



# Measurement of the cross section for electroweak production of $Z\gamma$ in association with two jets and constraints on anomalous quartic gauge couplings in proton–proton collisions at $\sqrt{s} = 8$ TeV



The CMS Collaboration\*

CERN, Switzerland

## ARTICLE INFO

### Article history:

Received 10 February 2017  
 Received in revised form 9 April 2017  
 Accepted 27 April 2017  
 Available online 2 May 2017  
 Editor: M. Doser

### Keywords:

CMS  
 Physics  
 aQGC  
 Electroweak production

## ABSTRACT

A measurement is presented of the cross section for the electroweak production of a Z boson and a photon in association with two jets in proton–proton collisions at  $\sqrt{s} = 8$  TeV. The Z bosons are identified through their decays to electron or muon pairs. The measurement is based on data collected with the CMS detector corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . The electroweak contribution has a significance of 3.0 standard deviations, and the measured fiducial cross section is  $1.86_{-0.75}^{+0.90} (\text{stat})_{-0.26}^{+0.34} (\text{syst}) \pm 0.05 (\text{lumi}) \text{ fb}$ , while the summed electroweak and quantum chromodynamic total cross section in the same region is observed to be  $5.94_{-1.35}^{+1.53} (\text{stat})_{-0.37}^{+0.43} (\text{syst}) \pm 0.13 (\text{lumi}) \text{ fb}$ . Both measurements are consistent with the leading-order standard model predictions. Limits on anomalous quartic gauge couplings are set based on the  $Z\gamma$  mass distribution.

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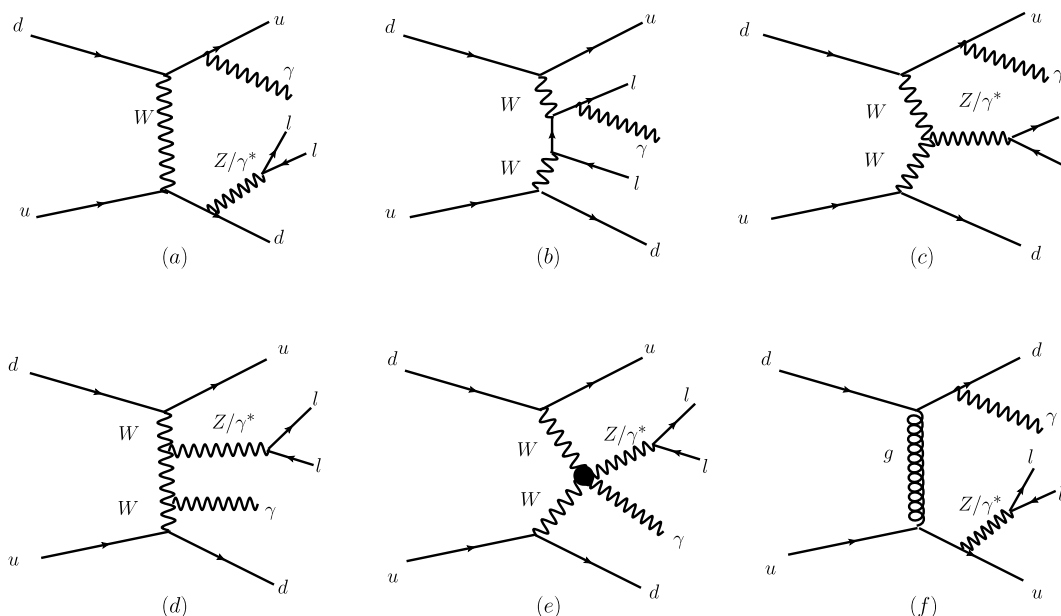
## 1. Introduction

With the discovery of the Higgs boson at the CERN LHC [1, 2], the standard model (SM) became a great success. The high energy and luminosity of the LHC provides the opportunity to observe many processes that are predicted by the SM, including electroweak production of multiple gauge bosons ( $WV\gamma$  [3],  $V\gamma\gamma$  [4–6]), vector boson scattering (VBS) (same charge  $W^\pm W^\pm$  scattering [7–9],  $\gamma\gamma \rightarrow W^+W^-$  [10], EW  $W\gamma jj$  [11],  $W^\pm Z$  [12]), and vector boson fusion (VBF) (EW  $W(Z)jj$  [13–16]). Same charge  $W^\pm W^\pm$  scattering has been observed by ATLAS, and the exclusive  $\gamma\gamma \rightarrow W^+W^-$  process by CMS, both with significances larger than 3 standard deviations. The triboson final state  $Z\gamma\gamma$  has been observed by ATLAS and CMS with a significance larger than 5 standard deviations. The EW production of a Z boson (decaying into two oppositely-charged leptons), a photon, and two jets (henceforth denoted  $Z\gamma jj$ ) has never been studied before, and is the subject of this paper. While the cross section for quantum chromodynamic (QCD) induced  $Z\gamma jj$  production is orders of magnitude larger than the one for EW production, the latter can be used to perform important tests of the SM, and to search for contribu-

tions from physics beyond the SM that could manifest themselves as anomalous trilinear or quartic gauge boson couplings (aTGC or aQGC [3–7,9–12]).

This letter presents a measurement of the associated EW production of  $Z\gamma jj$ , using the 8 TeV proton–proton collision data recorded by the CMS detector. The major processes contributing to EW  $Z\gamma jj$  production are represented by the Feynman diagrams in Fig. 1. They are (a) bremsstrahlung, (b) multiperipheral (or non-resonant) production, (c, d) VBF with either two trilinear gauge boson couplings (TGC), or (e) VBS with quartic gauge boson couplings (QGC). The VBS processes are particularly interesting because they involve QGCs (e.g.  $WWZ\gamma$ ). It is not possible, however, to isolate the QGC processes from the other contributions, such as the double TGC processes that are topologically similar. The interference of the VBS diagrams ensures unitarity of the VBS cross section in the SM at high energy. We present measurements of the combined cross sections for all EW processes that result in the  $Z\gamma jj$  final state. The main background source is  $Z\gamma jj$  production where the associated jets are produced through QCD-induced processes (such as the Feynman diagram given in Fig. 1(f)). Other backgrounds include jets or leptons misidentified as photons, diboson processes in which a W or Z boson decays into two jets and the photon originates from initial or final-state radiation, and contributions from top quark pairs and single top quark production.

\* E-mail address: [cms-publication-committee-chair@cern.ch](mailto:cms-publication-committee-chair@cern.ch).



**Fig. 1.** Representative diagrams for EW  $Z\gamma jj$  production at the LHC: (a) bremsstrahlung, (b) multiperipheral, (c, d) VBF with TGC, (e) VBS including QGC, and (f) Example diagram for the QCD  $Z\gamma jj$  production.

## 2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity,  $\eta$ , coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The particle-flow (PF) event algorithm [17,18] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

In the barrel section of the ECAL, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The resolution for other photons in the barrel section is about 1.3% up to  $|\eta| = 1$ , rising to about 2.5% at  $|\eta| = 1.4$ . In the endcaps, the resolution for unconverted or late-converting photons is about 2.5%, and the resolution for the remaining photons in the endcap is between 3% and 4% [19]. When combining information from the entire detector, the jet energy resolution is typically 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

Muons are measured in the range of  $|\eta| < 2.4$ , with detection planes utilizing three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks

measured 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 electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with transverse momentum  $p_T \approx 45$  GeV from  $Z \rightarrow ee$  decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps. The dielectron mass resolution for  $Z \rightarrow ee$  decays is 1.9% when both electrons are in the ECAL barrel, and 2.9% when both electrons are in the endcaps.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [20].

## 3. Event reconstruction and selection

Candidate events are selected online with triggers that require two muons or electrons, where the leading and subleading leptons have  $p_T > 17$  and 8 GeV respectively, with  $|\eta| < 2.4$  (muons) or  $|\eta| < 2.5$  (electrons). The overall trigger efficiency is about 94% and 90% for muons and electrons, respectively, with a small dependence on  $p_T$  and  $\eta$ .

Muons are reconstructed with a global fit using both the inner tracking system and the muon spectrometer. An isolation requirement is applied in order to suppress the background from multijet events [21,22]. Electron candidates are reconstructed by matching energy deposits in the ECAL with reconstructed tracks; they must pass stringent quality criteria and an isolation requirement [23]. Charged leptons must originate from the primary vertex, which is defined as the vertex whose tracks have the highest sum of  $p_T^2$ . We require that each event has exactly two oppositely charged muons (electrons) with  $p_T > 20$  GeV and  $|\eta| < 2.4$  (2.5) and that the invariant mass of the dilepton system must satisfy  $70 < M_{\ell\ell} < 110$  GeV. The selection efficiencies for leptons are measured using the tag-and-probe method [24] and are approximately 96% for the muons [25] and 80% for the electrons [21].

Photon candidates are reconstructed from energy deposits in the ECAL with no associated track. Quality selection criteria [19]

**Table 1**

Summary of the three different event criteria: (1) selection for the EW signal measurement; (2) the cross section measurement; and (3) the selection for the aQGC search. “j1” and “j2” represent the jets that have the largest and second-largest  $p_T$ , “ $\ell 1$ ” and “ $\ell 2$ ” denote the lepton and antilepton from the decay of the Z boson,  $y$  is the rapidity,  $\Delta\phi_{Z\gamma,ij}$  is the absolute difference between  $\phi_{Z\gamma}$  and  $\phi_{ij}$ , and the angular separation  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

Common selection		
$p_T^{j1,j2} > 30$ GeV, $ \eta^{j1,j2}  < 4.7$		
$p_T^{\ell 1,\ell 2} > 20$ GeV, $ \eta^{\ell 1,\ell 2}  < 2.4$		
$ \eta^\gamma  < 1.4442$		
$M_{jj} > 150$ GeV		
$70 < M_{\ell\ell} < 110$ GeV		
EW signal measurement	Fiducial cross section	aQGC search
$p_T^\gamma > 25$ GeV	$p_T^\gamma > 20$ GeV	$p_T^\gamma > 60$ GeV
$ \Delta\eta_{jj}  > 1.6$	$ \Delta\eta_{jj}  > 2.5$	$ \Delta\eta_{jj}  > 2.5$
$\Delta R_{j\ell} > 0.3$ , $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$	$\Delta R_{jj,\gamma j,\gamma\ell,j\ell} > 0.4$	$\Delta R_{j\ell} > 0.3$ , $\Delta R_{jj,\gamma j,\gamma\ell} > 0.5$
$ y_{Z\gamma} - (y_{j1} + y_{j2})/2  < 1.2$	$M_{jj} > 400$ GeV	$M_{jj} > 400$ GeV
$\Delta\phi_{Z\gamma,ij} > 2.0$ radians		
$M_{jj} > 400$ GeV with two divided regions		
$400 < M_{jj} < 800$ GeV and $M_{jj} > 800$ GeV		

are applied to the reconstructed photons to suppress the background from hadrons misidentified as photons. The observables used in the photon selection are: (1) PF-based isolation variables that are corrected for the contribution from additional proton–proton collisions in the same bunch crossing (pileup); (2) a small ratio of hadronic energy in the HCAL to electromagnetic energy in the ECAL matched in  $(\eta, \phi)$  (where  $\phi$  is azimuthal angle in radians); (3) the transverse width of the electromagnetic shower along the  $\eta$  direction [19]; and (4) an electron track veto. We consider only photons in the ECAL barrel region ( $|\eta| < 1.44$ ) with  $p_T > 25$  GeV. Events with the photon candidate in one of the end-caps ( $|\eta| > 1.57$ ) are excluded from the selection because their signal purity is lower and systematic uncertainties are large.

Hadronic jets are formed from the particles reconstructed by the PF algorithm, using the FASTJET software package [26] and the anti- $k_T$  jet clustering algorithm [27] with a distance parameter of 0.5. To reduce the contamination from pileup, charged PF candidates in the tracker acceptance region  $|\eta| < 2.4$ , are excluded from the jet clustering procedure if associated with pileup vertices. The contribution of neutral particles from pileup events to the jet energy is taken into account by means of a correction based on the projected area of the jet on the front face of the calorimeter. Jet energy corrections are derived from a measurement of the  $p_T$  balance in dijet and photon + jet events in data [28]. Further residual corrections as functions of  $p_T$  and  $\eta$  are applied to the data to correct for the small differences between data and simulation. Additional quality criteria are applied to the jets in order to remove spurious jet-like features originating from isolated noise patterns in the calorimeters or in the tracker [29]. The two jets with the highest  $p_T$  are tagged as the signal jets and are required to have  $p_T > 30$  GeV and  $|\eta| < 4.7$ . Since we are primarily interested in the VBS topologies, we require that the invariant mass of the two jets,  $M_{jj} > 150$  GeV.

Table 1 presents a summary of the three different section criteria that are used for (1) the SM EW signal search, (2) the SM fiducial cross section measurement, and (3) the aQGC searches. The criteria isolate events consistent with the VBS topology of two high-energy scattered jets separated by a large rapidity gap. The cross section measurement adds two variables sensitive to the VBS process:  $|y_{Z\gamma} - (y_{j1} + y_{j2})/2|$ , which ensures the  $Z\gamma$  system is located between the scattered jets in eta; and  $\Delta\phi_{Z\gamma,ij}$ , which requires the  $Z\gamma$  system transverse momentum is consistent with recoiling against the transverse momentum of the two combined jets. The fiducial cross section criteria constrain the VBS topology with only basic kinematic cuts that define the acceptance of the

CMS detector and a simple two dimensional requirement on the rapidity separation and invariant mass of the jets. A tight  $p_T^\gamma$  selection is applied to reach a higher expected significance in a search for a possible aQGC signal in the EW  $Z\gamma jj$  process.

#### 4. Data and simulation

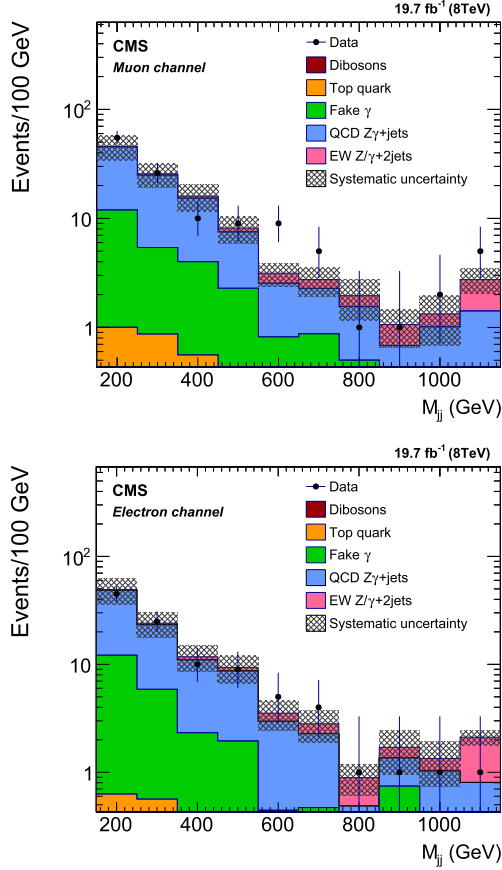
We use data collected with the CMS detector, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ , at proton–proton center-of-mass energy of 8 TeV.

The EW signal,  $Z\gamma jj$ , at leading-order (LO), and the main background, QCD  $Z\gamma$  with 0–3 additional jets, for which the next-to-leading-order (NLO) QCD prediction has been taken from Ref. [30], matched with parton shower based on the so-called “MLM prescription” [31,32], are simulated using MADGRAPH v5.1.3.30 [33] interfaced with PYTHIA v6.424 [34] for hadronization and showering, using a CTEQ6L1 parton distribution function (PDF) set [35]. The second significant background contribution comes from processes where a jet is misidentified as a photon (fake photon), and this contribution is estimated from data. Other background contributions come from diboson processes (WW/WZ/ZZ) simulated by PYTHIA, single top processes simulated by POWHEG, and  $t\bar{t}\gamma$  simulated using MADGRAPH interfaced with PYTHIA. The next-to-leading-order QCD cross sections are used to normalize these simulated samples, except for  $t\bar{t}\gamma$  where an LO prediction is taken.

All the simulated events are processed through a GEANT4 [36] simulation of the CMS detector. The tag-and-probe technique is used to correct for data-Monte Carlo (MC) differences in the trigger efficiency, as well as the reconstruction and selection efficiencies. Additional proton–proton interactions are superimposed over the hard scattering interaction with the distribution of primary vertices matching that obtained from the collision data.

#### 5. Background modeling

The dominant source of background to the EW signal is QCD  $Z\gamma$  + jets production. The shape of this background is taken from MC simulation and the normalization is evaluated from data in a control region, defined as  $150 < M_{jj} < 400$  GeV, where the signal contribution is below 1%. The simulated MC events correctly reproduce the yield of these events with a correction factor of  $1.00 \pm 0.22$  for the combined  $Z \rightarrow \mu^+\mu^-$  and  $Z \rightarrow e^+e^-$  channels. The value is comparable with the NLO QCD  $K$  factor from Ref. [30], which is around 1.1 for  $M_{jj} < 400$  GeV.



**Fig. 2.** The  $M_{jj}$  distributions measured in (top) muon and (bottom) electron channels. The data (solid symbols with error bars representing the statistical uncertainties) are compared to a data-driven background estimate, combined with MC predictions for the signal contribution. The hashed bands represent the full uncertainty in the predictions, as described in Section 6. The last bin includes overflow events.

The background from fake photons arises mainly from Z+jets events where one jet satisfies the photon ID criteria. The estimation is based on events similar to the ones selected with the baseline selection described in Table 1, except that the photon must fail the tight photon ID and satisfy a looser ID requirement based on the charged isolation variable. This selection ensures that the photon arises from a jet, but still has kinematic properties similar to a genuine photon satisfying the tight photon ID. We select genuine photons using  $\sigma_{\eta\eta}$ , a photon identification variable that exploits the small lateral extension of the electromagnetic shower [25,19]. Based on the difference between the  $\sigma_{\eta\eta}$  distributions for fake photons and genuine photons, a fit is made to normalize the number of events with fake photons to the number of events with genuine photons and obtain the probability to have a fake photon. The fake photon probability is calculated based on different  $p_T^\gamma$  regions in a manner similar to that described in Ref. [37].

Other backgrounds, including top quark and diboson production processes are estimated from MC simulations and normalized to the integrated luminosity of the data sample. The contribution from these backgrounds is less than 10% after applying the kinematic selection (Section 3) and is negligible once the final EW and aQGC selection criteria (Sections 7 and 8) are applied.

The  $M_{jj}$  distributions for the  $Z \rightarrow \mu^+\mu^-$  and  $e^+e^-$  channels after the selection requirements described in Section 3 are shown in Fig. 2. The observed distributions are compared to the combined prediction of the backgrounds and of the EW  $Z\gamma jj$  signal.

**Table 2**  
Summary of the major uncertainties.

Source	Uncertainty
QCD $Z\gamma$ + jets normalization	22% ( $400 < M_{jj} < 800$ GeV) 24% ( $M_{jj} > 800$ GeV)
Fake photon from jet ( $p_T^\gamma$ dependent)	15% (20–30 GeV) 22% (30–50 GeV) 49% (>50 GeV)
Trigger efficiency	1.2% ( $Z \rightarrow \mu^+\mu^-$ ), 1.7% ( $Z \rightarrow e^+e^-$ )
Lepton selection efficiency	1.9% ( $Z \rightarrow \mu^+\mu^-$ ), 1.0% ( $Z \rightarrow e^+e^-$ )
Jet energy scale and resolution	14% ( $M_{jj} > 400$ GeV)
$\bar{t}t\gamma$ cross section	20% [3]
Pileup modeling	1.0%
Renormalization/factorization scale (signal)	9.0% ( $400 < M_{jj} < 800$ GeV) 12% ( $M_{jj} > 800$ GeV) (SM) 14% (aQGC)
PDF (signal)	4.2% ( $400 < M_{jj} < 800$ GeV) 2.4% ( $M_{jj} > 800$ GeV) (SM) 4.3% (aQGC)
Interference (signal)	18% ( $400 < M_{jj} < 800$ GeV) 11% ( $M_{jj} > 800$ GeV) (SM)
Luminosity	2.6%

## 6. Systematic uncertainties

The systematic uncertainty in the QCD  $Z\gamma$  + jets background estimation is 22% for both  $Z \rightarrow \mu^+\mu^-$  and  $Z \rightarrow e^+e^-$ ; it is dominated by the large statistical uncertainty in the control region used for normalization. The shape uncertainties that are related to the extrapolation of the normalization factor to the signal region ( $M_{jj} > 400$  GeV) are determined by varying the renormalization and factorization scales as well as the MLM matching scale [31,32] up and down by a factor of two. Finally, we combine both the normalization factor uncertainty and the shape uncertainty to obtain the total uncertainty.

The systematic uncertainty in the background estimation from fake photons arises from the variation in the choice of the charged isolation sideband and the  $\sigma_{\eta\eta}$  distribution used for estimating the fake photon probability. The total uncertainties in the fake photon background estimation can be found in Table 2. The theoretical uncertainty in the top quark background is 20% [3].

The systematic uncertainties in the estimation of the trigger efficiency, measured using the tag-and-probe technique, are 1.2% and 1.7% for the  $Z \rightarrow \mu^+\mu^-$  and  $Z \rightarrow e^+e^-$  channels, respectively. Using similar methods, the systematic uncertainties in the efficiencies for lepton reconstruction and identification in the two channels are 1.9% and 1.0%, respectively. The systematic uncertainty in the jet energy scale and resolution is estimated by varying the jet energy scale and resolution up and down within their  $p_T$ - and  $\eta$ -dependent uncertainties [28]. The uncertainty is 14% for  $M_{jj} > 400$  GeV. Another source of uncertainty is the modeling of the pileup. The inelastic cross section is varied by  $\pm 5\%$  in order to evaluate this contribution. The uncertainty in the integrated luminosity is 2.6% [38].

There are also three sources of theoretical uncertainties applied to the signal only. The PDF uncertainty for the signal is estimated with the CT10 [39] PDF set, following the asymmetric Hessian method introduced in Refs. [40,41]. The scale uncertainty is evaluated by varying the renormalization and factorization scales independently by a factor of two. The magnitude of the interference between QCD and EW  $Z\gamma jj$  processes is assigned as systematic uncertainties in the two  $M_{jj}$  ranges.

All the systematic uncertainties described are applied to both the signal significance measurement and the aQGC search. They are also propagated to the uncertainty in the measured fiducial

**Table 3**

Signal and background yields after the final selection for the SM measurement, for the two bins of  $400 < M_{jj} < 800$  GeV (upper) and  $M_{jj} > 800$  GeV (lower). Only statistical uncertainties are reported.

$400 < M_{jj} < 800$ GeV	Muon	Electron
Fake photon from jet	$3.4 \pm 0.8$	$1.7 \pm 0.5$
Other background	$0.1 \pm 0.1$	$0.1 \pm 0.1$
QCD $Z\gamma jj$	$4.8 \pm 0.9$	$5.0 \pm 1.0$
EW $Z\gamma jj$	$1.7 \pm 0.1$	$1.8 \pm 0.1$
Total background	$8.3 \pm 1.2$	$6.8 \pm 1.1$
Data	13	8
$M_{jj} > 800$ GeV	Muon	Electron
Fake photon from jet	$0.4 \pm 0.3$	$0.1 \pm 0.1$
Other background	$0 \pm 0$	$0 \pm 0$
QCD $Z\gamma jj$	$0.4 \pm 0.1$	$1.1 \pm 0.2$
EW $Z\gamma jj$	$1.8 \pm 0.1$	$1.8 \pm 0.1$
Total background	$0.8 \pm 0.3$	$1.2 \pm 0.2$
Data	5	2

cross section, with the exception of the theoretical uncertainty associated with the signal cross section.

All the uncertainties in our analysis are summarized in Table 2.

## 7. Measurement of the signal significance and fiducial cross section

As shown in Table 1, in addition to the common selection, we apply three further requirements to isolate the EW signal:  $|y_{Z\gamma} - (y_{j1} + y_{j2})/2| < 1.2$ ,  $|\Delta\eta_{jj}| > 1.6$ , and  $\Delta\phi_{Z\gamma, jj} > 2.0$  radians. The selection requirements are chosen by optimizing the expected significance. We apply the  $CL_s$  criterion described in Refs. [42, 43] to assess the signal significance, based on the binned  $M_{jj}$  distribution, using only the two rightmost bins corresponding to  $400 < M_{jj} < 800$  GeV and  $M_{jj} > 800$  GeV. We consider QCD  $Z\gamma jj$  production and events without  $Z\gamma$  as background and EW  $Z\gamma jj$  production as signal.

Table 3 summarizes the number of events predicted for each process with the number of events observed. For EW  $Z\gamma jj$  production, the observations are found to be compatible with expectations in the different channels. By combining both channels, we find evidence for EW  $Z\gamma jj$  production with an observed and expected significance of 3.0 and 2.1 standard deviations, respectively. We determine the ratio of the observed signal to that expected from the SM for LO EW  $Z\gamma jj$  production as  $\hat{\mu} = 1.5^{+0.9}_{-0.6}$  using a binned likelihood fit over the two ranges of the  $M_{jj}$  distribution.

Applying the same criteria, we can also measure the significance of the combined EW and QCD  $Z\gamma jj$  process. As shown in Table 3, with the two decay channels combined in the search region, of the signal events 7.0 (38.4%) are estimated to come from EW production and the remaining 11.3 from QCD production. As a result, the observed (expected) significance for the combined EW and QCD  $Z\gamma jj$  process is 5.7 (5.5) standard deviations.

To determine the cross section for EW  $Z\gamma jj$  production we use a fiducial kinematic region based on the acceptance of the CMS detector with a minimal selection on the  $M_{jj}$  and  $\Delta\eta_{jj}$  variables to select the VBS topology. The fiducial region is defined as described in Table 1. We define the cross section in the fiducial region as  $\sigma_f = \sigma_g \hat{\mu} \alpha_{gf}$  where  $\sigma_g$  is the cross section for generated signal events,  $\hat{\mu}$  is the signal strength, and  $\alpha_{gf}$  is the acceptance for the generated events in the fiducial region, evaluated through simulation. The fiducial cross section for EW  $Z\gamma jj$  production is  $1.86^{+0.90}_{-0.75}$  (stat) $^{+0.34}_{-0.26}$  (syst)  $\pm 0.05$  (lumi) fb, consistent with the theoretical prediction at LO of  $1.27 \pm 0.11$  (scale)  $\pm 0.05$  (PDF) fb calculated using MADGRAPH.

The cross section for all processes that produce the  $Z\gamma jj$  final state can be compared to theoretical predictions. The fiducial region studied here lies in a particularly interesting region of phase space because of the substantial contribution to  $Z\gamma jj$  from EW production. By restricting the phase space to the fiducial region for the EW process as defined before, the expected fraction of EW events in the combined sample of EW and QCD signal events is 26%, and the cross section of the combined process is  $5.94^{+1.53}_{-1.35}$  (stat) $^{+0.43}_{-0.37}$  (syst)  $\pm 0.13$  (lumi) fb, which is consistent with the theoretical prediction at LO calculated using MADGRAPH:  $5.05 \pm 1.22$  (scale)  $\pm 0.31$  (PDF) fb.

## 8. Search for anomalous quartic gauge couplings

The effects of any new physics between the TeV and the Planck scale might be significant in the high energy tails of measurements at the LHC and can be parameterized via effective anomalous couplings. With the discovery of the Higgs boson, higher-dimensional operators can be introduced in a linear way [44]:

$$\begin{aligned}
\mathcal{L}_{\text{aQGC}} = & \frac{f_{M0}}{\Lambda^4} \text{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \\
& + \frac{f_{M1}}{\Lambda^4} \text{Tr}[\mathbf{W}_{\mu\nu}\mathbf{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi] \\
& + \frac{f_{M2}}{\Lambda^4} [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi] \\
& + \frac{f_{M3}}{\Lambda^4} [B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi] \\
& + \frac{f_{T0}}{\Lambda^4} \text{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times \text{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}] \\
& + \frac{f_{T2}}{\Lambda^4} \text{Tr}[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times \text{Tr}[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}] \\
& + \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} + \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha},
\end{aligned} \tag{1}$$

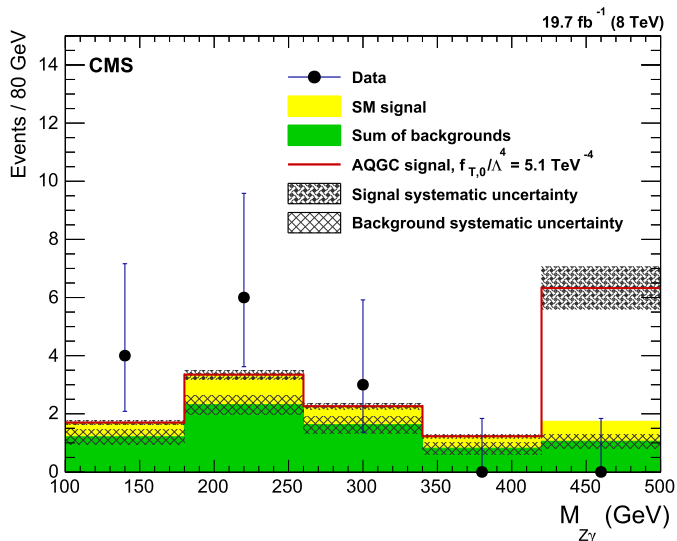
where  $f_{M0,1,2,3}$  and  $f_{T0,2,8,9}$  are coefficients of relevant effective operators, and  $\Lambda$  represents the scale of new physics responsible for anomalous couplings. The Lagrangian of the aQGCs is implemented within the MADGRAPH package.

We study the distribution of the mass of the dilepton and photon system,  $M_{Z\gamma}$ , to search for contributions from aQGCs. The effects of new physics would be seen at higher energy and modify the interference of VBS diagrams. To select the region sensitive to new physics, we require  $p_T^\gamma > 60$  GeV. The selection for the aQGC analysis is described in Table 1. The  $Z\gamma$  mass distribution is shown in Fig. 3, where the last bin includes all events with  $M_{Z\gamma} > 420$  GeV. Because no significant excess is seen in the  $M_{Z\gamma}$  distribution, we use the shape of the  $M_{Z\gamma}$  distribution to extract limits on aQGC contributions.

With the parameterization of signals and related systematic uncertainties, for each aQGC parameter, we reweight the SM signal shape to the aQGC shape. The following test statistic is used:

$$t_{\alpha_{\text{test}}} = -2 \ln \frac{\mathcal{L}(\alpha_{\text{test}}, \hat{\theta})}{\mathcal{L}(\hat{\alpha}, \hat{\theta})}, \tag{2}$$

where the likelihood function ( $\mathcal{L}$ ) is constructed for both lepton channels and combined, using a bin-wise Poisson distribution with profiled nuisance parameters ( $\theta$ ).  $\alpha_{\text{test}}$  represents the aQGC point being tested. The symbol  $\hat{\theta}$  represents the values corresponding to the maximum of the likelihood at the point  $\alpha_{\text{test}}$ , while  $\hat{\alpha}$  and  $\hat{\theta}$  correspond to the global maximum of the likelihood. This test statistic is assumed to follow a  $\chi^2$  distribution [45], from which one can extract limits. Exclusion limits are shown in Table 4. Each



**Fig. 3.** The invariant mass distribution of the  $Z\gamma$  system for events that pass the aQGC selection. The highest mass bin includes events with  $M_{Z\gamma} > 420$  GeV. Error bars represent the statistical uncertainty in the data, while the systematic uncertainties in the aQGC signal and background estimate are shown as hatched bands.

**Table 4**

Observed and expected shape-based exclusion limits for each aQGC parameter at 95% CL, without a form factor applied.

Observed limits ( $\text{TeV}^{-4}$ )	Expected limits ( $\text{TeV}^{-4}$ )
$-71 < f_{M0}/\Lambda^4 < 75$	$-109 < f_{M0}/\Lambda^4 < 111$
$-190 < f_{M1}/\Lambda^4 < 182$	$-281 < f_{M1}/\Lambda^4 < 280$
$-32 < f_{M2}/\Lambda^4 < 31$	$-47 < f_{M2}/\Lambda^4 < 47$
$-58 < f_{M3}/\Lambda^4 < 59$	$-87 < f_{M3}/\Lambda^4 < 87$
$-3.8 < f_{T0}/\Lambda^4 < 3.4$	$-5.1 < f_{T0}/\Lambda^4 < 5.1$
$-4.4 < f_{T1}/\Lambda^4 < 4.4$	$-6.5 < f_{T1}/\Lambda^4 < 6.5$
$-9.9 < f_{T2}/\Lambda^4 < 9.0$	$-14.0 < f_{T2}/\Lambda^4 < 14.5$
$-1.8 < f_{T8}/\Lambda^4 < 1.8$	$-2.7 < f_{T8}/\Lambda^4 < 2.7$
$-4.0 < f_{T9}/\Lambda^4 < 4.0$	$-6.0 < f_{T9}/\Lambda^4 < 6.0$

coupling parameter is varied over a set of discrete values, keeping the other parameters fixed to zero.

An effective theory is only valid at energies lower than the scale of new physics, and high-dimensional operators with nonzero aQGC values can lead to unitarity violation at sufficiently high energies. For each aQGC listed in Table 4, we checked the stated upper limit against the unitary bound [46] obtained with  $\text{vBFNLO}$  [47]. In general, we find the limits on all aQGC parameters are set in the unitary unsafe region, except for  $f_{T9}$  where the unitarity bound is up to 6 TeV. Form factors can be introduced to unitarize the high energy contribution, however it is difficult to compare results from different experiments and it is not theoretically well motivated. In this study all of the aQGC limits shown are evaluated without a form factor, and can be directly compared to limits set in references [3–7,9–12].

## 9. Conclusions

The measurement of the cross section for the electroweak production of a Z boson and a photon in association with two jets, where the Z boson decays into electron or muon pairs, was presented. The measurement is based on a sample of proton–proton collisions collected with the CMS detector at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of  $19.7 \text{ fb}^{-1}$ . We find evidence for EW  $Z\gamma jj$  production with an ob-

served (expected) significance of 3.0 (2.1) standard deviations. The fiducial cross section for EW  $Z\gamma jj$  production is measured to be  $1.86^{+0.90}_{-0.75} (\text{stat})^{+0.34}_{-0.26} (\text{syst}) \pm 0.05 (\text{lumi}) \text{ fb}$ , consistent with the theoretical prediction. The fiducial cross section for combined EW and QCD  $Z\gamma jj$  production is  $5.94^{+1.53}_{-1.35} (\text{stat})^{+0.43}_{-0.37} (\text{syst}) \pm 0.13 (\text{lumi}) \text{ fb}$ , which is also consistent with the leading-order theoretical prediction.

In the framework of dimension-eight effective field theory operators, limits on the aQGC parameters  $f_{M0,1,2,3}$  and  $f_{T0,1,2,8,9}$  are set at 95% confidence level. This is the first constraints on the neutral aQGC parameters  $f_{T8}$ .

## Acknowledgements

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

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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## The CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

*Yerevan Physics Institute, Yerevan, Armenia*

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik, Wien, Austria*

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

*National Centre for Particle and High Energy Physics, Minsk, Belarus*

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

*Universiteit Antwerpen, Antwerpen, Belgium*

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

*Vrije Universiteit Brussel, Brussel, Belgium*

H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>2</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

*Ghent University, Ghent, Belgium*

C. Beluffi<sup>3</sup>, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, S. De Visscher, C. Delaere, M. Delcourt, L. Forthomme, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

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

N. Belyi

*Université de Mons, Mons, Belgium*

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>4</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>4</sup>, A. Vilela Pereira

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



S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>b</sup>, S. Dogra<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, C.S. Moon<sup>a,5</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas

<sup>a</sup> Universidade Estadual Paulista, São Paulo, Brazil

<sup>b</sup> Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

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

*University of Sofia, Sofia, Bulgaria*

W. Fang<sup>6</sup>

*Beihang University, Beijing, China*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen<sup>7</sup>, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

*Institute of High Energy Physics, Beijing, China*

Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, D. Yang, Z. Zhang

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

*Universidad de Los Andes, Bogota, Colombia*

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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

Z. Antunovic, M. Kovac

*University of Split, Faculty of Science, Split, Croatia*

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic

*Institute Rudjer Boskovic, Zagreb, Croatia*

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

*University of Cyprus, Nicosia, Cyprus*

M. Finger<sup>8</sup>, M. Finger Jr.<sup>8</sup>

*Charles University, Prague, Czech Republic*

E. Carrera Jarrin

*Universidad San Francisco de Quito, Quito, Ecuador*

S. Elgammal<sup>9</sup>, A. Mohamed<sup>10</sup>, Y. Mohammed<sup>11</sup>, E. Salama<sup>9,12</sup>

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

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

P. Eerola, J. Pekkanen, M. Voutilainen

*Department of Physics, University of Helsinki, Helsinki, Finland*

J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Peltola, J. Tuominiemi, E. Tuovinen, L. Wendland

*Helsinki Institute of Physics, Helsinki, Finland*

J. Talvitie, T. Tuuva

*Lappeenranta University of Technology, Lappeenranta, Finland*

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*

J.-L. Agram<sup>13</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>13</sup>, X. Coubez, J.-C. Fontaine<sup>13</sup>, D. Gelé, U. Goerlach, A.-C. Le Bihan, J.A. Merlin<sup>14</sup>, K. Skovpen, P. Van Hove

*Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, France*

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>15</sup>, D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

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

A. Khvedelidze<sup>8</sup>

*Georgian Technical University, Tbilisi, Georgia*

I. Bagaturia<sup>16</sup>

*Tbilisi State University, Tbilisi, Georgia*

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J.F. Schulte, J. Schulz, T. Verlage, H. Weber, V. Zhukov<sup>15</sup>

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

M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teysier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl<sup>14</sup>

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

M. Aldaya Martin, C. Asawatangtrakuldee, I. Asin, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras<sup>17</sup>, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, E. Gallo<sup>18</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>19</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>19</sup>, M. Kasemann, J. Keaveney, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>19</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, K.D. Trippkewitz, G.P. Van Onsem, R. Walsh, C. Wissing

*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, K. Goebel, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, J. Ott, F. Pantaleo<sup>14</sup>, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderren, A. Vanhoefer, B. Vormwald

*University of Hamburg, Hamburg, Germany*

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann<sup>14</sup>, S.M. Heindl, U. Husemann, I. Katkov<sup>15</sup>, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

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

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

*National and Kapodistrian University of Athens, Athens, Greece*

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

*University of Ioánnina, Ioánnina, Greece*

N. Filipovic

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

G. Bencze, C. Hajdu, P. Hidas, D. Horvath<sup>20</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>21</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>22</sup>, A. Makovec, J. Molnar, Z. Szillasi

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>21</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

*Institute of Physics, University of Debrecen, Hungary*

S. Bahinipati, S. Choudhury<sup>23</sup>, P. Mal, K. Mandal, A. Nayak<sup>24</sup>, D.K. Sahoo, N. Sahoo, S.K. Swain

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

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

*Panjab University, Chandigarh, India*

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

*University of Delhi, Delhi, India*

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

*Saha Institute of Nuclear Physics, Kolkata, India*

P.K. Behera

*Indian Institute of Technology Madras, Madras, India*

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>14</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

*Tata Institute of Fundamental Research-A, Mumbai, India*

S. Banerjee, S. Bhowmik<sup>25</sup>, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>25</sup>, G. Majumder, K. Mazumdar, B. Parida, T. Sarkar<sup>25</sup>, N. Wickramage<sup>26</sup>

*Tata Institute of Fundamental Research-B, Mumbai, India*

S. Chauhan, S. Dube, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S. Chenarani<sup>27</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>27</sup>, A. Fahim<sup>28</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>29</sup>, M. Zeinali

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

M. Felcini, M. Grunewald

*University College Dublin, Dublin, Ireland*

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</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>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a,14</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

<sup>a</sup> INFN Sezione di Bari, Bari, Italy

<sup>b</sup> Università di Bari, Bari, Italy

<sup>c</sup> Politecnico di Bari, Bari, Italy

G. Abbiendi<sup>a</sup>, C. Battilana, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<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>, S.S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b,14</sup>

<sup>a</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>b</sup> Università di Bologna, Bologna, Italy

S. Albergo<sup>a,b</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

<sup>a</sup> INFN Sezione di Catania, Catania, Italy

<sup>b</sup> Università di Catania, Catania, Italy

G. Barbagli <sup>a</sup>, V. Ciulli <sup>a,b</sup>, C. Civinini <sup>a</sup>, R. D'Alessandro <sup>a,b</sup>, E. Focardi <sup>a,b</sup>, V. Gori <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, G. Sguazzoni <sup>a</sup>, L. Viliani <sup>a,b,14</sup>

<sup>a</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>b</sup> Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera <sup>14</sup>

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli <sup>a,b</sup>, F. Ferro <sup>a</sup>, M. Lo Vetere <sup>a,b</sup>, M.R. Monge <sup>a,b</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Genova, Genova, Italy

<sup>b</sup> Università di Genova, Genova, Italy

L. Brianza, M.E. Dinardo <sup>a,b</sup>, S. Fiorendi <sup>a,b</sup>, S. Gennai <sup>a</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, S. Malvezzi <sup>a</sup>, R.A. Manzoni <sup>a,b,14</sup>, B. Marzocchi <sup>a,b</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, D. Pedrini <sup>a</sup>, S. Pigazzini, S. Ragazzi <sup>a,b</sup>, T. Tabarelli de Fatis <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>b</sup> Università di Milano-Bicocca, Milano, Italy

S. Buontempo <sup>a</sup>, N. Cavallo <sup>a,c</sup>, G. De Nardo, S. Di Guida <sup>a,d,14</sup>, M. Esposito <sup>a,b</sup>, F. Fabozzi <sup>a,c</sup>, A.O.M. Iorio <sup>a,b</sup>, G. Lanza <sup>a</sup>, L. Lista <sup>a</sup>, S. Meola <sup>a,d,14</sup>, M. Merola <sup>a</sup>, P. Paolucci <sup>a,14</sup>, C. Sciacca <sup>a,b</sup>, F. Thyssen

