EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-145
2021/03/02

CMS-SMP-19-001

Measurements of pp $\to$ ZZ production cross sections and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

arXiv:2009.01186v3 [hep-ex] 1 Mar 2021

Abstract

The production of Z boson pairs in proton-proton (pp) collisions, pp $\to$ $(\text{Z}/\gamma^*)(\text{Z}/\gamma^*) \to 2\ell 2\ell'$, where ℓ, ℓ' = e or μ, is studied at a center-of-mass energy of 13 TeV with the CMS detector at the CERN LHC. The data sample corresponds to an integrated luminosity of 137 fb^{-1}, collected during 2016–2018. The ZZ production cross section, $\sigma_{\text{tot}}(\text{pp} \to \text{ZZ}) = 17.4 \pm 0.3\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})\,\text{pb}$, measured for events with two pairs of opposite-sign, same-flavor leptons produced in the mass region $60 < m_{\ell^+\ell^-} < 120\,\text{GeV}$ is consistent with standard model predictions. Differential cross sections are also measured and agree with theoretical predictions. The invariant mass distribution of the four-lepton system is used to set limits on anomalous ZZZ and ZZγ couplings.

"Published in the European Physical Journal C as doi:10.1140/epjc/s10052-020-08817-8."

© 2021 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members

1 Introduction

Measurements of diboson production in proton-proton (pp) collisions, such as Z boson pair (ZZ) production, at the CERN LHC allow precision tests of the standard model (SM). In the SM, ZZ production proceeds mainly through quark-antiquark t- and u-channel scattering diagrams. In calculations at higher orders in quantum chromodynamics (QCD), gluon-gluon fusion also contributes via box diagrams with quark loops. There are no tree-level contributions to ZZ production from triple gauge boson vertices in the SM. Anomalous triple gauge couplings (aTGC) ZZZ and ZZγ are introduced using an effective Lagrangian following Ref. [1]. In this parametrization, two ZZZ and two ZZγ couplings are allowed by the electromagnetic gauge invariance and Lorentz invariance for on-shell Z bosons and are parametrized by two CP-violating (f_4^{V}) and two CP-conserving (f_5^{V}) parameters, where $\mathrm{V} = (\mathrm{Z}, \gamma)$. Nonzero aTGC values could be induced by new physics models such as supersymmetry [2]. The results can be also expressed in terms of parameters calculated within the effective field theory (EFT) framework, per convention used in Ref. [3] and references therein. In contrast to the anomalous couplings of electroweak (EW) vector bosons, the EFT framework allows an unambiguous calculation of loop effects and provides a simpler interpretation of the results than the aTGC framework.

Previous measurements of the production cross section for pairs of on-shell Z bosons at the LHC were performed by the CMS Collaboration with data sets corresponding to integrated luminosities of 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV [4] and 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV [5, 6] in the $\mathrm{ZZ} \to 2\ell 2\ell''$ and $\mathrm{ZZ} \to 2\ell 2\nu$ decay channels, where $\ell =$ e or μ and $\ell'' =$ e, μ, or τ; and with an integrated luminosity of 2.6 fb^{-1} [7] and 35.9 fb^{-1} [8] at $\sqrt{s} = 13$ TeV in the $\mathrm{ZZ} \to 2\ell 2\ell'$ decay channel, where $\ell' =$ e or μ. All of the results agree with SM predictions. The ATLAS Collaboration reported similar results at $\sqrt{s} = 7$, 8, and 13 TeV [9–14], which also agree with SM predictions. These measurements are important to test predictions that were recently made available at next-to-next-to-leading order (NNLO) in QCD [15–17]. A comparison of these predictions with data for a range of center-of-mass energies provides an insight into the structure of the EW gauge sector of the SM.

This paper reports a study of the ZZ production in the four-lepton decay channel ($\mathrm{pp} \to 2\ell 2\ell'$, where 2ℓ and $2\ell'$ indicate pairs of opposite-sign electrons or muons) at $\sqrt{s} = 13$ TeV, with a data set corresponding to an integrated luminosity of 137 fb^{-1} recorded in 2016–2018. Both Z bosons are selected to be on-shell, defined as the mass range 60–120 GeV. Fiducial and total cross sections are measured, differential cross sections are presented as a function of different kinematic variables. The invariant mass distribution of the four-lepton system is used to search for anomalous ZZZ and ZZγ couplings.

2 The CMS detector

A 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. [18].

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 a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, which provide coverage in pseudorapidity $|\eta| < 1.479$ in a cylindrical barrel and $1.479 < |\eta| < 3.0$ in two endcap regions. Forward calorimeters extend the coverage provided by the barrel and endcap detectors to $|\eta| < 5.0$. Muons are detected in gas-ionization

detectors embedded in the steel flux-return yoke outside the solenoid in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers.

Electron momenta are estimated by combining energy measurements in the ECAL with momentum measurements in the tracker. The momentum resolution for electrons with transverse momentum $p_T \approx 45\,\text{GeV}$ 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 [19]. Matching muons to tracks identified in the silicon tracker results in a p_T resolution for muons with $20 < p_T < 100\,\text{GeV}$ 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 [20, 21].

Events of interest are selected using a two-tiered trigger system [22]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

3 Signal and background simulation

Several Monte Carlo (MC) samples are used in the analysis to optimize the selection, calculate the signal efficiency, and estimate background contamination. The PYTHIA 8.226 and 8.230 [23, 24] packages are used for parton showering, hadronization, and the underlying event simulation with the CUETP8M1 tune [25] and the parton distribution function (PDF) NNPDF23_lo_as_0130 [26] for the 2016 data-taking period, and the CP5 tune [27] and the NNPDF 31_nnlo_as_0118 PDF for the 2017 and 2018 data-taking periods.

Signal events are generated with POWHEG 2.0 [24, 28–31] at next-to-leading order (NLO) in QCD for quark-antiquark ($q\bar{q}$) processes and leading order (LO) for quark-gluon processes. This includes ZZ, $Z\gamma^*$, Z, $\gamma^*\gamma^*$ with a constraint of $m_{\ell\ell'} > 4\,\text{GeV}$ applied to all pairs of oppositely charged leptons at the generator level to avoid infrared divergences. The gluon-gluon loop-induced process, $gg \to ZZ$, is simulated at LO with MCFM v7.0 [32]. It also includes interference with the SM Higgs off-shell production. The SM Higgs decay is modeled with JHUGEN 3.1.8 [33–35] at LO. The cross sections are scaled to correspond to cross section values calculated at NNLO in QCD for $q\bar{q} \to ZZ$ [15] (with a K factor of 1.1) and at NLO in QCD for $gg \to ZZ$ [36] (K factor of 1.7). Electroweak ZZ production in association with two jets is generated with MADGRAPH [37] at LO. It amounts to approximately 1% of the total number of ZZ events.

Simulated events for the irreducible background processes containing four prompt leptons in the final state, such as $t\bar{t}Z$, WWZ, WZZ, and ZZZ, where the last three are combined and denoted as VVV, are generated with MADGRAPH5_aMC@NLO v2.4.2 [37] at NLO with zero or one outgoing partons in the matrix element calculation and merged with the parton shower using the FXFX scheme [38]. The same MC is used for WZ simulation.

Event samples with aTGC contributions included are generated at LO with SHERPA v2.1.1 [39]. The distributions from the SHERPA samples are normalized such that the total yield of the SM sample is the same as that of the POWHEG+MCFM sample. More details are discussed in Section 10.

The detector response is simulated using a detailed description of the CMS detector imple-

mented with the GEANT4 package [40]. The reconstruction in simulation and data uses the same algorithms. The simulated samples include additional interactions per bunch crossing, referred to as pileup. The simulated events are weighted so that the pileup distribution matches the data.

Results are also compared to fixed-order predictions produced via the MATRIX framework [41], a parton-level MC generator that uses tree and one-loop amplitudes from OpenLoops 2 [42] and two-loop amplitudes from Ref. [43], capable of producing differential predictions at up to NNLO in QCD and NLO in EW, as implemented in MATRIX v2.0.0_beta1 [44]. The calculation is performed with the NNPDF31_nnlo_as_0118_luxqed [45] PDF set with dynamic renormalization (μ_R) and factorization scales (μ_F) set to the four lepton mass for the differential and fiducial predictions, and with fixed scale set to the nominal Z boson mass for the total cross section. The quark-induced processes are calculated at NNLO in QCD and NLO in EW. The gluon-induced contribution is calculated at NLO in QCD [46]. Photon-induced contributions are also included at up to NLO EW. The calculation uses massless leptons, which leads to a divergence at low dilepton mass. To avoid this divergence, we impose the requirement $p_T^\ell > 5\,\text{GeV}$ on the photon-induced component for total cross section predictions. With this condition, the photon-induced contribution is less than 1% of the total production rate. The quark-induced NNLO QCD and NLO EW contributions are combined multiplicatively, and the gluon- and photon-induced contributions are combined additively following the procedure described in Ref. [44]. The predictions reported here are consistent with those published in Refs. [15–17].

4 Event reconstruction

Individual particles—electrons, muons, photons, charged and neutral hadrons—in each collision event are identified and reconstructed with the CMS particle-flow (PF) algorithm [47] from a combination of signals from all subdetectors. Reconstructed electrons [19] and muons [20] are considered as lepton candidates if they have $p_T^e > 7\,\text{GeV}$ and $|\eta^e| < 2.5$ or $p_T^\mu > 5\,\text{GeV}$ and $|\eta^\mu| < 2.4$.

Lepton candidates are also required to originate from the primary vertex, defined as the reconstructed pp interaction vertex with the largest value of summed physics object p_T^2. The physics objects used in the primary vertex definition are the objects returned by a jet-finding algorithm [48, 49] applied to all charged tracks associated with the vertex. The distance of closest approach between each lepton track and the primary vertex is required to be less than 0.5 cm in the plane transverse to the beam axis, and less than 1 cm in the direction along the beam axis. Furthermore, the significance of the three-dimensional impact parameter relative to the primary vertex, SIP_{3D}, is required to satisfy $\text{SIP}_{3D} \equiv |\text{IP}/\sigma_{\text{IP}}| < 4$ for each lepton, where IP is the distance of closest approach of each lepton track to the primary vertex and σ_{IP} is its associated uncertainty.

