Higgs Cascade Decays and the LHC

SB, Freese, Shakya, Shah; 1703.07800 (Phys. Rev. D)
SB, Shah; 1807.XXXXX
SB, Shah, Freese; 180X.XXXXX

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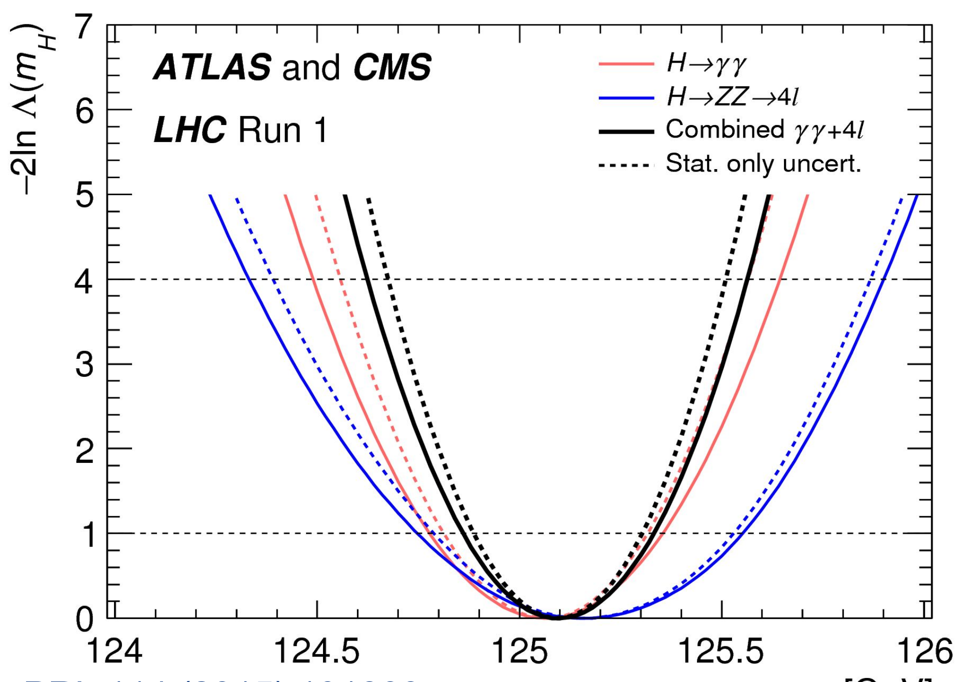
SUSY 2018
Barcelona

All the Higgses that we know

- Mass ≈ 125 GeV
- Largest couplings within 10% of the SM expectation



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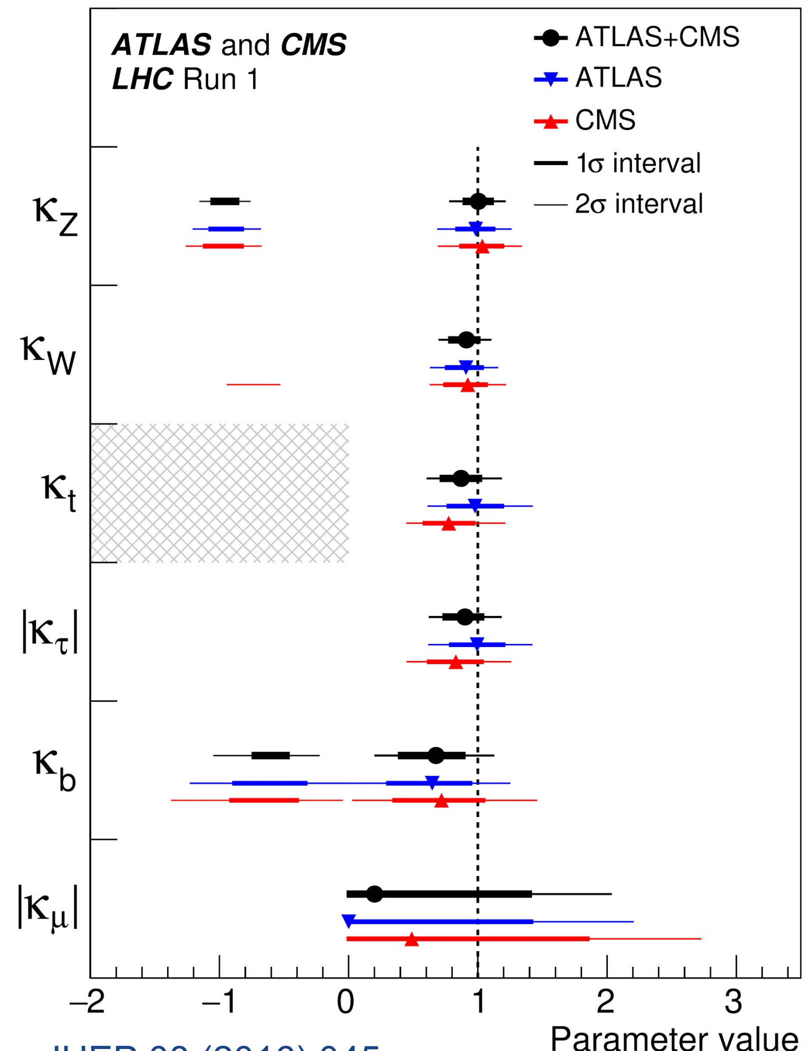

JHEP 08 (2016) 045

Why do we want more Higgses?

Many shortcomings of the SM are intimately linked to the Higgs sector

- Hierarchy Problem
- Baryogenesis
- (Meta-)Stability Problem
- Flavor Structure

The Higgs sector is least well measured in the SM

Why 2HDM+S?

- 2HDM sector ubiquitous in BSM physics, e.g. SUSY
- SM gauge-singlets useful for
  - Baryogenesis [Profumo+ 0705.2425, Barger+ 0811.0393, Cline+ 1210.4196]
  - Constructing DM Models [SB+ 1712.09873]
- Same scalar sector as in well-motivated High-Scale models, e.g. the Next-to-Minimal Supersymmetric Standard Model

2HDM+S

- 2 SU(2)-doublets Φ_1, Φ_2, and 1 (complex) SM singlet S
- Most general CP-conserving scalar potential has 27 physical d.o.f., which can be re-parameterized by 6 physical masses, 4 mixing angles, 3 vevs, 10 trilinear and 4 quartic couplings
  [SB, Shah 1807.XXXXX]
- Rotate to Higgs basis

$$\begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(H^{\rm SM} + iG^0\right) \end{bmatrix} = \sin\beta\Phi_1 + \cos\beta\Phi_2$$

$$\begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(H^{\rm NSM} + iA^{\rm NSM}\right) \end{bmatrix} = \cos\beta\Phi_1 - \sin\beta\Phi_2$$

$$\frac{1}{\sqrt{2}}\left(H^{\rm S} + iA^{\rm S}\right) = S\ ,$$

- 7 degrees of freedom after EW symmetry breaking:
  $\{H^{\rm SM}, H^{\rm NSM}, H^{\rm S}\}$; $\{A^{\rm NSM}, A^{\rm S}\}$; $H^\pm$

Alignment and Mass Eigenstates

$$h_i = S_{h_i}^{\rm SM} H^{\rm SM} + S_{h_i}^{\rm NSM} H^{\rm NSM} + S_{h_i}^{\rm S} H^{\rm S} \ , \ h_i = \{h_{125}, H, h\}$$

$$a_i = P_{a_i}^{\rm NSM} A^{\rm NSM} + P_{a_i}^{\rm S} A^{\rm S} \ , \ a_i = \{A, a\}$$

- SM-like nature of the observed 125 GeV state requires a mass eigenstate approximately aligned with $H^{\rm SM}$

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Alignment by decoupling

- Suppress mixing by choosing $\{H^{\rm NSM}, H^{\rm S}\}$ heavy wrt. $H^{\rm SM}$

⇒ Additional Higgses out of LHC reach

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Alignment by decoupling

- Suppress mixing by choosing $\{H^{\mathrm{NSM}}, H^{\mathrm{S}}\}$ heavy wrt. H^{SM}

⇒ Additional Higgses out of LHC reach

Alignment without decoupling

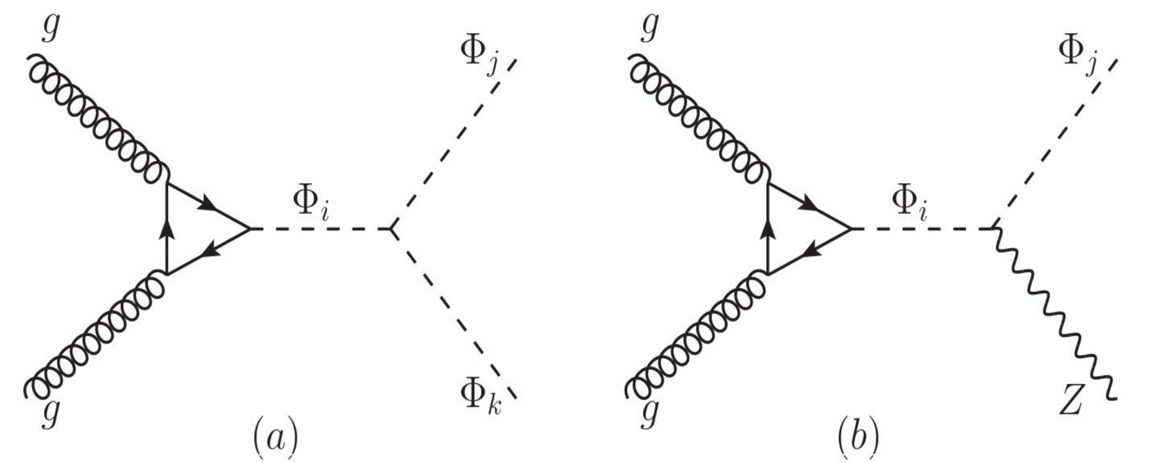
- Suppress mixing by conspiracy of parameters

⇒ Additional Higgses can remain light and thus accessible at LHC!

Cascade Decays

Complexity of Higgs sector allows for new decay modes

- $(h_i \to h_j h_k)$, $(h_i \to a_j a_k)$, $(a_i \to h_j a_k)$
- $(h_i \to Z a_j)$, $(a_i \to Z h_j)$



Alignment suppressed $(H \to h_{125} h_{125})$ $(A \to Z h_{125})$

Cascade Decays

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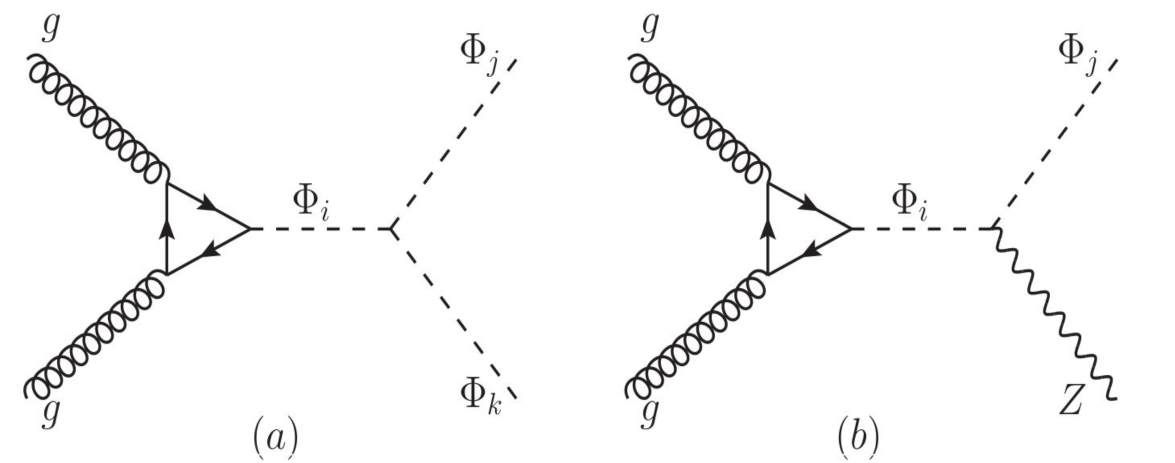


Dominant modes:

$(H \to h_{125} h)$ $(H \to Z a)$

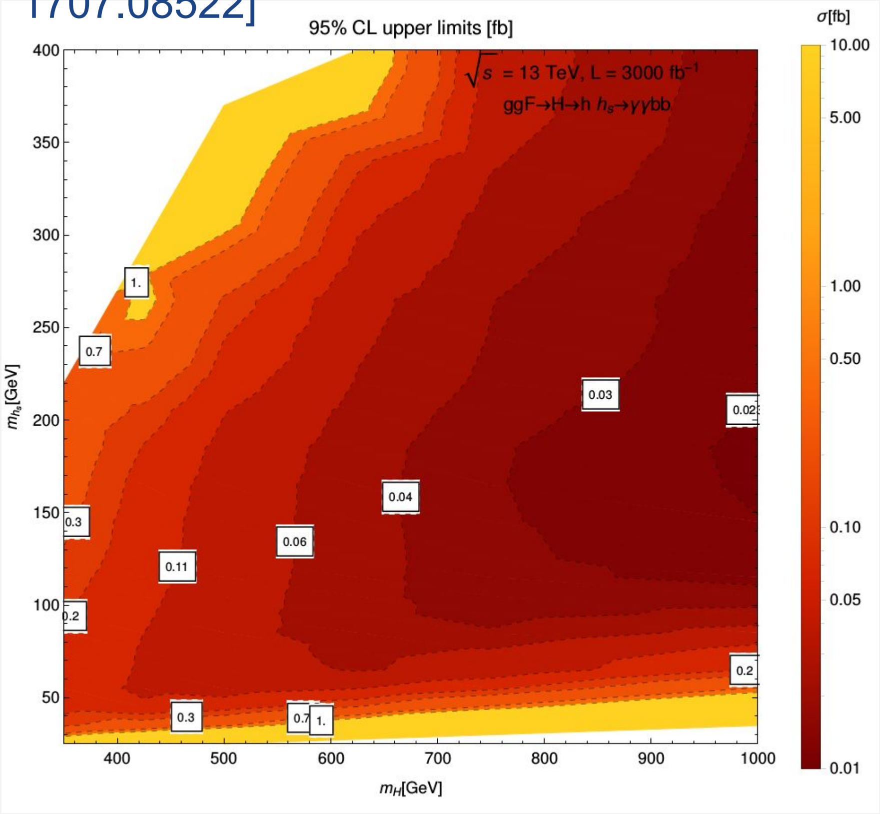
$(A \to h_{125} a)$ $(A \to Z h)$

LHC Reach: SM decays of additional light states

Higgs + visible reach in

bbbb and $bb\gamma\gamma$ final states:

[Ellwanger, Rodriguez-Vazquez 1707.08522]

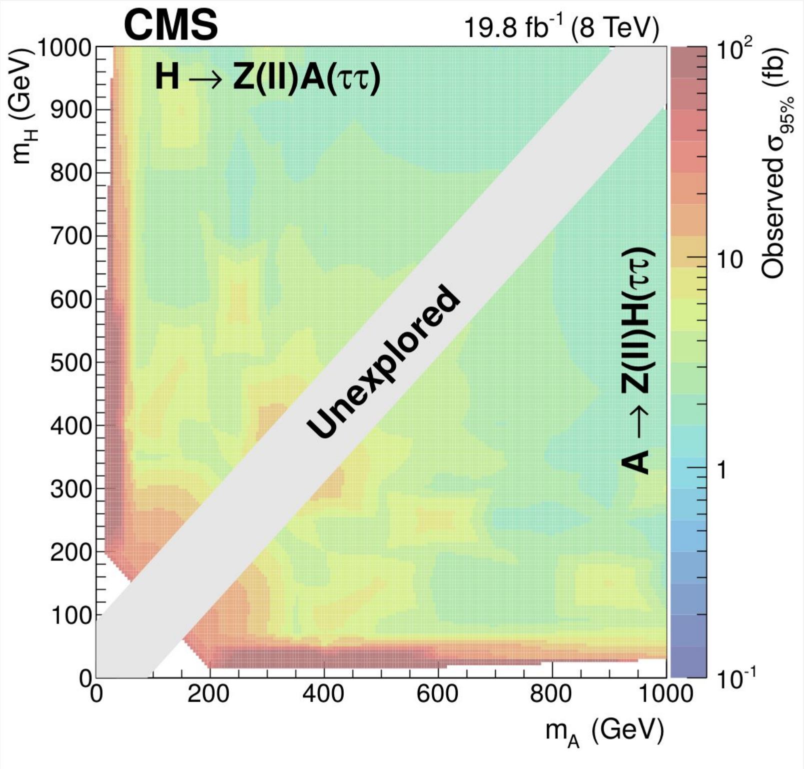


Z + visible reach in

$\ell\ell bb$ and $\ell\ell\tau\tau$ final states

extrapolated from CMS limit

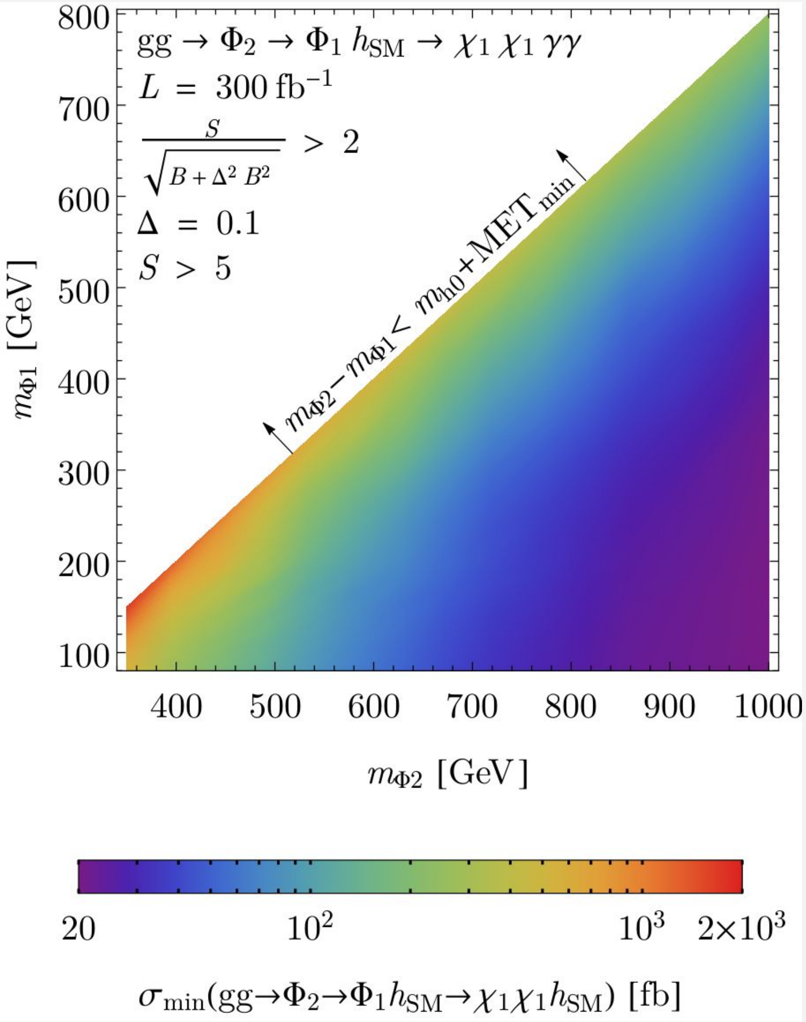
[CMS 1603.02991]



LHC Reach: MET (DM) decays of additional light states

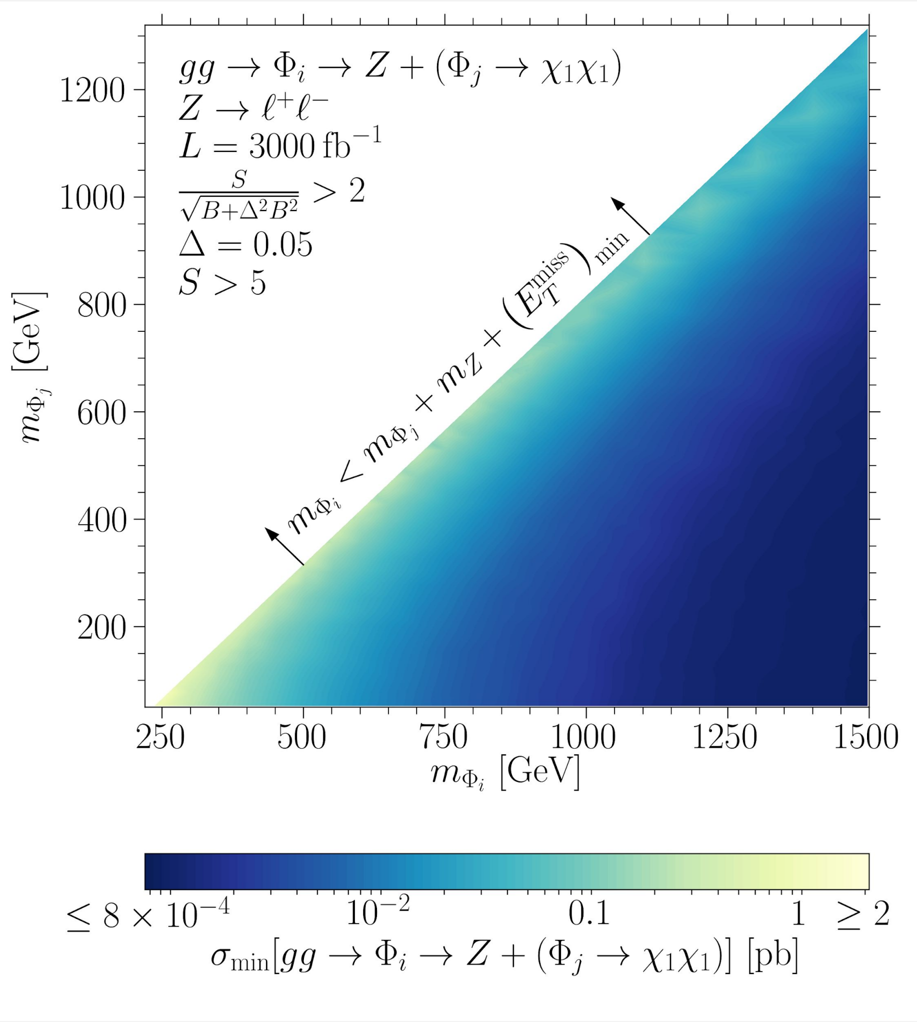
mono-Higgs reach:

[SB, Freese, Shah, Shakya 1703.07800]



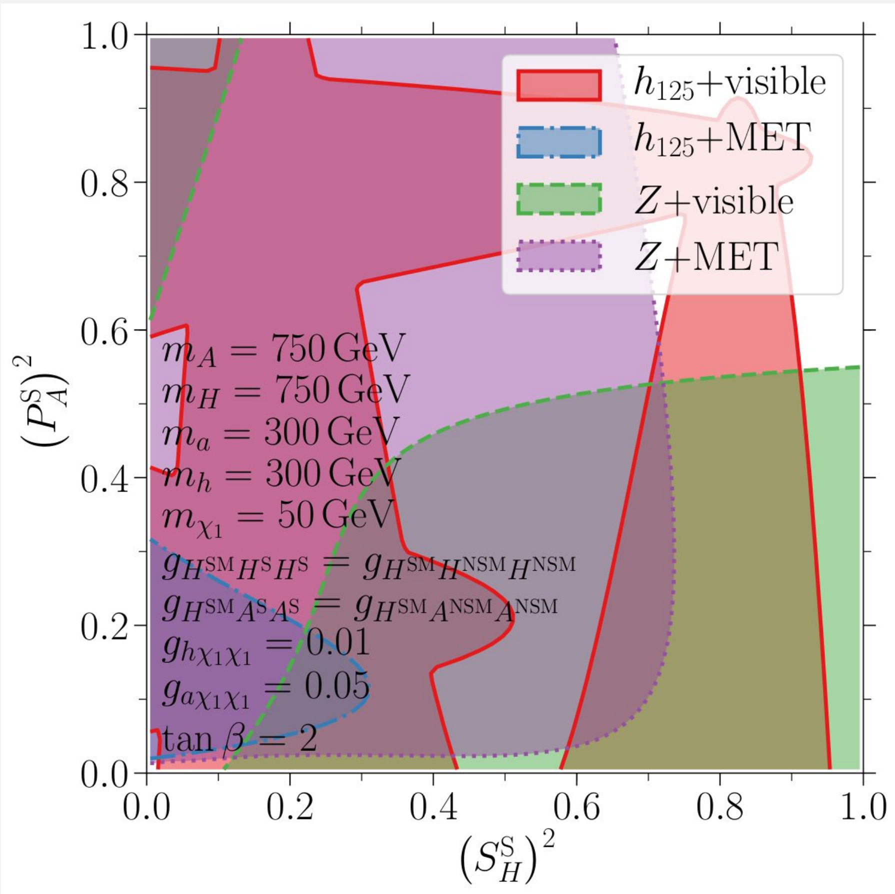
mono-Z reach

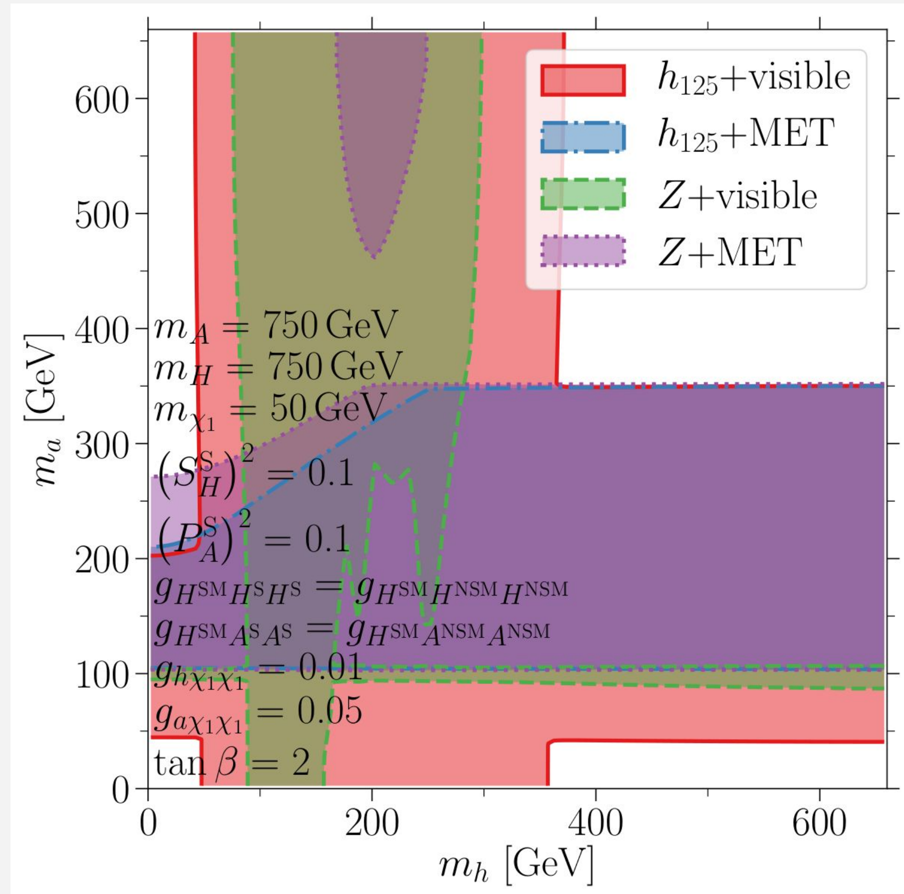
[SB, Shah 1807.XXXXX]



Coverage

[SB, Shah 1807. XXXXX]





Next-to-Minimal Supersymmetric Standard Model

$$W \supset \lambda \widehat{S}\,\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

- MSSM particle content + chiral superfield (singlet under SM)
- 2HDM+S Higgs sector, but only 6 free parameters (after fixing *v* = 174 GeV)

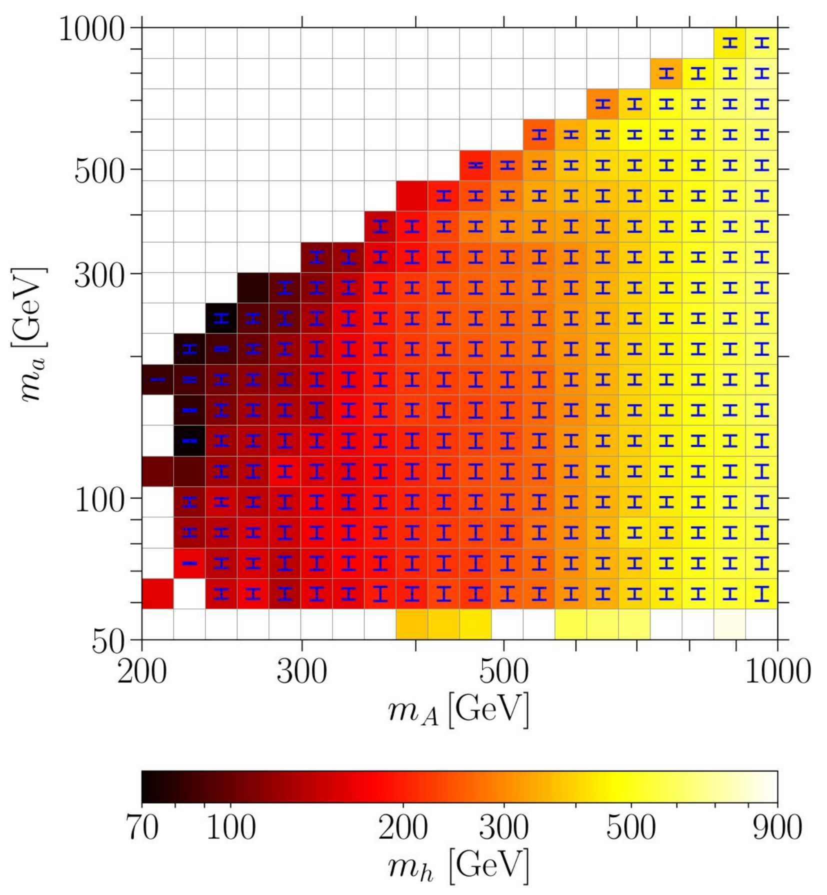
Acceptable pheno of 125 GeV Higgs most easily obtained for λ~0.6.
Alignment and ~125 GeV at tree level!
[Carena+ 1510.09137]
[SB, Freese, Shakya, Shah 1703.07800]

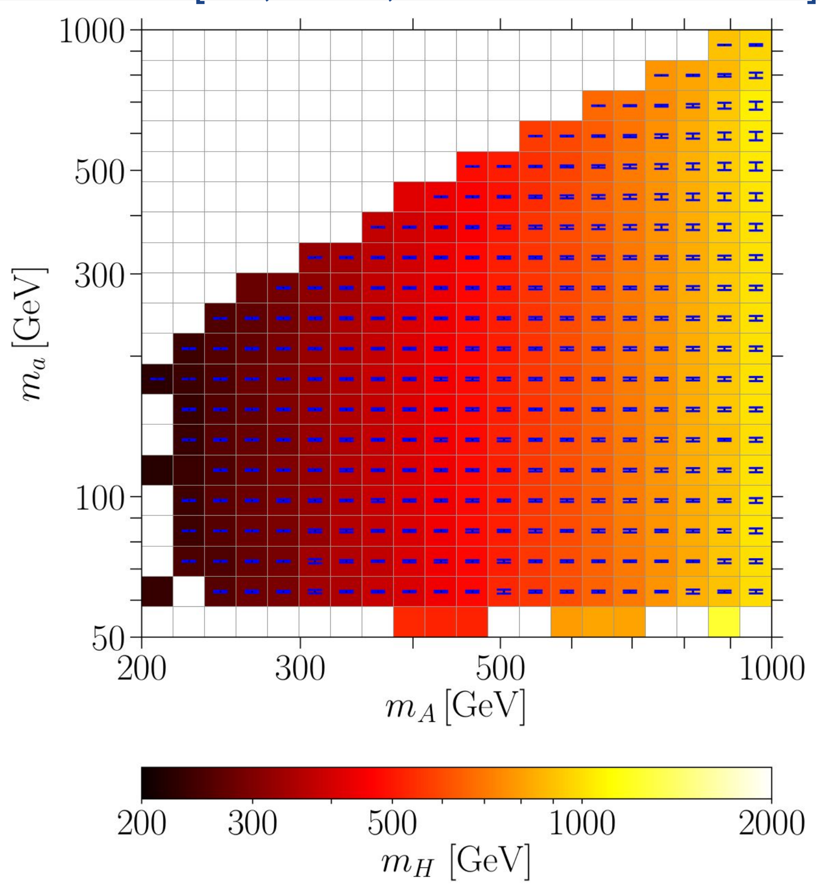
- Correlations of masses in Higgs & Neutralino sector allows for effective re-parametrization in terms of $\{\tan(\beta), m_A, m_a, P_A^S; \lambda, \kappa\}$

[SB, Shah, Freese 180X.XXXXX]

Correlation of Higgs Masses

[SB, Shah, Freese 180X.XXXXX]





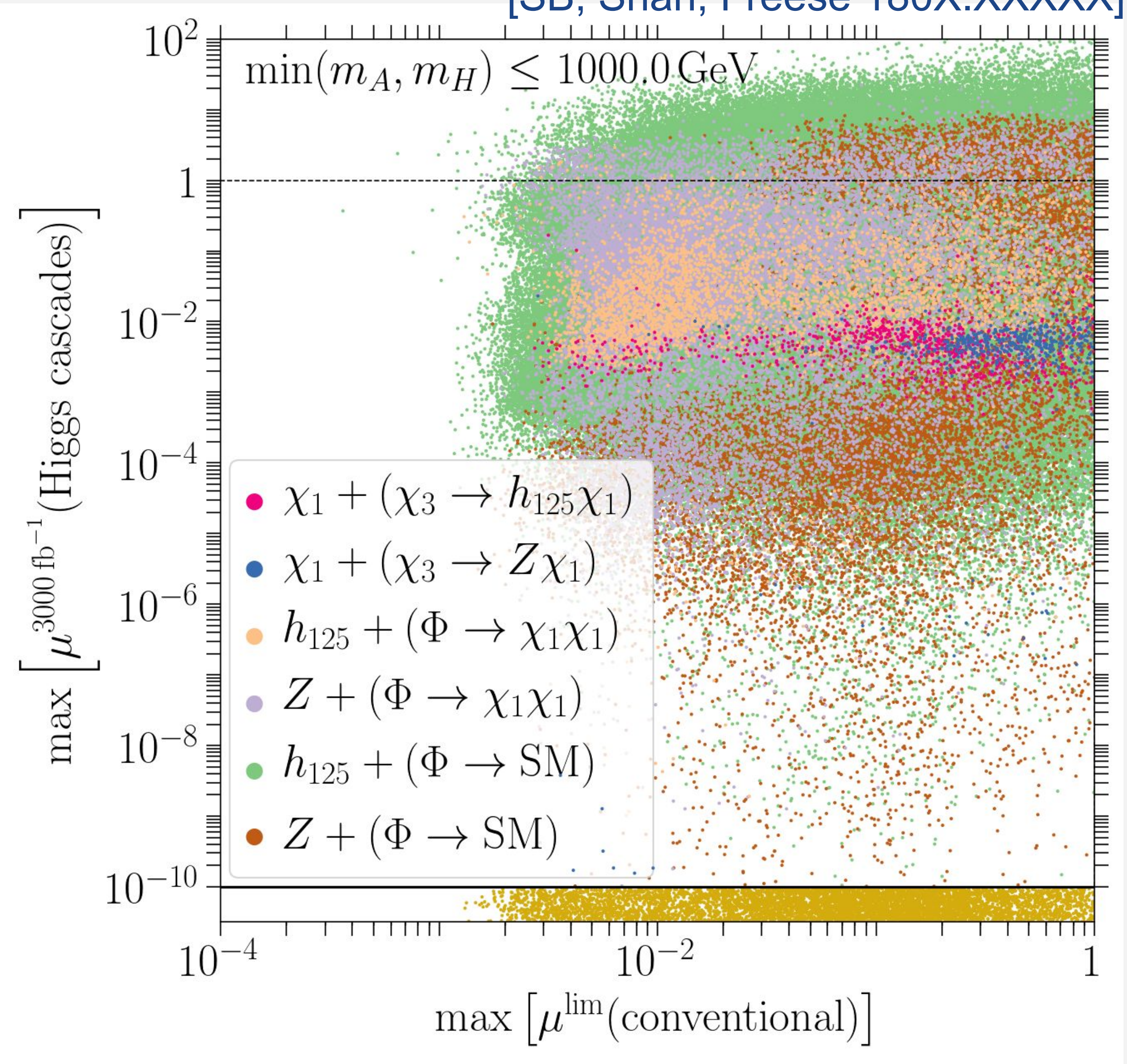
$$m_h^2 \simeq \frac{\kappa\mu}{\lambda}\left(A_\kappa + \frac{4\kappa\mu}{\lambda}\right) + \lambda^2 v^2 s_{2\beta}^4 \frac{M_A^2}{4\mu^2} - \frac{\lambda\kappa v^2}{2} s_{2\beta}\left(1 + 2c_{2\beta}^2\right) - \kappa^2 v^2 \frac{\mu^2}{M_A^2} c_{2\beta}^2 \,,$$

$$m_a^2 \simeq 3\kappa v^2 \left[\frac{3}{2}\lambda s_{2\beta} - \left(\frac{1}{\lambda}\frac{\mu A_\kappa}{v^2} + 3\kappa \frac{\mu^2}{M_A^2}\right)\right] \,.$$

Power of Cascades + Conventional Searches

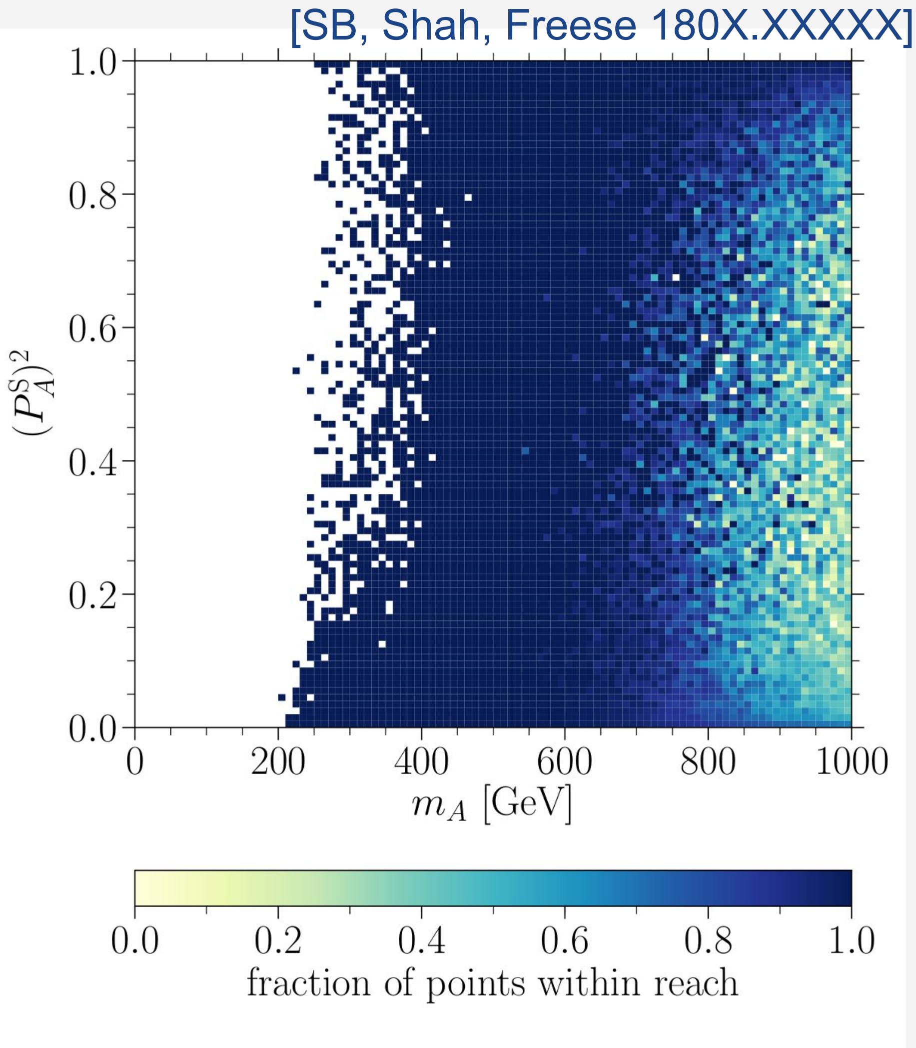
[SB, Shah, Freese 180X.XXXXX]

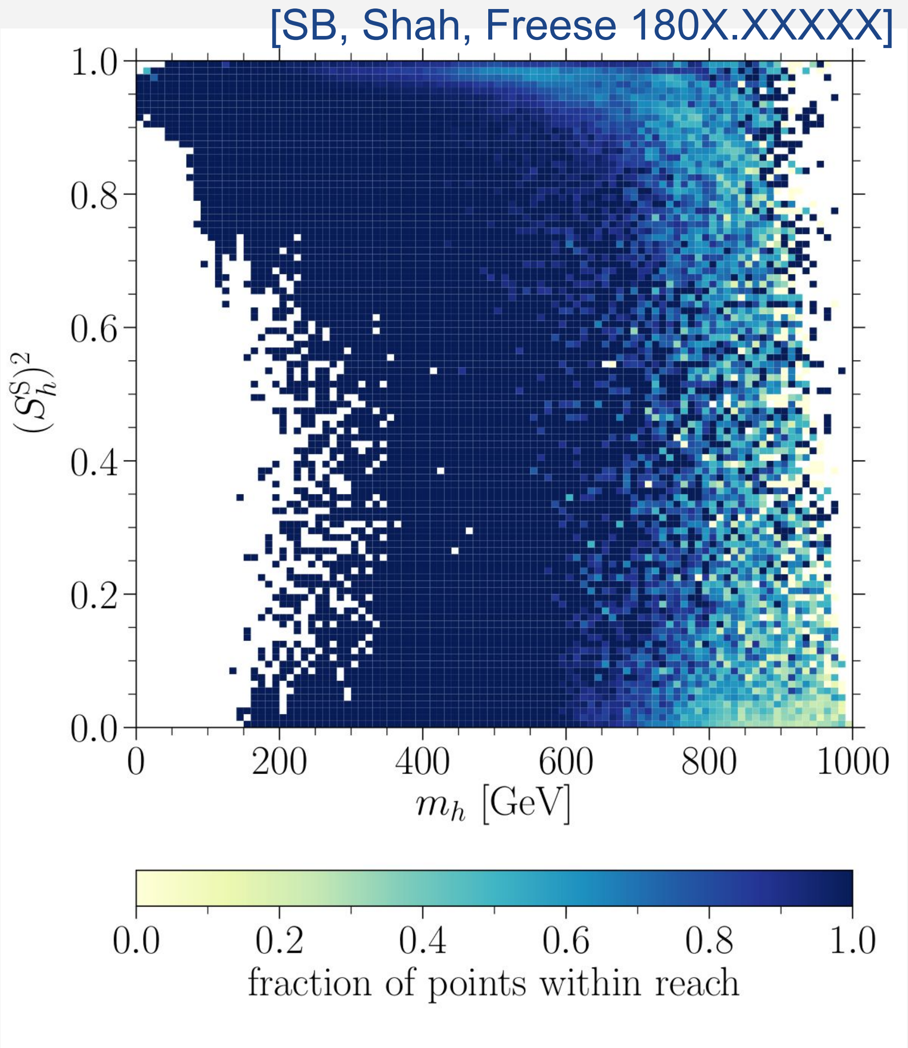
HL-LHC Cascade Projections



Current Bounds from conventional $pp \to H/A \to$ SM SM searches

Coverage of NMSSM parameter space





[Trusting LHC-experiments to improve conventional limits by factor 100
(30 -> 3000/fb + better bkg rejection) and Cascade projections by factor 10]

Conclusions

- Seemingly complicated Higgs sectors can be described effectively by approximate alignment + physically intuitive parameters such as masses and mixing angles
- Higgs Cascades provide a powerful tool to constrain models with Higgs sectors larger than 2HDM
  - Remain effective in large m_A - low $\tan(\beta)$ regime
  - Need to consider all Higgs Cascade modes to cover parameter space
  - In combination with conventional searches, much progress to complete coverage of the NMSSM parameter space with a Higgs sector below 1 TeV can be made!
- In case of discovery, measuring the effects of the singlet is crucial from differentiating the 2HDM+S (NMSSM) from a 2HDM (MSSM)

EXTRA SLIDES

NMSSM parameter scan

[SB, Freese, Shakya, Shah; 1703.07800]

	"standard"	"light subset"
$\tan\beta$	$[1; 5]$	$[1; 5]$
λ	$[0.5; 2]$	$[0.5; 1]$
κ	$[-1; +1]$	$[-0.5; +0.5]$
A_λ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
A_κ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
μ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
M_{Q_3}	$[1; 10]$ TeV	$[1; 10]$ TeV

Table 1. NMSSM parameter ranges used in NMSSMTools scans.

- 10^8 points for each parameter set
- All sfermion mass parameters (except stop) set to 3 TeV
- $M_1 = M_2 = 1$ TeV , $M_3 = 2$ TeV

LHC searches used to constrain parameter scan

decay channel	NMSSM Higgs tested	Reference $\sqrt{s} = 8\,\text{TeV}$	Reference $\sqrt{s} = 13\,\text{TeV}$
$H \to \tau^+\tau^-$	h_i, H_3, A_1, A_2	[52–54]	[55–58]
$H \to b\bar{b}$	h_1, H_3, A_1, A_2	–	[59]
$H \to \gamma\gamma$	h_i, H_3, A_1, A_2	[60–62]	[63–66]
$H \to ZZ$	h_1, H_3	[67]	[68–76]
$H \to WW$	h_i, H_3	[77–79]	[80–85]
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\tau^+\tau^-$	h_i, H_3	[86–88]	[89–91]
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\ell\nu_\ell\ell\nu_\ell$	h_i, H_3	–	[92, 93]
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}b\bar{b}$	h_i, H_3	[94, 95]	[96–99]
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\gamma\gamma$	h_i, H_3	[100, 101]	[102–104]
$A \to Zh_{\rm SM} \to Zb\bar{b}$	A_1, A_2	[105, 106]	[107, 108]
$A \to Zh_{\rm SM} \to Z\tau^+\tau^-$	A_1, A_2	[86, 105]	–
$h_{\rm SM} \to AA \to \tau^+\tau^-\tau^+\tau^-$	A_1, A_2	[109]	–
$h_{\rm SM} \to AA \to \mu^+\mu^-b\bar{b}$	A_1, A_2	[109]	–
$h_{\rm SM} \to AA \to \mu^+\mu^-\tau^+\tau^-$	A_1, A_2	[109]	–
$h_{\rm SM} \to AA \to \mu^+\mu^-\mu^+\mu^-$	A_1, A_2	–	[110]
$A/H \to Zh_i/A_1$	$A_2/H_3, h_i/A_1$	[44]	–

Table 2. Direct Higgs searches at the LHC used for this work. $h_i = h_2$ (h_1) if the (second) lightest scalar is SM-like.