<sup>a</sup> INFN Sezione di Napoli, Napoli, Italy

<sup>b</sup> Università di Napoli 'Federico II', Napoli, Italy

<sup>c</sup> Università della Basilicata, Potenza, Italy

<sup>d</sup> Università G. Marconi, Roma, Italy

P. Azzi <sup>a,14</sup>, N. Bacchetta <sup>a</sup>, L. Benato <sup>a,b</sup>, D. Bisello <sup>a,b</sup>, A. Boletti <sup>a,b</sup>, R. Carlin <sup>a,b</sup>, A. Carvalho Antunes De Oliveira <sup>a,b</sup>, P. Checchia <sup>a</sup>, M. Dall'Osso <sup>a,b</sup>, P. De Castro Manzano <sup>a</sup>, T. Dorigo <sup>a</sup>, U. Dosselli <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, A. Gozzelino <sup>a</sup>, S. Lacaprara <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, J. Pazzini <sup>a,b,14</sup>, N. Pozzobon <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, E. Torassa <sup>a</sup>, M. Zanetti, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Padova, Padova, Italy

<sup>b</sup> Università di Padova, Padova, Italy

<sup>c</sup> Università di Trento, Trento, Italy

A. Braghieri <sup>a</sup>, A. Magnani <sup>a,b</sup>, P. Montagna <sup>a,b</sup>, S.P. Ratti <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a,b</sup>, P. Vitulo <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Pavia, Pavia, Italy

<sup>b</sup> Università di Pavia, Pavia, Italy

L. Alunni Solestizi <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>, R. Leonardi <sup>a,b</sup>, G. Mantovani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, A. Saha <sup>a</sup>, A. Santocchia <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>b</sup> Università di Perugia, Perugia, Italy

K. Androsov <sup>a,30</sup>, P. Azzurri <sup>a,14</sup>, G. Bagliesi <sup>a</sup>, J. Bernardini <sup>a</sup>, T. Boccali <sup>a</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,30</sup>, R. Dell'Orso <sup>a</sup>, S. Donato <sup>a,c</sup>, G. Fedi, A. Giassi <sup>a</sup>, M.T. Grippo <sup>a,30</sup>, F. Ligabue <sup>a,c</sup>, T. Lomtadze <sup>a</sup>, L. Martini <sup>a,b</sup>, A. Messineo <sup>a,b</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>, A. Savoy-Navarro <sup>a,31</sup>, P. Spagnolo <sup>a</sup>, R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, A. Venturi <sup>a</sup>, P.G. Verdini <sup>a</sup>

<sup>a</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>b</sup> Università di Pisa, Pisa, Italy

<sup>c</sup> Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone <sup>a,b</sup>, F. Cavallari <sup>a</sup>, M. Cipriani <sup>a,b</sup>, G. D'imperio <sup>a,b,14</sup>, D. Del Re <sup>a,b,14</sup>, M. Diemoz <sup>a</sup>, S. Gelli <sup>a,b</sup>, C. Jorda <sup>a</sup>, E. Longo <sup>a,b</sup>, F. Margaroli <sup>a,b</sup>, P. Meridiani <sup>a</sup>, G. Organtini <sup>a,b</sup>, R. Paramatti <sup>a</sup>, F. Preiato <sup>a,b</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Roma, Roma, Italy

<sup>b</sup> Università di Roma, Roma, Italy

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c,14</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, N. Bartosik <sup>a</sup>, R. Bellan <sup>a,b</sup>, C. Biino <sup>a</sup>, N. Cartiglia <sup>a</sup>, F. Cenna <sup>a,b</sup>, M. Costa <sup>a,b</sup>, R. Covarelli <sup>a,b</sup>, A. Degano <sup>a,b</sup>, N. Demaria <sup>a</sup>, L. Finco <sup>a,b</sup>, B. Kiani <sup>a,b</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.M. Obertino <sup>a,b</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>, F. Ravera <sup>a,b</sup>, A. Romero <sup>a,b</sup>, M. Ruspa <sup>a,c</sup>, R. Sacchi <sup>a,b</sup>, K. Shchelina <sup>a,b</sup>, V. Sola <sup>a</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, P. Traczyk <sup>a,b</sup>

<sup>a</sup> INFN Sezione di Torino, Torino, Italy

<sup>b</sup> Università di Torino, Torino, Italy

<sup>c</sup> Università del Piemonte Orientale, Novara, Italy

S. Belforte <sup>a</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, G. Della Ricca <sup>a,b</sup>, C. La Licata <sup>a,b</sup>, A. Schizzi <sup>a,b</sup>, A. Zanetti <sup>a</sup>

<sup>a</sup> INFN Sezione di Trieste, Trieste, Italy

<sup>b</sup> Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, A. Lee

Chonbuk National University, Jeonju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, S.B. Oh, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, D. Kim, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenias, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali <sup>32</sup>, F. Mohamad Idris <sup>33</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz <sup>34</sup>, A. Hernandez-Almada, R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

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

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

Universidad Iberoamericana, Mexico City, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

**A. Morelos Pineda***Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico***D. Krofcheck***University of Auckland, Auckland, New Zealand***P.H. Butler***University of Canterbury, Christchurch, New Zealand***A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas***National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan***H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski***National Centre for Nuclear Research, Swierk, Poland***K. Bunkowski, A. Byszuk<sup>35</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak***Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland***P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia***Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal***P. Bunin, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev<sup>36,37</sup>, V.V. Mitsyn, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, A. Zarubin***Joint Institute for Nuclear Research, Dubna, Russia***L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova<sup>39</sup>, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev***Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia***Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin***Institute for Nuclear Research, Moscow, Russia***V. Epshteyn, V. Gavrillov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin***Institute for Theoretical and Experimental Physics, Moscow, Russia***M. Chadeeva<sup>40</sup>, M. Danilov<sup>40</sup>, O. Markin***National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia***V. Andreev, M. Azarkin<sup>37</sup>, I. Dremin<sup>37</sup>, M. Kirakosyan, A. Leonidov<sup>37</sup>, S.V. Rusakov, A. Terkulov***P.N. Lebedev Physical Institute, Moscow, Russia***A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>41</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev***Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*

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

*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*

P. Adzic<sup>42</sup>, P. Cirkovic, D. Devetak, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

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

J.F. de Trocóniz, M. Missiroli, D. Moran

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, J.M. Vizán García

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, E. Di Marco<sup>43</sup>, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, V. Knünz, A. Kornmayer<sup>14</sup>, M.J. Kortelainen, K. Kourouris, M. Krammer<sup>1</sup>, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli<sup>44</sup>, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi<sup>45</sup>, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>46</sup>, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns<sup>47</sup>, G.I. Veres<sup>21</sup>, N. Wardle, H.K. Wöhri, A. Zagozdinska<sup>35</sup>, W.D. Zeuner

*CERN, European Organization for Nuclear Research, Geneva, Switzerland*

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

*Paul Scherrer Institut, Villigen, Switzerland*

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte<sup>†</sup>, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nelli-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönemberger, A. Starodumov<sup>48</sup>, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*



