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

The CMS and TOTEM Collaborations*

Abstract

A search is presented for high-mass exclusive diphoton production via photon-photon fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV in events where both protons survive the interaction. The analysis utilizes data corresponding to an integrated luminosity of 103 fb^{-1} collected in 2016–2018 with the central CMS detector and the CMS and TOTEM precision proton spectrometer (PPS). Events that have two photons with high transverse momenta ($p_T^\gamma > 100$ GeV), back-to-back in azimuth, and with a large diphoton invariant mass ($m_{\gamma\gamma} > 350$ GeV) are selected. To remove the dominant inclusive diphoton backgrounds, the kinematic properties of the protons detected in PPS are required to match those of the central diphoton system. Only events having opposite-side forward protons detected with a fractional momentum loss between 0.035 and 0.15 (0.18) for the detectors on the negative (positive) side of CMS are considered. One exclusive diphoton candidate is observed for an expected background of 1.1 events. Limits at 95% confidence level are derived for the four-photon anomalous coupling parameters $|\zeta_1| < 0.073 \text{ TeV}^{-4}$ and $|\zeta_2| < 0.15 \text{ TeV}^{-4}$, using an effective field theory. Additionally, upper limits are placed on the production of axion-like particles with coupling strength to photons f^{-1} that varies from 0.03 TeV^{-1} to 1 TeV^{-1} over the mass range from 500 to 2000 GeV.

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1 Introduction

While the standard model (SM) of particle physics has been largely successful in describing the known elementary particles and interactions, there are still many observed phenomena that suggest it is incomplete. These include the unknown nature of dark matter, the origin of matter-antimatter asymmetry, the generation of neutrino masses, and the absence of charge-parity (CP) symmetry violation in the theory of the strong interaction. Studying photon-photon interactions in proton-proton (pp) collisions at the Large Hadron Collider (LHC) probes theories that go beyond the standard model (BSM) and that feature anomalous quartic gauge couplings (aQGC) at energies so-far unexplored. At the LHC, when the protons interact purely electromagnetically the final state can be particularly simple with a C-even, neutral system produced exclusively in the central detector and the two protons remaining intact (Fig. 1). A process of interest is that of the exclusive production of two photons in photon fusion, usually called light-by-light (LbL) scattering [1], which allows the probing of multiple BSM phenomena including the production of axion-like particles (ALPs) [2, 3], monopoles [4], and massive gravitons [5–7], as well as searches for Born–Infeld nonlinear extensions of quantum electrodynamics [8], extra spatial dimensions [9], etc.

Both the CMS and ATLAS collaborations have presented evidence or observation of the SM LbL process in electromagnetic ultraperipheral collisions (UPCs) of heavy ions [10, 11]. However, UPCs with ions cannot reach two-photon invariant masses ($m_{\gamma\gamma}$) much above 100 GeV [12, 13], where larger contributions to the four-photon (4γ) interaction from BSM physics can be expected. Proton-proton collisions, on the other hand, feature larger beam energies and luminosities, and harder photon spectra than heavy ion UPCs. By tagging the surviving final state protons, one can better identify the process and study 4γ anomalous couplings at the multi-TeV scale [14]. Different particles can contribute to the four-photon interaction shown in Fig. 1. This can include loops of SM or of new charged fermions or bosons. In other BSM scenarios, a C-even scalar, pseudoscalar, or tensor neutral resonance can be produced that decays back to two photons.

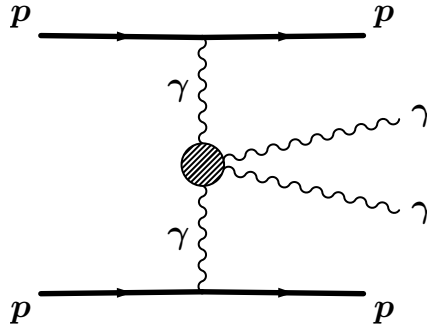


Figure 1: Diagram of diphoton production via photon fusion with intact protons in the final state. The four-photon vertex includes virtual contributions from SM or BSM charged fermions or bosons. In other BSM scenarios, a new heavy particle can be produced in the s -channel, such as an axion-like particle that decays into two photons.

As shown in Ref. [14], with the assumption of a new mass scale heavier than the current experimentally reachable energy, the anomalous 4γ interactions can be described by an effective Lagrangian density using dimension-8 operators,

$$\mathcal{L}_{4\gamma} = \zeta_1 F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2 F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu}, \quad (1)$$

where F is the electromagnetic field tensor. These ζ_1 and ζ_2 parameters are identically zero in

the SM, but this would not be so if BSM particles contribute to the 4γ process. In this latter case, from Eq. (1), the differential cross section for the anomalous four-photon production can be written as

$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2 s} (s^2 + t^2 + st)^2 [48\zeta_1^2 + 40\zeta_1\zeta_2 + 11\zeta_2^2],$$

where s and t are the Mandelstam variables.

The s -channel production of a pseudoscalar particle, such as an ALP, can also give rise to an increased production rate of the LbL process with respect to the SM expectations [3]. The production of ALPs is often characterized by two parameters: the ALP mass and its photon coupling, $f^{-1} \equiv C_{\gamma\gamma}/\Lambda$ [15], where $C_{\gamma\gamma} = 0-1$ is a dimensionless coefficient, and Λ is a high-energy scale associated with the spontaneous breaking of an approximate Peccei–Quinn global U(1) symmetry [16]. Our analysis considers ALPs that couple only to photons in a photophilic scenario with $C_{\gamma\gamma} = 1$, as often considered in the literature [17].

The strategy of this study is to search for central diphoton events exhibiting kinematic properties consistent with their exclusive production through photon fusion, in coincidence with two opposite-side protons having a momentum loss compatible with the rapidity of the diphoton system. Compared to the previous exclusive diphoton result reported by the CMS and TOTEM Collaborations [18], the integrated luminosity has been increased by more than a factor of ten, and a set of new techniques are used to improve the sensitivity to the 4γ process. The new techniques include a more efficient photon identification algorithm, improved forward proton reconstruction, and a more robust background estimation. Tabulated results are provided in the HEPData record for this analysis [19].

2 The CMS detector and event selection and reconstruction

This analysis relies equally on the central CMS and Precision Proton Spectrometer (PPS) detectors shown in Fig. 2. Both of these are described below along with the event reconstruction algorithms.

2.1 The central CMS detector

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

The electromagnetic calorimeter consists of 75 848 lead tungstate crystals, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.0$ in two endcap regions (EE). Preshower detectors consisting of two planes of silicon sensors interleaved with a total of three radiation lengths of lead are located in front of each EE detector.

In the EB, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$. In the endcaps, the resolution of unconverted or late-converting photons is about 2.5%, while the remaining endcap photons have a resolution between 3 and 4% [20].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in [21].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about $4 \mu\text{s}$ [22]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [23].

The global event reconstruction (also called particle-flow (PF) event reconstruction [24]) aims to reconstruct and identify each individual particle in an event, with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged or neutral hadron) plays an important role in the determination of the particle direction and energy. Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged particle trajectory to the ECAL. Electrons are identified by a primary charged particle track and potentially many ECAL energy clusters corresponding to the extrapolation of this track to the ECAL as well as possible bremsstrahlung photons emitted along the way through the tracker material. Muons (e.g., from semileptonic decays of heavy-quark hadrons) are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Charged hadrons are identified as charged particle tracks that are not identified as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged hadron energy deposit.

The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons associated with the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared- and collinear-safe anti- k_T algorithm [25, 26] with a distance parameter of 0.4. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions.

2.2 The Precision Proton Spectrometer

The PPS detectors were developed by a collaboration between the CMS and TOTEM experiments (previously named CT-PPS) [27]. These detectors extend the CMS physics program to study central-exclusive production processes [28] under high-luminosity conditions at the LHC, in the context of both SM and BSM physics studies. The PPS detectors are located approximately 210 and 220 m away from the LHC interaction point 5 (IP5) on both sides of CMS, as shown in Fig. 2 for one side.

After a pp collision at IP5, if a proton remains intact in the final state, it may continue to travel

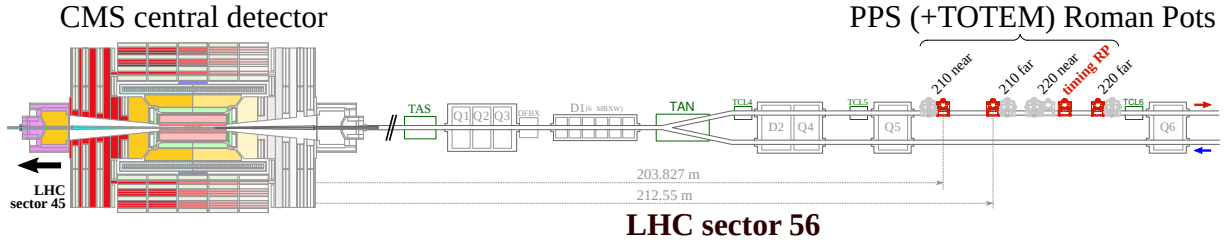


Figure 2: A schematic view of one side of the PPS detector with respect to the central CMS detector. The stations labeled as (or located at) 210 and 220 m house the Roman Pot detectors. Timing detector stations are also shown, although they are not used in this analysis. A symmetric set of detectors exists on the opposite side of CMS as well.

down the LHC beam line, guided by the LHC magnets, until it interacts with the PPS detectors in the forward regions. The horizontal distance of the proton from the center of the beam is proportional to the momentum loss of the proton, and in this way the LHC magnetic lattice acts as a mass spectrometer for measuring protons. The main observable used in the analysis is the fractional momentum loss of the proton, denoted as ζ . When measuring each of the final-state protons from an exclusive event, their ζ_p value can be used to derive the mass and rapidity of the centrally produced system at the pp center-of-mass energy \sqrt{s} , as follows:

$$m_{pp} = \sqrt{s \zeta_p^+ \zeta_p^-}, \quad y_{pp} = \frac{1}{2} \log \left(\frac{\zeta_p^+}{\zeta_p^-} \right). \quad (2)$$

The positive and negative indices of ζ_p refer to protons moving in the positive and negative z directions, respectively. The PPS detectors located in the positive- z direction from CMS are referred to as sector-45 (for the region between IP4 and IP5), and the PPS detectors located in the negative- z direction from CMS are referred to as sector-56 (for the region between IP5 and IP6) as shown in Fig. 2. At each of the 210 and 220 m stations, movable, near-beam insertions called Roman Pots (RPs) provide the housing for the proton tracking detectors. The PPS tracking detector configuration was different for each of the three data-taking years: in 2016 with silicon microstrip detectors in both tracking Roman pots in the same arm, in 2017 with silicon microstrip detectors in the one and silicon pixel detectors in the other Roman pot in the same arm, and finally in 2018 with silicon pixel detectors in both. The protons are reconstructed using a “multi-RP” algorithm, which combines tracks reconstructed in both of the tracking Roman pots in each arm of PPS. A detailed description of the PPS detector system, alignment, optics, and simulation can be found in [29].

During 2016–2018, PPS collected proton-proton collision data corresponding to an integrated luminosity of 107.7 fb^{-1} . Using data from 2016, corresponding to an integrated luminosity of 9.4 fb^{-1} , the first validation of the PPS system resulted in the observation of the SM exclusive production of a pair of charged leptons, $\gamma\gamma \rightarrow \ell^+\ell^-$ [30]. Signal events were selected by requiring a match between the dilepton and forward protons kinematic properties. This study revealed a signal yield corresponding to a significance greater than 5.1 standard deviations above the background-only expectation, and constituted the first observation of this process at masses around and above the electroweak scale.

3 Data sets and simulated samples

This analysis uses data sets of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ collected by the CMS and TOTEM experiments in 2016, 2017, 2018, corresponding to integrated luminosities of 9.8 [31], 37.2 [32],

and 55.7 [33] fb^{-1} , respectively. The data sets comprise the LHC running periods where all central CMS and PPS detectors were operating simultaneously and included in the data acquisition.

Simulated Monte Carlo (MC) samples are used to model the signal and SM backgrounds. The dominant background is due to inclusive $\gamma\gamma + \text{jet(s)}$ production, where “jet(s)” is loosely used to indicate any additional energy in the event. Subleading backgrounds include $t\bar{t} + \text{jet(s)}$ and $V + \gamma$ processes, where V represents a weak boson. The decay channels considered in the latter samples are $Z \rightarrow \ell^+\ell^-$ and $W^\pm \rightarrow \ell^\pm\nu_\ell$. Background samples are modeled with the MADGRAPH5_AMC@NLO [34] package, with the 2016 samples generated using the NNPDF3.0 parton distribution functions (PDFs) at next-to-leading order (NLO) accuracy, and the other samples with NNPDF3.1 PDFs at next-to-NLO accuracy. To estimate additional backgrounds from quantum chromodynamics (QCD) jet production, an electron- and photon-enriched QCD sample generated with PYTHIA 8.2 [35] and the CP5 underlying event tune [36] is utilized.

The LbL signal samples are generated using the Forward Physics Monte Carlo (FPMC) code [37] assuming collinear photon emission from both incoming protons. The photon fluxes from each proton are modelled using the Budnev *et al.* parameterization [38]. For the simulated conditions of each data-taking year, various $\gamma\gamma \rightarrow \gamma\gamma$ aQGC signal samples are generated for representative ζ_1 and ζ_2 values. Kinematic distributions of the simulated aQGC events are shown in Fig. 3. Additionally, samples modeling ALP production via s -channel exchange, $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$, are produced for twelve different ALP masses in the range of 500–2000 GeV where the analysis reaches the best sensitivity. These simulated data samples are used to derive the corresponding reconstruction efficiencies. Kinematic distributions for various ALP mass samples are shown in Fig. 4. The shape of these distributions are independent of the coupling strength, f^{-1} [3]. It should be noted that the LbL, aQGC, and ALP processes at any given photon-photon mass value all have similar kinematic properties, and are studied using the same event selection criteria.

