

Search for direct production of GeV-scale resonances decaying to a pair of muons in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$

The CMS Collaboration*

Abstract

A search for direct production of low-mass dimuon resonances is performed using $\sqrt{s} = 13 \text{ TeV}$ proton-proton collision data collected by the CMS experiment during the 2017–2018 operation of the CERN LHC with an integrated luminosity of 96.6 fb^{-1} . The search exploits a dedicated high-rate trigger stream that records events with two muons with transverse momenta as low as 3 GeV but does not include the full event information. The search is performed by looking for narrow peaks in the dimuon mass spectrum in the ranges of $1.1\text{--}2.6 \text{ GeV}$ and $4.2\text{--}7.9 \text{ GeV}$. No significant excess of events above the expectation from the standard model background is observed. Model-independent limits on production rates of dimuon resonances within the experimental fiducial acceptance are set. Competitive or world's best limits are set at 90% confidence level for a minimal dark photon model and for a scenario with two Higgs doublets and an extra complex scalar singlet (2HDM+S). Values of the squared kinetic mixing coefficient ϵ^2 in the dark photon model above 10^{-6} are excluded over most of the mass range of the search. In the 2HDM+S, values of the mixing angle $\sin(\theta_H)$ above 0.08 are excluded over most of the mass range of the search with a fixed ratio of the Higgs doublets vacuum expectation $\tan \beta = 0.5$.

Submitted to the Journal of High Energy Physics

1 Introduction

Searches for resonant particle pair production in accelerator experiments have played a significant role in the development of the standard model (SM). The observation of resonant production of electron-positron pairs and muon-antimuon pairs signaled the discovery of the charm [1, 2] and bottom [3] quarks, respectively. The Z boson was discovered through the observation of resonant production of both electron-positron and muon-antimuon pairs [4]. More recently, findings of resonant production of photon pairs and Z boson pairs were central to the discovery of the Higgs boson at the CERN LHC by the ATLAS [5] and CMS [6, 7] Collaborations. Searches for new particles at the TeV scale are an important component of the LHC physics program. Resonant searches in dilepton channels are a large part of this effort, however, they have so far yielded results consistent with SM predictions [8, 9]. Interest has therefore grown in extending resonance searches to explore the phase space of lower masses and very small effective couplings to SM particles, which is becoming possible thanks to the large amount of data delivered by the LHC. The GeV scale is particularly interesting because a new vector boson in that mass range could provide an explanation for several astrophysical observations [10].

This paper describes a search for production of a narrow resonance that decays promptly to a pair of oppositely charged muons using proton-proton (pp) collision data recorded by the CMS experiment. The explored mass ranges are 1.1–2.6 GeV and 4.2–7.9 GeV. These ranges exclude the regions around the J/ψ , $\psi(2S)$, and $Y(1S)$ resonances. Previous limits on dimuon resonance production in these mass ranges have been set by the BaBar [11] and LHCb [12, 13] Collaborations. This search is an extension of a previous CMS analysis for higher masses [14], with trigger selection and muon identification optimized for the very low-mass region. It assumes that the natural width of the resonance is much smaller than the detector dimuon mass resolution ($\approx 1.3\%$), and that its decay is consistent with originating from the primary pp collision vertex within the instrumental resolution. The sensitivity of this analysis is enhanced by the use of high-rate (“scouting”) triggers [15] that select a larger fraction of signal-like events as compared with the standard CMS triggers, by recording only a small part of the event information, consisting of trigger objects as opposed to the full detector readout.

We also provide an interpretation of the result in the context of two specific beyond the SM scenarios. The first scenario involves the introduction of a new gauge field $U(1)_D$ that undergoes kinetic mixing with the SM hypercharge gauge field $U(1)_Y$ [16, 17]. Such mixing, controlled by the parameter ϵ , results in a dark photon (Z_D), a possibly massive, neutral vector boson. In the mass ranges probed by this search, it is coupled dominantly to the electric charges of SM particles with a coupling strength suppressed by a factor ϵ . It is assumed to be produced via the Drell–Yan (DY) mechanism, which is the dominant production mechanism in the mass range of interest [18]. The second scenario is a two Higgs doublet model with an extra complex scalar singlet (2HDM+S) [19]. The relevant feature of this model is the presence of a light pseudoscalar boson (a) that can decay into a dimuon pair. In this model, the couplings of the light pseudoscalar a to the SM particles are determined by its mixing with the Higgs doublets and parameterized by the mixing angle (θ_H) and the ratio of the Higgs doublet vacuum expectation values ($\tan\beta$). It is assumed that the light pseudoscalar a is predominantly produced via gluon-gluon fusion (ggF). The interpretation is provided in the specific 2HDM+S scenario of type IV with $\tan\beta = 0.5$ given the enhanced coupling to the up-type quarks, predicted in this model. The same model is targeted by the LHCb experiment [20] because it represents the most sensitive one in experiments at pp colliders and allows meaningful bounds to be set on the sine of the mixing angle θ_H . Example Feynman diagrams for the production of both particles are presented in Fig. 1.

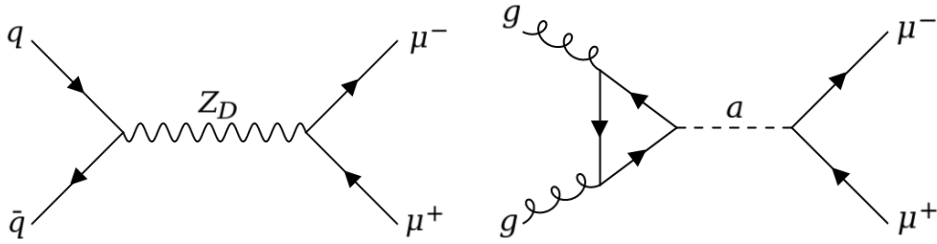


Figure 1: Expected dominant production modes for a dark photon Z_D (left) and light beyond-SM pseudoscalar boson a (right).

This paper is organized as follows. We begin with the CMS detector description in Section 2 and elaborate on the relevant triggers (Section 3) and the simulated data samples used in the analysis (Section 4). Sections 5 and 6 detail the event selection and the signal and background modeling, respectively. Section 7 explains the systematic uncertainties and the results are presented in Section 8, followed by a summary in Section 9. Tabulated results are provided in the HEPData record for this analysis [21].

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, and both a lead tungstate crystal electromagnetic and a brass/scintillator calorimeter, which consist of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity η coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is given in Ref. [22].

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. 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.

3 Triggers and Data sets

Events of interest are selected using a two-tiered trigger system [23], the level-1 (L1) and high-level (HLT) triggers. The L1, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The HLT consists of a farm of CPU processors running a version of the CMS full event reconstruction software optimized for fast event data processing. Events passing the full set of HLT selection criteria are saved for permanent storage at an overall rate of about 1 kHz.

A set of four different L1 trigger algorithms are utilized in this analysis, defined by requiring the presence of at least two muons with various additional requirements. The simplest of these (1) only requires two muons with $p_T > 15$ GeV and > 7 GeV, respectively. The remaining three triggers all share the requirement that the two muons be oppositely charged, together with the additional conditions: (2) each muon has $|\eta| < 2.0$ and $p_T > 4.5$ GeV, and that the dimuon mass ($m_{\mu\mu}$) is between 7–18 GeV; or (3) each muon has $p_T > 4.0$ (4.5) GeV in 2017 (2018) and the two muons must have an angular separation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.2$ and ϕ is the

azimuthal angle; or (4) both muons have $|\eta| < 1.5$ and are separated by $\Delta R < 1.4$, with no restriction on p_T . These criteria are summarized in Table 1.

Table 1: The set of dimuon L1 requirements applied in the high-rate triggers.

L1 path	p_T [GeV]	$ \eta $	ΔR	$m_{\mu\mu}$ [GeV]	Charge
(1)	$>15/7$	—	—	—	—
(2)	>4.5	<2.0	—	7–18	Opposite sign
(3)	>4.0 (2017)/ 4.5 (2018)	—	<1.2	—	Opposite sign
(4)	—	<1.5	<1.4	—	Opposite sign

At the HLT, our analysis makes use of the CMS high-rate data scouting trigger system [15] in which the information associated with the selected events is much reduced, permitting the recording of larger data samples. This technique has been used in previous resonant searches performed by the CMS experiment including dimuon [14] and hadronic [24] final states. Events are directly reconstructed in the HLT and are required to have at least two muons with $p_T > 3$ GeV. The dimuon events selected by the data scouting trigger are written to disk with an event size of about 4 (8) kB for data taken in 2017 (2018). The stored information includes tracking hits, calorimeter clusters, muon hits, and trigger primitives, along with their reconstructed quantities. By contrast the size of a standard raw event is closer to 1 MB. These dimuon scouting triggers were fully commissioned during 2017 [25] and recorded events at a rate of approximately 2 kHz at the peak instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, whereas the standard dimuon triggers recorded approximately 0.45 kHz at the same instantaneous luminosity. Data corresponding to an integrated luminosity of 96.6 fb^{-1} were collected with these triggers in 2017–2018. Figure 2 shows the efficiency of the dimuon scouting triggers in conjunction with the four L1 triggers for both data periods. This is measured by sampling events from another CMS data set which does not trigger on any muon related information in the event, but may include pairs of muons occasionally produced in association with the main physics object. For this sample of unbiased dimuon pairs, we count the number that also triggered the dimuon scouting path and at least one of the four L1 triggers, and compare that to the total number of reconstructed dimuon events in that data set that pass our fiducial selections. The ratio of these two counts is the efficiency of our trigger.

