CERN-EP-2021-191  
2022/06/30CMS-EXO-18-014  
TOTEM-2021-002

# First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS and TOTEM Collaborations\*

## Abstract

A search for exclusive two-photon production via photon exchange in proton-proton collisions,  $pp \rightarrow p\gamma\gamma p$  with intact protons, is presented. The data correspond to an integrated luminosity of  $9.4 \text{ fb}^{-1}$  collected in 2016 using the CMS and TOTEM detectors at a center-of-mass energy of 13 TeV at the LHC. Events are selected with a diphoton invariant mass above 350 GeV and with both protons intact in the final state, to reduce backgrounds from strong interactions. The events of interest are those where the invariant mass and rapidity calculated from the momentum losses of the forward-moving protons matches the mass and rapidity of the central, two-photon system. No events are found that satisfy this condition. Interpreting this result in an effective dimension-8 extension of the standard model, the first limits are set on the two anomalous four-photon coupling parameters. If the other parameter is constrained to its standard model value, the limits at 95% CL are  $|\zeta_1| < 2.9 \times 10^{-13} \text{ GeV}^{-4}$  and  $|\zeta_2| < 6.0 \times 10^{-13} \text{ GeV}^{-4}$ .

*Published in Physical Review Letters as doi:10.1103/PhysRevLett.129.011801.*



In the classical theory of electrodynamics, photons ( $\gamma$ ), having neither mass nor charge, lack self interactions. However, because of the characteristics of the vacuum, photons with sufficient energy may fluctuate into charged particle-antiparticle pairs, thus giving rise to photon-photon interactions. When two photons interact in this way through an intermediate charged particle loop to create two different outgoing photons, the process is known as light-by-light (LbL) scattering. Evidence for this process has been sought in laboratory experiments for decades [1–4], and has been studied indirectly by the measurement of the anomalous magnetic moments of the electron [5] and the muon [6, 7].

By exploiting the large photon fluxes produced by ultrarelativistic ion beams at the LHC, as proposed in Ref. [8], the ATLAS and CMS experiments recently reported measurements of LbL scattering [9–11] through exclusive diphoton production in ultraperipheral lead-lead collisions [12]. Analyses based on heavy ion collision data find results consistent with the standard model (SM) expectations. However, these analyses probe the production of LbL candidates in the diphoton mass ( $m_{\gamma\gamma}$ ) range of a few GeV. Complementary to these searches, an exclusive  $m_{\gamma\gamma}$  spectrum search starting from 350 GeV is performed in this Letter for the first time.

The LbL scattering process, which can be studied at the electroweak energy scale and above in proton-proton (pp) collisions at the LHC, is of great interest because of its sensitivity to many extensions of the SM [8, 13–19]. Some of these can be described by a purely effective extension of the SM Lagrangian using charge conjugation conserving operators, leading to a dimension-8 term for the four-photon coupling. This term contains the electromagnetic field tensor,  $F$ , and the two parameters  $\zeta_{1,2}$ :

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\mu\rho} F_{\rho\sigma} F^{\sigma\nu}. \quad (1)$$

The contribution from the anomalous four-photon coupling would dominate the LbL cross section at high masses, as compared to the SM contribution [20], for even the small values of the coupling constants of order  $10^{-14} \text{ GeV}^{-4}$  to which the analysis is sensitive. Observing two intact protons and two photons in the CMS detector with the present accumulated luminosity would be a clear signal for beyond-the-SM physics. A similar approach was used in Refs. [21–23] for the  $\gamma\gamma W^+ W^-$  quartic coupling.

In pp collisions, LbL scattering (pictured in Fig. 1) can be identified through the measurement of two exclusively produced photons and two intact protons detected in very forward detectors along both beam directions. In this Letter, a search for this process is performed in pp collisions at a center-of-mass energy of 13 TeV using data collected with the CMS and TOTEM detectors in 2016, corresponding to an integrated luminosity of  $9.4 \text{ fb}^{-1}$ . Tabulated results are provided in the HEPData record for this analysis [24].

The basic feature of the CMS detector is the 3.8 T magnetic field produced by a superconducting solenoid. Within this field are located a silicon pixel and strip tracker with coverage in pseudorapidity up to  $|\eta| = 2.5$ , surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL) directly outside the ECAL, each composed of a barrel and two endcap sections. The ECAL consists of about 76 000  $\text{PbWO}_4$  crystals, each with a transverse dimension approximately matching the Molière radius of the material. This radius roughly corresponds to a  $\Delta\eta \times \Delta\phi$  granularity (where  $\phi$  is azimuthal angle in radians) of  $0.0174 \times 0.0174$  in the barrel, and extending up to  $0.05 \times 0.05$  in both endcaps. The muon detection system consists of three types of gas-ionization detectors located in the steel flux-return yoke of the solenoid. Events are selected online and stored at a maximal rate of about 1 kHz using a two-tier triggering system [25]. A more detailed description of the apparatus, with a definition of the coordinate system used and the relevant kinematic variables, can

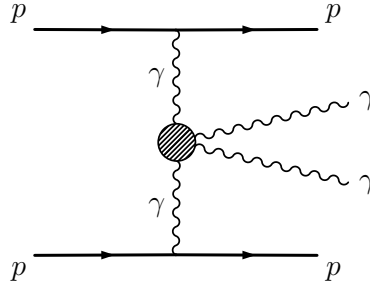


Figure 1: The process for diphoton production via photon exchange with intact protons in the final state. Several couplings may enter the four-photon shaded area such as a loop (box) of charged fermions or bosons. The model can be extended with intermediate interactions of new physics objects, such as a loop of a heavy charged particle or an  $s$ -channel process producing a scalar axion-like resonance that decays into two photons.

be found in Ref. [26].

The CMS-TOTEM precision proton spectrometer (CT-PPS) [27] is an array of movable, near-beam “Roman pot” (RPs) devices containing tracking and timing detectors located with their inner edge at a distance of 1.5 mm from the nominal axis of the LHC beam, whose transverse width is about 0.1 mm. The detectors are used to reconstruct the flight path and time of arrival of protons coming from the interaction point (IP) to a point 210 m down the LHC beamline. In this study, two tracking stations per side, or “arm”, of CMS are used. These tracking stations provide a measurement of the proton trajectories with respect to the beam position. Knowledge of the magnetic fields traversed by the proton from the IP to the RPs allows for the reconstruction of its fractional momentum loss  $\xi = \Delta p/p \sim x/D_x$  with respect to the momentum of the incident proton, with  $x$  being the horizontal displacement of the scattered proton, and  $D_x$  being the horizontal dispersion of the beam. In the 2016 data taking configuration, the CT-PPS tracking component consisted of silicon strip detectors, with acceptance for  $\xi$  of 2.4–15% and 3.7–15%, respectively, for the two arms of the spectrometer. The upper limit on this range reflects the acceptance expected from the nominal position of the physical apertures of optical elements in the beamline lattice in front of the RPs. The techniques used for the alignment and calibration of the apparatus are detailed in Refs. [28, 29]. Combining the uncertainties in the alignment and spatial resolution of the RPs, the beam transverse size and angular spread, and the horizontal dispersion, a total relative uncertainty between 6–10% is estimated for  $\xi$  over the range of the detector acceptance. The performance of CT-PPS and its potential for high-mass exclusive measurements were validated by the observation of proton-tagged  $\gamma\gamma$  collisions in 2016 [30]. The CT-PPS silicon strips, by design, can only reconstruct one proton at a time. This feature leads to a failure of the event reconstruction when multiple candidates are observed in the same RP for the same bunch crossing, leading to an inefficiency of 30% or less in both arms of CT-PPS for the entire data taking period considered in this study. Additionally, the acceptance is restricted to the regions of the silicon strips where the radiation-induced inefficiency remains below 10%. This region, asymmetric in proton momentum losses, corresponds to  $0.07 < \xi^- < 0.111$  and  $0.07 < \xi^+ < 0.138$ .

