battilana\textsuperscript{a,b}, D. Bonacorsia\textsuperscript{a,b}, L. Borgonovi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, R. Campaninid\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, S.S. Chhibra\textsuperscript{a,b}, C. Ciocca\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, F. Iemmi\textsuperscript{a,b}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, A. Montanari\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, A. Perrotta\textsuperscript{a}, F. Primavera\textsuperscript{a,b,18}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{a}

\textbf{INFN Sezione di Catania} \textsuperscript{a}, Università di Catania \textsuperscript{b}, Catania, Italy
S. Albero\textsuperscript{a,b}, A. Di Mattia\textsuperscript{a}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

\textbf{INFN Sezione di Firenze} \textsuperscript{a}, Università di Firenze \textsuperscript{b}, Firenze, Italy
G. Barbaglia\textsuperscript{a}, K. Chatterjee\textsuperscript{a,b}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, G. Latino, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, L. Russo\textsuperscript{a,b,31}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Viliani\textsuperscript{a}

\textbf{INFN Laboratori Nazionali di Frascati, Frascati, Italy}
L. Benussi, S. Bianco, F. Fabbrì, D. Piccolo

\textbf{INFN Sezione di Genova} \textsuperscript{a}, Università di Genova \textsuperscript{b}, Genova, Italy
F. Ferro\textsuperscript{a}, F. Ravera\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

\textbf{INFN Sezione di Milano-Bicocca} \textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy
A. Benaglia\textsuperscript{a}, A. Beschi\textsuperscript{a}, L. Brianza\textsuperscript{a,b}, F. Brivio\textsuperscript{a,b}, V. Ciriolo\textsuperscript{a,b,18}, S. Di Guida\textsuperscript{a,d,18}, M.E. Dinardo\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M. Malberti\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, A. Massironi\textsuperscript{a,b}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, T. Tabarelli de Fatis\textsuperscript{a,b}, D. Zuolo

\textbf{INFN Sezione di Napoli} \textsuperscript{a}, Università di Napoli ‘Federico II’ \textsuperscript{b}, Napoli, Italy, Università della Basilicata \textsuperscript{c}, Potenza, Italy, Università G. Marconi \textsuperscript{d}, Roma, Italy
S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, A. Di Crescenzo\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a}, G. Galati\textsuperscript{a}, A.O.M. Iorio\textsuperscript{a,b}, W.A. Khan\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,18}, P. Paolucci\textsuperscript{a,18}, C. Sciacca\textsuperscript{a,b}, E. Voevodina\textsuperscript{a,b}

\textbf{INFN Sezione di Padova} \textsuperscript{a}, Università di Padova \textsuperscript{b}, Padova, Italy, Università di Trento \textsuperscript{c}, Trento, Italy
P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a}, D. Bisello\textsuperscript{a,b}, A. Boletti\textsuperscript{a,b}, A. Bragagnolo, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, M. Dall’Osso\textsuperscript{a,b}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Gasparini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, S.Y. Hoh, S. Lapcun\textsuperscript{a}, P. Lujan, M. Massignon\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Fazzini\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, R. Rossini\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, A. Tiko, E. Torassa\textsuperscript{a}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

\textbf{INFN Sezione di Pavia} \textsuperscript{a}, Università di Pavia \textsuperscript{b}, Pavia, Italy
A. Braghieri\textsuperscript{a}, A. Magnani\textsuperscript{a}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}

\textbf{INFN Sezione di Perugia} \textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy
L. Alunni Solestizi\textsuperscript{a,b}, M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fanò\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardii\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, P. Spiga\textsuperscript{a}
INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy

INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy

INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, F. Vazzoler, A. Zanetti

Kyoungpook National University

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J. Goh, T.J. Kim

Korea University, Seoul, Korea

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea

University of Seoul, Seoul, Korea

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

Universidad de Sonora (UNISON), Hermosillo, Mexico
A. Castaneda Hernandez, J.A. Murillo Quijada

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

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

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

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

Joint Institute for Nuclear Research, Dubna, Russia

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

Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, 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

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
M. Chadeeva, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, M. Dubinin, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, T. Dimova, L. Kardapoltsev, D. Shtol, Y. Skovpen

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

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

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

Universität Zürich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

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

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

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek
Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya\textsuperscript{60}, O. Kaya\textsuperscript{61}, S. Tekten, E.A. Yetkin\textsuperscript{62}

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen\textsuperscript{63}

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

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

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

Catholic University of America, Washington DC, USA
R. Bartek, A. Domínguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

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

Brown University, Providence, USA

University of California, Davis, USA
University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA

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

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA

University of Colorado Boulder, Boulder, 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

Cornell University, Ithaca, USA

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA
Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA

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

The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros
University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA

Northeastern University, Boston, USA

Northwestern University, Evanston, USA

University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

University of Rochester, Rochester, USA

Rutgers, The State University of New Jersey, Piscataway, USA
University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA

Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, 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

Wayne State University, Detroit, USA

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, 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, Korea