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

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BSM Higgs Sector?

2 Higgs Doublet + Singlet
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2HDM: SUSY
S: SUSY + EWPT + DM + flavor...
Where to Start?

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2 Higgs Doublet + Singlet

Dark Matter?
Singlet Fermion
Where to Start?

BSM Higgs Sector
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Simplified Model, EFT, SUSY (NMSSM)
2 Higgs Doublet Model (2HDM).

\[ <H_1>, <H_2> \rightarrow <H>, \tan \beta \]

2 Higgs doublets (Type II):
- \( H_u \) – Couples only to up-type quarks
- \( H_d \) – Couples only to down-type quarks and leptons.

\[
m_A \sim m_H \\
\tan \beta = \frac{v_u}{v_d}
\]

5 Physical Higgs bosons:
- CP-Even: \( h, H \)
- CP-Odd: \( A \)
- Charged Higgs: \( H^{+,-} \)
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!

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

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

$v \sin^2 \beta$

$v \cos^2 \beta$

$<H_d> = v \cos \beta$

$<H_u> = v \sin \beta$

$\Rightarrow <h_{125}> = v$

$<H> = 0$

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

\[
\langle H_u \rangle = v_u \\
\langle H_d \rangle = v_d \\
t_\beta = v_u/v_d \\
\langle S \rangle = \mu/\lambda
\]
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  - \(H_u\): Couples only to up-type fermions
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• “Extended” Higgs basis: \((H_{NSM}, H_{SM}, S)\)
  - \(H_{NSM}\): \((\text{down, up, } V) = (y_d, t_\beta, y_u / t_\beta, 0)\)
  - \(H_{SM}\): \((\text{down, up, } V) = (y_d, y_u, g_{hVV})\)

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

Only SM state couples to WW or ZZ!!

\(\langle H_{NSM} \rangle = 0\)
\(\langle H_{SM} \rangle = v\)

**CP-Even Higgs Bases**
• Interaction basis: \((H_u, H_d, S)\)
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• Mass basis: \((H^3, H^2, H^1)\)
  \[-H^i = k_{NSM}^i H_{NSM} + k_{SM}^i H_{SM} + k_S^i S\]

\(<H_u> = v_u\\
<H_d> = v_d\\
t_\beta = v_u/v_d\\
<S> = \mu/\lambda\\

<H_{NSM}> = 0\\
<H_{SM}> = v\\

\textbf{CP-Even Higgs Bases}
• Interaction basis: \((H_u, H_d, S)\)
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\[
\begin{align*}
<H_u> &= v_u \\
<H_d> &= v_d \\
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\end{align*}
\]

• “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, \(V\)) = \((y_d, y_u, g_{hVV})\)

\[
\begin{align*}
<H_{NSM}> &= 0 \\
<H_{SM}> &= v
\end{align*}
\]

• 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: 27 parameters!!

\[
\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] + Y_4 S^\dagger S \\
+ [C_1 H_1^\dagger H_1 S + C_2 H_2^\dagger H_2 S + C_3 H_1^\dagger H_2 S + C_4 H_2^\dagger H_1 S + C_5 (S^\dagger S) S + C_6 S^3 + \text{h.c.}] \\
+ \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1) (H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2) (H_2^\dagger H_1) \\
+ \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + [Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\} \\
+ S^\dagger S [Z_{s1} H_1^\dagger H_1 + Z_{s2} H_2^\dagger H_2 + (Z_{s3} H_1^\dagger H_2 + \text{h.c.}) + Z_{s4} S^\dagger S] \\
+ \left\{ Z_{s5} H_1^\dagger H_1 S^2 + Z_{s6} H_2^\dagger H_2 S^2 + Z_{s7} H_1^\dagger H_2 S^2 + Z_{s8} H_2^\dagger H_1 S^2 + Z_{s9} S^\dagger S S^2 + Z_{s10} S^4 + \text{h.c.}\right\}.
\]
• Many parameters related to entries of the mass matrices.

• Certain trilinear couplings suppressed by SM-like nature of $h_{125}$ (alignment), for e.g:

$$\left\{ g_{H^{SM}H^{SM}H^{NSM}}, \quad g_{H^{SM}H^{SM}H^{S}} \right\} \rightarrow 0$$

• 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 parameters of Higgs potential: more physically meaningful

\[ m_{h_{125}}, m_H, m_h, m_A, m_a, S_{h_{125}}^S, S_{h_{125}}^{NSM}, S_H^S, P_A^S; \]

\[ v, \tan \beta, v_S; \]

\[ m_{H^\pm}; \]

\[ \{ g_{H^{NSM} H^{NSM} H^{NSM}}, g_{H^{SM} H^{SM} H^{SM}}, g_{H^{SM} A^S A^S} \}, \]

\[ \{ g_{H^{NSM} H^{NSM} H^{NSM}}, g_{H^{NSM} H^{NSM} H^{SM}}, g_{H^{SM} H^{SM} H^{SM}}, g_{H^{NSM} A^S A^S} \}, \]

\[ \{ g_{H^{SM} H^{SM} H^{SM}}, g_{H^{SM} A^S A^S} \}. \]

\[ \{ \lambda_{H^{NSM} H^{NSM} H^{SM} H^{SM}}, \lambda_{H^{NSM} H^{NSM} A^S A^S}, \lambda_{H^{NSM} A^S A^S}, \lambda_{A^S A^S A^S} \}. \]
• Interesting cascade decays due to presence of additional Higgs bosons:
  – Eg: $H_{\text{NSM}} \rightarrow h H_{\text{SM}}$ or $H_{\text{NSM}} \rightarrow a Z$

\[ H_{\text{NSM}} \rightarrow H_{\text{SM}} H_{\text{SM}} \text{ or } A \rightarrow Z H_{\text{SM}} \text{ suppressed due to alignment} \]
\[ \Gamma(h_i \to ZZ) = \frac{(S_{h_i}^{SM})^2 m_Z^4}{16 \pi m_{h_i} v^2} \left( 3 - \frac{m_{h_i}^2}{m_Z^2} + \frac{m_{h_i}^4}{4 m_Z^4} \right) \sqrt{1 - 4 \frac{m_Z^2}{m_{h_i}^2}} , \]

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

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

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

\[ \Gamma(\Phi_i \to Z \Phi_j) = \frac{(C_{\Phi_i}^{NSM} C_{\Phi_j}^{NSM})^2}{32 \pi} \frac{m_Z^2}{m_{\Phi_i} v^2} \left[ \frac{m_{\Phi_i}^2}{m_Z^2} \left( \frac{m_{\Phi_i}^2 - m_{\Phi_j}^2}{m_Z^2} \right)^2 - 2 \left( \frac{m_{\Phi_i}^2}{m_{\Phi_j}^2} + m_{\Phi_j}^2 \right) \right] \]

\[ \quad \times \sqrt{1 - 2 \frac{m_{\Phi_j}^2 + m_Z^2}{m_{\Phi_i}^2} + \left( \frac{m_{\Phi_j}^2 - m_Z^2}{m_{\Phi_i}^2} \right)^2} , \quad (2. \]

\[ \Gamma(\Phi_i \to \chi_j \chi_k) = \left( \frac{2}{1 + \delta_{ij}} \right) \frac{g_{\Phi_i \chi_j \chi_k}^2}{16 \pi} m_{\Phi_i} \left[ 1 - \frac{(m_{\chi_j} + m_{\chi_k})^2}{m_{\Phi_i}^2} \right]^{(1+\gamma)} \left[ 1 - \frac{(m_{\chi_j} - m_{\chi_k})^2}{m_{\Phi_i}^2} \right]^{(1-\gamma)} \]
$h_{125} \Phi$ or $Z \Phi$, Who Wins??

$g_{h_{125}Hh} = \frac{S_{H}^{NSM}}{\sqrt{2v}} S_{H}^{S} \left\{ [1 - 2(S_{H}^{S})^2] (m_{H}^2 - m_{h}^2) + \sqrt{2v} \tilde{g}_{H} \right\}$

$g_{h_{125}Aa} = \frac{P_{A}^{NSM} P_{A}^{S}}{\sqrt{2v}} \left\{ [1 - 2(P_{A}^{S})^2] (m_{A}^2 - m_{a}^2) + \sqrt{2v} \tilde{g}_{A} \right\}$

$g_{H_{NSM}^{ANSM}Z} = \frac{1}{2} i \sqrt{g_{1}^2 + g_{2}^2} (p - p')^{\mu}$

S. Baum & N.R.S., '18
• Decay visibly to SM particles via mixing with doublets (either NSM or SM components)
h / a Decays

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- Decay invisibly to possible DM particles
$
\text{\textbf{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
  – $h_{125} + \text{visibles}$
  – $\text{mono-h}_{125}$
  – $Z + \text{visibles}$
  – $\text{mono-Z}$
\[ \frac{S}{\sqrt{B + \Delta^2 B^2}} > 2 \quad \text{and} \quad S > 5 \]

See the Cascades!!

S. Baum & N.R.S., ‘18

Convolute everything!

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

Scale up current limits + various projections in the literature + our simulation for mono-Z/H
BM DM coupling chosen such that:

- $h \rightarrow$ visible
- $a \rightarrow$ invisible

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

$A \rightarrow Z \, h \rightarrow Z + \text{visibles}$

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

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

$H \rightarrow h_{125} \, h \rightarrow h_{125} + \text{visibles}$
If either $m_a$ or $m_h > 350$ GeV, can decay predominantly to $t\bar{t}$.

Could be hidden in $h_{125} t\bar{t}$?
Displayed cross sections don’t include SM-like $h_{125}$ BR

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

S. Baum & N.R.S., ’19
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
$W = \lambda S H_u H_d + \frac{\kappa}{3} S^3$

- 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: $2 \kappa \mu / \lambda$
SM - like $h_{125}$: Large Correlations

NMSSMTools scan with consistent $h_{125}$ pheno

S. Baum, N.R.S, K. Freese, '19
LHC All Searches: \(3000 \text{ fb}^{-1}\) NMSSM Higgs Sector

Optimistic scenario shown!  
S. Baum, N.R.S, K. Freese, ’19

Expect \(\sim 50\%\) scanned region with \(m_A < 1\) TeV probed.

\(\sim 90\%\) if improvements by 1 order of magnitude wrt our projections, & 2 orders of magnitude in conventional search channels wrt current limits.
What are the right questions?

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 + Theory: Where to look next!

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

“May we live in interesting times.”
• 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:
  - \( g_{hgg} = (\kappa_{SM} + \kappa_{NSM}/t_\beta) \)
  - \( g_{hdd} = (\kappa_{SM} - \kappa_{NSM} t_\beta) \)
  - \( g_{hVV} = \kappa_{SM} \)
• How much “non-standardness” is allowed by h125 measurements??

\[ \kappa_{\text{NSM}} H_{\text{NSM}} + \kappa_{\text{SM}} H_{\text{SM}} + \kappa_S S \]

• Singlet: Only coupling to Higgs

• Ratios to SM:
  - \( g_{hgg} = \left( \kappa_{\text{SM}} + \kappa_{\text{NSM}} / \tan \beta \right) \)
  - \( g_{hdd} = \left( \kappa_{\text{SM}} - \kappa_{\text{NSM}} \tan \beta \right) \)
  - \( g_{hVV} = \kappa_{\text{SM}} \)

• Significant \( \kappa_S \) OK
• Large \( \kappa_{\text{NSM}} \) 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 GeV < m_{hS} < 350 GeV
  - BR(WW+ZZ) ~1
  - gF production XS impacted.

- **With κ^{h125}_{NSM} \sim 0**
  - κ^{hS}_{SM} \sim κ^{h125}_S
  - κ^{h125}_S smaller than allowed by h125 measurements!
NMSSM: 125 GeV Higgs Naturally!

Well Known

- 125 GeV Higgs
  - Tree-level contribution to Higgs mass from $\lambda$.
  - $\lambda \sim 0.65$-0.7
- Low $\tan\beta$
- Light Stops

Alignment (No-Mixing):

$$m_{h}^2 \approx \frac{\lambda^2 v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta\tilde{t}$$

$$\Delta\tilde{t} = - \cos 2\beta (m_{h}^2 - M_Z^2)$$

$\lambda_{alt}$, $m_h=125$ GeV
• Perturbative up to GUT scale.
  – \( \lambda_{\text{max}} \sim 0.7, \kappa_{\text{max}} \sim \lambda/2 \)

**Not so well known:**

• Leads to excellent Alignment (very little mixing with Heavy Higgs) in the \( m_A - \tan\beta \) plane.

\[
\lambda^2_{\text{alt}} = \frac{m_h^2 - M_Z^2 c_{2\beta}}{v^2 s_{2\beta}^2}
\]

M. Carena, H. Haber, I. Low, N.R.S., C. Wagner, ’15
Singlet Alignment

\[ M_{A}^{\text{alt}} \, (\text{GeV}), \quad \kappa = \lambda^{\text{alt}}/2, \quad m_h = 125 \, \text{GeV} \]

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

\[ \lambda^{\text{alt}}, \quad \kappa = \lambda^{\text{alt}}/2, \quad m_{h_5} \, (\text{GeV}), \quad t_\beta = 2, \quad m_h = 125 \, \text{GeV} \]

CP-even/odd singlet masses anti-correlated

\[ h_{125} = H_{\text{SM}} \]

LIGHT SPECTRUM

Singlino: \( 2 \frac{\kappa \mu/\lambda}{\sim < \mu} \)
Cascade Prospects

L = 3000 fb⁻¹