

CERN-EP-2023-083  
2023/05/22

CMS-EXO-20-010

# Search for inelastic dark matter in events with two displaced muons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

A search for dark matter in events with a displaced muon pair and missing transverse momentum is presented. The analysis is performed using an integrated luminosity of  $138 \text{ fb}^{-1}$  of proton-proton (pp) collision data at a center-of-mass energy of 13 TeV produced by the LHC in 2016–2018. No significant excess over the predicted backgrounds is observed. Upper limits are set on the product of the inelastic dark matter production cross section  $\sigma(\text{pp} \rightarrow A' \rightarrow \chi_1 \chi_2)$  and the decay branching fraction  $\mathcal{B}(\chi_2 \rightarrow \chi_1 \mu^+ \mu^-)$ , where  $A'$  is a dark photon and  $\chi_1$  and  $\chi_2$  are dark matter states with near mass degeneracy. This is the first dedicated collider search for inelastic dark matter.

*Submitted to Physical Review Letters*



The presence of dark matter (DM) is strongly supported by observations [1–3], but its nature remains largely unknown. Dedicated experiments (e.g., Refs. [4–7]) have searched for DM directly, but no signal has yet been detected. Particle colliders are a complementary tool in this effort. Several searches for minimal models of DM have been carried out at the CERN LHC, such as those predicting weakly interacting massive particles [8–11]. Collider-based searches for long-lived particles (LLPs) can probe a wider range of DM models [12–14] than previously explored. These particles can travel macroscopic distances before decaying inside the detector, leaving unique signatures. Several theoretical mechanisms predict a suppressed phase space for the production and decay of DM states [12], which would lead to long-lived DM phenomenology at the LHC. Moreover, targeting LLPs has the considerable advantage of reducing or even eliminating a large class of standard model (SM) backgrounds.

In this Letter, we present a novel search for DM production in LHC proton-proton (pp) collisions that targets displaced-decay signatures. Specifically, we probe an inelastic DM (IDM) model [15–17] that postulates the existence of at least two DM states accompanied by a dark photon that kinetically mixes with the SM hypercharge [18]. In inelastic coupling scenarios, the DM states cannot scatter elastically with other particles (e.g., nucleons) [15]. These models predict an off-diagonal vector coupling between the DM states, such that both are produced simultaneously. A small mass gap between the lighter and heavier DM states leads to a compressed phase space and increased lifetime of the heavier state, thus producing LLP decay signatures in the CMS detector. Such models can account for the observed thermal-relic abundance [16], which is the density of dark matter energy left over from the early evolution of the universe, while evading the increasingly stringent experimental constraints set by other DM searches [4–7, 9, 10, 19, 20]. Previous studies [16, 21, 22] have placed bounds on the IDM production cross section for lighter dark matter masses ( $< 1$  GeV) by reinterpreting existing results from previous experiments [23–26]. The work described here is the first dedicated collider search for IDM, which provides new sensitivity to heavier DM masses ( $\approx 3 - 80$  GeV). This is achieved via the use of a dedicated displaced muon reconstruction algorithm and optimized event selection criteria, including isolation requirements. The signal selection efficiencies may be as low as  $10^{-4}$  for low DM masses and highly-displaced signal hypotheses, but the predicted IDM production cross sections can be as large as a few picobarns. Tabulated results are provided in the HEPData record for this analysis [27].

The process of interest includes a dark photon  $A'$  that is produced in the pp collision and recoils from an initial-state radiation jet, which is needed for efficient triggering on the event. The  $A'$  decays promptly to two DM states  $\chi_1$  and  $\chi_2$  with a near mass-degeneracy, as illustrated in Fig. 1. The light state  $\chi_1$  (with mass  $m_1$ ) is stable and not detected. The heavy state  $\chi_2$  (with mass  $m_2$ ) travels a measurable distance before decaying to another  $\chi_1$  and a pair of SM particles via an off-shell dark photon. The mass splitting between the two DM states  $\Delta \equiv m_2 - m_1$  is relatively small, between 10–40% of  $m_1$ , resulting in decay products that are “soft” (transverse momentum  $p_T \lesssim 15$  GeV) and have small angular separation. Here we focus on final states with muons because of the powerful reconstruction and identification tools available for displaced muons and the higher purity of the reconstruction compared to that of soft electrons. The escaping  $\chi_1$  particles are collimated with the soft muons and lead to sizeable  $\vec{p}_T^{\text{miss}}$ , defined as the projection onto the plane perpendicular to the beam axis of the negative vector momentum sum of all reconstructed objects in an event. Its magnitude is referred to as  $p_T^{\text{miss}}$ .

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The solenoid volume contains a silicon pixel and strip tracker (extending in radius from 4 to 110 cm and covering the range of pseudorapidity  $|\eta| < 2.4$ ), a lead tungstate crystal electromagnetic calorimeter, and a brass-scintillator hadron

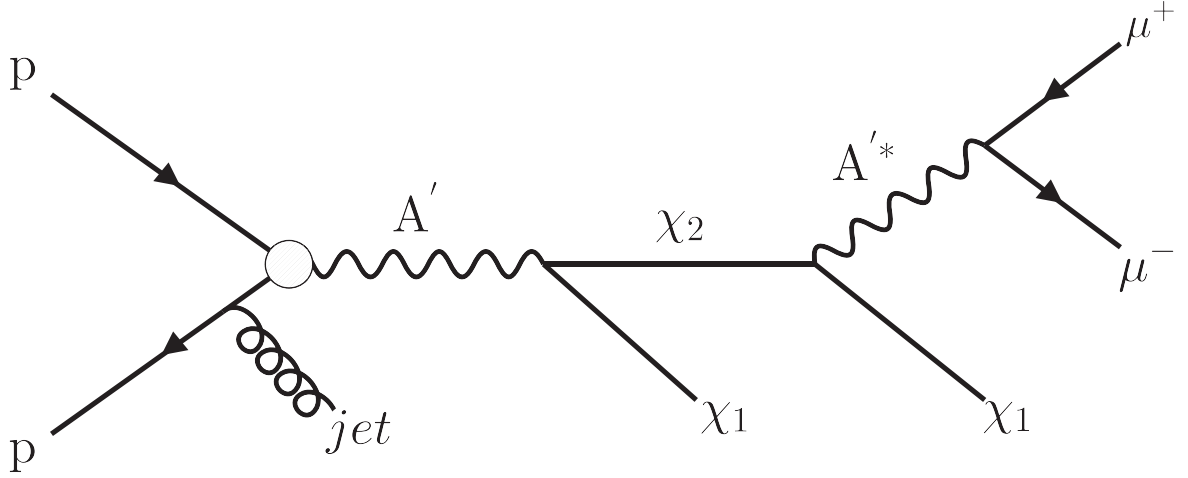


Figure 1: Feynman diagram of IDM production and decay in pp collisions. The heavier DM state  $\chi_2$  can be long-lived, and decays to  $\chi_1$  and to a muon pair via an off-shell dark photon  $A'$ .

calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the  $\eta$  coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, extending radially from about 4 to 7 meters and covering the range  $|\eta| < 2.4$ . A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [28]. A particle-flow (PF) algorithm [29] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector.