The parton showering, hadronization, and particle decays in the simulated background samples are carried out with PYTHIA 8.230 for the 2016 and 2018 samples, and 8.226 for the 2017 samples. All generated samples are subsequently passed through the GEANT4 simulated response of the CMS detector [39]. In all cases, the pileup distribution in the simulated events is weighted to match that observed in data.

4 Photon identification and isolation

A multivariate analysis (MVA) utilizing a boosted decision tree (BDT) is used for identification (ID) and isolation of photons. This technique allows for the definition of a single discriminating variable, based on many parameters for each photon candidate, that helps separate prompt isolated photons from backgrounds. The inputs to the BDT are shower shape and isolation variables, as well as quantities used to minimize the pileup present in the event [20], described next. The $\sigma_{i\eta i\eta}$ variable is the second-order spatial moment of the photon candidate with respect to η [40]. The R_9 and $R_9(5 \times 5)$ variables are calculated as the sum of the energy contained in the 3×3 matrix centered on the most energetic crystal of the supercluster (cluster of clusters) divided, respectively, by the supercluster energy or by the energy contained in a 5×5 matrix. The $q_{\eta\phi}$ variable represents the elements of the covariance matrix of the single-crystal energy values in η and ϕ for the 5×5 array of crystals centered on the highest energy crystal. The S_4 variable is the energy contained in the most energetic 2×2 array of crystals (containing the seed crystal) divided by the energy of the supercluster. The BDT also considers the η and ϕ width of the electromagnetic shower, and the H/E ratio, defined as the ratio between the

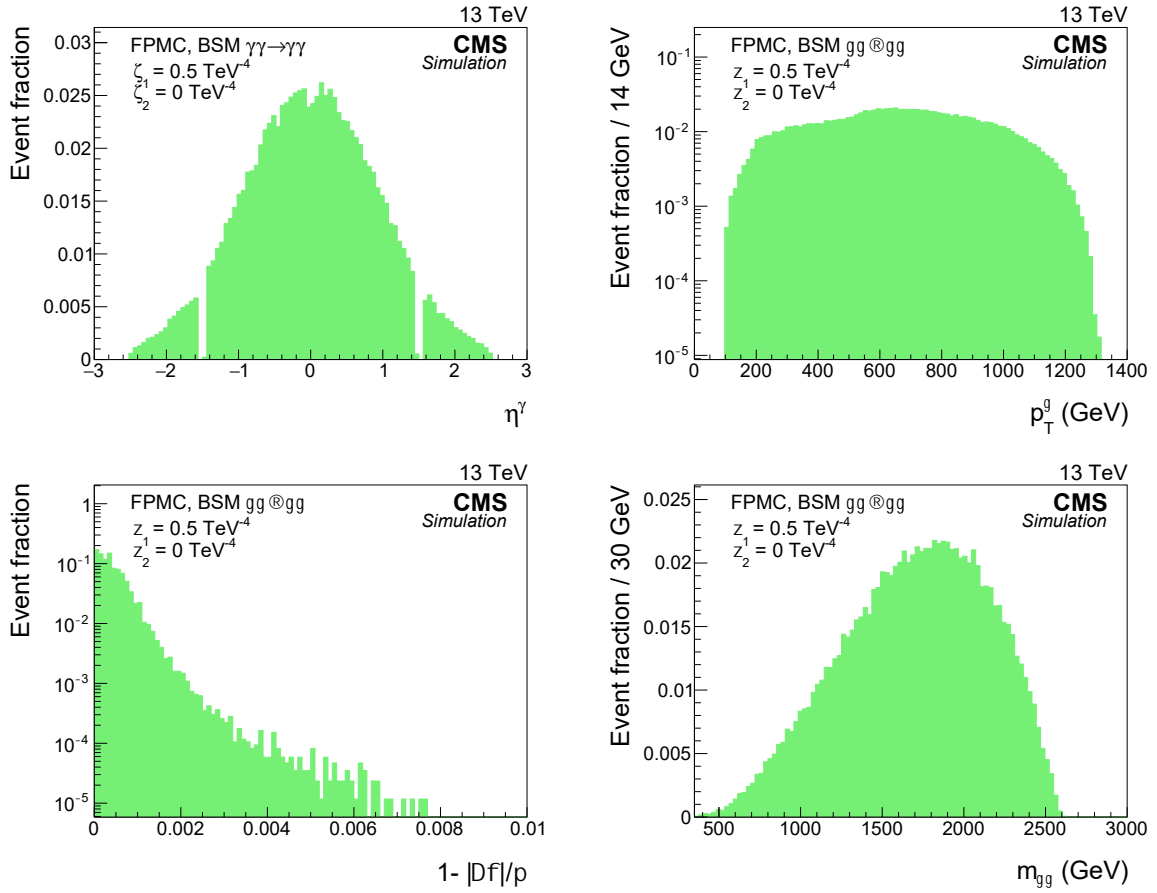


Figure 3: Kinematic distributions of simulated aQGC $\gamma\gamma \rightarrow \gamma\gamma$ events: Single-photon η (upper left) and p_T (upper right), and diphoton acoplanarity (lower left) and mass (lower right). The events are generated with FPMC, reconstructed accounting for the full CMS detector response, for aQGC parameters $\zeta_1 = 0.5 \text{ TeV}^{-4}$ and $\zeta_2 = 0 \text{ TeV}^{-4}$. A preselection is applied to these events as described in Section 5.

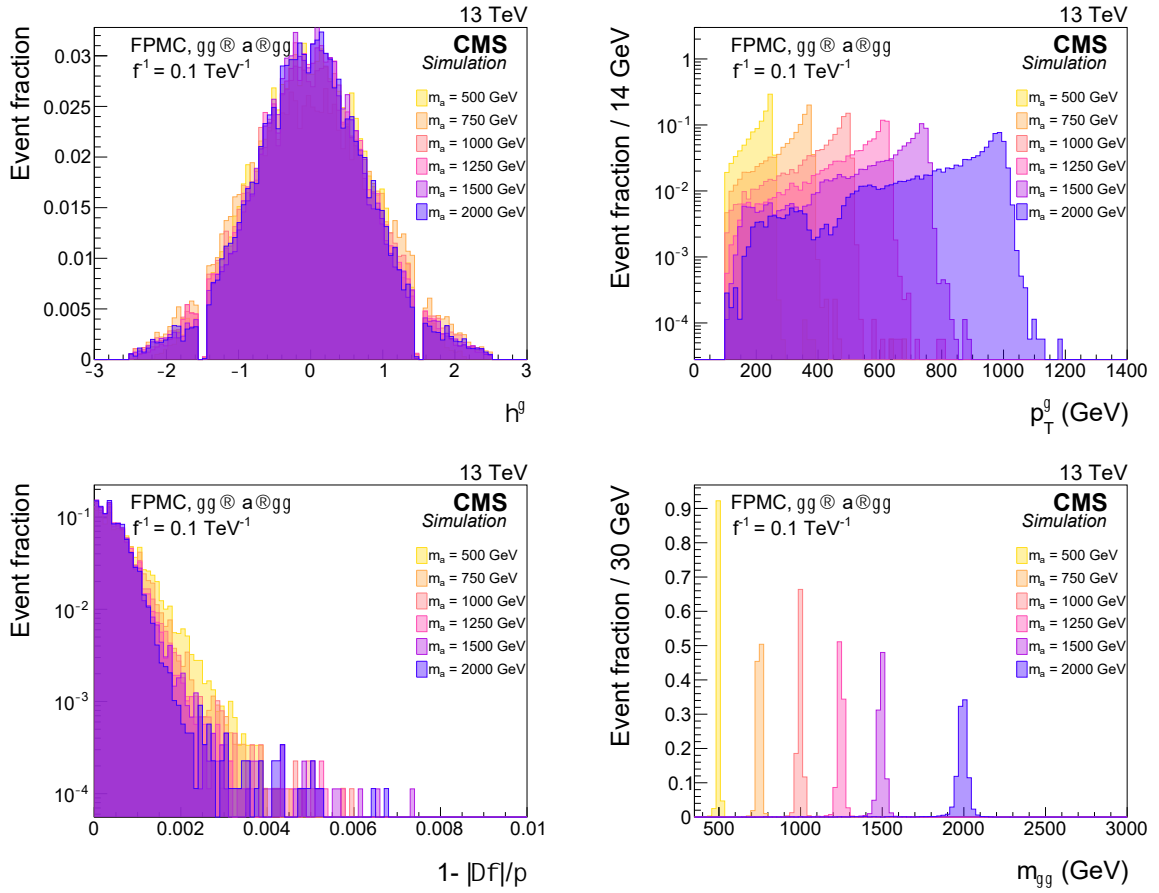


Figure 4: Kinematic distributions of simulated ALP $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ events: Single-photon η (upper left) and p_T (upper right), and diphoton acoplanarity (lower left) and mass (lower right). The events are generated with FPMC, reconstructed accounting for the full CMS detector response, for a value $f^{-1} = 0.1 \text{ TeV}^{-1}$ of the ALP-photon coupling. A preselection is applied to these events as described in Section 5.

energy deposits in the hadronic and electromagnetic calorimeters. The photon isolation variables that are considered, based on the PF algorithm, are I_γ , I_{ch} , and I_n . These are obtained by summing the transverse momenta of the photons, charged hadrons, and neutral hadrons, respectively, inside an isolation region of radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ around the photon candidate [40]. Other variables used as inputs are the raw supercluster energy and supercluster η of the photon candidate as well as the average energy density of the event. Specifically for photon candidates in the endcap, the preshower energy spread in the η direction and the preshower energy divided by the supercluster energy are provided to the decision tree.

The BDT is trained on simulated $\gamma + \text{jet(s)}$ events where the photon candidates have passed the set of preselection criteria listed in Table 1. Photons can belong to four different categories based on their barrel or endcap location and R_9 value, and each category has its own preselection criteria based on H/E , $\sigma_{i\eta i\eta}$, $R_9(5\times 5)$, I_γ , and I_{trk} . The latter variable is a tracker hollow-cone isolation defined as the sum of the transverse momenta of all tracks inside a cone around the photon candidate. A working point is defined where the BDT output gives a signal efficiency of around 90% for identifying photons.

Table 1: Selection criteria applied to simulated $\gamma + \text{jet(s)}$ samples to train the BDT for signal photon identification.

Region	R_9	H/E	$\sigma_{i\eta i\eta}$	$R_9(5\times 5)$	$I_\gamma(\text{GeV})$	$I_{\text{trk}}(\text{GeV})$
EB	>0.85	<0.08	—	>0.5	—	—
EB	≤ 0.85	<0.08	<0.015	>0.5	<4.0	<6.0
EE	>0.9	<0.08	—	>0.8	—	—
EE	≤ 0.9	<0.08	<0.035	>0.8	<4.0	<6.0

The MVA ID applies identification and isolation requirements on the reconstructed particle in the ECAL, but does not distinguish between photons and electrons. For this reason, an additional veto is employed to filter out electrons from the photon candidates [20]. For the signal samples described in Section 3, the MVA ID is found to be 84.8% efficient, and the electron veto is found to be 96.2% efficient for the combination of both signal photons passing the ID.

5 Event selection

For the 2016 data the HLT trigger required a photon candidate with a transverse momentum greater than 60 GeV, and an H/E ratio below 0.15. For 2017 and 2018 data, the transverse momentum requirement was raised to 70 GeV. The efficiency of each of these triggers has been studied as a function of p_T , and selections safely above the trigger threshold (trigger-safe p_T selections) are applied to the data. For the 2016 data, the trigger-safe p_T selection is placed at 75 GeV and, for the 2017 and 2018 data, the p_T selection is placed at 100 GeV. Additionally, a trigger-safe H/E selection requirement of $H/E < 0.10$ is applied.

In addition to the HLT selection, the preselection introduces special criteria to ensure the quality of the diphoton events. To ensure that the electromagnetic objects selected by the trigger are photons, we use the MVA photon ID and electron veto described in Section 4. Furthermore, the single-photon pseudorapidity is constrained to be within the region $|\eta^\gamma| < 2.5$, with an additional veto between $1.444 < |\eta^\gamma| < 1.566$ to avoid the EE-EB transition region. Finally, the mass of the diphoton pair must be greater than 350 GeV, a region where the cross section for the SM LbL process is negligible, as motivated in [14].

In order to reconstruct the exclusive $\gamma\gamma \rightarrow \gamma\gamma$ process, photons are selected that are back-to-

back in azimuthal angle ϕ [1], by using the acoplanarity variable defined as

$$A_\phi \equiv 1 - |\Delta\phi^{\gamma\gamma}/\pi|, \text{ where } \Delta\phi^{\gamma\gamma} = \phi^{\gamma 2} - \phi^{\gamma 1}. \quad (3)$$

Requiring $A_\phi < 0.0025$ results in a significant rejection of inclusive diphoton backgrounds.

The final step in the event selection is based on the $\xi_{\gamma\gamma}^+$ and $\xi_{\gamma\gamma}^-$ variables of the diphoton system measured in the central CMS detectors, and defined as

$$\xi_{\gamma\gamma}^\pm = \frac{1}{\sqrt{s}} \sum_{i=1}^2 p_T^{\gamma i} e^{\pm\eta_{\gamma i}}. \quad (4)$$

In the case of a truly exclusive photon-fusion event, the ξ values of the two intact protons must be compatible with those derived from the central photons as given by Eq. (4). Therefore, if events are required to have forward protons within the acceptance of PPS, the diphoton $\xi_{\gamma\gamma}$ values must also be within the PPS ξ range, namely they both are required to satisfy $0.02 < \xi_{\gamma\gamma}^\pm < 0.20$.