Events are required to pass a trigger that selects a pair of photon candidates, with each photon having a transverse momentum  $p_T > 60$  GeV each and a ratio of energy deposits in the HCAL to ECAL less than 0.15. This trigger was designed for, and used in, the CMS inclusive high-mass diphoton searches [31]. In the case of an elastic, photon-induced process, the photon pair is expected to have different kinematic properties compared to inclusive processes where the

photons are produced together with other particles. In particular, the back-to-back momentum balance in the transverse plane between the two exclusive photons is used to select the exclusive two-photon events.

A boosted decision tree discriminant is used for the photon identification, following the procedure introduced in Refs. [31, 32]. Since the reconstruction algorithms in the ECAL do not make assumptions as to whether the energy deposits are from a photon or an electron, photon reconstruction can be validated using  $Z \rightarrow e^+e^-$  events [33]. For this analysis, electrons are vetoed by the presence of hits in the central tracker that are inconsistent with a converted photon.

Several sources of nonexclusive backgrounds are considered for this search. The leading inclusive  $\gamma\gamma$  background as well as the  $W\gamma$  and  $Z\gamma$  subleading backgrounds are simulated by MADGRAPH5\_aMC@NLO 2.2.2 [34] at next-to-leading order (NLO) precision with NNPDF3.0 parton distribution functions (PDFs) at next-to-NLO precision [35]. Other subleading backgrounds, namely photon-enriched quantum chromodynamics (QCD) processes, photon-enriched inclusive  $\gamma + \text{jet}$ , and inclusive  $t\bar{t}$  processes, are generated at leading order (LO) by PYTHIA 8.205 [36] with NNPDF3.0 PDFs at LO precision. The exclusive SM LbL process contribution is expected to be negligible at a mass range above 350 GeV [20]. Less than 0.02 events are expected for the luminosity used in this study. It is considered as a background and is simulated using the Forward Physics Monte Carlo (FPMC) program [37] based on the description in Ref. [17]. All samples considered in this search are processed with a GEANT4 [38] simulation of the CMS central detector.

The selection is performed in the few steps detailed below, which are summarized in Table 1. A preselection of events requires each photon to have  $p_T > 75$  GeV to ensure a fully efficient trigger,  $|\eta| < 2.5$  with a veto on the ECAL barrel-endcap transition region ( $1.4442 < |\eta| < 1.5660$ ), and  $m_{\gamma\gamma} > 350$  GeV. The minimum diphoton mass corresponds to the minimum measurable proton momentum loss detectable by the CT-PPS.

For events passing the preselection criteria, an elastic selection region is constructed based on the expected back-to-back emission in the transverse plane of two final-state photons from exclusive elastic processes. The diphoton acoplanarity  $a \equiv 1 - |\Delta\phi_{\gamma\gamma}/\pi|$ , where  $\Delta\phi_{\gamma\gamma}$  is the azimuthal separation of the two photons, is then used as a discriminating variable, and diphoton candidates are selected with  $a < 0.005$ . To isolate photons in the ECAL, a lower threshold of 0.94 is set on the  $R_9$  variable, computed as the ratio between the energy in a  $3 \times 3$  area of crystals to the energy in a  $5 \times 5$  area of crystals, centered on the most energetic crystal of the photon energy deposit [33]. Using the criteria from the elastic selection based on the kinematic features of the two-photon system, which allows a selection from the central detector only, a tighter search can be defined with the detection of scattered protons for elastic production. It requires both  $\xi_{\gamma\gamma}^-$  and  $\xi_{\gamma\gamma}^+$  to be compatible with the CT-PPS proton  $\xi$  acceptance quoted earlier, where  $\xi_{\gamma\gamma}^\pm = (p_T^{\gamma 1} e^{\pm\eta^{\gamma 1}} + p_T^{\gamma 2} e^{\pm\eta^{\gamma 2}}) / \sqrt{s}$  is calculated from the two-photon system kinematic variables only and the + and - denote the positive and negative z sides of CMS, respectively. Because of the radiation damage to the detector regions closest to the beam, the track reconstruction efficiency varies with  $x$  (and hence  $\xi$ ), and decreases over time as radiation is accumulated. For that reason, the signal search region for this analysis is defined by requiring the two  $\xi_{\gamma\gamma}^\pm$  values to pass a tighter selection corresponding to the most efficient area of the CT-PPS detectors. In this region, equivalently noted as “tight  $\xi_{\gamma\gamma}^\pm$ ” in this study, the tracking efficiency in each RP is at least 90%.

Sensitivity to the LbL signal is enhanced by measuring the resulting final-state protons. In exclusive events, where the protons remain intact, momentum loss from the protons is related to the invariant mass of the diphoton system. Signal candidates are selected by requiring, in addi-

tion to the selection criteria defined above, a kinematic matching between the two systems, of the forward protons and the central photons, thus imposing conservation of momentum. It has been shown that matching mass and rapidity of the diphoton system and the scattered protons on an event-by-event basis significantly reduces the contribution of inclusive backgrounds [20]. In fact, the large majority of such events come from the coincidence of an inclusively-produced diphoton event with pileup protons from unrelated events. The kinematic matching ensures that the two systems originate from the same pp interaction. The kinematic variables of an opposite-arm, two-proton system are converted into missing mass and rapidity of the central system through  $m_{pp} = \sqrt{s\zeta^+\zeta^-}$ , and  $y_{pp} = (1/2) \log(\zeta^+/\zeta^-)$ , where  $\zeta^+$  and  $\zeta^-$  correspond to the  $\zeta$  of protons on the positive  $z$  and negative  $z$  sides of CT-PPS, respectively. In the case of exclusive diphoton production, both systems are correlated through  $m_{pp} = m_{\gamma\gamma}$  and  $y_{pp} = y_{\gamma\gamma}$ . The resolution of the diphoton mass as deduced from uncertainties in the photons' momenta is 2.0%. For the two-proton system, a diphoton mass resolution of 5.5–8.4% is expected from the proton fractional momentum loss uncertainties. Equivalently, the central two-photon rapidity resolution is 7.4%, while the uncertainty in  $y_{pp}$ , the forward two-proton rapidity, is bounded between 0.05–0.09 in absolute value. In this search, a  $2\sigma$  window is used in matching the difference, both in mass and rapidity, between the central and the two-proton systems following the tight  $\zeta_{\gamma\gamma}^{\pm}$  selection defined above; here  $\sigma$  indicates the combined resolution of the two systems.

One nonelastic background control region is used in the analysis. This control region satisfies the preselection criteria and is given a high efficiency for inclusive diphoton events with the requirement that photons have  $p_T > 200$  GeV and  $a > 0.025$ , with a looser  $R_9 > 0.85$  criteria to ensure a high yield of the selection. The acoplanarity selection suppresses exclusive production, which occurs at small acoplanarity values. A summary of the selection at different stages is shown in Table 1.

Table 1: Description of the selection stages applied on the photon and proton kinematic variables, and used in this study.

