



# Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

A search is conducted for new physics in a final state containing a photon and missing transverse momentum in proton-proton collisions at  $\sqrt{s} = 13$  TeV. The data collected by the CMS experiment at the CERN LHC correspond to an integrated luminosity of  $12.9 \text{ fb}^{-1}$ . No deviations are observed relative to the predictions of the standard model. The results are interpreted as exclusion limits on the dark matter production cross sections and parameters in models containing extra spatial dimensions. Improved limits are set with respect to previous searches using the monophoton final state. In particular, the limits on the extra dimension model parameters are the most stringent to date in this channel.

*Submitted to the Journal of High Energy Physics*



## 1 Introduction

One of the most intriguing open questions in physics is the nature of dark matter (DM). While DM is thought to be the dominant nonbaryonic contribution to the matter density of the universe [1], its detection and identification in terrestrial and spaceborne experiments remains elusive. At the CERN LHC, the DM particles may be produced in high-energy proton-proton collisions, if the DM particles interact with the standard model (SM) quarks or gluons via new couplings at the electroweak scale [2, 3]. Although DM particles cannot be directly detected at the LHC, their production could be inferred from an observation of events with a large transverse momentum imbalance (missing transverse momentum,  $p_T^{\text{miss}}$ , defined in Section 2).

Another highly important issue is the hierarchy problem, which involves the large energy gap between the electroweak ( $M_{EW}$ ) and Planck ( $M_{Pl}$ ) scales [4]. Proposed solutions to this problem include theories with large extra dimensions, such as the model of Arkani-Hamed, Dimopoulos, Dvali (ADD) [5, 6]. The ADD model postulates that there exist  $n$  compactified extra dimensions in which gravitons can propagate freely and that the true scale ( $M_D$ ) of the gravitational interaction in this  $4+n$  dimensional space-time is of the same order as  $M_{EW}$ . The compactification scale  $R$  of the additional dimensions is related to the two gravitational scales by  $M_{Pl} \sim R^n M_D^{n+2}$ . For  $M_D \sim M_{EW}$ ,  $R \gg 1/M_{EW}$  for a wide range of  $n$ , leading to a near-continuous mass spectrum of Kaluza–Klein graviton states. Although the gravitons would not be observed directly at the LHC, their production would be manifest as events broadly distributed in  $p_T^{\text{miss}}$ .

In generic models of DM and graviton production, various SM particles can recoil against these undetected particles, producing a variety of final states with significant  $p_T^{\text{miss}}$ . The monophoton, or  $\gamma + p_T^{\text{miss}}$ , final state has the advantage of being identifiable with high efficiency and purity. In DM production through a vector or axial vector mediator, a photon can be radiated from incident quarks (Fig. 1 left). Models of this process have been developed by the CMS-ATLAS Dark Matter Forum [7]. It is also possible that the DM sector couples preferentially to the electroweak sector, leading to an effective interaction  $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \gamma\chi\bar{\chi}$  [8], where  $\chi$  is the DM particle (Fig. 1 center). In ADD graviton production, the graviton can couple directly to the photon (Fig. 1 right) or to a quark. In this paper, we examine final states containing large  $p_T^{\text{miss}}$  in the presence of a photon with large transverse momentum ( $p_T$ ), and search for an excess of events over the SM prediction. Data collected by the CMS experiment in 2016 with an integrated luminosity of  $12.9 \text{ fb}^{-1}$  are analyzed. Results are interpreted in the context of these three models.

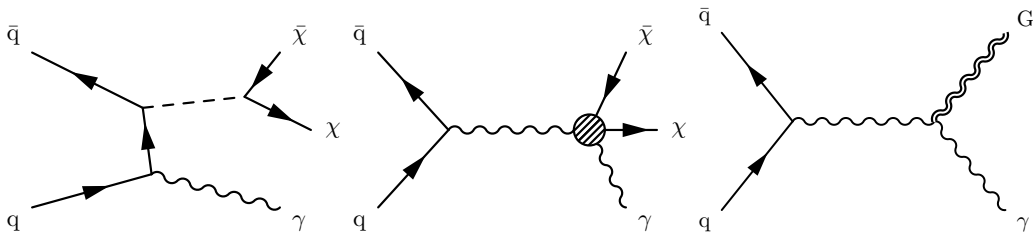


Figure 1: Leading-order diagrams of the simplified DM model (left), electroweak-DM effective interaction (center), and graviton (G) production in the ADD model (right), with a final state of  $\gamma$  and large  $p_T^{\text{miss}}$ .

The primary irreducible background for the  $\gamma + p_T^{\text{miss}}$  signal is SM Z boson production associated with a photon,  $Z(\rightarrow \nu\bar{\nu}) + \gamma$ . Other SM backgrounds include  $W(\rightarrow \ell\nu) + \gamma$  (having a final state photon, and a lepton  $\ell$  that escapes detection),  $W \rightarrow \ell\nu$  (where  $\ell$  is misidentified as

a photon),  $\gamma + \text{jets}$ , quantum chromodynamics (QCD) multijet events (with a jet misidentified as a photon),  $t\bar{t}\gamma$ ,  $VV\gamma$  (where  $V$  refers to a  $W$  or a  $Z$  boson),  $Z(\rightarrow \ell\bar{\ell}) + \gamma$ , and noncollision sources, such as beam halo interactions and detector noise.

A previous search in the  $\gamma + p_{\text{T}}^{\text{miss}}$  final state using  $p p$  collisions at  $\sqrt{s} = 8 \text{ TeV}$ , corresponding to an integrated luminosity of  $19.6 \text{ fb}^{-1}$ , was reported by the CMS experiment in Ref. [9]. The ATLAS experiment has also reported a similar search in  $3.2 \text{ fb}^{-1}$  of  $p p$  collisions at  $\sqrt{s} = 13 \text{ TeV}$  [10].

## 2 The CMS detector and candidate reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel ( $|\eta| < 1.48$ ) and two endcap ( $1.48 < |\eta| < 3.00$ ) sections, where  $\eta$  is the pseudorapidity. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

An energy resolution of about 1% is reached within the barrel section of the ECAL for unconverted or late-converting photons with  $p_{\text{T}} \geq 60 \text{ GeV}$ . The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of  $|\eta| = 1$ , rising to about 2.5% at  $|\eta| = 1.4$  [11]. The time resolution of photons at the ECAL is  $< 200 \text{ ps}$  for depositions  $> 10 \text{ GeV}$ . In the  $\eta$ - $\phi$  plane, where  $\phi$  is the azimuthal angle, and for  $|\eta| < 1.48$ , the HCAL cells map onto  $5 \times 5$  arrays of ECAL crystals to form calorimeter towers projecting radially outward from the center of the detector. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in Ref. [12].

Events of interest are selected using a two-tiered trigger system [13]. The first level (L1), 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 time interval of less than  $4 \mu\text{s}$ . 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 less than 1 kHz before data storage.

Event reconstruction is performed using a particle-flow (PF) technique [14, 15], which reconstructs and identifies individual particles using an optimized combination of information from all subdetectors. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Muon identification and momentum measurements are performed by combining the information from the inner trackers and outer muon chambers.

The PF candidates in each event are clustered into jets via the anti- $k_t$  algorithm [16] with a distance parameter of 0.4. Jet energies, computed from a simple sum of 4-momenta of the constituent PF candidates, are corrected to account for the contributions from particles associated with additional interactions within the same or nearby bunch crossings (pileup), as well as to compensate for the nonlinearities in the measured particle energies. Jet energy corrections are obtained from simulation, and are confirmed through in situ measurements of the energy momentum balance in dijet and photon + jet events.

The uncorrected missing transverse momentum vector ( $\vec{p}_T^{\text{miss}}$ ) is defined as the negative vector sum of the transverse momenta of all PF candidates in an event. This quantity is adjusted with the difference of uncorrected and corrected jets for a consistent and more accurate missing momentum measurement [17]. The magnitude of  $\vec{p}_T^{\text{miss}}$  is referred to as the missing transverse momentum,  $p_T^{\text{miss}}$ .

The reconstruction of photons and electrons begins with the identification of clusters of energy deposited in the ECAL with little or no observed energy in the corresponding HCAL region. For each candidate cluster, the reconstruction algorithm searches for hits in the pixel and strip trackers that can be associated with the cluster. Such associated hits are called electron seeds, and are used to initiate a special track reconstruction based on a Gaussian sum filter [18, 19], which is optimized for electron tracks. A “seed veto” removes photon candidates with an associated electron seed.

Selections based on calorimetric information and isolation are applied to distinguish photons from electromagnetic (EM) showers caused by hadrons. The calorimetric requirements for photons comprise  $H/E < 0.05$  and  $\sigma_{\eta\eta} < 0.0102$ , where  $H/E$  is the ratio of hadronic to EM energy deposition. The variable  $\sigma_{\eta\eta}$ , described in detail in Ref. [11], represents the width of the electromagnetic shower in the  $\eta$  direction, which is generally larger in showers from hadronic activity. For a photon candidate to be considered as isolated, scalar sums of the transverse momenta of PF charged hadrons, neutral hadrons, and photons within a cone of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$  around the candidate photon must individually fall below the bounds defined for 80% signal efficiency. Only the PF candidates that do not overlap with the EM shower of the candidate photon are included in the isolation sums.

Each PF charged hadron is reconstructed from a track and can be associated with an interaction vertex it originates from. Therefore, the isolation sum over PF charged hadrons should be computed using only the candidates sharing an interaction vertex with the photon candidate. However, because photon candidates are not reconstructed from tracks, their vertex association is ambiguous. When an incorrect vertex is assigned, photon candidates that are not isolated can appear otherwise. To mitigate the rate for accepting nonisolated candidates as photon candidates, the maximum charged hadron isolation value over all vertex hypotheses (worst isolation) is used.

Another consequence of calorimetry-driven reconstruction is that stray ECAL clusters produced by mechanisms other than p p collisions can be misidentified as photons. In particular, beam halo muons that accompany proton beams and penetrate the detector longitudinally, and the interaction of particles in the ECAL photodetectors (“ECAL spikes”) have been found to produce spurious photon candidates at nonnegligible rates. To reject these backgrounds, the ECAL signal in the seed crystal of the photon cluster is required to be within  $\pm 3$  ns of the arrival time expected for particles originating from a collision. In addition, the candidate cluster must comprise more than a single ECAL crystal. Furthermore, the maximum of the total energy along all possible paths of beam halo particles passing through the cluster is calculated for each photon candidate. This quantity, referred to as the halo total energy, is required to be below a threshold defined to retain 95% of the true photons, while rejecting 80% of the potential halo clusters.

### 3 Event selection

The integrated luminosity of the analyzed data sample, derived from a preliminary measurement using the method described in [20], is  $(12.9 \pm 0.8) \text{ fb}^{-1}$ . The data sample is collected with

a single-photon trigger that requires at least one photon candidate with  $p_T > 165$  GeV. The photon candidate must have  $H/E < 0.1$ , to reject jets. The photon energy reconstructed in the trigger is less precise relative to that derived later in the offline selection. Therefore, the thresholds in the trigger on both  $H/E$  and  $p_T^\gamma$ , where  $p_T^\gamma$  is the photon  $p_T$ , are less restrictive than their offline counterparts. The trigger efficiency is measured to be about 98% for events passing the analysis selection with  $p_T^\gamma > 175$  GeV.

From the recorded data, events are selected by requiring  $p_T^{\text{miss}} > 170$  GeV and at least one photon with  $p_T^\gamma > 175$  GeV in the fiducial region of the ECAL barrel ( $|\eta| < 1.44$ ). Events are rejected if the minimum opening angle between  $\vec{p}_T^{\text{miss}}$  and any of the four highest transverse momenta jets,  $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$ , is less than 0.5. This requirement significantly suppresses spurious  $p_T^{\text{miss}}$  backgrounds from mismeasured jets. Only jets with  $p_T > 30$  GeV and  $|\eta| < 5$  are considered in the  $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}})$  calculation. The candidate photon transverse momentum vector and  $\vec{p}_T^{\text{miss}}$  must be separated by more than 2 radians. Finally, to reduce the contribution from the  $W(\rightarrow \ell\nu) + \gamma$  process, events are vetoed if they contain an electron or a muon with  $p_T > 10$  GeV that is separated from the photon by  $\Delta R > 0.5$ .

## 4 Signal and background modeling

The SM backgrounds and signal are modeled using both simulated events and recorded data. The two methods are described in the following Sections.

### 4.1 Monte Carlo simulation for signal and background modeling

Monte Carlo (MC) simulation is used to model the signal and some classes of SM background events. For the SM backgrounds, the primary hard interaction is simulated using the MADGRAPH5\_aMC@NLO version 2.2.2 [21] or PYTHIA8.212 [22] generators employing the NNPDF3.0 [23] leading-order (LO) parton distribution function (PDF) set at the strong coupling value  $\alpha_S = 0.130$ . Parton showering and hadronization are provided in PYTHIA8.212 through the underlying-event tune CUETP8M1 [24]. Multiple minimum-bias events are overlaid on the primary interaction to model the distribution of pileup in data. Generated particles are processed through the full GEANT4-based simulation of the CMS detector [25, 26].

For the DM signal hypothesis, MC simulation samples are produced requiring  $p_T^\gamma > 130$  GeV and  $|\eta^\gamma| < 2.5$ . A large number of DM simplified model samples are generated, varying the masses of the mediator and DM particles. Similarly, electroweak-DM effective interaction samples are generated with a range of dark matter masses. For the ADD hypothesis, events are generated using PYTHIA8.212, requiring  $p_T^\gamma > 130$  GeV, with no restriction on the photon pseudorapidity. Samples are prepared in a grid of number of extra dimensions and  $M_D$ . The efficiency of the full event selection on these signal models ranges between 0.12 and 0.27 for the DM simplified models, 0.42 and 0.45 for electroweak DM production, and 0.22 and 0.28 for the ADD model, depending on the parameters of the models.

Predictions for signal and background MC yields are rescaled by an overall correction factor ( $\rho$ ) that accounts for the differences in event selection efficiency between data and simulation. The value of  $\rho = 0.94 \pm 0.06$  reflects the product of three correction factors:  $0.94 \pm 0.01$  for photon identification and isolation,  $1.00 \pm 0.01$  for the electron seed veto, and  $1.00 \pm 0.06$  for the combination of the worst isolation, the BHM total energy requirement, and the lepton veto. The selection efficiencies are measured in data using the tag-and-probe technique [27]. Events with  $Z \rightarrow ee$  decays are employed for measuring the photon identification and isolation efficiencies, while a  $Z \rightarrow \mu\mu\gamma$  sample is utilized to extract the other efficiency factors [28].

The most significant SM backgrounds in this search are from the associated production of a Z or W boson with a high-energy photon, denoted as  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$ . When the Z boson decays into a neutrino-antineutrino pair, the final state exhibits a high- $p_T$  photon and large  $p_T^{\text{miss}}$ . Similarly, if the W boson decays into a lepton-neutrino pair and the lepton escapes detection, the event appears to be  $\gamma + p_T^{\text{miss}}$ . Together, these processes account for approximately 70% of the SM background, with 50% from  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  alone.

The estimation of  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$  backgrounds is based on MADGRAPH5\_aMC@NLO simulations at LO in QCD and with up to two additional partons in the final state. In addition to the selection efficiency correction factor  $\rho$ , these samples are weighted event-by-event with the product of two factors. The first factor matches the distribution of the generator-level  $p_T^\gamma$  to that calculated at next-to-next-to-leading order (NNLO) in QCD using the DYRES program [29]. The second factor, taken from Refs. [30, 31], further corrects the backgrounds to account for next-to-leading order (NLO) electroweak effects. The estimated contributions from the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$  processes after applying the selections in Section 3 are given in Table 1, and amount to  $215 \pm 32$  and  $57.2 \pm 8.0$  events, respectively. Statistical and systematic uncertainties are combined in quadrature. The statistical uncertainty is subdominant and is due to the finite size of the simulation sample. Systematic uncertainties in the estimated  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$  yields have four contributions and are summarized in Table 2. The first is associated with the PDF and the choice of renormalization and factorization scales ( $\mu_R$  and  $\mu_F$ ) used in generating the events. The relative uncertainty from these sources are 5.4% and 8.9% in the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$  yields, respectively. Uncertainty from the PDF is evaluated by varying the weight of each event based on the standard deviation of the event weight distribution as given by the NNPDF set. Uncertainties from the choice of  $\mu_R$  and  $\mu_F$  are evaluated by setting the scales to twice or half the nominal values and taking the minima and maxima of the resulting event weights. Second, the uncertainty due to missing higher-order electroweak corrections is taken as the magnitude of the NLO correction. The uncertainty from this source is 11% for the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  process and 7% for  $W(\rightarrow \ell\nu) + \gamma$ . The third uncertainty is on the selection efficiency correction factor  $\rho$ , with the main contribution from the statistical uncertainties in individual efficiency measurements. A fourth uncertainty is assigned to cover the uncertainties in the jet energy scale [32], photon energy scale [33], pileup, and the scale and resolution in  $p_T^{\text{miss}}$ . The combined relative uncertainties from the third and fourth categories in the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $W(\rightarrow \ell\nu) + \gamma$  yields are 6% and 6.2%, respectively.

To validate the predictions from simulation, observed and MC simulated data are compared in two control regions. One region consists of events with two same-flavor leptons of opposite-charge and a photon, which is dominated by the  $Z(\rightarrow \ell\bar{\ell}) + \gamma$  process. The photon is selected by criteria identical to those used in the signal candidate event selection, while the leptons are required to have  $p_T > 10$  GeV and the dilepton invariant mass must lie between 60 and 120 GeV. Furthermore, the recoil  $U^{\ell\bar{\ell}} = |\vec{p}_T^{\text{miss}} + \vec{p}_T^\ell + \vec{p}_T^{\bar{\ell}}|$  [27] must be greater than 170 GeV to emulate the  $p_T^{\text{miss}}$  in  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  events. In addition to simulated  $Z(\rightarrow \ell\bar{\ell}) + \gamma$  events, MC samples of  $t\bar{t}\gamma$ ,  $Z(\rightarrow \ell\bar{\ell}) + \text{jets}$ , and multiboson events are also considered. In total,  $68.1 \pm 3.8$  events are predicted in the dilepton control region, and 64 events are observed. The dominant uncertainty is theoretical. Using the ratio of acceptances between the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  and  $Z(\rightarrow \ell\bar{\ell}) + \gamma$  simulations, this validation is used to predict the  $Z(\rightarrow \nu\bar{\nu}) + \gamma$  contribution to the candidate sample of  $242 \pm 35$ , which is in agreement with the purely simulation-based prediction given previously. The uncertainty in this prediction is mainly due to the limited event yields in the control samples.

The second region is defined by requirements of exactly one electron or muon with  $p_T >$

30 GeV, one photon with  $p_T > 175$  GeV,  $p_T^{\text{miss}} > 50$  GeV, and  $U^\ell = |\vec{p}_T^{\text{miss}} + \vec{p}_T^\ell| > 170$  GeV [17]. This region is dominated by  $W(\rightarrow \ell\nu) + \gamma$  production. A total of 108 events are observed in this region, where  $10.6 \pm 1.3$  non- $W + \gamma$  background events are expected. The ratio of the acceptance for  $W + \gamma$  events where the lepton is missed, compared to the acceptance for events where it is identified is estimated from simulation, and is multiplied with the background-subtracted observed yield of this control region. The product,  $69.2 \pm 7.6$ , gives a prediction of  $W(\rightarrow \ell\nu) + \gamma$  contribution in the signal region that is in agreement with the simulation-based estimate. As with the  $Z(\rightarrow \ell\bar{\ell}) + \gamma$  estimate, the dominant uncertainty is theoretical.

The SM  $t\bar{t}\gamma$ ,  $VV\gamma$ ,  $Z(\rightarrow \ell\bar{\ell}) + \gamma$ ,  $W \rightarrow \ell\nu$ , and  $\gamma + \text{jets}$  processes are minor ( $\sim 10\%$ ) backgrounds in the signal region. Although  $Z(\rightarrow \ell\bar{\ell}) + \gamma$  and  $\gamma + \text{jets}$  do not involve high- $p_T$  invisible particles, the former can exhibit large  $p_T^{\text{miss}}$  when the leptons are not reconstructed, and the latter when jet energy is severely mismeasured. The estimates for all five processes are taken from MADGRAPH5\_aMC@NLO simulations at leading order in QCD.

## 4.2 Background estimation using recorded data

An important background consists of  $W \rightarrow e\nu$  events in which the electron is misidentified as a photon. The misidentification occurs because of inefficiency in seeding electron tracks. A seeding efficiency of  $\epsilon = 0.977 \pm 0.002$  for electrons with  $p_T > 160$  GeV is measured in data using a tag-and-probe technique in  $Z \rightarrow ee$  events, and is verified with MC simulation. Misidentified electron events are modeled by a proxy sample of electron events, defined in data by requiring an ECAL cluster with a pixel seed. The proxy events must otherwise pass the same criteria used to select signal candidate events. The number of electron proxy events is then scaled by  $(1 - \epsilon)/\epsilon$  to yield an estimated contribution of  $52.7 \pm 4.2$  events from electron misidentification. The dominant uncertainty in this estimate is the statistical uncertainty in the measurement of  $\epsilon$ .

Electromagnetic showers from hadronic activity can also mimic a photon signature. This process is estimated by counting the numbers of events in two different subsets of a low- $p_T^{\text{miss}}$  multijet data sample. The first subset consists of events with a photon candidate that satisfies the signal selection criteria. These events contain both true photons and jets that are misidentified as photons. The second subset comprises events with a candidate photon that meets less stringent shower-shape requirements and inverted isolation criteria with respect to the signal candidates. Nearly all of the candidate photons in these events arise from jet misidentification. The hadron misidentification ratio is defined as the ratio between the number of the misidentified events in the first subset to the total number of events in the second subset. The numerator is estimated by fitting the shower shape distribution of the photon candidate in the first subset with template distributions. For true photons, a template for the shower width is formed using simulated  $\gamma + \text{jets}$  events. For jets misidentified as photons, the template is obtained from a sample selected by inverting the charged-hadron isolation and removing the shower-shape requirement entirely. Once the hadron misidentification ratio is computed, it is multiplied by the number of events in the high- $p_T^{\text{miss}}$  control sample with a photon candidate that satisfies the conditions used to select the second subset of the low- $p_T^{\text{miss}}$  control sample. The product,  $5.9 \pm 1.7$  events, is the estimate of the contribution of jet misidentification background in the signal region. The dominant uncertainty is systematic, and accounts for the effects of the fitting procedure, sample purity, photon candidate definition of the control samples, and the sample bias in the jet composition.

Finally, backgrounds from beam halo and spikes in the ECAL are estimated from fits of the angular and timing distributions of the calorimeter clusters. Energy clusters in the ECAL due



to beam halo muons are observed to concentrate around  $\phi \sim 0$  and  $\pi$ , while all other processes (collision-related processes and ECAL spikes) produce photon candidates that are uniformly distributed in  $\phi$ . The distribution of the cluster seed time provides a cross-check on this background estimate and an independent means to estimate the ECAL spikes contribution. Exploiting these features, a two-component fit of the  $\phi$  distribution with beam halo and uniform templates, and a three-component fit of the cluster seed time using the halo, spike, and prompt-photon templates are performed. In both fits, the halo template is obtained by requiring high halo total energy for candidate-like photon candidates. The timing distribution of the spike background is obtained by inverting the shower shape requirement in the candidate photon selection. The results of the two fits are combined into an uncertainty-weighted average. Beam halo and spike backgrounds of  $5.5^{+9.3}_{-5.5}$  and  $8.5 \pm 6.7$  events, respectively, are predicted, where the dominant uncertainty is statistical.

## 5 Results and interpretation

The estimated number of events and the associated uncertainty for each background process are given in Table 1. A total of 400 events are observed in data, which is in agreement with the total expected SM background of  $386 \pm 36$  events.

Distributions of  $p_T^\gamma$  and  $p_T^{\text{miss}}$  for the selected candidate events are shown in Fig. 2 together with their respective estimated background distributions. A summary of the systematic uncertainties for the background estimates is given in Table 2. The quoted systematic uncertainties in Table 2 follow the signal and background modeling discussion in Section 4.

Table 1: Summary of estimated background and observed candidate events. The quoted uncertainties for the background estimates are obtained by adding the systematic and statistical uncertainties in quadrature.

Process	Events
$Z(\rightarrow \nu\bar{\nu}) + \gamma$	$215 \pm 32$
$W(\rightarrow \ell\nu) + \gamma$	$57.2 \pm 8.0$
Electron misidentification	$52.7 \pm 4.2$
ECAL spikes	$8.5 \pm 6.7$
Beam halo	$5.5^{+9.3}_{-5.5}$
$\gamma + \text{jets}$	$10.1 \pm 5.7$
$W \rightarrow \mu\nu$	$8.5 \pm 3.0$
$t\bar{t}\gamma$	$8.2 \pm 0.6$
Jet misidentification	$5.9 \pm 1.7$
$VV\gamma$	$5.5 \pm 1.8$
$W \rightarrow \tau\nu$	$5.2 \pm 2.3$
$Z(\rightarrow \ell\bar{\ell}) + \gamma$	$2.9 \pm 0.2$
Total background	$386 \pm 36$
Data	400

No excess of data with respect to the SM prediction is observed and limits are set on the aforementioned DM and ADD models. The evaluation of systematic uncertainties for the simulated signal follows the same procedures used for simulated backgrounds (Section 4). For each signal model, a 95% confidence level (CL) cross section upper bound is obtained utilizing the asymptotic  $CL_s$  criterion [34–37]. In this method, a Poisson likelihood for the observed number of events is maximized under different signal strength hypotheses, taking the systematic

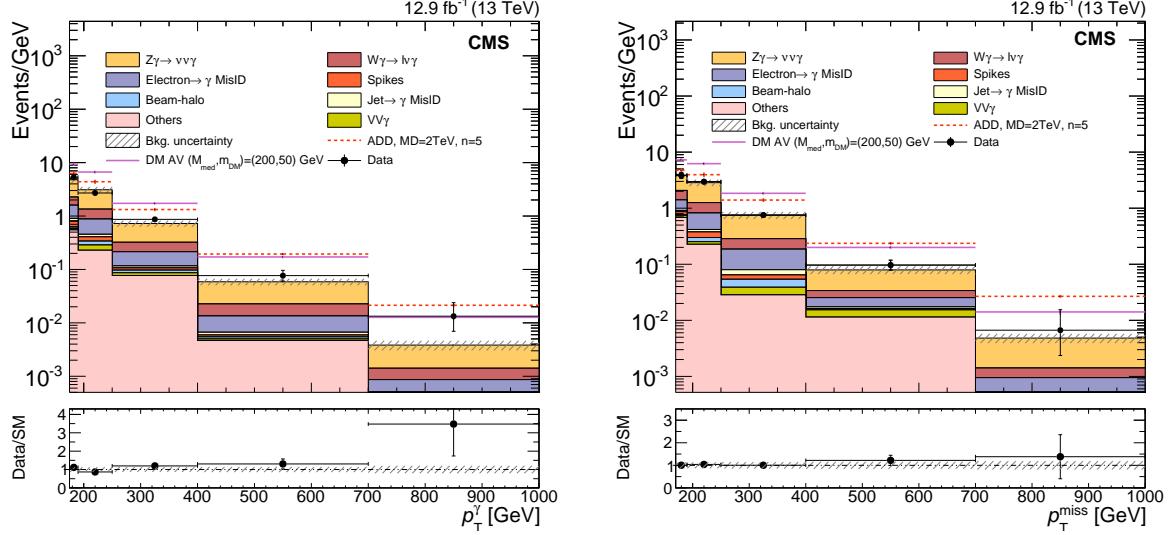


Figure 2: The  $p_T^\gamma$  (left) and  $p_T^{\text{miss}}$  (right) distributions for the candidate sample, compared with estimated contributions from SM backgrounds. In the legends, “others” includes the contribution from  $\gamma + \text{jets}$ ,  $W \rightarrow \ell\nu$ ,  $Z(\rightarrow \ell\bar{\ell}) + \gamma$ , and  $t\bar{t}\gamma$  backgrounds. The background uncertainties include statistical and systematic components. The last bin includes the overflow. The lower panel shows the ratio of data and SM background predictions, where the hatched band shows the systematic uncertainty.

Table 2: Summary of relative systematic uncertainties (%) for different background estimates. The middle column indicates the component of the estimated SM background that is affected by each uncertainty.

Source	Background component	Value
Integrated luminosity [20]	All simulation-based	6.2
Jet and $\gamma$ energy scale, $p_T^{\text{miss}}$ resolution	All simulation-based	3–4
Data/simulation factor	All simulation-based	6
PDF, $\mu_R$ and $\mu_F$	$Z(\rightarrow \nu\bar{\nu}) + \gamma$ , $W(\rightarrow \ell\nu) + \gamma$	5–9
Electroweak higher-order corrections	$Z(\rightarrow \nu\bar{\nu}) + \gamma$ , $W(\rightarrow \ell\nu) + \gamma$	7–11
Hadronic misidentification ratio	Jet misid.	29
Electron seeding $\epsilon$	Electron misid.	6
ECAL spikes template shape	ECAL spikes	75
Beam halo template shape	Beam halo	+169/–100
$\gamma + \text{jets}$ yield	$\gamma + \text{jets}$	54

uncertainties as nuisance parameters that modify the signal and background predictions. Each nuisance parameter is assigned a log-normal probability distribution, using the systematic uncertainty value as the width. The best fit background predictions differ from the original by at most 4%. Confidence intervals are drawn by comparing these maximum likelihood values to those computed from background-only and signal-plus-background pseudo-data.

### 5.1 Limits on simplified dark matter models

The simplified DM models proposed by the LHC Dark Matter Forum [7] are designed to facilitate the comparison and translation of various DM search results. In the models considered in this analysis, Dirac DM particles couple to a vector or axial-vector mediator, which in turn couples to the SM quarks. Model points are identified by a set of four parameters: the DM mass  $m_{\text{DM}}$ , the mediator mass  $M_{\text{med}}$ , the universal mediator coupling to quarks  $g_q$ , and the mediator coupling to DM particles  $g_{\text{DM}}$ . In this analysis, we fix the values of  $g_q$  and  $g_{\text{DM}}$  to 0.25 and 1.0, respectively, and scan the  $M_{\text{med}}-m_{\text{DM}}$  plane [38]. The search is not yet sensitive to the spin-0 mediator models defined in Ref. [7].

Figure 3 shows the 95% CL cross section upper limits with respect to the corresponding theoretical cross section ( $\mu_{95} = \sigma_{95\%}/\sigma_{\text{theory}}$ ) for the vector and axial-vector mediator scenarios, in the  $M_{\text{med}}-m_{\text{DM}}$  plane. The solid red (lighter) and black (darker) curves are the expected and observed contours of  $\mu_{95} = 1$  (exclusion contour). The region with  $\mu_{95} < 1$  is excluded under nominal  $\sigma_{\text{theory}}$  hypotheses. The uncertainty in the expected upper limit includes the experimental uncertainties. The uncertainty in the theoretical cross section is translated to the uncertainty in the observed exclusion contour. While there is little difference in kinematic properties between the two scenarios, the production cross section for heavier dark matter in the vector mediator scenario tends to be higher [7], and therefore the exclusion region broader. For the simplified DM models considered, mediator masses of up to 700 GeV are excluded for small  $m_{\text{DM}}$  values.

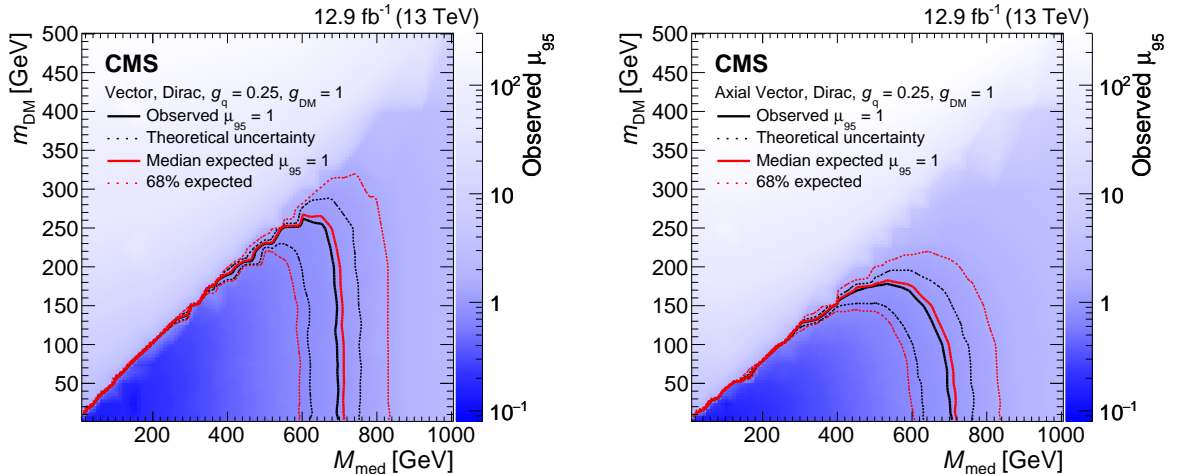


Figure 3: The ratio of 95% CL cross section upper limits to theoretical cross section ( $\mu_{95}$ ), for DM simplified models with vector (left) and axial-vector (right) mediators, assuming  $g_q = 0.25$  and  $g_{\text{DM}} = 1$ . Expected and observed  $\mu_{95} = 1$  contours are overlaid. The region below the observed contour is excluded.

The exclusion contours in Fig. 3 are also translated into the  $\sigma_{\text{SI/SD}}-m_{\text{DM}}$  plane, where  $\sigma_{\text{SI/SD}}$  are the spin-independent/dependent DM-nucleon scattering cross sections. The translation and

presentation of the result follows the prescription given in Ref. [38]. In particular, to enable a direct comparison with results from direct detection experiments, these limits are calculated at 90% CL [7]. When compared to the direct detection experiments, the limits obtained from this search provide stronger constraints for dark matter masses less than 2 and 200 GeV, assuming vector and axial-vector mediators, respectively.

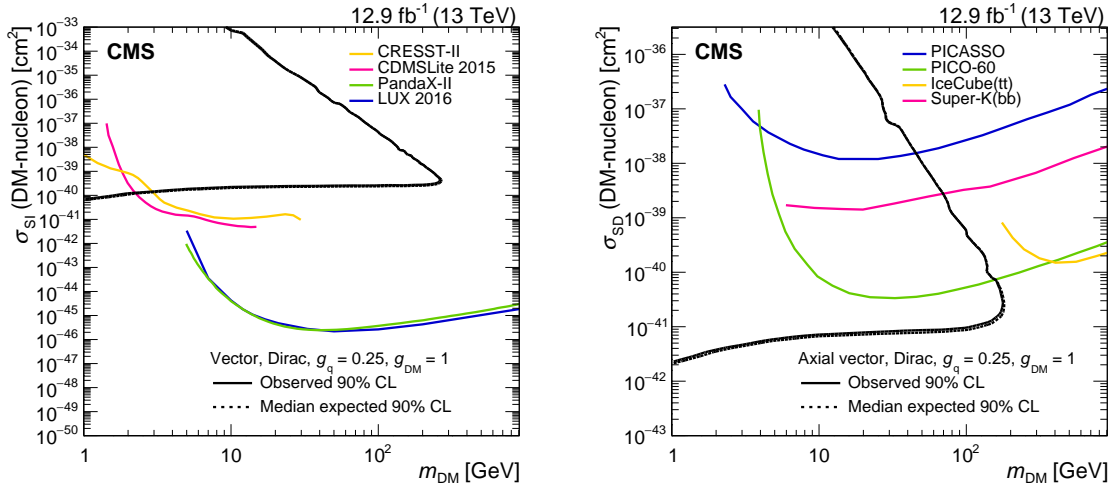


Figure 4: The 90% CL exclusion limits on the  $\chi$ -nucleon spin-independent (left) and spin-dependent (right) scattering cross sections involving vector and axial-vector operators, respectively, as a function of the  $m_{\text{DM}}$ . Simplified model DM parameters of  $g_q = 0.25$  and  $g_{\text{DM}} = 1$  are assumed. The region to the upper left of the contour is excluded. On the plots, the median expected 90% CL curve overlaps the observed 90% CL curve. Also shown are corresponding exclusion contours, where regions above the curves are excluded, from the recent results by CDMSLite [39], LUX [40], PandaX [41], CRESST-II [42], PICO-60 [43], IceCube [44], PICASSO [45] and Super-Kamiokande [46] Collaborations.

## 5.2 Limits on electroweak dark matter models

The DM effective field theory (EFT) model contains a dimension-7 contact interaction of type  $\gamma\gamma\chi\bar{\chi}$  [8]. The interaction is described by four parameters: the coupling to photons (parametrized in terms of coupling strengths  $k_1$  and  $k_2$ ), the DM mass  $m_{\text{DM}}$ , and the suppression scale  $\Lambda$ . Since the interaction cross section is directly proportional to  $\Lambda^{-6}$ , cross section upper limits are translated into lower limits on  $\Lambda$ . The expected and observed lower limits on  $\Lambda$  as a function of  $m_{\text{DM}}$  are shown in Fig. 5. Values of  $\Lambda$  up to 600 GeV are excluded at 95% CL.

## 5.3 Limits on the ADD model

Figure 6 shows the upper limit and the theoretically calculated ADD graviton production cross section for  $n = 3$  extra dimensions, as a function of  $M_D$ . Lower limits on  $M_D$  for various values of  $n$  extra dimensions are summarized in Table 3, and in Fig. 7 are compared to CMS results at  $\sqrt{s} = 8$  TeV [9]. Because the graviton production cross section scales as  $E^n / M_D^{n+2}$  [47], where  $E$  is the typical energy of the hard scattering,  $M_D$  can be an increasing or decreasing function of  $n$  for a fixed cross section value, approaching  $E$  as  $n \rightarrow \infty$ . Note that the value of  $E$  is dependent on the center-of-mass energy of the p p collision, and is  $\sim 2$  TeV for  $\sqrt{s} = 8$  TeV and  $\sim 3$  TeV for  $\sqrt{s} = 13$  TeV. Values of  $M_D$  up to 2.49 TeV for  $n = 6$  are excluded by the current analysis.

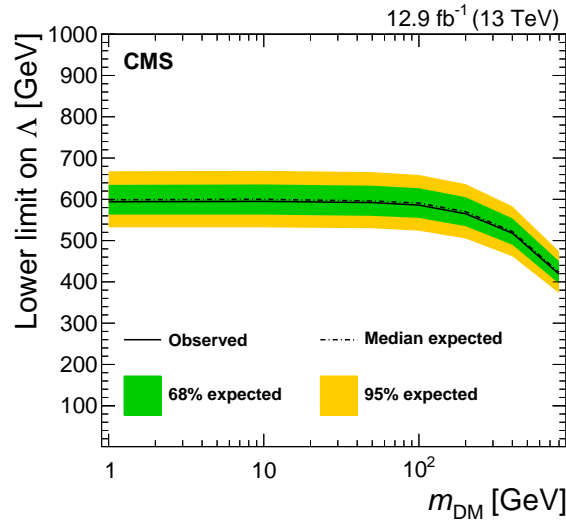


Figure 5: The 95% CL expected and observed lower limits on  $\Lambda$  as a function of  $m_{DM}$ , for a dimension-7 operator EFT model.

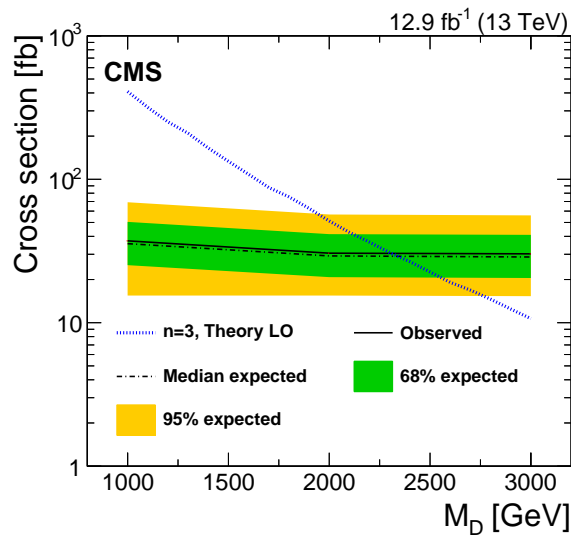


Figure 6: The 95% CL upper limits on the ADD graviton production cross section, as a function of  $M_D$  for  $n = 3$  extra dimensions.

Table 3: The 95% CL observed and expected lower limits on  $M_D$  as a function of  $n$ , the number of ADD extra dimensions.

$n$	Obs. limit (TeV)	Exp. limit (TeV)
3	2.31	2.34
4	2.36	2.38
5	2.43	2.46
6	2.49	2.51

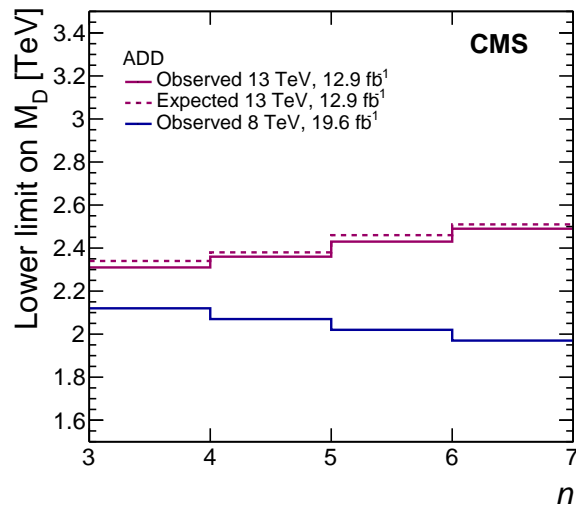


Figure 7: Lower limit on  $M_D$  as a function of  $n$ , the number of ADD extra dimensions.

## 6 Summary

Proton-proton collisions producing large missing transverse momentum and a high transverse momentum photon have been investigated to search for new phenomena, using a data set corresponding to  $12.9 \text{ fb}^{-1}$  of integrated luminosity recorded at  $\sqrt{s} = 13 \text{ TeV}$  at the CERN LHC. No deviations from the standard model predictions are observed. Constraints are set on the production cross sections for dark matter and large extra dimension gravitons at 95% confidence level, which are then translated to limits on the parameters of the individual models. For the simplified dark matter production models considered, the search excludes mediator masses of up to  $700 \text{ GeV}$  for low-mass dark matter. For an effective dimension-7 photon-dark matter contact interaction, values of  $\Lambda$  up to  $600 \text{ GeV}$  are excluded. For the ADD model with extra spatial dimensions, values of the fundamental Planck scale up to  $2.31\text{--}2.49 \text{ TeV}$ , depending on the number of extra dimensions, are excluded. These are the most stringent limits to date using the monophoton final state.

## Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New

Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

## References

- [1] R. J. Gaitskell, "Direct detection of dark matter", *Ann. Rev. Nucl. Part. Sci.* **54** (2004) 315, doi:10.1146/annurev.nucl.54.070103.181244.
- [2] P. J. Fox, R. Harnik, J. Kopp, and Y. Tsai, "Missing energy signatures of dark matter at the LHC", *Phys. Rev. D* **85** (2012) 056011, doi:10.1103/PhysRevD.85.056011, arXiv:1109.4398.
- [3] J. Goodman et al., "Constraints on dark matter from colliders", *Phys. Rev. D* **82** (2010) 116010, doi:10.1103/PhysRevD.82.116010, arXiv:1008.1783.
- [4] L. Susskind, "Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory", *Phys. Rev. D* **20** (1979) 2619, doi:10.1103/PhysRevD.20.2619.
- [5] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "The hierarchy problem and new dimensions at a millimeter", *Phys. Lett. B* **429** (1998) 263, doi:10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315.
- [6] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, "Phenomenology, astrophysics, and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity", *Phys. Rev. D* **59** (1999) 086004, doi:10.1103/PhysRevD.59.086004.
- [7] D. Abercrombie et al., "Dark matter benchmark models for early LHC Run-2 searches: Report of the ATLAS/CMS Dark Matter Forum", (2015). arXiv:1507.00966.
- [8] A. Nelson et al., "Confronting the Fermi line with LHC data: An effective theory of dark matter interaction with photons", *Phys. Rev. D* **89** (2014) 056011, doi:10.1103/PhysRevD.89.056011, arXiv:1307.5064.

- [9] CMS Collaboration, “Search for new phenomena in monophoton final states in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *Phys. Lett. B* **755** (2016) 102, doi:10.1016/j.physletb.2016.01.057, arXiv:1410.8812.
- [10] ATLAS Collaboration, “Search for new phenomena in events with a photon and missing transverse momentum in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector”, *JHEP* **06** (2016) 059, doi:10.1007/JHEP06(2016)059, arXiv:1604.01306.
- [11] 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.
- [12] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [13] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017), no. 01, P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [14] CMS Collaboration, “Particle-flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{\text{miss}}$ ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [15] CMS Collaboration, “Commissioning of the particle-flow reconstruction in minimum-bias and jet events from  $pp$  collisions at 7 TeV”, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, 2010.
- [16] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_r$  jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [17] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in  $pp$  data at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P02006, doi:10.1088/1748-0221/10/02/P02006, arXiv:1411.0511.
- [18] W. Adam and R. Fr “Reconstruction of electrons with the Gaussian-sum filter in the CMS tracker at the LHC”, *J. Phys. G* doi:10.1088/0954-3899/31/9/N01.
- [19] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [20] CMS Collaboration, “CMS luminosity calibration for the  $pp$  reference run at  $\sqrt{s} = 5.02$  TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-16-001, CERN, 2016.
- [21] 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.
- [22] 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.
- [23] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [24] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.



- [25] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [26] J. Allison et al., “GEANT4 developments and applications”, *IEEE Trans. Nucl. Sci* **53** (2006) 270, doi:10.1109/TNS.2006.869826.
- [27] CMS Collaboration, “Measurements of inclusive W and Z Cross Sections in pp collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **01** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
- [28] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at  $\sqrt{s} = 7$  TeV with the CMS experiment”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
- [29] S. Catani, D. de Florian, G. Ferrera, and M. Grazzini, “Vector boson production at hadron colliders: transverse-momentum resummation and leptonic decay”, *JHEP* **12** (2015) 047, doi:10.1007/JHEP12(2015)047, arXiv:1507.06937.
- [30] A. Denner, S. Dittmaier, M. Hecht, and C. Pasold, “NLO QCD and electroweak corrections to  $W+\gamma$  production with leptonic W-boson decays”, *JHEP* **04** (2015) 018, doi:10.1007/JHEP04(2015)018, arXiv:1412.7421.
- [31] A. Denner, S. Dittmaier, M. Hecht, and C. Pasold, “NLO QCD and electroweak corrections to  $Z+\gamma$  production with leptonic Z-boson decays”, *JHEP* **02** (2016) 057, doi:10.1007/JHEP02(2016)057, arXiv:1510.08742.
- [32] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.
- [33] CMS Collaboration, “Isolated photon reconstruction and identification at  $\sqrt{s} = 7$  TeV”, CMS Physics Analysis Summary CMS-PAS-EGM-10-006, 2011.
- [34] 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.
- [35] 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.
- [36] The ATLAS and CMS Collaborations and the LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, (2011).
- [37] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].
- [38] G. Busoni et al., “Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter”, (2016). arXiv:1603.04156.
- [39] SuperCDMS Collaboration, “New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment”, *Phys. Rev. Lett.* **116** (2016) 071301, doi:10.1103/PhysRevLett.116.071301, arXiv:1509.02448.

- [40] LUX Collaboration, “Results from a search for dark matter in the complete LUX exposure”, *Phys. Rev. Lett.* **118** (2017) 021303, doi:10.1103/PhysRevLett.118.021303, arXiv:1608.07648.
- [41] PandaX-II Collaboration, “Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment”, *Phys. Rev. Lett.* **117** (2016) 121303, doi:10.1103/PhysRevLett.117.121303, arXiv:1607.07400.
- [42] CRESST Collaboration, “Results on light dark matter particles with a low-threshold CRESST-II detector”, *Eur. Phys. J. C* **76** (2016) 25, doi:10.1140/epjc/s10052-016-3877-3, arXiv:1509.01515.
- [43] PICO Collaboration, “Dark Matter Search Results from the PICO-60 C<sub>3</sub>F<sub>8</sub> Bubble Chamber”, (2017). arXiv:1702.07666.
- [44] IceCube Collaboration, “Improved limits on dark matter annihilation in the Sun with the 79-string IceCube detector and implications for supersymmetry”, *JCAP* **04** (2016) 022, doi:10.1088/1475-7516/2016/04/022, arXiv:1601.00653.
- [45] E. Behnke et al., “Final results of the PICASSO dark matter search experiment”, *Astropart. Phys.* **90** (2017) 85, doi:10.1016/j.astropartphys.2017.02.005, arXiv:1611.01499.
- [46] Super-Kamiokande Collaboration, “Search for Neutrinos from Annihilation of Captured Low-Mass Dark Matter Particles in the Sun By Super-Kamiokande”, *Phys. Rev. Lett.* **114** (2015) 141301, doi:10.1103/PhysRevLett.114.141301, arXiv:1503.04858.
- [47] G. F. Giudice, R. Rattazzi, and J. D. Wells, “Quantum gravity and extra dimensions at high-energy colliders”, *Nucl. Phys. B* **544** (1999) 3, doi:10.1016/S0550-3213(99)00044-9, arXiv:hep-ph/9811291.

## A The CMS Collaboration

### **Yerevan Physics Institute, Yerevan, Armenia**

A.M. Sirunyan, A. Tumasyan

### **Institut für Hochenergiephysik, Wien, Austria**

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

### **Institute for Nuclear Problems, Minsk, Belarus**

O. Dvornikov, V. Makarenko, V. Mossolov, J. Suarez Gonzalez, V. Zykunov

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

N. Shumeiko

### **Universiteit Antwerpen, Antwerpen, Belgium**

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

### **Vrije Universiteit Brussel, Brussel, Belgium**

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

### **Université Libre de Bruxelles, Bruxelles, Belgium**

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

### **Ghent University, Ghent, Belgium**

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, M. Tytgat, W. Van Driessche, W. Verbeke, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

### **Université de Mons, Mons, Belgium**

N. Bely

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

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, A. Custódio, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

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

**University of Sofia, Sofia, Bulgaria**

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

**Beihang University, Beijing, China**

W. Fang<sup>5</sup>, X. Gao<sup>5</sup>

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

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, M. Ruan, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

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

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

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

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez<sup>6</sup>, J.C. Sanabria

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

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

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

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, T. Susa

**University of Cyprus, Nicosia, Cyprus**

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

**Charles University, Prague, Czech Republic**

M. Finger<sup>7</sup>, M. Finger Jr.<sup>7</sup>

**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**

E. El-khateeb<sup>8</sup>, S. Elgammal<sup>9</sup>, A. Mohamed<sup>10</sup>

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

M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

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

P. Eerola, J. Pekkanen, M. Voutilainen

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

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

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

J. Talvitie, T. Tuuva

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

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

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France**

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

**Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France**

J.-L. Agram<sup>11</sup>, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte<sup>11</sup>, X. Coubez, J.-C. Fontaine<sup>11</sup>, D. Gelé, U. Goerlach, A.-C. Le Bihan, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>12</sup>, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

**Georgian Technical University, Tbilisi, Georgia**

A. Khvedelidze<sup>7</sup>

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>7</sup>

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

C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage

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

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

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

V. Cherepanov, G. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl<sup>13</sup>

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

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras<sup>14</sup>, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo<sup>15</sup>, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, A. Harb, J. Hauk, M. Hempel<sup>16</sup>, H. Jung, A. Kalogeropoulos, O. Karacheban<sup>16</sup>, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann<sup>16</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo<sup>13</sup>, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

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

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann<sup>13</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>13</sup>, I. Katkov<sup>12</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

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

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

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

K. Kousouris

**University of Ioánnina, Ioánnina, Greece**

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

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

N. Filipovic, G. Pasztor

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

G. Bencze, C. Hajdu, D. Horvath<sup>17</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>18</sup>, A.J. Zsigmond

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

N. Beni, S. Czellar, J. Karancsi<sup>19</sup>, A. Makovec, J. Molnar, Z. Szillasi

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

M. Bartók<sup>18</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari

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

J.R. Komaragiri

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

S. Bahinipati<sup>20</sup>, S. Bhowmik<sup>21</sup>, S. Choudhury<sup>22</sup>, P. Mal, K. Mandal, A. Nayak<sup>23</sup>, D.K. Sahoo<sup>20</sup>, N. Sahoo, S.K. Swain

**Panjab University, Chandigarh, India**

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

**University of Delhi, Delhi, India**

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

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

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

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

P.K. Behera

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

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>13</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

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

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

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

S. Banerjee, R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>21</sup>, G. Majumder, K. Mazumdar, T. Sarkar<sup>21</sup>, N. Wickramage<sup>24</sup>

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

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani<sup>25</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>25</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>26</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>27</sup>, M. Zeinali

**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, C. Caputo<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a,b</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,13</sup>, R. Venditti<sup>a,b</sup>, P. Verwilligen<sup>a</sup>

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

G. Abbiendi<sup>a</sup>, C. Battilana, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>,

R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a,b,13</sup>

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

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

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

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,28</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a,b,13</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>13</sup>

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

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

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

L. Brianza<sup>a,b,13</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b,13</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, G. De Nardo<sup>a,b</sup>, S. Di Guida<sup>a,d,13</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,13</sup>, P. Paolucci<sup>a,13</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen<sup>a</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a,13</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, M. Dall'Osso<sup>a,b</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, U. Gasparini<sup>a,b</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, F. Montecassiano<sup>a</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, M. Sgaravatto<sup>a</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

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

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

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

L. Alunni Solestizi<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>

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

K. Androsov<sup>a</sup>, P. Azzurri<sup>a,13</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedi<sup>a</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,28</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,b</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A. Savoy-Navarro<sup>a,29</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

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

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, D. Del Re<sup>a,b,13</sup>, M. Diemoz<sup>a</sup>, S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, F. Margaroli<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>



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

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c,13</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, F. Ravera<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, P. Traczyk<sup>a,b</sup>

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

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

**Kyungpook National University, Daegu, Korea**

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

**Chonbuk National University, Jeonju, Korea**

A. Lee

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

H. Kim

**Hanyang University, Seoul, Korea**

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

**Korea University, Seoul, Korea**

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

**Seoul National University, Seoul, Korea**

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

**University of Seoul, Seoul, Korea**

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

**Sungkyunkwan University, Suwon, Korea**

Y. Choi, C. Hwang, J. Lee, I. Yu

**Vilnius University, Vilnius, Lithuania**

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>30</sup>, F. Mohamad Idris<sup>31</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>32</sup>, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

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

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

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

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

A. Morelos Pineda

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

D. Krofcheck

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

P.H. Butler

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

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

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

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

K. Bunkowski, A. Byszuk<sup>33</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, B. Calpas, A. Di Francesco, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev<sup>34,35</sup>, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

L. Chtchipoounov, V. Golovtsov, Y. Ivanov, V. Kim<sup>36</sup>, E. Kuznetsova<sup>37</sup>, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

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

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

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

T. Aushev, A. Bylinkin<sup>35</sup>

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

M. Chadeeva<sup>38</sup>, E. Popova, V. Rusinov

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

V. Andreev, M. Azarkin<sup>35</sup>, I. Dremin<sup>35</sup>, M. Kirakosyan, A. Leonidov<sup>35</sup>, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin<sup>39</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

**Novosibirsk State University (NSU), Novosibirsk, Russia**V. Blinov<sup>40</sup>, Y.Skovpen<sup>40</sup>, D. Shtol<sup>40</sup>**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

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

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**P. Adzic<sup>41</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

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

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

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

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, C. Erice, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, P. Vischia, J.M. Vizan Garcia

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

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

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, Y. Chen, A. Cimmino, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco<sup>42</sup>, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer<sup>13</sup>, M.J. Kortelainen, M. Krammer<sup>1</sup>, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic<sup>43</sup>, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi<sup>44</sup>, M. Rovere, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas<sup>45</sup>, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns<sup>46</sup>, G.I. Veres<sup>18</sup>, M. Verweij, N. Wardle, H.K. Wöhri, A. Zagozdinska<sup>33</sup>, W.D. Zeuner**Paul Scherrer Institut, Villigen, Switzerland**

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

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

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab,

C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quitnat, M. Rossini, M. Schönerberger, A. Starodumov<sup>47</sup>, V.R. Tavolaro, K. Theofilatos, R. Wallny

**Universität Zürich, Zurich, Switzerland**

T.K. Aarrestad, C. Amsler<sup>48</sup>, L. Caminada, M.F. Canelli, A. De Cosa, S. Donato, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Yang, A. Zucchetta

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

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

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

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

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

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

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

A. Adiguzel, F. Boran, S. Cerci<sup>49</sup>, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>50</sup>, E.E. Kangal<sup>51</sup>, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut<sup>52</sup>, K. Ozdemir<sup>53</sup>, D. Sunar Cerci<sup>49</sup>, B. Tali<sup>49</sup>, H. Topakli<sup>54</sup>, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

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

**Bogazici University, Istanbul, Turkey**

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

**Istanbul Technical University, Istanbul, Turkey**

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

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

B. Grynyov

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

L. Levchuk, P. Sorokin

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

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

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

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

**Imperial College, London, United Kingdom**

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne,

A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko<sup>47</sup>, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>64</sup>, T. Virdee<sup>13</sup>, J. Wright, S.C. Zenz

**Brunel University, Uxbridge, United Kingdom**

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

**Baylor University, Waco, USA**

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

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

R. Bartek, A. Dominguez

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

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, USA**

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

**Brown University, Providence, USA**

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

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

R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, M. Squires, D. Stolp, K. Tos, M. Tripathi

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

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, V. Valuev, M. Weber

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

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

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

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

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, M. Franco Sevilla, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

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

D. Anderson, J. Bendavid, A. Bornheim, J. Bunn, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

M.B. Andrews, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

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

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, T. Mulholland, K. Stenson, S.R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fairfield University, Fairfield, USA**

D. Winn

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

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

**University of Florida, Gainesville, USA**

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

**Florida International University, Miami, USA**

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

**Florida State University, Tallahassee, USA**

A. Ackert, T. Adams, A. Askew, S. Bein, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, T. Perry, H. Prosper, A. Santra, R. Yohay

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

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, H. Trauger, N. Varelas, H. Wang, Z. Wu, J. Zhang

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

B. Bilki<sup>66</sup>, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>67</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok<sup>68</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, USA**

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

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

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, L. Forthomme, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

**Kansas State University, Manhattan, USA**

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

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

F. Rebassoo, D. Wright

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

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

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

D. Abercrombie, B. Allen, A. Apyan, V. Azzolini, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

**University of Minnesota, Minneapolis, USA**

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

**University of Mississippi, Oxford, USA**

J.G. Acosta, S. Oliveros

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

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

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

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**

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

**Northwestern University, Evanston, USA**

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

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

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>34</sup>, M. Planer, A. Reinsvold, R. Ruchti, N. Rupperecht, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

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

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

**Princeton University, Princeton, USA**

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully

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

S. Malik

**Purdue University, West Lafayette, USA**

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, J.F. Schulte, J. Sun, F. Wang, W. Xie

**Purdue University Northwest, Hammond, USA**

N. Parashar, J. Stupak

**Rice University, Houston, USA**

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

**University of Rochester, Rochester, USA**

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

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

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

**University of Tennessee, Knoxville, USA**

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

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

O. Bouhali<sup>69</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon<sup>70</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov, K.A. Ulmer

**Texas Tech University, Lubbock, USA**

N. Akchurin, J. Damgov, F. De Guio, C. Dragoiu, P.R. Duderø, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

**Vanderbilt University, Nashville, USA**

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

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

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

D.A. Belknap, J. Buchanan, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods



†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 4: Also at Universidade Federal de Pelotas, Pelotas, Brazil
- 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
- 6: Also at Universidad de Antioquia, Medellin, Colombia
- 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 8: Now at Ain Shams University, Cairo, Egypt
- 9: Now at British University in Egypt, Cairo, Egypt
- 10: Also at Zewail City of Science and Technology, Zewail, Egypt
- 11: Also at Université de Haute Alsace, Mulhouse, France
- 12: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 13: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 14: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- 15: Also at University of Hamburg, Hamburg, Germany
- 16: Also at Brandenburg University of Technology, Cottbus, Germany
- 17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 18: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- 19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- 20: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Indian Institute of Science Education and Research, Bhopal, India
- 23: Also at Institute of Physics, Bhubaneswar, India
- 24: Also at University of Ruhuna, Matara, Sri Lanka
- 25: Also at Isfahan University of Technology, Isfahan, Iran
- 26: Also at Yazd University, Yazd, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at Purdue University, West Lafayette, USA
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 34: Also at Institute for Nuclear Research, Moscow, Russia
- 35: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 37: Also at University of Florida, Gainesville, USA
- 38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 39: Also at California Institute of Technology, Pasadena, USA
- 40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 42: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
- 43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences,

Belgrade, Serbia

44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

45: Also at National and Kapodistrian University of Athens, Athens, Greece

46: Also at Riga Technical University, Riga, Latvia

47: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

48: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

49: Also at Adiyaman University, Adiyaman, Turkey

50: Also at Istanbul Aydin University, Istanbul, Turkey

51: Also at Mersin University, Mersin, Turkey

52: Also at Cag University, Mersin, Turkey

53: Also at Piri Reis University, Istanbul, Turkey

54: Also at Gaziosmanpasa University, Tokat, Turkey

55: Also at Ozyegin University, Istanbul, Turkey

56: Also at Izmir Institute of Technology, Izmir, Turkey

57: Also at Marmara University, Istanbul, Turkey

58: Also at Kafkas University, Kars, Turkey

59: Also at Istanbul Bilgi University, Istanbul, Turkey

60: Also at Yildiz Technical University, Istanbul, Turkey

61: Also at Hacettepe University, Ankara, Turkey

62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

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

64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain

65: Also at Utah Valley University, Orem, USA

66: Also at BEYKENT UNIVERSITY, Istanbul, Turkey

67: Also at Erzincan University, Erzincan, Turkey

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

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

70: Also at Kyungpook National University, Daegu, Korea