Constraints on BSM physics through the Higgs couplings

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The Brout-Englert-Higgs mechanism

Crucial problem in particle physics: how to generate particle masses in an \( SU(2) \times U(1) \) gauge invariant way?

- Take an SU(2)-doublet of scalar fields \( \Phi = \left( \phi^+, \phi^0 \right) \), \( Y_\Phi = +1 \), with a Lagrangian invariant under \( SU(2)_L \times U(1)_Y \):
  \[
  L_S = (D_\mu \Phi)^\dagger D^\mu \Phi - V(\Phi), \quad V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad D_\mu = \partial_\mu - ig T^a W^a_\mu - ig' \frac{Y}{2} B_\mu
  \]

  \( T^a \) are the SU(2) generators & \( W^a_\mu \) are the SU(2) gauge bosons 
  \( Y \) is the hypercharge & \( B_\mu \) is the U(1) gauge boson

- \( \mu^2 > 0 \): 4 scalar particles & \( \mu^2 < 0 \): \( \Phi \) gets a V.E.V.
  \[
  \langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \text{ with } v = \sqrt{-\frac{\mu^2}{\lambda}} = 246 \text{ GeV}
  \]
  \[
  \Rightarrow \Phi(x) = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix}
  \]

  \( \Rightarrow \) three d.o.f. for \( M_{W^\pm} \) and \( M_Z \)

  Fermion masses: \( L_{Yuk} = -f_e (\bar{\nu}, \bar{\nu}) L \Phi e_R + ... \)

  \( \Rightarrow \) one residual scalar boson = the Higgs (\( M_H = 2\lambda v^2 \))

[Higgs (1964); Brout, Englert (1964); Hagen,Kibble,Guralnik (1964)]
The Higgs boson couplings

After EWSB, the Higgs boson couples to fermions, gauge bosons and itself as:

\[ g_{Hff} = \frac{m_f}{v} \times (-i) \]

\[ g_{HV\nu} = 2 \frac{M_V^2}{v} \times (ig_{\mu\nu}) \]

\[ g_{HHVV} = 2 \frac{M_V^2}{v^2} \times (ig_{\mu\nu}) \]

\[ g_{HHH} = 3 \frac{M_H^2}{v} \times (-i) \]

\[ g_{HHHH} = 3 \frac{M_H^2}{v^2} \times (-i) \]

- \( g_{Hff} \propto m_f \): Higgs couples mostly to top and bottom quarks fermion
- \( ggH \) and \( \gamma\gamma H \) couplings arise at one-loop level

\[ \rightarrow \text{Since } v \text{ is known, the only free parameter in the SM is } M_H \text{ (or } \lambda) \]
The 4th of July 2012: discovery of a new 125 GeV boson

ATLAS Prelim. $m_H = 125.5$ GeV

- \(H \rightarrow \gamma\gamma\): $\mu = 1.57^{+0.33}_{-0.28}$
- \(H \rightarrow ZZ^* \rightarrow 4l\): $\mu = 1.44^{+0.40}_{-0.35}$
- \(H \rightarrow WW^* \rightarrow h\bar{h}\): $\mu = 1.00^{+0.32}_{-0.29}$
- Combined \(H \rightarrow \gamma\gamma, ZZ^*, WW^*\): $\mu = 1.35^{+0.21}_{-0.20}$

- \(W,Z \rightarrow b\bar{b}\): $\mu = 0.2^{+0.7}_{-0.6}$
- \(H \rightarrow \tau\tau\) (8 TeV data only): $\mu = 1.4^{+0.5}_{-0.4}$
- Combined \(H \rightarrow b\bar{b}, \tau\tau\): $\mu = 1.09^{+0.36}_{-0.32}$

Total uncertainty $\pm 1\sigma$ on $\mu$

<table>
<thead>
<tr>
<th>$m_{\gamma\gamma}$ (GeV)</th>
<th>Events / 2 GeV</th>
</tr>
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<tbody>
<tr>
<td>100</td>
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<td>140</td>
<td>2500</td>
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<td>150</td>
<td>3000</td>
</tr>
</tbody>
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Data, Sig+Bkg Fit, Bkg (4th order polynomial)

CMS Preliminary $m_H = 125.7$ GeV

- $\sqrt{s} = 7$ TeV, $L = 5.1 \text{ fb}^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 5.3 \text{ fb}^{-1}$

$\mu = 0.80 \pm 0.14$

Best fit $\sigma / \sigma_{SM} = 0.94$

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Is it a Higgs?

Higgs couplings as predicted by Higgs mechanism
- couplings proportional to masses as expected
- couplings to $WW$, $ZZ$, $γγ$ roughly as expected

Is it a spin 0?
- state decays into $γγ$ ⇒ not spin-1 (Landau–Yang th.)
- is it a spin–2 like graviton?
  A priori no: $c_g ≠ c_γ$, $c_V ≫ 35c_γ$

Is it CP-even?

$$HV_μ V_μ \text{ vs } Hε^{μνρσ}Z_μ Z_ν Z_ρ Z_σ$$

$$⇒ \frac{dΓ(H→ZZ^*)}{dM^*} \text{ and } \frac{dΓ(H→ZZ)}{dϕ}$$

ATLAS/CMS: $\sim 3σ$ for CP-even

⇒ It is THE-A Higgs boson!
Outline

1. Constraints on SUSY models through the Higgs sector
2. Constraints on Dark-Matter models through the Higgs sector
Motivations for SUSY

- The hierarchy problem: why $M_H \ll M_{Pl}$?
  - The fermion 1-loop correction to the Higgs mass:

$$\delta^{(f)} m_H^2 \supset \frac{\lambda_F^2}{8\pi^2} \left[ -\Lambda^2 + 6m_F^2 \ln \frac{\Lambda}{m_F} \right]$$

- The scalar 1-loop correction to the Higgs mass:

$$\delta^{(s)} m_H^2 \supset \frac{\lambda_S^2}{16\pi^2} \left[ -\Lambda^2 + (2m_S^2 - 2\lambda_S v^2)\ln \left( \frac{\Lambda}{m_S} \right) \right]$$

- SUSY theory with $2N_F = N_S$ and with $\lambda_S = -\lambda_F^2$ ⇒ the quadratic divergences vanish (remain the logarithmic ones):

$$\delta^{(f+s)} m_H^2 = \frac{\lambda_S^2}{4\pi^2} \left[ (m_F^2 - m_S^2)\ln \left( \frac{\Lambda}{m_S} \right) + 3m_F^2\ln \left( \frac{m_S}{m_F} \right) \right]$$

⇒ the hierarchy and naturalness problems solved

if $m_F = m_S$ ⇒ $M_H$ is protected by SUSY
⇒ SUSY must be broken, $m_S \gg m_F$

- The gauge coupling unification
- A dark matter candidate (relies on R-parity)
The Minimal Supersymmetric Standard Model
Defined by 4 assumptions:

(a) **Minimal gauge group:** the MSSM is based on the group $SU(3)_C \times SU(2)_L \times U(1)_Y$, i.e. the SM gauge symmetry.

(b) **Minimal particle content:**
- gauge bosons + spin 1/2 SUSY partners: $\hat{G}^a, \hat{W}^a, \hat{B}$ (vector superfields)
- quarks and leptons + squarks and sleptons: $\hat{Q}, \hat{U}_R, \hat{D}_R, \hat{L}, \hat{E}_R$. (3 gen. of chiral superfields)
- 2 Higgs doublets + spin 1/2 SUSY partners: $\hat{H}_1, \hat{H}_2$

