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# 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\*

CERN, Switzerland

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## 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  $19.6\text{fb}^{-1}$  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  $50.0_{-2.2}^{+2.4}$  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.

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## 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  $19.6\text{fb}^{-1}$ . 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.

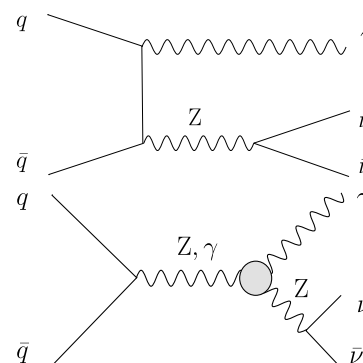


Fig. 1. Feynman diagrams of  $Z\gamma$  production via initial-state radiation in the SM at tree level (top), and via anomalous  $ZZ\gamma$  or  $Z\gamma\gamma$  trilinear gauge couplings (bottom).

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 (top). The s-channel production via a  $ZZ\gamma$  or  $Z\gamma\gamma$  aTGC is shown in Fig. 1 (bottom).

The most general Lorentz-invariant and gauge-invariant  $ZV\gamma$  vertex can be described by four coupling parameters  $h_i^V$  ( $i = 1, \dots, 4$ ) [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

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

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  $h_3^V$  and  $h_4^V$ .

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  $\vec{\cancel{E}}_T$  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  $\cancel{E}_T$ .

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  $W\gamma \rightarrow \ell\nu\gamma$  where  $\ell$  is a charged lepton (if the lepton escapes detection),

$W \rightarrow \ell\nu$  (if the lepton is misidentified as a photon),  $\gamma$  + jets (if the jets are misreconstructed, resulting in  $\cancel{E}_T$ ), QCD multijet production including  $Z(\nu\bar{\nu})$  + jets (if the jet is misidentified as a photon),  $Z\gamma \rightarrow \ell\ell\gamma$  (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  $W\gamma \rightarrow \ell\nu\gamma$ ,  $\gamma$  + jet,  $Z\gamma \rightarrow \ell\ell\gamma$ , and  $\gamma\gamma$  processes to the candidate event sample are estimated using Monte Carlo-based (MC) simulations. The  $W(\ell\nu)\gamma$  and  $Z \rightarrow \ell\ell\gamma$  samples are generated with MADGRAPH5v1.3.30 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  $\gamma$  + 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  $Z \rightarrow ee$  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  $W \rightarrow e\nu$  events.

## 4. Event selection

Events are selected using both a single-photon trigger that requires a photon with  $E_T^\gamma > 150$  GeV, and photon +  $\cancel{E}_T$  triggers with  $E_T^\gamma > 70$  GeV and  $\cancel{E}_T > 100$  GeV. The combination of these triggers is 96% efficient for events with photon transverse energy  $E_T^\gamma > 145$  GeV, photon pseudorapidity  $|\eta^\gamma| < 1.44$ , and  $\cancel{E}_T > 140$  GeV. Events are required to have at least one primary vertex reconstructed within a longitudinal distance of  $|z| < 24$  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  $\Delta R = 0.3$  around the supercluster, excluding a strip of width in  $\eta$  of 0.015, is required to be less than  $0.7 + 0.005 p_T^\gamma$ ; 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  $1.0 + 0.04 p_T^\gamma$ . 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  $\gamma + \cancel{E}_T$  final state (our estimate 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  $\cancel{E}_T > 140$  GeV. A topological requirement of  $\Delta\phi > 2$  rad between the direction of the photon candidate and the vector  $\cancel{E}_T$  is applied to reduce the contribution from the  $\gamma + \text{jet}$  background.

