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

The CMS Collaboration\*

## Abstract

The production of Z boson pairs in proton-proton (pp) collisions,  $pp \rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow 2\ell 2\ell'$ , where  $\ell, \ell' = e$  or  $\mu$ , 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  $137 \text{ fb}^{-1}$ , collected during 2016–2018. The ZZ production cross section,  $\sigma_{\text{tot}}(pp \rightarrow ZZ) = 17.4 \pm 0.3$  (stat)  $\pm 0.5$  (syst)  $\pm 0.4$  (theo)  $\pm 0.3$  (lumi) pb, measured for events with two pairs of opposite-sign, same-flavor leptons produced in the mass region  $60 < m_{\ell+\ell^-} < 120$  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 ZZ $\gamma$  couplings.

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## 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 ZZ $\gamma$  are introduced using an effective Lagrangian following Ref. [1]. In this parametrization, two ZZZ and two ZZ $\gamma$  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  $V = (Z, \gamma)$ . 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  $5.1 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  [4] and  $19.6 \text{ fb}^{-1}$  at  $\sqrt{s} = 8 \text{ TeV}$  [5, 6] in the  $ZZ \rightarrow 2\ell 2\ell'$  and  $ZZ \rightarrow 2\ell 2\nu$  decay channels, where  $\ell = e$  or  $\mu$  and  $\ell' = e, \mu, \text{ or } \tau$ ; and with an integrated luminosity of  $2.6 \text{ fb}^{-1}$  [7] and  $35.9 \text{ fb}^{-1}$  [8] at  $\sqrt{s} = 13 \text{ TeV}$  in the  $ZZ \rightarrow 2\ell 2\ell'$  decay channel, where  $\ell' = e$  or  $\mu$ . All of the results agree with SM predictions. The ATLAS Collaboration reported similar results at  $\sqrt{s} = 7, 8, \text{ and } 13 \text{ TeV}$  [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 ( $pp \rightarrow 2\ell 2\ell'$ , where  $2\ell$  and  $2\ell'$  indicate pairs of opposite-sign electrons or muons) at  $\sqrt{s} = 13 \text{ TeV}$ , with a data set corresponding to an integrated luminosity of  $137 \text{ fb}^{-1}$  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 ZZ $\gamma$  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  $p_T \approx 45$  GeV from  $Z \rightarrow e^+e^-$  decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [19]. Matching muons to tracks identified in the silicon tracker results in a  $p_T$  resolution for muons with  $20 < p_T < 100$  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  $4 \mu\text{s}$ . 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  $m_{\ell\ell'} > 4$  GeV applied to all pairs of oppositely charged leptons at the generator level to avoid infrared divergences. The gluon-gluon loop-induced process,  $gg \rightarrow ZZ$ , 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  $q\bar{q} \rightarrow ZZ$  [15] (with a  $K$  factor of 1.1) and at NLO in QCD for  $gg \rightarrow ZZ$  [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 ( $\mu_R$ ) and factorization scales ( $\mu_F$ ) 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  $SIP_{3D} \equiv |IP/\sigma_{IP}| < 4$  for each lepton, where IP is the distance of closest approach of each lepton track to the primary vertex and  $\sigma_{IP}$  is its associated uncertainty.

Lepton candidates are required to be isolated from other particles in the event. The relative isolation is defined as

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

where the sums run over the charged and neutral hadrons, and photons identified by the PF algorithm, in a cone defined by  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  around the lepton momentum direction, where  $\phi$  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  $p_T^{\text{PU}}$ . For electrons,  $p_T^{\text{PU}}$  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  $R_{\text{iso}} < 0.35$ .

The lepton reconstruction, identification, and isolation efficiencies are measured with a “tag-and-probe” technique [51] applied to a sample of  $Z \rightarrow \ell^+ \ell^-$  data events. The measurements are performed in several bins of  $p_T^\ell$  and  $|\eta^\ell|$ . The electron reconstruction and selection efficiency in the ECAL barrel (endcaps) varies from about 85 (77)% at  $p_T^e \approx 10$  GeV to about 95 (89)% for  $p_T^e \geq 20$  GeV, whereas in the barrel-endcap transition region this efficiency is about 85% averaged over electrons with  $p_T^e > 7$  GeV. The muons are reconstructed and identified with efficiencies above  $\sim 98\%$  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  $p_T^\ell > 17$  GeV, and the subleading lepton must have  $p_T^e > 12$  GeV if it is an electron or  $p_T^\mu > 8$  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  $Z/\gamma^*$  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  $p_T > 20$  GeV, and the second-highest  $p_T$  lepton must have  $p_T^e > 12$  GeV if it is an electron or  $p_T^\mu > 10$  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  $\Delta R(e, \mu) > 0.05$ .