Stage	Selection on photon variables
Preselection	$p_T^\gamma > 75$ GeV, $ \eta_\gamma  < 2.5$ with ECAL geometrical veto, $R_9 > 0.85$ , $m_{\gamma\gamma} > 350$ GeV
Nonelastic	Preselection, $p_T^\gamma > 200$ GeV, $a > 0.025$
Elastic	Preselection, $R_9 > 0.94$ , $a < 0.005$
Accept. $\zeta_{\gamma\gamma}^{\pm}$	Elastic selection, $0.024 < \zeta_{\gamma\gamma}^- < 0.15$ , $0.037 < \zeta_{\gamma\gamma}^+ < 0.15$
Tight $\zeta_{\gamma\gamma}^{\pm}$	Elastic selection, $0.07 < \zeta_{\gamma\gamma}^- < 0.111$ , $0.07 < \zeta_{\gamma\gamma}^+ < 0.138$
$2\sigma$ match.	Tight $\zeta_{\gamma\gamma}^{\pm}$ selection, $2\sigma$ matching of $m_{\gamma\gamma}$ and $y_{\gamma\gamma}$ with $m_{pp}$ and $y_{pp}$

The normalization and shape of the simulated background contributions in the signal search region are checked with the nonelastic-enriched sample introduced above. A slight deficit (9.9%) observed for the simulation of the nonelastic-enriched region is addressed by rescaling the dominant inclusive background to achieve an agreement between data and simulation. This background yield correction is applied to each of the selection regions.

The data and simulation events falling within the different selection regions described above and given in Table 1 can be seen in Fig. 2. For all selection regions used in this study, the data are found to be consistent with the background prediction within statistical uncertainties. A total of 266 diphoton candidates are found in the elastic region to be compared with the expectation of  $263.1 \pm 4.1$  (stat). The resulting  $m_{\gamma\gamma}$  spectrum of events passing the elastic selection can be seen in Fig. 3.

As shown in Fig. 2, only two events remain in the tight  $\zeta_{\gamma\gamma}^{\pm}$  signal search region with an

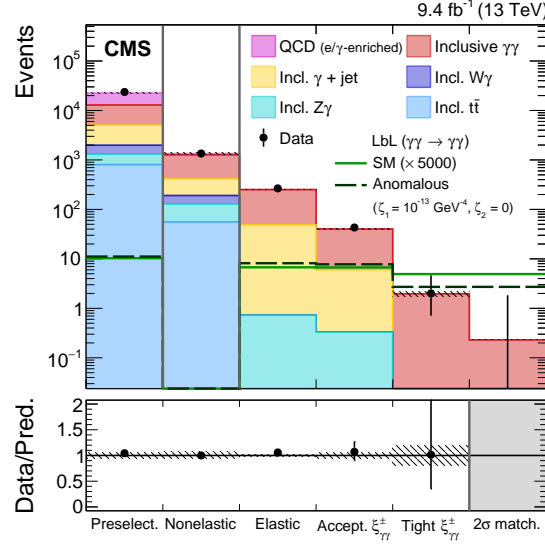


Figure 2: Numbers of simulated and observed events for the various selection regions described in the text. The shaded bands show the statistical uncertainties in the simulated backgrounds added in quadrature. All selection regions are sequential from left to right, with the exception of the nonelastic region used in the background yield correction, thus with a data-to-prediction ratio constrained to unity. Shown also are the theoretical contributions to the LbL signal from the SM and from an anomalous source whose yield at the parameters given is close to the sensitivity reached in this study.

expected background of  $2.1^{+1.0}_{-0.7}$  (stat) when no kinematic matching criteria between the two-photon and two-proton systems are applied. Neither of these events contains a pair of forward proton tracks, and thus there are no events in the  $2\sigma$  match region.

Background contributions are estimated following the procedure described in Ref. [30], where it is assumed that inclusive background processes involve a full decorrelation between central two-photon and forward two-proton systems. Pseudo-events are formed by combining diphoton kinematic distributions sampled from a template with the two-proton system variables randomly selected from real data events within the period of interest. The diphoton kinematic variables are sampled from an exponential fit to the two  $\xi_{\gamma\gamma}^{\pm}$  spectra of events passing the nonelastic background-enriched selection defined above. In order to match the observed yield in data for the tight  $\xi_{\gamma\gamma}^{\pm}$  selection and after checking that it does not show any kinematic dependence on the invariant mass, transverse momentum, and acoplanarity of the photon pair, or on the basic kinematic variables of single photons, a constant scaling factor is applied to the leading inclusive  $\gamma\gamma$  background. Using this method, the predicted number of events having an elastic diphoton pair in association with a pair of protons observed within the range where the proton detectors have a radiation inefficiency less than 10% is evaluated as  $0.83^{+0.28}_{-0.15}$  (stat) events. This prediction is without the requirement of any kinematic matching of the diphoton and proton systems. When constraining both the systems to the  $2\sigma$  and  $3\sigma$  matching windows, the background predictions are respectively  $0.23^{+0.08}_{-0.04}$  (stat) and  $0.43^{+0.14}_{-0.08}$  (stat) events.

Several sources of systematic uncertainties affecting the signal are considered. The uncertainty of 37% in the yield correction for the inclusive background selection estimated from the nonelastic-enriched selection as described above. This uncertainty is evaluated by varying the fit parameters within one standard deviation. There is an additional 33% uncertainty in the background estimate, evaluated by computing this yield after varying the exponential

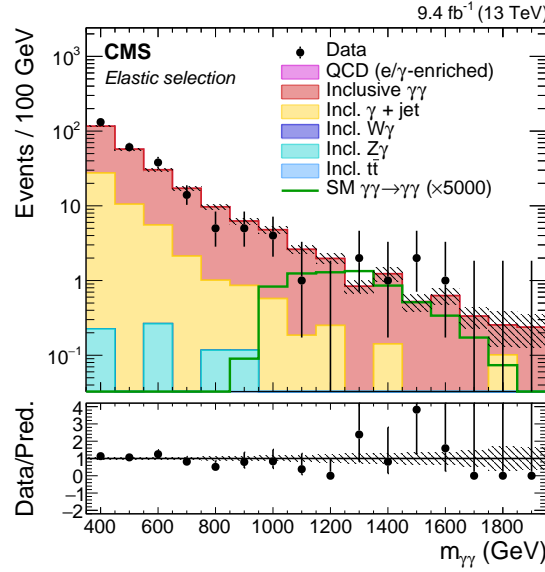


Figure 3: Invariant mass distribution of the diphoton pairs for the elastic selection region with events satisfying  $1 - |\Delta\phi_{\gamma\gamma}/\pi| < 0.005$  as described in the text, for data (dots) and MC simulations (histograms). The hatched bands indicate the statistical uncertainties in simulated samples added in quadrature.

fit parameters within one standard deviation. The variation on the functional form of the fit was also studied and was found to be well within the uncertainty quoted above. Subleading sources of uncertainties include radiation damage and tracking efficiency of the RPs (13%) [39], and the luminosity measurement (2.5%) [40]. Additionally, a signal cross section uncertainty of 10% is assumed to account for the rapidity gap survival probability in the high invariant mass region [41]. The rapidity gap survival probability [42] expresses the fraction of events in which no additional soft interactions occur between the two colliding protons, producing extra final-state particles and modifying the topology of exclusive events.

No diphoton candidates with exclusive kinematic features are observed in either of the  $2\sigma$  and  $3\sigma$  mass and rapidity matching windows, thus no observation of a central exclusive production of a photon pair with associated scattered proton tracks can be reported for the sample considered in this study.

