The Next-to-MSSM, the LHC, and Dark Matter

Sebastian Baum

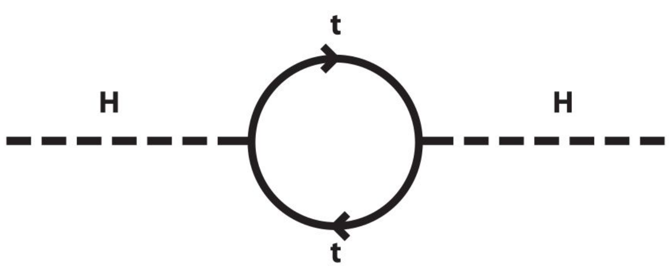
Oskar Klein Centre for Cosmoparticle Physics
Stockholm University

Advances in theoretical cosmology in light of data
July 3-28 2017
Nordita, Stockholm

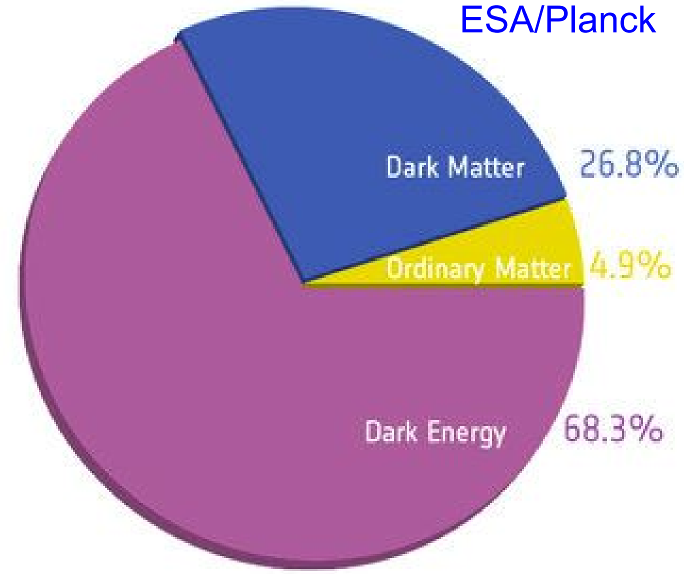
Why (low-scale) SUSY?

SM Problems

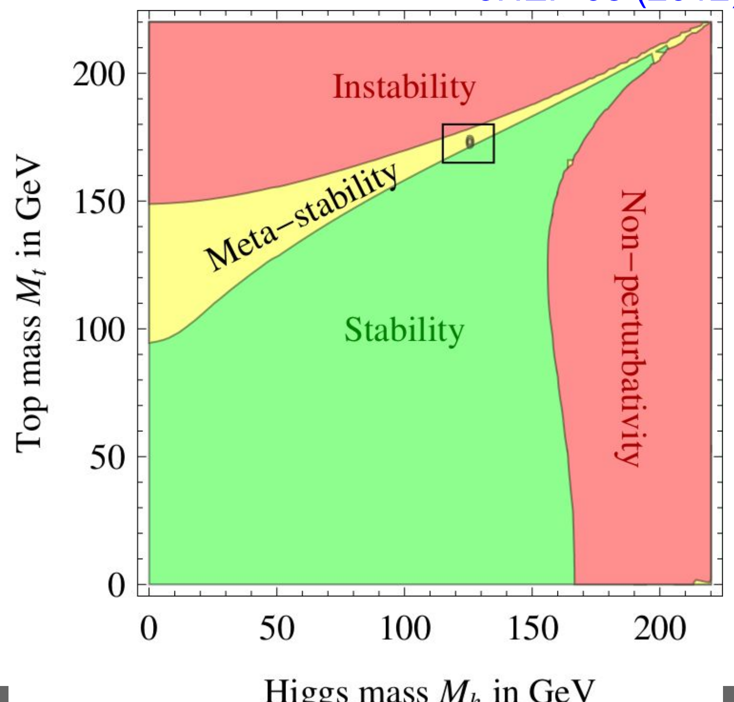
- EW hierarchy problem
- Dark matter
- Dark energy
- Baryon asymmetry
- Strong CP-problem
- Neutrino masses
- Higgs stability
- ...



ESA/Planck

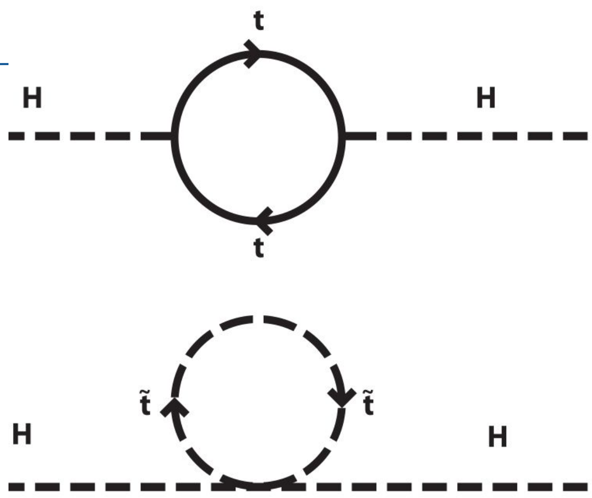


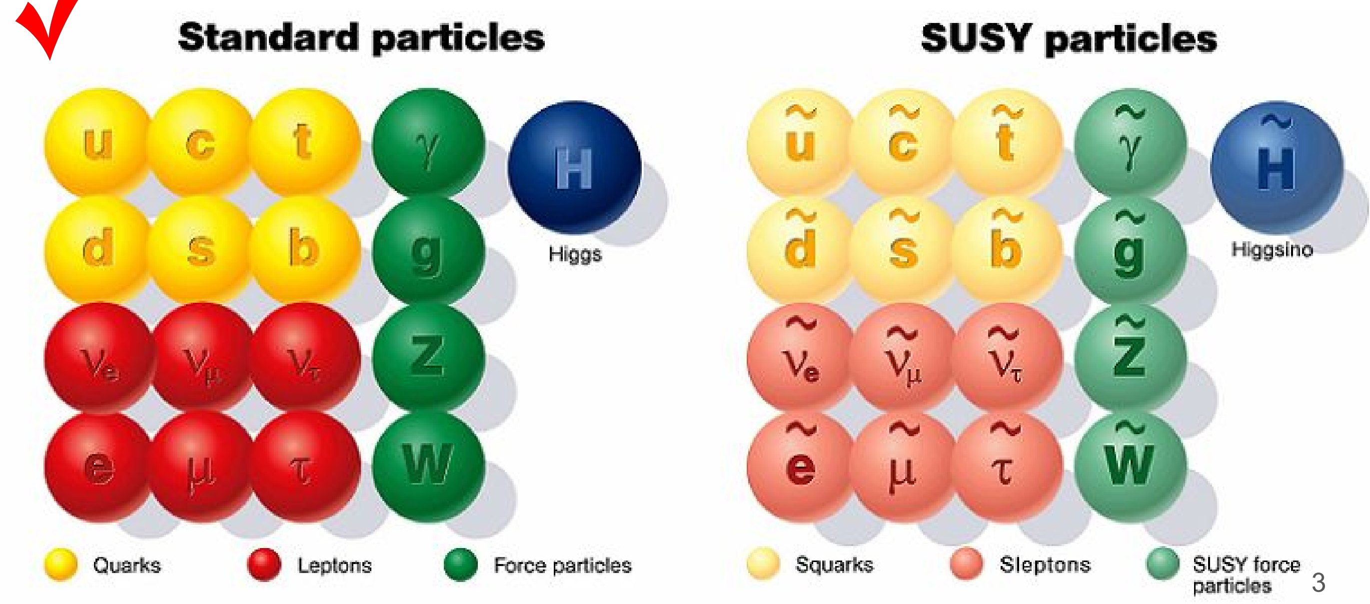
JHEP 08 (2012) 098



Why (low-scale) SUSY?

- EW hierarchy problem ✓
- Dark matter ✓
- Dark energy
- Baryon asymmetry ✓?
- Strong CP-problem (Still need axions...)
- Neutrino masses
- Higgs stability ✓
- ...





Why Next-to-MSSM?

The Minimal Supersymmetric SM

Credit: M. Kocic

Vector supermultiplets		Superfield	Adj. repr.	Spin-1 (gauge bosons)	Spin-1/2 (gauginos)	Aux.	Vector superfield (in Wess-Zumino gauge)
Gauge fields	$\mathrm{U}(1)_{\mathrm{Y}}$	V_{Y}	$\mathbf{1},\mathbf{1},0$	B_μ, B-boson	$\lambda_{\mathrm{Y}} \equiv \widetilde{B}$, bino	D_{Y}	$V_{\mathrm{Y}} \equiv \theta\,\sigma^\mu\,\bar\theta\,B_\mu + \theta\theta\,\bar\theta\bar\lambda_{\mathrm{Y}} + \bar\theta\bar\theta\,\theta\lambda_{\mathrm{Y}} + \frac{1}{2}\theta\theta\,\bar\theta\bar\theta\,D_{\mathrm{Y}}$
	$\mathrm{SU}(2)_{\mathrm{L}}$	V^i_{L}	$\mathbf{1},\mathbf{3},0$	W^i_μ, W-bosons	$\lambda^i_{\mathrm{L}} \equiv \widetilde{W}^i$, winos	D^i_{L}	$V^i_{\mathrm{L}} \equiv \theta\,\sigma^\mu\,\bar\theta\,W^i_\mu + \theta\theta\,\bar\theta\bar\lambda^i_{\mathrm{L}} + \bar\theta\bar\theta\,\theta\lambda^i_{\mathrm{L}} + \frac{1}{2}\theta\theta\,\bar\theta\bar\theta\,D^i_{\mathrm{L}}$
	$\mathrm{SU}(3)_{\mathrm{C}}$						$\bar\theta\,D^a_{\mathrm{C}}$

$$W_{\mathrm{MSSM}} = h_u \widehat{H}_u \cdot \widehat{Q}\,\widehat{U}^c_R + h_d \widehat{H}_d \cdot \widehat{Q}\,\widehat{D}^c_R + $$
$$+ h_e \widehat{H}_d \cdot \widehat{L}\,\widehat{E}^c_R + \underline{\mu \widehat{H}_u \cdot \widehat{H}_d}$$

Chiral supermultiplets		Su...					$\theta\sigma^\mu\bar\theta)$
Matter fields	quarks, s(calar) quarks						
		$U_I\ (\bar u_I)$	$\mathbf{3},\mathbf{1},-\frac{2}{3}$	$\bar u_{\mathrm{L}} = (u_{\mathrm{R}})^c,\ \chi_{\bar u}$	$\tilde{\bar u}_{\mathrm{L}},\ \phi_{\bar u}$	$F_{\bar u}$	$\bar u = U_1 = \phi_{\bar u} + \sqrt{2}\,\theta\chi_{\bar u} + \theta\theta\,F_{\bar u}$
		$D_I\ (\bar d_I)$					
	leptons, s(calar) leptons	L_I					
		$N_I\ (\bar\nu_I)$					
		$E_I\ (\bar e_I)$					
Higgs fields	higgsinos, higgs	H_u	$\mathbf{1},\mathbf{2},+\frac{1}{2}$	$\begin{pmatrix}\widetilde{H}^+_u\\ \widetilde{H}^0_u\end{pmatrix}$	$\begin{pmatrix}H^+_u\\ H^0_u\end{pmatrix}$	$\begin{pmatrix}F^+_{H_u}\\ F^0_{H_u}\end{pmatrix}$	$H_u = \begin{pmatrix}H^+_u + \sqrt{2}\,\theta\widetilde{H}^+_u + \theta\theta\,F^+_{H_u}\\ H^0_u + \sqrt{2}\,\theta\widetilde{H}^0_u + \theta\theta\,F^0_{H_u}\end{pmatrix}$
		H_d	$\mathbf{1},\mathbf{2},-\frac{1}{2}$	$\begin{pmatrix}\widetilde{H}^0_d\\ \widetilde{H}^-_d\end{pmatrix}$	$\begin{pmatrix}H^0_d\\ H^-_d\end{pmatrix}$	$\begin{pmatrix}F^+_{H_d}\\ F^0_{H_d}\end{pmatrix}$	$H_d = \begin{pmatrix}H^0_d + \sqrt{2}\,\theta\widetilde{H}^0_d + \theta\theta\,F^+_{H_d}\\ H^-_d + \sqrt{2}\,\theta\widetilde{H}^-_d + \theta\theta\,F^0_{H_d}\end{pmatrix}$

Tree level SM-like Higgs mass

$$m_h^2 \approx m_Z^2 \cos^2(2\beta) \lesssim (90\,\mathrm{GeV})^2$$

Why Next-to-MSSM?

MSSM particle content + chiral superfield uncharged under SM

$$W \supset \lambda \widehat{S}\,\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$ (Scale-invariant NMSSM)

SUSY breaking can generate a vev for the Singlet, solving the μ-problem: $\mu = \lambda \langle s \rangle / \sqrt{2}$

Extra contribution to the tree-level mass of the SM-like Higgs:

$$m_{h_{\rm SM}}^2 \approx m_Z^2 c_{2\beta}^2 + \underline{\frac{1}{2}\lambda^2 v^2 s_{2\beta}^2}$$

NMSSM Higgs sector

- Three neutral CP-even Higgses $H_u^R, \ H_d^R, \ H^S$
- Two neutral CP-odd Higgses A^{NSM}, A^S
- 1 charged Higgs $H^\pm$

Behavior controlled by $p_i = \{\lambda, \kappa, \tan\beta, \mu, A_\lambda, A_\kappa\}.$

NMSSM Neutralino sector

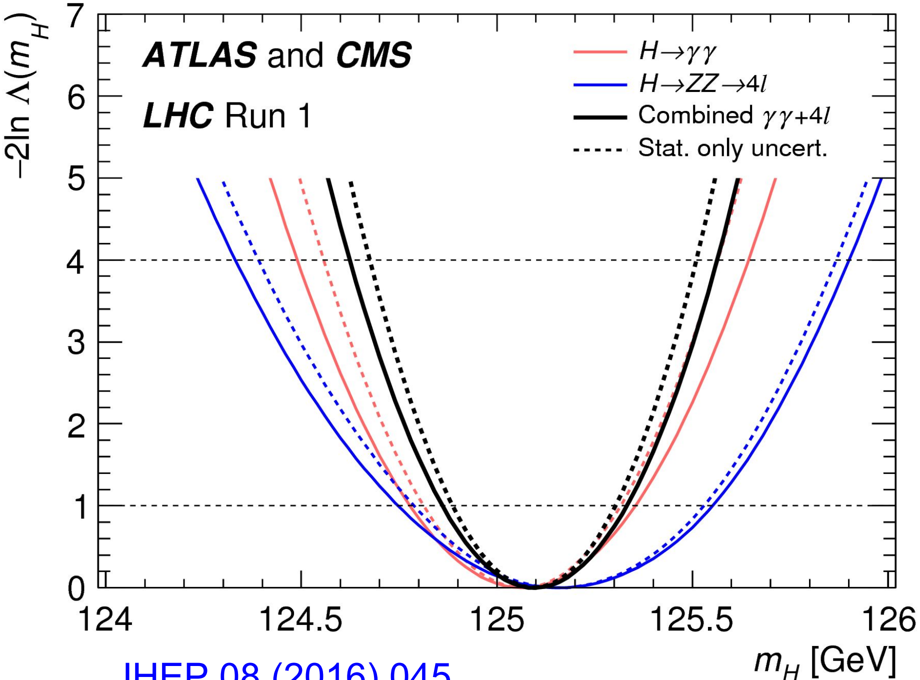
- Wino -- mass ~ M_2
- Bino -- mass ~ M_1
- 2 Higgsinos -- mass ~ $-\mu$
- Singlino -- mass ~ $2\kappa\mu/\lambda$

MSSM neutralino sector

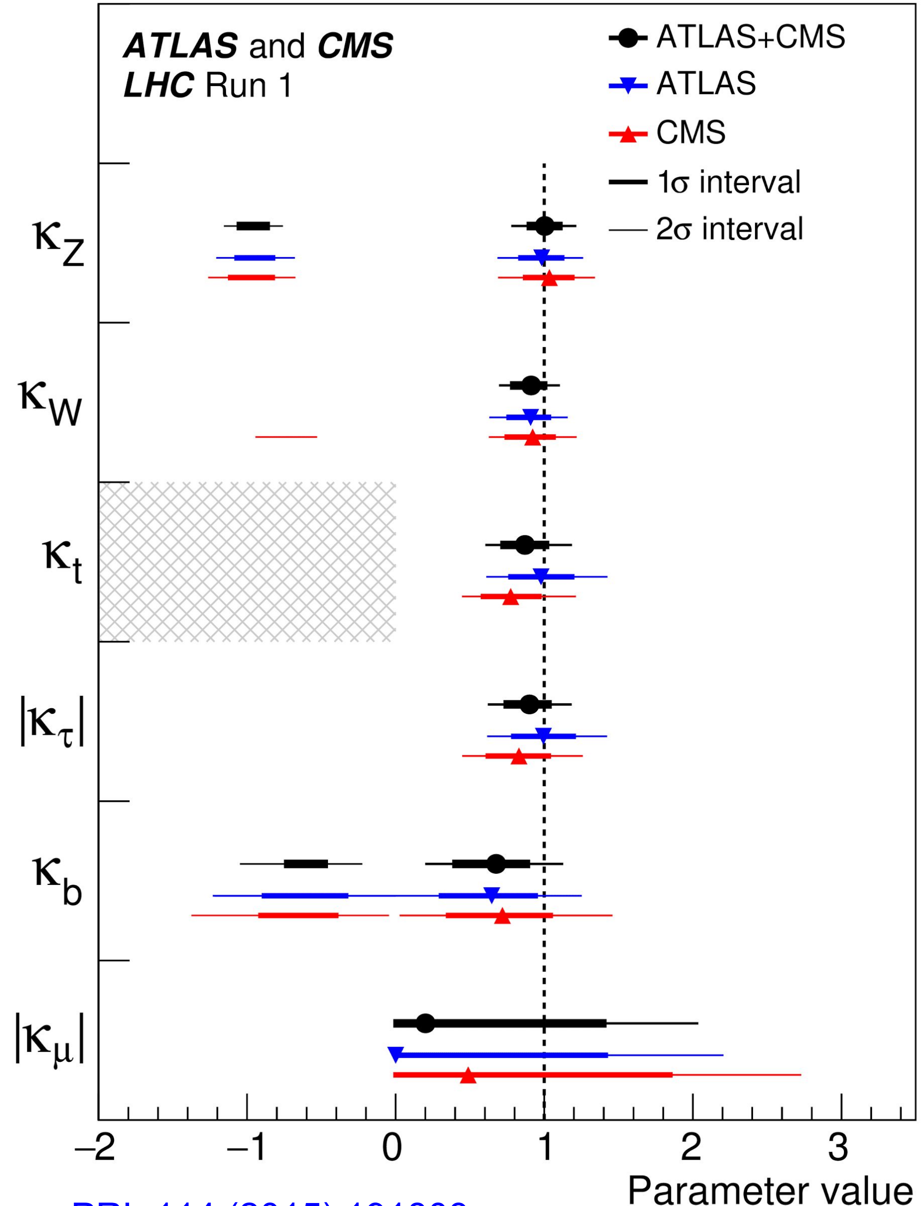
New in NMSSM

SM Higgs boson measurements

The NMSSM better have a 125 GeV Higgs with couplings $\lesssim$ 10 % away from SM



JHEP 08 (2016) 045



PRL 114 (2015) 191803

The SM-like Higgs and Alignment

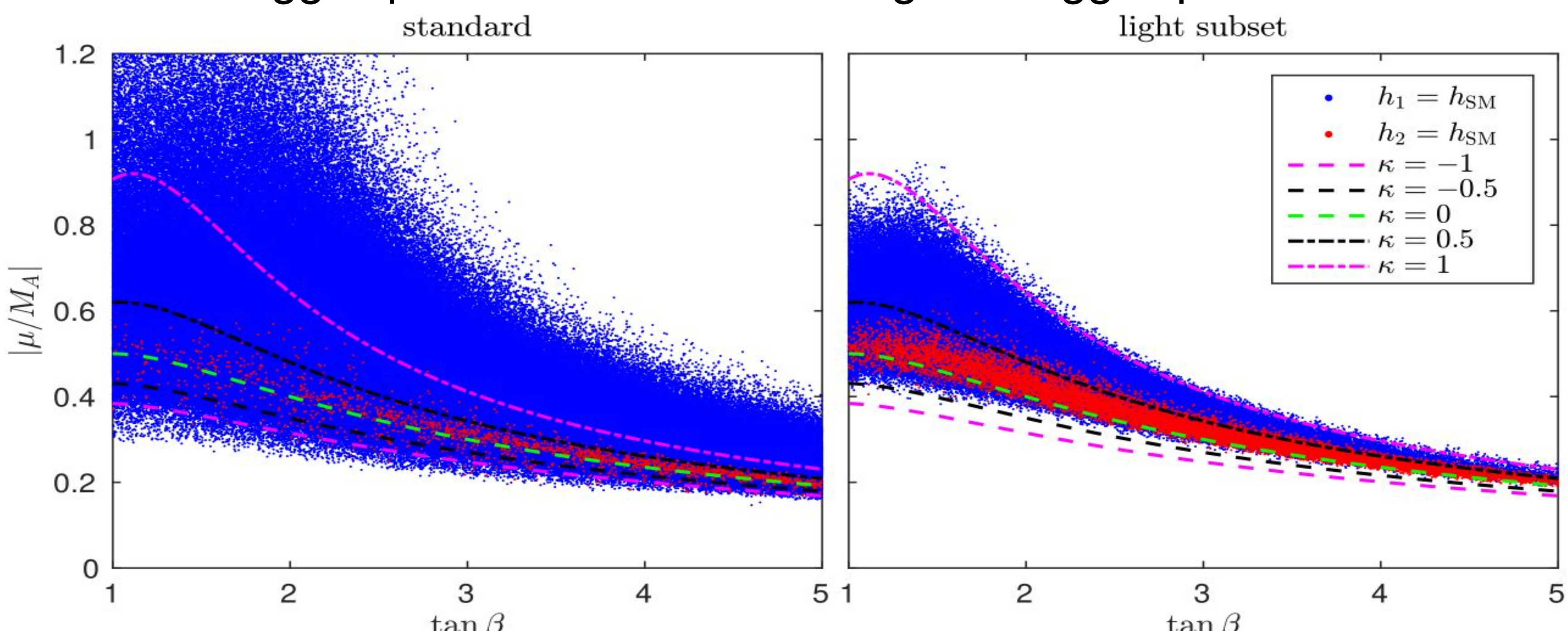
Carena+ 1510.09137

Alignment conditions: I) $$\boxed{\lambda^2 = \frac{m_{h_{\rm SM}}^2 - m_Z^2\cos(2\beta)}{v^2\sin^2\beta} = (0.6\ldots0.7)^2}$$

II) $$\boxed{\frac{M_A^2}{\mu^2} = \frac{4}{s_{2\beta}^2}\left(1-\frac{\kappa}{2\lambda}s_{2\beta}\right)}$$ where $$M_A^2 = \frac{2\mu\left(A_\lambda+\kappa\mu/\lambda\right)}{\sin 2\beta}$$

SB, Freese, Shakya, Shah 1703.07800

Heavier Higgs spectrum $\lesssim$ 3 TeV | Lighter Higgs spectrum $\lesssim$ 1 TeV



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Same value which gives

$$m^2_{h_{\rm SM}} \approx m_Z^2 c^2_{2\beta} + \frac{1}{2}\lambda^2 v^2 s^2_{2\beta} \sim (125\,\mathrm{GeV})^2$$

at tree level, for moderate tan β ≲ 5!

Approximately fixes 2 parameters

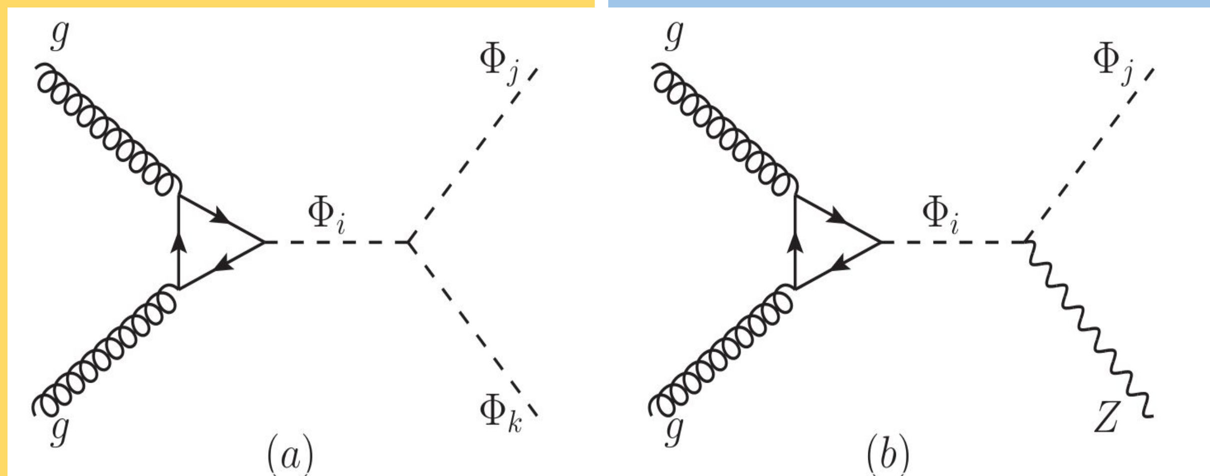
$$p_i = \{\cancel{\lambda}, \kappa, \tan\beta, \mu, \cancel{A_\lambda}, A_\kappa\}.$$

Conventional vs NMSSM specific Higgs searches

MSSM-like searches

- H/A ➔ bb / tt / ττ
- H ➔ γγ / ZZ / WW
- H ➔ $h_{SM}h_{SM}$
- A ➔ Z h_{SM}

NMSSM-specific strategies:



Dominant decay modes

- $gg \to H_3 \to h_{\rm SM} h_i$
- $gg \to A_2 \to h_{\rm SM} A_1$

- $gg \to H_3 \to Z A_1$
- $gg \to A_2 \to Z h_i$

Conventional vs NMSSM specific Higgs searches

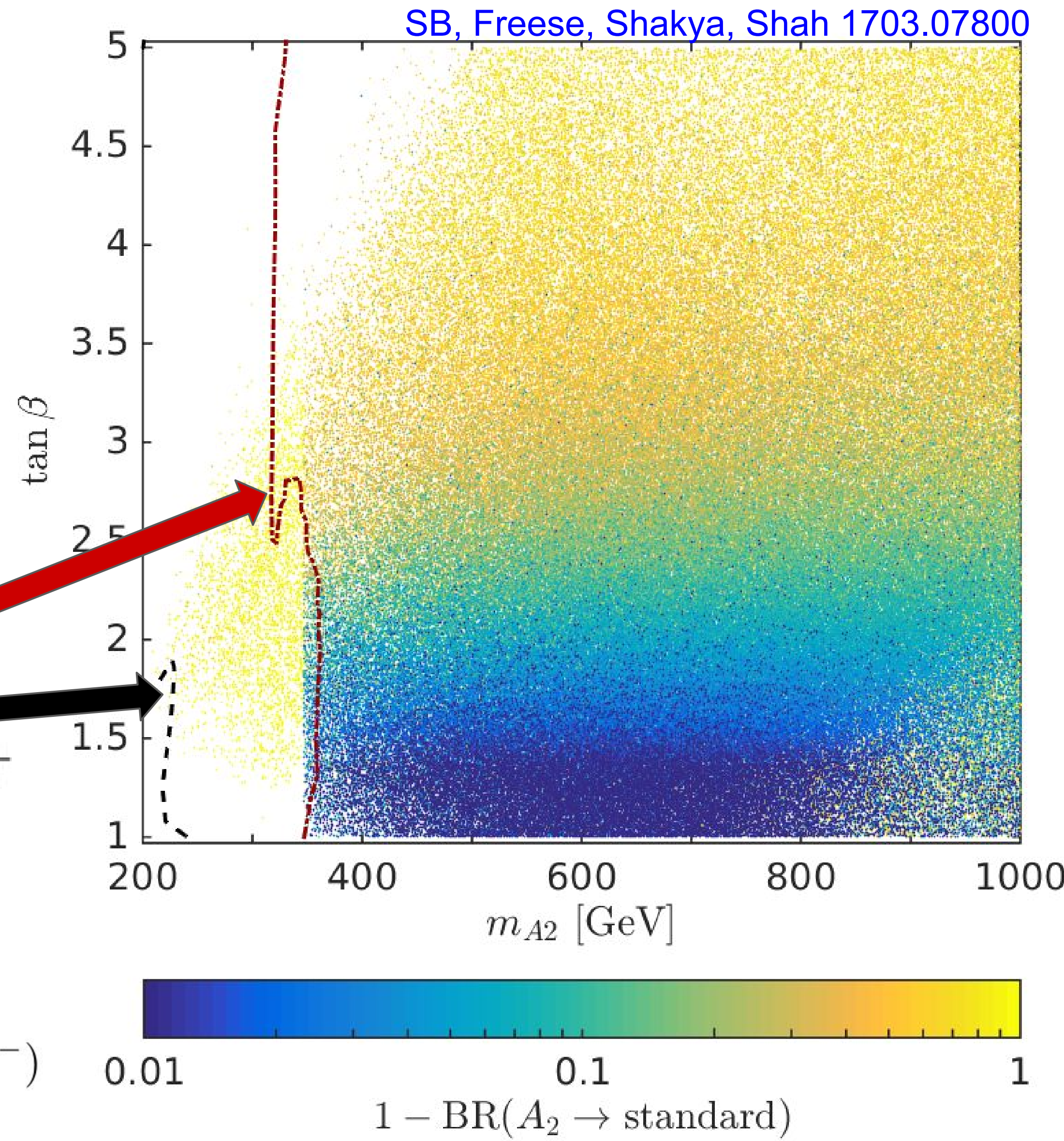
MSSM-like searches

- H/A ➔ bb / tt / ττ
- H ➔ γγ / ZZ / WW
- H ➔ $h_{SM}h_{SM}$
- A ➔ Z h_{SM}

8 TeV constraint on hMSSM

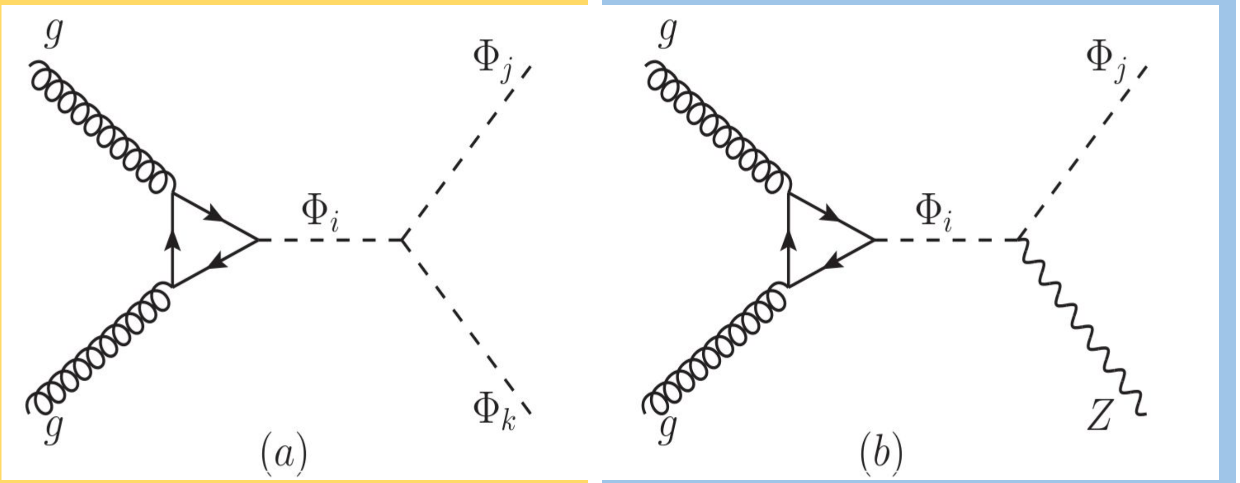
[CMS PAS-HIG-16-007]

$m_h^{\mathrm{mod}+}$



$$\mathrm{BR}(A_2 \to \mathrm{standard})$$
$$= \mathrm{BR}(A_2 \to t\bar{t}) + \mathrm{BR}(A_2 \to b\bar{b})$$
$$+ \mathrm{BR}(A_2 \to \tau^+\tau^-) + \mathrm{BR}(A_2 \to \mu^+\mu^-)$$
$$+ \mathrm{BR}(A_2 \to Zh_{\mathrm{SM}}) + \mathrm{BR}(A_2 \to \gamma\gamma).$$

NMSSM specific Higgs searches



Dominant decay modes

- $gg \to H_3 \to h_{\rm SM} h_i$
- $gg \to A_2 \to h_{\rm SM} A_1$

- $gg \to H_3 \to Z A_1$
- $gg \to A_2 \to Z h_i$

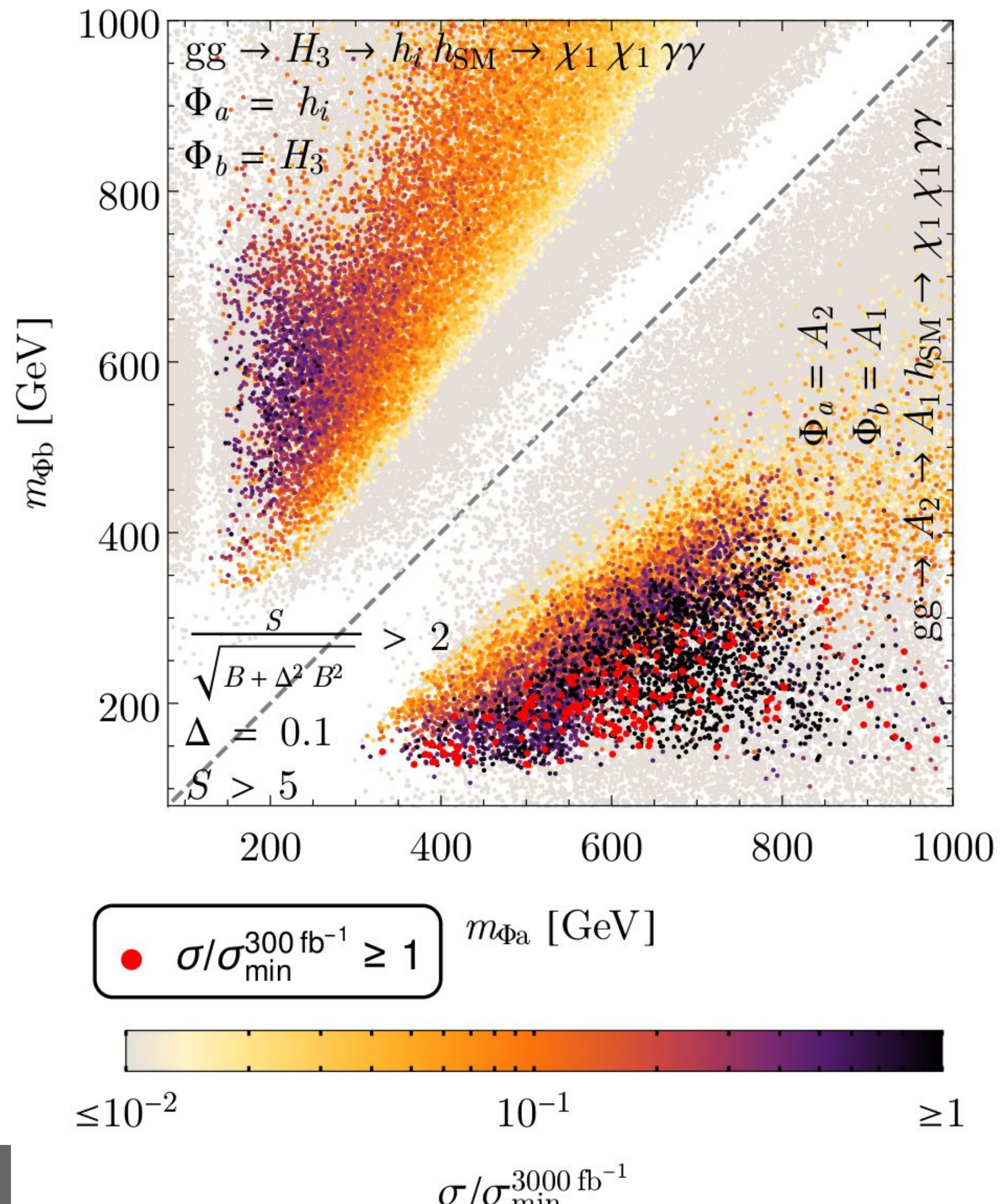
h_i/A_1 decay modes determined by mass spectrum:

- if kinematically accessible, $h_i/A_1 \to \chi_1 \chi_1$ usually sizeable

➔ Mono-Higgs and Mono-Z signatures!

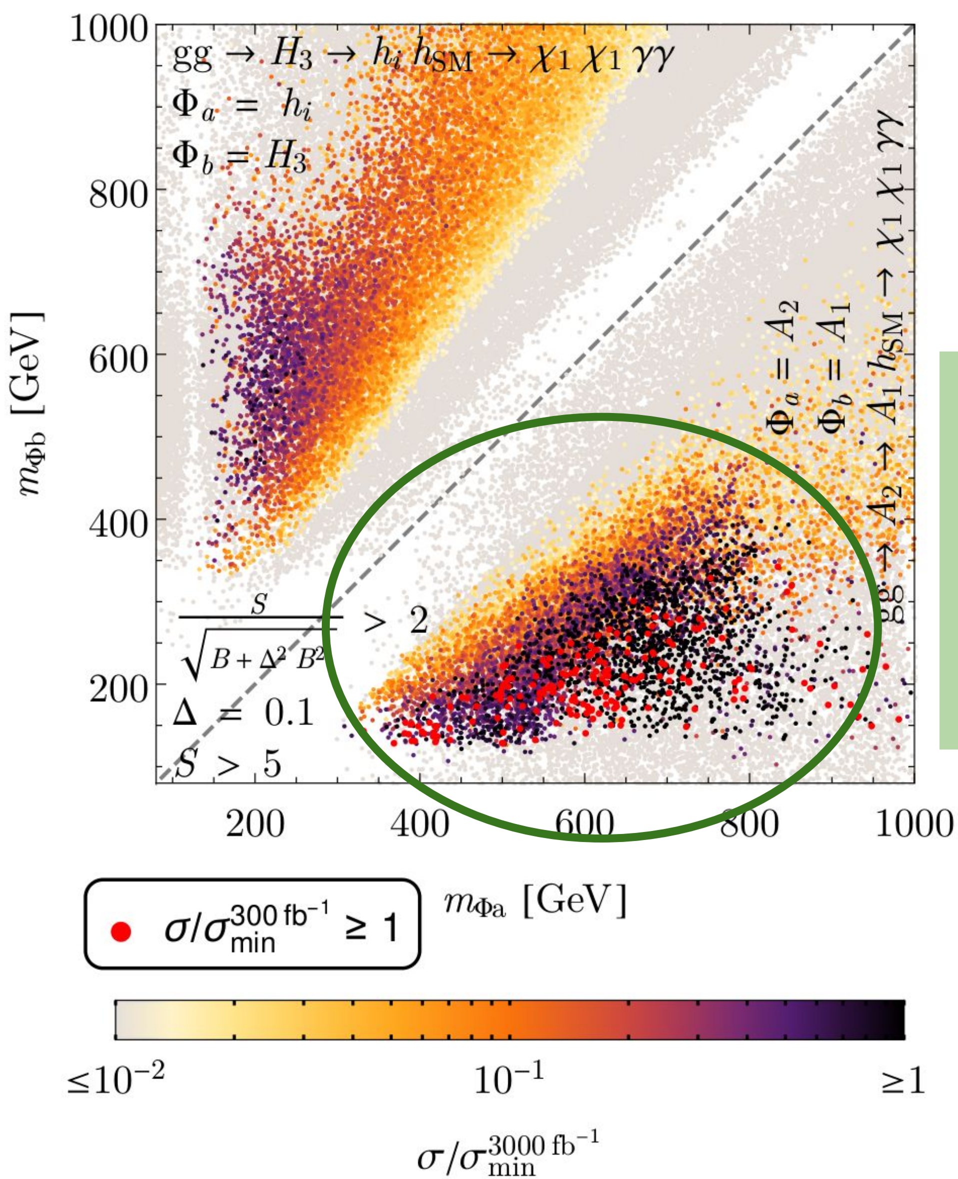
Mono-Higgs

SB, Freese, Shakya, Shah 1703.07800



Mono-Higgs

SB, Freese, Shakya, Shah 1703.07800



Most promising channel:

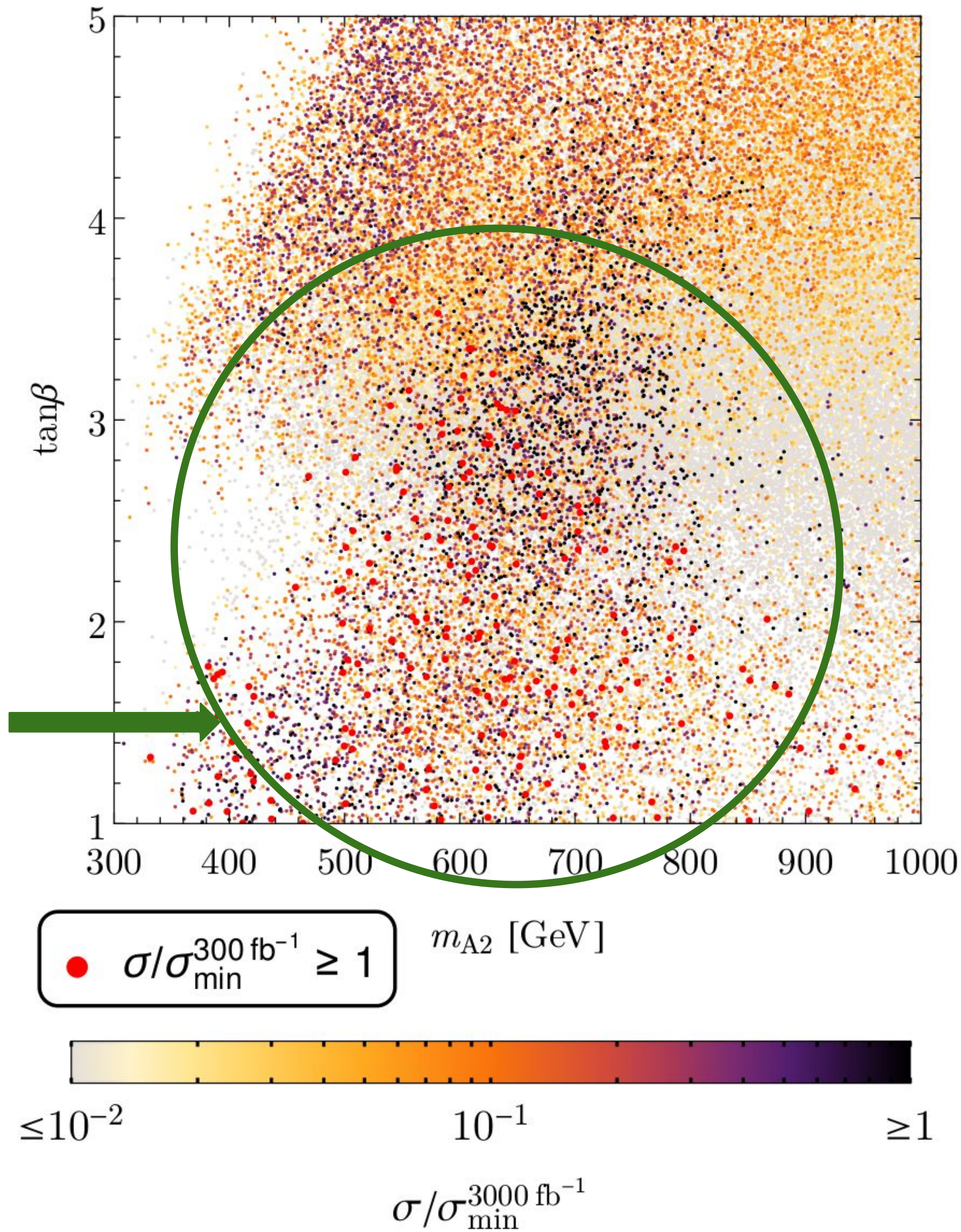
- production xSec $ggA_2 \sim 2\, ggH_3$
- Hard MET from back-to-back decays and large

$$\Delta m = m_{\Phi_2} - (m_{\Phi_1} + m_{h_{SM}})$$

Mono-Higgs

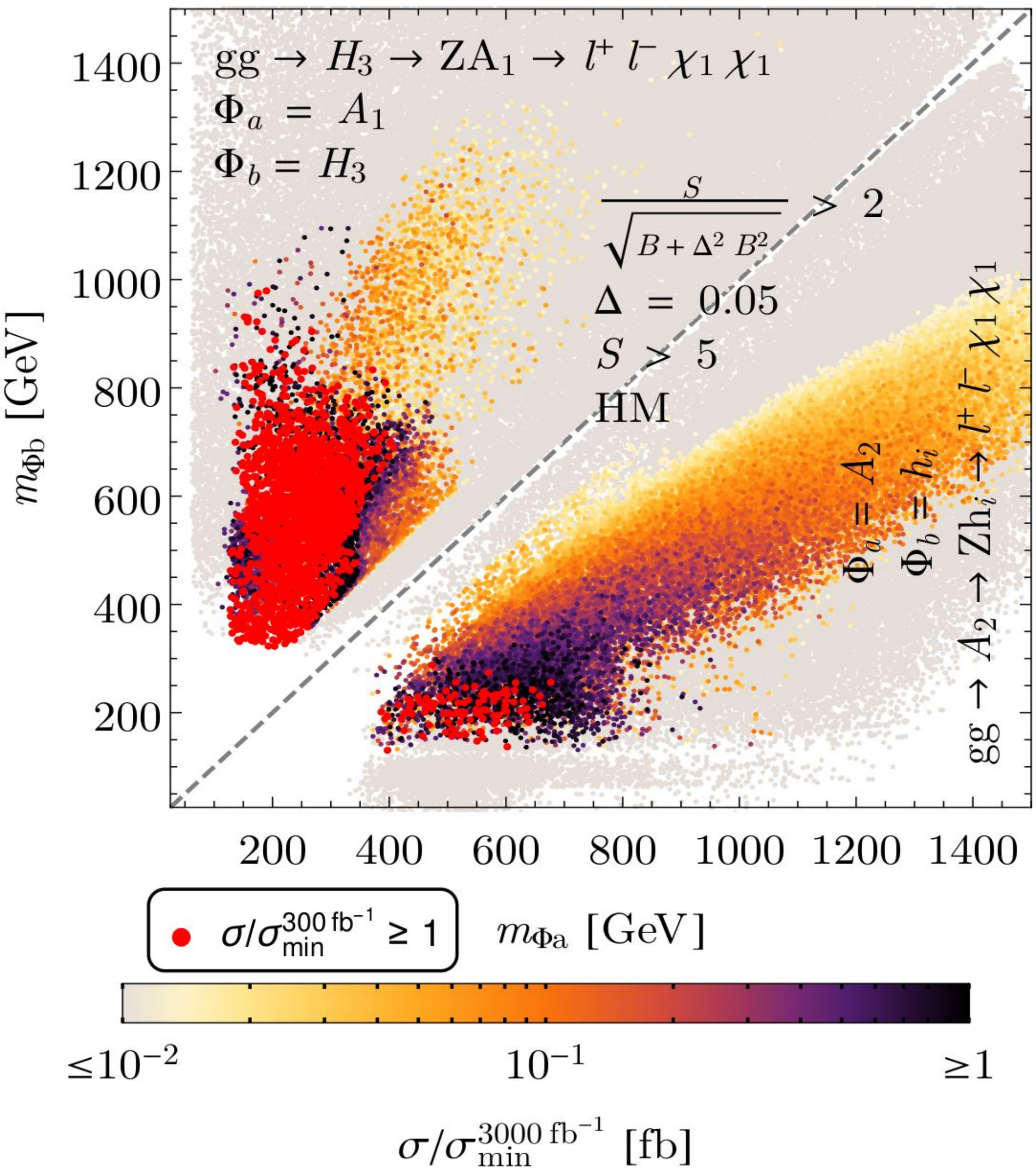
Combined reach of all mono-H channels:

- Hard MET spectrum requires large m_{A_2}
- ggA_2/H_3 suppressed for too heavy Higgses
- Most promising points lie in low tan β, $m_{A_2} > 2m_t$ region usually overwhelmed by $A_2 \to t\bar{t}$



Mono-Z

SB, Freese, Shakya, Shah; in preparation

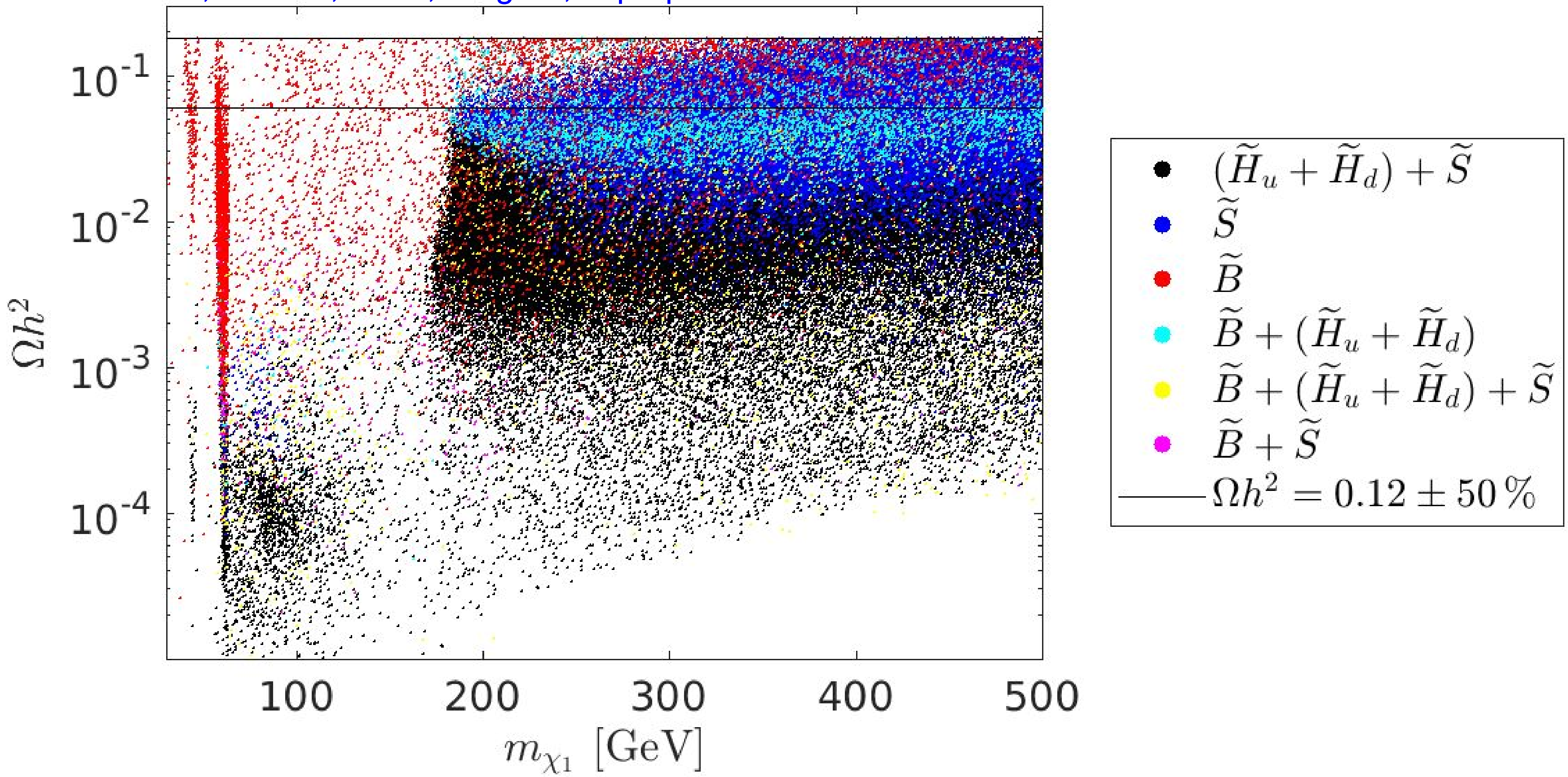


Dark Matter in the NMSSM

Singlino plays important role to get acceptable DM

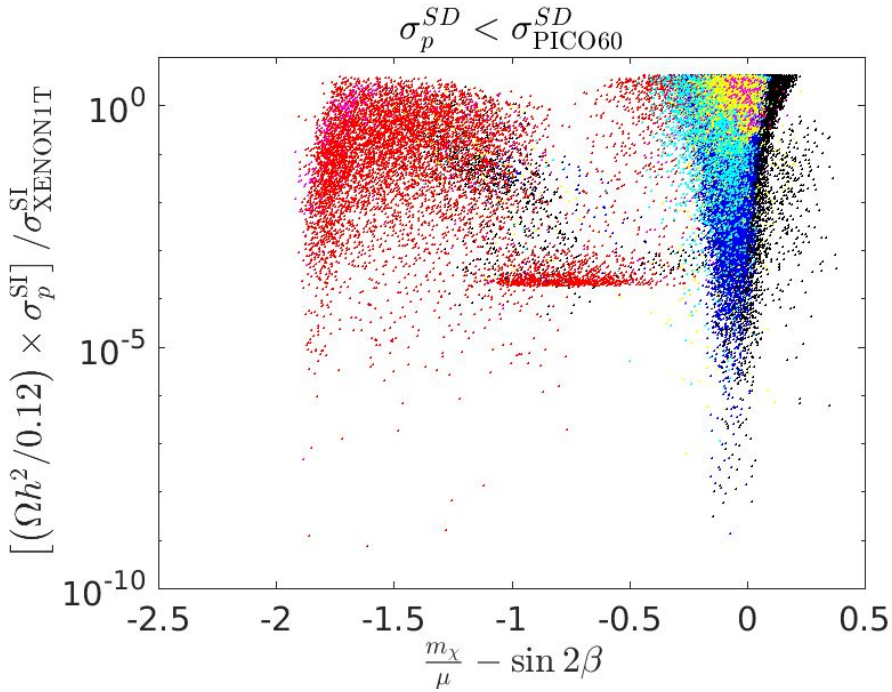
➔different pheno from MSSM!

SB, Carena, Shah, Wagner; in preparation



Direct Detection & Blind Spots

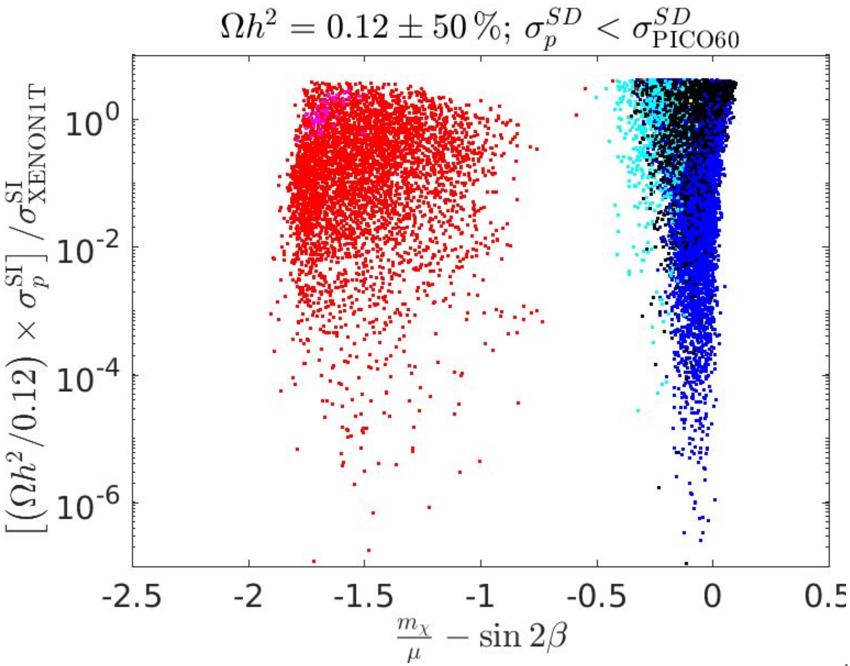
SB, Carena, Shah, Wagner; in preparation



Normalized to Xenon1T [1705.06655] and including PICO-60 [1702.07666]

- $(\widetilde{H}_u + \widetilde{H}_d) + \widetilde{S}$
- $\widetilde{S}$
- $\widetilde{B}$
- $\widetilde{B} + (\widetilde{H}_u + \widetilde{H}_d)$
- $\widetilde{B} + (\widetilde{H}_u + \widetilde{H}_d) + \widetilde{S}$
- $\widetilde{B} + \widetilde{S}$

Including correct relic density



Blind-spot condition for Higgsino-singlino DM

Cheung, Papucci, Sandford, Shah, Zurek 1406.6372

Badziak, Okechowski, Szczerbiak 1512.02471

Conclusions

- NMSSM motivated by μ-problem and 125 GeV Higgs
- presence of 125 GeV SM-like Higgs constraints NMSSM parameter space:
  - Alignment without decoupling: $\lambda \sim 0.65$, light Higgsinos/neutralinos, light Higgs spectrum
- mono-Higgs and mono-Z are clean and powerful probe, probing the low tan β, large $m_{A_2} > 2m_t$ region, which is usually overwhelmed by $t\bar{t}$
- Provides good DM candidate, direct detection limits evaded by cancellations ("Blind Spots")?
- Additional scalar gives room for strong 1st order phase transition…

Extra Slides

NMSSM scalar potential

MSSM particle content + chiral superfield uncharged under SM

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

Setup: Scale-invariant NMSSM.

Effective parameter: $\mu = \lambda \langle s \rangle / \sqrt{2}$

$$\begin{aligned} V = {} & m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + m_S^2 |S|^2 + \\ & + \lambda^2 |S|^2 \left(|H_u|^2 + |H_d|^2\right) + \left|\kappa S^2 - \lambda H_u H_d\right|^2 + \\ & + \left(\frac{\kappa}{3} A_\kappa S^3 - \lambda A_\lambda S H_u H_d + \text{h.c.}\right) \\ & + \frac{g_1^2 + g_2^2}{8} \left(|H_u|^2 - |H_d|^2\right)^2 \end{aligned}$$

Higgs Basis

Rotate CP-even neutral Higgses to basis where

$$\left\langle H^{\rm SM} \right\rangle = v, \quad \left\langle H^{NSM} \right\rangle = 0$$

$$\begin{pmatrix} H^{\rm SM} \\ H^{\rm NSM} \\ S^R \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} H_d^R \\ H_u^R \\ S^R \end{pmatrix}$$

In this basis, the couplings to Standard Model particles are

$$H^{\rm NSM}(\text{down}, \text{up}, \text{V}) = \left(g_{\rm SM} \tan\beta, \ \frac{g_{\rm SM}}{\tan\beta}, \ 0 \right)$$

No coupling to gauge bosons

$$H^{\rm SM}(\text{down}, \text{up}, \text{V}) = \left(g_{\rm SM}, \ g_{\rm SM}, \ g_{\rm SM} \right)$$

SM-like Higgs couplings

$$H^S(\text{down}, \text{up}, \text{V}) = (0, \ 0, \ 0)$$

No coupling to SM particles

CP-even Higgs mass matrix

$$M_A^2 = \frac{2\mu\left(A_\lambda + \kappa\mu/\lambda\right)}{\sin 2\beta}$$

$$\mathcal{M}_S^2 = \begin{pmatrix} m_Z^2 c_{2\beta}^2 + \frac{1}{2}\lambda^2 v^2 s_{2\beta}^2 & -\left(m_Z^2 - \frac{1}{2}\lambda^2 v^2\right) s_{2\beta} c_{2\beta} & \sqrt{2}\lambda v \mu \left(1 - \frac{M_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta}\right) \\ & M_A^2 + \left(m_Z^2 - \frac{1}{2}\lambda^2 v^2\right) s_{2\beta}^2 & -\frac{1}{\sqrt{2}}\lambda v \mu c_{2\beta}\left(\frac{M_A^2}{2\mu^2} s_{2\beta} + \frac{\kappa}{\lambda}\right) \\ & & \frac{1}{4}\lambda^2 v^2 s_{2\beta}\left(\frac{M_A^2}{2\mu^2} s_{2\beta} - \frac{\kappa}{\lambda}\right) + \frac{\kappa\mu}{\lambda}\left(A_\kappa + \frac{4\kappa\mu}{\lambda}\right) \end{pmatrix}$$

In Higgs Basis: $\{H^{\rm SM}, H^{\rm NSM}, S\}$

To get a SM-like Higgs, we need alignment:

$$\mathcal{M}_{S,12}^2, \mathcal{M}_{S,13}^2 \ll \mathcal{M}_{S,11}^2, \mathcal{M}_{S,22}^2, \mathcal{M}_{S,33}^2$$

And mass:

$$m_{h_{\rm SM}}^2 = m_Z^2 c_{2\beta}^2 + \frac{1}{2}\lambda^2 v^2 s_{2\beta}^2 + \frac{3 v^2 s_\beta^4 h_t^4}{8\pi^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right] = 125\,\text{GeV}$$

CP-odd Higgs & Neutralino mass matrix

Basis: $\{A^{\rm NSM}, A^S\}$

$$\mathcal{M}_P^2 = \begin{pmatrix} M_A^2 & \frac{1}{\sqrt{2}}\lambda v\left(\frac{M_A^2}{2\mu}s_{2\beta} - \frac{3\kappa\mu}{\lambda}\right) \\ \frac{1}{\sqrt{2}}\lambda v\left(\frac{M_A^2}{2\mu}s_{2\beta} - \frac{3\kappa\mu}{\lambda}\right) & \frac{1}{2}\lambda^2 v^2 s_{2\beta}\left(\frac{M_A^2}{4\mu^2}s_{2\beta} + \frac{3\kappa}{2\lambda}\right) - \frac{3\kappa A_\kappa \mu}{\lambda} \end{pmatrix}$$

Basis: $\{\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}\}$

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta & 0 \\ & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta & 0 \\ & & 0 & -\mu & -\lambda v s_\beta \\ & & & 0 & -\lambda v c_\beta \\ & & & & 2\kappa\mu/\lambda \end{pmatrix}$$

General picture of spectrum

- SM-like Higgs with mass ~125 GeV: h_{SM}
- Mostly-doublet like (pseudo-) scalar H (A), masses ~M_A
- Lighter mostly-singlet like (pseudo-) scalars

$$m_{h_S}^2 \simeq \frac{\kappa\mu}{\lambda}\left(A_\kappa + \frac{4\kappa\mu}{\lambda}\right) + \frac{\lambda^2 v^2 M_A^2}{8\mu^2} s_{2\beta}^4 - \frac{1}{4} v^2 \kappa\lambda \left(1 + 2c_{2\beta}^2\right) s_{2\beta} - \frac{1}{2} v^2 \kappa^2 \frac{\mu^2}{M_A^2} c_{2\beta}^2$$

$$m_{a_S}^2 \simeq 3\kappa \left[\frac{3}{4}\lambda v^2 s_{2\beta} - \mu\left(\frac{A_\kappa}{\lambda} + \frac{3v^2\kappa\mu}{2M_A^2}\right)\right]$$

- Higgsinos with mass ~μ
- Singlino with mass ~2κμ/λ

Recall: $$M_A^2 = \frac{2\mu\left(A_\lambda + \kappa\mu/\lambda\right)}{\sin 2\beta}$$

μ controls the masses of the Higgsinos/neutralinos and of all the beyond-SM Higgses, except a_S which can be tuned with A_κ

Numerical Scan w/ NMSSMTools

SB, Freese, Shakya, Shah 1703.07800

Demand:

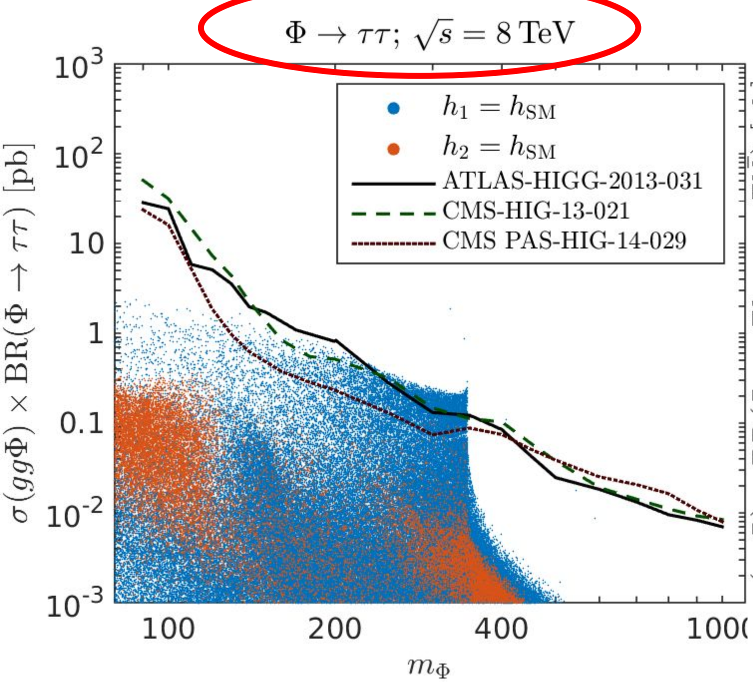
- Physical masses
- Physical global minimum
- Pass LEP
- Pass Tevatron
- LHC sparticle & H^+ searches
- SM-like Higgs with mass 125 GeV and couplings compatible with LHC
- Neutralino LSP

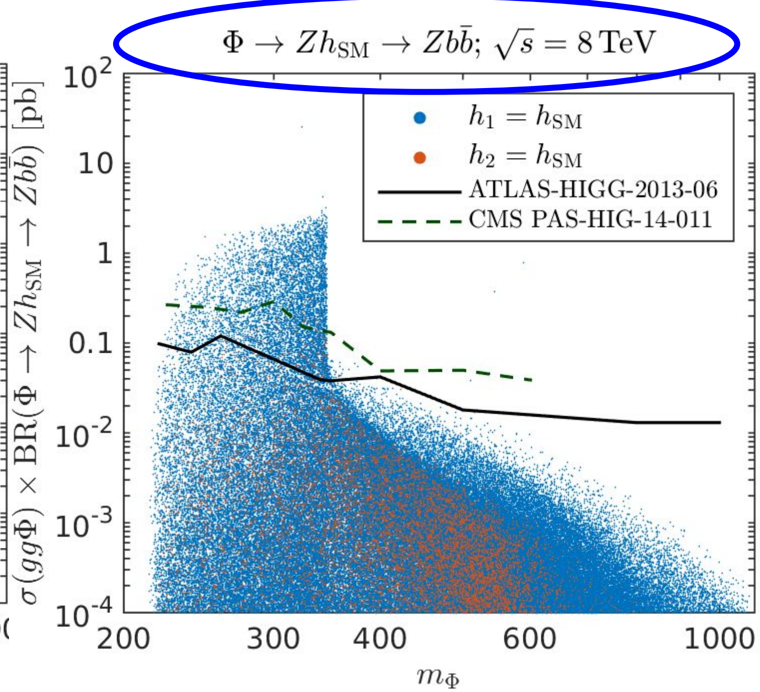
	"standard"	"light subset"
$\tan\beta$	$[1; 5]$	$[1; 5]$
λ	$[0.5; 2]$	$[0.5; 1]$
κ	$[-1; +1]$	$[-0.5; +0.5]$
A_λ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
A_κ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
μ	$[-1; +1]$ TeV	$[-0.5; +0.5]$ TeV
M_{Q_3}	$[1; 10]$ TeV	$[1; 10]$ TeV

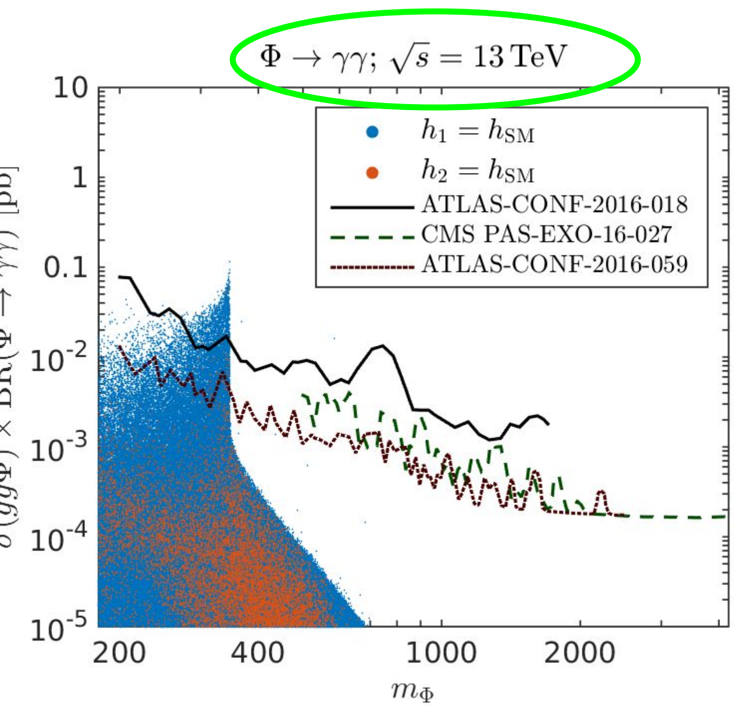
- Stop and sbottom mixing set to zero
- Sfermion masses set to 3 TeV
- Electroweakino masses M_1=M_2=1 TeV
- Gluino mass M_3=2 TeV

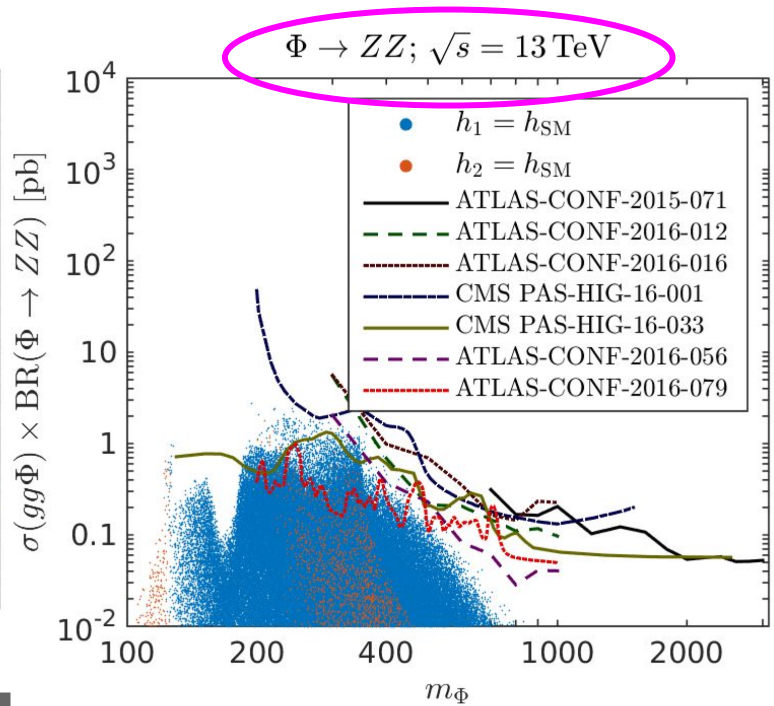
Constrain NMSSM dataset with direct Higgs searches

decay channel	NMSSM Higgs tested	Reference $\sqrt{s} = 8\,\mathrm{TeV}$	Reference $\sqrt{s} = 13\,\mathrm{TeV}$
$H \to \tau^+\tau^-$	h_i, H_3, A_1, A_2	[46–48]	[49, 50]
$H \to b\bar{b}$	h_1, H_3, A_1, A_2	–	[51]
$H \to \gamma\gamma$	h_i, H_3, A_1, A_2	[52–54]	[55–57]
$H \to ZZ$	h_1, H_3	[58]	[59–65]
$H \to WW$	h_i, H_3	[66–68]	[69–72]
$H \to h_{\rm SM} h_{\rm SM} \to b\bar{b}\tau^+\tau^-$	h_i, H_3	[73–75]	[76, 77]
$H \to h_{\rm SM} h_{\rm SM} \to b\bar{b}\ell\nu_\ell\ell\nu_\ell$	h_i, H_3	–	[78]
$H \to h_{\rm SM} h_{\rm SM} \to b\bar{b}b\bar{b}$	h_i, H_3	[79, 80]	[81–83]
$H \to h_{\rm SM} h_{\rm SM} \to b\bar{b}\gamma\gamma$	h_i, H_3	[84, 85]	[86, 87]
$A \to Z h_{\rm SM} \to Z b\bar{b}$	A_1, A_2	[88, 89]	[90]
$A \to Z h_{\rm SM} \to Z\tau^+\tau^-$	A_1, A_2	[73, 88]	–
$h_{\rm SM} \to AA \to \tau^+\tau^-\tau^+\tau^-$	$A_1,\ A_2$	[91]	–
$h_{\rm SM} \to AA \to \mu^+\mu^- b\bar{b}$	$A_1,\ A_2$	[91]	–
$h_{\rm SM} \to AA \to \mu^+\mu^-\tau^+\tau^-$	$A_1,\ A_2$	[91]	–
$h_{\rm SM} \to AA \to \mu^+\mu^-\mu^+\mu^-$	$A_1,\ A_2$	–	[92]
$A/H \to Z h_i/A_1$	$A_2/H_3,\ h_i/A_1$	[93]	–









decay channel
$H \to \tau^+\tau^-$
$H \to b\bar{b}$
$H \to \gamma\gamma$
$H \to ZZ$
$H \to WW$
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\tau^+\tau^-$
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\ell\nu_\ell\ell\nu_\ell$
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}b\bar{b}$
$H \to h_{\rm SM}h_{\rm SM} \to b\bar{b}\gamma\gamma$
$A \to Zh_{\rm SM} \to Zb\bar{b}$
$A \to Zh_{\rm SM} \to Z\tau^+\tau^-$
$h_{\rm SM} \to AA \to \tau^+\tau^-\tau^+\tau^-$
$h_{\rm SM} \to AA \to \mu^+\mu^-b\bar{b}$
$h_{\rm SM} \to AA \to \mu^+\mu^-\tau^+\tau^-$
$h_{\rm SM} \to AA \to \mu^+\mu^-\mu^+\mu^-$
$A/H \to Zh_i/A_1$

Couplings

Large NMSSM couplings λ and κ induce large Higgs-Higgs and Higgs-neutralino couplings

Suppressed

- $(H^{\rm SM} H^{\rm SM} H^{\rm NSM}) \propto \mathcal{M}^2_{S,12} \sim 0,$
- $(H^S H^{\rm SM} H^{\rm SM}) \propto \mathcal{M}^2_{S,13} \sim 0,$
- $(H^{\rm NSM} A^{\rm NSM} A^S) = 0$

Vanishing in Alignment limit

Large

- $(H^S H^{\rm SM} H^{\rm NSM})$
- $(H^{\rm SM} A^{\rm NSM} A^S)$

Visible final states, light h_i/A_1

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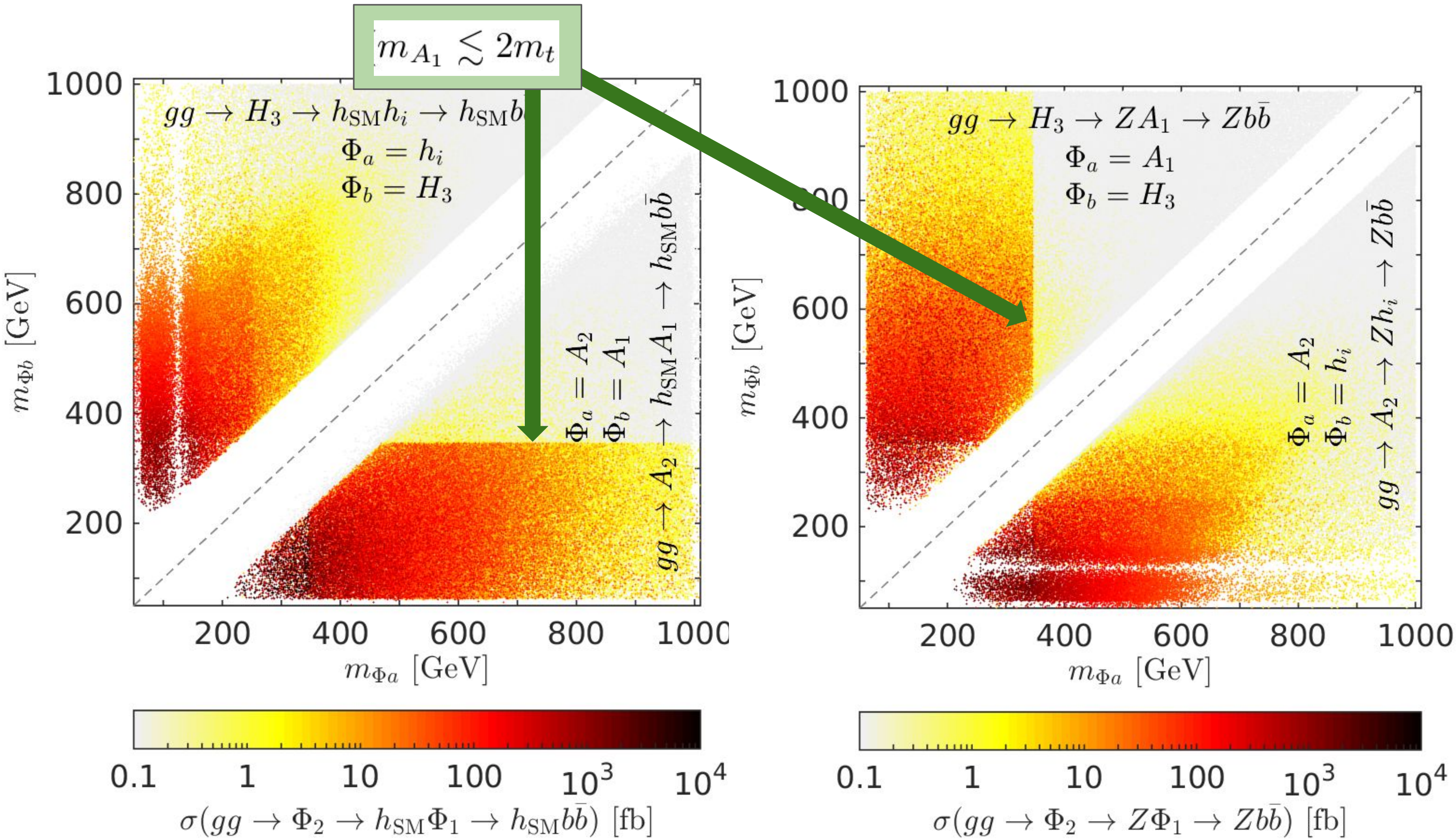

Visible final states, light h_i/A_1

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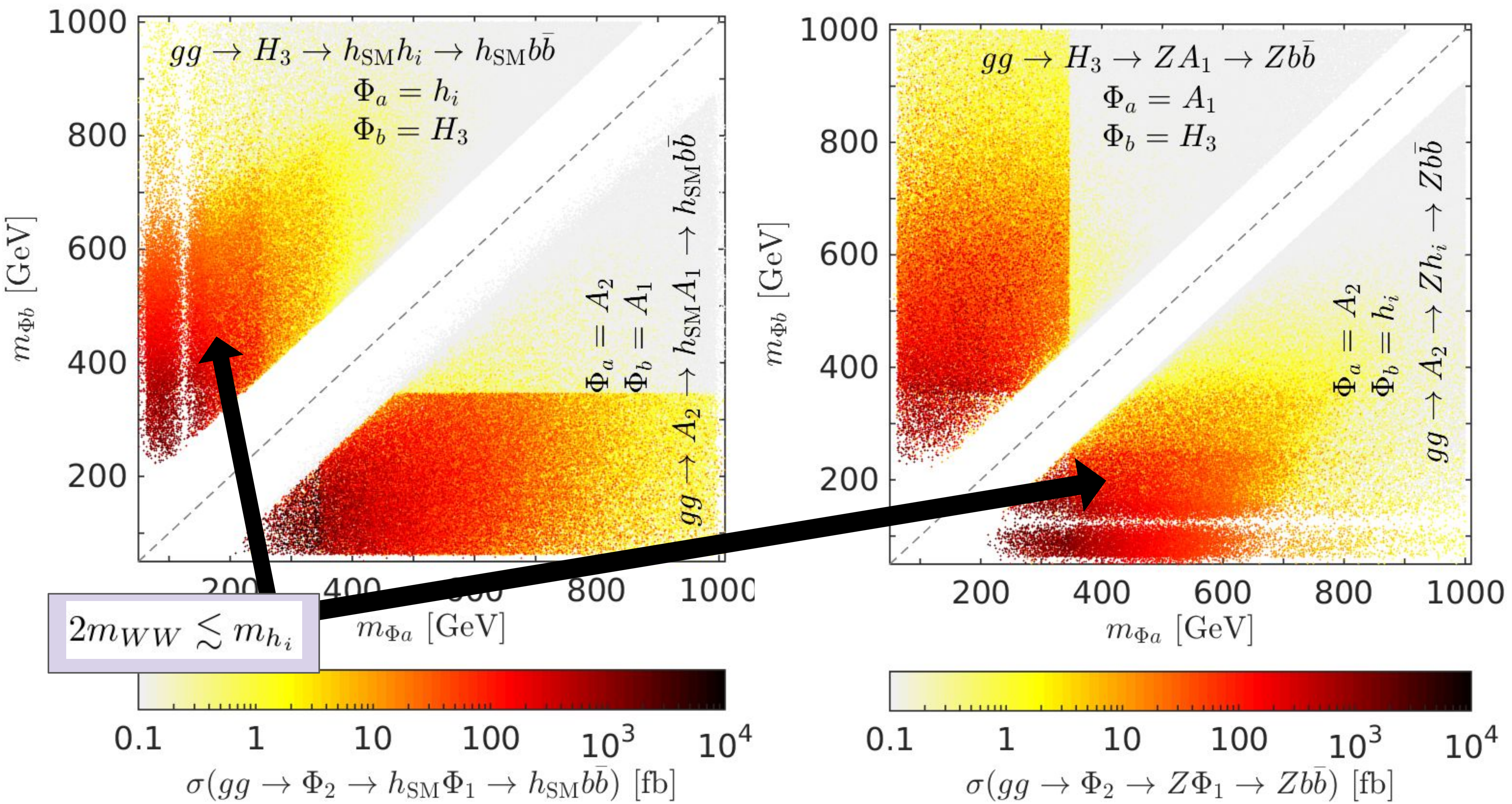

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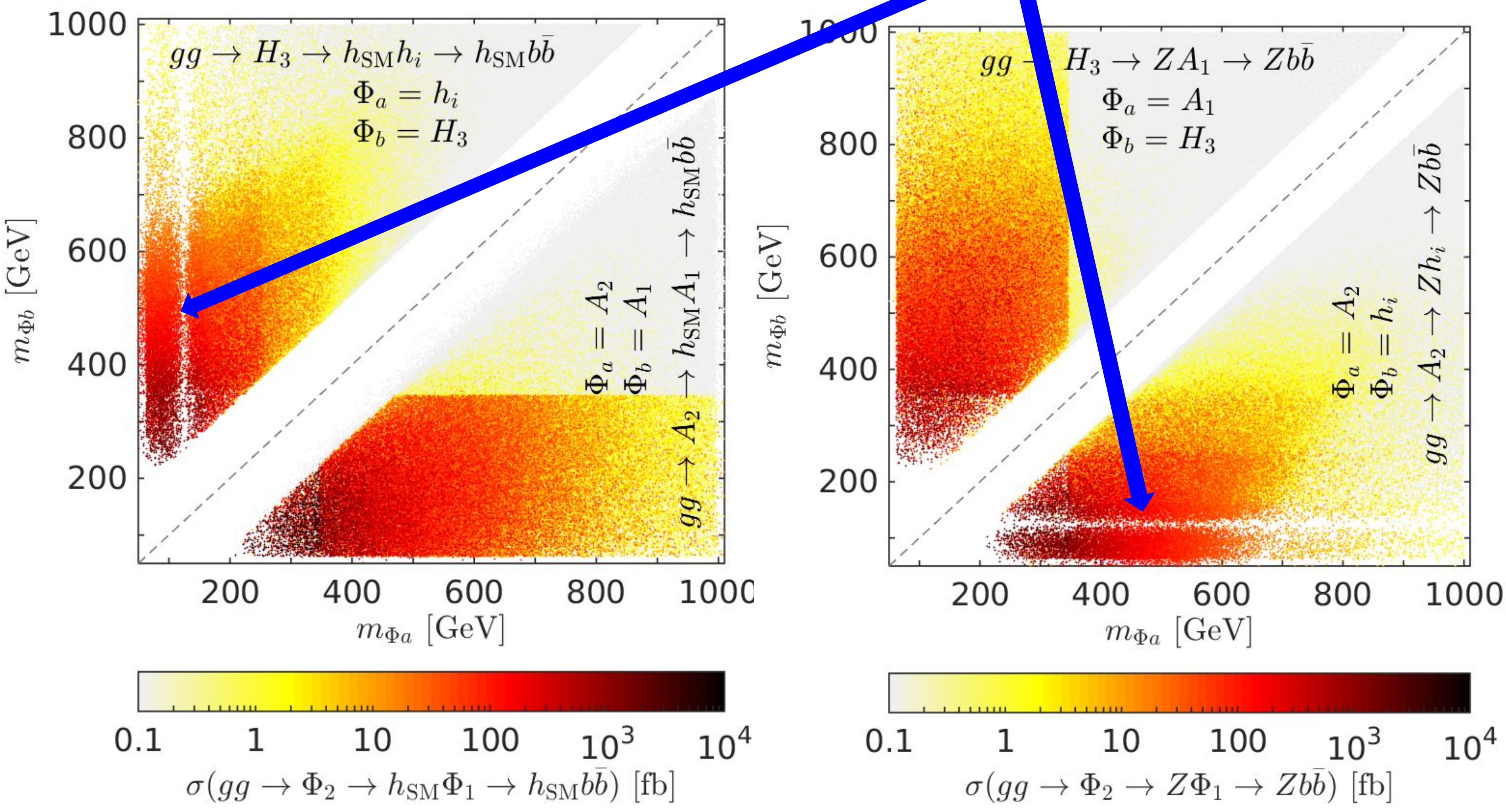
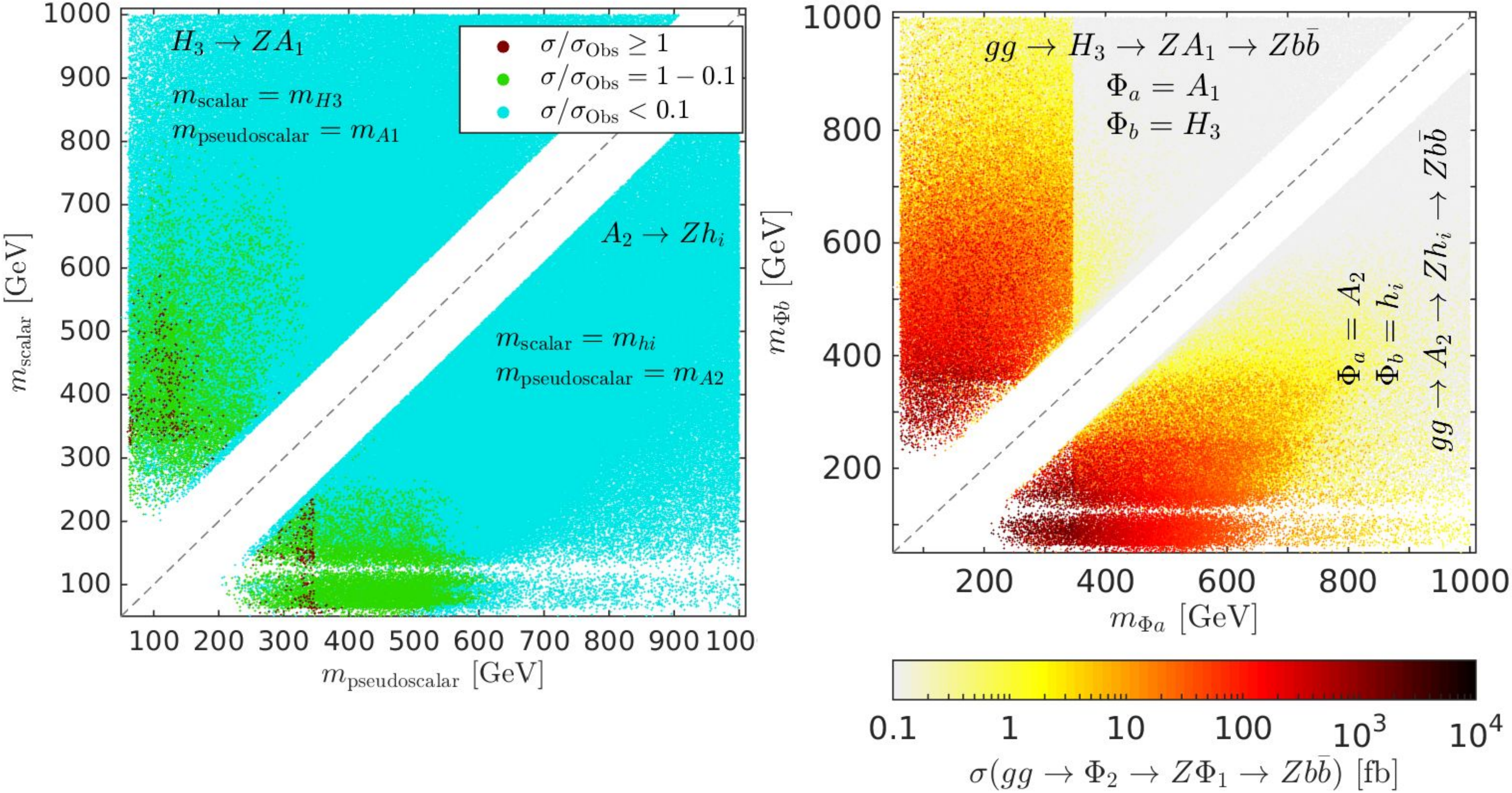
Visible final states, light h_i/A_1

Depletion from presence of 125 GeV SM-like higgs



Visible final states, light h_i/A_1

Limit from CMS-HIG-15-001 ($\sqrt{s}$ = 8 TeV)



Visible final states, heavy h_i/A_1

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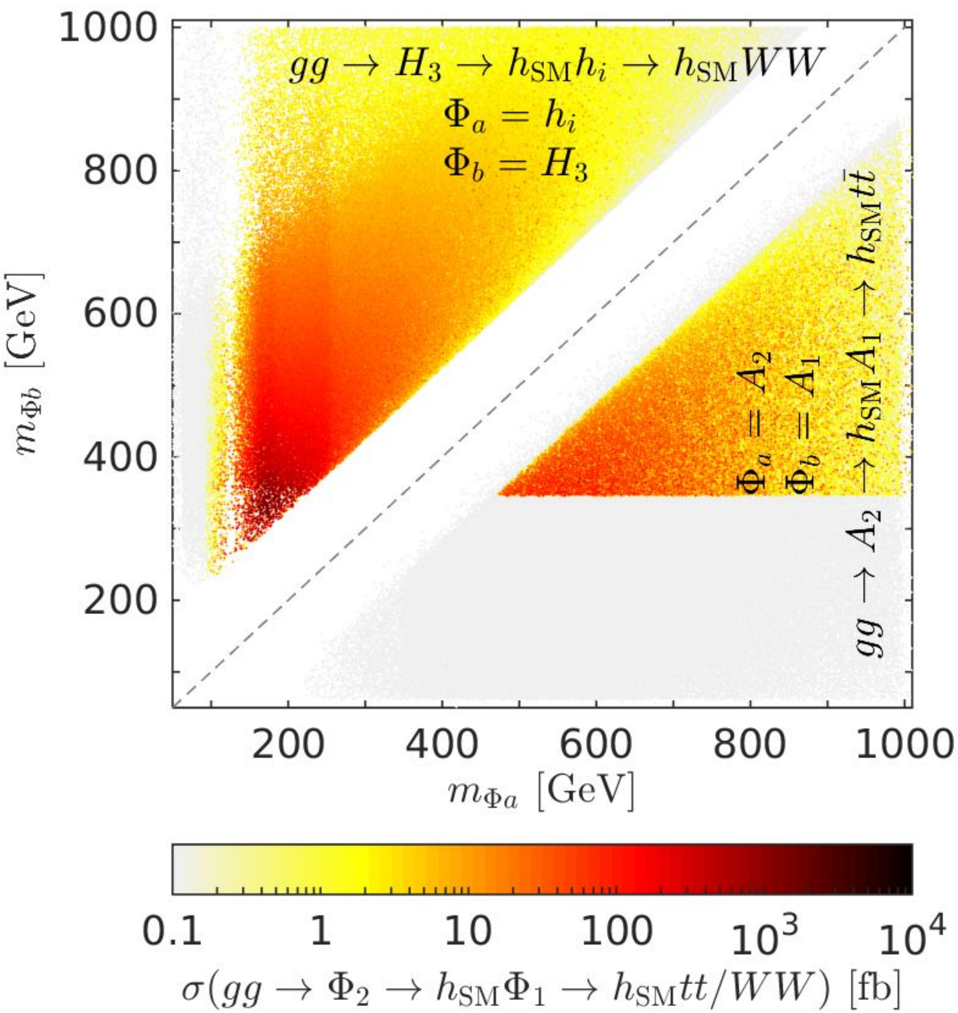

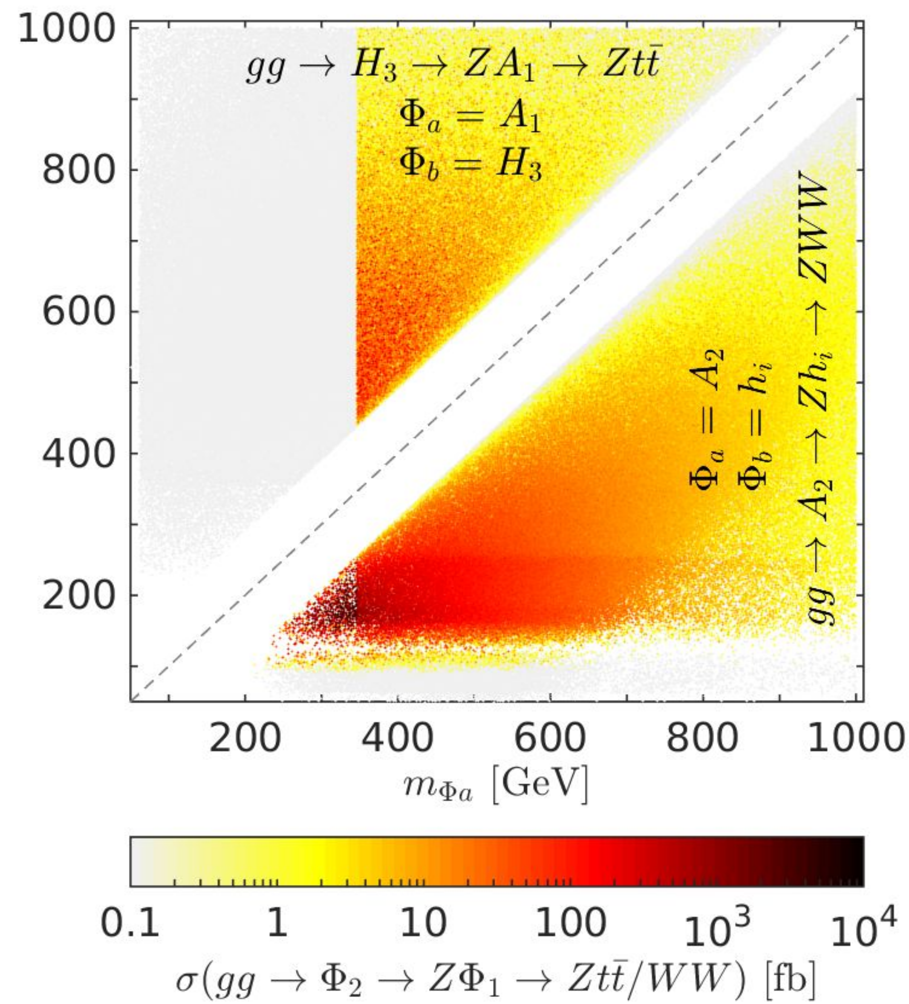

Invisible final states - mono-Higgs/mono-Z

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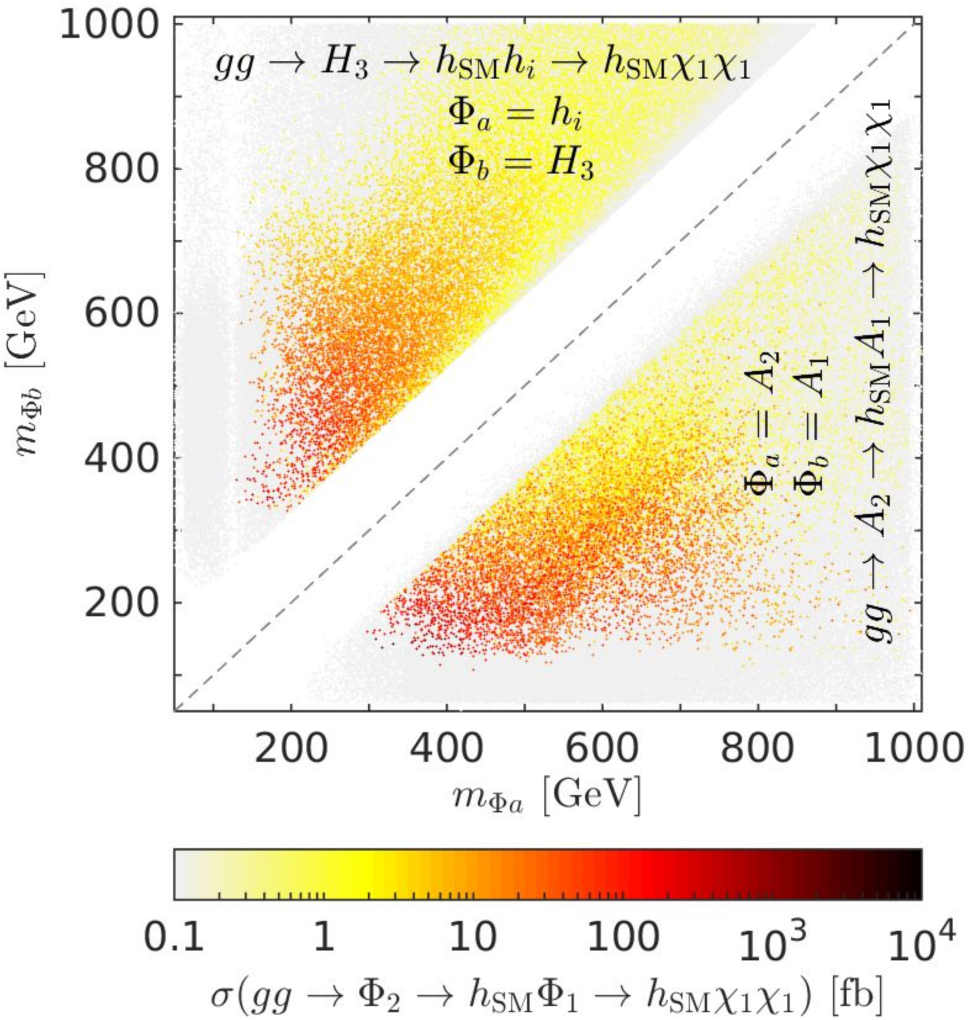

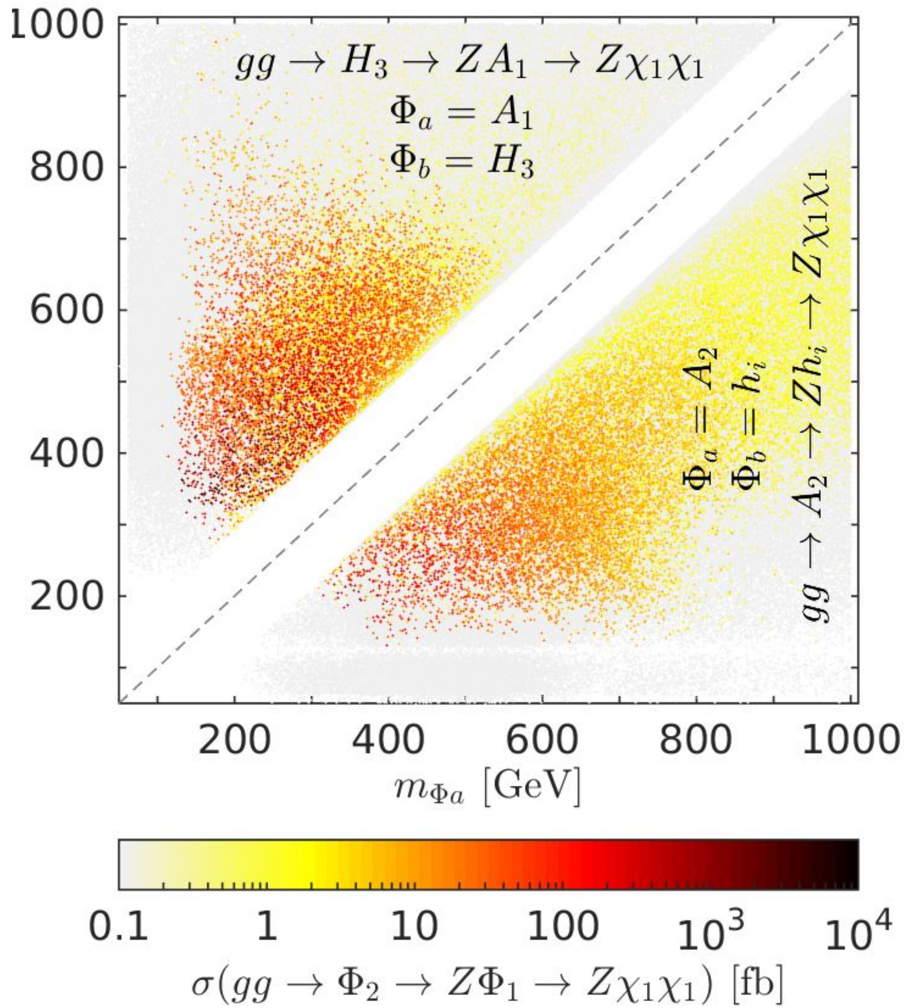

Mono-H/Mono-Z cross-sections, neutralino-topology

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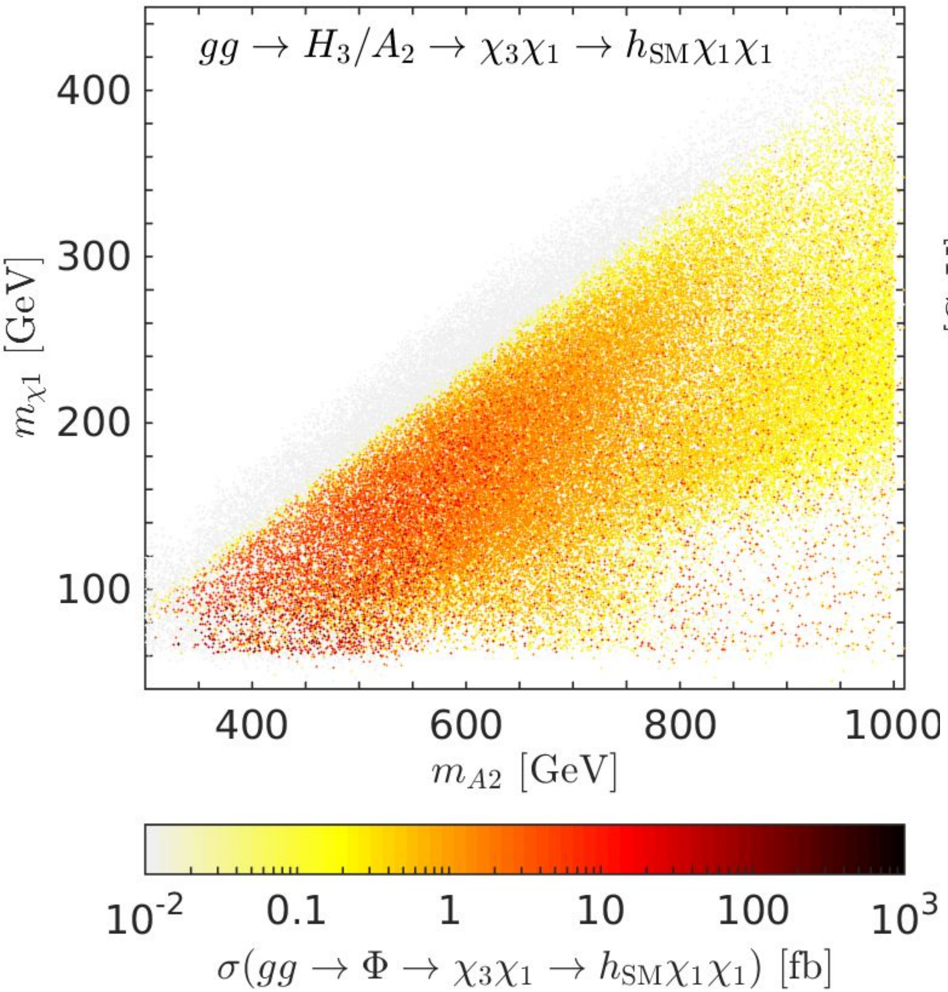

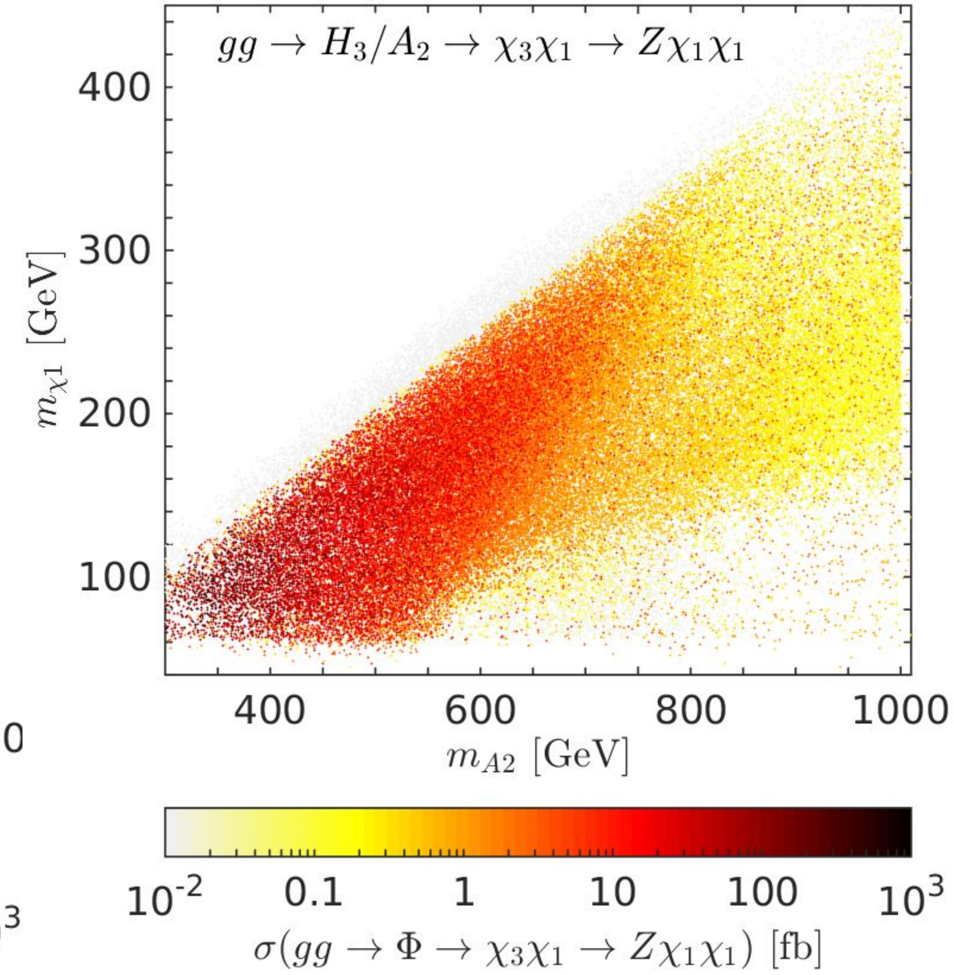

mono-Higgs reach

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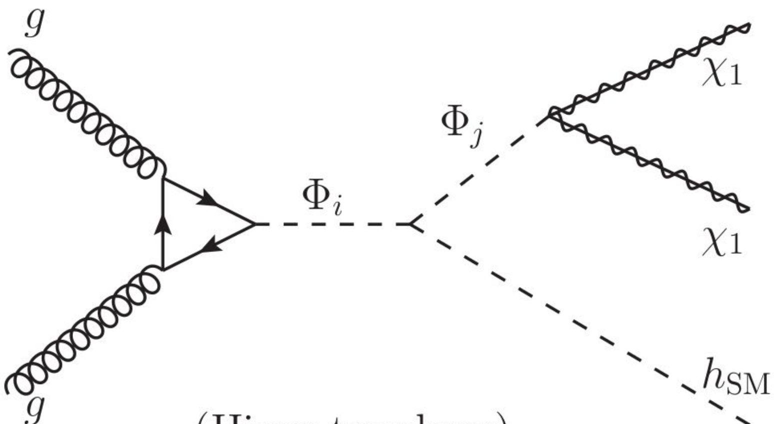
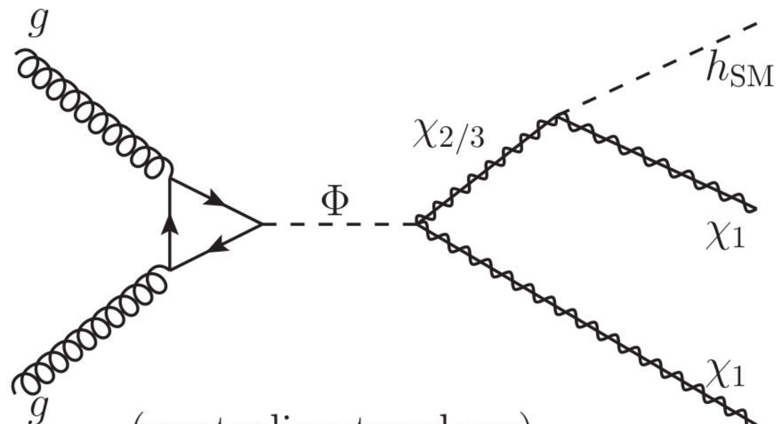


(Higgs topology)



(neutralino topology)

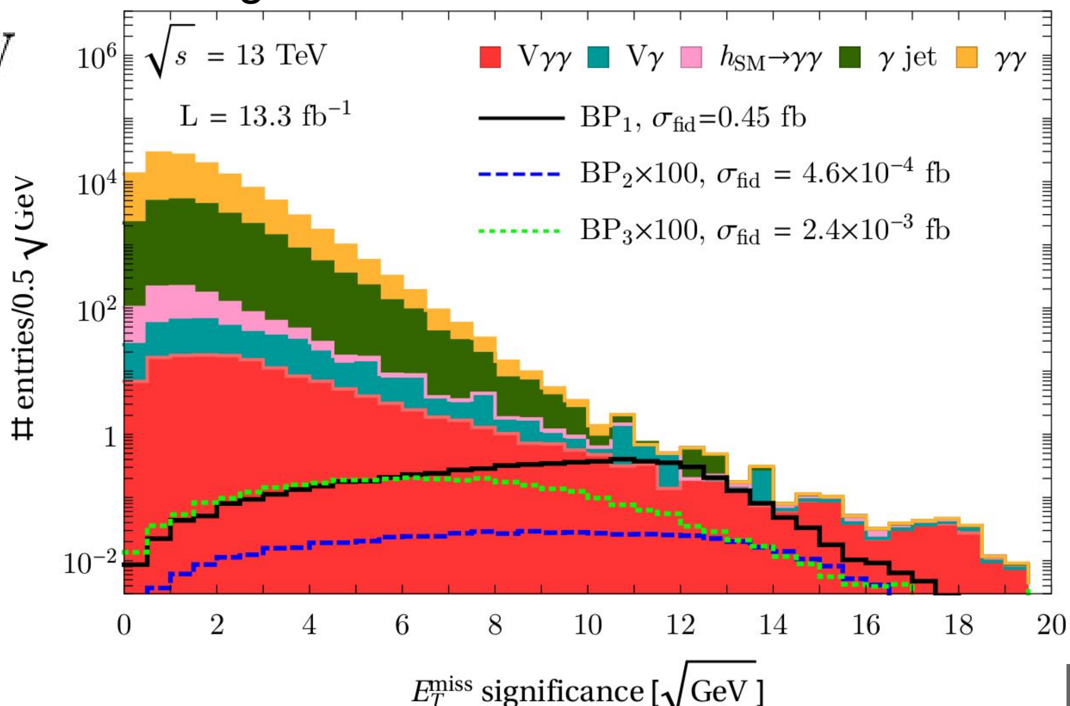
Background separation:

- $105\,\mathrm{GeV} < m_{\gamma\gamma} < 160\,\mathrm{GeV}$
- $S_{E_T^{\rm miss}} \equiv E_T^{\rm miss} / \sqrt{\sum E_T}$

Use $h_{SM} \to \gamma\gamma$ final state:

well measure objects and less background

Background from ATLAS-CONF-2017-087



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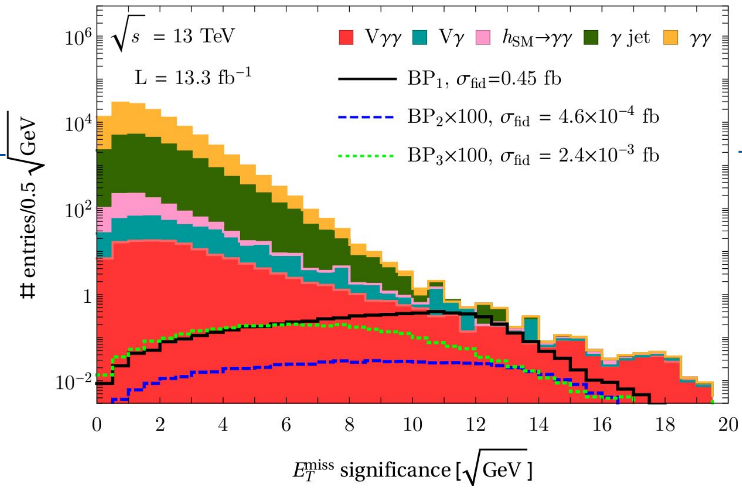
Benchmark Points

	BP_1	BP_2	BP_3
$\tan\beta$	2.17	2.16	2.24
λ	0.60	0.55	0.55
κ	-0.38	-0.33	-0.45
A_λ [GeV]	-554	-859	-539
A_κ [GeV]	-254	- 195	-497
μ [GeV]	-144	-222	-123
M_{Q_3} [TeV]	2.55	4.46	8.48
$m_{h_{SM}}$ [GeV]	122	123	126
m_{h_i} [GeV]	157	238	77.6
m_{H_3} [GeV]	421	650	390
m_{A_1} [GeV]	184	232	295
m_{A_2} [GeV]	457	669	464



	BP_1	BP_2	BP_3
m_{χ_1} [GeV]	69.5	156	73.1
m_{χ_2} [GeV]	158	238	139
m_{χ_3} [GeV]	268	343	270
$BR(A_2 \to A_1 h_{SM})$	18 %	31 %	0.10 %
$BR(A_1 \to \chi_1\chi_1)$	99 %	–	69 %
$BR(H_3 \to h_i h_{SM})$	9.3 %	5.0 %	14 %
$BR(h_i \to \chi_1\chi_1)$	98 %	–	–
$BR(A_2 \to \chi_3\chi_1)$	0.71 %	0.80 %	0.34 %
$BR(H_3 \to \chi_3\chi_1)$	0.57 %	0.28 %	1.1 %
$BR(\chi_3 \to \chi_1 h_{SM})$	3.2 %	6.1 %	11 %

Higgs topology

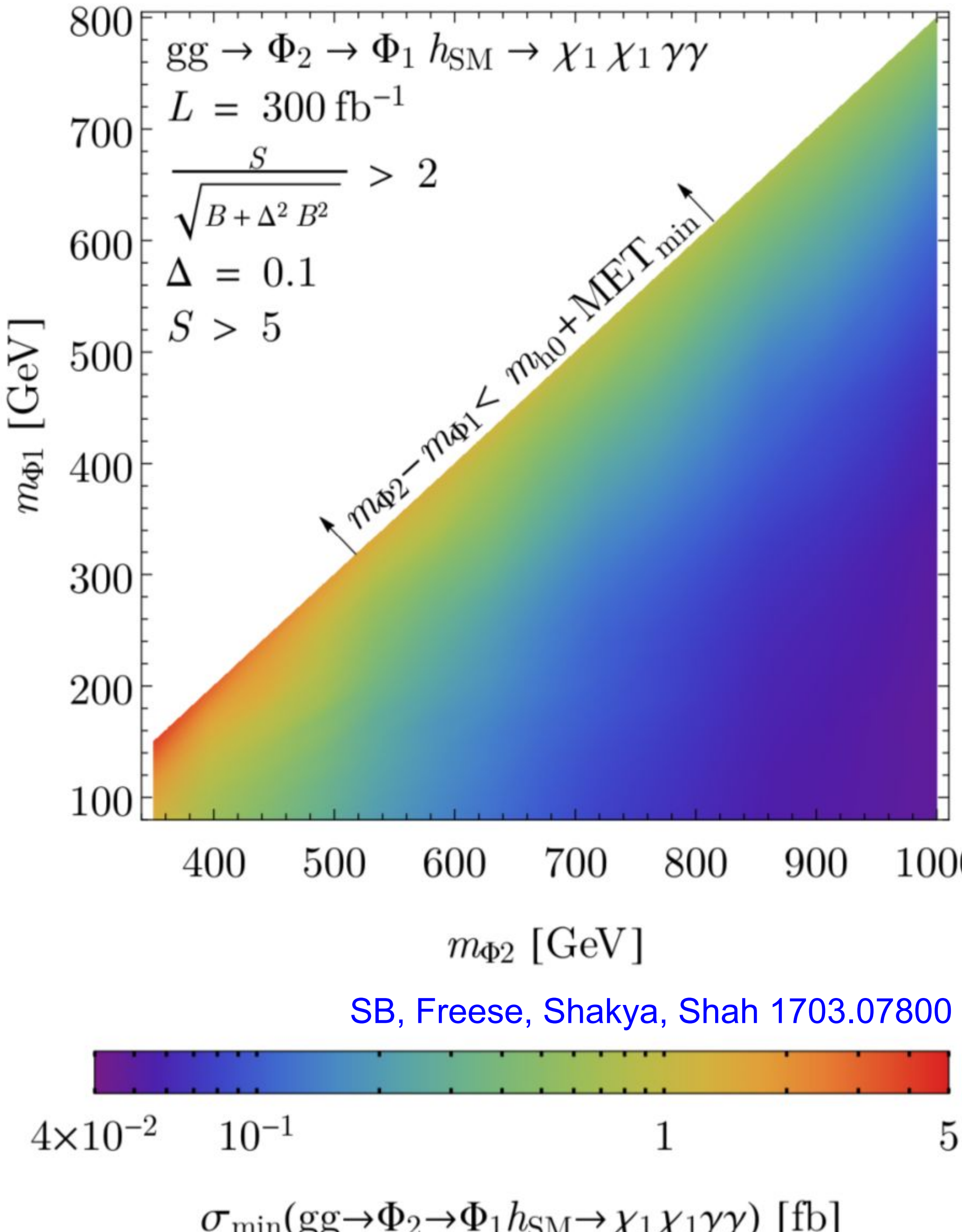
Optimize $E_T^{\rm miss}$ cut for each point

- $\frac{S}{\sqrt{B+\Delta^2 B^2}} > 2$
- $S > 5$

Reach depends primarily on:

- m_{Φ_2} controlling the overall energy scale
- $\Delta m = m_{\Phi_2} - (m_{\Phi_1} + m_{h_{\rm SM}})$ controlling the MET

Reach better than 0.1 fb maintained over most of parameter space



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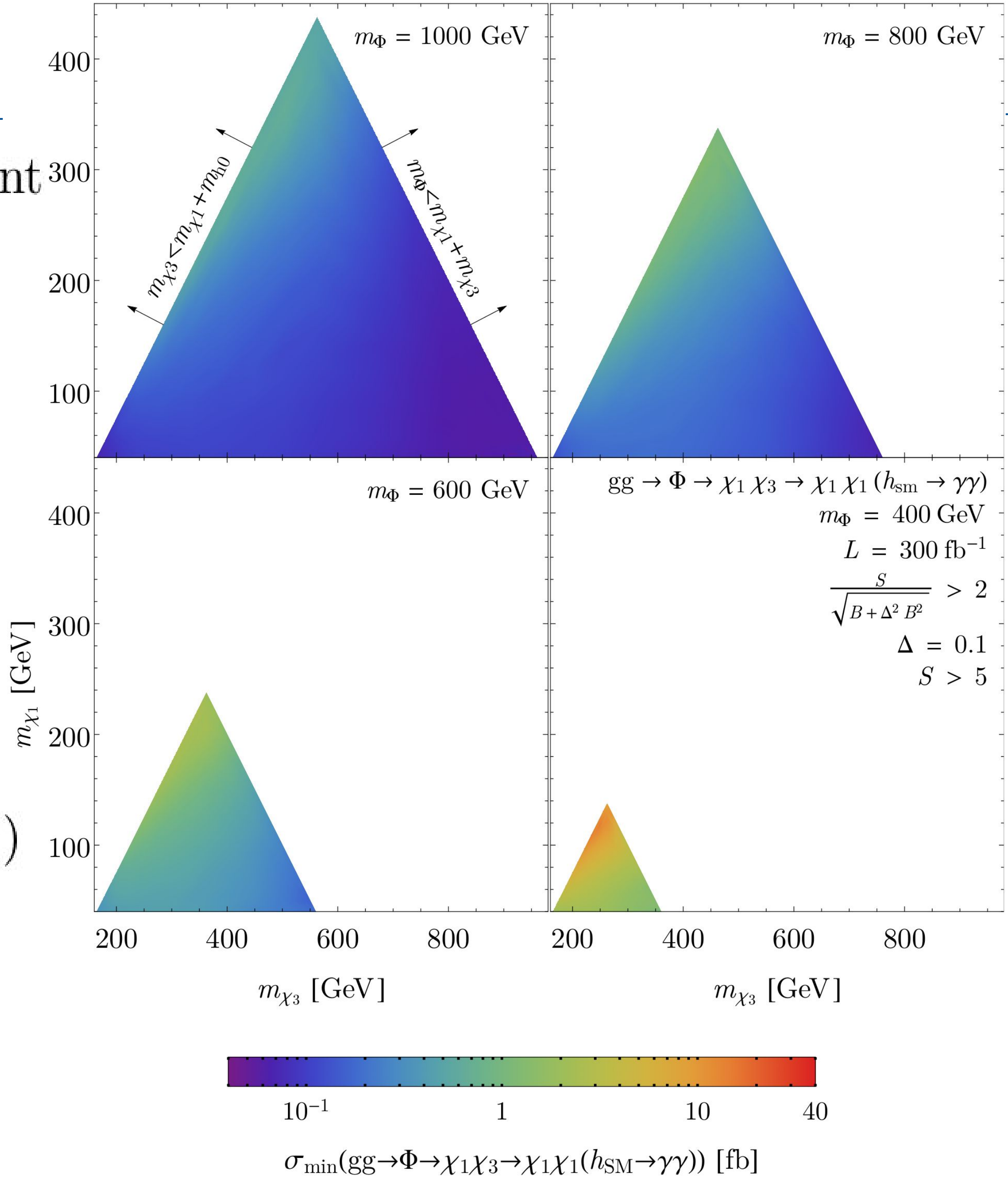
Neutralino topology

Optimize $E_T^{\rm miss}$ cut for each point

- $\frac{S}{\sqrt{B+\Delta^2 B^2}} > 2$
- $S > 5$



Reach depends primarily on:

- m_Φ controlling the overall energy scale
- $\Delta m_1 = m_\Phi - (m_{\chi_1} + m_{\chi_3})$
  $\Delta m_2 = m_{\chi_3} - (m_{\chi_1} + m_{h_{\rm SM}})$
  controlling the MET

Less good sensitivity since MET and SM-like Higgs not produced back to back

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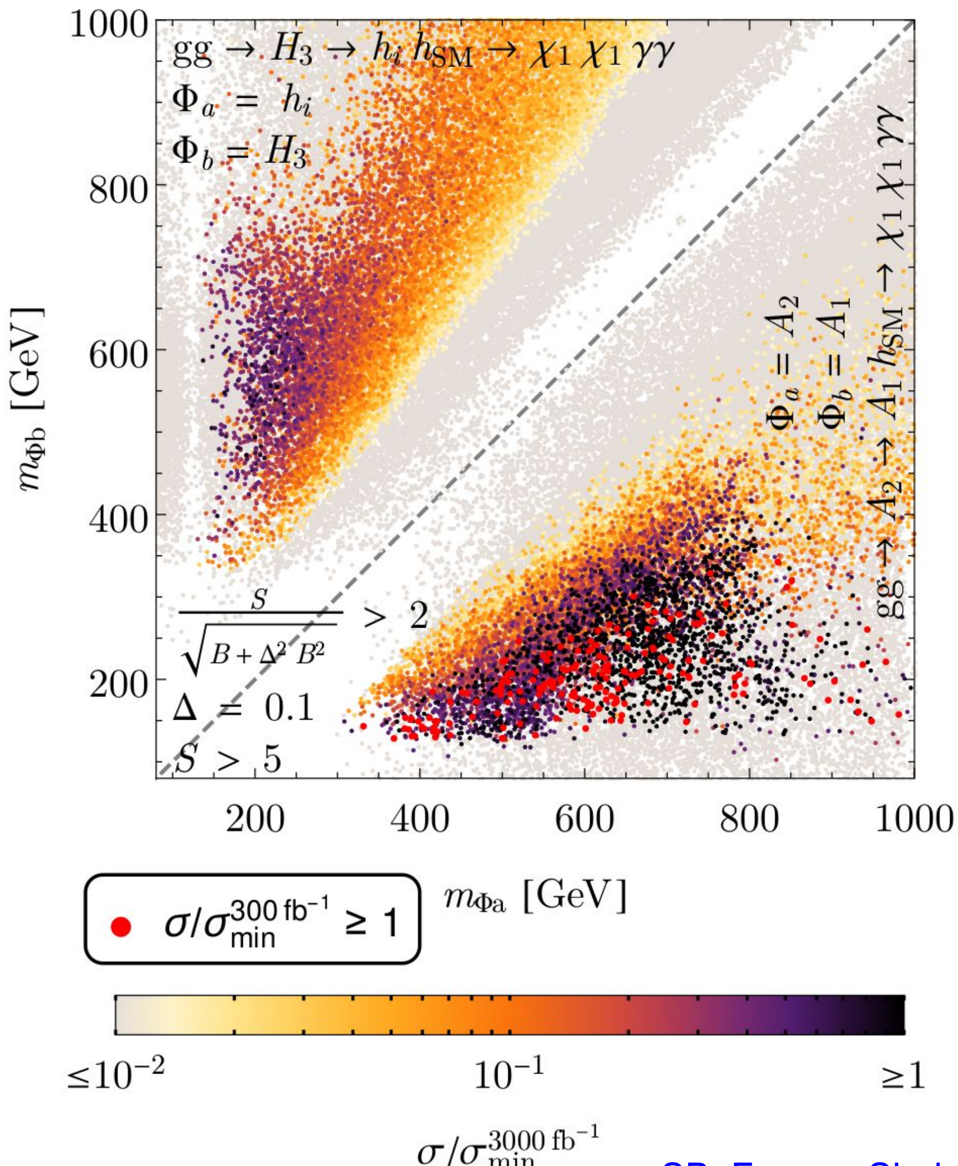
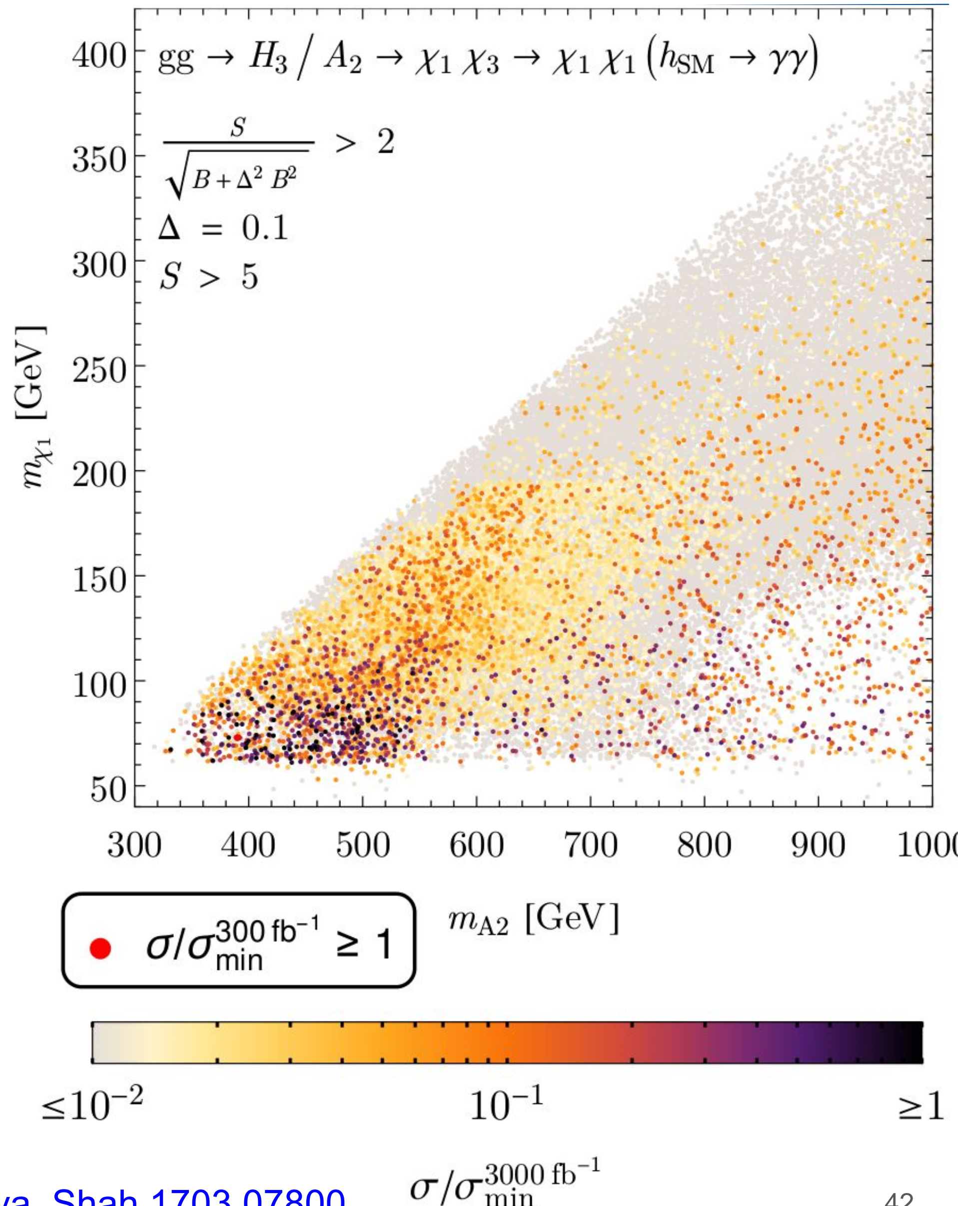
NMSSM Interpretation

For $m_{H_3} \approx m_{A_2}$, we add channels in neutralino topology





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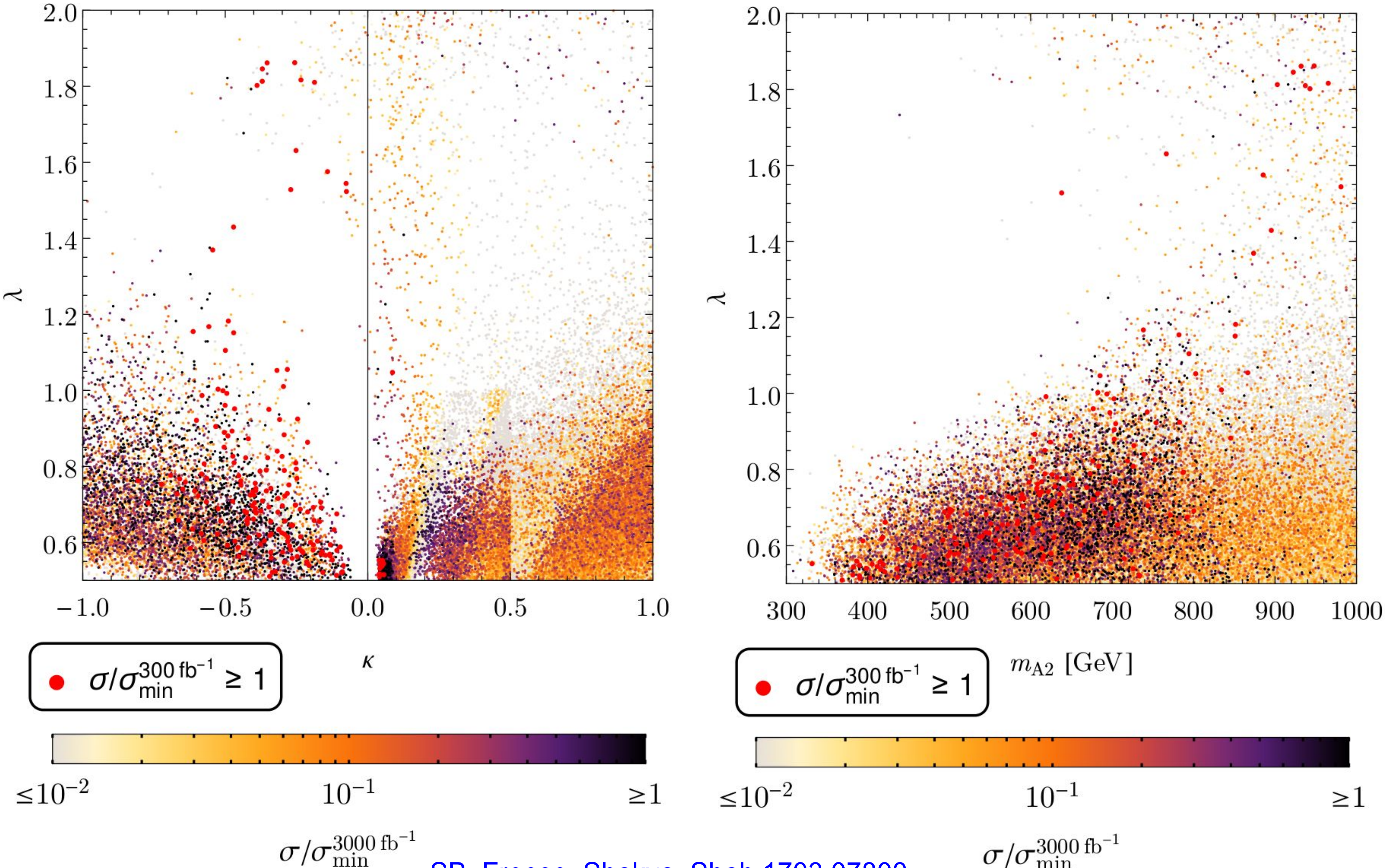
NMSSM Interpretation



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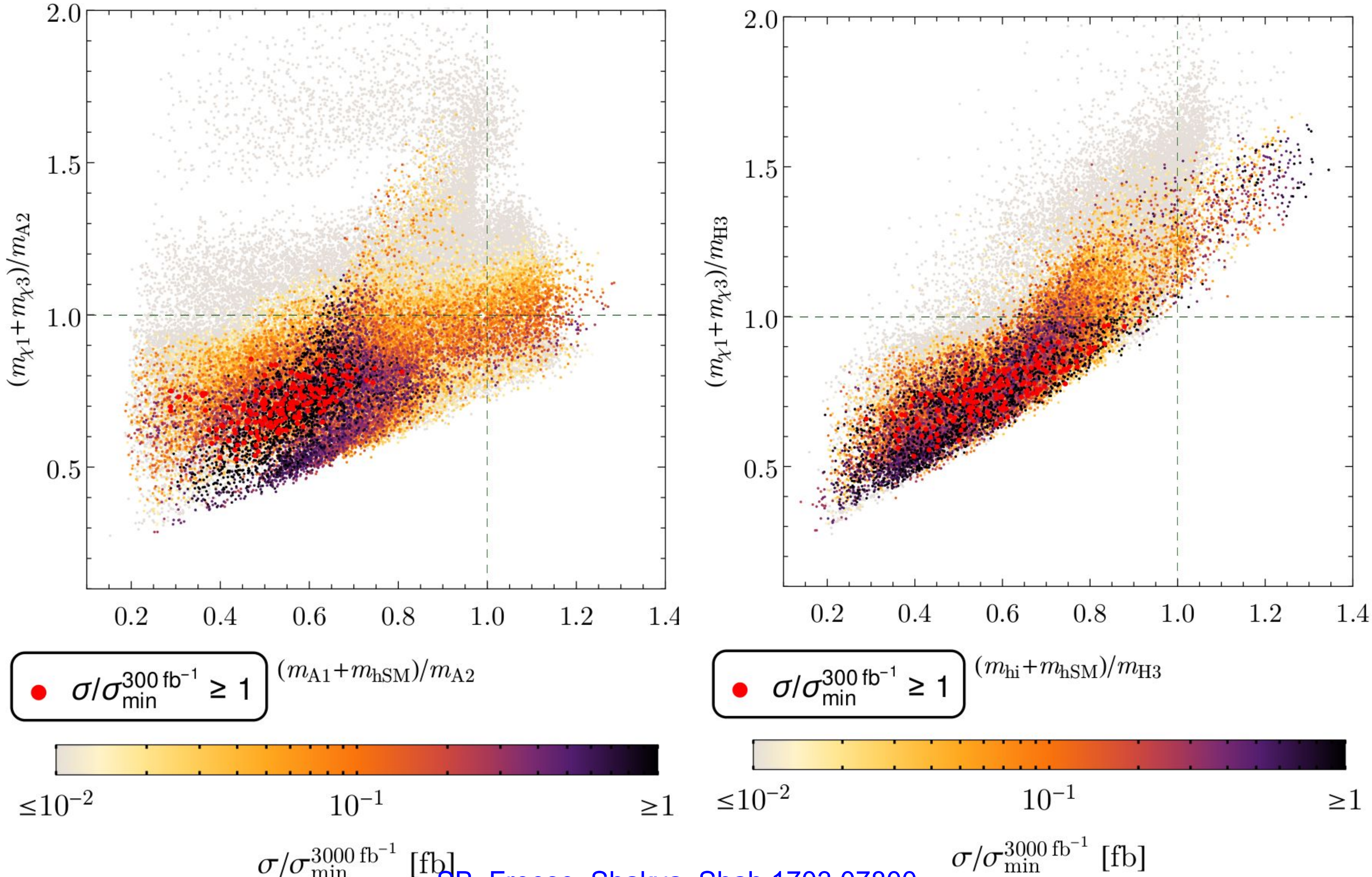
NMSSM Interpretation: mass splittings



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