4 Event simulation

The analysis employs an estimation of the SM background based on recorded data. However, simulations of certain SM processes are used for the validation of selection criteria, corrections to data driven efficiency measurements, as well as the corresponding systematic uncertainties in the signal predictions. These processes include DY production of dimuon pairs in the low $m_{\mu\mu}$ region ($1 < m_{\mu\mu} < 10$ GeV), as well as resonant dimuon production via J/ψ and $Y(1S)$ mesons. These processes are simulated at leading order (LO) in perturbative quantum chromodynamics with PYTHIA 8.230 [26]. In the 2HDM+S scenario, the production of the light pseudoscalar a is assumed to go via ggF and is also simulated at LO with PYTHIA 8.230. The Z_D signal is simulated at next-to-next-to-LO (NNLO) in perturbative quantum chromodynamics using the hidden Abelian Higgs model [18, 27, 28] implemented in the MADGRAPH5_aMC@NLO v3.4.1 generator [29]. The parton distribution function (PDF) set is NNPDF3.1 LO in the four-flavor scheme [30].

For all simulated samples, the parton showering and hadronization processes are performed

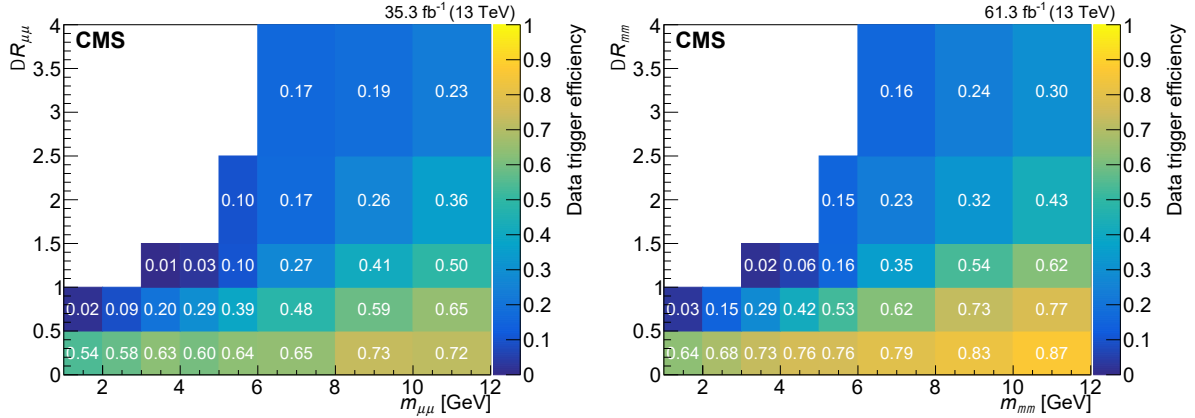


Figure 2: The measured 2017 (left) and 2018 (right) efficiencies of the dimuon scouting trigger and logical OR of all L1 triggers using 2017–2018 data. Each cell value represents the probability that a pair of muons meeting the trigger requirements will activate the dimuon scouting trigger. The x -axis shows the dimuon mass and includes the entire relevant range for this analysis. The y -axis shows the angular separation, ΔR , between the two muons. Statistical uncertainty on the value of each cell is less than 5%.

with PYTHIA 8.230 using the CP5 underlying event tune [31]. Events are passed through a full detector simulation performed with GEANT4 [32]. The simulated samples include additional pp interactions per bunch crossing, referred to as “pileup”. The effect of pileup is taken into account by generating minimum-bias collision events with PYTHIA. The simulated events are weighted such that the distribution of the number of pileup interactions matches that in data.

5 Event selection

A complete event reconstruction is performed by the HLT. The muons in the scouting data stream are reconstructed by combining the information from the silicon tracker and muon systems, and their momentum is determined from the curvature of the muon track. The muon momentum obtained with the HLT event reconstruction agrees with that obtained with the full CMS offline event reconstruction within 1–2%.

The event candidate is required to have at least one primary vertex (PV) reconstructed by the HLT system and to contain a pair of oppositely charged muons originating from this vertex. The absolute transverse distance of the PV to the beam axis, referred to as the vertex transverse displacement L_{xy} , is required to be less than 0.2 cm. Both muons are required to have $p_T > 4$ GeV and $|\eta| < 1.9$. The restriction on η is imposed to ensure optimal dimuon mass resolution without incurring a significant loss in acceptance. The muons are required to satisfy a muon identification based on multivariate analysis (MVA) techniques. Two MVA discriminants are used depending on the reconstructed $m_{\mu\mu}$, optimized for the signal kinematic properties in each mass range. The MVA identification utilizes information on the quality of the muon tracks, the relative isolation of the muon, and the vertex that the muons are associated with. The muon track quality parameters include the number of hits in the pixel detector, number of contributing layers in the strip tracker, and χ^2 of the muon track fit. The relative isolation of the muon is computed as the scalar p_T sum of reconstructed tracks in a cone of $\Delta R = 0.3$ around the muon candidate, divided by the muon p_T . The dimuon vertex information includes the χ^2 of the common vertex fit and L_{xy} . These parameters are combined into a single discriminator using a boosted decision tree (BDT) [33]. The choice of input parameters to the BDT and the

requirement on the discriminator are optimized to achieve the highest expected sensitivity to signal-like events.

The mass range 2.6–4.2 GeV is excluded because of the presence of the J/ψ and $\psi(2S)$ resonances. The MVA identification for $m_{\mu\mu} < 2.6$ GeV is trained using a partial J/ψ sample, whereas the identification for $m_{\mu\mu} > 4.2$ GeV is trained using an $Y(1S)$ sample. The efficiency of the muon MVA identification is determined from J/ψ and Y events using the “tag-and-probe technique” [34]. Background samples enriched with nonprompt and misidentified muons for the BDT training are extracted from the data events with only one pair of same-sign muons and a mass of $3 < m_{\mu\mu} < 10$ GeV.

At smaller values of $m_{\mu\mu}$, the dimuon system is more Lorentz boosted and the muons become more collinear, resulting in larger uncertainties in the reconstructed PV position. The L_{xy} distribution becomes broader, whereas the distribution of the vertex displacement significance remains stable. Therefore, we employ different displacement criteria depending on the mass value. For events with $m_{\mu\mu} < 2.6$ GeV we further require that L_{xy} divided by its uncertainty ($\sigma_{L_{xy}}$) be less than 3.5, and the L_{xy} value is not used in the BDT. Events with $m_{\mu\mu} > 4.2$ GeV are required to have $L_{xy} < 0.015$ cm to further suppress nonprompt backgrounds. Figure 3 shows the $m_{\mu\mu}$ distribution obtained from the dimuon scouting triggers. The average efficiency of the $Y(J/\psi)$ -trained muon MVA identification is around 85 (90)% estimated from the $Y(1S)$ (J/ψ) resonance. Compared with the simple cut-based selection used in the previous CMS search [14], the MVA identification provides a higher efficiency while still keeping the misidentification rate low, resulting in improvements to the final limits on the cross section by about 30%.

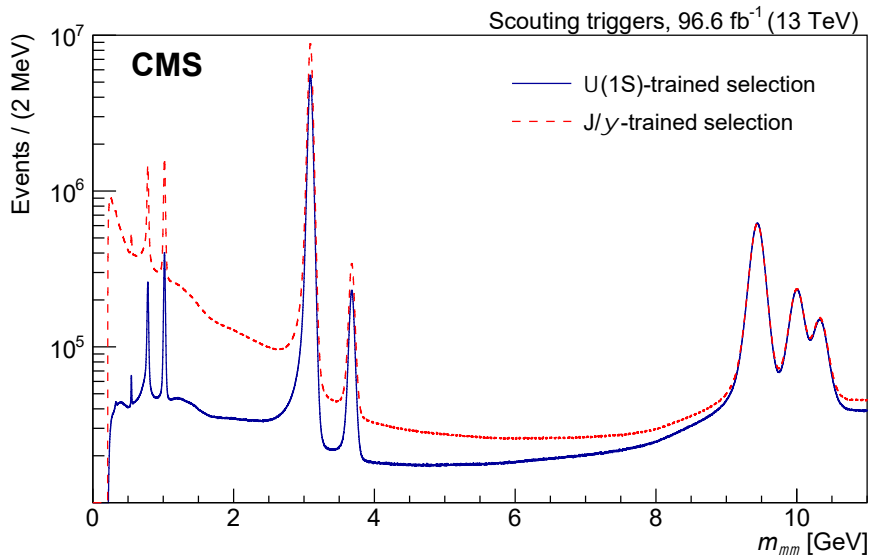


Figure 3: The $m_{\mu\mu}$ distribution obtained with the muon scouting data collected during 2017–2018 with two sets of selections: the $Y(1S)$ -trained muon MVA identification with $L_{xy} < 0.015$ cm (blue, solid), and the J/ψ -trained muon MVA identification with $L_{xy}/\sigma_{L_{xy}} < 3.5$ (red, dashed).