The analysis is carried out with data collected by the CMS Collaboration in 2016–2018 with a total integrated luminosity of  $138 \text{ fb}^{-1}$ . Simulated samples of signal and background events are used to optimize the event selection. Signal samples with dimuon decays are generated with MADGRAPH5\_aMC@NLO v.2.6.0 [30, 31] at leading order in quantum chromodynamics (QCD) and injected into PYTHIA v8.226 [32] for fragmentation and parton shower modeling. Motivated by Ref. [16] and other sources, we select parameters consisting of  $m_1$  in the range 3–80 GeV,  $m_{A'} = 3 m_1$ ,  $\Delta = \{0.1, 0.4\} m_1$ ,  $c\tau$  in the range 1–1000 mm, and  $\alpha_D = \{0.1, 0.4\}$ . Here,  $c\tau$  is the proper decay length of  $\chi_2$  and  $\alpha_D$  is the coupling strength of the  $U(1)_D$  in the dark sector. These five parameters fix the kinetic mixing coefficient  $\epsilon$ , which controls the amount of mixing between the dark photon and the SM hypercharge. The CUETP8M1 underlying event tune [33] is applied to 2016 samples and the CP5 tune [34] to 2017–2018 samples. Two parton distribution function sets are used: NNPDF3.0 [35] (2016) and NNPDF3.1 [36] (2017–2018). Additional pp interactions in the same or adjacent bunch crossings (pileup) are also simulated, with a frequency distribution matching that in data. Finally, the detector response is simulated with GEANT4 [37] and identical reconstruction algorithms are applied to collision and simulated samples.

The event selection exploits the unique features expected from IDM: large  $p_T^{\text{miss}}$ , at least one energetic jet, and a pair of displaced muons collimated with  $\vec{p}_T^{\text{miss}}$ . The trigger strategy relies on  $p_T^{\text{miss}}$  as the muons are too soft to be used for trigger selection. Candidate events are first selected with triggers with a minimum  $p_T^{\text{miss}}$  threshold of 120 GeV at the trigger level and 200 GeV in the offline selection, constructed excluding muons [38]. The leading jet in the event is required to have  $p_T > 80 \text{ GeV}$  and  $|\eta| < 2.4$ . To accommodate additional initial-state emissions, only one other jet, with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 5.0$ , is allowed per event. Limiting the

number of jets reduces the dominant background from events with jets produced through the strong interaction, referred to as QCD events. To suppress top quark backgrounds, events are vetoed if any jets are identified as originating from a bottom quark, based on the loose working point of the DEEPCSV algorithm [39, 40]. The leading (subleading) jet must be azimuthally separated from  $\vec{p}_T^{\text{miss}}$  by at least 1.50 (0.75) radians. These selections further suppress backgrounds by ensuring that the DM system is well isolated in the event.

Muons are reconstructed with a specialized algorithm designed to remain efficient even for large displacements of the muon-pair vertex of up to several meters from the luminous region. This displaced standalone algorithm (DSA) uses only information from the muon system and does not require muons to originate from the interaction point [41, 42]. In Fig. 2, the DSA reconstruction efficiency for a representative signal sample is compared to that of the standard global reconstruction algorithm [43], which requires both tracker and muon detector information. The efficiency is calculated vs. the distance  $v_{xy}$  in the transverse plane between the primary vertex (defined as the vertex with the largest value of summed charged particle  $p_T^2$ ) and the muon-pair vertex. The efficiency remains high even when the muon-pair vertex lies beyond the inner radius of the muon detector planes.

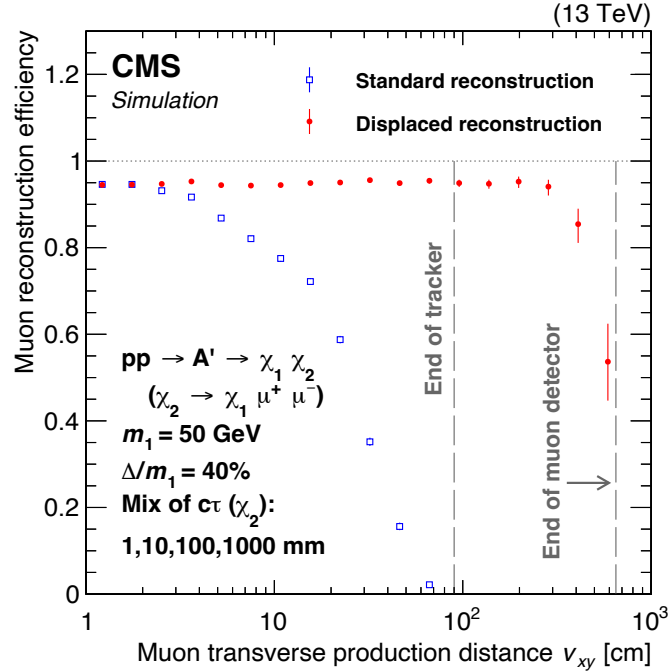


Figure 2: Simulated muon reconstruction efficiency of standard (blue squares) and displaced (red circles) reconstruction algorithms as a function of transverse vertex displacement  $v_{xy}$ . The two dashed vertical gray lines denote the ends of the fiducial tracker and muon detector regions, respectively.

The baseline muon selection requires at least two identified DSA muons. The identification criteria comprise  $>12$  hits across  $\geq 2$  different muon detector planes (and  $>18$  hits if no hits are found in the muon detector endcaps); track fit quality  $\chi^2/\text{dof} < 2.5$ ;  $p_T$  resolution  $\sigma_{p_T}/p_T < 1$ ;  $p_T > 5 \text{ GeV}$ ; and  $|\eta| < 2.4$ . The efficiency to identify such a DSA muon (about 90%) is measured with three different data samples providing complementary coverage of the kinematic phase space: cosmic ray muons (as a proxy for displaced muons); muon pairs from Z boson decays (high- $p_T$ ); and muon pairs from  $J/\psi$  meson decays (low- $p_T$ ). This efficiency is compared to that of the corresponding simulated sample and the efficiency ratio is param-

eterized as a function of muon  $p_T$ ,  $\eta$ , and transverse impact parameter  $d_{xy}$  (defined as the closest distance in the transverse plane between the track trajectory and the main vertex), and applied as a correction to simulated events. A cosmic ray muon veto is implemented by discarding events containing at least one pair of back-to-back DSA muons. At least one pair of oppositely charged DSA muons must form a well-reconstructed vertex (using a Kalman filtering algorithm [44]) as inferred from a vertex fit with quality  $\chi^2/\text{dof} < 4$ . The muon pair with the smallest  $\chi^2$  value is chosen. Finally, we require the muons to be collimated with  $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.9$ , and the dimuon  $p_T$  to be azimuthally aligned with the  $p_T^{\text{miss}}$  in the event,  $\Delta\phi_{\mu\mu}^{\text{miss}} \equiv |\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\mu\mu})| < 0.5$ . These requirements remove more than 90% of the electroweak SM backgrounds without incurring a significant loss of signal efficiency.