Additionally, for the pair of protons detected in the PPS, it was found that placing a lower requirement on the proton ξ values of 0.035 decreases the background (as discussed in Section 6.1) without significantly affecting the signal efficiency. An asymmetric selection is also placed on the upper end of the proton ξ spectrum to take into account the PPS acceptance. These asymmetric upper ξ selection criteria are placed at 0.15 for sector-45 and 0.18 for sector-56. The final selection criteria are listed in Table 2.

Table 2: Summary of the criteria applied to select exclusive diphoton events.

Selection type	Criteria
Preselection	Diphoton HLT $p_T^\gamma > 75$ (100) GeV for 2016 (2017–2018) $H/E < 0.10$ Photon ID with electron veto $ \eta^\gamma < 2.5$ (except $1.444 < \eta^\gamma < 1.566$, EB-EE transition veto) $m_{\gamma\gamma} > 350$ GeV
Acoplanarity	$A_\phi < 0.0025$
Diphoton $\xi_{\gamma\gamma}$	$0.02 < \xi_{\gamma\gamma}^\pm < 0.20$
Diproton ξ_p acceptance	$0.035 < \xi_p < 0.150$ (0.180) for sector-45 (sector-56)

Table 3 lists the number of simulated events for each background source that pass all selection criteria. The data to MC simulation agreement is shown for the sequential preselection, acoplanarity selection, and diphoton ξ selection in Fig. 5. Good agreement is observed, especially for the number of events after all selection criteria. The kinematic distributions of events passing all selections are shown in Fig. 6.

6 Results

After all selection criteria (Table 2) are applied, a comparison between the forward diproton and central diphoton kinematic properties is performed. To reiterate, the analysis strategy is based on a search for an excess above the background expectations for events where the mass

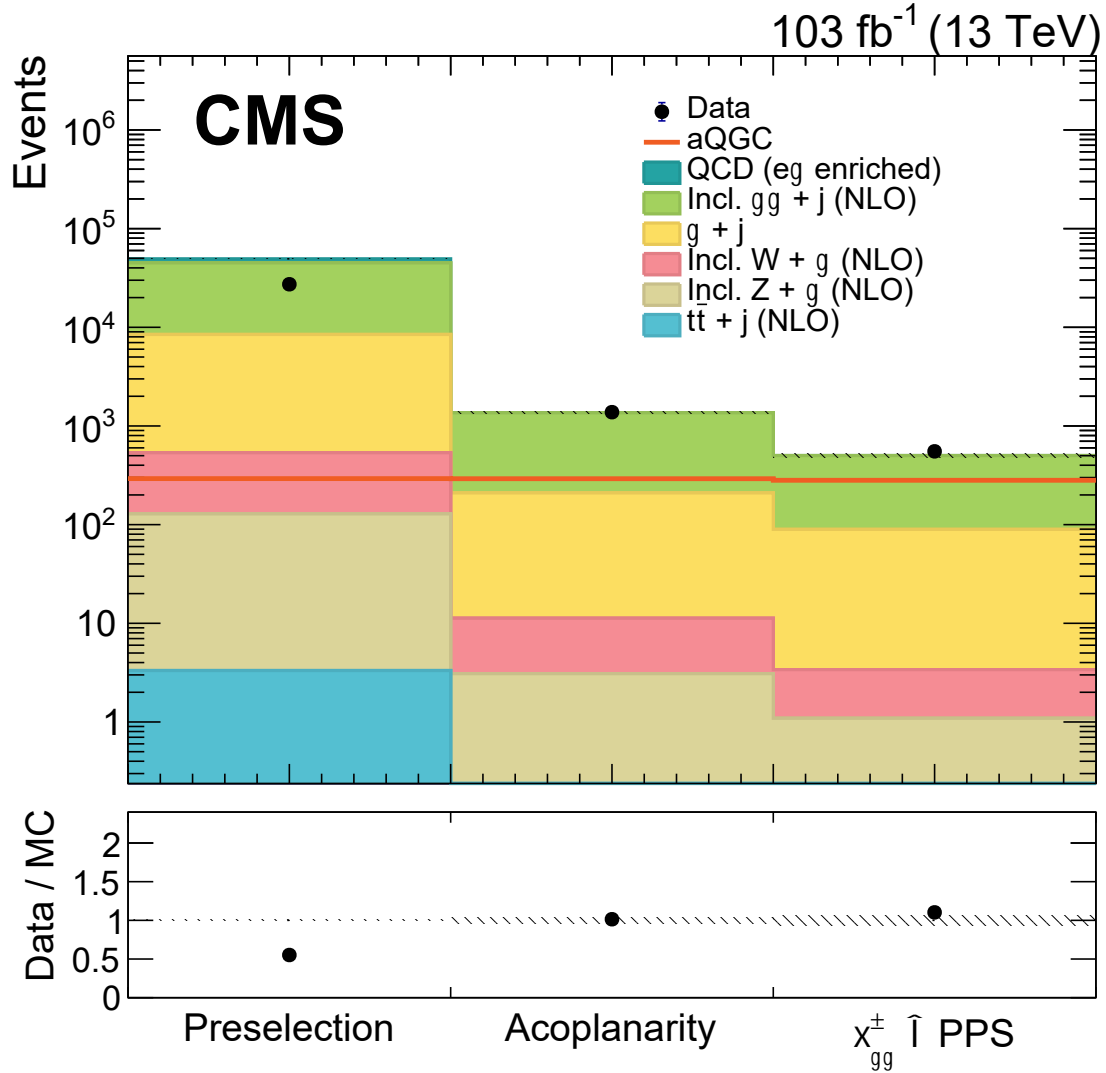


Figure 5: Number of events in data (black symbols) and simulated backgrounds (histograms) after each of the three consecutive selection criteria applied (upper plot), and ratio of data to sum of all backgrounds (lower plot). The first bin corresponds to the preselection region, the second bin to the acoplanarity criterion, and the third bin to the diphoton ζ selection defined in the text. The lined red histogram represents an aQGC signal with $\zeta_1 = 0.5 \text{ TeV}^{-4}$ and $\zeta_2 = 0.1 \text{ TeV}^{-4}$ for reference. Hatched bands indicate systematic uncertainties (statistical uncertainties are smaller than the symbols size).

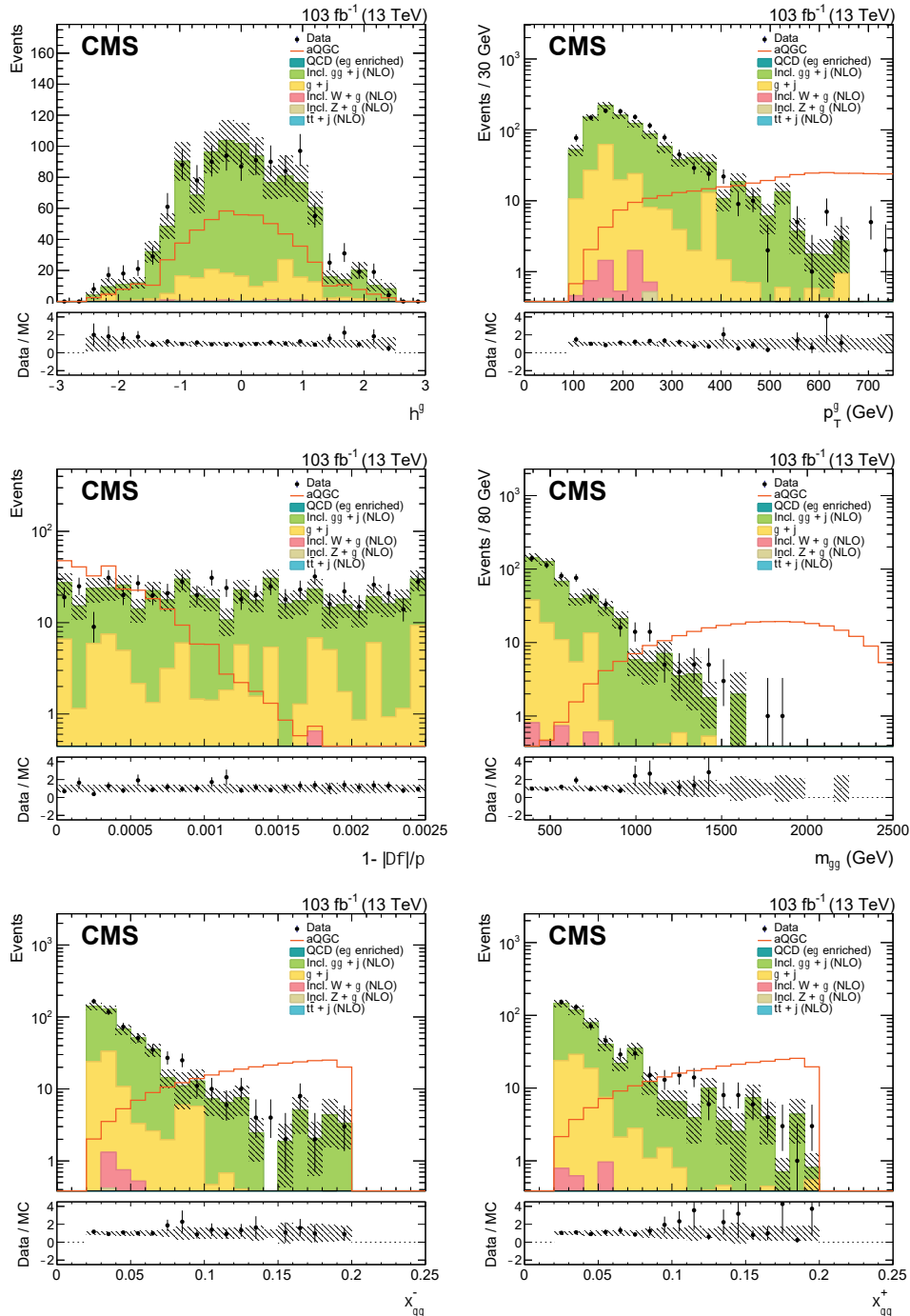


Figure 6: Kinematic distributions for events passing all selection criteria. From upper to lower and left to right are the single-photon η , and p_T , diphoton acoplanarity, mass, $\zeta_{\gamma\gamma}^-$, and $\zeta_{\gamma\gamma}^+$ distributions. The black dots represent the data, filled histograms represent the simulated SM backgrounds, and the lined red histogram represents an aQGC signal with $\zeta_1 = 50 \text{ TeV}^{-4}$ and $\zeta_2 = 100 \text{ TeV}^{-4}$ for reference. The lower panels in each plot show the ratio of the number of data events to the total SM background expectation. The dashed box indicates the systematic uncertainties.

Table 3: Summary of the predicted number of events for each SM background contributing to the $\zeta \in$ PPS selection region, their sum, and the observed number of events. The uncertainties quoted are statistical only.

Sample	Events
Inclusive $\gamma\gamma + \text{jet(s)}$	580 ± 41
Inclusive $\gamma + \text{jet(s)}$	110 ± 22
Inclusive $W\gamma$	4 ± 2
Inclusive $Z\gamma$	2 ± 1
Inclusive $t\bar{t} + \text{jet(s)}$	negligible
QCD jets	negligible
Total predicted	696 ± 47
Observed	735 ± 27
Data/MC	1.06 ± 0.08

and rapidity of the diphoton and diproton systems match. This is done by comparing the values calculated in Eqs. (2) and (4) taking into account their associated uncertainties given by

$$\frac{\delta m_{\text{pp}}}{m_{\text{pp}}} = \delta y_{\text{pp}} = \frac{1}{2} \left(\frac{\delta \zeta_{\text{p}}^+}{\zeta_{\text{p}}^+} \oplus \frac{\delta \zeta_{\text{p}}^-}{\zeta_{\text{p}}^-} \right) \quad (5)$$

where δm_{pp} , δy_{pp} , and $\delta \zeta_{\text{p}}^{\pm}$ represent the uncertainties on the diproton mass and rapidity, and the uncertainty on the positive and negative proton ζ , respectively.

An event is considered matched if the mass and rapidity of the forward and central systems are within two standard deviations of equivalence. The criteria for this matching are:

$$\begin{aligned} -2 < (m_{\text{pp}} - m_{\gamma\gamma}) / \delta (m_{\text{pp}} - m_{\gamma\gamma}) < 2 \\ -2 < (y_{\text{pp}} - y_{\gamma\gamma}) / \delta (y_{\text{pp}} - y_{\gamma\gamma}) < 2 \end{aligned}$$

where $\delta (m_{\text{pp}} - m_{\gamma\gamma})$ and $\delta (y_{\text{pp}} - y_{\gamma\gamma})$ are the uncertainties in the differences between the diphoton and diproton mass and rapidity, respectively. The uncertainties are clearly dominated by the diproton system, and derived event-by-event.

Figure 7 shows events from data as a function of how closely they match (in terms of standard deviations) in mass and rapidity. One event is observed within the matching window.

6.1 Background estimation

The signal region after forward-central matching is expected to have contamination from pileup events. The overlap of events with pileup protons detected in PPS and events with inclusively produced diphotons in the central CMS detectors can lead to accidental forward-central matchings. Such events are the only significant source of background for this analysis.

To quantify how these events contaminate the signal region, we use a fully data-driven approach to generate background-like pseudoevents. As inputs for the creation of the pseudoevents, diphoton events in the signal region are used as well as protons (detected in PPS) from all CMS events passing the diphoton trigger. Each pseudoevent is created by combining a diphoton pair with a diproton pair randomly added from the same run and LHC crossing-angle. We then check for the forward-central matching in mass and rapidity. This procedure is done for all diphoton events in the signal region to create one pseudoexperiment. Since the

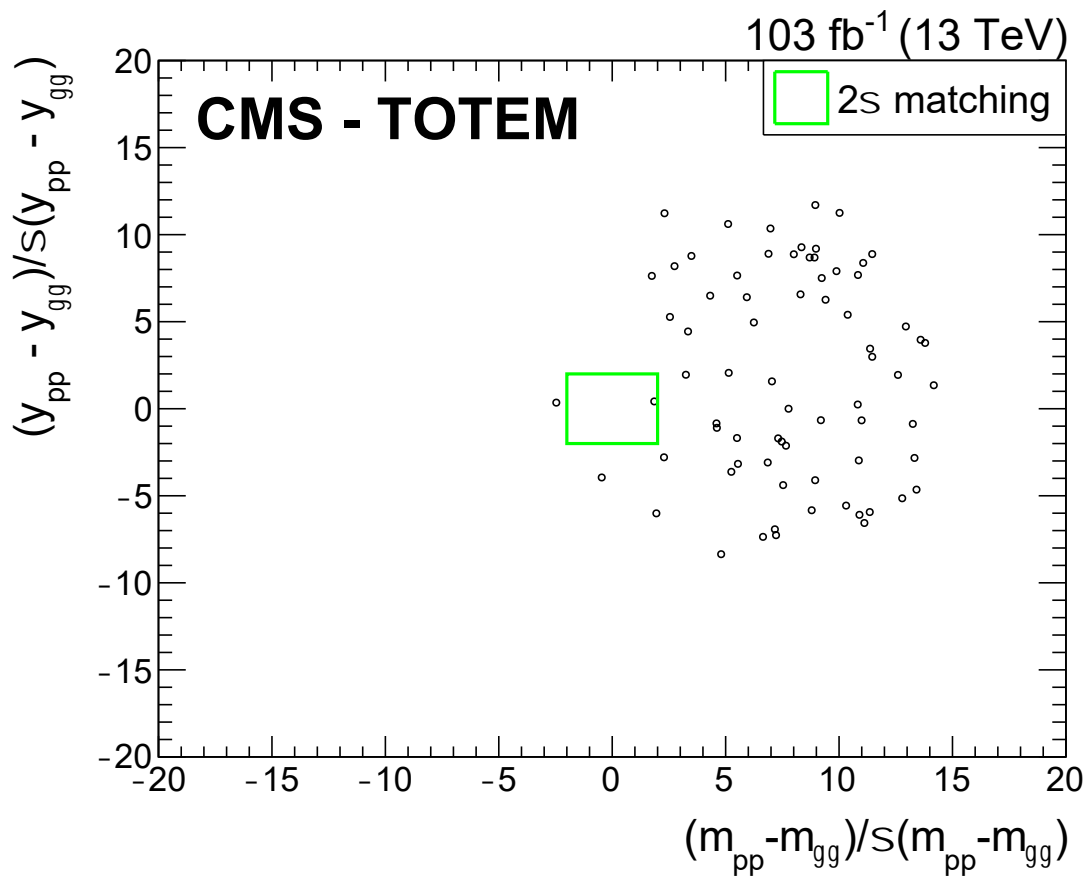


Figure 7: Mass versus rapidity matching distributions for events passing the diphoton and diproton selection criteria described in the text. The matching window is shown by a green rectangle corresponding to two standard deviations.

protons are randomly mixed with the diphotons, any matching that occurs is truly accidental and not due to a true correlation between the forward and central systems. As expected, the number of matching events for the pseudoexperiments follows a Poisson distribution. The background estimation is validated by using simulated diphoton events from the signal selection as an input to the pseudoexperiment. A second validation method uses diphoton events from an orthogonal selection (reversing the acoplanarity selection) as an input to the pseudoexperiments. Both validation methods give similar numbers of average matching events and are also used to extract the systematic uncertainty in the background estimation procedure.

The number of expected matching background events is 0.03, 0.16, and 0.91 for the 2016, 2017, and 2018 data taking, respectively. The total number of expected background events is 1.10 ± 0.00 (statistical uncertainty). The differences in the background estimations between the years are driven by their different luminosities, detector configurations, and efficiencies.

6.2 Systematic uncertainties

The integrated luminosities of the 2016, 2017, and 2018 data-taking periods are individually known with uncertainties in the 1.2–2.5% range [31–33], while the total integrated luminosity has an uncertainty of 1.9%, with an improvement in precision reflecting the (uncorrelated) time evolution of some systematic effects. A 23.3, 25.2, and a 20.9% systematic uncertainty in the background estimation procedure is assigned for 2016, 2017, and 2018, respectively, calculated as the largest relative difference in the number of estimated events between the default method and the two validation methods for the pseudoexperiments. For the signal efficiency in 2016, 2017, and 2018, uncertainties of 3.1, 7.0, and 2.9% are assigned, respectively, as derived from the photon ID and assuming that the ID efficiencies are uncorrelated. A 10% uncertainty is assigned to the theoretical proton survival probability, i.e., the probability that the interacting protons do not break up due to soft exchanges between their spectator partons, as estimated in [41] and considered in [42]. A 1.7% uncertainty is assumed for the particle shower reconstruction efficiency in the PPS detectors in 2018 [29]. The systematic uncertainties of the proton reconstruction are assigned on an event-by-event basis. All systematic uncertainties are applied to the signal, except the uncertainty from the background estimation procedure. All systematic uncertainties are applied to the background except the uncertainty from the proton survival probability. The systematic uncertainties described above are summarized in Table 4. Systematic uncertainties are treated as uncorrelated across the years.

Table 4: Systematic uncertainties corresponding to each year of data taking used in the analysis.

Source	2016	2017	2018
Integrated luminosity	1.2%	2.3%	2.5%
Background estimation	23.3%	25.2%	20.9%
Photon ID scale factors	3.1%	7.0%	2.9%
Proton survival probability	10%	10%	10%
Particle shower reconstruction in PPS	—	—	1.7%

6.3 Limit on anomalous quartic gauge couplings

With one event observed and 1.10 ± 0.24 (stat + syst) events expected, no excess is observed above the SM prediction. Limits are thereby placed on the anomalous coupling parameters, ζ_1 and ζ_2 .

The modified frequentist criterion CL_s [43, 44] with the profile likelihood ratio test statistic modified for upper limits [45] and determined by pseudoexperiments is used to evaluate the

observed and expected limits at 95% confidence level (CL) on the production cross section of aQGC LbL scattering within the fiducial region of the analysis defined as $p_T^\gamma > 100 \text{ GeV}$, $|\eta^\gamma| < 2.5$, $m_{\gamma\gamma} > 350 \text{ GeV}$, and fractional proton energy loss of $0.035 < \xi < 0.150$ (0.180) for the positive- z (negative- z) arm of PPS. The signal efficiency is evaluated over a wide range of the coupling parameters ζ_1 and ζ_2 using FPMC [37] and found approximately constant for each year in the search region.

The product of the efficiency (ϵ) and the acceptance (A) for the aQGC signal is used as an input to the limit setting tool. The ϵA distributions for the PPS detectors to reconstruct diffractively scattered protons as a function of the proton ξ areas shown in Fig. 8 for each running year. The ϵA values are calculated as the ratio of the number of reconstructed protons over that of generated protons using a simulation of the forward proton detectors. This simulation accounts for the LHC beam parameters, detector configuration, and detector technology used over the full data-taking period. The width of the 2016 reconstruction efficiency distribution is narrower than for the other years because of a different physical location of one of the two RPs used for tracking, limiting the overlapping ξ acceptance of the two tracking RPs in this year. The ϵA values of 2017 are overall lower than those of the other years because of the inability of the silicon strip detectors to reconstruct multiple protons within one bunch crossing. This inefficiency was intensified in 2017 as compared to 2016 because of the increase in the instantaneous luminosity of the LHC. The signal efficiency is highest in 2018 because of the use of pixel detector technology in all RPs, which do not suffer from the inefficiency of tracking multiple protons.

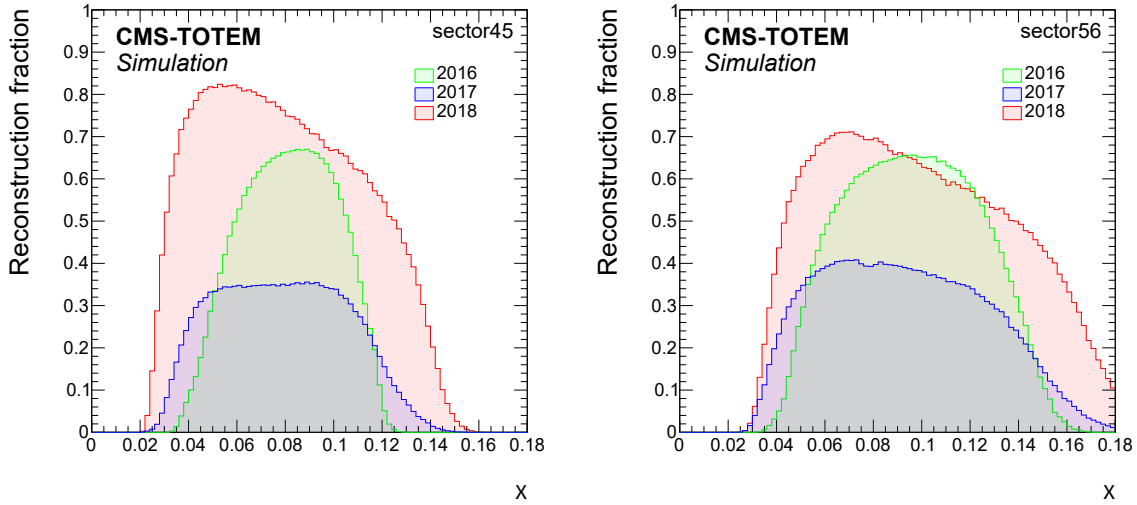


Figure 8: Distributions of combined efficiency-times-acceptance (ϵA) for diffractively scattered protons as a function of the proton ξ for each running year for PPS sectors 45 (left) and 56 (right), respectively. Differences in the overall reconstruction efficiency are explained by varying detector location, configuration, and design across the years.

The derived ϵA values for each year are listed in Table 5. Systematic uncertainties are included as nuisance parameters with log-normal probability density functions in the likelihood. The observed and expected 95% CL in the plane of (ζ_1, ζ_2) are shown in Fig. 9.

These anomalous 4γ coupling limits are equivalent to setting an upper limit on the fiducial LbL cross section of

$$\sigma(pp \rightarrow p\gamma\gamma p \mid \xi_p \in \xi^{\text{PPS}}) < 0.61 \text{ fb}, \quad (6)$$

Table 5: Product of efficiency and acceptance values for each year of data taking, for aQGC signal protons (populating mostly the high- ζ region in Fig. 8). The second column corresponds to the central CMS detectors, the third column to the PPS, and the fourth column is the product of the two previous ones.

Year	Central-CMS ϵA	PPS ϵA	Combined ϵA
2016	80.1%	6.5%	5.2%
2017	75.7%	3.3%	2.5%
2018	77.4%	18.4%	14.2%

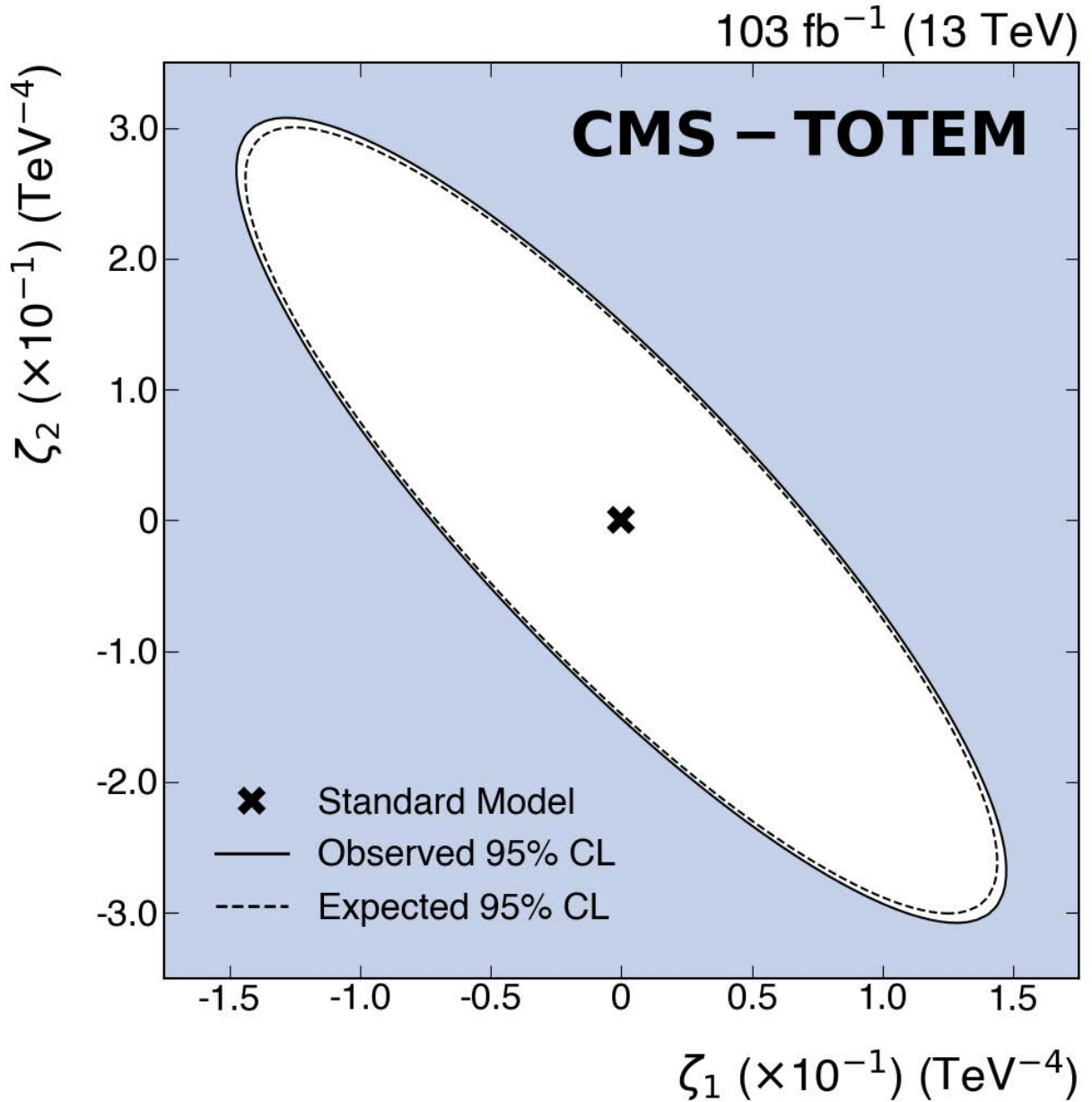


Figure 9: Observed (solid ellipse) and expected (dashed ellipse) exclusion limits at 95% CL on the anomalous coupling parameters ζ_1 and ζ_2 derived from the analysis of high-mass exclusive diphoton events in pp collisions at 13 TeV.

where $\zeta_p \in \zeta^{\text{PPS}}$ denotes that both protons are within the acceptance of PPS. This cross section upper limit is the strongest to date in this region of high diphoton masses.