In the search for a light pseudoscalar particle (the 2HDM+S scenario), the signal is produced via the ggF process, which results in a harder p_T distribution compared to the DY process, due to the enhanced probability for a jet to scatter off of an initial state gluon. Higher values of muon p_T are thus required to further improve the sensitivity for the pseudoscalar signal. The muons are required to have $p_T > 5$ GeV and the muon pair is required to have $p_T > 20$ (35) GeV for

$m_{\mu\mu} > 4.2 \text{ GeV}$ ($< 2.6 \text{ GeV}$). The J/ψ -trained muon MVA identification and $L_{xy}/\sigma_{L_{xy}} < 3.5$ are required for both $m_{\mu\mu} < 2.6 \text{ GeV}$ and $m_{\mu\mu} > 4.2 \text{ GeV}$. We refer to this as the high- p_T selection. All selection criteria for both categories are summarized in Table 2.

Table 2: Summary of all selection criteria for an event to enter the analysis in inclusive and high- p_T search categories.

Preselection	$L_{xy} < 0.2 \text{ cm}, \eta^\mu < 1.9, \text{ Opposite sign}$			
Signal selection	Inclusive		high- p_T	
Mass	$m_{\mu\mu} < 4 \text{ GeV}$	$m_{\mu\mu} > 4 \text{ GeV}$	$m_{\mu\mu} < 4 \text{ GeV}$	$m_{\mu\mu} > 4 \text{ GeV}$
p_T^μ	$> 4 \text{ GeV}$		$> 5 \text{ GeV}$	
Muon	J/ ψ ID	Y ID	J/ ψ ID	J/ ψ ID
Vertex	$L_{xy}/\sigma_{L_{xy}} < 3.5$	$L_{xy} < 0.015 \text{ cm}$	$L_{xy}/\sigma_{L_{xy}} < 3.5$	$L_{xy}/\sigma_{L_{xy}} < 3.5$
$p_T^{\mu\mu}$	—	—	$> 35 \text{ GeV}$	$> 20 \text{ GeV}$

The muon reconstruction and identification efficiency measured from data and the acceptance extracted from signal simulations are shown in Fig. 4. The efficiency of the vertex displacement requirement of the signal is corrected using the J/ψ and $Y(1S)$ samples from data and simulation. The total identification efficiency of the event is the product of the identification efficiencies of the two muons.

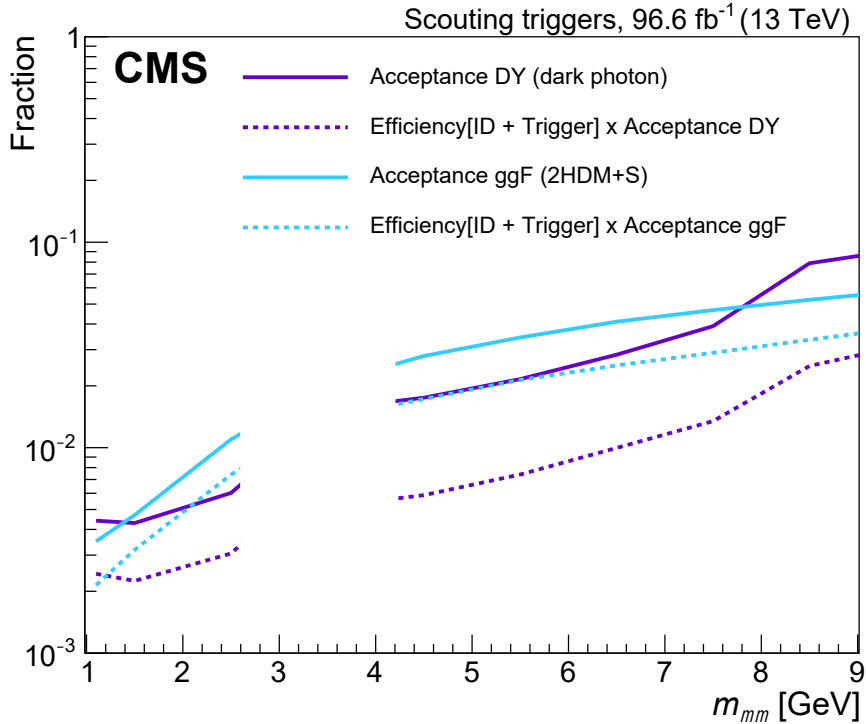


Figure 4: The signal acceptance and reconstruction efficiency are extracted from the dark photon (purple, dark) and pseudoscalar (cyan, light) simulations. The region at 2.6–4.2 GeV is excluded because of the presence of the J/ψ and $\psi(2S)$ resonances.

6 Signal and background model

The signal is extracted by performing simultaneous signal plus background maximum likelihood fits to the $m_{\mu\mu}$ distribution. For each mass hypothesis, the fit is performed over a mass window spanning ± 5 times the mass resolution around the nominal resonance mass. The mass resolution is determined from data to be roughly 1.3% across the entire mass range. This window size ensures sufficient sidebands for the background model fit, such that it will not be influenced by the presence of a signal at the central value. When fitting the mass distributions in the high- p_T selection category, the size of the window is increased to ± 8 times the mass resolution, to offset the fact that the number of events in the sideband is significantly reduced by the high p_T requirements. The probability density function (pdf) chosen to model the signal distribution is the sum of a double Crystal Ball [35, 36] and a Gaussian distribution. We limit the search to the case of narrow resonances with an intrinsic width much smaller than the experimental resolution. Since this same approximation holds for charmonium and Y resonances, the shape parameters for the signal pdf are determined from least square mass fits for the J/ψ , $\psi(2S)$, and $Y((1S), (2S), \text{ and } (3S))$ resonances. The signal pdf parameters, including the mass resolution, are found to have little dependence on the resonance mass. The only free parameter of the signal pdf in the final fit is the overall normalization, which is proportional to the production cross section of the new particle.

Several possible functions to model the background are investigated. We use empirical functions because the shape of the background in the search region is complicated by the presence of multiple known resonances and by the acceptance of the various triggers. The families of functions considered are Bernstein polynomials [37], a polynomial times an exponential, a sum of exponentials, and a sum of a Bernstein polynomial and a power law function. The optimal order for each function family is chosen by performing a Fisher F -test [38] with background-only fits to the dimuon mass distribution for each mass hypothesis. The order of the function family is chosen as the lowest one that keeps the number of fits with an F value above the critical value below the false-rejection probability ($\alpha < 0.05$). The potential bias of each function family is evaluated using simulations assuming either no signal or the presence of a small hypothetical signal. The bias for each function type, defined as the difference between the assumed and measured signal strength, is less than $\approx 20\%$ of the statistical uncertainty in the signal strength. Therefore, the added uncertainty due to the bias of the background function is negligible and is not included in the final fit. The discrete profiling method [39] is used to further suppress the bias which arises from the choice of the background function. The background model fit of the mass distribution becomes unreliable when the tails of J/ψ and $\psi(2S)$ resonances enter the mass window, so the mass range 2.6–4.2 GeV is excluded from the search.

Among all the known resonances, the D^0 meson contributes an apparent peak in the $m_{\mu\mu}$ continuum in the search range. When the pions and kaons from the $D^0 \rightarrow K^+K^-$ or $D^0 \rightarrow K^-\pi^+$ decays are misreconstructed as muons, the $m_{\mu\mu}$ distribution exhibits an enhancement at 1.72 or 1.58 GeV, respectively. The contamination of these processes in the signal region is estimated from a control region by a simultaneous fit to both regions. The control region is defined by requiring an $L_{xy}/\sigma_{L_{xy}}$ to be within 3.5–11.0. The pdf of the $D^0 \rightarrow K^+K^- (K^-\pi^+)$ dimuon peak is derived from simulation. The normalization is a free parameter that is constrained by a transfer factor between the signal and control regions from the simulation. The uncertainty in the transfer factor includes the statistical uncertainty of the simulated samples and the mismodeling of $L_{xy}/\sigma_{L_{xy}}$, which is quantified using the J/ψ peak in both data and simulation. The J/ψ events in the data are determined by subtracting the contribution from background and nonprompt J/ψ production, estimated through extrapolation from the distribution, where $8 < L_{xy}/\sigma_{L_{xy}} < 20$.

The contribution from the $D^0 \rightarrow \pi^+ \pi^-$ process is not modeled because pions are much less likely to be misidentified as muons compared to kaons and there are insufficient $D^0 \rightarrow \pi^+ \pi^-$ yields in the control region to properly constrain the process.

7 Systematic uncertainties

The signal extraction in this analysis is affected by several sources of systematic uncertainties. The measured integrated luminosity has an uncertainty of 2.3 (2.5)% for data collected in 2017 (2018) [40–42]. Roughly half of these values are attributed to correlated systematic effects between the years, and the remaining portion is uncorrelated, giving a combined uncertainty of about 2.0% between the two years. The uncertainty in the efficiency of the PV displacement requirement is 3% for $m_{\mu\mu} > 4.2$ GeV and is negligible for $m_{\mu\mu} < 2.6$ GeV.

The efficiency of the dimuon scouting triggers is measured with respect to fully reconstructed muons using events selected with independent standard triggers. The uncertainties in the trigger efficiency depend on the dimuon mass and vary from 1–16%, as determined from the difference between the trigger efficiency in data and simulation in each mass bin.

The efficiency of muon identification is measured with respect to trigger requirements. The uncertainties in the identification efficiency of the two muons vary from 4–20%, and include the statistical uncertainty of the measurement sample and the uncertainty associated with the modeling in the input parameters of the muon MVA identification between the data and simulation. The uncertainty is largest for muons with low p_T and low ΔR because of the reduced number of muons in this region in the simulated samples.

The per muon identification efficiency is applied to calculate the total reconstruction efficiency. The identification efficiency is measured from the resonances produced mainly through the gluon splitting process, though the signal production may proceed via other mechanisms. The identification efficiencies between the two muons are correlated because event observables are used in the MVA identification, whereas the efficiencies are treated as uncorrelated when calculating the total efficiency. To account for the efficiency variation caused by these effects, an additional 4 (8)% systematic uncertainty is assigned for $m_{\mu\mu} > 4.2$ GeV (< 2.6 GeV). The uncertainty in the transfer factor that connects the normalizations between the signal and control regions of the $D^0 \rightarrow K^+ K^- (K^- \pi^+)$ backgrounds is 20 (25)%.

The mass resolution of the signal is measured using different resonances in data. The variation in the observed mass resolutions is around 20% and is assigned as the systematic uncertainty. The signal shape uncertainty, which varies from 1.3–2.7%, is derived by using a double Gaussian as the signal template in the fit. A discrete parameter is used to assign an uncertainty in the background function choice as described in Section 6. Table 3 summarizes the systematic uncertainties in the search.

8 Results

The data are consistent with the continuum dimuon production. Limits at 95% confidence level (CL) are set on the product of the signal cross section, the branching fraction to a muon pair, and fiducial acceptance of a hypothetical resonance with a mass from 1.1–2.6 GeV or from 4.2–7.9 GeV. The computation of exclusion upper limits is performed using the CL_s criterion in the asymptotic approximation [43–45]. A profile likelihood ratio test statistic is built including the systematic uncertainties presented above as nuisance parameters. A log-normal pdf is used to describe each constrained nuisance parameter.

Table 3: Summary of the experimental systematic uncertainties for a signal model in the model independent search for a dimuon resonance.

Effect	$m_{\mu\mu} < 2.6 \text{ GeV}$	$m_{\mu\mu} > 4.2 \text{ GeV}$
Integrated luminosity	2.3–2.5%	
Mass resolution	20%	
Signal shape	1.3–2.7%	1.4–1.7%
Trigger efficiency	1–16%	
Muon ID efficiency	4–9%	12–20%
Vertex selection	—	3%
Efficiency application	8%	4%
D^0 meson normalization	20–25%	—

Figure 5 shows the expected and observed model independent limits for the inclusive and high- p_T selections. The 95% confidence level (CL) upper limit for the inclusive selection is of order 0.10 (0.15) pb in the mass range 1.1–2.6 (4.2–7.9) GeV. The 95% CL upper limit for the high- p_T selection is about 0.015 (0.024) pb in the mass range 1.1–2.6 (4.2–7.9) GeV. The upward deviations in the expected limits below 2 GeV are due to the peaking background associated with D^0 meson decays. The excess at 1.867 GeV in the inclusive selection may correspond to the $D^0 \rightarrow \pi^+\pi^-$ or $D^0 \rightarrow \mu^+\mu^-$ processes. Distinguishing between these two possibilities is beyond the scope of this paper. The observed limits exhibit oscillatory structures within some mass ranges, which result from statistical fluctuations modulated by the sliding mass window. No significant excess is observed beyond 2.6 (0.6) standard deviations local (global) significance from the SM background expectation in the high- p_T category. The model independent limits are exploited to constrain the dark photon [16, 17, 46] and 2HDM+S [19] scenarios.

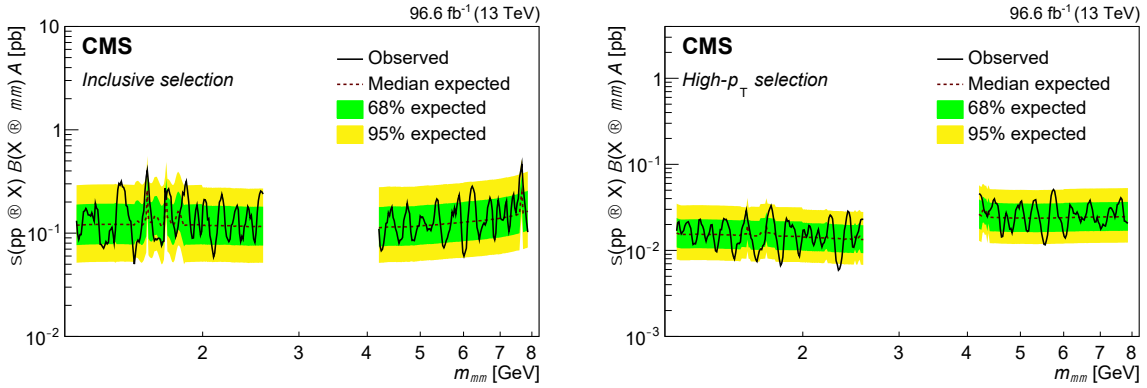


Figure 5: Left: Expected and observed model-independent upper limits at 95% CL on the product of the signal cross section (σ), the branching fraction to a pair of muons for the inclusive dimuon selection (\mathcal{B}), and fiducial acceptance (A). Right: The model-independent limits for the high- p_T selection. The mass region dominated by the J/ψ and $\psi(2S)$ resonances is excluded from the search.

In the first case, limits on the squared kinetic mixing coefficient ε^2 are extracted as a function of the dark photon mass (m_{Z_D}) according to the following relation:

$$\sigma_{pp \rightarrow Z_D} \varepsilon^2 \mathcal{B} A = \sigma_{\text{limit}}, \quad (1)$$

where $\sigma_{pp \rightarrow Z_D}$ is the dark photon cross section with $\varepsilon = 1$, \mathcal{B} is the branching fraction of $Z_D \rightarrow \mu^+\mu^-$, σ_{limit} is the model independent limit, and A is the acceptance. We use the

numerical software DYTURBO [47] to generate the DY process at NNLO with the renormalization and factorization scales set to $\mu = 0.5\sqrt{m_{\mu\mu}^2 + p_{T\mu\mu}^2}$ and to correct the dark photon cross section and extract the acceptance, because the dark photon is produced through the DY-like process. The interpretation of the cross section limit as a limit on the mixing coefficient ε^2 is subject to theoretical uncertainties. Uncertainties in the theoretical cross section are found by varying the renormalization and factorization scales up and down by a factor of 2, and the uncertainty in the acceptance is found by comparing the results between the DYTURBO and MADGRAPH5_aMC@NLO generators. The scale variations are between 3.5 and 9.7%, whereas the difference in acceptance is up to 31%. Upper limits at 90% CL on the mixing coefficient ε^2 are presented in Fig. 6, together with the LHCb and BaBar limits reinterpreted by DARKCAST [48]. The sensitivity becomes better at low masses because of the larger DY production cross section at lower energy scale. The kinetic mixing coefficient ε reflects the degree of mixing and the strength of the coupling of dark photon to other SM particles. The mixing coefficient ε^2 above 2 (9) $\times 10^{-7}$ is excluded at $m_{Z_D} = 2$ (7) GeV. These results complement the previous CMS search at larger masses [14].

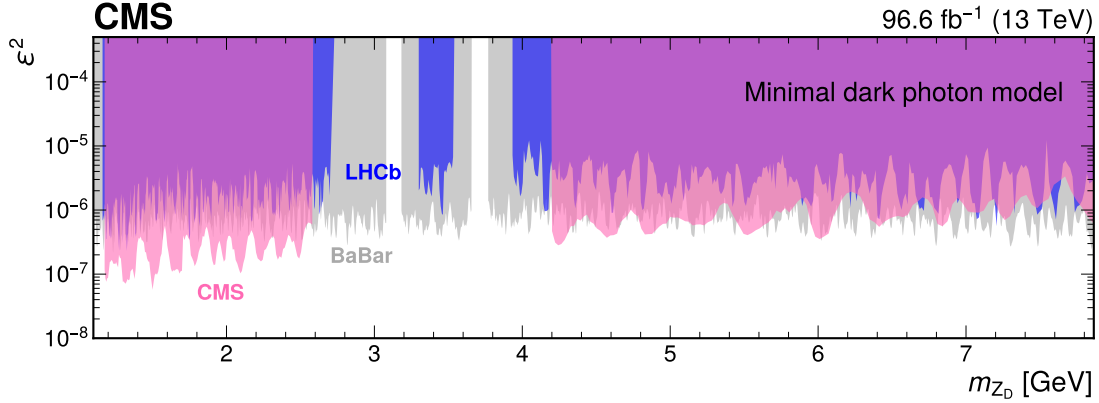


Figure 6: Observed upper limits at 90% CL on the square of the kinetic mixing coefficient ε in the minimal model of a dark photon from the CMS search in the mass ranges of 1.1–2.6 GeV and 4.2–7.9 GeV (pink). The CMS limits are compared with the existing limits at 90% CL provided by LHCb [13] (blue) and BaBar [11] (gray).

In the 2HDM+S scenarios, the limits from the high- p_T selection are converted to an upper limit on the mixing angle θ_H as a function of the light pseudoscalar-boson mass. The recasting of the limit is performed under the assumption of $\tan\beta = 0.5$ according to the following relation:

$$\sigma_{pp \rightarrow a} \sin^2(\theta_H) \mathcal{B}A = \sigma_{\text{limit}}, \quad (2)$$

where $\sigma_{pp \rightarrow a}$ is the production cross section of the light pseudoscalar a , σ_{limit} is the model independent limit, \mathcal{B} is the branching fraction of $a \rightarrow \mu^+ \mu^-$, and A is the acceptance. The $\sigma_{pp \rightarrow a}$ is computed from the HIGLU generator at NNLO using the NNPDF3.0 PDF set [30] and assuming renormalization and factorization scales $\mu = 0.5m_a$, as in the LHCb search [20]. Uncertainties in the theoretical cross section for pseudoscalar production via ggF are found by varying the renormalization and factorization scales by a factor of 2. These uncertainties are around 90% at $m_a = 1.18$ GeV and gradually reduce to 10% at $m_a > 4.2$ GeV. The uncertainty in the ggF acceptance is estimated by comparing the values obtained with MADGRAPH5_aMC@NLO and PYTHIA, and is about 30%.

Observed upper limits at 90% CL are presented in Fig. 7. Values of $\sin(\theta_H)$ above ≈ 0.01 (0.02) are excluded at $m_a = 2$ (7) GeV with fixed $\tan\beta = 0.5$. The limits derived from this search in the

low-mass region are competitive with recently reported results from the LHCb experiment [20] below the charmonium peaks and better above them.

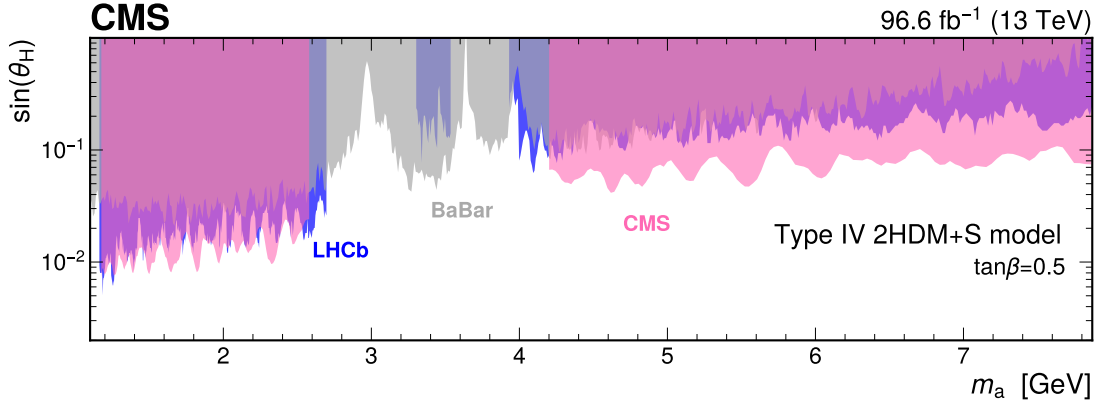


Figure 7: Observed upper limits at 90% CL on the mixing angle θ_H for the 2HDM+S scenario from the CMS search in the mass ranges of 1.1–2.6 GeV and 4.2–7.9 GeV (pink). The CMS limits are compared with the existing limits at 90% CL provided by LHCb [20] (blue) and BaBar [11] (gray).

9 Summary

A search for direct production of a narrow resonance decaying to a pair of muons has been presented using proton-proton collision data recorded by the CMS experiment at $\sqrt{s} = 13$ TeV in 2017–2018. The search is performed in the dimuon mass regions of 1.1–2.6 GeV and 4.2–7.9 GeV using data collected in a dedicated high-rate trigger stream, corresponding to an integrated luminosity of 96.6 fb^{-1} . A multivariate analysis method is used to identify muons to achieve a higher sensitivity. No significant excess of events above the expectation from the standard model background is observed. Model-independent limits on production rates of dimuon resonances within the experimental fiducial acceptance are set. Competitive or world’s best limits are set at 90% confidence level for a minimal dark photon model and for a scenario with two Higgs doublets and an extra complex scalar singlet (2HDM+S). Values of the squared kinetic mixing coefficient ϵ^2 in the dark photon model above 10^{-6} are excluded over most of the mass range of the search. In the 2HDM+S, values of the mixing angle $\sin(\theta_H)$ above 0.08 are excluded over most of the mass range of the search with a fixed ratio of the Higgs doublets vacuum expectation $\tan \beta = 0.5$.

Acknowledgments

We thank Stefano Camarda for suggesting the DYTURBO settings for calculating the DY cross section at low mass, for the dark photon interpretation. We also thank Philip Ilten for providing the details of the $pp \rightarrow a$ cross section calculation using the HIGLU generator, for the comparison of CMS and LHCb results.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid

and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TEN-MAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

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













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A The CMS Collaboration




Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan¹ 













Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , A. Escalante Del Valle , P.S. Hussain , M. Jeitler² , N. Krammer , D. Liko , I. Mikulec , J. Schieck² , R. Schöffbeck , D. Schwarz , M. Sonawane , S. Templ , W. Waltenberger , C.-E. Wulz² 















Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish³ , T. Janssen , P. Van Mechelen 








Vrije Universiteit Brussel, Brussel, Belgium

E.S. Bols , J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , H. El Faham , S. Lowette , I. Makarenko , A. Morton , D. Müller , A.R. Sahasransu , S. Tavernier , M. Tytgat⁴ , S. Van Putte , D. Vannerom 

Université Libre de Bruxelles, Bruxelles, Belgium

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






Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , J. Knolle , L. Lambrecht , G. Mestdach, C. Rendón, A. Samalan, K. Skovpen , N. Van Den Bossche , L. Wezenbeek 




















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

A. Benecke , G. Bruno , C. Caputo , C. Delaere , I.S. Donertas , A. Giammanco , K. Jaffel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , K. Mondal , T.T. Tran , S. Wertz 

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , C. Hensel , T. Menezes De Oliveira, A. Moraes , P. Rebello Teles , M. Soeiro

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

W.L. Aldá Júnior , M. Alves Gallo Pereira , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁵, E.M. Da Costa , G.G. Da Silveira⁶ , D. De Jesus Damiao , S. Fonseca De Souza , J. Martins⁷ , C. Mora Herrera , K. Mota Amarilo , L. Mundim , H. Nogima , A. Santoro , S.M. Silva Do Amaral , A. Sznajder , M. Thiel , A. Vilela Pereira 

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

C.A. Bernardes⁶ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , 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 , T. Ivanov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 



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

S. Keshri , S. Thakur 

Beihang University, Beijing, China

T. Cheng , Q. Guo, T. Javaid , M. Mittal , L. Yuan 

Department of Physics, Tsinghua University, Beijing, China

G. Bauer⁸, Z. Hu , K. Yi^{8,9} 

Institute of High Energy Physics, Beijing, China

G.M. Chen¹⁰ , H.S. Chen¹⁰ , M. Chen¹⁰ , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu¹¹ , F. Monti , R. Sharma , J.N. Song¹¹, J. Tao , J. Wang , H. Zhang 

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

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




Sun Yat-Sen University, Guangzhou, China

Z. You 

University of Science and Technology of China, Hefei, China

N. Lu 

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

X. Gao¹² , D. Leggat, H. Okawa , Y. Zhang 





Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 





Universidad de Los Andes, Bogota, Colombia

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

Universidad de Antioquia, Medellin, Colombia

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

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

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









University of Split, Faculty of Science, Split, Croatia

M. Kovac , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , S. Mishra , A. Starodumov¹³ , T. Susa 

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

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

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 



Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 










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

Y. Assran^{14,15}, S. Elgammal¹⁵




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

M. Abdullah Al-Mashad , M.A. Mahmoud 

















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

R.K. Dewanjee¹⁶ , 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 , E. Brücken , F. Garcia , J. Havukainen , K.T.S. Kallonen , M.S. Kim , R. Kinnunen, T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Lotti, L. Martikainen , M. Myllymäki , M.m. Rantanen , H. Siikonen , E. Tuominen , J. Tuominiemi 








Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow , T. Tuuva[†]








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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , V. Lohezic , J. Malcles , J. Rander, A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁷ , P. Simkina , M. Titov 








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

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




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

J.-L. Agram¹⁸ , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , C. Grimault, R. Haeberle , A.-C. Le Bihan , M.A. Sessini , P. Van Hove

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

S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , J. Choi , D. Contardo , P. Depasse , C. Dozen¹⁹ , H. El Mamouni, J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg, G. Grenier , B. Ille , I.B. Laktineh, M. Lethuillier , L. Mirabito, S. Perries, M. Vander Donckt , P. Verdier , J. Xiao

























Georgian Technical University, Tbilisi, Georgia

A. Khvedelidze¹³ , I. Lomidze , Z. Tsamalaidze¹³ 

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

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














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

S. Diekmann , A. Dodonova , N. Eich , D. Eliseev , F. Engelke , M. Erdmann , P. Fackeldey , B. Fischer , T. Hebbeker , K. Hoepfner , F. Ivone , A. Jung , M.y. Lee , L. Mastrolorenzo, M. Merschmeyer , A. Meyer , S. Mukherjee , D. Noll , A. Novak , F. Nowotny, A. Pozdnyakov , Y. Rath, W. Redjeb , F. Rehm, H. Reithler , V. Sarkisovi , A. Schmidt , S.C. Schuler, A. Sharma , A. Stein , F. Torres Da Silva De Araujo²⁰ , L. Vigilante, S. Wiedenbeck , S. Zaleski

















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

C. Dziwok , G. Flügge , W. Haj Ahmad²¹ , 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 , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , S. Bhattacharya , F. Blekman²² , K. Borras²³ , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina , S. Consuegra Rodriguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo²² , A. Geiser , A. Giraldi , G. Greau, V. Guglielmi , M. Guthoff , A. Hinzmann , A. Jafari²⁴ , L. Jeppe , N.Z. Jomhari , B. Kaech , M. Kasemann , H. Kaveh , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange, D. Leyva Pernia , K. Lipka²⁵ , W. Lohmann²⁶ , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , J. Metwally, A.B. Meyer , G. Milella , M. Mormile , A. Mussgiller , A. Nürnberg , Y. Otariid, D. Pérez Adán , E. Ranken , A. Raspereza , B. Ribeiro Lopes , J. Rübenach, A. Saggio , M. Scham^{27,23} , V. Scheurer, S. Schnake²³ , P. Schütze , C. Schwanenberger²² , M. Shchedrolosiev , R.E. Sosa Ricardo , L.P. Sreelatha Pramod , D. Stafford, F. Vazzoler , A. Ventura Barroso , R. Walsh , Q. Wang , Y. Wen , K. Wichmann, L. Wiens²³ , C. Wissing , S. Wuchterl , Y. Yang , A. Zimmermann Castro Santos

University of Hamburg, Hamburg, Germany

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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , M. Burkart, E. Butz , T. Chwalek , A. Dierlamm , A. Droll, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann²⁸ , M. Horzela , U. Husemann , M. Klute , R. Koppenhöfer , M. Link, A. Lintuluoto , S. Maier , S. Mitra , Th. Müller , M. Neukum, M. Oh , G. Quast , K. Rabbertz , I. Shvetsov , H.J. Simonis , N. Trevisani , R. Ulrich , J. van der Linden , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , S. Wunsch, X. Zuo


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

G. Anagnostou, P. Assiouras , G. Daskalakis , A. Kyriakis, A. Papadopoulos²⁸, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

D. Karasavvas, P. Kontaxakis , G. Melachroinos, A. Panagiotou, I. Papavergou , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 


National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsiopolitis, A. Zacharopoulou






University of Ioánnina, Ioánnina, Greece

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

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

M. Csanád , K. Farkas , M.M.A. Gadallah²⁹ , Á. Kadlecik , P. Major , K. Mandal , G. Pásztor , A.J. Rádl³⁰ , O. Surányi , G.I. Veres 



Wigner Research Centre for Physics, Budapest, Hungary

M. Bartók³¹ , C. Hajdu , D. Horvath^{32,33} , F. Sikler , V. Veszpremi 




Institute of Nuclear Research ATOMKI, Debrecen, Hungary

G. Bencze, S. Czellar, J. Karacsi³¹ , J. Molnar, Z. Szillasi

















Institute of Physics, University of Debrecen, Debrecen, Hungary

P. Raics, B. Ujvari³⁴ , G. Zilizi 

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

T. Csorgo³⁰ , F. Nemes³⁰ , T. Novak 

Panjab University, Chandigarh, India

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh³⁶ , A. Singla 
















University of Delhi, Delhi, India

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




Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁷ , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber³⁸ , P. Palit , G. Saha , B. Sahu³⁸ , S. Sarkar










Indian Institute of Technology Madras, Madras, India

P.K. Behera , S.C. Behera , S. Chatterjee , P. Jana , P. Kalbhor , J.R. Komaragiri³⁹ , D. Kumar³⁹ , M. Mohammad Mobassir Ameen , L. Panwar³⁹ , R. Pradhan , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , S. Verma 









Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

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

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

S. Bahinipati⁴⁰ , A.K. Das, C. Kar , D. Maity⁴¹ , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu⁴¹ , K. Naskar⁴¹ , A. Nayak⁴¹ , P. Sadangi, P. Saha , S.K. Swain , S. Varghese⁴¹ , D. Vats⁴¹ 

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

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

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi^{42,43} , E. Khazaie⁴³ , M. Zeinali⁴⁴ 
































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

S. Chenarani⁴⁵ , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























University College Dublin, Dublin, Ireland

M. Grunewald 





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

M. Abbrescia^{a,b} , R. Aly^{a,c,46} , A. Colaleo^a , D. Creanza^{a,c} , B. D' Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , A. Di Florio^{a,c} , W. Elmetenawee^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^{a,b} , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^a , G. Ramirez-Sanchez^{a,c} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,b} , Ü. Sözbilir^a , A. Stamerra^a , R. Venditti^a , P. Verwilligen^a , A. Zaza^{a,b} 

















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

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , L. Borgonovi^a , R. Campanini^{a,b} , P. Capiluppi^{a,b} , A. Castro^{a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , A. Fanfani^{a,b} , D. Fasanella^{a,b} , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,47} , L. Lunerti^{a,b} , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,48} , A. Di Mattia^a , R. Potenza^{a,b}, A. Tricomi^{a,b,48} , C. Tuve^{a,b} 

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

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
























INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁴⁹ , D. Piccolo 












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

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




























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

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












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

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b} , N. Cavallo^{a,c} , A. De Iorio^{a,b} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,50} , P. Paolucci^{a,28} , B. Rossi^a , C. Sciacca^{a,b} 
















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

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,51} , D. Bisello^{a,b} , P. Bortignon^a , A. Bragagnolo^{a,b} , R. Carlin^{a,b} , P. Checchia^a , T. Dorigo^a , S. Fantinel^a , F. Gasparini^{a,b} , U. Gasparini^{a,b} , G. Grosso^a, L. Layer^{a,52}, E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , G. Strong^a , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , H. Yarar^{a,b}, M. Zanetti^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b} 
































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

S. Abu Zeid^{a,53} , C. Aimè^{a,b} , A. Braghieri^a , S. Calzaferri^{a,b} , D. Fiorina^{a,b} , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 





















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

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






































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

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







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

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

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

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





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

S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^{a,b} ,
G. Della Ricca^{a,b} 

Kyungpook National University, Daegu, Korea

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





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

G. Bak , P. Gwak , H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , D. Kim , T.J. Kim , J.A. Merlin, J. Park 

Korea University, Seoul, Korea

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






Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh 









Sejong University, Seoul, Korea

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



Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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


Yonsei University, Department of Physics, Seoul, Korea

S. Ha , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

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


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

T. Beyrouthy, Y. Maghrbi 

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns⁵⁵ 

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

N. Bin Norjoharuddeen , I. Yusuff⁵⁶ , 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 , E. De La Cruz-Burelo , I. Heredia-De La Cruz⁵⁷ ,
R. Lopez-Fernandez , C.A. Mondragon Herrera, D.A. Perez Navarro ,
A. Sánchez Hernández 


Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , 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 , B. Boimska , M. Górski , M. Kazana , M. Szeleper ,
P. Zalewski 












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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski ,
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 , P. Faccioli ,
M. Gallinaro , J. Hollar , N. Leonardo , T. Niknejad , M. Pisano , J. Seixas , J. Varela 




























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. Rekoivic














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

M. Aguilar-Benitez, J. Alcaraz Maestre , M. Barrio Luna, Cristina F. Bedoya , M. Cepeda ,
M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , D. Fernández Del Val ,
J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez ,
J.M. Hernandez , M.I. Josa , J. León Holgado , D. Moran , C. M. Morcillo Perez ,
Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo ,
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







Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

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

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




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 , J. Duarte Campderros , M. Fernandez , C. Fernandez Madrazo , G. Gomez , C. Lasasa García , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , C. Prieels , L. Scodellaro , I. Vila , J.M. Vizan Garcia 

University of Colombo, Colombo, Sri Lanka

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













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

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
































CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler , D. Barney , A. Bermúdez Martínez , M. Bianco , B. Bilin , A.A. Bin Anuar , A. Bocci , E. Brondolin , C. Caillol , T. Camporesi , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , F. Fallavollita⁶⁰ , L. Forthomme , G. Franzoni , W. Funk , S. Giani , D. Gigi , K. Gill , F. Glege , L. Gouskos , M. Haranko , J. Hegeman , V. Innocente , T. James , P. Janot , J. Kieseler , N. Kratochwil , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , B. Maier , L. Malgeri , M. Mannelli , A.C. Marini , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Moortgat , M. Mulders , S. Orfanelli , F. Pantaleo , M. Peruzzi , A. Petrilli , G. Petrucciani , A. Pfeiffer , M. Pierini , D. Piparo , H. Qu , D. Rabady , G. Reales Gutiérrez , M. Rovere , H. Sakulin , S. Scarfi , M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶¹ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsiros , D. Walter , J. Wanczyk⁶² , K.A. Wozniak⁶³ , P. Zehetner , P. Zejdl , W.D. Zeuner 


















Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua⁶⁴ , L. Caminada⁶⁴ , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶⁴ , L. Noehte⁶⁴ , T. Rohe 

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



T.K. Aarrestad , K. Androsova⁶² , M. Backhaus , A. Calandri , C. Cazzaniga , K. Datta , A. De Cosa , G. Dissertori , M. Dittmar , M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani , L. Marchese , C. Martin Perez , A. Mascellani⁶² , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini , M.G. Ratti , M. Reichmann , C. Reissel , T. Reitenspiess , B. Ristic , F. Riti , D. Ruini , D.A. Sanz Becerra , R. Seidita , J. Steggemann⁶² , D. Valsecchi , R. Wallny 

Universität Zürich, Zurich, Switzerland










C. Amsler⁶⁵ , P. Bäertschi , C. Botta , D. Brzhechko , M.F. Canelli , K. Cormier , A. De Wit , R. Del Burgo , J.K. Heikkilä , M. Huwiler , W. Jin , A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liechti , A. Macchiolo , P. Meiring 

V.M. Mikuni , U. Molinatti , I. Neutelings , A. Reimers , P. Robmann, S. Sanchez Cruz , K. Schweiger , M. Senger , Y. Takahashi 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁶, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁹ , S.S. Yu 


















National Taiwan University (NTU), Taipei, Taiwan

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

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

C. Asawatrangkuldee , N. Srimanobhas , V. Wachirapusanand 

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

D. Agyel , F. Boran , Z.S. Demiroglu , F. Dolek , I. Dumanoglu⁶⁷ , E. Eskut , Y. Guler⁶⁸ , E. Gurpinar Guler⁶⁸ , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir⁶⁹ , A. Polatoz , B. Tali⁷⁰ , U.G. Tok , S. Turcpar , E. Uslan , I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

K. Ocalan⁷¹ , M. Yalvac⁷² 

Bogazici University, Istanbul, Turkey

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

Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak⁶⁷ , Y. Komurcu , S. Sen⁷⁶ 

Istanbul University, Istanbul, Turkey

O. Aydilek , S. Cerci⁷⁰ , V. Epshteyn , B. Hacisahinoglu , I. Hos⁷⁷ , B. Isildak⁷⁸ , B. Kaynak , S. Ozkorucuklu , H. Sert , C. Simsek , D. Sunar Cerci⁷⁰ , C. Zorbilmez 
















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 , L. Kreczko , B. Krikler , S. Paramesvaran , S. Seif El Nasr-Storey, V.J. Smith , N. Stylianou⁷⁹ , K. Walkingshaw Pass, R. White 

Rutherford Appleton Laboratory, Didcot, United Kingdom




A.H. Ball, K.W. Bell , A. Belyaev⁸⁰ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg⁸¹ , Sh. Jain , J. Linacre , K. Manolopoulos, D.M. Newbold , E. Olaiya, D. Petyt , T. Reis , G. Salvi , T. Schuh, C.H. Shepherd-Themistocleous , I.R. Tomalin , T. Williams

Imperial College, London, United Kingdom









R. Bainbridge , P. Bloch , C.E. Brown , O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya , G.S. Chahal⁸² , D. Colling , J.S. Dancu, P. Dauncey , G. Davies , J. Davies,

M. Della Negra , S. Fayer, G. Fedi , G. Hall , M.H. Hassanshahi , A. Howard, G. Iles , M. Knight , J. Langford , L. Lyons , A.-M. Magnan , S. Malik, A. Martelli , M. Mieskolainen , J. Nash⁸³ , M. Pesaresi, B.C. Radburn-Smith , A. Richards, A. Rose , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , L.H. Vage, T. Virdee²⁸ , 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 , B. Caraway , J. Dittmann , K. Hatakeyama , J. Hiltbrand , A.R. Kanuganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul , M. Toms , 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

R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio⁸⁴ , E. Usai , C. West , R. Yi 










Boston University, Boston, Massachusetts, USA

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






Brown University, Providence, Rhode Island, USA

G. Benelli , X. Coubez²³, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan⁸⁵ , T. Kwon , G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain[†] , N. Pervan , S. Sagir⁸⁶ , F. Simpson , W.Y. Wong, X. Yan , W. Zhang





University of California, Davis, Davis, California, USA

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










University of California, Los Angeles, California, USA

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

University of California, Riverside, Riverside, California, USA

R. Clare , M. Gordon, G. Hanson , W. Si , S. Wimpenny[†] 

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











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

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















L. Brennan , C. Campagnari , G. Collura , A. Dorsett , J. Incandela , M. Kilpatrick , J. Kim , A.J. Li , P. Masterson , H. Mei , M. Oshiro , J. Richman , U. Sarica

R. Schmitz , F. Setti , J. Sheplock , D. Stuart , S. Wang 














California Institute of Technology, Pasadena, California, USA

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

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

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









































































University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat , W.T. Ford , A. Hassani , G. Karathanasis , E. MacDonald, N. Manganello , F. Marini , A. Perloff , C. Savard , N. Schonbeck , K. Stenson ,
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











Cornell University, Ithaca, New York, USA

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan ,
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J. Thom , 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. Gece , L. Gray , D. Green, S. Grünendahl ,
D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer ,
L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. 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 , V. Papadimitriou , N. Pastika , K. Pedro ,
C. Pena⁸⁷ , F. Ravera , A. Reinsvold Hall⁸⁸ , L. Ristori , 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 , L. Cadamuro , P. Chang , V. Cherepanov ,
R.D. Field, E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K.H. Lo,
K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu , N. Rawal ,
D. Rosenzweig , S. Rosenzweig , K. Shi , J. Wang 























Florida State University, Tallahassee, Florida, USA

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












Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , T. Elkafrawy⁵³ , M. Hohlmann ,
R. Kumar Verma , M. Rahmani, F. Yumiceva 










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

M.R. Adams , C. Bennett, R. Cavanaugh , S. Dittmer , R. Escobar Franco , O. Evdoki-
mov , C.E. Gerber , D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills ,
S. Nanda , G. Oh , B. Ozek , D. Pilipovic , T. Roy , S. Rudrabhatla , M.B. Tonjes ,
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

