In order to suppress backgrounds from QCD multijet production and leptonic decay of  $W/Z + \text{jets}$ , 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  $\cancel{E}_T$  arising from instrumental effects, a  $\chi^2$  function is constructed and minimized

$$\chi^2 = \sum_{i=\text{photon, jets}} \left( \frac{(p_T^{\text{reco}})_i - (\tilde{p}_T)_i}{(\sigma_{p_T})_i} \right)^2 + \left( \frac{\tilde{E}_x}{\sigma_{\tilde{E}_x}} \right)^2 + \left( \frac{\tilde{E}_y}{\sigma_{\tilde{E}_y}} \right)^2, \quad (1)$$

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 recon-

structed (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  $\cancel{E}_T$  is obtained from Ref. [26]. Lastly,  $\tilde{E}_x$  and  $\tilde{E}_y$  are defined as

$$\begin{aligned} \tilde{E}_{x,y} &= E_{x,y}^{\text{reco}} + \sum_{i=\text{photon, jets}} (p_{x,y}^{\text{reco}})_i - (\tilde{p}_{x,y})_i \\ &= - \sum_{i=\text{photon, jets}} (\tilde{p}_{x,y})_i, \\ \tilde{E}_T &= \sqrt{\tilde{E}_x^2 + \tilde{E}_y^2}. \end{aligned} \quad (2)$$

For events with no true  $\cancel{E}_T$ , the  $\chi^2$  is expected to be small, with values of  $\tilde{E}_T$  close to 0, while for events with significant true  $\cancel{E}_T$  the minimization will result in high  $\chi^2$  values, with  $\tilde{E}_T$  close to the actual  $\cancel{E}_T$  in the event. An additional requirement of  $\tilde{E}_T > 120$  GeV reduces the number of  $\gamma + \text{jet}$  (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  $\gamma + \text{jet}$  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  $E_T > 100$  GeV. To estimate the final yield of this background, a factor

**Table 1**

Summary of estimated  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  signal, backgrounds, and observed total number of candidates. Backgrounds listed as “Others” include the small contributions from  $W \rightarrow \mu\nu$ ,  $Z\gamma \rightarrow \ell\ell\gamma$ ,  $\gamma\gamma$ , and  $\gamma + \text{jet}$ . Uncertainties include both statistical and systematic contributions.

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	$269 \pm 26$
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	$345 \pm 43$
Data	630
Data – background	$361 \pm 36$

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  $Z\gamma \rightarrow \nu\bar{\nu}\gamma$  signal events, obtained using MADGRAPH5 and corrected for NNLO effects, is  $345 \pm 43$ .

## 6. Cross section measurement

A summary of the backgrounds and data yields is given in Table 1, wherein the uncertainties in the background estimates include both statistical and systematic sources.

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

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

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

where  $N_{\text{data}}$  is the number of observed events,  $N_{\text{bkg}}$  is the estimated number of background events,  $A$  is the geometrical acceptance,  $\epsilon$  is the selection efficiency to select inclusive  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  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

**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 $\cancel{E}_T$ energy scale	+3.4, –5.0
Jet and $\cancel{E}_T$ energy scale	$\pm 2.3$
Jet energy resolution	$\pm 1.3$
Unclustered energy	$\pm 1.2$
Pileup	$\pm 0.3$
Luminosity	$\pm 2.6$
Correction factor $\rho$	$\pm 6.4$

the uncertainty is statistical.  $\rho$  is the correction factor defined in Section 3.

The photon, jet and  $\cancel{E}_T$  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  $^{+3.4}_{-5.0}\%$ , 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  $\cancel{E}_T$ , which give  $^{+2.3}_{-2.3}\%$  and  $^{+1.2}_{-1.4}\%$ , respectively, and the unclustered energy scale, which gives  $^{+1.9}_{-0.6}\%$ . 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 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  $\sigma(\text{pp} \rightarrow Z\gamma)\mathcal{B}(Z \rightarrow \nu\bar{\nu})$  for  $E_T^\gamma > 145 \text{ GeV}$  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  $E_T^\gamma > 145 \text{ GeV}$  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.

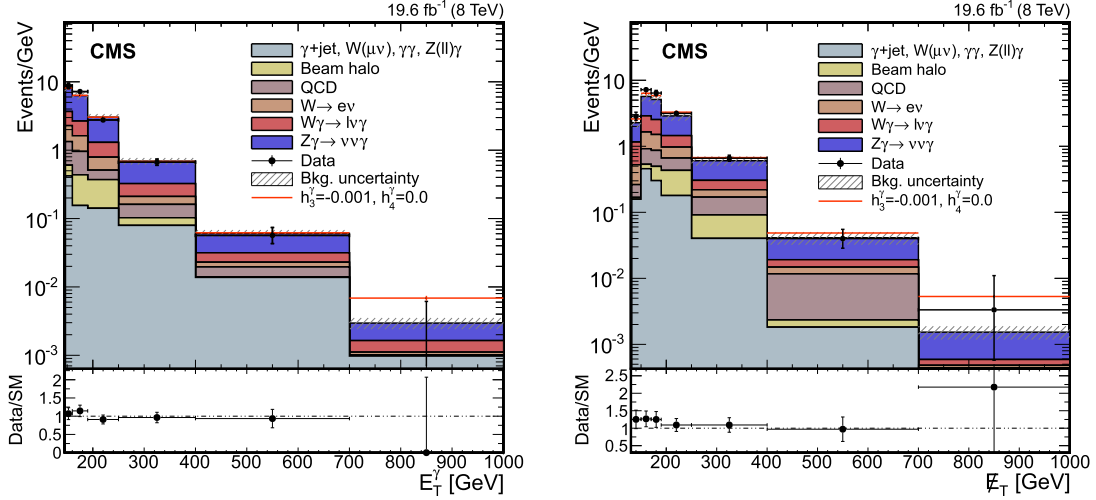
The distributions of photon transverse energy and  $\cancel{E}_T$  are shown in Fig. 2, with the signal and background predictions overlaid. The expected contribution from a  $Z\gamma\gamma$  aTGC signal with  $h_3^\gamma = -0.001$ ,  $h_4^\gamma = 0.0$  is also shown. No significant excess of events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

## 7. Limits on trilinear gauge couplings

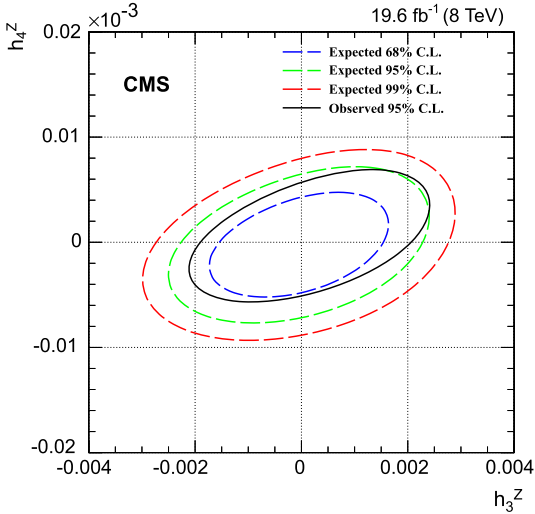
We use the  $E_T^\gamma$  spectrum to set limits on aTGCs by means of a likelihood formalism. In this study, we follow the CMS convention of not suppressing the aTGCs by an energy-dependent form factor.

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].

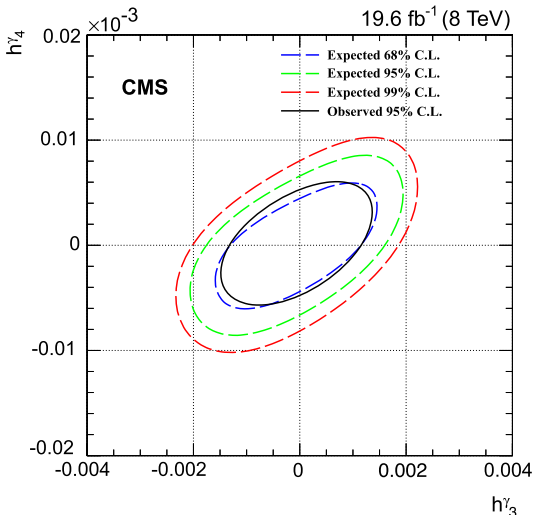
The best fit value from data for the aTGCs is very close to the SM values.



**Fig. 2.** The  $E_T^\gamma$  and  $\cancel{E}_T$  distributions in data (points with error bars) compared with the SM  $Z\gamma \rightarrow \nu\bar{\nu}\gamma$  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.



**Fig. 3.** Two-dimensional 95% CL limits on  $ZZ\gamma$  couplings.



**Fig. 4.** Two-dimensional 95% CL limits on  $Z\gamma\gamma$  couplings.

**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
$h_3^Z$	$[-1.5, 1.6] \times 10^{-3}$	$[-2.7, 2.7] \times 10^{-3}$
$h_4^Z$	$[-3.9, 4.5] \times 10^{-6}$	$[-1.3, 1.3] \times 10^{-5}$
$h_3^\gamma$	$[-1.1, 0.9] \times 10^{-3}$	$[-2.9, 2.9] \times 10^{-3}$
$h_4^\gamma$	$[-3.8, 4.3] \times 10^{-6}$	$[-1.5, 1.5] \times 10^{-5}$

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.

## 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  $19.6 \text{ fb}^{-1}$ . The measured cross section  $\sigma(\text{pp} \rightarrow Z\gamma) \mathcal{B}(Z \rightarrow \nu\bar{\nu})$  for photons with  $E_T^\gamma > 145$  GeV and  $|\eta^\gamma| < 1.44$  is  $52.7 \pm 2.1$  (stat)  $\pm 6.4$  (syst)  $\pm 1.4$  (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  $h_3^V$  and  $h_4^V$  parameters of  $ZZ\gamma$  and  $Z\gamma\gamma$  couplings:

$$\begin{aligned} -1.5 \times 10^{-3} &< h_3^Z < 1.6 \times 10^{-3} \\ -3.9 \times 10^{-6} &< h_4^Z < 4.5 \times 10^{-6} \\ -1.1 \times 10^{-3} &< h_3^\gamma < 0.9 \times 10^{-3} \\ -3.8 \times 10^{-6} &< h_4^\gamma < 4.3 \times 10^{-6}. \end{aligned}$$

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

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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>, V. Knünz, A. König, M. Krammer<sup>1</sup>, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady<sup>2</sup>, B. Rahbaran, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöffbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz<sup>1</sup>

*Institut für Hochenergiephysik der OeAW, Wien, Austria*

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

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

S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, M. Van De Klundert, H. Van Haeve, P. Van Mechelen, N. Van Remortel, A. Van Spilbeek

*Universiteit Antwerpen, Antwerpen, 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

*Vrije Universiteit Brussel, Brussel, 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. Perniè, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang<sup>3</sup>

*Université Libre de Bruxelles, Bruxelles, Belgium*

K. Beernaert, L. Benucci, A. Cimmino, S. Crucy, 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

*Ghent University, Ghent, Belgium*

S. Basegmez, C. Beluffi<sup>4</sup>, O. Bondu, S. Brochet, G. Bruno, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco<sup>5</sup>, A. Jafari, P. Jez, M. Komm, V. Lemaître, A. Mertens, M. Musich, C. Nuttens, L. Perrini, A. Pin, K. Piotrkowski, A. Popov<sup>6</sup>, L. Quertenmont, M. Selvaggi, M. Vidal Marono

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

N. Belyi, G.H. Hammad

*Université de Mons, Mons, Belgium*

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>7</sup>, 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<sup>7</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>, A. De Souza Santos<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,8</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad, 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*

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina<sup>9</sup>, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang

*Institute of High Energy Physics, Beijing, China*

C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

*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, B. Gomez Moreno, 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, K. Kadija, J. Luetic, 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. Bodlak, M. Finger<sup>10</sup>, M. Finger Jr.<sup>10</sup>

*Charles University, Prague, Czech Republic*

E. El-khateeb<sup>11</sup>, T. Elkafrawy<sup>11</sup>, A. Mohamed<sup>12</sup>, E. Salama<sup>13,11</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, 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, E. Tuominen, 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, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malcles, J. Neveu, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

*DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, 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

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

J.-L. Agram<sup>14</sup>, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>14</sup>, X. Coubez, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin<sup>2</sup>, K. Skovpen, P. Van Hove

*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*

S. Gadrat

*Centre de Calcul de l'Institut National de Physique Nucleaire 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, 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

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

T. Toriashvili<sup>15</sup>

*Georgian Technical University, Tbilisi, Georgia*

Z. Tsamalaidze<sup>10</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, J.F. Schulte, T. Verlage, H. Weber, V. Zhukov<sup>6</sup>

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

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

M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, K. Borras<sup>16</sup>, 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<sup>17</sup>, J. Garay Garcia, A. Geiser, A. Gikhko, P. Gunnellini, J. Hauk, M. Hempel<sup>18</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>18</sup>, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann<sup>18</sup>, 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

*Deutsches Elektronen-Synchrotron, 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<sup>2</sup>, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, C. Scharf, 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

*University of Hamburg, Hamburg, 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. Frensch, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann<sup>2</sup>, S.M. Heindl, U. Husemann, I. Katkov<sup>6</sup>, A. Kornmayer<sup>2</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, F.M. Stober, 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. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Psallidas, 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, J. Strologas

*University of Ioánnina, Ioánnina, Greece*

G. Bencze, C. Hajdu, A. Hazi, P. Hidas, D. Horvath<sup>19</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>20</sup>, A.J. Zsigmond

*Wigner Research Centre for Physics, Budapest, Hungary*

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, J. Molnar, Z. Szillasi<sup>2</sup>

*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

M. Bartók<sup>22</sup>, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

*University of Debrecen, Debrecen, Hungary*

S. Choudhury<sup>23</sup>, P. Mal, K. Mandal, 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. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

*University of Delhi, Delhi, India*

S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, Sa. Jain, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

*Saha Institute of Nuclear Physics, Kolkata, India*

A. Abdulsalam, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>2</sup>, L.M. Pant, P. Shukla, A. Topkar

*Bhabha Atomic Research Centre, Mumbai, India*

T. Aziz, S. Banerjee, S. Bhowmik<sup>24</sup>, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu<sup>25</sup>, G. Kole, S. Kumar, B. Mahakud, M. Maity<sup>24</sup>, G. Majumder, K. Mazumdar, S. Mitra, G.B. Mohanty, B. Parida, T. Sarkar<sup>24</sup>, N. Sur, B. Sutar, N. Wickramage<sup>26</sup>

*Tata Institute of Fundamental Research, Mumbai, India*

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

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

H. Bakhshiansohi, H. Behnamian, 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,c</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,2</sup>, R. Venditti<sup>a,b</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<sup>2</sup>, A.C. Benvenuti<sup>a</sup>, 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,2</sup>, R. Travaglini<sup>a,b</sup>

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

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

G. Cappello<sup>a</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,2</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>2</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>, R. Gerosa<sup>a,b</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b,2</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. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</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>, S. Di Guida<sup>a,d,2</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,2</sup>, M. Merola<sup>a</sup>, P. Paolucci<sup>a,2</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,2</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>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b,2</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>, M. Passaseo<sup>a</sup>, J. Pazzini<sup>a,b,2</sup>, M. Pegoraro<sup>a</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. Tosi<sup>a,b</sup>, S. Vanini<sup>a,b</sup>, M. Zanetti, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b,2</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,2</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<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,2</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,2</sup>, G. Fedi, L. Foà<sup>a,c,†</sup>, 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>, A.T. Serban<sup>a</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>, G. D'imperio<sup>a,b,2</sup>, D. Del Re<sup>a,b,2</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>, P. Traczyk<sup>a,b,2</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,2</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</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,2</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>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</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>, V. Candelise<sup>a,b</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, C. La Licata<sup>a,b</sup>, M. Marone<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

A. Kropivnitskaya, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

*Kyungpook National University, Daegu, Republic of Korea*

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

*Chonbuk National University, Jeonju, Republic of Korea*

S. Song

*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of 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

*Korea University, Seoul, Republic of Korea*

H.D. Yoo

*Seoul National University, Seoul, Republic of Korea*

M. Choi, 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, D. Kim, E. Kwon, J. Lee, I. Yu

*Sungkyunkwan University, Suwon, Republic of Korea*

V. Dudenas, 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

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

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

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

S. Carrillo Moreno, F. Vazquez Valencia

*Universidad Iberoamericana, Mexico City, Mexico*

I. Pedraza, H.A. Salazar Ibarguen

*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, T. Khurshid, M. Shoaib

*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*

G. Brona, 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, F. Nguyen, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev<sup>36,37</sup>, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

*Joint Institute for Nuclear Research, Dubna, Russia*

V. Golovtsov, Y. Ivanov, V. Kim<sup>38</sup>, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vasilov, 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. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, E. Vlasov, A. Zhokin

*Institute for Theoretical and Experimental Physics, Moscow, Russia*

A. Bylinkin

*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>, G. Mesyats, S.V. Rusakov

*P.N. Lebedev Physical Institute, Moscow, Russia*

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>39</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Myagkov, 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, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic<sup>40</sup>, P. Cirkovic, 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, J. Santaolalla, M.S. Soares

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

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

*Universidad Autónoma de Madrid, Madrid, Spain*

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, J.M. Vizan Garcia

*Universidad de Oviedo, Oviedo, Spain*

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, P. De Castro Manzano, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A.Y. Rodríguez-Marrero, 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, A. Benaglia, J. Bendavid, L. Benhabib, G.M. Berruti, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, R. Castello, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco<sup>41</sup>, M. Dobson, M. Dordevic, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli<sup>42</sup>, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, A. Racz, T. Reis, G. Rolandi<sup>43</sup>, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, M. Simon, P. Sphicas<sup>44</sup>, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Triossi, A. Tsirou, G.I. Veres<sup>20</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, D. Renker, 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, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov<sup>45</sup>, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. Wallny

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

T.K. Aarrestad, C. Amsler<sup>46</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, F.J. Ronga, D. Salerno, Y. Yang

*Universität Zürich, Zurich, Switzerland*

M. Cardaci, K.H. Chen, 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, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.f. Tsai, Y.M. Tzeng

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

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

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

A. Adiguzel, M.N. Bakirci<sup>47</sup>, Z.S. Demiroglu, C. Dozen, E. Eskut, F.H. Gecit, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal<sup>48</sup>, G. Onengut<sup>49</sup>, M. Ozcan, K. Ozdemir<sup>50</sup>, S. Ozturk<sup>47</sup>, D. Sunar Cerci<sup>51</sup>, B. Tali<sup>51</sup>, H. Topakli<sup>47</sup>, M. Vergili, C. Zorbilmez

*Cukurova University, Adana, Turkey*

I.V. Akin, B. Bilin, S. Bilmis, B. Isildak<sup>52</sup>, G. Karapinar<sup>53</sup>, M. Yalvac, M. Zeyrek

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

E. Gülmez, M. Kaya<sup>54</sup>, O. Kaya<sup>55</sup>, E.A. Yetkin<sup>56</sup>, T. Yetkin<sup>57</sup>

*Bogazici University, Istanbul, Turkey*

A. Cakir, K. Cankocak, S. Sen<sup>58</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, 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<sup>59</sup>, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, D. Smith, V.J. Smith

*University of Bristol, Bristol, United Kingdom*

K.W. Bell, A. Belyaev<sup>60</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, S.D. Worm

*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, G. Hall, G. Iles, R. Lane, R. Lucas<sup>59</sup>, L. Lyons, A.-M. Magnan, S. Malik, J. Nash, A. Nikitenko<sup>45</sup>, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, A. Richards, A. Rose, C. Seez, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>61</sup>, T. Virdee, S.C. Zenz

*Imperial College, London, 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

*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*

J. Alimena, E. Berry, D. Cutts, A. Ferapontov, A. Garabedian, J. Hakala, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif

*Brown University, Providence, USA*

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, 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, M. Ivova PANEVA, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Malberti, M. Olmedo Negrete, A. Shrinivas, H. Wei, S. Wimpenny, B.R. Yates

*University of California, Riverside, Riverside, USA*

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, M. Derdzinski, A. Holzner, R. Kelley, 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>62</sup>, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

*University of California, San Diego, La Jolla, USA*

J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, J. Incandela, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, I. Suarez, C. West, J. Yoo

*University of California, Santa Barbara, Santa Barbara, USA*

D. Anderson, A. Apresyan, 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, A. Calamba, 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, A. Gaz, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, U. Nauenberg, K. Stenson, S.R. Wagner

*University of Colorado Boulder, Boulder, USA*

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, W. Sun, S.M. Tan, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, P. Wittich

*Cornell University, Ithaca, 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, V.D. Elvira, I. Fisk, J. Freeman,

E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, 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, 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, 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

*Fermi National Accelerator Laboratory, Batavia, 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<sup>63</sup>, G. Mitselmakher, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

*University of Florida, Gainesville, USA*

S. Hewamanage, 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, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, M. Weinberg

*Florida State University, Tallahassee, USA*

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi<sup>64</sup>, M. Hohlmann, H. Kalakhety, 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

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

B. Bilki<sup>65</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>66</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>56</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

*The University of Iowa, Iowa City, 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

*Johns Hopkins University, Baltimore, 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

*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*

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, D. Kovalskyi, 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, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

*Massachusetts Institute of Technology, Cambridge, USA*

B. Dahmes, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, K. Klapoetke, 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, F. Meier, J. Monroy, F. Ratnikov, J.E. Siado, G.R. Snow

*University of Nebraska-Lincoln, Lincoln, USA*

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, 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, J. Zhang

*Northeastern University, Boston, USA*

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

*Northwestern University, Evanston, USA*

A. Brinkerhoff, N. Dev, M. Hildreth, 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*

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, W. Ji, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

*The Ohio State University, Columbus, USA*

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, H. Saka, 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, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, K. Jung, A. Kumar, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, 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. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, P. Tan, M. Verzetti

*University of Rochester, Rochester, USA*

J.P. Chou, E. Contreras-Campana, D. Ferencek, Y. Gershtein, E. Halkiadakis, D. Hidas, 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

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

M. Foerster, G. Riley, K. Rose, S. Spanier

*University of Tennessee, Knoxville, USA*

O. Bouhali<sup>67</sup>, A. Castaneda Hernandez<sup>67</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>68</sup>, V. Krutelyov, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer<sup>2</sup>

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

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

*Texas Tech University, Lubbock, 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

*Vanderbilt University, Nashville, 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

*University of Virginia, Charlottesville, USA*

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

*Wayne State University, Detroit, 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. Klabbbers, 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

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

<sup>†</sup> Deceased.

<sup>1</sup> Also at Vienna University of Technology, Vienna, Austria.

<sup>2</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

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