The observed (expected) 95% CL limits on the separate anomalous 4γ coupling parameters (setting the other to zero) are

$$|\zeta_1| < 0.073 \text{ (0.071) TeV}^{-4} (\zeta_2 = 0),$$

$$|\zeta_2| < 0.15 \text{ (0.15) TeV}^{-4} (\zeta_1 = 0).$$

6.4 Limit on axion-like particle production

The same limit setting procedure described above is applied to the s -channel production of a pseudoscalar ALP. Following the approach described in [3], this $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ process can be parameterized as a function of the ALP mass, m_a , and its photon coupling, f^{-1} .

For the diphoton invariant mass acceptance determined by the ζ ranges probed in this analysis, the selection efficiency depends only on the mass of the ALP. The ϵA product is shown in Fig. 10 as a function of ALP mass m_a for a fixed $f^{-1} = 0.1 \text{ TeV}^{-1}$ coupling, separately for each year of data taking (as well as for PPS only, and for central-CMS plus PPS detectors) and for the full 2016-2018 data set (Run-2 combined). The distributions of ϵA versus ALP mass are used as input to the limit-setting tool.

The observed and expected 95% CL limits resulting from the analysis are shown in Fig. 11. Limits on the production of ALPs coupling to photons with strengths $f^{-1} \geq 0.03$ to 1 TeV^{-1} are set over $m_a = 500\text{--}2000 \text{ GeV}$, a region of masses that has been barely explored so far [46]. For $m_a \gtrsim 0.7 \text{ TeV}$, these limits extend those derived in a recent similar analysis by ATLAS (using single-tagged forward protons) [47], and are the strongest to date in this mass range.

7 Summary

A search has been performed for events with a high-mass exclusive diphoton system and two intact protons produced in the final state, $pp \rightarrow p\gamma\gamma p$, in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. The data set corresponds to an integrated luminosity of 103 fb^{-1} collected with the CMS central detectors and the CMS and TOTEM precision proton spectrometer (PPS) in 2016–2018. Light-by-light (LbL) signal events are selected by requiring the measurement of two high- p_T photons emitted back-to-back, in coincidence with two opposite-side forward protons, measured in PPS, whose kinematic properties match those of the central diphoton system.

The data are found to be in agreement with the predicted standard model (SM) background, with one event observed and $1.10 \pm 0.00 \text{ (stat)} \pm 0.24 \text{ (syst)}$ events expected. An upper limit on the LbL cross section of $\sigma(pp \rightarrow p\gamma\gamma p) < 0.61 \text{ fb}$ is set within the fiducial range of the analysis defined as $p_T^\gamma > 100 \text{ GeV}$, $|\eta^\gamma| < 2.5$, $m_{\gamma\gamma} > 350 \text{ GeV}$, and fractional proton energy loss of $0.035 < \zeta_p < 0.150 \text{ (0.180)}$ for the positive- z (negative- z) arm of PPS. Limits at 95% confidence level are derived for the four-photon anomalous quartic gauge couplings (aQGC) parameters $|\zeta_1| < 0.073 \text{ TeV}^{-4}$ and $|\zeta_2| < 0.15 \text{ TeV}^{-4}$ (setting, alternatively, the other to zero), using an effective field theory. Additionally, limits on the production of axion-like particles (ALPs) coupling to photons with strengths $f^{-1} \approx 0.03$ to 1 TeV^{-1} are set over the mass range from 500 to 2000 GeV. These are the most restrictive limits to date on 4γ aQGC and on ALPs coupling to photons, in the very high mass phase space region.

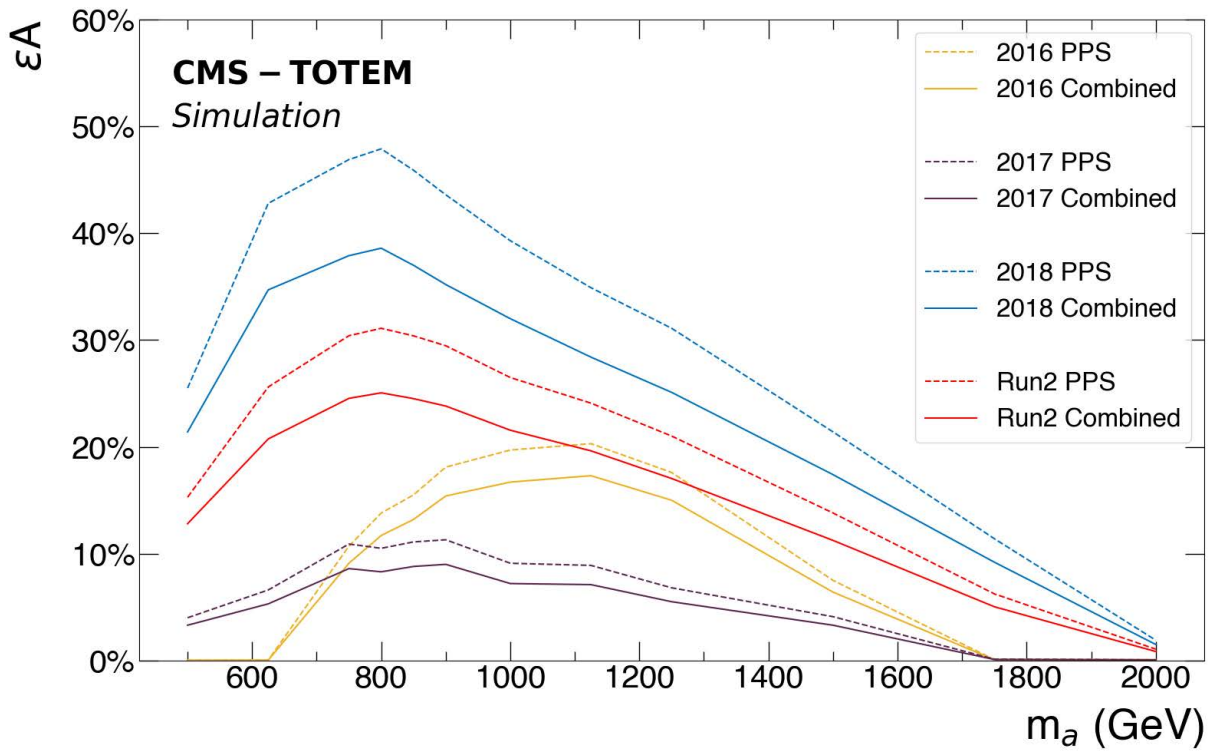


Figure 10: Product of the ALP efficiency and acceptance (ϵA) values as a function of mass m_a for samples generated with $f^{-1} = 0.1 \text{ TeV}^{-1}$ ALP- γ coupling, within the fiducial volume of this search. The curves shown correspond to the PPS ϵA values (dashed curves), as well as the latter convolved with the central-CMS ϵA (solid curves), for each data-taking year and for the full Run-2.

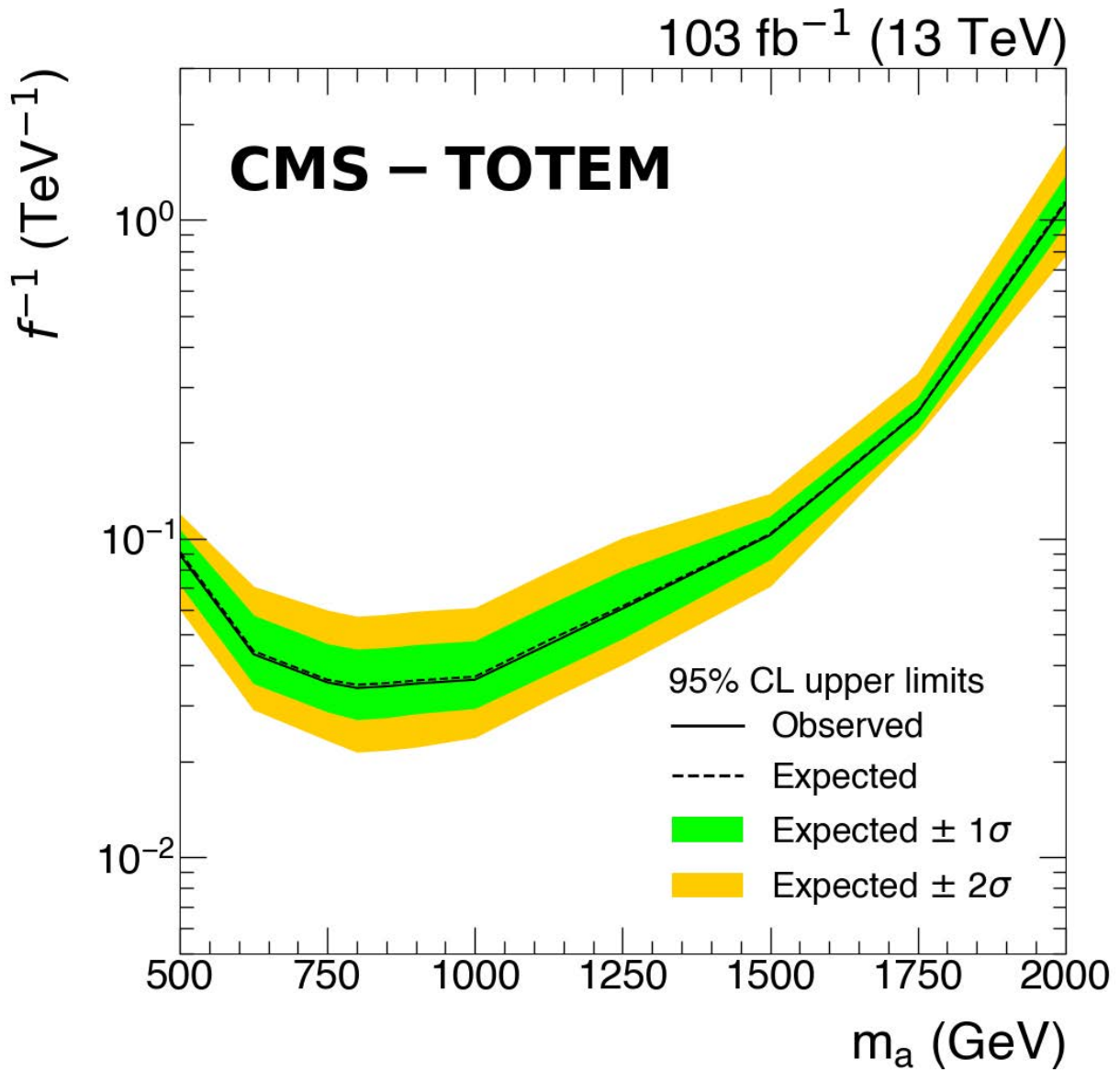


Figure 11: Upper limits at 95% CL on ALP-photon coupling strength as a function of the ALP mass. The shape of the limit curve is determined by the PPS efficiency-times-acceptance curve. The expected limits almost completely overlap with the observed ones.

