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

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## 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.

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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

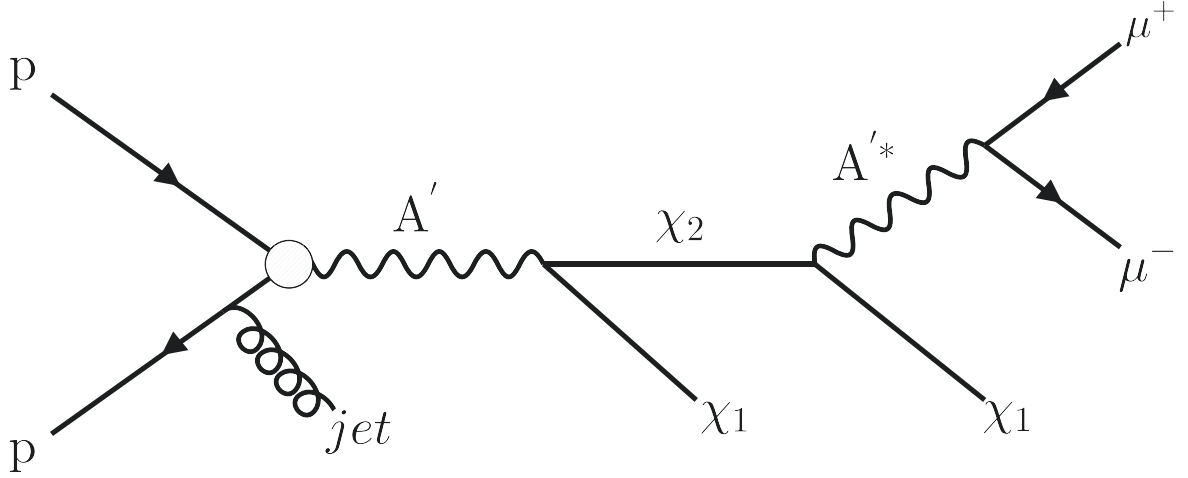


Figure 1: Feynman diagram of IDM production and decay in pp collisions. The heavier DM state  $\chi_2$  can be long-lived, and decays to  $\chi_1$  and to a muon pair via an off-shell dark photon  $A'$ .

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.

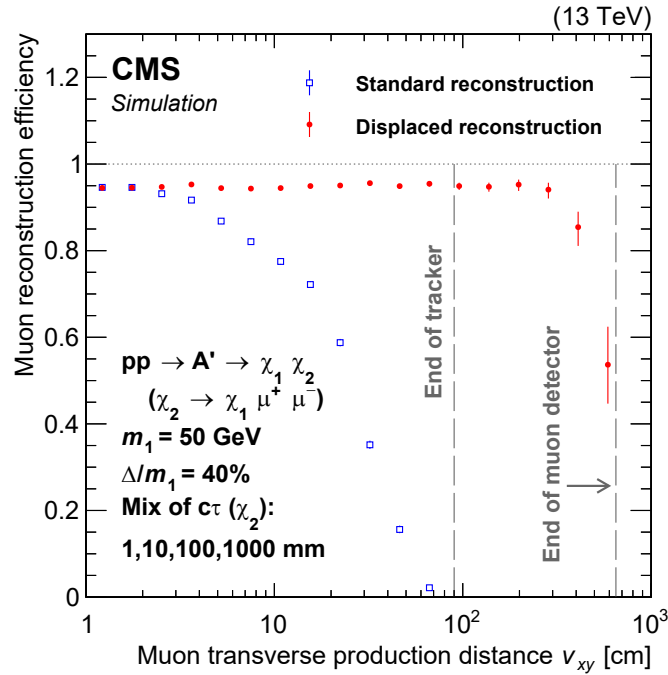


Figure 2: Simulated muon reconstruction efficiency of standard (blue squares) and displaced (red circles) reconstruction algorithms as a function of transverse vertex displacement  $v_{xy}$ . The two dashed vertical gray lines denote the ends of the fiducial tracker and muon detector regions, respectively.

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  $I_{\text{PF}}^{\text{rel}}$ , 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	$I_{\text{PF}}^{\text{rel}}$	$\min-d_{xy}$ [cm]	Events	$I_{\text{PF}}^{\text{rel}}$	$\min-d_{xy}$ [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	—	—	—

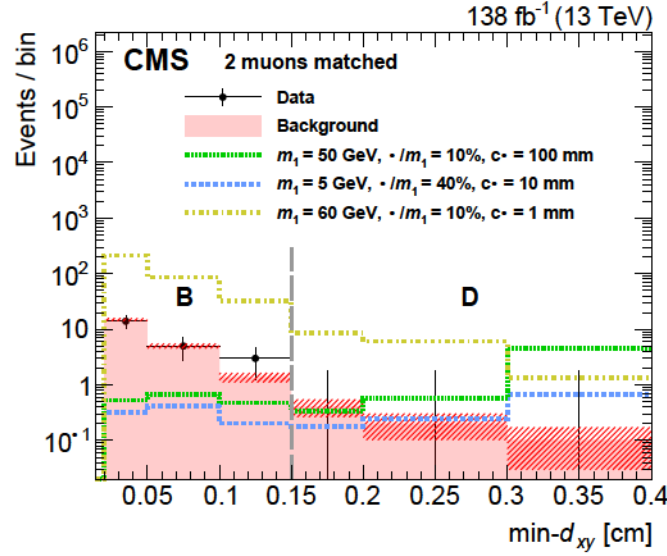


Figure 3: Measured  $\min-d_{xy}$  distribution in the 2-match category, after requiring the  $\min-d_{xy}$  muon to pass the isolation requirement  $I_{\text{PP}}^{\text{el}} < 0.25$  (i.e., the B and D bins of the ABCD plane). Overlaid with a red histogram is the background predicted from the region 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  $y \equiv \epsilon^2 \alpha_{\text{D}} (m_1 / m_{A'})^4$ . 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



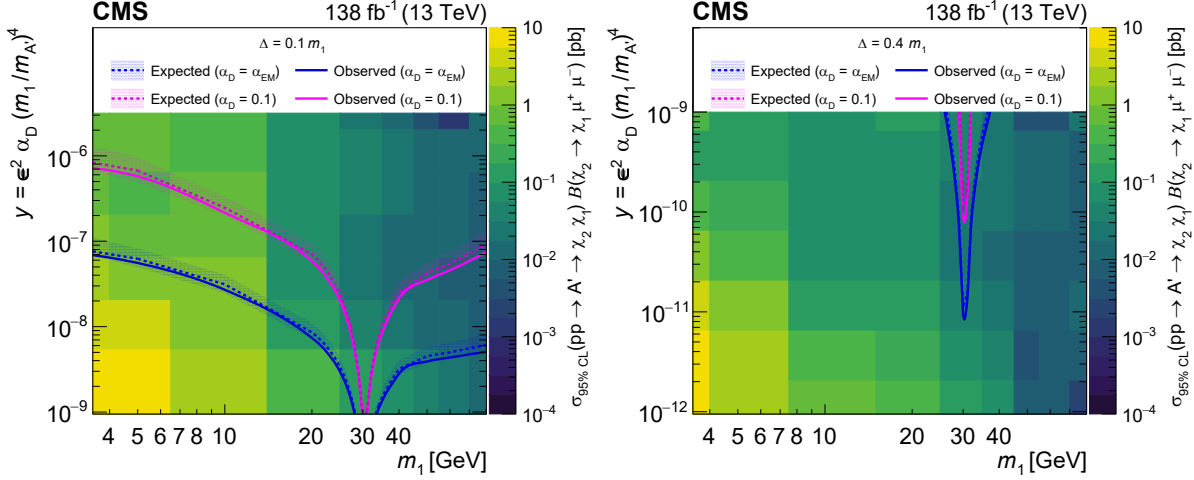


Figure 4: Two-dimensional observed limits on  $\sigma(\text{pp} \rightarrow A' \rightarrow \chi_1 \chi_2) \mathcal{B}(\chi_2 \rightarrow \chi_1 \mu^+ \mu^-)$ , for  $\Delta = 0.1 m_1$  (left) and  $0.4 m_1$  (right), as functions of the DM mass  $m_1$  and the interaction strength  $y$ , with  $m_{A'} = 3 m_1$ . 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.

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















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






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



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






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








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






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




























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









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







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


























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




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




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














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






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
































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




























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














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













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







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


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







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













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
























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









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


































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

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






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









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









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


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

















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















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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
























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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 

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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 

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


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 






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




















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














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A. Boyaryntsev, B. Grynyov 


















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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 

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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 

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M. Toms<sup>76</sup> , J. Wilson 
















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

















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R. Chudasama , S.I. Cooper , S.V. Gleyzer , C.U. Perez , P. Rumerio<sup>84</sup> , E. Usai ,  
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















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









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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





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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 ,  
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





















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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 

















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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 ,  
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


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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 ,  
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









**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 


















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







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





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














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

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


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







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





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
















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