Lepton candidates are required to be isolated from other particles in the event. 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 identified by the PF algorithm, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 0.3$ around the lepton momentum direction, where φ is the azimuthal angle in radians. 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 contribution of neutral particles from pileup is $p_{\mathrm{T}}^{\mathrm{PU}}$. For electrons, $p_{\mathrm{T}}^{\mathrm{PU}}$ is evaluated with the "jet area" method described in Ref. [50]; for muons, it is half of the summed p_{T} of all charged particles in the cone originating from pileup vertices. The average factor of one half accounts for the expected ratio of neutral to charged particle production in hadronic interactions. A lepton is considered isolated if $R_{\mathrm{iso}} < 0.35$.

The lepton reconstruction, identification, and isolation efficiencies are measured with a "tag-and-probe" technique [51] applied to a sample of $\mathrm{Z} \to \ell^+\ell^-$ data events. The measurements are performed in several bins of p_{T}^{ℓ} and $|\eta^{\ell}|$. The electron reconstruction and selection efficiency in the ECAL barrel (endcaps) varies from about 85 (77)% at $p_{\mathrm{T}}^{\mathrm{e}} \approx 10\,\mathrm{GeV}$ to about 95 (89)% for $p_{\mathrm{T}}^{\mathrm{e}} \geq 20\,\mathrm{GeV}$, whereas in the barrel-endcap transition region this efficiency is about 85% averaged over electrons with $p_{\mathrm{T}}^{\mathrm{e}} > 7\,\mathrm{GeV}$. The muons are reconstructed and identified with efficiencies above ~98% within $|\eta^{\mu}| < 2.4$.

5 Event selection

The primary triggers for this analysis require the presence of a pair of loosely isolated leptons of the same or different flavors [22]. The highest p_{T} lepton must have $p_{\mathrm{T}}^{\ell} > 17\,\mathrm{GeV}$, and the subleading lepton must have $p_{\mathrm{T}}^{\mathrm{e}} > 12\,\mathrm{GeV}$ if it is an electron or $p_{\mathrm{T}}^{\mu} > 8\,\mathrm{GeV}$ if it is a muon. The tracks of the triggering leptons are required to originate within 2 mm of each other in the plane transverse to the beam axis. Triggers requiring a triplet of lower-p_{T} leptons with no isolation criteria, or a single high-p_{T} electron or muon, are also used. An event is accepted if it passes any trigger regardless of the decay channel. The total trigger efficiency for events within the acceptance of this analysis is greater than 98%.

The four-lepton candidate selection is based on the one used in the recent CMS Higgs boson measurement [52]. A signal event must contain at least two Z/γ^* candidates, each formed from an oppositely charged pair of isolated electron or muon candidates. Among the four leptons, the highest p_{T} lepton must have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, and the second-highest p_{T} lepton must have $p_{\mathrm{T}}^{\mathrm{e}} > 12\,\mathrm{GeV}$ if it is an electron or $p_{\mathrm{T}}^{\mu} > 10\,\mathrm{GeV}$ if it is a muon. All leptons are required to be separated from each other by $\Delta R\,(\ell_1, \ell_2) > 0.02$, and electrons are required to be separated from muons by $\Delta R\,(\mathrm{e}, \mu) > 0.05$.

Within each event, all permutations of leptons giving a valid pair of Z/γ^* candidates are considered separately. Within each four-lepton candidate, the dilepton candidate with an invariant mass closest to 91.2 GeV, taken as the nominal Z boson mass [53], is denoted Z_1 and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2 and is required to have a mass greater than 4 GeV. Both m_{Z_1} and m_{Z_2} are required to be less than 120 GeV. All pairs of oppositely charged leptons in the four-lepton candidate are required to have $m_{\ell\ell'} > 4\,\mathrm{GeV}$ regardless of their flavor. In the rare case of further ambiguity, which occurs in less than 0.5% of events when five or more passing lepton candidates are found, the Z_2 candidate that maximizes the scalar p_{T} sum of the four leptons is chosen.

The $\mathrm{pp} \to \mathrm{ZZ}$ cross section is measured using events where both m_{Z_1} and m_{Z_2} are greater than 60 GeV. Decays of the Z bosons to τ leptons with subsequent decays to electrons and muons are heavily suppressed by the requirements on lepton p_{T}, and the contribution of such events is less than 0.5% of the total ZZ yield. If these events pass the selection requirements of the analysis, they are considered signal, although they are not considered at generator level in the cross section measurement procedure. Thus, the correction for possible τ decays is included in the efficiency calculation.

6 Background estimation

The requirement of four well-reconstructed and isolated lepton candidates strongly suppresses any background; therefore this analysis has very low background contributions, dominated by Z boson and WZ diboson production in association with jets, and by $\mathrm{t\bar{t}}$ production. In a small fraction of cases, particles from jet fragmentation satisfy both lepton identification and isolation criteria, and thus are misidentified as signal leptons. This background is estimated using control data samples, as decribed below.

The probability for such objects to be selected is measured from a sample of Z+$\ell_{\text{candidate}}$ events, where Z denotes a pair of oppositely charged, same-flavor leptons that pass all analysis requirements and satisfy $|m_{\ell^+\ell^-} - m_{\mathrm{Z}}| < 10\,\text{GeV}$, where m_{Z} is the nominal Z boson mass. Each event in this sample must have exactly one additional object $\ell_{\text{candidate}}$ that passes relaxed identification requirements with no isolation requirements applied. The misidentification probability for each lepton flavor, measured in bins of lepton candidate p_{T} and η, is defined as the ratio between the number of candidates that pass the final isolation and identification requirements and the total number of candidates in the sample. The number of Z+$\ell_{\text{candidate}}$ events is corrected for the contamination from WZ production and for ZZ events in which one lepton is not reconstructed. These events have a third genuine, isolated lepton that must be excluded from the misidentification probability calculation. The WZ contamination is suppressed by requiring the missing transverse momentum $p_{\mathrm{T}}^{\text{miss}}$ to be below 25 GeV. The $p_{\mathrm{T}}^{\text{miss}}$ is defined as the magnitude of the missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\text{miss}}$, the projection onto the plane transverse to the beams of the negative vector sum of the momenta of all reconstructed PF candidates in the event, corrected for the jet energy scale. The transverse mass, calculated as $m_{\mathrm{T}} \equiv \sqrt{(p_{\mathrm{T}}^{\ell} + p_{\mathrm{T}}^{\text{miss}})^2 - (\vec{p}_{\mathrm{T}}^{\,\ell} + \vec{p}_{\mathrm{T}}^{\,\text{miss}})^2}$, is required to be less than 30 GeV. The residual contribution of WZ and ZZ events, which can be up to a few percent of the events with $\ell_{\text{candidate}}$ passing all selection criteria, is estimated from simulation and subtracted.

To account for all sources of background events, two control samples are used to estimate the number of background events in the signal regions. Both are defined as samples that contain events with a dilepton candidate satisfying all requirements (Z_1) and two additional lepton candidates $\ell^+\ell^-$. In one control sample, enriched in WZ events, one ℓ candidate is required to satisfy the full identification and isolation criteria and the other must fail the full criteria and instead satisfy only the relaxed ones; in the other, enriched in Z+jets events, both ℓ candidates must satisfy the relaxed criteria, but fail the full criteria. The additional leptons must have opposite charges and the same flavor ($\mathrm{e^{\pm}e^{\mp}}$ and $\mu^{\pm}\mu^{\mp}$). From this set of events, the expected number of background events in the signal region, denoted "Z+X" in the figures, is obtained by scaling the number of observed $\mathrm{Z}_1 + \ell^+\ell^-$ events by the misidentification probability for each lepton failing the selection. The procedure is described in more detail in Ref. [54].

In addition to this reducible background, which contributes to approximately 1–2% of the ZZ events, the $\mathrm{t\bar{t}Z}$ and VVV processes with four prompt leptons are estimated from simulated samples to be around 1–1.5% of the expected $\mathrm{ZZ} \to 2\ell 2\ell'$ yield. The total background contributions to the $\mathrm{ZZ} \to 2\ell 2\ell'$ signal regions are summarized in Section 8.

7 Systematic uncertainties

The major sources of systematic uncertainty and their effect on the measured cross sections are summarized in Table 1. The lepton identification, isolation, and track reconstruction efficiencies in simulation are corrected with scaling factors derived with a tag-and-probe method and applied as a function of lepton p_{T} and η. To estimate the uncertainties associated with the tag-

and-probe technique, the total yield is recomputed with the scaling factors varied up and down by the tag-and-probe fit uncertainties. The uncertainties associated with the lepton efficiency in the $ZZ \to 2\ell 2\ell'$ signal regions are 5% in the 4e, 3% in the 2e2μ, and 2% in the 4μ final states.

In both data and simulated event samples, trigger efficiencies are evaluated with a tag-and-probe technique. The ratio of the trigger efficiency estimated using data to the one estimated with simulation is applied to simulated events, and the size of the resulting change in the expected yield is taken as the uncertainty in the determination of the trigger efficiency. This uncertainty is around 1–2% of the final estimated yield.

Table 1: The contributions of each source of systematic uncertainty in the cross section measurements. The integrated luminosity uncertainty, and the PDF and scale uncertainties, are considered separately. All other uncertainties are added in quadrature into a single systematic uncertainty. Uncertainties that vary by decay channel are listed as ranges.

Uncertainty	Range of values
Lepton efficiency	2–5%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
μ_R, μ_F	1%
PDF	1%
NNLO/NLO corrections	1%
Integrated luminosity	2.5% (2016), 2.3% (2017), 2.5% (2018)

The largest uncertainty in the estimated background yield arises from differences in sample composition between the $Z+\ell_{\text{candidate}}$ control sample used to calculate the lepton misidentification probability and the $Z + \ell^+\ell^-$ control sample. An additional uncertainty arises from the limited number of events in the $Z+\ell_{\text{candidate}}$ sample. A systematic uncertainty of 40% is applied to the lepton misidentification probability to cover both effects. Its impact varies by channel, but is of the order of 1% of the total expected yield.

The modeling of pileup relies on the total inelastic pp cross section [55]. The pileup uncertainty is evaluated by varying this cross section up and down by 5%.