Using a profile likelihood ratio as a test statistic [43], systematic uncertainties as nuisance parameters with a log-normal prior, and the background yields obtained above, the 95% confidence level (CL) [44, 45] observed frequentist upper limit of 4.4 fb is obtained for the LbL cross section within the fiducial region. This region is defined at the generator level in terms of the single-photon and diphoton selections described previously, with additional asymmetric selection criteria for the two arms of the spectrometer corresponding to the region with less than 10% inefficiency from the CT-PPS strips radiation damage and within beamline apertures. The SM LbL process has a combined two-photon and two-proton tagging signal efficiency of  $(6.7 \pm 0.9)\%$ . The dominant fraction of the uncertainty in this efficiency arises from the uncertainties in estimating radiation damage and reconstruction of multiple protons in the RPs, followed by a contribution driven by the limited number of SM LbL MC events satisfying the selection criteria.

For the anomalous quartic gauge coupling extension of the SM introduced earlier, an observed upper limit of 2.1 fb can be compared with the expected limit of 2.5 fb using the background-only hypothesis. This upper limit is used to place the first limits on the four-photon anomalous



quartic gauge couplings. It was studied that the signal efficiency does not vary strongly over a wide range of the couplings parameters  $\zeta_1$  and  $\zeta_2$  in the search region. It is evaluated at a combined  $(14.5 \pm 1.9)\%$  signal efficiency, significantly higher than for the SM LbL process. Figure 4 shows the region of the parameter phase space where the corresponding cross section is excluded by this measurement. Consequently, when one of the model parameters is assumed to be null, the other is limited to

$$|\zeta_1| < 2.9 \times 10^{-13} \text{ GeV}^{-4} (\zeta_2 = 0),$$

$$|\zeta_2| < 6.0 \times 10^{-13} \text{ GeV}^{-4} (\zeta_1 = 0).$$

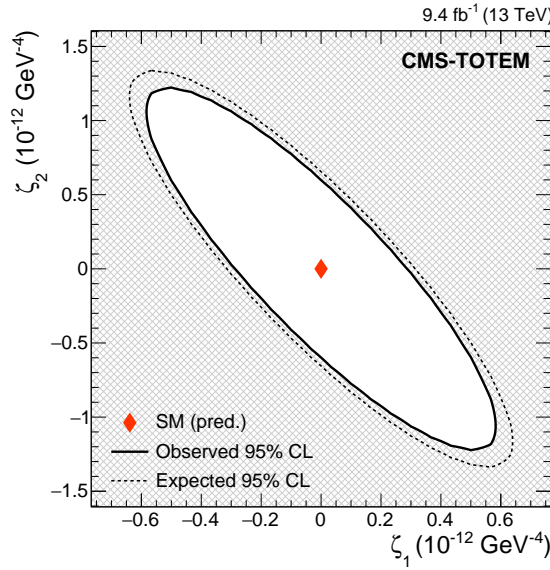


Figure 4: Two-dimensional limits on the anomalous four-photon couplings, derived from the observed upper limit on the diphoton production cross section. The shaded area depicts the excluded values of the coupling parameters  $\zeta_1$  and  $\zeta_2$ .

To summarize, the CMS-TOTEM precision proton spectrometer has proven the feasibility of continuously operating a near-beam proton spectrometer at a high-luminosity hadron collider. The first search for the  $\gamma\gamma \rightarrow \gamma\gamma$  process with forward proton tags is presented. The search uses an integrated luminosity of  $9.4 \text{ fb}^{-1}$  of proton-proton collisions collected at a 13 TeV center-of-mass energy at the LHC during 2016. No events are observed with a pair of proton tracks compatible with the diphoton kinematic properties with an expected background of 0.23 and 0.43 events for the 2 and 3 standard deviations windows, respectively. This provides the first limit for the standard model light-by-light production cross section at a scale of hundreds of GeV, and places limits on anomalous couplings for the four-photon interaction based on an effective field theory extension of the standard model.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS and TOTEM institutes for their contributions to the success of the common CMS-TOTEM effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers 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, the CMS and TOTEM detectors, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, Finnish Academy of Science and Letters (The Vilho Yrjö and Kalle Väisälä Fund), MEC, Magnus Ehrnrooth Foundation, HIP, and Waldemar von Frenckell Foundation (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); the Circles of Knowledge Club, NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

## References

- [1] S. L. Adler, "Photon splitting and photon dispersion in a strong magnetic field", *Annals Phys.* **67** (1971) 599, doi:10.1016/0003-4916(71)90154-0.
- [2] G. Jarlskog et al., "Measurement of Delbrück scattering and observation of photon splitting at high energies", *Phys. Rev. D* **8** (1973) 3813, doi:10.1103/PhysRevD.8.3813.
- [3] R. N. Li, A. I. Mil'shtein, and V. M. Strakhovenko, "Splitting of a high-energy photon in a strong Coulomb field", *J. Exp. Theor. Phys.* **85** (1997) 1049, doi:10.1134/1.558376, arXiv:hep-ph/9704230.
- [4] PVLAS Collaboration, "Limits on low energy photon-photon scattering from an experiment on magnetic vacuum birefringence", *Phys. Rev. D* **78** (2008) 032006, doi:10.1103/PhysRevD.78.032006, arXiv:0805.3036.
- [5] R. S. Van Dyck, P. B. Schwinberg, and H. G. Dehmelt, "New high precision comparison of electron and positron G factors", *Phys. Rev. Lett.* **59** (1987) 26, doi:10.1103/PhysRevLett.59.26.
- [6] Muon g-2 Collaboration, "Final report of the muon E821 anomalous magnetic moment measurement at BNL", *Phys. Rev. D* **73** (2006) 072003, doi:10.1103/PhysRevD.73.072003, arXiv:hep-ex/0602035.
- [7] Muon g-2 Collaboration, "Measurement of the positive muon anomalous magnetic moment to 0.46 ppm", *Phys. Rev. Lett.* **126** (2021) 141801, doi:10.1103/PhysRevLett.126.141801, arXiv:2104.03281.
- [8] D. d'Enterria and G. G. da Silva, "Observing light-by-light scattering at the Large Hadron Collider", *Phys. Rev. Lett.* **111** (2013) 080405, doi:10.1103/PhysRevLett.111.080405, arXiv:1305.7142. [Erratum: doi:10.1103/PhysRevLett.116.129901].

- [9] ATLAS Collaboration, “Observation of light-by-light scattering in ultraperipheral Pb+Pb collisions with the ATLAS detector”, *Phys. Rev. Lett.* **123** (2019) 052001, doi:10.1103/PhysRevLett.123.052001, arXiv:1904.03536.
- [10] CMS Collaboration, “Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV”, *Phys. Lett. B* **797** (2019) 134826, doi:10.1016/j.physletb.2019.134826, arXiv:1810.04602.
- [11] ATLAS Collaboration, “Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC”, *Nature Phys.* **13** (2017) 852, doi:10.1038/nphys4208, arXiv:1702.01625.
- [12] A. J. Baltz, “The physics of ultraperipheral collisions at the LHC”, *Phys. Rept.* **458** (2008) 1, doi:10.1016/j.physrep.2007.12.001, arXiv:0706.3356.
- [13] E. Chapon, C. Royon, and O. Kepka, “Anomalous quartic  $WW\gamma\gamma$ ,  $ZZ\gamma\gamma$ , and trilinear  $WW\gamma$  couplings in two-photon processes at high luminosity at the LHC”, *Phys. Rev. D* **81** (2010) 074003, doi:10.1103/PhysRevD.81.074003, arXiv:0912.5161.
- [14] I. Sahin and S. C. Inan, “Probe of unparticles at the LHC in exclusive two lepton and two photon production via photon-photon fusion”, *JHEP* **09** (2009) 069, doi:10.1088/1126-6708/2009/09/069, arXiv:0907.3290.
- [15] R. S. Gupta, “Probing quartic neutral gauge boson couplings using diffractive photon fusion at the LHC”, *Phys. Rev. D* **85** (2012) 014006, doi:10.1103/PhysRevD.85.014006, arXiv:1111.3354.
- [16] L. N. Epele et al., “Looking for magnetic monopoles at LHC with diphoton events”, *Eur. Phys. J. Plus* **127** (2012) 60, doi:10.1140/epjp/i2012-12060-8, arXiv:1205.6120.
- [17] S. Fichet et al., “Probing new physics in diphoton production with proton tagging at the Large Hadron Collider”, *Phys. Rev. D* **89** (2014) 114004, doi:10.1103/PhysRevD.89.114004, arXiv:1312.5153.
- [18] H. Sun, “Large extra dimension effects through light-by-light scattering at the CERN LHC”, *Eur. Phys. J. C* **74** (2014) 2977, doi:10.1140/epjc/s10052-014-2977-1, arXiv:1406.3897.
- [19] S. Fichet, “Shining light on polarizable dark particles”, *JHEP* **04** (2017) 088, doi:10.1007/JHEP04(2017)088, arXiv:1609.01762.
- [20] S. Fichet et al., “Light-by-light scattering with intact protons at the LHC: from standard model to new physics”, *JHEP* **02** (2015) 165, doi:10.1007/JHEP02(2015)165, arXiv:1411.6629.
- [21] CMS Collaboration, “Study of exclusive two-photon production of  $W^+W^-$  in pp collisions at  $\sqrt{s} = 7$  TeV and constraints on anomalous quartic gauge couplings”, *JHEP* **07** (2013) 116, doi:10.1007/JHEP07(2013)116, arXiv:1305.5596.
- [22] CMS Collaboration, “Evidence for exclusive  $\gamma\gamma \rightarrow W^+W^-$  production and constraints on anomalous quartic gauge couplings in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, *JHEP* **08** (2016) 119, doi:10.1007/JHEP08(2016)119, arXiv:1604.04464.

- 
- [23] ATLAS Collaboration, “Measurement of exclusive  $\gamma\gamma \rightarrow W^+W^-$  production and search for exclusive higgs boson production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV using the ATLAS detector”, *Phys. Rev. D* **94** (2016) 032011, doi:10.1103/PhysRevD.94.032011, arXiv:1607.03745.
- [24] “HEPData record for this analysis”, 2021. doi:10.17182/hepdata.113659.
- [25] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [26] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [27] CMS-TOTEM Collaboration, “CMS-TOTEM Precision Proton Spectrometer”, Technical Report CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13, 2014.
- [28] J. Kašpar, “Alignment of CT-PPS detectors in 2016, before TS2”, CERN-TOTEM-NOTE 2017-001, 2017.
- [29] F. Nemes, “LHC optics determination with proton tracks measured in the CT-PPS detectors in 2016, before TS2”, CERN-TOTEM-NOTE 2017-002, 2017.
- [30] CMS-TOTEM Collaboration, “Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in  $pp$  collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer”, *JHEP* **07** (2018) 153, doi:10.1007/JHEP07(2018)153, arXiv:1803.04496.
- [31] CMS Collaboration, “Search for high-mass diphoton resonances in proton-proton collisions at 13 TeV and combination with 8 TeV search”, *Phys. Lett. B* **767** (2017) 147, doi:10.1016/j.physletb.2017.01.027, arXiv:1609.02507.
- [32] CMS Collaboration, “Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC”, *JINST* **16** (2021) P05014, doi:10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
- [33] CMS Collaboration, “Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.
- [34] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [35] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [36] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [37] M. Boonekamp et al., “FPMC: A generator for forward physics”, 2011. arXiv:1102.2531.
- [38] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

- [39] CMS Collaboration, “Proton reconstruction with the Precision Proton Spectrometer (PPS) in Run 2”, Detector Performance Note 2020-047, 2020.
- [40] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [41] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, “Exclusive physics at the LHC with SuperChic 2”, *Eur. Phys. J. C* **76** (2016) 9, doi:10.1140/epjc/s10052-015-3832-8, arXiv:1508.02718.
- [42] L. A. Harland-Lang, V. A. Khoze, and M. G. Ryskin, “The photon PDF in events with rapidity gaps”, *Eur. Phys. J. C* **76** (2016) 255, doi:10.1140/epjc/s10052-016-4100-2, arXiv:1601.03772.
- [43] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [44] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [45] A. L. Read, “Presentation of search results: the  $CL_s$  technique”, in *Durham IPPP Workshop: Advanced Statistical Techniques in Particle Physics*, p. 2693. Durham, UK, March, 2002. [*J. Phys. G* **28** (2002) 2693]. doi:10.1088/0954-3899/28/10/313.



## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan

### Institut für Hochenergiephysik, Vienna, Austria

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

### Institute for Nuclear Problems, Minsk, Belarus

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

### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>2</sup>, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello<sup>3</sup>, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

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

### Université Libre de Bruxelles, Bruxelles, Belgium

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

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov<sup>4</sup>, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

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

G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, C. Hensel, A. Moraes

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

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. Brandao Malbouisson, W. Carvalho, J. Chinellato<sup>5</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>6</sup>, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins<sup>7</sup>, D. Matos Figueiredo, M. Medina Jaime<sup>8</sup>, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

### Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

### University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

**Beihang University, Beijing, China**

T. Cheng, W. Fang<sup>3</sup>, Q. Guo, H. Wang, L. Yuan

**Department of Physics, Tsinghua University, Tsinghua, China**

M. Ahmad, G. Bauer, Z. Hu, Y. Wang, K. Yi<sup>9,10</sup>

**Institute of High Energy Physics, Beijing, China**

E. Chapon, G.M. Chen<sup>11</sup>, H.S. Chen<sup>11</sup>, M. Chen, T. Javaid<sup>11</sup>, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu<sup>11</sup>, R. Sharma, A. Spiezia, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, S. Zhang<sup>11</sup>, J. Zhao

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

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

**Sun Yat-Sen University, Guangzhou, China**

Z. You

**Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China**

X. Gao<sup>3</sup>

**Zhejiang University, Hangzhou, China**

M. Xiao

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

**Universidad de Antioquia, Medellin, Colombia**

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

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

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

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

Z. Antunovic, M. Kovac, T. Sculac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov<sup>12</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, E. Erodou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

**Charles University, Prague, Czech Republic**

M. Finger<sup>13</sup>, M. Finger Jr.<sup>13</sup>, A. Kveton, J. Tomsa

**Escuela Politecnica Nacional, Quito, Ecuador**

E. Ayala

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin



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

S. Elgammal<sup>14</sup>, A. Ellithi Kamel<sup>15</sup>, S. Khalil<sup>16</sup>

**Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt**

M.A. Mahmoud, Y. Mohammed<sup>17</sup>

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

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

P. Eerola, H. Kirschenmann, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

E. Brücken, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

P. Luukka, T. Tuuva

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

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro<sup>18</sup>, M. Titov, G.B. Yu

**Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France**

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France**

J.-L. Agram<sup>19</sup>, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine<sup>19</sup>, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

**Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France**

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>20</sup>, Z. Tsamalaidze<sup>13</sup>

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

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad<sup>21</sup>, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl<sup>22</sup>, T. Ziemons

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>23</sup>, V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo<sup>24</sup>, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari<sup>25</sup>, N.Z. Jomhari, H. Jung, A. Kasem<sup>23</sup>, M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann<sup>26</sup>, T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otariid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

**University of Hamburg, Hamburg, Germany**

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

**Karlsruher Institut fuer Technologie, Karlsruhe, Germany**

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann<sup>22</sup>, C. Heidecker, U. Husemann, I. Katkov<sup>27</sup>, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoiiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski

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

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

**National Technical University of Athens, Athens, Greece**

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, K. Manitará, N. Manthos, I. Papadopoulos, J. Strologas

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

**Budapest, Hungary**

M. Bartók<sup>28</sup>, M.M.A. Gadallah<sup>29</sup>, S. Lökös<sup>30</sup>, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath<sup>31</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>

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

S. Czellar, J. Karancsi<sup>28</sup>, J. Molnar, Z. Szillasi, D. Teyssier

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

P. Raics, Z.L. Trocsanyi, B. Ujvari

**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

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

S. Bahinipati<sup>34</sup>, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak<sup>35</sup>, D.K. Sahoo<sup>34</sup>, N. Sur, S.K. Swain

**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra<sup>36</sup>, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi

**University of Delhi, Delhi, India**

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

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**

M. Bharti<sup>37</sup>, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber<sup>38</sup>, M. Maity<sup>39</sup>, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh<sup>37</sup>, S. Thakur<sup>37</sup>

**Indian Institute of Technology Madras, Madras, India**

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

**Bhabha Atomic Research Centre, Mumbai, India**

D. Dutta, V. Kumar, K. Naskar<sup>40</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla

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

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

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

S. Banerjee, S. Bhattacharya, S. Chatterjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

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

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

**Isfahan University of Technology, Isfahan, Iran**

H. Bakhshiansohi<sup>41</sup>, M. Zeinali<sup>42</sup>

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

S. Chenarani<sup>43</sup>, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, R. Aly<sup>a,b,44</sup>, C. Aruta<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, A. Di Pilato<sup>a,b</sup>, W. Elmetenawee<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, M. Gul<sup>a</sup>, G. Iaselli<sup>a,c</sup>, M. Ince<sup>a,b</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, I. Margjeka<sup>a,b</sup>, V. Mastrapasqua<sup>a,b</sup>, J.A. Merlin<sup>a</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, F.M. Simone<sup>a,b</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, C. Ciocca<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, T. Diotallevi<sup>a,b</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, E. Fontanesi<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, L. Giommi<sup>a,b</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, F. Iemmi<sup>a,b</sup>, S. Lo Meo<sup>a,45</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**S. Albergo<sup>a,b,46</sup>, S. Costa<sup>a,b,46</sup>, A. Di Mattia<sup>a</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,46</sup>, C. Tuve<sup>a,b</sup>**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**G. Barbagli<sup>a</sup>, A. Cassese<sup>a</sup>, R. Ceccarelli<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, F. Fiori<sup>a</sup>, E. Focardi<sup>a,b</sup>, G. Latino<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Lizzo<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, R. Seidita<sup>a,b</sup>, G. Sguazzoni<sup>a</sup>, L. Viliani<sup>a</sup>**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, D. Piccolo

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**F. Ferro<sup>a</sup>, R. Mulargia<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**A. Benaglia<sup>a</sup>, A. Beschi<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, F. Cetorelli<sup>a,b</sup>, V. Ciriolo<sup>a,b,22</sup>, F. De Guio<sup>a,b</sup>, M.E. Dinardo<sup>a,b</sup>, P. Dini<sup>a</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, L. Guzzi<sup>a,b</sup>, M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup>, A. Massironi<sup>a</sup>, D. Menasce<sup>a</sup>, F. Monti<sup>a,b</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>, D. Valsecchi<sup>a,b,22</sup>, D. Zuolo<sup>a,b</sup>**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli 'Federico II' <sup>b</sup>, Napoli, Italy, Università della Basilicata <sup>c</sup>, Potenza, Italy, Università G. Marconi <sup>d</sup>, Roma, Italy**S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, A. De Iorio<sup>a,b</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a,b</sup>, S. Meola<sup>a,d,22</sup>, P. Paolucci<sup>a,22</sup>, B. Rossi<sup>a</sup>, C. Sciacca<sup>a,b</sup>, E. Voevodina<sup>a,b</sup>**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Padova, Italy, Università di Trento <sup>c</sup>, Trento, Italy**P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, D. Bisello<sup>a,b</sup>, P. Bortignon<sup>a</sup>, A. Bragagnolo<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, S.Y. Hoh<sup>a,b</sup>, L. Layer<sup>a,47</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, M. Presilla<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, G. Strong<sup>a</sup>, M. Tosi<sup>a,b</sup>, H. YARAR<sup>a,b</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, A. Zucchetta<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**C. Aime<sup>a,b</sup>, A. Braghieri<sup>a</sup>, S. Calzaferri<sup>a,b</sup>, D. Fiorina<sup>a,b</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a</sup>, P. Vitulo<sup>a,b</sup>**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>,

V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, F. Moscatelli<sup>a</sup>, A. Piccinelli<sup>a,b</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>, T. Tedeschi<sup>a,b</sup>

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

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

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

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

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

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

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

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

**Kyungpook National University, Daegu, Korea**

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

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

H. Kim, D.H. Moon

**Hanyang University, Seoul, Korea**

B. Francois, T.J. Kim, J. Park

**Korea University, Seoul, Korea**

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

**Kyung Hee University, Department of Physics, Seoul, Republic of Korea**

J. Goh, A. Gurtu

**Sejong University, Seoul, Korea**

H.S. Kim, Y. Kim

**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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

**Yonsei University, Department of Physics, Seoul, Korea**

H.D. Yoo

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

**College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait**

Y. Maghrbi

**Riga Technical University, Riga, Latvia**

V. Veckalns<sup>48</sup>

**Vilnius University, Vilnius, Lithuania**

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

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

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

**Universidad de Sonora (UNISON), Hermosillo, Mexico**

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

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

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>49</sup>, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

A. Morelos Pineda

**University of Montenegro, Podgorica, Montenegro**

J. Mijuskovic<sup>4</sup>, N. Raicevic

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P.H. Butler

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

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

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Walczak

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

A. Baginyan, M. Gavrilenko, A. Golunov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, I. Kashunin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev<sup>50,51</sup>, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev<sup>52</sup>, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**

G. Gavrilo, V. Golovtsov, Y. Ivanov, V. Kim<sup>53</sup>, E. Kuznetsova<sup>54</sup>, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov<sup>†</sup>, A. Toropin

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

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, A. Nikitenko<sup>55</sup>, V. Popov, G. Safronov, A. Spiridonov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev

**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**

R. Chistov<sup>56</sup>, M. Danilov<sup>56</sup>, A. Oskin, P. Parygin, S. Polikarpov<sup>56</sup>

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>57</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, O. Lukina, S. Obraztsov, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>58</sup>, T. Dimova<sup>58</sup>, L. Kardapoltsev<sup>58</sup>, I. Ovtin<sup>58</sup>, Y. Skovpen<sup>58</sup>

**Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia**

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

**National Research Tomsk Polytechnic University, Tomsk, Russia**

A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

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

P. Adzic<sup>59</sup>, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran,

Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

**Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain**

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

**University of Colombo, Colombo, Sri Lanka**

M.K. Jayananda, B. Kailasapathy<sup>60</sup>, D.U.J. Sonnadara, D.D.C. Wickramarathna

**University of Ruhuna, Department of Physics, Matara, Sri Lanka**

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

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

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita<sup>61</sup>, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo<sup>22</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, T. Quast, D. Rabad, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>62</sup>, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

L. Caminada<sup>63</sup>, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Luster, M. A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann<sup>64</sup>, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>65</sup>, C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler,



A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi

**National Central University, Chung-Li, Taiwan**

C. Adloff<sup>66</sup>, C.M. Kuo, W. Lin, A. Roy, T. Sarkar<sup>39</sup>, S.S. Yu

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

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

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

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

M.N. Bakirci<sup>67</sup>, F. Boran, S. Damarseckin<sup>68</sup>, Z.S. Demiroglu, F. Dolek, C. Dozen<sup>69</sup>, I. Dumanoglu<sup>70</sup>, E. Eskut, Y. Guler, E. Gurpinar Guler<sup>71</sup>, I. Hos<sup>72</sup>, C. Isik, E.E. Kangal<sup>73</sup>, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, A. Polatoz, A.E. Simsek, B. Tali<sup>74</sup>, U.G. Tok, H. Topakli<sup>75</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak<sup>76</sup>, G. Karapinar<sup>77</sup>, K. Ocalan<sup>78</sup>, M. Yalvac<sup>79</sup>

**Bogazici University, Istanbul, Turkey**

I.O. Atakisi, E. Gülmez, M. Kaya<sup>80</sup>, O. Kaya<sup>81</sup>, Ö. Özçelik, S. Tekten<sup>82</sup>, E.A. Yetkin<sup>83</sup>

**Istanbul Technical University, Istanbul, Turkey**

A. Cakir, K. Cankocak<sup>70</sup>, Y. Komurcu, S. Sen<sup>84</sup>

**Istanbul University, Istanbul, Turkey**

F. Aydogmus Sen, S. Cerci<sup>74</sup>, S. Ozkorucuklu, D. Sunar Cerci<sup>74</sup>

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

B. Grynyov

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou<sup>85</sup>, J. Taylor, A. Titterton

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>86</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

**Imperial College, London, United Kingdom**

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal<sup>87</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash<sup>88</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee<sup>22</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, USA**

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

**Catholic University of America, Washington, DC, USA**

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

**The University of Alabama, Tuscaloosa, USA**

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio, C. West

**Boston University, Boston, USA**

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

**Brown University, Providence, USA**

G. Benelli, B. Burkle, X. Coubez<sup>23</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>89</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>90</sup>, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

**University of California, Davis, Davis, USA**

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

**University of California, Los Angeles, USA**

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

**University of California, Riverside, Riverside, USA**

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

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

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

**University of California, Santa Barbara - Department of Physics, Santa Barbara, USA**

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

**California Institute of Technology, Pasadena, USA**

A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, J. Ngadiuba, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

**University of Colorado Boulder, Boulder, USA**

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

**Cornell University, Ithaca, USA**

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

**Fermi National Accelerator Laboratory, Batavia, USA**

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena<sup>57</sup>, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

**University of Florida, Gainesville, USA**

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

**Florida State University, Tallahassee, USA**

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

**Florida Institute of Technology, Melbourne, USA**

M.M. Baarmand, S. Butalla, T. Elkafrawy<sup>91</sup>, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

**The University of Iowa, Iowa City, USA**

M. Alhousseini, K. Dilsiz<sup>92</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili<sup>93</sup>, A. Moeller, J. Nachtman, H. Ogul<sup>94</sup>, Y. Onel, F. Ozok<sup>95</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

**Johns Hopkins University, Baltimore, USA**

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

**The University of Kansas, Lawrence, USA**

P. Baringer, A. Bean, A. Bylinkin, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, G. Wilson

**Kansas State University, Manhattan, USA**

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

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

**Massachusetts Institute of Technology, Cambridge, USA**

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

**University of Minnesota, Minneapolis, USA**

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

**University of Mississippi, Oxford, USA**

J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, USA**

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, J.E. Siado, G.R. Snow<sup>†</sup>, W. Tabb, F. Yan

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

G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**

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

**Northwestern University, Evanston, USA**

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

**University of Notre Dame, Notre Dame, USA**

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko<sup>50</sup>, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

**The Ohio State University, Columbus, USA**

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

**Princeton University, Princeton, USA**

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

**University of Puerto Rico, Mayaguez, USA**

S. Malik, S. Norberg

**Purdue University, West Lafayette, USA**

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, G. Negro, N. Neumeister,

C.C. Peng, S. Piperov, A. Purohit, H. Qiu, J.F. Schulte, M. Stojanovic<sup>18</sup>, N. Trevisani, F. Wang, A. Wildridge, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, USA**

J. Dolen, N. Parashar

**Rice University, Houston, USA**

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts<sup>†</sup>, J. Rorie, W. Shi, A.G. Stahl Leiton

**University of Rochester, Rochester, USA**

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

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

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban<sup>26</sup>, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

**University of Tennessee, Knoxville, USA**

H. Acharya, A.G. Delannoy, S. Spanier

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

O. Bouhali<sup>96</sup>, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>97</sup>, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

**Texas Tech University, Lubbock, USA**

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

**Vanderbilt University, Nashville, USA**

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

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

P.E. Karchin, N. Poudyal, P. Thapa

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

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

†: Deceased

1: Also at TU Wien, Wien, Austria

2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

3: Also at Université Libre de Bruxelles, Bruxelles, Belgium

4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

5: Also at Universidade Estadual de Campinas, Campinas, Brazil

6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

- 7: Also at UFMS, Nova Andradina, Brazil
- 8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 9: Also at Nanjing Normal University Department of Physics, Nanjing, China
- 10: Now at The University of Iowa, Iowa City, USA
- 11: Also at University of Chinese Academy of Sciences, Beijing, China
- 12: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
- 13: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 14: Now at British University in Egypt, Cairo, Egypt
- 15: Now at Cairo University, Cairo, Egypt
- 16: Also at Zewail City of Science and Technology, Zewail, Egypt
- 17: Now at Fayoum University, El-Fayoum, Egypt
- 18: Also at Purdue University, West Lafayette, USA
- 19: Also at Université de Haute Alsace, Mulhouse, France
- 20: Also at Tbilisi State University, Tbilisi, Georgia
- 21: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- 22: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 23: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 24: Also at University of Hamburg, Hamburg, Germany
- 25: Also at Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
- 26: Also at Brandenburg University of Technology, Cottbus, Germany
- 27: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 28: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 29: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- 30: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- 31: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 32: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 33: Also at Wigner Research Centre for Physics, Budapest, Hungary
- 34: Also at IIT Bhubaneswar, Bhubaneswar, India
- 35: Also at Institute of Physics, Bhubaneswar, India
- 36: Also at G.H.G. Khalsa College, Punjab, India
- 37: Also at Shoolini University, Solan, India
- 38: Also at University of Hyderabad, Hyderabad, India
- 39: Also at University of Visva-Bharati, Santiniketan, India
- 40: Also at Indian Institute of Technology (IIT), Mumbai, India
- 41: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- 42: Also at Sharif University of Technology, Tehran, Iran
- 43: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- 44: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
- 45: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 46: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 47: Also at Università di Napoli 'Federico II', Napoli, Italy
- 48: Also at Riga Technical University, Riga, Latvia
- 49: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 50: Also at Institute for Nuclear Research, Moscow, Russia

- 
- 51: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 52: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
- 53: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 54: Also at University of Florida, Gainesville, USA
- 55: Also at Imperial College, London, United Kingdom
- 56: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 57: Also at California Institute of Technology, Pasadena, USA
- 58: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 59: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 60: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- 61: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- 62: Also at National and Kapodistrian University of Athens, Athens, Greece
- 63: Also at Universität Zürich, Zurich, Switzerland
- 64: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- 65: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- 66: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- 67: Also at Gaziosmanpasa University, Tokat, Turkey
- 68: Also at Şırnak University, Şırnak, Turkey
- 69: Also at Department of Physics, Tsinghua University, Beijing, China
- 70: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
- 71: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 72: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
- 73: Also at Mersin University, Mersin, Turkey
- 74: Also at Adiyaman University, Adiyaman, Turkey
- 75: Also at Tarsus University, MERSIN, Turkey
- 76: Also at Ozyegin University, Istanbul, Turkey
- 77: Also at Izmir Institute of Technology, Izmir, Turkey
- 78: Also at Necmettin Erbakan University, Konya, Turkey
- 79: Also at Bozok Universititesi Rektörlüğü, Yozgat, Turkey
- 80: Also at Marmara University, Istanbul, Turkey
- 81: Also at Milli Savunma University, Istanbul, Turkey
- 82: Also at Kafkas University, Kars, Turkey
- 83: Also at Istanbul Bilgi University, Istanbul, Turkey
- 84: Also at Hacettepe University, Ankara, Turkey
- 85: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 86: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 87: Also at IPPP Durham University, Durham, United Kingdom
- 88: Also at Monash University, Faculty of Science, Clayton, Australia
- 89: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 90: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 91: Also at Ain Shams University, Cairo, Egypt
- 92: Also at Bingol University, Bingol, Turkey
- 93: Also at Georgian Technical University, Tbilisi, Georgia

94: Also at Sinop University, Sinop, Turkey

95: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

96: Also at Texas A&M University at Qatar, Doha, Qatar

97: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea

## B The TOTEM Collaboration

G. Antchev<sup>a</sup>, P. Aspell<sup>9</sup>, I. Atanassov<sup>a</sup>, V. Avati<sup>7,9</sup>, J. Baechler<sup>9</sup>, C. Baldenegro Barrera<sup>11</sup>, V. Berardi<sup>4a,4b</sup>, M. Berretti<sup>2a</sup>, V. Borchsh<sup>8</sup>, E. Bossini<sup>6b,9</sup>, U. Bottigli<sup>6c</sup>, M. Bozzo<sup>5a,5b</sup>, H. Burkhardt<sup>9</sup>, F.S. Cafagna<sup>4a</sup>, M.G. Catanesi<sup>4a</sup>, M. Csanád<sup>3a,b</sup>, T. Csörgő<sup>3a,3b</sup>, M. Deile<sup>9</sup>, F. De Leonardis<sup>4a,4c</sup>, M. Doubek<sup>1c</sup>, D. Druzhkin<sup>8,9</sup>, K. Eggert<sup>10</sup>, V. Eremin<sup>d</sup>, A. Fiergolski<sup>9</sup>, L. Forthomme<sup>2a,2b</sup>, F. Garcia<sup>2a</sup>, V. Georgiev<sup>1a</sup>, S. Giani<sup>9</sup>, L. Grzanka<sup>7</sup>, J. Hammerbauer<sup>1a</sup>, T. Isidori<sup>11</sup>, V. Ivanchenko<sup>8</sup>, M. Janda<sup>1c</sup>, A. Karev<sup>9</sup>, J. Kašpar<sup>1b,9</sup>, B. Kaynak<sup>e</sup>, J. Kopal<sup>9</sup>, V. Kundrať<sup>1b</sup>, S. Lami<sup>6a</sup>, R. Linhart<sup>1a</sup>, C. Lindsey<sup>11</sup>, M.V. Lokajíček<sup>†,1b</sup>, L. Losurdo<sup>6c</sup>, F. Lucas Rodríguez<sup>9</sup>, M. Macrí<sup>5a</sup>, M. Malawski<sup>7</sup>, N. Minafra<sup>11</sup>, S. Minutoli<sup>5a</sup>, T. Naaranoja<sup>2a,2b</sup>, F. Nemes<sup>3a,9</sup>, H. Niewiadomski<sup>10</sup>, T. Novák<sup>3b</sup>, E. Oliveri<sup>9</sup>, F. Oljemark<sup>2a,2b</sup>, M. Oriunno<sup>f</sup>, K. Österberg<sup>2a,2b</sup>, P. Palazzi<sup>9</sup>, V. Passaro<sup>4a,4c</sup>, Z. Peroutka<sup>1a</sup>, J. Procházka<sup>1b</sup>, M. Quinto<sup>4a,4b</sup>, E. Radermacher<sup>9</sup>, E. Radicioni<sup>4a</sup>, F. Ravotti<sup>9</sup>, C. Royon<sup>11</sup>, G. Ruggiero<sup>9</sup>, H. Saarikko<sup>2a,2b</sup>, V.D. Samoylenko<sup>c</sup>, A. Scribano<sup>6a</sup>, J. Šíroký<sup>1a</sup>, J. Smajek<sup>9</sup>, W. Snoeys<sup>9</sup>, R. Stefanovitch<sup>9</sup>, J. Sziklai<sup>3a</sup>, C. Taylor<sup>10</sup>, E. Tcherniaev<sup>8</sup>, N. Turini<sup>6c</sup>, O. Urban<sup>1a</sup>, V. Vacek<sup>1c</sup>, O. Vavroch<sup>1a</sup>, J. Weltri<sup>2a,2b</sup>, J. Williams<sup>11</sup>, J. Zich<sup>1a</sup>, K. Zielinski<sup>7</sup>

†Deceased

<sup>1a</sup>University of West Bohemia, Pilsen, Czech Republic

<sup>1b</sup>Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic

<sup>1c</sup>Czech Technical University, Prague, Czech Republic

<sup>2a</sup>Helsinki Institute of Physics, University of Helsinki, Helsinki, Finland

<sup>2b</sup>Department of Physics, University of Helsinki, Helsinki, Finland

<sup>3a</sup>Wigner Research Centre for Physics, RMKI, Budapest, Hungary

<sup>3b</sup>Eszterhazy Karoly University KRC, Gyöngyös, Hungary

<sup>4a</sup>INFN Sezione di Bari, Bari, Italy

<sup>4b</sup>Dipartimento Interateneo di Fisica di Bari, University of Bari, Bari, Italy

<sup>4c</sup>Dipartimento di Ingegneria Elettrica e dell'Informazione — Politecnico di Bari, Bari, Italy

<sup>5a</sup>INFN Sezione di Genova, Genova, Italy

<sup>5b</sup>Università degli Studi di Genova, Genova, Italy

<sup>6a</sup>INFN Sezione di Pisa, Pisa, Italy

<sup>6b</sup>Università degli Studi di Pisa, Pisa, Italy

<sup>6c</sup>Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Siena, Italy

<sup>7</sup>Akademia Górniczo-Hutnicza (AGH) University of Science and Technology, Krakow, Poland

<sup>8</sup>Tomsk State University, Tomsk, Russia

<sup>9</sup>CERN, Geneva, Switzerland

<sup>10</sup>Case Western Reserve University, Department of Physics, Cleveland, Ohio, USA

<sup>11</sup>The University of Kansas, Lawrence, Kansas, USA



---

<sup>a</sup> INRNE-BAS, Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

<sup>b</sup> Department of Atomic Physics, Eötvös Loránd University, Budapest, Hungary

<sup>c</sup> NRC 'Kurchatov Institute'–IHEP, Protvino, Russia

<sup>d</sup> Ioffe Physical Technical Institute, Russian Academy of Sciences, St. Petersburg, Russian Federation

<sup>e</sup> Istanbul University, Istanbul, Turkey

<sup>f</sup> SLAC, Stanford University, California, USA