(c) **Minimal Yukawa interactions and R–parity conservation:** a discrete symmetry called
$R$–parity is imposed (enforce lepton and baryon number conservation)

$$R_p = (-1)^{2s+3B+L}; \quad R_p = \pm 1 \quad \text{for SM/SUSY particle}$$

(d) **Minimal set of soft SUSY–breaking terms:**
- Mass for gauginos: $-L_{gino} = \frac{1}{2} \left[ M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a\tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a\tilde{G}_a + \text{h.c.} \right]$
- Mass for sfermions: $-L_{sf} = \sum_{i=\text{gen}} m_{\tilde{Q}_i}^2 \tilde{Q}_i^\dagger \tilde{Q}_i + m_{\tilde{L}_i}^2 \tilde{L}_i^\dagger \tilde{L}_i + m_{\tilde{u}_R_i}^2 |\tilde{u}_R_i|^2 + m_{\tilde{d}_R_i}^2 |\tilde{d}_R_i|^2 + m_{\tilde{e}_R_i}^2 |\tilde{e}_R_i|^2$
- Mass and bilinear for the Higgs: $-L_{Higgs} = m_{H_2}^2 H_2^\dagger H_2 + m_{H_1}^2 H_1^\dagger H_1 + B\mu (H_2 \cdot H_1 + \text{h.c.})$
- Trilinear: $-L_{tril.} = \sum_{i,j=\text{gen}} \left[ A_{ij}^u Y_{ij}^u \tilde{u}_{R_i}^* H_2 \cdot \tilde{Q}_j + A_{ij}^d Y_{ij}^d \tilde{d}_{R_i}^* H_1 \cdot \tilde{Q}_j + A_{ij}^l Y_{ij}^l \tilde{e}_{R_i}^* H_1 \cdot \tilde{L}_j + \text{h.c.} \right]$

105 parameters (SSB) + 19 (SM) ⇒ phenomenological analysis complicated

Only 22 for the pMSSM:

$M_1, M_2, M_3, m_\tilde{q}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, A_u, A_d, A_e, m_j, m_{\tilde{e}_R}, m_Q, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_\tilde{l}, m_{\tilde{\tau}_R}, A_\tau, A_b, A_t, \tan \beta, m_{H_1}^2, m_{H_2}^2$
The Higgs sector of the MSSM

One needs 2 complex scalar doublets: \( H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \) and \( H_2 = \begin{pmatrix} H_2^0 \\ H_2^+ \end{pmatrix} \)

- give masses to respectively d and u fermions in SUSY invariant way
- cancel the chiral anomalies

After EWSB: 3 d.o.f. to make \( W_L^\pm, Z_L \Rightarrow 5 \) physical states left out: \( h, H, A, H^\pm \)

At tree-level only 2 free parameters \( \tan \beta, M_A \):

\[
M_{h,H}^2 = \frac{1}{2} \left[ M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4 M_A^2 M_Z^2 \cos^2 2\beta} \right], \quad \tan 2\alpha = \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}
\]

\[
M_{H^\pm}^2 = M_A^2 + M_W^2
\]

Important constraint on the MSSM Higgs boson masses:

\[
M_h \leq \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z, \quad M_H > \max(M_A, M_Z), \quad M_{H^\pm} > M_W
\]

\( M_A \gg M_Z \): decoupling regime, all Higgses heavy except \( h \):

\[
M_h \sim M_Z |\cos 2\beta| \leq M_Z, \quad M_H \sim M_{H^\pm} \sim M_A, \quad \alpha \sim \pi - \beta
\]

\( \Rightarrow \) Inclusion of radiative corrections to \( M_h \) are essential to explain \( M_h \approx 125 \text{ GeV} > M_Z \)
The radiative corrections to the Higgs mass

Dominant corrections are due to top (s)quark, at the one-loop level:

\[ M_h \xrightarrow{M_A \gg M_Z} M_Z |\cos 2\beta| + \frac{3\tilde{m}_t^4}{2\pi^2 v^2 \sin^2 \beta} \left[ \ln \frac{M_S^2}{\tilde{m}_t^2} + \frac{X_t^2}{2M_S^2} \left( 1 - \frac{X_t^2}{6M_S^2} \right) \right] \]

[Okada+Yamaguchi+Yanagida, Ellis+Ridolfi+Zwirner, Haber+Hempfling (1991)]

depending on \( \tan \beta \), \( M_S = \sqrt{\tilde{m}_{t1} \tilde{m}_{t2}} \), \( X_t = A_t - \frac{\mu}{\tan \beta} \):
\( M_h^{\text{max}} \rightarrow M_Z + 30 - 50 \text{ GeV} \)

The mass value \( 125 \text{ GeV} \) is near the upper limit for the MSSM h boson

Increase \( M_h \Rightarrow \) increase R.C. :

- decoupling regime with \( M_A \sim \mathcal{O} (\text{TeV}) \)

- large values of \( \tan \beta \gtrsim 10 \) to maximize tree-level value

- maximal mixing scenario: \( X_t = \sqrt{6}M_S \)

- heavy stops, i.e. large \( M_S = \sqrt{\tilde{m}_{t1} \tilde{m}_{t2}} \)

Perform a full scan of the pMSSM with 22+19 free parameters

- calculate the Higgs and SUSY spectrum in the MSSM with the full one–loop + dominant two–loop corrections.

- determine the regions of parameter space where \( 123 \leq M_h \leq 129 \text{ GeV} \) (3 GeV uncertainty includes both “experimental” and “theoretical” error)
Large $M_S$ values required:

- $M_S \sim 1$ TeV: only for maximal mixing
- $M_S \sim 3$ TeV: only for typical mixing

$\Rightarrow$ no-mixing scenario excluded (unless $M_S \gg 1$ TeV)

Large $\tan\beta$ values favored but $\tan\beta \sim 3$ allowed if $M_S \sim 3$ TeV

Constraints on sparticles: $m_{\tilde{t}_1} \sim 500$ GeV still possible!

$\Rightarrow$ maximal mixing disfavored for large $M_S$ and $\tan\beta$
Implication of a 125 GeV Higgs for the cMSSM

Concrete schemes: SSB occurs in hidden sector

Parameters obey boundary conditions ⇒ small number of inputs:

- **mSUGRA**: $\tan \beta$, $m_{1/2}$, $m_0$, $A_0$, $\text{sign}(\mu)$
- **GMSB**: $\tan \beta$, $\text{sign}(\mu)$, $M_{\text{mess}}$, $\Lambda_{SSB}$, $N_{\text{mess}}$
- **AMSB**: $m_0$, $m_{3/2}$, $\tan \beta$, $\text{sign}(\mu)$

Full scans of the model parameters with $123 \text{ GeV} \leq M_h \leq 129 \text{ GeV}$


<table>
<thead>
<tr>
<th>model</th>
<th>AMSB</th>
<th>GMSB</th>
<th>mSUGRA</th>
<th>no-scale</th>
<th>cNMSSM</th>
<th>VCMSSM</th>
<th>NUHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{h}^{\text{max}}$</td>
<td>121.0</td>
<td>121.5</td>
<td>128.0</td>
<td>123.0</td>
<td>123.5</td>
<td>124.5</td>
<td>128.5</td>
</tr>
</tbody>
</table>

End of AMSB and GMSB in their minimal versions!
As the scale $M_S$ seems to be large, we can consider 2 extreme possibilities:

- **Split SUSY**: allow fine-tuning
  - The SSB scalar mass terms at high scale (except 1 Higgs doublet)
  - Gauginos and higgsinos, are left at the EWSB scale (unification+DM still OK)
  - The parameters: $M_S$, 1 Higgs mass, $M_1$, $M_2$, $M_3$, $\mu$ and $\tan \beta$
  - Boundary condition on the quartic Higgs coupling:
    \[ \lambda(M_S) = \frac{1}{4} \left[ g_2^2(M_S) + g_2'^2(M_S) \right] \cos^2 2\beta \]
  - Heavy scalars $\Rightarrow$ R.C. in the Higgs sector enhanced by $\ln(M_{\text{EWSB}}/M_S)$

- **SUSY broken at the GUT scale**:
  - Abandon fine-tuning, DM, unification
  - SUSY/EWSB matching encoded in the Higgs quartic coupling $\lambda \propto M_h^2$ related to gauge couplings

In both cases small $\tan \beta$ needed!
The hMSSM

In the basis \((H_d, H_u)\), the CP–even Higgs mass matrix can be written as:

\[
M^2_S = M^2_Z \begin{pmatrix}
  c_\beta^2 & -s_\beta c_\beta \\
  -s_\beta c_\beta & s_\beta^2
\end{pmatrix} + M^2_A \begin{pmatrix}
  s_\beta^2 & -s_\beta c_\beta \\
  -s_\beta c_\beta & c_\beta^2
\end{pmatrix} + \begin{pmatrix}
  \Delta M^2_{11} \\
  \Delta M^2_{12}
\end{pmatrix}
\]

\(\Delta M^2_{ij}\): radiative corrections

One derives the neutral CP-even Higgs boson masses and the mixing angle \(\alpha\):

\[
M^2_{h/H} = f_{h/H}(M_A, \tan \beta, \Delta M_{11}, \Delta M_{12}, \Delta M_{22})
\]

\[
\tan \alpha = f_\alpha(M_A, \tan \beta, \Delta M_{11}, \Delta M_{12}, \Delta M_{22})
\]

\(M_h\) should be an input now...

The post-Higgs MSSM scenario:

- observation of the lighter \(h\) boson at a mass of \(\approx 125\) GeV
- non-observation of superparticles at the LHC

\(\text{MSSM} \Rightarrow \text{SUSY–breaking scale rather high, } M_S \gtrsim 1 \text{ TeV}\).

\(\Delta M^2_{22}\) involves the by far dominant stop–top sector correction: \(\Delta M^2_{22} \gg \Delta M^2_{11}, \Delta M^2_{12}\)

\(\rightarrow\) One can trade \(\Delta M^2_{22}(M_S)\) for the by now known \(M_h\).

In this case, one can simply describe the Higgs sector in terms of \(M_A, \tan \beta\) and \(M_h\):

\[
M^2_{H} = \frac{(M_A^2+M_Z^2-M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_\beta^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}
\]

\(\text{hMSSM:} \)

\[
\alpha = -\arctan \left( \frac{(M_Z^2+M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2} \right)
\]
Determination of the h boson couplings in a generic MSSM

Knowing \([\tan \beta, M_A]\) and fixing \(M_h = 125\) GeV, the couplings of the Higgs bosons can be derived, including the dominant radiative corrections that enter in the MSSM Higgs masses:

\[
c_V^0 = \sin(\beta - \alpha), \quad c_t^0 = \frac{\cos \alpha}{\sin \beta}, \quad c_b^0 = -\frac{\sin \alpha}{\cos \beta}
\]

However, there are also direct/vertex radiative corrections to the Higgs couplings not contained in the mass matrix. These can alter this simple picture!

The two important SUSY (QCD) corrections affect the t,b couplings:

\[
c_b \approx c_b^0 \times \left[1 - \frac{\Delta_b}{1 + \Delta_b} \times (1 + \cot \alpha \cot \beta)\right]
\]

\[
c_t \approx c_t^0 \times \left[1 + \frac{m_t^2}{4 m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - (A_t - \mu \cot \alpha)(A_t + \mu \tan \alpha))\right]
\]

- \(c_\tau\), \(c_c\) and \(c_t\) (from \(pp \rightarrow Ht\bar{t}\)) do not involve same vertex corrections
- \(gg \rightarrow h\) process has \(\tilde{t}, \tilde{b}\) loops and \(h \rightarrow \gamma\gamma\) has also \(\tilde{\tau}\) and \(\chi_i^{\pm}\) loops

\(\Rightarrow\) in general, we need (at least) 7 couplings \(c_t, c_b, c_c, c_\tau, c_V, c_g, c_\gamma\)

+ invisible decays? [Djouadi,Falkowski,Mambrini,JQ, arXiv:1205.3169]

8 parameters fit difficult! Simpler to make reasonable approximations:

- low sensitivity on \(h \rightarrow c\bar{c}, h \rightarrow \tau\tau\) and \(pp \rightarrow t\bar{t}H\) at the LHC
- in \(h \rightarrow \gamma\gamma\) additional contributions (\(\tilde{b}, \tilde{\tau}, \chi_i^{\pm}\)) smaller than those of \(\tilde{t}\)

\(\Rightarrow\) assume \(c_c = c_t, c_\tau = c_b\) and \(c_t(ttH) = c_t(ggF), c_\gamma \simeq c_g \simeq c_t\)

reduce the problem to a fit of three couplings: \(c_t, c_b, c_V\)
3D-Fit in the \([c_t, c_b, c_V]\) parameter space

- If large direct corrections \(\Rightarrow 3\) independent \(h\) couplings: \(c_c = c_t, c_\tau = c_b\) and \(c_V = c_V^0\)

- To study the \(h\) state at the LHC, we define the effective Lagrangian:
  \[
  \mathcal{L}_h = c_V \ g_{hWW} \ h \ W^+_\mu W^-_\mu + c_V \ g_{hZZ} \ h \ Z^0_\mu Z^0_\mu \\
  -c_t \ y_t \ h \bar{t}_L t_R - c_t \ y_c \ h \bar{c}_L c_R \\
  -c_b \ y_b \ h \bar{b}_L b_R - c_b \ y_\tau \ h \bar{\tau}_L \tau_R + \text{h.c.}
  \]

- We fit the Higgs signal strengths:
  \[
  \mu_X \simeq \frac{\sigma(pp\to h) \times \text{BR}(h\to XX)}{\sigma(pp\to h)_{\text{SM}} \times \text{BR}(h\to XX)_{\text{SM}}}
  \]

  Best-fit value: \(c_t = 0.89, c_b = 1.01\) and \(c_V = 1.02\) (ATLAS & CMS data)

If we neglect direct corrections \(\rightarrow 2\) parameter fits:

- best-fit points: \((c_t = 0.88, c_V = 1.0), (c_b = 0.97, c_V = 1.0)\) and \((c_t = 0.88, c_b = 0.97)\)
The 2D-fit in the hMSSM

Using the expressions defining the hMSSM one can perform a fit in the plane $[\tan \beta, M_A]$:

The best-fit point: $(\tan \beta = 1$ and $M_A = 557$ GeV) or $(M_H = 580$ GeV, $M_{H^\pm} = 563$ GeV, $\alpha = -0.837$ rad).
Direct heavy Higgs searches

- \( \tan \beta \lesssim 3 \) usually thought to be “excluded” by LEP2 \( (M_h \gtrsim 114 \text{ GeV}) \) but it assumes \( M_S \sim 1 \text{ TeV}! \)

- Caveat: ATLAS & CMS constraint apply for a specific benchmark: \( X_t/M_S = \sqrt{6} \) and \( M_S = 1 \text{ TeV} \) (the \( m_h^{\text{max}} \) scenario).

- But we can be more relaxed:
  with \( M_S \gg M_Z \), \( \tan \beta \approx 1 \) could be allowed!

\[ \Rightarrow \text{Let’s reopen the low } \tan \beta \text{ regime and heavy Higgs searches, but in a benchmark independent approach (hMSSM)} \]
The Higgs couplings and the approach to the decoupling limit

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\Phi \bar{u} u}$</th>
<th>$g_{\Phi \bar{d} d}$</th>
<th>$g_{\Phi V V}$</th>
<th>$g_{\Phi A Z} / g_{\Phi H^+ W^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>$\cos \alpha / \sin \beta$</td>
<td>$- \sin \alpha / \cos \beta$</td>
<td>$\sin (\beta - \alpha)$</td>
<td>$\propto \cos (\beta - \alpha)$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\sin \alpha / \sin \beta$</td>
<td>$\cos \alpha / \cos \beta$</td>
<td>$\cos (\beta - \alpha)$</td>
<td>$\propto \sin (\beta - \alpha)$</td>
</tr>
<tr>
<td>$A$</td>
<td>$\cot \beta$</td>
<td>$\tan \beta$</td>
<td>$0$</td>
<td>$\propto 0 / 1$</td>
</tr>
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</table>

The decoupling limit is controlled by $g_{H V V} = \cos (\beta - \alpha)$:

$$g_{H V V} \xrightarrow{M_A \gg M_Z} \chi \equiv \frac{1}{2} \frac{M_2^2}{M_A^2} \sin 4\beta - \frac{1}{2} \frac{M_{22}^2}{M_A^2} \sin 2\beta \rightarrow 0$$

**Tree–level part:** doubly suppressed in both the $\tan \beta \gg 1$ and $\tan \beta \sim 1$ cases.

$$\sin 4\beta = \frac{4 \tan \beta (1 - \tan^2 \beta)}{(1 + \tan^2 \beta)^2} \rightarrow \begin{cases} -4 / \tan \beta \text{ for } \tan \beta \gg 1 \\ 1 - \tan^2 \beta \text{ for } \tan \beta \sim 1 \end{cases} \rightarrow 0$$

**The radiative part:** behave as $-M_{22}^2 / M_A^2 \times \cot \beta$, also vanishes at high $\tan \beta$ values $\Rightarrow$ the decoupling limit $g_{H V V} \rightarrow 0$ is reached very quickly at high $\tan \beta$, as soon as $M_A \gtrsim M_h^{\text{max}}$. Instead, for $\tan \beta \approx 1$, this radiatively generated component is maximal. Departure from the decoupling limit!

$$g_{h u u} \xrightarrow{M_A \gg M_Z} 1 + \chi \cot \beta \rightarrow 1$$
$$g_{h d d} \xrightarrow{M_A \gg M_Z} 1 - \chi \tan \beta \rightarrow 1$$
$$g_{H u u} \xrightarrow{M_A \gg M_Z} - \cot \beta + \chi \rightarrow - \cot \beta$$
$$g_{H d d} \xrightarrow{M_A \gg M_Z} + \tan \beta + \chi \rightarrow + \tan \beta$$

At low $\tan \beta$ : $g_{H V V}$ is non–zero, $g_{H t t}$ and $g_{A t t}$ are significant. $\Rightarrow$ $H / A / H^\pm$ bosons can have sizable couplings to top quarks and massive gauge bosons if $\tan \beta \sim 3$.

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Higgs Physics Beyond the Standard Model  
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The main search channels for the H/A states:

- The $H/A \rightarrow \tau\tau$ channels
- The $H \rightarrow WW, ZZ$ channels
- The $A \rightarrow Zh$ channel
- The $H \rightarrow hh$ channel (estimation)
- The $H/A \rightarrow t\bar{t}$ channels (estimation)

Outline

1. Constraints on SUSY models through the Higgs sector
2. Constraints on Dark-Matter models through the Higgs sector
Dark matter evidences

Galactic rotation curves:

Gravitational lensing of the Bullet cluster:

Friedmann law (PLANCK):
Higgs-portal

Does the Higgs boson interact with a Hidden-Sector?

Motivation: $|H|^2$ is lowest dimension SM singlet, so SM singlet dark matter may naturally couple to SM via this operator

Higgs-portal models: [Silveira,Zee(1985); Shabinger,Wells(2005);Patt,Wilczek(2006)]

- Scalar DM: $\Delta \mathcal{L}_S = -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{hSS} H^\dagger H S^2$
- Vectorial DM: $\Delta \mathcal{L}_V = \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{4} \lambda_{hVV} H^\dagger H V_\mu V^\mu$
- Fermion DM (not renormalizable): $\Delta \mathcal{L}_f = -\frac{1}{2} m_f \bar{\chi} \chi - \frac{1}{4} \frac{\lambda_{hff}}{\Lambda} H^\dagger H \bar{\chi} \chi$

(DM stability ensured by a $Z_2$ parity)

→ 2 parameter model: phenomenology fully determined by the mass $m_{DM}$ and coupling $\lambda_{DM}$

What is the implication of a 125 GeV Higgs for the Higgs-portal models?
Higgs-portal: scalar case

\[ \langle \sigma^S_{\text{ferm}} v_r \rangle = \frac{\lambda^2_{hSS} m_{\text{ferm}}^2}{16\pi} \frac{1}{(4M_S^2 - m_h^2)^2} \]  \hspace{1cm} \text{(WMAP)}

\[ \Delta L_S \supset -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_{hSS} H^+ H S^2 \]

\[ \sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} \]  \hspace{1cm} \text{(XENON)}

\[ \Gamma_{\text{inv}}^{h \rightarrow SS} = \frac{\lambda^2_{hSS} v^2 \beta S}{64\pi m_h} \]  \hspace{1cm} \text{(LHC)}
Scalar, fermionic, vectorial Higgs-portal-DM

\[ \lambda_{hSS} \]

\[ \lambda_{hVV} \]

\[ \sigma_{SI} \] (pb)

[DJouadi, Lebedev, Mambrini, JQ (2012)]
Invisible Higgs and monojet searches [Djouadi, Falkowski, Mambrini, JQ (2012)]

Expected/Observed limit on:

\[ R_{inv}^{pp} = \frac{\sigma(pp \rightarrow H) \times BR(H \rightarrow inv)}{\sigma(pp \rightarrow H)_{SM}} \]

for ggF VBF+VH

95%CL limit on BSM events

<table>
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<tr>
<th>( p_T^{miss} ) [GeV]</th>
<th>( N_{inv}^{gg} )</th>
<th>( N_{inv}^{W/Z} )</th>
<th>( \Delta N_{exp}^{95%} )</th>
<th>( \Delta N_{obs}^{95%} )</th>
<th>( \text{exp. } R_{inv}^{pp} )</th>
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</table>

\[ \chi^2 = \sum_i \frac{[\Delta N_0^i - \delta N^i(R_{inv}^{pp})]^2}{[\Delta N_{1\sigma}^i]^2} \Rightarrow R_{inv}^{pp} \leq 1.10 \text{ at } 95\% \text{ CL. (CMS 5 fb}^{-1}) \]

Direct & Indirect Higgs width constraints:

\[ \Delta \mathcal{L} = \frac{c_{gg}}{4} H G_{\mu\nu}^a G^{\mu\nu, a} \]
Invisible Higgs and direct detections

\[ M_{DM} < M_h/2 \]

\[ r_\chi(M_\chi) = \Gamma(H \rightarrow \chi\chi)/\sigma_{\chi p}^{SI} \]

\[ \sigma_{SI} (\text{pb}) \]

- **LHC**: most sensible light DM detector
- **M_{S,F,V} < 60 \text{ GeV}**: excluded by both LHC and D.D.
- Light Higgs-portal DM should be non-thermal.

\[ M_{DM} = M_h/2 \text{ and } M_{DM} \gtrsim 100 \text{ GeV} \]

will be probed by D.D and L.C. in near future.
Conclusion

- $M_h \approx 125$ GeV and the non–observation of SUSY particles, seems to indicate that the soft–SUSY breaking scale might be large.

- We have discussed the hMSSM, i.e. the MSSM that we seem to have after the discovery of the Higgs boson at the LHC.
  - ⇒ the MSSM Higgs sector can be described by only $(\tan \beta, M_A)$.

- $H/A/H^\pm$ searches at the LHC are becoming very constraining.

- Some search channels at low $\tan \beta$ still relevant: $H \to \tau\tau, WW, ZZ, hZ, hh, tt$ ⇒ need to continue/adapt the SM Higgs searches at high masses!

- 7–8 TeV LHC for the lightest $h$ and 13–14 TeV LHC for $H/A/H^\pm$? and maybe some SUSY particles will show up?

- Light Higgs-portal DM, $M_{DM} \leq 60$ GeV is excluded by both LHC and Direct Detection.

- $M_{DM} \geq 60$ GeV will be probed by D.D and future $e^+e^-$ Linear Colliders.
Merci !