Why even more Higgs?

A layman's guide to Beyond SM Higgs sectors

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IMPRS colloquium
26.4.2018, München

SM Higgs sector - repetition

- SM Higgs potential:

$$V_{\rm SM}(\Phi) = \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{2}(\Phi^\dagger \Phi)^2$$

- $\mu, \lambda > 0 \to$ electroweak symmetry breaking, expand around $v = \sqrt{\mu^2/\lambda}$:

$$\Phi(x) = \begin{pmatrix} G^+(x) \\ v + \frac{1}{\sqrt{2}}(H(x) + iG^0(x)) \end{pmatrix}$$

- Minimal Higgs sector to achieve massive fermions and gauge bosons

$$M_W^2 = \frac{v^2}{2} g^2,\ M_Z^2 = \frac{v^2}{2}(g^2 + g'^2),\ M_f = y_f v,\ M_H^2 = 2\lambda v^2$$

(g: $SU(2)_L$ gauge coupling, g': $U(1)_Y$ gauge coupling)

Why should we go beyond this?

- Higgs boson discovered @ LHC so far is the only known fundamental spin-0 particle
  $\rightarrow$ Why should there only be one such particle?
- Higgs sector not yet measured precisely
  $\rightarrow$ ample room for BSM physics
- Other SM sectors well explored. Still open problems (DM, neutrino masses, baryogenesis, ...)
  $\rightarrow$ Can a BSM Higgs sector help to solve them?

Idea - add an extra (real) Higgs singlet to the SM

- SM gauge singlet does not couple directly to SM gauge bosons
- Only interacts with SM Higgs

$$V(\Phi, S) = \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{2}(\Phi^\dagger \Phi)^2 + \mu_S^2 S^2 - \frac{\lambda_S}{2} S^4 - \kappa S^2 \Phi^\dagger \Phi$$

Motivation:

- Simplest possible extension
- S can mediate between SM particles and other new particles → Higgs portal
- can be used to build e.g. DM models (add $y_\chi S \bar{\chi} \chi$ to Lagrangian)
- electroweak baryogenesis

Higgs mixing (I)

Also S can develop a vev:

$$S(x) = v_S + \frac{1}{\sqrt{2}} H_S(x)$$

Therefore, the Higgs mass terms read

$$V_{\text{mass}}(H, H_S) = \begin{pmatrix} H & H_S \end{pmatrix} \begin{pmatrix} 2\lambda v^2 & 2\kappa v v_S \\ 2\kappa v v_S & 2\lambda_S v_S^2 \end{pmatrix} \begin{pmatrix} H \\ H_S \end{pmatrix}$$

Introduce new states H_1, H_2 with

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ H_S \end{pmatrix}$$

Choose α such that mass matrix is diagonal.

Higgs mixing (II)

with $\tan(2\alpha) = \frac{2\kappa v v_S}{\lambda v^2 - \lambda_S v_S^2}$ we get:

$$V_{\text{mass}}(H_1, H_2) = \begin{pmatrix} H_1 & H_2 \end{pmatrix} \begin{pmatrix} m_{H_1}^2 & 0 \\ 0 & m_{H_2}^2 \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

Take home message

mass eigenstates are mixture of H and H_S

- similar to quark mixing, gauge boson mixing in SM
- immediate phenomenological consequences

Testing the model

- Search for second Higgs directly
- Check theoretical constraints (vacuum stability, unitarity, pertubativity, ...)
- Compare to electroweak precision data (W boson mass, Z width, ...)
- ...

other possibility: compare to LHC Higgs boson measurements!

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- Often signal strength is given:
  $\mu_i^f = \frac{\sigma_i \times \mathrm{BR}_{H_1 \to f}}{(\sigma_i \times \mathrm{BR}_{H_1 \to f})_{\mathrm{SM}}} = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \frac{\Gamma_{H_1 \to f}}{\Gamma^{\mathrm{SM}}_{H_1 \to f}} \frac{\Gamma^{\mathrm{tot,SM}}_{H_1}}{\Gamma^{\mathrm{tot}}_{H_1}} = \cos^2\alpha$

Higgs couplings (II)

$\Rightarrow$ Measurement of signal strength directly constrains α (or κ)

- $\cos^2\alpha \leq 1 \Rightarrow \mu_i^f \leq 1$

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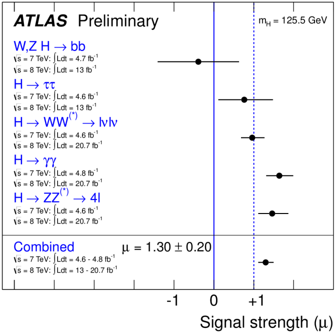


- caveats: no non-SM loop corrections considered, assumption of no additional decay/production channels, ...

Idea: Add a second Higgs doublet to the SM

$$
\begin{aligned}
&V_{\text{THDM}}(\Phi_1,\Phi_2) = \\
&m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) \\
&+ \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
&+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5\left((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right) \\
&+ \lambda_6(\Phi_1^\dagger\Phi_1)\left((\Phi_1^\dagger\Phi_2) + (\Phi_2^\dagger\Phi_1)\right) + \lambda_7(\Phi_2^\dagger\Phi_2)\left((\Phi_1^\dagger\Phi_2) + (\Phi_2^\dagger\Phi_1)\right)
\end{aligned}
$$

with

$$
\Phi_1(x) = \begin{pmatrix} G_1^+(x) \\ v_1 + \frac{1}{\sqrt{2}}(H_1(x) + iG_1^0(x)) \end{pmatrix},
$$

$$
\Phi_2(x) = \begin{pmatrix} G_2^+(x) \\ v_2 + \frac{1}{\sqrt{2}}(H_2(x) + iG_2^0(x)) \end{pmatrix}
$$

Motivation

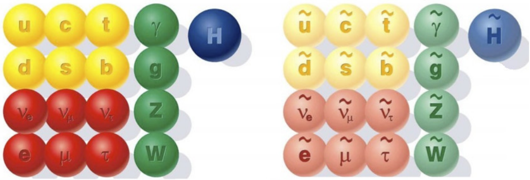
- might help to explain matter-antimattter assymetry of the universe
  - additional source of $\mathcal{CP}$ violation ($m_{12}^2, \lambda_{5,6,7}$ can be complex)
  - electroweak baryogenisis
- can provide a DM candidate
- flavour violation

Particle spectrum

- two complex doublets $\rightarrow 2 \cdot 4$ degrees of freedom
- gauge bosons 'eat' 3 degrees of freedom
  $\rightarrow 8 - 3 = 5$ physical Higgs bosons
- $\mathcal{CP}$-even h and H, $\mathcal{CP}$-odd A, charged $H^{\pm}$
- h and H are mixtures of H_1 and H_2

Minimal Supersymmetric Standard Model (I)

- SUSY relates bosons and fermions
- Each SM particle gets a superpartner with same properties apart of spin shifted by 1/2



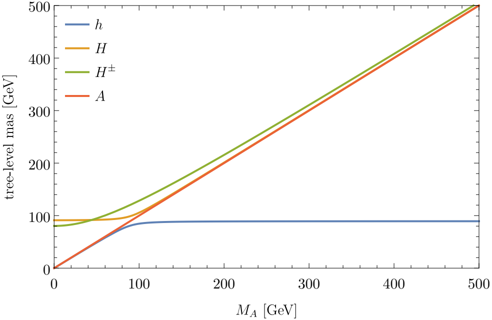
- Motivation: hierarchy problem, DM, gauge coupling unification, baryogenesis, flavour violation, EWSB, ...

Minimal Supersymmetric Standard Model (II)

MSSM also contains two Higgs doublets

- supersymmetry fixes couplings:
  $\lambda_1 = \lambda_2 = \frac{1}{4}(g^2 + g'^2), \lambda_3 = \frac{1}{4}(g^2 - g'^2), \lambda_2 = -\frac{1}{2}g^2, \lambda_{5,6,7} = 0$

Higgs sector completely determined by M_A and $\tan\beta = v_2/v_1$ at tree-level

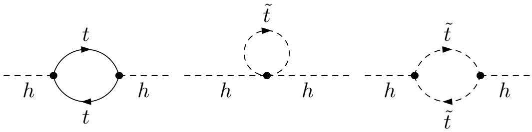


Minimal Supersymmetric Standard Model (III)

What's about SM-like Higgs mass?

$m_h^2 \lesssim M_Z^2 \cos(2\beta)^2 \leq M_Z^2 \rightarrow$ ruled out!?

No. Loop corrections from supersymmetric top partners yield a large upwards shift:



$$M_h^2 = M_Z^2 \cos(2\beta)^2 + \frac{3}{4\pi^2} m_t^2 y_t^2 \ln\left(\frac{M_S^2}{m_t^2}\right) + \ldots$$

with the stop mass scale $M_S^2 = m_{\tilde{t}_1} m_{\tilde{t}_2}$

- Present status: corrections up to N^{3}LO, NNLL

Other models

- add doublet and singlet
  - e.g. NMSSM (MSSM+singlet)
  - up to 5 Higgs bosons mix
- add triplet
  - can be used to explain neutrino masses
  - exotic states like H^{++}
- ...

Conclusions

- plenty of BSM Higgs models
  (singlet extension, THDM, MSSM, ...)
- BSM Higgs sectors may help to explain open problems of SM
- High experimental precision allows to probe them even without direct detection
- Experimental precision has to be matched by theoretical calculations (see MSSM Higgs mass)