THE Higgs and *more* Higgs,

2HDM + a complex S:
Making Sense out of Chaos

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Where to Start?

BSM Higgs Sector?

2 Higgs Doublet + Singlet

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2HDM: SUSY

S: SUSY + EWPT + DM + flavor…

Where to Start?

BSM Higgs Sector	Dark Matter?
2 Higgs Doublet + Singlet	**Singlet Fermion**

Where to Start?

BSM Higgs Sector	Dark Matter
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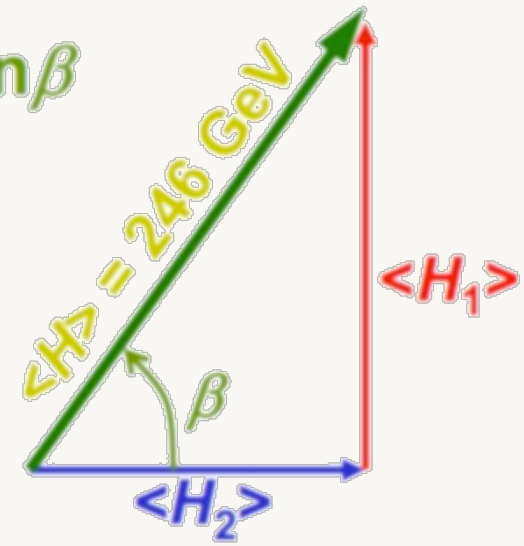
Simplified Model, EFT, SUSY (NMSSM)…

2 Higgs Doublet Model (2HDM).

$\langle H_1 \rangle$, $\langle H_2 \rangle$ → $\langle H \rangle$, $\tan\beta$



2 Higgs doublets (Type II):

$\mathbf{H_u}$ – Couples only to up-type quarks

$\mathbf{H_d}$ – Couples only to down-type quarks and leptons.

$$m_A \sim m_H$$

$$\tan\beta = v_u/v_d$$

5 Physical Higgs bosons:

CP-Even: **h, H**

CP-Odd: **A**

Charged Higgs: $\mathbf{H^{+,-}}$

SM-Like Higgs.

$v \sin^2 \beta$

$$H_{SM} = \sin\beta H_u + \cos\beta H_d$$

$v \cos^2 \beta$

$$H_{NSM} = -\cos\beta H_u + \sin\beta H_d$$

SM: Only 1 Higgs which then acquires a vev and leads to EWSB.

This is what we want!

Lighter (*h*) is 125 GeV SM-like Higgs.

Additional states can exist!

Additional States can be light!

Haber and Gunion, '03, M. Carena, I. Low, N.R.S. & C. Wagner, '13, A. Delgado, G. Nardini & M. Quiros, '13, N. Craig, J. Galloway & S. Thomas, '13, P. Dev, A. Pilaftsis '14, M. Carena, H. Haber, I. Low, N.R.S. & C. Wagner '14 & '15 etc ....

$\langle H_d \rangle = v \cos\beta$

$\langle H_u \rangle = v \sin\beta$

$\Rightarrow \langle h_{125} \rangle = v$

$\langle H \rangle = 0$

SM-like HIGGS

ALIGNMENT

- Interaction basis: (H_u, H_d, S)
  - H_u: Couples only to up-type fermions
  - H_d: Couples only to down-type fermions
  - S: Only couples to Higgs

$\langle H_u \rangle = v_u$
$\langle H_d \rangle = v_d$
$t_\beta = v_u/v_d$
$\langle S \rangle = \mu/\lambda$

CP-Even Higgs Bases

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- "Extended" Higgs basis: (H_{NSM}, H_{SM}, S)
  - H_{NSM}: (down, up, V) = $(y_d\, t_\beta,\ y_u/\, t_\beta,\ 0)$
  - H_{SM}: (down, up, V) = $(y_d,\ y_u,\ g_{hVV})$

Only SM state couples to WW or ZZ!!

$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

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$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

- Mass basis: (H^3, H^2, H^1)

$$-H^i = \kappa^i_{NSM}\, H_{NSM} + \kappa^i_{SM}\, H_{SM} + \kappa^i_S\, S$$

CP-Even Higgs Bases

- Interaction basis: (H_u, H_d, S)
  - H_u: Couples only to up-type fermions
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$\langle H_{NSM} \rangle = 0$
$\langle H_{SM} \rangle = v$

- Mass basis: $(H^3, H^2, H^1) \longrightarrow (H, h125, h)$

$$-H^i = \kappa^i_{NSM}\, H_{NSM} + \kappa^i_{SM}\, H_{SM} + \kappa^i_S\, S$$

CP-Even Higgs Bases

Higgs Potential?

- Higgs potential dictates Higgs interactions relevant for collider pheno.
- Arbitrary: 27 parameters!!

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15
S. Baum & N.R.S., '18

$$
\begin{aligned}
\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + Y_4 S^\dagger S \\
& + \left[C_1 H_1^\dagger H_1 S + C_2 H_2^\dagger H_2 S + C_3 H_1^\dagger H_2 S + C_4 H_2^\dagger H_1 S + C_5 (S^\dagger S) S + C_6 S^3 + \text{h.c.}\right] \\
& + \tfrac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \tfrac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) \\
& \qquad + \left\{ \tfrac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left[Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)\right] H_1^\dagger H_2 + \text{h.c.} \right\} \qquad \text{(A1)} \\
& + S^\dagger S \left[Z_{s1} H_1^\dagger H_1 + Z_{s2} H_2^\dagger H_2 + (Z_{s3} H_1^\dagger H_2 + \text{h.c.}) + Z_{s4} S^\dagger S\right] \\
& + \left\{ Z_{s5} H_1^\dagger H_1 S^2 + Z_{s6} H_2^\dagger H_2 S^2 + Z_{s7} H_1^\dagger H_2 S^2 + Z_{s8} H_2^\dagger H_1 S^2 + Z_{s9} S^\dagger S\, S^2 + Z_{s10} S^4 + \text{h.c.} \right\}.
\end{aligned}
$$

h_{125} to the Rescue!

- Many parameters related to entries of the mass matrices.
- Certain trilinear couplings suppressed by SM-like nature of h_{125} (alignment), for e.g:

$$\{g_{H^{\rm SM}H^{\rm SM}H^{\rm NSM}}, \quad g_{H^{\rm SM}H^{\rm SM}H^{\rm S}}\} \to 0$$

- Any additional scalar H decays to VV and h_{125} h_{125} BOTH suppressed by non-SM components of h_{125}!

Physical Higgs Parameters

- Re-parameterize 27 parameters of Higgs potential: more physically meaningful

known!

$$m_{h_{125}}\,,\quad m_H\,,\quad m_h\,,\quad m_A\,,\quad m_a\,,$$

~ Degenerate!

$$S^{\rm NSM}_{h_{125}}\,,\quad S^{\rm S}_{h_{125}}\,,\quad S^{\rm S}_H\,,\quad P^{\rm S}_A\,;$$

Small!

$$v\,,\quad \tan\beta\,,\quad v_S\,;$$

$$m_{H^\pm}\,;$$

~O(vevs)

$$\{g_{H^{\rm SM}H^{\rm NSM}H^{\rm NSM}},\quad g_{H^{\rm SM}H^{\rm S}H^{\rm S}},\quad g_{H^{\rm SM}A^{\rm S}A^{\rm S}}\},$$

$$\{g_{H^{\rm NSM}H^{\rm NSM}H^{\rm NSM}},\quad g_{H^{\rm NSM}H^{\rm NSM}H^{\rm S}},\quad \underline{g_{H^{\rm NSM}H^{\rm S}H^{\rm S}},\quad g_{H^{\rm NSM}A^{\rm S}A^{\rm S}}}\},$$

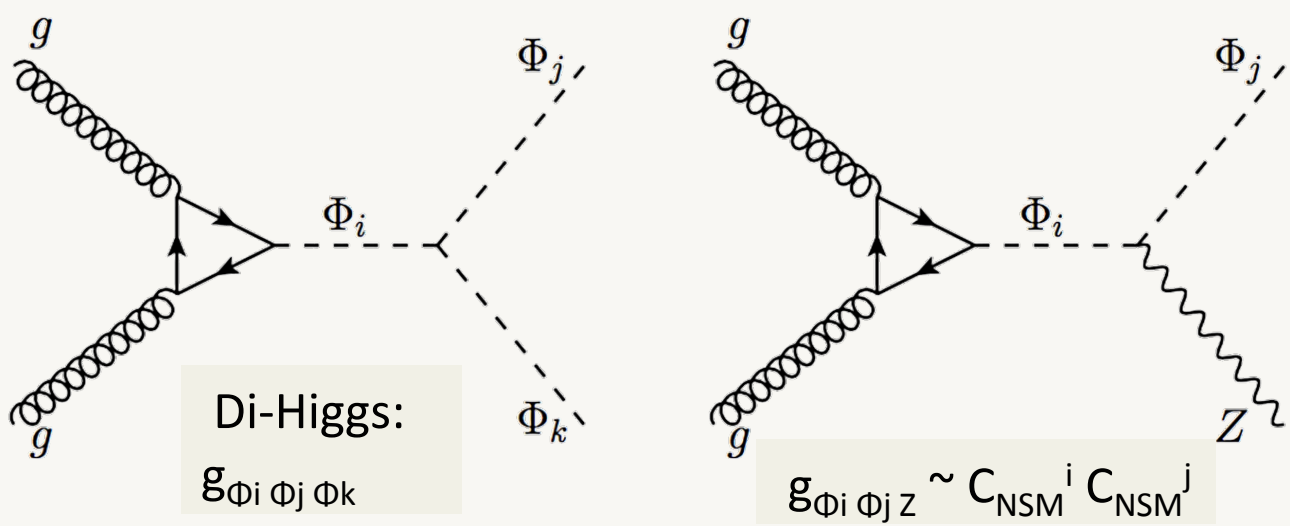
$$\{g_{H^{\rm S}H^{\rm S}H^{\rm S}},\quad \underline{g_{H^{\rm S}A^{\rm NSM}A^{\rm S}}},\quad g_{H^{\rm S}A^{\rm S}A^{\rm S}}\}\,.$$

$$\{\lambda_{H^{\rm NSM}H^{\rm NSM}H^{\rm S}H^{\rm S}},\quad \lambda_{H^{\rm NSM}H^{\rm NSM}A^{\rm S}A^{\rm S}},\quad \lambda_{H^{\rm S}H^{\rm S}A^{\rm S}A^{\rm S}},\quad \lambda_{A^{\rm S}A^{\rm S}A^{\rm S}A^{\rm S}}\}.$$

LHC ?

- Interesting cascade decays due to presence of additional Higgs bosons:
  - Eg: $H_{NSM} \rightarrow h\, H_{SM}$ or $H_{NSM} \rightarrow a\, Z$

$H_{NSM} \rightarrow H_{SM}\, H_{SM}$ or $A \rightarrow Z\, H_{SM}$ suppressed due to alignment



S. Baum & N.R.S., '18

Decay Widths

$$\Gamma(h_i \to ZZ) = \frac{\left(S_{h_i}^{\rm SM}\right)^2 m_Z^4}{16\pi m_{h_i} v^2}\left(3 - \frac{m_{h_i}^2}{m_Z^2} + \frac{m_{h_i}^4}{4m_Z^4}\right)\sqrt{1 - 4\frac{m_Z^2}{m_{h_i}^2}}\,,$$

$$\Gamma(h_i \to W^+W^-) = \frac{\left(S_{h_i}^{\rm SM}\right)^2 m_W^4}{8\pi m_{h_i} v^2}\left(3 - \frac{m_{h_i}^2}{m_W^2} + \frac{m_{h_i}^4}{4m_W^4}\right)\sqrt{1 - 4\frac{m_W^2}{m_{h_i}^2}}\,,$$

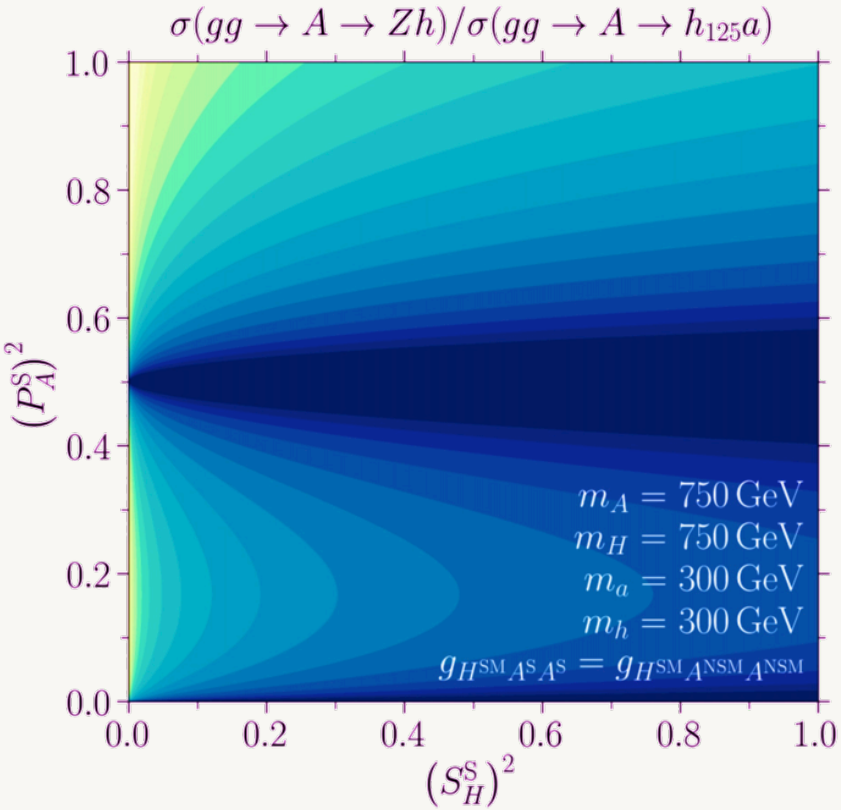
$$\Gamma(\Phi_i \to f\bar{f}) = \frac{N_c^f}{16\pi}\frac{m_f^2}{v^2} m_\Phi \left(1 - 4\frac{m_f^2}{m_{\Phi_i}^2}\right)^\gamma \times \begin{cases} \left(C_\Phi^{\rm SM} - C_\Phi^{\rm NSM}/\tan\beta\right)^2 & , \text{ for up} - \text{type quarks } f\,, \\ \left(C_\Phi^{\rm SM} + C_\Phi^{\rm NSM} \times \tan\beta\right)^2 & , \text{ for down} - \text{type quarks and leptons } f \end{cases}$$

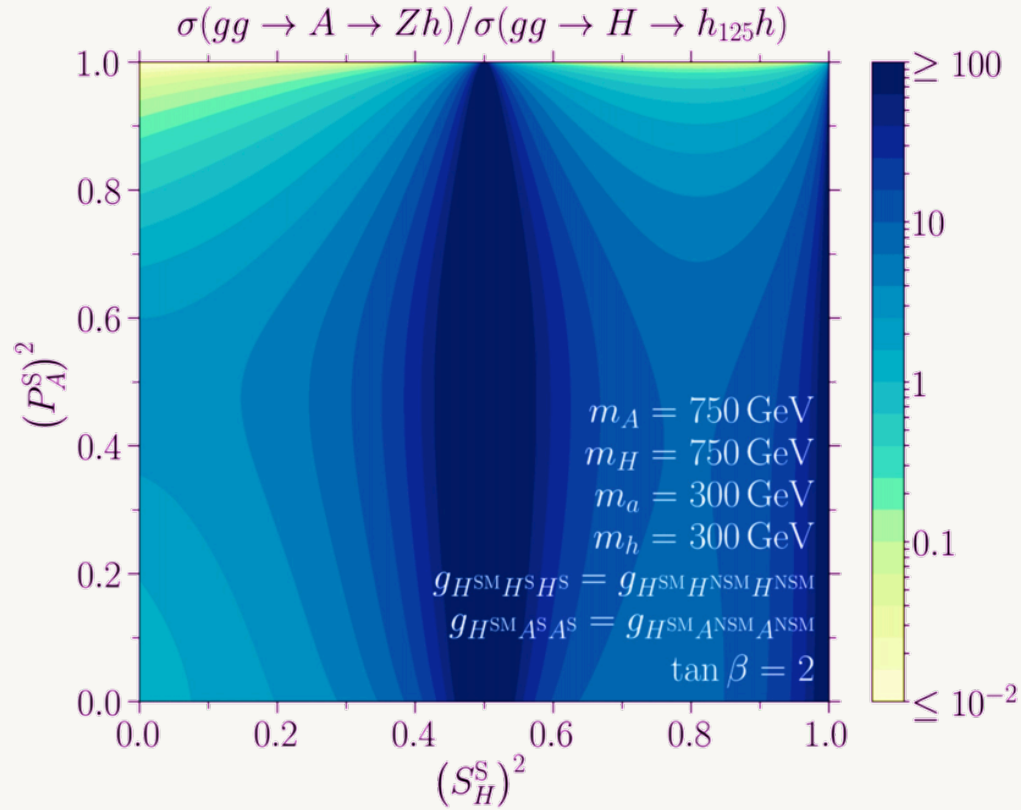
$$\Gamma\left(\Phi_i \to \Phi_j\Phi_k\right) = \frac{g_{\Phi_i\Phi_j\Phi_k}^2}{16\pi m_{\Phi_i}}\left(\frac{1}{1+\delta_{jk}}\right)\sqrt{1 - 2\frac{m_{\Phi_j}^2 + m_{\Phi_k}^2}{m_{\Phi_i}^2} + \frac{\left(m_{\Phi_j}^2 - m_{\Phi_k}^2\right)^2}{m_{\Phi_i}^4}}$$

$$\Gamma(\Phi_i \to Z\Phi_j) = \frac{\left(C_{\Phi_i}^{\rm NSM} C_{\Phi_j}^{\rm NSM}\right)^2}{32\pi}\frac{m_Z^2}{m_{\Phi_i} v^2}\left[\frac{\left(m_{\Phi_i}^2 - m_{\Phi_j}^2\right)^2}{m_Z^2} - 2\left(m_{\Phi_i}^2 + m_{\Phi_j}^2\right) + m_Z^2\right] \times \sqrt{1 - 2\frac{m_{\Phi_j}^2 + m_Z^2}{m_{\Phi_i}^2} + \frac{\left(m_{\Phi_j}^2 - m_Z^2\right)^2}{m_{\Phi_i}^4}}\,, \qquad (2.$$

$$\Gamma(\Phi_i \to \chi_j\chi_k) = \left(\frac{2}{1+\delta_{ij}}\right)\frac{g_{\Phi_i\chi_j\chi_k}^2}{16\pi} m_{\Phi_i}\left[1 - \frac{\left(m_{\chi_j} + m_{\chi_k}\right)^2}{m_{\Phi_i}^2}\right]^{(1+\gamma)}\left[1 - \frac{\left(m_{\chi_j} - m_{\chi_k}\right)^2}{m_{\Phi_i}^2}\right]^{(1-\gamma)}$$

$h_{125}\,\Phi$ or $Z\,\Phi$, Who Wins??





$$g_{h_{125}Hh} = \frac{S_H^{\rm NSM} S_H^{\rm S}}{\sqrt{2}v}\left\{\left[1-2(S_H^{\rm S})^2\right]\left(m_H^2 - m_h^2\right) + \sqrt{2}v\,\widetilde{g}_H\right\}$$

$$g_{h_{125}Aa} = \frac{P_A^{\rm NSM} P_A^{\rm S}}{\sqrt{2}v}\left\{\left[1-2(P_A^{\rm S})^2\right]\left(m_A^2 - m_a^2\right) + \sqrt{2}v\,\widetilde{g}_A\right\}.$$

S. Baum & N.R.S., '18

$$g_{H^{\rm NSM}A^{\rm NSM}Z} = \tfrac{1}{2}i\sqrt{g_1^2+g_2^2}\,(p-p')^\mu$$

h / a Decays

- Decay visibly to SM particles via mixing with doublets (either NSM or SM components)

h / a Decays

- Decay visibly to SM particles via mixing with doublets (either NSM or SM components)
- Decay invisibly to possible DM particles

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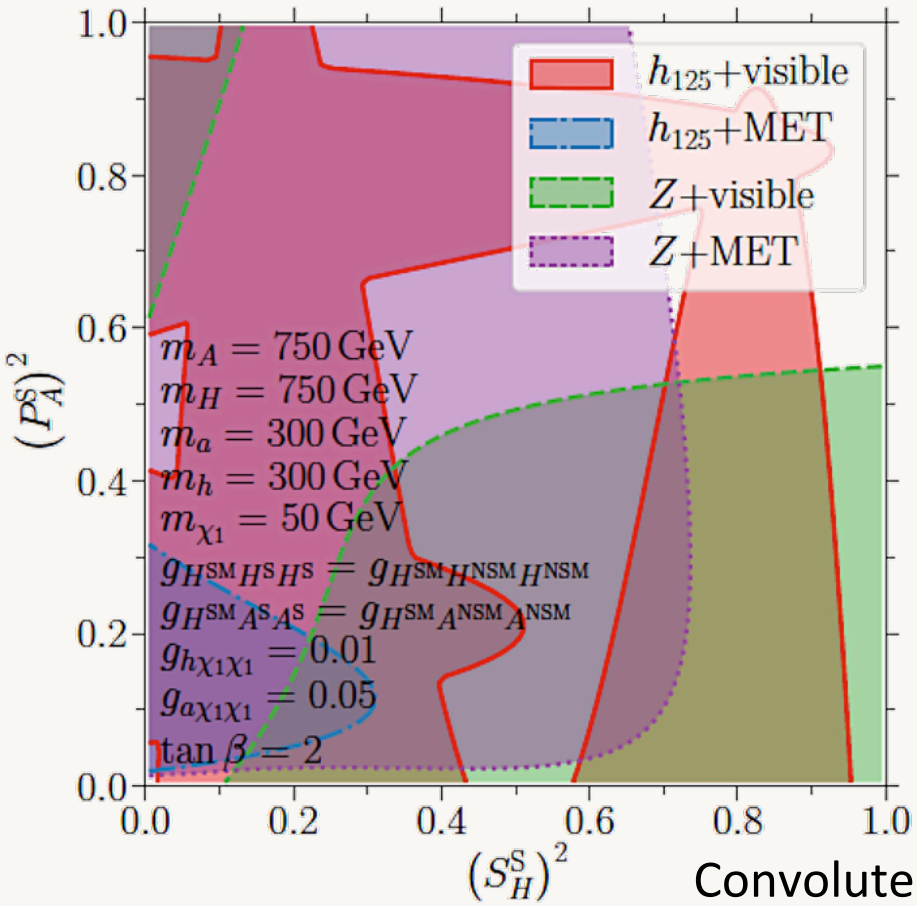
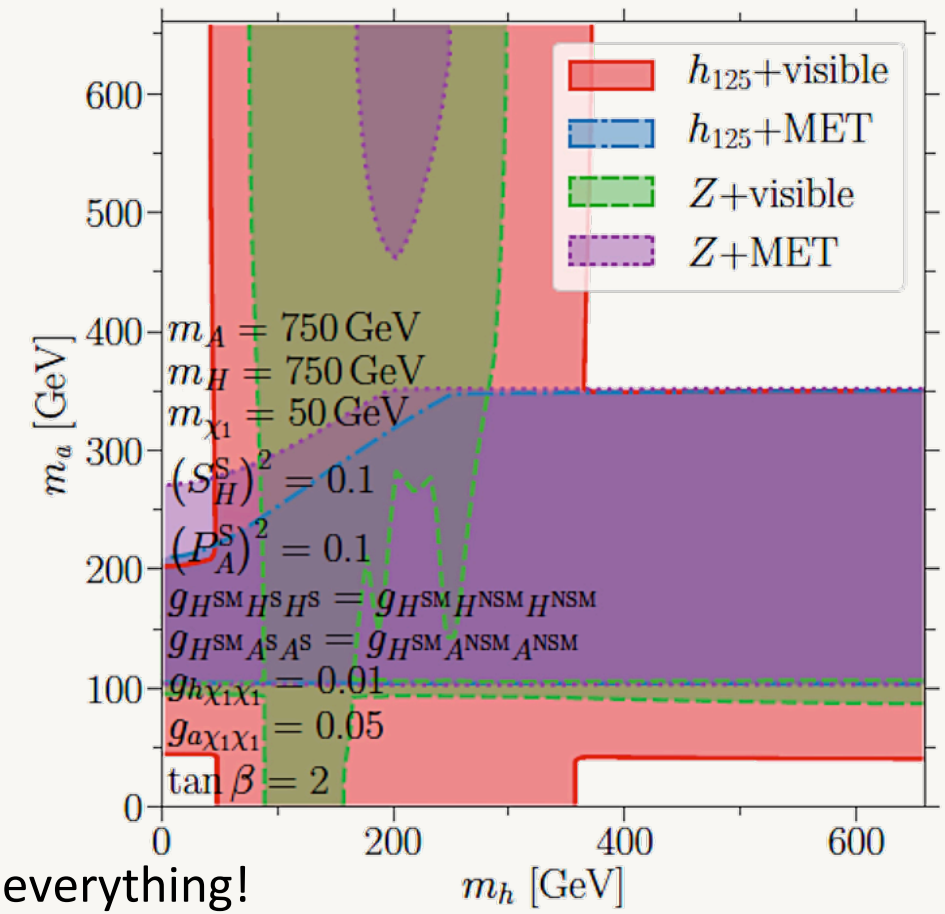
- Categorize final states as
  - **h_{125} + visibles**
  - **mono-h_{125}**
  - **Z + visibles**
  - **mono-Z**

$$\frac{S}{\sqrt{B+\Delta^2 B^2}} > 2 \quad \text{and} \quad S > 5$$

See the Cascades!!

S. Baum & N.R.S., '18





Convolute everything!

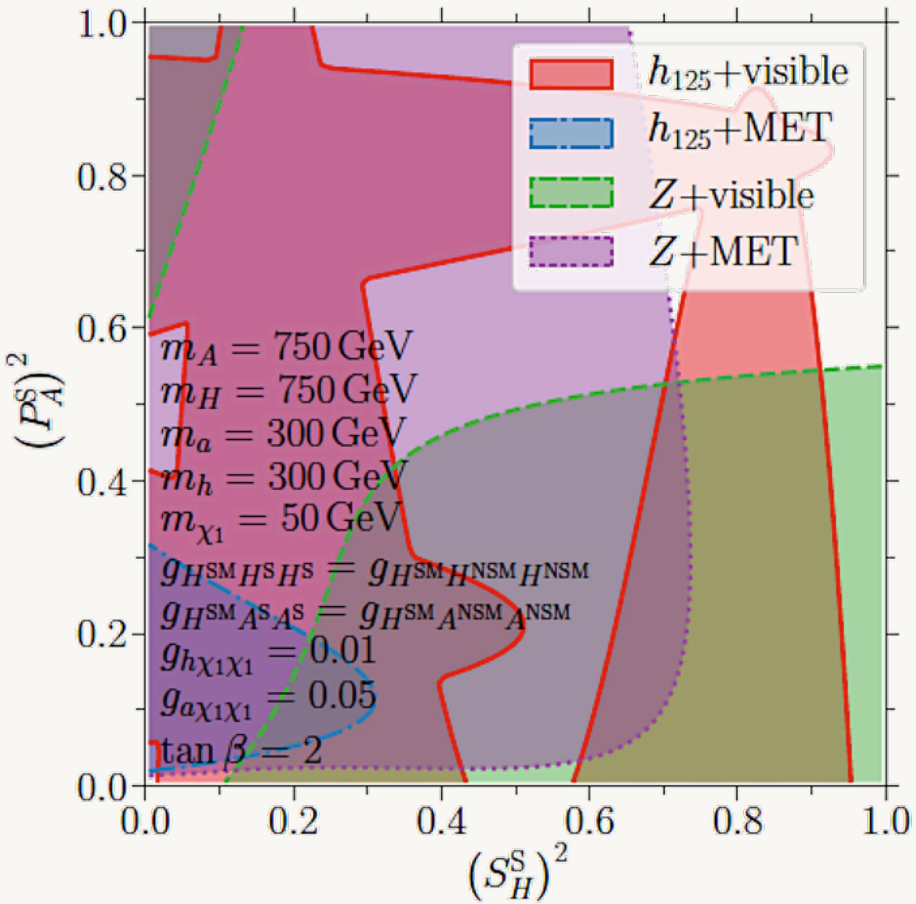
Future reach of the different Higgs Cascade search modes at the LHC with L = 3000 fb^{-1} of data.

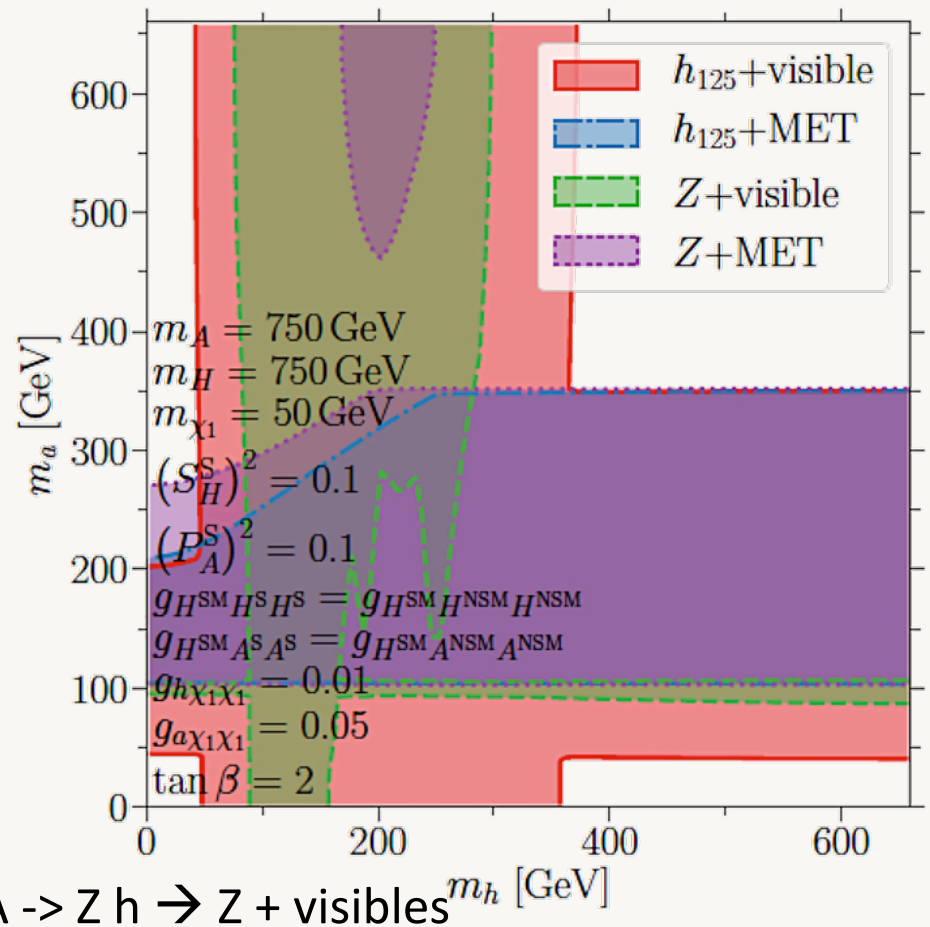
Scale up current limits + various projections in the literature + our simulation for mono-Z/H

See the Cascades!!

S. Baum & N.R.S., '18

BM DM coupling chosen such that:
h -> visibles
a -> invisibles



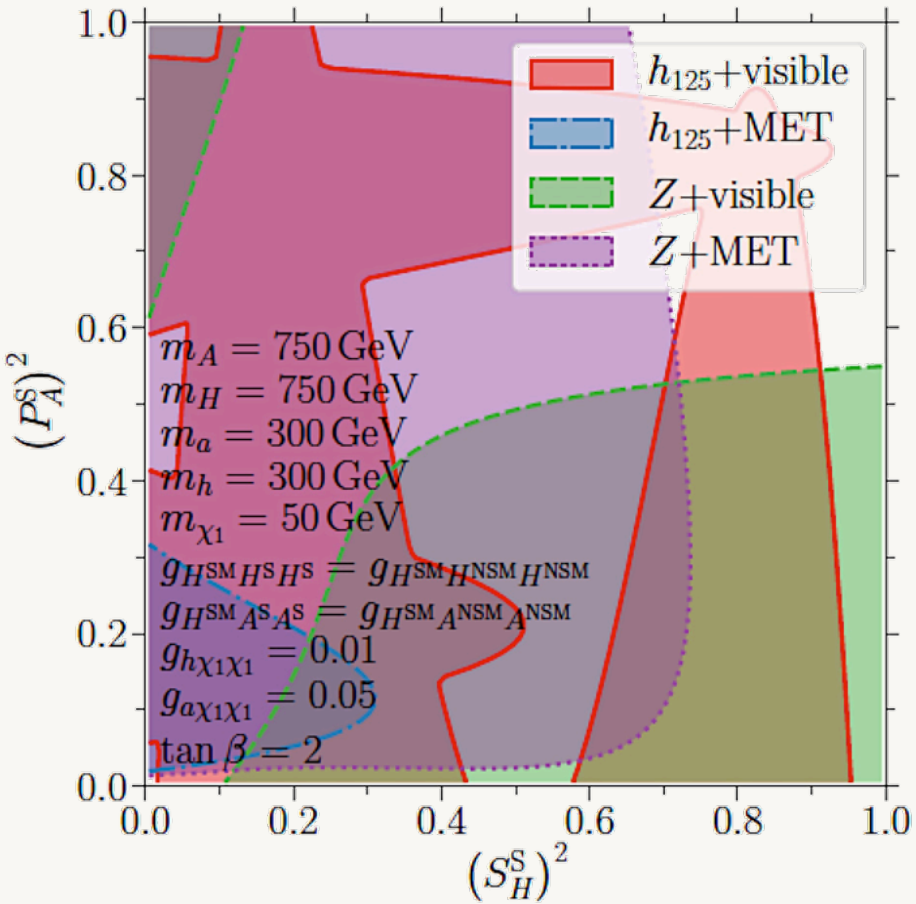


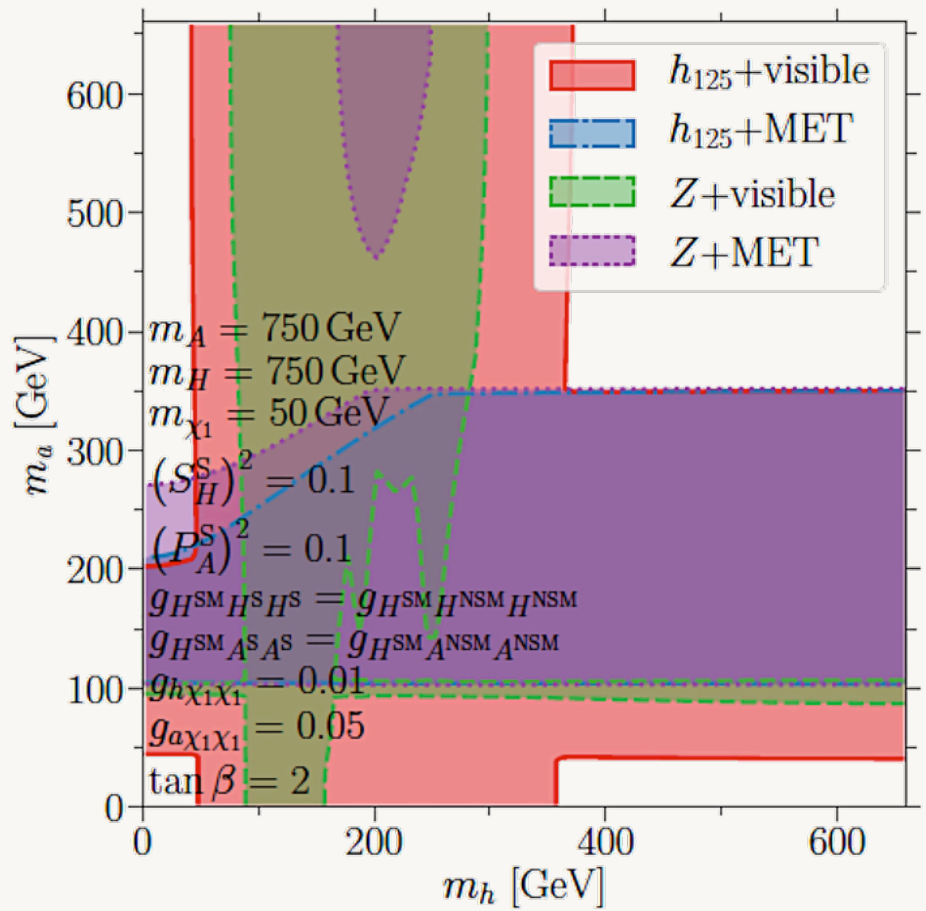
gg→ A > ~ 2 gg → H

A -> Z h → Z + visibles
H -> Z a → Z + invisibles
A -> h_{125} a → h_{125} + invisibles
H -> h_{125} h → h_{125} + visibles

See the Cascades!!

S. Baum & N.R.S., '18





If either m_a or m_h > 350 GeV, can decay predominantly to $t\bar{t}$.

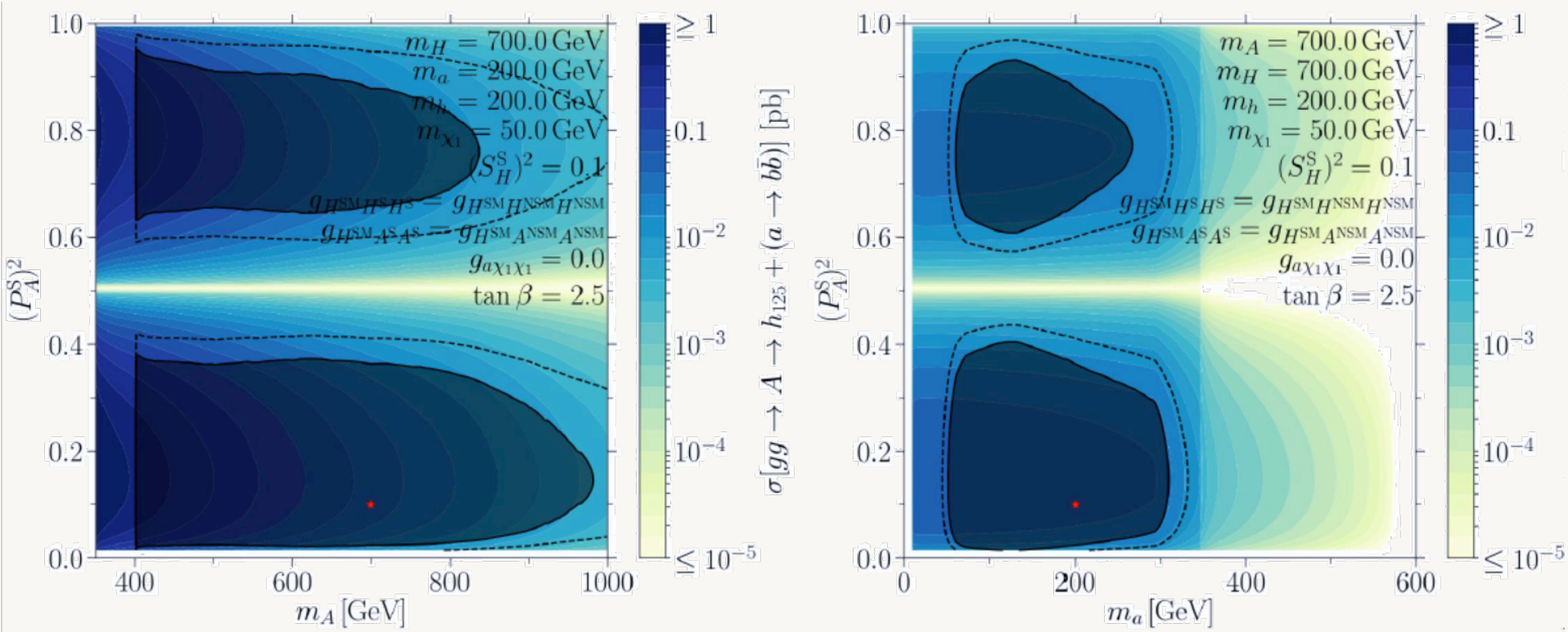
Could be hidden in h_{125} $t\bar{t}$?

$A \rightarrow h_{125}\, a \rightarrow bbbb$

Eg: 300 fb^{-1} for *Z-Phobic*

Displayed cross sections don't include SM-like h_{125} BR

S. Baum & N.R.S., '19



Benchmark suggestion optimizing scalar decays.
Significant regions probed even with 300 fb^{-1}.

Does this really work?

(aka UV completion)

General NMSSM maps to 2HDM +S (*S. Baum & N.R.S.,'18*)

- MSSM + one extra SM-singlet chiral superfield
- Same Higgs sector as our model (2HDM+S)
- Multiple Neutralinos as DM candidates
- Mature numerical tools to study collider pheno.

Results for (Z_3-invariant) NMSSM

- Beautiful alignment story. Will not discuss here.

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15

$$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

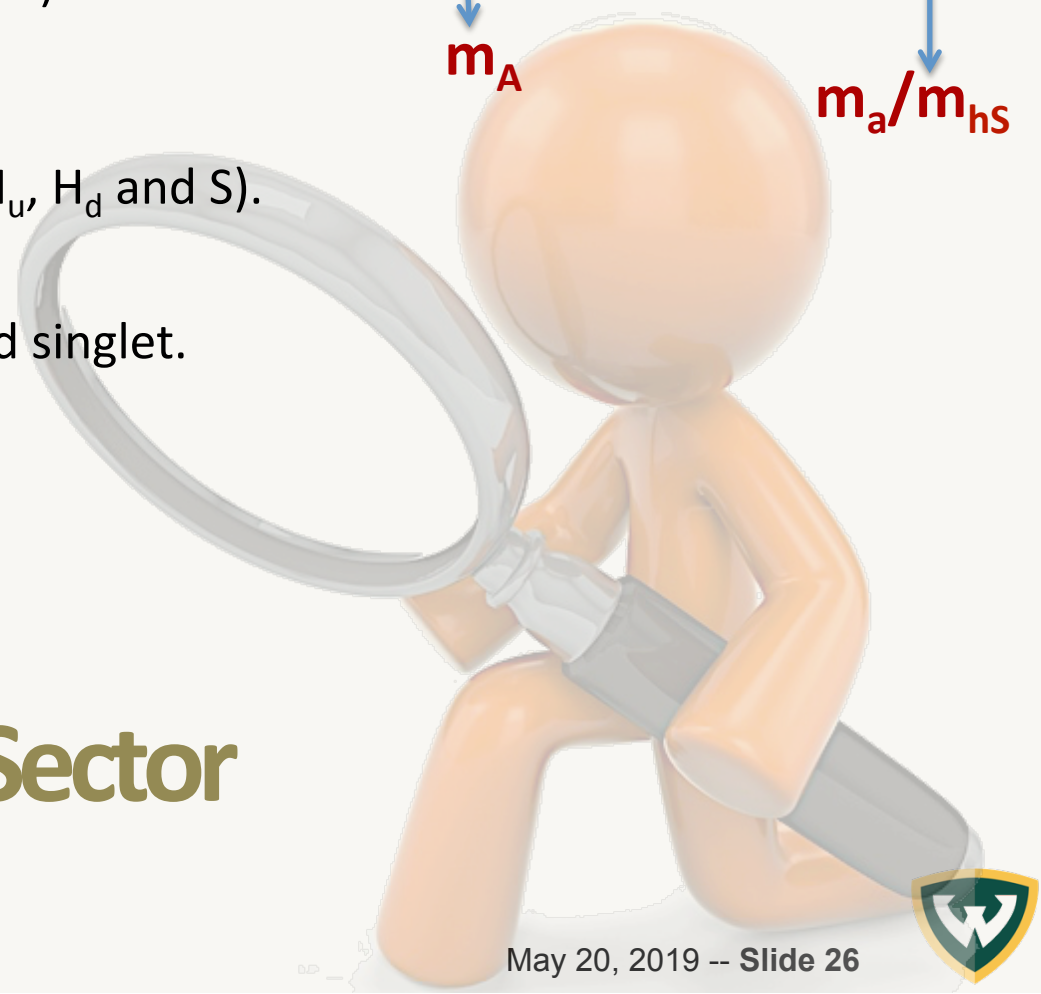
$$-\mathcal{L}_{\rm soft} = \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3$$

m_A m_a/m_{hS}

- 2 Doublets (H_u, H_d) **+ Singlet (S)**
- Singlet couples only to Higgs Sector.
- vevs: (H_u, H_d, S) =(v_u, v_d, v_S =μ/ λ)

- **3 CP-Even Higgs bosons:**
  - Mixing between all three (H_u, H_d and S).
- **2 CP-Odd Higgs bosons:**
  - Mixtures of "MSSM" m_A and singlet.
- **Charged Higgs bosons**

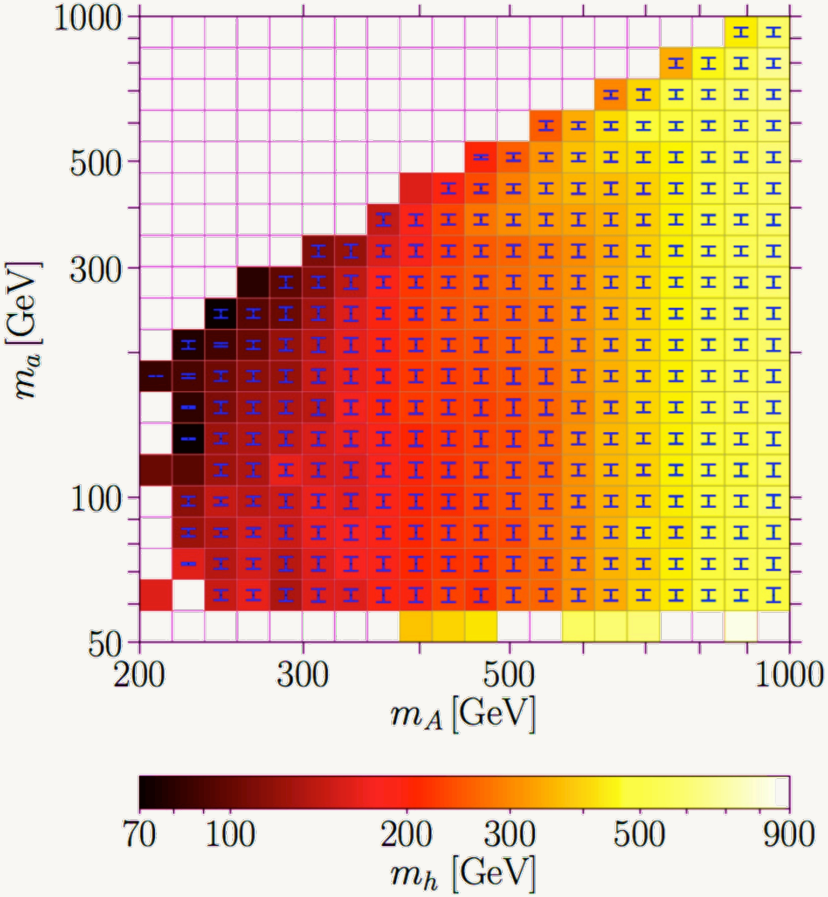
- **Singlino** mass: 2 κ μ/λ

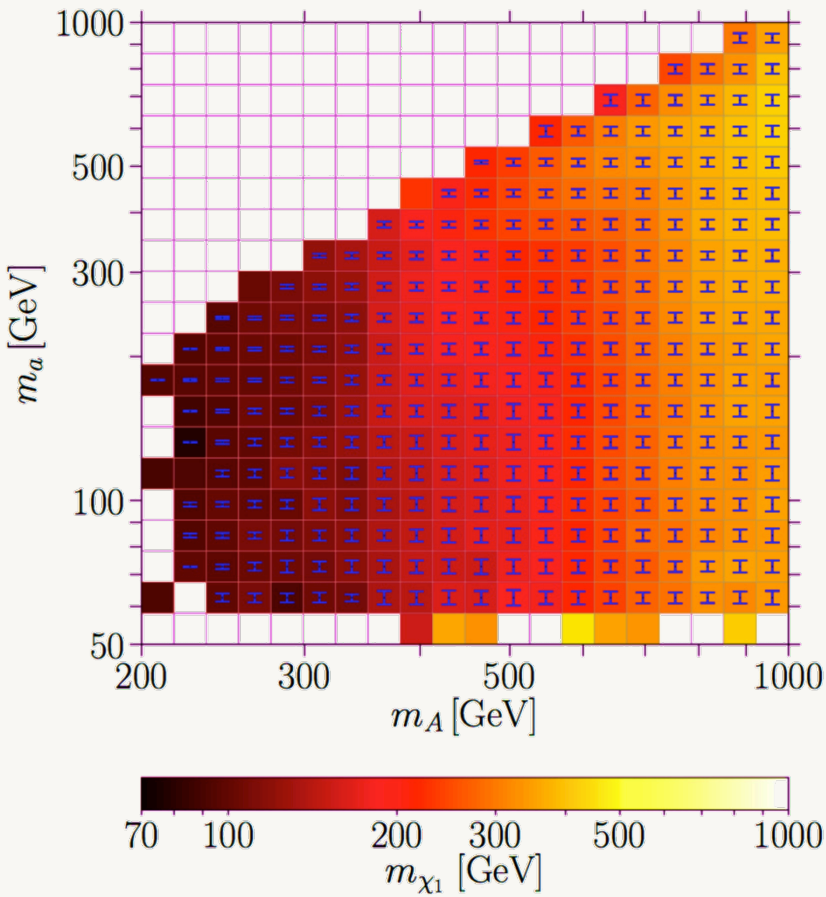


Z_3 NMSSM Higgs Sector

SM - like h_{125}: Large Correlations

S. Baum, N.R.S, K. Freese, '19



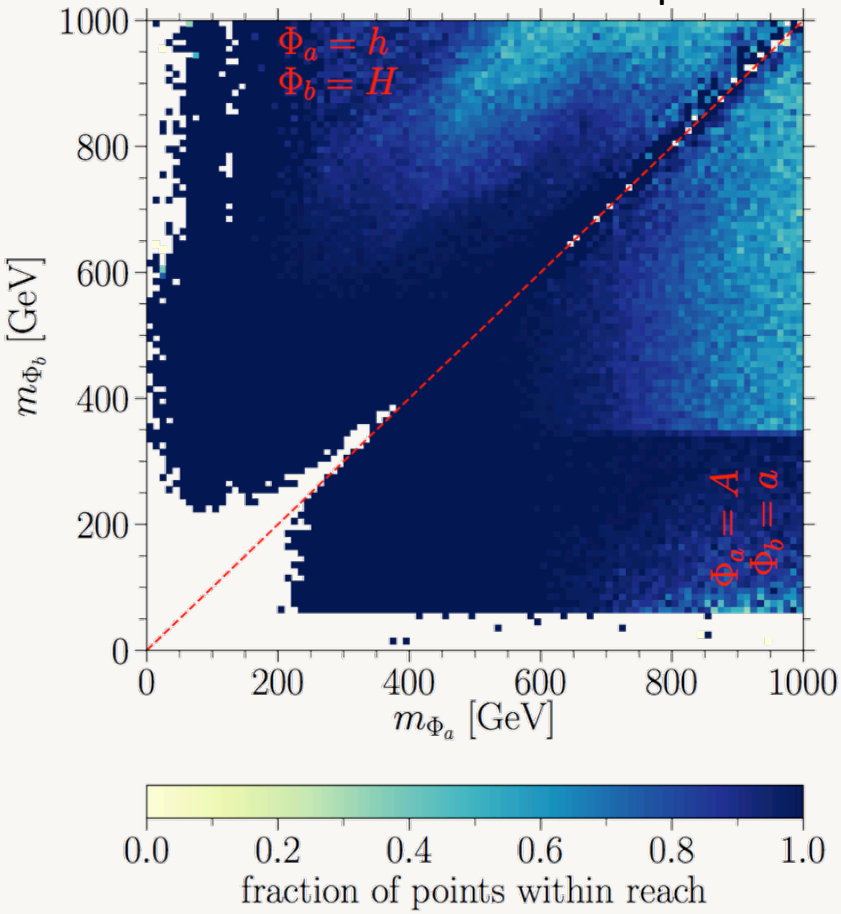


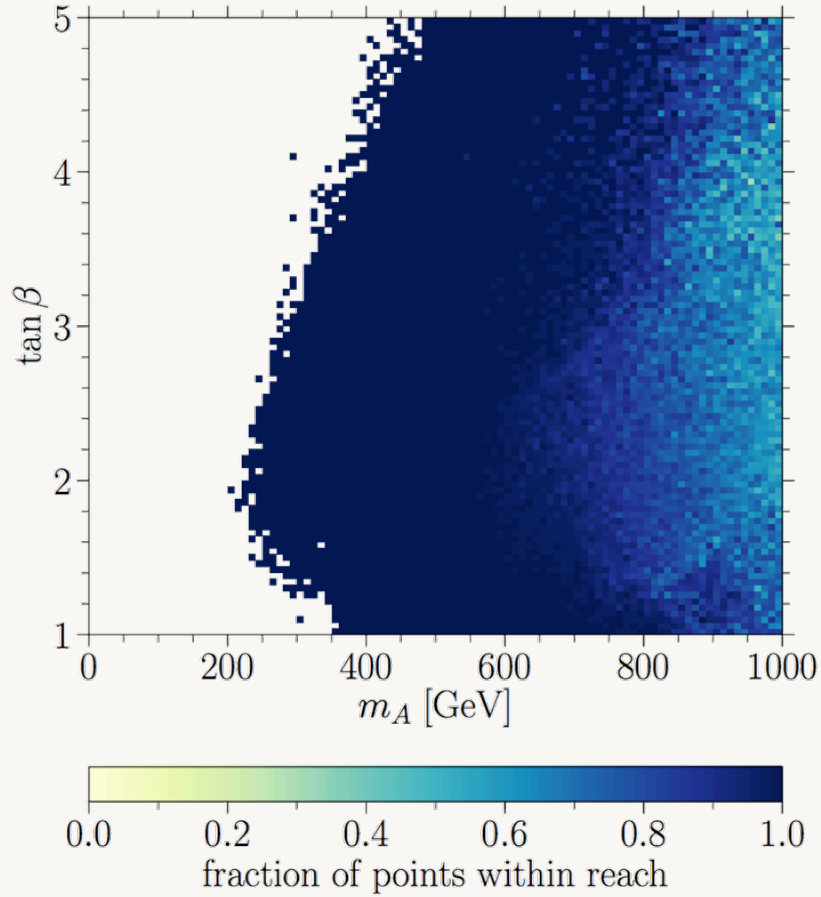
NMSSMTools scan with consistent h_{125} pheno

LHC All Searches: 3000 fb^{-1} NMSSM Higgs Sector

Optimistic scenario shown!

S. Baum, N.R.S, K. Freese, '19





Expect **~50%** scanned region with m_A < 1 TeV probed.

~90% if improvements by 1 order of magnitude wrt our projections, & 2 orders of magnitude in conventional search channels wrt current limits.

Thank You!

125 GeV Approximately SM-like Higgs

2HDM +S: well motivated extended Higgs sector

H/A decays to Double Higgs (h_{125})/h_{125}Z or ZZ/WW suppressed

H/A decays to h_{125} h/a, h/a Z NOT suppressed

h/a can decay visibly to SM final states via mixing with doublets

h/a can decay invisibly to DM

Interesting prospects for such "Higgs Cascades" at the LHC

What are the right questions?

Data + Theory: Where to look next!

Data-driven Age: What will the LHC bring next??

"May we live in interesting times."

BACK UP

- How much "non-standardness" is allowed by h125 measurements??

– $\kappa_{NSM} H_{NSM} + \kappa_{SM} H_{SM} + \kappa_S S$

- Singlet: Only coupling to Higgs

- Ratios to SM:
  - $g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/t_\beta)$
  - $g_{hdd} = (\kappa_{SM} - \kappa_{NSM}\, t_\beta)$
  - $g_{hVV} = \kappa_{SM}$

Contamination allowed in h125 ??

- How much "non-standardness" is allowed by h125 measurements??

– $\kappa_{NSM} H_{NSM} + \kappa_{SM} H_{SM} + \kappa_S S$

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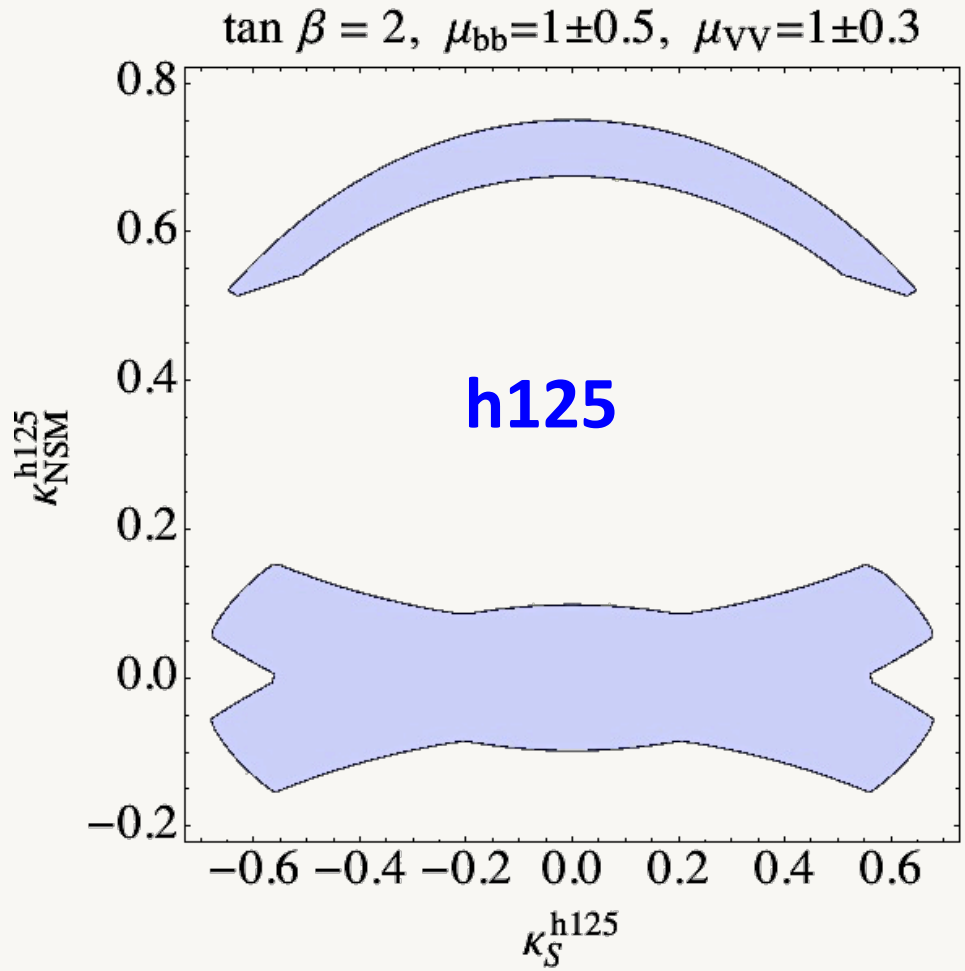
  - $g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/t_\beta)$
  - $g_{hdd} = (\kappa_{SM} - \kappa_{NSM}\, t_\beta)$
  - $g_{hVV} = \kappa_{SM}$

- Significant κ_S OK
- Large κ_{NSM} from sign change of g_{hdd}



Contamination allowed in h125 ??

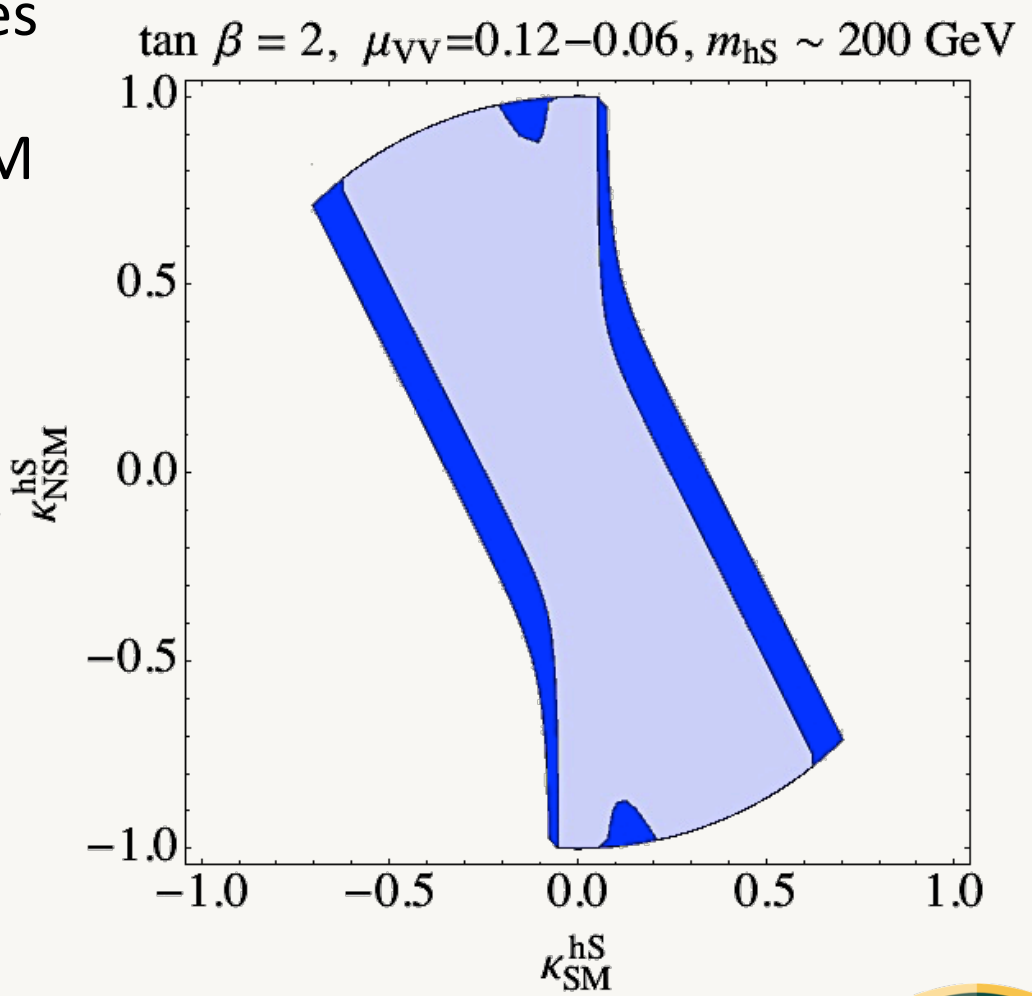
Direct Searches for heavy resonances?

- Strong constraints on SM-like Higgs decay to VV ~12-6% SM value for masses 160-500 GeV. CMS 1505.03831

Only SM component couples to WW or ZZ!!

- What does this imply for SM and NSM components of extra Higgs??
  - 160 GeV < m_{hS} < 350 GeV
  - BR(WW+ZZ) ~1
  - gF production XS impacted.

- With $\kappa^{h125}_{NSM} \sim 0$
  - $\kappa^{hS}_{SM} \sim \kappa^{h125}_{S}$
  - κ^{h125}_{S} smaller than allowed by h125 measurements!



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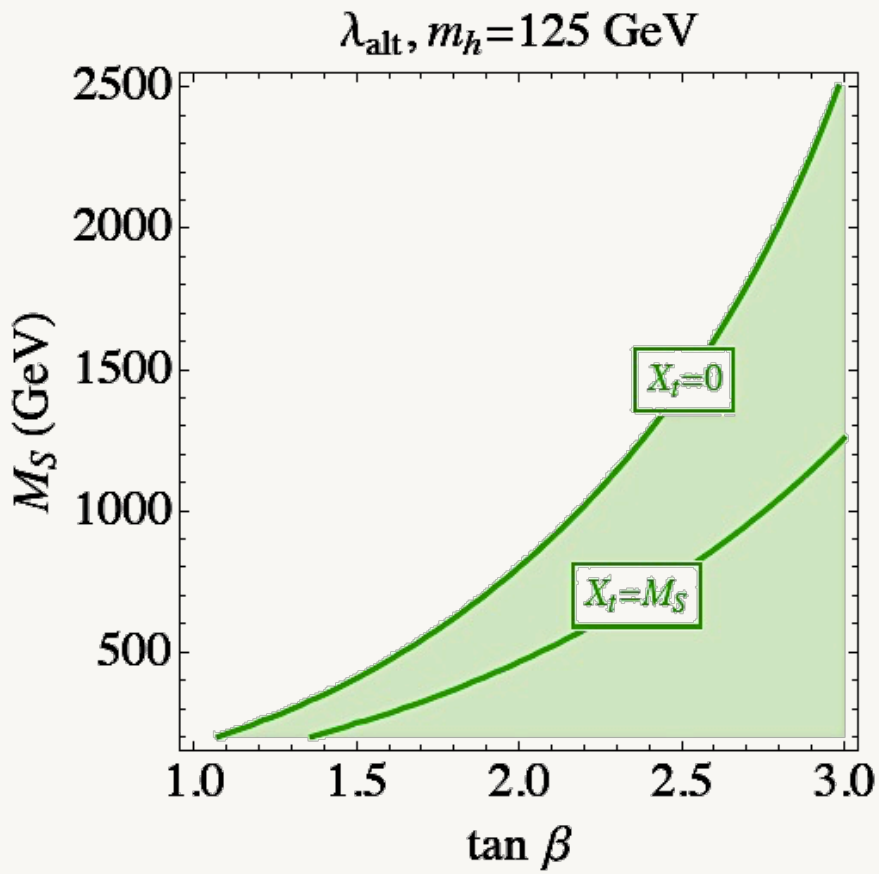


Alignment (No-Mixing):

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

$$\Delta_{\tilde{t}} = -\cos 2\beta (m_h^2 - M_Z^2)$$

Well Known

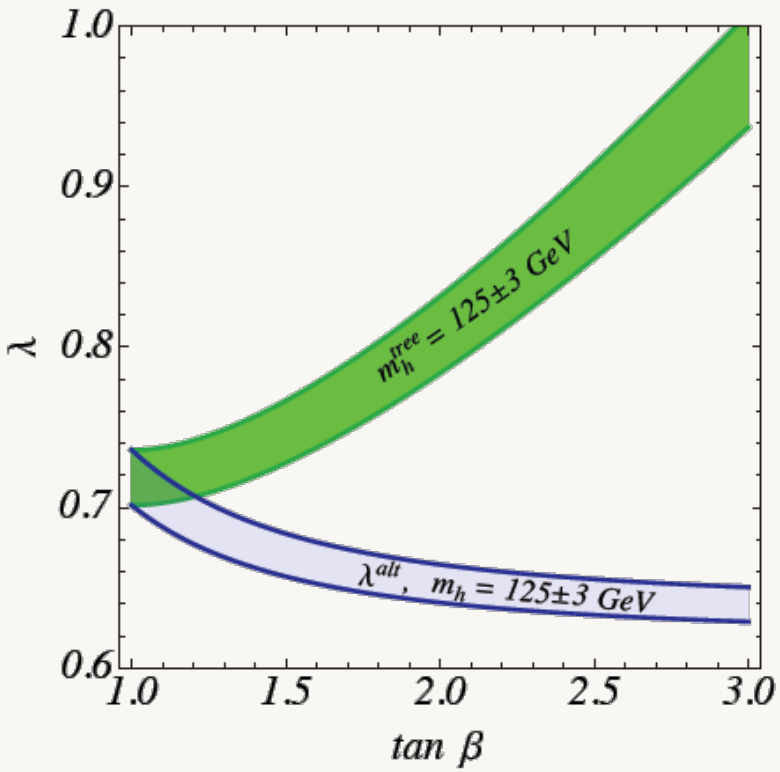
- 125 GeV Higgs
  - Tree-level contribution to Higgs mass from λ.
  - λ ~ 0.65-0.7
- Low tanβ
- Light Stops

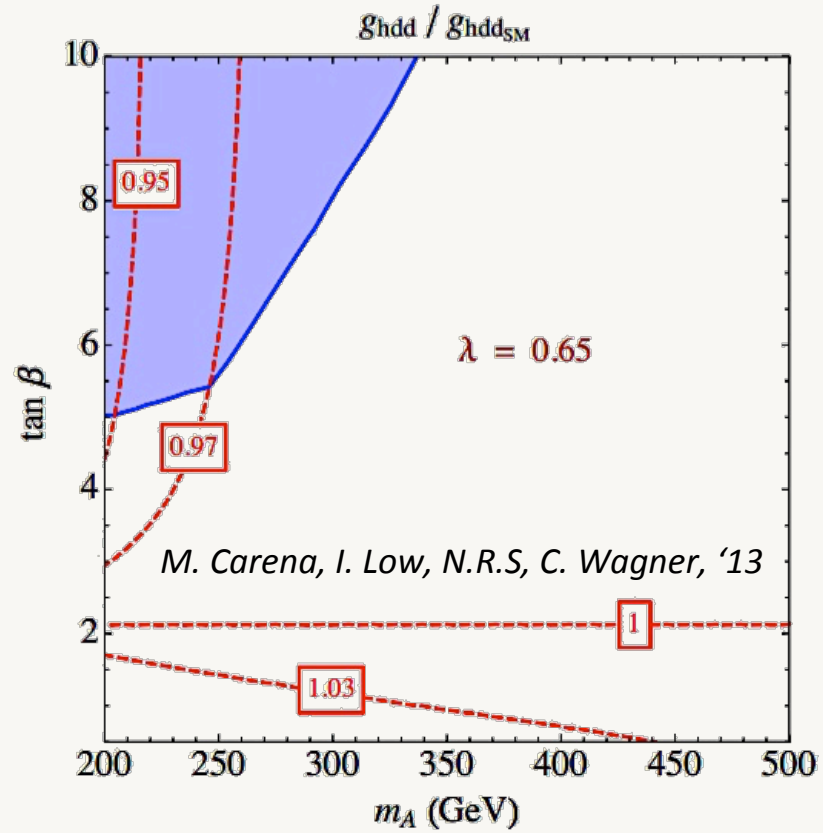
NMSSM: 125 GeV Higgs Naturally!

- Perturbative up to GUT scale.
  - $\lambda_{max} \sim 0.7$, $\kappa_{max} \sim \lambda/2$

Not so well known:

- Leads to excellent Alignment (very little mixing with Heavy Higgs) in the m_A- tanβ plane.





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$$\lambda_{\rm alt}^2 = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_\beta^2}$$

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SM-Like Higgs Naturally!

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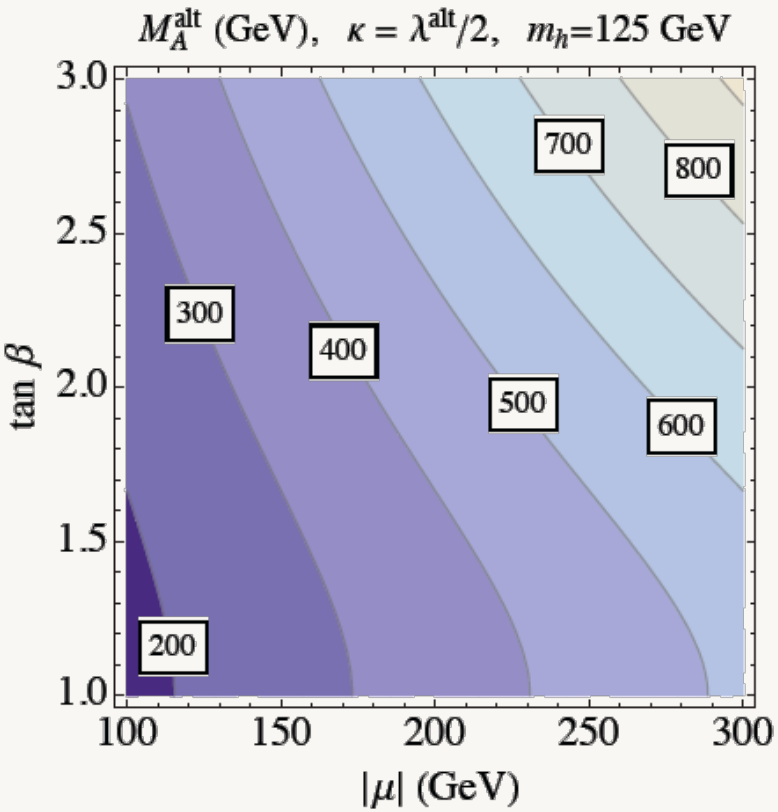

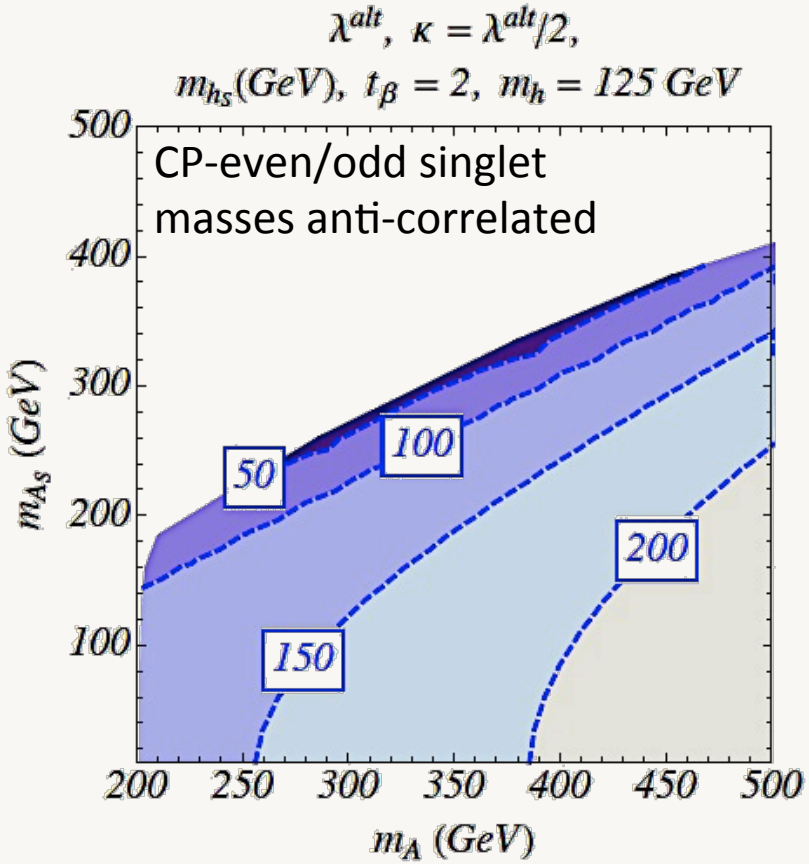

$$1 - \frac{m_A^2}{4\mu^2} s_{2\beta}^2 - \frac{\kappa}{2\lambda} s_{2\beta} = 0$$

h125 = H_{SM}

LIGHT SPECTRUM

Singlino: **$2\,\kappa\,\mu/\lambda \sim < \mu$**

Singlet Alignment

Cascade Prospects?

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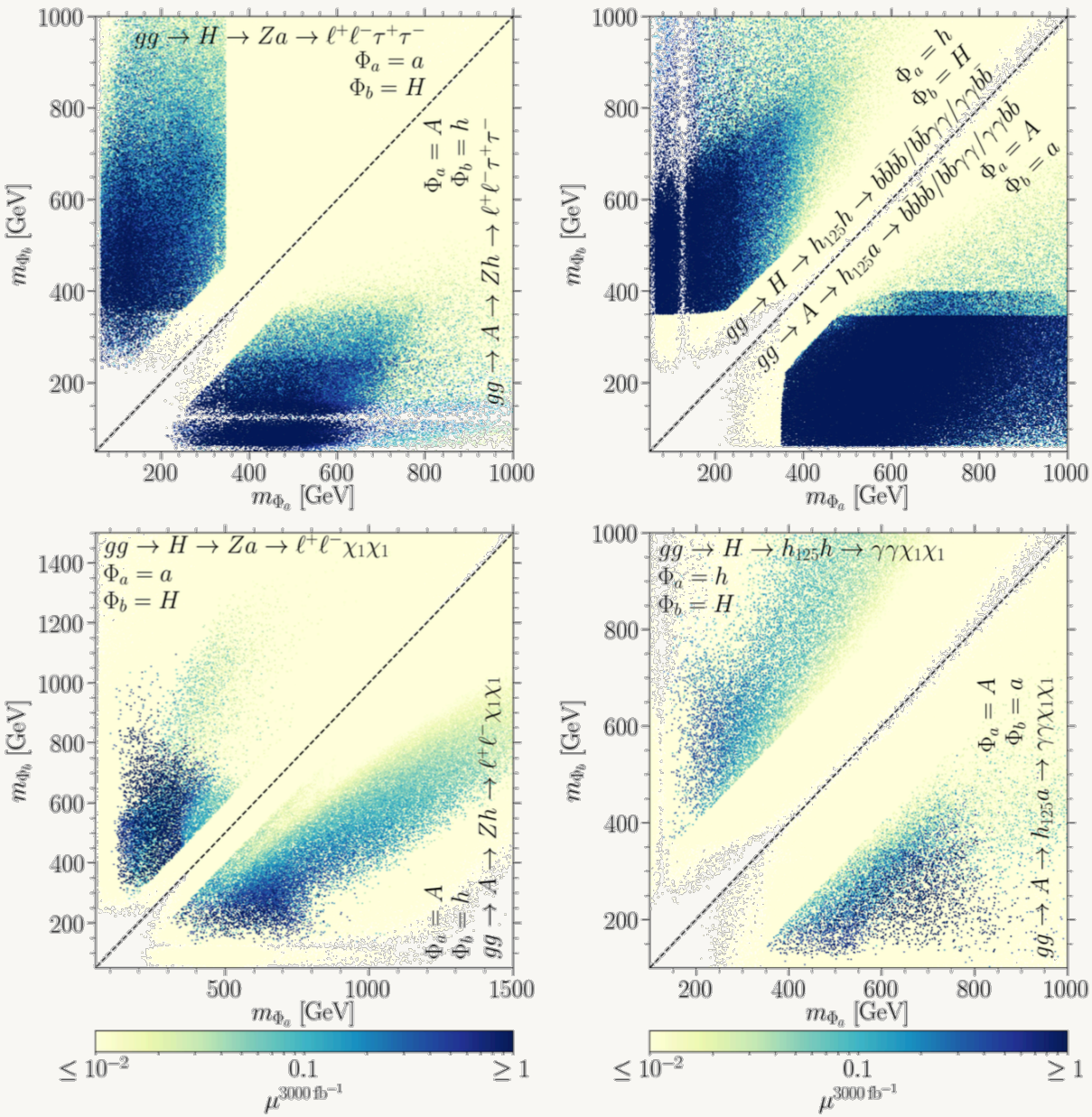

L = 3000 fb^{-1}