Semi-dark Higgs decays: sweeping the Higgs neutrino floor

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Based on work in collaboration with:
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Motivation

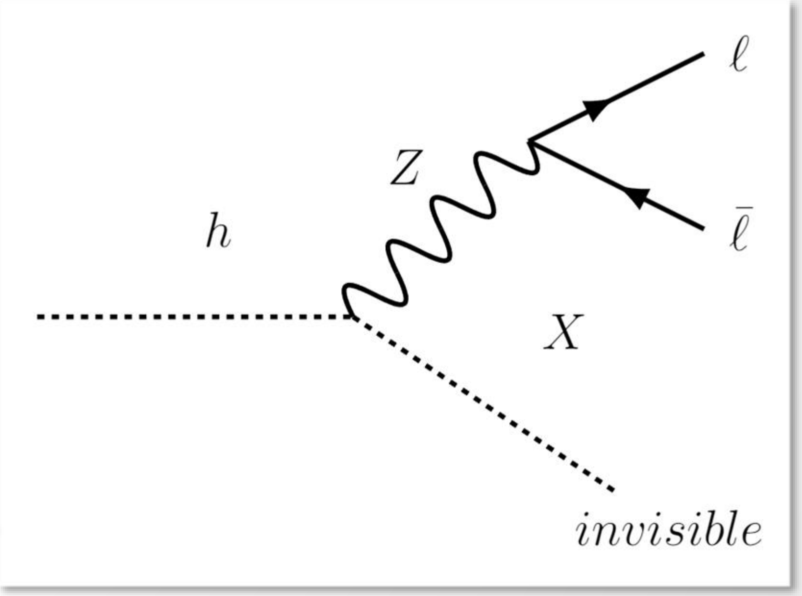
Highly theoretically motivated probe of new physics! The Higgs as the portal to a hidden "dark" sector?

Target of an intense experimental program at the **LHC** (also on the theory side). But mainly fully visible or invisible decays…

Semi-invisible Higgs decays remain poorly explored on both grounds (with notable exceptions, e.g. $h \to \gamma, b\bar{b} + invisible$, for a complete list see [1])

In particular there is a promising candidate which has NOT* been explored so far…

*Davoudiasl, Lee, Marciano, PRD **85** (2012) 115019 briefly discussed this possibility in the context of dark photons



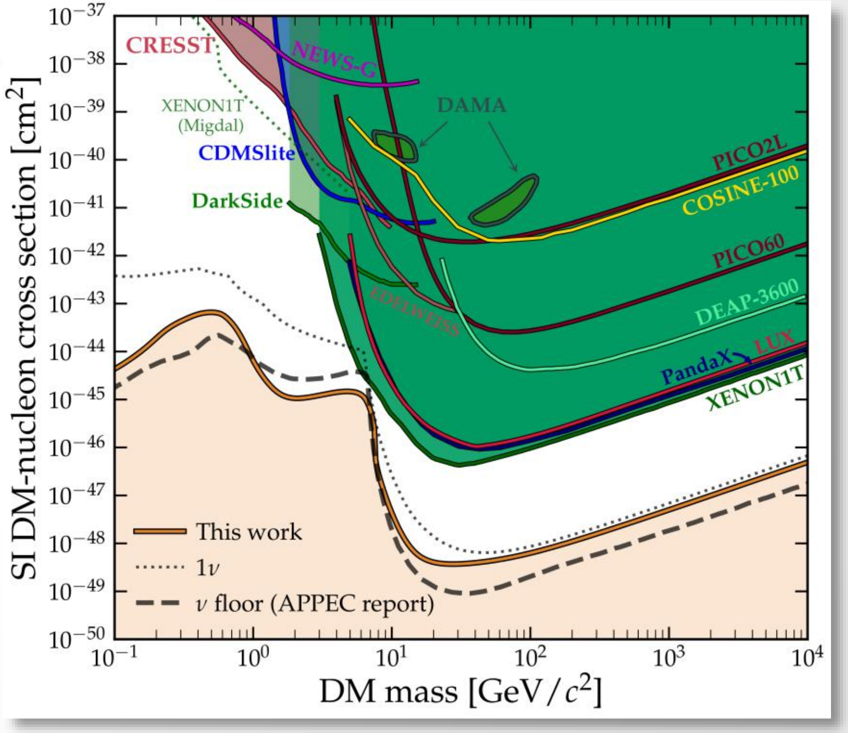
[1] Englert, Spannowsky, Wymant PLB **718** (2012), 538; Petersson, Romagnoni, Torre JHEP **10** (2012), 016; Curtin et al. PRD **90**, 075004; Cepeda, Gori, Outschoorn, Shelton 2111.12751; CMS: PLB **753** (2016) 363, JHEP **10** (2019) 139, JHEP **03** (2021) 011; ATLAS: 2109.00925, JHEP **01** (2022) 063

$h \to ZX(\to invisible)$

Note this topology is already present in the **SM**

$$h \to ZZ^* \to \ell\bar{\ell}\nu\bar{\nu}$$
(and $h \to WW^* \to \ell\bar{\ell}\nu\bar{\nu}$)

In analogy to what happens in DM direct detection experiments!
Where coherent elastic neutrino-nucleus scattering can pose an irreducible background.



O'Hare PRL **127** 251802 (2021)

We refer to the above as the "*Higgs neutrino floor*" and like its analogue, it provides a sensitivity target for experiments:

$$BR(h \to Z\nu\bar{\nu})_{SM} = 5.4 \cdot 10^{-3}$$

Collider search

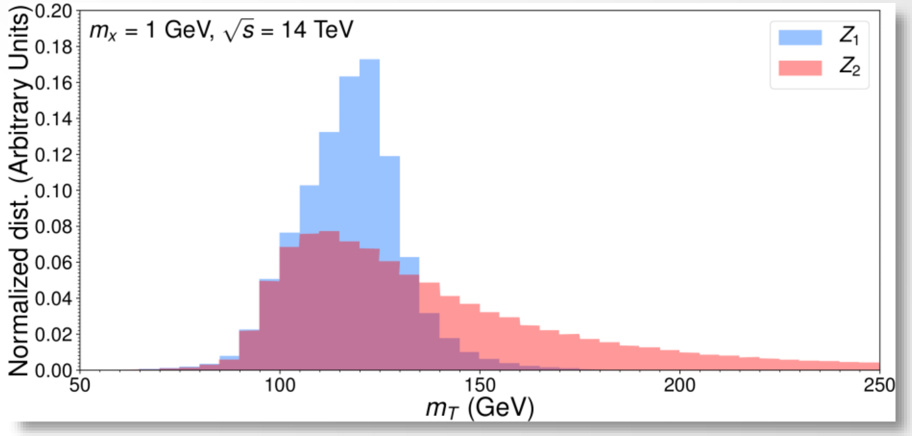
Best production channel to study this decay at the LHC?

ggF$(2\ell + MET)$*? **VBF**$(2\ell + 2j + MET)$?
large backgrounds and difficulties with MET…

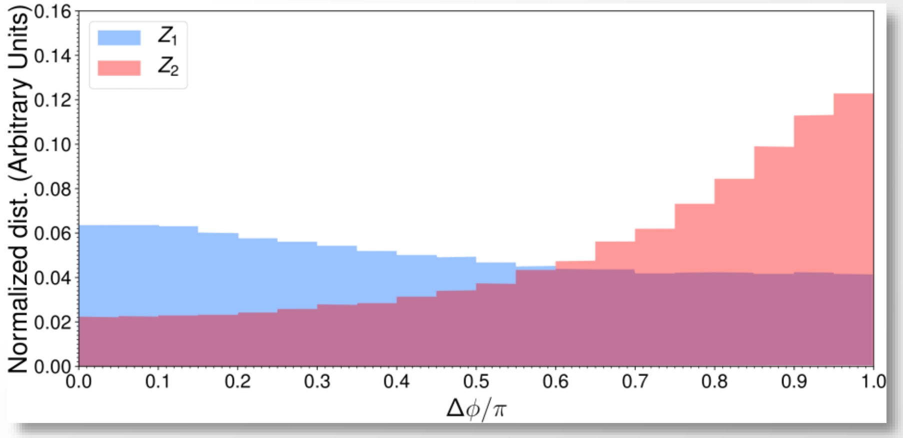
$$pp \to Zh \to 4\ell + MET$$ ✓

But note this poses a problem… how to identify the Z coming from the Higgs?

We build a **NN** taking as input:



$$M_T^2 = \left(\sqrt{m_{\ell\ell}^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \not{E}_T\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{\not{E}}_T\right|^2$$



$$\Delta\phi(Z, \vec{\not{E}}_T)$$

*$Z + MET$, mono-Z searches? not sensitive… (backup slides, ask me at the end!)

Collider search

Dominant SM backgrounds include:

- $ZZ \to 4\ell, 2\ell + 2\tau$
- $WW^{(*)}Z, ZZZ \to 4\ell + 2\nu$
- $t\bar{t}Z, tWZ \to 4\ell + 2\nu + jets$

We train another **NN** to separate signal from backgrounds, taking as inputs:

$$M_T \quad \not{E}_T$$

$$\Delta\phi(Z_1, \vec{\not{E}}_T)$$
$$\Delta\phi(Z_2, \vec{\not{E}}_T)$$

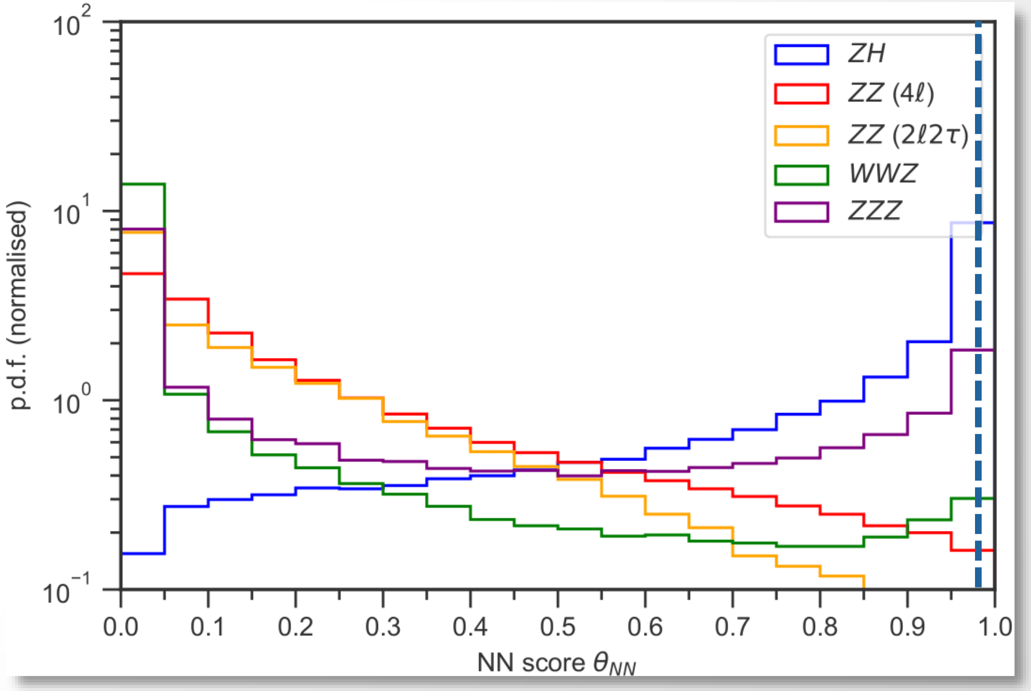
$$m_{4\ell}$$

$$m_{\ell\ell_1} \quad m_{\ell\ell_2}$$

$$p_T^{\ell\ell_1} \quad p_T^{\ell\ell_2}$$

$$p_T^{\ell_1},\ p_T^{\ell_2},\ p_T^{\ell_3},\ p_T^{\ell_4}$$

$$(p_T^{\ell\ell_2} + \not{E}_T)/p_T^{\ell\ell_1}$$

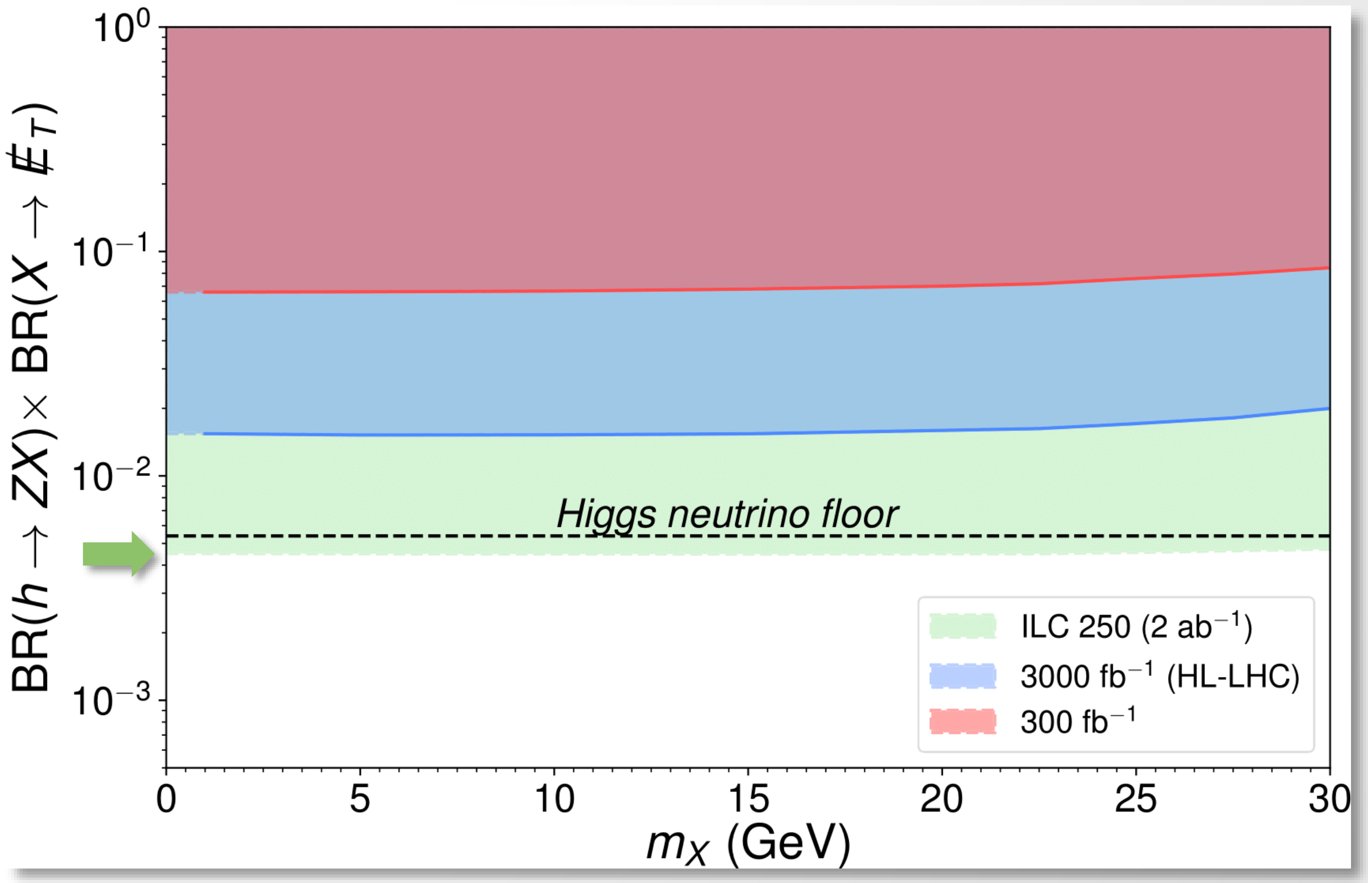


Optimal cut

Collider search

On the other hand, a **lepton** collider (like the **ILC**) would be particularly suited for the task:

- ✓ $e^+e^- \to Zh$ dominant Higgs production mechanism
- ✓ Full missing energy reconstruction
- ✓ Higgs **recoil mass** allows straightforward identification of the **Z**'s
- ✓ Cleaner environment



2HDM + a

Two Higgs doublet models extended by a singlet pseudoscalar mediator and a fermionic singlet **DM** particle constitute the minimal renormalizable realization of a pseudoscalar portal to **DM** [2]:

$$V = V_{2\text{HDM}} + \frac{\mu_{a_0}^2}{2} a_0^2 + m_\chi \bar{\chi}\chi + \frac{\lambda_a}{4} a_0^4 + \lambda_{a1}\, a_0^2\, |H_1|^2 + \lambda_{a2}\, a_0^2\, |H_2|^2 + i\,\kappa\, a_0\, H_1^\dagger H_2 + y_\chi\, a_0\, \bar{\chi} i \gamma^5 \chi + \text{h.c.}$$

χ
DM candidate
via **freeze-out**

The $h \to Za$ decay is generically present away from the alignment limit with:

$$\Gamma(h \to Za) = \frac{1}{16\pi} \sin^2\theta \cos^2(\beta - \alpha) \frac{m_h^3}{v^2} \lambda^{3/2}$$

$$\text{BR}(a \to \chi\bar{\chi}) \simeq 1$$

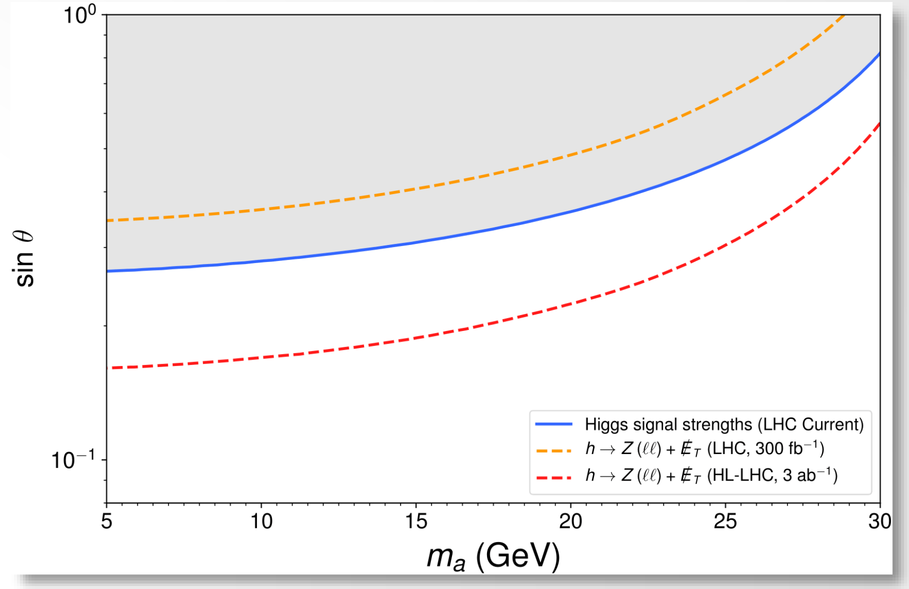
Note this model is further constrained by current (and future) Higgs signal strengths and fully invisible Higgs decays:

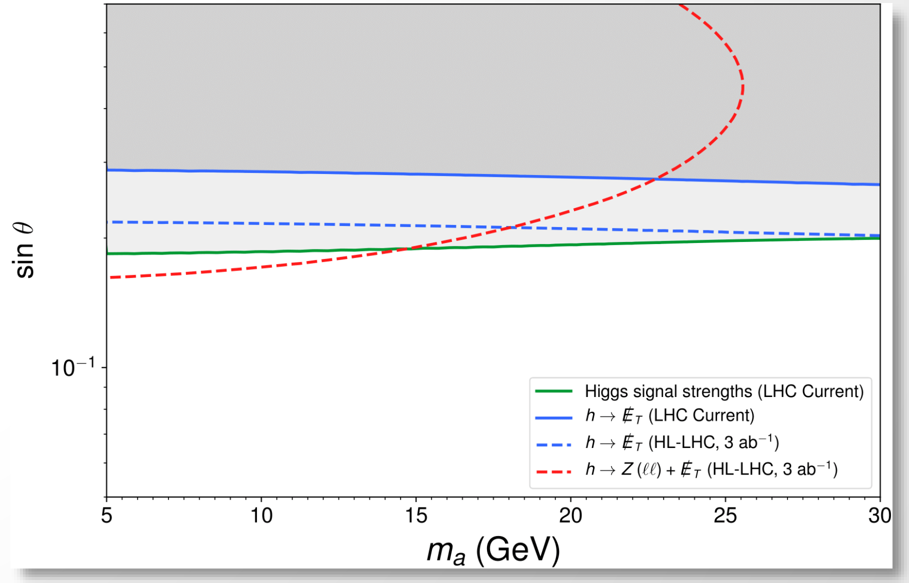
$h \to aa \to invisible$

[2]
Ipek, McKeen, Nelson PRD **90** (2014), 055021
No PRD **93** (2016), 031701
Goncalves, Machado, No PRD **95** (2017), 055027
Bauer, Haisch, Kahlhoefer JHEP **05** (2017), 138
Robens Symmetry **13** (2021) 2341

2HDM + a

Two benchmarks:





The $h \to Za$ decay is generically present away from the alignment limit with:

$$\begin{cases} \Gamma(h \to Za) = \dfrac{1}{16\pi} \sin^2\theta \cos^2(\beta - \alpha) \dfrac{m_h^3}{v^2} \lambda^{3/2} \\ \mathrm{BR}(a \to \chi\bar{\chi}) \simeq 1 \end{cases}$$

Note this model is further constrained by current (and future) Higgs signal strengths and fully invisible Higgs decays:

$h \to aa \to invisible$

Axion-like particles

Interactions between the **SM** Higgs and light axion-like particles (**ALPs**) are a well-motivated BSM possibility [5], with exotic Higgs decays representing a key experimental signature for these scenarios…

$$c_{a\gamma\gamma}/f_a \, a \, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

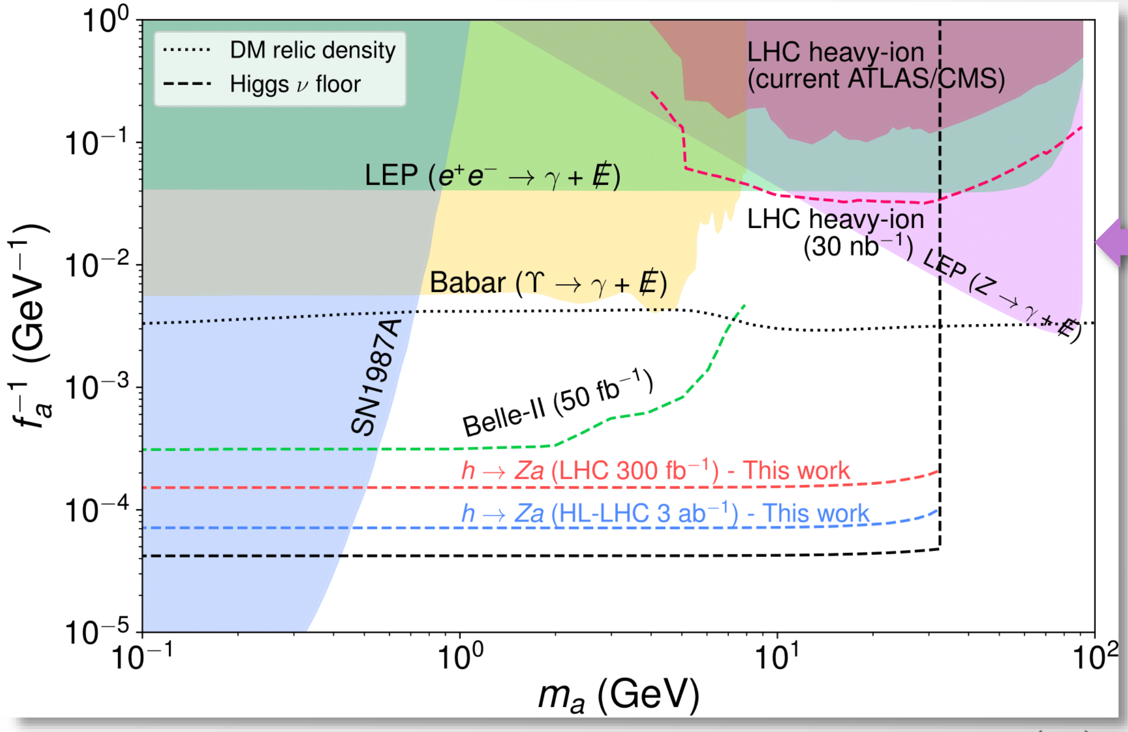
$$c_{aBB}/f_a \, a \, B^{\mu\nu}\tilde{B}_{\mu\nu}$$

$$+$$

$$y_\chi \, \bar{\chi}\gamma^\mu\gamma^5\chi \, \partial_\mu a/f_a$$

If a couples to some hidden sector particle(s) (see e.g. [6]), its dominant decay mode(s) may be into the **dark sector**, thus invisible at colliders. This encompasses the intriguing possibility that the **ALP** may be a mediator between the **SM** and the **DM** candidate.

$$\Gamma(h \to Za) = (m_h^3/16\pi f_a^2)\, c_{aZh}^2 \, \lambda^{3/2}$$



$$y_\chi = 1,\ c_{aZh} = 1,\ m_\chi = 0.45\, m_a \qquad c_{a\gamma\gamma} = \alpha_{\text{EM}}(Q)$$

5

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, EJPC **77** (2017) 8, 572
Bauer, Neubert, Thamm, JHEP **12** (2017), 044

6

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP **12** (2017) 094
Alves, Dias and Lopes, JHEP **08** (2020) 074

A comment on **dark photons**…

Light **dark photons** Z_D which interact with the SM via kinetic mixing (see e.g. [3])

$$\frac{1}{2}\epsilon F'_{\mu\nu}B^{\mu\nu}$$

give rise to the $h \to ZZ_D$ decay…

However, current 95% C.L. bounds on the kinetic mixing parameter from EW precision observables set $\epsilon \lesssim 0.02$ for dark photon masses $m_{Z_D} < 30$ GeV [4].

➡ The corresponding branching fraction is then $\mathrm{BR}(h \to ZZ_D) < 10^{-3}$, well below the Higgs neutrino floor.

Nevertheless, there could be additional sources of $Z - Z_D$ mass mixing contributing to the decay…

Davoudiasl, Lee, Marciano PRD **85** (2012) 115019 *

[3] Jaeckel, Jankowiak, Spannowsky Phys.Dark Univ. **2** (2013) 111-117; Fabbrichesi, Gabrielli, Lanfranchi Springer Briefs in Physics **2020**; …

Hook, Izaguirre, Wacker Adv. High Energy Phys. **2011** 859762; Curtin et al. PRD **90**, 075004 [4]

Key points

- Exotic Higgs decays $h \to ZX$ remain unexplored at large…
- The **SM** process $h \to Z\nu\bar{\nu}$ represents an irreducible *neutrino floor* background to these searches, providing also a target experimental sensitivity.
- Despite being a highly theoretically motivated place to look for new physics!
- Constraints provided both by the **LHC** and the **ILC** cover otherwise unexplored parameter space, the latter being able to reach the Higgs neutrino floor.
- This is true for the 2HDMa (and dark photons?) but particularly for ALPs, even at present luminosities!

Thank you

come chat for more details!

Backup

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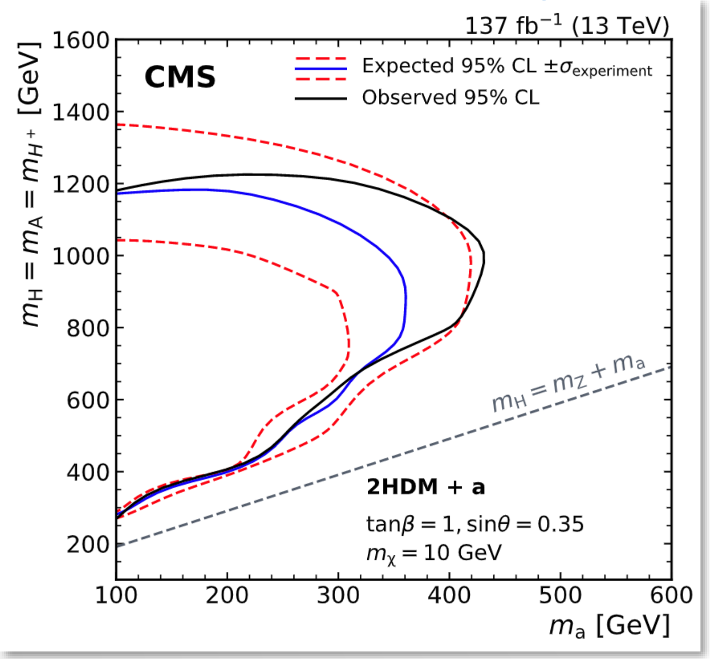
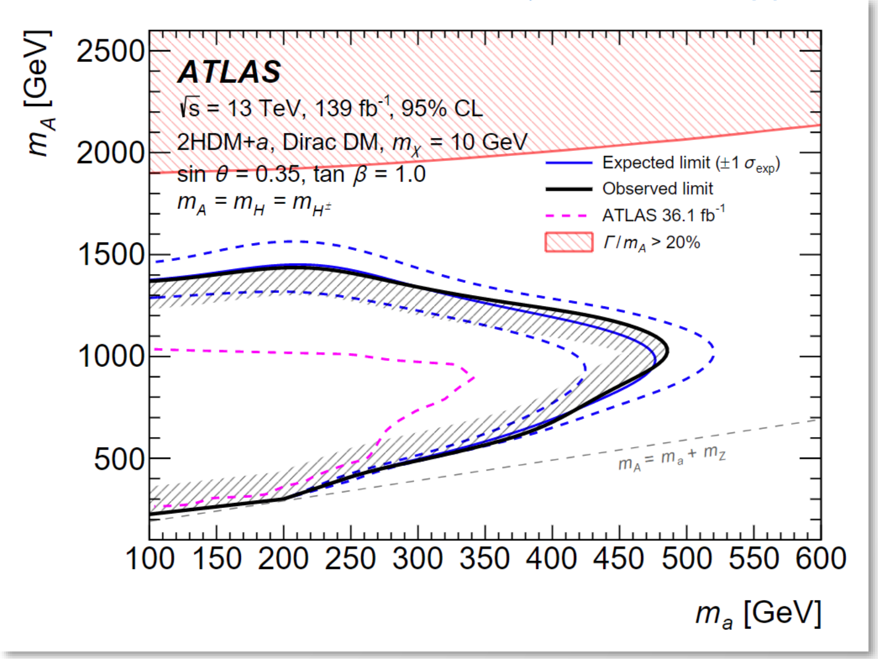
Mono-Z searches

CMS EPJC **81** 13 (2021)



ATLAS PLB **829** (2022) 137066



Ultimately neither is sensitive when considering the phase space for the 125 GeV Higgs decay…
owing to both hard cuts on missing energy (requiring a hard jet on **ggF**)
and transverse mass (expected to be $m_T \leq m_h$).

2HDM+a relic abundance

Annihilation cross-section:

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