Uncertainties because of factorization (μ_F) and renormalization (μ_R) scale choices on the $ZZ \to 2\ell 2\ell'$ acceptance are evaluated with POWHEG+MCFM by varying μ_F and μ_R up and down by a factor of two with respect to the default values $\mu_F = \mu_R = m_{ZZ}$, where m_{ZZ} is the invariant mass of the ZZ system. All combinations are considered except those in which μ_F and μ_R differ by a factor of four. Parametric uncertainties (PDF+α_S) are evaluated according to the PDF4LHC prescription [56] in the acceptance calculation, and with NNPDF3.0 [57] in the cross section calculations. An additional theoretical uncertainty arises from scaling the POWHEG $q\bar{q} \to ZZ$ simulated sample from its NLO cross section to the NNLO prediction, and the MCFM $gg \to ZZ$ samples from their LO cross sections to the NLO predictions. The change in the acceptance corresponding to this scaling procedure is about 1%.

The uncertainty in the integrated luminosity of the data samples is 2.5% (2016) [58], 2.3% (2017) [59], and 2.5% (2018) [60]. Since the luminosity uncertainty contains a significant uncorrelated portion, the relative luminosity uncertainty of the whole sample is smaller than for each individual year.

The same uncertainties are valid for both total and differential cross section measurements,

but for the differential one there is also an additional uncertainty related to the unfolding procedure described in Section 9. It is estimated using MADGRAPH5_aMC@NLO instead of POWHEG+MCFM in unfolding. The unfolding uncertainty is included in the results and plots together with other uncertainites, but its effect is small compared to the statistical uncertainties of the measurement.

8 Cross section measurement

The p_T and η distributions for individual leptons are shown in Fig. 1. Both distributions contain four leptons per event. The invariant mass of the ZZ system, the individual mass of reconstructed Z boson candidates in the ZZ events, and their corresponding p_T distributions are shown in Fig. 2. The last bins in m_{ZZ} and all p_T distributions contain events from the overflow. The m_Z and Z p_T distributions contain two Z candidates for each event. These distributions are shown for data and simulated events to demonstrate comparisons with SM expectations. The signal expectations include contributions from ZZ production shown separately for $q\bar{q} \to ZZ$, $gg \to ZZ$, and EW ZZ processes in all figures and combined as "Signal" in Table 2. The EW ZZ production contributes to approximately 1% of the total number of ZZ events.

The irreducible background, which amounts to 1–1.5% of the total ZZ yield, and reducible background are combined as "Background" in Table 2. The total background in this analysis is $\approx 3\%$. The estimated yields agree well with the measured ones. The individual distributions are well described, except the m_{ZZ} distribution at high values of invariant masses and the p_T^Z distribution at high values of p_T. These are regions where the EW corrections may become important and will be discussed later in Section 10.

Table 2: Observed and expected prefit yields of ZZ events, and estimated yields of background events, shown for each final state and combined. The statistical (first) and systematic (second) uncertainties are presented.

Process	eeee	ee$\mu\mu$	$\mu\mu\mu\mu$	$2\ell 2\ell'$
		2016		
Background	$6.7 \pm 0.6 \pm 1.8$	$11.4 \pm 0.8 \pm 1.9$	$5.5 \pm 0.5 \pm 0.9$	$23.6 \pm 1.1 \pm 4.1$
Signal	$167.7 \pm 1.0 \pm 10.0$	$434.2 \pm 1.6 \pm 17.3$	$273.3 \pm 1.3 \pm 8.2$	$875.2 \pm 2.3 \pm 31.1$
Total expected	$174.4 \pm 1.2 \pm 10.4$	$445.6 \pm 1.8 \pm 17.7$	$278.8 \pm 1.4 \pm 8.4$	$898.8 \pm 2.6 \pm 32.0$
Data	176	478	296	950
		2017		
Background	$6.3 \pm 0.4 \pm 1.5$	$12.1 \pm 0.8 \pm 1.8$	$7.9 \pm 0.7 \pm 1.6$	$26.3 \pm 1.2 \pm 4.5$
Signal	$200.8 \pm 0.3 \pm 12.0$	$511.7 \pm 0.6 \pm 20.4$	$322.5 \pm 0.5 \pm 9.6$	$1035.0 \pm 0.8 \pm 36.9$
Total expected	$207.1 \pm 0.6 \pm 12.4$	$523.8 \pm 1.0 \pm 20.9$	$330.4 \pm 0.8 \pm 9.9$	$1061.3 \pm 1.4 \pm 38.0$
Data	193	540	328	1061
		2018		
Background	$9.9 \pm 0.6 \pm 2.5$	$23.2 \pm 1.1 \pm 4.2$	$15.6 \pm 1.1 \pm 4.0$	$48.7 \pm 1.7 \pm 9.7$
Signal	$305.2 \pm 0.4 \pm 18.2$	$758.5 \pm 0.8 \pm 30.1$	$467.3 \pm 0.6 \pm 13.9$	$1531.0 \pm 1.0 \pm 54.7$
Total expected	$315.1 \pm 0.8 \pm 18.7$	$781.7 \pm 1.4 \pm 31.1$	$482.9 \pm 1.3 \pm 14.8$	$1579.7 \pm 2.0 \pm 56.6$
Data	309	797	480	1586

The measured yields are used to evaluate the ZZ production cross section in the fiducial phase space. The signal acceptance is evaluated from simulation and corrected for each individual lepton flavor in bins of p_T and η using factors obtained with the tag-and-probe technique. To include all final states in the cross section calculation, a simultaneous fit to the number of ob-

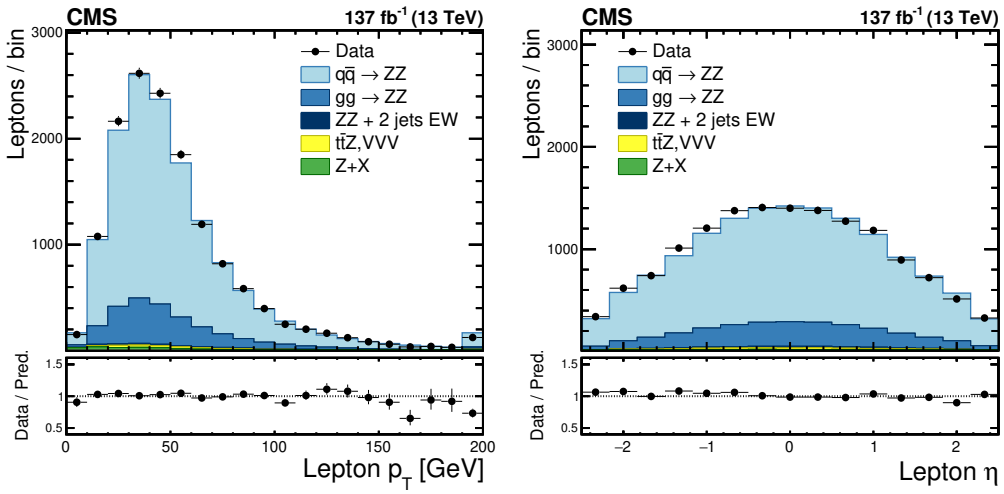


Figure 1: Distributions of (left) transverse momentum and (right) pseudorapidity for individual leptons. Points represent the data with error bars showing the statistical uncertainties, histograms the expected SM predictions and reducible background estimated from data. The p_{T} distributions includes overflow in the last bin.

served events in all decay channels is performed. The likelihood is composed as a combination of individual channel likelihoods for the signal and background hypotheses with the statistical and systematic uncertainties treated as scaling nuisance parameters. The combination of various data-taking periods is performed treating the theoretical uncertainties as fully correlated among various periods, whereas the experimental uncertainties are either correlated or uncorrelated, depending on their origin.

The fiducial phase space for the $\mathrm{ZZ} \to 2\ell 2\ell'$ cross section measurement is defined as: $p_{\mathrm{T}}^{\ell_1} > 20\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell_2} > 10\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\ell_{3,4}} > 5\,\mathrm{GeV}$, $|\eta^{\ell}| < 2.5$, $m_{2\ell} > 4\,\mathrm{GeV}$ (any opposite-sign same-flavor pair), $60 < m_{\mathrm{Z}_1}, m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$. The generator-level leptons used for the fiducial cross section calculation are "dressed" by adding the momenta of generator-level photons within $\Delta R\,(\ell, \gamma) < 0.1$ from the lepton momenta directions.

Table 3: Measured fiducial cross section for each data sample and combined. The first uncertainty is statistical, the second is experimental systematic, and the third is associated with the integrated luminosity.

Year	Fiducial cross section, fb
2016	$42.0 \pm 1.4\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})^{+1.1}_{-1.0}\,(\mathrm{lumi})$
2017	$39.6 \pm 1.2\,(\mathrm{stat})^{+1.3}_{-1.2}\,(\mathrm{syst})^{+1.0}_{-0.9}\,(\mathrm{lumi})$
2018	$39.7 \pm 1.0\,(\mathrm{stat})^{+1.3}_{-1.1}\,(\mathrm{syst}) \pm 1.0\,(\mathrm{lumi})$
Combined	$40.5 \pm 0.7\,(\mathrm{stat}) \pm 1.1\,(\mathrm{syst}) \pm 0.7\,(\mathrm{lumi})$

The measured ZZ fiducial cross section presented in Table 3 can be compared to $39.3^{+0.8}_{-0.7} \pm 0.6\,\mathrm{fb}$ calculated with POWHEG+MCFM using the same settings as the simulated samples with K factors applied. The first uncertainty corresponds to the factorization and renormalization scales and the second to PDF, as described above. The POWHEG calculations used dynamic factorization and renormalization scales $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = m_{2\ell 2\ell'}$, whereas the contribution from MCFM is computed with dynamic scales $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = 0.5 m_{2\ell 2\ell'}$. It can also be compared to the prediction from MATRIX v2.0.0_beta1 of $38.0^{+1.1}_{-1.0}$. The uncertainty in the MATRIX prediction includes only the uncertainty due to the variation of μ_{F} and μ_{R}.

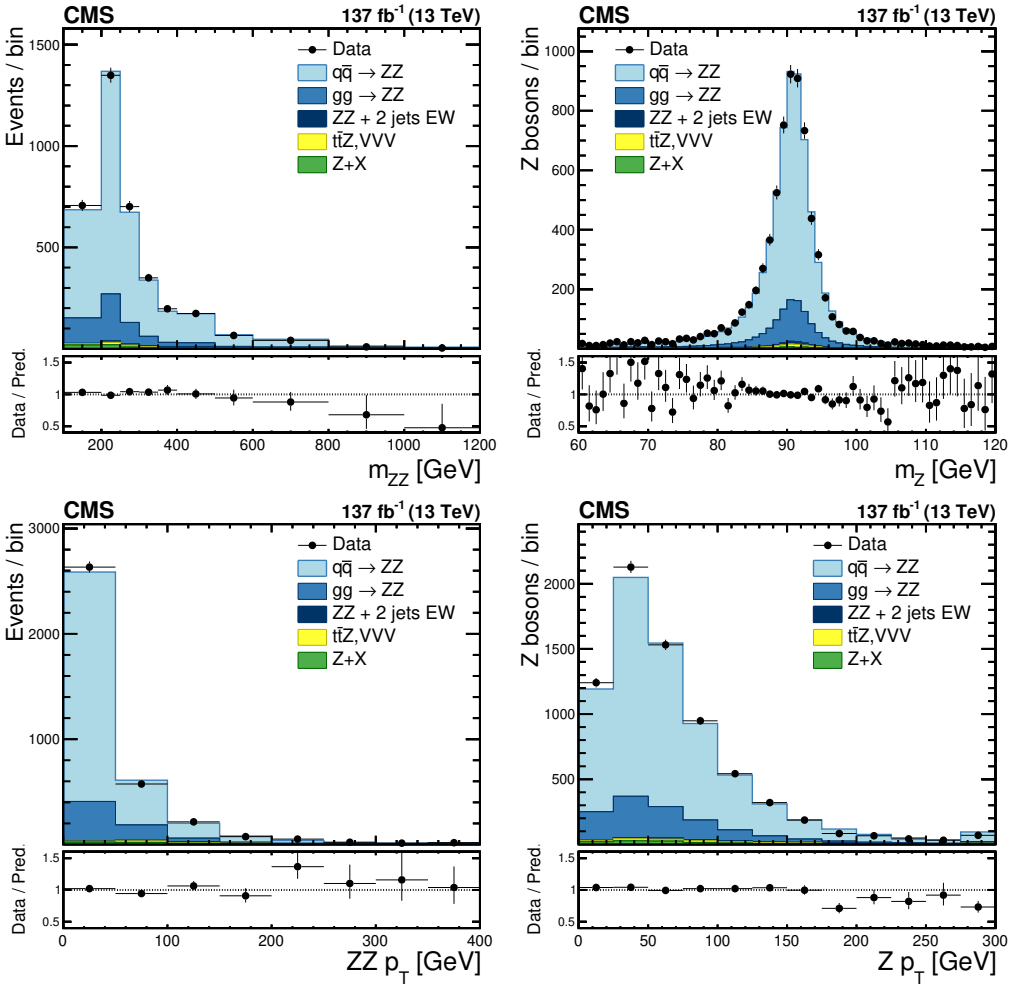


Figure 2: Distributions of (upper left) m_{ZZ} for ZZ events with $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$; (upper right) mass of selected Z boson candidates; (lower left) transverse momentum of the ZZ system; (lower right) transverse momentum of individual Z boson candidates. Points represent the data with error bars showing the statistical uncertainties, histograms the expected SM predictions and reducible background estimated from data. All p_T and m_{ZZ} distributions include overflow in the last bin.

Table 4: Measured total $\sigma(pp \to ZZ)$ cross section for each data sample and combined. The first uncertainty is statistical, the second is experimental systematic, the third is theoretical systematic. The fourth uncertainty is associated with the integrated luminosity.

Year	Total cross section, pb
2016	$18.1 \pm 0.6\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo})^{+0.5}_{-0.4}\,(\text{lumi})$
2017	$17.0 \pm 0.5\,(\text{stat})^{+0.6}_{-0.5}\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
2018	$17.1 \pm 0.4\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.4\,(\text{lumi})$
Combined	$17.4 \pm 0.3\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})$

The total ZZ production cross section for both dileptons produced in the mass range 60–120 GeV and $m_{\ell^+\ell'^-} > 4$ GeV is presented in Table 4. The nominal branching fraction $\mathcal{B}(Z \to \ell^+\ell^-) = 0.03366$ is used [53]. The measured total cross section can be compared to the theoretical value of $16.9^{+0.6}_{-0.5} \pm 0.2$ pb, calculated from POWHEG+MCFM with the same settings that is used for $\sigma_{\text{fid}}(pp \to ZZ \to 2\ell 2\ell')$. It can also be compared to $16.5^{+0.6}_{-0.5}$ pb, calculated with MATRIX v2.0.0_beta1, or $15.0^{+0.7}_{-0.6} \pm 0.2$ pb, calculated with MCFM at NLO in QCD with additional contributions from LO $gg \to ZZ$ diagrams and with the NLO NNPDF3.0 PDF set and fixed factorization and renormalization scales set to $\mu_F = \mu_R = m_Z$.

The total ZZ cross section is shown in Fig. 3 as a function of the pp center-of-mass energy. Results from CMS [4, 5] and ATLAS [9, 10, 14] are compared to predictions from MATRIX v2.0.0_beta1 and MCFM. The uncertainties are statistical (inner bars) and statistical and systematic combined, as obtained from the fit (outer bars). The band around the MATRIX predictions reflects scale uncertainties, while the band around the MCFM predictions reflects both scale and PDF uncertainties.

9 Differential cross sections

The differential distributions normalized to the fiducial cross sections are presented in Figs. 4–6 for the combination of the 4e, 2e2μ, and 4μ decay channels using the whole data sample. The fiducial cross section definition includes p_T^ℓ and $|\eta^\ell|$ selections on each lepton, and the 60–120 GeV mass requirement, as described in Section 4. Figure 4 shows the differential cross sections in bins of p_T for: (left) all leptons in the event, (right) both Z bosons in the event, and in Fig. 5 (left) for the p_T of the ZZ system. Figure 5 (right) shows the normalized $d\sigma/dm_{ZZ}$ distribution. All p_T and m_{ZZ} distributions include overflow in the last bin. Figure 6 shows the angular correlations between Z bosons. The data are corrected for background contributions and unfolded for detector effects using a matrix inversion method without regularization as described in Ref. [61], and compared with the theoretical predictions from POWHEG+MCFM, MADGRAPH5_aMC@NLO+MCFM and MATRIX. The distributions include both Z boson candidates or all four leptons, where applicable, and are normalized to the numbers of objects in the event and to the fiducial cross section. The bottom part of each plot shows the ratio of the measured to the predicted values. The bin sizes are chosen according to the resolution of the relevant variables, trying also to keep the statistical uncertainties at a similar level for all the bins.

The distributions predicted by POWHEG+MCFM and MADGRAPH5_aMC@NLO+MCFM agree well with data, except for m_{ZZ}. This distribution shows a small overestimate in the cross section at high invariant masses. The MATRIX predictions describe this region better, which can be explained by the presence of the EW corrections in the MATRIX calculations. The effect of EW corrections is in detail discussed in Ref. [44] and can reach 20–30% for $m_{ZZ} = 1$ TeV. On the other hand, the MATRIX predictions show some deviation from the measurements as a function of p_T^{ZZ} and for the azimuthal separation between the two Z bosons, which is not observed for POWHEG+MCFM and MADGRAPH5_aMC@NLO+MCFM predictions.

10 Limits on anomalous triple gauge couplings

The presence of aTGCs is expected to increase the event yield at high four-lepton masses. Figure 7 presents the distribution of the four-lepton reconstructed mass for the combined 4e, 2e2μ, and 4μ channels, for the SM and an example of nonzero aTGC value with f_4^γ=0, and f_4^Z=0.0015.

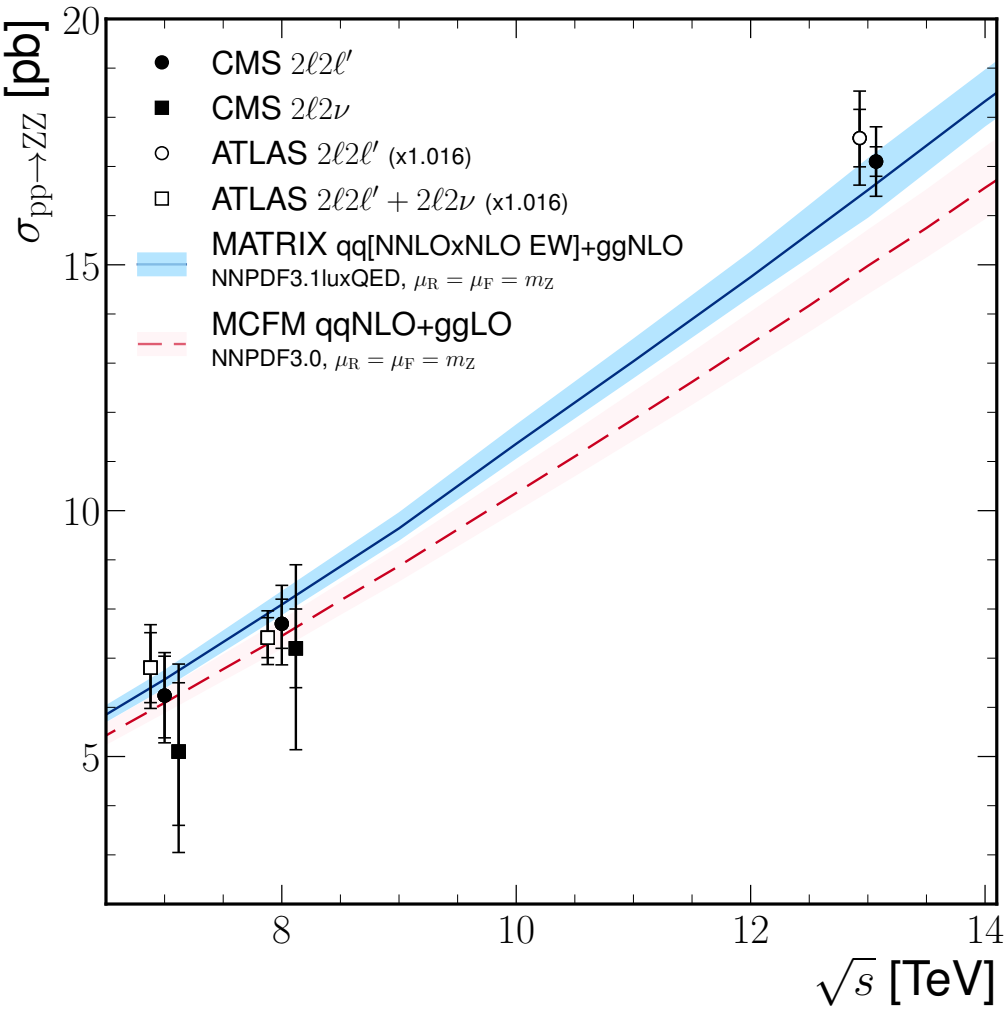


Figure 3: The total ZZ cross section as a function of the proton-proton center-of-mass energy. Results from the CMS [4, 5] and ATLAS [9, 10, 14] experiments are compared to predictions from MATRIX at NNLO in QCD and NLO in EW, and MCFM at NLO in QCD. The MCFM prediction also includes gluon-gluon initiated production at LO in QCD. The predictions use NNPDF31_nnlo_as_0118_luxqed and NNPDF3.0 PDF sets, respectively, and fixed factorization and renormalization scales $\mu_F = \mu_R = m_Z$. Details of the calculations and uncertainties are given in the text. The ATLAS measurements were performed with a Z boson mass window of 66–116 GeV, instead of 60–120 GeV used by CMS, and are corrected for the resulting 1.6% difference in acceptance. Measurements at the same center-of-mass energy are shifted slightly along the horizontal axis for clarity.

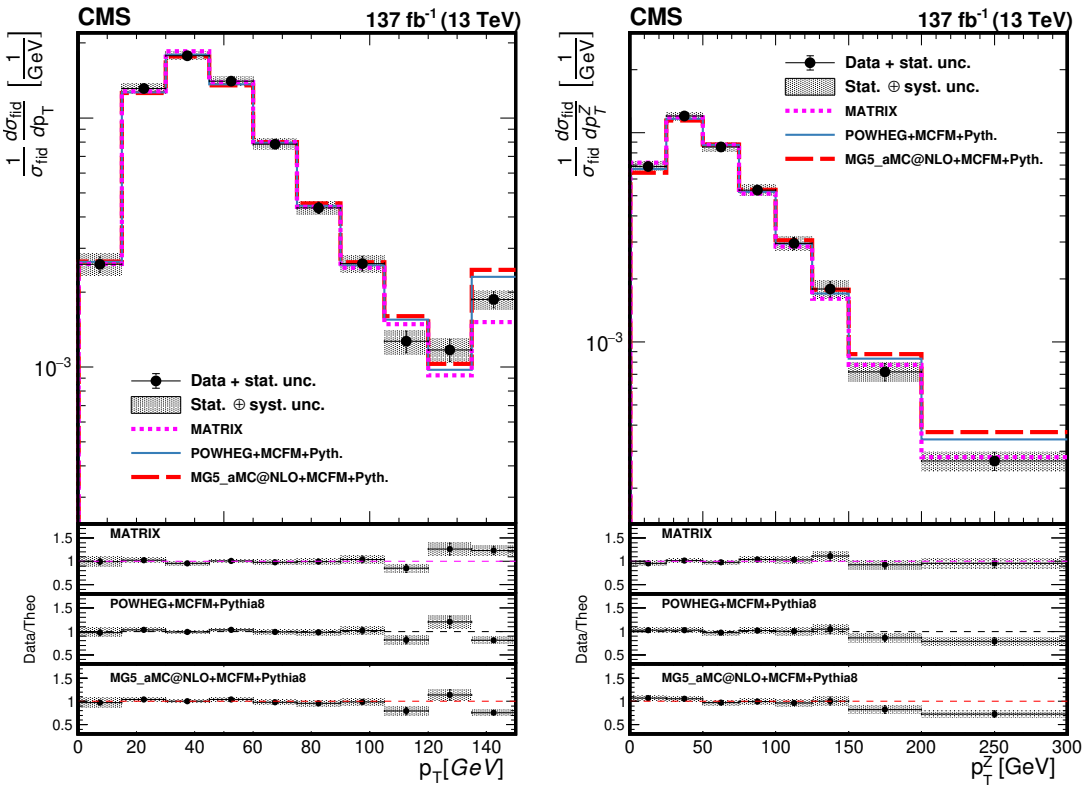


Figure 4: Differential cross sections normalized to the fiducial cross section for the combined 4e, 2e2μ, and 4μ decay channels as a function of p_{T} for (left) all leptons, (right) all Z bosons in the event. The points represent the unfolded data with error bars showing the statistical uncertainties, the shaded histogram the POWHEG+MCFM ZZ predictions, and the dashed curves correspond to the results of the MATRIX and MADGRAPH5_aMC@NLO+MCFM calculations. The three lower panels represent the ratio of the measured cross section to the expected distributions from MATRIX, POWHEG+MCFM and MADGRAPH5_aMC@NLO+MCFM. The shaded areas in all the panels represent the full uncertainties calculated as the quadratic sum of the statistical and systematic uncertainties, whereas the crosses represent only the statistical uncertainties.

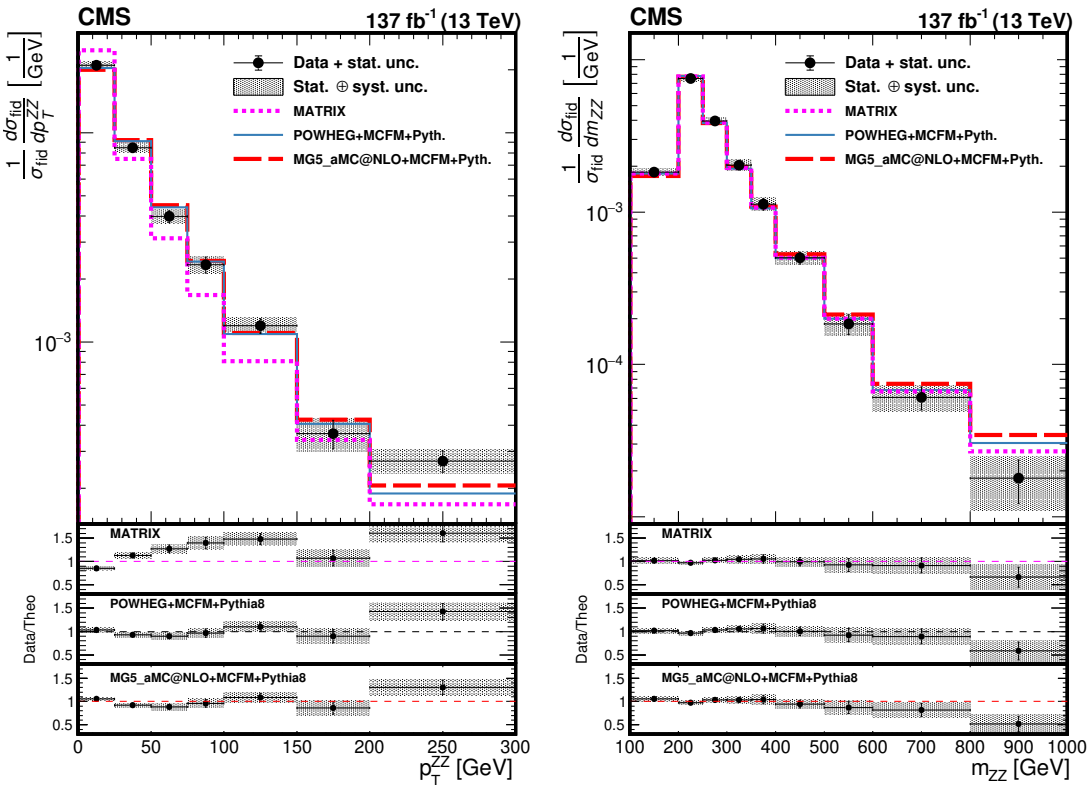


Figure 5: Differential cross sections normalized to the fiducial cross section for the combined 4e, 2e2μ, and 4μ decay channels as a function of (left) p_{T} of the ZZ system, (right) the invariant mass of the ZZ system. The points represent the unfolded data with error bars showing the statistical uncertainties, shaded histogram the POWHEG+MCFM ZZ predictions, and the dashed curves correspond to the results of the MATRIX and MADGRAPH5_aMC@NLO+MCFM calculations. The three lower panels represent the ratio of the measured cross section to the expected distributions from MATRIX, POWHEG+MCFM and MADGRAPH5_aMC@NLO+MCFM. The shaded areas in all the panels represent the full uncertainties calculated as the quadratic sum of the statistical and systematic uncertainties, whereas the crosses represent only the statistical uncertainties.

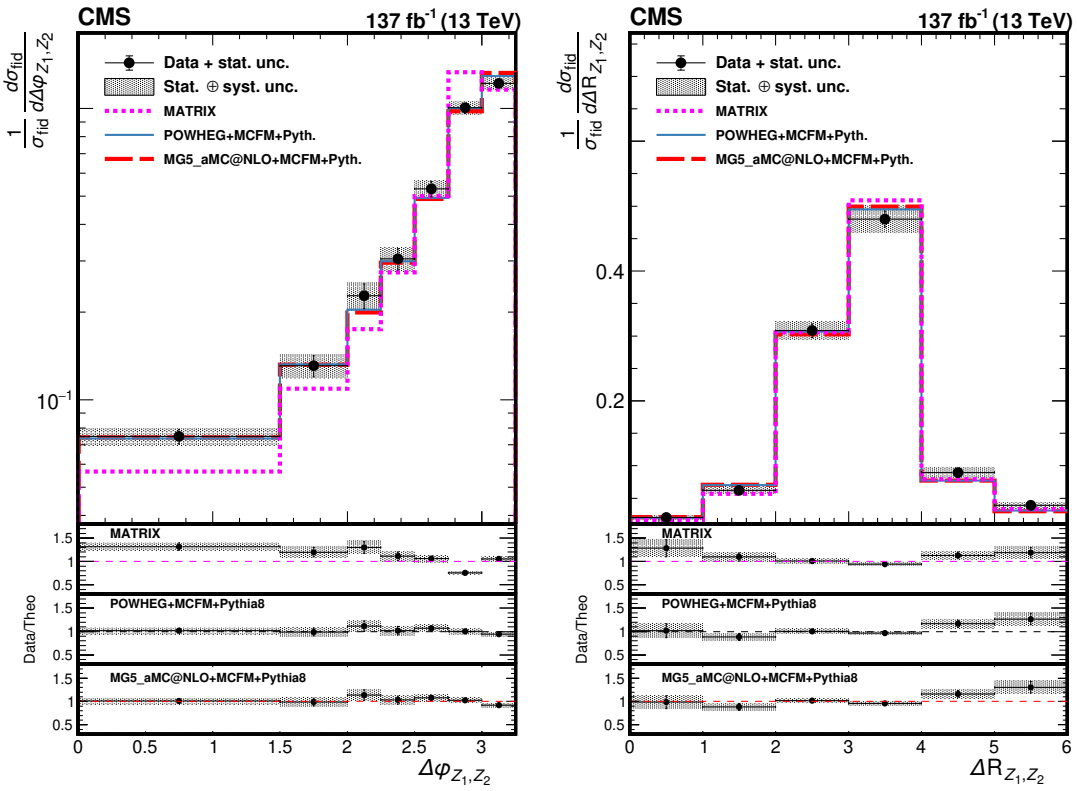


Figure 6: Differential cross sections normalized to the fiducial cross section for the combined 4e, 2e2μ, and 4μ decay channels as a function of the azimuthal (left) and ΔR (right) separation of the two Z bosons. The points represent the unfolded data with error bars showing the statistical uncertainties, the shaded histogram the POWHEG+MCFM ZZ predictions, and the dashed curves correspond to the results of the MATRIX and MADGRAPH5_aMC@NLO+MCFM calculations. The three lower panels represent the ratio of the measured cross section to the expected distributions from MATRIX, POWHEG+MCFM and MADGRAPH5_aMC@NLO+MCFM. The shaded areas in all the panels represent the full uncertainties calculated as the quadratic sum of the statistical and systematic uncertainties, whereas the crosses represent only the statistical uncertainties.

Limits on aTGCs are derived from fits to this distribution. The shaded histograms represent the SM predictions as described in the previous sections and the dashed curve shows the SHERPA prediction. The SHERPA SM predictions are normalized to the POWHEG+MCFM predictions including K factors and agree well with them in shape, as shown in Fig. 7. As a cross-check of the procedure, the SHERPA SM distribution was also corrected bin-by-bin to the POWHEG+MCFM distribution, no difference was observed in the extracted limits. The presence of aTGC contribution increases the expected event yields at masses above 1300 GeV. In the fit, described below, this region is subdivided into two bins: 1300–2000 GeV and above 2000 GeV. Typically 60–70% of the aTGC events have masses above 2000 GeV, whereas the expected SM contribution is approximately 2.4 and 0.2 events in the 1300–2000 GeV and above 2000 GeV bins, respectively.

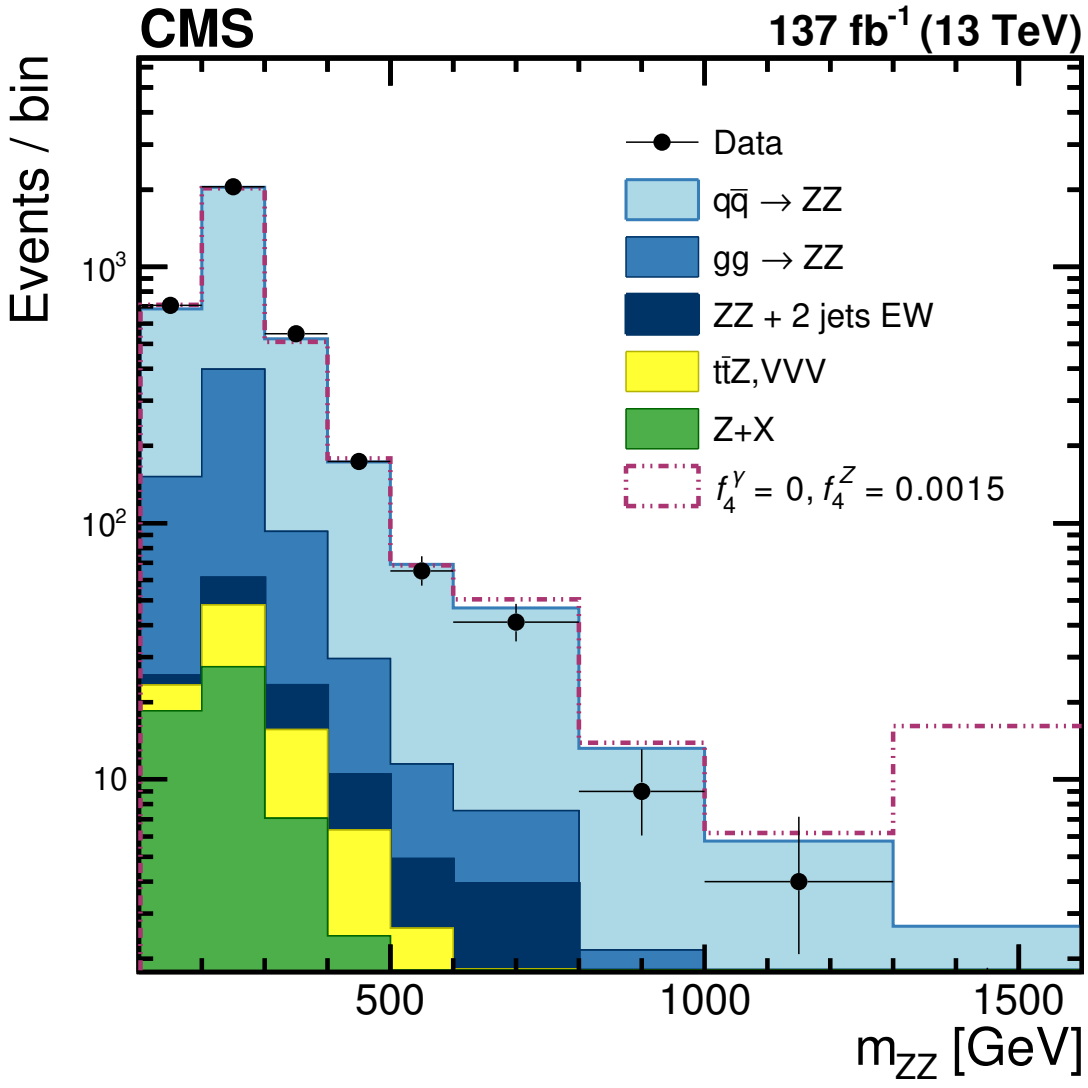


Figure 7: Distribution of the reconstructed ZZ mass for the combined 4e, 2e2μ, and 4μ channels. Points represent the data with error bars showing the statistical uncertainties, the shaded histograms represent the SM prediction including signal and irreducible background from simulation, and the reducible background estimate from data. Dashed histogram represents an example of the aTGC signal. The last bin includes contribution from all events with mass above 1300 GeV.

The invariant mass distributions are interpolated from those obtained from the SHERPA simula-

tion for different values of the anomalous couplings in the range between 0 and 0.03. For each distribution, only one or two couplings are varied while all others are set to zero, thus creating a grid of points in the (f_4^Z, f_4^γ) and (f_5^Z, f_5^γ) parameter planes and the corresponding invariant mass distributions. In each m_{ZZ} bin, expected signal values are interpolated between the two-dimensional grid points using a second-order polynomial, since the cross section for the signal depends quadratically on the coupling parameters. A simultaneous fit to the values of aTGCs is performed for all lepton channels, see Ref. [62] for details. A profile likelihood method [53], Wald Gaussian approximation, and Wilks theorem [63] are used to derive one- (1D) and two-dimensional limits at 68 and 95% confidence levels (CL) on each of the aTGC parameters and combination of two of them, while all other parameters are set to their SM values. All systematic uncertainties are included by varying the number of expected signal and background events within their uncertainties. An additional 10% uncertainty is applied on the predictions of the SM and aTGC models to account for possible differences between model predictions and the interpolation used in the fit. No form factor [64] is used when deriving the limits; the results assume that the energy scale of new physics is very high. The constraints on anomalous couplings are displayed in Fig. 8. The curves indicate 68 and 95% CL contours; the dots indicate where the likelihoods reach their maximum. Coupling values outside the contours are excluded at the corresponding CL. The crosses in the middle represent the observed 1D limits that are summarized in Table 5. The sensitivity is dominated by the statistical uncertainties.

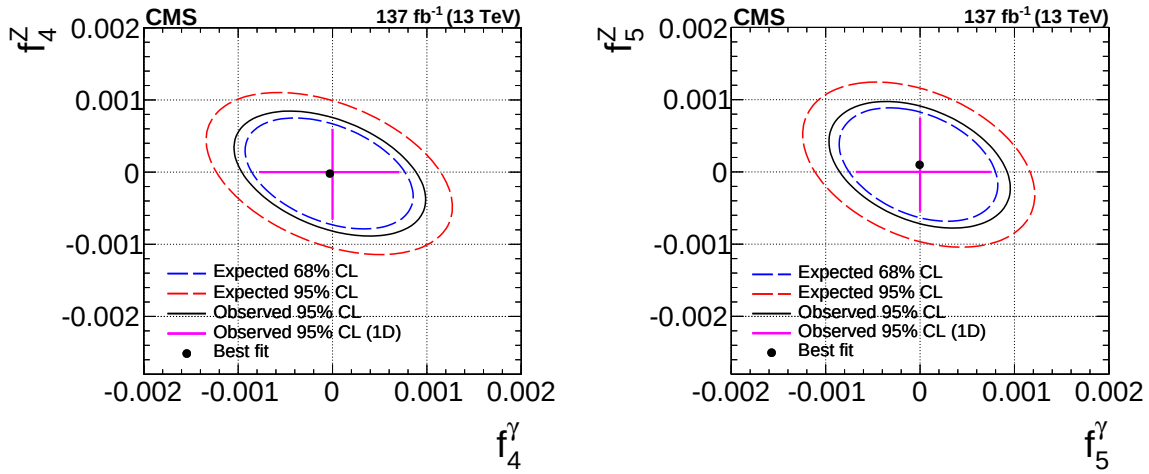


Figure 8: Two-dimensional observed (solid) and expected (dashed) contours exclusion limits at 95% CL, and at 68 and 95% CL, respectively, on the ZZZ and ZZγ aTGCs. The plots show the exclusion contours in the $(f_{4(5)}^Z, f_{4(5)}^\gamma)$ parameter planes. Dots show where the likelihoods reach their maximum. The coupling values outside the contours are excluded at the corresponding confidence level. The crosses in the middle represent the observed 1D limits. No form factor is used.

Complete one-loop EW corrections to massive vector boson pair production [66, 67] were applied as a cross-check. The EW corrections to the ZZ production cause the ZZ mass spectrum to fall more rapidly at large masses. In addition, the overall cross section decreases by about 4%. The effect of NLO EW corrections is estimated by reweighting the SM SHERPA sample as a function of m_{ZZ} using weights derived from the calculations described in Ref. [66]. This reweighting improves the expected limits by about 4–6%, whereas there is no effect on the observed limits. This is expected, since only the SM contribution is subject to the EW corrections; they are not applied on aTGCs. The limits are driven by the high mass tail above 1300 GeV. In this region the aTGC signal is much larger than the SM, and therefore the EW correction on the

Table 5: Expected and observed one-dimensional 95% CL limits on aTGC parameters. The corresponding constrains on EFT parameters are estimated using the transformation from Ref. [65].

	Expected 95% CL	Observed 95% CL
aTGC parameter	$\times 10^{-4}$	$\times 10^{-4}$
f_4^Z	-8.8 ; 8.3	-6.6 ; 6.0
f_5^Z	-8.0 ; 9.9	-5.5 ; 7.5
f_4^γ	-9.9 ; 9.5	-7.8 ; 7.1
f_5^γ	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV^{-4}	TeV^{-4}
$C_{\tilde{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
C_{WW}/Λ^4	-1.7 ; 1.6	-1.4 ; 1.2
C_{BW}/Λ^4	-1.8 ; 1.9	-1.4 ; 1.3
C_{BB}/Λ^4	-1.6 ; 1.6	-1.2 ; 1.2

SM part has a very small effect on the predictions of the SM+aTGC model. This correction is much smaller than the uncertainty we apply in the fit procedure.

These results can be also expressed in terms of EFT parameters. The numerical relations between aTGCs and EFT parameters are given in Ref. [65]. The expected and measured limits in terms of EFT are presented in Table 5.

11 Summary

Four-lepton final states have been studied in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ with the CMS detector at the CERN LHC. The data sample corresponds to an integrated luminosity of $137\,\text{fb}^{-1}$, collected during 2016–2018. The measured $\text{pp} \to \text{ZZ}$ total cross section is $\sigma_{\text{tot}}(\text{pp} \to \text{ZZ}) = 17.4 \pm 0.3\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.4\,(\text{theo}) \pm 0.3\,(\text{lumi})\,\text{pb}$, where the Z boson masses are in the range $60 < m_Z < 120\,\text{GeV}$. The results agree with the SM predictions, discussed in Section 8. The differential cross sections also agree well with the SM predictions. Improved limits on anomalous ZZZ and ZZγ triple gauge couplings are established. These are the most stringent limits to date on anomalous ZZZ and ZZγ triple gauge couplings and they improve the previous strictest results from CMS by ≈30–40%.

Acknowledgments

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: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT 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); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (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 Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306; 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, 125105, 128713, 128786, and 129058 (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 Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); 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 Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] K. Hagiwara, R. D. Peccei, and D. Zeppenfeld, "Probing the weak boson sector in $e^+e^- \to W^+W^-$", *Nucl. Phys. B* **282** (1987) 253, doi:10.1016/0550-3213(87)90685-7.

[2] G. J. Gounaris, J. Layssac, and F. M. Renard, "New and standard physics contributions to anomalous Z and γ self-couplings", *Phys. Rev. D* **62** (2000) 073013, doi:10.1103/PhysRevD.62.073013, arXiv:hep-ph/0003143.

[3] C. Degrande et al., "Effective field theory: a modern approach to anomalous couplings", *Annals Phys.* **335** (2013) 21, doi:10.1016/j.aop.2013.04.016, arXiv:1205.4231.

[4] 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", *JHEP* **01** (2013) 063, doi:10.1007/JHEP01(2013)063, arXiv:1211.4890.

[5] 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, doi:10.1016/j.physletb.2014.11.059, arXiv:1406.0113. [Corrigenum: doi:10.1016/j.physletb.2016.04.010].

[6] CMS Collaboration, "Measurements of the ZZ production cross sections in the $2\ell 2\nu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV and combined constraints on triple gauge couplings", *Eur. Phys. J. C* **75** (2015) 511, doi:10.1140/epjc/s10052-015-3706-0, arXiv:1503.05467.

[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, doi: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, doi:10.1140/epjc/s10052-018-5567-9, arXiv:1709.08601. [Erratum: doi:10.1140/epjc/s10052-018-5769-1].

[9] 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", *JHEP* **03** (2013) 128, doi:10.1007/JHEP03(2013)128, arXiv:1211.6096.

[10] ATLAS Collaboration, "Measurements of four-lepton production in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *Phys. Lett. B* **753** (2016) 552, doi:10.1016/j.physletb.2015.12.048, arXiv:1509.07844.

[11] 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, doi:10.1103/PhysRevLett.116.101801, arXiv:1512.05314.

[12] ATLAS Collaboration, "Measurement of the four-lepton invariant mass spectrum in 13 TeV proton-proton collisions with the ATLAS detector", *JHEP* **04** (2019) 048, doi:10.1007/JHEP04(2019)048, arXiv:1902.05892.

[13] ATLAS Collaboration, "Measurement of ZZ production in the $\ell\ell\nu\nu$ final state with the ATLAS detector in pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **10** (2019) 127, doi:10.1007/JHEP10(2019)127, arXiv:1905.07163.

[14] 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, doi:10.1103/PhysRevD.97.032005, arXiv:1709.07703.

[15] F. Cascioli et al., "ZZ production at hadron colliders in NNLO QCD", *Phys. Lett. B* **735** (2014) 311, doi:10.1016/j.physletb.2014.06.056, arXiv:1405.2219.

[16] M. Grazzini, S. Kallweit, and D. Rathlev, "ZZ production at the LHC: fiducial cross sections and distributions in NNLO QCD", *Phys. Lett. B* **750** (2015) 407, doi:10.1016/j.physletb.2015.09.055, arXiv:1507.06257.

[17] S. Kallweit and M. Wiesemann, "ZZ production at the LHC: NNLO predictions for $2\ell 2\nu$ and 4ℓ signatures", *Phys. Lett. B* **786** (2018) 382, doi:10.1016/j.physletb.2018.10.016, arXiv:1806.05941.

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

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

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

[21] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[22] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[23] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[24] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing nlo calculations in shower monte carlo programs: the POWHEG box", *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

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

[26] NNPDF Collaboration, "Parton distributions from high-precision collider data", *Eur. Phys. J. C.* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.

[27] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[28] S. Alioli, P. Nason, C. Oleari, and E. Re, "NLO vector-boson production matched with shower in {POWHEG}", *JHEP* **07** (2008) 060, doi:10.1088/1126-6708/2008/07/060, arXiv:0805.4802.

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

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

[31] T. Melia, P. Nason, R. Rontsch, and G. Zanderighi, "W^+W^-, WZ and ZZ production in the POWHEG BOX", *JHEP* **11** (2011) 078, doi:10.1007/JHEP11(2011)078, arXiv:1107.5051.

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

[33] Y. Gao et al., "Spin determination of single-produced resonances at hadron colliders", *Phys. Rev. D* **81** (2010) 075022, doi:10.1103/PhysRevD.81.075022, arXiv:1001.3396.

[34] S. Bolognesi et al., "Spin and parity of a single-produced resonance at the LHC", *Phys. Rev. D* **86** (2012) 095031, doi:10.1103/PhysRevD.86.095031, arXiv:1208.4018.

[35] I. Anderson et al., "Constraining anomalous HVV interactions at proton and lepton colliders", *Phys. Rev. D* **89** (2014) 035007, doi:10.1103/PhysRevD.89.035007, arXiv:1309.4819.

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

[37] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[38] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO", *JHEP* **12** (2012) 061, doi:10.1007/JHEP12(2012)061, arXiv:1209.6215.

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

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

[41] M. Grazzini, S. Kallweit, and M. Wiesemann, "Fully differential NNLO computations with MATRIX", *Eur. Phys. J. C* **78** (2018) 537, doi:10.1140/epjc/s10052-018-5771-7, arXiv:1711.06631.

[42] F. Buccioni et al., "Openloops 2", *Eur. Phys. J. C* **79** (2019) 866, doi:10.1140/epjc/s10052-019-7306-2, arXiv:1907.1307.

[43] T. Gehrmann, A. von Manteuffel, and L. Tancredi, "The two-loop helicity amplitudes for $q\overline{q}' \to V_1V_2 \to 4$ leptons", *JHEP* **09** (2015) 128, doi:10.1007/jhep09(2015)128, arXiv:1503.04812.

[44] M. Grazzini et al., "NNLO QCD + NLO EW with MATRIX+OpenLoops: precise predictions for vector-boson pair production", *JHEP* **02** (2020) 087, doi:10.1007/jhep02(2020)087, arXiv:1912.00068.

[45] V. Bertone, S. Carrazza, N. Hartland, and J. Rojo, "Illuminating the photon content of the proton within a global pdf analysis", *SciPost Physics* **5** (2018) 008, doi:10.21468/scipostphys.5.1.008, arXiv:1712.07053.

[46] M. Grazzini, S. Kallweit, M. Wiesemann, and J. Y. Yook, "ZZ production at the LHC: NLO QCD corrections to the loop-induced gluon fusion channel", *JHEP* **03** (2019) 070, doi:10.1007/jhep03(2019)070, arXiv:1811.09593.

[47] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

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

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

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

[51] CMS Collaboration, "Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.

