MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios for Run 2 and Beyond

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Why Benchmarks?

Experimentalists could just publish the results of Higgs searches in a model-independent way, and let the theorists interpret them in specific BSM scenarios.

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- BSM scenarios are constrained by different searches at once. Experimentalists are best placed to combine their own results, taking all correlations into account.
Why Benchmarks?

Experimentalists could just publish the results of Higgs searches in a model-independent way, and let the theorists interpret them in specific BSM scenarios.

However…

- Experimentalists too want to have fun!
- BSM scenarios are constrained by different searches at once. Experimentalists are best placed to combine their own results, taking all correlations into account.
- “Benchmark” scenarios can also be useful to draw experimentalists’ attention on exotic signatures of specific BSM models, and possibly suggest new searches.
The “Old” Benchmark Scenarios for the MSSM

[ proposed by Carena, Heinemeyer, Stål, Wagner & Weiglein, 1302.7033 ]

- $m_{h_{\text{max}}}$, $m_{h_{\text{mod}+}}$, $m_{h_{\text{mod}-}}$: TeV-scale sfermions & gluino, lighter EW-inos

- *light stop*: lightest stop with mass of 324 GeV, decaying only to $c\chi^0_1$

- *light stau*: staus with mass around 250 GeV, effects on $h \to \gamma\gamma$

- *tau-phobic*: rad. corrs suppress couplings of $h$ to down-type fermions

- *low-$M_H$*: the heavier MSSM scalar plays the role of the 125-GeV Higgs

For each scenario, the LHC-HXSWG produced ROOT files with Higgs masses, cross sections and BRs, widely used by ATLAS/CMS to interpret their results in the MSSM

[ masses & couplings from FeynHiggs, XS from SusHi, BRs from HDECAY + FeynHiggs ]
$m_h^{\text{mod+}}$ scenario, bounds from $H/A \rightarrow \tau\tau$

Points with $m_h = 125 \pm 3$ GeV accepted in view of the theoretical uncertainty of the Higgs-mass calculation (full 1-loop + dominant 2-loop)

\[
m_h = f(m_Z, m_A, \tan \beta) + \text{rad. corrs}
\]

computed with FeynHiggs 2.10.2 (2014)
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Since 2014, refinements in the
calculation of $m_h$ allowed for inclusion
of additional higher-order effects
(also, improvements in the calculation
of the XS & updates in the SM inputs)
$m_h$ computed with FeynHiggs 2.10.2 (2014)

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Points with $m_h = 125 \pm 3$ GeV accepted in view of the theoretical uncertainty of the Higgs-mass calculation (full 1-loop + dominant 2-loop)

Since 2014, refinements in the calculation of $m_h$ allowed for inclusion of additional higher-order effects (also, improvements in the calculation of the XS & updates in the SM inputs)

In addition, the scenarios have been further constrained by searches for SUSY particles (e.g., a 324-GeV stop decaying only to $c\chi_1^0$ now excluded by monojet searches)
New Benchmark Scenarios for the MSSM

[ Bahl, Fuchs, Hahn, Heinemeyer, Liebler, Patel, P.S., Stefaniak, Wagner & Weiglein, 1808.07542 ]

- $M_{h_{125}}$: “vanilla” scenario with all SUSY masses at or above 1 TeV

- $M_{h_{125}}(\tilde{\tau})$: light staus: sizable effects on $h \rightarrow \gamma \gamma$ at large $\tan\beta$

- $M_{h_{125}}(\tilde{\chi})$: light EW-inos: new decay channels for heavy Higgses

- $M_{h_{125}}$(alignment): $h$ couplings very SM-like even at low values of $m_A$

- $M_{H_{125}}$: the heavier MSSM scalar plays the role of the 125-GeV Higgs

- $M_{h_{125}}(CPV)$: interference effects suppress production of heavy Higgses
The $M_{h}^{125}$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 2$ TeV,

$\mu = 1$ TeV, $M_1 = 1$ TeV, $M_2 = 1$ TeV, $M_3 = 2.5$ TeV,

$X_t = 2.8$ TeV, $A_b = A_{\tau} = A_t$.

($M_{\tilde{f}} = 2$ TeV, $A_{\tilde{f}} = 0$ for 1st/2nd-gen. sfermions)

\[ \begin{align*}
\tan \beta & = 10 \\
M_{h} & = 122 \\
M_{h} & = 124 \\
M_{h} & = 125 \\
\end{align*} \]

(The one where SUSY is at 1 TeV)
The $M^{{125}}_h$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 2$ TeV,

$\mu = 1$ TeV, $M_1 = 1$ TeV, $M_2 = 1$ TeV, $M_3 = 2.5$ TeV,

$X_t = 2.8$ TeV, $A_b = A_{t'} = A_t$.

( $M_f = 2$ TeV, $A_f = 0$ for 1st/2nd-gen. sfermions)

Excluded by $m_h$ [FeynHiggs]

(the one where SUSY is at 1 TeV)
The $M_{h}^{125}$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 2$ TeV,

$\mu = 1$ TeV, $M_{1} = 1$ TeV, $M_{2} = 1$ TeV, $M_{3} = 2.5$ TeV,

$X_{t} = 2.8$ TeV, $A_{b} = A_{\tau} = A_{t}$.

($M_{f} = 2$ TeV, $A_{f} = 0$ for 1st/2nd-gen. sfermions)

Excluded by $h$ couplings [HiggsSignals] with 36 fb$^{-1}$ data

Excluded by $m_{h}$ [FeynHiggs] (the one where SUSY is at 1 TeV)
The $M_h^{125}$ scenario

$$M_{Q3} = M_{U3} = M_{D3} = 1.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 2 \text{ TeV},$$

$$\mu = 1 \text{ TeV}, \quad M_1 = 1 \text{ TeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$X_t = 2.8 \text{ TeV}, \quad A_b = A_\tau = A_t.$$ 

($M_f = 2 \text{ TeV}, A_f = 0$ for 1st/2nd-gen. sfermions)

Excluded by $h$ couplings [HiggsSignals] with 36 fb$^{-1}$ data

Excluded by BSM Higgs searches [HiggsBounds] with 36 fb$^{-1}$ data

Excluded by $m_h$ [FeynHiggs]

(\text{the one where SUSY is at 1 TeV})
The $M_h^{125}(\tilde{\tau})$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 350$ GeV,

$\mu = 1$ TeV, $M_1 = 180$ GeV, $M_2 = 300$ GeV, $M_3 = 2.5$ TeV,

$X_t = 2.8$ TeV, $A_b = A_t$, $A_{\tau} = 800$ GeV.

(the one with light staus)
The $M_{h}^{125}(\tilde{\tau})$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 350$ GeV, 

$\mu = 1$ TeV, $M_{1} = 180$ GeV, $M_{2} = 300$ GeV, $M_{3} = 2.5$ TeV, 

$X_{t} = 2.8$ TeV, $A_{b} = A_{t}$, $A_{\tau} = 800$ GeV.

$\tan \beta$
The $M_{h}^{125}(\tilde{\chi})$ scenario

\[ M_{Q3} = M_{U3} = M_{D3} = 1.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 2 \text{ TeV}, \]
\[ \mu = 180 \text{ GeV}, \quad M_{1} = 160 \text{ GeV}, \quad M_{2} = 180 \text{ GeV}, \quad M_{3} = 2.5 \text{ TeV}, \]
\[ X_{t} = 2.5 \text{ TeV}, \quad A_{b} = A_{\tau} = A_{t} . \]
The \( M_{h}^{125}(\tilde{\chi}) \) scenario

\[ M_{Q3} = M_{U3} = M_{D3} = 1.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 2 \text{ TeV}, \]
\[ \mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV}, \]
\[ X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t. \]

\[ \text{BR}(h \rightarrow \gamma\gamma) / \text{BR}(h \rightarrow \gamma\gamma)_{\text{SM}} \]

\( (\text{the one with light EW-inos}) \)
The $M_{h}^{125}(\tilde{\chi})$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5$ TeV, $M_{L3} = M_{E3} = 2$ TeV,

$\mu = 180$ GeV, $M_{1} = 160$ GeV, $M_{2} = 180$ GeV, $M_{3} = 2.5$ TeV,

$X_{t} = 2.5$ TeV, $A_{b} = A_{\tau} = A_{t}$.

(the one with light EW-inos)
The $M^{125}_{h} (\tilde{\chi})$ scenario

$M_{Q3} = M_{U3} = M_{D3} = 1.5 \text{ TeV}, \quad M_{L3} = M_{E3} = 2 \text{ TeV},$

$\mu = 180 \text{ GeV}, \quad M_1 = 160 \text{ GeV}, \quad M_2 = 180 \text{ GeV}, \quad M_3 = 2.5 \text{ TeV},$

$X_t = 2.5 \text{ TeV}, \quad A_b = A_\tau = A_t.$

(The one with light EW-inos)
BSM-Higgs decays to EW-inos in the $M_{h_{125}}$($\tilde{\chi}$) scenario
BSM-Higgs decays to EW-inos in the $M_h^{125}(\tilde{\chi})$ scenario

• A sizable region of the parameter space could be probed by $H, A, H^\pm \rightarrow \tilde{\chi}\tilde{\chi}$ searches

• Only very early studies of the discovery potential by CMS (2007) and ATLAS (2009)

• We propose these decays as a target of dedicated searches at the LHC
The $M_{h}^{125}$ (alignment) scenario

$M_{Q_{3}} = M_{U_{3}} = M_{D_{3}} = 2.5$ TeV, $M_{L_{3}} = M_{E_{3}} = 2$ TeV,

$\mu = 7.5$ TeV, $M_{1} = 500$ GeV, $M_{2} = 1$ TeV, $M_{3} = 2.5$ TeV,

$A_{t} = A_{b} = A_{\tau} = 6.25$ TeV.

(the one where $h$ is SM-like even at low $M_{A}$)
The $M_{H}^{125}$ scenario

\[ \begin{align*} 
M_{Q_3} &= M_{U_3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV}) , \\
\mu &= [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] \frac{M_{Q_3}}{(750 \text{ GeV})} , \\
A_t = A_b = A_\tau &= 0.65 M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV} , \\
M_1 &= M_{Q_3} - 75 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} . 
\end{align*} \]

$M_h, M_H, M_A$ [GeV]

$(the$ $one$ $where$ $the$ $heavy$ $Higgs$ $is$ $SM-like)$
The $M_{H}^{125}$ scenario

$M_{Q3} = M_{U3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV})$

$\mu = [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] \frac{M_{Q3}}{(750 \text{ GeV})}$

$A_t = A_b = A_\tau = 0.65 M_{Q3}$, $M_{D3} = M_{L3} = M_{E3} = 2 \text{ TeV}$

$M_1 = M_{Q3} - 75 \text{ GeV}$, $M_2 = 1 \text{ TeV}$, $M_3 = 2.5 \text{ TeV}$

$M_h, M_H, M_A$ [GeV]

$M_{H^\pm}$ [GeV]

$(the \ one \ where \ the \ heavy \ Higgs \ is \ SM-like)$
The $M_H^{125}$ scenario

$M_{Q3} = M_{U3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV})$ ,
$\mu = [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] \frac{M_{Q3}}{(750 \text{ GeV})}$ ,
$A_t = A_b = A_\tau = 0.65 \frac{M_{Q3}}{(750 \text{ GeV})}$ ,
$M_1 = M_{Q3} - 75 \text{ GeV}$ ,
$M_2 = 1 \text{ TeV}$ ,
$M_3 = 2.5 \text{ TeV}$ .

$M_h, M_H, M_A \text{ [GeV]}$

Excluded by $A \to \tau\tau$

Excluded by $H \to hh$

(the one where the heavy Higgs is SM-like)
The $M_H^{125}$ scenario

$$M_{Q_3} = M_{U_3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV}) \ ,$$

$$\mu = [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] \frac{M_{Q_3}}{(750 \text{ GeV})} \ ,$$

$$A_t = A_b = A_\tau = 0.65 M_{Q_3}, \quad M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV} \ ,$$

$$M_1 = M_{Q_3} - 75 \text{ GeV}, \quad M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} \ .$$

$(the \ one \ where \ the \ heavy \ Higgs \ is \ SM-like)$
The $M^{125}_H$ scenario

$M_{Q3} = M_{U3} = 750 \text{ GeV} - 2 (M_{H^\pm} - 150 \text{ GeV})$,

$\mu = [5800 \text{ GeV} + 20 (M_{H^\pm} - 150 \text{ GeV})] \frac{M_{Q3}}{750 \text{ GeV}}$,

$A_t = A_b = A_\tau = 0.65 M_{Q3}$, $M_{D3} = M_{L3} = M_{E3} = 2 \text{ TeV}$,

$M_1 = M_{Q3} - 75 \text{ GeV}$, $M_2 = 1 \text{ TeV}$, $M_3 = 2.5 \text{ TeV}$.

$\text{BR}(H^\pm \rightarrow W^\pm h)$

(the one where the heavy Higgs is SM-like)
The $M_{h_1}^{125}$ (CPV) scenario

$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2$ TeV,

$\mu = 1.65$ TeV, $M_1 = M_2 = 1$ TeV, $M_3 = 2.5$ TeV,

$|A_t| = \mu \cot \beta + 2.8$ TeV, $\phi_{A_t} = \frac{2\pi}{15}$, $A_b = A_\tau = |A_t|$.

When CP is violated, all the neutral Higgses mix:

$h, H, A \rightarrow h_1, h_2, h_3$

Here $h_1$ is SM-like, $h_2$ and $h_3$ are mixed and mass-degenerate

(the one where CP is violated)
The $M_{h_1}^{125}$ (CPV) scenario

$$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2 \text{ TeV},$$

$$\mu = 1.65 \text{ TeV}, \quad M_1 = M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV},$$

$$|A_t| = \mu \cot \beta + 2.8 \text{ TeV}, \quad \phi_{A_t} = \frac{2\pi}{15}, \quad A_b = A_\tau = |A_t|.$$

When CP is violated, all the neutral Higgses mix:

$$h, H, A \rightarrow h_1, h_2, h_3$$

Here $h_1$ is SM-like, $h_2$ and $h_3$ are mixed and mass-degenerate

Interference in production and decay of $h_2$ and $h_3$:

$$1 + \eta \equiv \frac{\sigma(|h_2 + h_3|^2)}{\sigma(|h_2|^2 + |h_3|^2)}$$

(the one where CP is violated)
The $M_{h_1}^{125}$ (CPV) scenario

When CP is violated, all Higgses mix:

- $h_1$, $h_2$, $h_3$

- $M$-like, $h_2$ and $h_3$ mass-degenerate

Interference in production is of $h_2$ and $h_3$:

$$\frac{\sigma(|h_2 + h_3|^2)}{\sigma(|h_2|^2 + |h_3|^2)}$$

(the one where CP is violated)
The $M_{h_1}^{125}$ (CPV) scenario

“When the sensitivity of our measurement is more than one order of magnitude better than any previous measurement.”


When CP is violated, all three neutral Higgses mix:

$h, H, A \rightarrow h_1, h_2, h_3$

$h_1$ is SM-like, $h_2$ and $h_3$ are mass-degenerate and have in production a non-zero interference of $h_2$ and $h_3$:

$$\sigma(|h_2 + h_3|^2) = \frac{\sigma(|h_2|^2 + |h_3|^2)}{2}$$

(the one where CP is violated)
The $M_{h_1}^{125}$ (CPV) scenario

$M_{Q_3} = M_{U_3} = M_{D_3} = M_{L_3} = M_{E_3} = 2$ TeV,

$\mu = 1.65$ TeV, \quad $M_1 = M_2 = 1$ TeV, \quad $M_3 = 2.5$ TeV,

$|A_t| = \mu \cot \beta + 2.8$ TeV, \quad $\phi_{A_t} = \frac{2\pi}{15}$, \quad $A_b = A_\tau = |A_t|$

When CP is violated, all the neutral Higgses mix:

$h, H, A \rightarrow h_1, h_2, h_3$

Here $h_1$ is SM-like, $h_2$ and $h_3$ are mixed and mass-degenerate

Interference in production and decay of $h_2$ and $h_3$:

$1 + \eta \equiv \frac{\sigma(|h_2 + h_3|^2)}{\sigma(|h_2|^2 + |h_3|^2)}$

(the one where CP is violated)
ROOT files with Higgs masses, BRs and cross sections for the new scenarios are being developed by S. Liebler & Sven for the LHC-HXSWG, and they will be available within a few weeks (a public note with detailed instructions will also follow)
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Download and enjoy!