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Search for long-lived particles decaying into muons in proton-proton collisions at $\sqrt{s} = 13.6$ TeV using data scouting



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Abstract: A search for long-lived particles decaying into muons is performed using proton-proton collisions at $\sqrt{s} = 13.6$ TeV, collected by the CMS experiment at the LHC in 2022 and 2023, corresponding to an integrated luminosity of 62.4 fb^{-1}. The data were collected using dedicated dimuon triggers with low transverse momentum thresholds, recorded with a high-rate data scouting trigger stream. This data stream retains a reduced amount of information at the high-level trigger, to explore otherwise inaccessible phase space at low multimuon invariant mass and nonzero displacement from the primary interaction vertex. No significant excess of events above the standard model prediction is found. Upper limits on branching fractions at 95% confidence level are set for a wide range of mass and lifetime hypotheses in several beyond the standard model frameworks, where the Higgs boson decays into long-lived dark photons or into dark partons that produce showers containing long-lived particles, or where a long-lived scalar resonance is produced from the decay of a b hadron. The resulting constraints improve and extend existing ones in large regions of the parameter space.

Keywords: Beyond Standard Model, Dark Matter, Hadron-Hadron Scattering

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Contents

1 Introduction 1

2 The CMS detector 4

3 Data sets and triggers 5

4 Monte Carlo simulation 6

5 Event selection and categorization 8
- 5.1 Event selection 8
- 5.2 Event categorization 9

6 Parameterization of the invariant mass distribution 12

7 Results and interpretation 15
- 7.1 Systematic uncertainties in the signal yields 15
- 7.2 Constraints on models of BSM physics 18

8 Summary 23

The CMS collaboration 30

1 Introduction

The origin of dark matter remains one of the outstanding puzzles in particle physics and cosmology, in spite of the cosmological evidence of its existence [1–4]. Dark matter is expected to interact very weakly, if at all, with standard model (SM) particles, except via gravity. This introduces the possibility of a hidden (dark) sector of matter [5–7]. Particles in the dark sector would interact with the SM particles only via weakly interacting mediators.

One dark-matter scenario, referred to as the hidden Abelian Higgs model (HAHM), involves a spontaneously broken dark $U(1)_{\mathrm{D}}$ gauge symmetry, mediated by a dark photon, $\mathrm{Z_D}$ [6]. In this scenario, the only renormalizable interaction with SM particles occurs via the kinetic mixing of a dark photon with a hypercharge gauge boson. In addition, if a dark Higgs mechanism is responsible for the spontaneous breaking of the $U(1)_{\mathrm{D}}$ gauge symmetry, then the dark Higgs boson ($\mathrm{H_D}$) has a renormalizable coupling to the 125 GeV SM-like Higgs boson (H), resulting in mixing between the two physical scalar states. Thus, the hidden sector may interact with the SM sector either through the hypercharge portal via the kinetic mixing parameter ϵ, or through the Higgs portal via the Higgs mixing parameter κ. The dark photon $\mathrm{Z_D}$ may also mix with the SM photon (γ) and the Z boson through the hypercharge portal. If there are no hidden-sector states below the $\mathrm{Z_D}$ boson mass, the $\mathrm{Z_D}$ decays exclusively into SM particles, with a sizable branching fraction to leptons, where the coupling of the SM fermions to the $\mathrm{Z_D}$ boson is proportional to ϵ. The $\mathrm{Z_D}$ boson is expected to be long-lived if $\epsilon \lesssim 10^{-4}$, with a mean proper decay length $c\tau_0^{\mathrm{Z_D}} \gtrsim 1$ μm, proportional to ϵ^{-2}. In this regime, the

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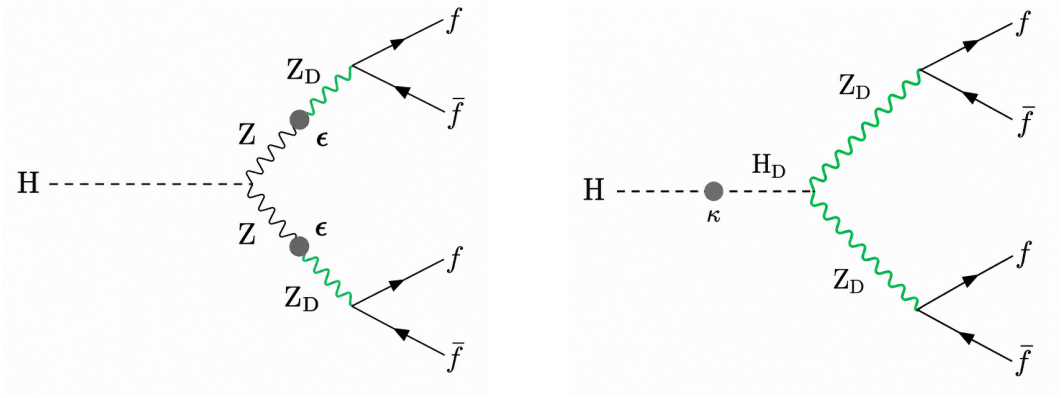

Figure 1. Diagrams illustrating an SM-like Higgs boson (H) decay to four fermions (f) via two intermediate dark photons, $\mathrm{Z_D}$ [6]: through the hypercharge portal (left) and the Higgs portal (right) via a dark Higgs boson ($\mathrm{H_D}$). The long-lived particles are highlighted in green.

decays $\mathrm{H} \to \mathrm{Z}\mathrm{Z_D}$ and $\mathrm{H} \to \mathrm{Z_D}\mathrm{Z_D}$ through the hypercharge portal have negligible branching fractions, hence the decays through the Higgs portal are expected to dominate. The diagrams in figure 1 illustrate the production of a pair of $\mathrm{Z_D}$ bosons in a Higgs boson decay.

In other hidden-sector models [8], a new, confining dark gauge group is introduced, which can produce events with multiple nonisolated dark particles, referred to as "dark showers", analogous to phenomena in the quantum chromodynamics sector of the SM. A spontaneously broken $U(1)$ gauge symmetry is involved, mediated by a dark photon A' that couples to the SM photon. The confining dark gauge group dynamically breaks the hidden-sector $SU(2) \otimes SU(2)$ flavor symmetry, resulting in the addition of a set of three dark pions ($\widetilde{\pi}_1$, $\widetilde{\pi}_2$, and $\widetilde{\pi}_3$) and a heavier dark meson, $\widetilde{\eta}$. In these models, the SM Higgs boson can decay into a pair of dark partons $\Psi\overline{\Psi}$, which then undergo showering and hadronization within the dark sector. Different scenarios are considered: a model where the dark photon A' is long-lived, referred to as *Scenario A* [8], and a model where the dark pion $\widetilde{\pi}_3$ is long-lived instead, referred to as *Scenario B1* [8]. In both scenarios, it is assumed that the three dark pions $\widetilde{\pi}_1$, $\widetilde{\pi}_2$, and $\widetilde{\pi}_3$ have nearly degenerate masses $m_{\widetilde{\pi}}$ and arise from the decay of $\widetilde{\eta}$, $\widetilde{\eta} \to 3\widetilde{\pi}$, with the $\widetilde{\eta}$ meson mass $m_{\widetilde{\eta}} > 3m_{\widetilde{\pi}}$. On average, five dark mesons per event are produced. The dark pion $\widetilde{\pi}_3$ is assumed to decay, in turn, into a pair of dark photons A', while $\widetilde{\pi}_1$ and $\widetilde{\pi}_2$ are assumed to be stable. Thus, Scenario A yields final states where multiple fermion pairs are produced in as many distinct vertices, each corresponding to the decay of a dark photon A'. Conversely, Scenario B1 yields final states where four fermions emerge from the same displaced vertex. Diagrams illustrating Scenarios A and B1 are shown in figure 2.

Constraints have been placed on visible dark-photon decays by beam dump [9], fixed-target [10], $\mathrm{e^+e^-}$ collider [11], and rare-decay experiments [12], as well as by the LHCb [13–15], ATLAS [16–18], and CMS [19–23] experiments at the CERN LHC.

Other scenarios of physics beyond the SM (BSM) are also considered that may produce a long-lived, low-mass resonance decaying into a muon pair. In one of the minimal extensions of the SM a singlet scalar field ϕ is added, which mixes with the Higgs boson with a mixing angle θ and thereby couples to all SM fermions [24, 25]. The ϕ boson is expected to be

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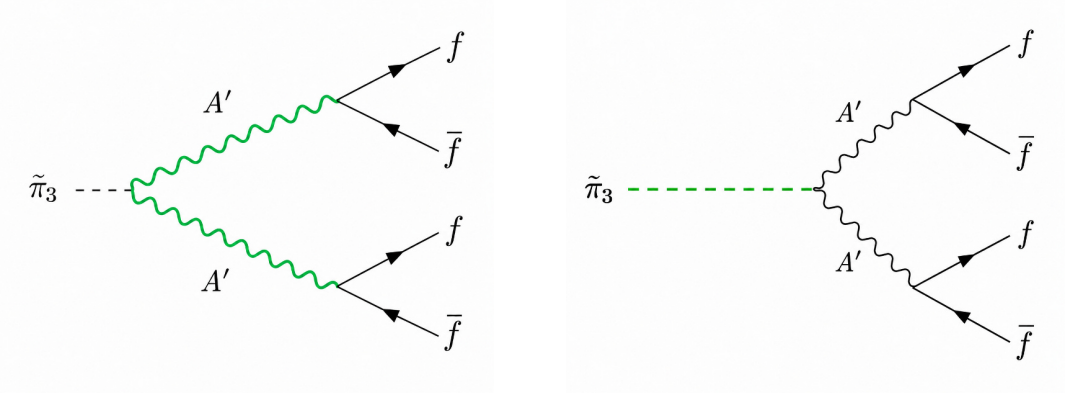

Figure 2. Diagrams illustrating two dark-shower scenarios [8], where a dark meson $\widetilde{\eta}$ is allowed to decay into dark pions ($\widetilde{\pi}_3$), which in turn decay into pairs of dark photons (A′). Scenario A (left) assumes prompt $\widetilde{\pi}_3$ decays into a pair of long-lived dark photons, A′, each decaying into fermions. Scenario B1 (right) assumes long-lived $\widetilde{\pi}_3$ decays into a pair of promptly decaying dark photons (A′). The long-lived particles are highlighted in green.

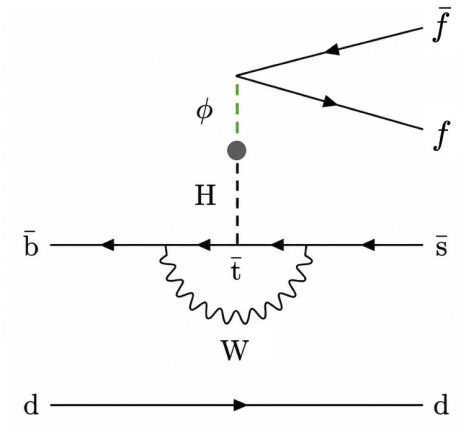

Figure 3. Diagram illustrating the production of a scalar resonance ϕ in a b hadron decay, through the mixing with an SM-like Higgs boson (H). The long-lived particle ϕ is highlighted in green.

long-lived under the hypothesis of weak couplings to SM fermions, corresponding to $\theta \lesssim 10^{-3}$. Such a scalar resonance can be produced in decays of b hadrons, $h_b \to \phi X$. This process is depicted in figure 3. Constraints on this model have been previously set by the CHARM [26], LHCb [27, 28], and CMS [20] experiments.

This paper presents a search for narrow, long-lived multimuon resonances, based on data collected with the CMS experiment in proton-proton (pp) collisions at $\sqrt{s} = 13.6$ TeV in 2022 and 2023. A dedicated dimuon trigger stream (*scouting* [29]) with low transverse momentum (p_T) thresholds, recorded at high rate by retaining a reduced amount of information at the high-level trigger (HLT) is used. The rate of scouting triggers is higher than that of the standard triggers owing to less stringent requirements that enable multimuon resonance searches across mass and lifetime ranges that are otherwise inaccessible. The selected data

JHEP11(2026)004

correspond to a total integrated luminosity of 62.4 fb^{-1} (34.6 and 27.8 fb^{-1} collected in 2022 and 2023, respectively).

The search targets narrow, low-mass, long-lived resonances decaying into pairs of oppositely charged muons, where the lifetime of the long-lived particle is such that the transverse displacement (l_{xy}) of its decay vertex is within roughly 70 cm of the primary vertex (PV) of the hard scattering, i.e., sufficiently within the volume of the tracker detector to ensure accurate measurements. The signal is expected to appear as a narrow peak on top of a smooth multimuon invariant mass distribution, with a resonance width that is assumed to be smaller than the experimental mass resolution. The search is performed by looking for localized excesses in the multimuon invariant mass spectrum across different ranges of l_{xy}. We probe, for the first time in CMS, multimuon final states with large displacements and masses below 10 GeV, which have not been explored so far owing to the limitations of the standard trigger streams and of the dimuon scouting triggers used by CMS before 2022. In particular, the improvements in the dimuon scouting triggers allow for the reconstruction of displaced muon pairs beyond 11 cm in l_{xy}, which was a limitation of the analysis presented in ref. [20], where data collected with the scouting triggers available in 2017 and 2018 were used. Moreover, the extended event content available in the scouting data collected since 2022 [29] is exploited to further improve the sensitivity of the search.

This paper is organized as follows. The CMS detector, and the data sets and triggers used in the analysis are described in sections 2 and 3, respectively. The signal Monte Carlo (MC) samples for each interpretation are presented in section 4. The event selection and categorization strategies are discussed in section 5, while section 6 outlines the modeling of the signal and the background. Finally, results are presented in section 7, and the paper is summarized in section 8. Tabulated results are available in the HEPData record for this analysis [30].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors interleaved with the layers of the steel flux-return yoke outside the solenoid. A global "particle-flow" (PF) algorithm [31] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the calorimeters with data from the gas-ionization muon detectors. The pixel tracker consists of four concentric barrel layers at radii of 2.9, 6.8, 10.9, and 16.0 cm, and three disks on each end at distances of 29.1, 39.6, and 51.6 cm from the center of the detector [32]. The region between 20 and 116 cm is occupied by the silicon strip tracker. Four barrel layers, supplemented by three disk in the endcaps, compose the tracker inner barrel and disks, which extends the radius up to 55 cm. Beyond this range, the tracker outer barrel and the tracker endcaps are situated, adding six layers and nine additional disks at each end.

JHEP11(2026)004

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 refs. [33, 34].

A two-level trigger system is used to select events of potential physics interest. The first level of the CMS trigger system (L1) [35], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest in a fixed time interval of about 4 μs. The HLT processor farm further decreases the event rate from around 100 kHz to a few kHz, before data storage. A more detailed description of the CMS trigger system can be found in refs. [36, 37].

In addition to the standard HLT selection streams, a dedicated set of triggers exists that allows the exploration of additional phase space. This approach is referred to as *data scouting* [29]. The scouting trigger algorithms used in this search select events containing muon pairs with a dimuon invariant mass greater than the muon mass ($m_{\mu\mu} \gtrsim 2m_{\mu}$) at a rate of a few kHz. In order to allow the large rate within an acceptable bandwidth, the event size is reduced by up to a factor of 1000 by only retaining limited information, as reconstructed at the HLT.

3 Data sets and triggers

The standard trigger streams typically select events containing at least one particle (e.g., a lepton) or jet with large p_{T}. Thus, such triggers are not necessarily ideal in a generic search for light, narrow resonances decaying into two muons with $p_{\mathrm{T}} \lesssim 10$ GeV. Muons are reconstructed at the HLT by combining the information from the tracker and the muon detectors. The retained limited information includes their four-momenta, the number of hits left in the tracker and in the muon detectors, and detailed information on the muon tracks. These muon tracks are used in pairs to form dimuon vertices, considering all possible pairs. In the following, these vertices are called secondary vertices (SVs), and they may be either displaced from the PV or not. Candidate pp interaction vertices are formed using tracks reconstructed from hits only in the pixel detector, and the candidate vertex with the largest value of summed track p_{T}^2 is taken to be the PV of the pp interaction. Events in the scouting data sets contain information on the normalized χ^2 of all reconstructed vertices, together with their position with respect to the nominal interaction point.

Between 2018 and 2022, the CMS muon scouting triggers [38] were updated, broadening the accessible phase space and increasing the amount of information retained for each event. The main improvement arises from the removal of the pixel hit multiplicity requirement, which previously prevented any muon with <2 pixel hits from being accepted by the scouting triggers. As a result, the muons with $l_{\mathrm{xy}} > 11$ cm are now accessible for the first time in a search using scouting data. Additionally, more detailed information on tracks and PF candidates is retained and used to improve the background rejection, as described in section 5.1.

Events are preselected at the L1 trigger with at least two muons passing requirements on the p_{T}, η and charge of each muon and on their angular separation, defined as $\Delta R(\mu_1, \mu_2) = \sqrt{[\Delta\phi(\mu_1, \mu_2)]^2 + [\Delta\eta(\mu_1, \mu_2)]^2}$, where ϕ is the azimuthal angle and μ_1 (μ_2) is the leading (subleading) muon.

JHEP11(2026)004

In 2022, events were required to pass at least one of three criteria:

- the presence of at least two opposite-sign (OS) L1 muons with $p_{\mathrm{T}}^{\mu} > 4\,\mathrm{GeV}$ and $\Delta R(\mu_1, \mu_2) < 1.2$;
- the presence of at least two OS L1 muons with $p_{\mathrm{T}}^{\mu} > 4.5\,\mathrm{GeV}$ and $|\eta^{\mu}| < 2.0$; or
- the presence of at least two L1 muons with $p_{\mathrm{T}}^{\mu_1} > 15\,\mathrm{GeV}$ and $p_{\mathrm{T}}^{\mu_2} > 7\,\mathrm{GeV}$.

In 2023, two additional L1 triggers were added, requiring:

- the presence of at least two OS L1 muons with $|\eta^{\mu}| < 1.4$ and $\Delta R(\mu_1, \mu_2) < 1.4$; or
- the presence of at least two L1 muons with $p_{\mathrm{T}}^{\mu} > 8\,\mathrm{GeV}$.

The measurement of the muon momentum at the L1 trigger relies only on the information from the muon detectors. After the L1 trigger preselections, only events containing two OS muons with $p_{\mathrm{T}}^{\mu} > 3\,\mathrm{GeV}$ and $|\eta^{\mu}| < 2.4$ are retained at the HLT, where the inner tracker information improves the muon p_{T} measurement and spatial resolution.

The efficiency of the scouting triggers is measured in data, as a function of the dimuon l_{xy} and of the minimum p_{T}^{μ} of the pair, using events with at least two muons selected with independent, orthogonal triggers based on calorimeter energy deposits. The measured efficiency and its uncertainty are accounted for in the normalization of simulated events, as discussed in section 4.

Because only a reduced amount of information is available in the scouting data, no additional calibration is performed for the muons used in this search. The resulting dimuon mass resolution was measured to differ by less than 1% from that obtained using muons that undergo the full offline reconstruction [29], which has a negligible effect on the results presented in this paper.

4 Monte Carlo simulation

The SM background is estimated directly from data in the dimuon ($m_{\mu\mu}$) or four-muon ($m_{4\mu}$) invariant mass spectrum, parameterized by smooth analytical functions. Thus, the search does not rely on MC simulation in order to estimate the background.

On the other hand, MC simulations of BSM signals are used to interpret the results of the search. In particular, a model of Higgs boson production via the dominant mode of gluon-gluon fusion is simulated, with $\mathrm{H} \to \mathrm{Z_D Z_D}$, where $\mathrm{Z_D}$ is a long-lived resonance and at least one $\mathrm{Z_D}$ decays into a pair of OS muons. The phenomenology of this model is defined by four parameters:

- the kinetic mixing ϵ;
- the mass of the dark photon, $m_{\mathrm{Z_D}}$;
- the Higgs portal coupling, κ; and
- the mass of the dark Higgs boson, $m_{\mathrm{H_D}}$.

JHEP11(2026)004

In the simulation used in this search, m_{H_D} and κ are fixed to 400 GeV and 0.01, respectively, in a regime where $H \to H_D H_D$ decays are kinematically forbidden. Instead, the Higgs boson is set to always decay into a pair of Z_D bosons, which in turn decay into SM fermions with branching fractions that depend on their mass [6]. The branching fraction for Z_D decays into muon pairs varies from about 50% at a mass of 0.5 GeV to about 9% at a mass of 50 GeV. The lifetime of the Z_D boson for a given mass hypothesis is determined by ϵ. In this paper, dark photons are simulated with $c\tau_0^{Z_D} = 0.1$, 1, 10, and 100 cm, except for masses below 1 GeV, where only $c\tau_0^{Z_D} = 0.1$ and 1 cm scenarios are simulated to account for the variation in acceptance due to the large Lorentz boost of the particles, which results in longer decay lengths for low-mass resonances. A lifetime-based reweighting procedure is additionally employed to probe intermediate lifetime values. The production of dark photons is modeled at leading order (LO) with MadGraph5_aMC@NLO 2.9.9 [39]. While only the dominant gluon-gluon fusion production mechanism is considered for the generation, the Higgs boson production cross section is normalized to the most recent theoretical prediction for the sum of all production modes for the mass of Higgs boson $m_H = 125$ GeV at $\sqrt{s} = 13.6$ TeV, which is 59.8 pb [40, 41]. Other Higgs boson production mechanisms are not considered in the generation for simplicity, because they have negligible effects on the analysis acceptance. The decays of dark photons are simulated using pythia 8.306 [42]. These samples are used to set upper limits on the branching fraction $\mathcal{B}(H \to Z_D Z_D)$, using values of $\mathcal{B}(Z_D \to \mu\mu)$ from the model of ref. [6].

Dark-shower signal models are simulated at LO with pythia 8.309 for selected mass combinations of Scenarios A and B1, considering two dark flavors and three dark colors. In these models, the SM Higgs boson is set to decay into a pair of dark partons $\Psi\overline{\Psi}$, which then undergo showering and hadronization within the dark sector. The Higgs boson production cross section is normalized to 59.8 pb [40, 41]. The mass scale is set by assuming $\tilde{\Lambda} = m_{\widetilde{\eta}} = 4m_{\widetilde{\pi}}$, where $\tilde{\Lambda}$ is the dark-sector confinement scale. The coupling of the dark photon to dark-sector quarks controls the isospin violation through the mixing angle θ. We consider $\sin\theta = 0.1$ to ensure that isospin breaking remains relatively small, resulting in the dark pions having nearly degenerate masses. The branching fraction $\mathcal{B}(\widetilde{\pi}_3 \to A'A')$ is set to unity. Samples are generated with different mass hypotheses for the $\widetilde{\pi}_3$ and the A' particles, and with mean proper decay lengths ranging from 0.01 to 100 cm for A' ($\widetilde{\pi}_3$) in Scenario A (B1). These samples are used to set upper limits on the branching fraction $\mathcal{B}(H \to \Psi\overline{\Psi})$.

For models where a long-lived scalar resonance ϕ arises from the decay of a b hadron, the production of b hadrons is initially generated at LO using pythia 8.306, where the ϕ boson decays into a pair of OS muons with 100% probability. Subsequently, a fixed-order calculation at next-to-leading logarithmic (FONLL) precision in the strong coupling constant α_S is used to normalize the signal and to reweight the p_T spectrum of b hadrons. These samples are used to set upper limits on the branching fraction product $\mathcal{B}(h_b \to \phi X)\mathcal{B}(\phi \to \mu\mu)$.

The generators use the CP5 tune [43] and the NNPDF3.1 sets of parton distribution functions (PDFs) [44] at next-to-next-to-LO. The interactions of particles with the CMS detector are simulated using Geant4 [45]. Simulated minimum bias events are superimposed on the hard pp interaction to describe the effect of additional inelastic interactions within the same or neighboring bunch crossings (pileup). The simulation is reweighted to match the

JHEP11(2026)004

distribution of the number of interactions per bunch crossing observed in data. All simulated events are reconstructed with the same algorithms used for data.

5 Event selection and categorization

5.1 Event selection

The events collected using the scouting triggers (section 3) are further selected to contain at least one pair of OS muons associated with an SV that satisfies a number of quality criteria:

- $l_{xy} < 70\,\text{cm}$;
- x coordinate uncertainty $<0.05\,\text{cm}$;
- y coordinate uncertainty $<0.05\,\text{cm}$;
- z coordinate uncertainty $<0.10\,\text{cm}$;
- The SV fit χ^2 normalized to the number of degrees of freedom (dof) $\left(\chi^2/\text{dof}\right)_{\text{SV}} < 3$.

The $\left(\chi^2/\text{dof}\right)_{\text{track}}$ of each muon track is also required to be less than 3. Furthermore, any SV located within a tracker module is not considered in order to suppress the contribution from material interaction vertices, i.e., vertices from particles produced in the interactions with the detector material.

A large fraction of events contain only one OS muon pair and an associated SV. Among the events with more than one pair of OS muons, the pairs are ordered according to increasing $(\chi^2/\text{dof})_{\text{SV}}$ and only the first or the first two pairs are used in this search. If two muon pairs are reconstructed, the positions of the corresponding SVs may be spatially resolved or may overlap within uncertainties, thus appearing as a single four-muon (4μ) vertex. In this case, the average position of the two overlapping SVs is used as the position of the 4μ vertex, and the selections are adapted accordingly, as detailed in the following.

For decays of BSM particles into a single muon pair, we expect the transverse momentum of the dimuon system, $\overrightarrow{p}_{\text{T}}^{\mu\mu}$, to be collinear with the SV vector, which is defined as the vector $\overrightarrow{\text{SV}}$ connecting the PV to the SV. This does not apply to a muon pair where the two muons originate from different vertices and erroneously form a common SV because their trajectories accidentally cross. In order to suppress this background, we require both the azimuthal angle ($|\Delta\phi(\overrightarrow{p}_{\text{T}}^{\mu\mu}, \overrightarrow{\text{SV}})|$) and the three-dimensional angle between the two vectors to be less than $\pi/2$. This requirement is used in events with one or two resolved SVs. In events where four muons are selected from two SVs that overlap in space within uncertainties, hereafter referred to as *overlapping* SVs, we require the four-muon transverse momentum, $\overrightarrow{p}_{\text{T}}^{4\mu}$, to be collinear with the vector connecting the PV with the overlapping SVs. The same requirements on the azimuthal and three-dimensional angles are applied.

Similarly, the opening angle between two muons erroneously forming a common SV tends to be very large, independently of the boost of the dimuon system. Hence, in order to further reduce the background from events with an erroneous muon SV association, we also require both the azimuthal and three-dimensional angles between the muons to be <2.8. The main

JHEP11(2026)004

goal of such selections is to suppress background where SVs are formed by cosmic ray muons, muons from pileup interactions, and muons from back-to-back quantum chromodynamics dijet events or Drell-Yan events.

Muons from pileup vertices can overlap in the r-ϕ plane, despite being separated in r-z at their origin, and, as a consequence, they can be wrongly associated with a common SV. These muon pairs are characterized by a large $\Delta\eta(\mu_1, \mu_2)$ and a small $\Delta\phi(\mu_1, \mu_2)$. We exploit this feature to suppress this background contribution with the requirement $\log_{10}(|\Delta\eta_{\mu\mu}|/|\Delta\phi_{\mu\mu}|) < 1.25$. This requirement is not applied in cases with two selected muon pairs.

Additional background may arise from "prompt" (i.e., nondisplaced) muons. Muons from truly displaced vertices do not leave hits in the tracker layers between the interaction point and the SV. Therefore, this background can be suppressed by applying a selection on the number of hits associated with each muon between the PV and the SV, referred to as $N^{\mu\mu}_{\text{excess}}$:

- $N^{\mu\mu}_{\text{excess}} = 0$ for $l_{\text{xy}} < 11\,\text{cm}$;
- $N^{\mu\mu}_{\text{excess}} \leq 1$ for $l_{\text{xy}} \in [11, 16]\,\text{cm}$;
- $N^{\mu\mu}_{\text{excess}} \leq 2$ for $l_{\text{xy}} \in [16, 70]\,\text{cm}$.

The requirement is loosened for higher displacements, because at large values of l_{xy} it is more likely that random hits are wrongly associated with displaced muon tracks, and is fully relaxed in events where four muons from two overlapping SVs are selected.

In order to identify SVs of interest, the muon track transverse impact parameter, d_{xy}, is also used. Specifically, we select events based on the d_{xy} significance ($|d_{\text{xy}}|/\sigma_{d_{\text{xy}}}$) and the lifetime-scaled d_{xy} ($|d_{\text{xy}}|/(l_{\text{xy}} m_{\mu\mu}/p_{\text{T}}^{\mu\mu})$). The first expression normalizes d_{xy} to its measurement uncertainty ($\sigma_{d_{\text{xy}}}$), while the second normalizes d_{xy} to the lifetime corresponding to the observed SV transverse displacement. This allows the same selection requirements to be used for all lifetime hypotheses. We require each muon in dimuon events to satisfy:

- $|d_{\text{xy}}|/\sigma_{d_{\text{xy}}} > 2$;
- $|d_{\text{xy}}|/(l_{\text{xy}} m_{\mu\mu}/p_{\text{T}}^{\mu\mu}) > 0.1$.

In events with two muon pairs, where there are few background events, the selected muons are only required to have $|d_{\text{xy}}|/\sigma_{d_{\text{xy}}} > 2$.

Finally, in events with two muon pairs from spatially resolved SVs, the two dimuon invariant masses are further required to differ by less than 5% of their average.

The muon isolation is measured as the scalar p_{T} sum of the additional PF candidates within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around its direction, including corrections for the contributions from pileup. A muon is considered isolated if its isolation is less than 8 GeV and less than 20% of its p_{T}. These isolation criteria are only used to categorize events with only one selected muon pair, as described in section 5.2.

5.2 Event categorization

Once the objects have been selected, three types of events are considered in the search:

- events with one muon pair;

JHEP11(2026)004

- events with two muon pairs from two SVs whose positions are spatially resolved; and
- events with two muon pairs from two SVs whose positions overlap within uncertainties, consistent with a single 4μ vertex.

Because 4μ events are expected to provide sensitivity to a range of BSM scenarios and are depleted in background, we first select events with two muon pairs. If an event contains four muons from two resolved SVs, we then assign the event to the so-called *multivertex* category. If instead we identify four muons from two overlapping SVs, we assign the event to the *overlapping vertex* category. In both cases, the signal would appear as a narrow peak in the $m_{4\mu}$ spectrum.

If only one muon pair is found, the event is categorized as a dimuon event. For dimuon events, we first define two orthogonal regions in $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mu\mu}, \overrightarrow{\mathrm{SV}})|$, distinguishing *pointing* and *nonpointing* topologies, with $|\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mu\mu}, \overrightarrow{\mathrm{SV}})| < 0.02$ and $0.02 < |\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\mu\mu}, \overrightarrow{\mathrm{SV}})| < \pi/2$, respectively.

Dimuon events in both the pointing and nonpointing categories are then further split according to l_{xy}, to maximize the sensitivity to different lifetime hypotheses. We define eight bins in l_{xy}, following the detector geometry:

- within the beam pipe: [0, 0.2] cm; [0.2, 1] cm; [1, 2.4] cm;
- between the beam pipe and the first pixel tracker layer: [2.4, 3.1] cm;
- between the first and second pixel tracker layers: [3.1, 7] cm;
- between the second and third pixel tracker layers: [7, 11] cm;
- between the third and fourth pixel tracker layers: [11, 16] cm; and
- outside the pixel tracker: [16, 70] cm.

The last two l_{xy} intervals probe phase space that was inaccessible to previous results using scouting data [20].

The overall signal acceptance times efficiency ($\mathcal{A}\varepsilon$) in the different l_{xy} categories is shown in figure 4 for representative HAHM dark photon mass hypotheses, $m_{\mathrm{Z_D}} = 2, 5, 12$ and 20 GeV, as a function of the dark photon mean proper decay length, $c\tau_0^{\mathrm{Z_D}}$. The signal $\mathcal{A}\varepsilon$ is defined as the fraction of events with at least one dark photon decaying into a muon pair, reconstructed as a single dimuon candidate within the specified displacement range. It is a luminosity-weighted average over the 2022 and 2023 data-taking periods. The increase in acceptance resulting from the newly accessible $11 < l_{\mathrm{xy}} < 70$ cm interval is apparent for all $m_{\mathrm{Z_D}}$ hypotheses, extending the analysis sensitivity up to $c\tau_0^{\mathrm{Z_D}} \gtrsim 1$ m, and enhancing it for $c\tau_0^{\mathrm{Z_D}} \gtrsim 10$ mm at small $m_{\mathrm{Z_D}}$.

Within each displacement interval, the events belonging to the pointing category are also categorized according to muon isolation, distinguishing between isolated and nonisolated topologies, and $p_{\mathrm{T}}^{\mu\mu}$. Isolated topologies consist of events where both muons are isolated; nonisolated topologies consist of events where at least one of the two muons fails the isolation criteria defined in section 5.1. The splitting in isolation aims at covering scenarios where the

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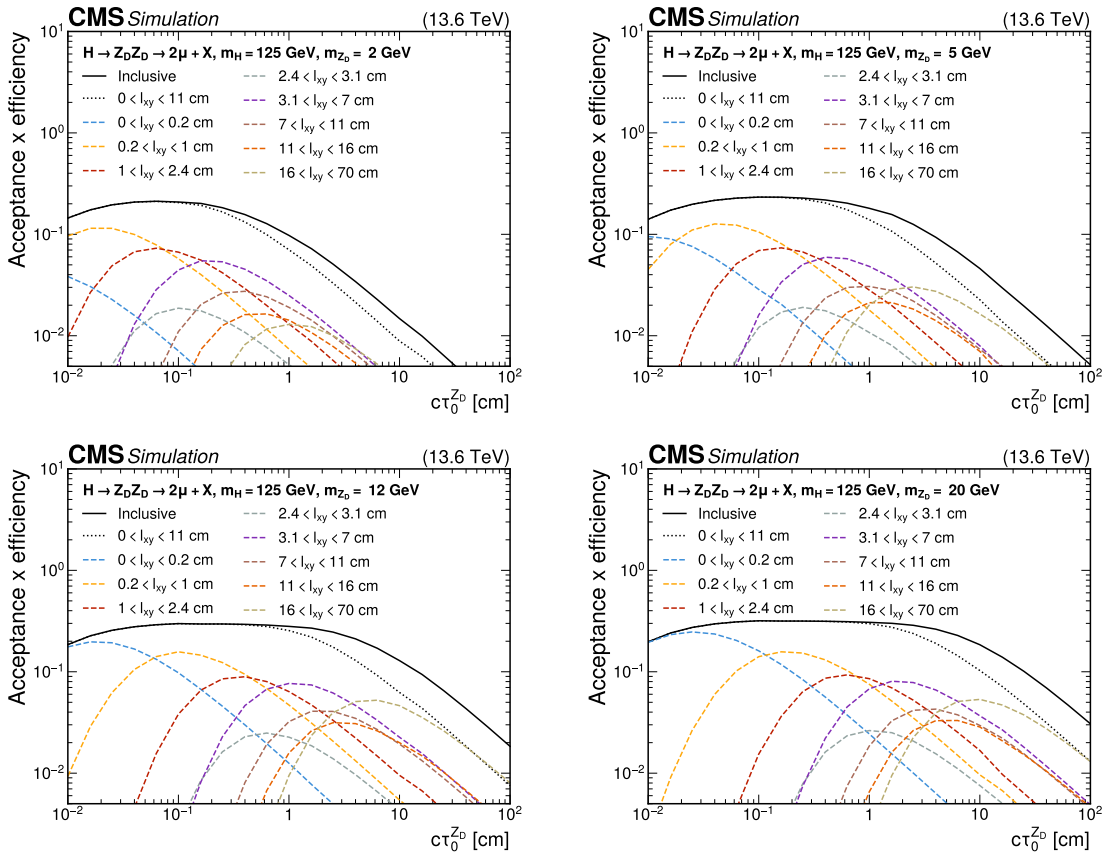

Figure 4. Overall signal acceptance times efficiency ($\mathcal{A}\varepsilon$) as measured for the HAHM signal model with $m_{Z_D} = 2, 5, 12$, and 20 GeV, as a function of the mean proper decay length of the dark photon, $c\tau_0^{Z_D}$. The signal $\mathcal{A}\varepsilon$ is defined as the fraction of events with at least one dark photon decaying into a muon pair, reconstructed as a dimuon candidate within the l_{xy} bins of $[0, 0.2, 1, 2.4, 3.1, 7, 11, 16, 70]$ cm. The average $\mathcal{A}\varepsilon$ over the simulated samples corresponding to the 2022 and 2023 data-taking periods is shown.

long-lived particle is created with hadronic activity in its vicinity, such as scalars produced in b hadron decays, and those where the displaced muons are produced alone, such as in $Z_D \to \mu\mu$ decays. Two categories are defined in $p_T^{\mu\mu}$:

- $p_T^{\mu\mu} < 25$ GeV;
- $p_T^{\mu\mu} > 25$ GeV.

The categorization in $p_T^{\mu\mu}$ aims at covering a wide spectrum of possible production scenarios, depending on the particles involved in the process and on their multiplicity. For example, dimuon pairs produced from a decay of a light particle, e.g., a b hadron, have lower $p_T^{\mu\mu}$ than others originating from a much heavier particle, such as a Higgs boson.

A total of 40 dimuon categories are defined, which are considered together with two four-muon categories. In each event category, we define mass windows that slide along the multimuon invariant mass spectrum (as described in section 6) and perform a search for a resonant peak within each mass window. Mass regions corresponding to known SM resonances

JHEP11(2026)004

Resonance	Mean mass [GeV]	σ_{mass} [MeV]	Window [GeV] (mean $\pm$ 5σ_{mass})
K^0_S	0.46	9	[0.41, 0.50]
η	0.55	8	[0.51, 0.59]
$\rho^0(770)/\omega(782)$	0.78	11	[0.73, 0.83]
$\phi(1020)$	1.02	12	[0.96, 1.08]
J/ψ	3.09	35	[2.91, 3.27]
$\psi(2S)$	3.68	42	[3.47, 3.89]
$\Upsilon(1S)$	9.45	93	[8.99, 9.91]
$\Upsilon(2S)$	10.10	91	[9.64, 10.56]
$\Upsilon(3S)$	10.34	87	[9.90, 10.78]

Table 1. List of known SM resonances and corresponding masked mass windows, equal to $\pm 5\sigma_{\text{mass}}$ around the mean mass, where mean and resolution (σ_{mass}) are determined from a fit to data.

decaying either into muon pairs or in a pair of charged hadrons are not considered, i.e., they are "masked". The masked resonances are listed in table 1. For events with four selected muons, if any of the muon pairs is found within a masked region, this pair is rejected and the event is treated as a dimuon event.

As an example, in figure 5 we show the $m_{4\mu}$ spectrum in the multivertex and overlapping vertex categories. In figures 6 and 7 (8 and 9), we show the $m_{\mu\mu}$ distribution in bins of l_{xy}, as obtained from selected dimuon events where both muons are isolated and have $p_T^{\mu\mu}$ above (below) 25 GeV.

In each mass window, the SM background is modeled by fitting the multimuon invariant mass distribution in data, as further described in section 6. Finally, the mass windows in all search bins are used in combination as input to a final likelihood fit for the interpretation of the results, as described in section 7.

6 Parameterization of the invariant mass distribution

The search is performed by fitting the sum of signal and the SM background models to mass distributions in the various categories, which are separate for the 2022 and 2023 data-taking periods. We target low-mass multimuon resonances whose intrinsic width is assumed to be much narrower than the detector resolution. The signal multimuon invariant mass resolution ($\sigma^{\mu\mu}_{\text{mass}}/m_{\mu\mu} \sim \sigma^{4\mu}_{\text{mass}}/m_{4\mu}$) is estimated from simulated events to be about 1.8% of the mass, with an uncertainty of about 50%, and both are independent of the signal mass and lifetime hypotheses. We use the sum of a Gaussian function and a double-sided Crystal Ball function [46, 47], with common mean and width (σ_{mass}) parameters, to model signal invariant mass distributions in dimuon and 4μ events. The parameters are determined by fitting the corresponding signal MC simulation. Additionally, an interpolation of the signal model parameters is performed between different mass hypotheses to provide a continuous description of the signal shape across the probed mass range.

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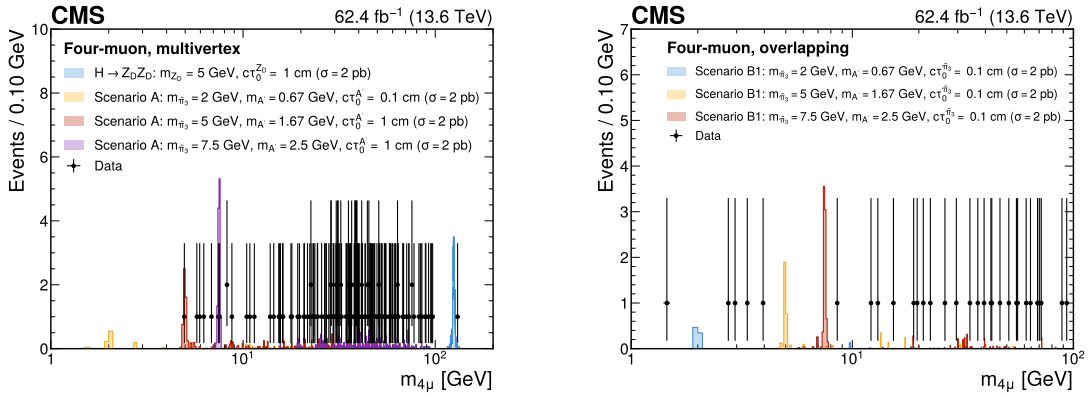

Figure 5. Four-muon invariant mass distributions of selected events in the multivertex (left) and overlapping vertex (right) categories, for data (black points with uncertainties) and representative signal models (colored histograms), assuming a cross section $\sigma = 2$ pb for all models, for visualization purposes.

In each event category, the SM background is modeled in sliding windows of $\pm 5\sigma_{\text{mass}}$ around the considered signal mass hypothesis. These windows are required not to overlap with the masked mass regions corresponding to known SM resonances (as discussed in section 5.2). A number of functional forms are considered in order to model the background mass distribution. These include Bernstein polynomials, power law, and exponential functions. For each family of functional forms, the best order in each mass window and event category is selected by means of a Fisher test [48]. First, the lowest order (N) function is used to fit the data. Then, the next-order ($N+1$) is used, and the difference $2\Delta\text{NLL}_{N+1} = 2(\text{NLL}_N - \text{NLL}_{N+1})$ (with NLL denoting the negative logarithm of the likelihood of the fit) is evaluated to determine whether the data support the need for a higher-order function. This decision is based on the fact that $2\Delta\text{NLL}_{N+1}$ is asymptotically described by a χ^2 distribution with M degrees of freedom, where M is the difference in the number of free parameters in the $(N+1)$th and Nth order functions (in this case $M = 1$). A p-value [49] is calculated as $P_M(\chi^2 > 2\Delta\text{NLL}_{N+1})$ where $P_M(\chi^2_{\text{min}})$ is the χ^2 tail probability for M degrees of freedom. If the p-value is less than 0.05, the higher-order function is retained, since it is determined to significantly improve the description of the data. Once the best order N for each family of functions has been determined, the corresponding functional forms are included in an envelope, which is then used in the discrete profiling method [50], where the choice of the background function is treated as a discrete nuisance parameter in the fit to account for the uncertainty associated with the arbitrary choice of the function. In addition, we use a goodness-of-fit test to remove background models that do not describe the data appropriately. The test is based on a χ^2 test statistic, which is converted into a p-value through a set of pseudo-experiments. Models with $p < 0.01$ are not considered.

The potential presence of a bias in the measurement of a signal due to the choice of the functional forms used to model the SM background is also assessed by means of pseudo-experiments. First, a varying amount of signal is injected on top of the background generated according to the selected functional form. Then, a background + signal fit is performed, allowing the signal yield to float freely. The case of a zero injected signal is also considered.

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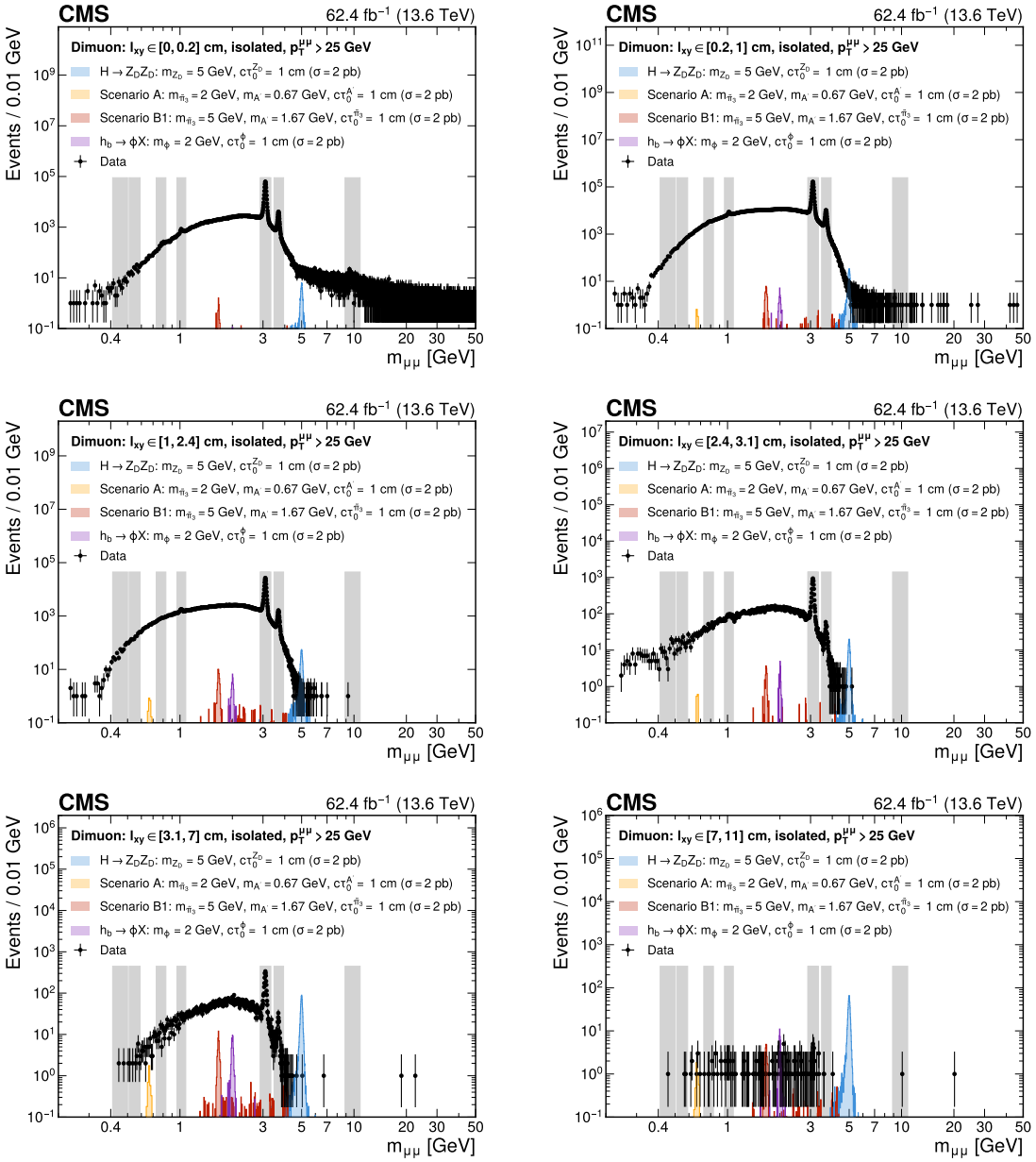

Figure 6. Dimuon invariant mass distributions of selected events with a single, isolated muon pair with $p_{\mathrm{T}}^{\mu\mu} > 25\,\mathrm{GeV}$. Distributions are shown separately for each of the six $l_{\mathrm{xy}} < 11\,\mathrm{cm}$ bins. The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. Distributions are shown as obtained in data (black points with uncertainties) and for representative signal models (colored histograms), assuming a cross section $\sigma = 2\,\mathrm{pb}$ for all models, for visualization purposes.

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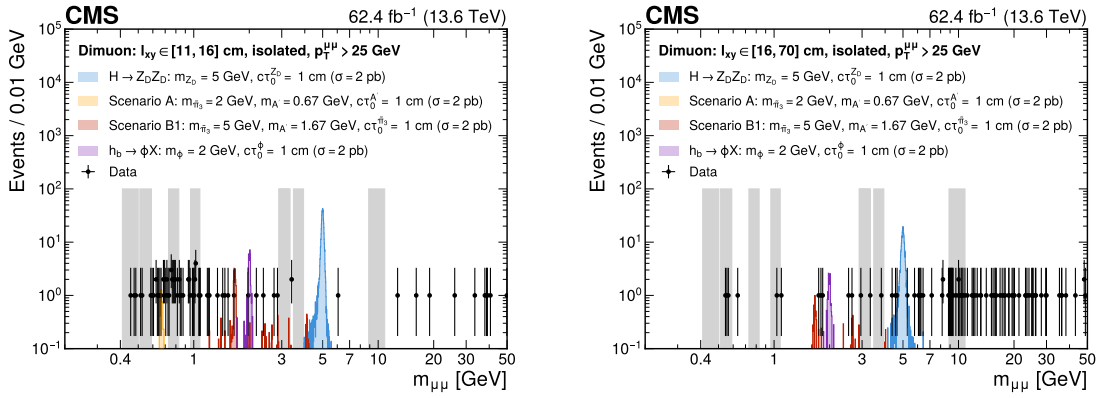

Figure 7. Dimuon invariant mass distributions of selected events with a single, isolated muon pair with $p_T^{\mu\mu} > 25$ GeV. Distributions are shown separately for each of the two $l_{xy} > 11$ cm bins (i.e., for the displacement range inaccessible to the previous results presented in ref. [20]). The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. Distributions are shown as obtained in data (black points with uncertainties) and for representative signal models (colored histograms), assuming a cross section $\sigma = 2$ pb for all models, for visualization purposes.

The bias, quantified as the difference between the measured and injected signal yields relative to the statistical uncertainty in the measured signal yield, is found to be negligible.

The background-only fit results for the selected functional forms in one of the dimuon search bins using 2022 data are shown in figure 10, as an example, together with the dimuon invariant mass distribution expected for a representative signal hypothesis.

7 Results and interpretation

Unbinned maximum likelihood fits to the data are performed simultaneously in all search bins, under either background-only or background + signal hypotheses, using background and signal models and uncertainties described in section 6. Additional log-normal constraint terms are used to account for the uncertainties in the signal yields, when considered (section 7.1).

No significant peak-like structures are observed in data. The background+signal fits are used to set 95% confidence level (CL) upper limits on the branching fractions for the signal models under consideration. Limits are set using a modified frequentist approach, employing the CL_s criterion [51–53] within the CMS statistical analysis tool COMBINE [54], which is based on the ROOFIT [55] and ROOSTATS [56] frameworks. These limits are then used, in conjunction with the theoretical cross section calculations, to exclude ranges of masses and/or lifetimes for the BSM particles of the signal models.

7.1 Systematic uncertainties in the signal yields

A systematic uncertainty in the trigger efficiency (discussed in section 3) is assessed to be in the range between 1 and 15%, depending on the p_T and displacement of the muons. A separate systematic uncertainty is considered, ranging from 1 to 30% (largest for high-l_{xy} bins), to account for the potential mismodeling of the signal simulation that may introduce a

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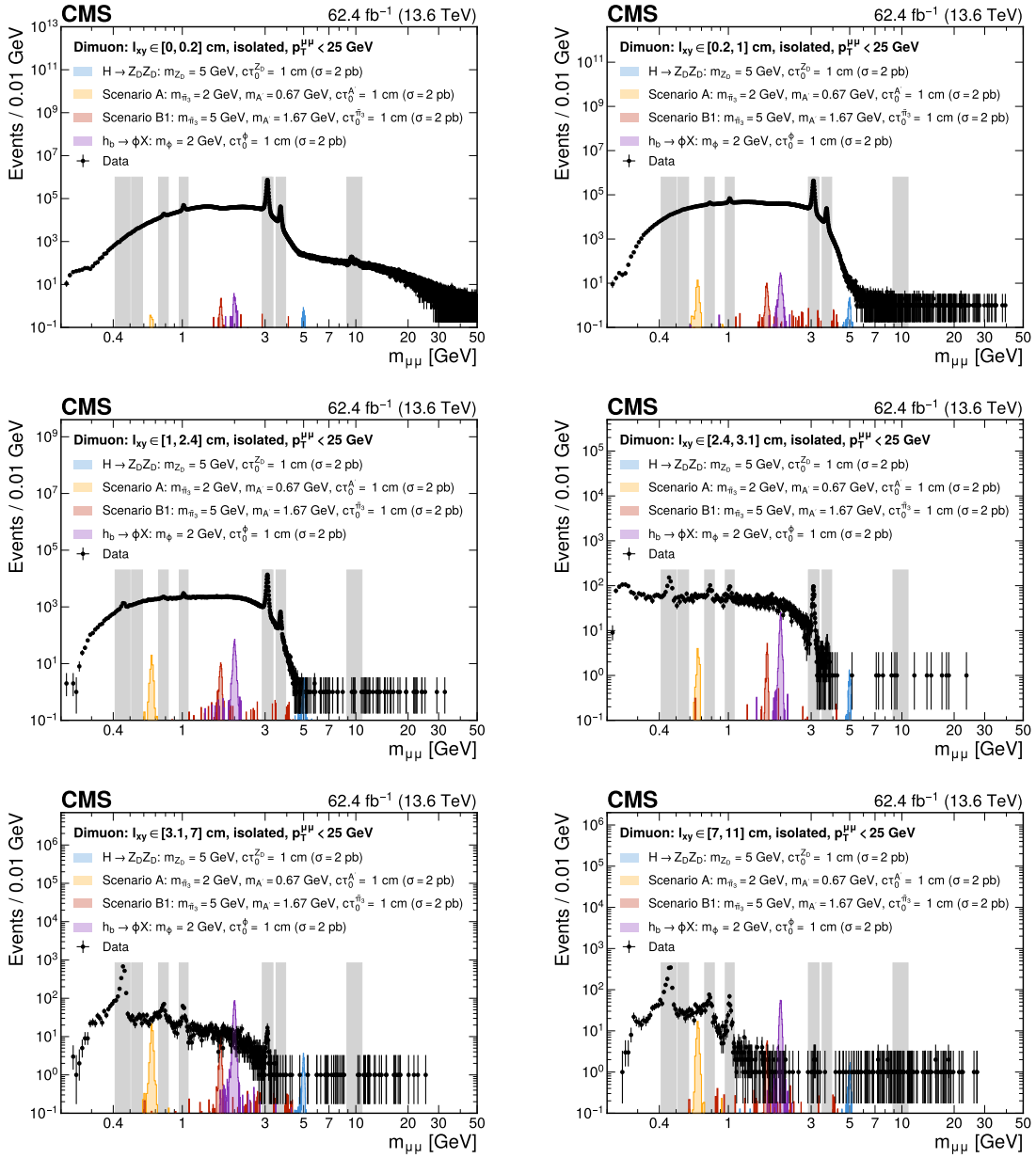

Figure 8. Dimuon invariant mass distributions of selected events with a single, isolated muon pair with $p_{\mathrm{T}}^{\mu\mu} < 25\,\mathrm{GeV}$. Distributions are shown separately for each of the six $l_{\mathrm{xy}} < 11\,\mathrm{cm}$ bins. The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. Distributions are shown as obtained in data (black points with uncertainties) and for representative signal models (colored histograms), assuming a cross section $\sigma = 2\,\mathrm{pb}$ for all models, for visualization purposes.

JHEP11(2026)004

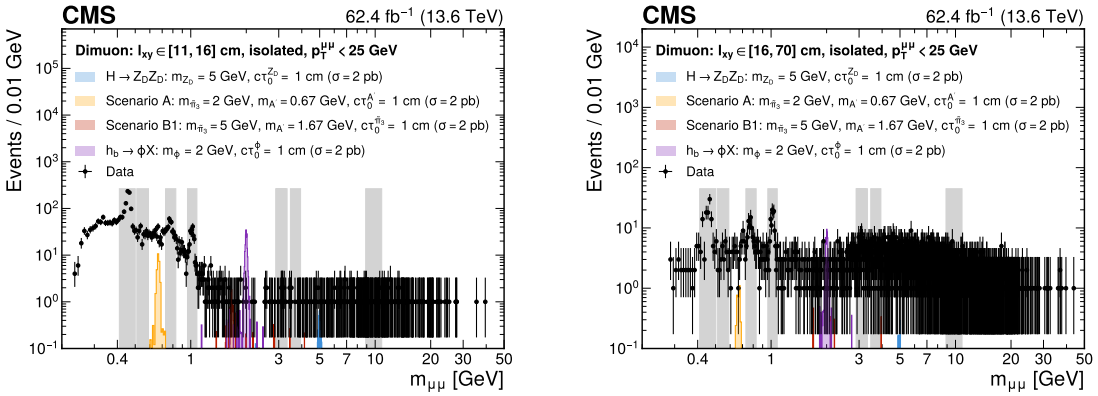

Figure 9. Dimuon invariant mass distributions of selected events with a single, isolated muon pair with $p_{\mathrm{T}}^{\mu\mu} < 25\,\mathrm{GeV}$. Distributions are shown separately for each of the two $l_{\mathrm{xy}} > 11\,\mathrm{cm}$ bins (i.e., for the displacement range inaccessible to the previous results presented in ref. [20]). The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. Distributions are shown as obtained in data (black points with uncertainties) and for representative signal models (colored histograms), assuming a cross section $\sigma = 2\,\mathrm{pb}$ for all models, for visualization purposes.

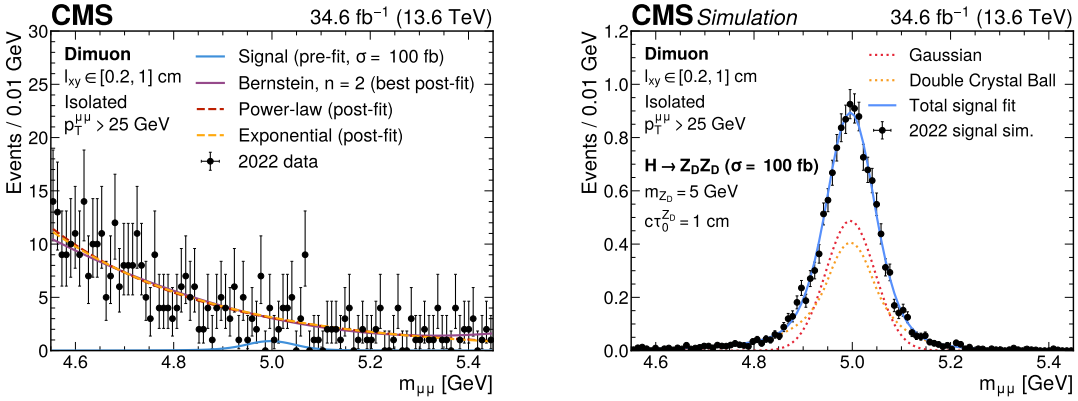

Figure 10. The dimuon invariant mass distribution (left) is shown for data collected in 2022 (black markers) in a mass window centered around 5 GeV, in one of the dimuon search bins ($0.2 < l_{\mathrm{xy}} < 1\,\mathrm{cm}$, $p_{\mathrm{T}}^{\mu\mu} > 25\,\mathrm{GeV}$, with two isolated muons). The results of background+signal fits to the data of three selected functional forms are also shown (different colors, partially overlapping lines), highlighting the Bernstein polynomial as the best fit (solid, purple line) for this mass window. The corresponding pre-fit function (solid blue line) for a representative $\mathrm{H} \to \mathrm{Z_D Z_D}$ signal, with $m_{\mathrm{Z_D}} = 5\,\mathrm{GeV}$ and $c\tau_0^{\mathrm{Z_D}} = 1\,\mathrm{cm}$, assuming a cross section $\sigma(\mathrm{H} \to \mathrm{Z_D Z_D}) = 100\,\mathrm{fb}$, is shown for visualization purposes. The fit (solid blue line for the total fit function, and dashed red and orange lines for its individual components) to the dimuon invariant mass distribution (right) expected in the same dimuon search bin is shown for the same signal (black markers).

JHEP11(2026)004

difference in the event selection acceptance for the selection described in section 5.1. Both uncertainties are derived from studies of $J/\psi \to \mu^+\mu^-$ data and account for the differences between the measurements in data and simulation. Additionally, we assess a systematic uncertainty in the expected signal yields arising from the uncertainty in the integrated luminosity measurement, of 1.4 (1.3)% for 2022 (2023) data [57–59]. The overall uncertainty in the luminosity measurement for the 2022–2023 period is 1.01%. Finally, we account for uncertainties resulting from the limited size of the simulated signal samples. Uncertainties arising from the choice of the PDFs, and of the renormalization and factorization scales used in the event generators are negligible compared to others. Uncertainties in the trigger efficiency and integrated luminosity are treated as correlated across the search bins. Other uncertainties are taken as uncorrelated. Since we find no significant difference between 2022 and 2023 data and simulations, all uncertainties are treated as correlated across the two data-taking periods.

7.2 Constraints on models of BSM physics

We set upper limits at 95% CL on the branching fraction $\mathcal{B}(H \to Z_D Z_D)$, using values of $\mathcal{B}(Z_D \to \mu\mu)$ from the model of ref. [6]. The constraints we obtain are the most stringent to date for a wide range of signal hypotheses. Upper limits are shown in figure 11 as functions of the mass of the dark photon, m_{Z_D}, for dark photon lifetimes $c\tau_0^{Z_D} = 0.1$, 1, 10, and 100 cm, and in figure 12 as functions of the dark photon lifetime for a representative set of m_{Z_D} hypotheses. We improve and extend the constraints from previous results [20, 22] at small m_{Z_D} and large $c\tau_0^{Z_D}$. Compared to ref. [20], this is achieved despite the smaller amount of available data, thanks to the improved muon scouting triggers, which allow for the reconstruction of displaced muons with $l_{xy} > 11$ cm, and to the refined event selection and categorization. Compared to ref. [22], we are able to probe masses $m_{Z_D} < 10$ GeV, thanks to the lower muon p_T thresholds required in the scouting triggers used in this search.

We also set upper limits at 95% CL on the branching fraction $\mathcal{B}(H \to \Psi\overline{\Psi})$ considering two different dark shower scenarios. Mean proper decay lengths of A' and $\widetilde{\pi}_3$ ranging from 0.01 to 100 cm are constrained for Scenarios A and B1, respectively. Results are presented in figures 13 and 14 for representative mass hypotheses of the dark pion $\widetilde{\pi}_3$ and of the dark photon A' in Scenarios A and B1, respectively. The results are compared with those previously obtained in ref. [23], rescaled to the same Higgs boson production cross section of 59.8 pb [40, 41], showing the complementarity of the two analysis strategies. The constraints set in this paper extend the previous limits on the mean proper decay length of the A' ($\widetilde{\pi}_3$) in Scenario A (B1) in the range from 10 to 100 cm, thanks to the removal of the pixel hit multiplicity requirement in the scouting trigger streams used in this search, extending the sensitivity to larger lifetime hypotheses.

Finally, we set 95% CL upper limits on the branching fraction product $\mathcal{B}(h_b \to \phi X)\mathcal{B}(\phi \to \mu\mu)$ in a model where a long-lived scalar resonance ϕ arises from the decay of a b hadron. Figure 15 shows the limits obtained as functions of m_ϕ, for $c\tau_0^\phi = 0.1$, 1, and 10 cm. They are found to be mostly consistent with the ones set in ref. [20], because for such signatures the smaller amount of available data is compensated by the improvements in the scouting triggers and analysis strategy.

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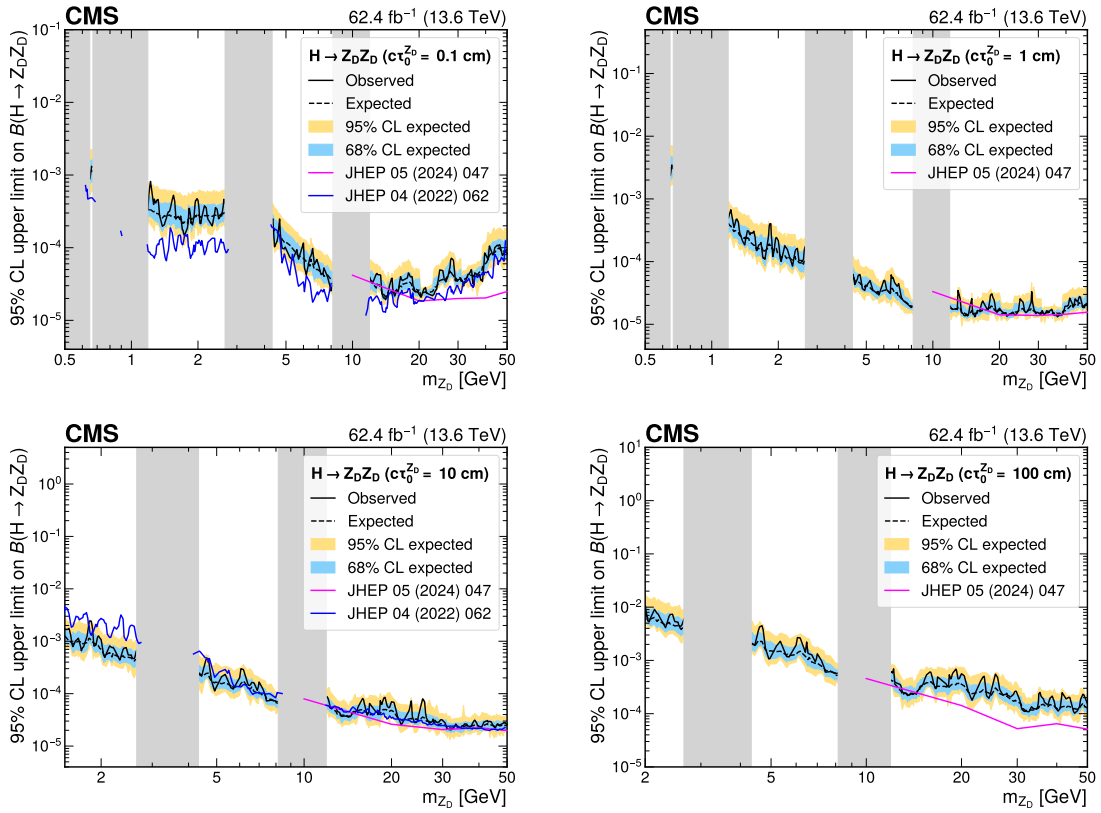

Figure 11. Upper limits at 95% CL on the branching fraction $\mathcal{B}(\mathrm{H} \to \mathrm{Z_D Z_D})$ as functions of the dark-photon mass, $m_{\mathrm{Z_D}}$, for $c\tau_0^{\mathrm{Z_D}} = 0.1$ (upper left), 1 (upper right), 10 (lower left), and 100 cm (lower right). The solid black (dashed black) line represents the observed (median expected) exclusion. The inner blue (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis. The limits are obtained using the combination of all event categories. The dark blue (magenta) solid line represents the observed upper limits previously set in ref. [20] ([22]). The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. The blue (magenta) line can overlap with the gray bands, owing to the different mass ranges covered by the results from ref. [20] ([22]).

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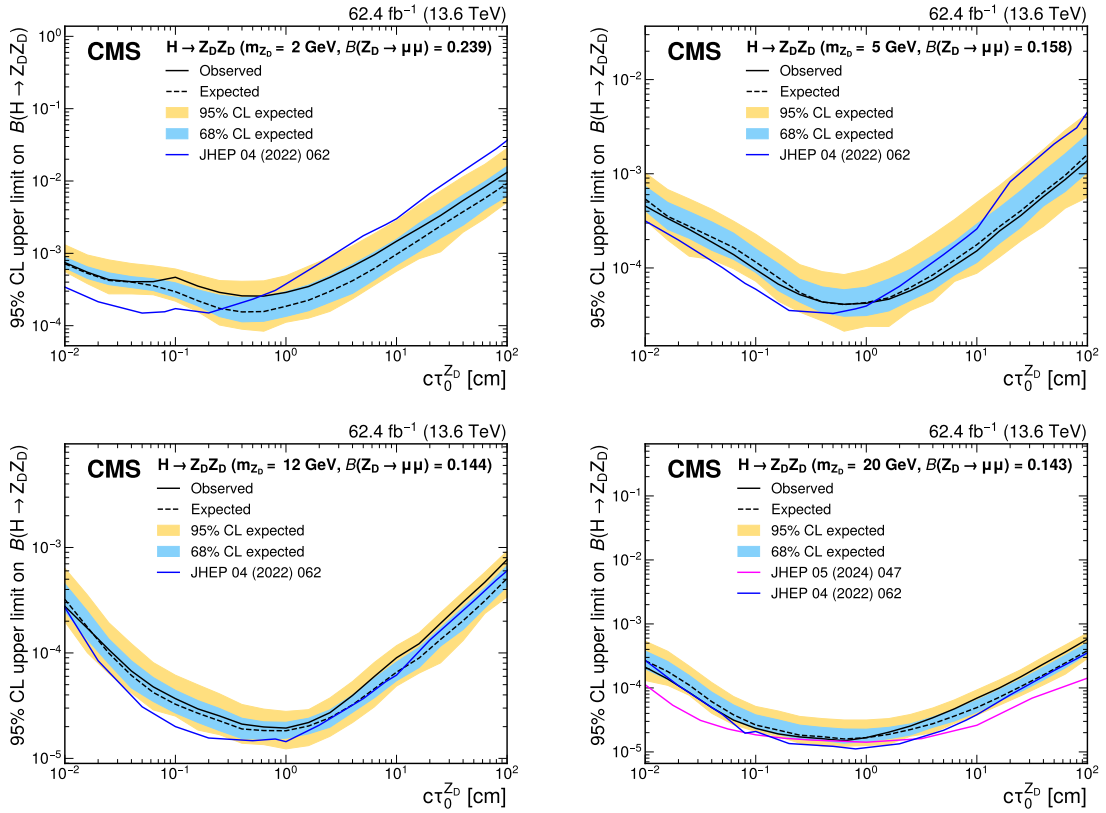

Figure 12. Upper limits at 95% CL on the branching fraction $\mathcal{B}(\mathrm{H} \to \mathrm{Z_D Z_D})$ as functions of $c\tau_0^{\mathrm{Z_D}}$, for representative mass hypotheses, $m_{\mathrm{Z_D}} = 2$ (upper left), 5 (upper right), 12 (lower left), and 20 (lower right) GeV. The solid black (dashed black) line represents the observed (median expected) exclusion. The inner blue (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis. The limits are obtained using the combination of all event categories. The dark blue (magenta) solid line represents the observed upper limits previously set in ref. [20] ([22]).

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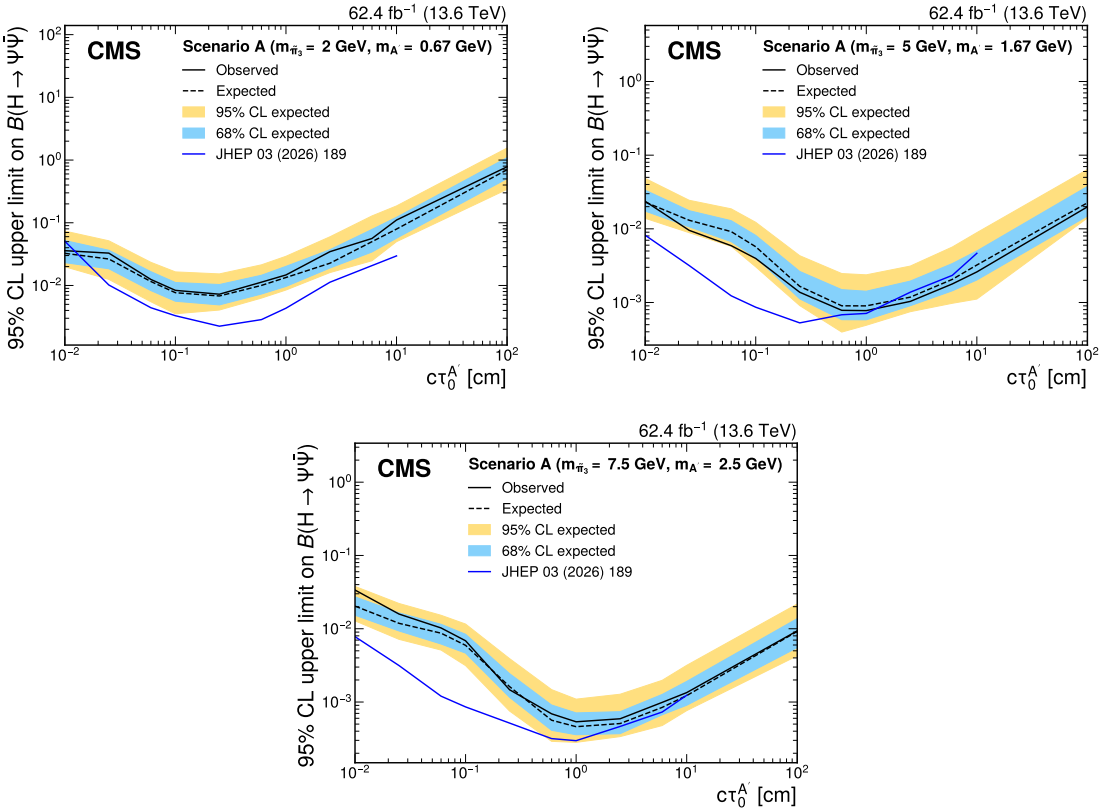

Figure 13. Upper limits at 95% CL on the branching fraction $\mathcal{B}(\mathrm{H} \to \Psi\overline{\Psi})$, for representative mass hypotheses of the Scenario A dark-shower model. Limits are shown as functions of $c\tau_0^{\mathrm{A}'}$, for $m_{\widetilde{\pi}} = 2\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 0.67\,\mathrm{GeV}$ (upper left), $m_{\widetilde{\pi}} = 5\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 1.67\,\mathrm{GeV}$ (upper right), and $m_{\widetilde{\pi}} = 7.5\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 2.5\,\mathrm{GeV}$ (lower). For this model, it is assumed $\tilde{\Lambda} = m_{\widetilde{\eta}} = 4m_{\widetilde{\pi}}$, $\sin\theta = 0.1$ and $\mathcal{B}(\widetilde{\pi}_3 \to \mathrm{A}'\mathrm{A}') = 1$. The solid black (dashed black) line represents the observed (median expected) exclusion. The inner blue (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis. The limits are obtained using the combination of all event categories. The dark blue solid line represents the observed upper limits previously set in ref. [23], rescaled to the same Higgs boson production cross section of 59.8 pb [40, 41].

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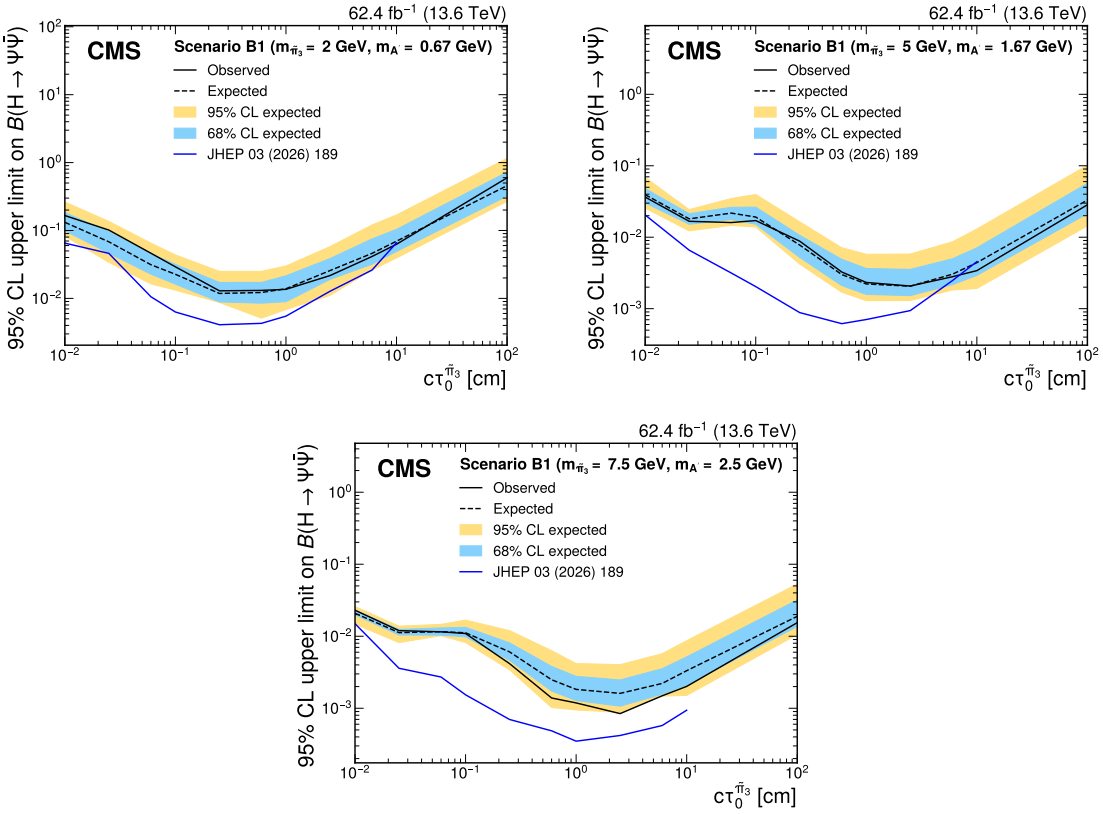

Figure 14. Upper limits at 95% CL on the branching fraction $\mathcal{B}(\mathrm{H} \to \Psi\overline{\Psi})$, for representative mass hypotheses of the Scenario B1 dark-shower model. Limits are shown as functions of $c\tau_0^{\widetilde{\pi}_3}$, for $m_{\widetilde{\pi}} = 2\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 0.67\,\mathrm{GeV}$ (upper left), $m_{\widetilde{\pi}} = 5\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 1.67\,\mathrm{GeV}$ (upper right), and $m_{\widetilde{\pi}} = 7.5\,\mathrm{GeV}$ and $m_{\mathrm{A}'} = 2.5\,\mathrm{GeV}$ (lower). For this model, it is assumed $\tilde{\Lambda} = m_{\widetilde{\eta}} = 4m_{\widetilde{\pi}}$, $\sin\theta = 0.1$ and $\mathcal{B}(\widetilde{\pi}_3 \to \mathrm{A}'\mathrm{A}') = 1$. The solid black (dashed black) line represents the observed (median expected) exclusion. The inner blue (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis. The limits are obtained using the combination of all event categories. The dark blue solid line represents the observed upper limits previously set in ref. [23], rescaled to the same Higgs boson production cross section of 59.8 pb [40, 41].

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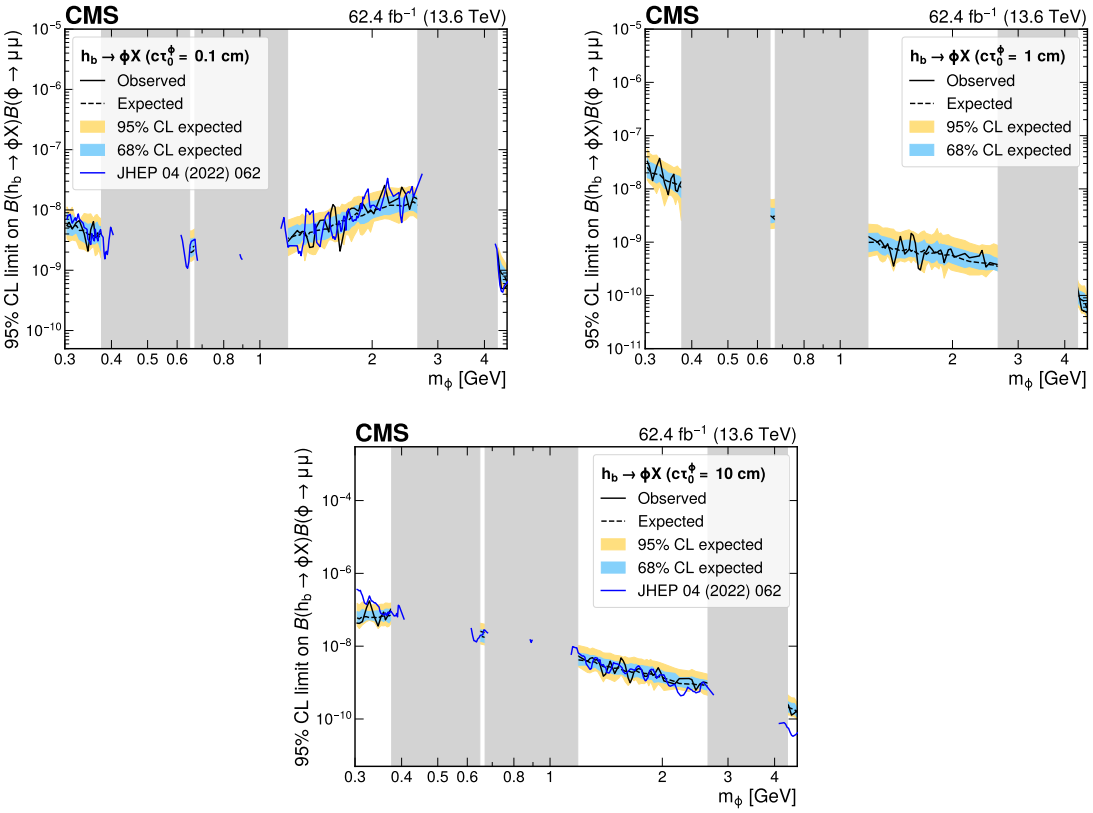

Figure 15. Upper limits at 95% CL on the branching fraction product $\mathcal{B}(\mathrm{h_b} \to \phi X)\mathcal{B}(\phi \to \mu\mu)$ as functions of the long-lived scalar resonance mass, m_ϕ, for $c\tau_0^\phi = 0.1$ (upper left), 1 (upper right), and 10 cm (lower). The solid black (dashed black) line represents the observed (median expected) exclusion. The inner blue (outer yellow) band indicates the region containing 68 (95)% of the distribution of limits expected under the background-only hypothesis. The limits are obtained using the combination of all dimuon event categories. The dark blue solid line represents the exclusion limits previously set in ref. [20]. The vertical gray bands indicate mass ranges containing known SM resonances, which are masked for the purpose of this search. The blue line can overlap with the gray bands, owing to the different mass ranges covered by the results from ref. [20].

8 Summary

A search for displaced multimuon resonances has been performed using proton-proton collisions at a center-of-mass energy of 13.6 TeV, collected by the CMS experiment at the LHC in 2022 and 2023, corresponding to an integrated luminosity of 62.4 fb^{-1}. The data were collected using a dedicated dimuon trigger stream with low transverse momentum thresholds, recorded at high rate by retaining a reduced amount of information at the high-level trigger, to explore otherwise inaccessible phase space at low multimuon invariant mass and nonzero displacement from the primary interaction vertex. No significant excess above the standard model prediction is found. The data are used to set constraints on a wide range of mass and lifetime hypotheses for various scenarios of physics beyond the standard model. Three sets of models are considered: the hidden Abelian Higgs model, where the Higgs boson decays into a pair of long-lived dark photons; dark-shower models, where dark showers originate from

JHEP11(2026)004

the Higgs boson decays into dark quarks; and models where a long-lived scalar resonance is produced from the decay of a b hadron. In the hidden Abelian Higgs model, the most stringent limits to date are obtained for dark-photon proper decay lengths greater than 1 cm and dark-photon masses less than 5 GeV. In the dark-shower models, the most stringent limits to date are set for proper decay lengths larger than 10 cm. In models with a b hadron, the improved trigger and analysis strategy compensate for the smaller data set, leading to constraints comparable to the previous results.

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JHEP11(2026)004

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Code Availability Statement. The CMS core software is publicly available on GitHub.

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JHEP11(2026)004

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JHEP11(2026)004

M. Mulders[13], M. Musich[13], I. Neutelings[13], S. Orfanelli[13], F. Pantaleo[13], M. Pari[13], F. Pereira Carneiro[13], G. Petrucciani[13], A. Pfeiffer[13], M. Pierini[13], M. Pitt[13], H. Qu[13], A. Reimers[13], B. Ribeiro Lopes[13], F. Riti[13], P. Rosado[13], M. Rovere[13], H. Sakulin[13], R. Salvatico[13], S. Scarfi[13], S.F. Schaefer[13], M. Selvaggi[13], P. Silva[13], P. Sphicas[13,i], A.G. Stahl Leiton[13], A. Steen[13], S. Summers[13], G. Terragni[13], D. Treille[13], P. Tropea[13], E. Vernazza[13], M. Vojinovic[13], J. Wanczyk[13,j], S. Wuchterl[13], M. Zarucki[13], P. Zehetner[13], P. Zejdl[13], G. Zevi Della Porta[13], S. Keshri[14], D.N. Laroze Navarrete[14], M. Meena[14], S. Thakur[14], W. Brooks[15], T. Cheng[16], L. Wang[16], L. Yuan[16], J. Gu[17], Z. Hu[17], Z. Liang[17], J. Liu[17], X. Wang[17], Y. Wang[17], H. Yang[17], S. Zhang[17], Y. Zhao[17], N. Bi[18,k], G.M. Chen[18,k], H.S. Chen[18,k], M. Chen[18,k], Y. Chen[18], B. Hou[18,k], Q. Hou[18], F. Iemmi[18], C.H. Jiang[18], P.z. Lai[18], H. Liao[18], G. Liu[18], Z. Liu[18,k], S. Song[18,k], J. Tao[18], C. Wang[18,k], J. Wang[18], A. Zada[18,k], H. Zhang[18], J. Zhao[18], Y. Ban[19], A. Carvalho Antunes De Oliveira[19], S. Deng[19], X. Geng[19], B. Guo[19], Q. Guo[19], Z. He[19], C. Jiang[19], A. Levin[19], C. Li[19], L. Li[19], Q. Li[19], Y. Mao[19], S. Qian[19], S.J. Qian[19], X. Qin[19], C. Quaranta[19], X. Sun[19], D. Wang[19], J. Wang[19], T. Yang[19], M. Zhang[19], M. Zhang[19], Y. Zhao[19], C. Zhou[19], X. Hua[20], S. Yang[20], Z. You[21], N. Lu[22], G. Bauer[23,l,m], L. Chen[23], Z. Cui[23,m], B. Li[23,n], H. Wang[23], K. Yi[23,o], J. Zhang[23], F. Zhu[23], C. Li[24], Y. Li[25], Z. Wang[25], Y. Zhou[25,p], Z. Lin[26], C. Lu[26], M. Xiao[26,q], C. Avila[27], A. Cabrera[27], C. Florez[27], J.A. Reyes Vega[27], C. Rendón[28], M. Rodriguez[28], A.A. Ruales Barbosa[28], J.D. Ruiz Alvarez[28], N. Godinovic[29], D. Lelas[29], I. Puljak[29], A. Sculac[29], M. Kovac[30], A. Petkovic[30], T. Sculac[30], P. Bargassa[31], V. Brigljevic[31], D. Ferencek[31], K. Jakovcic[31], A. Starodumov[31], T. Susa[31], A. Attikis[32], S. Konstantinou[32], C. Leonidou[32], L. Paizanos[32], F. Ptochos[32], P.A. Razis[32], H. Saka[32], A. Stepennov[32], M. Finger[33], M. Finger Jr.[33], A. Kveton[33], E. Acurio[34], E. Carrera Jarrin[35], B. El-mahdy[36,r], S. Khalil[36,s], E. Salama[36,t,u], A. Hussein[37], M. Mahmoud[37], H. Mohammed[37], M.A.A. Muhammad[37], K. Jaffel[38], M. Kadastik[38], T. Lange[38], C. Nielsen[38], J. Pata[38], M. Raidal[38], N. Seeba[38], L. Tani[38], E. Brücken[39], A. Milieva[39], K. Osterberg[39], M. Voutilainen[39], F.I. Garcia Fuentes[40], T. Hilden[40], P. Inkaew[40], K.T.S. Kallonen[40], R. Kumar Verma[40], T. Lampén[40], K. Lassila-Perini[40], B. Lehtela[40], S. Lehti[40], T. Lindén[40], N.R. Mancilla Xinto[40], M. Myllymäki[40], M.m. Rantanen[40], S. Saariokari[40], N.T. Toikka[40], J. Tuominiemi[40], E. Veikkola[40], N. Bin Norjoharuddeen[41], H. Kirschenmann[41], P.R. Luukka[41], H. Petrow[41], M. Besancon[42], F. Couderc[42], M. Dejardin[42], D. Denegri[42], P. Devouge[42], J.L. Faure[42], F. Ferri[42], P. Gaigne[42], S. Ganjour[42], P. Gras[42], F. Guilloux[42], G. Hamel de Monchenault[42], M. Kumar[42], V. Lohezic[42], Y. Maidannyk[42], J. Malcles[42], F. Orlandi[42], L. Portales[42], S. Ronchi[42], M.Ö. Sahin[42], P. Simkina[42], M. Titov[42], M. Tornago[42], R. Amella Ranz[43], F. Beaudette[43], K. Biriukov[43], G. Boldrini[43], P. Busson[43], C. Charlot[43], M. Chiusi[43], T.D. Cuisset[43], O. Davignon[43], A. De Wit[43], T. Debnath[43], I.T. Ehle[43], S. Ghosh[43], A. Gilbert[43], R. Granier de Cassagnac[43], M. Manoni[43], M. Nguyen[43], S. Obraztsov[43], C. Ochando[43], L.m. Rabour[43], R. Salerno[43], J.B. Sauvan[43], Y. Sirois[43], G. Sokmen[43], Y. Song[43], L. Urda Gómez[43], B. Voirin[43], A. Zabi[43], A. Zghiche[43], J.L. Agram[44,v], J. Andrea[44], D. Bloch[44], E.C. Chabert[44], C. Collard[44], G. Coulon[44], C. Eschenlauer[44], S. Falke[44], U. Goerlach[44], A.C. Le Bihan[44],

JHEP11(2026)004

G. Saha[44], A. Savoy-Navarro[44,w], P. Vaucelle[44], A. Di Florio[45], G. Mauceri[45], B. Orzari[45], D. Amram[46], S. Beauceron[46], B. Blancon[46], G. Boudoul[46], N. Chanon[46], D. Contardo[46], J. Daniel[46], P. Depasse[46], H. El Mamouni[46], J. Fay[46], E. Fillaudeau[46], S. Gascon[46], M. Gouzevitch[46], C. Greenberg[46], B. Ille[46], E. Jourd'Huy[46], M. Lethuillier[46], K. Long[46], B. Massoteau[46], L. Mirabito[46], A. Purohit[46], M. Vander Donckt[46], C. Verollet[46], D. Chokheli[47], I. Lomidze[47], Z. Tsamalaidze[47,x], K.F. Adamowicz[48], V. Botta[48], S. Consuegra Rodríguez[48], L. Feld[48], K. Klein[48], M. Lipinski[48], P. Nattland[48], V. Oppenländer[48], A. Pauls[48], D. Pérez Adán[48], C. Daumann[49], S. Diekmann[49], E. Ehlert[49], N. Eich[49], D. Eliseev[49], F. Engelke[49], J. Erdmann[49], M. Erdmann[49], M.Z. Farkas[49], B. Fischer[49], T. Hebbeker[49], K. Hoepfner[49], A. Jung[49], N. Kumar[49], M.y. Lee[49], F. Mausolf[49], M. Merschmeyer[49], A. Meyer[49], A. Pozdnyakov[49], W. Redjeb[49], H. Reithler[49], U. Sarkar[49], V. Sarkisovi[49], A. Schmidt[49], J.G. Schulz[49], C. Seth[49], A. Sharma[49], J.L. Spah[49], V. Vaulin[49], U. Willemsen[49], S. Zaleski[49], F.P. Zinn[49], M.R. Beckers[50], G. Flügge[50], N. Hoeflich[50], T. Kress[50], A. Nowack[50], O. Pooth[50], A. Stahl[50], A. Abel[51], A. Akhil[51], M. Aldaya Martin[51], J. Alimena[51], Y. An[51], I. Andreev[51], J. Bach[51], S. Baxter[51], H. Becerril Gonzalez[51], O. Behnke[51], F. Blekman[51,y], K. Borras[51,z], A. Campbell[51], S. Chatterjee[51], L.X. Coll Saravia[51], G. Eckerlin[51], D. Eckstein[51], E. Gallo[51,y], A. Geiser[51], M. Guthoff[51], A. Hinzmann[51], U. Husemann[51], M. Kasemann[51], C. Kleinwort[51], R. Kogler[51], M. Komm[51], D. Krücker[51], F. Labe[51], W. Lange[51], D. Leyva Pernia[51], J.h. Li[51], K.y. Lin[51], K. Lipka[51,aa], W. Lohmann[51,h], J. Malvaso[51], R. Mankel[51], I.A. Melzer-Pellmann[51], M. Mendizabal Morentin[51], A.B. Meyer[51], G. Milella[51], K. Moral Figueroa[51], A. Mussgiller[51], L.P. Nair[51], J. Niedziela[51], A. Nürnberg[51], J. Park[51], E. Ranken[51], A. Raspereza[51], D. Rastorguev[51], L. Rygaard[51], M. Scham[51,ab,z], S. Schnake[51,z], P. Schütze[51], C. Schwanenberger[51,y], D. Schwarz[51], D. Selivanova[51], K. Sharko[51], M. Shchedrolosiev[51], A. Sritharan[51], D. Stafford[51], M. Torkian[51], S. Vashishtha[51], A. Ventura Barroso[51], R. Walsh[51], D. Wang[51], Q. Wang[51], K. Wichmann[51], L. Wiens[51,z], C. Wissing[51], Y. Yang[51], S. Zakharov[51], A. Zimermmane Castro Santos[51], A.R. Alves Andrade[52], M. Antonello[52], S. Bollweg[52], M. Bonanomi[52], L. Ebeling[52], K. El Morabit[52], Y. Fischer[52], M. Frahm[52], P.P. Gadow[52], E. Garutti[52], A. Grohsjean[52], A.A. Guvenli[52], J. Haller[52], D. Hundhausen[52], M. Jalalvandi[52], G. Kasieczka[52], P. Keicher[52], R. Klanner[52], W. Korcari[52], T. Kramer[52], C.c. Kuo[52], J. Lange[52], A. Lobanov[52], J. Matthiesen[52], L. Moureaux[52], K. Nikolopoulos[52], K.J. Pena Rodriguez[52], N. Prouvost[52], B. Raciti[52], M. Rieger[52], D. Savoiu[52], P. Schleper[52], M. Schröder[52], J. Schwandt[52], M. Sommerhalder[52], H. Stadie[52], G. Steinbrück[52], T. von Schwartz[52], R. Ward[52], B. Wiederspan[52], M. Wolf[52], C. Yede[52], J. Ahäuser[53], A. Brusamolino[53], E. Butz[53], Y.M. Chen[53], T. Chwalek[53], A. Dierlamm[53], G.G. Dincer[53], U. Elicabuk[53], N. Faltermann[53], M. Giffels[53], A. Gottmann[53], F. Hartmann[53,ac], F. Hummer[53], J. Kieseler[53], M. Klute[53], H.A. Krause[53], R. Kunnilan Muhammed Rafeek[53], O. Lavoryk[53], J.M. Lawhorn[53], S. Maier[53], N. Meenamthuruthil Radhakrishnan[53], T. Mehner[53], M. Molch[53], A.A. Monsch[53], M. Mormile[53], T. Müller[53], E. Pfeffer[53], M. Presilla[53], G. Quast[53], K. Rabbertz[53], B. Regnery[53], R. Schmieder[53], T. Selezneva[53], N. Shadskiy[53], L. Sowa[53], L. Stockmeier[53], M. Toms[53], B. Topko[53], N. Trevisani[53], C. Verstege[53], T. Voigtländer[53],

JHEP11(2026)004

R.F. Von Cube[53], J. Von Den Driesch[53], C. Winter[53], R. Wolf[53], W.D. Zeuner[53], X. Zuo[53], G. Anagnostou[54], G. Daskalakis[54], A. Kyriakis[54], P. Iosifidou[55], P. Katris[55], M. Kotsarini[55], G. Melachroinos[55], Z. Painesis[55], N. Plastiras[55], N. Saoulidou[55], K. Theofilatos[55], E. Tzovara[55], K. Vellidis[55], I. Zisopoulos[55], T. Chatzistavrou[56], G. Karapostoli[56], K. Kousouris[56], K. Paschos[56], L.P. Rouseliotaki[56], E. Siamarkou[56], A. Taxeidi[56], G. Tsipolitis[56], I. Evangelou[57], C. Foudas[57], P. Katsoulis[57], P. Kokkas[57], P.G. Kosmoglou Kioseoglou[57], N. Manthos[57], I. Papadopoulos[57], J. Strologas[57], E. Tziaferi[58], C. Hajdu[59], D. Horvath[59,ad,ae], Á. Kadlecsik[59], C. Lee[59], K. Márton[59], A.J. Rádl[59,af], F. Sikler[59], V. Veszpremi[59], G. Balint[60], M. Csanad[60], K. Farkas[60], A. Fehérkuti[60,ag], M.M.A. Gadallah[60,ah], M. León Coello[60], G. Pasztor[60], G.I. Veres[60], B. Ujvari[61], G. Zilizi[61], G. Bencze[62], S. Czellar[62], J. Molnar[62], Z. Szillasi[62], T.F. Csorgo[63,ag], F. Nemes[63,ag], T. Novak[63], I. Szanyi[63,ai], J.R. Komaragiri[64], S. Bahinipati[65], R. Raturi[65], S. Bansal[66], V. Bhatnagar[66], B. Chauhan[66], S. Chauhan[66], N. Dhingra[66,aj], A. Kaur[66], H. Kaur[66], S. Kumar[66], T. Sheokand[66], A. Singla[66], K. Verma[66], A. Bhardwaj[67], A. Chhetri[67], B.C. Choudhary[67], A. Kumar[67], A. Kumar[67], M. Naimuddin[67], S. Phor[67], C. Prakash[67], K. Ranjan[67], M.K. Saini[67], M. Kumari[68], P. Palni[68], S. Rana[68], A. Rathore[68], A. Sarkar[68], S. Acharya[69,ak], B. Gomber[69], S.K. Satapathy[69], S. Mukherjee[70], S. Bhattacharya[71], S. Das Gupta[71], S. Dutta[71], S. Dutta[71], S. Sarkar[71], M.M. Ameen[72], P.K. Behera[72], S. Chatterjee[72], G. Dash[72], A. Dattamunsi[72], P. Jana[72], P. Kalbhor[72], S. Kamble[72], P.R. Pujahari[72], A.K. Sikdar[72], R.K. Singh[72], P. Verma[72], S. Verma[72], A. Vijay[72], A. Chauhan[73], S. Nayak[73], H. Rajpoot[73], B.K. Sirasva[73], L. Bhatt[74], S. Dugad[74], T. Mishra[74], G.B. Mohanty[74], M. Shelake[74], P. Suryadevara[74], A. Bala[75], S. Banerjee[75], S. Barman[75,al], R.M. Chatterjee[75], J. Chhikara[75], M. Guchait[75], S. Jain[75], A. Jaiswal[75], S. Kumar[75], M. Maity[75,al], G. Majumder[75], K. Mazumdar[75], R. Pramanik[75], R. Saxena[75], P. Sharma[75], A. Thachayath[75], R. Kumar Agrawal[76], D. Maity[76,am], P. Mal[76], K. Naskar[76,am], A. Nayak[76,am], K. Pal[76], P. Sadangi[76], S. Shuchi[76], S.K. Swain[76], S. Varghese[76,am], D. Vats[76,am], S. Dube[77], P. Hazarika[77], B. Kansal[77], A. Laha[77], R. Sharma[77], S. Sharma[77], K.Y. Vaish[77], C. Agrawal[78], B. Babu[78], S. Ghosh[78], H. Bakhshiansohi[79,an], A. Jafari[79,ao], V. Sedighzadeh Dalavi[79], M. Zeinali[79,ap], S. Bashiri[80], S. Chenarani[80,aq], S.M. Etesami[80], Y. Hosseini[80], M. Khakzad[80], E. Khazaie[80], M. Mohammadi Najafabadi[80], M. Nourbakhsh[80], S. Tizchang[80,ar], M. Felcini[81], M. Grunewald[81], M. Abbrescia[82a,82b], M. Buonsante[82a,82b], A. Colaleo[82a,82b], D. Creanza[82a,82c], N. De Filippis[82a,82c], M. De Palma[82a,82b], W. Elmetenawee[82a,82b,as], N. Ferrara[82a,82c], L. Fiore[82a], L. Generoso[82a,82b], L. Longo[82a], M. Louka[82a,82b], G. Maggi[82a,82c], M. Maggi[82a], S. My[82a,82b], F. Nenna[82a,82b], S. Nuzzo[82a,82b], A. Pellecchia[82a,82b], A. Pompili[82a,82b], F.M. Procacci[82a,82b], G. Pugliese[82a,82c], R. Radogna[82a,82b], D. Ramos[82a], A. Ranieri[82a], L. Silvestris[82a], F.M. Simone[82a,82b], Ü. Sözbilir[82a,at], A. Stamerra[82a,82b], D. Troiano[82a,82b], R. Venditti[82a,82b], P. Verwilligen[82a], A. Zaza[82a,82b], G. Abbiendi[83a], S. Balducci[83a,83b], C. Battilana[83a,83b], D. Bonacorsi[83a,83b], P. Capiluppi[83a,83b], F.R. Cavallo[83a], M. Cruciani[83a,83b], M. Cuffiani[83a,83b], G.M. Dallavalle[83a], T. Diotalevi[83a,83b], F. Fabbri[83a], A. Fanfani[83a,83b], R. Farinelli[83a], D. Fasanella[83a], L. Ferragina[83a,83b], C. Grandi[83a], L. Guiducci[83a,83b], M. Lorusso[83a,83b], L. Lunerti[83a], S. Marcellini[83a], G. Masetti[83a], F. Navarria[83a,83b],

JHEP11(2026)004

G. Paggi[83a,83b], A. Perrotta[83a], A. Rossi[83a,83b], S. Rossi Tisbeni[83a,83b], T. Rovelli[83a,83b], S. Costa[84a,84b,au], A. Di Mattia[84a], A. Lapertosa[84a], R. Potenza[84a,84b], A. Tricomi[84a,84b,au], J. Altork[85a,85b], G. Barbagli[85a], G. Bardelli[85a], A. Calandri[85a,85b], B. Camaiani[85a,85b], A. Cassese[85a], R. Ceccarelli[85a], V. Ciulli[85a,85b], C. Civinini[85a], R. D'Alessandro[85a,85b], L. Damenti[85a,85b], E. Focardi[85a,85b], T. Kello[85a], G. Latino[85a,85b], P. Lenzi[85a,85b], M. Lizzo[85a], M. Meschini[85a], S. Paoletti[85a], A. Papanastassiou[85a,85b], G. Sguazzoni[85a], L. Viliani[85a], L. Benussi[86], S. Colafranceschi[86,av], S. Meola[86,aw], D. Piccolo[86], M. Alves Gallo Pereira[87a], F. Ferro[87a], E. Robutti[87a], S. Tosi[87a,87b], A. Benaglia[88a], F. Brivio[88a], V. Camagni[88a,88b], F. Cetorelli[88a,88b], F. De Guio[88a,88b], M.E. Dinardo[88a,88b], P. Dini[88a], S. Gennai[88a], R. Gerosa[88a,88b], A. Ghezzi[88a,88b], P. Govoni[88a,88b], L. Guzzi[88a], G. Lavizzari[88a,88b], M.T. Lucchini[88a,88b], M. Malberti[88a], S. Malvezzi[88a], A. Massironi[88a], L. Moroni[88a], M. Paganoni[88a,88b], S. Palluotto[88a,88b], D. Pedrini[88a], A. Perego[88a,88b], T. Tabarelli de Fatis[88a,88b], S. Buontempo[89a], F. Confortini[89a,89b], C. Di Fraia[89a,89b], F. Fabozzi[89a,89c], L. Favilla[89a,89d], A.O.M. Iorio[89a,89b], L. Lista[89a,89b,ax], P. Paolucci[89a,ac], B. Rossi[89a], P. Azzi[90a], N. Bacchetta[90a,ay], D. Bisello[90a,90b], L. Borella[90a], P. Bortignon[90a,90c], G. Bortolato[90a,90b], A.C.M. Bulla[90a,90c], R. Carlin[90a,90b], P. Checchia[90a], T. Dorigo[90a,az], F. Gasparini[90a,90b], U. Gasparini[90a,90b], S. Giorgetti[90a], P. Grutta[90a], N. Lai[90a], E. Lusiani[90a], M. Margoni[90a,90b], A.T. Meneguzzo[90a,90b], M. Missiroli[90a], J. Pazzini[90a,90b], F. Primavera[90a,90b], P. Ronchese[90a,90b], R. Rossin[90a,90b], F. Simonetto[90a,90b], M. Toffano[90a], M. Tosi[90a,90b], A. Triossi[90a,90b], S. Ventura[90a], M. Zanetti[90a,90b], P. Zotto[90a,90b], A. Zucchetta[90a,90b], G. Zumerle[90a,90b], S. A. AbuZeid[91a,u], C. Aimè[91a], A. Braghieri[91a], M. Brunoldi[91a,91b], P. Montagna[91a,91b], M. Pelliccioni[91a,91b], V. Re[91a], C. Riccardi[91a,91b], P. Salvini[91a], I. Vai[91a,91b], P. Vitulo[91a,91b], S. Ajmal[92a,92b], M.E. Ascioti[92a,92b], G.M. Bilei[92a], W.D. Buitrago Ceballos[92a,92b], C. Carrivale[92a,92b], D. Ciangottini[92a,92b], L. Della Penna[92a,92b], L. Fanò[92a,92b], V. Mariani[92a,92b], M. Menichelli[92a], F. Moscatelli[92a,ba], F. Napolitano[92a], A. Rossi[92a,92b], A. Santocchia[92a,92b], D. Spiga[92a], T. Tedeschi[92a,92b], C.A. Alexe[93a,93c], P. Asenov[93a,93b], P. Azzurri[93a], G. Bagliesi[93a], L. Bianchini[93a,93b], T. Boccali[93a], E. Bossini[93a], D. Bruschini[93a,93c], R. Castaldi[93a], F. Cattafesta[93a,93c], M.A. Ciocci[93a,93d], M. Cipriani[93a,93b], R. Dell'Orso[93a], S. Dhani[93a,93d], S. Donato[93a,93b], A. Feliziani[93a,93d], R. Forti[93a,93b], A. Giassi[93a], F. Ligabue[93a,93c], A.C. Marini[93a,93b], A. Messineo[93a,93b], S. Mishra[93a], V.K. Muraleedharan Nair Bindhu[93a,93b], S. Nandan[93a], F. Palla[93a], M. Riggirello[93a,93c], A. Rizzi[93a,93b], G. Rolandi[93a,93c], A. Scribano[93a], P. Solanki[93a,93b], P. Spagnolo[93a], F. Tenchini[93a,93b], R. Tenchini[93a], G. Tonelli[93a,93b], N. Turini[93a,93d], F. Vaselli[93a,93c], A. Venturi[93a], P.G. Verdini[93a], P. Akrap[94a,94b], C. Basile[94a,94b], S.C. Behera[94a], F. Cavallari[94a], L. Cunqueiro Mendez[94a,94b], F. De Riggi[94a,94b], D. Del Re[94a,94b], M. Del Vecchio[94a,94b], E. Di Marco[94a], M. Diemoz[94a], F. Errico[94a], L. Frosina[94a,94b], R. Gargiulo[94a,94b], B. Harikrishnan[94a,94b], F. Lombardi[94a,94b], L. Martikainen[94a,94b], G. Organtini[94a,94b], N. Palmeri[94a,94b], R. Paramatti[94a,94b], T. Pauletto[94a,94b], S. Rahatlou[94a,94b], C. Rovelli[94a], F. Santanastasio[94a,94b], L. Soffi[94a], V. Vladimirov[94a,94b], N. Amapane[95a,95b], R. Arcidiacono[95a,95c], S. Argiro[95a,95b], M. Arneodo[95a,95c], N. Bartosik[95a,95c], F. Bashir[95a,95b], R. Bellan[95a,95b], A. Bellora[95a,95b], C. Biino[95a], C. Borca[95a,95b], N. Cartiglia[95a], M. Costa[95a,95b], R. Covarelli[95a,95b],

JHEP11(2026)004

N. Demaria[95a], E. Ferrando[95a,95b], L. Finco[95a], M. Grippo[95a,95b], B. Kiani[95a,95b], L. Lanteri[95a,95b], F. Luongo[95a,95b], M. Marchisio Caprioglio[95a,95b], C. Mariotti[95a,bb], S. Maselli[95a], A. Mecca[95a,95b], L. Menzio[95a,95b], P. Meridiani[95a], E. Migliore[95a,95b], M. Monteno[95a], M.M. Obertino[95a,95b], G. Ortona[95a], L. Pacher[95a,95b], N. Pastrone[95a], M. Ruspa[95a,95c], F. Siviero[95a,95b], V. Sola[95a,95b], A. Solano[95a,95b], A. Staiano[95a], C. Tarricone[95a,95b], D. Trocino[95a], G. Umoret[95a,95b], E. Vlasov[95b], R. White[95a,95b], J. Babbar[96a,96b,bc], S. Belforte[96a], V. Candelise[96a,96b], M. Casarsa[96a], F. Cossutti[96a], K. De Leo[96a], G. Della Ricca[96a,96b], R. Delli Gatti[96a,96b], C. Giraldin[96a,96b], S. Dogra[97], J. Hong[97], J. Kim[97], J. Kim[97], T. Kim[97], D. Lee[97], H. Lee[97], J. Lee[97], S.W. Lee[97], C.S. Moon[97], Y.D. Oh[97], S. Sekmen[97], B. Tae[97], Y.C. Yang[97], M.S. Kim[98], G. Bak[99], P. Gwak[99], H. Kim[99], H. Lee[99], S. Lee[99], D.H. Moon[99], J. Seo[99], K. Lee[100], Y. Lee[100], E. Asilar[101], F. Carnevali[101], J. Choi[101,bd], T.J. Kim[101], Y. Ryou[101], J. Song[101], T. Yang[101], S. Ha[102], B.S. Hong[102], J. Kim[102], K. Lee[102], K. Lee[102], S. Lee[102], J. Padmanaban[102], B.A.N. Putra[102], J. Yoo[102], J. Goh[103], J. Shin[103], S. Yang[103], L. Kalipoliti[104], Y. Kang[104], H. Kim[104], Y. Kim[104], B. Ko[104], S. Lee[104], J.H. Bhyun[105], J. Choi[105], J. Choi[105], W. Jun[105], H. Kim[105], J. Kim[105], J. Kim[105], T. Kim[105], Y. Kim[105], Y.W. Kim[105], S. Ko[105], H. Lee[105], J. Lee[105], J. Lee[105], B.H. Oh[105], J. Shin[105], U. Yang[105], I. Yoon[105], S. Calzaferri[106], W. Heo[106], W. Jang[106], D. Kim[106], S. Kim[106], J.S.H. Lee[106], Y. Roh[106], I. J. Watson[106], G. Cho[107], Y. Eo[107], K. Hwang[107], H. Jang[107], B. Kim[107], D. Kim[107], S. Kim[107], G. Mocellin[107], H.D. Yoo[107], Y. Lee[108], I. Yu[108], T. Beyrouthy[109], Y. Gharbia[109], F. Alazemi[110], K. Dreimanis[111], O.M. Eberlins[111], A. Gaile[111], J.K. Heikkilä[111], M. Klevs[111], C. Munoz Diaz[111], D. Osite[111], G. Pikurs[111], R. Plese[111], A. Potrebko[111], M. Seidel[111], D. Sidiropoulos Kontos[111], N.R. Strautnieks[112], M. Ambrozas[113], A. Juodagalvis[113], S. Nargelas[113], S. Nayak[113], G. Tamulaitis[113], I. Yusuff[114,be], Z. Zolkapli[114], J.P. Barajas Ibarria[115], J.F. Benitez[115], A. Castaneda Hernandez[115], A. Cota Rodriguez[115], L.E. Cuevas Picos[115], H.A. Encinas Acosta[115], L.G. Gallegos Maríñez[115], J.A. Murillo Quijada[115], L. Valencia Palomo[115], G. Ayala[116], H. Castilla-Valdez[116], H. Crotte Ledesma[116], R. Lopez-Fernandez[116], J. Mejia Guisao[116], R. Reyes-Almanza[116], A. Sánchez Hernández[116], C. Oropeza Barrera[117], M. Ramírez García[117], D.L. Ramirez Guadarrama[117], I. Bautista[118], F.E. Neri Huerta[118], I. Pedraza[118], H.A. Salazar Ibarguen[118], C. Uribe Estrada[118], I. Bubanja[119], J. Mijuskovic[119], N. Raicevic[119], A. Ahmad[120], M.I. Asghar[120], A. Awais[120], M.I.M. Awan[120], W.A. Khan[120], I. Sohail[120], V. Avati[121], L. Forthomme[121], L. Grzanka[121], M. Malawski[121], K. Piotrzkowski[121], H. Awedikian[122], M. Bluj[122], M. Ghimiray[122], M. Górski[122], M. Kazana[122], M. Szleper[122], P. Zalewski[122], K. Bunkowski[123], K. Doroba[123], A. Kalinowski[123], M. Konecki[123], J. Krolikowski[123], W. Matyszkiewicz[123], A. Muhammad[123], S. Slawinski[123], P. Fokow[124], K. Pozniak[124], W. Zabolotny[124], M. Araujo[125], C. Beirão Da Cruz E Silva[125], A. Boletti[125], M. Bozzo[125], T. Camporesi[125,bb,bf], G. Da Molin[125], M. Gallinaro[125], R. Guitton[125], J. Hollar[125], H. Legoinha[125], N. Leonardo[125,bg], G.B. Marozzo[125], A. Petrilli[125], M. Pisano[125], J. Seixas[125], J. Varela[125], J.W. Wulff[125], P. Adzic[126], L. Markovic[126], P. Milenovic[126], V. Milosevic[126], D. Devetak[127], M. Dordevic[127], J. Milosevic[127], L. Nadderd[127], V. Rekovic[127], M. Stojanovic[127], M. Alcalde Martinez[128], J. Alcaraz Maestre[128],

JHEP11(2026)004

J.A. Brochero Cifuentes[128], M. Cepeda[128], M. Cerrada[128], N. Colino[128], B. De La Cruz[128], A. Escalante Del Valle[128], C. Fernandez Bedoya[128], D. Fernández Del Val[128], J.P. Fernández Ramos[128], J. Flix[128], M.C. Fouz[128], M. Gonzalez Hernandez[128], O. Gonzalez Lopez[128], S. Goy Lopez[128], J.M. Hernandez[128], M.I. Josa[128], J. Llorente Merino[128], O. Manzanilla[128], C. Martin Perez[128], E. Martin Viscasillas[128], D. Moran[128], C.M. Morcillo Perez[128], Á. Navarro Tobar[128], A.M. Pérez-Calero Yzquierdo[128], J. Puerta Pelayo[128], I. Redondo[128], D.D. Redondo Ferrero[128], J. Vazquez Escobar[128], J.F. de Trocóniz[129], E. Aller Gutierrez[130], B. Alvarez Gonzalez[130], J. Ayllon Torresano[130], A. Cardini[130], J. Cuevas[130], J. Del Riego Badas[130], D. Estrada Acevedo[130], J. Fernandez Menendez[130], S. Folgueras[130], I. Gonzalez Caballero[130], P. Leguina[130], M. Obeso Menendez[130], E. Palencia Cortezon[130], J. Prado Pico[130], S. Sanchez Cruz[130], A. Soto Rodríguez[130], P. Vischia[130], S. Blanco Fernández[131], I.J. Cabrillo[131], A. Calderon[131], M. Caserta[131], J. Duarte Campderros[131], M. Fernandez[131], G. Gomez[131], C. Lasaosa García[131], R. Lopez Ruiz[131], C. Martinez Rivero[131], P. Martinez Ruiz del Arbol[131], F. Matorras[131], P. Matorras Cuevas[131], E. Navarrete Ramos[131], J. Piedra Gomez[131], C. Quintana San Emeterio[131], V. Rodriguez[131], L. Scodellaro[131], I. Vila[131], R. Vilar Cortabitarte[131], J.M. Vizan Garcia[131], B. Kailasapathy[132,bh], W.G. Dharmaratna[133,bi], N. Perera[133], L. Caminada[134,bj], W. Erdmann[134], R. Horisberger[134], Q. Ingram[134], H.C. Kaestli[134], D. Kotlinski[134], C. Lange[134], U. Langenegger[134], A. Nigamova[134], L. Noehte[134,bj], L. Redard-Jacot[134,bj], T. Rohe[134], A. Samalan[134], T.K. Aarrestad[135], M. Backhaus[135], A. Belvedere[135], T. Bevilacqua[135,bj], G. Bonomelli[135], C. Cazzaniga[135], K. Datta[135], P. De Bryas Dexmiers D'Archiacchiac[135,j], A. De Cosa[135], G. Dissertori[135], M. Dittmar[135], M. Donegà[135], F. Glessgen[135], C. Grab[135], N. Härringer[135], T.G. Harte[135], B. Kaynak[135], M. Koppel[135], W. Lustermann[135], M. Malucchi[135], R.A. Manzoni[135], L. Marchese[135], F. Nessi-Tedaldi[135], F. Pauss[135], A.A. Petre[135], J. Prendi[135], B. Ristic[135], S. Rohletter[135], P.M. Sander[135], R. Seidita[135], J. Steggemann[135,j], A. Tarabini[135], C.Z. Tee[135], D. Valsecchi[135], P.H. Wagner[135], R. Wallny[135], C. Amsler[136,bk], P. Bärtschi[136], F. Bilandzija[136], M.F. Canelli[136], G. Celotto[136], Z. Ghafoor[136], T.A. Goldschmidt[136], V. Guglielmi[136], A. Jofrehei[136], B. Kilminster[136], T.H. Kwok[136], S. Leontsinis[136], V. Lukashenko[136], A. Macchiolo[136], F. Meng[136], J. Motta[136], P. Robmann[136], E. Shokr[136], F. Stäger[136], R. Tramontano[136], P. Viscone[136], D. Bhowmik[137], Y.h. Chou[137], C.M. Kuo[137], P.K. Rout[137], S. Taj[137], P.C. Tiwari[137,bl], L. Ceard[138], K.F. Chen[138], Z.g. Chen[138], A. De Iorio[138], G.W.S. Hou[138], T.h. Hsu[138], Y.w. Kao[138], S. Karmakar[138], F. Khuzaimah[138], G. Kole[138], Y.y. Li[138], R.S. Lu[138], E. Paganis[138], X.f. Su[138], J. Thomas-Wilsker[138], L.s. Tsai[138], D. Tsionou[138], H.y. Wu[138], E. Yazgan[138], C. Asawatangtrakuldee[139], N. Srimanobhas[139], Y. Maghrbi[140], D. Agyel[141], F. Dolek[141], I. Dumanoglu[141,bm], Y. Guler[141,bn], E. Gurpinar Guler[141,bn], A. Kayis Topaksu[141], G. Onengut[141], K. Ozdemir[141,bo], B. Tali[141,bp], U.G. Tok[141], E. Uslan[141], S. Sen[142], B. Akgun[143], I.O. Atakisi[143,bq], E. Gulmez[143], M. Kaya[143,br], O. Kaya[143,bs], M.A. Sarkisla[143,bt], S. Tekten[143,bu], D. Boncukcu[144], A. Cakir[144], K. Cankocak[144,bm,bv], M. Gumustekin[144], A.D. Gungordu[144], B. Hacisahinoglu[145], I. Hos[145,bw], S. Ozkorucuklu[145], O. Potok[145], H. Sert[145], C. Simsek[145], C. Zorbilmez[145], S. Cerci[146], C. Dozen[146,bx],

JHEP11(2026)004

E. Iren[146,by], B. Isildak[146], E. Simsek[146], D. Sunar Cerci[146], T. Yetkin[146,bx], O. Dadazhanova[147], B. Grynyov[147], K. Klimenko[148], O. Kurov[148], L. Levchuk[148], S. Lukyanenko[148], A. Pristavka[148], D. Soroka[148], J.J. Brooke[149], A. Bundock[149], F.J.J. Bury[149], E. Clement[149], D. Cussans[149], D. Dharmender[149], H. Flacher[149], J. Goldstein[149], H.F. Heath[149], M.l. Holmberg[149], A. Karakoulaki[149], L. Kreczko[149], S. Paramesvaran[149], L. Robertshaw[149], M.S. Sanjrani[149,an], J. Segal[149], V.J. Smith[149], A. Ball[150], K.W. Bell[150], A. Belyaev[150,bz], C. Brew[150], R.M. Brown[150], D.J. Cockerill[150], A. Elliot[150], K.V. Ellis[150], J. Gajownik[150], K. Harder[150], S. Harper[150], J. Linacre[150], K. Manolopoulos[150], M. Moallemi[150], D.M. Newbold[150], E. Olaiya[150], D. Petyt[150], T. Reis[150], A.R. Sahasransu[150], T. Schuh[150], C. Shepherd-Themistocleous[150], I.R. Tomalin[150], K.C. Whalen[150], T. Williams[150], I. Andreou[151], S. Awan[151], R. Bainbridge[151], P. Bloch[151], O. Buchmuller[151], C.A. Carrillo Montoya[151], D. Colling[151], A. Cox[151], I. Das[151], P. Dauncey[151], G. Davies[151], M. Della Negra[151], S. Fayer[151], G. Fedi[151], G. Hall[151], H.R. Hoorani[151], A. Howard[151], G. Iles[151], C.R. Knight[151], P. Krueper[151], J. Langford[151], K.H. Law[151], L. Lyons[151], A.M. Magnan[151], B. Maier[151], S. Mallios[151], A. Mastronikolis[151], J. Nash[151,ca], M. Pesaresi[151], P.B. Pradeep[151], E.V. Protopapa[151], B.C. Radburn-Smith[151], A. Richards[151], A. Rose[151], T.B. Runting[151], L. Russell[151], K. Savva[151], R. Schmitz[151], C. Seez[151], R. Shukla[151], A. Tapper[151], T. Travis[151], K. Uchida[151], G.P. Uttley[151], T. Virdee[151,ac], N. Wardle[151], D. Winterbottom[151], J. Xiao[151], J. Cole[152], L. Juckett[152], A. Khan[152], P. Kyberd[152], I. Reid[152], B. Bam[153], A. Buchot Perraguin[153], S. Campbell[153], R. Chudasama[153], S. Cooper[153], C. Crovella[153], G. Fidalgo[153], S.V. Gleyzer[153], R. Kaur[153], A. Khukhunaishvili[153], K. Matchev[153], E. Pearson[153], P. Rumerio[153,cb], E. Usai[153], R. Yi[153], S. Abbott[154], S. Baradia[154], B. Barton[154], R. Breedon[154], H. Cai[154], M. Calderon De La Barca Sanchez[154], E. Cannaert[154], M. Chertok[154], M. Citron[154], J. Conway[154], P.T. Cox[154], F. Eble[154], R. Erbacher[154], C. Fairchild[154], O. Kukral[154], S. Ostrom[154], I. Salazar Segovia[154], J.H. Steenis[154], J.S. Tafoya Vargas[154], W. Wei[154], S. Yoo[154], A. Aportela[155], A. Arora[155], J.G. Branson[155], S. Cittolin[155], B. D'Anzi[155], D. Diaz[155], J. Duarte[155], L. Giannini[155], Y. Gu[155], J. Guiang[155], V. Krutelyov[155], R. Lee[155], J. Letts[155], H. Li[155], R. Marroquin Solares[155], M. Masciovecchio[155], F. Mokhtar[155], S. Morovic[155], S. Mukherjee[155], M. Pieri[155], D. Primosch[155], M. Quinnan[155], V. Sharma[155], M. Tadel[155], E. Vourliotis[155], F. Würthwein[155], A. Yagil[155], Z. Zhao[155], K. Adamidis[156], H. Ancelin[156], M. Bachtis[156], D. Campos[156], R. Cousins[156], S. Crossley[156], G. Flores Avila[156], J. Hauser[156], M. Ignatenko[156], M.A. Iqbal[156], T. Lam[156], Y.f. Lo[156], A. Nunez Del Prado[156], D. Saltzberg[156], V. Valuev[156], A. Albert[157], S. Bhattacharya[157], A. Bornheim[157], O. Cerri[157], Z. Hao[157], L. Mori[157], H.B. Newman[157], G. Reales Gutiérrez[157], T. Sievert[157], P. Simmerling[157], E. Sledge[157], M. Spiropulu[157], C. Sun[157], J.R. Vlimant[157], R.A. Wynne[157], S. Xie[157], R.Y. Zhu[157], R. Clare[158], J.W. Gary[158], G. Hanson[158], A. Barzdukas[159], L. Brennan[159], C. Campagnari[159], S. Carron Montero[159,cc], K. Downham[159], C. Grieco[159], J.S. Guo[159], M.M. Hussain[159], D. Imani[159], J. Incandela[159], M.W.K. Lai[159], A.J. Li[159], P. Masterson[159], J.J.H. Ockenfuss[159], J. Richman[159], S.N. Santpur[159], D. Stuart[159], T.Á. Vámi[159], X. Yan[159], D. Zhang[159], J.P. Cumalat[160], W.T. Ford[160], J. Fraticelli[160], A. Hart[160],

JHEP11(2026)004

M. Herrmann[160], S. Kwan[160], J. Pearkes[160], N. Schonbeck[160], K. Stenson[160], K. Ulmer[160], S.R. Wagner[160], N. Zipper[160], D. Zuolo[160], R. Bartek[161], A. Dominguez[161], S. Raj[161], B. Sahu[161], A.E. Simsek[161], B. Singhal[161], S.S. Yu[161], C. Aruta[162], P. Avery[162], D. Bourilkov[162], P. Chang[162], V. Cherepanov[162], M. Dittrich[162], R.D. Field[162], C. Huh[162], E. Koenig[162], M. Kolosova[162], J. Konigsberg[162], A. Korytov[162], G. Mitselmakher[162], K. Mohrman[162], A. Muthirakalayil Madhu[162], N. Rawal[162], S. Rosenzweig[162], Y. Takahashi[162], J. Wang[162], B. Alsufyani[163], S. Das[163], S. Demarest[163], L. Hasa[163], M. Hohlmann[163], M. Lavinsky[163], E. Yanes[163], T. Adams[164], A. Al Kadhim[164], D. Alam[164], A. Askew[164], S. Bower[164], R. Goff[164], R. Hashmi[164], A. Hassani[164], T. Kolberg[164], G. Martinez[164], M. Mazza[164], H. Prosper[164], P.R. Prova[164], R. Yohay[164], M. Albrow[165], M. Alyari[165], O. Amram[165], G. Apollinari[165], A. Apresyan[165], L.A. Bauerdick[165], D. Berry[165], J. Berryhill[165], P.C. Bhat[165], K. Burkett[165], J.N. Butler[165], A. Canepa[165], G.B. Cerati[165], H. Cheung[165], F. Chlebana[165], C. Cosby[165], G. Cummings[165], I. Dutta[165], V.D. Elvira[165], J. Freeman[165], A. Gandrakota[165], Z. Gecse[165], L. Gray[165], D. Green[165], A. Grummer[165], S. Grünendahl[165], D. Guerrero[165], O. Gutsche[165], R.M. Harris[165], J. Hirschauer[165], V. Innocente[165], B. Jayatilaka[165], S. Jindariani[165], M. Johnson[165], R.S. Kim[165], S. Lammel[165], D. Lincoln[165], R. Lipton[165], T. Liu[165], K. Maeshima[165], D. Mason[165], P. McBride[165], P. Merkel[165], S. Mrenna[165], S. Nahn[165], J. Ngadiuba[165], D. Noonan[165], S. Norberg[165], V. Papadimitriou[165], N. Pastika[165], K. Pedro[165], C. Pena[165,cd], C.E. Perez Lara[165], V. Perovic[165], F. Ravera[165], A. Reinsvold Hall[165,ce], L. Ristori[165], M. Safdari[165], E. Sexton-Kennedy[165], E. Smith[165], N. Smith[165], A. Soha[165], L. Spiegel[165], S. Stoynev[165], J. Strait[165], L. Taylor[165], S. Tkaczyk[165], N.V. Tran[165], L. Uplegger[165], E.W. Vaandering[165], C. Wang[165], I. Zoi[165], M.R. Adams[166], N. Barnett[166], A. Baty[166], C. Bennett[166], N. Brandman-hughes[166], R. Cavanaugh[166], S.J. Das[166], R. Escobar Franco[166], O. Evdokimov[166], C.E. Gerber[166], H. Gupta[166], M. Hawksworth[166], A. Hingrajiya[166], D.J. Hofman[166], Z. Huang[166], J.h. Lee[166], C. Mills[166], S. Nanda[166], G. Nigmatkulov[166], B. Ozek[166], V. Pant[166], T. Phan[166], D. Pilipovic[166], R. Pradhan[166], E. Prifti[166], T. Roy[166], D. Shekar[166], N. Singh[166], F. Strug[166], A. Thielen[166], M. Tonjes[166], N. Varelas[166], M.A. Wadud[166], A. Wang[166], J. Yoo[166], S. Dittmer[167], K.A. Hahn[167], S. King[167], D. Li[167], M. Mcginnis[167], Y. Miao[167], D.G. Monk[167], M.H. Schmitt[167], A. Taliercio[167], M. Velasco[167], J. Wang[167], D. Wilbern[167], N. Parashar[168], A. Pathak[168], E. Shumka[168], G. Agarwal[169], R. Band[169], R. Bucci[169], S. Castells[169], A. Das[169], A. Datta[169], A. Ehnis[169], R. Goldouzian[169], M. Hildreth[169], T. Ivanov[169], C. Jessop[169], K. Lannon[169], J. Lawrence[169], D. Lutton[169], J. Mariano[169], N. Marinelli[169], P. Mastrapasqua[169], A. Masud[169], T. McCauley[169], C. Mcgrady[169], C. Moore[169], Y. Musienko[169,cf], H. Nelson[169], M. Osherson[169], A. Piccinelli[169], R. Ruchti[169], A. Townsend[169], Y. Wan[169], M. Wayne[169], H. Yockey[169], S. Chandra[170], A. Gu[170], L. Gutay[170], L. He[170], M. Huwiler[170], M. Jones[170], A.W. Jung[170], I.G. Karslioglu[170], D. Kondratyev[170], J. Li[170], M. Liu[170], M. Macedo[170], G. Negro[170], N. Neumeister[170], G. Paspalaki[170], S. Piperov[170], N.R. Saha[170], J.F. Schulte[170], R. Sharma[170], F. Wang[170], A.L. Wesolek[170], A. Wildridge[170], W. Xie[170], Y. Yao[170], Y. Zhong[170], M. Alhusseini[171], D. Blend[171], K. Dilsiz[171,cg], O.K. Köseyan[171], A. Mestvirishvili[171,bf], O. Neogi[171], H. Ogul[171,ch], Y. Onel[171], A. Penzo[171], C. Snyder[171],

JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004

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JHEP11(2026)004