T.K. Aarrestad, C. Amsler<sup>49</sup>, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang

*Universität Zürich, Zurich, Switzerland*

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

*National Central University, Chung-Li, Taiwan*

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

*National Taiwan University (NTU), Taipei, Taiwan*

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

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

A. Adiguzel, S. Damarseekin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>50</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut<sup>51</sup>, K. Ozdemir<sup>52</sup>, S. Ozturk<sup>53</sup>, A. Polatoz, B. Tali<sup>54</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

*Cukurova University – Physics Department, Science and Art Faculty, Turkey*

B. Bilin, S. Bilmis, B. Isildak<sup>55</sup>, G. Karapinar<sup>56</sup>, M. Yalvac, M. Zeyrek

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

E. Gülmez, M. Kaya<sup>57</sup>, O. Kaya<sup>58</sup>, E.A. Yetkin<sup>59</sup>, T. Yetkin<sup>60</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak, S. Sen<sup>61</sup>

*Istanbul Technical University, Istanbul, Turkey*

B. Grynyov

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

L. Levchuk, P. Sorokin

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

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold<sup>62</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-Storey, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>63</sup>, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

*Rutherford Appleton Laboratory, Didcot, United Kingdom*

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, R. Lane, C. Laner, R. Lucas<sup>62</sup>, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko<sup>48</sup>, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>64</sup>, T. Virdee<sup>14</sup>, S.C. Zenz

*Imperial College, London, United Kingdom*

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

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

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

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

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif  
*Brown University, Providence, USA*

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

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

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

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech <sup>65</sup>, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta  
*University of California, San Diego, La Jolla, USA*

R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo  
*University of California, Santa Barbara – Department of Physics, Santa Barbara, USA*

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

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

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

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek  
*Cornell University, Ithaca, USA*

## D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes<sup>†</sup>, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic<sup>66</sup>, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi<sup>67</sup>, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, Z. Wu, M. Zakaria, J. Zhang

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

B. Bilki<sup>68</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>69</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>70</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, J. Bowen, C. Bruner, J. Castle, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

D. Lange, F. Rebassoo, D. Wright

*Lawrence Livermore National Laboratory, Livermore, USA*

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

*University of Maryland, College Park, USA*

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

*University of Minnesota, Minneapolis, USA*

J.G. Acosta, S. Oliveros

*University of Mississippi, Oxford, USA*

E. Avdeeva, R. Bartek, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, D. Knowlton, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

*State University of New York at Buffalo, Buffalo, USA*

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

*Northeastern University, Boston, USA*

S. Bhattacharya, K.A. Hahn, A. Kubik, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

*Northwestern University, Evanston, USA*

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>36</sup>, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, N. Valls, M. Wayne, M. Wolf, A. Woodard

*University of Notre Dame, Notre Dame, USA*

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, J. Luo, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

*Princeton University, Princeton, USA*

**S. Malik**

*University of Puerto Rico, Mayaguez, USA*

A. Barker, V.E. Barnes, D. Benedetti, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

*Purdue University, West Lafayette, USA*

**N. Parashar, J. Stupak**

*Purdue University Calumet, Hammond, USA*

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

*Rice University, Houston, USA*

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

*University of Rochester, Rochester, USA*

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

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

M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>71</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon<sup>72</sup>, V. Krutelyov, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

*Texas A&M University, College Station, USA*

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderø, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev, Z. Wang

*Texas Tech University, Lubbock, USA*

A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

*Vanderbilt University, Nashville, USA*

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

*University of Virginia, Charlottesville, USA*

C. Clarke, R. Harr, P.E. Karchin, P. Lamichhane, J. Sturdy

*Wayne State University, Detroit, USA*

D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

*University of Wisconsin–Madison, Madison, WI, USA*

† Deceased.

- 1 Also at Vienna University of Technology, Vienna, Austria.
- 2 Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
- 3 Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France.
- 4 Also at Universidade Estadual de Campinas, Campinas, Brazil.
- 5 Also at Centre National de la Recherche Scientifique (CNRS) – IN2P3, Paris, France.
- 6 Also at Université Libre de Bruxelles, Bruxelles, Belgium.
- 7 Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- 8 Also at Joint Institute for Nuclear Research, Dubna, Russia.
- 9 Now at British University in Egypt, Cairo, Egypt.
- 10 Also at Zewail City of Science and Technology, Zewail, Egypt.
- 11 Now at Fayoum University, El-Fayoum, Egypt.
- 12 Now at Ain Shams University, Cairo, Egypt.
- 13 Also at Université de Haute Alsace, Mulhouse, France.
- 14 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- 15 Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- 16 Also at Ilia State University, Tbilisi, Georgia.
- 17 Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- 18 Also at University of Hamburg, Hamburg, Germany.
- 19 Also at Brandenburg University of Technology, Cottbus, Germany.
- 20 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- 21 Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- 22 Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- 23 Also at Indian Institute of Science Education and Research, Bhopal, India.
- 24 Also at Institute of Physics, Bhubaneswar, India.
- 25 Also at University of Visva-Bharati, Santiniketan, India.
- 26 Also at University of Ruhuna, Matara, Sri Lanka.
- 27 Also at Isfahan University of Technology, Isfahan, Iran.
- 28 Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
- 29 Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- 30 Also at Università degli Studi di Siena, Siena, Italy.
- 31 Also at Purdue University, West Lafayette, USA.
- 32 Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- 33 Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- 34 Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- 35 Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- 36 Also at Institute for Nuclear Research, Moscow, Russia.
- 37 Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- 38 Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- 39 Also at University of Florida, Gainesville, USA.
- 40 Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- 41 Also at California Institute of Technology, Pasadena, USA.
- 42 Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- 43 Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.
- 44 Also at National Technical University of Athens, Athens, Greece.
- 45 Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- 46 Also at National and Kapodistrian University of Athens, Athens, Greece.
- 47 Also at Riga Technical University, Riga, Latvia.
- 48 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- 49 Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- 50 Also at Mersin University, Mersin, Turkey.
- 51 Also at Cag University, Mersin, Turkey.
- 52 Also at Piri Reis University, Istanbul, Turkey.
- 53 Also at Gaziosmanpasa University, Tokat, Turkey.
- 54 Also at Adiyaman University, Adiyaman, Turkey.
- 55 Also at Ozyegin University, Istanbul, Turkey.
- 56 Also at Izmir Institute of Technology, Izmir, Turkey.
- 57 Also at Marmara University, Istanbul, Turkey.
- 58 Also at Kafkas University, Kars, Turkey.
- 59 Also at Istanbul Bilgi University, Istanbul, Turkey.
- 60 Also at Yildiz Technical University, Istanbul, Turkey.
- 61 Also at Hacettepe University, Ankara, Turkey.
- 62 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- 63 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 64 Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- 65 Also at Utah Valley University, Orem, USA.
- 66 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- 67 Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.
- 68 Also at Argonne National Laboratory, Argonne, USA.

<sup>69</sup> Also at Erzincan University, Erzincan, Turkey.

<sup>70</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

<sup>71</sup> Also at Texas A&M University at Qatar, Doha, Qatar.

<sup>72</sup> Also at Kyungpook National University, Daegu, Korea.