The University of Iowa, Iowa City, Iowa, USA

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









Johns Hopkins University, Baltimore, Maryland, USA

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

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , P. Baringer , A. Bean , Z. Flowers , D. Grove, J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , C. Lindsey, J. Marquez , N. Minafra , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹³ , C. Rogan , C. Royon , R. Salvatico , S. Sanders , C. Smith , Q. Wang , G. Wilson 














Kansas State University, Manhattan, Kansas, USA

B. Allmond , A. Ivanov , K. Kaadze , A. Kalogeropoulos , D. Kim, Y. Maravin , K. Nam, J. Natoli , D. Roy , G. Sorrentino 

























Lawrence Livermore National Laboratory, Livermore, California, USA

F. Rebassoo , D. Wright 














University of Maryland, College Park, Maryland, USA

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

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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















University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , B.M. Joshi , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , S. Pandey , M. Revering , R. Rusack , R. Saradhy , N. Schroeder , N. Strobbe , M.A. Wadud 

University of Mississippi, Oxford, Mississippi, USA

L.M. Cremaldi 


















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

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









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

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

























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , Y. Haddad , Y. Han , A. Krishna , J. Li , M. Lu , G. Madigan , B. Marzocchi , D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , A. Tishelman-Charny , B. Wang , D. Wood 










Northwestern University, Evanston, Illinois, USA

S. Bhattacharya , J. Bueghly, Z. Chen , 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

R. Band , R. Bucci, S. Castells , M. Cremonesi, A. Das , R. Goldouzian , M. Hildreth , K.W. Ho , K. Hurtado Anampa , C. Jessop , K. Lannon , J. Lawrence , N. Loukas , L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , K. Mohrman , C. Moore , Y. Musienko¹³ , H. Nelson , M. Osherson , R. Ruchti , A. Townsend , 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 , A. Lesauvage , M. Nunez Ornelas , K. Wei, B.L. Winer , B. R. Yates 






















Princeton University, Princeton, New Jersey, USA

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




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik 















Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi , V.E. Barnes , S. Chandra , R. Chawla , S. Das , A. Gu , L. Gutay, M. Jones , A.W. Jung , D. Kondratyev , A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov , A. Purohit , J.F. Schulte , M. Stojanovic¹⁷ , J. Thieman , A. K. Viridi , F. Wang , W. Xie 












Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 


Rice University, Houston, Texas, USA

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

















University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , C. Fallon, A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , P. Parygin , E. Popova , R. Taus , G.P. Van Onsem 









The Rockefeller University, New York, New York, USA

K. Goulianos 















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

B. Chiarito, J.P. Chou , Y. Gershtein , E. Halkiadakis , A. Hart , M. Heindl , D. Jaroslowski , O. Karacheban²⁶ , I. Laflotte , A. Lath , R. Montalvo, K. Nash, H. Routray , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora , H. Wang 












University of Tennessee, Knoxville, Tennessee, USA

H. Acharya, D. Ally , A.G. Delannoy , S. Fiorendi , T. Holmes , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 

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

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





Texas Tech University, Lubbock, Texas, USA

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

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , 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. Ledovskoy , A. Li , C. Neu , C.E. Perez Lara 

Wayne State University, Detroit, Michigan, USA

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 , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

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S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov⁹⁶, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , M. Chadeeva⁹⁶ , V. Chekhovsky, R. Chistov⁹⁶ , A. Dermenev , T. Dimova⁹⁶ , D. Druzhkin⁹⁷ , M. Dubinin⁸⁷ , L. Dudko , A. Ershov , G. Gavrilov , V. Gavrilov , S. Gninenko , V. Golovtsov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov , V. Kachanov , L. Kardapoltsev⁹⁶ , V. Karjavine , A. Karneyeu , V. Kim⁹⁶ , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova⁹⁸ , D. Konstantinov , V. Korenkov , A. Kozyrev⁹⁶ , N. Krasnikov , A. Lanev , P. Levchenko⁹⁹ , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev⁹⁶ , V. Murzin , A. Nikitenko^{100,98} , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , S. Petrushanko , S. Polikarpov⁹⁶ , V. Popov, O. Radchenko⁹⁶ , M. Savina , V. Savrin , D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen⁹⁶ , S. Slabospitskii , V. Smirnov , A. Snigirev , D. Sosnov , V. Sulimov , E. Tcherniaev , A. Terkulov , O. Teryaev , I. Tlisova , A. Toropin , L. Uvarov , A. Uzunian , A. Vorobyev[†], N. Voytishin , B.S. Yuldashev¹⁰¹, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

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

⁴Also at Ghent University, Ghent, Belgium

⁵Also at Universidade Estadual de Campinas, Campinas, Brazil

-
- ⁶Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
- ⁷Also at UFMS, Nova Andradina, Brazil
- ⁸Also at Nanjing Normal University, Nanjing, China
- ⁹Now at The University of Iowa, Iowa City, Iowa, USA
- ¹⁰Also at University of Chinese Academy of Sciences, Beijing, China
- ¹¹Also at University of Chinese Academy of Sciences, Beijing, China
- ¹²Also at Université Libre de Bruxelles, Bruxelles, Belgium
- ¹³Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- ¹⁴Also at Suez University, Suez, Egypt
- ¹⁵Now at British University in Egypt, Cairo, Egypt
- ¹⁶Also at Birla Institute of Technology, Mesra, Mesra, India
- ¹⁷Also at Purdue University, West Lafayette, Indiana, USA
- ¹⁸Also at Université de Haute Alsace, Mulhouse, France
- ¹⁹Also at Department of Physics, Tsinghua University, Beijing, China
- ²⁰Also at The University of the State of Amazonas, Manaus, Brazil
- ²¹Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ²²Also at University of Hamburg, Hamburg, Germany
- ²³Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁴Also at Isfahan University of Technology, Isfahan, Iran
- ²⁵Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁶Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁷Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁸Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ²⁹Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁰Also at Wigner Research Centre for Physics, Budapest, Hungary
- ³¹Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- ³²Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ³³Now at Universitatea Babeş-Bolyai - Facultatea de Fizică, Cluj-Napoca, Romania
- ³⁴Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- ³⁵Also at Punjab Agricultural University, Ludhiana, India
- ³⁶Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- ³⁷Also at University of Visva-Bharati, Santiniketan, India
- ³⁸Also at University of Hyderabad, Hyderabad, India
- ³⁹Also at Indian Institute of Science (IISc), Bangalore, India
- ⁴⁰Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴¹Also at Institute of Physics, Bhubaneswar, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Helwan University, Cairo, Egypt
- ⁴⁷Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁸Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁴⁹Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵⁰Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵¹Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA

- ⁵²Also at Università di Napoli 'Federico II', Napoli, Italy
- ⁵³Also at Ain Shams University, Cairo, Egypt
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Riga Technical University, Riga, Latvia
- ⁵⁶Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁷Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶⁰Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
- ⁶¹Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶²Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶³Also at University of Vienna Faculty of Computer Science, Vienna, Austria
- ⁶⁴Also at Universität Zürich, Zurich, Switzerland
- ⁶⁵Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁶Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁷Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁸Also at Konya Technical University, Konya, Turkey
- ⁶⁹Also at Izmir Bakircay University, Izmir, Turkey
- ⁷⁰Also at Adiyaman University, Adiyaman, Turkey
- ⁷¹Also at Necmettin Erbakan University, Konya, Turkey
- ⁷²Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷³Also at Marmara University, Istanbul, Turkey
- ⁷⁴Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁵Also at Kafkas University, Kars, Turkey
- ⁷⁶Also at Hacettepe University, Ankara, Turkey
- ⁷⁷Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁸Also at Ozyegin University, Istanbul, Turkey
- ⁷⁹Also at Vrije Universiteit Brussel, Brussel, Belgium
- ⁸⁰Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁸¹Also at University of Bristol, Bristol, United Kingdom
- ⁸²Also at IPPP Durham University, Durham, United Kingdom
- ⁸³Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸⁴Also at Università di Torino, Torino, Italy
- ⁸⁵Also at Bethel University, St. Paul, Minnesota, USA
- ⁸⁶Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁸⁷Also at California Institute of Technology, Pasadena, California, USA
- ⁸⁸Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸⁹Also at Bingol University, Bingol, Turkey
- ⁹⁰Also at Georgian Technical University, Tbilisi, Georgia
- ⁹¹Also at Sinop University, Sinop, Turkey
- ⁹²Also at Erciyes University, Kayseri, Turkey
- ⁹³Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁹⁴Also at Texas A&M University at Qatar, Doha, Qatar
- ⁹⁵Also at Kyungpook National University, Daegu, Korea

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

⁹⁷Also at Universiteit Antwerpen, Antwerpen, Belgium

⁹⁸Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁹Also at Northeastern University, Boston, Massachusetts, USA

¹⁰⁰Also at Imperial College, London, United Kingdom

¹⁰¹Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan