When the NMSSM Meets the LHC: Conventional Higgs Searches and the Power of Mono-Higgs

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Why (low-scale) SUSY?

SM Problems

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

Why (low-scale) SUSY?

SM Problems   SUSY fixes (?)

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

Why Next-to-MSSM?

The Minimal Supersymmetric SM

The μ-problem

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

Tree level SM-like Higgs mass

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

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:

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

Consider NMSSM with heavy sleptons/squarks

Higgs sector

- Three neutral CP-even Higgses
- Two neutral CP-odd Higgses
- 1 charged Higgs

$H_u^R,\ H_d^R,\ H^S$

$A^{\mathrm{NSM}},\ A^S$

$H^\pm$

MSSM Higgs sector (H_u^R, H_d^R, A^{NSM}, $H^\pm$)

New in NMSSM (H^S, A^S)

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

Neutralino sector

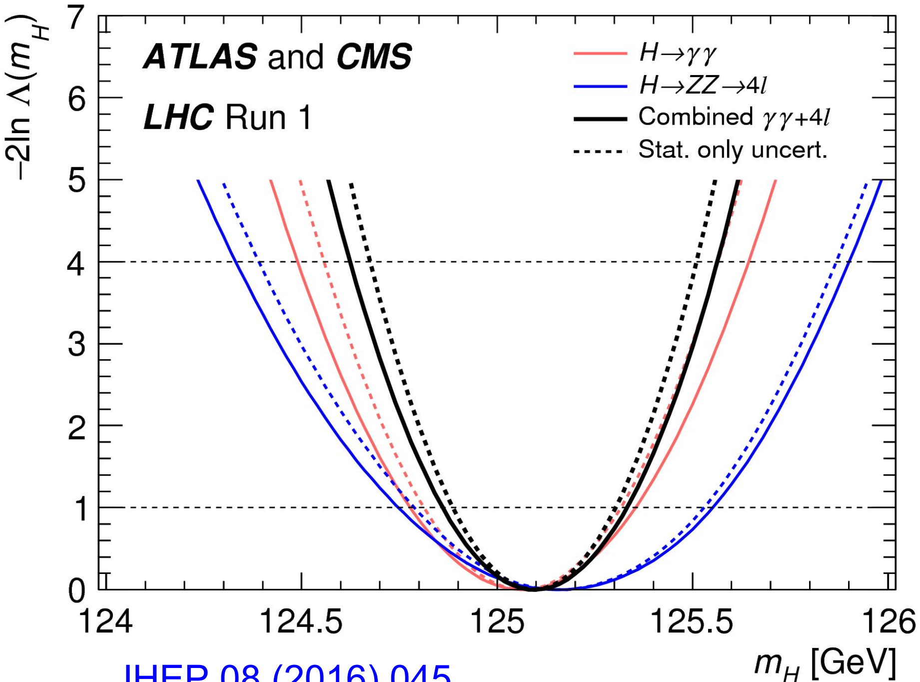
- Wino -- mass ~ M_2
- Bino -- mass ~ M_1
- 2 Higgsinos -- mass ~ -μ
- Singlino -- mass ~ 2κμ/λ

MSSM neutralino sector (Wino, Bino, 2 Higgsinos)

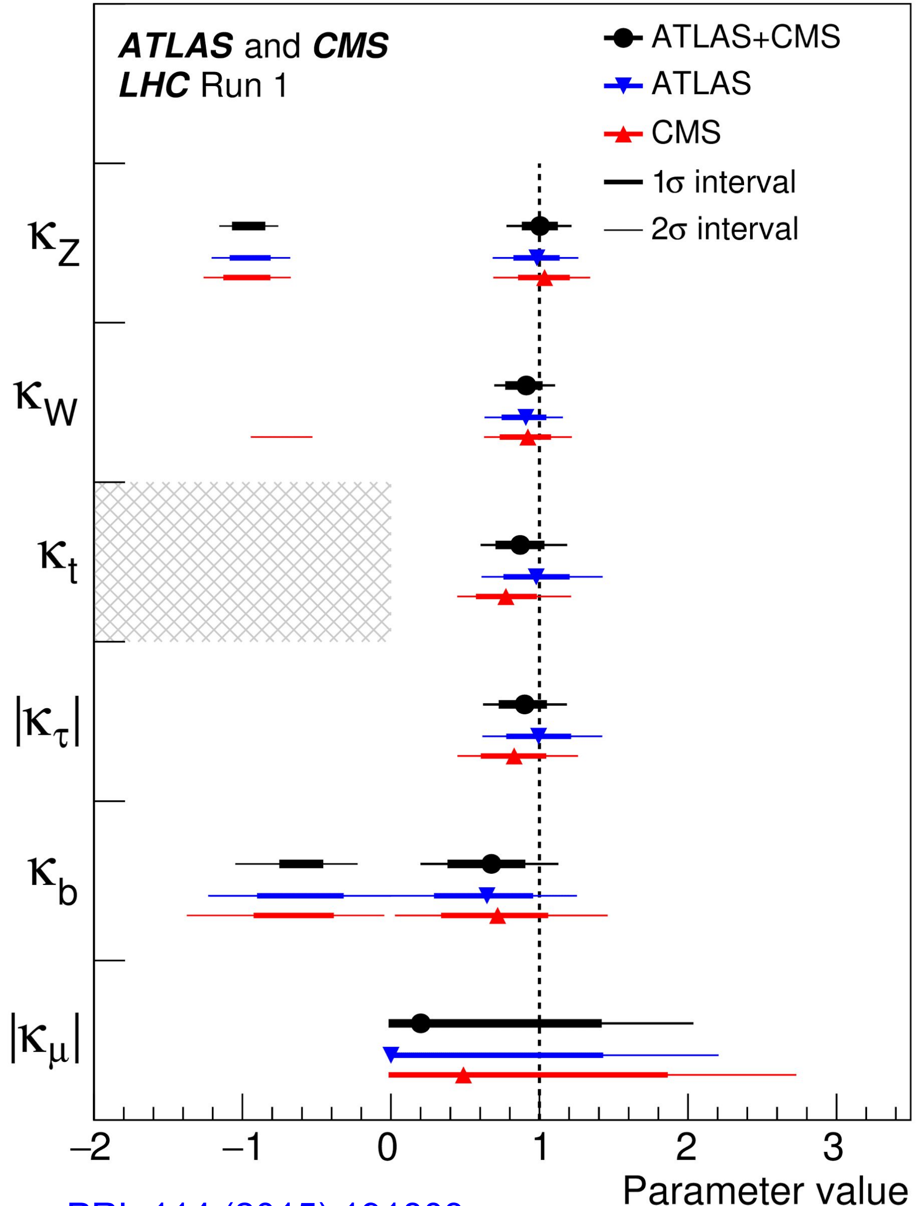
New in NMSSM (Singlino)

SM Higgs boson measurements

The NMSSM better have a 125 GeV Higgs with couplings ≲ 10 % away from SM



JHEP 08 (2016) 045



PRL 114 (2015) 191803

The SM-like Higgs and Alignment

Carena+ 1510.09137

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

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

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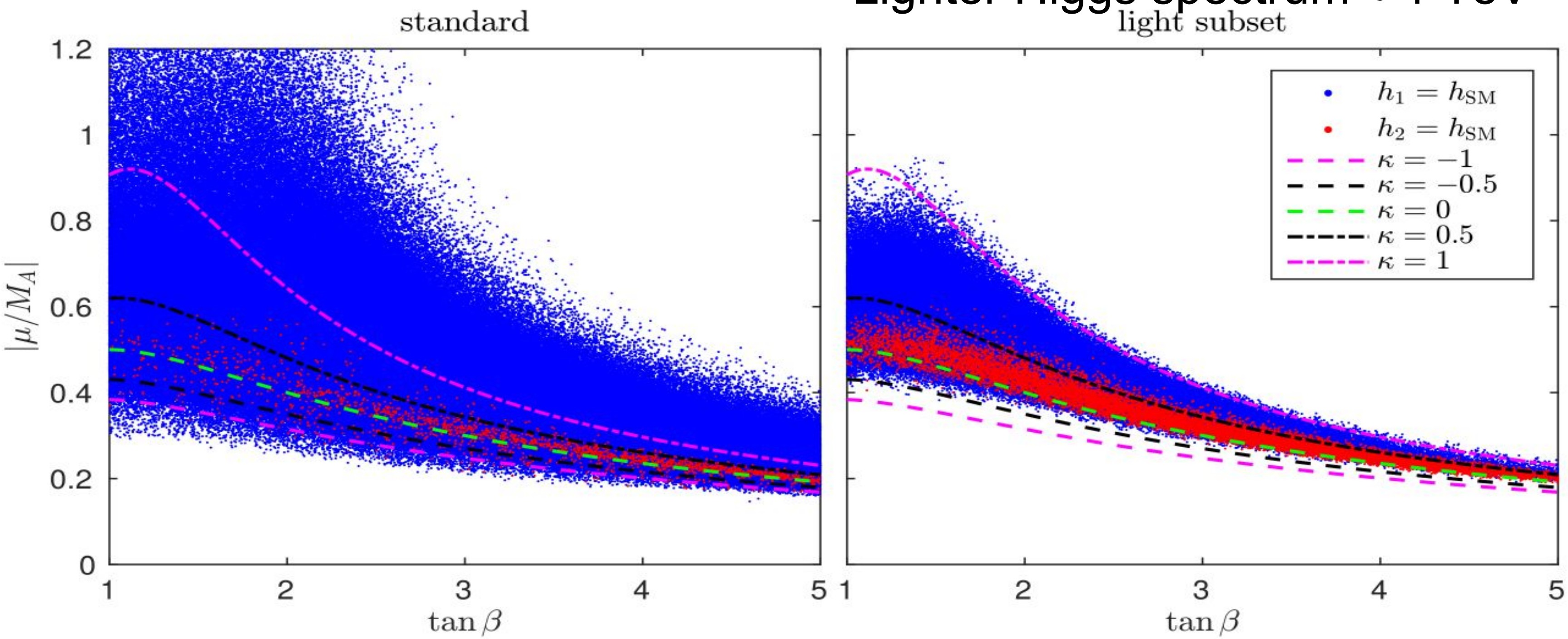
Heavier Higgs spectrum $\lesssim$ 3 TeV

Lighter Higgs spectrum $\lesssim$ 1 TeV

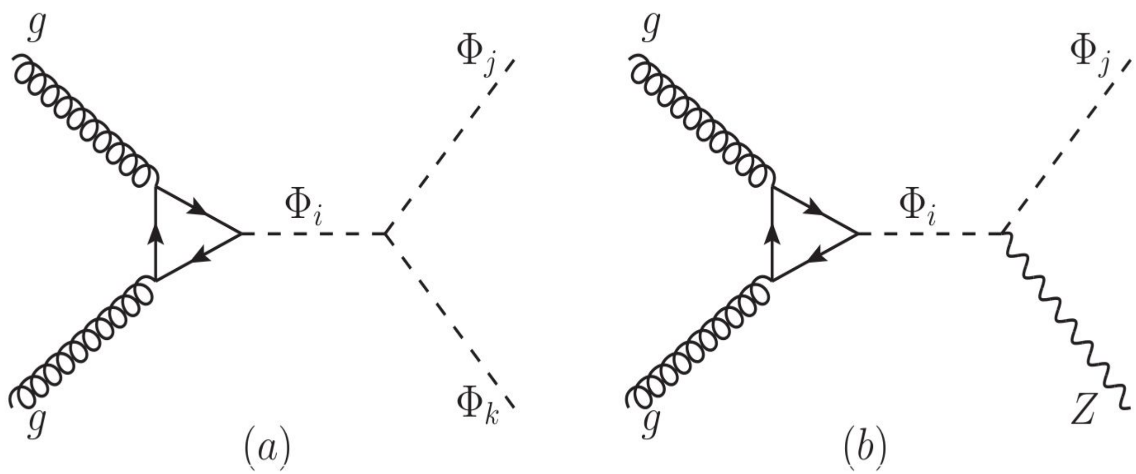


Conventional vs NMSSM specific Higgs searches

MSSM-like

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

NMSSM-specific:



Conventional Higgs searches

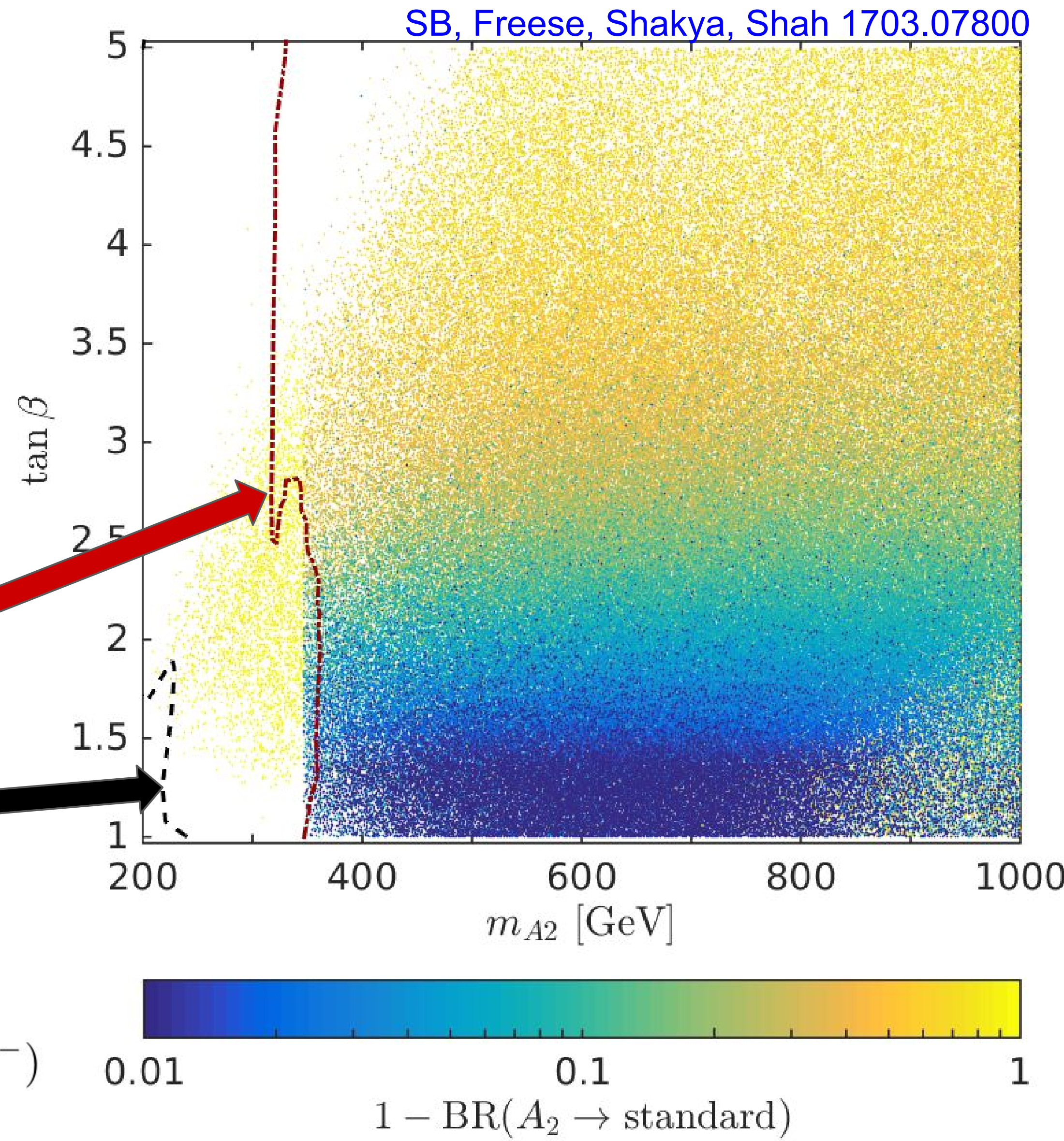
MSSM-like searches

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

8 TeV constraint on hMSSM

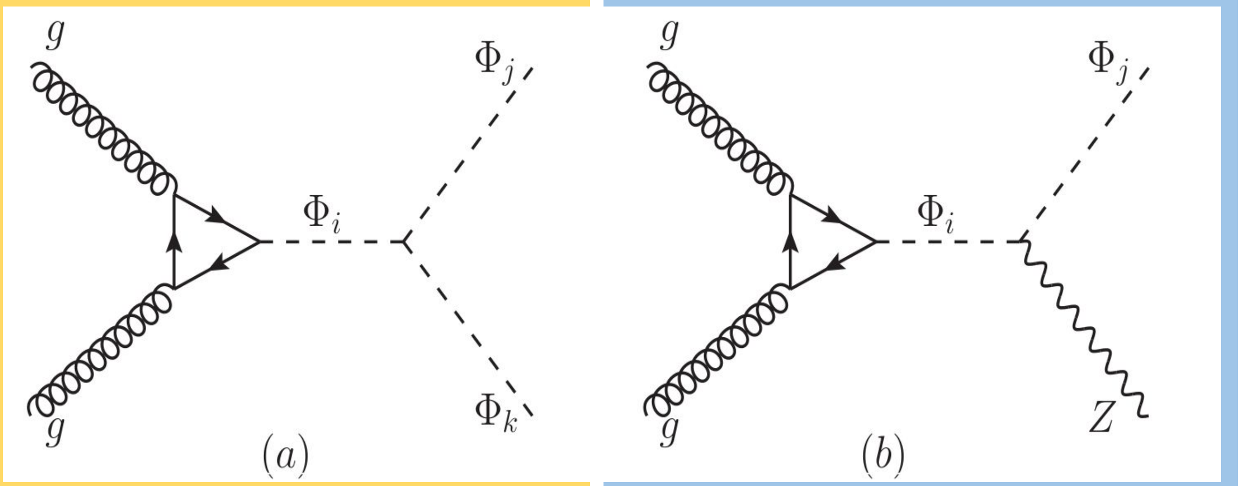
[CMS PAS-HIG-16-007]

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



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

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!

Visible final states, light h_i/A_1

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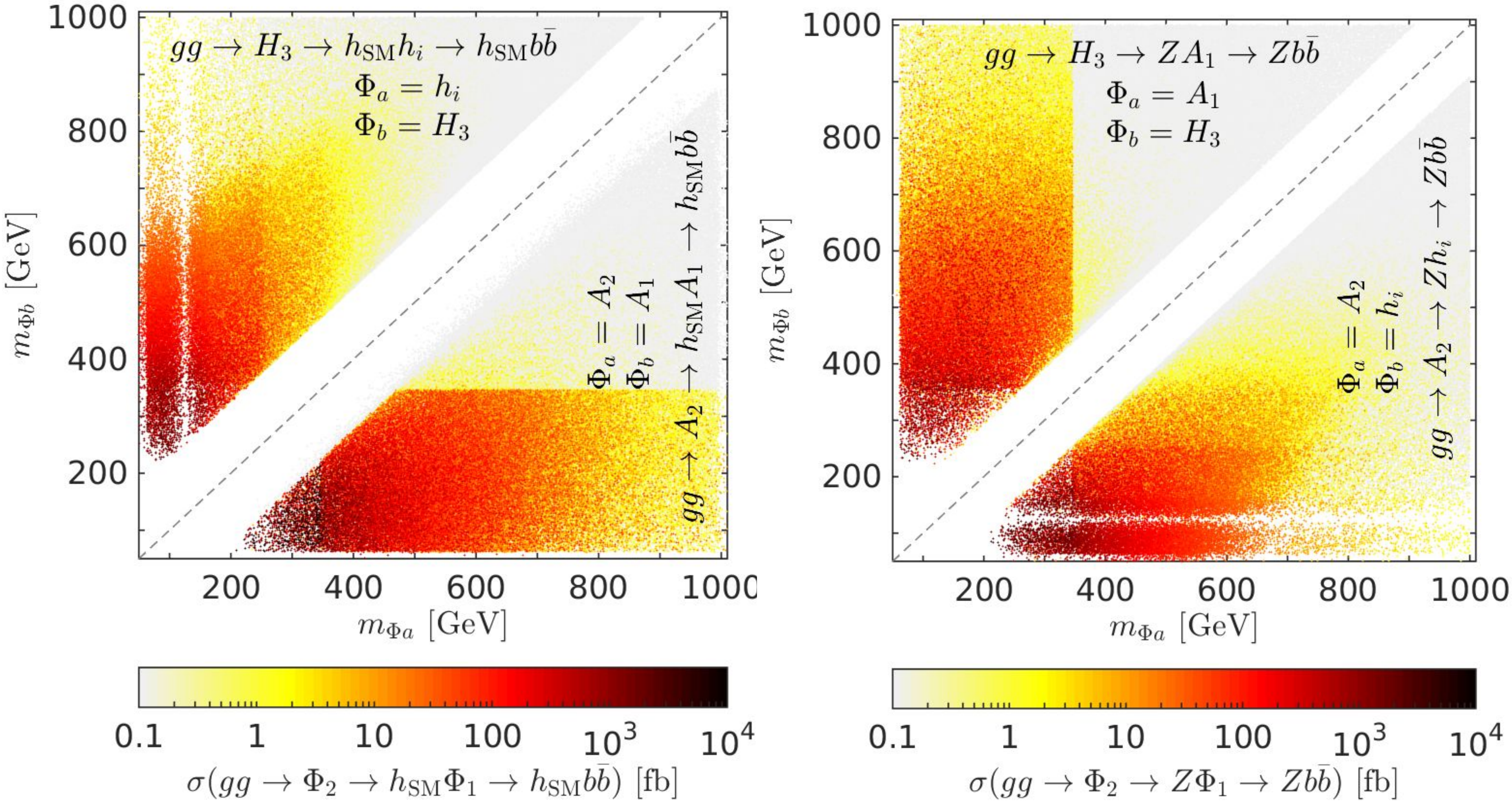

See also Ellwanger, Rodriguez-Vazquez 1707.08533

Invisible final states - mono-Higgs/mono-Z

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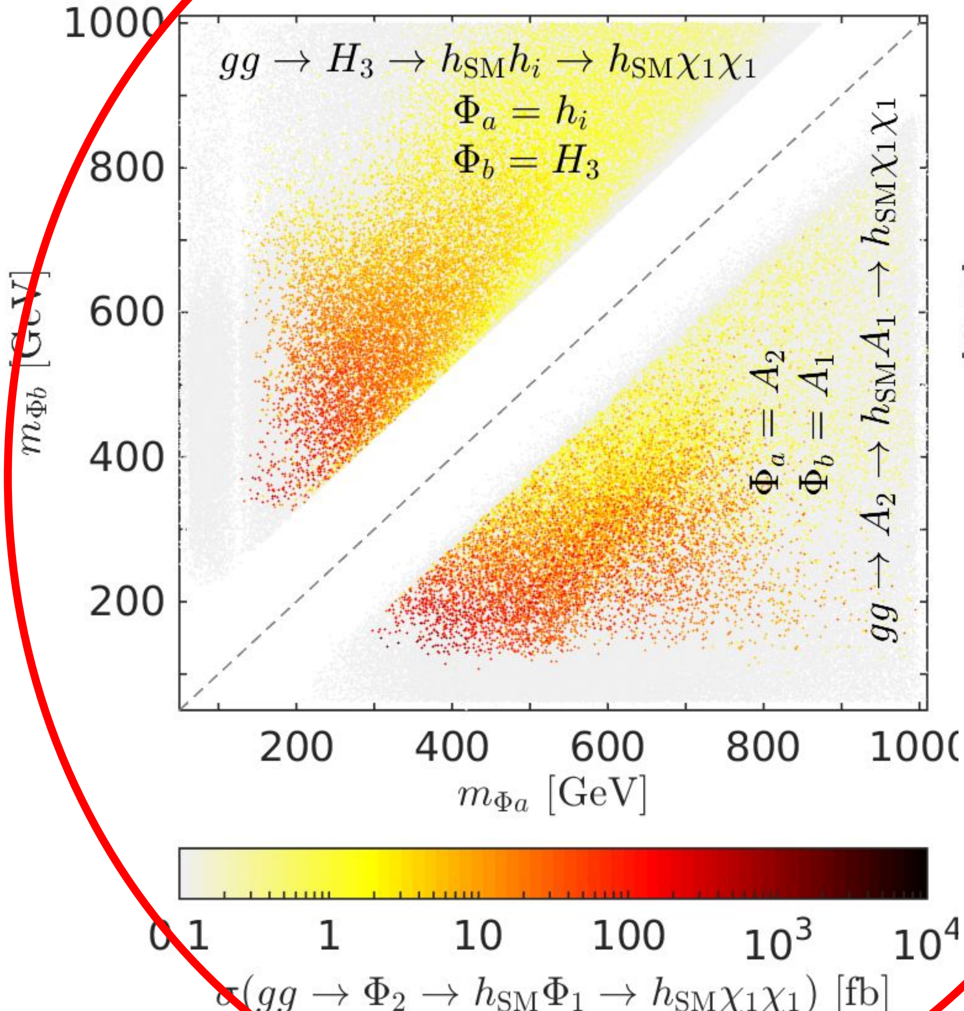

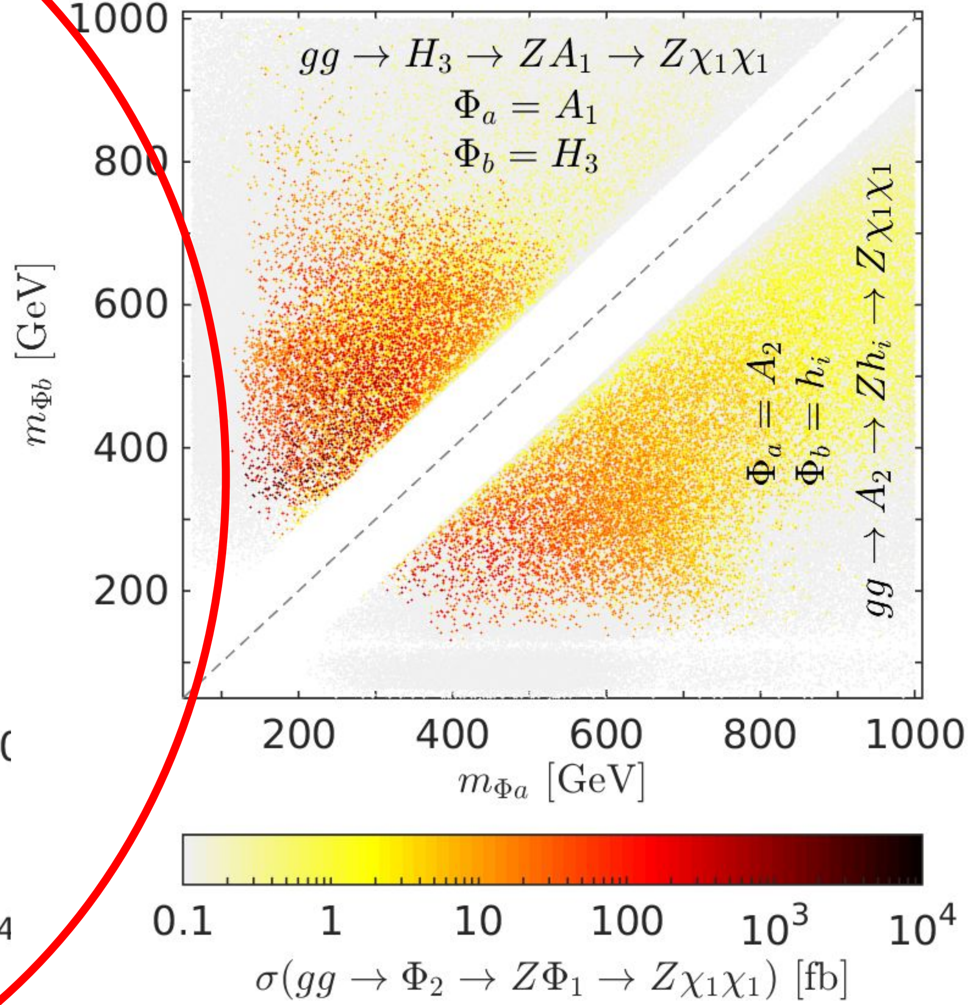

Mono-Higgs

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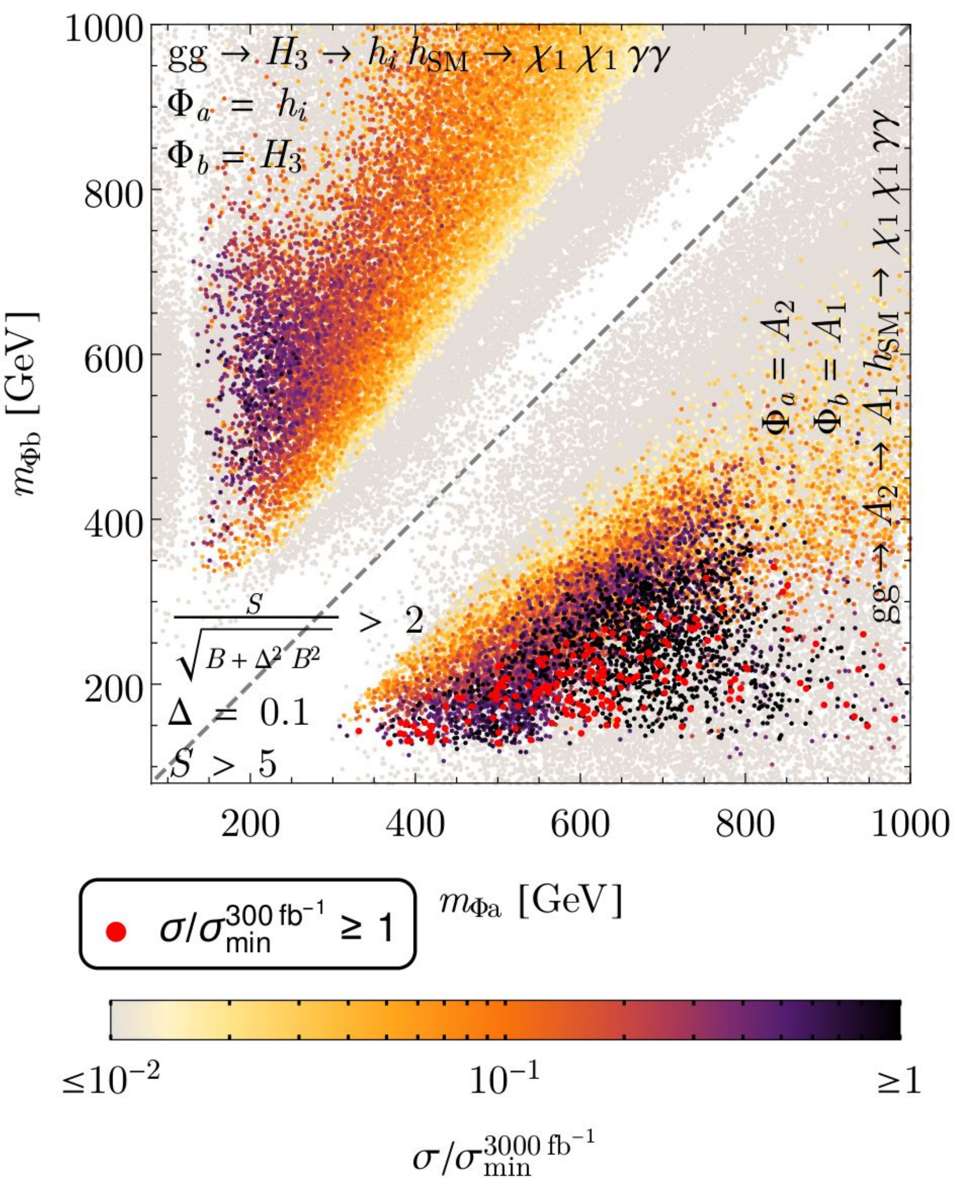

Mono-Higgs

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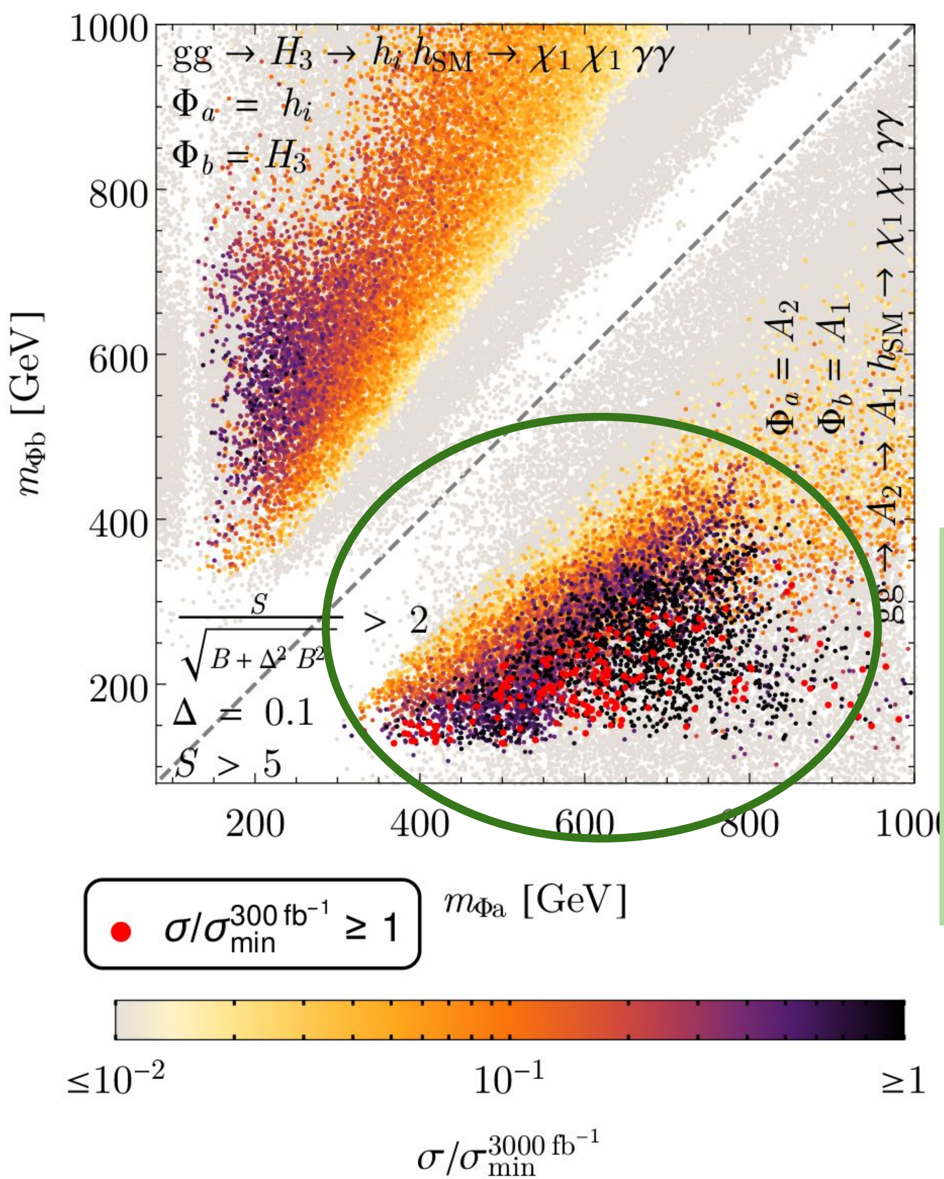


Since couplings are approximately fixed, reach is driven by mass spectrum

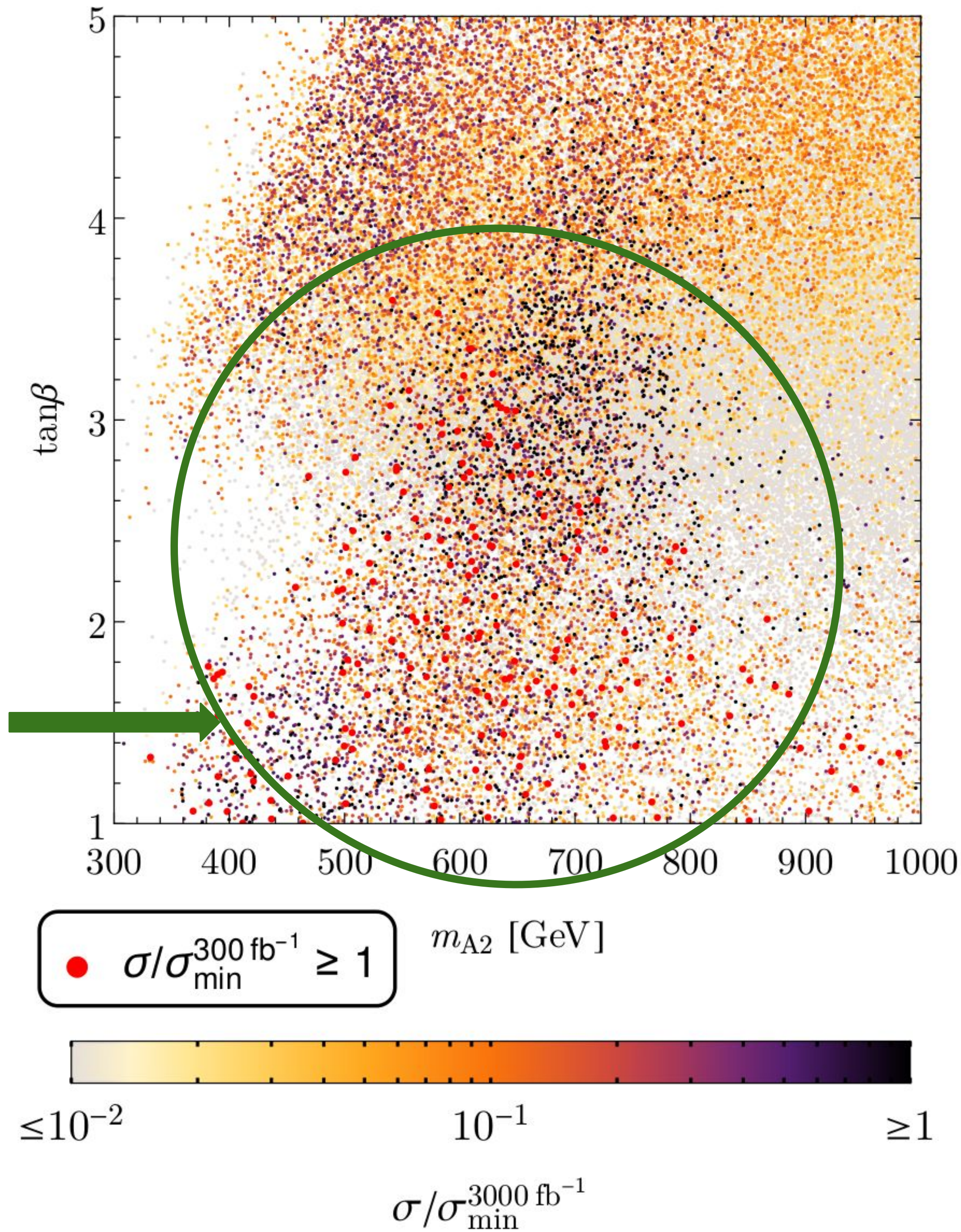
Most promising channel:

- 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

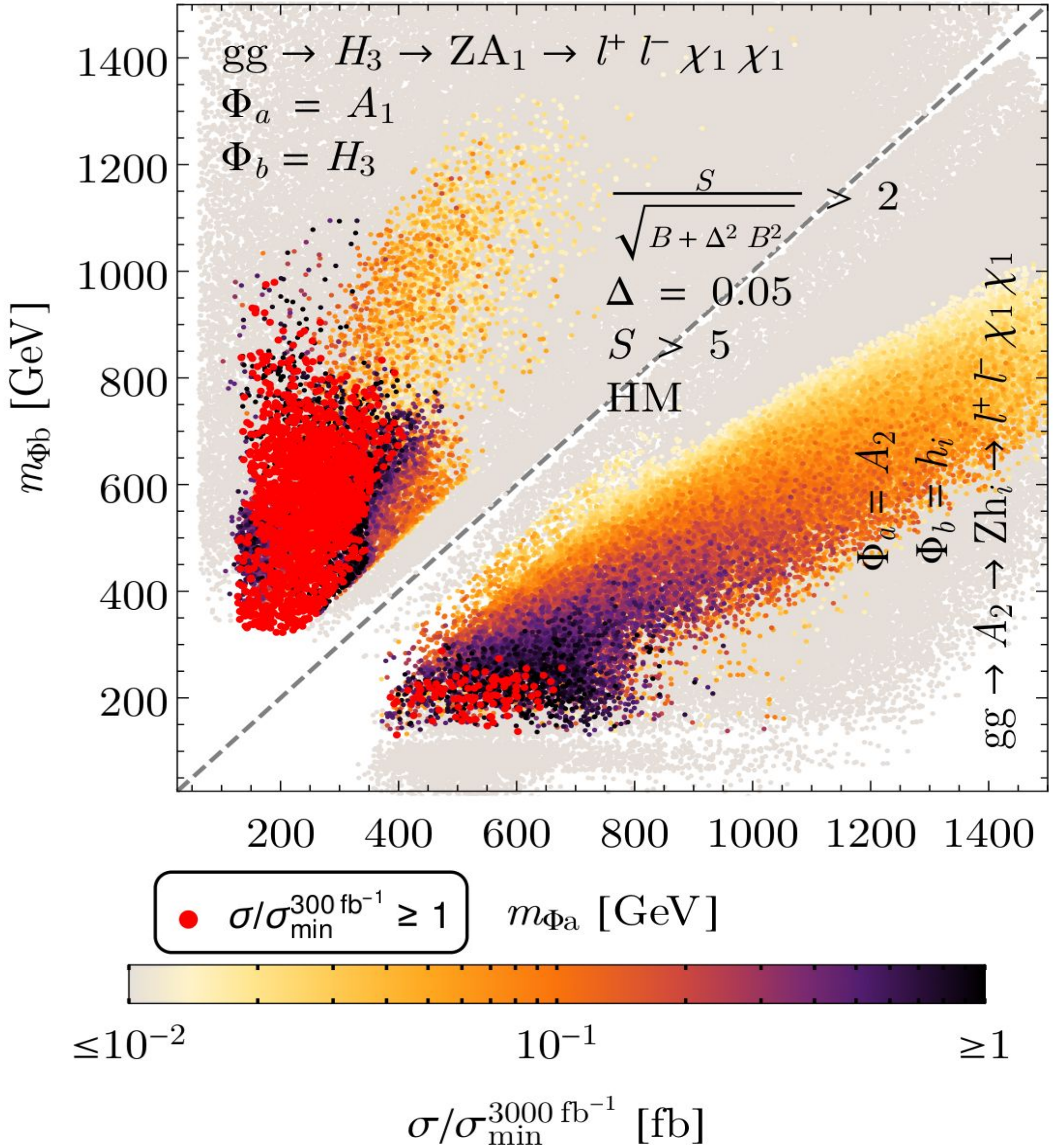
Combined reach of all mono-H channels:

- 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



Conclusions

- NMSSM motivated by μ-problem and 125 GeV Higgs
- presence of 125 GeV SM-like Higgs constrains NMSSM parameter space:
- Large NMSSM couplings λ & κ induce large Higgs-Higgs, Higgs-neutralino couplings, which warrants NMSSM specific search channels
- mono-Higgs and mono-Z are clean and powerful probes, probing the low tan β, large $m_{A_2} > 2m_t$ region, which is usually overwhelmed by $t\bar{t}$

Extra Slides

Higgs Basis

Rotate CP-even neutral Higgses to basis where

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

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

In this basis, the couplings to Standard Model particles are

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

← No coupling to gauge bosons

$$H^{\mathrm{SM}}(\mathrm{down}, \mathrm{up}, \mathrm{V}) = (g_{\mathrm{SM}}, \ g_{\mathrm{SM}}, \ g_{\mathrm{SM}})$$

← SM-like Higgs couplings

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

← No coupling to SM particles

Numerical Scan w/ NMSSMTools

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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

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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]
$A \to Zh_{\rm SM} \to Zb\bar{b}$	A_1, A_2	[88, 89]	[90]
$A \to Zh_{\rm SM} \to Z\tau^+\tau^-$	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]
$A/H \to Zh_i/A_1$	$A_2/H_3,\ h_i/A_1$	[93]	–

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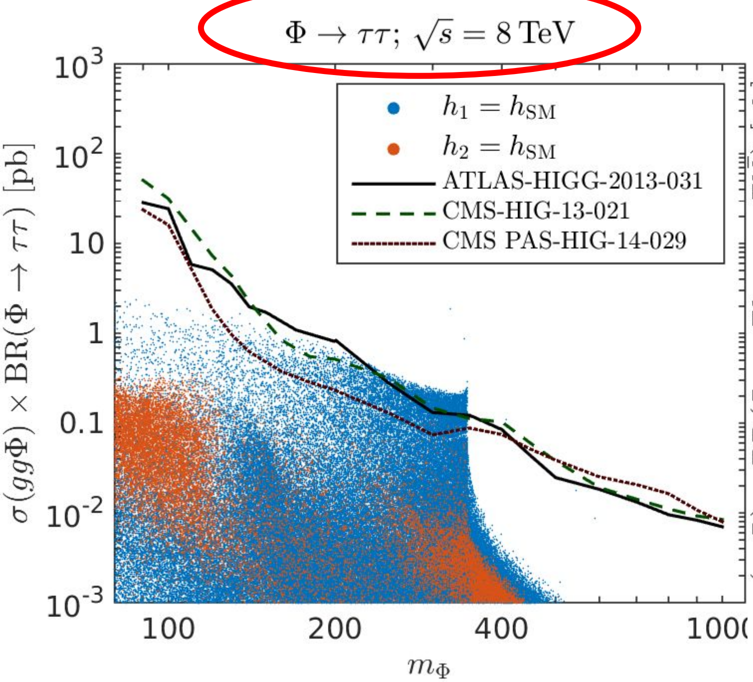
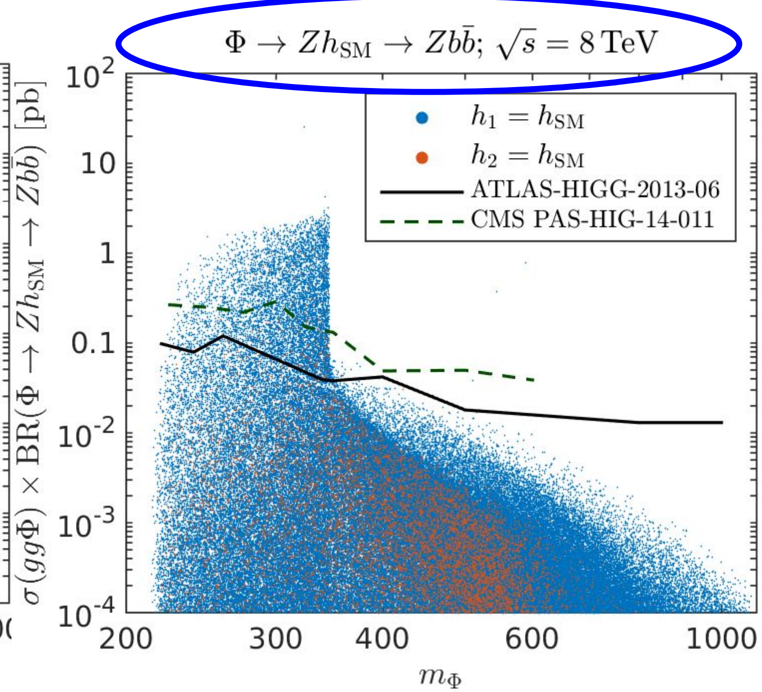
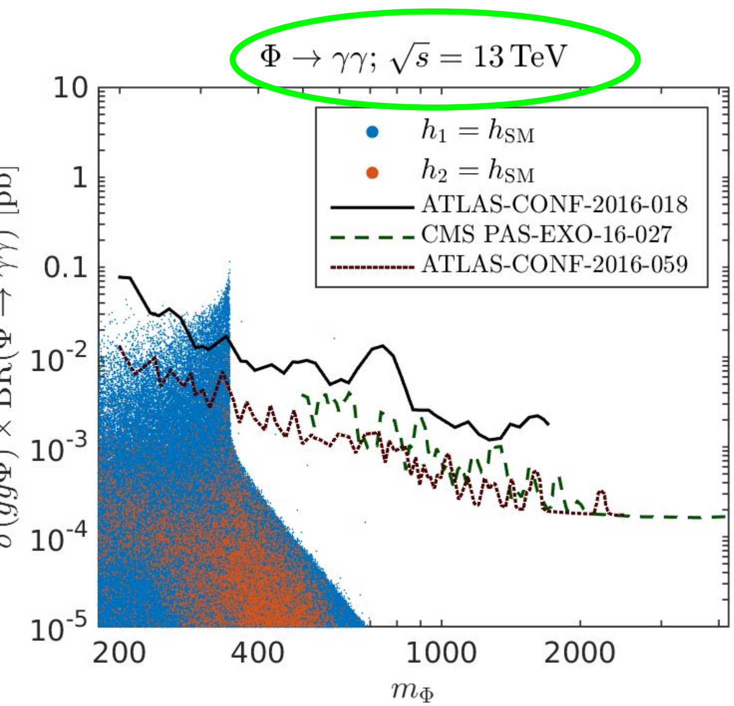
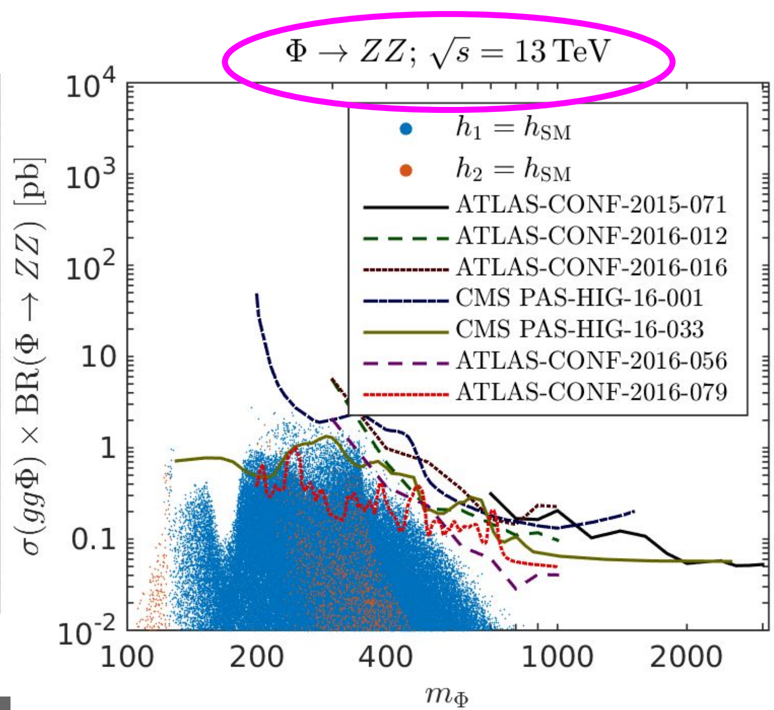




decay channel
$H \to \tau^+\tau^-$
$H \to b\bar{b}$
$H \to \gamma\gamma$
$H \to ZZ$
$H \to WW$
$H \to h_{SM}h_{SM} \to b\bar{b}\tau^+\tau^-$
$H \to h_{SM}h_{SM} \to b\bar{b}\ell\nu_\ell\ell\nu_\ell$
$H \to h_{SM}h_{SM} \to b\bar{b}b\bar{b}$
$H \to h_{SM}h_{SM} \to b\bar{b}\gamma\gamma$
$A \to Zh_{SM}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





Visible final states, light h_i/A_1

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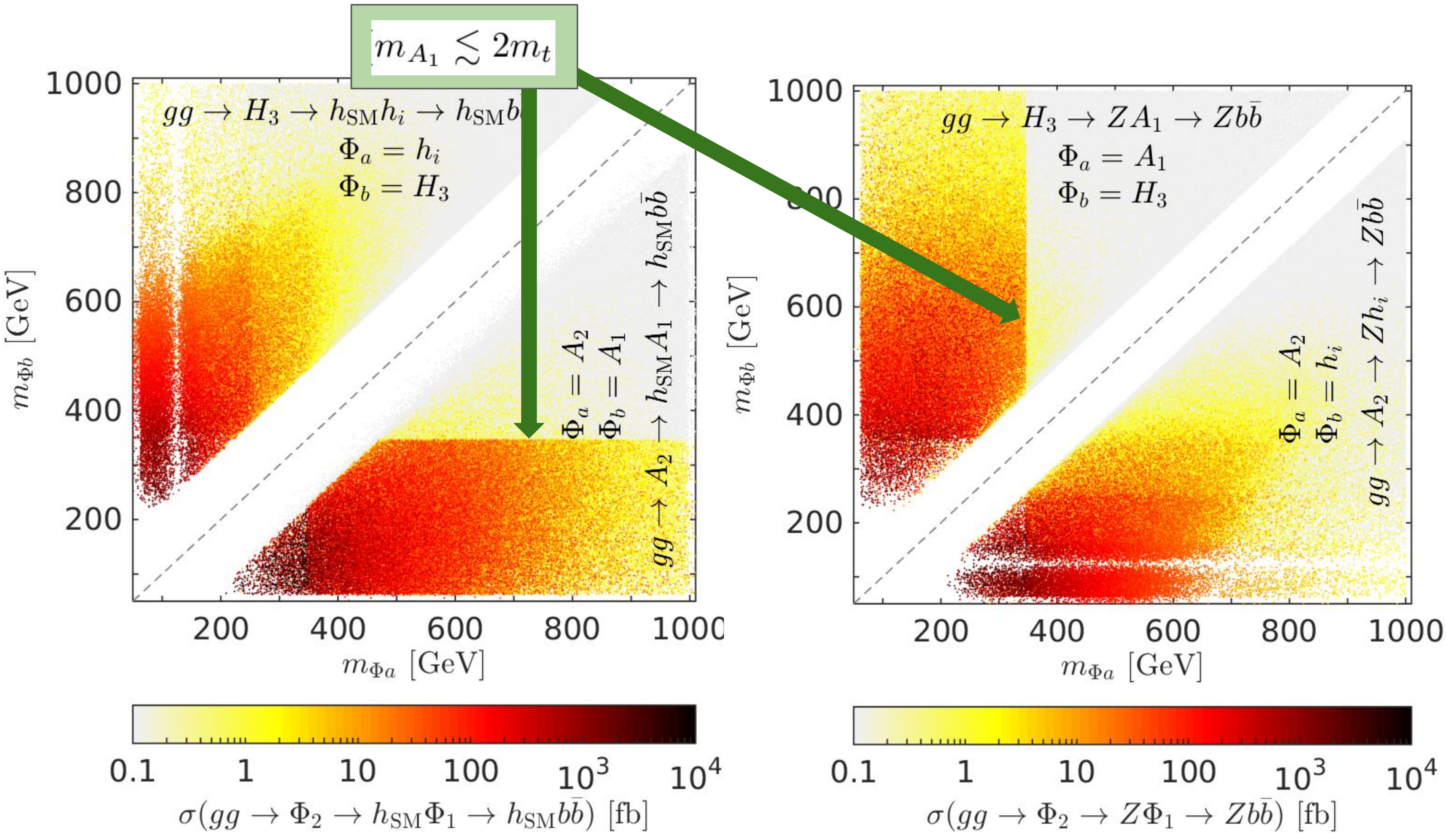

Visible final states, light h_i/A_1

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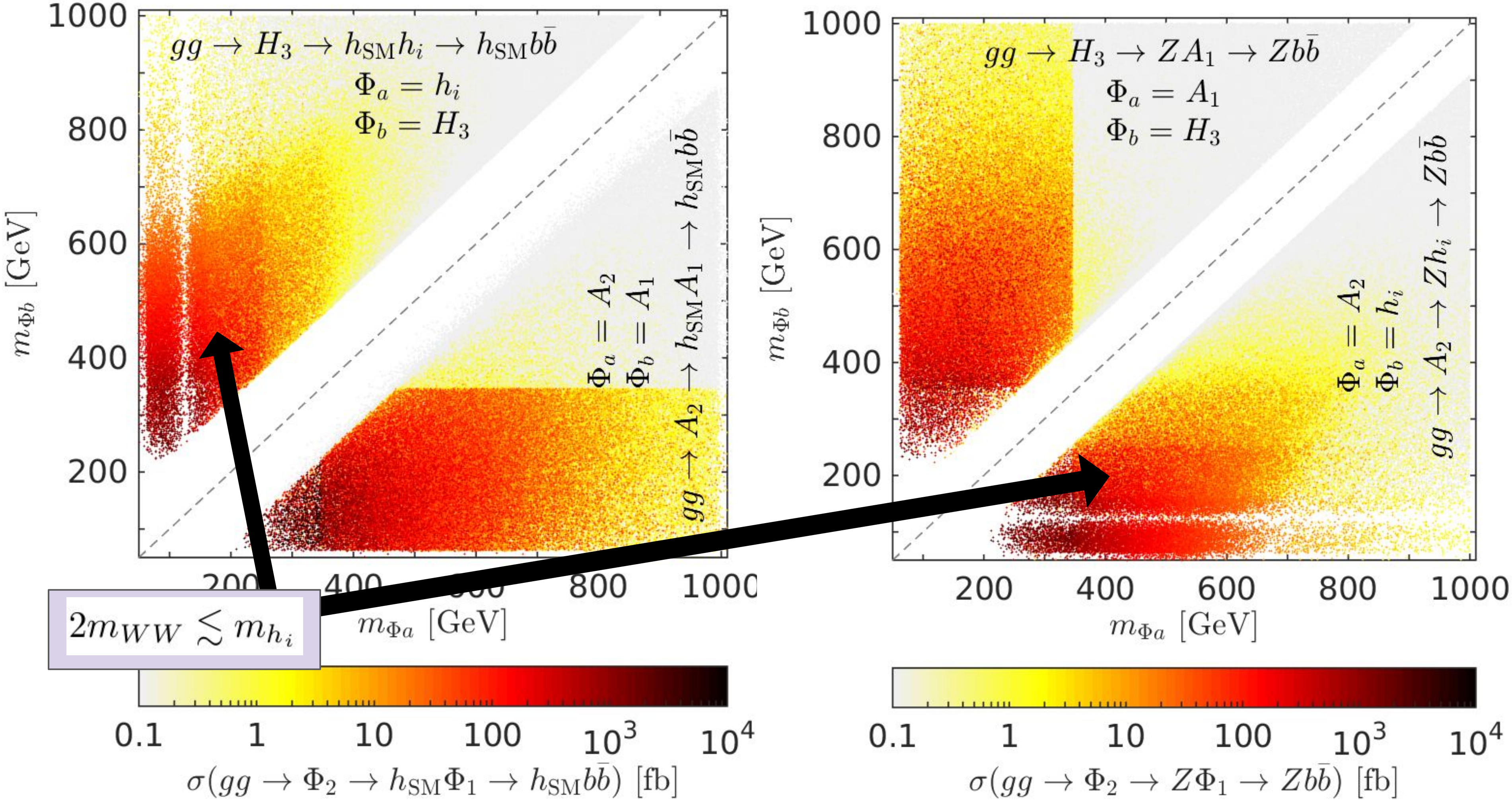

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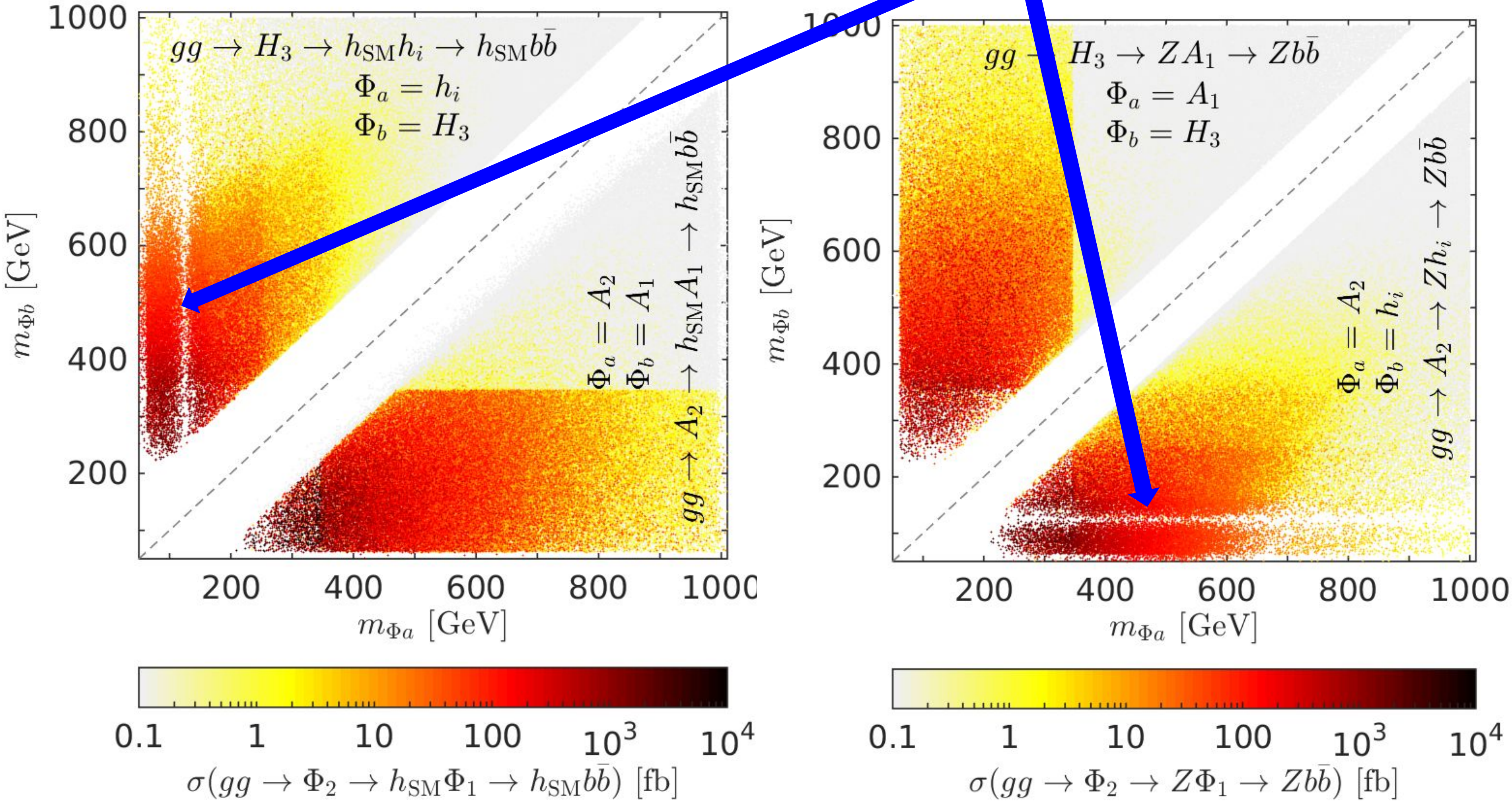
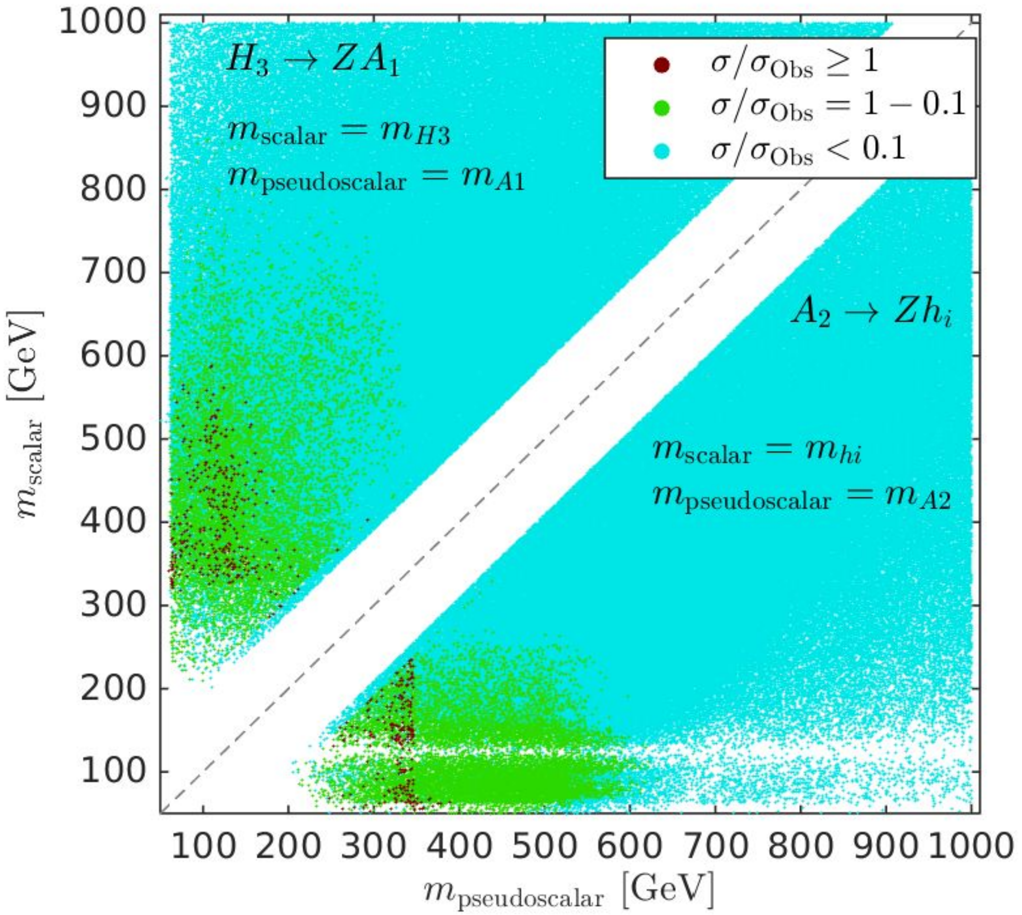
Visible final states, light h_i/A_1

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)



mono-Higgs reach

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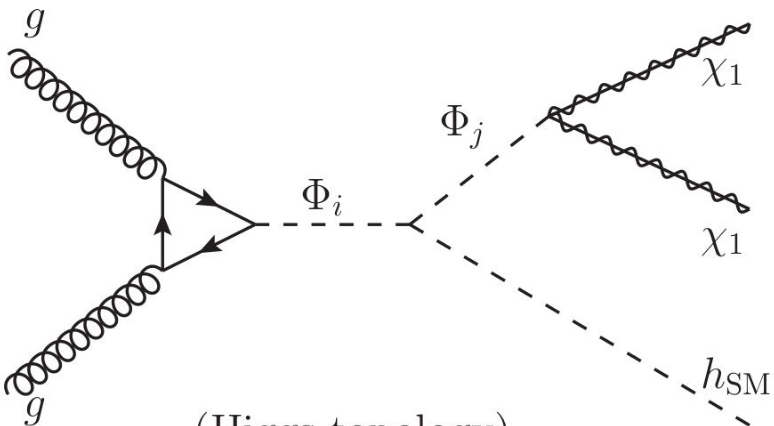
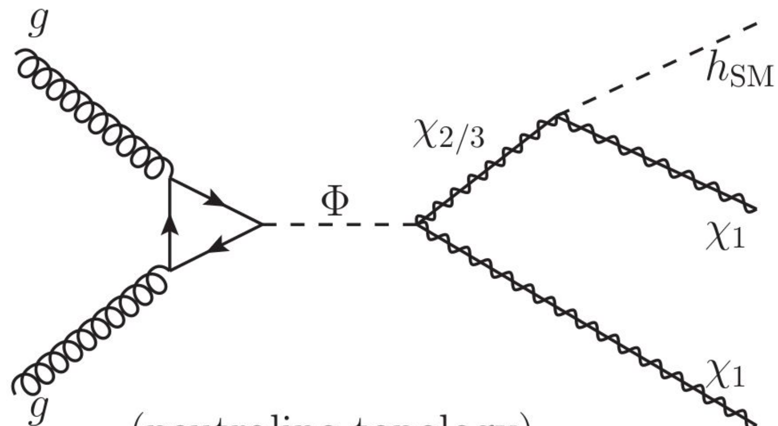


(Higgs topology)



(neutralino topology)

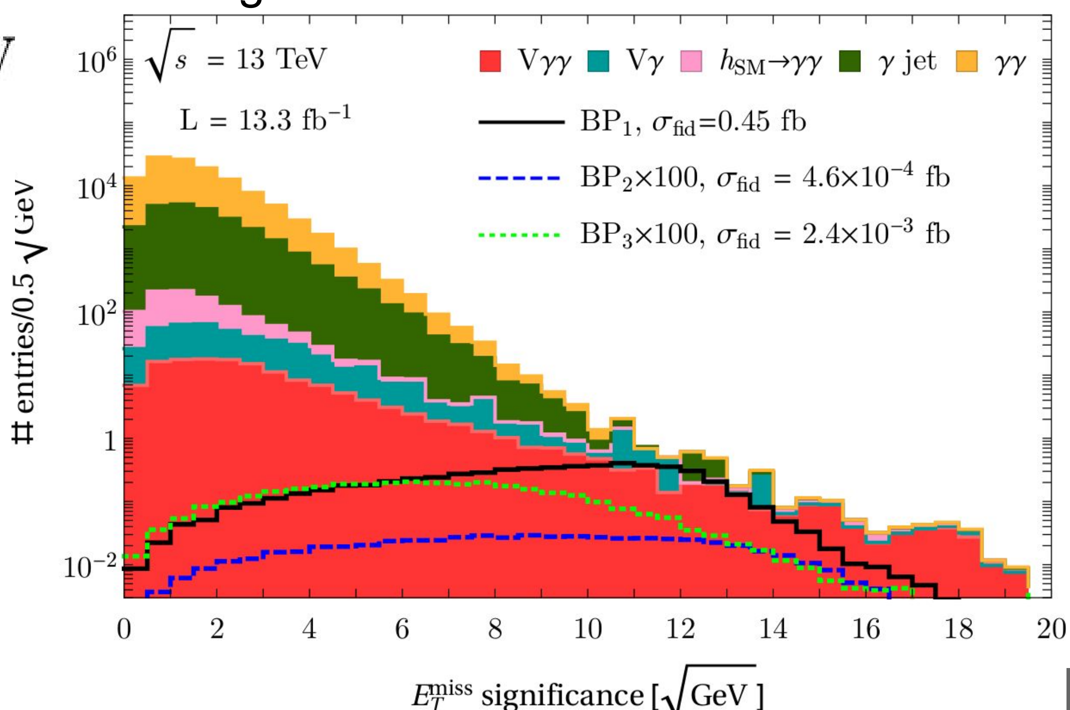
Background separation:

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

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

well measure objects and
less background

Background from ATLAS-CONF-2017-087



Higgs topology

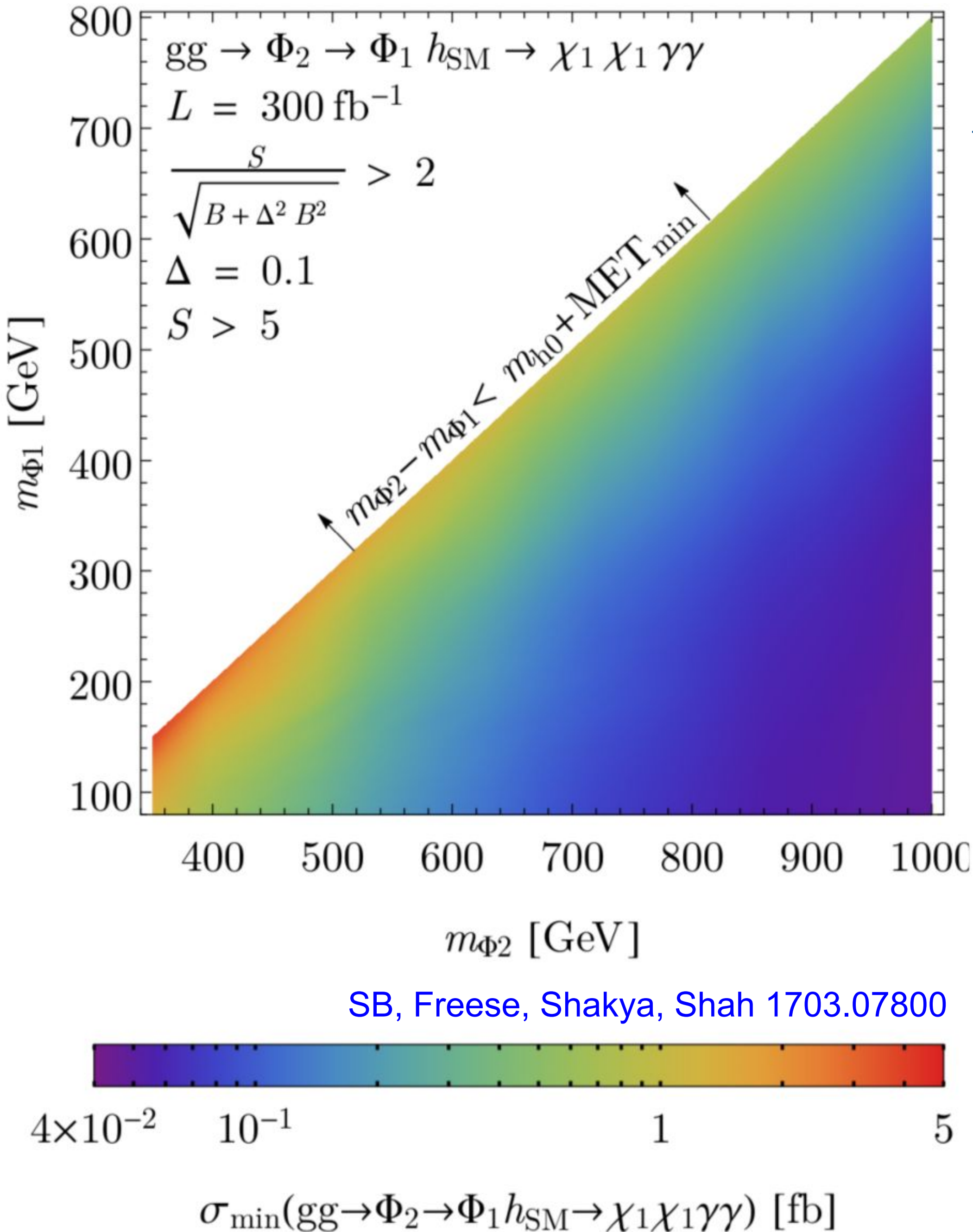
Optimize E_T^{miss} cut for each point

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

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

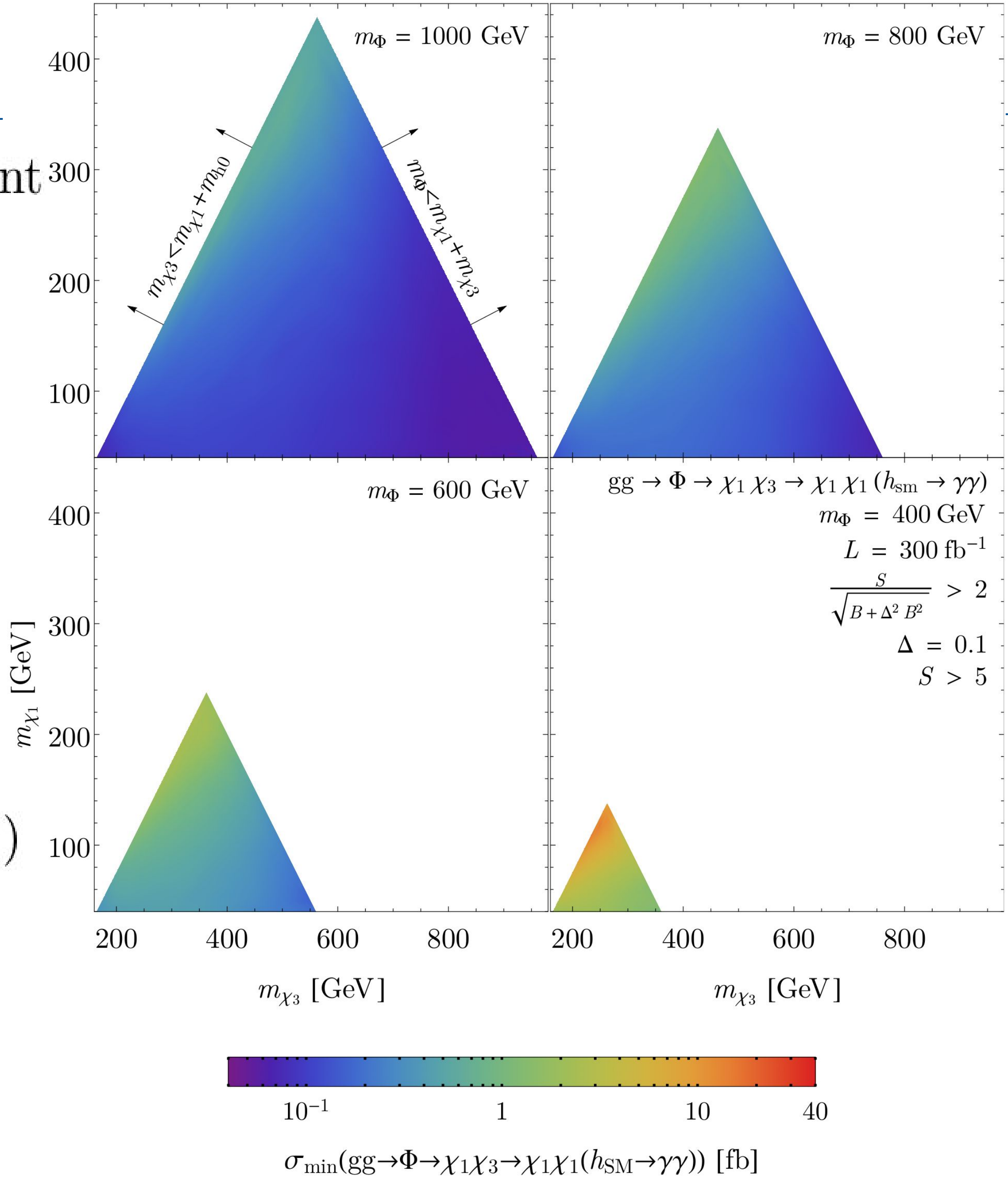
Optimize $E_T^{\rm miss}$ cut for each point

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

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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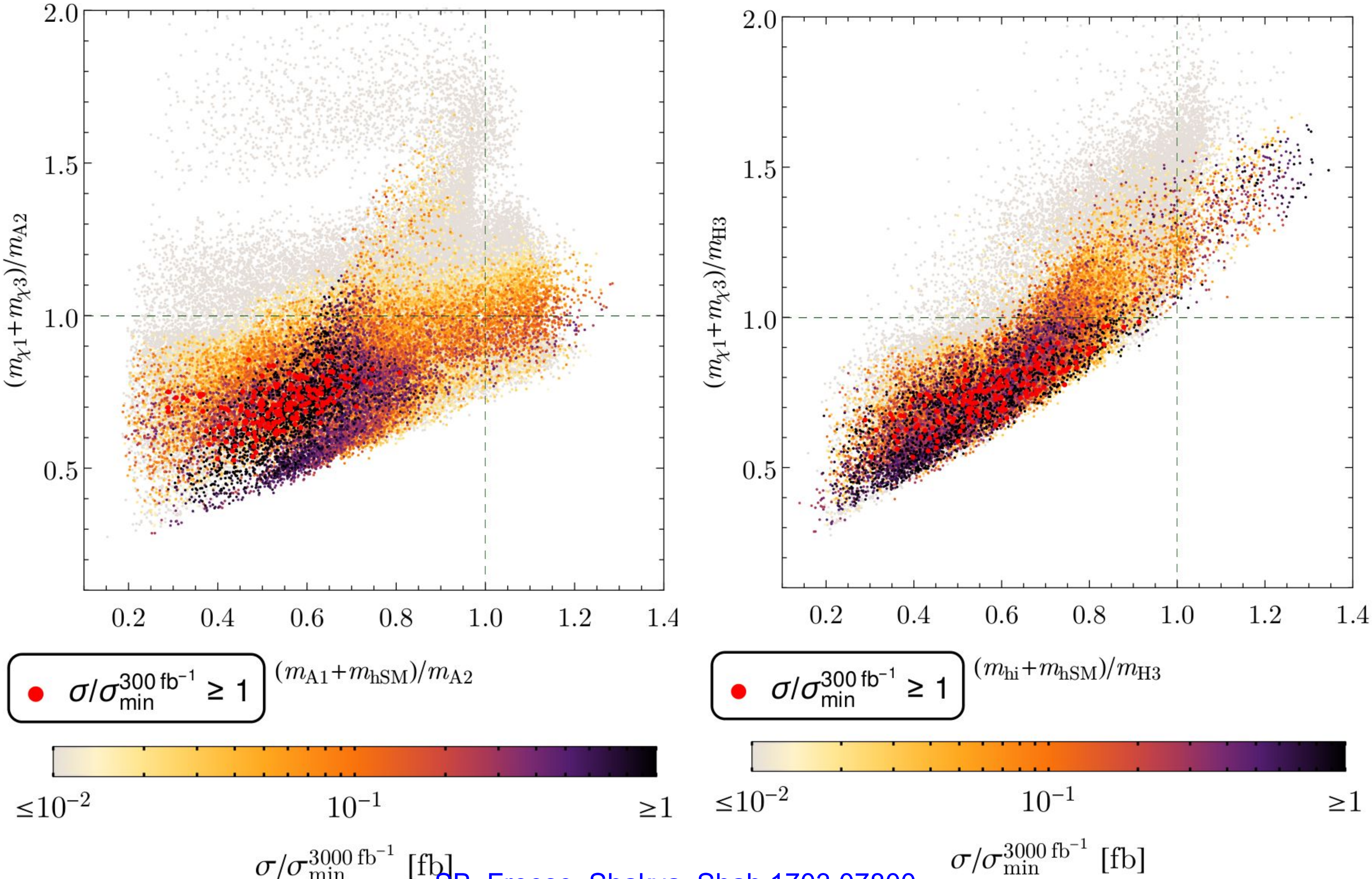
NMSSM Interpretation: mass splittings



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