Within each event, all permutations of leptons giving a valid pair of  $Z/\gamma^*$  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  $m_{\ell\ell'} > 4$  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  $pp \rightarrow ZZ$  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  $\tau$  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  $\tau$  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  $t\bar{t}$  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 described 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  $|m_{\ell^+\ell^-} - m_Z| < 10 \text{ GeV}$ , 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  $\eta$ , 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  $p_T^{\text{miss}}$  to be below 25 GeV. The  $p_T^{\text{miss}}$  is defined as the magnitude of the missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$ , 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  $m_T \equiv \sqrt{(p_T^\ell + p_T^{\text{miss}})^2 - (\vec{p}_T^\ell + \vec{p}_T^{\text{miss}})^2}$ , 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  $\ell$  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  $\ell$  candidates must satisfy the relaxed criteria, but fail the full criteria. The additional leptons must have opposite charges and the same flavor ( $e^\pm e^\mp$  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  $Z_1 + \ell^+\ell^-$  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  $t\bar{t}Z$  and VVV processes with four prompt leptons are estimated from simulated samples to be around 1–1.5% of the expected  $ZZ \rightarrow 2\ell 2\ell'$  yield. The total background contributions to the  $ZZ \rightarrow 2\ell 2\ell'$  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  $\eta$ . 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  $ZZ \rightarrow 2\ell 2\ell'$  signal regions are 5% in the  $4e$ , 3% in the  $2e2\mu$ , and 2% in the  $4\mu$  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%
$\mu_R, \mu_F$	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 ( $\mu_F$ ) and renormalization ( $\mu_R$ ) scale choices on the  $ZZ \rightarrow 2\ell 2\ell'$  acceptance are evaluated with POWHEG+MCFM by varying  $\mu_F$  and  $\mu_R$  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  $\mu_F$  and  $\mu_R$  differ by a factor of four. Parametric uncertainties (PDF+ $\alpha_s$ ) 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  $q\bar{q} \rightarrow ZZ$  simulated sample from its NLO cross section to the NNLO prediction, and the MCFM  $g\bar{g} \rightarrow ZZ$  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 uncertainties, but its effect is small compared to the statistical uncertainties of the measurement.

## 8 Cross section measurement

The  $p_T$  and  $\eta$  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  $q\bar{q} \rightarrow ZZ$ ,  $gg \rightarrow ZZ$ , 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  $\eta$  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-

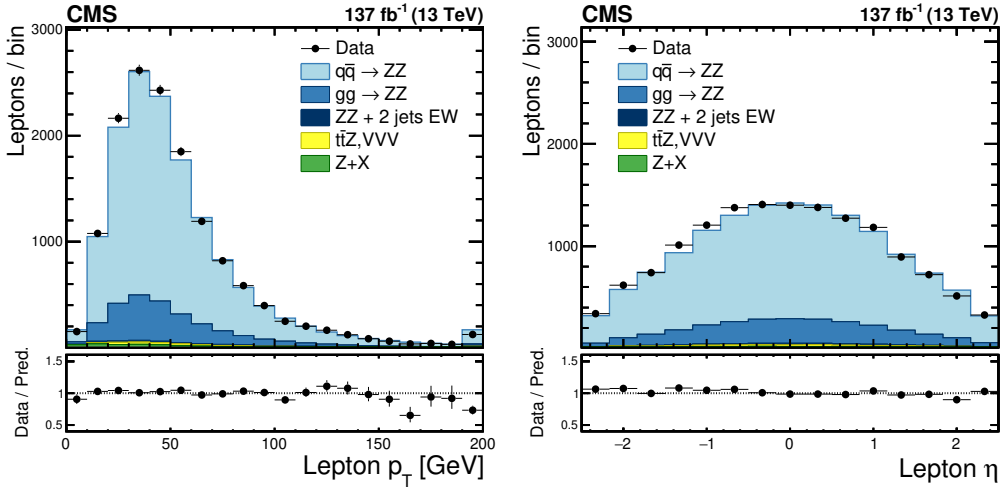


Figure 1: Distributions of (left) transverse momentum and (right) pseudorapidity for individual leptons. Points represent the data with error bars showing the statistical uncertainties, histograms the expected SM predictions and reducible background estimated from data. The  $p_T$  distributions includes 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  $ZZ \rightarrow 2\ell 2\ell'$  cross section measurement is defined as:  $p_T^{\ell_1} > 20 \text{ GeV}$ ,  $p_T^{\ell_2} > 10 \text{ GeV}$ ,  $p_T^{\ell_{3,4}} > 5 \text{ GeV}$ ,  $|\eta^\ell| < 2.5$ ,  $m_{2\ell} > 4 \text{ GeV}$  (any opposite-sign same-flavor pair),  $60 < m_{Z_1}, m_{Z_2} < 120 \text{ GeV}$ . 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	$42.0 \pm 1.4 \text{ (stat)} \pm 1.3 \text{ (syst)}^{+1.1}_{-1.0} \text{ (lumi)}$
2017	$39.6 \pm 1.2 \text{ (stat)}^{+1.3}_{-1.2} \text{ (syst)}^{+1.0}_{-0.9} \text{ (lumi)}$
2018	$39.7 \pm 1.0 \text{ (stat)}^{+1.3}_{-1.1} \text{ (syst)} \pm 1.0 \text{ (lumi)}$
Combined	$40.5 \pm 0.7 \text{ (stat)} \pm 1.1 \text{ (syst)} \pm 0.7 \text{ (lumi)}$

The measured  $ZZ$  fiducial cross section presented in Table 3 can be compared to  $39.3^{+0.8}_{-0.7} \pm 0.6 \text{ fb}$  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  $\mu_F = \mu_R = m_{2\ell 2\ell'}$ , whereas the contribution from MCFM is computed with dynamic scales  $\mu_F = \mu_R = 0.5m_{2\ell 2\ell'}$ . 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  $\mu_F$  and  $\mu_R$ .

