Some original SUSY literature:

The reports of my death have been greatly exaggerated.

~ Mark Twain
New SUSY Higgs Benchmarks for the LHC – HL-LHC and ILC implications

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Corpus Cristi, 05/2019

• Motivation
• New MSSM Higgs Benchmarks for the LHC
• Implications for the HL-LHC and the ILC
• Conclusions
1. Motivation

Two facts:

- We have a discovery!
- The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs”!
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Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q’: Which model?
1. Motivation

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- The SM cannot be the ultimate theory!

Conclusion: It cannot be “the SM Higgs”!

Q: Does the BSM physics have any (relevant) impact on the Higgs?

Q’: Which model?

A1: check changed properties

A2: check for additional Higgs bosons

A2’: check for additional Higgs bosons above and below 125 GeV
Models with extended Higgs sectors:

1. SM with additional Higgs singlet
2. Two Higgs Doublet Model (THDM): type I, II, III, IV
3. Minimal Supersymmetric Standard Model (MSSM)
4. MSSM with one extra singlet (NMSSM)
5. MSSM with more extra singlets
6. SM/MSSM with Higgs triplets
7. . . .

→ BSM models without extended Higgs sectors still have changed Higgs properties (quantum corrections!)
→ SM + vector-like fermions, Higgs portal, Higgs-radion mixing, . . .
Which model should we focus on?
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Some “recent” measurements:

- top quark mass
- Higgs boson mass
- Higgs boson “couplings”
- Dark Matter (properties)
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Which model should we focus on? ⇒ experimental data as guidance!

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Simple SUSY models predicted correctly:
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⇒ good motivation to look at SUSY! :-)

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The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature has so many free parameters!
A. Unconstrained models (MSSM):
agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms
most general case: 105 new parameters: masses, mixing angles, phases
⇒ many (close to) zero according to experimental data
⇒ no model missed (within the MSSM)
⇒ $O(100)$ parameters difficult to handle

B. Constrained models:
CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, FUTs, . . . :
assumption on the scenario that achieves spontaneous SUSY breaking
⇒ prediction for soft SUSY-breaking terms
   in terms of small set of parameters
⇒ easy to handle, but not all relevant phenomenology captured

C. Benchmark scenarios:
fix all-2 MSSM parameters in a smart way, explore benchmark planes
⇒ easy to handle, interesting phenomenology captured!
The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

\[ H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \\ \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \]

\[ H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \\ \phi_2^+ \end{pmatrix} \]

\[ V = m_1^2 H_1^1 \bar{H}_1^1 + m_2^2 H_2^1 \bar{H}_2^1 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \]

\[ + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \]

gauge couplings, in contrast to SM

physical states: \( h^0, H^0, A^0, H^\pm \)  

Goldstone bosons: \( G^0, G^\pm \)

Input parameters: (to be determined experimentally)

\[ \tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2 (\tan \beta + \cot \beta) \]
The MSSM Higgs sector: with $\mathcal{CP}$ violation

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_2^2 \\ H_1^2 \\ H_2^1 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \\ \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$  Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_{H^\pm}^2$$

2 $\mathcal{CP}$-violating phases: $\xi, \arg(m_{12})$ $\Rightarrow$ can be set/rotated to zero
The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

- $\mu$ : Higgsino mass parameter
- $A_{t,b,\tau}$ : trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^*\{\cot\beta, \tan\beta\}$ complex
- $M_{1,2}$ : gaugino mass parameter (one phase can be eliminated)
- $M_3$ : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

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

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions
2. New MSSM Higgs Benchmarks for the LHC
Search for the MSSM Higgs bosons:
Smart choice of MSSM parameters?
→ investigate benchmark scenarios:

→ Vary only $M_A$ (or $M_{H\pm}$) and $\tan\beta$
→ Keep all other SUSY parameters fixed


1. $M_{h_{125}}$ scenario: 2HDM-like model
2. $M_{h_{125}}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
3. $M_{h_{125}}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
4. $M_{h_{125}}$ (alignment) scenario: $h$ SM-like for very low $M_A$
5. $M_{H_{125}}$ scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_{125}}^1$ (CPV) scenario: complex phases, $h_2-h_3$ interference
Not covered:

Set of benchmarks for low tan$\beta$

[H. Bahl, S. Liebler, T. Stefaniak ’19]

- use 2HDM as low-energy model

- (mainly) EFT calculation, RGE running to $M_{\text{SUSY}}$

- implemented in FeynHiggs (so far priv.)

Heavy SUSY particles: $M_{h,\text{EFT}}^{125}$

light EW-inos: $M_{h,\text{EFT}}^{125}(\tilde{\chi})$
Data to be taken into account:

- Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs
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− SUSY searches (LHC)
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- Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds
- SUSY searches (LHC)

Data on purpose not to be taken into account:

- electroweak precision data
- flavor data
- astrophysical data (DM properties)
New benchmark: $M_{h}^{125}$

$M_{Q_{3}} = M_{U_{3}} = M_{D_{3}} = 1.5$ TeV

$M_{L_{3}} = M_{E_{3}} = 2$ TeV

$\mu = 1$ TeV, $M_{1} = 1$ TeV

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

$X_{t} = 2.8$ TeV

$A_{t} = A_{b} = A_{T}$

⇒ new vanilla benchmark model
New benchmark: $M_h^{125}(\tilde{\tau})$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{L_3} = M_{\tilde{E}_3} = 350$ GeV

$\mu = 1$ TeV, $M_1 = 180$ GeV

$M_2 = 300$ GeV, $M_3 = 2.5$ TeV

$X_t = 2.8$ TeV

$A_t = A_b, A_\tau = 800$ GeV

$\Rightarrow$ slightly reduced heavy Higgs coverage
New benchmark: $M_h^{125}(\tilde{\tau})$

$\tilde{Q}_3 = \tilde{U}_3 = \tilde{D}_3 = 1.5$ TeV

$\tilde{L}_3 = \tilde{E}_3 = 350$ GeV

$\mu = 1$ TeV, $M_1 = 180$ GeV

$M_2 = 300$ GeV, $M_3 = 2.5$ TeV

$X_t = 2.8$ TeV

$A_t = A_b, A_\tau = 800$ GeV

⇒ strong impact on $\Gamma(h \to \gamma\gamma)$
New benchmark: $M_{h}^{125}(\tilde{\chi})$

$M_{Q_{3}} = M_{U_{3}} = M_{D_{3}} = 1.5$ TeV
$M_{L_{3}} = M_{E_{3}} = 2$ TeV
$\mu = 180$ GeV, $M_{1} = 160$ GeV
$M_{2} = 180$ GeV, $M_{3} = 2.5$ TeV
$X_{t} = 2.5$ TeV
$A_{t} = A_{b} = A_{\tau}$

$\Rightarrow$ strongly reduced heavy Higgs coverage
**New benchmark: $M_h^{125}$**

$M_{Q_3} = M_{U_3} = M_{D_3} = 1.5$ TeV
$M_{L_3} = M_{E_3} = 2$ TeV
$\mu = 1$ TeV, $M_1 = 1$ TeV
$M_2 = 1$ TeV, $M_3 = 2.5$ TeV
$X_t = 2.8$ TeV
$A_t = A_b = A_{\tau}$

$\Rightarrow \text{new vanilla benchmark model}$
New benchmark: $M^{125}_h(\tilde{\chi})$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV
$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV
$\mu = 180$ GeV, $M_1 = 160$ GeV
$M_2 = 180$ GeV, $M_3 = 2.5$ TeV
$X_t = 2.5$ TeV
$A_t = A_b = A_\tau$

⇒ strongly reduced heavy Higgs coverage
New benchmark: $M_{h}^{125}(\tilde{\chi})$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 180$ GeV, $M_1 = 160$ GeV

$M_2 = 180$ GeV, $M_3 = 2.5$ TeV

$X_t = 2.5$ TeV

$A_t = A_b = A_\tau$

⇒ Huge BR of heavy Higgses to EW-inos
New benchmark: $M_h^{125\text{(align)}}$

$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5\ \text{TeV}$

$M_{L_3} = M_{E_3} = 2\ \text{TeV}$

$\mu = 7.5\ \text{TeV}, \ M_1 = 500\ \text{GeV}$

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

$A_t = A_b = A_\tau = 6.25\ \text{TeV}$

$\Rightarrow h\ \text{SM-like for very low } M_A$
LHC Higgs searches for complex parameters:

\[ h_1 \sim H_{125}, \ M_{h_2} \approx M_{h_3}, \ \text{CPV: large } h_2-h_3 \text{ mixing possible:} \]

Higgs bosons as intermediate states in \( \{b\bar{b}, gg\} \rightarrow h_\alpha \rightarrow \tau\tau \)
New benchmark: $M_{h_1}^{125}(CPV)$

$M_{Q_3} = M_{U_3} = M_{D_3} = 2$ TeV

$M_{L_3} = M_{E_3} = 2$ TeV

$\mu = 1.65$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$|A_t| = \mu / \tan \beta + 2.8$ TeV

$\phi_A = 2/15 \pi$

$|A_t| = A_b = A_\tau$

⇒ reduced coverage due to $h_2-h_3$ interference
New benchmark: $M_{h_1}^{125}$(CPV)

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 2$ TeV

$M_{\tilde{L}_3} = M_{\tilde{E}_3} = 2$ TeV

$\mu = 1.65$ TeV, $M_1 = 1$ TeV

$M_2 = 1$ TeV, $M_3 = 2.5$ TeV

$|A_t| = \mu / \tan \beta + 2.8$ TeV

$\phi_{A_t} = 2/15 \pi$

$|A_t| = A_b = A_\tau$

$\Rightarrow$ reduced coverage due to $h_2$-$h_3$ interference
New benchmark: $M_{H}^{125}$

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

$M_{L3} = M_{E3} = M_{D3} = 2 \text{ TeV}$

$\mu = [5.8 \text{ TeV} + 20(M_{H^+} - 150 \text{ GeV})] \times \frac{M_{Q3}}{750 \text{ GeV}}$

$M_1 = M_{Q3} - 75 \text{ GeV}$

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

$A_t = A_b = A_{\tau} = 0.65M_{Q3}$

⇒ exotic solution still viable!

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New benchmark: $M_{H}^{125}$

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

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

$\mu = [5.8 \text{ TeV} + 20(M_{H^\pm} - 150 \text{ GeV})] \times M_{Q_3}/750 \text{ GeV}$

$M_1 = M_{Q_3} - 75 \text{ GeV}$

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

$A_t = A_b = A_\tau = 0.65M_{Q_3}$

$\Rightarrow \text{large BR}(H^\pm \to W^\pm h)$
3. Implications for the HL-LHC and the ILC


**HL-LHC:**
- will improve direct search limits
- will improve rate measurements (production $\times$ decay)
  systematic/theory uncertainties: S2 scenario

[M. Cepeda et al. ’19 – YR18]

**ILC:**
- will improve rate measurements (no theory assumptions!)
  - 250 fb$^{-1}$ at ILC250 $\oplus$ 500 fb$^{-1}$ at ILC500
  - polarization: $P(e^-, e^+) = (-80\%, +30\%)$

HL-LHC reach in $M_h^{125}$ scenario

$H/A \rightarrow \tau^+\tau^-$ expected exclusion (95% C.L.)

- ATLAS 3 ab$^{-1}$ ⊕ CMS 3 ab$^{-1}$
- ATLAS 36.1 fb$^{-1}$ [JHEP 01(2018)055]
- CMS 35.9 fb$^{-1}$ [JHEP 09(2018)007]

$h(125)$ rates $M_h \neq (125 \pm 3)$ GeV
- ATLAS 36.1 fb$^{-1}$ ⊕ CMS 35.9 fb$^{-1}$
- ATLAS 3 ab$^{-1}$ ⊕ CMS 3 ab$^{-1}$

$⇒$ direct and indirect measurements: $M_A \gtrsim 1200$ GeV
HL-LHC reach in $M_{h}^{125}(\tilde{\chi})$ scenario

$H/A \rightarrow \tau^+\tau^-$ expected exclusion (95% C.L.)

- ATLAS 3 ab$^{-1}$ + CMS 3 ab$^{-1}$
- ATLAS 36.1 fb$^{-1}$ [JHEP 01(2018)055]
- CMS 35.9 fb$^{-1}$ [JHEP 09(2018)007]

$h(125)$ rates $M_h \neq (125 \pm 3)$ GeV
- ATLAS 36.1 fb$^{-1}$ + CMS 35.9 fb$^{-1}$
- ATLAS 3 ab$^{-1}$ + CMS 3 ab$^{-1}$

$\Rightarrow$ direct and indirect measurements: $M_A \gtrsim 1200$ GeV
Indirect HL-LHC reach in $M_{h,EFT}^{125}(\tilde{\chi})$ scenario [H. Bahl et al., PRELIMINARY]

⇒ reach for charginos (mainly) via $h \to \gamma\gamma$:

$\Rightarrow$ strong reach for low $\tan\beta$

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Relevance of ILC improvement:

- Assume a realization of an MSSM point
- What limits can be set from rate/coupling measurements?

⇒ small improvements for $M_A = 700$ GeV
⇒ only ILC measurements give upper limit for $M_A = 1000$ GeV
4. Conclusions

- **SUSY** is (still) the best-motivated BSM scenario
  - unconstrained MSSM: 105 new parameters
  - constrained: CMSSM, NUHM, SU(5), mAMSB, sub-GUT, FUT, ...
  - benchmark models: parameter planes

- **Benchmark scenarios/searches:** Data taken into account: Higgs/SUSY
  Data on purpose not taken into account: EW/Flavor/DM

- **New benchmark proposal:**
  - $M_{125}^{h}$ scenario: 2HDM-like model
  - $M_{125}^{h}(\tilde{\tau})$ scenario: light staus: $h \rightarrow \gamma\gamma$, $H/A \rightarrow \tilde{\tau}\tilde{\tau}$
  - $M_{125}^{h}(\tilde{\chi})$ scenario: light EW-inos: $H/A \rightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$
  - $M_{125}^{h}$ (alignment) scenario: $h$ SM-like for very low $M_A$
  - $M_{125}^{H}$ scenario: $M_H \sim 125$ GeV, all Higgses light
  - $M_{125}^{h_1}$ (CPV) scenario: complex phases, $h_2-h_3$ interference

- **Implications for HL-LHC and ILC:**
  - direct $\oplus$ indirect HL-LHC reach: $M_A \gtrsim 1200$ GeV
  - interesting reach for charginos via $h \rightarrow \gamma\gamma$
  - ILC measurements can be crucial to set upper limits on $M_A$
Higgs Days at Santander 2019
Theory meets Experiment
16.-20. September

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Further Questions?
HL-LHC reach in $M_{h,EFT}^{125}(\tilde{\chi})$ scenario

$H/A \rightarrow \tau^+\tau^-$ expected exclusion (95% C.L.)

- ATLAS 3 ab$^{-1} \oplus$ CMS 3 ab$^{-1}$
- ATLAS 36.1 fb$^{-1}$ [JHEP 01(2018)055]
- CMS 35.9 fb$^{-1}$ [JHEP 09(2018)007]

$\pm 1\sigma$
$\pm 2\sigma$

$M_{h,EFT}^{125}$ scenario

$H \rightarrow hh$ exp. exclusion (95% C.L.)
- CMS 36.1 fb$^{-1}$
- ATLAS 3 ab$^{-1} \oplus$ CMS 3 ab$^{-1}$

$h(125)$ rates $M_h\neq(125 \pm 3)$ GeV
- ATLAS 36.1 fb$^{-1} \oplus$ CMS 35.9 fb$^{-1}$
- ATLAS 3 ab$^{-1} \oplus$ CMS 3 ab$^{-1}$

$\Rightarrow$ indirect measurements stronger at low $\tan \beta$: $M_A \gtrsim 1000$ GeV

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