HAVE YOU HEARD?
THEY DISCOVERED
THE GOD PARTICLE...

IT'S CALLED THE
HIGGS
BOSON!
Higgs Bosons below 125 GeV?!

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

Osaka, 02/2019

• Motivation
• What to expect from SUSY Higgs Bosons
• A Higgs Boson at 96 GeV?!
• Conclusions
1. Motivation: Two Facts:

1: We have a discovery!

2: The SM cannot be the ultimate theory!
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Q: Does the BSM physics have any (relevant) impact on the Higgs?
Q’: Which model?
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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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⇒ good motivation to look at SUSY! :-)

Sven Heinemeyer – HPNP 2019, Osaka, 20.02.2019
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
(\Rightarrow many (close to) zero according to experimental data)
\Rightarrow no model missed (within the MSSM)
\Rightarrow \mathcal{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
\Rightarrow prediction for soft SUSY-breaking terms
   in terms of small set of parameters
\Rightarrow easy to handle, but not all relevant phenomenology captured

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

Enlarged Higgs sector: Two Higgs doublets

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

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

\[ V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2 \]

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)

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

Enlarged Higgs sector: Two Higgs doublets

\[
\begin{align*}
H_1 & = \begin{pmatrix} H_1^1 \\ H_1^2 \\ H_1^3 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 & = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}
\end{align*}
\]

\[
V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \frac{g'^2 + g^2}{8} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \frac{g^2}{2} |H_1 \bar{H}_2|^2
\]

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 $CP$-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. What to expect from SUSY Higgs Bosons
Latest results for neutral heavy Higgs bosons: [CMS '18]

MSSM Higgs exclusion contours in $M_A$–$\tan \beta$ plane: $b\bar{b}, gg \rightarrow h, H, A \rightarrow \tau^+\tau^-$

$\Rightarrow$ limits obtained in certain benchmark scenario!
We have a $\sim 125$ GeV SM-like Higgs boson

⇒ What are the options?

1. Decoupling limit:
   $M_A \gg M_Z$ ⇒ the light Higgs becomes SM-like

2. Alignment without decoupling:
   ⇒ a $CP$-even Higgs becomes SM-like due to an “accidental” cancellation

3. Heavy Higgs SM-like: (in the “alignment w/o decoupling” scen.)
   ⇒ is the case with the heavy $CP$-even Higgs being SM-like
   ⇒ a case with a Higgs below 125 GeV!
   ⇒ (still) a viable solution?!
Obtaining a light Higgs with SM-like couplings

[J. Gunion, H. Haber, hep-ph/0207010]

$\rightarrow$ CP conserving 2HDM in the Higgs basis ($\langle H_1 \rangle = v/\sqrt{2}$, $\langle H_2 \rangle = 0$)

$\mathcal{V} = \ldots + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \ldots + \left[ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + Z_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.} \right] + \ldots$

$\Rightarrow$ CP-even mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & M_A^2 + Z_5 v^2 \end{pmatrix}$$

with mixing angle $\cos(\beta - \alpha) \equiv c_{\beta-\alpha}$

**Decoupling limit:** $M_A^2 \gg Z_i v^2$

$\Rightarrow m_h^2 \sim Z_1 v^2$, $|c_{\beta-\alpha} | \ll 1$, $h$ is SM-like

**Alignment limit:** $Z_6 = 0$ and $Z_1 < Z_5 + M_A^2/v^2$

$\Rightarrow h$ is identical to the SM Higgs, $c_{\beta-\alpha} = 0$

$Z_6 = 0$ and $Z_1 > Z_5 + M_A^2/v^2$

$\Rightarrow H$ is identical to the SM Higgs, $c_{\beta-\alpha} = 1$
**Alignment limit:** see e.g. [M. Carena, I. Low, N. Shah, C. Wagner '13][M. Carena, H. Haber, I. Low, N. Shah, C. Wagner '14]

In the MSSM $Z_6 = 0$ can be obtained through an “accidental” cancellation between tree-level and loop contribution, roughly at:

$$\tan \beta \sim \left[ M_h^2 + M_Z^2 + \frac{3m_t^2\mu^2}{4\pi^2v^2M_S^2} \left( \frac{A_t^2}{2M_S^2} - 1 \right) \right] / \left[ \frac{3m_t^2\mu A_t}{4\pi^2v^2M_S^2} \left( \frac{A_t^2}{6M_S^2} - 1 \right) \right]$$

Compare: $m_h^{\text{mod+}}$ and $m_h^{\text{alt}}$:

- $A_t/M_S = 2.45$, $A_t = A_f$,
- $M_S = m_f \geq 1$ TeV, $m_\tilde{g} = 1.5$ TeV,
- $M_2 = 2M_1 = 200$ GeV, $\mu$ adjustable

(low $M_A$ and $\tan \beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all $M_A$
Alignment limit: see e.g. 
[M. Carena, I. Low, N. Shah, C. Wagner ’13][M. Carena, H. Haber, I. Low, N. Shah, C. Wagner ’14]

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$m_h^{\text{alt}}$: HiggsSignals [P. Bechtle et al. ’15]

$A_t/M_S = 2.45$, $A_t = A_f$,

$M_S = m_f \geq 1$ TeV, $m\bar{g} = 1.5$ TeV,

$M_2 = 2M_1 = 200$ GeV, $\mu$ adjustable

(low $M_A$ and $\tan \beta$: tune $M_S \geq 1$ TeV to obtain $M_h \geq 122$ GeV)

$\Rightarrow$ SM-like Higgs for all $M_A$
Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

→ investigate benchmark scenarios:

→ Vary only $M_A$ 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: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
3. $M_{h^{125}}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm \tilde{\chi}_l^\mp$
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. $M_{h_1^{125}}$ (CPV) scenario: complex phases, $h_2$-$h_3$ interference
New benchmark: $M_{h}^{125}$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 1.5$ TeV
$M_{L_3} = M_{\tilde{E}_3} = 2$ TeV
$\mu = 1$ TeV, $M_1 = 1$ TeV
$M_2 = 1$ TeV, $M_3 = 2.5$ TeV
$X_t = 2.8$ TeV
$A_t = A_b = A_\tau$

⇒ new vanilla benchmark model
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
$A_t = A_b = A_\tau$

⇒ strongly reduced heavy Higgs coverage
New benchmark: $M_{h_{125}}$ 

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

$M_{L_3} = M_{\tilde{E}_3} = 2 \text{ TeV}$

$\mu = 1 \text{ TeV}, M_1 = 1 \text{ TeV}$

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

$X_t = 2.8 \text{ TeV}$

$A_t = A_b = A_{\tau}$

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$X_t = 2.5$ TeV
$A_t = A_b = A_\tau$

$\Rightarrow$ Huge BR of heavy Higgses to EW-inos
New benchmark: $M_H^{125}$

$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = 750 \text{ GeV}$

$- 2(M_{H^\pm} - 150 \text{ GeV})$

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

$\mu = [5.8 \text{ TeV} + 20(M_{H^\pm} - 150 \text{ GeV})] \times M_{\tilde{Q}_3}/750 \text{ GeV}$

$M_1 = M_{\tilde{Q}_3} - 75 \text{ GeV}$

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

$A_t = A_b = A_\tau = 0.65M_{\tilde{Q}_3}$

$\Rightarrow$ exotic solution still viable! $\Rightarrow$ scenario with a Higgs below 125 GeV!
New benchmark: $M_H^{125}$

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

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

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

$M_1 = M_{Q_3} - 75$ GeV

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

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

$\Rightarrow$ large $\text{BR}(H^\pm \rightarrow W^\pm h)$
Interesting case: light singlet

Singlet does not couple to SM particles!
Interesting case: light singlet

Singlet does not couple to SM particles!

“Non-interacting particles are hard to detect.”

[F. Klinkhamer]
Interesting case: light singlet

Singlet does not couple to SM particles!

“Non-interacting particles are hard to detect.”  

“Easily” possible in the NMSSM:

Light, singlet-like Higgs below 125 GeV

Which collider can find them?
NMSSM parameter scan:

Parameters:
\[
\begin{align*}
\tan \beta &= 8, \quad M_A = 1 \text{ TeV}, \quad A_\kappa = -2 \ldots 0 \text{ TeV}, \quad \mu = 120 \ldots 2000 \text{ GeV}, \\
2M_1 &= M_2 = 500 \text{ GeV}, \quad M_3 = 1.5 \text{ TeV}, \quad m_{\tilde{Q}_3} = 1 \text{ TeV}, \quad m_{\tilde{Q}_{1,2}} = 1.5 \text{ TeV}, \\
A_t &= -2 \text{ TeV}, \quad A_{b,\tau} = -1.5 \text{ TeV}.
\end{align*}
\]

⇒ light Higgs below 125 GeV
⇒ strongly reduced couplings to gauge bosons!
⇒ possibly within ILC reach!
3. A Higgs Boson at 96 GeV?!

- What was seen in Run I?
- What was seen in Run II?
- What was seen at LEP?
- Should we get excited?
- Which model fits?
- Implications for the ILC250
What was seen at Run I?

[S. Shotkin, talk at HDays17]

```
h --> γγ (65-110 GeV) Run 1

• ~2σ excursion @~97.5 GeV

S. Shotkin, talk at HDays17

• ~2σ excursion @~80 GeV

S. Gascon-Shotkin HDays17, Santander, ES Sept 22 2017
```
What was seen at Run II?

**h-->γγ (70-110 GeV) Runs 1+2**

- 8 TeV limits on $\sigma \times Br$ redone with 0.1 GeV step. Production processes assumed in SM proportions. No significant excess with respect to expected limits observed.

8 TeV:
minimum(maximum) limit on $\sigma \times Br$:
31(133) fb at $m=102.8(91.1)$ GeV

13 TeV:
minimum(maximum) limit on $\sigma \times Br$:
26(161) fb at $m=103.0(89.9)$ GeV

[S. Shotkin, talk at HDays17]
What was seen at Run II?

All experimental + theoretical systematic uncertainties assumed uncorrelated except for those on signal acceptance due to scale variations + those on production cross sections (assumed 100% correlated).

- Combined 8 TeV+13 TeV $\sigma \times BR$ limit normalized to SM expectation (production processes assumed in SM proportions ). No significant excess with respect to expected limits observed.

S. Gaseon-Shotkin HDays17, Santander, ES Sept. 22 2017

8 TeV+13 TeV: minimum(maximum) limit on $(\sigma \times Br)/(\sigma \times Br)_{SM}$ : 0.17(1.15) at $m=103.0(90.0)$GeV
What was seen at Run II?

S. Shotkin, talk at HDays17

CMS Preliminary 19.7 fb^{-1} (8 TeV) + 35.9 fb^{-1} (13 TeV)

h --> \gamma\gamma (70-110 GeV) Runs 1+ 2

8 TeV: Excess with \sim 2.0 \sigma local significance at m=97.6 GeV

13 TeV: Excess with \sim 2.9 \sigma local (1.47 \sigma global) significance at m=95.3 GeV

8 TeV+13 TeV: Excess with \sim 2.8 \sigma local (1.3 \sigma global) significance at m=95.3 GeV

More data are required to ascertain the origin of this excess.

• Expected and observed local p-values for 8 TeV, 13 TeV and their combination

S. Gascon-Shotkin HDays17, Santander, ES Sept. 22 2017
What was seen at Run II?

\[ h \rightarrow \gamma \gamma \ (70\text{-}110 \ \text{GeV}) \text{ Runs 1+2} \]

‘Signal’ strengths for the 7 event classes and overall, in the 8 TeV+13TeV combination, fixing \( m_H = 95.3 \ \text{GeV} \)

More data are required to ascertain the origin of this excess

\[ \mu_{\text{CMS}}(96 \ \text{GeV}) = [\sigma(pp \rightarrow h_1) \times \text{BR}(h_1 \rightarrow \gamma \gamma)]_{\exp/\text{SM}} = 0.6 \pm 0.2 \]
What about ATLAS?

Note: ATLAS gives fiducial cross section! Conversion factor: $1/0.45$

⇒ ATLAS exclusion limit even weaker than CMS!

Q: why does ATLAS has same sensitivity with twice amount of data?
CMS and ATLAS in direct comparison:

⇒ everything well compatible with the excess!
What was seen at LEP?

\[ \mu_{\text{LEP}}(98 \text{ GeV}) = \left[ \sigma(e^+e^- \rightarrow Zh_1) \times \text{BR}(h_1 \rightarrow b\bar{b}) \right]_{\text{exp}/\text{SM}} = 0.117 \pm 0.057 \]
Should we get excited?

- **Combined 8 TeV + 13 TeV** $\sigma \times \text{BR}$ limit normalized to SM expectation:
  - Production processes assumed in SM proportions
  - **No significant excess** with respect to background expectations
  - Expected and observed local p-values for **8 TeV, 13 TeV** and their **combination**

---

**Q:** When do you dare to something “significant”?
What about the MSSM?


⇒ too small rates!
What about the NMSSM? [F. Domingo, S.H., S. Passehr, G. Weiglein ’18]

Parameters:
\[ \lambda = 0.6, \kappa = 0.035, \tan \beta = 2, \mu_{\text{eff}} = (397 + 15x) \text{ GeV}, M_{H^\pm} = 1 \text{ TeV}, A_\kappa = -325 \text{ GeV}, M_{\text{SUSY}} = 1 \text{ TeV}, A_t = A_b = 0 \]

\[ \xi_b \equiv \frac{\Gamma[h_1 \to ZZ] \cdot \text{BR}[h_1 \to b\bar{b}]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to ZZ] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to b\bar{b}]} \sim \frac{\sigma[e^+ e^- \to Z(h_1 \to b\bar{b})]}{\sigma[e^+ e^- \to Z(H_{\text{SM}}(M_{h_1}) \to b\bar{b})]} \]

\[ \xi_\gamma \equiv \frac{\Gamma[h_1 \to gg] \cdot \text{BR}[h_1 \to \gamma\gamma]}{\Gamma[H_{\text{SM}}(M_{h_1}) \to gg] \cdot \text{BR}[H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \sim \frac{\sigma[gg \to h_1 \to \gamma\gamma]}{\sigma[gg \to H_{\text{SM}}(M_{h_1}) \to \gamma\gamma]} \cdot \]

\[ \Rightarrow \text{both “excesses” can be fitted simultaneously!} \]
What about the $\mu\nu$SSM?

$\mu\nu$SSM: [D. Lopez-Fogliani, C. Muñoz '06]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)

$\Rightarrow$ EW scale seesaw to reproduce the neutrino data
What about the $\mu\nu$SSM?

$\mu\nu$SSM: [D. Lopez-Fogliani, C. Muñoz '06]

$\mu\nu$SSM: NMSSM + well motivated RPV (in simple terms)
   $\Rightarrow$ EW scale seesaw to reproduce the neutrino data

Can the $\mu\nu$SSM explain the two "excesses"?
[T. Biekötter, S.H., C. Muñoz '17]

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</table>
Can the $\mu\nu$SSM explain the two “excesses”?

[T. Biekötter, S.H., C. Muñoz ’17]

⇒ Yes, it can! :-)

(at the $1 - 1.5 \sigma$ level)
Implications for the ILC250:
Implications for the ILC250: reach for light Higgs bosons:

Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb\(^{-1}\) to a new light Higgs

\[ \left( \frac{g_{hZZ}}{g_{H^{SM}ZZ}} \right)^2 \]

\[ [P. Drechsel et al. '17] \]

Indirect LHC sensitivity from measurements of the Higgs at 125 GeV

Could probe the "CMS bump" at 95 GeV

Higgs factory sensitivity: \( h \rightarrow bb \) search

\( M_h/\text{GeV} \)

\( \Rightarrow \) Higgs factory at 250 GeV will explore a large untested region!

