Semi-invisible $h \to Z\,X$ Higgs decays:

Extended scalar windows into dark matter

Based on: Aguilar-Saavedra, Cano, Cerdeño, JMN, ***PRD106 115023 (2206.01214)***

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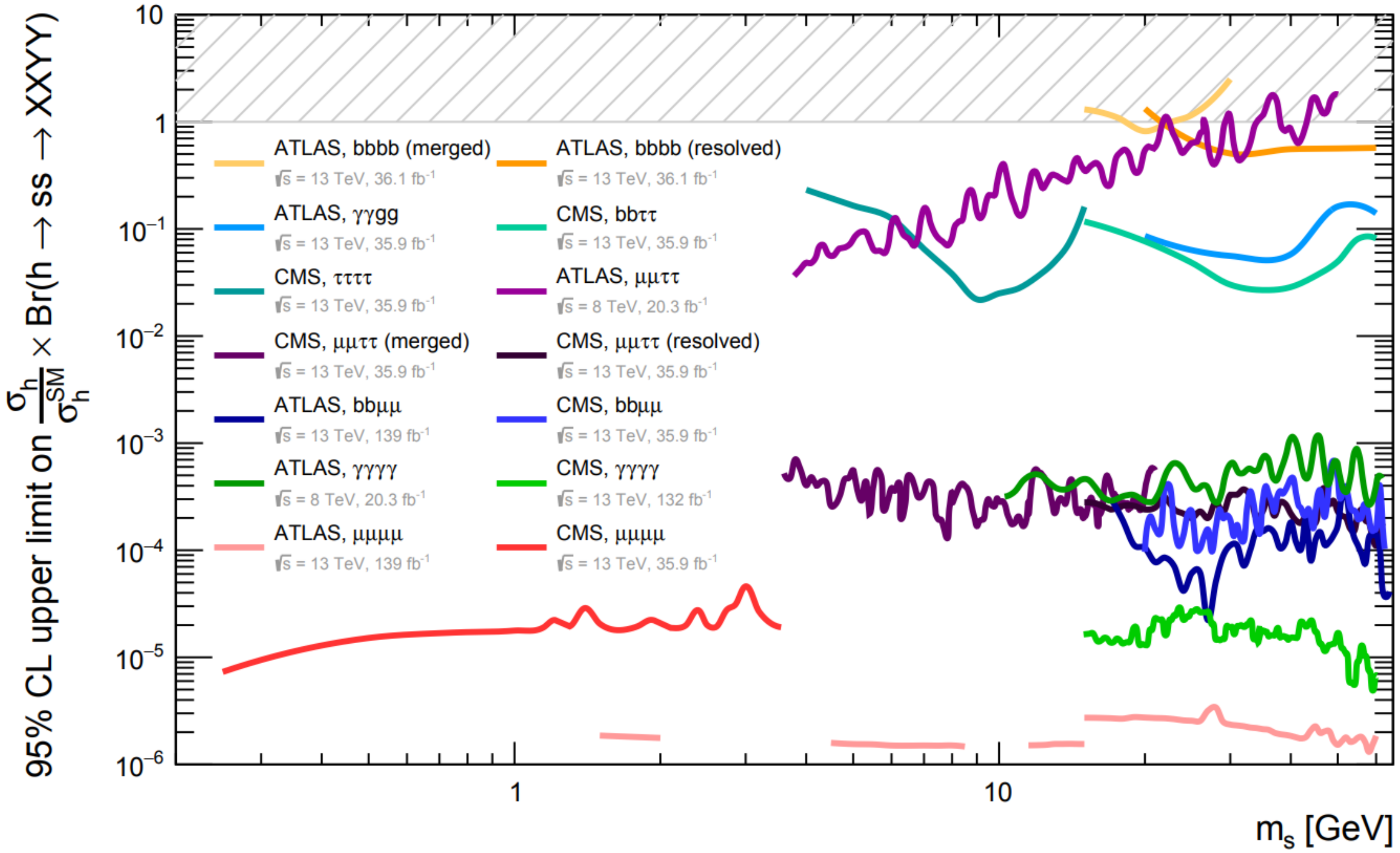
Why *semi-invisible (exotic) Higgs boson decays?*

Exotic Higgs decays

“The Classic”

○ Higgs → visible

e.g. $h \to ss \to XXYY$



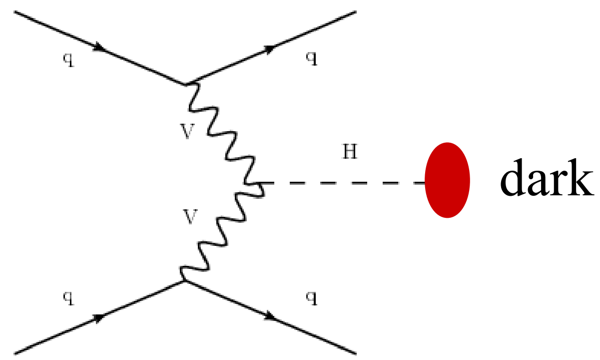
M. Cepeda et al. (arXiv:2111.12751)

State-of-Art Exotic Higgs decay review

(focused on experiment)

Exotic Higgs decays

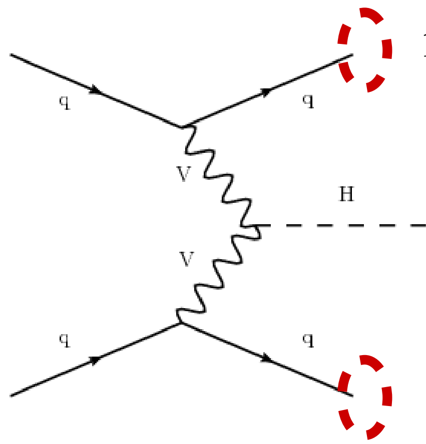
- Higgs → visible
- Higgs → invisible (dark sector) 



“The Classic”
(Dark Ed.)

Exotic Higgs decays

- Higgs → visible
- Higgs → invisible (dark sector)



need recoiling objec(s)

Exotic Higgs decays

- Higgs → visible
- Higgs → invisible (dark sector)
- Higgs → **semi**-invisible 

(visible part allows to access properties of dark sector)

Exotic Higgs decays

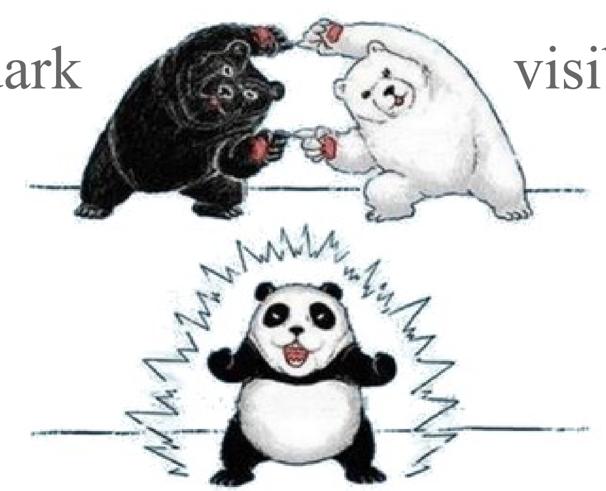
- Higgs → visible

- Higgs → invisible (dark sector)

- Higgs → **semi**-invisible

(visible part allows to access properties of dark sector)

dark visible



Critical information on Higgs interactions with dark sector

Exotic Higgs decays

- Higgs → visible
- Higgs → invisible

Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	m (GeV)	Interpretations
			$h \to ss/aa/vv$			
$eeee$ (r)	ggF	CMS [79]	13	137	4-8, 11.5-62.5	SM+v, SM+ALP
(r)	ggF	ATLAS [80]	13	139	15-60	SM+s, SM+v
$ee\mu\mu$ (r)	ggF	CMS [79]	13	137	4-8, 11.5-62.5	SM+v, SM+ALP
(r)	ggF	ATLAS [80]	13	139	15-60	SM+v
$\mu\mu\mu\mu$(m)	ggF	D0 [81]	1.96	4.2	0.2143-3	SM+s, SM+v
(r)	ggF	CMS [78]	13	35.9	0.25-8.5	SM+s, dark SUSY
(r)	ggF	CMS [79]	13	137	4-8, 11.5-60	SM+v, SM+ALP
(m/r)	ggF	ATLAS [80]	13	139	1.2-2, 4.4-8, 12-60	SM+s, SM+v
$\mu\mu\tau\tau$ (m/r)	ggF	D0 [81]	1.96	4.2	3.6-19	SM+s
(m/r)	ggF	ATLAS [82]	8	20.3	3.7-50	SM+s
(m/r)	ggF	CMS [83]	13	35.9	3.6-21	SM+s
(r)	ggF	CMS [84]	13	35.9	15-62.5	SM+s
$\tau\tau\tau\tau$ (m)	ggF	CMS [77]	13	35.9	4-15	SM+s
$bb\mu\mu$ (r)	ggF	ATLAS [85]	13	139	18-60	SM+s
(r)	ggF	CMS [86]	13	35.9	20-62.5	SM+s
$bb\tau\tau$ (r)	ggF	CMS [87]	13	35.9	15-60	SM+s
$bbbb$ (m)	Zh	ATLAS [88]	13	36.1	15-30	SM+s
(r)	Wh/Zh	ATLAS [76]	13	36.1	20-60	SM+s
$\gamma\gamma\gamma\gamma$ (r)	ggF	ATLAS [89]	8	20.3	10-62	SM+s
(r)	ggF	CMS [90]	13	132	15-60	SM+s
$\gamma\gamma gg$ (r)	VBF	ATLAS [91]	13	36.7	20-60	SM+s
			$h \to Za/Zv$			
gg (m)	ggF	ATLAS [92]	13	139	0.5-4	SM+s
ss (m)	ggF	ATLAS [92]	13	139	1.5-3	SM+s
ee (r)	ggF	CMS [79]	13	137	4-8, 11.5-35	SM+v
(r)	ggF	ATLAS [80]	13	139	15-55	SM+v
$\mu\mu$ (r)	ggF	CMS [79]	13	137	4-8, 11.5-35	SM+v
(r)	ggF	ATLAS [80]	13	139	15-30/15-55	SM+s, SM+v

		$h \to \mathrm{E}_T^{\mathrm{miss}}$			
Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	Br(H→Inv) UL
$\mathrm{E}_T^{\mathrm{miss}}$	VBF	ATLAS [117]	13	139	0.13 (0.13)
	VBF	CMS [118]	13	138	0.17 (0.11)
	$Z(ll)h$	ATLAS [111]	13	139	0.18 (0.18)
	$Z(ll)h$	CMS [112]	13	137	0.29 (0.25)
	ggF	ATLAS [119]	13	139	0.34 (0.39)
	ggF, $V(qq)h$	CMS [120]	13	137	0.278 (0.253)
	tth	ATLAS [110]	13	139	0.40 (0.36)
	tth	CMS [121]	13	35.9	0.46 (0.48)
	Combination	ATLAS [110]	7, 8, 13	4.7+20.3+139	0.11 (0.11)
	Combination	CMS [122]	7, 8, 13	4.9+19.7+38.2	0.19 (0.15)

M. Cepeda et al. (arXiv:2111.12751)

Widely explored experimentally (& theoretically!)

(many Higgs production & decay modes covered)

Exotic Higgs decays

- Higgs $\rightarrow$ visible

- Higgs $\rightarrow$ invisible

- **Higgs $\rightarrow$ semi-invisible** **poorly explored so far…**

Th.

Englert, Spannowsky, Wymant, Phys.Lett.B 718 (2012), 538

$h \rightarrow aa$ (jets + MET)

Petersson, Romagnoni, Torre, JHEP 10 (2012), 016

$h \rightarrow \gamma$ + MET

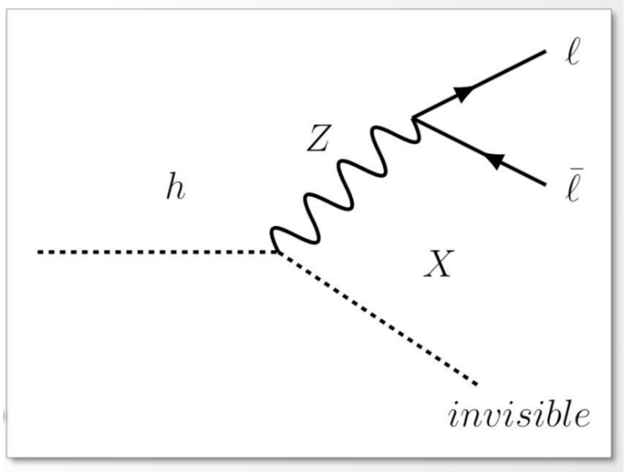
Reviews by Curtin et al. (1312.4992), Cepeda et al. (2111.12751) cover few more channels/models:

bb + MET, $\tau\tau$ + MET, $\gamma\gamma$ + MET…

Exp.

$h \rightarrow s/v + E_T^{miss}$					
Decay	Mode	Reference	$\sqrt{s}$ (TeV)	$\int \mathcal{L}$ (fb^{-1})	Interpretations
$E_T^{miss} + \gamma$	VBF	CMS [113]	13	130	SM+v
	VBF	ATLAS [114]	13	139	SM+v
	Zh	CMS [109]	13	137	SM+v
	ggF, Zh	CMS [115]	8	19.4	Other
$E_T^{miss} + bb$	Zh	ATLAS [116]	13	139	NMSSM

BSM Higgs boson decay $h \to ZX$ ($X \to invisible$)

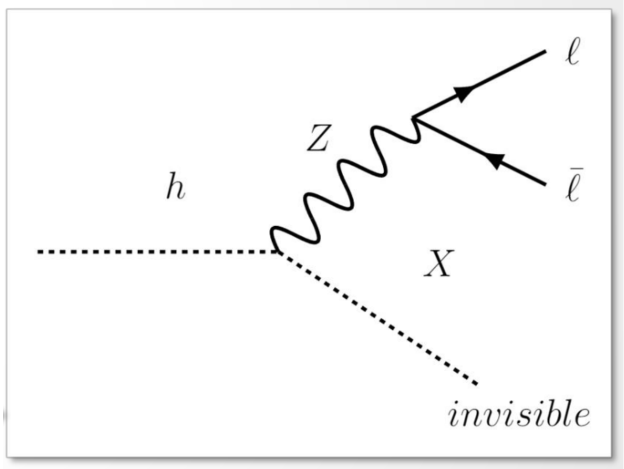


Aguilar-Saavedra, Cano, Cerdeño, No, 2206.01214

Decay channel <u>previously unexplored</u> in literature…

(… LHC $h \to ZX$ searches with **<u>visible</u>** X ($\ell\ell$ or $\gamma\gamma$) exist)

BSM Higgs boson decay $h \to ZX$ ($X \to invisible$)



Aguilar-Saavedra, Cano, Cerdeño, No, 2206.01214

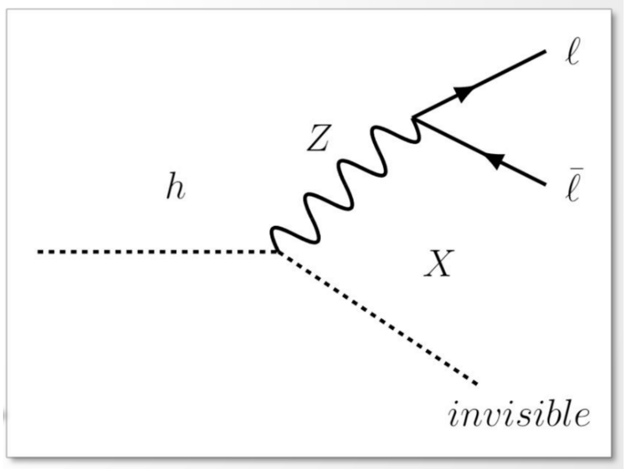
Decay channel previously unexplored in literature…

- Model-independent sensitivity analysis for **HL-LHC**

- BSM model interpretations:

  Extended Higgs sector portal to DM
  Axion-like particles (ALPs)

BSM Higgs boson decay $h \to ZX$ ($X \to invisible$)



Aguilar-Saavedra, Cano, Cerdeño, No, 2206.01214

Decay channel <u>previously unexplored</u> in literature...

- Model-independent sensitivity analysis for HL-LHC
- BSM model interpretations:

Extended Higgs sector portal to DM
Axion-like particles (ALPs)

$h \to Z\,(\ell\ell) + invisible$

○ Already present in SM: $h \to ZZ^* \to \ell\ell\,\nu\nu$

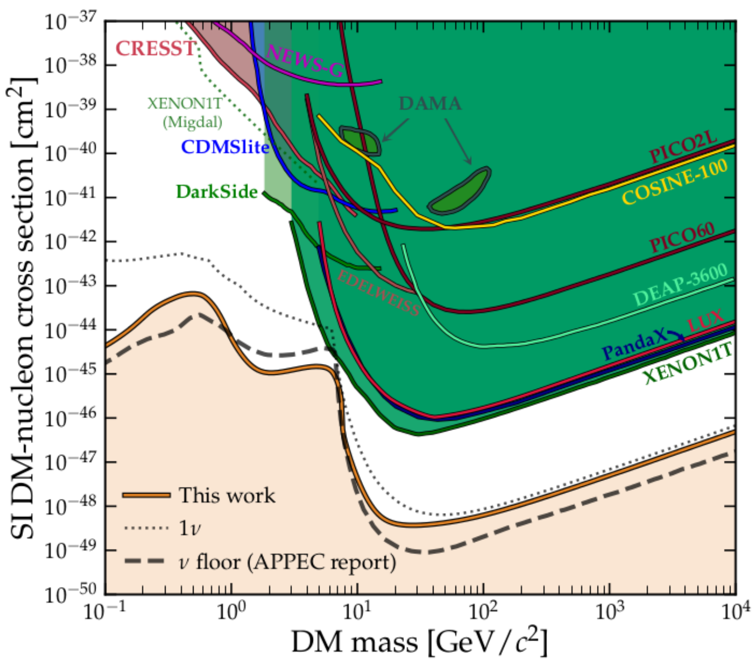
Irreducible SM background for BSM $h \to Z\,(\ell\ell) + invisible$

$h \rightarrow Z\,(\ell\ell) + invisible$

- <u>Already present in SM</u>: $h \rightarrow ZZ^* \rightarrow \ell\ell\,\nu\nu$

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

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



O' Hare, 2109.03116

$h \rightarrow Z\,(\ell\ell) + invisible$

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

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

Target sensitivity for HL-LHC

$$\mathbf{Br}_{h \rightarrow Z + \text{invisible}} \simeq \mathbf{0.0053}$$

$$h \to Z(\ell\ell) + invisible$$

- Which Higgs production mode @LHC?

ggF $(pp \to 2\ell + \mathrm{MET})$ ✗ Too much background

$h \to Z\,(\ell\ell) + invisible$

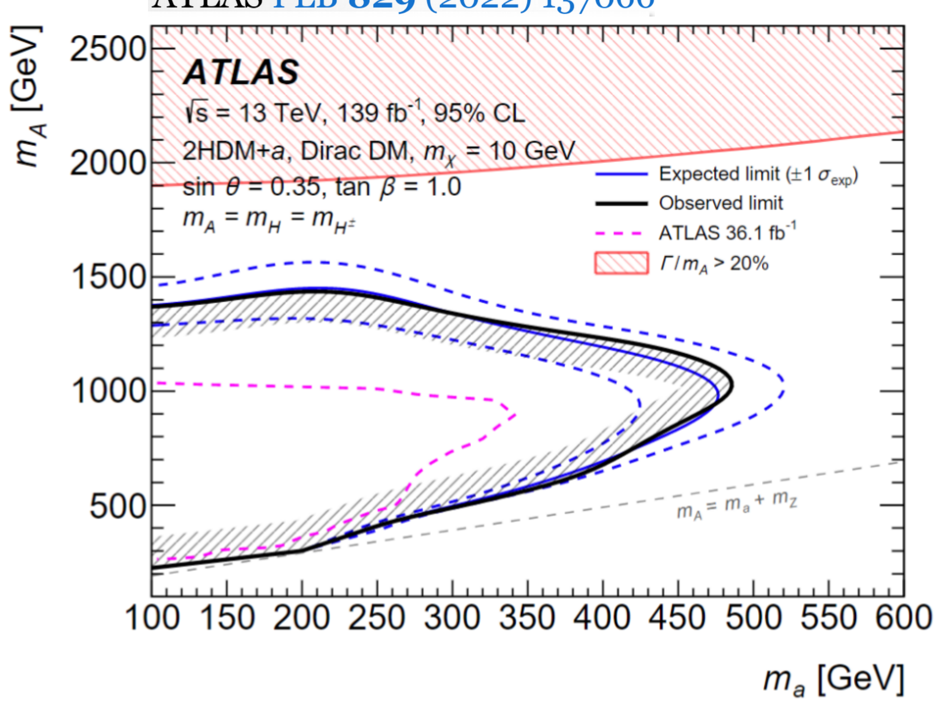
○ <u>Which Higgs production mode @LHC?</u>

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

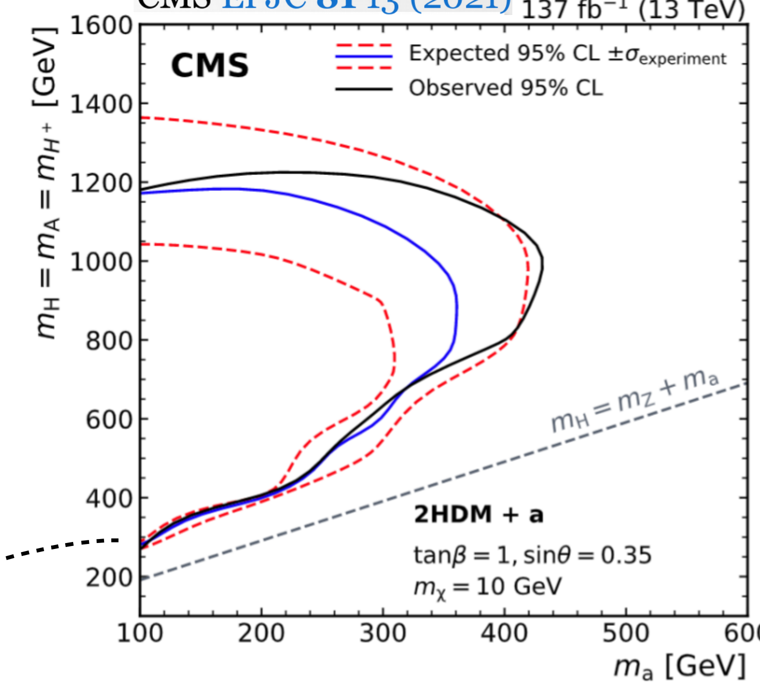
e.g. Seen explicitly in ATLAS/CMS searches for "mono-Z"

$$\text{ggF} \to H,\ H \to Z + a\ (invisible)$$

ATLAS PLB **829** (2022) 137066



CMS EPJC **81** 13 (2021)



$E_T^{miss} > 90$ GeV
$m_T > 200$ GeV

insensitive to $m_H = m_h = 125$ GeV

$h \longrightarrow Z\,(\ell\ell) + invisible$

- <u>Which Higgs production mode @LHC?</u>

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

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

Zh $(pp \to 4\ell + \text{MET})$ ✓ very clean

$pp \rightarrow Z\,h,\ h \rightarrow Z\,(\ell\ell) + invisible$

Our initial event selection:

→ Two (SF,OS) lepton pairs

→ Pass 1-, 2- or 3-lepton ATLAS (2018) Triggers

→ Veto high-p_T jets ($p_T > 50$ GeV)

→ If multiple lepton combinations in event, minimize Δ

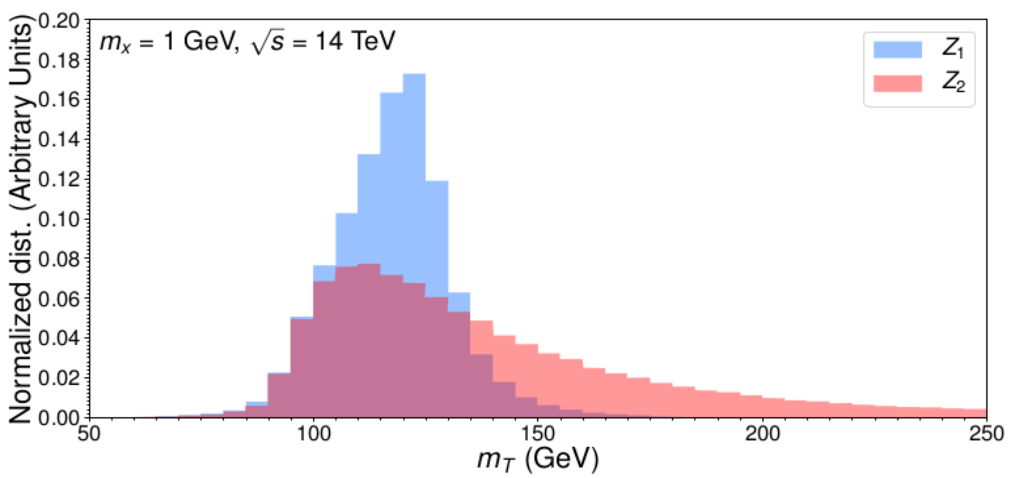
$$\Delta^2 = m_Z^{-2}[(m_{\ell\ell_1} - m_Z)^2 + (m_{\ell\ell_2} - m_Z)^2]$$

$pp \to Z\,h,\ h \to\ Z\,(\ell\ell) + invisible$

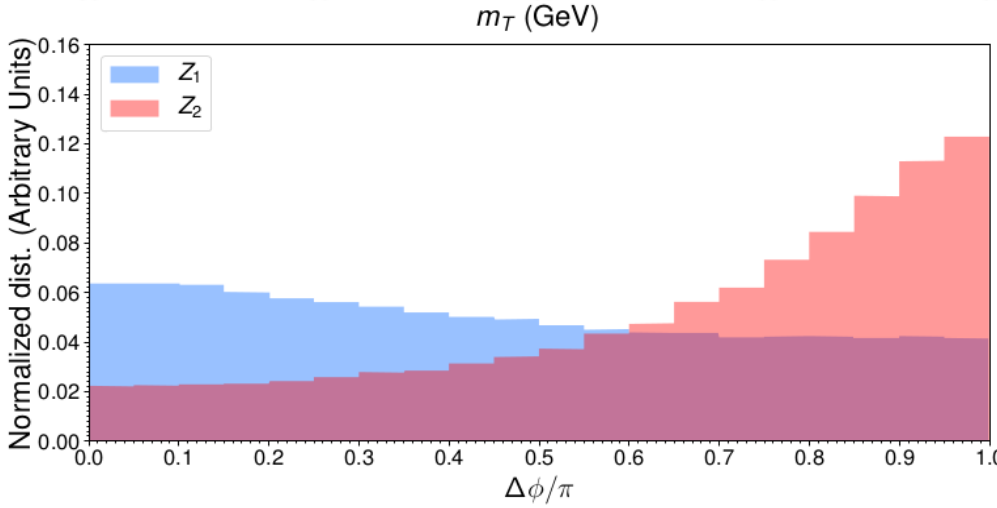
❶ Small Cross-section: $\sigma(pp \to 4\ell + \text{inv}) \simeq 3.8\ \text{fb} \times \text{BR}(h \to Z + inv)$ (@13 TeV LHC)

❷ How to choose Z boson "from Higgs decay"? (Z_1)

Discriminating kinematic variables



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



$$\Delta\phi_{\ell\ell,\not{E}_T}$$

$pp \to Z\,h,\ h \to Z\,(\ell\ell) + invisible$

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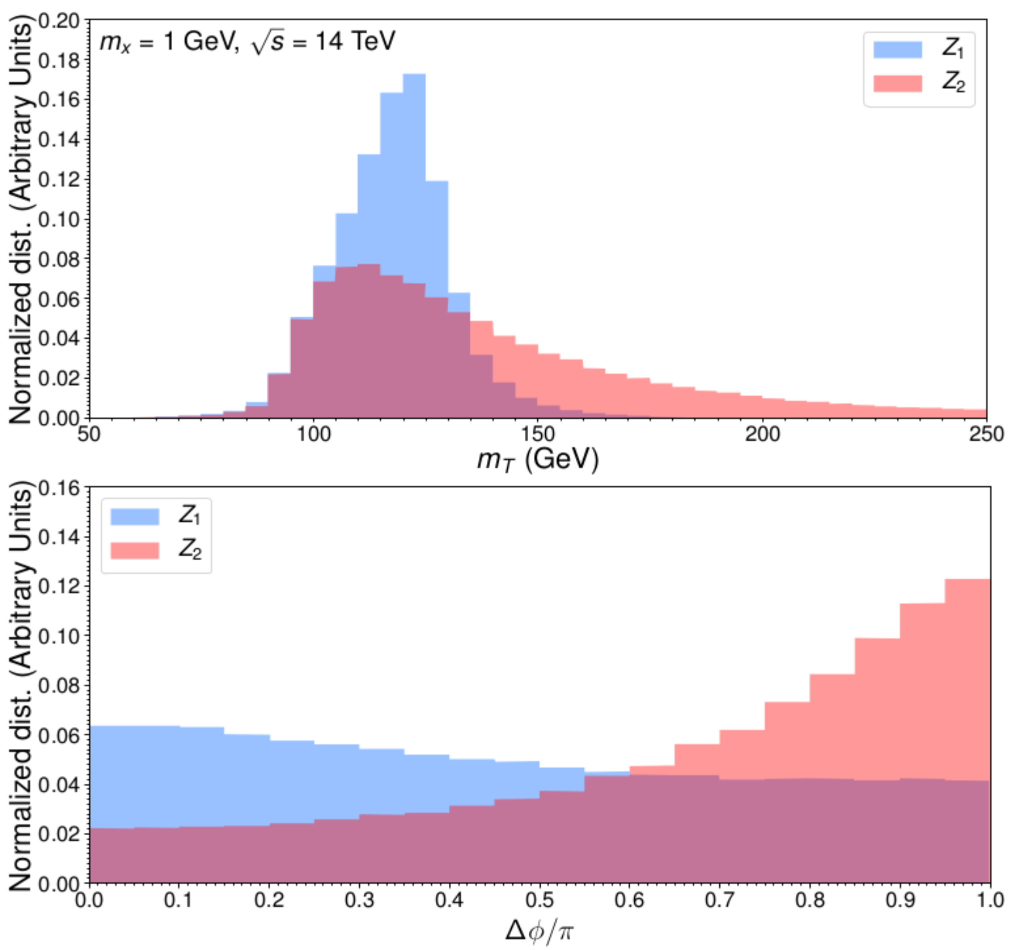
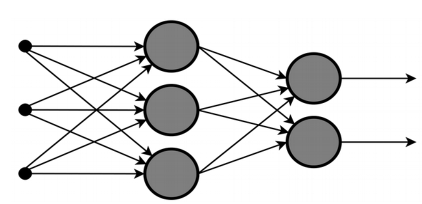
Discriminating kinematic variables



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

$$\Delta\phi_{\ell\ell,\not{E}_T}$$

We build a Neural Network to select Z_1 based on kinematics (2 variables)



~73% success rate

$pp \to Z\,h,\ h \to\ Z\,(\ell\ell) + invisible$

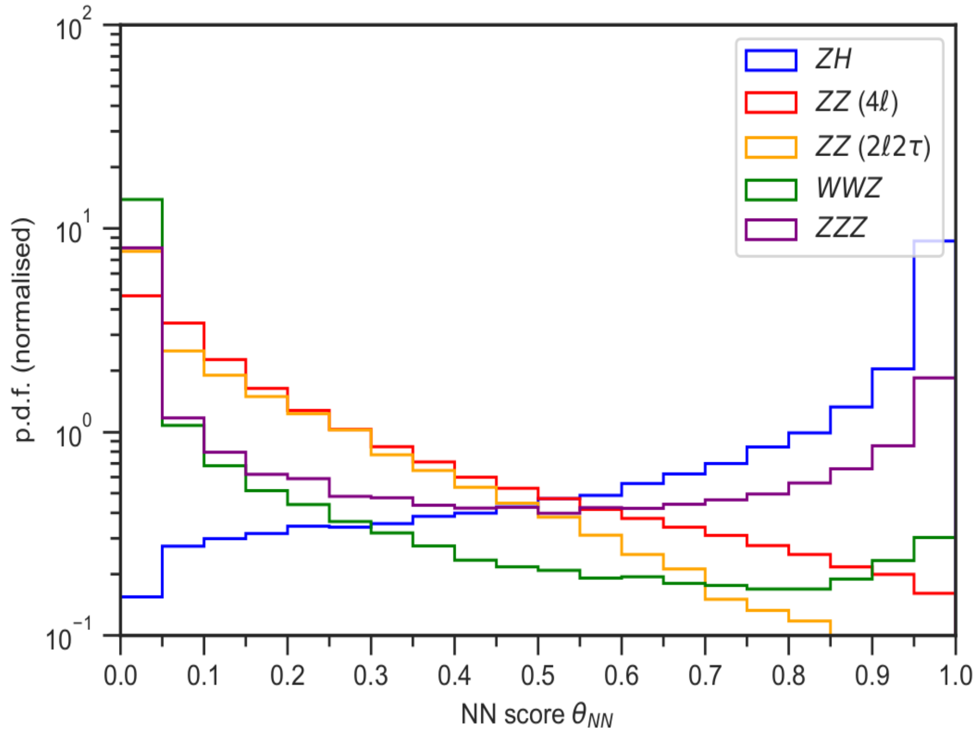
(HL-)LHC sensitivity:

SM backgrounds

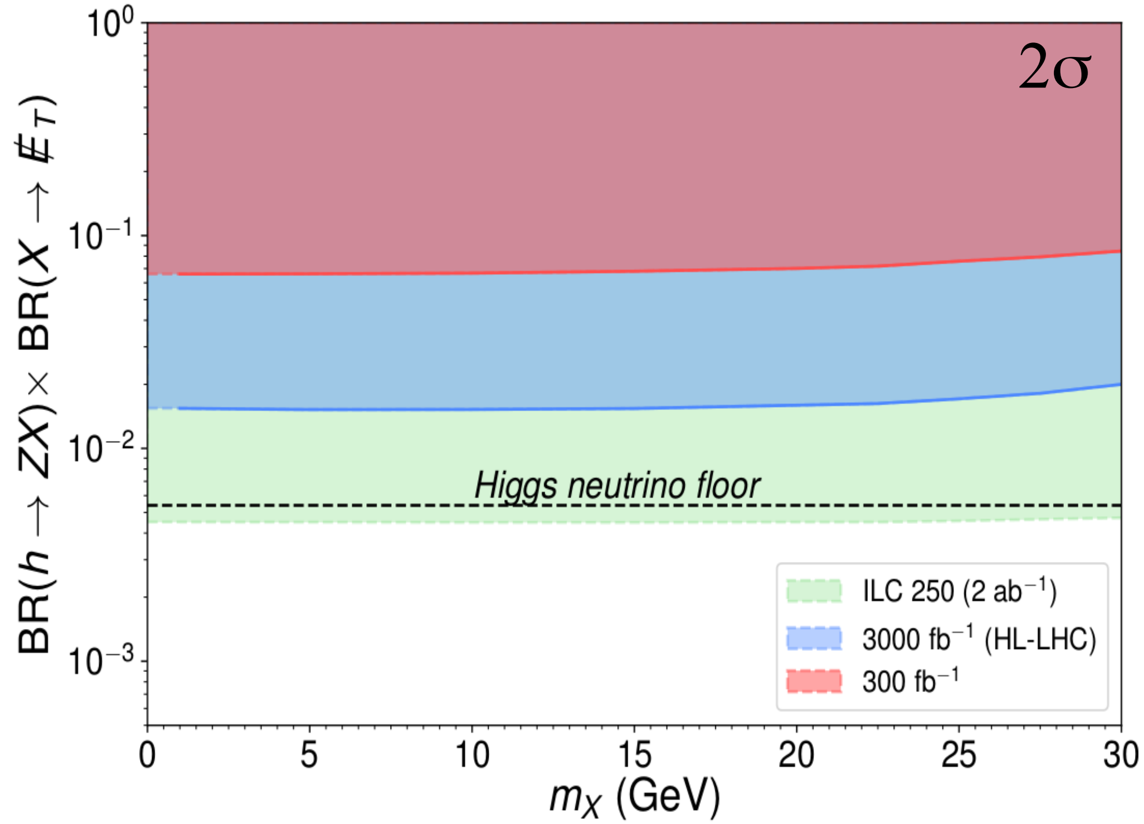
$ZZ \to 4\ell, 2\ell + 2\tau$

$WW^{(*)}Z, ZZZ \to 4\ell + 2\nu$

$t\bar{t}Z, tWZ \to 4\ell + 2\nu + jets$



Multivariate (NN) analysis



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

BSM Models

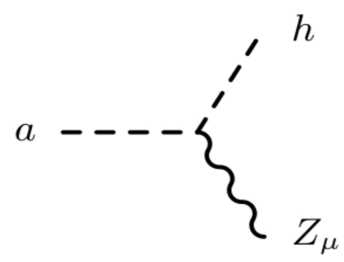
Axion-like particles (ALPs)

- ALP may have:

ALP - Higgs interactions

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, EJPC 77 (2017) 8, 572

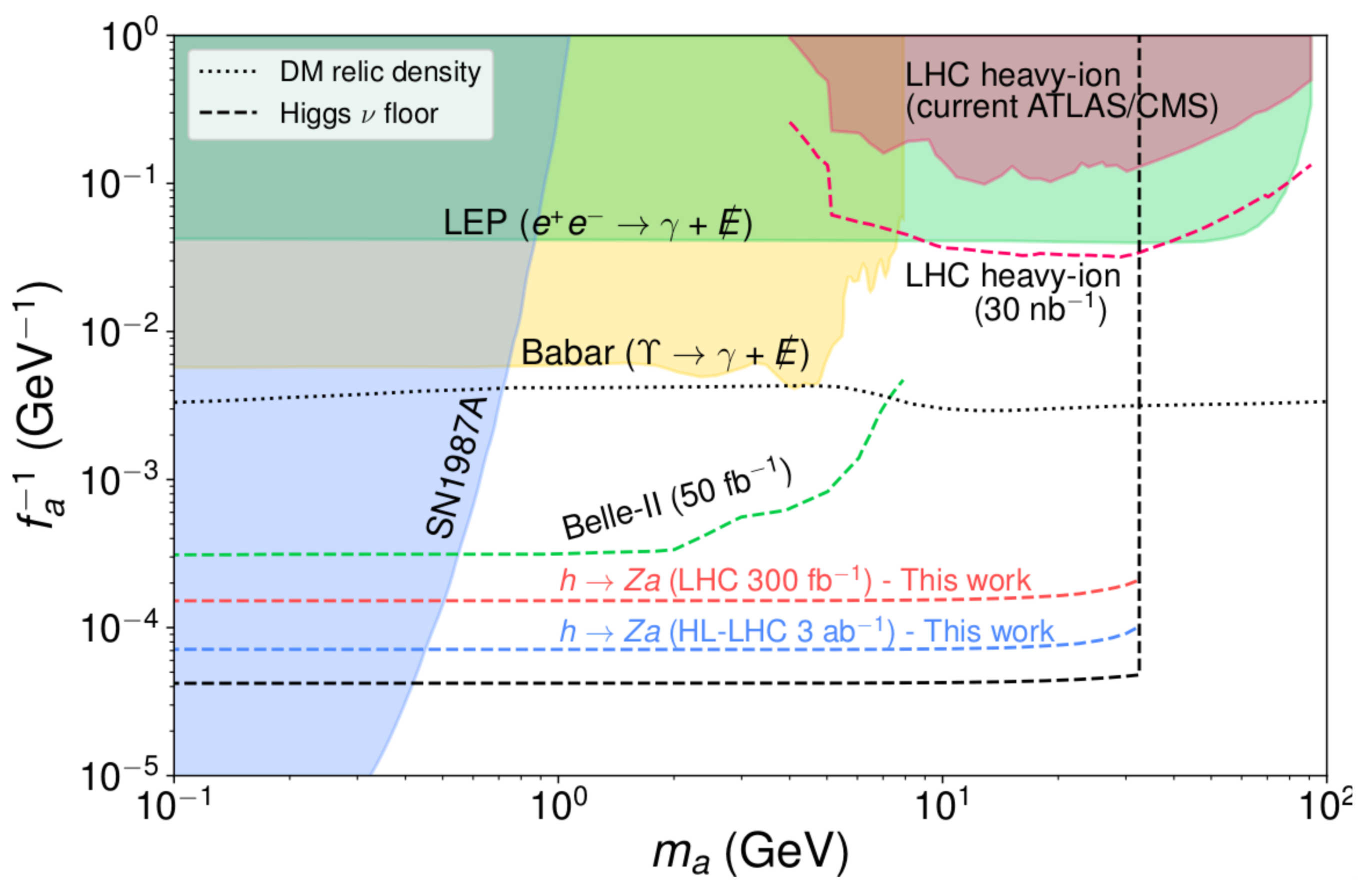
Bauer, Neubert, Thamm, JHEP 12 (2017), 044



ALP - Dark sector interactions

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

(dark decay of ALP) "ALP portal to DM"



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

<u>BSM ALP setup</u>

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

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

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

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

BSM Models

2HDM + *a* → *"Pseudoscalar portal to DM"*

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

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

BSM Models

2HDM + *a* $\longrightarrow$ *"Pseudoscalar portal to DM"*

Pseudoscalar mediator

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

Dirac Fermion DM

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

BSM Models

2HDM + *a* $\longrightarrow$ *"Pseudoscalar portal to DM"*

Singlet-doublet mixing

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

Portal coupling

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

BSM Models

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$$+ y_\chi\, a_0\, \bar{\chi} i \gamma^5 \chi$$

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$$+ \frac{\lambda_1}{2}\, |H_1|^4 + \frac{\lambda_2}{2}\, |H_2|^4 + \lambda_3\, |H_1|^2\, |H_2|^2$$
$$+ \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + {\rm h.c.}\right]$$

Why?

DM-SM interactions via pseudoscalar mediator avoid stringent bounds from DM direct detection experiments (e.g. XENON 1T)

Simplest renormalizable model: **2HDM + *a***

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]
Abe et al, Phys. Dark. Univ. 27 (2020), 100351

BSM Models

2HDM + *a* $\longrightarrow$ *"Pseudoscalar portal to DM"*

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

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

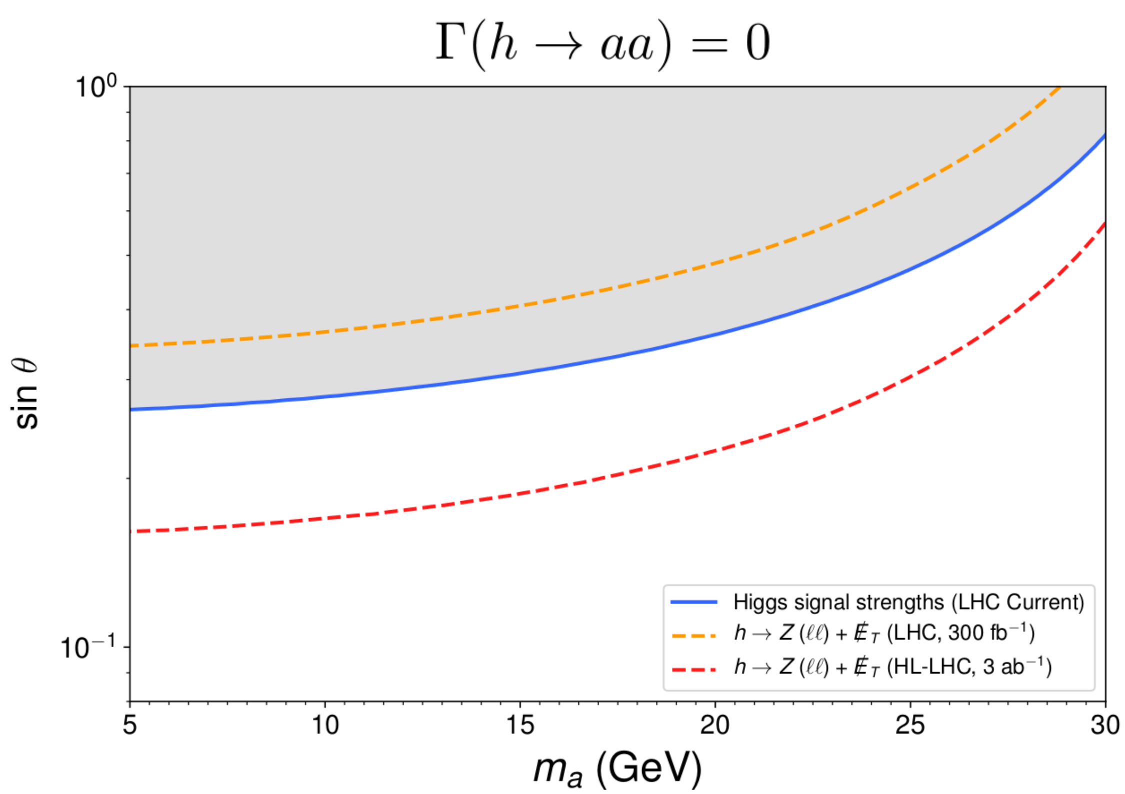
$$\Gamma(h \to Za) = \frac{1}{16\pi}\sin^2\theta\cos^2(\beta-\alpha)\frac{m_h^3}{v^2}\lambda^{3/2}$$

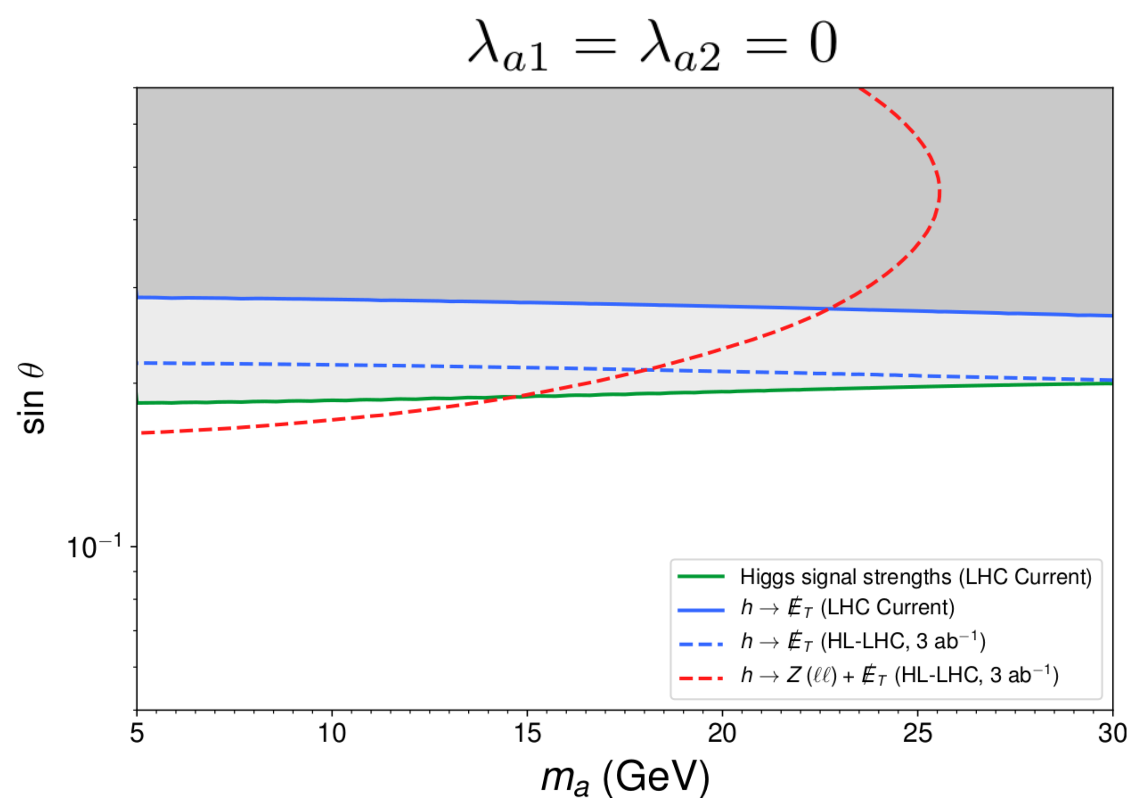
(decay present away from 2HDM aligment)

BSM Models

2HDM + *a* $\longrightarrow$ *"Pseudoscalar portal to DM"*

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





Competitive/complementary to probes via:

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

Summary

- Semi-dark Higgs decays: key info on Higgs portal (to dark sector) physics

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

  - Present in SM ($BR_{SM} \simeq 0.0053$) → BSM Target sensitivity for Colliders (Higgs ν floor)
  - HL-LHC can probe $BR_{BSM} \simeq 0.01 - 0.02$ (?)

- Powerful constraints on BSM scenarios:

  - Extended scalar sectors (2HDMa)
  - ALPs (ALP portal to dark sector)
  - Dark photons...

thank you


KEEP
CALM
AND
BACKUP
YOUR
WORK

$e^+e^- \to Z\,h$ $h \to Z(\ell\ell) + invisible$ **@ILC!**

- Lepton colliders: Ideally suited for **semi-dark Higgs decay** searches

c.o.m. frame = lab frame
(knowledge of longitudinal momentum)

- $e^+e^- \to Z\,h$ ILC $\sqrt{s} = 250$ GeV

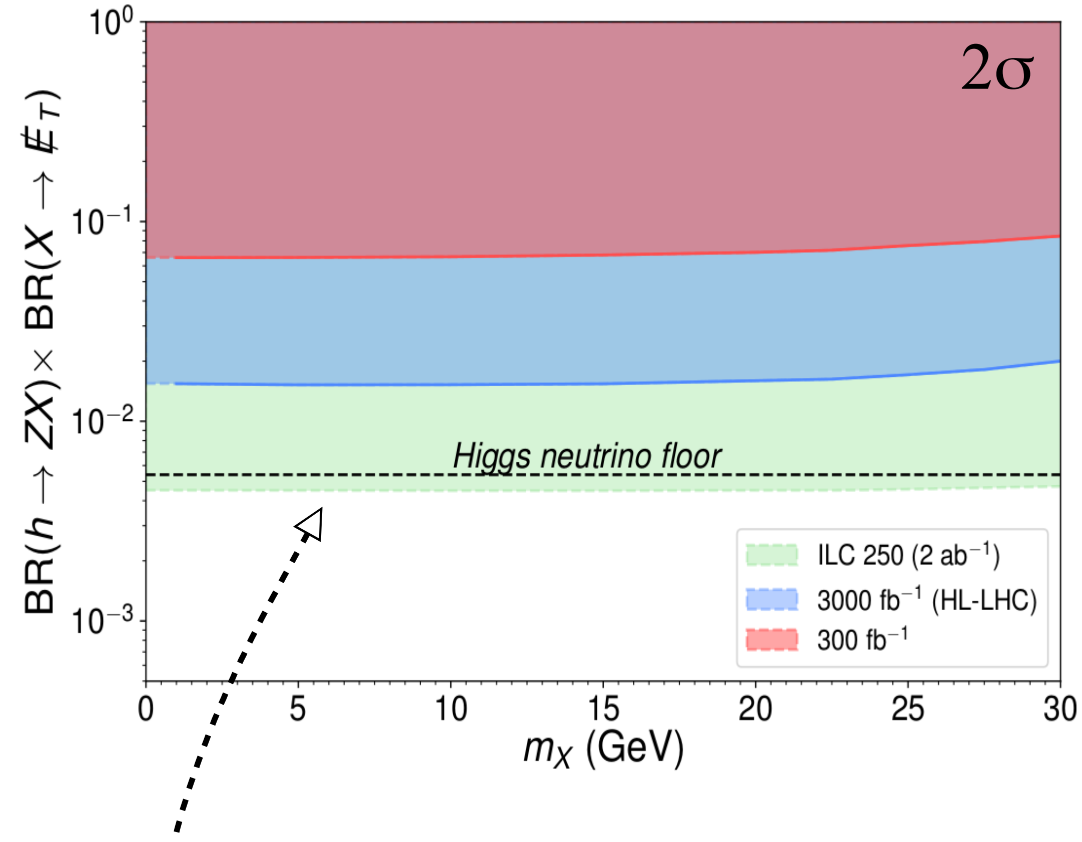
→ Higgs recoil mass for $Z_{1,2}$ ID

$$M^2_{\rm reco} = s + m^2_{Z_2} - 2E_{Z_2}\sqrt{s}$$

→ (semi-visible) Higgs invariant mass for signal discrimination

$$(m^{\rm miss}_{Z_1})^2 = \left(\sqrt{m^2_{Z_1} + p^2_{Z_1}} + \not{E}\right)^2 - \left|\vec{p}_{Z_1} + \vec{\not{E}}\right|^2$$

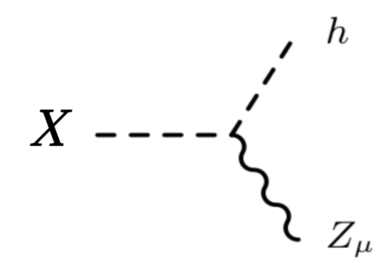
(No need for multivariate analysis)



BR($h \to$ ZX) < 0.5% reachable (95% C.L.)

What about existing data? (LEP)

- Searches for $e^+e^- \to Z^* \to h + X\,(invisible)$



$$\exists\ h \to \mathrm{Z} + \mathrm{X}\ \text{decay} \quad \Rightarrow \quad m_X < 35\ \text{GeV}$$

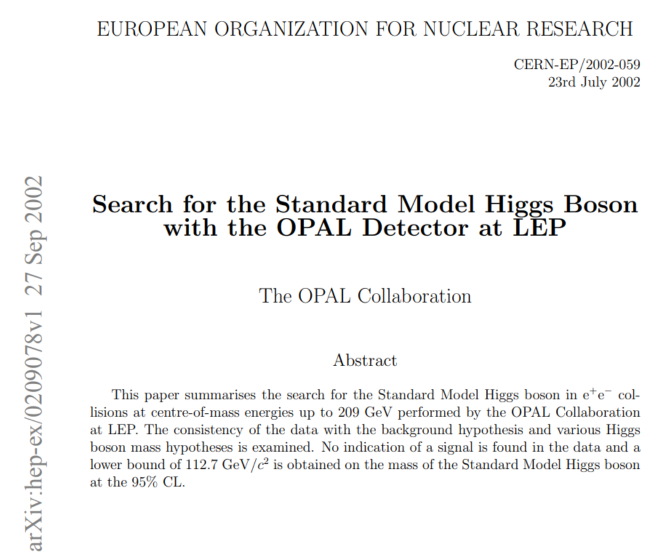
$e^+e^- \to h + X$ **within LEP2 kinematic reach!**

However, LEP $h + invisible$ searches target $h + Z\,(\nu\nu)$

e.g. OPAL
ArXiv/hep-ex/0209078

$$50\ \text{GeV} < M_{\text{miss}} < 130\ \text{GeV}$$

m_X


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/2002-059
23rd July 2002

arXiv:hep-ex/0209078v1 27 Sep 2002

Search for the Standard Model Higgs Boson with the OPAL Detector at LEP

The OPAL Collaboration

Abstract

This paper summarises the search for the Standard Model Higgs boson in e^+e^- collisions at centre-of-mass energies up to 209 GeV performed by the OPAL Collaboration at LEP. The consistency of the data with the background hypothesis and various Higgs boson mass hypotheses is examined. No indication of a signal is found in the data and a lower bound of 112.7 GeV/c^2 is obtained on the mass of the Standard Model Higgs boson at the 95% CL.

… insensitive to $m_X < 50$ GeV

No LEP constraints

BSM Models

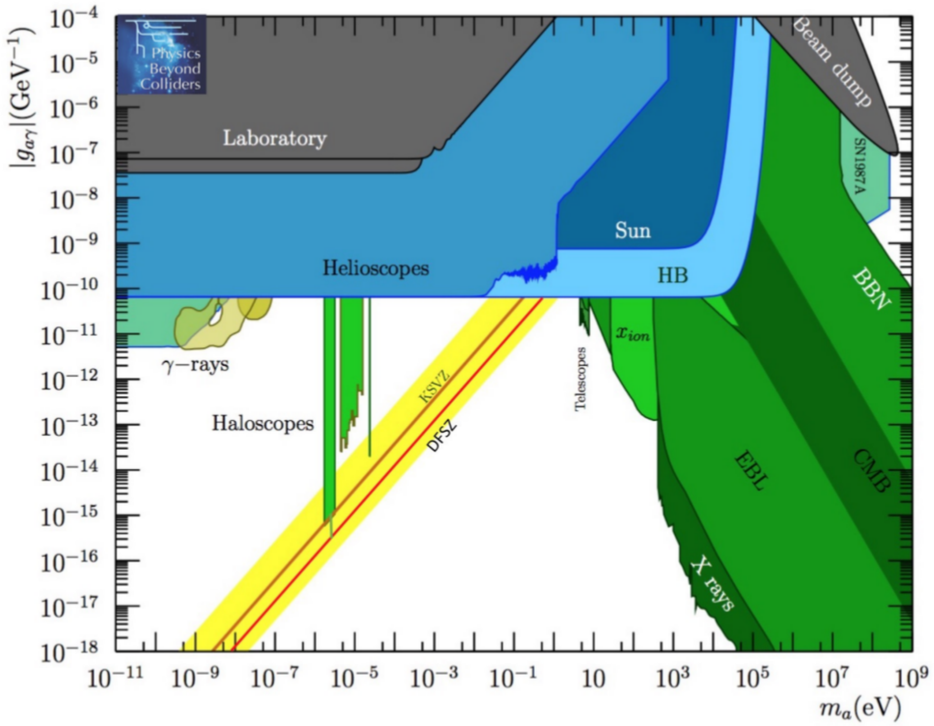
Axion-like particles (ALPs)

- QCD Axion = hypothetical particle from the PQ solution to strong-CP problem

$$g_{agg} = -\frac{1}{2\pi f_a}\alpha_s$$

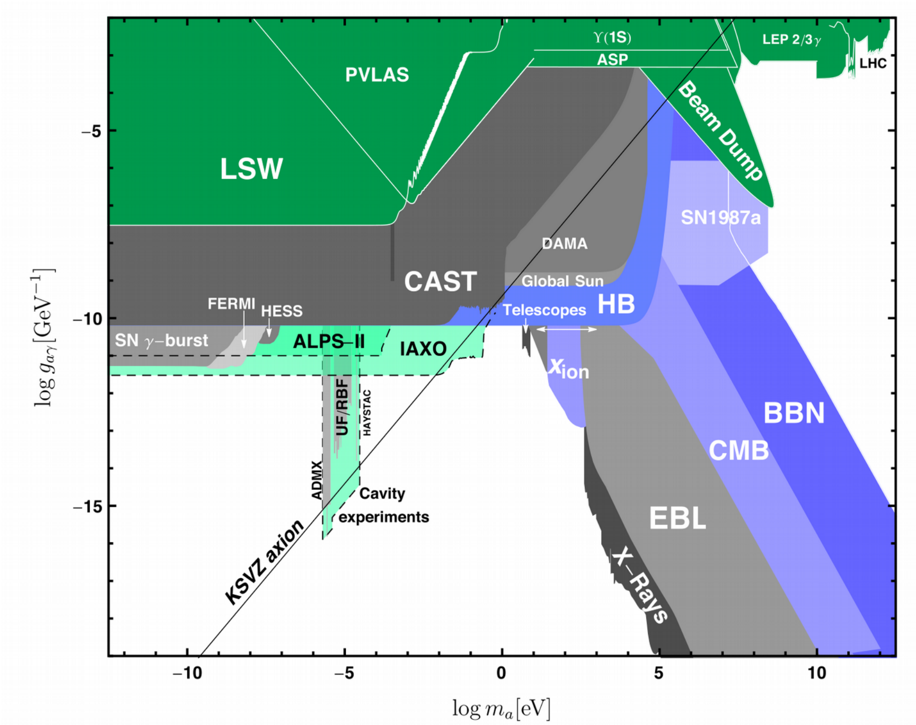
$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right)$$

$$\frac{1}{4} g_{agg}\, a\, G\tilde{G} + \frac{1}{4} g_{a\gamma\gamma}\, a\, F\tilde{F}$$



PBC CERN Report, arXiv:1901.09966

$$m_a^2 \simeq \frac{f_\pi^2 m_\pi^2}{f_a^2}\frac{m_u m_d}{(m_u+m_d)^2}$$



MADMAX Collaboration, Eur. Phys. J. C79 (2019), 3, 186

- ALPs = particle with properties similar to Axion, yet not strict QCD Axion mass-coupling relation

(*may* not solve strong-CP problem)

(general pseudo-Goldstone bosons)

BSM Models

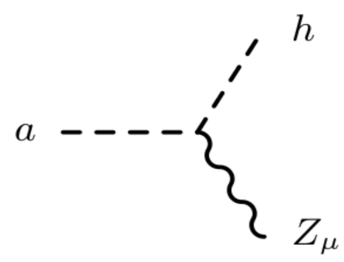
Axion-like particles (ALPs)

- ALP may have:

ALP - Higgs interactions

Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz, EJPC 77 (2017) 8, 572

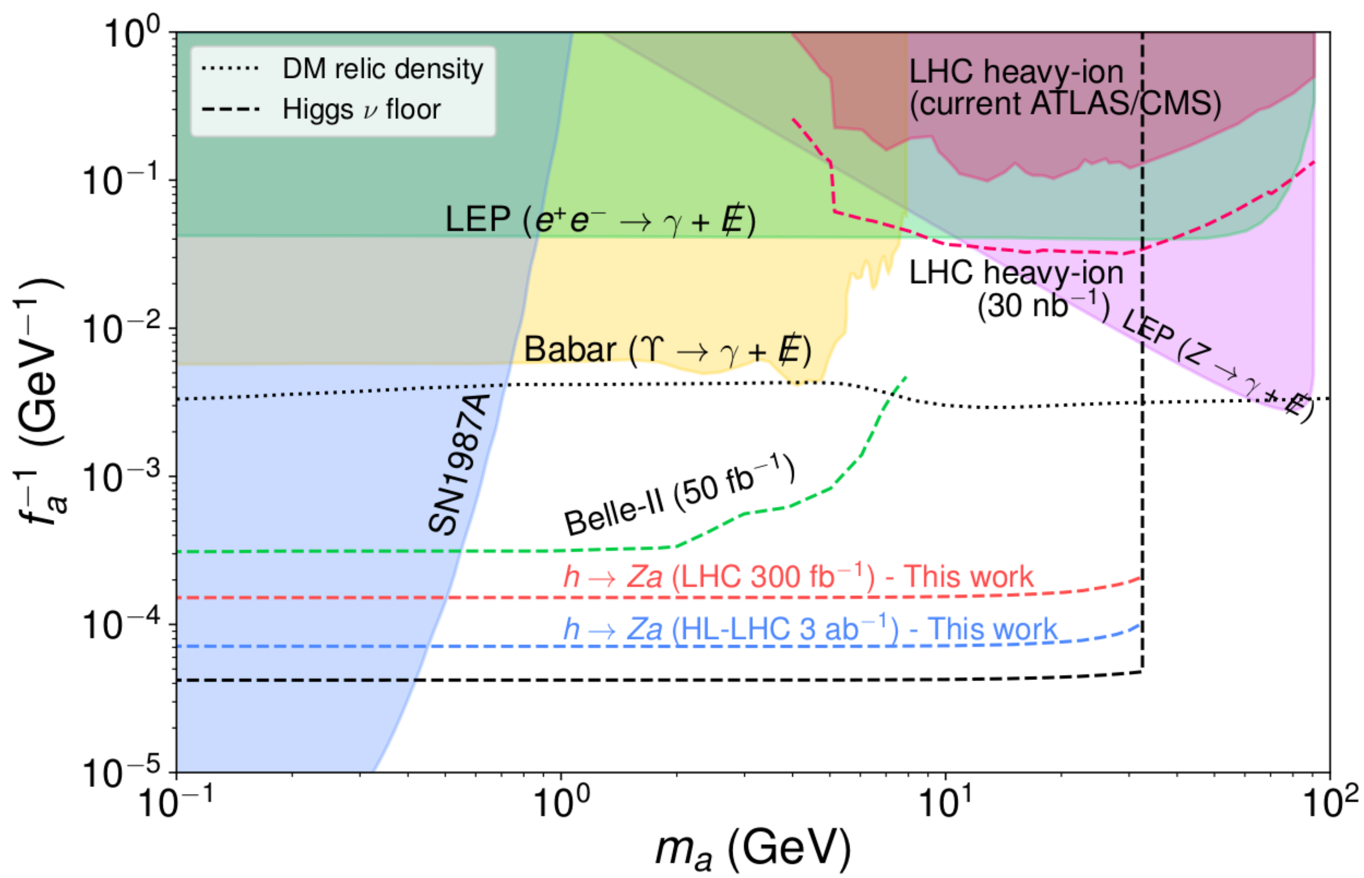
Bauer, Neubert, Thamm, JHEP 12 (2017), 044



ALP - Dark sector interactions

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

(dark decay of ALP) "ALP portal to DM"



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

BSM ALP setup

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

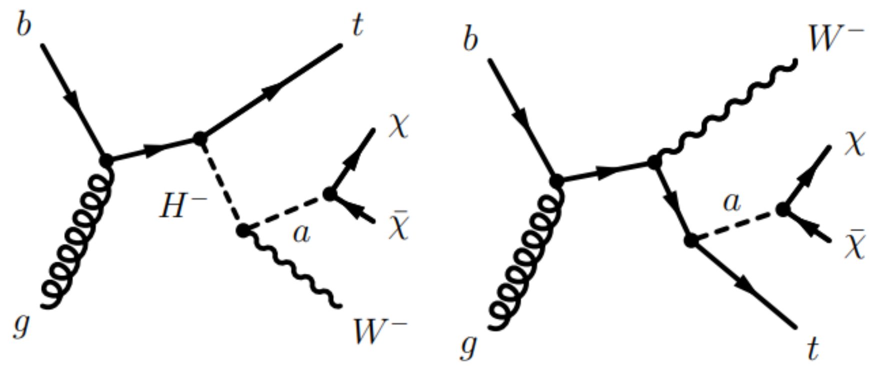
ALP-DM: $y_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\, \partial_\mu a/f_a$

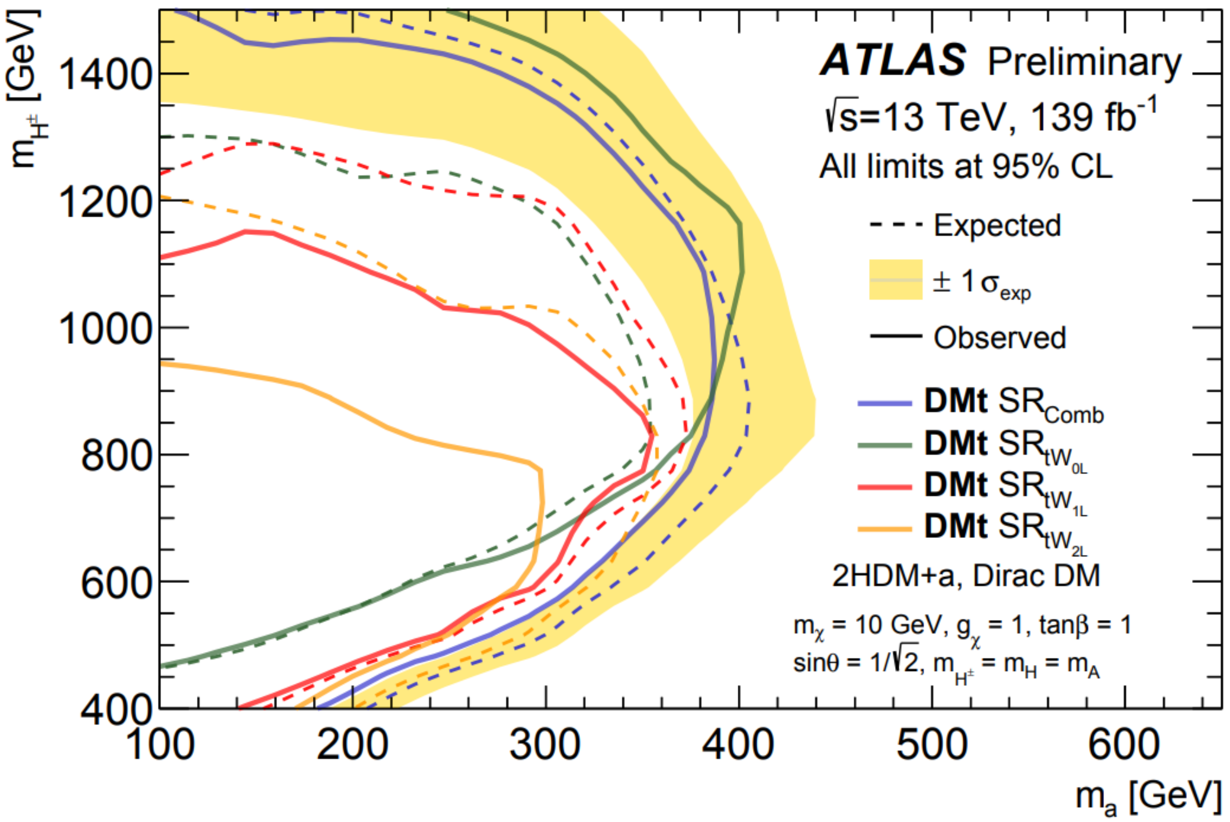
ALP-Photons: $c_{aBB}/f_a\; a\, B^{\mu\nu}\tilde{B}_{\mu\nu}$

BSM Models

2HDM + a **[LHC DM WG Benchmark Model]**

e.g.





ATLAS-CONF-22-012