Measurement of the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson couplings

The CMS Collaboration

Abstract

An inclusive measurement of the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV is presented, using data corresponding to an integrated luminosity of 19.6 fb$^{-1}$ collected with the CMS detector at the LHC. This measurement is based on the observation of events with large missing energy and with a single photon with transverse momentum above 145 GeV and absolute pseudorapidity in the range $|\eta| < 1.44$. The measured $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section, $52.7 \pm 2.1$ (stat) $\pm 6.4$ (syst) $\pm 1.4$ (lumi) fb, agrees well with the standard model prediction of $50.0^{+2.4}_{-2.2}$ fb. A study of the photon transverse momentum spectrum yields the most stringent limits to date on the anomalous $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson couplings.

Published in Physics Letters B as doi:10.1016/j.physletb.2016.06.080.
1 Introduction

The study of the production of boson pairs provides an important test of the electroweak sector of the standard model (SM), since this production is a consequence of the non-Abelian nature of the underlying $SU(2) \times U(1)$ symmetry. Trilinear gauge boson vertices are a consequence of this symmetry, and the values of the self-couplings are fixed in the SM. Any measured deviation would be an indication of physics beyond the standard model at that vertex. For production of a $Z$ boson and a photon, these couplings are zero in the SM. New symmetries or new particles that only become relevant at higher energies could result in a cross section that differs from the SM prediction [1, 2], particularly for final-state bosons with high transverse momentum.

In this letter a measurement is presented of the production of a $Z$ boson, which decays into a pair of neutrinos, and a photon in proton-proton collisions, at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, using data collected by the CMS experiment corresponding to an integrated luminosity of 19.6 fb$^{-1}$. This result extends previous measurements at the LHC [3–5]. We describe a measurement of the production cross section as well as the extraction of limits on anomalous $ZV\gamma$ couplings, where $V = Z, \gamma$. In this search for anomalous trilinear gauge couplings (aTGCs), the final-state boson transverse momentum is used as a sensitive observable.

The $\nu\bar{\nu}\gamma$ final state can be produced through initial-state radiation (where a photon is emitted by an initial-state parton) or through anomalous coupling vertices. The allowed electroweak tree-level diagram in the SM for $Z\gamma$ production in $pp$ collisions is shown in Fig. 1 (left). The $s$-channel production via a ZZ$\gamma$ or $Z\gamma\gamma$ aTGC is shown in Fig. 1 (right).

Figure 1: Feynman diagrams of $Z\gamma$ production via initial-state radiation in the SM at tree level (left), and via anomalous ZZ$\gamma$ or $Z\gamma\gamma$ trilinear gauge couplings (right).

The most general Lorentz-invariant and gauge-invariant $ZV\gamma$ vertex can be described by four coupling parameters $h^V_i (i = 1, \ldots, 4)$ [6,7]. The first two couplings ($i = 1, 2$) are CP-violating, while the latter two ($i = 3, 4$) are CP-conserving [7, 8]. At tree level in the SM, the individual values of these aTGCs are zero. The photon transverse momentum spectrum has similar sensitivity to CP-violating and CP-conserving couplings. The results are generally interpreted in terms of the CP-conserving aTGCs $h^V_3$ and $h^V_4$.

The sensitivity to aTGCs in $Z\gamma$ production is higher in the $Z \rightarrow \nu\bar{\nu}$ decay mode than in $Z$ boson decay modes with charged leptons, because the branching fraction for a $Z$ boson decay to a pair of neutrinos is six times higher than for a decay to a particular charged lepton pair, and the acceptance in the neutrino channel is higher.

The fiducial phase space for this measurement is defined by the requirements of photon transverse energy $E_T^\gamma > 145$ GeV and photon pseudorapidity $|\eta^\gamma| < 1.44$, where the contamination from other particles misidentified as photons is lower [9].
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 superconducting 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 \((|\eta| < 1.479)\) and two endcap \((1.479 < |\eta| < 3.0)\) sections, where \(\eta\) is the pseudorapidity. Extensive forward calorimetry complements the 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 energy resolution for photons with transverse momentum \(\geq 60\) GeV varies between 1% and 2.5% over the solid angle of the ECAL barrel, and from 2.5% to 3.5% in the endcaps \[9\]. The timing measurement of the ECAL has a resolution better than 200 ps for energy deposits larger than 10 GeV \[9\]. In the \(\eta\)-\(\phi\) plane, where \(\phi\) is the azimuthal angle and for \(|\eta| < 1.48\), the HCAL cells map onto 5 \times 5 arrays of ECAL crystals to form calorimeter towers projecting radially outward from the nominal interaction point.

The event reconstruction is performed using a particle-flow (PF) algorithm \[10, 11\], which reconstructs and identifies individual particles using an optimized combination of information from all subdetectors. Photons are identified as energy clusters in the ECAL. These energy clusters are merged to form superclusters that are five crystals wide in \(\eta\), centered around the most energetic crystal, and have a variable width in \(\phi\). The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are formed from these reconstructed particles with the infrared- and collinear-safe anti-\(k_T\) algorithm \[12\], using a distance parameter \(\Delta R = 0.5\), where \(\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}\) and \(\Delta \eta\) and \(\Delta \phi\) are the pseudorapidity and azimuthal angle difference between the jet axis and the particle direction. The missing transverse momentum vector \(\vec{E}_T\) is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF candidates in an event; its magnitude is referred to as \(E_T\).

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. \[13\].

3 Signal and background modeling

The final state consisting of an energetic photon accompanied by an imbalance in transverse energy can be mimicked by several other processes in the SM. These processes include \(W\gamma \to \ell\nu\gamma\) where \(\ell\) is a charged lepton (if the lepton escapes detection), \(W \to \ell\nu\) (if the lepton is misidentified as a photon), \(\gamma\) + jets (if the jets are misreconstructed, resulting in \(E_T\)), QCD multijet production including \(Z(\nu\bar{\nu})\) + jets (if the jet is misidentified as a photon), \(Z\gamma \to \ell\ell\gamma\) (if both leptons escape detection), \(\gamma\gamma\) events (if one of the photons escapes detection), and also backgrounds from beam halo.

The contributions from the \(W\gamma \to \ell\nu\gamma\), \(\gamma\) + jets, \(Z\gamma \to \ell\ell\gamma\), and \(\gamma\gamma\) processes to the candidate event sample are estimated using Monte Carlo-based (MC) simulations. The \(W(\ell\nu)\gamma\) and \(Z\to\ell\ell\gamma\) samples are generated with MadGraph5aMC at leading order (LO) \[14\] and then processed with the Pythia 6.426 event generator \[15\] for showering and hadronization. The other samples are generated with the Pythia 6.426 generator \[15\] at LO. All the samples are generated using the CTEQ6L1 \[16\] parton distribution function (PDF) set, processed through...
the CMS detector simulation based on GEANT4 [17, 18], and reconstructed in the same manner as collision data.

The cross section for the SM background process \(W\gamma \rightarrow \ell\nu\gamma\) with at most one jet is corrected with an \(E_T^\gamma\) dependent K factor estimated from MCFM [19] to account for next-to-leading-order (NLO) effects. The PDF4LHC Working Group recommendations [20–22] are used to estimate the uncertainty in the central value of the NLO cross section arising from the PDFs, the strong coupling constant \(\alpha_s\), and its scale dependence. The \(\gamma+\text{jet}\) cross section is corrected to include NLO effects.

To determine the efficiency for the SM \(Z(\nu\bar{\nu})\gamma\) production cross section measurement, events are produced with the MADGRAPH5v1.3.30 generator at LO with a maximum of two additional partons and simulated through the full reconstruction chain. Simulated samples of the \(Z\gamma\) signal for a grid of aTGC values are produced using the SHERPA v1.2.2 generator [23]. The cross section with at most one extra parton is corrected with an \(E_T^\gamma\) dependent K factor estimated from MCFM [19] to account for NLO effects. The inclusive measurement has been compared with a theoretical calculation accurate up to next-to-next-to-leading order (NNLO).

To account for differences arising from imperfect modeling of the data in the simulation, a total correction factor \(\rho\) of \(0.94 \pm 0.06\) is applied to all MC-based background estimates. This is the product of individual correction factors defined as ratios of the efficiencies measured in data and in simulation. They include \(0.97 \pm 0.02\) for photon identification measured using \(Z \rightarrow \ell\ell\) events, \(0.99 \pm 0.03\) for timing requirements measured using a sample of electron events, and \(0.99 \pm 0.02\) and \(0.99 \pm 0.05\) for lepton and jet vetoes measured using \(W \rightarrow \ell\nu\) events.

## 4 Event selection

Events are selected using both a single-photon trigger that requires a photon with \(E_T^\gamma > 150\text{ GeV}\), and photon+\(E_T\), triggers with \(E_T^\gamma > 70\text{ GeV}\) and \(E_T > 100\text{ GeV}\). The combination of these triggers is 96% efficient for events with photon transverse energy \(E_T^\gamma > 145\text{ GeV}\), photon pseudorapidity \(|\eta^\gamma| < 1.44\), and \(E_T > 140\text{ GeV}\). Events are required to have at least one primary vertex reconstructed within a longitudinal distance of \(|z| < 24\text{ cm}\) of the center of the detector and at a distance <2 cm from the \(z\) axis. The primary vertex is chosen to be the vertex with the highest \(p_T^2\) sum of its associated tracks, where \(p_T\) is the transverse momentum.

We impose additional requirements on the energy deposits in the calorimeters to distinguish photons from misidentified jets [9]. The energy in the HCAL associated with the photon supercluster should not exceed 5% of its energy as measured in the ECAL. Moreover, the photon candidates must have a shower distribution in the ECAL consistent with that expected for an electromagnetic (EM) shower [9]. To further reduce photon contamination arising from misidentified jets, isolation requirements on photon candidates are imposed. Energy deposits for isolation are obtained by considering particles in a cone around the axis defined by the supercluster position and the primary vertex [9]. In particular, the scalar sum of transverse momenta (in GeV) of all photons within a cone of \(\Delta R = 0.1\) around the supercluster, excluding a strip of width in \(\eta\) of 0.015, is required to be less than \(0.7 + 0.005p_T^\gamma\); the scalar sum of the transverse momenta (in GeV) of all charged hadrons, associated with the primary vertex, within a hollow cone of \(0.02 < \Delta R < 0.30\) around the supercluster is required to be less than 1.5; and the scalar sum of the transverse momenta (in GeV) of all neutral hadrons within a cone of \(\Delta R = 0.3\) around the supercluster is required to be less than \(1.0 + 0.04p_T^\gamma\). Due to the large number of additional proton-proton interactions (pileup) in the same bunch crossing at the LHC, it is difficult to know the true origin of the photon for a \(\gamma+E_T\) final state (our esti-
mate is correct 50% of the time), which could lead to an underestimation of isolation values. Therefore, an additional PF-based charged particle isolation is calculated for each vertex and the largest value of this isolation sum is required to be smaller than the nominal threshold used for charged particle isolation.

Photon candidates are required to have the energy deposited in the highest energy crystal within the EM cluster to be within $\pm 3$ ns of the time expected for particles from a collision. This requirement reduces instrumental background arising from showers induced by bremsstrahlung from muons in the beam halo or in cosmic rays. To further reduce this background, we exploit the characteristic signature of showers from beam halo in the ECAL. A search region is defined around the highest energy crystal of the EM cluster in a narrow $\phi$ window and over a wide $\eta$ range, after removal of the EM shower in a $5 \times 5$ array. A straight line, parallel to the beam direction, is fitted over the remaining cells within this region. Events are tagged as minimum ionizing particle (MIP tag) if the total energy deposited in the crystals associated with the straight-line fit is greater than 6.3 GeV.

Spurious signals can be embedded within EM showers by direct ionization of the avalanche photodiode sensitive volume by highly ionizing particles. These signals, which would otherwise pass the EM shower selection criteria, are eliminated by requiring consistency among the energy deposition times for all crystals within an EM shower. Photon candidates are also removed if they are likely to be electrons, as inferred from patterns of hits in the pixel detector, called “pixel seeds”, that are matched to the EM clusters [24].

Events containing good photon candidates are then required to have $E_T > 140$ GeV. A topological requirement of $\Delta \phi > 2$ rad between the direction of the photon candidate and the vector $\vec{E}_T$ is applied to reduce the contribution from the $\gamma$+jet background.

In order to suppress backgrounds from QCD multijet production and leptonic decay of W/Z+jets, events are vetoed if they contain significant hadronic/leptonic activity defined by: (i) more than one jet with $p_T > 30$ GeV not passing the pileup jet identification criteria [25], separated from the photon by $\Delta R > 0.5$, or (ii) an electron or a muon with $p_T > 10$ GeV and separated from the photon by $\Delta R > 0.5$.

To reduce the contamination from events with $E_T$ arising from instrumental effects, a $\chi^2$ function is constructed and minimized

$$\chi^2 = \sum_{i=\text{photon, jets}} \left( \frac{(p_{T}^{\text{reco}})_i - (\tilde{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left( \frac{\tilde{E}_x}{\sigma_{\tilde{E}_x}} \right)^2 + \left( \frac{\tilde{E}_y}{\sigma_{\tilde{E}_y}} \right)^2,$$

where the sum runs over the photon and all the jets in the event. The $(\sigma_{p_T})_i$ are the expected momentum resolutions of the reconstructed (reco) photon and jets, and the $(\tilde{p}_T)_i$ are the free parameters allowed to vary in order to minimize the function. The resolution parametrization associated with the $E_T$ is obtained from Ref. [26]. Lastly, $\tilde{E}_x$ and $\tilde{E}_y$ are defined as

$$\tilde{E}_{x,y} = E_{x,y}^{\text{reco}} + \sum_{i=\text{photon, jets}} (p_{x,y}^{\text{reco}})_i - (\tilde{p}_{x,y})_i = - \sum_{i=\text{photon, jets}} (\tilde{p}_{x,y})_i,$$

$$\tilde{E}_T = \sqrt{\tilde{E}_x^2 + \tilde{E}_y^2}.$$
to the actual $E_T$ in the event. An additional requirement of $\mathbf{E}_T > 120\text{ GeV}$ reduces the number of $\gamma+$jet (QCD multijet) events by 80% (35%), while keeping 99.5% of signal events.

After applying these requirements, 630 candidate events are observed in data.

5 Background estimation

The largest contribution is found in the $W\gamma \rightarrow \ell\nu\gamma$ process and is estimated to be $103 \pm 21$ events. The contributions from other processes, a small fraction of the total background, amount to $36 \pm 3$ events.

The most significant background contribution estimated using simulation is also validated in a control region dominated by $W(\ell\nu)\gamma$ events. Events are selected using the full candidate selection but with the lepton veto inverted. In data, 104 events are observed, consistent with an expectation of $126 \pm 23$ events.

The background originating from jets misidentified as photons is estimated using a data driven method. The method is based on a class of jets, referred to as “photon-like” jets, that have properties similar to electromagnetic objects. Photon-like jets are required to pass a very loose photon selection but at the same time fail one of the isolation requirements. The method also relies on the ratio of jets passing the full photon selection to those identified as photon-like jets. This ratio is measured in a control sample enriched in QCD multijet events. To suppress the contribution of electroweak processes, the missing transverse energy in this control sample is required to be smaller than 30 GeV. Because this sample also contains true isolated photons from QCD direct photon production, this contribution must be subtracted from the numerator of the ratio. The required correction is estimated by performing a fit to the distribution of the candidate shower width variable $\sigma_{\eta\eta}$ [9]. Two shower shape profiles are used in this fit, the shower shape of true photons, obtained from simulated $\gamma+$jet events, and the shower shape of photon-like jets, obtained from the charged hadron isolation sideband in data. This corrected ratio is used to weight a set of data events where the photon candidate passes the photon-like jet selection criteria. The estimated number of background events is found to be $45 \pm 14$, where the uncertainty reflects an uncertainty in the estimation of the ratio, as well as the statistical uncertainty of the sample scaled for the final estimate.

An instrumental background caused by electrons arises due to the imperfect efficiency for reconstructing and associating pixel seeds with clusters. For our kinematic requirements, this background largely originates from $W$ boson ($W \rightarrow e\nu$) production, and is estimated from data. The pixel seed efficiency $\epsilon_{\text{pix}}$ is measured in $Z \rightarrow ee$ events using the standard “tag-and-probe” method [27] and is estimated to be $0.984 \pm 0.002$ for electrons with $E_T > 100\text{ GeV}$. To estimate the final yield of this background, a factor of $(1-\epsilon_{\text{pix}})/\epsilon_{\text{pix}}$ is applied to a set of events in the data with the same candidate event selection as the signal candidates and with the additional requirement of a pixel seed match. The resulting contribution is estimated to be $60 \pm 6$ events, where the uncertainty is dominated by the uncertainty in the measurement of $\epsilon_{\text{pix}}$.

Since photon candidates are only identified within the ECAL, the candidate sample is susceptible to contamination from noncollision backgrounds. These backgrounds arise from interactions in the calorimeter of accelerator related particles (beam halo), spurious signals in the ECAL itself, and particles originating from cosmic ray interactions. The timing distribution measured from the ECAL for each of these backgrounds is distinctly different from the arrival time distribution for photons produced in collisions. A fit is performed to the candidate time distributions using shapes derived from data. The background distribution are constructed
by inverting MIP tag (beam halo) and shower shape (anomalous signal) requirements. The arrival time for photons from the interaction region is modeled using $W \rightarrow e\nu$ candidates in data. From the result of the fit, the only significant noncollision background is found to be from beam halo events, and its contribution is estimated to be $25 \pm 6$ events.

The total number of expected background events is $269 \pm 26$, as mentioned in Table 1. The number of signal events (data - expected background) is $361 \pm 36$, where the uncertainty is obtained by adding in quadrature the uncertainty from the data and the background estimation. The expected number of $Z\gamma \rightarrow \nu\nu\gamma$ signal events, obtained using MADGRAPH5 and corrected for NNLO effects, is $345 \pm 43$.

### Table 1: Summary of estimated $Z(\rightarrow \nu\nu) + \gamma$ signal, backgrounds, and observed total number of candidates.

| Process                | Estimate  |
|------------------------|-----------|
| $W(\rightarrow \ell\nu) + \gamma$ | $103 \pm 21$ |
| $W \rightarrow e\nu$   | $60 \pm 6$  |
| jet $\rightarrow \gamma$ MisID | $45 \pm 14$  |
| Beam halo              | $25 \pm 6$  |
| Others                 | $36 \pm 3$  |
| Total background       | $269 \pm 26$ |
| $Z(\rightarrow \nu\nu) + \gamma$ | $345 \pm 43$ |
| Data                   | $630$      |
| Data - background      | $361 \pm 36$ |

The $Z\gamma \rightarrow \nu\nu\gamma$ cross section for $E_T^{\gamma} > 145$ GeV and $|\eta| < 1.44$ is calculated using the following formulae:

$$\sigma B = \frac{N_{data} - N_{bkg}}{A \epsilon L},$$

$$A \epsilon = (A \epsilon)_{\text{sim}} \rho,$$

where $N_{data}$ is the number of observed events, $N_{bkg}$ is the estimated number of background events, $A$ is the geometrical acceptance, $\epsilon$ is the selection efficiency to select inclusive $Z(\rightarrow \nu\nu) + \gamma$ events offline, and $L$ is the integrated luminosity. The product of $A \epsilon$ is estimated from the simulation to be $0.377 \pm 0.001$, where the uncertainty is statistical. $\rho$ is the correction factor defined in Section 3.

The photon, jet and $E_T$ energy scales and resolutions, pileup, correction factor $\rho$, and the uncertainties in the PDFs are considered as sources of systematic uncertainty in the acceptance calculation. The uncertainty in the photon energy scale is about 1.5%, which translates into an uncertainty in $A \epsilon$ of $+3.4\%$ and $-5.0\%$, where $A$ is the geometrical and kinematic acceptance of the selection criteria, and $\epsilon$ is the signal selection efficiency. Additionally, there are systematic uncertainties due to the jet energy scale and jet resolution in the measurement of $E_T$, which give $+2.3\%$ and $-1.2\%$, respectively, and the unclustered energy scale, which gives $+19\%$. For pileup, a central value for the total inelastic cross section of $69.4$ mb [28, 29] is used. A variation of $\pm 5\%$ in the number of interactions is used to cover the uncertainty in $A \epsilon$ due to pileup modeling, which
Table 2: Systematic uncertainties considered in $A\epsilon$ for the $Z(\nu\bar{\nu})\gamma$ signal sample from various sources.

| Source                      | $Z(\nu\bar{\nu})\gamma$ [%] |
|-----------------------------|-------------------------------|
| Photon and $E_T$ energy scale | +3.4, -5.0                   |
| Jet and $E_T$ energy scale   | ±2.3                          |
| Jet energy resolution        | ±1.3                          |
| Unclustered energy           | ±1.2                          |
| Pileup                       | ±0.3                          |
| Luminosity                   | ±2.6                          |
| Correction factor $\rho$     | ±6.4                          |

is 0.3%. The uncertainty in the integrated luminosity [30] is 2.6%. Other sources include the uncertainty in the correction factor $\rho$, which contributes 6.4%.

A summary of the systematic uncertainties in $A\epsilon$ for the $Z(\nu\bar{\nu})\gamma$ signal sample is shown in Table 2.

The measured production cross section $\sigma(pp \to Z\gamma) B(Z \to \nu\bar{\nu})$ for $E_T^\gamma > 145$ GeV and $|\eta| < 1.44$ is $52.7 \pm 2.1$ (stat) $\pm 6.4$ (syst) $\pm 1.4$ (lumi) fb.

The expected cross section of the signal process for $E_T^\gamma > 145$ GeV and $|\eta|^\gamma < 1.44$, obtained with the NLO generator MCFM, is $40.7 \pm 4.9$ fb. The quoted uncertainty in the prediction takes into account the PDF and scale uncertainties. The NNLO theoretical prediction [31, 32] is $50.0^{+2.4}_{-2.2}$ fb, where the uncertainty includes only scale variations.

The distributions of photon transverse energy and $E_T$ are shown in Fig. 2, with the signal and background predictions overlaid. The expected contribution from a $Z\gamma$ aTGC signal with $h_3^\gamma = -0.001, h_4^\gamma = 0.0$ is also shown. No significant excess of events over the SM expectation is observed.

Figure 2: The $E_T^\gamma$ and $E_T$ distributions in data (points with error bars) compared with the SM $Z\gamma \to \nu\bar{\nu}\gamma$ signal and estimated contributions from backgrounds. A typical aTGC signal from $Z\gamma\gamma$ with $h_3^\gamma = -0.001, h_4^\gamma = 0.0$ would provide an excess, as shown in the dot-dashed histogram. The background uncertainty includes statistical and systematic components.
### 7 Limits on trilinear gauge couplings

We use the $E_T^\gamma$ spectrum to set limits on aTGCs by means of a likelihood formalism. In this study, we follow the CMS convention of not suppressing the aTGCs by an energy-dependent form factor.

The probability of observing the number of data events in a given range of $E_T^\gamma$ is estimated using a Poisson distribution given by the expected signal and background predictions. Limits on aTGCs are calculated on the basis of a profile likelihood method as described in Ref. [33]. In the fit to the observed spectra, systematic uncertainties are represented by nuisance parameters with log-normal prior probability density functions. The changes in shape of the observed spectra that result from varying the photon energy scale and the theoretical differential cross section within their respective uncertainties are treated using a morphing technique [34].

The best fit value from data for the aTGCs is very close to the SM values.

Limits at 95% confidence level (CL) are set on pairs of aTGC parameters $(h_3^Z, h_4^Z)$ and $(h_3^\gamma, h_4^\gamma)$,
as presented in Fig. 3 and Fig. 4, respectively. Furthermore, one-dimensional 95% CL limits are obtained for a given aTGC while setting the other neutral aTGCs to their SM values, i.e., to zero. A summary of the one-dimensional limits along with 7 TeV is given in Table 3.

Table 3: One-dimensional 95% CL limits on \( ZV\gamma \) anomalous trilinear gauge couplings from the \( Z\gamma \rightarrow \nu\bar{\nu}\gamma \) channel. The limits obtained from data with \( \sqrt{s} = 7 \) TeV are also shown.

| Coupling | \( \sqrt{s} = 8 \) TeV | \( \sqrt{s} = 7 \) TeV |
|----------|--------------------------|--------------------------|
| \( h_{Z}^{3} \) | \([-1.5, 1.6] \times 10^{-3}\) | \([-2.7, 2.7] \times 10^{-3}\) |
| \( h_{Z}^{4} \) | \([-3.9, 4.5] \times 10^{-6}\) | \([-1.3, 1.3] \times 10^{-5}\) |
| \( h_{\gamma}^{3} \) | \([-1.1, 0.9] \times 10^{-3}\) | \([-2.9, 2.9] \times 10^{-3}\) |
| \( h_{\gamma}^{4} \) | \([-3.8, 4.3] \times 10^{-6}\) | \([-1.5, 1.5] \times 10^{-5}\) |

8 Summary

We have presented an inclusive measurement of the \( Z\gamma \rightarrow \nu\bar{\nu}\gamma \) production cross section in pp collisions at \( \sqrt{s} = 8 \) TeV using data collected with the CMS experiment in 2012, corresponding to an integrated luminosity of 19.6 fb\(^{-1}\). The measured cross section \( \sigma(pp \rightarrow Z\gamma)B(Z \rightarrow \nu\bar{\nu}) \) for photons with \( E_{T}^{\gamma} > 145 \) GeV and \( |\eta^{\gamma}| < 1.44 \) is 52.7 ± 2.1 (stat) ± 6.4 (syst) ± 1.4 (lumi) fb, in agreement with the NNLO prediction \([31, 32]\) of 50.0\(^{+2.4}_{-2.2}\) fb. No evidence was found for anomalous neutral trilinear gauge couplings in \( Z\gamma \) production. Limits at 95% CL were placed on the \( h_{Z}^{3} \) and \( h_{Z}^{4} \) parameters of \( ZZ\gamma \) and \( Z\gamma\gamma \) couplings:

\[-1.5 \times 10^{-3} < h_{Z}^{3} < 1.6 \times 10^{-3}\]
\[-3.9 \times 10^{-6} < h_{Z}^{4} < 4.5 \times 10^{-6}\]
\[-1.1 \times 10^{-3} < h_{\gamma}^{3} < 0.9 \times 10^{-3}\]
\[-3.8 \times 10^{-6} < h_{\gamma}^{4} < 4.3 \times 10^{-6}\]

These results yield the most stringent limits to date on anomalous neutral trilinear gauge couplings.

Acknowledgements

We thank Massimiliano Grazzini and Dirk Rathlev for providing us with the NNLO calculation of the cross section. 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); 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); NRF and WCU (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan);
MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

[1] J. Ellison and J. Wudka, “Study of trilinear gauge-boson couplings at the Tevatron collider”, Ann. Rev. Nucl. Part. Sci. 48 (1998) 33, 
doi:10.1146/annurev.nucl.48.1.33

[2] K. Hagiwara, R. D. Peccei, and D. Zeppenfeld, “Probing the weak boson sector in e⁺e⁻ → W⁺W⁻”, Nucl. Phys. B 282 (1987) 253,
doi:10.1016/0550-3213(87)90685-7.

[3] CMS Collaboration, “Measurement of the production cross section for Zγ → ννγ in pp collisions at √s = 7 TeV and limits on ZZγ and Zγγ triple gauge boson couplings”, JHEP 10 (2013) 164, 
doi:10.1007/JHEP10(2013)164,arXiv:1309.1117.

[4] ATLAS Collaboration, “Measurements of Wγ and Zγ production in pp collisions at √s = 7 TeV with the ATLAS detector at the LHC”, Phys. Rev. D 87 (2013) 112003,
doi:10.1103/PhysRevD.87.112003,arXiv:1302.1283 [Erratum: 
doi:10.1103/PhysRevD.91.119901].

[5] CMS Collaboration, “Measurement of the Zγ production cross section in pp collisions at 8 TeV and search for anomalous triple gauge boson couplings”, JHEP 04 (2015) 164, 
doi:10.1007/JHEP04(2015)164,arXiv:1502.05664.

[6] G. J. Gounaris, J. Layssac, and F. M. Renard, “Signatures of the anomalous Zγ and ZZ production at the lepton and hadron colliders”, Phys. Rev. D 61 (2000) 073013,
doi:10.1103/PhysRevD.61.073013.

[7] U. Baur and E. L. Berger, “Probing the weak boson sector in Zγ production at hadron colliders”, Phys. Rev. D 47 (1993) 4889, doi:10.1103/PhysRevD.47.4889

[8] U. Baur, S. Errede, and J. Ohnemus, “Ratio of W±γ and Zγ cross sections: new tools in probing the weak boson sector at the Tevatron”, Phys. Rev. D 48 (1993) 4103, 
doi:10.1103/PhysRevD.48.4103.

[9] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at √s = 8 TeV”, JINST 10 (2015) P08010, 
doi:10.1088/1748-0221/10/08/P08010,arXiv:1502.02702.

[10] CMS Collaboration, “Particle-flow event reconstruction in CMS and performance for jets, taus, and EmissT”,CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.

[11] CMS Collaboration, “Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV”, Technical Report CMS-PAS-PFT-10-002, Geneva, 2010.

[12] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-k_t jet clustering algorithm”, JHEP 04 (2008) 063, 
doi:10.1088/1126-6708/2008/04/063,arXiv:0802.1189.
[13] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[14] J. Alwall et al., “MadGraph 5: going beyond”, *JHEP* 06 (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.

[15] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* 05 (2006) 26, doi:10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[16] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis”, *JHEP* 07 (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.

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

[18] J. Allison et al., “GEANT4 developments and applications”, *IEEE Trans. Nucl. Sci.* 53 (2006) 270, doi:10.1109/TNS.2006.869826.

[19] J. Campbell, R. Ellis, and C. Williams, “MCFM v6.1: A Monte Carlo for FeMtobarn processes at hadron colliders”, 2011, http://mcfm.fnal.gov/mcfm.pdf.

[20] S. Alekhin et al., “The PDF4LHC Working Group interim report”, (2011), arXiv:1101.0536.

[21] M. Botje et al., “The PDF4LHC Working Group Interim Recommendations”, (2011), arXiv:1101.0538.

[22] NNPDF Collaboration, “Impact of heavy quark masses on parton distributions and LHC phenomenology”, *Nucl. Phys. B* 849 (2011) 296, doi:10.1016/j.nuclphysb.2011.03.021, arXiv:1101.1300.

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

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

[25] CMS Collaboration, “Pileup jet identification”, CMS Physics Analysis Summary CMS-PAS-JME-13-005, 2013.

[26] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV”, *JINST* 10 (2015) P02006, doi:10.1088/1748-0221/10/02/P02006, arXiv:1411.0511.

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

[28] G. Antchev et al., “First measurement of the total proton-proton cross section at the LHC energy of $\sqrt{s} = 7$ TeV”, *Europhys. Lett.* 96 (2011) 21002, doi:10.1209/0295-5075/96/21002, arXiv:1110.1395.
[29] CMS Collaboration, “Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **06** (2012) 036, [doi:10.1007/JHEP06(2012)036](http://dx.doi.org/10.1007/JHEP06(2012)036) [arXiv:1202.0704](http://arxiv.org/abs/1202.0704).

[30] CMS Collaboration, “CMS luminosity based on pixel cluster counting - Summer 2013 update”, CMS Physics Analysis Summary CMS-PAS-LUM-13-001, 2013.

[31] M. Grazzini, S. Kallweit, D. Rathlev, and A. Torre, “$Z\gamma$ production at hadron colliders in NNLO QCD”, *Phys. Lett. B* **731** (2014) 204, [doi:10.1016/j.physletb.2014.02.037](http://dx.doi.org/10.1016/j.physletb.2014.02.037) [arXiv:1309.7000](http://arxiv.org/abs/1309.7000).

[32] M. Grazzini, S. Kallweit, and D. Rathlev, “$W\gamma$ and $Z\gamma$ production at the LHC in NNLO QCD”, in *Proceedings, 12th International Symposium on Radiative Corrections (Radcor 2015) and LoopFest XIV (Radiative Corrections for the LHC and Future Colliders)*, 2016. [arXiv:1601.06751](http://arxiv.org/abs/1601.06751).

[33] Particle Data Group Collaboration, “Review of Particle Physics”, *Chin. Phys. C* **38** (2014) 090001, [doi:10.1088/1674-1137/38/9/090001](http://dx.doi.org/10.1088/1674-1137/38/9/090001).

[34] J. S. Conway, “Nuisance parameters in likelihoods for multisource spectra”, in *Proceedings of PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding*, H. B. Prosper and L. Lyons, eds., p. 115. CERN, Geneva, Switzerland, 2011. [doi:10.5170/CERN-2011-006](http://dx.doi.org/10.5170/CERN-2011-006).
A The CMS Collaboration

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

Institut für Höchenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth\textsuperscript{1}, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler\textsuperscript{1}, V. Knünz, A. König, M. Krammer\textsuperscript{1}, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady\textsuperscript{2}, B. Rahbaran, H. Rohringer, J. Schieck\textsuperscript{1}, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz\textsuperscript{1}

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perini, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang\textsuperscript{3}

Ghent University, Ghent, Belgium
K. Beernaert, L. Benucci, A. Cimmino, S. Cruyck, D. Dobur, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi\textsuperscript{4}, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silva, C. Delaere, D. Favart, L. Forthomme, A. Giammanco\textsuperscript{5}, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, M. Musich, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov\textsuperscript{6}, L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, M. Hamer, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato\textsuperscript{7}, A. Custódio, E.M. Da Costa, 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\textsuperscript{7}, A. Vilela Pereira
Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja b, C.A. Bernardo b, A. De Souza Santos b, S. Dogra a, T.R. Fernandez Perez Tomei a, E.M. Gregores b, P.G. Mercadante b, C.S. Moon a, S.F. Novaes a, Sandra S. Padula a, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina 9, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, S. Micanovic, L. Sudic

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

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger 10, M. Finger Jr. 10

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
E. El-khateeb 11, T. Elkafrawy 11, A. Mohamed 12, E. Salama 13,11

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

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

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri,
Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, N. Filipovic, R. Granier de Cassagnac, M. Jo, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte, X. Coubez, J.-C. Fontaine, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin, K. Skovpen, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
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, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, J.F. Schulte, T. Verlage, H. Weber, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, 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, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padéken, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, K. Borras, A. Burgmeier, A. Campbell, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. G Zhko, P. Gunnellini, J. Hauk, M. Hempel, H. Jung, A. Kalogeropoulos, O. Karacheban, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann,
A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, D. Nowatschin, J. Ott, F. Pantaleo\(^2\), T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, C. Schaefer, P. Schleper, E. Schlieckau, A. Schmidt, S. Schumann, J. Schwandt, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamm, S. Fink, F. Freisch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann\(^2\), S.M. Heindl, U. Husemann, I. Kattrögel, A. Kornmayer\(^2\), 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, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamsom, C. Wöhrlmann, R. Wolf

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

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

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

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

**University of Ioάnnina, Ioάnnina, Greece**

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Parasas, J. Strologas

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath\(^19\), F. Sikler, V. Veszpremi, G. Vesztergombi\(^20\), A.J. Zsigmond

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

N. Beni, S. Czellar, J. Karancsi\(^21\), J. Molnar, Z. Szillasi\(^2\)

**University of Debrecen, Debrecen, Hungary**

M. Bartók\(^22\), A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

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

S. Choudhury\(^23\), P. Mal, K. Mandal, D.K. Sahoo, N. Sahoo, S.K. Swain

**Panjab University, Chandigarh, 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

**University of Delhi, Delhi, India**

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma
Saha Institute of Nuclear Physics, Kolkata, India
S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, S. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

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

Tata Institute of Fundamental Research, Mumbai, India
T. Aziz, S. Banerjee, S. Bhowmik, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu, G. Kole, S. Kumar, B. Mahakud, M. Maity, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar, N. Sur, B. Sutar, N. Wickramage

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami, A. Fahim, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

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

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, C. Calabria, C. Caputo, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis, M. De Palma, L. Fiore, G. Iaselli, G. Maggi, M. Maggi, G. Miniello, S. My, S. Nuzzo, A. Pompili, G. Pugliese, R. Radonna, A. Ranieri, G. Selvaggi, L. Silvestris, R. Venditti

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, A.C. Benvenuti, D. Bonacorsio, S. Braibant-Giacomelli, L. Brigliadori, R. Campanini, P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, G. Codispoti, M. Cuffiani, G.M. Dallavalle, F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini, G. Masetti, A. Montanari, F.L. Navarra, A. Perrotta, A.M. Rossi, T. Rovelli, G.P. Siroli, N. Tosi, R. Travaglini

INFN Sezione di Catania, Università di Catania, Catania, Italy
G. Cappello, M. Chiorboli, S. Costa, A. Di Mattia, F. Giordano, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze, Firenze, Italy
G. Barbaglio, V. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, V. Gori, P. Lenzi, M. Meschini, S. Paoletti, G. Sguazzoni, L. Viliani

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

INFN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli, F. Ferro, M. Lo Vetere, M.R. Monge, E. Robutti, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
L. Brianza, M.E. Dinardo, S. Fiorendi, S. Gennai, R. Gerosa, A. Ghezzi, P. Govoni
S. Malvezzi, R.A. Manzoni, B. Marzocchi, D. Menasce, L. Moroni, M. Paganoni, D. Pedrini, S. Ragazzi, N. Redaelli, T. Tabarelli de Fatis

INFN Sezione di Napoli, Università di Napoli 'Federico II', Napoli, Italy, Università della Basilicata, C, Potenza, Italy, Università G. Marconi, Roma, Italy

S. Buontempo, N. Cavallo, S. Di Guida, M. Esposito, F. Fabozzi, A.O.M. Iorio, G. Lanza, L.Lista, S. Meola, M. Merola, P. Paolucci, C. Sciacca, F. Thyssen

INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy

P. Azzi, N. Bacchetta, L. Benato, A. Boletti, R. Carlin, P. Checchia, M. Dall’Osso, T. Dorigo, L. Dosselli, F. Gasparini, A. Gozzelino, S. Lacaprara, M. Margonini, A.T. Meneguzzo, M. Passaseo, J. Pazzini, M. Pegoraro, N. Pozzobon, R. Ronchese, F. Simonetto, E. Torassa, M. Tosi, S. Vanini, M. Zanetti, P. Zotto, A. Zucchetta, G. Zumerle

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy

A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy

L. Alunni Solestizi, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, G. Mantovani, M. Menichelli, A. Saha, A. Santocchia

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy

K. Androsov, P. Azzurri, G. Bagliesi, J. Bernardini, T. Boccali, R. Castaldi, M.A. Ciocci, R. Dell’Orso, S. Donato, G. Fedi, L. Foà, A. Giassi, M.T. Grippi, F. Ligabue, T. Lomtadze, L. Martin, A. Messineo, F. Palla, A. Rizzoli, A. Savoy-Navarro, A.T. Serban, P. Spagnolo, R. Tenchini, G. Tonelli, A. Ventura, P.G. Verdini

INFN Sezione di Roma, Università di Roma, Roma, Italy

L. Barone, F. Cavallari, G. D’imperio, D. Del Re, M. Diemoz, S. Gelli, C. Jordà, E. Longo, F. Margaroni, P. Meridiani, G. Organtini, R. Paramatti, F. Preiatò, S. Rahatlou, C. Rovelli, F. Santanastasio, P. Traczyk

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

N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, C. Biino, N. Cartiglia, M. Costa, R. Covarelli, A. Degano, N. Demaria, L. Finco, B. Kiani, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, E. Montei, M.M. Obertino, L. Pacher, N. Pastrone, M. Pelliccioni, G.L. Pinna Angioni, F. Ravera, A. Romero, M. Ruspa, R. Sacchi, A. Solano, A. Staiano

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy

S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, A. Schizzi, A. Zanetti

Kangwon National University, Chunchon, Korea

A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

J.A. Brochero Cifuentes, H. Kim, T.J. Kim
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea  
S. Song

Korea University, Seoul, Korea  
S. Choi, Y. Go, D. Gyun, B. Hong, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea  
H.D. Yoo

University of Seoul, Seoul, Korea  
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

Sungkyunkwan University, Suwon, Korea  
Y. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania  
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia  
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali32, F. Mohamad Idris33, W.A.T. Wan Abdullah, M.N. Yusli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico  
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz34, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico  
I. Pedraza, H.A. Salazar Ibarguen

Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico  
A. Morelos Pineda

University of Auckland, Auckland, New Zealand  
D. Krofcheck

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan  
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland  
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland  
G. Brona, K. Bunkowski, A. Byyszuk35, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Laboratário de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal  
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, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

**Institute for Theoretical and Experimental Physics, Moscow, Russia**
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

**National Research Nuclear University ’Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia**
A. Bylinkin

**P.N. Lebedev Physical Institute, Moscow, Russia**
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov

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

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**
P. Adzic, P. Cirkovic, J. Milosevic, V. Rekovic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**
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, J. Santaolalla, M.S. Soares

**Universidad Autónoma de Madrid, Madrid, Spain**
C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimateobhas, N. Suwongjandee

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, Z.S. Demiroglu, C. Dozen, E. Eskut, F.H. Gecit, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, G. Onengut, M. Ozcan, K. Ozdemir, S. Ozturk, D. Sunar Cerci, B. Tali, H. Topakli, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, B. Bilin, S. Bilmis, B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gulmez, M. Kaya, E.A. Yetkin, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen

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, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, J.A. Cockerill, A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, S.D. Worn

Imperial College, London, 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, G. Hall, G. Iles, R. Lane, R. Lucas, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, S.C. Zenz

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

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

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

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou
E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, 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

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, S.V. Gleyzer, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, P. Milenovic, G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, H. Kalakhety, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, 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

The University of Iowa, Iowa City, USA
B. Bilki, W. Clarida, K. Dilsiz, S. Durgut, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B.A. Barnett, B. Blumenfeld, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, A. Sady, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, C. Bruner, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, S. Sanders, R. Stringer, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

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

University of Maryland, College Park, 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

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, R. Barbieri, A. Baty, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, Y. Iiyama, G.M. Innocenti, M. Klute,
Rice University, Houston, 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

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, P. Tan, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
J.P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, K. Nash, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
M. Foerster, G. Riley, K. Rose, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali, A. Castaneda Hernandez, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin - Madison, Madison, WI, USA
D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, P. Verwilligen, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Ain Shams University, Cairo, Egypt
12: Also at Zewail City of Science and Technology, Zewail, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Also at Université de Haute Alsace, Mulhouse, France
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at Indian Institute of Science Education and Research, Bhopal, India
24: Also at University of Visva-Bharati, Santiniketan, India
25: Now at King Abdulaziz University, Jeddah, Saudi Arabia
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 California Institute of Technology, Pasadena, USA
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
42: Also at National Technical University of Athens, Athens, Greece
43: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Gaziosmanpasa University, Tokat, Turkey
48: Also at Mersin University, Mersin, Turkey
49: Also at Cag University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Marmara University, Istanbul, Turkey
55: Also at Kafkas University, Kars, Turkey
56: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, USA
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
65: Also at Argonne National Laboratory, Argonne, USA
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Texas A&M University at Qatar, Doha, Qatar
68: Also at Kyungpook National University, Daegu, Korea