The DSA muons have higher reconstruction efficiencies but degraded momentum resolution and impact parameter resolution compared to muons reconstructed with the standard algorithm. This is due to the smaller lever arm and lack of tracker information. To recover some of the performance at lower displacements, a match-and-replace procedure is implemented whereby DSA muon system tracks that are found close to muons reconstructed with the PF algorithm (PF muons) are replaced with the latter. The matching requirement is  $\Delta R < 0.2$  at the location of the innermost muon spectrometer track hit. The vertex is then refitted and again required to pass the  $\chi^2/\text{dof} < 4$  threshold. We divide the signal region into three categories (0–2) based on the number of PF-DSA matches found. Highly displaced signal events fall in the 0-match category, since typically no PF muons are reconstructed, while signal events with slightly displaced muons fall in the 1- or 2-match categories, like most SM backgrounds. This categorization thus further enhances the search sensitivity for displaced signal models in the 0-match category.

Backgrounds passing the event selection consist mainly of three types: QCD events with genuine or misidentified muons (dominant in all match categories);  $W$ +jets events where the  $W$  boson decays to a muon and a muon-neutrino and a misidentified muon is selected (contributing to the 1-match category); and  $Z$ +jets events where the  $Z$  boson decays to two neutrinos and two misidentified muons are selected (contributing to the 0- and 1-match categories). Misidentified muons may be associated with pileup interactions or the underlying event and therefore not correlate with the hard scatter in the event, or they may arise from instrumental deficiencies. No backgrounds from cosmic ray muons or other noncollisional contributions are expected because of the highly selective event requirements and the use of  $p_T^{\text{miss}}$  triggers.

A modified matrix (“ABCD”) method is employed to estimate the backgrounds, relying on two independent variables to discriminate between signal and background. The two-dimensional plane formed by these variables is divided into four bins (A–D). Because the variables are independent, all four bins can be described using only three parameters: a normalization rate plus a vertical and a horizontal transfer coefficient. The final degree of freedom is then used to fit the signal rate across all bins [45].

To maximize sensitivity, different variables are used in each match category. All three match categories use the minimum  $d_{xy}$  of the two muons, referred to as  $\text{min-}d_{xy}$ . In the 1- and 2-match categories, the second discriminating variable is the relative PF isolation  $I_{\text{PF}}^{\text{rel}}$  of the  $\text{min-}d_{xy}$  muon, defined as the  $p_T$  sum of all photons, charged and neutral hadrons found within a  $\Delta R < 0.4$  cone of a muon, divided by its  $p_T$ . Unlike in QCD events, where muons originate from parton fragmentation and hadronization processes, muons in IDM should be isolated. In the 0-match category, where no PF muons are identified, the second ABCD variable is  $\Delta\phi_{\mu\mu}^{\text{miss}}$ . The assumption of independence between all variables is extensively checked. The simultaneous fit accounts for the presence of signal in all ABCD bins, but a higher concentration is expected

for high  $\min-d_{xy}$ , low  $I_{PF}^{\text{rel}}$ , and small  $\Delta\phi_{\mu\mu}^{\text{miss}}$ .

To validate the background estimation and to optimize the ABCD binning, a multijet validation region (VR) enriched with backgrounds and devoid of signal is defined by inverting the requirement on the number of jets in the event, demanding at least three jets. Several sets of ABCD bins are defined in the VR and the agreement between predicted and observed yields in bin D is confirmed for each set. Therefore, no systematic uncertainties are applied to the background prediction in the analysis. The optimal ABCD binning (reported in Table 1 for each match category) is determined by requiring enough background events across all bins of the ABCD plane, which is needed for a reasonable background estimation.

Table 1: Definition of ABCD bins and yields in data, per match category. The predicted yield in the bin with the smallest backgrounds (bin D) is extracted from the simultaneous four-bin fit by assuming zero signal, which corresponds to  $(\text{Obs. B} \times \text{Obs. C}) / (\text{Obs. A})$  in this limit.

Bin	0-match			1-match			2-match		
	$\Delta\phi_{\mu\mu}^{\text{miss}}$ [rad]	$\min-d_{xy}$ [cm]	Events	$I_{PF}^{\text{rel}}$	$\min-d_{xy}$ [cm]	Events	$I_{PF}^{\text{rel}}$	$\min-d_{xy}$ [cm]	Events
Obs. A	0–0.25	3–15	68	>0.25	0.02–0.75	716	>0.25	0.02–0.15	424
Obs. B	0.25–0.50	3–15	9	<0.25	0.02–0.75	33	<0.25	0.02–0.15	22
Obs. C	0–0.25	>15	9	>0.25	>0.75	12	>0.25	>0.15	10
Obs. D			2			0			0
Pred. D	0.25–0.50	>15	$1.2 \pm 0.6$	<0.25	>0.75	$0.5 \pm 0.2$	<0.25	>0.15	$0.5 \pm 0.2$

The dominant signal uncertainties in the analysis are either statistical, arising from a low selection efficiency for some signal hypotheses, or systematic due to imperfect knowledge of efficiencies, energy corrections, and the integrated luminosity [46–48]. The total signal systematic uncertainties averaged over all years are approximately 20, 30, and 40% for the 0-, 1-, and 2-match categories, respectively (with a yearly breakdown shown in Table 2). These are applied uniformly to all signal hypotheses, unlike the statistical uncertainty, which depends on the signal efficiency of each hypothesis.

The observed yields in data are used to perform a simultaneous fit to the four ABCD bins in each match category, and the fit results are found to be consistent with the background-only hypothesis, as illustrated in Table 1. Figure 3 shows the measured  $\min-d_{xy}$  distribution in the 2-match category, for the subset of events passing the isolation requirement (B and D bins). To

Table 2: Systematic uncertainties in the analysis, in percent. The jet uncertainties are larger in 2017 because of noise issues with the ECAL endcap. The tracking inefficiency in 2016 is caused by the unexpected saturation of photodiode signals in the tracker.