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References

- [1] D. d’Enterria and G. G. da Silveira, “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].
- [2] S. Knapen, T. Lin, H. K. Lou, and T. Melia, “Searching for axionlike particles with ultraperipheral heavy-ion collisions”, *Phys. Rev. Lett.* **118** (2017) 171801, doi:10.1103/PhysRevLett.118.171801, arXiv:1607.06083.
- [3] C. Baldenegro, S. Fichet, G. von Gersdorff, and C. Roynon, “Searching for axion-like particles with proton tagging at the LHC”, *JHEP* **06** (2018) 131, doi:10.1007/JHEP06(2018)131, arXiv:1803.10835.
- [4] Y. Kurochkin et al., “On production of magnetic monopoles via $\gamma\gamma$ fusion at high energy pp collisions”, *Mod. Phys. Lett. A* **21** (2006) 2873, doi:10.1142/S0217732306022237.
- [5] D. Atwood, S. Bar-Shalom, and A. Soni, “Graviton production by two photon processes in Kaluza-Klein theories with large extra dimensions”, 1999. arXiv:hep-ph/9903538.
- [6] S. C. Inan, “Direct graviton production via photon-photon fusion at the CERN-LHC”, *Chin. Phys. Lett.* **29** (2012) 031301, doi:10.1088/0256-307X/29/3/031301.
- [7] D. d’Enterria et al., “Collider constraints on massive gravitons coupling to photons”, *Phys. Lett. B* **846** (2023) 138237, doi:10.1016/j.physletb.2023.138237, arXiv:2306.15558.
- [8] J. Ellis, N. E. Mavromatos, and T. You, “Light-by-light scattering constraint on Born-Infeld theory”, *Phys. Rev. Lett.* **118** (2017) 261802, doi:10.1103/PhysRevLett.118.261802, arXiv:1703.08450.
- [9] S. M. Lietti and C. G. Roldao, “Radion and Higgs signals in peripheral heavy ion collisions at the LHC”, *Phys. Lett. B* **540** (2002) 252, doi:10.1016/S0370-2693(02)02148-2, arXiv:hep-ph/0205256.
- [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, “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.
- [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] R. Bruce et al., “New physics searches with heavy-ion collisions at the CERN Large Hadron Collider”, *J. Phys. G* **47** (2020) 060501, doi:10.1088/1361-6471/ab7ff7, arXiv:1812.07688.
- [14] 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.
- [15] M. Bauer, M. Neubert, and A. Thamm, “Collider probes of axion-like particles”, *JHEP* **12** (2017) 044, doi:10.1007/JHEP12(2017)044, arXiv:1708.00443.
- [16] R. D. Peccei and H. R. Quinn, “CP conservation in the presence of instantons”, *Phys. Rev. Lett.* **38** (1977) 1440, doi:10.1103/PhysRevLett.38.1440.
- [17] P. Agrawal et al., “Feebly-interacting particles: FIPs 2020 workshop report”, *Eur. Phys. J. C* **81** (2021) 1015, doi:10.1140/epjc/s10052-021-09703-7, arXiv:2102.12143.
- [18] CMS and TOTEM Collaborations, “First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **129** (2022) 011801, doi:10.1103/PhysRevLett.129.011801, arXiv:2110.05916.
- [19] HEPData record for this analysis, 2023. doi:10.17182/hepdata.142335.
- [20] 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.
- [21] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [22] CMS Collaboration, “Performance of the CMS level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, doi:10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
- [23] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [24] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [25] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [26] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [27] CMS and TOTEM Collaborations, “CMS-TOTEM Precision Proton Spectrometer”, Technical Report CERN-LHCC-2014-021, TOTEM-TDR-003, CMS-TDR-13, 2014.
- [28] LHC Forward Physics Working Group Collaboration, “LHC forward physics”, *J. Phys. G* **43** (2016) 110201, doi:10.1088/0954-3899/43/11/110201, arXiv:1611.05079.
- [29] CMS and TOTEM Collaborations, “Proton reconstruction with the CMS-TOTEM Precision Proton Spectrometer”, *JINST* **18** (2023) P09009, doi:10.1088/1748-0221/18/09/P09009, arXiv:2210.05854.

- [30] CMS and TOTEM Collaborations, “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, “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.
- [32] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [33] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV”, Technical Report CMS-PAS-LUM-18-002, 2019.
- [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] 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.
- [36] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [37] M. Boonekamp et al., “FPMC: a generator for forward physics”, 2011. arXiv:1102.2531.
- [38] V. M. Budnev, I. F. Ginzburg, G. V. Meledin, and V. G. Serbo, “The two photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation”, *Phys. Rept.* **15** (1975) 181, doi:10.1016/0370-1573(75)90009-5.
- [39] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [40] 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.
- [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] CMS, TOTEM Collaboration, “Search for high-mass exclusive $\gamma\gamma \rightarrow WW$ and $\gamma\gamma \rightarrow ZZ$ production in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **07** (2023) 229, doi:10.1007/JHEP07(2023)229, arXiv:2211.16320.
- [43] 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.
- [44] A. L. Read, “Presentation of search results: The CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.




















- [45] ATLAS and CMS Collaborations and LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in summer 2011”, Technical Report CMS-NOTE-2011-005. ATL-PHYS-PUB-2011-11, 2011.
- [46] D. d’Enterria, “Collider constraints on axion-like particles”, in *Workshop on Feebly Interacting Particles*. 2021. [arXiv:2102.08971](https://arxiv.org/abs/2102.08971).
- [47] ATLAS Collaboration, “Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS”, *JHEP* **07** (2023) 234, [doi:10.1007/JHEP07\(2023\)234](https://doi.org/10.1007/JHEP07(2023)234), [arXiv:2304.10953](https://arxiv.org/abs/2304.10953).

A The CMS Collaboration



Yerevan Physics Institute, Yerevan, Armenia

A. Tumasyan 













Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler¹ , N. Krammer , L. Lechner , D. Liko , I. Mikulec , P. Paulitsch, F.M. Pitters, J. Schieck¹ , R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz¹ 

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish² , T. Janssen , T. Kello³, H. Rejeb Sfar, P. Van Mechelen 










Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , S. Moortgat , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , W. Van Doninck, D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux , G. De Lentdecker , L. Favart , D. Hohov , J. Jaramillo , K. Lee , M. Mahdavihorrani , I. Makarenko , A. Malara , S. Paredes , L. Pétré , N. Postiau, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 

Ghent University, Ghent, Belgium

D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach, M. Niedziela , C. Rendón, C. Roskas , A. Samalan, K. Skovpen , M. Tytgat , N. Van Den Bossche , B. Vermassen, L. Wezenbeek 






















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

A. Benecke , G. Bruno , F. Bury , C. Caputo , P. David , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaître, K. Mondal , A. Taliercio , T.T. Tran , P. Vischia , S. Wertz 








Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , A. Moraes , P. Rebello Teles 

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁴, E.M. Da Costa , G.G. Da Silveira⁵ , D. De Jesus Damiao , V. Dos Santos Sousa , S. Fonseca De Souza , J. Martins⁶ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , F. Torres Da Silva De Araujo⁷ , A. Vilela Pereira 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁵ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , P.G. Mercadante , S.F. Novaes , Sandra S. Padula 


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 , E. Shumka 





Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Thakur 









Beihang University, Beijing, China

T. Cheng , T. Javaid⁸ , M. Mittal , L. Yuan 









Department of Physics, Tsinghua University, Beijing, China

M. Ahmad , G. Bauer⁹, Z. Hu , S. Lezki , K. Yi^{9,10} 

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Kou , H. Liao , Z.-A. Liu¹¹ , V. Milosevic , F. Monti , R. Sharma , J. Tao , J. Thomas-Wilsker , J. Wang , H. Zhang , J. Zhao


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

A. Agapitos , Y. An , Y. Ban , C. Chen, A. Levin , C. Li , Q. Li , X. Lyu, Y. Mao, S.J. Qian , X. Sun , D. Wang , J. Xiao , H. Yang




Sun Yat-Sen University, Guangzhou, China

M. Lu , Z. You 

University of Science and Technology of China, Hefei, China

N. Lu 





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

X. Gao³ , D. Leggat, H. Okawa , Y. Zhang 


Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga 

Universidad de Antioquia, Medellin, Colombia

J. Mejia Guisao , F. Ramirez , M. Rodriguez , J.D. Ruiz Alvarez 








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 , B.K. Chitroda , D. Ferencek , S. Mishra , M. Roguljic , A. Starodumov¹² , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , M. Kolosova , S. Konstantinou , J. Mousa , C. Nicolaou, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 


Charles University, Prague, Czech Republic

M. Finger , M. Finger Jr. , A. Kveton 

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. Elgammal¹³, A. Ellithi Kamel¹⁴




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

M.A. Mahmoud , Y. Mohammed 


















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik , R.K. Dewanjee , K. Ehataht , M. Kadastik , T. Lange , S. Nandan , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola , H. Kirschenmann , M. Voutilainen 




















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , E. Brücken , J. Havukainen , M.S. Kim , R. Kinnunen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti , L. Martikainen , M. Myllymäki , J. Ott , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 





























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow , 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 , P. Gras , G. Hamel de Monchenault , P. Jarry , V. Lohezic , J. Malcles , J. Rander , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁵ , P. Simkina , M. Titov 























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

C. Baldenegro Barrera , F. Beaudette , A. Buchot Perraguin , P. Busson , A. Cappati , C. Charlot , F. Damas , O. Davignon , B. Diab , G. Falmagne , B.A. Fontana Santos Alves , S. Ghosh , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , G. Liu , J. Motta , M. Nguyen , C. Ochando , L. Portales , R. Salerno , U. Sarkar , J.B. Sauvan , Y. Sirois , A. Tarabini , E. Vernazza , A. Zabi , A. Zghiche 

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

J.-L. Agram¹⁶ , J. Andrea , D. Apparou , D. Bloch , G. Bourgatte , J.-M. Brom , E.C. Chabert , C. Collard , D. Darej , U. Goerlach , C. Grimault , A.-C. Le Bihan , P. Van Hove 

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

S. Beauceron , B. Blancon , G. Boudoul , A. Carle , N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen¹⁷ , H. El Mamouni , J. Fay , S. Gascon , M. Gouzevitch , G. Grenier , B. Ille , I.B. Laktineh , M. Lethuillier , L. Mirabito , S. Perries , L. Torterotot , M. Vander Donckt , P. Verdier , S. Viret 


























Georgian Technical University, Tbilisi, Georgia

G. Adamov , I. Lomidze , Z. Tsamalaidze¹² 










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

V. Botta , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , N. Röwert , M. Teroerde 


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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , M. Erdmann , P. Fackeldey , D. Fasanella , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mondal , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , H. Reithler , A. Schmidt , S.C. Schuler, A. Sharma , A. Stein , L. Vigilante, S. Wiedenbeck , S. Zaleski








































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

C. Dziwok , G. Flügge , W. Haj Ahmad¹⁸ , O. Hlushchenko, T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 
































Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , P. Asmuss, S. Baxter , M. Bayatmakou , O. Behnke , A. Bermúdez Martínez , S. Bhattacharya , A.A. Bin Anuar , F. Blekman¹⁹ , K. Borrás²⁰ , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , L. Didukh , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo¹⁹ , A. Geiser , A. Giraldi , G. Greau, A. Grohsjean , V. Guglielmi , M. Guthoff , A. Jafari²¹ , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²² , W. Lohmann²³ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , A. Saibel , M. Savitskyi , M. Scham^{24,20} , V. Scheurer, S. Schnake²⁰ , P. Schütze , C. Schwanenberger¹⁹ , M. Shchedrolosiev , R.E. Sosa Ricardo , D. Stafford, N. Tonon[†] , M. Van De Klundert , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Walter , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²⁰ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos 

University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , M. Bonanomi , P. Connor , K. De Leo , M. Eich, K. El Morabit , F. Feindt, A. Fröhlich, C. Garbers , E. Garutti , M. Hajheidari, J. Haller , A. Hinzmann , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , A. Mehta , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , M. Rieger , O. Rieger, D. Savoiu , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 









Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , R. Caspart , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , J.O. Gosewisch, A. Gottmann , F. Hartmann²⁵ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , J. Rausser, M. Schnepf, D. Seith, I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , R. Wolf , S. Wozniewski , S. Wunsch, X. Zuo 




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

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Stakia 








National and Kapodistrian University of Athens, Athens, Greece

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis , A. Manousakis-Katsikakis , A. Panagiotou, I. Papavergou , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






National Technical University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou , C. Foudas, P. Gianneios , C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók²⁶ , G. Bencze, C. Hajdu , D. Horvath^{27,28} , F. Sikler , V. Veszpremi 


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

M. Csanád , K. Farkas , M.M.A. Gadallah²⁹ , S. Lökös³⁰ , P. Major , K. Mandal , G. Pásztor , A.J. Rádl³¹ , O. Surányi , G.I. Veres 

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni , S. Czellar, J. Karancsi²⁶ , J. Molnar, Z. Szillasi, D. Teyssier 


















Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³² 

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³¹ , T. Novak 









Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³³ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁴ , A. Singla , A. K. Viridi 














University of Delhi, Delhi, India

A. Ahmed , A. Bhardwaj , B.C. Choudhary , A. Kumar , M. Naimuddin , K. Ranjan , S. Saumya 


Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁵ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁶ , M. Maity³⁵, P. Palit , G. Saha , B. Sahu , S. Sarkar

Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , P. Kalbhor , J.R. Komaragiri³⁷ , D. Kumar³⁷ , A. Muhammad , L. Panwar³⁷ , R. Pradhan , P.R. Pujahari , A. Sharma , A.K. Sikdar , P.C. Tiwari³⁷ , S. Verma 










Bhabha Atomic Research Centre, Mumbai, India

K. Naskar³⁸ 

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, I. Das , S. Dugad, M. Kumar , G.B. Mohanty , P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee , R. Chudasama , M. Guchait , S. Karmakar , S. Kumar , G. Majumder ,
K. Mazumdar , S. Mukherjee , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati³⁹ , A.K. Das, C. Kar , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴⁰ , A. Nayak⁴⁰ , P. Saha , S.K. Swain , D. Vats⁴⁰ 

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

A. Alpana , S. Dube , B. Kansal , A. Laha , S. Pandey , A. Rastogi , S. Sharma 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi^{41,42} , E. Khazaie⁴² , M. Zeinali⁴³ 

































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

S. Chenarani⁴⁴ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b} , R. Aly^{a,b,45} , C. Aruta^{a,b} , A. Colaleo^a , D. Creanza^{a,c} ,
N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,b} , W. Elmetenawee^{a,b} , F. Errico^{a,b} ,
L. Fiore^a , G. Iaselli^{a,c} , M. Ince^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} ,
V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} ,
G. Pugliese^{a,c} , R. Radogna^a , D. Ramos^a , A. Ranieri^a , G. Selvaggi^{a,b} ,
L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a ,
P. Verwilligen^a 


















INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , L. Brigliadori^a,
R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} ,
G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , P. Giacomelli^a ,
L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,46} , L. Lunerti^{a,b} ,
S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} ,
A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Costa^{a,b,47} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,47} , C. Tuve^{a,b} 






INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^{a,b} ,
V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , G. Latino^{a,b} ,
P. Lenzi^{a,b} , M. Lizzo^{a,b} , M. Meschini^a , S. Paoletti^a , R. Seidita^{a,b} , G. Sguazzoni^a ,
L. Viliani^a 






















INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola²⁵ , D. Piccolo 

INFN Sezione di Genova^a, Università di Genova^b, Genova, Italy

P. Chatagnon^a , F. Ferro^a , R. Mulargia^a , E. Robutti^a , S. Tosi^{a,b} 






















INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^a , G. Boldrini^a , F. Brivio^{a,b} , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^{a,b} , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , D. Pedrini^a , B.S. Pinolini^a, S. Ragazzi^{a,b} , N. Redaelli^a , T. Tabarelli de Fatis^{a,b} , D. Zuolo^{a,b}












INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Università G. Marconi^d, Roma, Italy

S. Buontempo^a , F. Carnevali^{a,b}, N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,48} , P. Paolucci^{a,25} , B. Rossi^a , C. Sciacca^{a,b} 















INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

P. Azzi^a , N. Bacchetta^{a,49} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , U. Gasparini^{a,b} , G. Grosso^a, L. Layer^{a,50}, E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , M. Michelotto^a , F. Montecassiano^a , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , G. Strong^a , M. Tosi^{a,b} , H. Yarar^{a,b}, M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}






















INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

S. Abu Zeid^{a,51} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^a , P. Vitulo^{a,b} 

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

P. Asenov^{a,52} , G.M. Bilei^a , D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , G. Mantovani^{a,b}, V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,52} , A. Piccinelli^{a,b} , M. Presilla^{a,b} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b} 






















INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy; Università di Siena^d, Siena, Italy

P. Azzurri^a , G. Bagliesi^a , V. Bertacchi^{a,c} , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^{a,b} , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , M.R. Di Domenico^{a,d} , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , G. Mandorli^{a,c} , D. Matos Figueiredo^a , A. Messineo^{a,b} , M. Musich^{a,b} , F. Palla^a , S. Parolia^{a,b} , G. Ramirez-Sanchez^{a,c} , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , N. Shafiei^{a,b} , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , A. Venturi^a , P.G. Verdini^a








INFN Sezione di Roma^a, Sapienza Università di Roma^b, Roma, Italy

P. Barria^a , M. Campana^{a,b} , F. Cavallari^a , D. Del Re^{a,b} , E. Di Marco^a , M. Diemoz^a , E. Longo^{a,b} , P. Meridiani^a , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a , F. Santanastasio^{a,b} , L. Soffi^a , R. Tramontano^{a,b} 














INFN Sezione di Torino^a, Università di Torino^b, Torino, Italy; Università del Piemonte Orientale^c, Novara, Italy

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , M. Grippone^{a,b} , B. Kiani^{a,b} , F. Leggera^a , C. Mariotti^a , S. Maselli^a , A. Mecca^{a,b} , E. Migliore^{a,b} , E. Monteil^{a,b} , M. Monteno^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , K. Shchelina^a , F. Siviero^{a,b} , V. Sola^a , A. Solano^{a,b} , D. Soldi^{a,b} , A. Staiano^a , M. Tornago^{a,b} , D. Trocino^a , G. Umoret^{a,b} , A. Vagnerini^{a,b}

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , A. Da Rold^{a,b} ,
G. Della Ricca^{a,b} , G. Sorrentino^{a,b} 




Kyungpook National University, Daegu, Korea

S. Dogra , C. Huh , B. Kim , D.H. Kim , G.N. Kim , J. Kim, J. Lee , S.W. Lee ,
C.S. Moon , Y.D. Oh , S.I. Pak , M.S. Ryu , 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

E. Asilar , T.J. Kim , J. Park 

Korea University, Seoul, Korea

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , J. Lim, J. Park, S.K. Park, J. Yoo 

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 

Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee



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 ,
S. Lee, B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 






University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , D. Kim , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , J.A. Merlin,
I.C. Park , Y. Roh, D. Song, I.J. Watson , S. Yang 


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 




Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee, Y. Lee , Y. Lee , I. Yu 

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

T. Beyrouthy, Y. Maghrbi 




Riga Technical University, Riga, Latvia

K. Dreimanis , G. Pikurs, M. Seidel , V. Veckalns⁵³ 



Vilnius University, Vilnius, Lithuania

M. Ambrozas , A. Carvalho Antunes De Oliveira , A. Juodagalvis , A. Rinkevicius ,
G. Tamulaitis 

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

N. Bin Norjoharuddeen , S.Y. Hoh⁵⁴ , I. Yusuff⁵⁴ , Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez,
M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , I. Heredia-De La Cruz⁵⁵ , R. Lopez-Fernandez ,
C.A. Mondragon Herrera, D.A. Perez Navarro , A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , F. Vazquez Valencia 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic⁵⁶ , N. Raicevic 






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

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

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , B. Boimska , M. Górski , M. Kazana , M. Szeleper ,
P. Zalewski 

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

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





























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 , M. Pisano , J. Seixas , J. Varela 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

P. Adzic⁵⁷ , 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 , M. Barrio Luna,
Cristina F. Bedoya , C.A. Carrillo Montoya , M. Cepeda , M. Cerrada , N. Colino ,
B. De La Cruz , A. Delgado Peris , D. Fernández Del Val , J.P. Fernández Ramos ,
J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez ,
M.I. Josa , J. León Holgado , D. Moran , C. Perez Dengra , A. Pérez-Calero Yzquierdo ,
J. Puerta Pelayo , I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas ,
J. Sastre , L. Urda Gómez , J. Vazquez Escobar , C. Willmott


















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero ,
J.R. González Fernández , E. Palencia Cortezon , C. Ramón Álvarez ,
V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba 





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

J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez ,
C. Fernandez Madrazo , A. García Alonso, G. Gomez , C. Lasiosa García ,
C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas ,
J. Piedra Gomez , C. Prieels, A. Ruiz-Jimeno , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

M.K. Jayananda , B. Kailasapathy⁵⁸ , D.U.J. Sonnadara , D.D.C. Wickramarathna 

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

W.G.D. Dharmaratna⁵⁹ , K. Liyanage , N. Perera , N. Wickramage 





































CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , J. Alimena , E. Auffray , G. Auzinger , P. Baillon[†], D. Barney , J. Bendavid , M. Bianco , B. Bilin , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , S.S. Chhibra , S. Choudhury, M. Cipriani , L. Cristella , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Dobson , M. Dünser , N. Dupont, F. Fallavollita⁶⁰, A. Florent , L. Forthomme , G. Franzoni , W. Funk , S. Ghosh , D. Gigi, K. Gill , F. Glege , L. Gouskos , E. Govorkova , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , F. Moortgat , M. Mulders , S. Orfanelli, L. Orsini, F. Pantaleo , E. Perez, M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , M. Pitt , H. Qu , T. Quast, D. Rabadý , A. Racz, G. Reales Gutiérrez, M. Rovere , H. Sakulin , J. Salfeld-Nebgen , S. Scarfi , M. Selvaggi , A. Sharma , P. Silva , P. Sphicas⁶¹ , A.G. Stahl Leiton , S. Summers , K. Tatar , V.R. Tavolaro , D. Treille , P. Tropea , A. Tsirou, J. Wanczyk⁶² , K.A. Wozniak , W.D. Zeuner
























Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁶³ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶³ , L. Noehte⁶³ , T. Rohe 

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

T.K. Aarrestad , K. Androsov⁶² , M. Backhaus , P. Berger, A. Calandri , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar, M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , T.A. Gómez Espinosa , C. Grab , D. Hits , W. Lustermaan , A.-M. Lyon , R.A. Manzoni , L. Marchese , C. Martin Perez , A. Mascellani⁶² , F. Nessi-Tedaldi , J. Niedziela , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini, D.A. Sanz Becerra , J. Steggemann⁶² , D. Valsecchi²⁵ , R. Wallny 









Universität Zürich, Zurich, Switzerland

C. Amsler⁶⁴ , P. Bäertschi , C. Botta , D. Brzhechko, M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo, J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁵, C.M. Kuo, W. Lin, P.K. Rout , S.S. Yu 





















National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, Y. Chao , K.F. Chen , P.s. Chen, H. Cheng , W.-S. Hou , R. Khurana, G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , A. Psallidas, A. Steen , H.y. Wu, E. Yazgan , P.r. Yu


High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁶ , E. Eskut , Y. Guler⁶⁷ , E. Gurpinar Guler⁶⁷ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁸ , A. Polatoz , A.E. Simsek , B. Tali⁶⁹ , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁷⁰, K. Ocalan⁷¹ , M. Yalvac⁷² 

Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷³ , O. Kaya⁷⁴ , S. Tekten⁷⁵ 


Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁶ , Y. Komurcu , S. Sen⁶⁶ 


Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁶⁹ , B. Hacisahinoglu , I. Hos⁷⁶ , B. Isildak⁷⁷ , C. Simsek , D. Sunar Cerci⁶⁹ 
















Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

B. Grynyov 



















National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 



































University of Bristol, Bristol, United Kingdom

D. Anthony , E. Bhal , J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , M. Glowacki, J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁸ , K. Walkingshaw Pass, R. White 




Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell , A. Belyaev⁷⁹ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸⁰ , Sh. Jain , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams 

Imperial College, London, United Kingdom

R. Bainbridge , P. Bloch , S. Bonomally, J. Borg , C.E. Brown , O. Buchmuller, V. Cacchio, V. Cepaitis , G.S. Chahal⁸¹ , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies, M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , D.G. Monk , J. Nash⁸² , M. Pesaresi, B.C. Radburn-Smith , D.M. Raymond, A. Richards, A. Rose , E. Scott , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁵ , M. Vojinovic , N. Wardle , S.N. Webb , D. Winterbottom 





Brunel University, Uxbridge, United Kingdom

K. Coldham, J.E. Cole , A. Khan, P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , A.R. Kanuganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , J. Wilson 

















Catholic University of America, Washington, DC, USA

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






















The University of Alabama, Tuscaloosa, Alabama, USA

S.I. Cooper , D. Di Croce , S.V. Gleyzer , C. Henderson , C.U. Perez , P. Rumerio⁸³ , C. West 


















Boston University, Boston, Massachusetts, USA

A. Akpinar , A. Albert , D. Arcaro , C. Cosby , Z. Demiragli , C. Erice , E. Fontanesi , D. Gastler , S. May , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , S. Yuan 















Brown University, Providence, Rhode Island, USA

G. Benelli , B. Burkle , X. Coubez²⁰ , D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁴ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , M. Narain , N. Pervan , S. Sagir⁸⁵ , F. Simpson , E. Usai , W.Y. Wong , X. Yan , D. Yu , W. Zhang 










University of California, Davis, Davis, California, USA

J. Bonilla , C. Brainerd , R. Breedon , M. Calderon De La Barca Sanchez , M. Chertok , J. Conway , P.T. Cox , R. Erbacher , G. Haza , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , D. Pellett , B. Regnery , Y. Yao , F. Zhang 
























University of California, Los Angeles, California, USA

M. Bachtis , R. Cousins , A. Datta , D. Hamilton , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , E. Manca , W.A. Nash , S. Regnard , D. Saltzberg , B. Stone , V. Valuev 























University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , M. Gordon , G. Hanson , G. Karapostoli , O.R. Long , N. Manganeli , W. Si , S. Wimpenny 














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

J.G. Branson , P. Chang , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , R. Gerosa , L. Giannini , J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , M. Pieri , B.V. Sathia Narayanan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil 














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

N. Amin , C. Campagnari , M. Citron , G. Collura , A. Dorsett , V. Dutta , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , M. Quinnan , J. Richman , U. Sarica , R. Schmitz , F. Setti , J. Shephlock , P. Siddireddy , D. Stuart , S. Wang 














California Institute of Technology, Pasadena, California, USA

A. Bornheim , O. Cerri , I. Dutta , A. Latorre , J.M. Lawhorn , J. Mao , H.B. Newman , T. Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 


















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , M.B. Andrews , P. Bryant , T. Ferguson , A. Harilal , C. Liu , T. Mudholkar , S. Murthy , M. Paulini , A. Roberts , A. Sanchez , W. Terrill 







































































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald , F. Marini , A. Perloff , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper 



















Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , K.F. Di Petrillo , J. Dickinson , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁶ , F. Ravera , A. Reinsvold Hall⁸⁷ , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 







University of Florida, Gainesville, Florida, USA

P. Avery , D. Bourilkov , L. Cadamuro , V. Cherepanov , R.D. Field, M. Kim, E. Koenig , J. Konigsberg , A. Korytov , E. Kuznetsova⁸⁸ , K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal , D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang , Z. Wu 



















Florida State University, Tallahassee, Florida, USA

T. Adams , A. Askew , R. Habibullah , V. Hagopian , T. Kolberg , G. Martinez, H. Prosper , O. Viazlo , M. Wulansatiti , R. Yohay , J. Zhang













Florida Institute of Technology, Melbourne, Florida, USA

M.M. Baarmand , S. Butalla , T. Elkafrawy⁵¹ , M. Hohlmann , R. Kumar Verma , M. Rahmani, F. Yumiceva 

University of Illinois Chicago, Chicago, USA, Chicago, USA

M.R. Adams , H. Becerril Gonzalez , R. Cavanaugh , S. Dittmer , O. Evdokimov , C.E. Gerber , D.J. Hofman , D. S. Lemos , A.H. Merrit , C. Mills , G. Oh , T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , X. Wang , Z. Ye , J. Yoo 




















The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , K. Dilsiz⁸⁹ , L. Emediato , R.P. Gandrajula , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁹⁰ , J. Nachtman , O. Neogi, H. Ogul⁹¹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹² 






Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , C. Rogan , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 


















Kansas State University, Manhattan, Kansas, USA

B. Allmond , S. Duric, A. Ivanov , K. Kaadze , D. Kim, Y. Maravin , T. Mitchell, A. Modak, K. Nam, D. Roy 























Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 















University of Maryland, College Park, Maryland, USA

E. Adams , A. Baden , O. Baron, A. Belloni , A. Bethani , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , L. Wang , K. Wong 


Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

D. Abercrombie, W. Busza , I.A. Cali , Y. Chen , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, P. Harris, M. Hu , D. Kovalskyi , J. Krupa , Y.-J. Lee , K. Long , C. Mironov , C. Paus , D. Rankin , C. Roland , G. Roland , Z. Shi , G.S.F. Stephans , J. Wang, Z. Wang , B. Wyslouch , T. J. Yang 

University of Minnesota, Minneapolis, Minnesota, USA

R.M. Chatterjee, B. Crossman , A. Evans , J. Hiltbrand , B.M. Joshi , C. Kapsiak , M. Krohn , Y. Kubota , J. Mans , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 




















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , M. Bryson, D.R. Claes , C. Fangmeier , L. Finco , F. Golf , C. Joo , R. Kamalieddin, I. Kravchenko , I. Reed , J.E. Siado , G.R. Snow[†], W. Tabb , A. Wightman , F. Yan , A.G. Zecchinelli 







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

G. Agarwal , H. Bandyopadhyay , L. Hay , I. Iashvili , A. Kharchilava , C. McLean , M. Morris , D. Nguyen , J. Pekkanen , S. Rappoccio , A. Williams 





















Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , J. Lidrych , 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, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , A. Gilbert , K.A. Hahn , Y. Liu , N. Odell , M.H. Schmitt , M. Velasco













University of Notre Dame, Notre Dame, Indiana, USA

R. Band , R. Bucci, M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹² , R. Ruchti , A. Townsend , M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

The Ohio State University, Columbus, Ohio, USA

B. Bylsma, M. Carrigan , L.S. Durkin , B. Francis , C. Hill , M. Joyce , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 

Princeton University, Princeton, New Jersey, USA




















F.M. Addesa , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg , N. Haubrich , S. Higginbotham , A. Kalogeropoulos , G. Kopp , S. Kwan , D. Lange 

D. Marlow , K. Mei , I. Ojalvo , J. Olsen , D. Stickland , C. Tully 

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , S. Norberg
















Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , R. Chawla , S. Das , L. Gutay, M. Jones , A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic¹⁵ , J. Thieman , F. Wang , R. Xiao , W. Xie 












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar 


Rice University, Houston, Texas, USA

D. Acosta , A. Baty , T. Carnahan , M. Decaro, S. Dildick , K.M. Ecklund , P.J. Fernández Manteca , S. Freed, P. Gardner, F.J.M. Geurts , A. Kumar , W. Li , B.P. Padley , R. Redjimi, J. Rotter , W. Shi , S. Yang , E. Yigitbasi , L. Zhang⁹³, Y. Zhang 

















University of Rochester, Rochester, New York, 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 , G.P. Van Onsem 

The Rockefeller University, New York, New York, USA

K. Goulianos 














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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslowski , O. Karacheban²³ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, M. Osherson , H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, H. Wang 

University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, A.G. Delannoy , S. Fiorendi , T. Holmes , E. Nibigira , S. Spanier 










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

O. Bouhali⁹⁴ , M. Dalchenko , A. Delgado , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁵ , H. Kim , S. Luo , S. Malhotra, R. Mueller , D. Overton , D. Rathjens , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , S. Greene, A. Gurrola , W. Johns , A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 









University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , B. Cox , G. Cummings , J. Hakala , R. Hirosky , A. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara , B. Tannenwald 

Wayne State University, Detroit, Michigan, USA

P.E. Karchin , N. Poudyal 

University of Wisconsin - Madison, Madison, Wisconsin, USA

S. Banerjee , K. Black , T. Bose , S. Dasu , I. De Bruyn , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, A. Loeliger , R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁹⁶, E. Boos , D. Budkouski , V. Chekhovsky, R. Chistov⁹⁶ , A. Dermenev , T. Dimova⁹⁶ , I. Dremin , M. Dubinin⁸⁶ , L. Dudko , V. Epshteyn , A. Ershov , G. Gavrillov , V. Gavrillov , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁶ , V. Karjavine , A. Karneyeu , V. Kim⁹⁶ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁷ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁶ , N. Krasnikov , A. Lanev , P. Levchenko , A. Litomin, O. Lukina , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁶ , V. Murzin , A. Nikitenko⁹⁸ , S. Obraztsov , A. Oskin, I. Ovtin⁹⁶ , V. Palichik , P. Parygin , V. Perelygin , S. Petrushanko , S. Polikarpov⁹⁶ , V. Popov, E. Popova , O. Radchenko⁹⁶ , M. Savina , V. Savrin , D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁶ , S. Slabospitskii , V. Smirnov , D. Sosnov , V. Sulimov , A. Terkulov , O. Teryaev , I. Tlisova , M. Toms , A. Toropin , L. Uvarov , A. Uzunian , E. Vlasov , A. Vorobyev, N. Voytishin , B.S. Yuldashev⁹⁹, A. Zarubin , I. Zhizhin , A. Zhokin

†: Deceased

¹Also at TU Wien, Vienna, Austria

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

³Also at Université Libre de Bruxelles, Bruxelles, Belgium

⁴Also at Universidade Estadual de Campinas, Campinas, Brazil

⁵Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁶Also at UFMS, Nova Andradina, Brazil

⁷Also at The University of the State of Amazonas, Manaus, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at Nanjing Normal University, Nanjing, China

¹⁰Now at The University of Iowa, Iowa City, Iowa, USA

¹¹Also at University of Chinese Academy of Sciences, Beijing, China

¹²Also at an institute or an international laboratory covered by a cooperation agreement with CERN

¹³Now at British University in Egypt, Cairo, Egypt

¹⁴Now at Cairo University, Cairo, Egypt

¹⁵Also at Purdue University, West Lafayette, Indiana, USA

¹⁶Also at Université de Haute Alsace, Mulhouse, France

¹⁷Also at Department of Physics, Tsinghua University, Beijing, China

¹⁸Also at Erzincan Binali Yildirim University, Erzincan, Turkey

¹⁹Also at University of Hamburg, Hamburg, Germany

²⁰Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²¹Also at Isfahan University of Technology, Isfahan, Iran

-
- ²²Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²³Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁴Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁵Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²⁶Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ²⁷Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ²⁸Now at Universitatea Babeș-Bolyai - Facultatea de Fizică, Cluj-Napoca, Romania
- ²⁹Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁰Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ³¹Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³²Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³³Also at Punjab Agricultural University, Ludhiana, India
- ³⁴Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁵Also at University of Visva-Bharati, Santiniketan, India
- ³⁶Also at University of Hyderabad, Hyderabad, India
- ³⁷Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁸Also at Indian Institute of Technology (IIT), Mumbai, India
- ³⁹Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴⁰Also at Institute of Physics, Bhubaneswar, India
- ⁴¹Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴²Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴³Also at Sharif University of Technology, Tehran, Iran
- ⁴⁴Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁵Also at Helwan University, Cairo, Egypt
- ⁴⁶Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁷Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁸Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁴⁹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁰Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Ain Shams University, Cairo, Egypt
- ⁵²Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵³Also at Riga Technical University, Riga, Latvia
- ⁵⁴Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁵Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁶Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ⁵⁷Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶⁰Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁶¹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶²Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶³Also at Universität Zürich, Zurich, Switzerland
- ⁶⁴Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁵Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁶Also at Near East University, Research Center of Experimental Health Science, Mersin,

Turkey

⁶⁷Also at Konya Technical University, Konya, Turkey

⁶⁸Also at Izmir Bakircay University, Izmir, Turkey

⁶⁹Also at Adiyaman University, Adiyaman, Turkey

⁷⁰Also at Istanbul Gedik University, Istanbul, Turkey

⁷¹Also at Necmettin Erbakan University, Konya, Turkey

⁷²Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey

⁷³Also at Marmara University, Istanbul, Turkey

⁷⁴Also at Milli Savunma University, Istanbul, Turkey

⁷⁵Also at Kafkas University, Kars, Turkey

⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

⁷⁷Also at Ozyegin University, Istanbul, Turkey

⁷⁸Also at Vrije Universiteit Brussel, Brussel, Belgium

⁷⁹Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

⁸⁰Also at University of Bristol, Bristol, United Kingdom

⁸¹Also at IPPP Durham University, Durham, United Kingdom

⁸²Also at Monash University, Faculty of Science, Clayton, Australia

⁸³Also at Università di Torino, Torino, Italy

⁸⁴Also at Bethel University, St. Paul, Minnesota, USA

⁸⁵Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁶Also at California Institute of Technology, Pasadena, California, USA

⁸⁷Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁸Also at University of Florida, Gainesville, Florida, USA

⁸⁹Also at Bingol University, Bingol, Turkey

⁹⁰Also at Georgian Technical University, Tbilisi, Georgia

⁹¹Also at Sinop University, Sinop, Turkey

⁹²Also at Erciyes University, Kayseri, Turkey

⁹³Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

⁹⁴Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁵Also at Kyungpook National University, Daegu, Korea

























⁹⁶Also at another institute or international laboratory covered by a cooperation agreement with CERN


























⁹⁷Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁸Also at Imperial College, London, United Kingdom

⁹⁹Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

B The TOTEM Collaboration

G. Antchev ^a, P. Aspell⁸, I. Atanassov ^a, V. Avati^{7,8}, J. Baechler⁸, C. Baldenegro Barrera ¹¹, V. Berardi ^{4a,4b}, M. Berretti ^{2a}, V. Borshch ¹², E. Bossini ^{6a}, U. Bottigli ^{6b}, M. Bozzo ^{5a,5b}, H. Burkhardt⁸, F.S. Cafagna ^{4a}, M.G. Catanesi ^{4a}, M. Deile ⁸, F. De Leonardis^{4a,4c}, M. Doubek ^{1c}, D. Druzhkin^{3a,8}, K. Eggert¹⁰, V. Eremin^c, A. Fiergolski⁸, F. Garcia ^{2a}, V. Georgiev^{1a}, S. Giani⁸, L. Grzanka ⁷, J. Hammerbauer^{1a}, T. Isidori ¹¹, V. Ivanchenko ¹², M. Janda ^{1c}, A. Karev⁸, J. Kašpar ^{1b,8}, B. Kaynak ⁹, J. Kopal ⁸, V. Kundrať ^{1b}, S. Lami ^{6a}, R. Linhart^{1a}, C. Lindsey¹¹, M.V. Lokajíček ^{†,1b},

L. Losurdo ^{6b}, F. Lucas Rodríguez⁸, M. Macri^{†,5a}, M. Malawski ⁷, N. Minafra ¹¹, S. Minutoli^{5a}, K. Misan ⁷, T. Naaranoja ^{2a,2b}, F. Nemes ^{3a,3b,8}, H. Niewiadomski¹⁰, E. Oliveri ⁸, F. Oljemark ^{2a,2b}, M. Oriunno^b, K. Österberg ^{2a,2b}, S. Ozkorucuklu ⁹, P. Palazzi ⁸, V. Passaro ^{4a,4c}, Z. Peroutka^{1a}, O. Potok ⁹, J. Procházka ^{1b}, M. Quinto ^{4a,Ab}, E. Radermacher⁸, E. Radicioni ^{4a}, F. Ravotti ⁸, C. Royon ¹¹, G. Ruggiero⁸, H. Saarikko^{2a,2b}, V.D. Samoylenko^c, A. Scribano ^{6a,11}, J. Šíroký^{1a}, J. Smajek⁸, W. Snoeys ⁸, R. Stefanovitch^{3a,8}, C. Taylor ¹⁰, E. Tcherniaev ¹², N. Turini ^{6b}, O. Urban^{1a}, V. Vacek ^{1c}, O. Vavroch^{1a}, J. Weltri^{2a,2b}, J. Williams ¹¹, J. Zich^{1a}

†Deceased

^{1a}University of West Bohemia, Pilsen, Czech Republic

^{1b}Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic

^{1c}Czech Technical University, Prague, Czech Republic

^{2a}Helsinki Institute of Physics, University of Helsinki, Helsinki, Finland

^{2b}Department of Physics, University of Helsinki, Helsinki, Finland

^{3a}Wigner Research Centre for Physics, RMKI, Budapest, Hungary

^{3b}MATE Institute of Technology KRC, Gyöngyös, Hungary

^{4a}INFN Sezione di Bari, Bari, Italy

^{4b}Dipartimento Interateneo di Fisica di Bari, University of Bari, Bari, Italy

^{4c}Dipartimento di Ingegneria Elettrica e dell'Informazione — Politecnico di Bari, Bari, Italy

^{5a}INFN Sezione di Genova, Genova, Italy

^{5b}Università degli Studi di Genova, Genova, Italy

^{6a}INFN Sezione di Pisa, Pisa, Italy

^{6b}Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Siena, Italy

⁷Akademia Górniczo-Hutnicza (AGH) University of Kraków, Faculty of Computer Science, Kraków, Poland

⁸CERN, Geneva, Switzerland

⁹Istanbul University, Istanbul, Turkey

¹⁰Case Western Reserve University, Department of Physics, Cleveland, Ohio, USA

¹¹The University of Kansas, Lawrence, Kansas, USA

¹²Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

^a INRNE-BAS, Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

^b SLAC, Stanford University, California, USA

^c Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN