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

In Collaboration with J. A. Aguilar-Saavedra, J. M. Cano, D. Cerdeño,
will appear on arXiv very soon!

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IFT-UAM/CSIC, Madrid



Exotic Higgs decays

(Very) well-motivated
probe of BSM physics

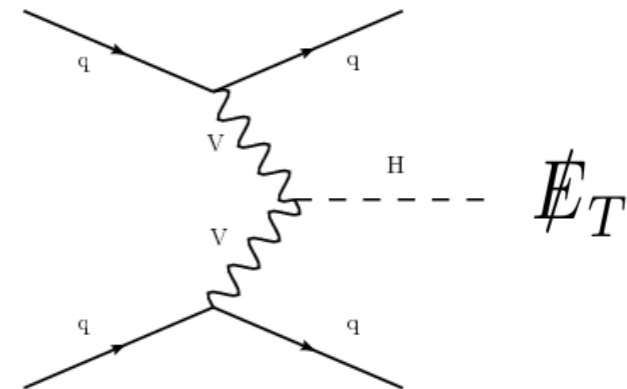


Exotic Higgs decays

(Very) well-motivated
probe of BSM physics

Higgs portal to dark sector

Higgs \rightarrow Invisible





Exotic Higgs decays



**Higgs portal
to dark sector**

Higgs \rightarrow **Semi**-invisible

(Provide key information on Higgs interactions with dark sector)



Exotic Higgs decays



Higgs portal
to dark sector

Higgs \rightarrow **Semi**-invisible

- Poorly explored so far from theory side ...

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

Petersson, Romagnoni, Torre, JHEP 10 (2012), 016 $h \rightarrow \gamma + \text{MET}$

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



Exotic Higgs decays

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- + very few experimental analyses ...

CMS: CMS-HIG-14-025, CMS-EXO-19-007, CMS-EXO-20-005. $h \rightarrow \gamma + \text{MET}$

ATLAS: 2109.00925. $h \rightarrow \gamma + \text{MET}$ 2109.02447. $h \rightarrow bb + \text{MET}$



Exotic Higgs decays



Higgs portal to dark sector

Higgs \rightarrow **Semi**-invisible

- ~~Poorly~~ explored
NOT

$$h \rightarrow Za \quad (a \rightarrow \text{MET})$$

Connection to DM (pseudoscalar portal) & ALPs

Aguilar-Saavedra, Cano, Cerdeño, No, 2205.XXXXX

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

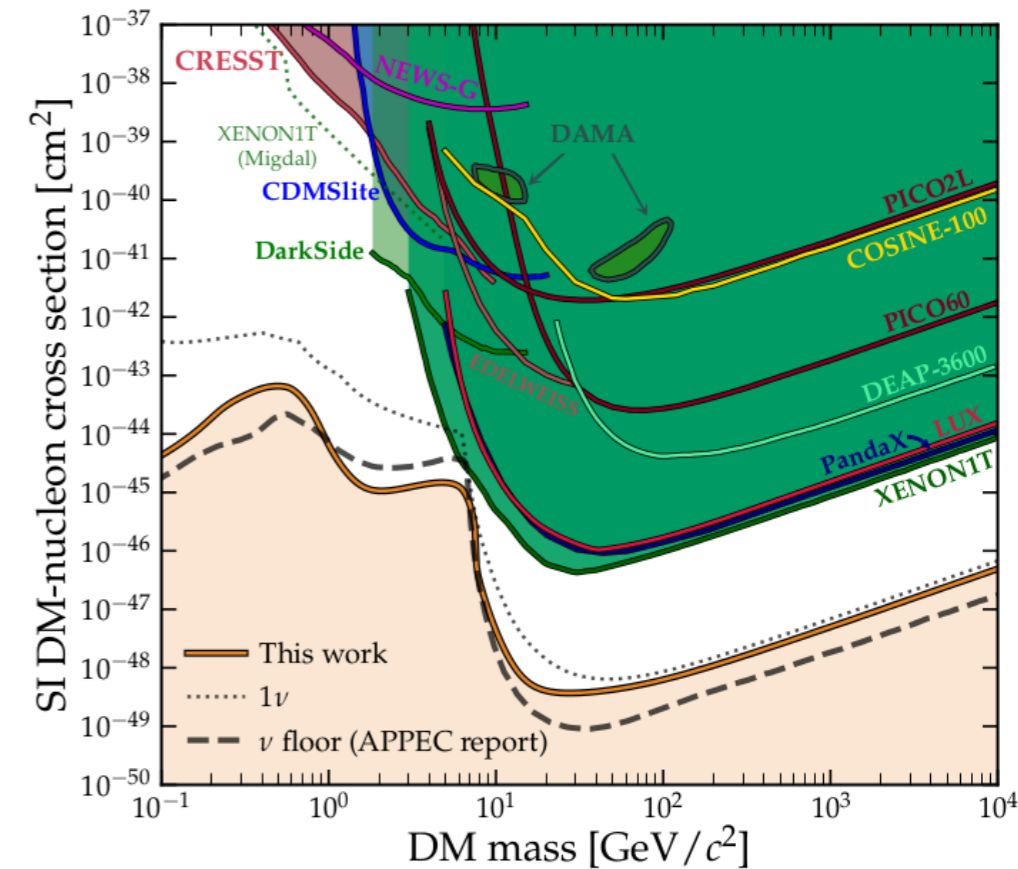
- Already present in SM: $h \rightarrow ZZ^* \rightarrow \ell\ell + \nu\nu$

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

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SM “Higgs **neutrino floor**” for
BSM $h \rightarrow Z (\ell\ell) + \text{MET}$

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



O' Hare, 2109.03116

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

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

Target sensitivity for
Colliders (HL-LHC, ILC)

SM “Higgs neutrino floor” for
BSM $h \rightarrow Z (\ell\ell) + \text{MET}$

$$\text{BR}_{Z+\text{MET}} \approx 0.0053$$

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

- 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...

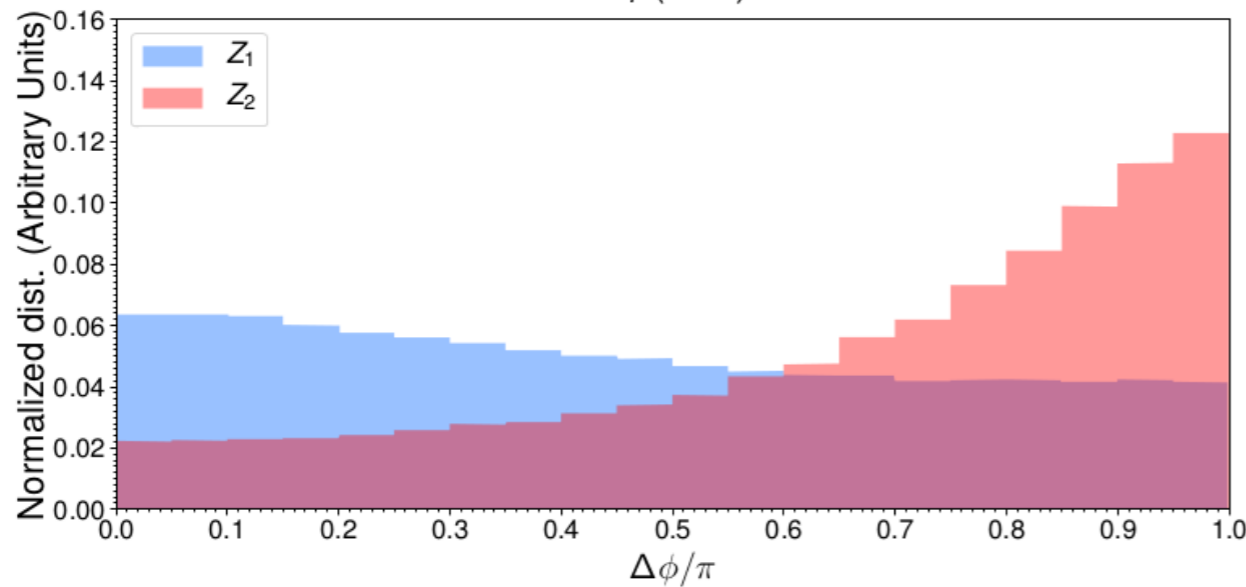
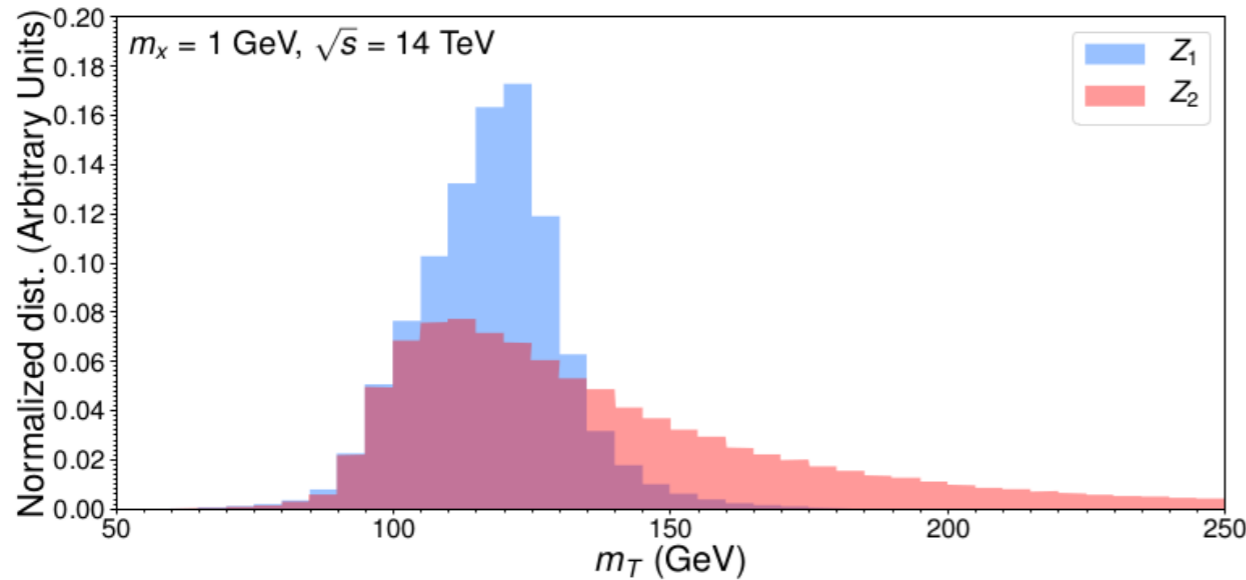
VBF ($pp \rightarrow 2\ell + \text{MET} + 2j$) ✗ Too much background?

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

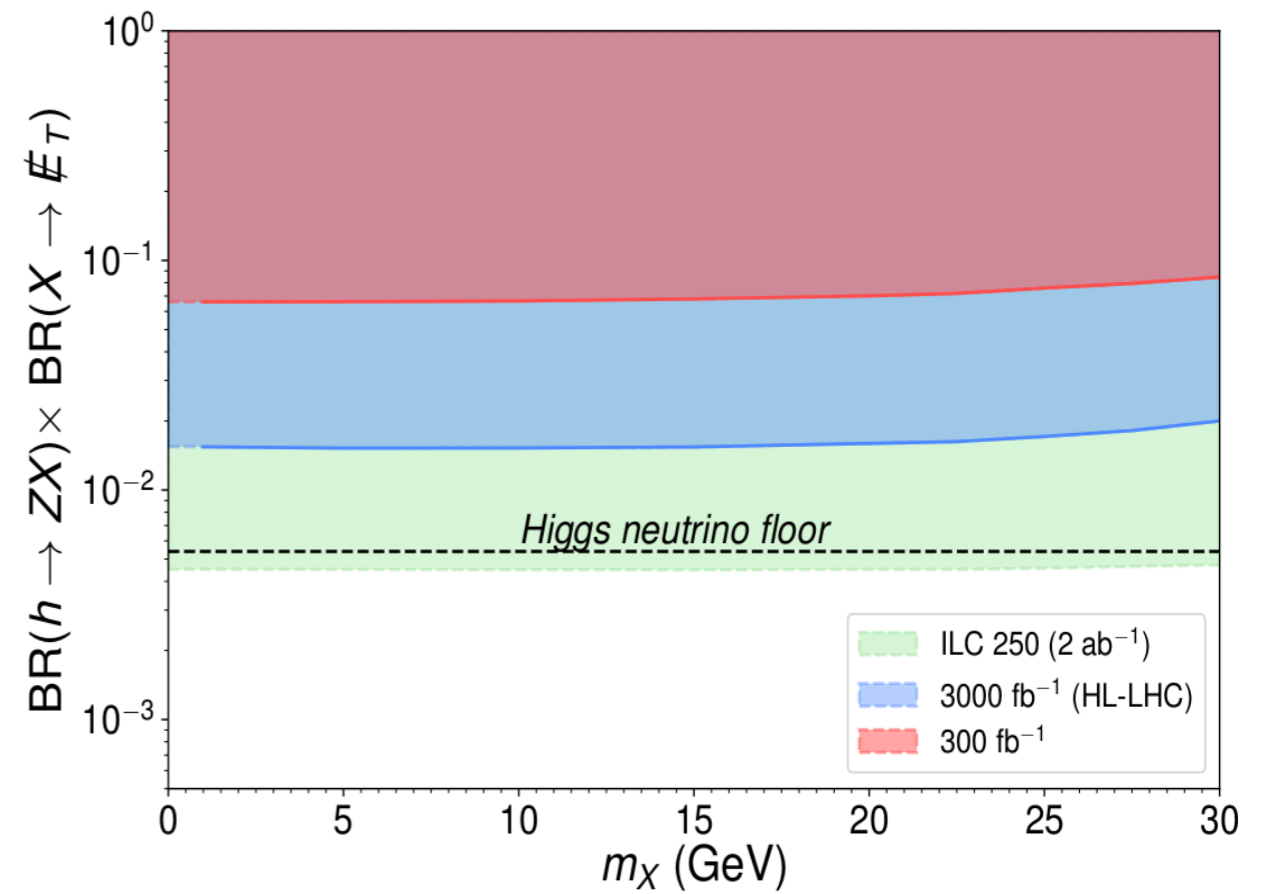
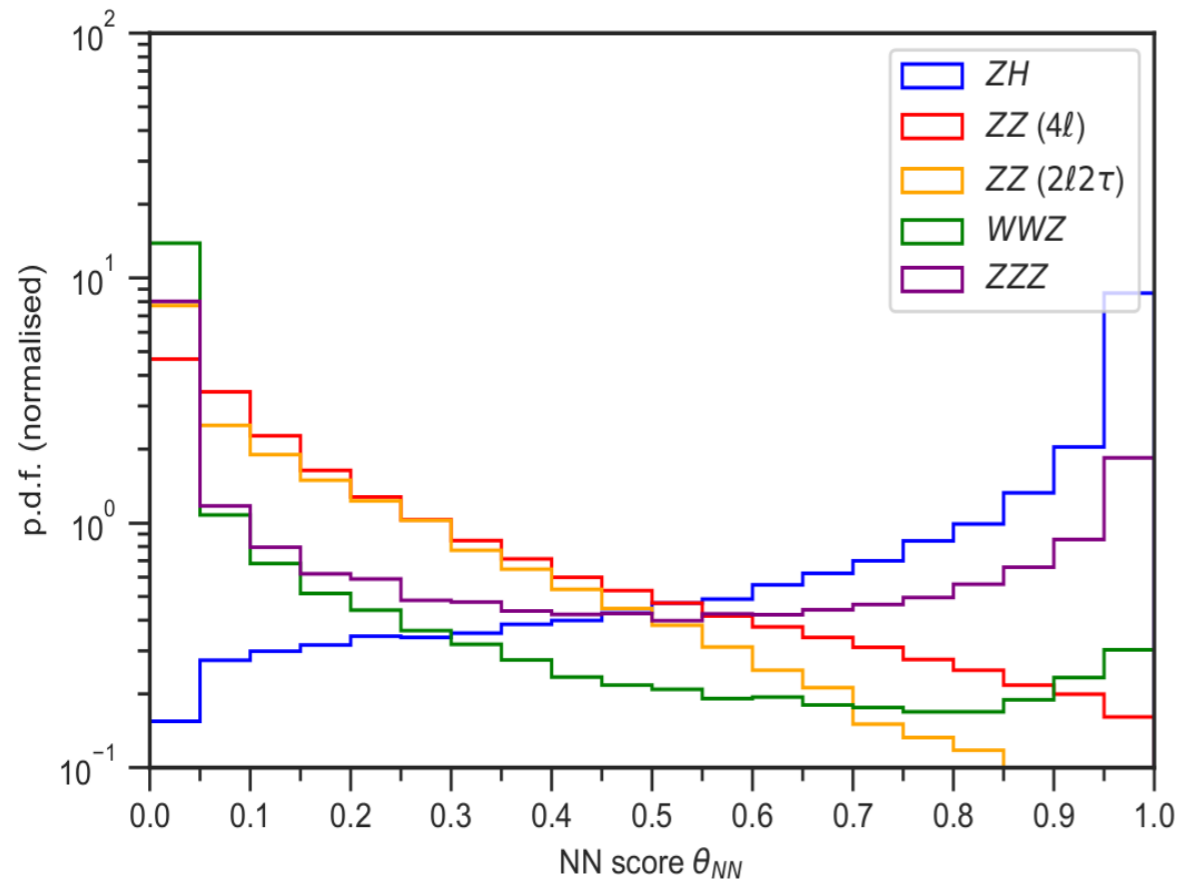
$pp \rightarrow Z h, h \rightarrow Z (\ell\ell) + \text{MET}$

- Choose Z boson “from Higgs decay”! (Z_1)

Key kinematic variables: $\Delta\phi_{\ell\ell, \cancel{E}_T}$ $M_T^2 = \left(\sqrt{M_Z^2 + |\vec{p}_T^Z|^2} + \cancel{E}_T \right)^2 - \left| \vec{p}_T^Z + \vec{\cancel{E}}_T \right|^2$



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



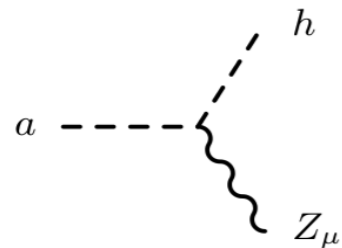
HL-LHC probes $BR(h \rightarrow Za) \sim 1-2\%$

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

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We consider:

(ALP-Higgs)

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

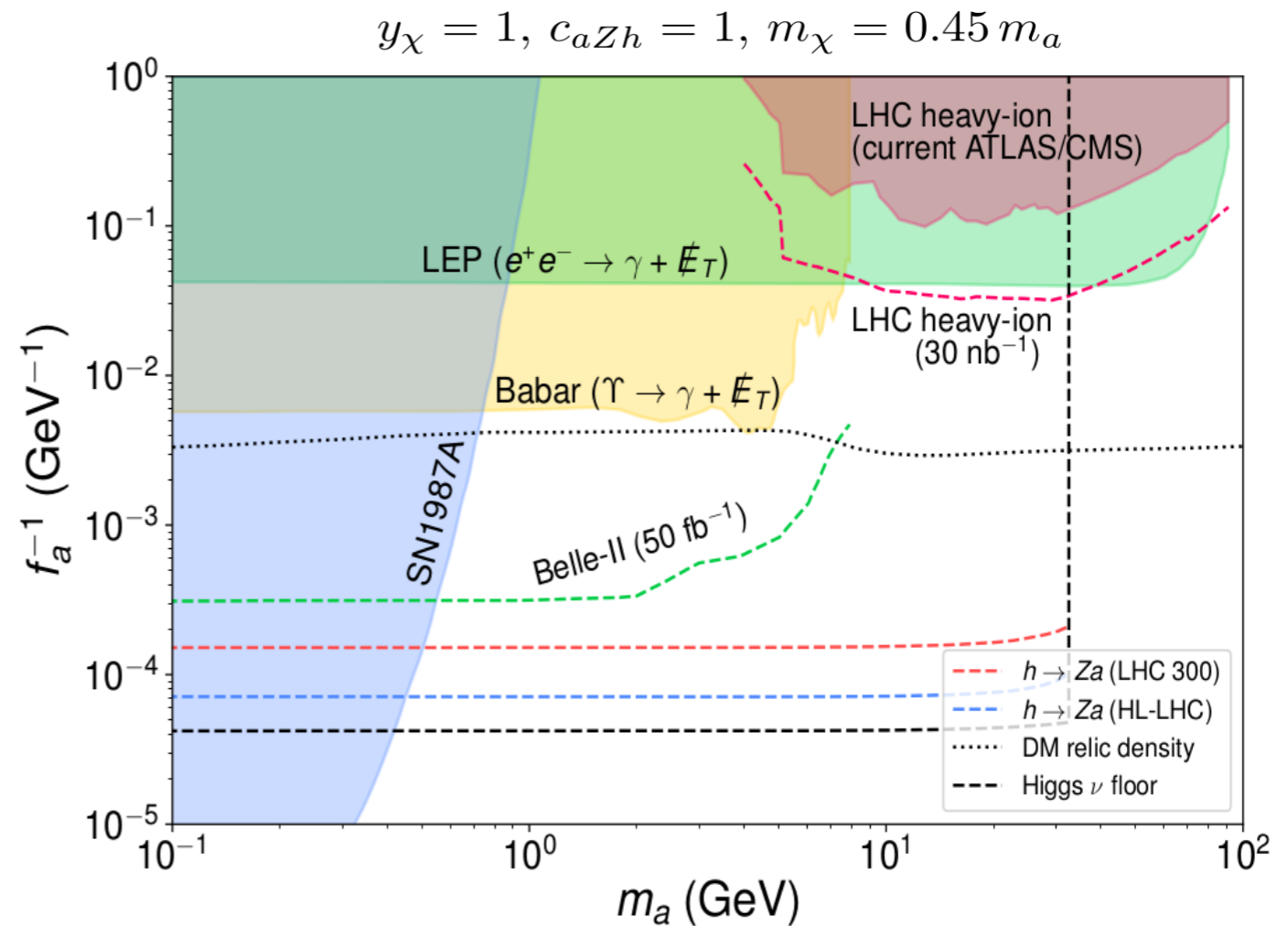
ALP-Dark Fermions: $y_\chi \bar{\chi} \gamma^\mu \gamma^5 \chi \partial_\mu a / f_a$

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

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

ALP - Dark sector interactions

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



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

Probing BSM Models

- 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

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

[LHC DM WG Benchmark Model]

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

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[LHC DM WG Benchmark Model]

Pseudoscalar mediator Singlet-doublet mixing

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

Portal coupling

Dirac Fermion DM

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

(decay present away from 2HDM alignment)