Uncertainty	2016	2017	2018	Correlation
PF displaced ID	5	5	5	Total
PF prompt ID	3.2	2.8	3.0	Total
DSA displaced reco.	2	2	2	Total
DSA displaced ID	2	2	2	Total
DSA prompt ID	0.6	0.7	0.6	Total
b quark jet ID	0.5	0.5	0.5	Total
Electron & photon ID	0.5	0.5	0.5	Total
Trigger	1.5	1.5	1.5	Total
Jet energy resolution	1.0	9.0	2.5	None
Jet energy scale	2.0	6.0	2.0	Total
Luminosity	1.2	2.3	2.5	Partial
Tracking inefficiency	10	—	—	—

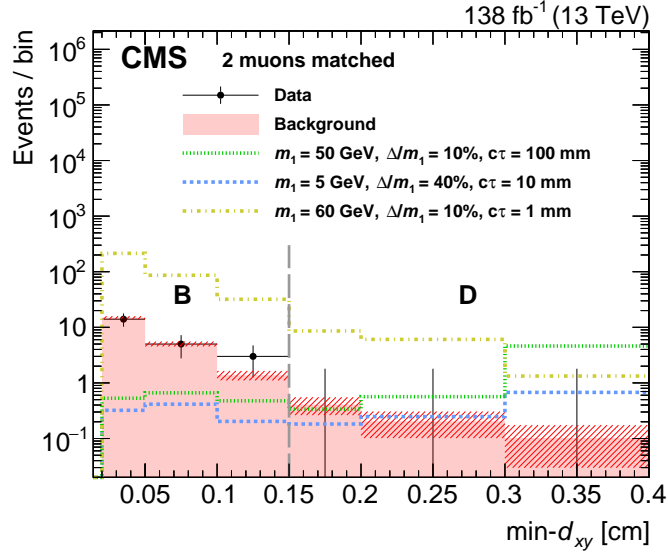


Figure 3: Measured  $\min-d_{xy}$  distribution in the 2-match category, after requiring the  $\min-d_{xy}$  muon to pass the isolation requirement  $I_{\text{PF}}^{\text{rel}} < 0.25$  (i.e., the B and D bins of the ABCD plane). Overlaid with a red histogram is the background predicted from the region of the ABCD plane failing the same requirement (the A and C bins), as well as three signal benchmark hypotheses (as defined in the legends), assuming  $\alpha_{\text{D}} = \alpha_{\text{EM}}$  (the fine-structure constant). The red hatched bands correspond to the background prediction uncertainty. The last bin includes the overflow.

derive the background prediction shown in Fig. 3, the observed distribution in bins A and C is normalized to the sum of yields counted in bins B and D under the no-signal assumption.

We assess 95% confidence level (CL) limits on the product of the DM production cross section and decay branching fraction  $\sigma(\text{pp} \rightarrow A' \rightarrow \chi_2 \chi_1) \mathcal{B}(\chi_2 \rightarrow \chi_1 \mu^+ \mu^-)$  using a modified frequentist criterion  $\text{CL}_s$  with the likelihood ratio test statistic [49, 50]. The upper limits are shown in Fig. 4 as a function of the mass  $m_1$  of the lighter DM state and the interaction strength  $y \equiv e^2 \alpha_{\text{D}} (m_1/m_{A'})^4$ . This choice of parameterization allows the relevant variables to be scaled with the thermal-relic abundance in a straightforward way, as explored in Ref. [16]. The exclusion curves (in blue and magenta) depend more strongly on the choices of  $\alpha_{\text{D}}$  and of  $m_{A'}$  than the cross section limits because of the resonant enhancement arising from the mixing between the  $A'$  and  $Z$  bosons when  $m_{A'} \approx m_Z$ . Results are shown for  $m_{A'} = 3 m_1$ . Regions of parameter space are excluded in both mass-splitting scenarios: for  $\Delta = 0.1 m_1$ , values of  $y$  above  $\sim 10^{-7}$ – $10^{-6}$  and above  $\sim 10^{-8}$ – $10^{-7}$ , depending on the choice of  $\alpha_{\text{D}}$ , are excluded at  $m_1 = 3$  and 80 GeV, respectively. For  $\Delta = 0.4 m_1$ , the sensitivity is weaker because of the smaller production cross sections, which scale as  $1/\Delta^5$  when all other parameters are fixed. Only the region near the  $A'$ - $Z$  resonance is excluded in this scenario.

In summary, a search has been presented for inelastically coupled dark matter (DM) with a unique final-state signature including a soft, displaced muon pair collimated with the missing transverse momentum vector. The analysis is performed using proton-proton collision data produced by the LHC at a center-of-mass energy of 13 TeV and collected with the CMS experiment in 2016–2018. The data sample corresponds to an integrated luminosity of  $138 \text{ fb}^{-1}$ . Control samples in data are used to predict the background, and no significant excess is observed over standard model expectations. Upper limits are set on the product of the DM production cross section and decay branching fraction into muons as a function of DM mass  $m_1$  and interaction strength. This is the first dedicated collider search for inelastic dark matter and it

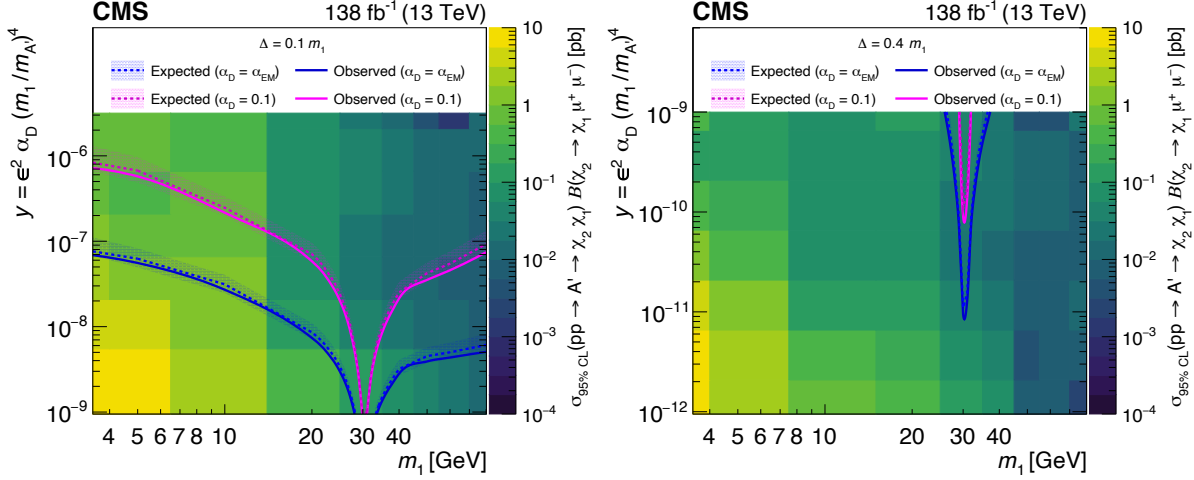


Figure 4: Two-dimensional observed limits on  $\sigma(\text{pp} \rightarrow A' \rightarrow \chi_1 \chi_2) \mathcal{B}(\chi_2 \rightarrow \chi_1 \mu^+ \mu^-)$ , for  $\Delta = 0.1 m_1$  (left) and  $0.4 m_1$  (right), as functions of the DM mass  $m_1$  and the interaction strength  $y$ , with  $m_{A'} = 3 m_1$ . Solid (dashed) curves denote the observed (expected) exclusion limits at 95% CL, with 68% CL uncertainty bands around the expectation. Regions above the curves are excluded, depending on the  $\alpha_D$  hypothesis:  $\alpha_D = \alpha_{EM}$  (dark blue) or 0.1 (light magenta).

significantly expands the sensitivity to  $m_1$  above the GeV scale.

## Acknowledgments

We thank Brian Shuve for providing calculations for some of the cross sections used in this paper.