[52] CMS Collaboration, "Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **11** (2017) 047, doi:10.1007/JHEP11(2017)047, arXiv:1706.09936.

[53] Particle Data Group, M. Tanabashi et al., "Review of particle physics", *Phys. Rev. D* **98** (2018) 030001, doi:10.1103/PhysRevD.98.030001.

[54] CMS Collaboration, "Measurement of the properties of a Higgs boson in the four-lepton final state", *Phys. Rev. D* **89** (2014) 092007, doi:10.1103/PhysRevD.89.092007, arXiv:1312.5353.

[55] CMS Collaboration, "Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV", *JHEP* **07** (2018) 161, doi:10.1007/JHEP07(2018)161, arXiv:1802.02613.

[56] J. Butterworth et al., "PDF4LHC recommendations for LHC Run II", *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[57] NNPDF Collaboration, "Parton distributions for the LHC run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[58] CMS Collaboration, "CMS luminosity measurements for the 2016 data-taking period", CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

[59] CMS Collaboration, "CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[60] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[61] 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*, H. Prosper and L. Lyons, eds., p. 313, CERN. Geneva, Switzerland, 17–20 January, 2011. arXiv:1105.1160. doi:10.5170/CERN-2011-006.313.

[62] ATLAS, CMS, and the LHC Higgs Combinaiton Group Collaboration, "Procedure for the LHC Higgs boson search combination in summer 2011", Technical Report CMS-NOTE-2011-005, ATL-PHYS-Pub-2011-11, CERN, 2011.

[63] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

[64] U. Baur and D. L. Rainwater, "Probing neutral gauge boson selfinteractions in ZZ production at hadron colliders", *Phys. Rev. D* **62** (2000) 113011, doi:10.1103/PhysRevD.62.113011, arXiv:hep-ph/0008063.

[65] C. Degrande, "A basis of dimension-eight operators for anomalous neutral triple gauge boson interactions", *JHEP* **02** (2014) 101, doi:10.1007/JHEP02(2014)101, arXiv:1308.6323.

[66] A. Bierweiler, T. Kasprzik, and J. H. Kuhn, "Vector-boson pair production at the LHC to $\mathcal{O}(\alpha^3)$ accuracy", *JHEP* **12** (2013) 071, doi:10.1007/JHEP12(2013)071, arXiv:1305.5402.

[67] J. Baglio, L. D. Ninh, and M. M. Weber, "Massive gauge boson pair production at the LHC: a next-to-leading order story", *Phys. Rev. D* **88** (2013) 113005, doi:10.1103/PhysRevD.88.113005, arXiv:1307.4331.

A The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[2], E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello[3], A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov[4], M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato[5], E. Coelho, E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], D. Matos Figueiredo, M. Medina Jaime[8], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[5], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
C.A. Bernardes[a,a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[a,b], D.S. Lemos[a], P.G. Mercadante[a,b], S.F. Novaes[a], Sandra S. Padula[a]

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

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
W. Fang[3], Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen[9], H.S. Chen[9], M. Chen, T. Javaid[9], A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China
Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[3]

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, 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, D. Majumder, M. Roguljic, A. Starodumov[10], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[11], M. Finger Jr.[11], A. Kveton, J. Tomsa

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
H. Abdalla[12], Y. Assran[13,14], A. Mohamed[15]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, 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, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[16], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[17], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine[17], D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[18], Z. Tsamalaidze[11]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee,

D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[19], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[20], T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[21], V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo[22], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari[23], N.Z. Jomhari, H. Jung, A. Kasem[21], M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[24], R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann[20], C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov[25], P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

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

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[26], R. Chudasama, M. Csanad, M.M.A. Gadallah[27], S. Lökös[28], P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[29], F. Sikler, V. Veszpremi, G. Vesztergombi†

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi[26], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, G. Zilizi

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, F. Nemes, T. Novak

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

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[30], D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak[31], D.K. Sahoo[30], N. Sur, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[32], R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[33], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber[34], M. Maity[35], S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh[33], S. Thakur[33]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Kumar, K. Naskar[36], P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[37]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[38], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,39], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], M. Gul[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], J.A. Merlin[a], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, 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], C. Ciocca[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,40], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b,41], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,41], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], F. Fiori[a], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

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

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], F. Cetorelli[a,b], V. Ciriolo[a,b,20], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,20], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], F. Fienga[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,20], P. Paolucci[a,20], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], S.Y. Hoh[a,b], L. Layer[a,42], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Presilla[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], A. Tiko[a], M. Tosi[a,b], H. YARAR[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
C. Aime'[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], 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], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a], A. Piccinelli[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], M.R. Di Domenico[a,b], S. Donato[a], 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], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b], R. Tramontano[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], 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], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], M. Ruspa[a,c], R. Salvatico[a,b], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], D. Trocino[a,b]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

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

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
H.D. Yoo

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

College of Engineering and Technology, American University of the Middle East (AUM)
Y. Maghrbi

Riga Technical University, Riga, Latvia
V. Veckalns[43]

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[44], R. Lopez-Fernandez, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, 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 Montenegro, Podgorica, Montenegro
J. Mijuskovic[4], N. Raicevic

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.I. Asghar, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[45], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[46,47], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[48], E. Kuznetsova[49], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov†, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[50], V. Popov, G. Safronov, A. Spiridonov, A. Stepennov, 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
O. Bychkova, M. Chadeeva[51], R. Chistov[52], P. Parygin, E. Popova

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

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[53], L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[54], T. Dimova[54], L. Kardapoltsev[54], I. Ovtin[54], Y. Skovpen[54]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[55], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
MK Jayananda, B. Kailasapathy[56], D.U.J. Sonnadara, DDC Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[57], D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo[20], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[58], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[59], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler[60], C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

National Central University, Chung-Li, Taiwan
C. Adloff[61], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[35], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[62], Z.S. Demiroglu, F. Dolek, C. Dozen[63], I. Dumanoglu[64], E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler[65], I. Hos[66], C. Isik, E.E. Kangal[67], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, A.E. Simsek, B. Tali[69], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[70], G. Karapinar[71], K. Ocalan[72], M. Yalvac[73]

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[74], O. Kaya[75], Ö. Özçelik, S. Tekten[76], E.A. Yetkin[77]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[64], Y. Komurcu, S. Sen[78]

Istanbul University, Istanbul, Turkey
F. Aydogmus Sen, S. Cerci[69], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[69]

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
E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal[80], D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[81], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee[20], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

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

Baylor University, Waco, USA
A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

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

Boston University, Boston, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez[21], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[82], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir[83], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena[53], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[84], M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, K. Dilsiz[85], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[86], A. Moeller, J. Nachtman, H. Ogul[87], Y. Onel, F. Ozok[88], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi[89]

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

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

University of Maryland, College Park, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts†, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

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

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow†, B. Stieger, W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko[46], R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA
P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

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

Purdue University, West Lafayette, USA
V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, M. Stojanovic[16], N. Trevisani, F. Wang, R. Xiao, W. Xie

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

Rice University, Houston, USA
A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, W. Shi, A.G. Stahl Leiton

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban[24], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[90], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[91], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov, J. Sturdy

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, P. Thapa

University of Wisconsin - Madison, Madison, WI, USA
K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at UFMS, Nova Andradina, Brazil
8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
11: Also at Joint Institute for Nuclear Research, Dubna, Russia
12: Also at Cairo University, Cairo, Egypt
13: Also at Suez University, Suez, Egypt
14: Now at British University in Egypt, Cairo, Egypt
15: Also at Zewail City of Science and Technology, Zewail, Egypt
16: Also at Purdue University, West Lafayette, USA
17: Also at Université de Haute Alsace, Mulhouse, France
18: Also at Tbilisi State University, Tbilisi, Georgia
19: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
20: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
21: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
22: Also at University of Hamburg, Hamburg, Germany
23: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
24: Also at Brandenburg University of Technology, Cottbus, Germany
25: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
26: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
29: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
30: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
31: Also at Institute of Physics, Bhubaneswar, India
32: Also at G.H.G. Khalsa College, Punjab, India
33: Also at Shoolini University, Solan, India
34: Also at University of Hyderabad, Hyderabad, India
35: Also at University of Visva-Bharati, Santiniketan, India
36: Also at Indian Institute of Technology (IIT), Mumbai, India
37: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany

38: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
39: Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
40: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
41: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
42: Also at Università di Napoli 'Federico II', NAPOLI, Italy
43: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
44: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
45: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
46: Also at Institute for Nuclear Research, Moscow, Russia
47: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
48: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
49: Also at University of Florida, Gainesville, USA
50: Also at Imperial College, London, United Kingdom
51: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
52: Also at P.N. Lebedev Physical Institute, Moscow, Russia
53: Also at California Institute of Technology, Pasadena, USA
54: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
55: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
56: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
57: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
58: Also at National and Kapodistrian University of Athens, Athens, Greece
59: Also at Universität Zürich, Zurich, Switzerland
60: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
61: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
62: Also at Şırnak University, Sirnak, Turkey
63: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
64: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
65: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
66: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
67: Also at Mersin University, Mersin, Turkey
68: Also at Piri Reis University, Istanbul, Turkey
69: Also at Adiyaman University, Adiyaman, Turkey
70: Also at Ozyegin University, Istanbul, Turkey
71: Also at Izmir Institute of Technology, Izmir, Turkey
72: Also at Necmettin Erbakan University, Konya, Turkey
73: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
74: Also at Marmara University, Istanbul, Turkey
75: Also at Milli Savunma University, Istanbul, Turkey
76: Also at Kafkas University, Kars, Turkey
77: Also at Istanbul Bilgi University, Istanbul, Turkey
78: Also at Hacettepe University, Ankara, Turkey
79: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

80: Also at IPPP Durham University, Durham, United Kingdom
81: Also at Monash University, Faculty of Science, Clayton, Australia
82: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
83: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
84: Also at Ain Shams University, Cairo, Egypt
85: Also at Bingol University, Bingol, Turkey
86: Also at Georgian Technical University, Tbilisi, Georgia
87: Also at Sinop University, Sinop, Turkey
88: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
89: Also at Nanjing Normal University Department of Physics, Nanjing, China
90: Also at Texas A&M University at Qatar, Doha, Qatar
91: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea