Sweeping the *Higgs neutrino floor* with semi-invisible Higgs decays

In Collaboration with J. A. Aguilar-Saavedra, J. M. Cano, D. Cerdeño, ***ArXiv:2206.01214***

Jose Miguel No
IFT-UAM/CSIC, Madrid

Exotic Higgs decays

(Very) well-motivated
probe of BSM physics

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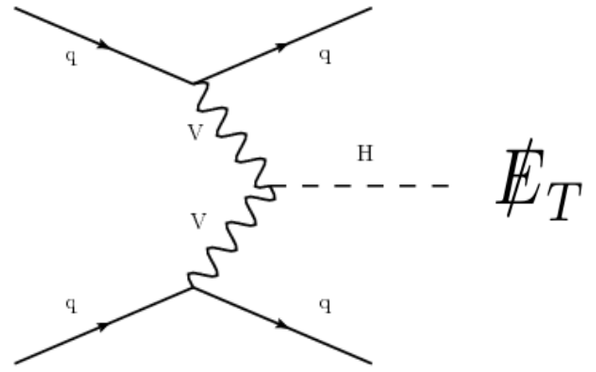
Higgs portal to dark sector

Higgs → Invisible



Exotic Higgs decays

Higgs portal to dark sector

Higgs → **Semi**-invisible

(Provide key information on Higgs interactions with dark sector)

Exotic Higgs decays

Higgs portal to dark sector

Higgs → **Semi**-invisible

- Poorly explored so far from theory side …

Englert, Spannowsky, Wymant, Phys.Lett.B 718 (2012), 538 $h \to aa$ (jets + MET)

Petersson, Romagnoni, Torre, JHEP 10 (2012), 016 $h \to \gamma$ + MET

Exotic Higgs decay reviews by Curtin et al. (1312.4992) and by Cepeda et al. (2111.12751) cover some more channels/models: bb + MET, $\tau\tau$ + MET, $\gamma\gamma$ + MET...

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- \+ very few experimental analyses …

CMS: CMS-HIG-14-025, CMS-EXO-19-007, CMS-EXO-20-005. $h \to \gamma$ + MET

ATLAS: 2109.00925. $h \to \gamma$ + MET 2109.02447. $h \to bb$ + MET

Exotic Higgs decays

Higgs portal to dark sector

Higgs → **Semi**-invisible

- ~~Poorly~~ explored

  NOT

$$h \to \mathrm{ZX} \quad (\mathrm{X} \to \mathrm{MET})$$

Connection to DM (pseudoscalar portal) & ALPs

Aguilar-Saavedra, Cano, Cerdeño, No, 2206.01214

$h \rightarrow$ Z $(\ell\ell)$ + MET

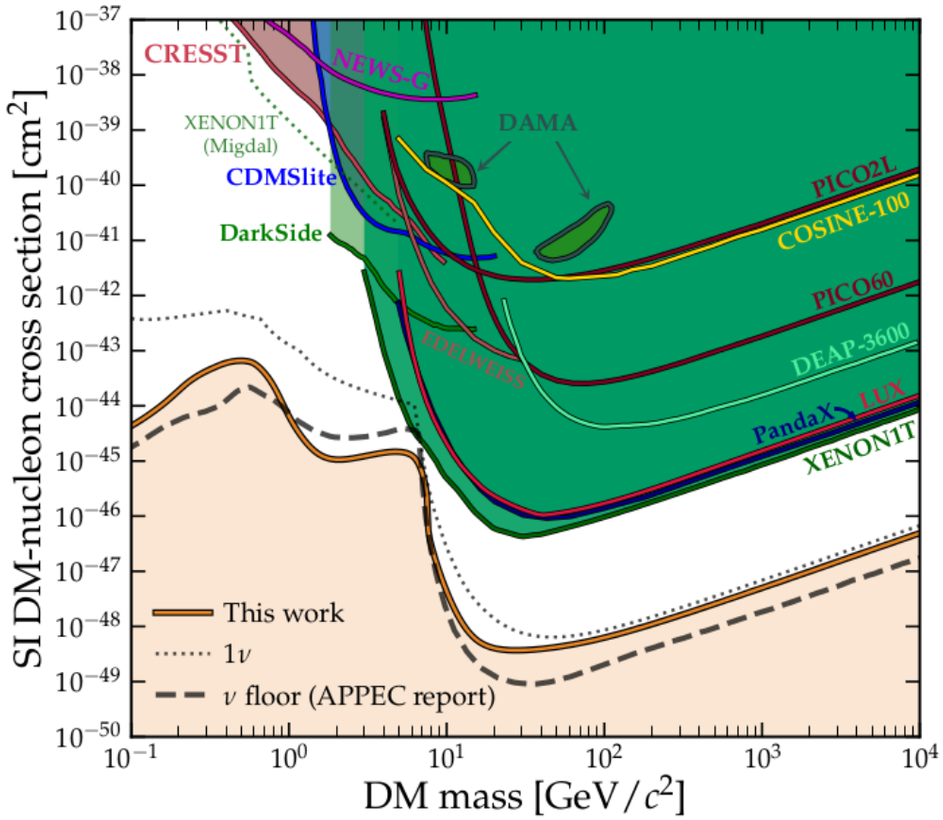
- Already present in SM: $h \rightarrow$ ZZ* $\rightarrow \ell\ell + \nu\nu$

$h \to Z\,(\ell\ell) + \text{MET}$

- Already present in SM: $h \to ZZ^* \to \ell\ell + \nu\nu$

SM "Higgs neutrino floor" for BSM $h \to Z\,(\ell\ell) + \text{MET}$

"in analogy to the neutrino floor (from coherent neutrino-nucleus scattering) in DM direct detection experiments"



O' Hare, 2109.03116

$h \rightarrow$ Z ($\ell\ell$) + MET

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Target sensitivity for Colliders (HL-LHC, ILC)

SM "Higgs neutrino floor" for BSM $h \rightarrow$ Z ($\ell\ell$) + MET

$BR_{Z + MET} \simeq 0.0053$

$h \rightarrow$ Z ($\ell\ell$) + MET

- Already present in SM: $h \rightarrow ZZ^* \rightarrow \ell\ell + \nu\nu$

Target sensitivity for Colliders (HL-LHC, ILC)

- *Which Higgs production mode?*

ggF ($pp \rightarrow 2\ell + \text{MET}$) ✗ Too much background...

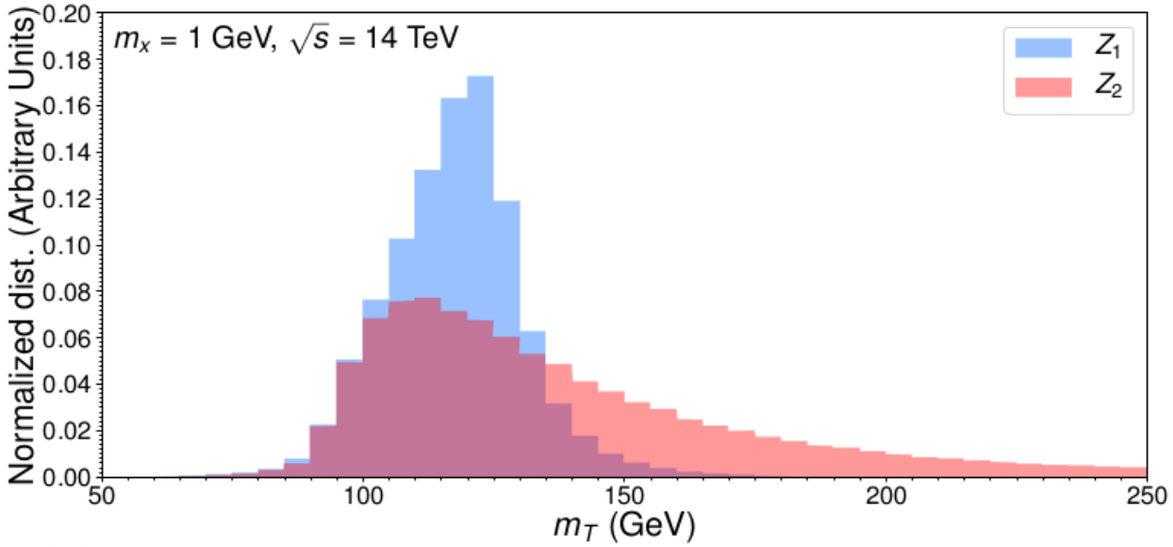
VBF ($pp \rightarrow 2\ell + \text{MET} + 2j$) ✗ Too much background?

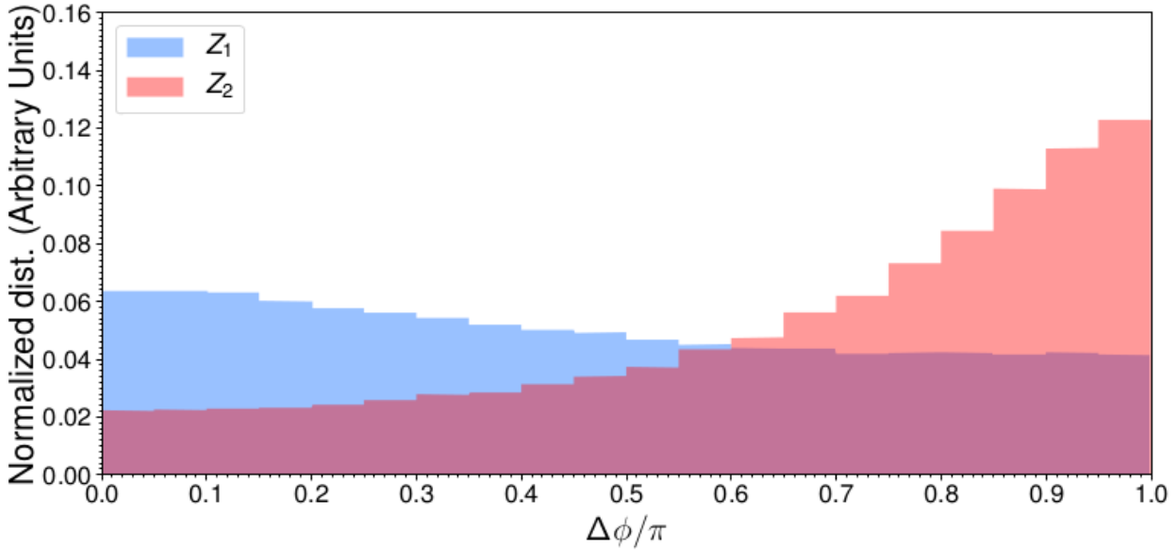
Z h ($pp \rightarrow 4\ell + \text{MET}$) ✓

$pp \to Z\,h,\ h \to\ Z\,(\ell\ell) + \text{MET}$

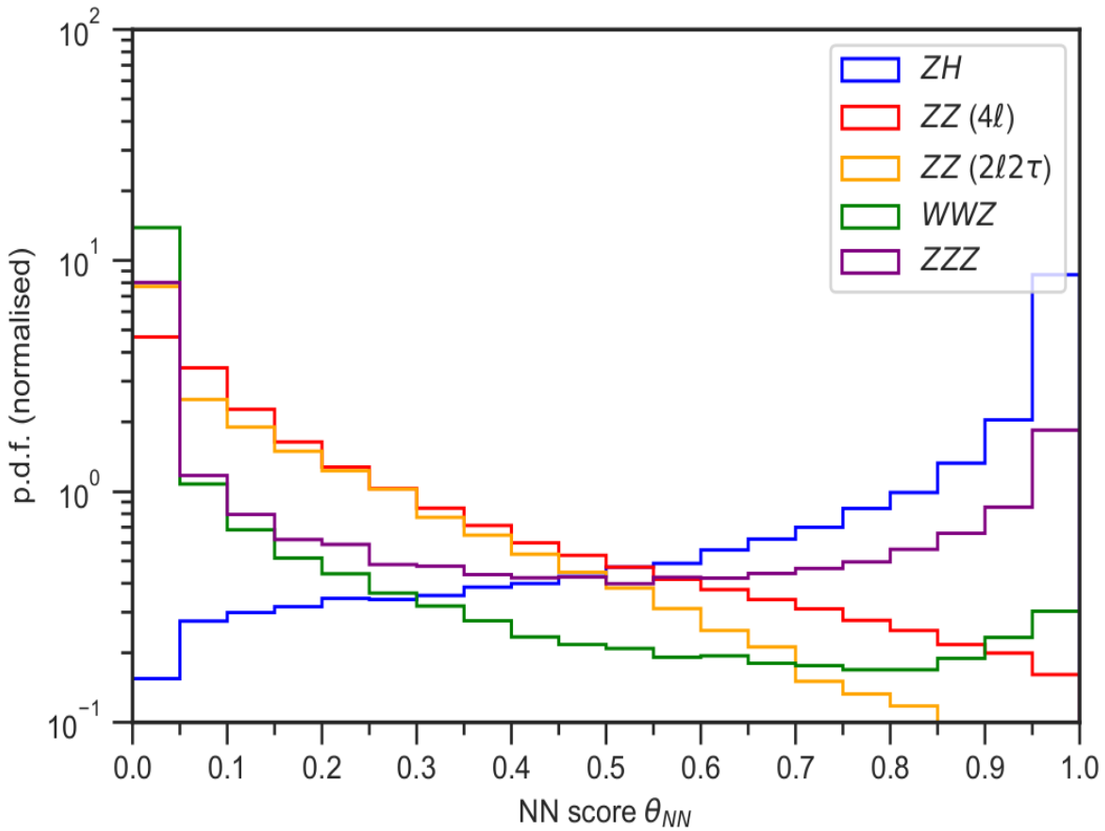
- Choose Z boson "from Higgs decay"! (Z_1)

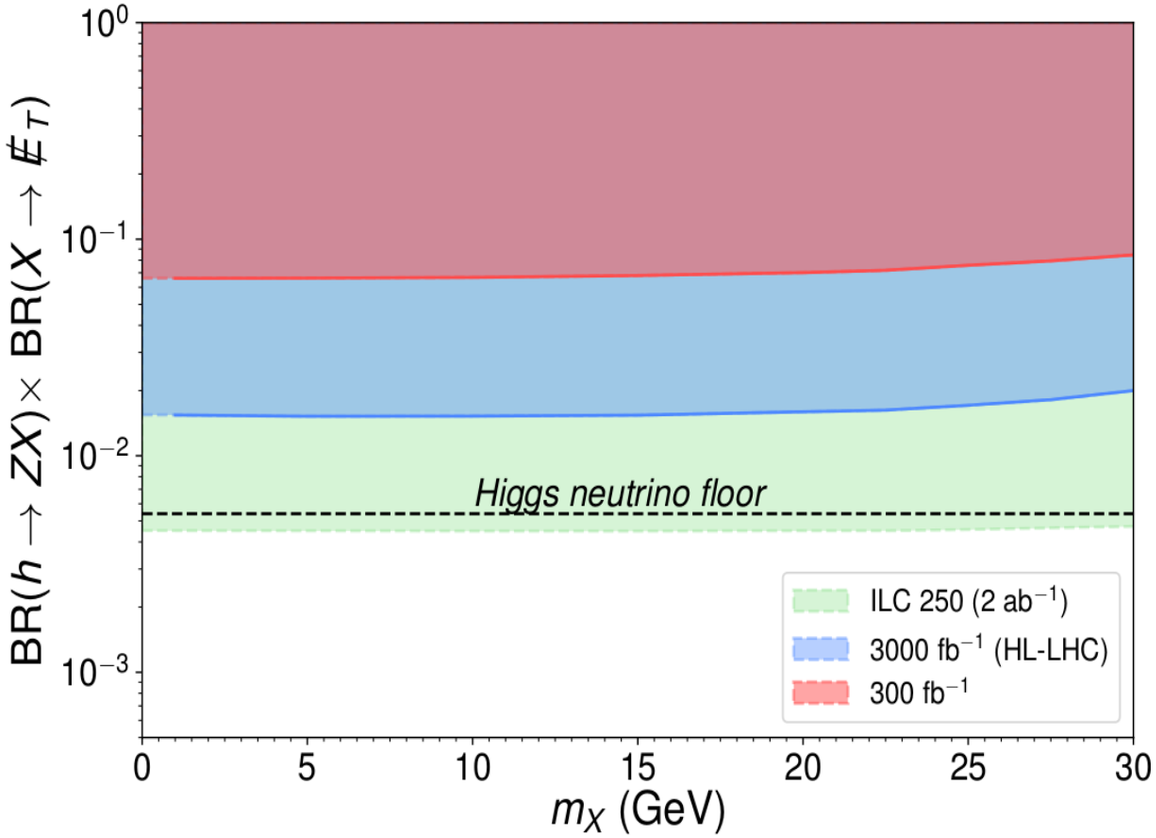
Key kinematic variables: $\Delta\phi_{\ell\ell,\not{E}_T}$ $M_T{}^2 = \left(\sqrt{M_Z{}^2 + |\vec{p}_T^{\,Z}|^2} + \not{E}_T\right)^2 - \left|\vec{p}_T^{\,Z} + \vec{\not{E}}_T\right|^2$





$pp \to Z\,h,\ h \to\ Z\,(\ell\ell) + \text{MET}$





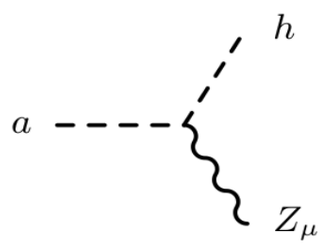
HL-LHC probes BR($h \to$ ZX) ~ 1-2%

Probing BSM Models

- Axion-like particles (ALPs)

ALP-Higgs interactions

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



ALP - Dark sector interactions

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 12 (2017) 094

(dark decay of ALP)

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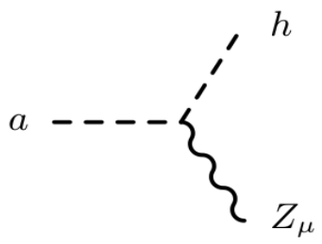

We consider:

(ALP-Higgs)

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

ALP-Dark Fermions: $y_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\, \partial_\mu a/f_a$

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

$$c_{a\gamma\gamma} \sim \alpha_{\rm EM}$$

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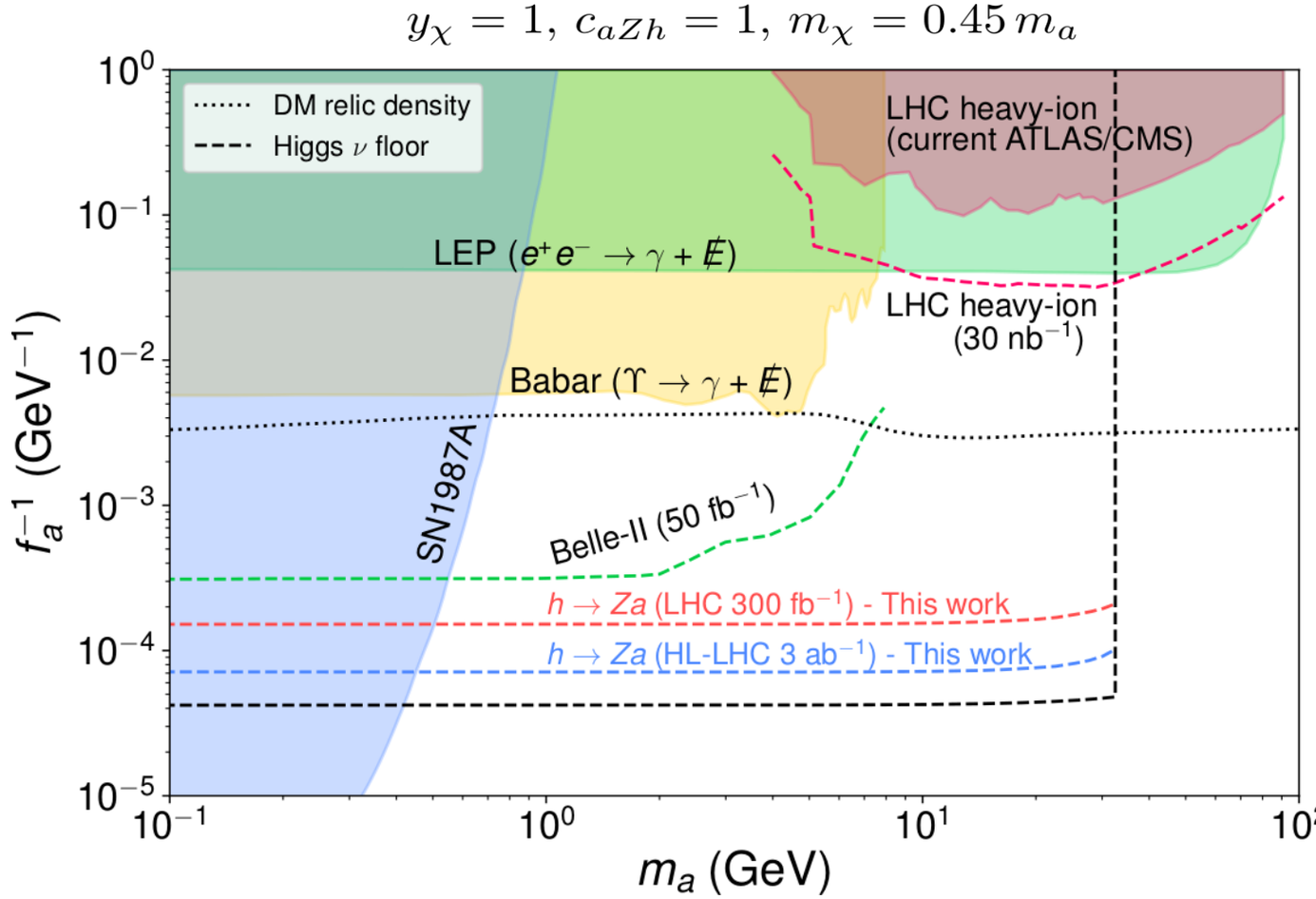

$\lambda = (1-(m_Z^2-m_a^2)/m_h^2)^2 - 4\, m_Z^2 m_a^2/m_h^4$

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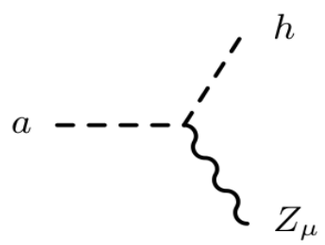

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ALP-Hypercharge: $c_{aBB}/f_a\, a\, B^{\mu\nu}\tilde{B}_{\mu\nu}$

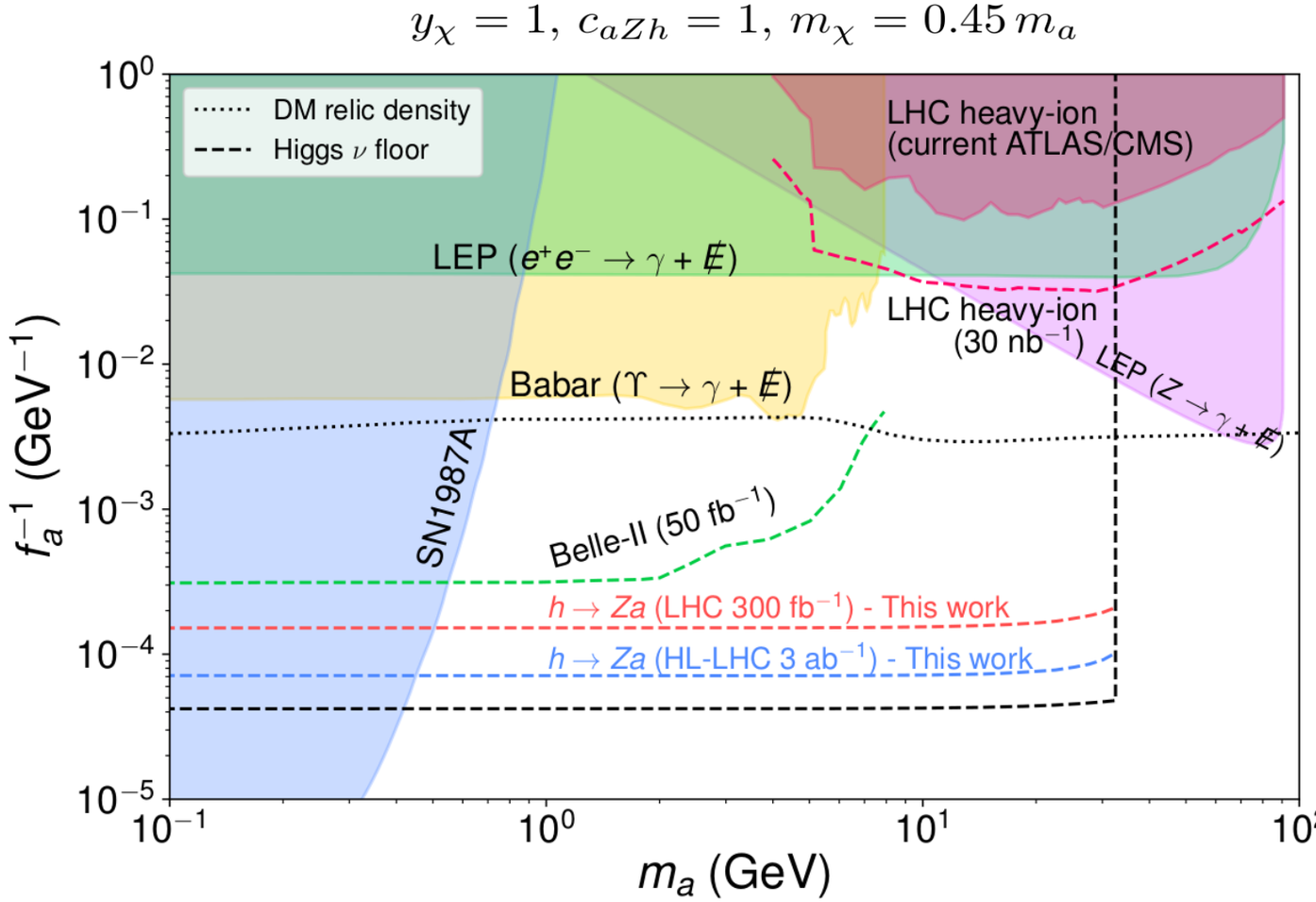
$$c_{a\gamma\gamma} \sim \alpha_{\rm EM}$$

ALP - Dark sector interactions

Dolan, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, JHEP 12 (2017) 094

(dark decay of ALP)

$$y_\chi = 1,\ c_{aZh} = 1,\ m_\chi = 0.45\, m_a$$



$\lambda = (1-(m_Z^2-m_a^2)/m_h^2)^2 - 4\, m_Z^2 m_a^2/m_h^4$

Probing BSM Models

$$V_{\rm 2HDM} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$

- Axion-like particles (ALPs)

- 2HDM+*a* *(pseudoscalar portal to DM)*

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

[LHC DM WG Benchmark Model]

$$V = V_{\rm 2HDM} + \frac{\mu_{a0}^2}{2} a_0^2 + \frac{\lambda_a}{4} a_0^4 + i\,\kappa\, a_0\, H_1^\dagger H_2 + \text{h.c.} + \lambda_{a1}\, a_0^2 |H_1|^2 + \lambda_{a2}\, a_0^2 |H_2|^2 + m_\chi\, \bar{\chi}\chi + y_\chi\, a_0\, \bar{\chi} i\gamma^5 \chi$$

Probing BSM Models

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Pseudoscalar mediator Singlet-doublet mixing

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

Dirac Fermion DM

Portal coupling

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

(decay present away from 2HDM aligment)

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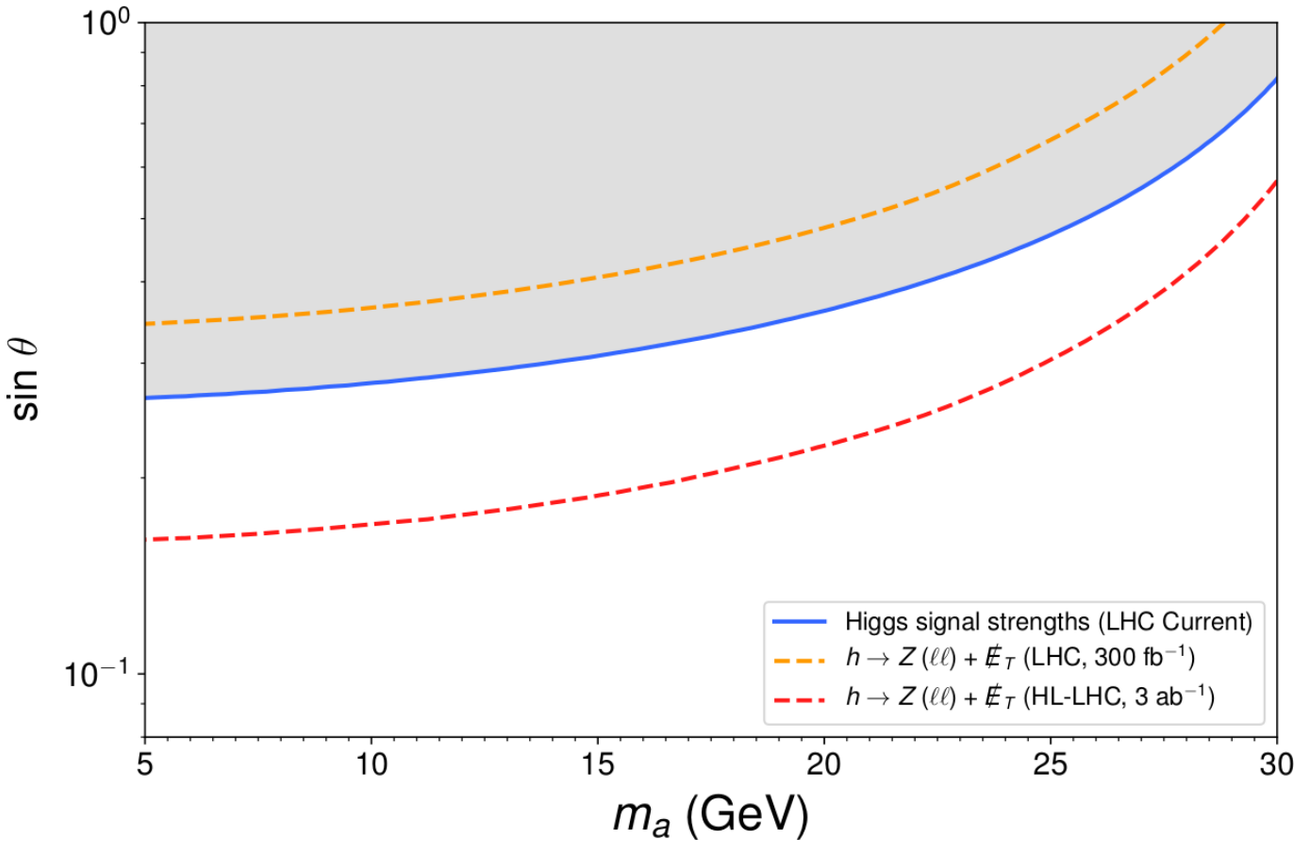
$$M = 600 \text{ GeV}, \; m_{H_0} = m_{H^\pm} = m_{A_0} = 700 \text{ GeV}$$
$$\tan\beta = 6, \; c_{\beta-\alpha} = 0.2, \; m_\chi = 0.45\, m_a$$

We set $\Gamma(h \to aa) = 0$



Competitive with probes via:

❍ Higgs signal strength measurements *(indirect)*

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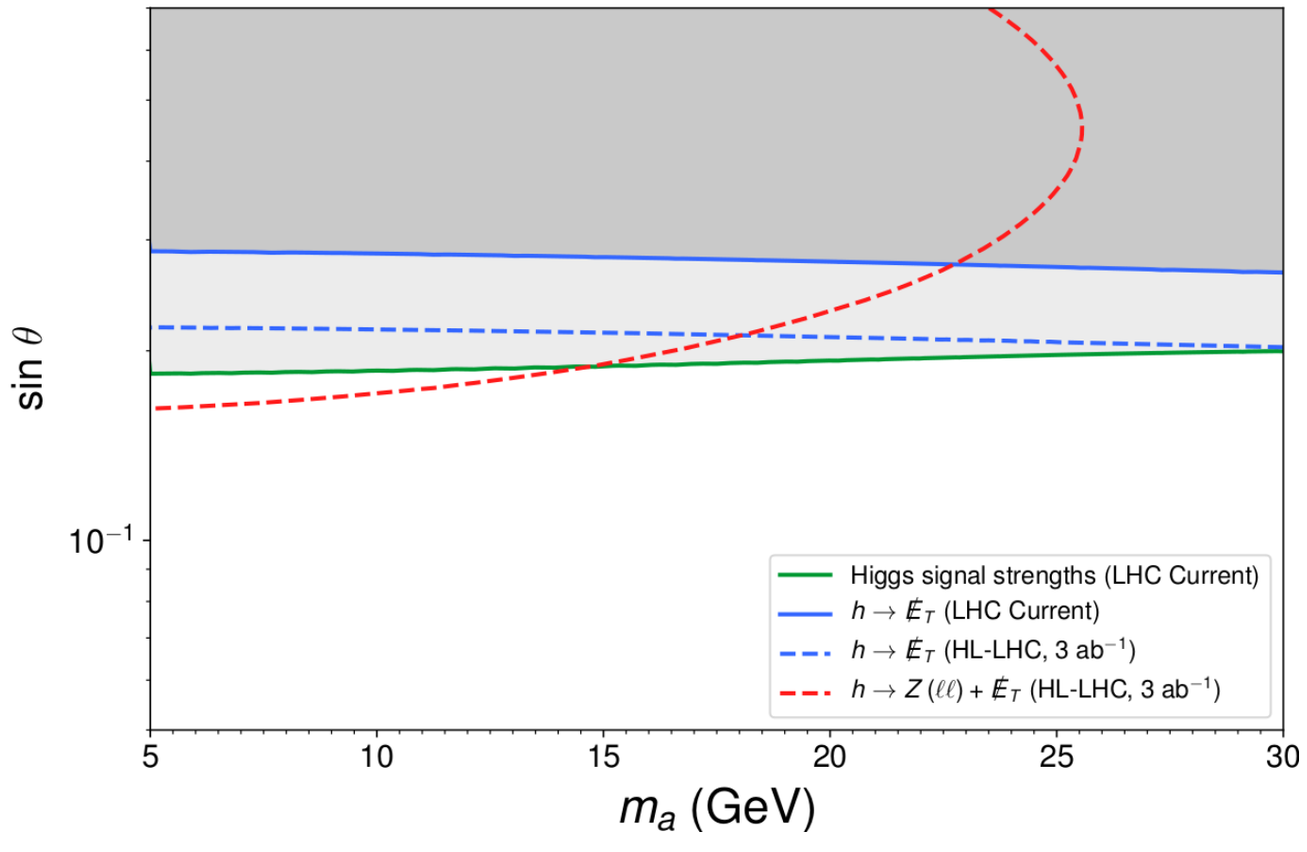
$$\lambda_{a1} = \lambda_{a2} = 0$$



Competitive with probes via:

- Higgs signal strength measurements *(indirect)*
- **Higgs → Invisible** ($h \to aa$) *(direct)*

Summary & Conclusions

(Exotic!)

- Semi-dark Higgs decays: Key information of Higgs connection to dark sector

- $h \to ZX\ (X \to \not{E}_T)$ so far unexplored

  - Present in SM ($h \to ZZ^* \to \ell\ell + \nu\nu$)

$$BR_{Z+MET} \simeq 0.0053$$

BSM Target sensitivity for Colliders

"Higgs neutrino floor"

  - HL-LHC can probe $BR_{Z+MET} \simeq 0.01 - 0.02$
  - ILC250 could probe $BR_{Z+MET} < 0.005$

- Powerful constraints on BSM scenarios:

  - ALPs (e.g ALP portal to dark sector)
  - Extended scalar sectors (e.g 2HDMa + DM)

  ...

  - Dark photons