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: 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); 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); MHEESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

## References

- [1] D. Clowe, A. Gonzalez, and M. Markevitch, “Weak-lensing mass reconstruction of the interacting cluster 1E 0657-558: Direct evidence for the existence of dark matter”, *Astrophys. J.* **604** (2004) 596, doi:10.1086/381970, arXiv:astro-ph/0312273.
- [2] E. Komatsu et al., “Five-year Wilkinson Microwave Anisotropy Probe observations: Cosmological interpretation”, *Astrophys. J. Suppl.* **180** (2009) 330, doi:10.1088/0067-0049/180/2/330, arXiv:0803.0547.
- [3] Planck Collaboration, “Planck 2015 results. XIII. cosmological parameters”, *Astronomy & Astrophys.* **594** (2016) A13, doi:10.1051/0004-6361/201525830, arXiv:1502.01589.
- [4] SuperCDMS Collaboration, “Search for low-mass weakly interacting massive particles with SuperCDMS”, *Phys. Rev. Lett.* **112** (2014) 241302, doi:10.1103/PhysRevLett.112.241302, arXiv:1402.7137.
- [5] Fermi-LAT Collaboration, “Searching for dark matter annihilation from milky way dwarf spheroidal galaxies with six years of Fermi Large Area Telescope data”, *Phys. Rev. Lett.* **115** (2015) 231301, doi:10.1103/PhysRevLett.115.231301, arXiv:1503.02641.
- [6] LUX Collaboration, “Results from a search for dark matter in the complete LUX exposure”, *Phys. Rev. Lett.* **118** (2017) 021303, doi:10.1103/PhysRevLett.118.021303, arXiv:1608.07648.
- [7] XENON Collaboration, “Search for inelastic scattering of WIMP dark matter in XENON1T”, *Phys. Rev. D* **103** (2021) 063028, doi:10.1103/PhysRevD.103.063028, arXiv:2011.10431.
- [8] CMS Collaboration, “Search for dark matter particles produced in association with a Higgs boson in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JHEP* **03** (2020) 025, doi:10.1007/JHEP03(2020)025, arXiv:1908.01713.
- [9] ATLAS Collaboration, “Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector”, *Phys. Rev. D* **103** (2021) 112006, doi:10.1103/PhysRevD.103.112006, arXiv:2102.10874.
- [10] CMS Collaboration, “Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JHEP* **11** (2021) 153, doi:10.1007/JHEP11(2021)153, arXiv:2107.13021.
- [11] ATLAS Collaboration, “Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using  $139 \text{ fb}^{-1}$  of proton-proton data recorded by the ATLAS experiment”, *JHEP* **08** (2022) 104, doi:10.1007/JHEP08(2022)104, arXiv:2202.07953.
- [12] J. Alimena et al., “Searching for long-lived particles beyond the standard model at the Large Hadron Collider”, *J. Phys. G* **47** (2020) 090501, doi:10.1088/1361-6471/ab4574, arXiv:1903.04497.
- [13] ATLAS Collaboration, “Search for light long-lived neutral particles produced in pp collisions at  $\sqrt{s} = 13$  TeV and decaying into collimated leptons or light hadrons with the

- ATLAS detector”, *Eur. Phys. J. C* **80** (2020) 450, doi:10.1140/epjc/s10052-020-7997-4, arXiv:1909.01246.
- [14] CMS Collaboration, “Search for long-lived particles decaying into muon pairs in proton-proton collisions at  $\sqrt{s} = 13$  TeV collected with a dedicated high-rate data stream”, *JHEP* **04** (2022) 062, doi:10.1007/JHEP04(2022)062, arXiv:2112.13769.
- [15] D. Smith and N. Weiner, “Inelastic dark matter”, *Phys. Rev. D* **64** (2001) 043502, doi:10.1103/PhysRevD.64.043502, arXiv:hep-ph/0101138.
- [16] E. Izaguirre, G. Krnjaic, and B. Shuve, “Discovering inelastic thermal-relic dark matter at colliders”, *Phys. Rev. D* **93** (2016) 063523, doi:10.1103/PhysRevD.93.063523, arXiv:1508.03050.
- [17] A. Berlin and F. Kling, “Inelastic dark matter at the LHC lifetime frontier: ATLAS, CMS, LHCb, CODEX-b, FASER, and MATHUSLA”, *Phys. Rev. D* **99** (2019) 015021, doi:10.1103/PhysRevD.99.015021, arXiv:1810.01879.
- [18] B. Holdom, “Two U(1)’s and epsilon charge shifts”, *Phys. Lett. B* **166** (1986) 196, doi:10.1016/0370-2693(86)91377-8.
- [19] CMS Collaboration, “Search for dark matter produced with an energetic jet or a hadronically decaying W or Z boson at  $\sqrt{s} = 13$  TeV”, *JHEP* **07** (2017) 14, doi:10.1007/JHEP07(2017)014, arXiv:1703.01651.
- [20] ATLAS Collaboration, “Constraints on mediator-based dark matter and scalar dark energy models using  $\sqrt{s} = 13$  TeV pp collision data collected by the ATLAS detector”, *JHEP* **05** (2019) 142, doi:10.1007/JHEP05(2019)142, arXiv:1903.01400.
- [21] B. Batell, R. Essig, and Z. Surujon, “Strong constraints on sub-GeV dark sectors from SLAC beam dump E137”, *Phys. Rev. Lett.* **113** (2014) 171802, doi:10.1103/physrevlett.113.171802, arXiv:1406.2698.
- [22] E. Izaguirre, Y. Kahn, G. Krnjaic, and M. Moschella, “Testing light dark matter coannihilation with fixed-target experiments”, *Phys. Rev. D* **96** (2017) 055007, doi:10.1103/PhysRevD.96.055007, arXiv:1703.06881.
- [23] J. D. Bjorken et al., “Search for neutral metastable penetrating particles produced in the SLAC beam dump”, *Phys. Rev. D* **38** (1988) 3375, doi:10.1103/PhysRevD.38.3375.
- [24] LSND Collaboration, “Measurement of electron-neutrino electron elastic scattering”, *Phys. Rev. D* **63** (2001) 112001, doi:10.1103/PhysRevD.63.112001, arXiv:hep-ex/0101039.
- [25] A. Hook, E. Izaguirre, and J. G. Wacker, “Model independent bounds on kinetic mixing”, *Adv. High Energy Phys.* **2011** (2011) 859762, doi:10.1155/2011/859762, arXiv:1006.0973.
- [26] BaBar Collaboration, “Search for invisible decays of a dark photon produced in  $e^+e^-$  collisions at BaBar”, *Phys. Rev. Lett.* **119** (2017) 131804, doi:10.1103/physrevlett.119.131804, arXiv:1702.03327.
- [27] HEPData record for this analysis, 2023. doi:10.17182/hepdata.140434.


- 
- [28] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [29] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [30] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [31] J. Alwall et al., “Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions”, *Eur. Phys. J. C* **53** (2007) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.
- [32] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [33] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [34] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
- [35] R. D. Ball et al., “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 40, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [36] R. D. Ball et al., “Parton distributions from high-precision collider data”, *Eur. Phys. J. C* **77** (2017) 663, doi:10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
- [37] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [38] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [39] CMS Collaboration, “Identification of heavy-flavour jets with the cms detector in pp collisions at 13 tev”, *JINST* **13** (2017) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.
- [40] CMS Collaboration, “Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector”, CMS Detector Performance Note CMS-DP-2023-005, 2023.
- [41] CMS Collaboration, “The CMS muon system in Run2: Preparation, status and first results”, Technical Report CMS CR-2015/237, 2015. arXiv:1510.05424.
- [42] CMS Collaboration, “Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JHEP* **05** (2018) 127, doi:10.1007/JHEP05(2018)127, arXiv:1801.00359.
- [43] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

- [44] R. Frühwirth, “Application of Kalman filtering to track and vertex fitting”, *Nucl. Instrum. Meth. A* **262** (1987) 444, doi:10.1016/0168-9002(87)90887-4.
- [45] CMS Collaboration, “Search for long-lived particles using delayed photons in proton-proton collisions at  $\sqrt{s} = 13$  TeV”, *Phys. Rev. D* **100** (2019) 112003, doi:10.1103/PhysRevD.100.112003, arXiv:1909.06166.
- [46] CMS Collaboration, “Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  tev in 2015 and 2016 at CMS”, *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
- [47] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at  $\sqrt{s} = 13$  TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
- [48] CMS Collaboration, “CMS luminosity measurement for the 2018 data-taking period at  $\sqrt{s} = 13$  TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.
- [49] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [50] A. L. Read, “Presentation of search results: the  $CL_s$  technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.





















## A The CMS Collaboration




### Yerevan Physics Institute, Yerevan, Armenia

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













### Institut für Hochenergiephysik, Vienna, Austria

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














### Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish<sup>3</sup> , T. Janssen , 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. Tytgat<sup>4</sup> , 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. Mahdavihorrami , 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 Físicas, 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. Chinellato<sup>5</sup>, E.M. Da Costa , G.G. Da Silveira<sup>6</sup> , D. De Jesus Damiao , S. Fonseca De Souza , J. Martins<sup>7</sup> , 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. Bernardes<sup>6</sup> , 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. Bauer<sup>8</sup>, Z. Hu , K. Yi<sup>8,9</sup> 


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

G.M. Chen<sup>10</sup> , H.S. Chen<sup>10</sup> , M. Chen<sup>10</sup> , F. Iemmi , C.H. Jiang, A. Kapoor , H. Liao , Z.-A. Liu<sup>11</sup> , F. Monti , R. Sharma , J.N. Song<sup>11</sup>, 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. Gao<sup>12</sup> , 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. Starodumov<sup>13</sup> , 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<sup>14,15</sup>, S. Elgammal<sup>15</sup>




**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. Dewanjee<sup>16</sup> , 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<sup>†</sup>













**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-Navarro<sup>17</sup> , 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. Agram<sup>18</sup> , 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. Dozen<sup>19</sup> , 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**

D. Chokheli , I. Lomidze , Z. Tsamalaidze<sup>13</sup> 

**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 Araujo<sup>20</sup> , L. Vigilante, S. Wiedenbeck , S. Zaleski

























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

C. Dziwok , G. Flügge , W. Haj Ahmad<sup>21</sup> , 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. Blekman<sup>22</sup> , K. Borras<sup>23</sup> , D. Brunner , A. Campbell , A. Cardini , C. Cheng, F. Colombina, S. Consuegra Rodríguez , G. Correia Silva , M. De Silva , G. Eckerlin, D. Eckstein , L.I. Estevez Banos , O. Filatov , E. Gallo<sup>22</sup> , A. Geiser , A. Giraldi , G. Greau, V. Guglielmi , M. Guthoff , A. Hinzmann , A. Jafari<sup>24</sup> , 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. Lipka<sup>25</sup> , W. Lohmann<sup>26</sup> , 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<sup>27,23</sup> , V. Scheurer, S. Schnake<sup>23</sup> , P. Schütze , C. Schwanenberger<sup>22</sup> , 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. Wiens<sup>23</sup> , 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. Hartmann<sup>28</sup> , 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. Papadopoulos<sup>28</sup>, 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. Gadallah<sup>29</sup> , Á. Kadlecik , P. Major , K. Mandal , G. Pásztor , A.J. Rádl<sup>30</sup> , O. Surányi , G.I. Veres 



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

M. Bartók<sup>31</sup> , C. Hajdu , D. Horvath<sup>32,33</sup> , F. Sikler , V. Veszpremi 




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

G. Bencze, S. Czellar, J. Karancsi<sup>31</sup> , J. Molnar, Z. Szillasi

















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

P. Raics, B. Ujvari<sup>34</sup> , G. Zilizi 

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

T. Csorgo<sup>30</sup> , F. Nemes<sup>30</sup> , T. Novak 


**Panjab University, Chandigarh, India**

J. Babbar , S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra<sup>35</sup> , R. Gupta, A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , P. Kumari , M. Meena , K. Sandeep , T. Sheokand, J.B. Singh<sup>36</sup> , 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. Barman<sup>37</sup> , S. Bhattacharya , D. Bhowmik, S. Dutta , S. Dutta, B. Gomber<sup>38</sup> , P. Palit , G. Saha , B. Sahu<sup>38</sup> , S. Sarkar










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

P.K. Behera , S.C. Behera , S. Chatterjee , P. Jana , P. Kalbhor , J.R. Komaragiri<sup>39</sup> , D. Kumar<sup>39</sup> , M. Mohammad Mobassir Ameen , L. Panwar<sup>39</sup> , 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. Bahinipati<sup>40</sup> , A.K. Das, C. Kar , D. Maity<sup>41</sup> , P. Mal , T. Mishra , V.K. Muraleedharan Nair Bindhu<sup>41</sup> , K. Naskar<sup>41</sup> , A. Nayak<sup>41</sup> , P. Sadangi, P. Saha , S.K. Swain, S. Varghese<sup>41</sup> , D. Vats<sup>41</sup> 





#### 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<sup>42,43</sup> , E. Khazaie<sup>43</sup> , M. Zeinali<sup>44</sup> 
































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

S. Chenarani<sup>45</sup> , S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 




























#### University College Dublin, Dublin, Ireland

M. Grunewald 





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

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

















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

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

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

S. Costa<sup>a,b,48</sup> , A. Di Mattia<sup>a</sup> , R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b,48</sup> , C. Tuve<sup>a,b</sup> 

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

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
























#### INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola<sup>49</sup> , D. Piccolo 












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

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































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

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












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

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

















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

R. Ardino<sup>a</sup> , P. Azzi<sup>a</sup> , N. Bacchetta<sup>a,51</sup> , P. Bortignon<sup>a</sup> , A. Bragagnolo<sup>a,b</sup> , R. Carlin<sup>a,b</sup> , P. Checchia<sup>a</sup> , T. Dorigo<sup>a</sup> , F. Fanzago<sup>a</sup> , U. Gasparini<sup>a,b</sup> , F. Gonella<sup>a</sup> , G. Grosso<sup>a</sup> , L. Layer<sup>a,52</sup> , E. Lusiani<sup>a</sup> , M. Margoni<sup>a,b</sup> , A.T. Meneguzzo<sup>a,b</sup> , M. Migliorini<sup>a,b</sup> , J. Pazzini<sup>a,b</sup> , P. Ronchese<sup>a,b</sup> , R. Rossin<sup>a,b</sup> , F. Simonetto<sup>a,b</sup> , G. Strong<sup>a</sup> , M. Tosi<sup>a,b</sup> , A. Triossi<sup>a,b</sup> , S. Ventura<sup>a</sup> , H. Yarar<sup>a,b</sup> , M. Zanetti<sup>a,b</sup> , P. Zotto<sup>a,b</sup> , A. Zucchetta<sup>a,b</sup> , G. Zumerle<sup>a,b</sup> 
































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

S. Abu Zeid<sup>a,53</sup> , C. Aimè<sup>a,b</sup> , A. Braghieri<sup>a</sup> , S. Calzaferri<sup>a,b</sup> , D. Fiorina<sup>a,b</sup> , P. Montagna<sup>a,b</sup> , V. Re<sup>a</sup> , C. Riccardi<sup>a,b</sup> , P. Salvini<sup>a</sup> , I. Vai<sup>a,b</sup> , P. Vitulo<sup>a,b</sup> 





















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

S. Ajmal<sup>a,b</sup> , P. Asenov<sup>a,54</sup> , G.M. Bilei<sup>a</sup> , D. Ciangottini<sup>a,b</sup> , L. Fanò<sup>a,b</sup> , M. Magherini<sup>a,b</sup> , G. Mantovani<sup>a,b</sup> , V. Mariani<sup>a,b</sup> , M. Menichelli<sup>a</sup> , F. Moscatelli<sup>a,54</sup> , A. Piccinelli<sup>a,b</sup> , M. Presilla<sup>a,b</sup> , A. Rossi<sup>a,b</sup> , A. Santocchia<sup>a,b</sup> , D. Spiga<sup>a</sup> , T. Tedeschi<sup>a,b</sup> 









































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

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







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

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

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

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

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

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

**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 ,  
Watson, I.J. , 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. Veckalns<sup>55</sup> 

**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. Yusuff<sup>56</sup> , Z. Zolkapli 

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

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



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

G. Ayala , H. Castilla-Valdez , E. De La Cruz-Burelo , I. Heredia-De La Cruz<sup>57</sup> ,  
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 Science and Technology 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 

**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. Rekovic














**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 ,  
I. Redondo , D.D. Redondo Ferrero , L. Romero, S. Sánchez Navas , L. Urda Gómez ,  
J. Vazquez Escobar , C. Willmott


















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

J.F. de Trocóniz 

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

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

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

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. Kailasapathy<sup>58</sup> , D.U.J. Sonnadara , D.D.C. Wickramarathna 













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

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


















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

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. Fallavollita<sup>59</sup>, 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. Rabadý , G. Reales Gutiérrez, M. Rovere , H. Sakulin , S. Scarfi , M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas<sup>60</sup> , A.G. Stahl Leiton , A. Steen , S. Summers , D. Treille , P. Tropea , A. Tsirou, D. Walter , J. Wanczyk<sup>61</sup> , K.A. Wozniak<sup>62</sup> , P. Zehetner, P. Zejdl , W.D. Zeuner
























**Paul Scherrer Institut, Villigen, Switzerland**

T. Bevilacqua<sup>63</sup> , L. Caminada<sup>63</sup> , A. Ebrahimi , W. Erdmann , R. Horisberger , Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli<sup>63</sup> , L. Noehte<sup>63</sup> , T. Rohe 




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

T.K. Aarrestad , K. Androsov<sup>61</sup> , 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. Mascellani<sup>61</sup> , 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. Steggemann<sup>61</sup> , D. Valsecchi , R. Wallny 










**Universität Zürich, Zurich, Switzerland**

C. Amsler<sup>64</sup> , 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. Adloff<sup>65</sup>, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari<sup>39</sup> , 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 

**Chulalongkorn University, Faculty of Science, Department of Physics, 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. Dumanoglu<sup>66</sup> , E. Eskut , Y. Guler<sup>67</sup> , E. Gurpinar Guler<sup>67</sup> , C. Isik , O. Kara, A. Kayis Topaksu , U. Kiminsu , G. Onengut , K. Ozdemir<sup>68</sup> , A. Polatoz , B. Tali<sup>69</sup> , U.G. Tok , S. Turkcapar , E. Uslan , I.S. Zorbakir 

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

K. Ocalan<sup>70</sup> , M. Yalvac<sup>71</sup> 

**Bogazici University, Istanbul, Turkey**

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya<sup>72</sup> , O. Kaya<sup>73</sup> , S. Tekten<sup>74</sup> 


**Istanbul Technical University, Istanbul, Turkey**

A. Cakir , K. Cankocak<sup>66</sup> , Y. Komurcu , S. Sen<sup>75</sup> 

**Istanbul University, Istanbul, Turkey**

O. Aydilek , S. Cerci<sup>69</sup> , V. Epshteyn<sup>76</sup> , B. Hacisahinoglu , I. Hos<sup>77</sup> , B. Isildak<sup>78</sup> , B. Kaynak , S. Ozkorucuklu , H. Sert , C. Simsek , D. Sunar Cerci<sup>69</sup> , 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. Stylianou<sup>79</sup> , K. Walkingshaw Pass, R. White 

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

A.H. Ball, K.W. Bell , A. Belyaev<sup>80</sup> , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , K.V. Ellis, K. Harder , S. Harper , M.-L. Holmberg<sup>81</sup> , 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. Chahal<sup>82</sup> , 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. Nash<sup>83</sup> , 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. Virdee<sup>28</sup> ,  
M. Vojinovic , N. Wardle , D. Winterbottom 


**Brunel University, Uxbridge, United Kingdom**

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

**Baylor University, Waco, Texas, USA**

S. Abdullin , A. Brinkerhoff , B. Caraway , J. Dittmann , K. Hatakeyama , J. Hiltbrand , A.R. Kanuganti , B. McMaster , M. Saunders , S. Sawant , C. Sutantawibul ,  
M. Toms<sup>76</sup> , 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. Rumerio<sup>84</sup> , E. Usai ,  
C. West , R. Yi 




















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

A. Akpınar , 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. Coubez<sup>23</sup>, D. Cutts , M. Hadley , U. Heintz , J.M. Hogan<sup>85</sup> , T. Kwon ,  
G. Landsberg , K.T. Lau , D. Li , J. Luo , S. Mondal , M. Narain<sup>†</sup> , N. Pervan ,  
S. Sagir<sup>86</sup> , 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<sup>†</sup> 






**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 , K.A. Ulmer , S.R. Wagner , N. Zipper 




















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

J. Alexander , S. Bright-Thonney , X. Chen , D.J. Cranshaw , J. Fan , X. Fan , D. Gadkari , S. Hogan , J. Monroy , J.R. Patterson , J. Reichert , M. Reid , A. Ryd , 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. Gecse , L. Gray , D. Green, S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig , J. Hirschauer , L. Horyn , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , C. Mantilla , D. Mason , P. McBride , P. Merkel , S. Mrenna , S. Nahn , J. Ngadiuba , D. Noonan , V. Papadimitriou , N. Pastika , K. Pedro , C. Pena<sup>87</sup> , F. Ravera , A. Reinsvold Hall<sup>88</sup> , L. Ristori , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , 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. Elkafrawy<sup>53</sup> , M. Hohlmann , R. Kumar Verma , M. Rahmani, F. Yumiceva 

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

M.R. Adams , C. Bennett, R. Cavanaugh , S. Dittmer , R. Escobar Franco , O. Evdokimov , 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 , N. Varelas , X. Wang , Z. Ye , J. Yoo 

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
























M. Alhousseini , D. Blend, K. Dilsiz<sup>89</sup> , L. Emediato , G. Karaman , O.K. Köseyan , J.-

P. Merlo, A. Mestvirishvili<sup>90</sup> , J. Nachtman , O. Neogi, H. Ogul<sup>91</sup> , Y. Onel , A. Penzo , C. Snyder, E. Tiras<sup>92</sup> 









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

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz , 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. Popescu<sup>93</sup> , 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 





#### **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. Kovalskyi , 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<sup>†</sup>, 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. Musienko<sup>13</sup> , 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. Stojanovic<sup>17</sup> , 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<sup>94</sup> , R. Taus , G.P. Van Onsem 









#### **The Rockefeller University, New York, New York, USA**

K. Goulios 















#### **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. Karacheban<sup>26</sup> , 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. Bouhali<sup>95</sup> , M. Dalchenko , R. Eusebi , J. Gilmore , T. Huang , T. Kamon<sup>96</sup> , 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 

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

S. Afanasiev , V. Andreev , Yu. Andreev , T. Aushev , M. Azarkin , A. Babaev , A. Belyaev , V. Blinov<sup>97</sup>, E. Boos , V. Borshch , D. Budkouski , V. Bunichev , V. Chekhovsky, R. Chistov<sup>97</sup> , M. Danilov<sup>97</sup> , A. Dermenev , T. Dimova<sup>97</sup> , D. Druzhkin<sup>98</sup> , M. Dubinin<sup>87</sup> , L. Dudko , A. Ershov , G. Gavrilov , V. Gavrilov , S. Gninenko , V. Golovtcov , N. Golubev , I. Golutvin , I. Gorbunov , A. Gribushin , Y. Ivanov , V. Kachanov , L. Kardapoltsev<sup>97</sup> , V. Karjavine , A. Karneyeu , V. Kim<sup>97</sup> , M. Kirakosyan, D. Kirpichnikov , M. Kirsanov , V. Klyukhin , O. Kodolova<sup>99</sup> , D. Konstantinov , V. Korenkov , A. Kozyrev<sup>97</sup> , N. Krasnikov , A. Lanev , P. Levchenko<sup>100</sup> , N. Lychkovskaya , V. Makarenko , A. Malakhov , V. Matveev<sup>97</sup> , V. Murzin , A. Nikitenko<sup>101,99</sup> , S. Obraztsov , V. Oreshkin , V. Palichik , V. Perelygin , M. Perfilov, S. Polikarpov<sup>97</sup> , V. Popov, O. Radchenko<sup>97</sup> , M. Savina , V. Savrin , D. Selivanova , V. Shalaev , S. Shmatov , S. Shulha , Y. Skovpen<sup>97</sup> , 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<sup>†</sup>, N. Voytishin , B.S. Yuldashev<sup>102</sup>, A. Zarubin , I. Zhizhin , A. Zhokin 

†: Deceased

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

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

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

<sup>4</sup>Also at Ghent University, Ghent, Belgium

<sup>5</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil

<sup>6</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

<sup>7</sup>Also at UFMS, Nova Andradina, Brazil

<sup>8</sup>Also at Nanjing Normal University Department of Physics, Nanjing, China

<sup>9</sup>Now at The University of Iowa, Iowa City, Iowa, USA

- 
- <sup>10</sup>Also at University of Chinese Academy of Sciences, Beijing, China
- <sup>11</sup>Also at University of Chinese Academy of Sciences, Beijing, China
- <sup>12</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium
- <sup>13</sup>Also at an institute or an international laboratory covered by a cooperation agreement with CERN
- <sup>14</sup>Also at Suez University, Suez, Egypt
- <sup>15</sup>Now at British University in Egypt, Cairo, Egypt
- <sup>16</sup>Also at Birla Institute of Technology, Mesra, Mesra, India
- <sup>17</sup>Also at Purdue University, West Lafayette, Indiana, USA
- <sup>18</sup>Also at Université de Haute Alsace, Mulhouse, France
- <sup>19</sup>Also at Department of Physics, Tsinghua University, Beijing, China
- <sup>20</sup>Also at The University of the State of Amazonas, Manaus, Brazil
- <sup>21</sup>Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- <sup>22</sup>Also at University of Hamburg, Hamburg, Germany
- <sup>23</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>24</sup>Also at Isfahan University of Technology, Isfahan, Iran
- <sup>25</sup>Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- <sup>26</sup>Also at Brandenburg University of Technology, Cottbus, Germany
- <sup>27</sup>Also at Forschungszentrum Jülich, Juelich, Germany
- <sup>28</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- <sup>29</sup>Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- <sup>30</sup>Also at Wigner Research Centre for Physics, Budapest, Hungary
- <sup>31</sup>Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
- <sup>32</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- <sup>33</sup>Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
- <sup>34</sup>Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
- <sup>35</sup>Also at Punjab Agricultural University, Ludhiana, India
- <sup>36</sup>Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
- <sup>37</sup>Also at University of Visva-Bharati, Santiniketan, India
- <sup>38</sup>Also at University of Hyderabad, Hyderabad, India
- <sup>39</sup>Also at Indian Institute of Science (IISc), Bangalore, India
- <sup>40</sup>Also at IIT Bhubaneswar, Bhubaneswar, India
- <sup>41</sup>Also at Institute of Physics, Bhubaneswar, India
- <sup>42</sup>Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- <sup>43</sup>Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
- <sup>44</sup>Also at Sharif University of Technology, Tehran, Iran
- <sup>45</sup>Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- <sup>46</sup>Also at Helwan University, Cairo, Egypt
- <sup>47</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- <sup>48</sup>Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- <sup>49</sup>Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- <sup>50</sup>Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- <sup>51</sup>Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- <sup>52</sup>Also at Università di Napoli 'Federico II', Napoli, Italy
- <sup>53</sup>Also at Ain Shams University, Cairo, Egypt
- <sup>54</sup>Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- <sup>55</sup>Also at Riga Technical University, Riga, Latvia

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

<sup>98</sup>Also at Universiteit Antwerpen, Antwerpen, Belgium

<sup>99</sup>Also at Yerevan Physics Institute, Yerevan, Armenia

<sup>100</sup>Also at Northeastern University, Boston, Massachusetts, USA

<sup>101</sup>Also at Imperial College, London, United Kingdom

<sup>102</sup>Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan