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Probing the pseudoscalar portal to dark matter via $\bar{b}bZ(\to \ell\ell)+\not{E}_T$: From the LHC to the Galactic Center excess

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We propose a new search for dark matter at the LHC, characteristic of scenarios beyond the Standard Model with a pseudoscalar portal between the visible and dark sectors. This search, leading to a $\bar{b}bZ(\to \ell\ell)+\not{E}_T$ final state, reaches large regions of parameter space not probed by dark matter searches via multijet $+\not{E}_T$, searches for new scalars and flavor bounds. We show that this search could be used to test the dark matter origin of the gamma-ray Galactic Center excess with LHC Run 2 data.

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I. INTRODUCTION

The nature of dark matter (DM) is an unsolved mystery at the interface of particle physics and cosmology. One widely studied DM candidate is the weakly interacting massive particle (WIMP), whose relic abundance is obtained via thermal freeze-out in the early Universe with a mass in the range GeV–TeV (see Ref. [1] for a review).

There is an ongoing multipronged experimental effort to search for WIMP DM via its interactions with Standard Model particles: indirectly by measuring the energetic particles produced by DM annihilations in space and directly by measuring the scattering of ambient DM from nuclei. The observed gamma-ray excess in the Fermi-LAT space telescope observations of the Milky Way Galactic Center [2] may be interpreted as the existence of weak-scale DM annihilating into $\bar{b}b$ pairs [3–6] (see Ref. [7] for a recent exhaustive analysis of the excess and its DM interpretation). While arguably there is some tension between the DM interpretation of the gamma-ray excess at the Galactic Center and the nonobservation of emission due to DM annihilation in dwarf spheroidal galaxies [8],[1] the self-annihilation cross section needed to explain the excess can be consistent with that required to generate the observed relic abundance through thermal freeze-out in the early Universe $\langle \sigma v\rangle \simeq 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$. At the same time, current limits on the spin-independent DM interaction cross section with nuclei by the LUX [10] and PandaX [11] experiments strongly constrain DM masses in the range 10–100 GeV. A compelling DM interpretation of the gamma-ray Galactic Center excess (GCE) in combination with the nonobservation of a signal in DM direct detection experiments is via the existence of a pseudoscalar mediator between the visible and DM sectors [12–14], which yields spin-dependent DM-nucleon interactions, for which experimental limits are much less stringent. Pseudoscalar-mediated DM-nucleon interactions generally lie well below the reach of present DM direct detection experiments.

Direct and indirect probes of DM are complemented by searches at colliders, where pairs of DM particles could be produced. These escape the detector and manifest themselves as events possessing an imbalance in momentum conservation, via the presence of missing transverse momentum $\not{E}_T$ recoiling against a visible final state X. Searches for events with large $\not{E}_T$ are currently a major focus at the Large Hadron Collider (LHC) largely due to their connection to DM [15]. In this work we present a new search avenue for DM at the LHC, characteristic of renormalizable, gauge-invariant scenarios beyond the Standard Model with a pseudoscalar portal between the visible and dark sectors. The search is characterized by a $b\bar{b}Z(Z\to \ell\ell)+\not{E}_T$ final state. We show that this new DM search channel of a leptonically decaying Z boson, two bottom quarks and missing transverse momentum will yield a powerful probe of the region of parameter space consistent with a DM interpretation of the GCE through LHC Run 2 data.

II. THE PSEUDOSCALAR PORTAL INTO DARK MATTER

We focus our analysis on scenarios with a pseudoscalar mediator between DM and the SM fermions. These can yield a compelling GCE through DM annihilation into b quarks (see e.g. Refs. [13,14]). For concreteness we consider DM to be a Dirac fermion χ with mass m_χ, singlet under the SM gauge interactions and coupling to a real singlet pseudoscalar mediator a_0 via

$$V_{\mathrm{dark}} = \frac{m_{a_0}^2}{2}a_0^2 + m_\chi\bar{\chi}\chi + y_\chi a_0\bar{\chi}i\gamma^5\chi. \tag{1}$$

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[1] However we are also aware that the errors on the astrophysical J-factors used in [8] are somewhat small and allowing more freedom in the fit and adding a systematic error representing the possibility of triaxiality in the halos could reduce this disagreement somewhat [9].

However, for the pseudoscalar to be able to mediate interactions between DM and the SM fermions, $SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$ gauge invariance requires the existence of new states beyond the SM in addition to the DM particle and the pseudoscalar mediator [16,17]. A renormalizable and gauge-invariant realization of the pseudoscalar portal between DM and the SM leads to the extension of the SM Higgs sector with a second Higgs doublet, as first noted in Ref. [16]. A theory with the required ingredients then naturally resembles a two-Higgs-doublet model (2HDM) [16–19]. We note that this also yields a compelling explanation for the preferential coupling of the pseudoscalar mediator to third-generation SM fermions (b quarks and τ leptons), in relation to the GCE.

In the following we provide a brief review of the 2HDM aspects of relevance to us (for a general review of 2HDM theory and phenomenology, see e.g. Ref. [20]). The two-Higgs doublets are $H_j = (\phi_j^+, (v_j + h_j + i\eta_j)/\sqrt{2})^T$, with $(j = 1,\ 2)$. v_j are the vacuum expectation values of the doublets ($\sqrt{v_1^2 + v_2^2} = v$ and $v_2/v_1 \equiv \tan\beta$). We consider a 2HDM scalar potential with charge-parity (CP) conservation and a softly broken $\mathbb{Z}_2$ symmetry. The presence of this $\mathbb{Z}_2$ symmetry in the couplings of the doublets H_j to fermions allows to forbid dangerous tree-level flavor-changing neutral currents, by forcing each fermion type to couple to one doublet only [21]. In the Type I 2HDM all fermions couple to H_2, while for the Type II 2HDM up-type quarks couple to H_2 and down-type quarks and leptons couple to H_1. The scalar spectrum of the 2HDM contains a charged scalar $H^\pm = \cos\beta\phi_2^\pm - \sin\beta\phi_1^\pm$, a neutral CP-odd scalar $A_0 = \cos\beta\eta_2 - \sin\beta\eta_1$ and two neutral CP-even scalars $h = \cos\alpha h_2 - \sin\alpha h_1$, $H_0 = -\sin\alpha h_2 - \cos\alpha h_1$. We identify h with the 125 GeV Higgs state, which has SM-like properties when the mixing angle α in the neutral CP-even sector satisfies $\beta - \alpha = \pi/2$.

As we show now, the 2HDM allows for pseudoscalar-mediated interactions between the visible sector and the DM candidate χ in Eq. (1). The portal between the visible and dark sectors occurs via

$$V_{\text{portal}} = i\kappa a_0 H_1^\dagger H_2 + \text{H.c.} \tag{2}$$

which causes the would-be 2HDM state A_0 to mix with a_0, yielding two pseudoscalar mass eigenstates a, A: $a = c_\theta a_0 - s_\theta A_0$, $A = c_\theta A_0 + s_\theta a_0$, with $c_\theta \equiv \cos\theta$ and $s_\theta \equiv \sin\theta$. This mixing allows both a and A to couple simultaneously to DM and the SM fermions, providing the portal between the visible and DM sectors. The coupling of a (A) to DM is given by $s_\theta y_\chi$ ($c_\theta y_\chi$). Regarding the pseudoscalar couplings to SM fermions, these are given by $g_{\text{SM}} \times y_f/\sqrt{2}$ (where y_f is the Yukawa coupling of the fermion). We consider here a Type II 2HDM, for which the g_{SM} coupling of a (A) is given by $s_\theta \tan^{-1}\beta$ ($c_\theta \tan^{-1}\beta$) for up-type quarks and $s_\theta \tan\beta$ ($c_\theta \tan\beta$) for down-type quarks and charged leptons. To simplify the following discussion, we also restrict ourselves to $\beta - \alpha = \pi/2$ (the so-called alignment limit) where h behaves exactly as the SM Higgs [22]. We note that for a Type II 2HDM, deviations from the alignment limit are strongly constrained by LHC Higgs measurements [23].

For the rest of this work, we consider the benchmark value $m_\chi = 45$ GeV: for a pseudoscalar mediator, the authors of Ref. [7] found a preferred range $m_\chi \in [50, 170]$ GeV if DM annihilates into b-quark pairs, and $m_\chi \in [10, 20]$ GeV if it annihilates into leptons, concerning the GCE. In the present case, DM annihilates dominantly into b quarks, with a small (~10%) annihilation component into τ leptons. We also consider the mediator A (doublet-like) to be much heavier than a (singlet-like). For $m_\chi < m_a \ll m_A$, DM annihilates to SM particles through s-channel a exchange. The velocity-averaged annihilation cross section for $\chi\bar{\chi} \to \text{SM}$ in the nonrelativistic limit is

$$\langle \sigma \mathrm{v} \rangle = \frac{y_\chi^2}{2\pi} \frac{m_\chi^2}{m_a^4} s_\theta^2 c_\theta^2 \tan^2\beta \left[\left(1 - \frac{4m_\chi^2}{m_a^2} \right)^2 + \frac{\Gamma_a^2}{m_a^2} \right]^{-1} \times \sum_f N_C \frac{m_f^2}{v^2} \sqrt{1 - \frac{m_f^2}{m_a^2}} \tag{3}$$

where Γ_a is the decay width of a. The sum is over quarks ($N_C = 3$) and charged leptons ($N_C = 1$). Reproducing the observed DM relic density requires $\langle \sigma \mathrm{v} \rangle \simeq 3 \times 10^{-26}\,\text{cm}^3/\text{s}$, which favors large values of $\tan\beta$ (particularly for not too large values of y_χ).

Flavor constraints from $\bar{B} \to X_s\gamma$ decays yield a lower bound on $m_{H^\pm}$ in the Type II 2HDM, given by $m_{H^\pm} > 480$ GeV at 95% C.L. [24]. In addition, electroweak precision observables strongly constrain the splitting between the charged scalar $H^\pm$ and either of the neutral states H_0, A [25]. Combined, these yield m_A, m_{H_0}, $m_{H^\pm} \gtrsim 500$ GeV. On the other hand m_A, m_{H_0}, $m_{H^\pm}$ may not be taken arbitrarily high if s_θ and/or m_a are kept fixed due to unitarity constraints. For $m_a \sim 100$ GeV and $\theta = \pi/4$ the unitarity bounds on m_A, m_{H_0} are respectively $m_A \leq 1.4$ TeV, $m_{H_0} \leq 1$ TeV [17]. In the following we take as benchmarks $m_{H^\pm} = m_{H_0} = 600$ GeV, 800 GeV (and assume a somewhat larger m_A).

III. EXPERIMENTAL CONSTRAINTS ON THE DARK PORTAL

The above pseudoscalar dark portal scenario is constrained in a variety of ways. Besides the aforementioned flavor bound $m_{H^\pm} > 480$ GeV from $\bar{B} \to X_s\gamma$ decays, the existence of a light pseudoscalar a coupling to SM fermions can be probed by its contributions to the decay

$B_s \to \mu^+\mu^-$ [26,27], which for $m_a \gg m_{B_s} \simeq 5.36$ GeV may be expressed as[2]

$$\begin{aligned}\mathrm{Br}(B_s \to \mu^+\mu^-) &\\ \simeq \mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} &\\ \times \left(\left| 1 + x_B \tan^2\beta \frac{f(x_t, x_a, r)}{4Y(x_t)} \right|^2 + \left| x_B \tan^2\beta \frac{g(r)}{4Y(x_t)} \right|^2 \right), &\end{aligned} \tag{4}$$

with $x_B = m_b m_{B_s}/m_W^2$, $x_t = m_t^2/m_W^2$, $x_a = m_a^2/m_A^2$, $r = m_{H^\pm}^2/m_t^2$, $r_t = x_t r$, $g(r) = \log(r)/(r-1)$,

$$\begin{aligned} f(x_t, x_a, r) = g(r) + \frac{s_\theta^2}{(r-1)} [2c_\theta^2(x_a + x_a^{-1} - 1) - 1] &\\ \times \left(\frac{r_t \log r_t}{(r_t - 1)} - \frac{x_t \log x_t}{(x_t - 1)} \right), &\end{aligned} \tag{5}$$

and $Y(x)$ is the Inami-Lim function,

$$Y(x) = \frac{x}{8(x-1)^2} [4 - 5x + x^2 + 3x \log x]. \tag{6}$$

The average of the LHCb and CMS measurements of this mode from LHC 7 and 8 TeV data is $\mathrm{Br}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$ [28–30] which may be compared against the SM prediction $(3.65 \pm 0.23) \times 10^{-9}$ [31,32].

For $m_a < m_h/2$ the presence of the decay $h \to aa$ yields stringent constraints on the model [14], and consequently we only consider here the case $m_a > m_h/2$ for which nonstandard Higgs decays are suppressed (note that for $m_\chi = 45$ GeV the three-body decay $h \to a\bar{\chi}\chi$ is also kinematically forbidden above $m_a = 35$ GeV).

LHC searches for the states H_0, A and a decaying to $\tau^+\tau^-$ also place important constraints at large $\tan\beta$ ($a \to \bar{b}b$ has also been considered; see e.g. Ref. [33]). Focusing on $\phi = H_0, a$, the latest CMS search for $\bar{b}b\phi(\phi \to \tau^+\tau^-)$ with an integrated luminosity of 12.9 fb^{-1} [34] yields limits on the parameter space for m_a, m_{H_0}, s_θ, $\tan\beta$.

Finally, the pseudoscalar portal to DM can be probed at the LHC in the $\bar{t}t + \not{E}_T$ and $\bar{b}b + \not{E}_T$ channels (see Ref. [35] for a recent discussion), and in multijet $+ \not{E}_T$ [36]. Using the results from Ref. [37] we find that $\bar{b}b + \not{E}_T$ searches at $\tan\beta \gg 1$ yield significantly weaker constraints than the ones discussed above (e.g. $B_s \to \mu^+\mu^-$). At the same time, $\bar{t}t + \not{E}_T$ searches are currently only sensitive to $\tan\beta < 1$. For multijet $+ \not{E}_T$ searches, using the analysis from Ref. [36] we find that these yield an important constraint at low $\tan\beta$, while still being subdominant to those from the searches discussed in the next section.

IV. A NEW LHC PROBE OF DARK MATTER

Remarkably, when $m_{H_0} \gg m_a$ the decay $H_0 \to Za$ yields a new avenue to probe DM at the LHC. For $\tan\beta \gg 1$ as favored by the GCE, a novel DM search channel presents itself: $pp \to b\bar{b}H_0$, $H_0 \to Za$ $(Z \to \ell^+\ell^-, a \to \bar{\chi}\chi)$. This topology for the final state $\bar{b}b\ell^+\ell^- + \not{E}_T$ has not yet been explored at the LHC, and we show here that this signature allows to probe a wide range of parameter space for pseudoscalar portal scenarios, in particular within the region consistent with a DM interpretation of the GCE.

In order to study the prospects for this signature at the LHC with $\sqrt{s} = 13$ TeV c.m. energy, we require events with two oppositely charged electrons/muons in the invariant mass window $m_{\ell\ell} \in [76, 106]$ GeV, with $p_T^\ell > 20$ GeV and rapidity $|\eta^\ell| < 2.5$. Our event selection further requires $|p_T^{\ell\ell} - \not{E}_T|/p_T^{\ell\ell} < 0.5$ and a separation $\Delta R_{\ell\ell} > 0.4$ between the same-flavor lepton pair. We also demand at least one b-tagged jet with[3] $p_T^b > 30$ GeV.

The main SM backgrounds are $t\bar{t}$ and diboson (WZ and ZZ) + jets production.[4] The requirement of one or more b-tagged jets acts as an effective suppressor of the latter, while the invariant mass window $m_{\ell\ell}$ helps diminish the $t\bar{t}$ background. In order to further reduce SM backgrounds we take advantage of the boosted configuration of the signal for $m_{H_0} \gg m_a + m_Z$, and demand the leading lepton in p_T^ℓ to satisfy $p_T^{\ell_1} > 80$ GeV as well as $p_T^{\ell_1} + p_T^{\ell_2} > 150$ GeV. Finally we use $\not{E}_T$ and the variable m_{T2} [40] to define our signal region. We calculate m_{T2} using Ref. [41] as

$$m_{T2}^2 \equiv \min_{\vec{k_T} + \vec{q_T} = \vec{\not{p}}_T} \{ \max [m_T^2(p_T^{\vec{\ell}^+}, \vec{k_T}), m_T^2(p_T^{\vec{\ell}^-}, \vec{q_T})] \} \tag{7}$$

where minimization is over all possible vectors $\vec{k_T}$ and $\vec{q_T}$ that satisfy $\vec{k_T} + \vec{q_T} = \vec{\not{p}}_T$ (with $|\vec{\not{p}}_T| = \not{E}_T$). Our signal region is defined as[5] $\not{E}_T > 110$ GeV, $m_{T2} > 110$ GeV.

We generate our signal and background event samples at leading order (LO) in MadGraph5_MC@NLO [42] and perform showering in Pythia 8 [43]. For the ZZ and WZ backgrounds we include up to two additional jets in the

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[2] We note the important $H^\pm$ contribution in the limit $s_\theta \to 0$ (see Ref. [27]) which was missed in Ref. [14].

[3] We note that a very low value of the chosen p_T^b cut (for a very high value of m_{H_0}) could result in a breakdown of the perturbative expansion [38] for the $\bar{b}b$-associated production of H_0 (we thank Richard Ruiz for pointing out this issue to us). Using SusHi [39] we have estimated our $b\bar{b}H_0$ next-to-leading-order (NLO) k-factor to be ~1.4, close to the perturbative expansion validity limit, but arguably safe [38].

[4] The WW diboson background is strongly suppressed by the $m_{\ell\ell}$ selection in combination with a large amount of $\not{E}_T$. Other potential backgrounds become negligible when demanding a significant amount of $\not{E}_T$ in the event.

[5] The m_{T2} cut is chosen conservatively to ensure the background prediction is not dominated by the Monte Carlo statistical uncertainty. An analysis performed by the experimental collaborations would achieve better sensitivity through a stronger cut on m_{T2}.

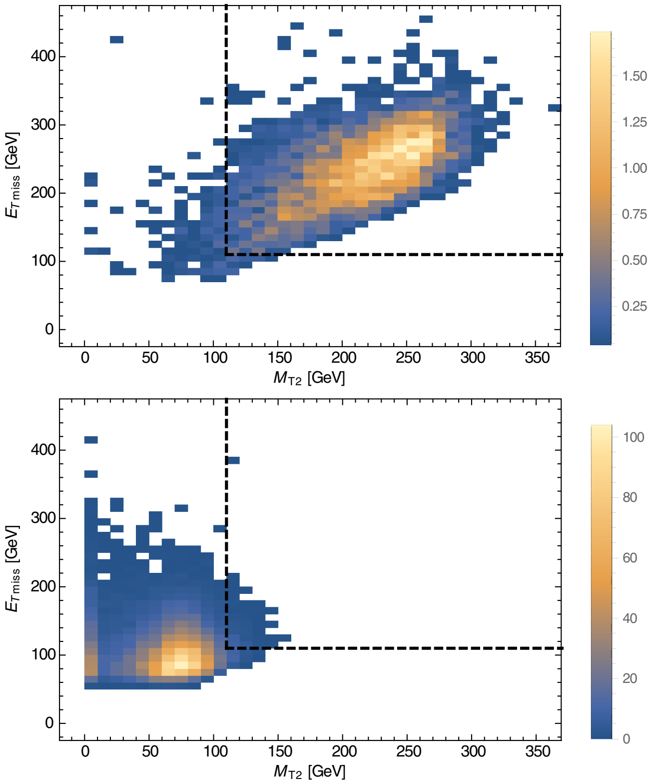

FIG. 1. $m_{H_0} = 600$ GeV, $m_a = 150$ GeV signal (top) and $t\bar{t}$ background (bottom) events after event selection with 300 fb^{-1}, in the $(m_{T2}, \not{E}_T)$ plane. The dashed line corresponds to the signal region $\not{E}_T, m_{T2} > 110$ GeV.

final state, matched to the parton shower. We replace a full detector simulation with a Gaussian smearing of the p_T of final-state particles: we define jets, well-isolated charged leptons and photons, and $\not{E}_T$ as the relevant final-state objects. Jets are constructed with the FastJet package [44] using the anti-k_T algorithm [45] with $R = 0.4$, and are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. We smear the p_T of the visible particles and calculate both the truth $\not{E}_T$ and the reconstructed value calculated from the smeared visible objects. We then smear the difference between the truth and reconstructed $\not{E}_T$. The functions for the smearing of the visible objects and $\not{E}_T$, as well as the b-tagging efficiency and mistag rates, are chosen to match the ATLAS performance reported in Ref. [46] for the leptons and $\not{E}_T$, [47] for the jets and [48] for the b tagging. We derive the projected sensitivity of our search using the CL_s method [49], and assume a conservative 20% background systematic uncertainty added in quadrature to a $1/\sqrt{N}$ Monte Carlo uncertainty (N is the number of generated background Monte Carlo events in the signal region).

For a benchmark signal $m_{H_0} = 600$ GeV, $m_a = 150$ GeV, $\tan\beta = 15$, $s_\theta = 0.3$ the background and signal samples surviving event selection are shown in Fig. 1 in the $(\not{E}_T, m_{T2})$ plane, highlighting the choice of signal region $\not{E}_T, m_{T2} > 110$ GeV as tailored for a clean signal extraction. In Fig. 2 we show the 95% C.L. sensitivity of our proposed search (hatched region) with 300 fb^{-1} of integrated luminosity in the $(s_\theta, \tan\beta)$ plane for $(m_{H_0}, m_a) = (600, 150)$ GeV (left) and (800,150) GeV (right), demanding $\langle\sigma v\rangle \simeq 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ to fix y_χ in terms of $\tan\beta$ and s_θ in each case. We demand perturbativity $y_\chi < 4\pi$, and show the lines $y_\chi = 1$ (dotted grey) and $y_\chi = 0.1$ (dot-dashed grey) for guidance.

The decay $H_0 \to Za$ $(a \to \bar{\chi}\chi)$ may be probed also by ATLAS/CMS mono-Z searches in the $\ell^+\ell^- + \not{E}_T$ channel [50,51], both for gluon-fusion (GF) production of H_0 and for $b\bar{b}$-associated production (if both b jets are missed, since the authors of Refs. [50,51] imposed jet/b-jet vetoes). We follow the LHC 13 TeV analysis selection of ATLAS [50] with 13.3 fb^{-1} to derive present 95% C.L. constraints on our signal in the $(s_\theta, \tan\beta)$ plane, shown in Fig. 2 for GF (yellow region) for $m_{H_0} = 600$ GeV, $m_a = 150$ GeV (left) and $m_{H_0} = 800$ GeV, $m_a = 150$ GeV (right). We also show the LHC projections to 300 fb^{-1} (dashed lines) using a naive $\sqrt{\mathcal{L}}$ increase in the signal cross section sensitivity (we note that even in this case, the ATLAS mono-Z search from $b\bar{b}$-associated production is not sensitive enough to provide a constraint). In both cases, the coupling y_χ is fixed at each point to match the DM relic density. In addition, Fig. 2 shows the present and projected to 300 fb^{-1} (when possible) constraints on the dark portal discussed in the previous section: the exclusion from CMS/LHCb 8 TeV $B_s \to \mu^+\mu^-$ measurements (red), the multijet $+ \not{E}_T$ (black), and the $\bar{b}b$-associated production of $H_0 \to \tau\tau$ (blue) and $a \to \tau\tau$ (brown). For the latter two, we use SusHi to obtain the next-to-next-to-LO (NNLO) H_0, a production cross section in association with $\bar{b}b$ at 13 TeV LHC.[6] We note that $\bar{t}t + \not{E}_T$ and $\bar{b}b + \not{E}_T$ are not sensitive enough to provide a constraint in Fig. 2.

As Fig. 2 highlights, the ATLAS mono-Z search will be able to probe the $\tan\beta \lesssim 5$ region (for GF production), while $B_s \to \mu^+\mu^-$ and the projected $H_0 \to \tau\tau$ combined could strongly constrain the very high $\tan\beta$ region ($\tan\beta > 10$ for $m_{H_0} = 600$ GeV, $\tan\beta > 20$ for $m_{H_0} = 800$ GeV); meanwhile, the proposed search $pp \to \bar{b}b\ell^+\ell^- + \not{E}_T$ would yield access to the intermediate $\tan\beta$ region, probing also values of the mixing down to $s_\theta \sim 0.1$.

We note that in the above analysis, we have fixed $\Gamma_{H_0 \to aa} = 0$ (as can be done by an appropriate choice of the soft $\mathbb{Z}_2$ symmetry breaking term in the 2HDM scalar potential; see e.g. Ref. [19]). A nonvanishing $\Gamma_{H_0 \to aa}$ would weaken the constraints from mono-Z, our new signature $pp \to \bar{b}b\ell^+\ell^- + \not{E}_T$ and from $H_0 \to \tau\tau$, but would at the

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[6] We note that by performing the analysis of mono-Z and our $\bar{b}bZ(\to \ell\ell) + \not{E}_T$ signature at LO, as compared to H_0, $a \to \tau\tau$ at NNLO, we are being conservative by underestimating the constraining power of the former two signatures.

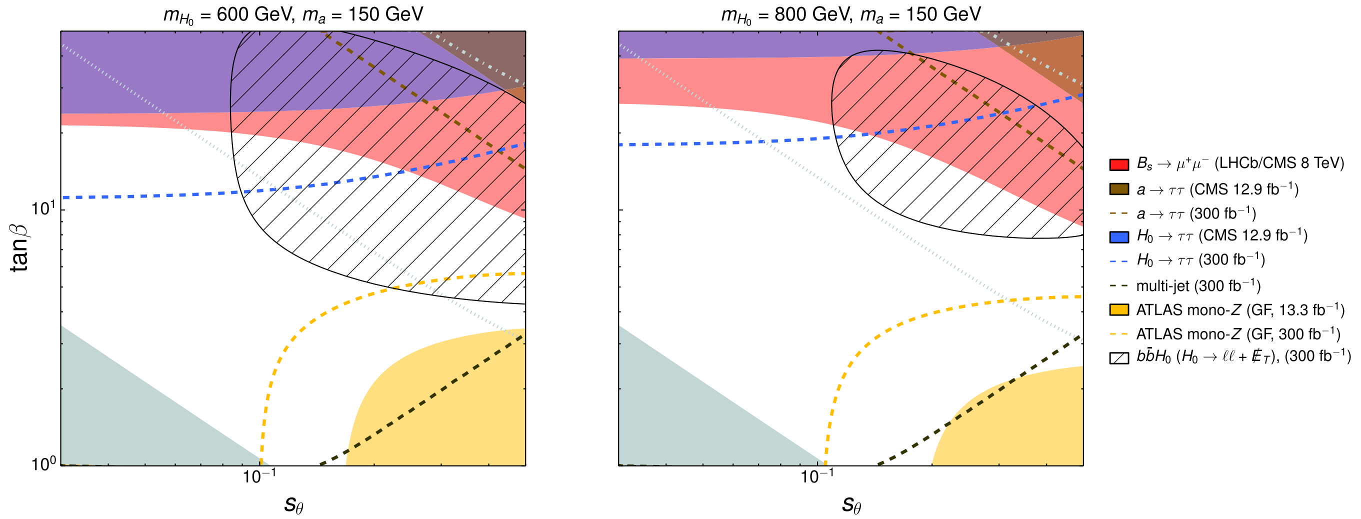

FIG. 2. Current (solid) and projected LHC with $\mathcal{L} = 300\ \mathrm{fb}^{-1}$ (dashed lines) 95% C.L. exclusion regions in the (s_θ, tan β) plane for $(m_{H_0}, m_a) = (600, 150)$ GeV (left) and (800,150) GeV (right) with a DM mass $m_\chi = 45$ GeV, from $H_0 \to \tau^+\tau^-$ (blue), $a \to \tau^+\tau^-$ (brown), multijet $+ \not{E}_T$ (black) and ATLAS mono-Z GF (yellow). Exclusion from CMS/LHCb 8 TeV $B_s \to \mu^+\mu^-$ measurements is shown in red. The dashed region corresponds to the 95% C.L. sensitivity for our proposed search, $pp \to b\bar{b}\ell\ell + \not{E}_T$, with $\mathcal{L} = 300\ \mathrm{fb}^{-1}$. The coupling y_χ is fixed at each point to match the DM relic density. The perturbativity excluded region $y_\chi > 4\pi$ is depicted in grey. The lines $y_\chi = 1$ (dotted grey) and $y_\chi = 0.1$ (dot-dashed grey) are shown for guidance.

same time yield new avenues to probe the pseudoscalar portal. We do not consider this scenario here for simplicity.

Finally, in Fig. 3 we show the various constraints and projected sensitivities discussed above in the (m_a, s_θ) plane for a benchmark $m_{H^\pm} = m_{H_0} = 600$ GeV, tan $\beta = 10$ and $y_\chi = 1$, together with the $\langle \sigma v \rangle = (2\text{–}4) \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ region where the observed DM relic density is obtained (green). This highlights the sensitivity of the proposed search to the parameter space region with the correct DM relic density (and favored by the GCE excess) as compared to other experimental probes of the pseudoscalar portal to DM.

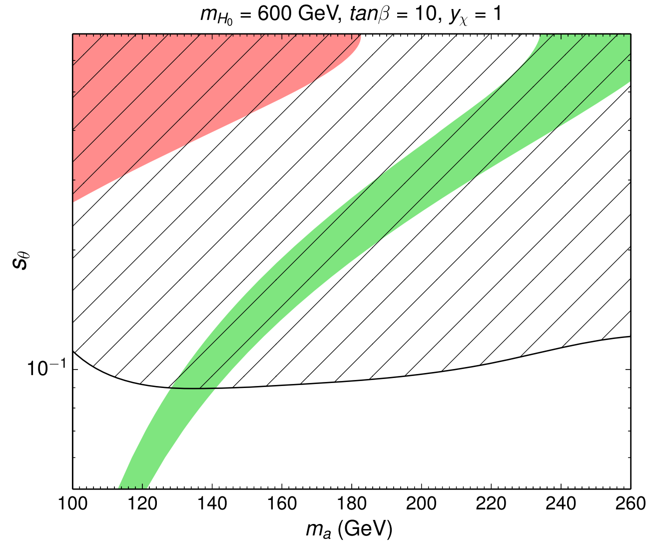

FIG. 3. 95% C.L. sensitivity of the proposed search $pp \to b\bar{b}\ell\ell + \not{E}_T$ with $\mathcal{L} = 300\ \mathrm{fb}^{-1}$ (dashed region) in the (m_a, s_θ) plane for $m_{H_0} = 600$ GeV, tan $\beta = 10$, $y_\chi = 1$. The red region is excluded by $B_s \to \mu^+\mu^-$, while the green band yields the observed DM relic density. The DM mass is $m_\chi = 45$ GeV.

V. CONCLUSIONS

DM that interacts with the visible sector via a pseudoscalar mediator is an appealing scenario, naturally avoiding the limits from DM direct detection searches while generating a rich LHC phenomenology and yielding a possible explanation for the Fermi gamma-ray Galactic Center excess. Generating a pseudoscalar coupling to SM fields in a consistent way implies the existence of additional beyond-the-SM particles, as in theories with two-Higgs doublets where the necessary coupling is naturally generated when the pseudoscalar mediator and that of the two-Higgs-doublet scenario mix. We have shown that such scenarios give rise to a new LHC DM search channel $\bar{b}bH_0$, $H_0 \to Za(Z \to \ell^+\ell^-, a \to \bar{\chi}\chi)$. The final state with a leptonically decaying Z boson, b-tagged jet(s) and large $\not{E}_T$ has not been explored yet at the LHC in the DM context.

We found that a large region of parameter space which gives the observed DM relic abundance (yielding at the same time an explanation for the Galactic Center excess) can be explored using the proposed search, showing in particular that it can reach a wide region of parameter space that cannot be probed by other means, notably $B_s \to \mu^+\mu^-$ decays, heavy Higgs (H_0) decays into tau-lepton pairs, and mono-Z

searches. This novel search can thus be very valuable in probing pseudoscalar portal DM scenarios at the LHC.

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