

THE Higgs and *more* Higgs, 2HDM + a complex S: Making Sense out of Chaos

S. Baum, & NRS arXiv:1808.02667

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Double Higgs Productions at Colliders

Friday September 7, 2018



Where to Start?

BSM Higgs Sector?

2 Higgs Doublet + Singlet



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BSM Higgs Sector?

2 Higgs Doublet + Singlet

2HDM: SUSY

S: SUSY + EWPT + DM + flavor...

See talk by I. Lewis



Where to Start?

BSM Higgs Sector

2 Higgs Doublet + Singlet

Dark Matter?

Singlet Fermion



Where to Start?

BSM Higgs Sector

2 Higgs Doublet + Singlet

Dark Matter

Singlet Fermion

Simplified Model, EFT, SUSY (NMSSM)...



2 Higgs Doublet Model (2HDM).

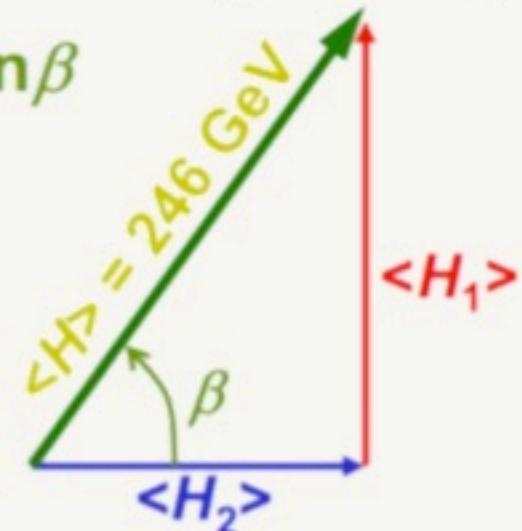
$$\langle H_1 \rangle, \langle H_2 \rangle \rightarrow \langle H \rangle, \tan\beta$$

2 Higgs doublets (Type II):

H_u – Couples only to up-type quarks

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: $H^+, -$



SM-Like Higgs.

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

$v \sin^2 \beta$  $v \cos^2 \beta$ 

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.

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

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

$$\Rightarrow \langle h \rangle = v$$

$$\langle H \rangle = 0$$

SM-like HIGGS

ALIGNMENT

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....



- 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

$$\begin{aligned}\langle H_u \rangle &= v_u \\ \langle H_d \rangle &= v_d \\ t_\beta &= v_u/v_d \\ \langle S \rangle &= \mu/\lambda\end{aligned}$$

CP-Even Higgs Bases



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- “Extended” Higgs basis: (H_{NSM} , H_{SM} , S)
 - H_{NSM} : (down, up, V) = (y_d , y_u , t_β , 0)
 - H_{SM} : (down, up, V) = (y_d , y_u , g_{hVV})

Only SM state
couples to WW
or ZZ!!

$$\begin{aligned}\langle H_{NSM} \rangle &= 0 \\ \langle H_{SM} \rangle &= v\end{aligned}$$

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_β , 0)
- H_{SM} : (down, up, V) = (y_d , y_u , g_{hVV})

$$\begin{aligned}\langle H_{NSM} \rangle &= 0 \\ \langle H_{SM} \rangle &= v\end{aligned}$$

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

$$-H^i = \kappa_{NSM}^i H_{NSM} + \kappa_{SM}^i H_{SM} + \kappa_S^i S$$

CP-Even Higgs Bases



- 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

$$\begin{aligned}\langle H_u \rangle &= v_u \\ \langle H_d \rangle &= v_d \\ t_\beta &= v_u/v_d \\ \langle S \rangle &= \mu/\lambda\end{aligned}$$

- “Extended” Higgs basis: (H_{NSM} , H_{SM} , S)

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- H_{SM} : (down, up, V) = (y_d , y_u , g_{hVV})

$$\begin{aligned}\langle H_{NSM} \rangle &= 0 \\ \langle H_{SM} \rangle &= v\end{aligned}$$

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

$$-H^i = \kappa_{NSM}^i H_{NSM} + \kappa_{SM}^i H_{SM} + \kappa_S^i S$$

CP-Even Higgs Bases



Higgs Potential?

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

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

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

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



h_{125} to the Rescue!

- Many of the quartics related to entries of the mass matrices.
- Certain trilinear couplings suppressed by SM-like nature of h_{125} (alignment), for e.g:
$$\{g_{H^{\text{SM}} H^{\text{SM}} H^{\text{NSM}}}, \quad g_{H^{\text{SM}} H^{\text{SM}} H^{\text{S}}}\} \rightarrow 0$$
- 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 quartics of Higgs potential in terms of more physically meaningful parameters

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

$$S_{h_{125}}^{\text{NSM}}, \quad S_{h_{125}}^{\text{S}}, \quad S_H^{\text{S}}, \quad P_A^{\text{S}};$$

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

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

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

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

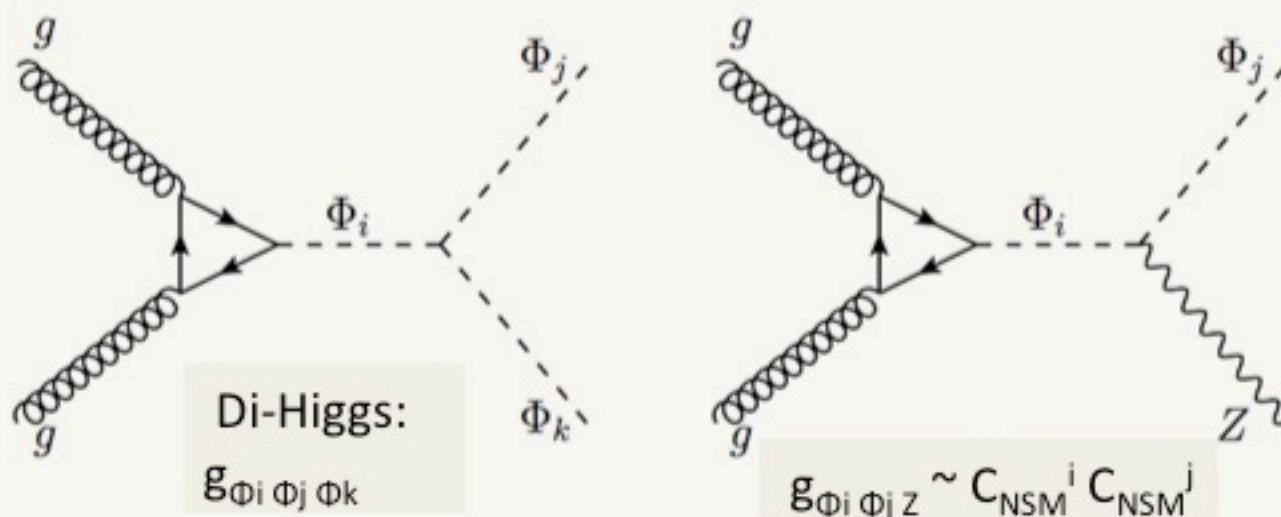
$$\{g_{H^{\text{S}} H^{\text{S}} H^{\text{S}}}, \quad g_{H^{\text{S}} A^{\text{NSM}} A^{\text{S}}}, \quad g_{H^{\text{S}} A^{\text{S}} A^{\text{S}}}\}.$$

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



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

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



Decay Widths

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

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

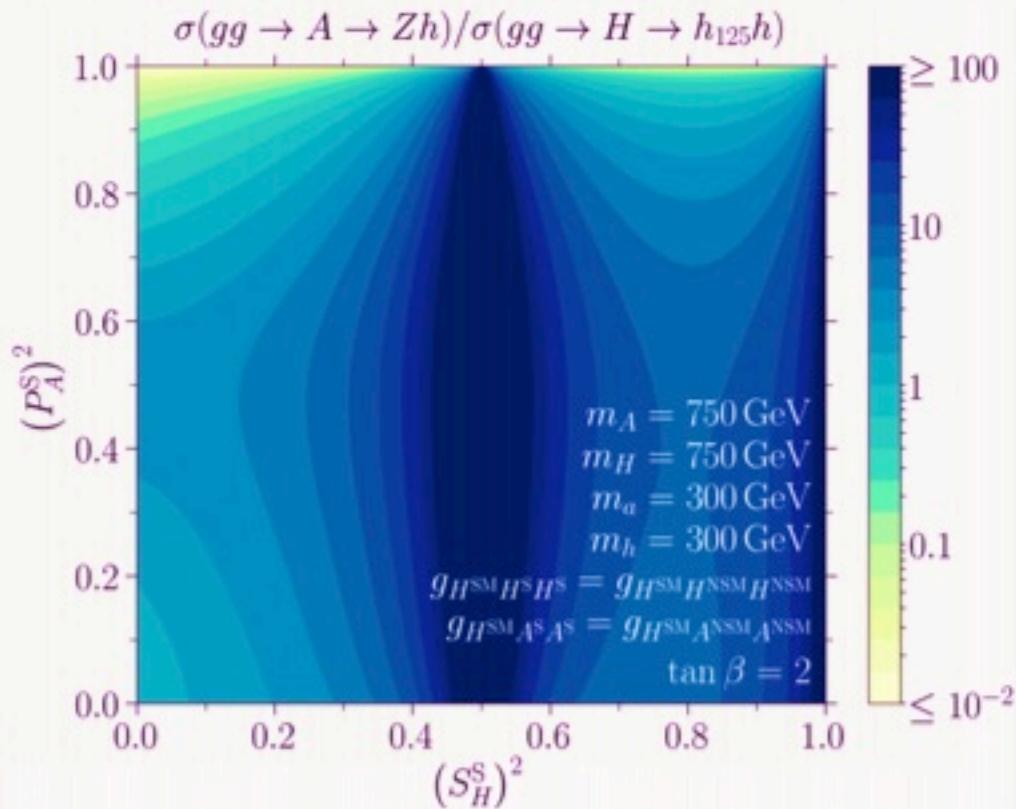
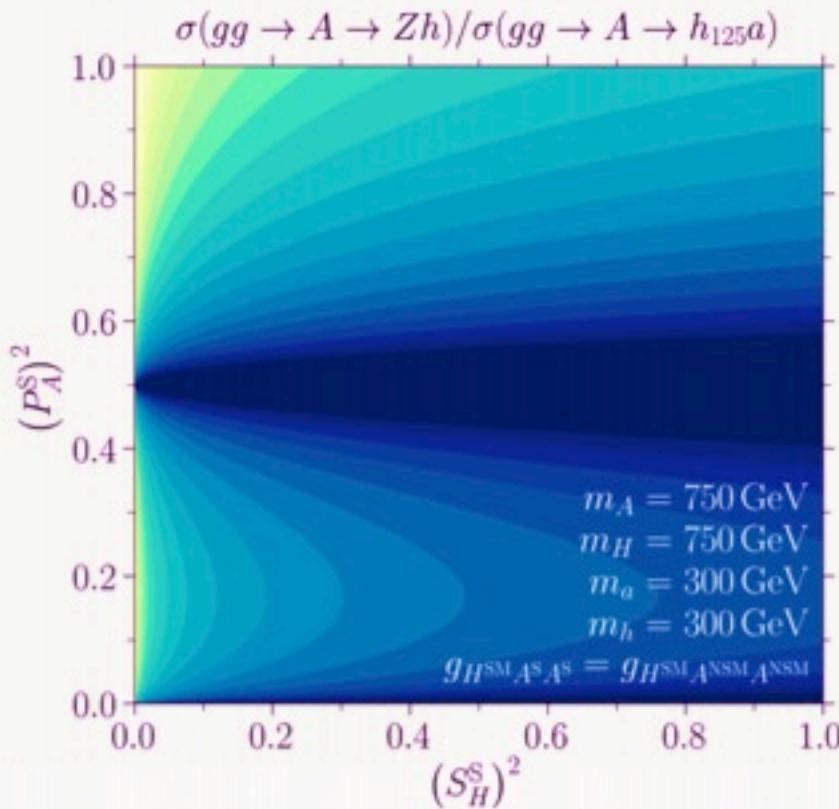
$$\begin{aligned} \Gamma(\Phi_i \rightarrow f\bar{f}) &= \frac{N_c^f}{16\pi} \frac{m_f^2}{v^2} m_\Phi \left(1 - 4 \frac{m_f^2}{m_{\Phi_i}^2} \right)^\gamma \\ &\times \begin{cases} (C_\Phi^{\text{SM}} - C_\Phi^{\text{NSM}} / \tan \beta)^2 & , \text{ for up-type quarks } f, \\ (C_\Phi^{\text{SM}} + C_\Phi^{\text{NSM}}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

$$\begin{aligned} \Gamma(\Phi_i \rightarrow \Phi_j \Phi_k) &= \frac{g_{\Phi_i \Phi_j \Phi_k}^2}{16\pi m_{\Phi_i}} \left(\frac{1}{1 + \delta_{jk}} \right) \sqrt{1 - 2 \frac{m_{\Phi_j}^2 + m_{\Phi_k}^2}{m_{\Phi_i}^2} + \frac{(m_{\Phi_j}^2 - m_{\Phi_k}^2)^2}{m_{\Phi_i}^4}} \\ \Gamma(\Phi_i \rightarrow Z\Phi_j) &= \frac{(C_{\Phi_i}^{\text{NSM}} C_{\Phi_j}^{\text{NSM}})^2}{32\pi} \frac{m_Z^2}{m_{\Phi_i} v^2} \left[\frac{(m_{\Phi_i}^2 - m_{\Phi_j}^2)^2}{m_Z^2} - 2(m_{\Phi_i}^2 + m_{\Phi_j}^2) + m_Z^2 \right] \\ &\times \sqrt{1 - 2 \frac{m_{\Phi_j}^2 + m_Z^2}{m_{\Phi_i}^2} + \frac{(m_{\Phi_j}^2 - m_Z^2)^2}{m_{\Phi_i}^4}}, \end{aligned} \quad (2)$$

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



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



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

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

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

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



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



h/a Decays

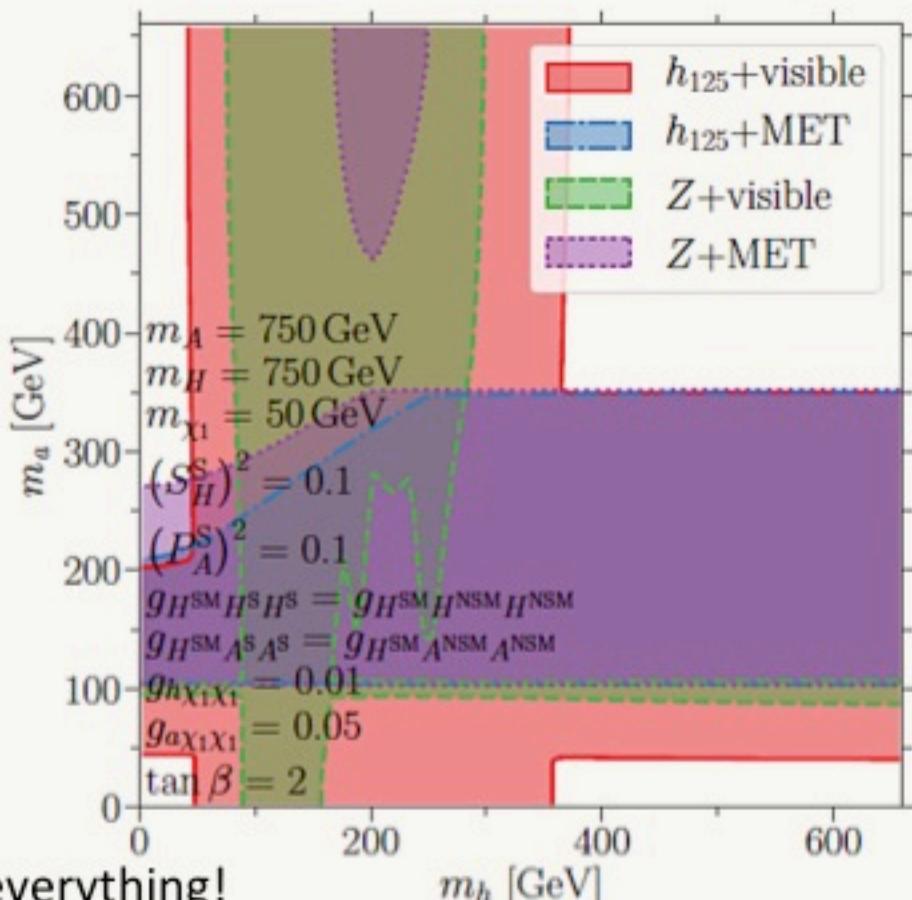
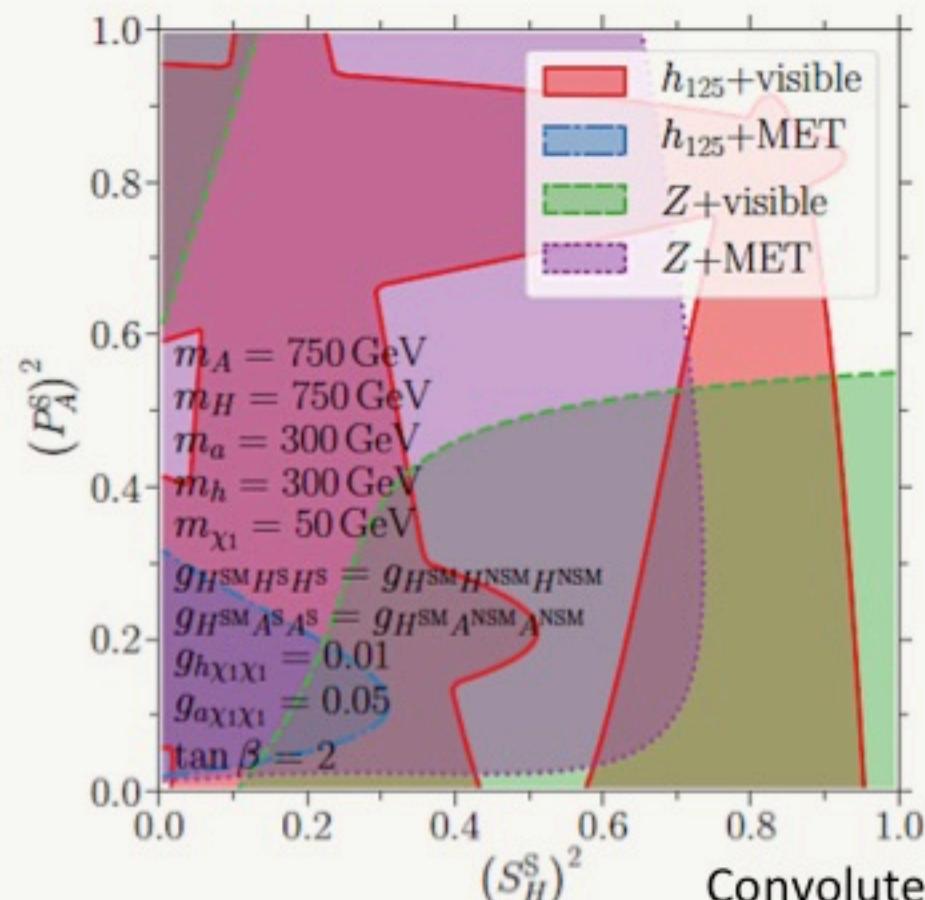
- Decay visibly to SM particles via mixing with doublets (either NSM or SM components)
- Decay invisibly to possible DM particles
- Categorize final states as
 - $h_{125} + \text{visibles}$
 - mono- h_{125}
 - $Z + \text{visibles}$
 - mono- Z



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

See the Cascades!!

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



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

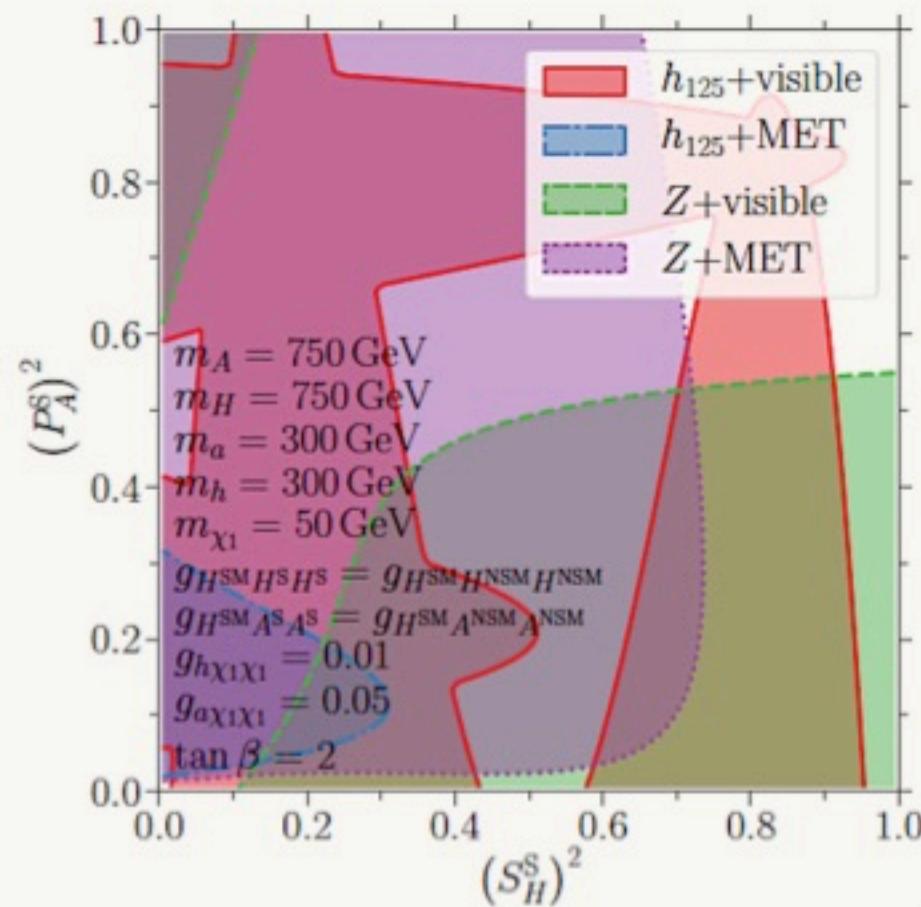
Scale up current limits + various projections in the literature + our simulation for mono-Z/H



BM DM coupling chosen such that:

$h \rightarrow$ visibles

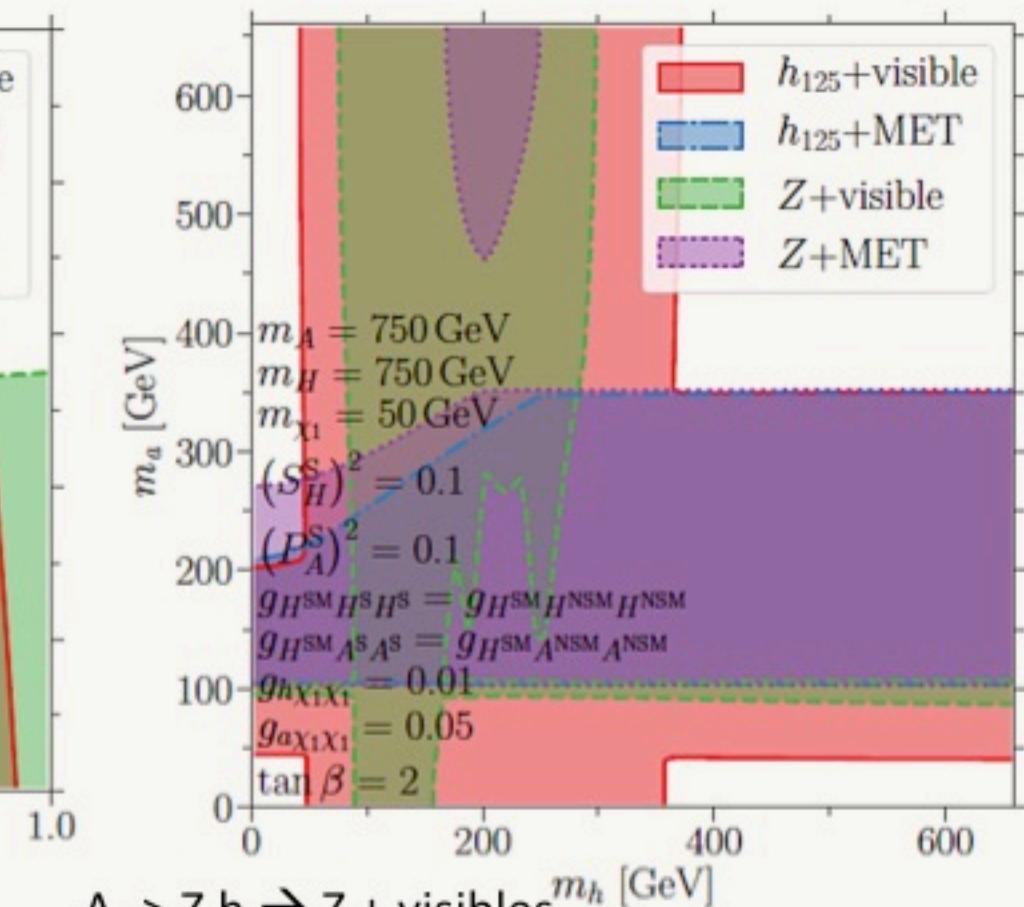
$a \rightarrow$ invisibles



$gg \rightarrow A \rightarrow \sim 2 gg \rightarrow H$

See the Cascades!!

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$A \rightarrow Z h \rightarrow Z + \text{visibles}$ m_h [GeV]

$H \rightarrow Z a \rightarrow Z + \text{invisibles}$

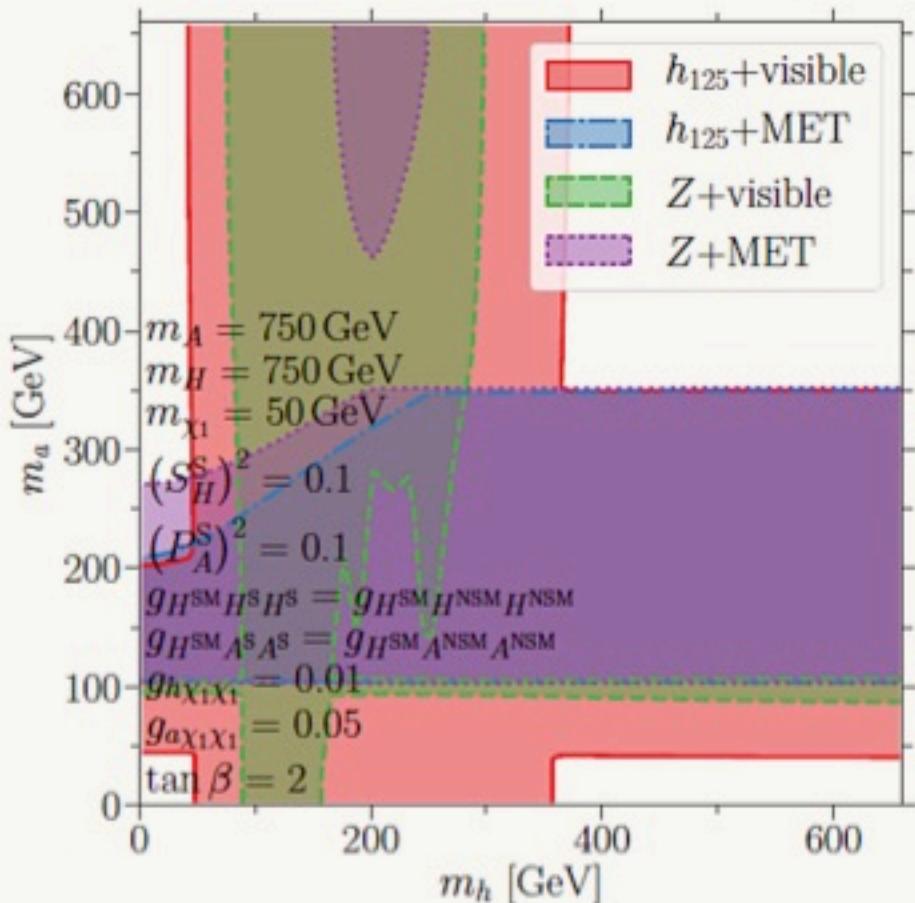
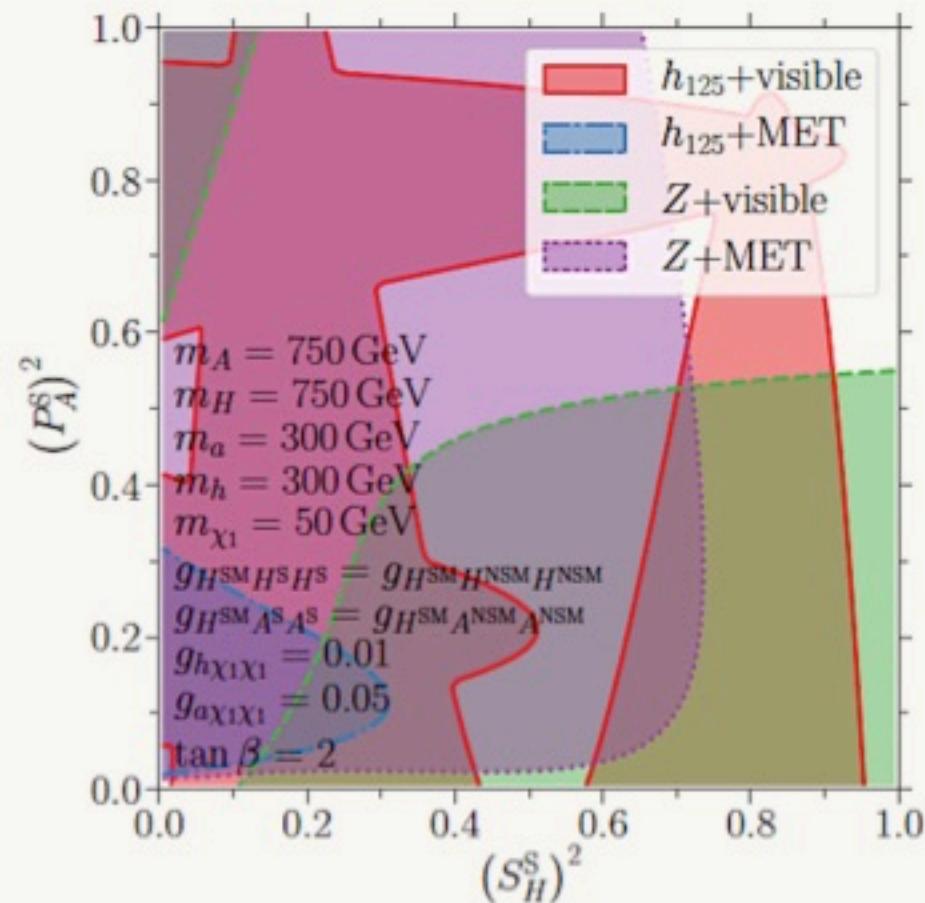
$A \rightarrow h_{125} a \rightarrow h_{125} + \text{invisibles}$

$H \rightarrow h_{125} h \rightarrow h_{125} + \text{visibles}$



See the Cascades!!

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



If either m_a or $m_h > 350 \text{ GeV}$, can decay predominantly to $t\bar{t}$.
Could be hidden in $h_{125} t\bar{t}$?



Does this really work? (aka UV completion)

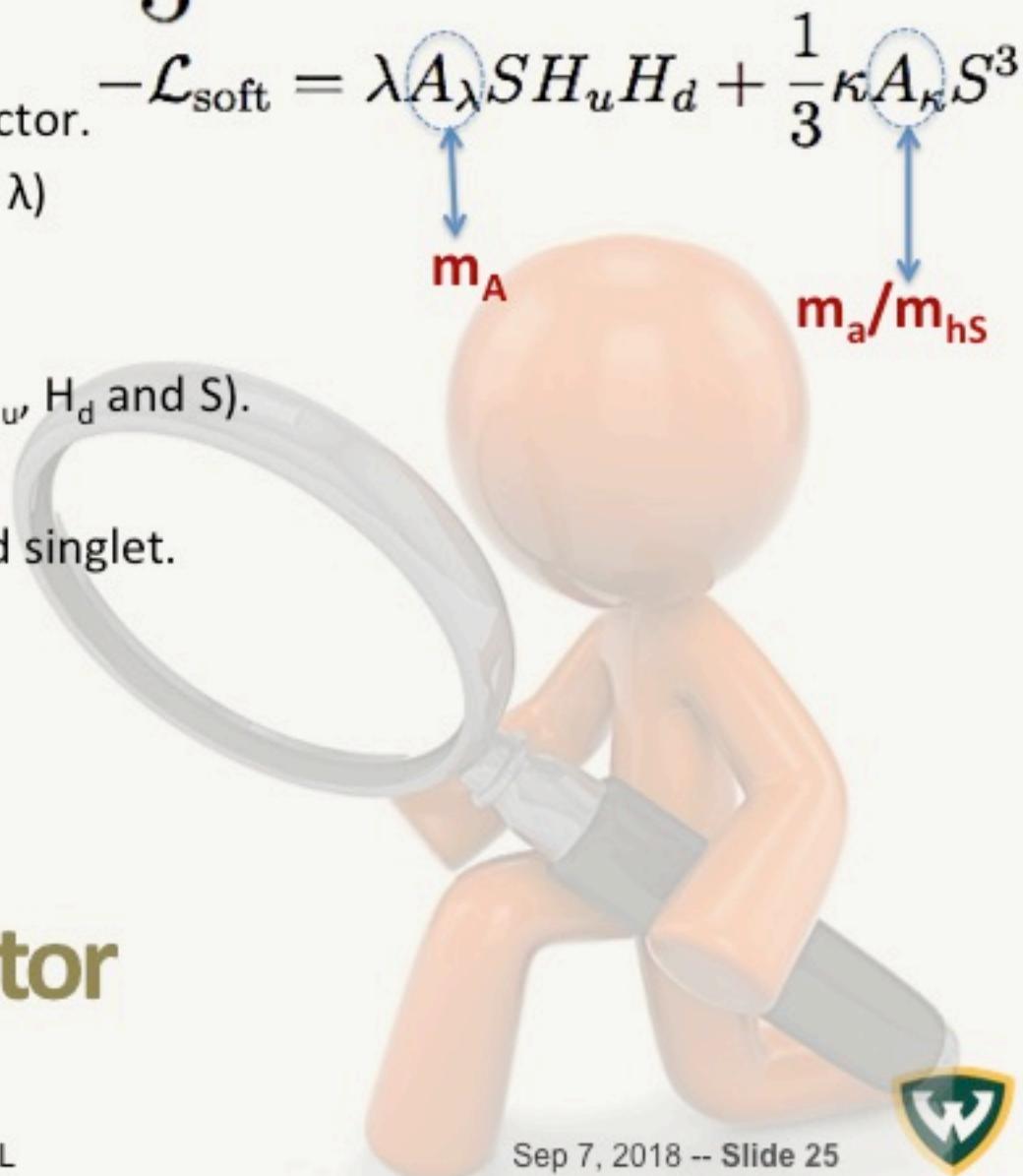
(Z_3 -invariant) NMSSM

- 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.



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

- 2 Doublets (H_u, H_d) + Singlet (S)
- Singlet couples only to Higgs Sector.
- vevs: $(H_u, H_d, S) = (v_u, v_d, v_S = \mu/\lambda)$
- **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:** $2\kappa\mu/\lambda$

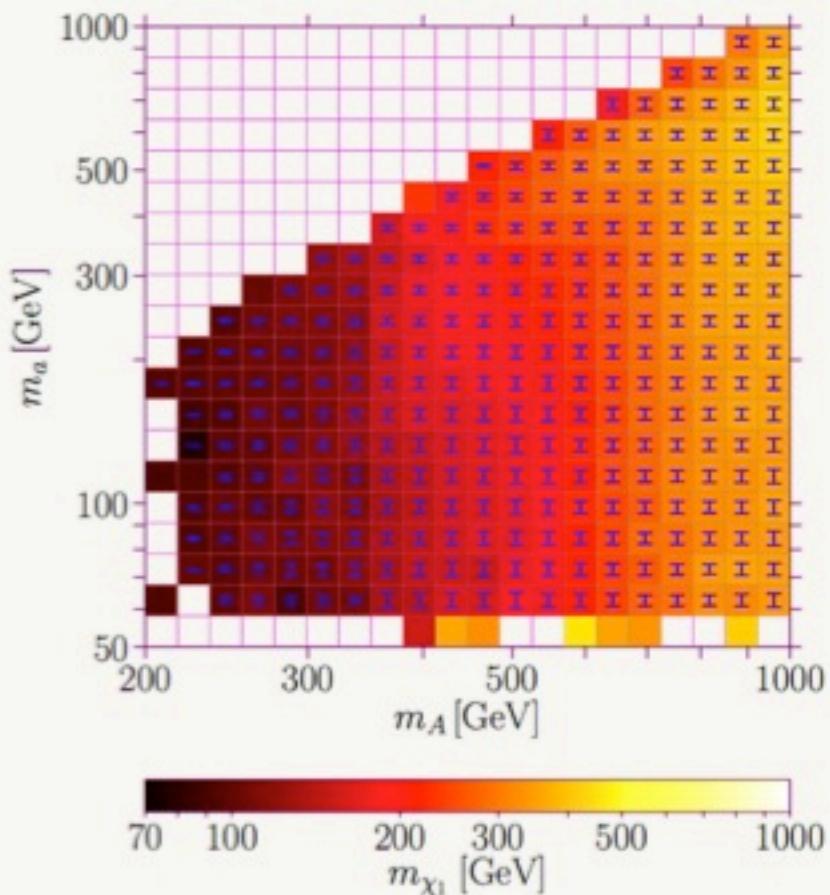
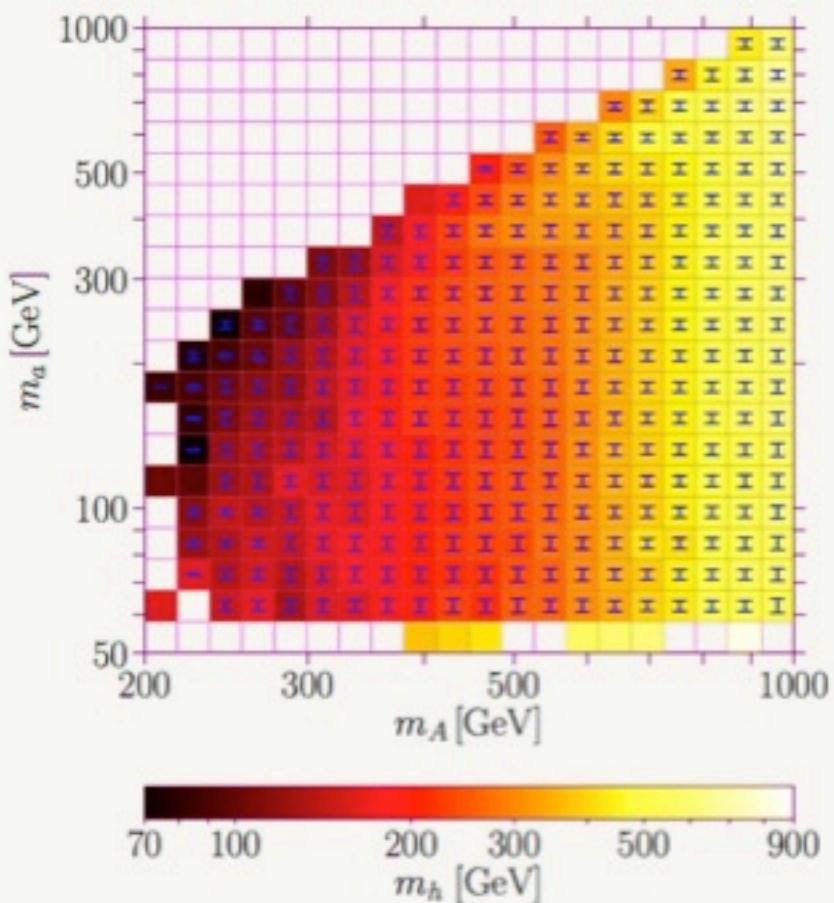


NMSSM Higgs Sector



SM-like h_{125} : Large Correlations

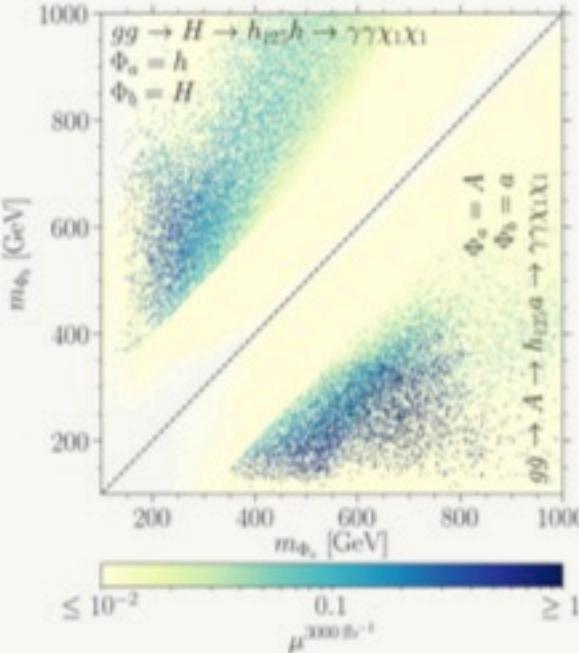
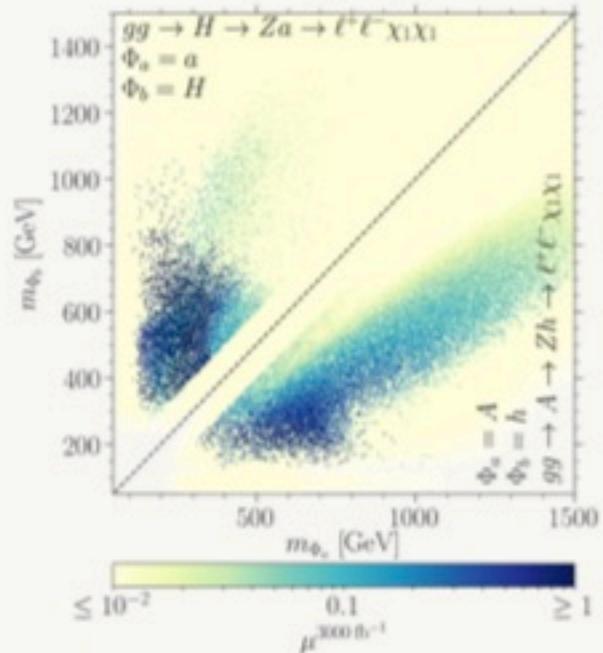
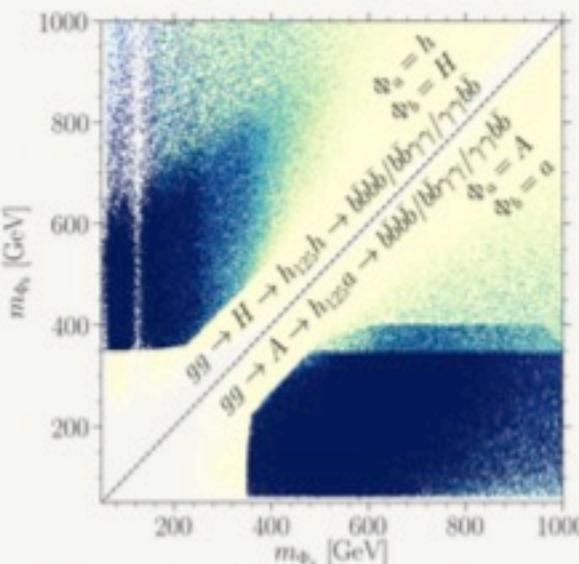
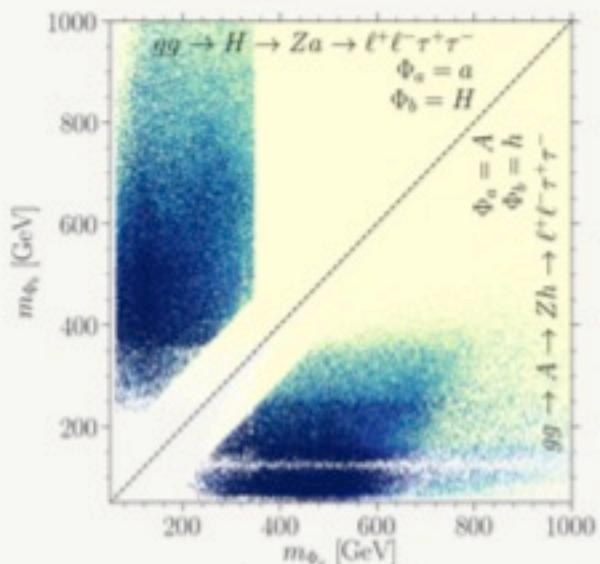
Preliminary, S. Baum, N.R.S, K. Freese



NMSSMTools scan with consistent h_{125} pheno

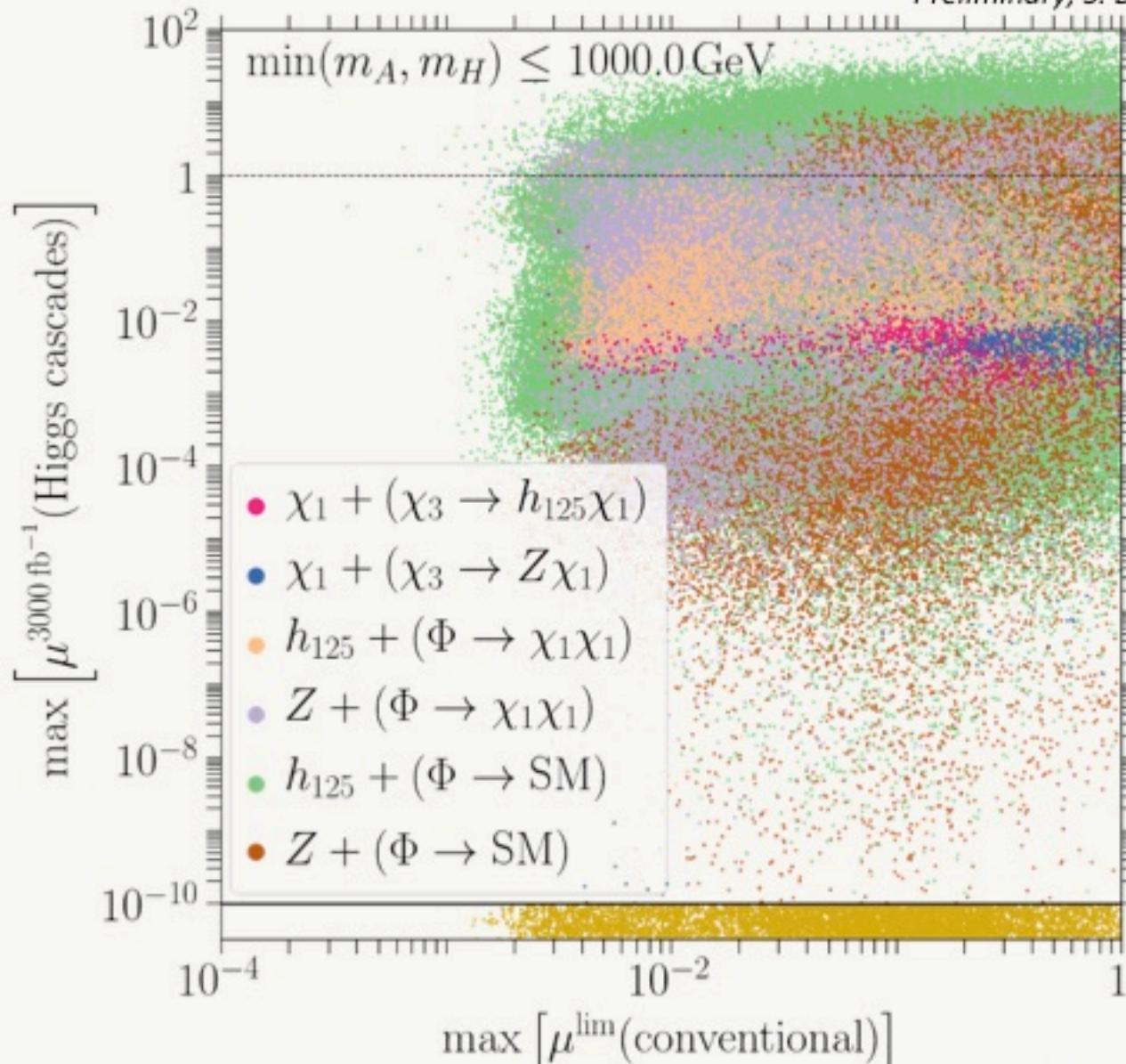


Cascade Prospects?

 $L = 3000 \text{ fb}^{-1}$ 

LHC: Coverage of NMSSM Higgs Sector

Preliminary, S. Baum, N.R.S, K. Freese



Thank You!



What are the right questions?

Data + Theory:
Where to look next!

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

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

“May we live
in interesting times.”



BACK UP

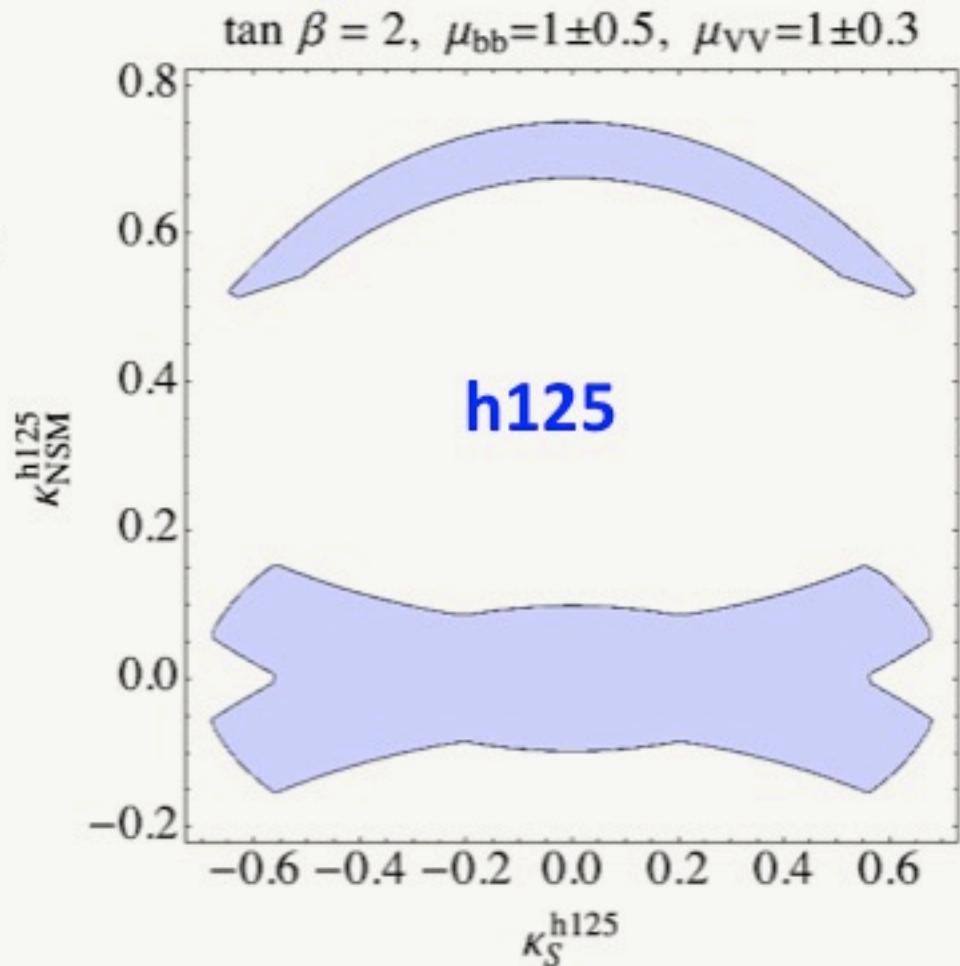


- How much “non-standardness” is allowed by h125 measurements??
 - $\kappa_{NSM} H_{NSM} + \kappa_{SM} H_{SM} + \kappa_S S$
 - Singlet: Only coupling to Higgs
 - Ratios to SM:
 - $g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/t_\beta)$
 - $g_{hdd} = (\kappa_{SM} - \kappa_{NSM} t_\beta)$
 - $g_{hVV} = \kappa_{SM}$

Contamination allowed in h125 ??



- How much “non-standardness” is allowed by h125 measurements??
- $\kappa_{NSM} H_{NSM} + \kappa_{SM} H_{SM} + \kappa_S S$
- Singlet: Only coupling to Higgs
- Ratios to SM:
 - $g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/\tan\beta)$
 - $g_{hdd} = (\kappa_{SM} - \kappa_{NSM} \tan\beta)$
 - $g_{hvv} = \kappa_{SM}$
- Significant κ_S OK
- Large κ_{NSM} from sign change of g_{hdd}



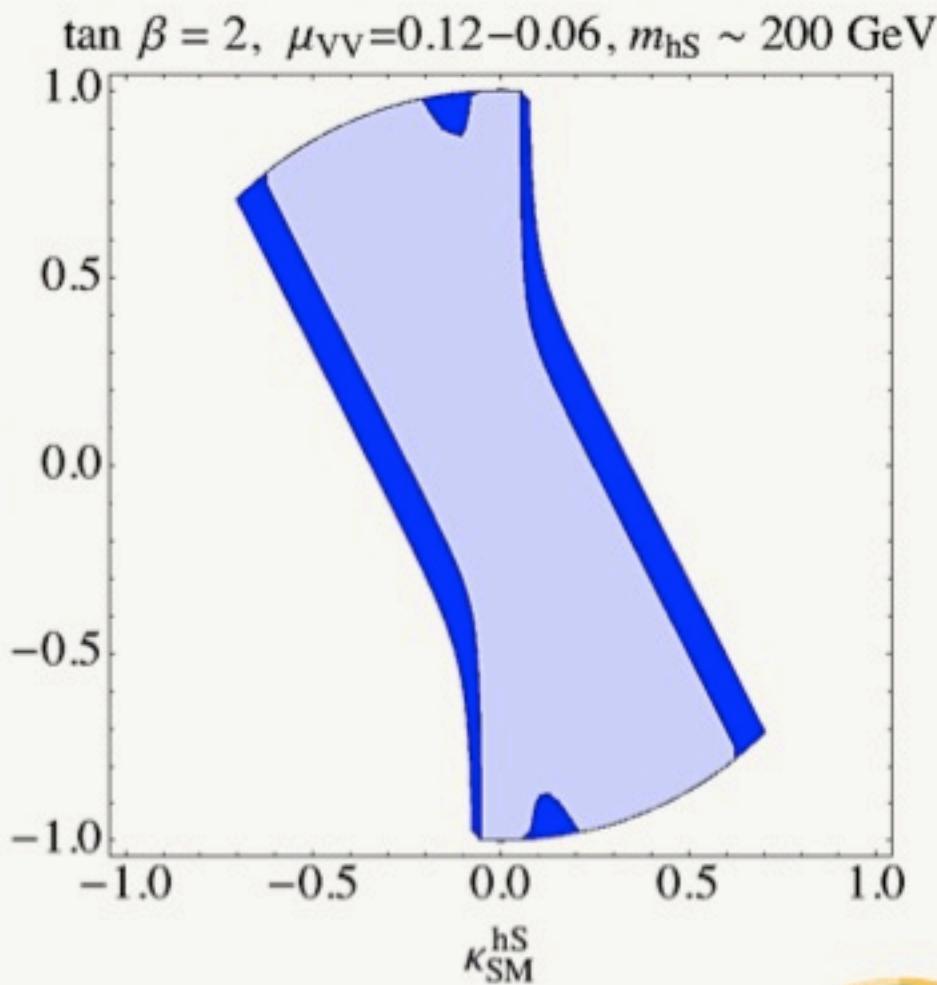
Contamination allowed in h125 ??

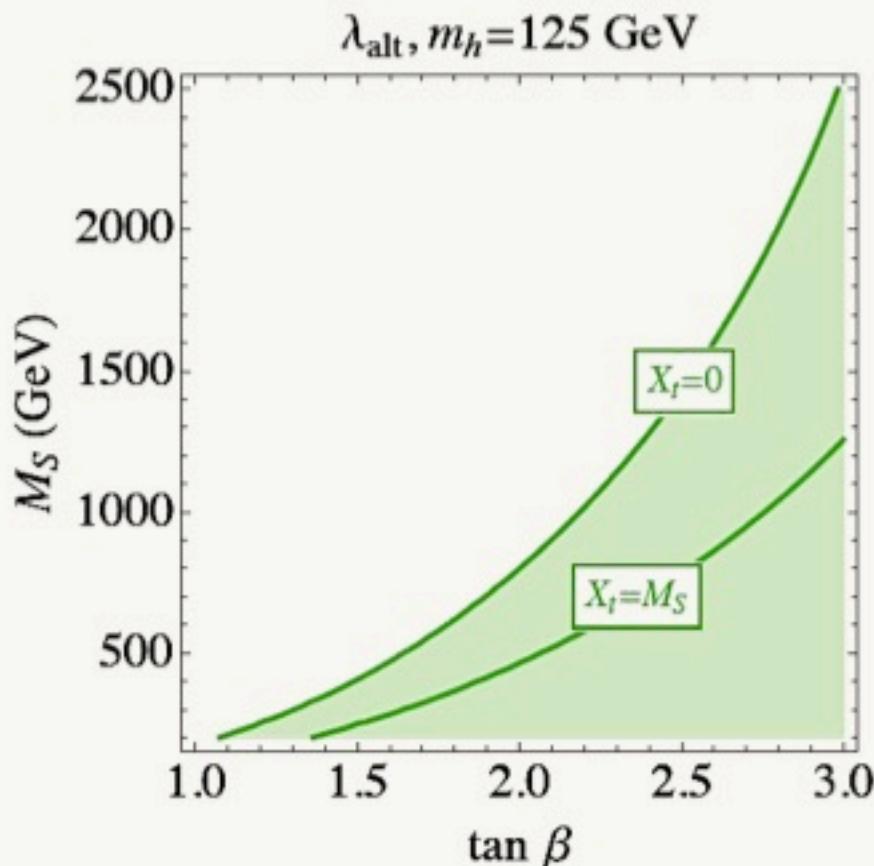


Direct Searches for heavy resonances?

- Strong constraints on SM-like Higgs decay to VV ~12-6% SM value for masses 160-500 GeV. CMS 1505.03831
- What does this imply for SM and NSM components of extra Higgs??
 - $160 \text{ GeV} < m_{hS} < 350 \text{ GeV}$
 - $\text{BR}(WW+ZZ) \sim 1$
 - gF production XS impacted.
- With $\kappa_{\text{NSM}}^{h125} \sim 0$
 - $\kappa_{\text{SM}}^{hS} \sim \kappa_s^{h125}$
 - κ_s^{h125} smaller than allowed by h125 measurements!

Only SM component couples to WW or ZZ!!





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 .
 - $\lambda \sim 0.65-0.7$
- Low $\tan \beta$
- Light Stops

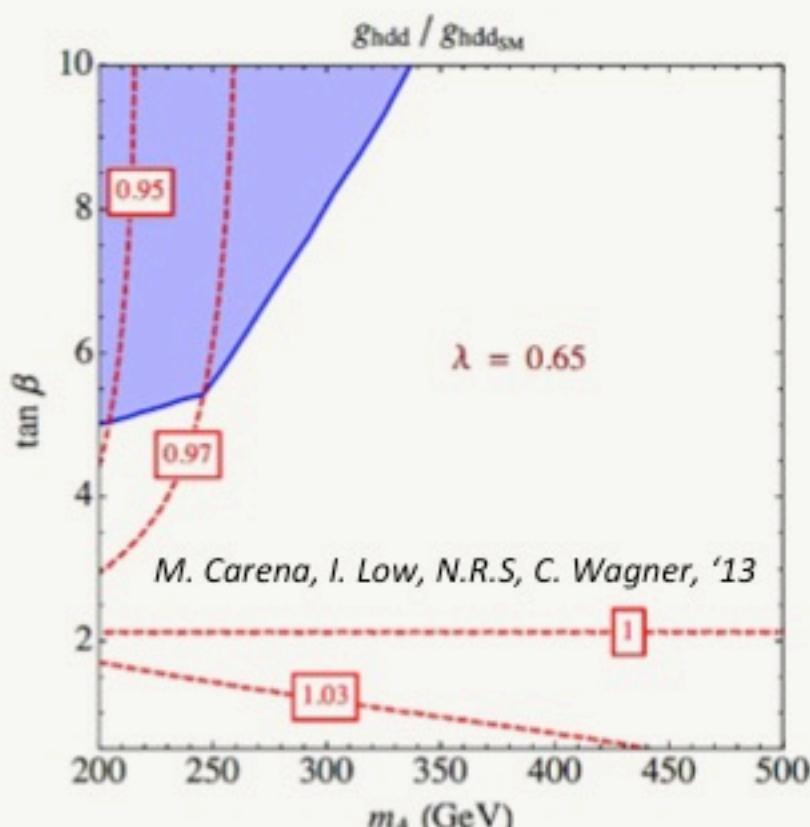
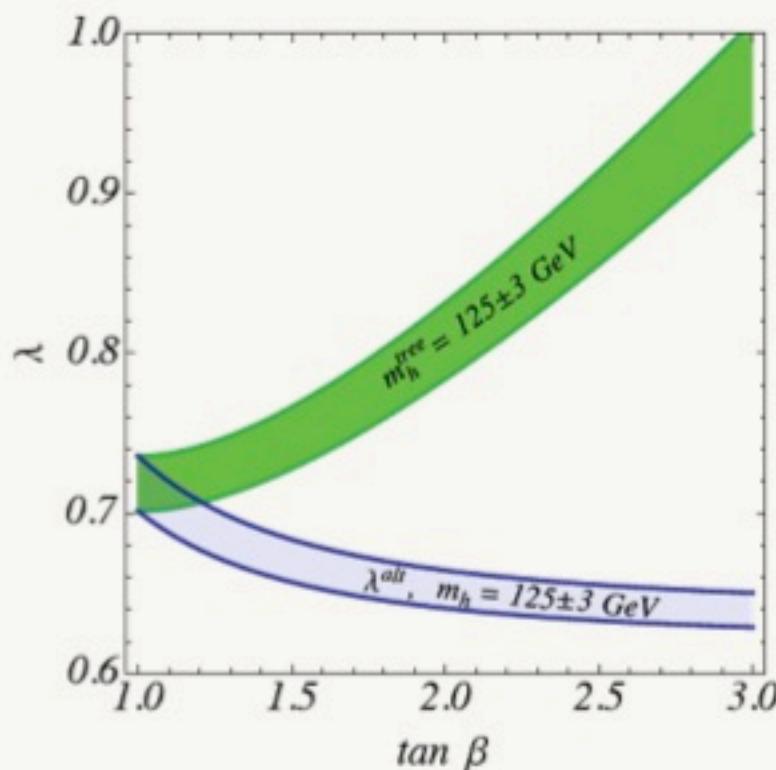
**NMSSM:
125 GeV Higgs Naturally!**



- 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 - $\tan\beta$ plane.

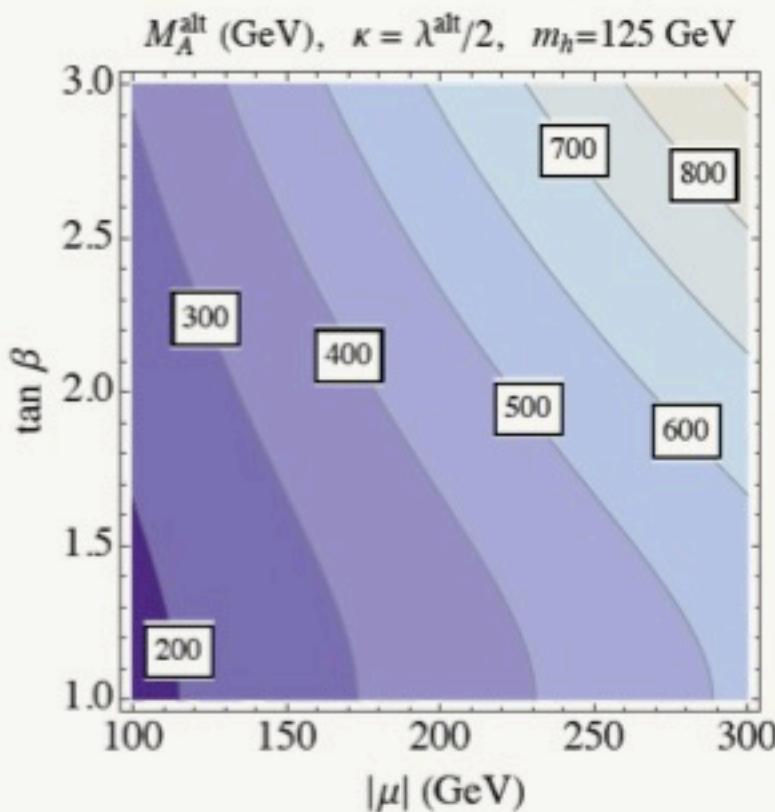


$$\lambda_{\text{alt}}^2 = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_{\beta}^2}$$

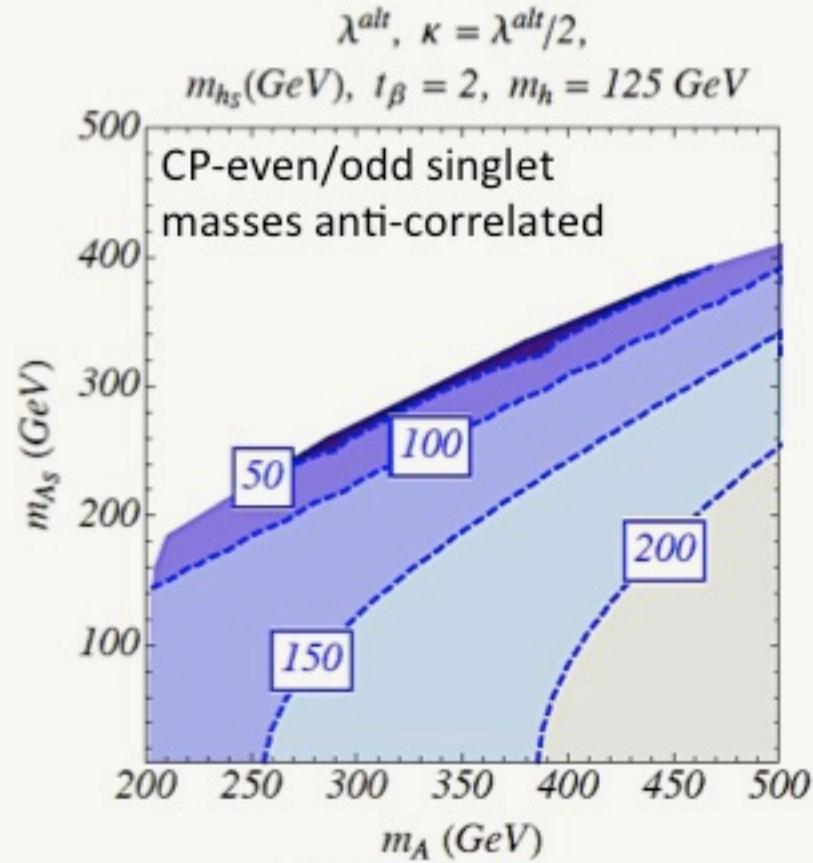
M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, '15

SM-Like Higgs Naturally!





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



h125 = H_{SM}
LIGHT SPECTRUM

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

Singlet Alignment