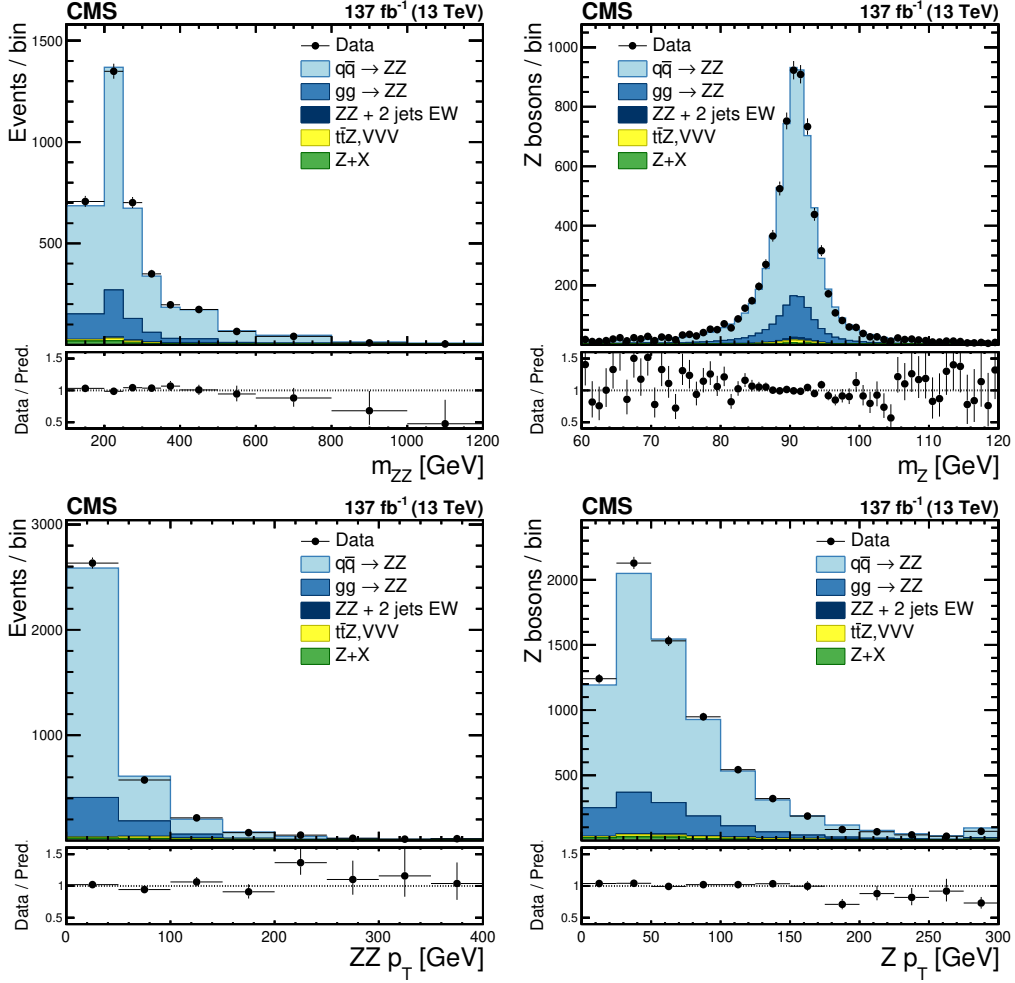


Figure 2: Distributions of (upper left)  $m_{ZZ}$  for ZZ events with  $60 < m_{Z_1, Z_2} < 120$  GeV; (upper right) mass of selected Z boson candidates; (lower left) transverse momentum of the ZZ system; (lower right) transverse momentum of individual Z boson candidates. Points represent the data with 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  $\sigma(pp \rightarrow ZZ)$  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	$18.1 \pm 0.6$ (stat) $^{+0.6}_{-0.5}$ (syst) $\pm 0.4$ (theo) $^{+0.5}_{-0.4}$ (lumi)
2017	$17.0 \pm 0.5$ (stat) $^{+0.6}_{-0.5}$ (syst) $\pm 0.4$ (theo) $\pm 0.4$ (lumi)
2018	$17.1 \pm 0.4$ (stat) $\pm 0.5$ (syst) $\pm 0.4$ (theo) $\pm 0.4$ (lumi)
Combined	$17.4 \pm 0.3$ (stat) $\pm 0.5$ (syst) $\pm 0.4$ (theo) $\pm 0.3$ (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  $\mathcal{B}(Z \rightarrow \ell^+\ell^-) = 0.03366$  is used [53]. The measured total cross section can be compared to the theoretical value of  $16.9_{-0.5}^{+0.6} \pm 0.2$  pb, calculated from POWHEG+MCFM with the same settings that is used for  $\sigma_{\text{fid}}(\text{pp} \rightarrow ZZ \rightarrow 2\ell 2\ell')$ . It can also be compared to  $16.5_{-0.5}^{+0.6}$  pb, calculated with MATRIX v2.0.0\_beta1, or  $15.0_{-0.6}^{+0.7} \pm 0.2$  pb, calculated with MCFM at NLO in QCD with additional contributions from LO  $g g \rightarrow ZZ$  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  $4e$ ,  $2e2\mu$ , and  $4\mu$  decay channels using the whole data sample. The fiducial cross section definition includes  $p_T^\ell$  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  $4e$ ,  $2e2\mu$ , and  $4\mu$  channels, for the SM and an example of nonzero aTGC value with  $f_4^\gamma = 0$ , and  $f_4^Z = 0.0015$ .

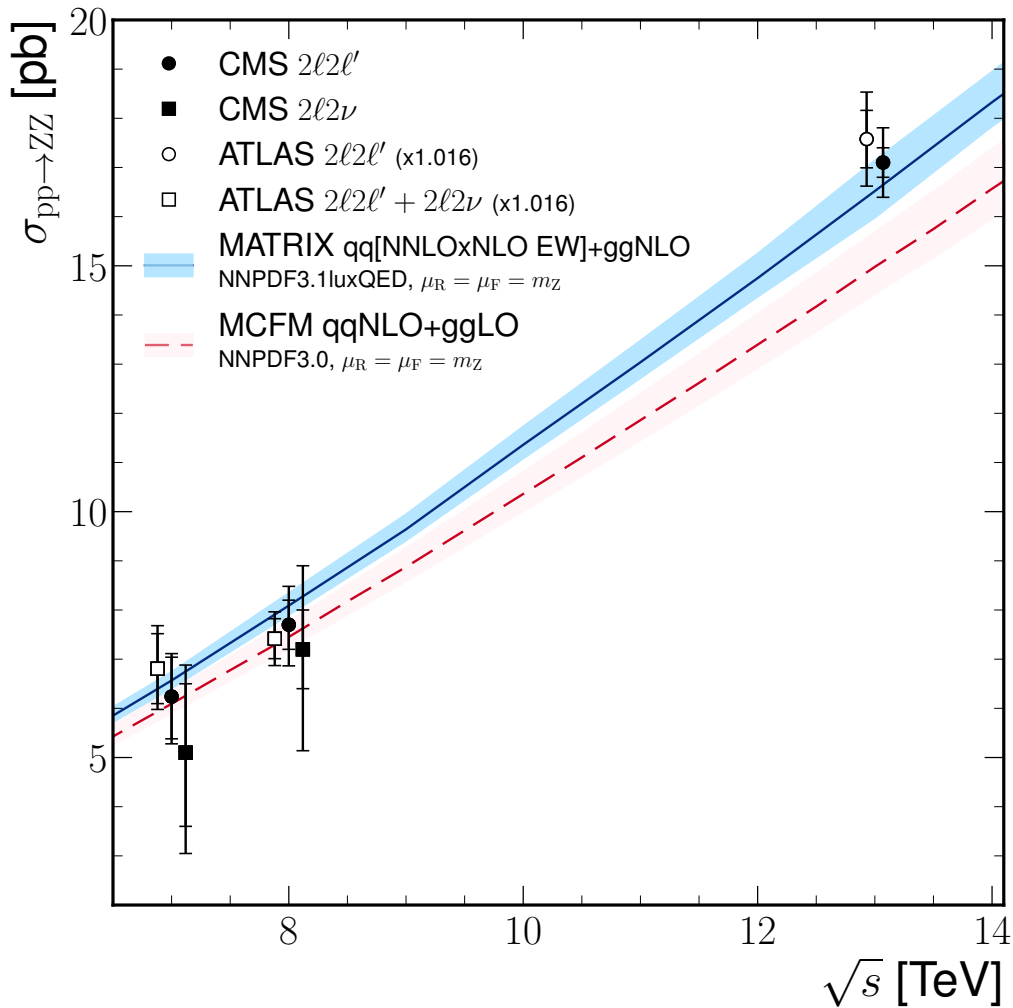


Figure 3: The total ZZ cross section as a function of the proton-proton center-of-mass energy. Results from the CMS [4, 5] and ATLAS [9, 10, 14] experiments are compared to predictions from MATRIX at NNLO in QCD and NLO in EW, and MCFM at NLO in QCD. The MCFM prediction also includes gluon-gluon initiated 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.

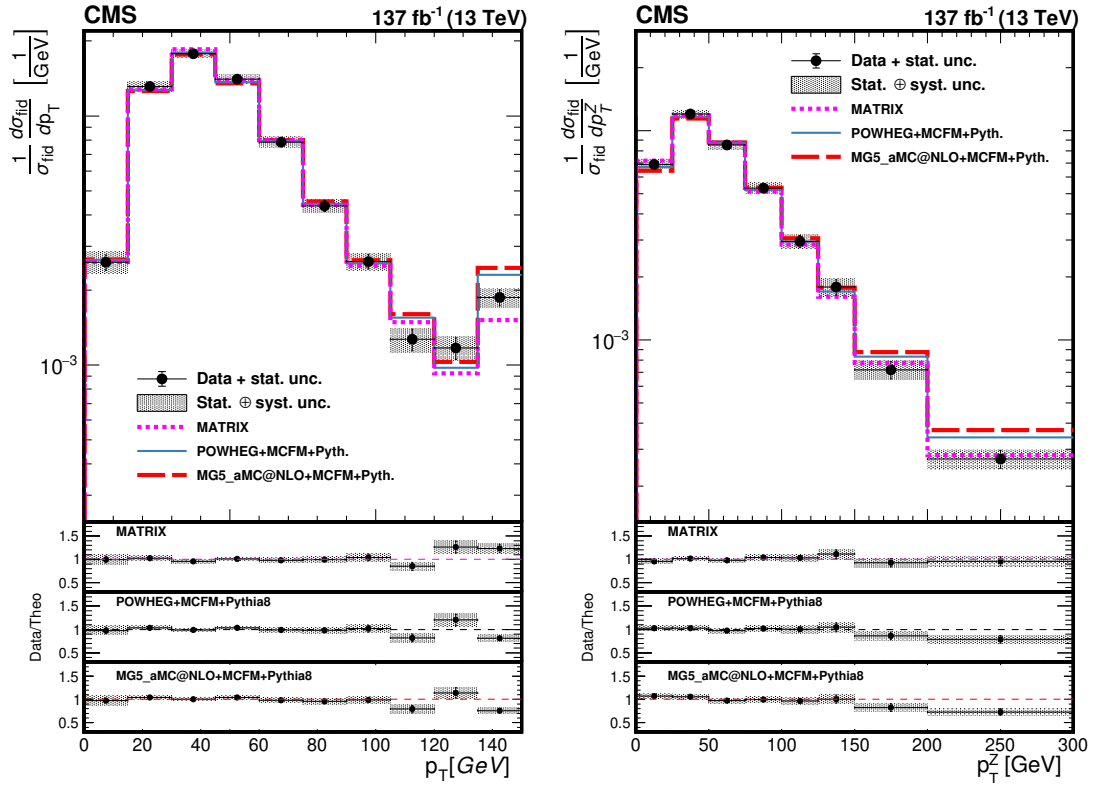


Figure 4: Differential cross sections normalized to the fiducial cross section for the combined  $4e$ ,  $2e2\mu$ , and  $4\mu$  decay channels as a function of  $p_T$  for (left) all leptons, (right) all  $Z$  bosons in the event. The points represent the unfolded data with error bars showing the statistical 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.