[Taken from G. Weiglein '18]
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 not necessarily taken into account: EW/Flavor/DM

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

- **A light Higgs at 96 GeV?** \( \Rightarrow \) perfect case for the ILC250

new CMS/ATLAS result \( \oplus \) old LEP result possibly interesting!
  - NMSSM can explain CMS(/ATLAS) and LEP “excesses”
  - \( \mu\nu \)SSM can explain CMS(/ATLAS) and LEP “excesses”
Katharsis of Ultimate Theory Standards

10th meeting: 08.-10. April 2019 (Dresden Univ.)

Precise Calculation of Higgs Boson masses

Organized by:
M. Carena, H. Haber
R. Harlander, S. Heinemeyer
W. Hollik, P. Slavich, G. Weiglein

Local organizer: D. Stoeckinger
Workshop announcement:

Opportunities at Future High Energy Colliders

Workshop dates: June 11 - July 05 2019 (IFT, Madrid, Spain)

The workshop will bring together key theorists and experimentalists to address these questions, aiming at a more coherent, global view of the opportunities and rationale for the next generation of high energy colliders.

Program of the workshop:

- first week: dark matter and implications from cosmology
- second week: origin of lepton and quark flavour structure; fundamental symmetry tests
- third week: electroweak symmetry breaking; naturalness
- final week: discussion of complementary of the different collider opportunities as pertains to the physics themes.
Further Questions?
Data to be taken into account:

- Higgs boson mass (LHC) ⇒ FeynHiggs
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- SUSY searches (LHC)
Data to be taken into account:

- Higgs boson mass (LHC) ⇒ FeynHiggs
- Higgs boson signal strengths (LHC) ⇒ HiggsSignals/SusHi
- Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds
- SUSY searches (LHC)

Data not necessarily to be taken into account:

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

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

$M_{L_3} = M_{E_3} = 350$ 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: $M_h^{125}(\tilde{\tau})$

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

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$X_t = 2.8$ TeV

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

$\Rightarrow$ strong impact on $\Gamma(h \rightarrow \gamma\gamma)$
New benchmark: $M_h^{125}$(align)

$M_{Q_3} = M_{U_3} = M_{D_3} = 2.5$ 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

⇒ $h$ SM-like for very low $M_A$
LHC Higgs searches for complex parameters:

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

Higgs bosons as intermediate states in \( \{b\bar{b}, gg\} \rightarrow h_a \rightarrow \tau\tau \)

\[ \sum_{a=1}^{3} \quad 2 \]
New benchmark: $M_{h_1}^{125}(\text{CPV})$

\[ M_{Q_3} = M_{U_3} = M_{D_3} = 2 \text{ TeV} \]
\[ M_{L_3} = M_{E_3} = 2 \text{ TeV} \]
\[ \mu = 1.65 \text{ TeV}, \quad M_1 = 1 \text{ TeV} \]
\[ M_2 = 1 \text{ TeV}, \quad M_3 = 2.5 \text{ TeV} \]
\[ |A_t| = \mu / \tan \beta + 2.8 \text{ TeV} \]
\[ \phi_{A_t} = 2/15 \pi \]
\[ |A_t| = A_b = A_\tau \]

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

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

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

$\mu = 1.65 \text{ TeV}, M_1 = 1 \text{ TeV}$

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

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

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

$|A_t| = A_b = A_\tau$

⇒ reduced coverage due to $h_2$-$h_3$ interference
Future (HL-)LHC projections:

⇒ strong (HL-)LHC limits
Sum rule in the MSSM with $h$ SM-like: $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) \approx 0$

Search for neutral SUSY Higgs bosons:

$e^+ e^- \rightarrow Z h, Z H$

$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$

$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$

$e^+ e^- \rightarrow A h, A H$

$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$

$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}}) \sigma_{hZ}^{\text{SM}}$

$\Rightarrow$ only pair production of heavy Higgs bosons!

reach: $M_A \lesssim \sqrt{s}/2$
CLIC reach:

$L. \text{Linssen et al. '12}$

$⇒$ close to kinematic limit

$⇒$ CLIC $\sqrt{s} = 3 \text{ TeV}$

$e^+e^- \rightarrow HA$

$\tan \beta$

$CP - \text{odd Higgs mass } M_A$ [GeV]
“Simple” LC reach in the MSSM (neglecting $t\bar{t}$ final states)

⇒ unique opportunities!