

# Model-independent search for pair production of new bosons decaying into muons in proton-proton collisions at $\sqrt{s} = 13$ TeV



## The CMS collaboration

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

**ABSTRACT:** The results of a model-independent search for the pair production of new bosons within a mass range of  $0.21 < m < 60$  GeV, are presented. This study utilizes events with a four-muon final state. We use two data sets, comprising  $41.5 \text{ fb}^{-1}$  and  $59.7 \text{ fb}^{-1}$  of proton-proton collisions at  $\sqrt{s} = 13$  TeV, recorded in 2017 and 2018 by the CMS experiment at the CERN LHC. The study of the 2018 data set includes a search for displaced signatures of a new boson within the proper decay length range of  $0 < c\tau < 100$  mm. Our results are combined with a previous CMS result, based on  $35.9 \text{ fb}^{-1}$  of proton-proton collisions at  $\sqrt{s} = 13$  TeV collected in 2016. No significant deviation from the expected background is observed. Results are presented in terms of a model-independent upper limit on the product of cross section, branching fraction, and acceptance. The findings are interpreted across various benchmark models, such as an axion-like particle model, a vector portal model, the next-to-minimal supersymmetric standard model, and a dark supersymmetric scenario, including those predicting a non-negligible proper decay length of the new boson. In all considered scenarios, substantial portions of the parameter space are excluded, expanding upon prior results.

**KEYWORDS:** Beyond Standard Model, Hadron-Hadron Scattering

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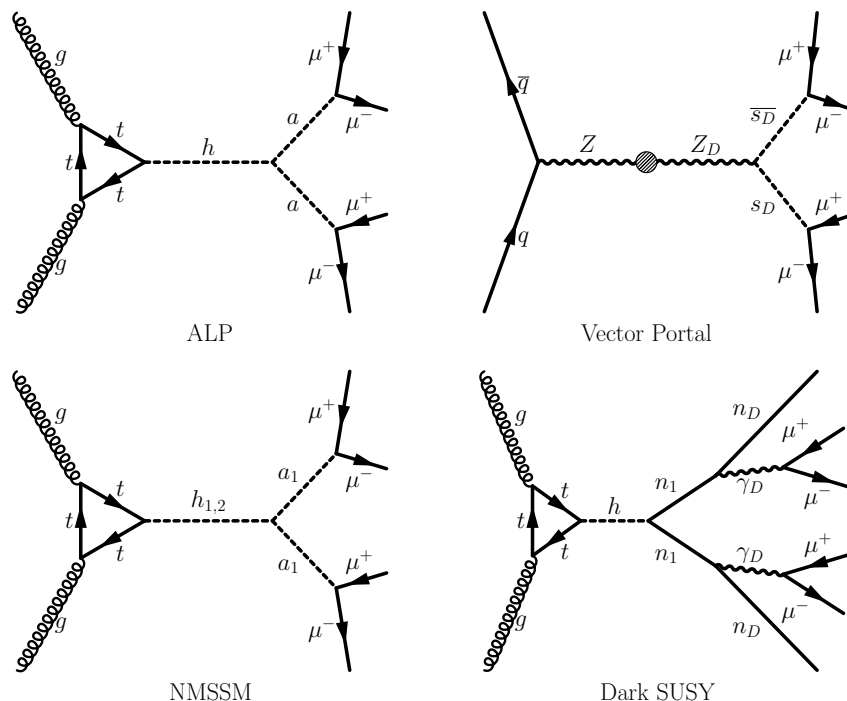
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**1 Introduction**

Although the standard model (SM) [1–3] of particle physics provides a multitude of high-precision predictions consistent with decades of experimental results, it does not explain the existence of dark matter [4, 5]. Many models have been proposed that predict new bosons as dark matter candidates [6–8]. To date, no direct experimental evidence has materialized for particles beyond the SM (BSM), and in that context the idea of new bosons with non-negligible proper decay length [9] is of increasing interest. In this paper, we present a model-independent search for the pair production of a new boson that decays into a pair of oppositely charged muons. This can happen in proton-proton (pp) collisions as  $pp \rightarrow 2a + X \rightarrow 4\mu + X$ , where  $a$  is the new neutral boson and  $X$  are possible spectator particles [10]. The new boson,  $a$ , can be produced via various “portals” connecting to a hidden sector, such as a Higgs boson portal (either SM or non-SM) or a vector boson portal [8, 11, 12]. Here, the production vertices of dimuons, i.e., pairs of oppositely-charged muons in the final state, can be either prompt or displaced. The displaced case results from the decays of long-lived BSM bosons. This generic signature enables us to set a model-independent limit on the product of the new boson production cross section, branching fraction to muons squared, and acceptance. With this model-independent limit, further interpretation is possible in models with four muons in the final state.

We interpret the model-independent results in the context of several BSM benchmarks, including an axion-like particle (ALP) model [7, 13–16], a vector portal model with a dark scalar boson  $s_D$  [17–22], the next-to-minimal supersymmetric standard model (NMSSM) [6, 23–30], and supersymmetry (SUSY) models with hidden sectors (dark SUSY) [8, 22, 31]. In the ALP model [15], the SM-like Higgs boson,  $h$ , decays to the ALP,  $a$ , via  $h \rightarrow 2a$ . The ALP



**Figure 1.** The Feynman diagrams of the benchmark signal models in the  $s$ -channel. Time moves from left to right.

then promptly decays into a dimuon. In the vector portal model, a massive dark vector boson  $Z_D$  decays to two new scalar bosons  $s_D$ , via  $Z_D \rightarrow s_D \bar{s}_D$ , where we assume that the  $s_D$  is not self-conjugate, i.e., it is not equal to its antiparticle. The dark scalar boson  $s_D$  promptly decays to a dimuon. In the NMSSM, two of the three charge parity (CP) even, neutral Higgs bosons  $h_1$  or  $h_2$  (generically denoted  $h_{1,2}$ ) can decay to one of the two CP-odd neutral Higgs bosons  $a_1$  via  $h_{1,2} \rightarrow 2a_1$ . The CP-odd boson  $a_1$  promptly decays to a dimuon. In the dark SUSY scenario, the breaking of a new  $U(1)_D$  symmetry gives rise to a massive dark photon  $\gamma_D$ . This dark photon can couple to SM photons via a small kinetic mixing parameter,  $\varepsilon$ . The proper decay length of the dark photon depends on its mass,  $m_{\gamma_D}$ , and  $\varepsilon$ . We use a signal topology where an SM-like  $h$  decays to the lightest non-dark neutralino,  $n_1$ , via  $h \rightarrow 2n_1$ . These neutralinos then decay via  $n_1 \rightarrow n_D + \gamma_D$ , where  $n_D$  is an undetectable dark neutralino. The dark photon  $\gamma_D$  then decays to a dimuon. Figure 1 displays the Feynman diagrams of the benchmark signal models.

The search presented in this analysis improves upon the previous result published by the CMS collaboration in ref. [32]. Compared to this study, we add more data and add two new benchmark models, the ALP and vector portal models, and probe a larger mass range of the new, neutral boson  $a$  ( $0.21 < m_a < 60$  GeV, compared to  $0.25 < m_a < 8.5$  GeV in ref. [32]). Other searches at the LHC for  $h \rightarrow 2a$  include the  $4\mu$  [32–35],  $4\tau$  [36, 37],  $4\ell$  [38–42],  $4b$  [43, 44],  $4\gamma$  [45],  $2b\ 2\tau$  [46, 47],  $2\mu\ 2\tau$  [48, 49],  $6q$  [50], and collimated fermions [51, 52] final states. This model-independent analysis considers both promptly-decaying and long-lived ( $c\tau < 100$  mm) bosons, and it is complementary to those studies exploring  $\varepsilon$  in models with promptly-decaying [53, 54] and long-lived [55, 56] bosons that decay to a dimuon.

Two data sets are used for this analysis, which include data collected using multiple triggers in 2017 and 2018. These data sets correspond to integrated luminosities of 41.5 and 59.7 fb<sup>-1</sup> of pp collisions at a center-of-mass energy of  $\sqrt{s} = 13$  TeV, respectively. The results of the 2017 and 2018 data sets are first combined, corresponding to a total integrated luminosity of 101 fb<sup>-1</sup>. For the search mass range below 9 GeV, we also combine these two data sets with a previously published analysis that examined the 2016 data-taking period [32], leading to results in the search mass range up to 9 GeV that correspond to a combined integrated luminosity of 137 fb<sup>-1</sup>. Due to triggers using a primary vertex constraint in 2017, only 2018 data are used for the displaced signatures searches.

The CMS detector is improved in this data run with a new silicon pixel tracking detector [57] installed and commissioned in 2017 [58]. It features a larger detector volume with four layers in the barrel and three layers in the endcaps. Compared to the previous pixel detector, the innermost layer is positioned closer to the interaction point (IP) and the outermost layer is located farther from the IP. The new pixel detector can cope with a higher particle rate, improves impact parameter resolution, and increases the tracking efficiency. The performance of the hardware trigger algorithms for muons is also improved [59]. The analysis criteria are modified to accommodate the search in an extended model parameter space as compared to ref. [32]. New benchmark models are added to further test the model independence and diversify the interpretation.

This paper is organized as follows: first, we discuss the layout and operation of the CMS detector in section 2. Next, we review the simulation of signal samples in section 3, event selection criteria in section 4, and signal shape modeling in section 5. We then present the processes of background estimation in section 6, followed by a discussion of the systematic uncertainties in section 7. Finally, we provide the results of this analysis in section 8, which is followed by a brief summary in section 9. Tabulated results are provided in the HEPData record for this analysis [60].

## 2 The CMS detector

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

Muons are measured in the pseudorapidity range  $|\eta| < 2.4$ , with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single muon trigger efficiency exceeds 90% over the full  $\eta$  range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum ( $p_T$ ) resolution of 1% in the barrel and 3% in the endcaps, for muons with  $p_T$  up to 100 GeV. The  $p_T$  resolution in the barrel is better than 7% for muons with  $p_T$  up to 1 TeV [61].

Events of interest are selected using a two-tiered trigger system [62]. The first level (L1), is composed of custom hardware processors, and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of about  $4 \mu\text{s}$ . 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. The HLT further reduces the event rate to around 1 kHz before the data are sent for permanent storage [62].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [63].

### 3 Benchmark signal models

Simulated signal events are generated with Monte Carlo (MC) simulations and are used to determine the effect of the data selection criteria (described in section 4) on the various signal models. In the ALP model, production of the SM-like  $h$  via gluon-gluon ( $gg$ ) fusion and its subsequent decays are simulated at next-to-leading order (NLO) with the matrix-element generator MADGRAPH5\_aMC@NLO2.4.2 [64, 65]. The mass of the SM-like  $h$  is fixed to 125 GeV and masses between 0.5 and 30 GeV for the ALP are simulated. For the vector portal model, production of the spin-1  $Z_D$  and its subsequent decays are simulated at NLO with MADGRAPH5\_aMC@NLO2.6.5. Masses of the  $Z_D$  between 85 and 200 GeV are simulated, thereby including the maximum  $Z_D$  production cross section [11]; the masses of the scalar boson  $s_D$  are simulated from 5 to 55 GeV depending on the kinematic constraints set by the  $Z_D$  mass.

For the NMSSM, production of the CP-even  $h_{1,2}$  via  $gg$  fusion and its decay to the CP-odd  $a_1$  is carried out at leading order with PYTHIA8.230 [66]. Since the  $h_{1,2}$  might not be the observed SM Higgs boson [67–69], mass values of  $m_{h_{1,2}}$  between 90 and 150 GeV are simulated. This range is motivated by constraints set by the relic density measurements from WMAP [70], Planck [71], and searches at LEP [72–77]. The mass of the boson  $a_1$  is set to vary between 0.5 and 3 GeV as motivated in ref. [78].

In the dark SUSY model, production of the SM-like Higgs boson via  $gg$  fusion and its decays are simulated at NLO with MADGRAPH5\_aMC@NLO2.4.2. The masses of the SM-like Higgs boson, the neutralino  $n_1$ , and the dark neutralino  $n_D$  are fixed to 125, 60, and 1 GeV, respectively. Dark photon masses  $m_{\gamma_D}$  are simulated between 0.25 and 58 GeV and only the decays to oppositely charged muons are considered. Since the dark photon interacts weakly with SM particles, its decay width is negligible compared to the dimuon mass resolution.

Discussed in greater detail in section 4, we consider displaced tracks and vertices for the case of long-lived mediators in the 2018 analysis only. This is because the 2017 data set lacks triggers that are comparable to those used in the 2018 analysis for displaced signatures. When considering muon displacement for the 2018 analysis, we model the displaced vertices in the lab frame via an exponential distribution with  $c\tau_{\gamma_D}$  between 0 and 100 mm. This proper decay length of 0 to 100 mm is required to achieve a uniform distribution of  $\epsilon_{\text{Full}}/\alpha_{\text{Gen}}$  (see section 4) and to ensure that the displaced signal decays within the pixel detector volume so that at least one pixel hit can be required in the dimuon selection.

For all benchmark samples, pp collisions at 13 TeV are simulated using a set of parton distribution functions (PDFs) provided by NNPDF3.1 [79]. The parton shower, underlying event activity, and hadronization processes at the LHC are modeled with the MC event generator PYTHIA8.230 using the CP5 tune [80]. Pileup (PU), or additional collisions, are added to these events, which are run through the full CMS detector simulation based on GEANT4 [81]. These events are then reconstructed with the same algorithms that are used for the data.

#### 4 Event selection

Several triggers were used to collect the data used in this study, all exhibiting a total efficiency that exceeds 90% for all signal benchmarks described in section 3. For the 2017 data set, we employ a double muon trigger with  $p_T$  thresholds of 23 and 12 GeV. Three additional triggers with lower  $p_T$  thresholds are implemented to further improve the trigger efficiency for potential signals: a double muon trigger requiring muons of the same sign, with  $p_T$  thresholds of 18 and 9 GeV, a triple muon trigger with  $p_T$  thresholds of 12, 5, and 5 GeV, and a triple tracker muon trigger with  $p_T$  thresholds of 12, 10, and 5 GeV. This last trigger requires “tracker muons” for which the tracker muon algorithm matches candidate muon segments from the tracker to segments from the innermost muon station [61].

The 2018 data set retains the last three triggers used in the 2017 data set but replaces the first trigger by one that is sensitive to displaced signatures. The so-called “double standalone” (SA) muon trigger requires at least two muons reconstructed using the muon detectors only [61], with a transverse momentum and pseudorapidity of  $p_T > 23$  GeV and  $|\eta| < 2$ , respectively. This trigger was operated in 2018 and is used in the 2018 analysis. This double SA muon trigger does not rely on a primary vertex (PV) constraint for the track fit and is sensitive to both the prompt and displaced muons probed in this search. The PV is taken to be the vertex corresponding to the hard scattering location of the original pp collision, evaluated using tracking information alone [82]. There was no equivalent trigger in 2017; a study on 2017 data of the comparable double SA muon triggers available in 2018 either showed poor efficiencies for displaced muons in the pixel volume of the CMS experiment or negligible effective luminosities, thereby eliminating the possibility of investigating displaced track and vertex signatures in the 2017 analysis.

For both the 2017 and 2018 analyses, we require at least four offline reconstructed muons in each event. Among these muons, the 2017 analysis requires all muons to be reconstructed with the particle-flow (PF) algorithm [83], which performs a global fit that combines information from each subdetector, while the 2018 analysis requires at least three muons to be reconstructed with the PF algorithm and at most one SA muon reconstructed using only the information from the muon system. Selecting one possible SA muon in the 2018 analysis mitigates the efficiency lost for displaced muon reconstruction in the tracker by roughly 30%. Additional offline selection criteria are as follows: each muon in the 2017 and 2018 analyses must have  $p_T > 8$  GeV and  $|\eta| < 2.4$ . For the 2017 analysis, we require at least two “high- $p_T$  muons”, i.e., muons with  $p_T > 13$  GeV. In the 2018 analysis, we require a higher threshold for these two “high- $p_T$  muons”, with  $p_T > 24$  GeV. For both the 2017 and 2018 analyses, we also require that these “high- $p_T$  muons” are located in the region  $|\eta| < 2$ .

For both the 2017 and 2018 analyses the following selections are made: any two oppositely charged muons in the event are paired as long as their invariant mass is below 60 GeV. The decay vertices of each dimuon in each event are reconstructed using the Kalman filtering (KF) technique [84], and only those vertices with a valid fitted vertex are retained. We then select the two dimuons closest in invariant mass. These two dimuons must not have any muons in common with each other. A dimuon that does not contain a high- $p_T$  muon is labeled a low- $p_T$  dimuon (denoted as  $\mu\mu_2$ ), while the other dimuon, which includes at least one high- $p_T$  muon, is called a high- $p_T$  dimuon (denoted as  $\mu\mu_1$ ). In the scenario where both dimuons contain a high- $p_T$  muon, the dimuons are randomly labeled to prevent bias in the kinematic distributions. All single muons not included in the two dimuons are called orphan muons. No requirements are applied to the orphan muons. We require that each of the two dimuons contain at least one muon that has at least one valid hit in any of the layers of the pixel detector. This requirement ensures the selected dimuons originate from the signal bosons that decay in the pixel detectors.

To further ensure that the signal muons in each dimuon decay from the same boson, we require a limit on the Kalman-fitted dimuon vertex probability,  $P_{\mu\mu}$ . For the 2017 analysis, this level is set to 15%. As the dimuon transverse displacement ( $L_{xy}$ ) and the opening angle of the two muons ( $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ ) increases, the fitted vertex probability decreases. As the 2018 analysis considers displaced signals, we account for this difference by defining a probability threshold that is a function of  $L_{xy}$ ,  $\Delta R$ , and the number of SA muons,  $N_{SA}$ , and select valid fitted vertices based on the criterion  $P_{\mu\mu} > P(L_{xy}, \Delta R, N_{SA})$ .

The model independence of the results in this search is confirmed by verifying that the ratio of the full reconstruction efficiency  $\epsilon_{Full}$  over the generator level acceptance  $\alpha_{Gen}$  is independent of all signal benchmarks. The acceptance  $\alpha_{Gen}$  is defined as the fraction of MC-generated signal events that pass the generator-level kinematic and geometric selection criteria. The parameter  $\epsilon_{Full}$  is defined as the fraction of MC-generated events that pass the trigger and full event selection criteria. The valid-vertices criterion is particularly important, as this selection contributes to the overall uniformity of the distribution in  $\epsilon_{Full}/\alpha_{Gen}$ . The ratio  $\epsilon_{Full}/\alpha_{Gen}$  is found to be insensitive to variations in all signal benchmark parameters: over all of the MC samples, an average value of  $0.403 \pm 0.001$  ( $0.418 \pm 0.001$ ) for  $\epsilon_{Full}/\alpha_{Gen}$  is obtained for the 2017 (2018) analysis, along with its statistical uncertainty.

Finally, we place a selection on the transverse displacement of  $L_{xy} < 16$  cm and on the longitudinal displacement of  $L_z < 51.6$  cm. The upper bounds on  $L_{xy}$  and  $L_z$  correspond to the dimensions of the outermost layers of the CMS pixel system and define the volume in which the decay of a new boson can be probed by this analysis.

We also require that each dimuon is sufficiently isolated by having a total isolation sum of less than 2.3 GeV. This isolation sum,  $Iso_{\mu\mu} = \sum_{tracks} p_T(\text{track})$ , is calculated as the scalar sum of the transverse momenta of all reconstructed tracks with  $p_T > 0.5$  GeV in the vicinity of the dimuon, i.e., within  $\Delta R < 0.4$  and  $|z_{\text{track}} - z_{\mu\mu}| < 0.1$  cm. Here,  $z_{\text{track}}$  is defined as the  $z$  coordinate of the point of closest approach of the track to the primary vertex along the beam axis, while  $z_{\mu\mu}$  is the  $z$  position of the vertex associated with the dimuon propagated back to the beamline along the dimuon direction vector. Tracks included in the dimuon reconstruction are excluded from the isolation calculation. Requiring  $Iso_{\mu\mu} < 2.3$  GeV

Selection	Additional information	Requirement	
		2017	2018
Signal muon candidates	All 4 signal muons	4 PF loose muons	$\geq 3$ PF loose muons and $\leq 1$ SA muon
$p_T$ ( $ \eta $ )	All 4 signal muons	$p_T > 8 \text{ GeV}$ ( $ \eta  < 2.4$ )	$p_T > 8 \text{ GeV}$ ( $ \eta  < 2.4$ )
	2 signal muons	$p_T > 13 \text{ GeV}$ ( $ \eta  < 2.0$ )	$p_T > 24 \text{ GeV}$ ( $ \eta  < 2.0$ )
Invariant mass	Each dimuon	$m_{\mu\mu_{1,2}} < 60 \text{ GeV}$	$m_{\mu\mu_{1,2}} < 60 \text{ GeV}$
Fitted dimuon vertex probability	Each dimuon	$P_{\mu\mu_{1,2}} > 0.15$	$P_{\mu\mu_{1,2}} > P(L_{xy}, \Delta R, N_{SA})$
Dimuon isolation	Each dimuon	$\text{Iso}_{\mu\mu_{1,2}} < 2.3 \text{ GeV}$ ( $\Delta R < 0.4$ )	$\text{Iso}_{\mu\mu_{1,2}} < 2.3 \text{ GeV}$ ( $\Delta R < 0.4$ )
Fiducial volume	Each dimuon	—	$L_{xy} < 16.0 \text{ cm}$ $L_z < 51.6 \text{ cm}$

**Table 1.** The event selection requirements for the 2017 and 2018 analyses. In the signal muon selection row, the particle-flow loose muons refer to those muons that have tracks in both the tracker and the muon system, which is contrasted with the standalone (SA) muon selection, which only requires tracks in the muon system.

effectively removes about 72% of the quantum chromodynamic (QCD) background radiation. For a comprehensive and compact representation of all selection criteria, see table 1.

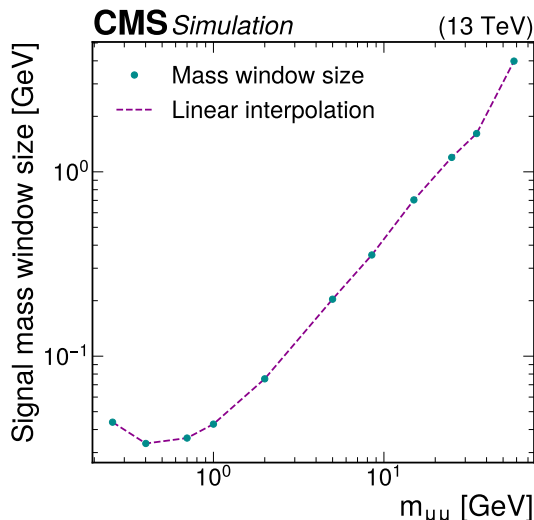
## 5 Signal shape modeling and signal region definition

The target new boson is presumed to be weakly coupled to SM particles with a narrow width; therefore, the shape of the dimuon invariant mass distribution is fully determined by the detector resolution and final-state radiation (FSR) from the muons.

The signal region (SR), defined by the signal mass window in the two-dimensional (2D) plane of  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ , is determined by fitting the prompt signal shape distributions of the MC signal samples with a double-sided Crystal Ball (CB) function (modified from [85] to include a tail on each side of the Gaussian function). The fitting results for the displaced signal show no significant difference within the statistical fluctuations. This composite function consists of a Gaussian core and two power-law tails. The sigma parameter of the CB function describes the width of the Gaussian fit to the signal and, consequently, the signal resolution. To set the mass window size across the signal mass phase space, we extract the sigma parameter from the mass fit for each simulated mass point and plot it as a function of the invariant dimuon mass. To create a continuous signal mass window, we use the values obtained by linearly interpolating the plotted data points.

Because the two dimuons originate from identical bosons, the signal mass window selection is motivated by the requirement of consistent invariant masses of the dimuons. This





**Figure 2.** The mass window size as a function of invariant dimuon mass. It is derived from a Crystal Ball function fitting to MC signal events to contain 90% of events. The wider mass window size around  $m_{\mu\mu} \lesssim 0.4$  GeV is due to the deteriorating mass resolution for near-collinear dimuons in the decays of low-mass bosons.

requirement is displayed in equation (5.1) below,

$$|m_{\mu\mu_1} - m_{\mu\mu_2}| < W((m_{\mu\mu_1} + m_{\mu\mu_2})/2) \quad (5.1)$$

where  $W$  is a function of the dimuon invariant masses  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ , and is based on the interpolation of the sigma parameters previously discussed. To determine the best signal significance,  $S/\sqrt{S+B}$ , where  $S$  is the signal and  $B$  is the expected background in the SR, thereby maximizing the discovery potential of this work, we examine the effect of four different signal efficiencies for prompt signals: 80%, 85%, 90%, and 95%.

For all signal efficiencies chosen, the signal significance decreases as the dimuon mass increases. However, over the entire mass range probed,  $0.21 < m_{\mu\mu} < 60$  GeV, a signal mass window providing a 90% efficiency on signal events yielded the best signal significance. Figure 2 displays the size of the signal mass window as a function of invariant dimuon mass (green dots) with the line derived from linear interpolation (dashed, purple line). Thus, given the combination of the mass window size and placement in the  $(m_{\mu\mu_1}, m_{\mu\mu_2})$  mass phase space, we achieve the optimal balance of signal significance and efficiency across the entire signal mass range, which we use to define the signal region (SR). This selection ultimately carves out the signal region in the 2D plane of  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ , as illustrated by the dashed lines in figures 3 and 4.

## 6 Background estimation

To estimate the background, we first divide the mass range into regions below and above the  $Y$  resonances and then split the range below the  $Y$  further at the location of the  $J/\psi$  resonance. We exclude the mass ranges that contain the  $J/\psi$  (2.72–3.24 GeV) and the  $Y$  (9–11 GeV) resonances. For the following discussion, we estimate the background in each region using fully data-driven methods based on data collected with the CMS detector.

## 6.1 Background below the $Y$ resonances

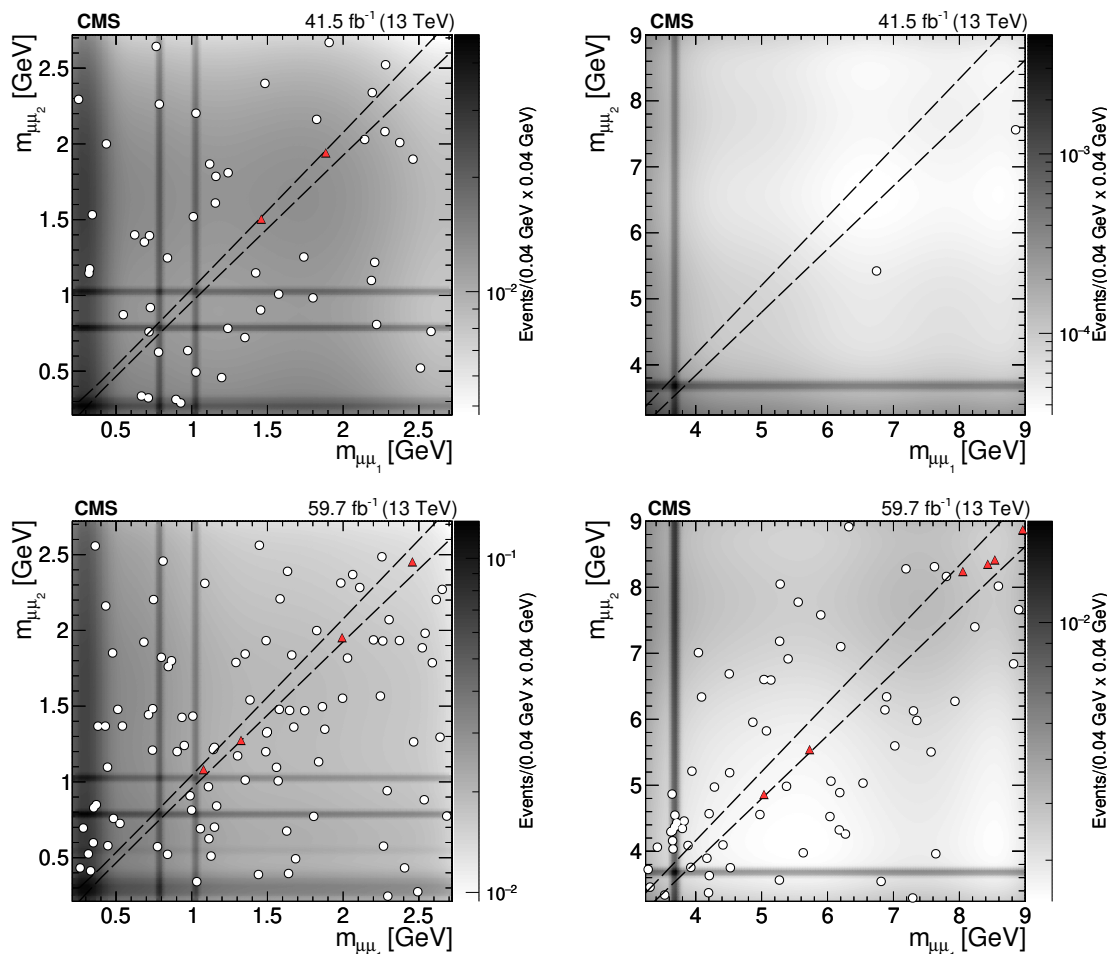
The major background contribution below the  $Y$  resonances originates from QCD multijet processes. The QCD multijet background is dominated by events in which two  $b$  quarks decay to  $2\mu + X$  or decay through low-mass meson resonances such as  $\omega$ ,  $\rho$ ,  $\phi$ , and  $\psi(2S)$ . A two-dimensional template  $T(m_{\mu\mu_1}, m_{\mu\mu_2})$  is constructed in the plane of the two dimuon invariant masses to estimate the QCD background.

For both the 2017 and 2018 analyses the template is constructed over several steps. First, a control sample is selected from the data. Events are required to have only one dimuon, at least one orphan muon, and pass the event selection criteria as applied to signal candidates, including the vertex probability and isolation selection on the only dimuon, the pixel hit requirements, and all of the signal triggers. The primary HLT used in this study is a high- $p_T$ , double muon trigger; consequently, the three muon selection requirement must contain two high- $p_T$  muons. If an event includes more than one orphan muon, the muon with the highest  $p_T$  is selected. Depending on where the high- $p_T$  muons are, these events are separated into two categories. The first category corresponds to events where both muons in the only dimuon are high- $p_T$  muons, the mass of this dimuon system is used to model the  $m_{\mu\mu_1}$  template. The second category contains events where the orphan muon is a high- $p_T$  muon and the dimuon contains another high- $p_T$  muon, the mass of the dimuon defines, in that case, the  $m_{\mu\mu_2}$  variable. This procedure ensures that kinematic differences between signal events that have exactly two high- $p_T$  dimuons or just one high- $p_T$  dimuon are accounted for. For the 2018 analysis, the only dimuon in the event is required to have at most one SA muon, pass the selection on fitted vertex probability, and have at least one hit in the pixel system as explained in section 4.

Next, two one-dimensional (1D) dimuon mass templates,  $T_I(m_{\mu\mu_1})$  and  $T_{II}(m_{\mu\mu_2})$ , are obtained from the control sample. Each distribution is fitted with a function comprised of a Gaussian distribution for each light meson resonance and a set of sixth-degree Bernstein polynomials for the continuum background shape. The 2D template  $T(m_{\mu\mu_1}, m_{\mu\mu_2})$  is obtained by taking the tensor product of the 1D templates,  $T_I(m_{\mu\mu_1}) \otimes T_{II}(m_{\mu\mu_2})$ .

Finally, the 2D template is normalized to unity in the dimuon-dimuon mass space for the region below and above the  $J/\psi$  resonance. The template is represented as a smooth function of the Cartesian product of  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ , and is shown by the greyscale colormap in figure 3. Here, the SR defined in section 4 is bounded by the dashed lines. The region of the mass space outside the SR represents the control region (CR) for the QCD background. The ratio between the integral of the template in the SR ( $I_{SR}$ ) and the CR ( $I_{CR}$ ), or  $R = I_{SR}/I_{CR}$ , is calculated for both the region below and above the  $J/\psi$ . For the 2017 analysis, the ratios in the region below and above the  $J/\psi$  are 0.046 and 0.096, respectively. Similarly, the ratios obtained for the 2018 analysis below and above the  $J/\psi$  are 0.044 and 0.093, respectively. The same figure also displays the events found in the data that pass all selection criteria except the consistent mass requirement, thus falling outside of the SR (represented as white dots).

For the 2017 (2018) analysis, there are in total 49 and 2 (98 and 66) events in the CR below and above the  $J/\psi$  resonance, respectively. We then estimate the number of background events in the SR below and above the  $J/\psi$  using the ratio  $R$ . In 2017, these values are  $2.26 \pm 0.32$  (stat) and  $0.19 \pm 0.14$  (stat), below and above the  $J/\psi$ , respectively. In 2018, these



**Figure 3.** Two-dimensional distribution of the invariant masses  $m_{\mu\mu_1}$  vs.  $m_{\mu\mu_2}$  below (left) and above (right) the  $J/\psi$  resonance, for the 2017 (top row) and 2018 (bottom row) analyses. The greyscale heatmaps show the normalized QCD background templates, and the black vertical and horizontal bands correspond to the regions around the  $\eta$ ,  $\omega(783)$ ,  $\phi(1020)$ , and  $\psi(2S)$  resonances. The white dots represent data events that pass all selection criteria but fall outside the SR  $m_{\mu\mu_1} \simeq m_{\mu\mu_2}$  (outlined by dashed lines), and the red triangles represent data events passing all selection criteria. As discussed in section 6.1, the paucity of events in the CR for the 2017 analysis, particularly the region above  $J/\psi$ , is a result of the triggers selected for this data-taking period.

values are  $4.34 \pm 0.44$  (stat) and  $6.16 \pm 0.76$  (stat), below and above the  $J/\psi$ , respectively. The statistical uncertainty is calculated as the product of the ratio  $R$  with the square root of the number of CR events, or  $R\sqrt{N_{\text{CR}}}$ . Since  $R$  effectively normalizes this value, it is also referred to as the normalization uncertainty. These values are also listed in table 2 for convenience.

This method of estimating the QCD background is further validated by performing a Baker-Cousins (BC)  $\chi^2$  test [86] for the data in the CR and the constructed template. Both the 2D template  $T(m_{\mu\mu_1}, m_{\mu\mu_2})$  and data events in the CR are projected into 1D histograms. The template integral is then scaled to the data entries. To calibrate the statistical test we randomly generated one million sets of pseudo-data based on the template. The  $\chi^2$  statistic of the BC test is calculated for each pseudo-data set and the template to obtain a distribution of the  $\chi^2$  values. The final calibrated p-value is obtained by calculating the  $\chi^2$  between the

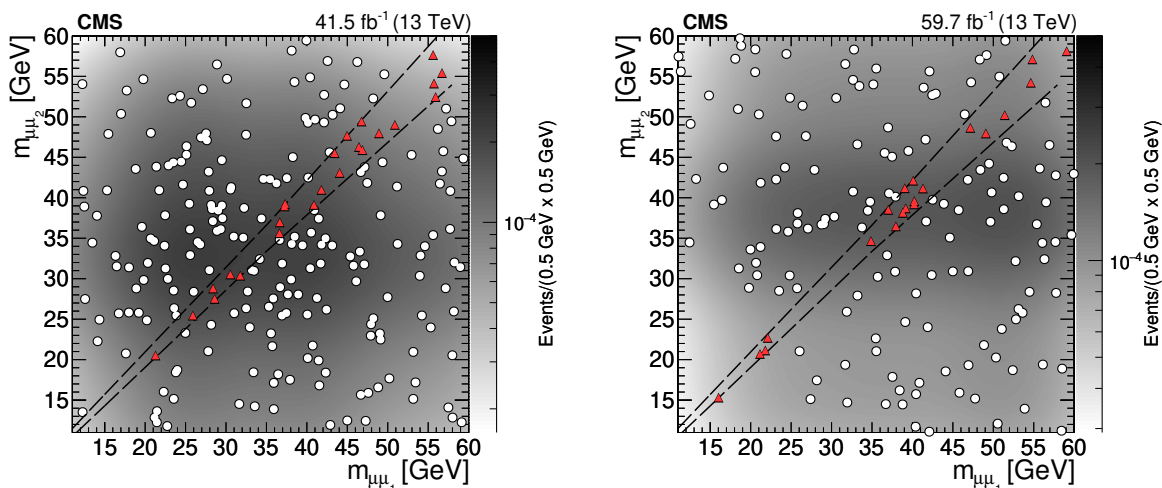
actual data and the template and quoting the fraction above the observed  $\chi^2$  statistic in the  $\chi^2$  distribution. Because we are considering a total mass phase space trifurcated by the  $J/\psi$  and  $Y$  resonances in two separate analyses (2017 and 2018), we perform the BC test for each of these regions and for both analyses. All p-values for  $m_{\mu\mu_1}$  are contained in  $[0.043, 0.924]$ , and all p-values for  $m_{\mu\mu_2}$  are contained within  $[0.164, 0.889]$  for both the 2017 and 2018 analyses in the region below the  $Y$  resonances. Note that the lower range of p-values results from the paucity of background events in the 2017 data set. For a complete list of p-values, see table 4.

## 6.2 Background above the $Y$ resonances

Electroweak processes with two  $Z$  bosons, the  $t\bar{t}$  process, and the Drell-Yan (DY) process all contribute to the background above the  $Y$  resonances. Additionally, we consider the possibility of a radiated photon in the DY process that converts into a dimuon. Such an event could become a non-negligible background when a photon-converted muon is paired with an oppositely charged muon from the DY process. Most of these events, however, fail the requirement of consistent dimuon masses and reside in the CR. The limited number of such events in the data makes it difficult to model the shape of their distribution. To veto these events, the trailing mass  $m_{\text{trailing}}^{\text{alt}}$  and trailing opening angle  $\Delta R_{\text{trailing}}^{\text{alt}}$  from the alternative pairs are used. These variables are calculated as follows: once two dimuons are obtained from the normal muon pairing algorithm mentioned in section 4, we alternatively pair these muons by taking one muon from each dimuon and pairing it with the oppositely charged muon in the other dimuon; the smaller invariant mass of alternative pairs is  $m_{\text{trailing}}^{\text{alt}}$  and the smaller opening angle of two muons in alternative pairs is  $\Delta R_{\text{trailing}}^{\text{alt}}$ . This alternative pairing restores dimuons that come from the DY process and the radiated photon. Compared to the dimuon from the DY process, the photon-converted dimuon usually has a smaller invariant mass and a smaller opening angle between the two muons. A final requirement of  $m_{\text{trailing}}^{\text{alt}} > 3 \text{ GeV}$ , or  $\Delta R_{\text{trailing}}^{\text{alt}} > 0.2$ , is used to veto these background events.

The selection of events with at most one SA muon in two dimuons also causes extra background that is hard to model with MC samples. For example, in the  $t\bar{t}$  process, one SA muon from the  $b$  quark decay can be paired with an oppositely charged muon from the  $W$  boson decay to form a dimuon. These dimuons are almost exclusively prompt. However, in the signal MC data, events that contain one SA muon often happen when the signal boson is displaced. To minimize the contamination of the actual data with these background events, we reject two-dimuon events containing one SA muon if both dimuons are prompt-like with  $L_{xy} < 0.1 \text{ cm}$ . Also, SA muons in background events are usually caused by underlying event activity or punch-through effects. Such SA muons have fewer reconstructed muon segments in the muon detector than those from signal events. We require the SA muon to have at least two valid muon segments, which further rejects the background caused by the SA muon.

Because the template method [32] fails to describe the background above the  $Y$  resonances accurately, we use the kernel density estimate (KDE) method [87] to model the background in the region above the  $Y$  for both the 2017 and 2018 data sets. The KDE method is specifically chosen because it is a non-parametric method that operates on unbinned data, thereby eliminating the reliance on the input parameters typically used in the template method. The 2D probability density function (pdf) is built via the KDE method in two steps: first, the



**Figure 4.** Two-dimensional distribution of the invariant masses  $m_{\mu\mu_1}$  vs.  $m_{\mu\mu_2}$  above the Y resonances for the 2017 analysis (left) and the 2018 analysis (right). The greyscale heatmaps represent the normalized 2D probability density function of the background data. White dots represent data events that pass all selection criteria but fall outside the SR  $m_{\mu\mu_1} \simeq m_{\mu\mu_2}$  (outlined by dashed lines), and the red triangles represent data events passing all selection criteria.

1D pdf, using a Gaussian kernel with an adaptive bandwidth, is taken for both  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ . The 2D pdf is then formed via the outer product of the pdfs for  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ , i.e.,  $\hat{f}(m_{\mu\mu_1}, m_{\mu\mu_2}) = f_{\text{I}}(m_{\mu\mu_1}) \otimes f_{\text{II}}(m_{\mu\mu_2})$ , where  $f_{\text{I,II}}(m_{\mu\mu})$  are the 1D pdfs. Figure 4 displays the 2D pdfs in the form of greyscale colormaps for the 2017 analysis (left) and the 2018 analysis (right). The dashed lines bound the SR, i.e.,  $\text{SR}(m_{\mu\mu_1} \simeq m_{\mu\mu_2})$ , and the white dots represent data events that fall outside this SR. The number of events in the CR above the Y resonances is 212 and 143 for the 2017 and 2018 data sets, respectively. In the mass region above the Y resonances, the ratio  $R$  is 0.085 (0.097) for the 2017 (2018) analyses. We then estimate the number of expected background events in the SR. For 2017, we expect  $18.10 \pm 1.23$  (stat) events, and for 2018, we expect  $13.81 \pm 1.16$  (stat) events. The systematic uncertainties are explained in detail in section 7. For comparison across years and mass regions, these values and those from the low-mass regions are listed in table 2 and a summary of the background estimation and mitigation method across mass regions is listed in table 3.

To assess the goodness-of-fit of the pdfs produced via the KDE method, we perform the BC  $\chi^2$  test. Just like the template method, the 2D pdfs are separated into the 1D pdfs individually representing  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$ . The BC test is then performed on each 1D pdf in the same manner as described in section 6.1, the results of which yield p-values in the range of [0.513, 0.974] for both invariant dimuon masses and both analyses. For completeness, we tabulate all p-values for both  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$  in all three mass regions for both the 2017 and 2018 analyses in table 4.

## 7 Systematic uncertainties

The leading source of experimental uncertainty in the signal prediction comes from the measurement of the integrated luminosity recorded by the CMS detector: during the 2017

Region	Quantity	Year		
		2017	2018	
Below $J/\psi$	Obs. events in CR		49	98
	Exp. events in SR	$2.26 \pm 0.32$ (stat) $\pm 0.14$ (syst)	$4.34 \pm 0.44$ (stat) $\pm 0.18$ (syst)	
	Obs. events in SR		2	4
Above $J/\psi$ , Below $Y$	Obs. events in CR		2	66
	Exp. events in SR	$0.19 \pm 0.14$ (stat) $\pm 0.01$ (syst)	$6.16 \pm 0.76$ (stat) $\pm 0.09$ (syst)	
	Obs. events in SR		0	6
Above $Y$	Obs. events in CR		212	143
	Exp. events in SR	$18.10 \pm 1.23$ (stat) $\pm 4.49$ (syst)	$13.81 \pm 1.16$ (stat) $\pm 5.39$ (syst)	
	Obs. events in SR		24	20

**Table 2.** The number of observed events in the CR and the expected and observed number of events in the SR in the three mass regions considered in this analysis.

Region	Method	Selection
Below $Y$	Template	Signal-like three-muon events
Above $Y$	KDE	CR events
	Background mitigation	Veto $m_{\text{trailing}}^{\text{alt}} > 3 \text{ GeV}$ or $\Delta R_{\text{trailing}}^{\text{alt}} > 0.2$ events

**Table 3.** The background estimation and mitigation method are divided into two mass regions below and above the  $Y$  resonance. The region below the  $Y$  uses the template method to estimate the background PDFs with signal-like three-muon events, which include only one dimuon and one orphan muon. The region above the  $Y$  uses the KDE method with events in the control region and involves further event selection for background mitigation.

Region	p-value			
	2017		2018	
	$m_{\mu\mu_1}$	$m_{\mu\mu_2}$	$m_{\mu\mu_1}$	$m_{\mu\mu_2}$
Below $J/\psi$	0.333	0.889	0.186	0.164
Above $J/\psi$ , below $Y$	0.043	0.172	0.924	0.375
Above $Y$	0.974	0.695	0.768	0.513

**Table 4.** Results of the Baker-Cousins  $\chi^2$  test for goodness-of-fit between the modeled background and the actual background events in the control regions. For background below the  $Y$  resonances, the 2D background templates are projected into one dimension, and the test is conducted, comparing background data and template values, yielding two p-values per region per data set. A similar procedure is followed for background above the  $Y$  resonances: the 2D pdfs are projected into one dimension and the BC test is conducted, yielding two p-values for each dimuon invariant mass for both 2017 and 2018. Note that the low p-values for the mass region above  $J/\psi$  and below  $Y$  for the 2017 data set result from the low number of background events in the data.

(2018) data-taking period, this uncertainty was 2.3% [88] (2.5% [89]). Other experimental uncertainties include the uncertainty on the final signal efficiency at high PU conditions (2.3% in 2017 and 1.8% in 2018), the selection of consistent masses of the two dimuons (0.24% for both 2017 and 2018), the uncertainty in the signal trigger scale factor that corrects for different trigger efficiencies in the data and MC simulation (0.9% in 2017 and 0.6% in 2018), and the uncertainty in the modeling of the PU distribution (0.1% in 2017 and 0.05% in 2018). The uncertainty on the reconstruction of displaced tracks and vertices contributes to the total systematic uncertainty of the 2018 analysis only, and is quoted at 1.0%, with 0.5% contributing from each displaced dimuon vertex fit [90]. The experimental uncertainties due to muon identification, dimuon isolation, and reconstruction of close muons in the tracker and the muon system can be found in ref. [32], and are reproduced in table 5. The theoretical uncertainties include the uncertainty in the PDFs, knowledge of the strong coupling constant  $\alpha_S$ , the renormalization and factorization scales, and the production cross section of the Higgs boson and its branching fractions — all of these uncertainties can be found in ref. [32] as well, and are also reproduced in table 5.

We also consider systematic uncertainties for the estimated background. The dimuon isolation threshold described in section 4 is varied by 5% around the threshold to achieve a total variation of 10%; the final number of expected background events in the SR is recomputed. The changes in the expected background events are quoted as a systematic uncertainty for the region below  $J/\psi$  (6.6% in 2017 and 4.1% in 2018), between  $J/\psi$  and  $Y$  (5.9% in 2017 and 1.5% in 2018), and above  $Y$  (1.2% in 2017 and 2.3% in 2018).

For the region above the  $Y$  resonances, we determine a systematic uncertainty on the pdf background shape by examining the number of estimated events for two scenarios in which the number of CR events is reduced by half. This is accomplished by applying selections to the events in the CR, which reduce their number by 50% and comparing the estimated number of events in the SR resulting from these selections. For all selections placed, we first keep the SR constant and then impose two different linear inequalities that eliminate roughly half of the events in the CR, which are given by  $0 \leq \zeta m_{\mu\mu_1} - \theta m_{\mu\mu_2}$  and  $0 \geq \theta m_{\mu\mu_1} - \zeta m_{\mu\mu_2}$ , where  $\zeta$  and  $\theta$  are arbitrary parameters chosen such that the desired 50% reduction of CR events is achieved.

We use these inequalities to exclude data to determine how the number of expected events in the SR changes, which provides a measure of the uncertainty on the background pdf shape. To produce this result, we consider two scenarios for both the 2017 and 2018 analyses: for the first scenario, we set the parameters  $\zeta = 1.6$  and  $\theta = 1$ , and determine the number of expected events in the SR. For the second scenario, we swap the values of  $\zeta$  and  $\theta$  and again determine the number of events in the SR. The ratio of the SR and CR background yields, i.e.,  $I_{\text{SR}}/I_{\text{CR}}$ , are computed and the expected background yields are compared to the nominal case where no selection is applied. The uncertainty on the background pdf shape is then taken as the largest percent difference, resulting in a 23.6% and 36.7% uncertainty for 2017 and 2018, respectively. Note that we do not include uncertainty on the background shape below the  $Y$  resonances because this region was estimated using the template method. Table 5 presents all uncertainties used in this analysis.

During the 2017 and 2018 data-taking periods, an issue affecting the L1 trigger was detected [59, 91], affecting muon candidates' bunch crossing assignment. Here, the limited

Source of uncertainty	Value	
	2017	2018
<b>Experimental signal uncertainties</b>		
Integrated luminosity	2.3%	2.5%
Muon ID	$4 \times 0.6\%$	$4 \times 0.6\%$
Dimuon isolation	$2 \times 0.1\%$	$2 \times 0.1\%$
Reco. of close muons in tracker (signal mass < 9 GeV)	$2 \times 1.2\%$	$2 \times 1.2\%$
Reco. of close muons in muon system (signal mass < 9 GeV)	$2 \times 1.3\%$	$2 \times 1.3\%$
Muon HLT	0.9%	0.6%
Reconstruction of displaced track/vertex	—	$2 \times 0.5\%$
PU distribution	0.1%	0.05%
PU effect on signal efficiency	2.3%	1.8%
Dimuon mass consistency	0.24%	0.24%
<b>Experimental background uncertainties below <math>J/\psi</math> (0.21–2.72 GeV)</b>		
Normalization	14.2%	10.1%
Systematic	6.6%	4.1%
<b>Experimental background uncertainties above <math>J/\psi</math> and below <math>Y</math> (3.24–9 GeV)</b>		
Normalization	73.5%	12.3%
Systematic	5.9%	1.5%
<b>Experimental background uncertainties above <math>Y</math> (11–60 GeV)</b>		
Normalization	6.9%	8.4%
Systematic	1.2%	2.3%
Shape	23.6%	36.7%
<b>Theoretical signal uncertainties</b>		
PDF + $\alpha_S$ + QCD scales	8%	8%
Higgs cross-section and BR <sup>a</sup>	3.8%	3.8%
NNLO Higgs $p_T$ re-weighting <sup>a</sup>	2%	2%

<sup>a</sup>Uncertainty is not used in the vector portal model.

**Table 5.** The systematic uncertainties for the 2017 and 2018 analyses, including the experimental uncertainties on the signal and background, as well as the theoretical uncertainties. The experimental uncertainties on the muon identification (ID), the dimuon isolation, and the reconstruction of close muons in both the tracker and the muon system have been reproduced from [32]. Additionally, all theoretical uncertainties have been reproduced from [32].



time resolution of the muon detectors could erroneously register a hit and fire the L1 trigger. To assess the impact of this L1 trigger issue, we re-weight the signal MC samples by the muon  $p_T$  and  $\eta$  and obtained a corrected value of  $\epsilon_{\text{Full}}$ . From this re-weighting, we conclude that this L1 trigger issue has a negligible effect on  $\epsilon_{\text{Full}}$ , causing an impact of less than 1%.

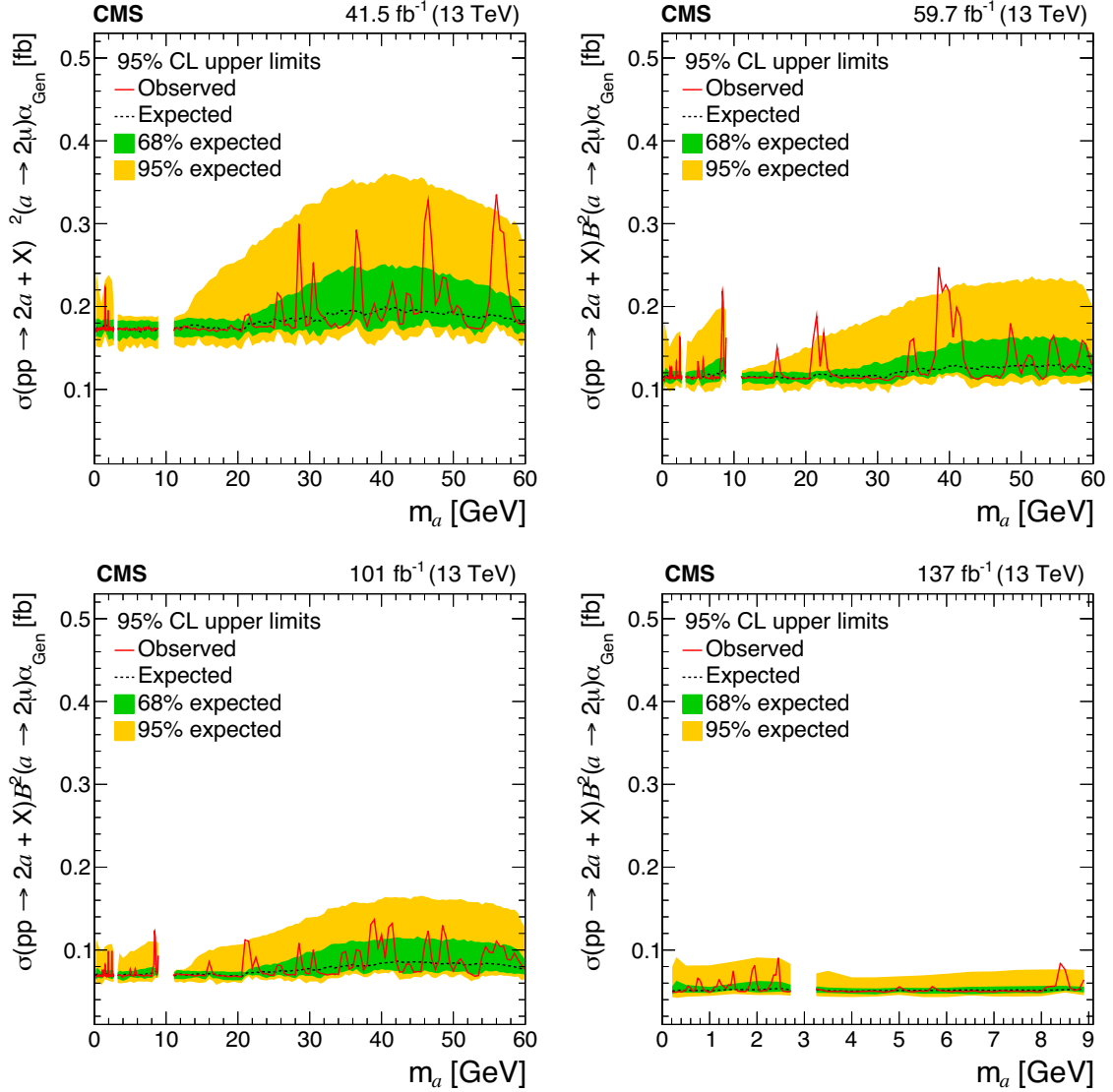
## 8 Results

After applying all selection criteria to the data sample, 26 (30) events are found in the full mass range in SR for the 2017 (2018) analysis. Their distribution in the  $m_{\mu\mu_1}$  and  $m_{\mu\mu_2}$  phase space is shown in figures 3 and 4. This result is consistent with the sum of all background estimates described in section 6. Model-independent observed upper limits at a 95% confidence level (CL) are set on the product of the production cross section of pairs of new bosons, the square of the branching fraction to dimuons, and the acceptance. Limits are set using the  $\text{CL}_s$  method [92, 93]. The test statistic used is based on the logarithm of the likelihood ratio [94]. The systematic uncertainties and their correlations have been accounted for by profiling the likelihood with respect to the nuisance parameters for each value of the signal strength. The following results have been determined using the CMS statistical analysis tool COMBINE [95].

The limit is shown as a function of  $m_a$  in figure 5 over the range  $0.21 < m_a < 60$  GeV for the 2017 and 2018 analyses (top left and top right, respectively), for the combined 2017 and 2018 data set over the range  $0.21 < m_a < 60$  GeV (bottom left), and for the combined 2016, 2017, and 2018 data set over the range  $0.21 < m_a < 9$  GeV (bottom right), where the analysis presented in ref. [32] provides the input data for the 2016 data set. Overall, the limit for the 2018 data set, the combination of the 2017 and 2018 data sets, and the combination of the 2016, 2017, and 2018 analyses varies between 0.049 and 0.247 fb for the model-independent interpretation. We now interpret this result in the context of the signal benchmark models.

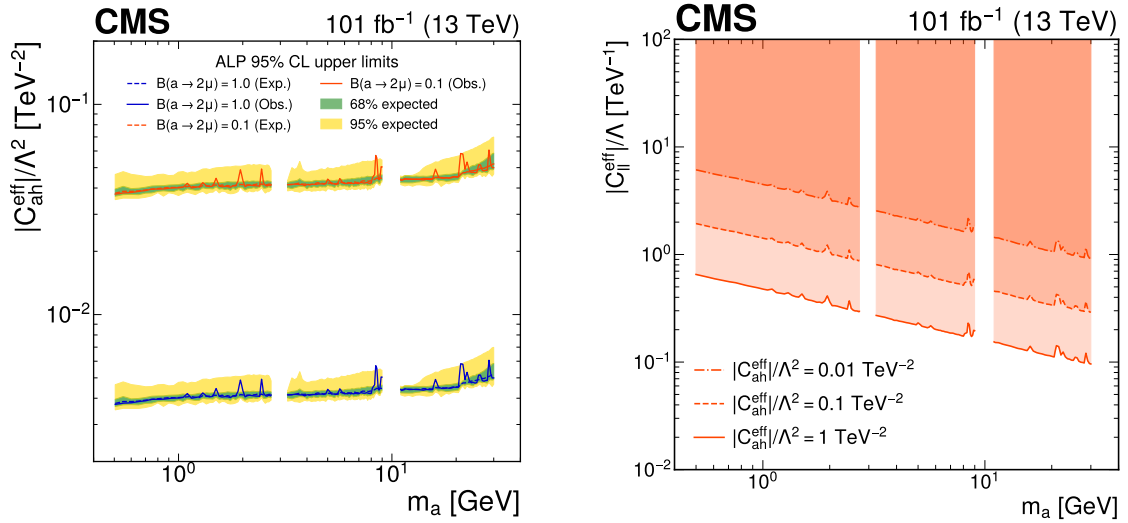
For the ALP scenario, the model-independent limit in figure 5 can be used to set the limit on the ratio of the effective coupling between the ALP and the SM Higgs boson,  $C_{ah}^{\text{eff}}$ , and the square of the new-physics energy scale,  $\Lambda$ , or  $C_{ah}^{\text{eff}}/\Lambda^2$ . The partial width of the Higgs boson decay to two ALPs can be found in ref. [15]. We assume the Higgs boson mass is 125 GeV, the partial width of Higgs boson decay to SM particles is 4.1 MeV, the production cross section of the SM H via gg fusion at the LHC is 48.93 pb at a center-of-mass energy of 13 TeV [96], the vacuum expectation value of the Higgs field is 246 GeV, and the branching fraction of the ALP to muons is 100% (or 10%). The observed 95% CL upper limit on  $C_{ah}^{\text{eff}}/\Lambda^2$  as a function of the ALP mass  $m_a$  is shown in figure 6 (left). Through this analysis, we achieve further reach and greater sensitivity than Run 1 LHC searches [36, 97, 98] (summarized in ref. [15]). Similarly, with different choices of  $C_{ah}^{\text{eff}}/\Lambda^2$  (1 TeV<sup>-2</sup>, 0.1 TeV<sup>-2</sup> and 0.01 TeV<sup>-2</sup>), and a decay width of the ALP to leptons as presented in ref. [15], we set limits on the ratio of the effective coupling between the ALP and SM leptons,  $C_{ll}^{\text{eff}}$ , to the new-physics energy scale, or  $C_{ll}^{\text{eff}}/\Lambda$ , as shown in figure 6 (right). The limit on  $C_{ll}^{\text{eff}}/\Lambda$  depends directly on the value assumed for the total ALP width. We fix the ALP total width to a constant reference point of 10<sup>-5</sup> GeV for all mass points.

For the vector portal benchmark model, we set a 95% CL upper limit on the product of the production cross section of the  $Z_D$ , the branching fraction of the decay of  $Z_D$  to  $s_D$

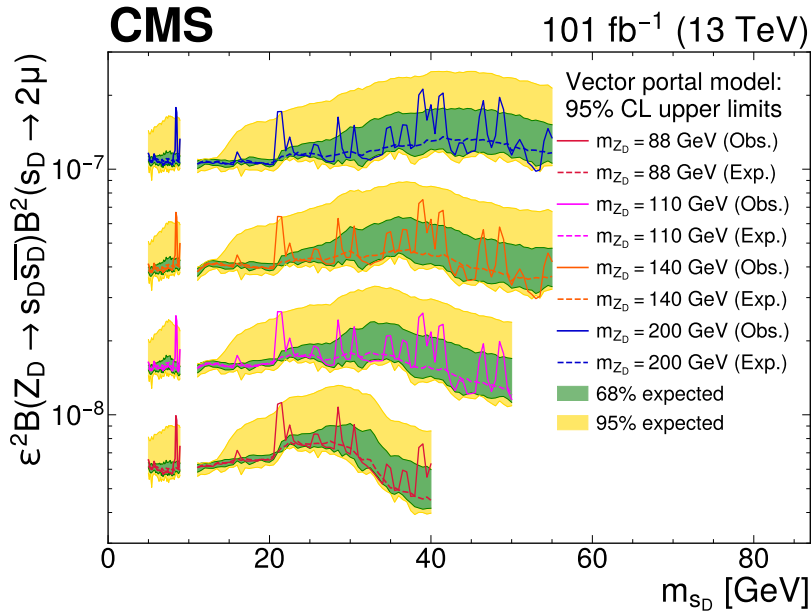


**Figure 5.** The model-independent 95% CL expected and observed upper limits set on  $\sigma(\text{pp} \rightarrow 2a + X)\mathcal{B}^2(a \rightarrow 2\mu)\alpha_{\text{Gen}}$  over the range  $0.21 < m_a < 60 \text{ GeV}$  for the 2017 and 2018 analyses (top left and top right, respectively), over the range  $0.21 < m_a < 60 \text{ GeV}$  for the combined 2017 and 2018 analyses (bottom left), and over the range  $0.21 < m_a < 9 \text{ GeV}$  for the combined 2016, 2017, and 2018 analyses (bottom right). Mass ranges that overlap with  $J/\psi$  and  $Y$  resonances are excluded from the search.

and  $\bar{s}_D$ , and the squared branching fraction of the decay of  $s_D$  to two oppositely charged muons:  $\sigma(\text{pp} \rightarrow Z_D)\mathcal{B}(Z_D \rightarrow s_D\bar{s}_D)\mathcal{B}^2(s_D \rightarrow 2\mu)$  as a function of the dark scalar mass  $m_{s_D}$  and the dark vector boson mass  $m_{Z_D}$ . This limit is subsequently translated to the limit on the product of the square of the kinetic mixing parameter,  $\varepsilon^2$ , times the branching fraction of the decay of  $Z_D$  to a pair of dark scalar bosons  $s_D$ , times the squared branching fraction of the decay of the  $s_D$  to a dimuon:  $\varepsilon^2\mathcal{B}(Z_D \rightarrow s_D\bar{s}_D)\mathcal{B}^2(s_D \rightarrow 2\mu)$ . As the  $s_D$  may also decay into SM particles other than dimuons, the branching fraction of its decay into dimuons must be taken into account in this limit, for various  $m_{s_D}$  and  $m_{Z_D}$ , which is shown in figure 7 for various  $m_{s_D}$  and  $m_{Z_D}$ .

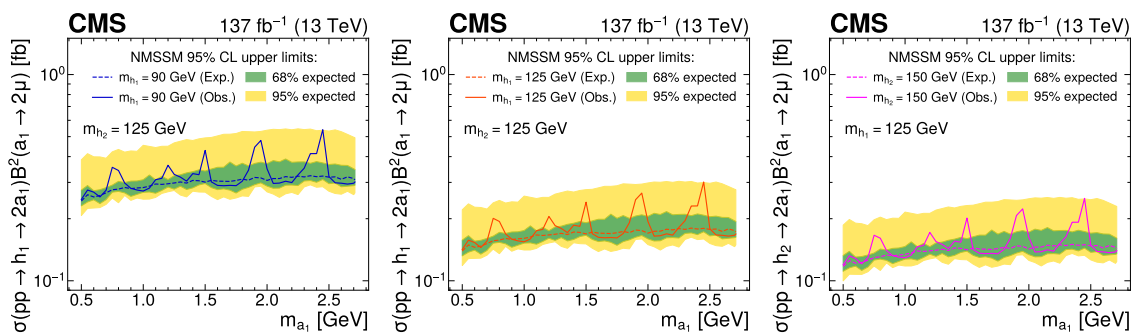


**Figure 6.** Left: the 95% CL observed upper limits on the effective coupling  $C_{ah}^{\text{eff}}/\Lambda^2$  of the ALP to the SM Higgs assuming the branching fraction of the ALP to muons is 1 (blue) and 0.1 (orange), for both the expected (dashed) and observed (solid) limits. Right: the 95% CL observed upper limits on the effective coupling  $C_{lu}^{\text{eff}}/\Lambda$  of the ALP to the SM leptons. The orange shaded region represents the parameter space excluded by this search under three choices of  $C_{ah}^{\text{eff}}/\Lambda^2$ :  $1 \text{ TeV}^{-2}$  (solid),  $0.1 \text{ TeV}^{-2}$  (dashed), and  $0.01 \text{ TeV}^{-2}$  (dotted).



**Figure 7.** The 95% CL observed upper limits on  $\varepsilon^2 \mathcal{B}(Z_D \rightarrow s_D \bar{s}_D) \mathcal{B}^2(s_D \rightarrow 2\mu)$  for the vector portal model as a function of the dark scalar mass  $m_{s_D}$  and dark vector boson mass  $m_{Z_D}$ .

For the NMSSM scenario, the 95% CL observed upper limits are derived for  $\sigma(\text{pp} \rightarrow h_{1,2} \rightarrow 2a_1) \mathcal{B}^2(a_1 \rightarrow 2\mu)$  as a function of  $m_{a_1}$  with  $m_{h_1} = 90 \text{ GeV}$  (figure 8 left)



**Figure 8.** The 95% CL observed upper limits for  $\sigma(\text{pp} \rightarrow h_{1,2} \rightarrow 2a_1)\mathcal{B}^2(a_1 \rightarrow 2\mu)$  for the NMSSM as a function of  $m_{a_1}$  for three choices of  $m_{h_{1,2}}$ . The left and middle plots have  $m_{h_2}$  fixed to 125 GeV and the right plot has  $m_{h_1}$  fixed to 125 GeV. The data presented here reflect the results of the 2017 and 2018 data sets combined with the previously published results of the 2016 data set in [32].

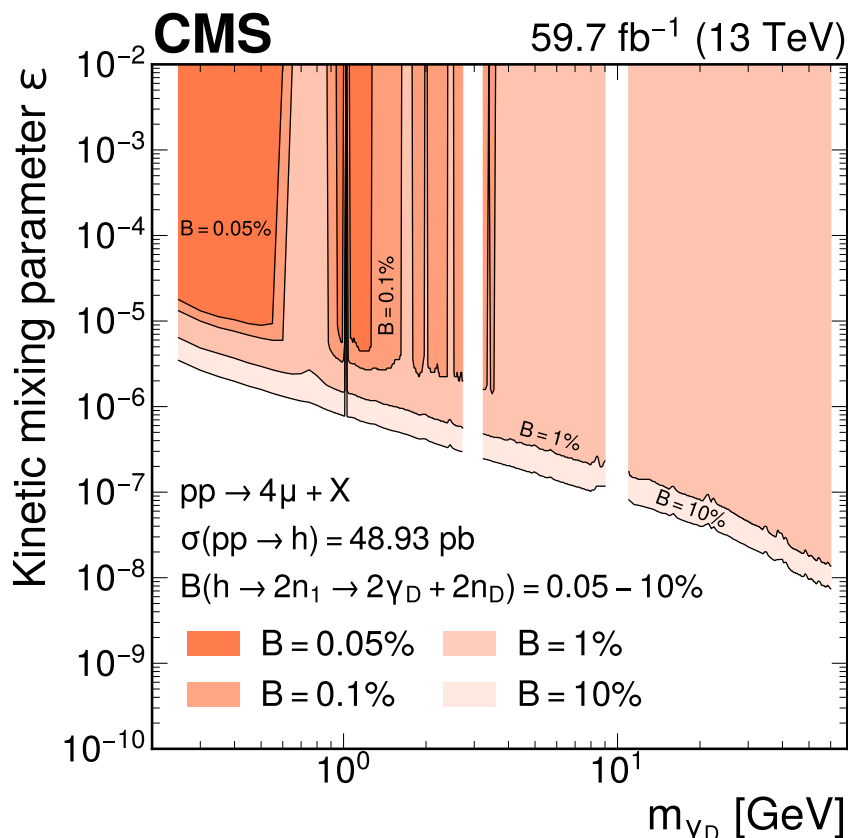
and  $m_{h_1} = 125$  GeV (figure 8 middle), with  $m_{h_2}$  fixed at 125 GeV; and  $m_{h_2} = 150$  GeV (figure 8 right) with  $m_{h_1}$  fixed at 125 GeV. It is assumed that all contributions come from either  $h_1$  or  $h_2$ ; there is no case in which both  $h_1$  and  $h_2$  decay to the  $a_1$ . The branching fraction of the  $a_1$  decay to a dimuon is dependent on the  $a_1$  mass [78].

For the dark SUSY scenario, a 95% CL observed upper limit is set on the product of the  $h$  production cross section and the branching fractions of the  $h$  decay to a pair of dark photons. The limit set by this experimental search is presented in figure 9 as areas excluded in a two-dimensional plane of  $\varepsilon$  and  $m_{\gamma_D}$ . Here, the Higgs boson mass is taken to be 125 GeV, and the production cross section of the Higgs boson via  $gg$  fusion at the LHC is 48.93 pb at 13 TeV [96].

For this search, limits are shown for the branching fraction of the  $h$  decay to two dark photons in the range 0.05–10%. The kinetic mixing parameter,  $\varepsilon$ , the mass of the dark photon  $m_{\gamma_D}$ , the branching fraction of the  $\gamma_D$  decays to a dimuon, and the proper decay length of the dark photon  $c\tau_{\gamma_D}$  are related via an analytic function that is solely dependent on the dark photon mass [99]. The proper decay length of the dark photon is allowed to vary from 0 to 100 mm and  $m_{\gamma_D}$  can range from 0.25 to 58 GeV. With the extended ranges in dimuon mass (0.21–60 GeV), this analysis excludes a previously unexplored area in the parameter space of  $\varepsilon$  and  $m_{\gamma_D}$  compared to the previous model-independent search (0.25–8.5 GeV) [32].

## 9 Summary

A search for pairs of new bosons  $a$  that subsequently decay to pairs of oppositely charged muons is presented. This search is performed using data samples collected by the CMS experiment in 2017 and 2018, corresponding to  $41.5 \text{ fb}^{-1}$  for the prompt signal in 2017 and  $59.7 \text{ fb}^{-1}$  for both the prompt and displaced signals in 2018, for proton-proton collisions at  $\sqrt{s} = 13$  TeV. The results are also combined with a similar analysis performed by the CMS collaboration [32], which analyzed a smaller data set collected in 2016 corresponding to  $35.9 \text{ fb}^{-1}$  of proton-proton collisions at  $\sqrt{s} = 13$  TeV. Additionally, both the mass range of the boson  $a$  and the maximum possible displacement of its decay vertex are extended



**Figure 9.** The 95% CL observed upper limits (black solid curves) from this search as interpreted in the dark SUSY scenario for the process  $pp \rightarrow h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D \rightarrow 4\mu + X$ , with  $m_{n_1} = 60$  GeV and  $m_{n_D} = 1$  GeV. The limits are presented in the plane of  $\varepsilon$  and  $m_{\gamma_D}$ . The color gradient represents different branching fraction assumptions for  $\mathcal{B}(h \rightarrow 2n_1 \rightarrow 2\gamma_D + 2n_D)$ , ranging from dark orange (0.05%) to light orange (10%). The degradation of the limit around 1 GeV is attributed to the drop in the dimuon branching fraction  $\mathcal{B}(\gamma_D \rightarrow 2\mu)$  due to the dimuon resonance of the  $\phi$  meson [99].

compared to the previous version of this analysis. The distribution of events in the signal region is consistent with standard model expectations. Model-independent 95% confidence level upper limits on the product of the production cross section of pairs of new bosons, the square of the branching fraction to dimuons, and the acceptance are set over the mass range  $0.21 < m_a < 60$  GeV and are found to vary between 0.049 and 0.247 fb. These model-independent limits are then interpreted in the context of an axion-like particle model, a vector portal model, a next-to-minimal supersymmetric standard model, and a dark supersymmetry scenario with non-negligible boson proper decay length of up to  $c\tau = 100$  mm.

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## The CMS collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan <sup>1</sup>













### Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler <sup>2</sup>, N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck <sup>2</sup>, R. Schöfbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz <sup>2</sup>

















### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish <sup>3</sup>, T. Janssen , T. Van Laer, P. Van Mechelen 













### Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D’Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat <sup>4</sup>, G.P. Van Onsem , S. Van Putte , D. Vannerom 















### Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , J. Jaramillo , A. Khalilzadeh, F.A. Khan , K. Lee , M. Mahdavihorrani , A. Malara , S. Paredes , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 











### Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , Y. Hong , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , A. Samalan, K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 

















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

A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Wertz 



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

G.A. Alves , M. Alves Gallo Pereira , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera <sup>5</sup>, A. Moraes , P. Rebello Teles , M. Soeiro, A. Vilela Pereira <sup>5</sup>

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

W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato<sup>6</sup>, E.M. Da Costa , G.G. Da Silveira <sup>7</sup>, D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, M. Macedo , J. Martins <sup>8</sup>, L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

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

C.A. Bernardes <sup>7</sup>, L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores ,  
B. Lopes Da Costa, I. Maietto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari ,  
Sandra S. Padula 

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

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

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 

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

S. Keshri , S. Thakur 













**Beihang University, Beijing, China**

T. Cheng , T. Javaid , L. Yuan 

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

Z. Hu , Z. Liang, J. Liu, K. Yi <sup>9,10</sup>

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

G.M. Chen <sup>11</sup>, H.S. Chen <sup>11</sup>, M. Chen <sup>11</sup>, F. Iemmi , C.H. Jiang, A. Kapoor <sup>12</sup>, H. Liao ,  
Z.-A. Liu <sup>13</sup>, R. Sharma <sup>14</sup>, J.N. Song<sup>13</sup>, J. Tao , C. Wang<sup>11</sup>, J. Wang , Z. Wang<sup>11</sup>, H. Zhang ,  
J. Zhao 

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

A. Agapitos , Y. Ban , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao,  
S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, L. Zhang , Y. Zhao, C. Zhou 

**Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China**

S. Yang 

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

Z. You 

**University of Science and Technology of China, Hefei, China**

K. Jaffel , N. Lu 

**Nanjing Normal University, Nanjing, China**

G. Bauer<sup>15</sup>, B. Li, J. Zhang 

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

X. Gao <sup>16</sup>

**Zhejiang University, Hangzhou, Zhejiang, China**

Z. Lin , C. Lu , M. Xiao 





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

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

**Universidad de Antioquia, Medellin, Colombia**

F. Ramirez , C. Rendón, M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

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

D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 









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

M. Kovac , A. Petkovic, T. Sculac 

**Institute Rudjer Boskovic, Zagreb, Croatia**

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovic, S. Mishra , A. Starodumov <sup>17</sup>, T. Susa 

**University of Cyprus, Nicosia, Cyprus**

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 

**Charles University, Prague, Czech Republic**

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

**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**

Y. Assran<sup>18,19</sup>, B. El-mahdy, S. Elgammal<sup>19</sup>

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

A. Lotfy , Y. Mohammed 









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

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

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

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















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

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew ,  
K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , L. Martikainen ,  
M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 




























**Lappeenranta-Lahti University of Technology, Lappeenranta, Finland**

P. Luukka , H. Petrow 


















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour ,  
P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi ,  
L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro <sup>20</sup>, P. Simkina , M. Titov ,  
M. Tornago 

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

F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , F. Damas ,  
O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert ,  
R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen ,  
C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza ,  
A. Zabi , A. Zghiche 


















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

J.-L. Agram <sup>21</sup>, J. Andrea , D. Apparu , D. Bloch , J.-M. Brom , E.C. Chabert ,  
C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet ,  
G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 


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

A. Di Florio 

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

D. Amram, S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo ,  
P. Depasse , C. Dozen <sup>22</sup>, H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg,  
G. Grenier , B. Ille , E. Jourdhuy, I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries,  
A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 














**Georgian Technical University, Tbilisi, Georgia**

I. Bagaturia <sup>23</sup>, I. Lomidze , Z. Tsamalaidze <sup>17</sup>

















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

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser ,  
A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 









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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , J. Erdmann ,  
M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung 




M.y. Lee , F. Mausolf , M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , A. Sharma , J.L. Spah , A. Stein , F. Torres Da Silva De Araujo <sup>24</sup>, S. Wiedenbeck , S. Zaleski







































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

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 






































### Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso, Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman <sup>25</sup>, K. Borrás <sup>26</sup>, A. Campbell , A. Cardini , C. Cheng, F. Colombina , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo <sup>25</sup>, A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmänn , L. Jeppe , B. Kaeck , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka <sup>27</sup>, W. Lohmann <sup>28</sup>, F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otarić, J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach, L. Rygaard, A. Saggio , M. Scham <sup>29,26</sup>, S. Schnake <sup>26</sup>, P. Schütze , C. Schwanenberger <sup>25</sup>, D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , Y. Wen , K. Wichmann, L. Wiens <sup>26</sup>, C. Wissing , Y. Yang , A. Zimmermann Castro Santos 

### University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bein , L. Benato , S. Bollweg, M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , H.R. Jabusch , G. Kasieczka , P. Keicher, R. Klanner , W. Korcari , T. Kramer , C.c. Kuo, V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz, A. Nigamova , Y. Nissan, A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews, M. Wolf 

### Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann <sup>30</sup>, R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , R. Koppenhöfer , J.M. Lawhorn , M. Link, A. Lintuluoto , B. Maier , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis, A. Papadopoulos<sup>30</sup>, A. Stakia 







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

P. Kontaxakis , G. Melachroinos, Z. Painesis , I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






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

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**University of Ioánnina, Ioánnina, Greece**

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

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

C. Hajdu , D. Horvath <sup>31,32</sup>, K. Márton, A.J. Rádl <sup>33</sup>, F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkúti <sup>34</sup>, M.M.A. Gadallah <sup>35</sup>, Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 

**Faculty of Informatics, University of Debrecen, Debrecen, Hungary**

B. Ujvari , G. Zilizi 















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

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

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

F. Nemes <sup>34</sup>, T. Novak 

**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra <sup>36</sup>, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , K. Sandeep , T. Sheokand, J.B. Singh , A. Singla 
















**University of Delhi, Delhi, India**

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

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

S. Baradia , S. Barman <sup>37</sup>, S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar










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

M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana , P. Kalbhor , S. Kamble , J.R. Komaragiri <sup>38</sup>, D. Kumar <sup>38</sup>, P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh, P. Verma, S. Verma , A. Vijay












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

S. Dugad, G.B. Mohanty , B. Parida , M. Shelake, P. Suryadevara










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A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar ,  
G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

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

S. Bahinipati <sup>39</sup>, C. Kar , D. Maity <sup>40</sup>, P. Mal , T. Mishra ,  
V.K. Muraleedharan Nair Bindhu <sup>40</sup>, K. Naskar <sup>40</sup>, A. Nayak <sup>40</sup>, S. Nayak, K. Pal, P. Sadangi,  
S.K. Swain , S. Varghese <sup>40</sup>, D. Vats <sup>40</sup>








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

S. Acharya <sup>41</sup>, A. Alpana , S. Dube , B. Gomber <sup>41</sup>, P. Hazarika , B. Kansal , A. Laha ,  
B. Sahu <sup>41</sup>, S. Sharma , K.Y. Vaish 

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

H. Bakhshiansohi <sup>42</sup>, A. Jafari <sup>43</sup>, M. Zeinali <sup>44</sup>
































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

S. Bashiri, S. Chenarani <sup>45</sup>, S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie <sup>46</sup>,  
M. Mohammadi Najafabadi , S. Tizchang <sup>47</sup>






























**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>, A. Colaleo <sup>a,b</sup>, D. Creanza <sup>a,c</sup>, B. D'Anzi <sup>a,b</sup>, N. De Filippis <sup>a,c</sup>,  
M. De Palma <sup>a,b</sup>, W. Elmetenawee <sup>a,b,48</sup>, L. Fiore <sup>a</sup>, G. Iaselli <sup>a,c</sup>, L. Longo <sup>a</sup>, M. Louka <sup>a,b</sup>,  
G. Maggi <sup>a,c</sup>, M. Maggi <sup>a</sup>, I. Margjeka <sup>a</sup>, V. Mastrapasqua <sup>a,b</sup>, S. My <sup>a,b</sup>, S. Nuzzo <sup>a,b</sup>,  
A. Pellecchia <sup>a,b</sup>, A. Pompili <sup>a,b</sup>, G. Pugliese <sup>a,c</sup>, R. Radogna <sup>a,b</sup>, D. Ramos <sup>a</sup>, A. Ranieri <sup>a</sup>,  
L. Silvestris <sup>a</sup>, F.M. Simone <sup>a,c</sup>, Ü. Sözbilir <sup>a</sup>, A. Stamerra <sup>a,b</sup>, D. Troiano <sup>a,b</sup>, R. Venditti <sup>a,b</sup>,  
P. Verwilligen <sup>a</sup>, A. Zaza <sup>a,b</sup>


















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

G. Abbiendi <sup>a</sup>, C. Battilana <sup>a,b</sup>, D. Bonacorsi <sup>a,b</sup>, P. Capiluppi <sup>a,b</sup>, A. Castro <sup>†,a,b</sup>,  
F.R. Cavallo <sup>a</sup>, M. Cuffiani <sup>a,b</sup>, G.M. Dallavalle <sup>a</sup>, T. Diotallevi <sup>a,b</sup>, F. Fabbri <sup>a</sup>,  
A. Fanfani <sup>a,b</sup>, D. Fasanella <sup>a</sup>, P. Giacomelli <sup>a</sup>, L. Giommi <sup>a,b</sup>, C. Grandi <sup>a</sup>, L. Guiducci <sup>a,b</sup>,  
S. Lo Meo <sup>a,49</sup>, M. Lorusso <sup>a,b</sup>, L. Lunerti <sup>a</sup>, S. Marcellini <sup>a</sup>, G. Masetti <sup>a</sup>, F.L. Navarria <sup>a,b</sup>,  
G. Paggi <sup>a,b</sup>, A. Perrotta <sup>a</sup>, F. Primavera <sup>a,b</sup>, A.M. Rossi <sup>a,b</sup>, S. Rossi Tisbeni <sup>a,b</sup>,  
T. Rovelli <sup>a,b</sup>, G.P. Siroli <sup>a,b</sup>

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

S. Costa <sup>a,b,50</sup>, A. Di Mattia <sup>a</sup>, A. Lapertosa <sup>a</sup>, R. Potenza <sup>a,b</sup>, A. Tricomi <sup>a,b,50</sup>, C. Tuve <sup>a,b</sup>

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

P. Assiouras <sup>a</sup>, G. Barbagli <sup>a</sup>, G. Bardelli <sup>a,b</sup>, B. Camaiani <sup>a,b</sup>, A. Cassese <sup>a</sup>, R. Ceccarelli <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>, T. Kello <sup>a</sup>, G. Latino <sup>a,b</sup>, P. Lenzi <sup>a,b</sup>, M. Lizzo <sup>a</sup>, M. Meschini <sup>a</sup>, S. Paoletti <sup>a</sup>, A. Papanastassiou<sup>a,b</sup>, G. Sguazzoni <sup>a</sup>, L. Viliani <sup>a</sup>






















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

L. Benussi <sup>a</sup>, S. Bianco <sup>a</sup>, S. Meola <sup>51</sup>, D. Piccolo <sup>a</sup>








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

P. Chatagnon <sup>a</sup>, F. Ferro <sup>a</sup>, E. Robutti <sup>a</sup>, S. Tosi <sup>a,b</sup>
















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

A. Benaglia <sup>a</sup>, F. Brivio <sup>a</sup>, F. Cetorelli <sup>a,b</sup>, F. De Guio <sup>a,b</sup>, M.E. Dinardo <sup>a,b</sup>, P. Dini <sup>a</sup>, S. Gennai <sup>a</sup>, R. Gerosa <sup>a,b</sup>, A. Ghezzi <sup>a,b</sup>, P. Govoni <sup>a,b</sup>, L. Guzzi <sup>a</sup>, M.T. Lucchini <sup>a,b</sup>, M. Malberti <sup>a</sup>, S. Malvezzi <sup>a</sup>, A. Massironi <sup>a</sup>, D. Menasce <sup>a</sup>, L. Moroni <sup>a</sup>, M. Paganoni <sup>a,b</sup>, S. Palluotto <sup>a,b</sup>, D. Pedrini <sup>a</sup>, A. Perego <sup>a,b</sup>, B.S. Pinolini<sup>a</sup>, G. Pizzati<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; Scuola Superiore Meridionale (SSM)<sup>d</sup>, Napoli, Italy**

S. Buontempo <sup>a</sup>, A. Cagnotta <sup>a,b</sup>, F. Carnevali<sup>a,b</sup>, N. Cavallo <sup>a,c</sup>, F. Fabozzi <sup>a,c</sup>, A.O.M. Iorio <sup>a,b</sup>, L. Lista <sup>a,b,52</sup>, P. Paolucci <sup>a,30</sup>













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

R. Ardino <sup>a</sup>, P. Azzi <sup>a</sup>, N. Bacchetta <sup>a,53</sup>, D. Bisello <sup>a,b</sup>, P. Bortignon <sup>a</sup>, G. Bortolato<sup>a,b</sup>, A. Bragagnolo <sup>a,b</sup>, A.C.M. Bulla <sup>a</sup>, R. Carlin <sup>a,b</sup>, T. Dorigo <sup>a</sup>, F. Gasparini <sup>a,b</sup>, U. Gasparini <sup>a,b</sup>, E. Lusiani <sup>a</sup>, M. Margoni <sup>a,b</sup>, A.T. Meneguzzo <sup>a,b</sup>, M. Migliorini <sup>a,b</sup>, F. Montecassiano <sup>a</sup>, J. Pazzini <sup>a,b</sup>, P. Ronchese <sup>a,b</sup>, R. Rossin <sup>a,b</sup>, F. Simonetto <sup>a,b</sup>, M. Tosi <sup>a,b</sup>, A. Triossi <sup>a,b</sup>, S. Ventura <sup>a</sup>, M. Zanetti <sup>a,b</sup>, P. Zotto <sup>a,b</sup>, A. Zucchetta <sup>a,b</sup>, G. Zumerle <sup>a,b</sup>













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























C. Aimè <sup>a</sup>, A. Braghieri <sup>a</sup>, S. Calzaferri <sup>a</sup>, D. Fiorina <sup>a</sup>, P. Montagna <sup>a,b</sup>, V. Re <sup>a</sup>, C. Riccardi <sup>a,b</sup>, P. Salvini <sup>a</sup>, I. Vai <sup>a,b</sup>, P. Vitulo <sup>a,b</sup>

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





















S. Ajmal <sup>a,b</sup>, M.E. Ascioti<sup>a,b</sup>, G.M. Bilei <sup>a</sup>, C. Carrivale<sup>a,b</sup>, D. Ciangottini <sup>a,b</sup>, L. Fanò <sup>a,b</sup>, M. Magherini <sup>a,b</sup>, V. Mariani <sup>a,b</sup>, M. Menichelli <sup>a</sup>, F. Moscatelli <sup>a,54</sup>, A. Rossi <sup>a,b</sup>, A. Santocchia <sup>a,b</sup>, D. Spiga <sup>a</sup>, T. Tedeschi <sup>a,b</sup>

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








C.A. Alexe <sup>a,c</sup>, P. Asenov <sup>a,b</sup>, P. Azzurri <sup>a</sup>, G. Bagliesi <sup>a</sup>, R. Bhattacharya <sup>a</sup>, L. Bianchini <sup>a,b</sup>, T. Boccali <sup>a</sup>, E. Bossini <sup>a</sup>, D. Bruschini <sup>a,c</sup>, R. Castaldi <sup>a</sup>, M.A. Ciocci <sup>a,b</sup>, M. Cipriani <sup>a,b</sup>

V. D'Amante <sup>a,d</sup>, R. Dell'Orso <sup>a</sup>, S. Donato <sup>a</sup>, A. Giassi <sup>a</sup>, F. Ligabue <sup>a,c</sup>, A.C. Marini <sup>a</sup>,  
 D. Matos Figueiredo <sup>a</sup>, A. Messineo <sup>a,b</sup>, M. Musich <sup>a,b</sup>, F. Palla <sup>a</sup>, A. Rizzi <sup>a,b</sup>,  
 G. Rolandi <sup>a,c</sup>, S. Roy Chowdhury <sup>a</sup>, T. Sarkar <sup>a</sup>, A. Scribano <sup>a</sup>, P. Spagnolo <sup>a</sup>,  
 R. Tenchini <sup>a</sup>, G. Tonelli <sup>a,b</sup>, N. Turini <sup>a,d</sup>, F. Vaselli <sup>a,c</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>, Roma, Italy

C. Baldenegro Barrera <sup>a,b</sup>, P. Barria <sup>a</sup>, C. Basile <sup>a,b</sup>, M. Campana <sup>a,b</sup>, F. Cavallari <sup>a</sup>,  
 L. Cunqueiro Mendez <sup>a,b</sup>, D. Del Re <sup>a,b</sup>, E. Di Marco <sup>a,b</sup>, M. Diemoz <sup>a</sup>, F. Errico <sup>a,b</sup>,  
 E. Longo <sup>a,b</sup>, J. Mijuskovic <sup>a,b</sup>, G. Organtini <sup>a,b</sup>, F. Pandolfi <sup>a</sup>, R. Paramatti <sup>a,b</sup>,  
 C. Quaranta <sup>a,b</sup>, S. Rahatlou <sup>a,b</sup>, C. Rovelli <sup>a</sup>, F. Santanastasio <sup>a,b</sup>, L. Soffi <sup>a</sup>















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

N. Amapane <sup>a,b</sup>, R. Arcidiacono <sup>a,c</sup>, S. Argiro <sup>a,b</sup>, M. Arneodo <sup>a,c</sup>, N. Bartosik <sup>a</sup>,  
 R. Bellan <sup>a,b</sup>, A. Bellora <sup>a,b</sup>, C. Biino <sup>a</sup>, C. Borca <sup>a,b</sup>, N. Cartiglia <sup>a</sup>, M. Costa <sup>a,b</sup>,  
 R. Covarelli <sup>a,b</sup>, N. Demaria <sup>a</sup>, L. Finco <sup>a</sup>, M. Grippo <sup>a,b</sup>, B. Kiani <sup>a,b</sup>, F. Legger <sup>a</sup>,  
 F. Luongo <sup>a,b</sup>, C. Mariotti <sup>a</sup>, L. Markovic <sup>a,b</sup>, S. Maselli <sup>a</sup>, A. Mecca <sup>a,b</sup>, L. Menzio <sup>a,b</sup>,  
 P. Meridiani <sup>a</sup>, E. Migliore <sup>a,b</sup>, M. Monteno <sup>a</sup>, R. Mulargia <sup>a</sup>, M.M. Obertino <sup>a,b</sup>,  
 G. Ortona <sup>a</sup>, L. Pacher <sup>a,b</sup>, N. Pastrone <sup>a</sup>, M. Pelliccioni <sup>a</sup>, M. Ruspa <sup>a,c</sup>, F. Siviero <sup>a,b</sup>,  
 V. Sola <sup>a,b</sup>, A. Solano <sup>a,b</sup>, A. Staiano <sup>a</sup>, C. Tarricone <sup>a,b</sup>, D. Trocino <sup>a</sup>, G. Umoret <sup>a,b</sup>,  
 R. White <sup>a,b</sup>

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

S. Belforte <sup>a</sup>, V. Candelise <sup>a,b</sup>, M. Casarsa <sup>a</sup>, F. Cossutti <sup>a</sup>, K. De Leo <sup>a</sup>, G. Della Ricca <sup>a,b</sup>





### Kyungpook National University, Daegu, Korea

S. Dogra <sup>a</sup>, J. Hong <sup>a</sup>, C. Huh <sup>a</sup>, B. Kim <sup>a</sup>, J. Kim <sup>a</sup>, D. Lee <sup>a</sup>, H. Lee <sup>a</sup>, S.W. Lee <sup>a</sup>, C.S. Moon <sup>a</sup>,  
 Y.D. Oh <sup>a</sup>, M.S. Ryu <sup>a</sup>, S. Sekmen <sup>a</sup>, B. Tae <sup>a</sup>, Y.C. Yang <sup>a</sup>

### Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim <sup>a</sup>








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

G. Bak <sup>a</sup>, P. Gwak <sup>a</sup>, H. Kim <sup>a</sup>, D.H. Moon <sup>a</sup>

### Hanyang University, Seoul, Korea

E. Asilar <sup>a</sup>, J. Choi <sup>a</sup>, D. Kim <sup>a</sup>, T.J. Kim <sup>a</sup>, J.A. Merlin <sup>a</sup>, Y. Ryou <sup>a</sup>

### Korea University, Seoul, Korea

S. Choi <sup>a</sup>, S. Han <sup>a</sup>, B. Hong <sup>a</sup>, K. Lee <sup>a</sup>, K.S. Lee <sup>a</sup>, S. Lee <sup>a</sup>, J. Yoo <sup>a</sup>

### Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh <sup>a</sup>, S. Yang <sup>a</sup>








### Sejong University, Seoul, Korea

H.S. Kim <sup>a</sup>, Y. Kim <sup>a</sup>, S. Lee <sup>a</sup>



**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

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

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

S. Ha , H.D. Yoo 

**Sungkyunkwan University, Suwon, Korea**

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

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

T. Beyrouthy, Y. Gharbia


**Kuwait University - College of Science - Department of Physics, Safat, Kuwait**

F. Alazemi 

**Riga Technical University, Riga, Latvia**

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , D. Sidiropoulos Kontos


**University of Latvia (LU), Riga, Latvia**

N.R. Strautnieks 







**Vilnius University, Vilnius, Lithuania**

M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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

I. Yusuff <sup>55</sup>, Z. Zolkapli

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

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

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

















































G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo ,  
I. Heredia-De La Cruz <sup>56</sup>, R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera,  
A. Sánchez Hernández 

**Universidad Iberoamericana, Mexico City, Mexico**















C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 

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




















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

**University of Montenegro, Podgorica, Montenegro**I. Bubanja , N. Raicevic **University of Canterbury, Christchurch, New Zealand**P.H. Butler **National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan **AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland**V. Avati, L. Grzanka , M. Malawski **National Centre for Nuclear Research, Swierk, Poland**H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szeleper , P. Zalewski **Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolkowski , A. Muhammad **Warsaw University of Technology, Warsaw, Poland**K. Pozniak , W. Zabolotny **Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**M. Araujo , D. Bastos , C. Beirão Da Cruz E. Silva , A. Boletti , M. Bozzo , T. Camporesi , G. Da Molin , M. Gallinaro , J. Hollar , N. Leonardo , G.B. Marozzo, T. Niknejad , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff**Faculty of Physics, University of Belgrade, Belgrade, Serbia**P. Adzic , P. Milenovic **VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia**M. Dordevic , J. Milosevic , V. Rekovic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**J. Alcaraz Maestre , Cristina F. Bedoya , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , E. Martin Viscasillas , D. Moran , C.M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar **Universidad Autónoma de Madrid, Madrid, Spain**J.F. de Trocóniz 

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

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras ,  
I. Gonzalez Caballero , J.R. González Fernández , P. Leguina , E. Palencia Cortezon ,  
J. Prado Pico, C. Ramón Álvarez , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote ,  
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**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

S. Bhowmik , S. Blanco Fernández , J.A. Brochero Cifuentes , I.J. Cabrillo , A. Calderon ,  
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C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas ,  
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






























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

B. Kailasapathy <sup>57</sup>, D.D.C. Wickramaratna 

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

W.G.D. Dharmaratna <sup>58</sup>, K. Liyanage , N. Perera 






















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

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney ,  
A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Borgonovi , C. Botta ,  
E. Brondolin , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d’Enterria , A. Dabrowski ,  
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V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban <sup>28</sup>, S. Laurila ,  
P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman,  
A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat ,  
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S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva ,  
P. Sphicas <sup>59</sup>, A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea ,  
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





**Paul Scherrer Institut, Villigen, Switzerland**

T. Bevilacqua <sup>61</sup>, L. Caminada <sup>61</sup>, A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram ,  
H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli <sup>61</sup>, L. Noehte <sup>61</sup>, T. Rohe 




















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

T.K. Aarrestad <sup>60</sup>, K. Androsov <sup>60</sup>, M. Backhaus , G. Bonomelli, A. Calandri , C. Cazzaniga ,  
K. Datta , P. De Bryas Dexmiers D’Archiac <sup>60</sup>, A. De Cosa , G. Dissertori , M. Dittmar,  
M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer ,  
T.G. Harte, D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani 



L. Marchese , C. Martin Perez , A. Mascellani <sup>60</sup>, F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , C. Reissel , B. Ristic , F. Riti , R. Seidita , J. Steggemann <sup>60</sup>, A. Tarabini , D. Valsecchi , R. Wallny 












### Universität Zürich, Zurich, Switzerland

C. Amsler <sup>62</sup>, P. Bäertschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring , F. Meng , U. Molinatti , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger , R. Tramontano 

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

C. Adloff<sup>63</sup>, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari <sup>38</sup>, S.S. Yu 



















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

L. Ceard, K.F. Chen , P.s. Chen, Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao, S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker , L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan 

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

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu <sup>64</sup>, E. Eskut , Y. Guler <sup>65</sup>, E. Gurpinar Guler <sup>65</sup>, C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir <sup>66</sup>, A. Polatoz , B. Tali <sup>67</sup>, U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

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

G. Sokmen, M. Yalvac <sup>68</sup>










### Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya <sup>69</sup>, O. Kaya <sup>70</sup>, S. Tekten <sup>71</sup>

### Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak <sup>64,72</sup>, G.G. Dincer <sup>64</sup>, Y. Komurcu , S. Sen <sup>73</sup>

### Istanbul University, Istanbul, Turkey

O. Aydilek <sup>74</sup>, B. Hacisahinoglu , I. Hos <sup>75</sup>, B. Kaynak , S. Ozkorucuklu , O. Potok , H. Sert , C. Simsek , C. Zorbilmez 

### Yildiz Technical University, Istanbul, Turkey

S. Cerci <sup>67</sup>, B. Isildak <sup>76</sup>, D. Sunar Cerci , T. Yetkin 


















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

A. Boyaryntsev , B. Grynyov 

























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

L. Levchuk 














































## University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , S. Seif El Nasr-Storey , V.J. Smith , N. Stylianou <sup>77</sup>, K. Walkingshaw Pass

## Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball , K.W. Bell , A. Belyaev <sup>78</sup>, C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 

## Imperial College, London, United Kingdom

I. Andreou , R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller , V. Cacchio , C.A. Carrillo Montoya , G.S. Chahal <sup>79</sup>, D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , J. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard , G. Iles , M. Knight , J. Langford , J. León Holgado , L. Lyons , A.-M. Magnan , S. Mallios , M. Mieskolainen , J. Nash <sup>80</sup>, M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage , T. Virdee <sup>30</sup>, M. Vojinovic , N. Wardle , D. Winterbottom 







## Brunel University, Uxbridge, United Kingdom

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








## Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , E. Collins , J. Dittmann , K. Hatakeyama , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















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

R. Bartek , A. Dominguez , C. Huerta Escamilla , A.E. Simsek , R. Uniyal , A.M. Vargas Hernandez 


















## The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio <sup>81</sup>, E. Usai , R. Yi 




















## Boston University, Boston, Massachusetts, USA

A. Akpinar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O’Cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 












**Brown University, Providence, Rhode Island, USA**

G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , J.M. Hogan <sup>82</sup>, T. Kwon ,  
G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , N. Pervan , T. Russell, S. Sagir <sup>83</sup>,  
F. Simpson , M. Stamenkovic , N. Venkatasubramanian, X. Yan 

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

S. Abbott , C. Brainerd , R. Breedon , H. Cai , M. Calderon De La Barca Sanchez ,  
M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral ,  
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






















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

M. Bachtis , R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko ,  
M.A. Iqbal , T. Lam , E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 


















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

R. Clare , J.W. Gary , M. Gordon, G. Hanson , W. Si 









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

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte ,  
L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts ,  
M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , M. Quinnan ,  
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A. Yagil 
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , J. Incandela ,  
J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica ,  
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







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

A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez,  
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













**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson ,  
T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy ,  
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




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

J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , G. Karathanasis , N. Manganelli ,  
C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 










**Cornell University, Ithaca, New York, USA**

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , S. Hogan ,  
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P. Wittich , R. Zou 










### Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijnsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena <sup>84</sup>, F. Ravera , A. Reinsvold Hall <sup>85</sup>, L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






### University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 









### Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , V. Hagopian , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang









### Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy <sup>86</sup>, M. Hohlmann , M. Rahmani, E. Yanes







### University of Illinois Chicago, Chicago, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D.S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 
























### The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend, K. Dilsiz <sup>87</sup>, L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili <sup>88</sup>, O. Neogi, H. Ogul <sup>89</sup>, Y. Onel , A. Penzo , C. Snyder, E. Tiras <sup>90</sup>









### Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 
















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

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean ,  
 Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu ,  
 J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu <sup>91</sup>, C. Rogan , C. Royon ,  
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




**Kansas State University, Manhattan, Kansas, USA**

B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli ,  
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








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

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley ,  
 S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey ,  
 S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, L. Wang 



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

J. Bendavid , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer ,  
 G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa ,  
 L. Lavezzo , Y.-J. Lee , K. Long , C. McGinn, A. Novak , C. Paus , C. Roland ,  
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







**University of Minnesota, Minneapolis, Minnesota, USA**

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi ,  
 R. Rusack , R. Saradhy , N. Strobbe 

















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

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , J.E. Siado ,  
 W. Tabb , A. Vagnerini , A. Wightman , F. Yan , D. Yu 

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

H. Bandyopadhyay , L. Hay , H.w. Hsia, I. Iashvili , A. Kalogeropoulos , A. Kharchilava ,  
 M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams , P. Young 

















**Northeastern University, Boston, Massachusetts, USA**











G. Alverson , E. Barberis , J. Bonilla , J. Dervan, Y. Haddad , Y. Han , A. Krishna ,  
 J. Li , M. Lu , G. Madigan , R. Mccarthy , D.M. Morse , V. Nguyen , T. Orimoto ,  
 A. Parker , L. Skinnari , D. Wood 

**Northwestern University, Evanston, Illinois, USA**

J. Bueghly, S. Dittmer , K.A. Hahn , Y. Liu , Y. Miao , D.G. Monk , M.H. Schmitt ,  
 A. Taliercio , M. Velasco

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


















G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,  
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C. Moore , Y. Musienko <sup>17</sup>, H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti ,  
A. Townsend , Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygala 

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

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


















### **Princeton University, Princeton, New Jersey, USA**

H. Bouchamaoui , P. Das , G. Dezoort , P. Elmer , A. Frankenthal , B. Greenberg ,  
N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange , A. Loeliger , D. Marlow ,  
I. Ojalvo , J. Olsen , A. Shevelev , D. Stickland , C. Tully 

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

S. Malik 














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A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung ,  
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J.F. Schulte , M. Stojanovic , J. Thieman , A.K. Viridi , F. Wang , W. Xie 

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J. Dolen , N. Parashar , A. Pathak 





















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F.J.M. Geurts , W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter ,  
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








### **University of Rochester, Rochester, New York, USA**

A. Bodek , P. de Barbaro , R. Demina , A. Garcia-Bellido , O. Hindrichs ,  
A. Khukhunaishvili , N. Parmar, P. Parygin <sup>92</sup>, E. Popova <sup>92</sup>, R. Taus 














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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis ,  
M. Heindl , C. Houghton , D. Jaroslawski , S. Konstantinou , I. Laflotte , A. Lath ,  
R. Montalvo, K. Nash, J. Reichert , H. Routray , P. Saha , S. Salur , S. Schnetzer,  
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



### **University of Tennessee, Knoxville, Tennessee, USA**

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti ,  
N. Karunaratna , L. Lee , E. Nibigira , S. Spanier 












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

D. Aebi , M. Ahmad , T. Akhter , O. Bouhali <sup>93</sup>, R. Eusebi , J. Gilmore , T. Huang ,  
T. Kamon <sup>94</sup>, H. Kim , S. Luo , R. Mueller , D. Overton , D. Rathjens , A. Safonov 




**Texas Tech University, Lubbock, Texas, USA**

N. Akchurin , J. Damgov , N. Gogate , V. Hegde , A. Hussain , Y. Kazhykarim,  
K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

**Vanderbilt University, Nashville, Tennessee, USA**

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli ,  
A. Melo , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 























**University of Virginia, Charlottesville, Virginia, USA**

B. Cardwell , B. Cox , J. Hakala , R. Hirosky , A. Ledovsky , C. Neu 

**Wayne State University, Detroit, Michigan, USA**

S. Bhattacharya , P.E. Karchin 


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

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

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

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin <sup>†</sup>, I. Gorbunov , V. Karjavine ,  
V. Korenkov , A. Lanev , A. Malakhov , V. Matveev <sup>95</sup>, V. Palichik , V. Perelygin ,  
M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin ,  
B.S. Yuldashev<sup>96</sup>, A. Zarubin , I. Zhizhin , G. Gavrillov , V. Golovtsov , Y. Ivanov ,  
V. Kim <sup>95</sup>, P. Levchenko <sup>97</sup>, V. Murzin , V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov ,  
A. Vorobyev<sup>†</sup>, Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu ,  
D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin , T. Aushev ,  
V. Gavrillov , N. Lychkovskaya , A. Nikitenko <sup>98,99</sup>, V. Popov , A. Zhokin , M. Chadeeva <sup>95</sup>,  
R. Chistov <sup>95</sup>, S. Polikarpov <sup>95</sup>, V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov ,  
E. Boos , V. Bunichev , M. Dubinin <sup>84</sup>, L. Dudko , A. Gribushin , V. Klyukhin ,  
O. Kodolova <sup>99</sup>, S. Obraztsov , M. Perfilov, S. Petrushanko , V. Savrin , G. Vorotnikov ,  
V. Blinov<sup>95</sup>, T. Dimova <sup>95</sup>, A. Kozyrev <sup>95</sup>, O. Radchenko <sup>95</sup>, Y. Skovpen <sup>95</sup>, V. Kachanov ,  
D. Konstantinov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin <sup>100</sup>

**Authors affiliated with an institute formerly covered by a cooperation agreement with CERN**

V. Chekhovsky, V. Makarenko 

<sup>†</sup> *Deceased*

<sup>1</sup> *Also at Yerevan State University, Yerevan, Armenia*

<sup>2</sup> *Also at TU Wien, Vienna, Austria*

<sup>3</sup> *Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt*

- <sup>4</sup> Also at Ghent University, Ghent, Belgium
- <sup>5</sup> Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
- <sup>6</sup> Also at Universidade Estadual de Campinas, Campinas, Brazil
- <sup>7</sup> Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- <sup>8</sup> Also at UFMS, Nova Andradina, Brazil
- <sup>9</sup> Also at Nanjing Normal University, Nanjing, China
- <sup>10</sup> Now at The University of Iowa, Iowa City, Iowa, USA
- <sup>11</sup> Also at University of Chinese Academy of Sciences, Beijing, China
- <sup>12</sup> Also at China Center of Advanced Science and Technology, Beijing, China
- <sup>13</sup> Also at University of Chinese Academy of Sciences, Beijing, China
- <sup>14</sup> Also at China Spallation Neutron Source, Guangdong, China
- <sup>15</sup> Now at Henan Normal University, Xinxiang, China
- <sup>16</sup> Also at Université Libre de Bruxelles, Bruxelles, Belgium
- <sup>17</sup> Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- <sup>18</sup> Also at Suez University, Suez, Egypt
- <sup>19</sup> Now at British University in Egypt, Cairo, Egypt
- <sup>20</sup> Also at Purdue University, West Lafayette, Indiana, USA
- <sup>21</sup> Also at Université de Haute Alsace, Mulhouse, France
- <sup>22</sup> Also at Istinye University, Istanbul, Turkey
- <sup>23</sup> Also at Ilia State University, Tbilisi, Georgia
- <sup>24</sup> Also at The University of the State of Amazonas, Manaus, Brazil
- <sup>25</sup> Also at University of Hamburg, Hamburg, Germany
- <sup>26</sup> Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>27</sup> Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- <sup>28</sup> Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>29</sup> Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>30</sup> Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>31</sup> Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- <sup>32</sup> Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>33</sup> Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- <sup>34</sup> Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- <sup>35</sup> Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>36</sup> Also at Punjab Agricultural University, Ludhiana, India
- <sup>37</sup> Also at University of Visva-Bharati, Santiniketan, India
- <sup>38</sup> Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>39</sup> Also at IIT Bhubaneswar, Bhubaneswar, India
- <sup>40</sup> Also at Institute of Physics, Bhubaneswar, India
- <sup>41</sup> Also at University of Hyderabad, Hyderabad, India
- <sup>42</sup> Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>43</sup> Also at Isfahan University of Technology, Isfahan, Iran
- <sup>44</sup> Also at Sharif University of Technology, Tehran, Iran
- <sup>45</sup> Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>46</sup> Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>47</sup> Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- <sup>48</sup> Also at Helwan University, Cairo, Egypt
- <sup>49</sup> Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>50</sup> Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>51</sup> Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>52</sup> Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>53</sup> Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>54</sup> Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy



- <sup>55</sup> Also at *Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*
- <sup>56</sup> Also at *Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*
- <sup>57</sup> Also at *Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*
- <sup>58</sup> Also at *Saegis Campus, Nugegoda, Sri Lanka*
- <sup>59</sup> Also at *National and Kapodistrian University of Athens, Athens, Greece*
- <sup>60</sup> Also at *Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*
- <sup>61</sup> Also at *Universität Zürich, Zurich, Switzerland*
- <sup>62</sup> Also at *Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*
- <sup>63</sup> Also at *Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*
- <sup>64</sup> Also at *Near East University, Research Center of Experimental Health Science, Mersin, Turkey*
- <sup>65</sup> Also at *Konya Technical University, Konya, Turkey*
- <sup>66</sup> Also at *Izmir Bakircay University, Izmir, Turkey*
- <sup>67</sup> Also at *Adiyaman University, Adiyaman, Turkey*
- <sup>68</sup> Also at *Bozok Universitetesi Rektörlüğü, Yozgat, Turkey*
- <sup>69</sup> Also at *Marmara University, Istanbul, Turkey*
- <sup>70</sup> Also at *Milli Savunma University, Istanbul, Turkey*
- <sup>71</sup> Also at *Kafkas University, Kars, Turkey*
- <sup>72</sup> Now at *Istanbul Okan University, Istanbul, Turkey*
- <sup>73</sup> Also at *Hacettepe University, Ankara, Turkey*
- <sup>74</sup> Also at *Erzincan Binali Yildirim University, Erzincan, Turkey*
- <sup>75</sup> Also at *Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey*
- <sup>76</sup> Also at *Yildiz Technical University, Istanbul, Turkey*
- <sup>77</sup> Also at *Vrije Universiteit Brussel, Brussel, Belgium*
- <sup>78</sup> Also at *School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom*
- <sup>79</sup> Also at *IPPP Durham University, Durham, United Kingdom*
- <sup>80</sup> Also at *Monash University, Faculty of Science, Clayton, Australia*
- <sup>81</sup> Also at *Università di Torino, Torino, Italy*
- <sup>82</sup> Also at *Bethel University, St. Paul, Minnesota, USA*
- <sup>83</sup> Also at *Karamanoğlu Mehmetbey University, Karaman, Turkey*
- <sup>84</sup> Also at *California Institute of Technology, Pasadena, California, USA*
- <sup>85</sup> Also at *United States Naval Academy, Annapolis, Maryland, USA*
- <sup>86</sup> Also at *Ain Shams University, Cairo, Egypt*
- <sup>87</sup> Also at *Bingol University, Bingol, Turkey*
- <sup>88</sup> Also at *Georgian Technical University, Tbilisi, Georgia*
- <sup>89</sup> Also at *Sinop University, Sinop, Turkey*
- <sup>90</sup> Also at *Erciyes University, Kayseri, Turkey*
- <sup>91</sup> Also at *Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania*
- <sup>92</sup> Now at *another institute or international laboratory covered by a cooperation agreement with CERN*
- <sup>93</sup> Also at *Texas A&M University at Qatar, Doha, Qatar*
- <sup>94</sup> Also at *Kyungpook National University, Daegu, Korea*
- <sup>95</sup> Also at *another institute or international laboratory covered by a cooperation agreement with CERN*
- <sup>96</sup> Also at *Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan*
- <sup>97</sup> Also at *Northeastern University, Boston, Massachusetts, USA*
- <sup>98</sup> Also at *Imperial College, London, United Kingdom*
- <sup>99</sup> Now at *Yerevan Physics Institute, Yerevan, Armenia*
- <sup>100</sup> Also at *Universiteit Antwerpen, Antwerpen, Belgium*