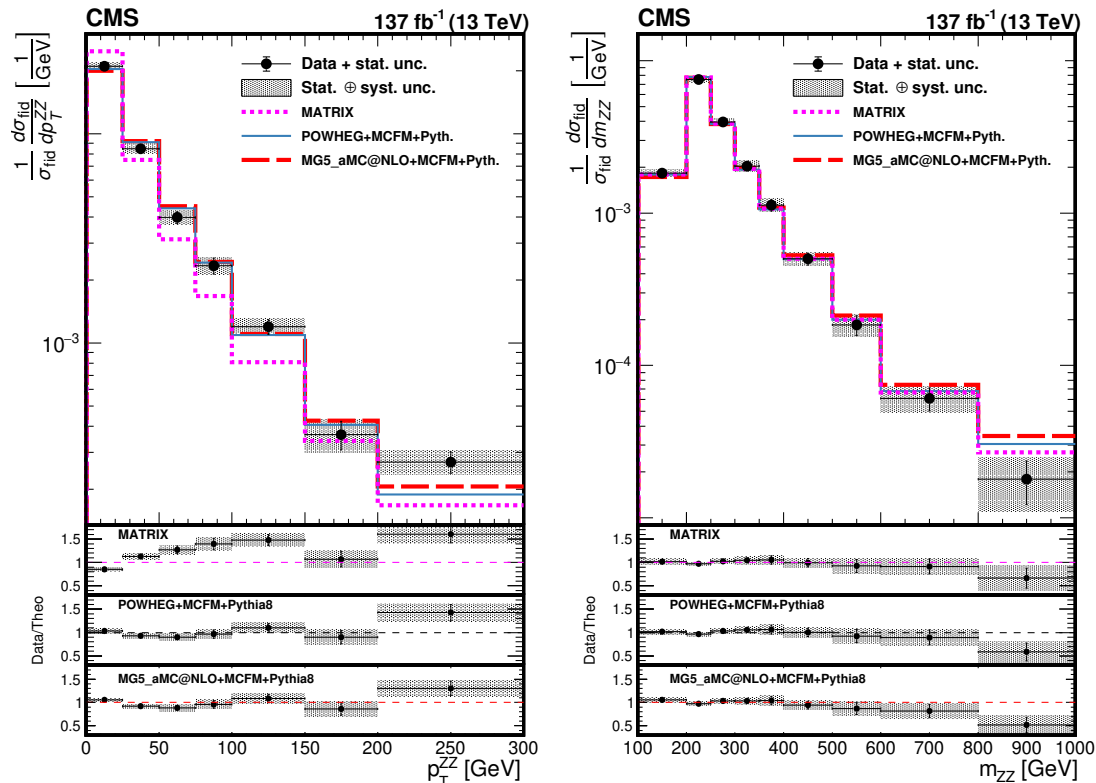


Figure 5: Differential cross sections normalized to the fiducial cross section for the combined  $4e$ ,  $2e2\mu$ , and  $4\mu$  decay channels as a function of (left)  $p_T$  of the  $ZZ$  system, (right) the invariant mass of the  $ZZ$  system. The points represent the unfolded data with error bars 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.

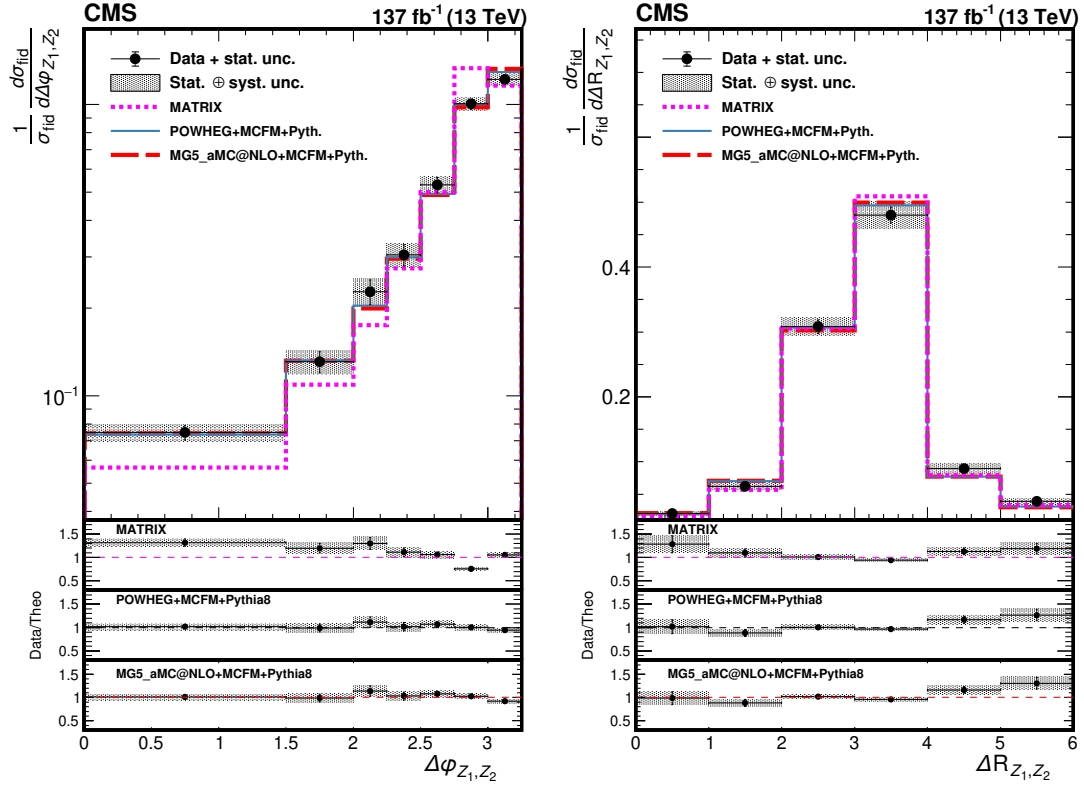


Figure 6: Differential cross sections normalized to the fiducial cross section for the combined  $4e$ ,  $2e2\mu$ , and  $4\mu$  decay channels as a function of the azimuthal (left) and  $\Delta R$  (right) separation of the two  $Z$  bosons. The points represent the unfolded data with error bars showing 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.

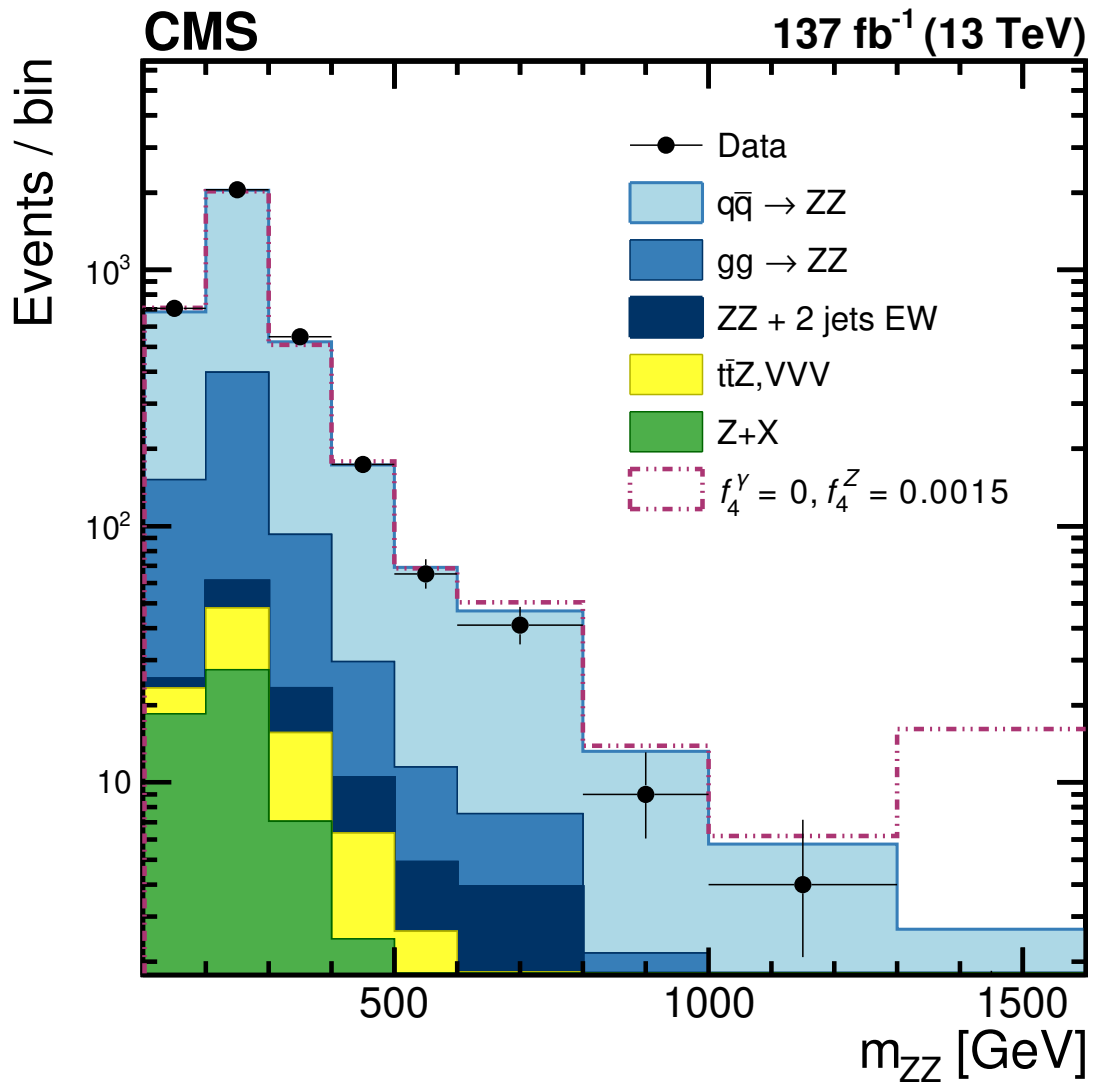


Figure 7: Distribution of the reconstructed  $ZZ$  mass for the combined  $4e$ ,  $2e2\mu$ , and  $4\mu$  channels. Points represent the data with error bars showing the statistical uncertainties, the shaded histograms represent the SM prediction including signal and irreducible background from simulation, 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  $(f_4^Z, f_4^\gamma)$  and  $(f_5^Z, f_5^\gamma)$  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.

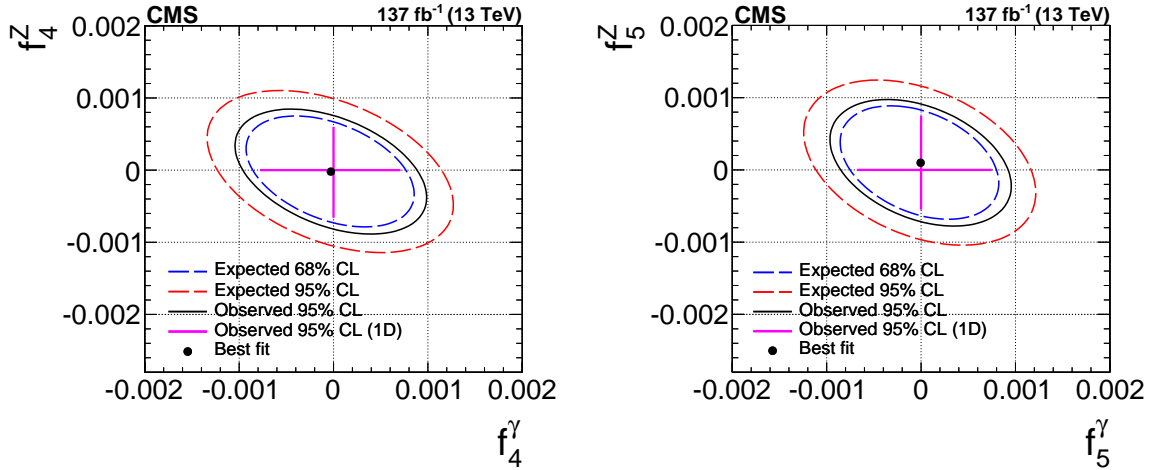


Figure 8: Two-dimensional observed (solid) and expected (dashed) contours exclusion limits at 95% CL, and at 68 and 95% CL, respectively, on the ZZZ and ZZ $\gamma$  aTGCs. The plots show the exclusion contours in the  $(f_{4(5)}^Z, f_{4(5)}^\gamma)$  parameter planes. Dots show where the likelihoods 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 constraints on EFT parameters are estimated using the transformation from Ref. [65].

aTGC parameter	Expected 95% CL $\times 10^{-4}$	Observed 95% CL $\times 10^{-4}$
$f_4^Z$	-8.8 ; 8.3	-6.6 ; 6.0
$f_5^Z$	-8.0 ; 9.9	-5.5 ; 7.5
$f_4^\gamma$	-9.9 ; 9.5	-7.8 ; 7.1
$f_5^\gamma$	-9.2 ; 9.8	-6.8 ; 7.5
EFT parameter	TeV <sup>-4</sup>	TeV <sup>-4</sup>
$C_{\bar{B}W}/\Lambda^4$	-3.1 ; 3.3	-2.3 ; 2.5
$C_{WW}/\Lambda^4$	-1.7 ; 1.6	-1.4 ; 1.2
$C_{BW}/\Lambda^4$	-1.8 ; 1.9	-1.4 ; 1.3
$C_{BB}/\Lambda^4$	-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  $\sqrt{s} = 13$  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  $pp \rightarrow ZZ$  total cross section is  $\sigma_{\text{tot}}(pp \rightarrow ZZ) = 17.4 \pm 0.3 (\text{stat}) \pm 0.5 (\text{syst}) \pm 0.4 (\text{theo}) \pm 0.3 (\text{lumi}) \text{ pb}$ , 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 ZZ $\gamma$  triple gauge couplings are established. These are the most stringent limits to date on anomalous ZZZ and ZZ $\gamma$  triple gauge couplings and they improve the previous strictest results from CMS by  $\approx 30\text{--}40\%$ .

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan<sup>†</sup>, A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth<sup>1</sup>, M. Jeitler<sup>1</sup>, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovskiy, A. Litomin, V. Makarenko, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>2</sup>, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello<sup>3</sup>, 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. Lontkovskiy, 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. Clerboux, 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<sup>4</sup>, 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. Taliencio, 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<sup>5</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>6</sup>, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins<sup>7</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>8</sup>, 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<sup>5</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

### Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil

C.A. Bernardes<sup>a,a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>a,b</sup>, D.S. Lemos<sup>a</sup>, P.G. Mercadante<sup>a,b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>

### 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<sup>3</sup>, 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<sup>9</sup>, H.S. Chen<sup>9</sup>, M. Chen, T. Javaid<sup>9</sup>, 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<sup>3</sup>

**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<sup>10</sup>, 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<sup>11</sup>, M. Finger Jr.<sup>11</sup>, 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<sup>12</sup>, Y. Assran<sup>13,14</sup>, A. Mohamed<sup>15</sup>

**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<sup>16</sup>, 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<sup>17</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine<sup>17</sup>, 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<sup>18</sup>, Z. Tsamalaidze<sup>11</sup>

**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<sup>19</sup>, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>20</sup>, 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. Borrás<sup>21</sup>, 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<sup>22</sup>, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari<sup>23</sup>, N.Z. Jomhari, H. Jung, A. Kasem<sup>21</sup>, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>24</sup>, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otari, 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. Zlebick

**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<sup>20</sup>, C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov<sup>25</sup>, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoii, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniowski

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Gerasis, 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. Giannelos, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strolagos

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

M. Bartók<sup>26</sup>, R. Chudasama, M. Csanad, M.M.A. Gadallah<sup>27</sup>, S. Lökös<sup>28</sup>, 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<sup>29</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

S. Czellar, J. Karancsi<sup>26</sup>, 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<sup>30</sup>, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>31</sup>, D.K. Sahoo<sup>30</sup>, N. Sur, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra<sup>32</sup>, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

**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<sup>33</sup>, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>34</sup>, M. Maity<sup>35</sup>, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh<sup>33</sup>, S. Thakur<sup>33</sup>

**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<sup>36</sup>, 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<sup>37</sup>

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani<sup>38</sup>, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,39</sup>, C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, M. Gul<sup>a</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup>, J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, C. Ciocca<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, T. Diotallevi<sup>a,b</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Giommi<sup>a,b</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,40</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**S. Albergo<sup>a,b,41</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,41</sup>, C. Tuve<sup>a,b</sup>**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**G. Barbagli<sup>a</sup>, A. Cassese<sup>a</sup>, R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, F. Fiori<sup>a</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Lizzo<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, R. Seidita<sup>a,b</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**M. Bozzo<sup>a,b</sup>, F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, F. Ceteorelli<sup>a,b</sup>, V. Ciriolo<sup>a,b,20</sup>, F. De Guio<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,20</sup>, D. Zuolo<sup>a,b</sup>**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,20</sup>, P. Paolucci<sup>a,20</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, S.Y. Hoh<sup>a,b</sup>, L. Layer<sup>a,42</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Presilla<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, G. Strong<sup>a</sup>, A. Tiko<sup>a</sup>, M. Tosi<sup>a,b</sup>, H. YARAR<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>



**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

C. Aime<sup>a,b</sup>, A. Braghieri<sup>a</sup>, S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, F. Moscatelli<sup>a</sup>, A. Piccinelli<sup>a,b</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>, T. Tedeschi<sup>a,b</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a</sup>, G. Bagliesi<sup>a</sup>, V. Bertacchi<sup>a,c</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, M.R. Di Domenico<sup>a,b</sup>, S. Donato<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a</sup>, F. Ligabue<sup>a,c</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, G. Ramirez-Sanchez<sup>a,c</sup>, A. Rizzi<sup>a,b</sup>, G. Rolandi<sup>a,c</sup>, S. Roy Chowdhury<sup>a,c</sup>, A. Scribano<sup>a</sup>, N. Shafiei<sup>a,b</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, N. Turini<sup>a</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Sapienza Università di Roma <sup>b</sup>, Rome, Italy**

F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a</sup>, M. Diemoz<sup>a</sup>, E. Longo<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, C. Quaranta<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>, L. Soffi<sup>a,b</sup>, R. Tramontano<sup>a,b</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, A. Bellora<sup>a,b</sup>, C. Biino<sup>a</sup>, A. Cappati<sup>a,b</sup>, N. Cartiglia<sup>a</sup>, S. Cometti<sup>a</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, F. Legger<sup>a</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, G. Ortona<sup>a</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Salvatico<sup>a,b</sup>, F. Siviero<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, D. Soldi<sup>a,b</sup>, A. Staiano<sup>a</sup>, D. Trocino<sup>a,b</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, A. Da Rold<sup>a,b</sup>, G. Della Ricca<sup>a,b</sup>, F. Vazzoler<sup>a,b</sup>

**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<sup>43</sup>

**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<sup>44</sup>, 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 Ibarquen, C. Uribe Estrada

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

A. Morelos Pineda

**University of Montenegro, Podgorica, Montenegro**

J. Mijuskovic<sup>4</sup>, 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<sup>45</sup>, 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<sup>46,47</sup>, P. Moiseenz, 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. Gavrillov, V. Golovtsov, Y. Ivanov, V. Kim<sup>48</sup>, E. Kuznetsova<sup>49</sup>, 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<sup>†</sup>, A. Toropin

**Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia**

V. Epshteyn, V. Gavrillov, N. Lychkovskaya, A. Nikitenko<sup>50</sup>, V. Popov, G. Safronov, A. Spiridonov, A. Stepenov, 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<sup>51</sup>, R. Chistov<sup>52</sup>, 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<sup>53</sup>, 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<sup>54</sup>, T. Dimova<sup>54</sup>, L. Kardapoltsev<sup>54</sup>, I. Ovtin<sup>54</sup>, Y. Skovpen<sup>54</sup>

**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<sup>55</sup>, 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. Kailaspathy<sup>56</sup>, 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<sup>57</sup>, 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<sup>20</sup>, 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<sup>58</sup>, 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<sup>59</sup>, 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. Luster, M. Lyon, 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. Reitspiess, 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<sup>60</sup>, 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<sup>61</sup>, C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>35</sup>, 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. Damarcekin<sup>62</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>63</sup>, I. Dumanoglu<sup>64</sup>, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler<sup>65</sup>, I. Hos<sup>66</sup>, C. Isik, E.E. Kangal<sup>67</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir<sup>68</sup>, A. Polatoz, A.E. Simsek, B. Tali<sup>69</sup>, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

B. Isildak<sup>70</sup>, G. Karapinar<sup>71</sup>, K. Ocalan<sup>72</sup>, M. Yalvac<sup>73</sup>

**Bogazici University, Istanbul, Turkey**

I.O. Atakisi, E. Gülmez, M. Kaya<sup>74</sup>, O. Kaya<sup>75</sup>, Ö. Özçelik, S. Tekten<sup>76</sup>, E.A. Yetkin<sup>77</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>64</sup>, Y. Komurcu, S. Sen<sup>78</sup>

**Istanbul University, Istanbul, Turkey**

F. Aydogmus Sen, S. Cerci<sup>69</sup>, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci<sup>69</sup>

**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<sup>79</sup>, 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<sup>80</sup>, 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<sup>81</sup>, 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<sup>20</sup>, 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. Akpınar, 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<sup>21</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>82</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>83</sup>, 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<sup>†</sup>, 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<sup>53</sup>, 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<sup>84</sup>, 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. Alhousseini, K. Dilsiz<sup>85</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>86</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>87</sup>, Y. Onel, F. Ozok<sup>88</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi<sup>89</sup>

**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<sup>†</sup>, 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<sup>†</sup>, 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<sup>46</sup>, 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<sup>16</sup>, 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<sup>†</sup>, 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<sup>24</sup>, 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<sup>90</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>91</sup>, 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

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- 38: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 39: Now at INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, 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 <sup>a</sup>, Università di Pavia <sup>b</sup>, 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, Şırnak, 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 Aydın 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 Rektörlüğü, 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