Search for Dark Matter Produced in Association with a Dark Higgs Boson in the $b\bar{b}$ Final State Using pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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(Received 19 July 2024; accepted 20 February 2025; published 26 March 2025)

A search is performed for dark matter particles produced in association with a resonantly produced pair of b-quarks with $30 < m_{bb} < 150$ GeV using 140 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector at the LHC. This signature is expected in extensions of the standard model predicting the production of dark matter particles, in particular those containing a dark Higgs boson s that decays into $b\bar{b}$. The highly boosted $s \to b\bar{b}$ topology is reconstructed using jet reclustering and a new identification algorithm. This search places stringent constraints across regions of the dark Higgs model parameter space that satisfy the observed relic density, excluding dark Higgs bosons with masses between 30 and 150 GeV in benchmark scenarios with Z' mediator masses up to 4.8 TeV at 95% confidence level.

DOI: 10.1103/PhysRevLett.134.121801

Multiple astrophysical observations [1–4] indicate that a large fraction of the matter density of the universe is in the form of dark matter (DM). Its nature is a major open question in physics, for the standard model (SM) of particle physics does not provide any suitable DM candidates. Many extensions of the SM propose DM candidates that are stable, neutral, massive weakly interacting particles [4], which determine the DM relic abundance via thermal freeze-out. The search for DM candidates is being pursued actively in direct and indirect detection experiments in addition to collider experiments [5–11]. Once produced in colliders, DM would be undetected and must be inferred from the imbalance of the transverse momentum $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, [12] with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$, observed from the detected SM particles.

This Letter presents a novel DM search using a $X + E_{\mathrm{T}}^{\mathrm{miss}}$ signature in which X is a hypothetical particle that decays into a b-quark pair, $b\bar{b}$. This signature of large $E_{\mathrm{T}}^{\mathrm{miss}}$ and resonant $b\bar{b}$ production has not been probed directly for invariant masses $m_{bb} < 150$ GeV, except for when X is the SM Higgs boson, h [13,14]. Signal regions (SRs) are defined by requiring significant $E_{\mathrm{T}}^{\mathrm{miss}}$ consistent with the presence of DM, in association with a $b\bar{b}$ decay, which is usually the dominant branching fraction for a low mass X with SM Higgs boson couplings. The background is dominated by vector-boson production in association with jets, referred to as $V + \mathrm{jets}$, with top quark pair ($t\bar{t}$) production also significant at lower $E_{\mathrm{T}}^{\mathrm{miss}}$ values. To constrain and improve the modeling of these background contributions, control regions (CRs) are defined that require either a single muon (μ) or a pair of charged leptons $\ell^{\pm}\ell^{\mp}$ ($\ell = e, \mu$) in the final state.

The optimization and interpretation of the search is based on a dark Higgs model [15] that explains mass generation for DM particles (χ) through a Higgs mechanism in the dark sector and Yukawa interactions with a new massive dark Higgs boson (s). This model satisfies the observed DM relic density as, when the dark Higgs boson s is lighter than the DM particle χ, additional annihilation channels such as $\chi\chi \to ss$ can be dominant. Thus it offers a widespread, generic ability to reproduce the observed relic density. In this two-mediator DM model, Majorana DM particles interact with the SM via the exchange of new spin-1 "mediator" particles carrying a new $\mathrm{U}(1)'$ gauge symmetry (e.g., a new Z' gauge boson), which can be probed at colliders [15] through s-channel processes. Since large dark sector couplings usually reproduce the relic density, the probability for a Z' to radiate a dark Higgs boson can be large. Annihilation signals in these models are suppressed, as is direct detection sensitivity for Majorana DM particles; thus colliders provide unique discovery potential. The key model parameters are the Majorana DM candidate's mass m_{χ}, the Z' mass $m_{Z'}$, the dark Higgs boson mass m_s, the two couplings of the Z' boson to quarks g_q and to DM g_{χ}, and the mixing angle between the SM and dark Higgs bosons θ. In this model, the Z' decays dominantly into DM, which recoils against the dark Higgs boson and its visible decay products. If the dark

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Higgs boson is the lightest dark sector state, exploring the dominant decays of low-mass s bosons is vital. For $m_s < 150$ GeV, decays into a b-quark pair dominate, with the Lorentz boost and collimated decay, generating a merged topology signature of a single large-radius (large-R) jet containing two b-quarks. The experimental challenges of this final state are identifying the massive jet and its b-quarks and maintaining sensitivity to $m_s < 50$ GeV. For $m_{Z'} < 2$ TeV and $m_s > 70$ GeV, the greater separation of the b-quark pair motivates a resolved topology of two small-radius (small-R) b-quark jets.

The analysis is performed using 140 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector [16,17] in 2015–2018 during good operating conditions [18]. Monte Carlo (MC) simulations are used to model the kinematics of SM background processes and the $s + \chi\chi$ signal. A detailed simulation of the ATLAS detector [19] based on GEANT4 [20] was used to simulate the detector response for MC event samples. Further description of the ATLAS detector and the triggers used, along with a signal diagram and details of the event simulation configurations used for signal and background processes, can be found in the Appendix.

Signal simulations for the $pp \to Z' \to s\chi\chi \to b\bar{b}\chi\chi$ process in three interpretation scenarios are used to investigate interesting phase spaces of the model. Scenario 1 simulations were generated in the $(m_{Z'}, m_s)$ plane, covering 30–150 GeV in m_s and $m_{Z'}$ up to 4 TeV. Other parameter values were $m_\chi = 200$ GeV to avoid $s \to \chi\chi$ decays, $g_q = 0.25$ [21,22], $g_\chi = 1.0$, and $\sin\theta = 0.01$ [15], defining a conventional benchmark used in previous studies in different final states [23–25]. Two other scenarios are developed, where the coupling parameter g_χ is varied (instead of being set to unity) to ensure that all signal points are compatible with the observed relic density, $\Omega h^2 = 0.12$ [26], calculated using MADDM [27]. This requirement usually indicates large g_χ couplings, especially for larger $m_{Z'}$, which enhances the sensitivity of dark Higgs boson signatures and reduces that of others, e.g., where the Z' decays into quarks. Signal simulations for scenario 2 were generated in the $(m_{Z'}, m_s)$ plane, but with $m_\chi = 900$ GeV to enable a match with the relic density across the investigated parameter plane. Finally, scenario 3 explores the $(m_{Z'}, m_\chi)$ plane for a fixed dark Higgs boson mass $m_s = 70$ GeV that coincides with the highest analysis sensitivity. The other parameters (g_q and $\sin\theta$) in these scenarios match those of scenario 1.

At least one pp collision vertex reconstructed from at least two inner detector (ID) tracks with $p_T > 0.5$ GeV is required in each event. The vertex with the highest $\sum(p_T)^2$ is designated the primary vertex (PV) [28]. Electrons are reconstructed by matching a cluster of energy in the calorimeter to an ID track. Electron candidates are identified using a likelihood-based method and must satisfy the "loose" requirement [29] and have $|\eta| < 2.47$. Muons are reconstructed by matching a track or track segment found in the muon spectrometer to an ID track. Muons must satisfy "loose" requirements [30] and have $|\eta| < 2.5$. Electrons and muons must be isolated according to the track proximity criteria defined in Ref. [31]. Hadronic τ-lepton decays are identified by an algorithm based on a boosted decision tree [32] that combines calorimeter and ID information. Events with τ-leptons satisfying $p_T > 20$ GeV and "very loose" requirements [33] within $|\eta| = 2.5$ are rejected.

Small-R jets are formed with the anti-k_t algorithm [34,35], using a radius parameter $R = 0.4$, from ID tracks associated with the PV and three-dimensional clusters of calorimeter cells selected by a particle-flow reconstruction algorithm [36]. "Central" small-R jets satisfy $|\eta| < 2.5$ and $p_T > 20$ GeV while "forward" jets satisfy $2.5 < |\eta| < 4.5$ and $p_T > 30$ GeV. Corrections for pileup [37] and the jet energy scale (JES) and resolution (JER) [38] are applied. The PV origin of central small-R jets with $20 < p_T < 60$ GeV and $|\eta| < 2.4$ is required, using an associated-track-based discriminant [39]. Small-R jets closer than $\Delta R = 0.2$ to an e or μ are rejected. Two types of large-R jets are reconstructed using the anti-k_t algorithm with radius $R = 1.0$. "Reclustered" large-R jets (J) are derived by clustering small-R jets (j) [40]; these are used for the merged analysis with the intention of capturing the dark Higgs boson decay in full, providing sensitivity and good mass resolution across the full jet mass range (down to $m_J = 30$ GeV). Their flavor content is evaluated through their associated variable-radius (VR) track-jets [41,42] or the $\mathrm{D_{Xbb}}$ discriminant score of the corresponding calorimeter large-R jet, as described below. "Calorimeter" large-R jets are clustered from topological clusters calibrated to the hadronic scale using the local hadronic cell weighting scheme [43]. All large-R jets are trimmed [44] to minimize the impact of pileup and underlying event. The JES and jet mass scale (JMS) of trimmed jets are calibrated following techniques described in Ref. [45].

To suppress contributions from processes that involve light quarks or gluons, two multivariate algorithms are used to identify jets containing b-hadrons (b-tagging) [46]. The algorithm `DL1r` is used at an operating point evaluated to be 77% efficient at b-jet identification on $t\bar{t}$ simulation [47], with a light jet rejection factor of around 200. For $m_J < 50$ GeV, this algorithm and operating point are applied to VR track-jets with $p_T > 10$ GeV and $|\eta| < 2.5$ formed from ID tracks using the anti-k_t algorithm and a p_T-dependent radius parameter. It is also applied to the small-R jets in the resolved channel. A second, new tagging algorithm $\mathrm{D_{Xbb}}$ [48,49], developed specifically for the $X \to b\bar{b}$ topology, combines the flavor information of up to three VR track-jets within the large-R jet. This mass-agnostic neural network exploits the powerful tagging capability of individual track-jets and their discriminant correlations, together with the knowledge of the large-R jet kinematics. The algorithm is trained on calorimeter large-R

jets with masses above 50 GeV, where the axes of the large-R jet and the reclustered large-R jet lie within $\Delta R = 1.0$. An operating point evaluated to be 50% efficient at selecting Higgs bosons with $p_{\mathrm{T}} > 250$ GeV and a multijet rejection factor of around 110 is employed. It is calibrated using $Z(\to b\bar{b}) +$ jets and $Z(\to b\bar{b}) + \gamma$ data samples in four p_{T} regions, supported by $t\bar{t}$ and $g \to b\bar{b}$ topologies. It is estimated that the $\mathrm{D_{Xbb}}$ algorithm improves the sensitivity by a factor of up to 50% in expected median discovery significance compared with an $E_{\mathrm{T}}^{\mathrm{miss}} + h(b\bar{b})$ analysis [13] using VR track-jet b-tagging, neglecting systematic uncertainties.

The $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is computed as the negative vector sum of the transverse momenta of the identified and calibrated physics objects in the event, plus a term accounting for low-energy charged particles, using the "tight" operating point defined in Ref. [50]. An object-based $E_{\mathrm{T}}^{\mathrm{miss}}$ significance $\mathcal{S}$ [50] discriminates events with genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ produced by neutrinos or possible weakly interacting exotic particles from those events in which $E_{\mathrm{T}}^{\mathrm{miss}}$ is caused by mismeasurements or resolution effects.

The signal is characterized by high $E_{\mathrm{T}}^{\mathrm{miss}}$ from the DM particle production and substantial hadronic activity from $s \to b\bar{b}$ decays that results in an invariant mass consistent with m_s. Thus events in the SR are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, either two b-tagged small-R jets or a large-R jet containing two b-quarks, and no isolated e or μ. Events in the SR are rejected if a "loose" electron or muon with $p_{\mathrm{T}} > 7$ GeV is present.

The smallest azimuthal angle between the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and any of the three highest-p_{T} (leading) small-R jets is required to be at least 20° to reduce the multijet background arising from mismeasured jet momenta. For signal events the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the reconstructed dark Higgs boson candidate (p_{T}^{jj} in the resolved region or p_{T}^{J} in the merged region) are correlated through the production process. Their ratio is required to be between 0.8 and 1.3 to reduce the contributions from $t\bar{t}$ and $W +$ jets events.

In the merged channel, to ensure the decay products are contained in the large-R jet, a $2m_J/p_{\mathrm{T}}^{J} < 0.6$ requirement is applied. The dark Higgs boson candidate jet is required to have at least two nonoverlapping VR track-jets associated with it. Events with an additional b-tagged VR track-jet not associated with the large-R jet are rejected to suppress top quark pair production. In the resolved channel, the dominant background process is $t\bar{t}$ production. This background is reduced by the variables $m_{\mathrm{T}}^{b,\mathrm{min/max}} = \sqrt{2p_{\mathrm{T}}^{b,\mathrm{min/max}} E_{\mathrm{T}}^{\mathrm{miss}}[1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{b,\mathrm{min/max}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]}$ and a requirement of $m_{\mathrm{T}}^{b,\mathrm{min}} > 170$ GeV and $m_{\mathrm{T}}^{b,\mathrm{max}} > 200$ GeV, where $p_{\mathrm{T}}^{b,\mathrm{min}}$ and $p_{\mathrm{T}}^{b,\mathrm{max}}$ are defined as the p_{T} of the b-jet that is closer to (min) or further from (max) $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in ϕ. To suppress $t\bar{t}$ processes further, the central small-R jet multiplicity is required to be ≤ 4. An $\mathcal{S} > 12$ requirement is also applied and results in negligible multijet background.

The largest SR background contributions come from SM $Z(\to \nu\bar{\nu}) +$ jets processes (48%–60%), increasing in higher $E_{\mathrm{T}}^{\mathrm{miss}}$ categories. In the merged topology, SM diboson production (17%) and $W(\to \ell\nu) +$ jets (9%–13%) provide subleading contributions; top quark pair production (10%–30%) and $W(\to \ell\nu) +$ jets processes (13%–15%) contribute in the resolved toplogy. Two CRs are defined to improve the modeling of the $V +$ jets background: the single-muon CR (1μ-CR) enriched in $W +$ jets and $t\bar{t}$ and the two-lepton CR (2ℓ-CR) dominated by $Z +$ jets. The 1μ-CR follows the same selection and $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger as the SR, except that events must contain exactly one "medium" muon [51] with $p_{\mathrm{T}} > 27$ GeV and no "loose" electrons with $p_{\mathrm{T}} > 7$ GeV. It is split into two regions depending on the muon charge to provide additional discrimination between these two backgrounds, due to the larger cross-section for W^+ boson production in pp collisions. Events in the 2ℓ-CR are selected using the same requirements as in the SR, except that events must contain exactly two oppositely charged "loose" electrons or "medium" muons and satisfy $\mathcal{S} > 12$, with an additional requirement that this significance be lower than 5 when considering $E_{\mathrm{T}}^{\mathrm{miss}}$ calculated with the two visible leptons. The leading electon (muon) must fulfill $p_{\mathrm{T}} > 27(25)$ GeV, while the subleading lepton must satisfy $p_{\mathrm{T}} > 7$ GeV. The dilepton system mass and p_{T} must be consistent with the Z boson hypothesis of $|m_{\ell\ell} - m_Z| < 10$ GeV and $p_{\mathrm{T}}^{\ell\ell} > 150$ GeV.

To maintain sensitivity to signals generating higher $E_{\mathrm{T}}^{\mathrm{miss}}$ values and constrain background processes more effectively, events are further categorized in $E_{\mathrm{T}}^{\mathrm{miss}}$/GeV: [150, 200), [200, 350), and [350, 500) in the resolved category and $E_{\mathrm{T}}^{\mathrm{miss}}$/GeV: [500, 750), ≥ 750 in the merged category. The CRs in the resolved category are divided in the same way. The boundary between resolved and merged categories at 500 GeV is optimized for search sensitivity. To match the $E_{\mathrm{T}}^{\mathrm{miss}}$ kinematics of $V +$ jets processes in the SR, $\vec{E}_{\mathrm{T},\mu}^{\mathrm{miss}} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\mu}$ is used in the 1μ-CR, incorporating the p_{T} of the W boson. Similarly, the addition of $\vec{p}_{\mathrm{T}}^{\ell\ell}$ in the 2ℓ-CR provides an analog to the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the SR.

Experimental systematic uncertainties affect the reconstruction of the dark Higgs boson candidate. These include uncertainties in the JMS [45] and the JES and JER [38] of both the small-R and large-R jets and uncertainties in the calibrations of the b-jet identification algorithms [47,52,53]. Uncertainties in the lepton identification efficiencies [29,30], $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger efficiency, energy scale, and resolution [50] are found to be negligible, as is the uncertainty in the luminosity [54]. Theoretical systematic uncertainties originate from the modeling of the signal and major background processes and are detailed in the Appendix.

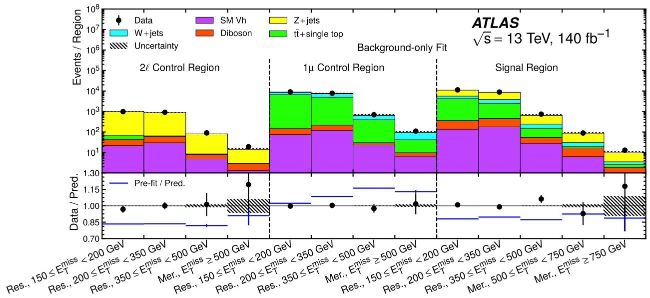

FIG. 1. Data and predicted SM background yields after a simultaneous background-only fit to each resolved (Res.) and merged (Mer.) SR and CR E_T^{miss} category. The ratio of the data to the SM expectation is shown in the lower panel; the lines give the ratios of the prefit to the postfit background predictions, and the shaded areas indicate the total uncertainty in the predictions.

Limits on DM signals are extracted via a simultaneous maximum-likelihood fit [55,56] of signal and background simulations to the binned candidate mass distributions in the SR and to the event yields in the CRs. The normalizations of $Z+$jets, $t\bar{t}$, and $W+$jets processes are free parameters in the fit and are constrained by the total event yields, considering each E_T^{miss} region separately in the SR and CRs. Systematic uncertainties are parameterized as nuisance parameters with Gaussian prior probabilities and constrain the fit templates and normalizations [57]. Statistical uncertainties in the data are the largest source of uncertainty (75%–85% of the total), with systematic uncertainties, specifically those in the calibration of the large-R jet b-tagging algorithm, becoming more important at larger p_T and $m_{Z'}$ values (20%–47%). The largest theoretical uncertainties are in the modeling of $Z+$jets processes (15%–25%) and those associated with the normalization of $V+$jets processes (10%–15%). At $m_s \approx$ 50 GeV and high $m_{Z'}$, the predominance of $Z+$jets increases the impact of its normalization uncertainty (up to 41% of the total).

The observed and fitted yields in the SR and CR categories obtained after a simultaneous fit under the hypothesis that only SM contributions are present ("background-only fit") are shown in Fig. 1. The overall yields in the CRs and the SR are found to be well described by SM expectations, with the fit favoring a mild increase (∼20%) of the $Z+$jets contribution. The prefit uncertainties cover the differences between the data and prefit background predictions. Figure 2 shows the mass distributions m_{bb} of the s candidate mass in the SR categories after the background-only fit. The MC simulations agree well with the data in the CRs, indicating that $V+$jets background processes are well modeled. The data exceed the SM

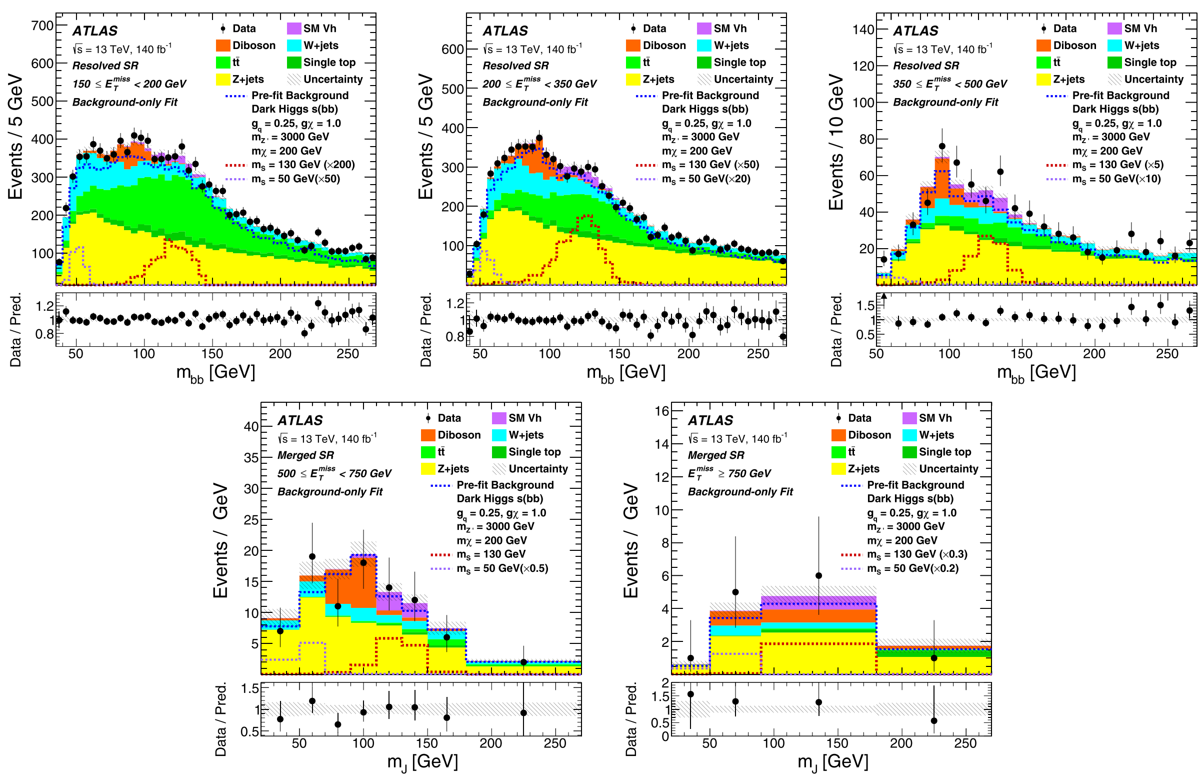

FIG. 2. The m_{bb} distributions for data and SM expectations in the different E_T^{miss} regions for the resolved (top row) and merged (bottom row) topologies after a background-only simultaneous fit to data. The shaded area represents the total uncertainty in the predicted yields. Two signal distributions are overlaid, multiplied in each E_T^{miss} region by a scale factor indicated in the legend for visibility. The lower panels show the ratios of the data to the predictions.

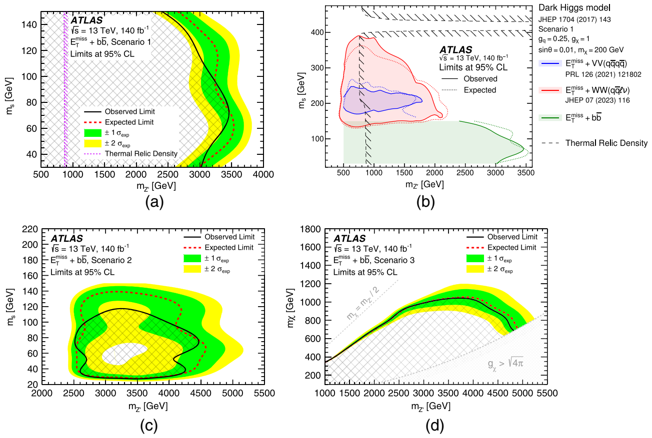

FIG. 3. Observed (expected) exclusion regions at 95% CL for (a),(b) scenario 1, (c) scenario 2, and (d) scenario 3. The $\pm 1\sigma$ ($\pm 2\sigma$) expected exclusion intervals are shown as the filled inner (outer) bands (a),(c),(d). The observed relic density is indicated with a dashed line for scenario 1 (a),(b), with the diagonal lines indicating an overabundance of DM. The filled areas of (b) are excluded, with the open contours indicating regions not explored for a given signature. The lower right shaded area indicates the region beyond the g_χ perturbative limit for scenario 3(d).

expectation slightly around $m_s = 60$ GeV in the $350 \leq E_T^{\text{miss}} < 500$ GeV category. Its local significance is 1.6 standard deviations (σ). A smaller, very localized excess is also seen near $m_s = 130$ GeV in the same category and is narrower than the resolution in m_s. The observed results in the SR indicate that the data are in agreement with SM predictions with no significant evidence of a DM signal.

Consequently, upper limits are set on the product of the $pp \to s\chi\chi$ production crosssection and branching fraction $\mathcal{B}(s \to b\bar{b})$), using a modified frequentist approach (CL_s) [58] with a test statistic based on the profile likelihood in the asymptotic approximation [59]. Exclusion contours at 95% confidence level (CL) for the dark Higgs model are presented in Fig. 3. The two-dimensional $(m_{Z'}, m_s)$ plane for scenarios 1 and 2 are shown in Figs. 3(a)–3(c). In scenario 1, with $g_\chi = 1$ and $m_\chi = 200$ GeV, $m_{Z'}$ values are excluded up to 3.4 TeV at $m_s = 70$ GeV, which are the highest mass exclusions for this conventional benchmark model. Figure 3(b) summarizes the exclusions on this model. The observed relic density is obtained for $m_{Z'} = 850$ GeV and for $m_s \simeq 2m_\chi = 400$ GeV where dark Higgs boson annihilation processes are greatly enhanced and deplete the relic abundance for all $m_{Z'}$ values.

In scenario 2 [Fig. 3(c)], the DM coupling g_χ varies to satisfy the observed relic density throughout; thus the exclusion behavior is more complex. The increased DM mass ($m_\chi = 900$ GeV) leads to reduced crosssections, with $m_{Z'}$ masses around $m_{Z'} = 2.5$ TeV having g_χ values near unity and lying close to the expected exclusions. The relic density constraint requires larger g_χ values for larger $m_{Z'}$ values, as the DM annihilation process $\chi\chi \to Z' \to q\bar{q}$ becomes more inefficient. The increasing coupling, and thus greater probability for the Z' to emit a dark Higgs boson and decay into DM, increases the crosssection, extending sensitivity to higher masses, where $m_{Z'}$ values can be excluded up to 4.5 TeV for $m_s = 75$ GeV. Below $m_{Z'} = 2.5$ TeV, and especially for $m_{Z'} \sim 2m_\chi$, the annihilation process above becomes very efficient, and the small g_χ couplings that match the relic density lead to crosssections that are too small to be excluded. The observed exclusion range in $m_{Z'}$ becomes narrower than expected at higher m_s values owing to the small excesses in data near $m_{bb} = 50$ GeV and $m_{bb} = 130$ GeV discussed above.

The exclusion limits on the $m_{Z'}$ and m_χ plane for scenario 3 are shown in Fig. 3(d). Again, the relic density depends upon the efficiency of the $\chi\chi \to Z' \to q\bar{q}$ process, resulting in increasing g_χ values for higher $m_{Z'}$ values and lower χ masses (lower right of figure). For DM masses up to 700 GeV, $m_{Z'}$ values up to the perturbative limit are excluded, reaching a maximum of 4.8 TeV at that m_χ. The merged SR dominates the sensitivity at low m_s and high $m_{Z'}$, while the resolved SR contributes for $m_{Z'} < 2$ TeV.

In conclusion, this Letter reports a novel search for dark matter in a final state with large E_T^{miss} and a resonant $b\bar{b}$ pair with $30 < m_{bb} < 150$ GeV using 140 fb^{-1} of 13 TeV pp data collected by the ATLAS detector at the LHC. The analysis employs jet reclustering and a new $X \to b\bar{b}$ tagging algorithm to provide sensitivity to low m_{bb} and highly boosted bb-jets. No excess over the expected background prediction is observed, and 95% CL exclusions are placed on dark Higgs boson models with $m_s < 150$ GeV. In this dark Higgs boson mass range, Z' mediators are excluded with masses up to 3.4 TeV, for a benchmark model with $g_\chi = 1$, $g_q = 0.25$, and $\sin\theta = 0.01$ and up to 4.8 TeV in a relic density inspired benchmark model in which couplings vary more widely. This first experimental search for this signature significantly extends existing exclusions on this model and strongly constrains regions compatible with the observed DM relic density, which occur primarily when the dark Higgs boson is comparable or lighter in mass than the DM candidate, such that related annihilation processes dominate. These results complement other higher-mass dark Higgs boson and collider DM searches.

Acknowledgments—We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK), and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [60]. We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC, and CFI, Canada; CERN; ANID, Chile; CAS, MOST, and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF, and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; and DOE and NSF, United States of America. Individual groups and members have received support from BCKDF, CANARIE, CRC, and DRAC, Canada; CERN-CZ, FORTE, and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU, and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex, and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales, and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya, and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; and The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members wish to acknowledge support from CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1190886, FONDECYT 1230812, FONDECYT 1230987); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC—12175119, NSFC 12275265, NSFC-12075060); Czech Republic: Czech Science Foundation (GACR—24-11373S), Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC—101002463); European Union: European Research Council (ERC—948254, ERC 101089007), Horizon 2020 Framework Programme (MUCCA—CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002), Investissements d'Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG—469666862, DFG—CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (PRIN—20223N7F8K—PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP21H05085, JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020—VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, NCN & H2020 MSCA 945339, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I), PROMETEO and GenT Programmes Generalitat Valenciana (CIDEGENT/2019/023, CIDEGENT/2019/027); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2018-00482, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR grant 2021-03651), Knut and Alice Wallenberg Foundation (KAW 2018.0157, KAW 2018.0458, KAW 2019.0447, KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF—PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); and United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

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End Matter

Appendix—The ATLAS detector and trigger system: The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a superconducting solenoid, sampling electromagnetic and hadronic calorimeters, and a muon spectrometer with three toroidal superconducting magnets. A two-level trigger system [61] selects events for offline analysis. Events in the SR and the single-muon CR were collected by triggers on the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstructed from calorimeter information only [62] above a threshold that varied from 90 to 110 GeV. Events in the two-lepton CR were recorded using single-lepton triggers with p_{T} thresholds of 24–26 GeV [63,64], depending on the data taking period. An extensive software suite [65] is used in the experiment.

Simulation of signal and background processes: Simulated signal samples for the $pp \to Z' \to s\chi\chi \to b\bar{b}\chi\chi$ process, illustrated in Fig. 4, were generated at leading order (LO) in quantum chromodynamics (QCD) with up to one additional parton in the event, using MADGRAPH5_AMC@NLO2.9.3 [66] interfaced to PYTHIA8.245[67], both using the NNPDF3.0 LO parton distribution function (PDF) set [68] with $\alpha_s = 0.13$ [68] and the A14 set of tuned parameters [69].

The $V+$jets background was simulated with SHERPA2.2.11 [70], using next-to-leading-order (NLO) matrix elements for up to two partons and LO matrix elements for up to five partons calculated with the COMIX [71] and OPENLOOPS [72–74] libraries. The matching to the SHERPA parton shower [75] used the MEPS@NLO prescription [76–79] with the set of tuned parameters developed by the SHERPA authors. The NNPDF 3.0 NNLO set of PDFs [68] was used, and the samples were normalized to the next-to-next-to-leading-order (NNLO) prediction [80]. Backgrounds from $t\bar{t}$ production and single top quark production were generated at NLO in QCD with POWHEG BOXv2 [81–84] using the NNPDF3.0 NLO PDF set, interfaced to PYTHIA8.230. Parton shower simulations with PYTHIA8.230 used the A14 set of tuned parameters [69] with the NNPDF2.3 LO PDF set. The $t\bar{t}$ samples were normalized using calculations at NNLO in QCD including next-to-next-to-leading logarithmic soft-gluon terms calculated using TOP++ 2.0 [85–91]. The single-top-quark processes were normalized to crosssections at NLO in QCD from HATHORv2.1 [92,93]. Samples of diboson final states (VV) were simulated with the SHERPA2.2.1 or 2.2.2 [70] generator depending on the process and normalized using calculations at NNLO in QCD using the NNPDF3.0 NNLO PDF set. Backgrounds from associated Vh production were generated at NLO in QCD with POWHEG BOX interfaced to PYTHIA8.186 using the NNPDF3.0 NLO PDF set. The $qq \to Vh$ and $gg \to Vh$ processes were normalized using calculations at NNLO in QCD and at NLO in QCD combined with next-to-leading-logarithmic order corrections, respectively [94–100]. Top quarks were decayed at LO using MADSPIN [101,102] to preserve all spin correlations. The decays of bottom and charm hadrons were simulated using the EVTGEN1.6.0 program [103]. For all signal and background simulations, contributions from additional pp interactions in the same and neighboring bunch crossings (pileup) were simulated through the overlay of inelastic pp simulations from PYTHIA8.186 [104] using the A3 set of tuned parameters [105] and the NNPDF2.3 LO PDF set [106].

Theoretical and modelling uncertainties assessed include those from the choice of PDFs and the factorization and renormalization scales. Additionally, uncertainties in the choice of the matrix element and parton shower generator are assessed through dedicated, alternative MC simulations. For top quark processes, uncertainties in the choice of generator were evaluated by comparison with event samples generated with MADGRAPH5_AMC@NLO2.6.0 interfaced to PYTHIA8.230 and the nominal POWHEG generator hadronized by HERWIG7.04 [107,108], using the H7UE set of tuned parameters [108] and the MMHT2014 LO PDF set [109]. For single top quark production in the tW channel, an alternative sample was generated using the diagram subtraction scheme [110,111] to estimate the uncertainty arising from the interference with $t\bar{t}$ production. For $V+$jets processes, a sample generated with MADGRAPH5_AMC@NLO2.6.2 at LO in QCD with up to four parton emissions using the NNPDF2.3 LO PDF set and interfaced to PYTHIA8.230 using a merging scale of $Q_{\mathrm{cut}} =$ 30 GeV was employed. Uncertainties in the matching parameter and resummation scale were also assessed.

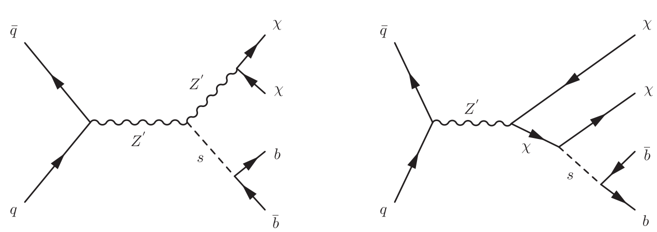

FIG. 4. Signal diagrams illustrating the resonant $pp \to Z' \to s\chi\chi \to b\bar{b}\chi\chi$ process.

G. Aad,[104] E. Aakvaag,[17] B. Abbott,[123] S. Abdelhameed,[119a] K. Abeling,[56] N. J. Abicht,[50] S. H. Abidi,[30] M. Aboelela,[45] A. Aboulhorma,[36e] H. Abramowicz,[155] H. Abreu,[154] Y. Abulaiti,[120] B. S. Acharya,[70a,70b,b] A. Ackermann,[64a] C. Adam Bourdarios,[4] L. Adamczyk,[87a] S. V. Addepalli,[27] M. J. Addison,[103] J. Adelman,[118] A. Adiguzel,[22c] T. Adye,[137] A. A. Affolder,[139] Y. Afik,[40] M. N. Agaras,[13] J. Agarwala,[74a,74b] A. Aggarwal,[102] C. Agheorghiesei,[28c] F. Ahmadov,[39,c] W. S. Ahmed,[106] S. Ahuja,[97] X. Ai,[63e] G. Aielli,[77a,77b] A. Aikot,[166] M. Ait Tamlihat,[36e] B. Aitbenchikh,[36a] M. Akbiyik,[102] T. P. A. Åkesson,[100] A. V. Akimov,[38] D. Akiyama,[171] N. N. Akolkar,[25] S. Aktas,[22a] K. Al Khoury,[42] G. L. Alberghi,[24b] J. Albert,[168] P. Albicocco,[54] G. L. Albouy,[61] S. Alderweireldt,[53] Z. L. Alegria,[124] M. Aleksa,[37] I. N. Aleksandrov,[39] C. Alexa,[28b] T. Alexopoulos,[10] F. Alfonsi,[24b] M. Algren,[57] M. Alhroob,[170] B. Ali,[135] H. M. J. Ali,[93] S. Ali,[32] S. W. Alibocus,[94] M. Aliev,[34c] G. Alimonti,[72a] W. Alkakhi,[56] C. Allaire,[67] B. M. M. Allbrooke,[150] J. F. Allen,[53] C. A. Allendes Flores,[140f] P. P. Allport,[21] A. Aloisio,[73a,73b] F. Alonso,[92] C. Alpigiani,[142] Z. M. K. Alsolami,[93] M. Alvarez Estevez,[101] A. Alvarez Fernandez,[102] M. Alves Cardoso,[57] M. G. Alviggi,[73a,73b] M. Aly,[103] Y. Amaral Coutinho,[84b] A. Ambler,[106] C. Amelung,[37] M. Amerl,[103] C. G. Ames,[111] D. Amidei,[108] K. Amirie,[158] S. P. Amor Dos Santos,[133a] K. R. Amos,[166] S. An,[85] V. Ananiev,[128] C. Anastopoulos,[143] T. Andeen,[11] J. K. Anders,[37] A. C. Anderson,[60] S. Y. Andrean,[48a,48b] A. Andreazza,[72a,72b] S. Angelidakis,[9] A. Angerami,[42] A. V. Anisenkov,[38] A. Annovi,[75a] C. Antel,[57] E. Antipov,[149] M. Antonelli,[54] F. Anulli,[76a] M. Aoki,[85] T. Aoki,[157] M. A. Aparo,[150] L. Aperio Bella,[49] C. Appelt,[19] A. Apyan,[27] S. J. Arbiol Val,[88] C. Arcangeletti,[54] A. T. H. Arce,[52] E. Arena,[94] J-F. Arguin,[110] S. Argyropoulos,[55] J.-H. Arling,[49] O. Arnaez,[4] H. Arnold,[149] G. Artoni,[76a,76b] H. Asada,[113] K. Asai,[121] S. Asai,[157] N. A. Asbah,[37] R. A. Ashby Pickering,[170] K. Assamagan,[30] R. Astalos,[29a] K. S. V. Astrand,[100] S. Atashi,[162] R. J. Atkin,[34a] M. Atkinson,[165] H. Atmani,[36f] P. A. Atmasiddha,[131] K. Augsten,[135] S. Auricchio,[73a,73b] A. D. Auriol,[21] V. A. Austrup,[103] G. Avolio,[37] K. Axiotis,[57] G. Azuelos,[110,d] D. Babal,[29b] H. Bachacou,[138] K. Bachas,[156,e] A. Bachiu,[35] F. Backman,[48a,48b] A. Badea,[40] T. M. Baer,[108] P. Bagnaia,[76a,76b] M. Bahmani,[19] D. Bahner,[55] K. Bai,[126] J. T. Baines,[137] L. Baines,[96] O. K. Baker,[175] E. Bakos,[16] D. Bakshi Gupta,[8] L. E. Balabram Filho,[84b] V. Balakrishnan,[123] R. Balasubramanian,[117] E. M. Baldin,[38] P. Balek,[87a] E. Ballabene,[24b,24a] F. Balli,[138] L. M. Baltes,[64a] W. K. Balunas,[33] J. Balz,[102] I. Bamwidhi,[119b] E. Banas,[88] M. Bandieramonte,[132] A. Bandyopadhyay,[25] S. Bansal,[25] L. Barak,[155] M. Barakat,[49] E. L. Barberio,[107] D. Barberis,[58b,58a] M. Barbero,[104] M. Z. Barel,[117] K. N. Barends,[34a] T. Barillari,[112] M-S. Barisits,[37] T. Barklow,[147] P. Baron,[125] D. A. Baron Moreno,[103] A. Baroncelli,[63a] G. Barone,[30] A. J. Barr,[129] J. D. Barr,[98] F. Barreiro,[101] J. Barreiro Guimarães da Costa,[14] U. Barron,[155] M. G. Barros Teixeira,[133a] S. Barsov,[38] F. Bartels,[64a] R. Bartoldus,[147] A. E. Barton,[93] P. Bartos,[29a] A. Basan,[102] M. Baselga,[50] A. Bassalat,[67,f] M. J. Basso,[159a] S. Bataju,[45] R. Bate,[167] R. L. Bates,[60] S. Batlamous,[101] B. Batool,[145] M. Battaglia,[139] D. Battulga,[19] M. Bauce,[76a,76b] M. Bauer,[80] P. Bauer,[25] L. T. Bazzano Hurrell,[31] J. B. Beacham,[52] T. Beau,[130] J. Y. Beaucamp,[92] P. H. Beauchemin,[161] P. Bechtle,[25] H. P. Beck,[20,g] K. Becker,[170] A. J. Beddall,[83] V. A. Bednyakov,[39] C. P. Bee,[149] L. J. Beemster,[16] T. A. Beermann,[37] M. Begalli,[84d] M. Begel,[30] A. Behera,[149] J. K. Behr,[49] J. F. Beirer,[37] F. Beisiegel,[25] M. Belfkir,[119b] G. Bella,[155] L. Bellagamba,[24b] A. Bellerive,[35] P. Bellos,[21] K. Beloborodov,[38] D. Benchekroun,[36a] F. Bendebba,[36a] Y. Benhammou,[155] K. C. Benkendorfer,[62] L. Beresford,[49] M. Beretta,[54] E. Bergeaas Kuutmann,[164] N. Berger,[4] B. Bergmann,[135] J. Beringer,[18a] G. Bernardi,[5] C. Bernius,[147] F. U. Bernlochner,[25] F. Bernon,[37,104] A. Berrocal Guardia,[13] T. Berry,[97] P. Berta,[136] A. Berthold,[51] S. Bethke,[112] A. Betti,[76a,76b] A. J. Bevan,[96] N. K. Bhalla,[55] S. Bhatta,[149] D. S. Bhattacharya,[169] P. Bhattarai,[147] K. D. Bhide,[55] V. S. Bhopatkar,[124] R. M. Bianchi,[132] G. Bianco,[24b,24a] O. Biebel,[111] R. Bielski,[126] M. Biglietti,[78a] C. S. Billingsley,[45] M. Bindi,[56] A. Bingul,[22b] C. Bini,[76a,76b] A. Biondini,[94] G. A. Bird,[33] M. Birman,[172] M. Biros,[136] S. 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Cheong,[147] A. Cheplakov,[39] E. Cheremushkina,[49] E. Cherepanova,[117] R. Cherkaoui El Moursli,[36e] E. Cheu,[7] K. Cheung,[66] L. Chevalier,[138] V. Chiarella,[54] G. Chiarelli,[75a] N. Chiedde,[104] G. Chiodini,[71a] A. S. Chisholm,[21] A. Chitan,[28b] M. Chitishvili,[166] M. V. Chizhov,[39,l] K. Choi,[11] Y. Chou,[142] E. Y. S. Chow,[116] K. L. Chu,[172] M. C. Chu,[65a] X. Chu,[14,114c] Z. Chubinidze,[54] J. Chudoba,[134] J. J. Chwastowski,[88] D. Cieri,[112] K. M. Ciesla,[87a] V. Cindro,[95] A. Ciocio,[18a] F. Cirotto,[73a,73b] Z. H. Citron,[172] M. Citterio,[72a] D. A. Ciubotaru,[28b] A. Clark,[57] P. J. Clark,[53] N. Clarke Hall,[98] C. Clarry,[158] J. M. Clavijo Columbie,[49] S. E. Clawson,[49] C. Clement,[48a,48b] Y. Coadou,[104] M. Cobal,[70a,70c] A. Coccaro,[58b] R. F. Coelho Barrue,[133a] R. Coelho Lopes De Sa,[105] S. Coelli,[72a] B. Cole,[42] J. Collot,[61] P. Conde Muiño,[133a,133g] M. P. Connell,[34c] S. H. Connell,[34c] E. I. Conroy,[129] F. Conventi,[73a,m] H. G. Cooke,[21] A. M. Cooper-Sarkar,[129] F. A. Corchia,[24b,24a] A. Cordeiro Oudot Choi,[130] L. D. Corpe,[41] M. Corradi,[76a,76b] F. Corriveau,[106,n] A. Cortes-Gonzalez,[19] M. J. Costa,[166] F. Costanza,[4] D. Costanzo,[143] B. M. Cote,[122] J. Couthures,[4] G. Cowan,[97] K. Cranmer,[173] D. Cremonini,[24b,24a] S. Crépé-Renaudin,[61] F. Crescioli,[130] M. Cristinziani,[145] M. Cristoforetti,[79a,79b] V. Croft,[117] J. E. Crosby,[124] G. Crosetti,[44b,44a] A. Cueto,[101] H. Cui,[98] Z. Cui,[7] W. R. Cunningham,[60] F. Curcio,[166] J. R. Curran,[53] P. Czodrowski,[37] M. M. Czurylo,[37] M. J. Da Cunha Sargedas De Sousa,[58b,58a] J. V. Da Fonseca Pinto,[84b] C. Da Via,[103] W. Dabrowski,[87a] T. Dado,[50] S. Dahbi,[152] T. Dai,[108] D. Dal Santo,[20] C. Dallapiccola,[105] M. Dam,[43] G. D'amen,[30] V. D'Amico,[111] J. Damp,[102] J. R. Dandoy,[35] D. Dannheim,[37] M. Danninger,[146] V. Dao,[149] G. Darbo,[58b] S. J. Das,[30,o] F. Dattola,[49] S. D'Auria,[72a,72b] A. D'Avanzo,[73a,73b] C. David,[34a] T. Davidek,[136] I. Dawson,[96] H. A. Day-hall,[135] K. De,[8] R. De Asmundis,[73a] N. De Biase,[49] S. De Castro,[24b,24a] N. De Groot,[116] P. de Jong,[117] H. De la Torre,[118] A. De Maria,[114a] A. De Salvo,[76a] U. De Sanctis,[77a,77b] F. De Santis,[71a,71b] A. De Santo,[150] J. B. De Vivie De Regie,[61] D. V. Dedovich,[39] J. Degens,[94] A. M. Deiana,[45] F. Del Corso,[24b,24a] J. Del Peso,[101] F. Del Rio,[64a] L. Delagrange,[130] F. Deliot,[138] C. M. Delitzsch,[50] M. Della Pietra,[73a,73b] D. Della Volpe,[57] A. Dell'Acqua,[37] L. Dell'Asta,[72a,72b] M. Delmastro,[4] P. A. Delsart,[61] S. Demers,[175] M. Demichev,[39] S. P. Denisov,[38] L. D'Eramo,[41] D. Derendarz,[88] F. Derue,[130] P. Dervan,[94] K. Desch,[25] C. Deutsch,[25] F. A. Di Bello,[58b,58a] A. Di Ciaccio,[77a,77b] L. Di Ciaccio,[4] A. Di Domenico,[76a,76b] C. Di Donato,[73a,73b]

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