FeynHiggs - da weiß man, was man hat. Guten Abend!
Impact of Improved SUSY Higgs-boson mass predictions

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with E. Bagnaschi, J. Ellis, J. Evans, K. Olive, I. Sobolev, J. Zheng

- The Quest for Precision
- MSSM Higgs mass calculations
- Improved predictions for MSSM scenarios
- Conclusions
1. The Quest for Precision

\[ \begin{align*}
\sqrt{s} = 7 \text{ TeV}: & \int \mathcal{L} dt = 4.6-4.8 \text{ fb}^-1 \\
\sqrt{s} = 8 \text{ TeV}: & \int \mathcal{L} dt = 5.8-5.9 \text{ fb}^-1 
\end{align*} \]

⇒ clear discovery at \( \sim 125 \text{ GeV} \)!
⇒ can be interpreted as the light(/heavy) \( CP \)-even MSSM Higgs

\( \sigma \)
The Higgs mass accuracy: experiment vs. theory:

Experiment:

ATLAS: \[ M_{h}^{\text{exp}} = 125.36 \pm 0.37 \pm 0.18 \text{ GeV} \]

CMS: \[ M_{h}^{\text{exp}} = 125.03 \pm 0.27 \pm 0.15 \text{ GeV} \]

combined: \[ M_{h}^{\text{exp}} = 125.09 \pm 0.21 \pm 0.11 \text{ GeV} \]
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**MSSM theory:**

LHCHXSWG adopted FeynHiggs for the prediction of MSSM Higgs boson masses and mixings (considered to be the code containing the most complete implementation of higher-order corrections)

FeynHiggs: \( \delta M_{h}^{\text{theo}} \sim 3 \text{ GeV} \) (now 2 GeV?)

→ rough estimate, FeynHiggs contains algorithm to evaluate uncertainty, depending on parameter point
Katharsis of Ultimate Theory Standards

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

Precise Calculation of

(N)

Higgs Boson masses

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

⇒ next meeting: 11/2019 at MPI Munich, Germany
The MSSM:

⇒ Superpartners for Standard Model particles
Enlarged Higgs sector: Two Higgs doublets

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

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

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

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

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)

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

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

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

gauge couplings, in contrast to SM

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

2 $\mathcal{CP}$-violating phases: $\xi, \arg(m_{12}) \Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

\[ \tan \beta = \frac{v_2}{v_1}, \quad M_{H^\pm}^2 \]
2. MSSM Higgs mass calculationss

**Method I**

Higher-order corrections in the Feynman diagrammatic method:

Propagator/Mass matrix at tree-level:

\[
\begin{pmatrix}
q^2 - m_H^2 & 0 \\
0 & q^2 - m_h^2
\end{pmatrix}
\]

Propagator / mass matrix with higher-order corrections (→ Feynman-diagrammatic approach):

\[
M_{hH}^2(q^2) = \begin{pmatrix}
q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\
\hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2)
\end{pmatrix}
\]

\[\hat{\Sigma}_{ij}(q^2) \ (i, j = h, H) : \text{renormalized Higgs self-energies}\]

\[\text{CP-even fields can mix}\]

⇒ complex roots of \(\det(M_{hH}^2(q^2))\):

\[\mathcal{M}_{h_i}^2(i = 1, 2) : \mathcal{M}^2 = M^2 - i M \Gamma\]
Structure of higher-order corrections:

One-loop: \[ \Delta M_h^2 \sim m_t^2 \alpha_t \left[ L + L^0 \right], \quad L := \log \left( \frac{m_\tilde{t}}{m_t} \right) \]

Two-loop: \[ \Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s \left[ L^2 + L + L^0 \right] + \alpha_t^2 \left[ L^2 + L + L^0 \right] \right\} \]

Three-loop: \[ \Delta M_h^2 \sim m_t^2 \left\{ \alpha_t \alpha_s^2 \left[ L^3 + L^2 + L + L^0 \right] + \alpha_t^2 \alpha_s \left[ L^3 + L^2 + L + L^0 \right] + \alpha_t^3 \left[ L^3 + L^2 + L + L^0 \right] \right\} \]

Partial results: [S. Martin '07] [R. Harlander, P. Kant, L. Mihaila, M. Steinhauser '08] [R. Harlander, J. Klappert, A. Ochoa, A. Voigt '18] \( \Rightarrow \) H3m/Himalaya

**H3m** adds \( \mathcal{O}(\alpha_t \alpha_s^2) \) corrections to **FeynHiggs**

**Himalaya** can be linked to other codes

Large \( m_\tilde{t} \) \( \Rightarrow \) large \( L \) \( \Rightarrow \) resummation of logs necessary \( \Rightarrow \) Method II
Advantages of Feynman-diagrammatic method:

- all contributions at fixed order are captured
- trivial to include many SUSY scales
- full control over Higgs boson self-energies
  → needed for other quantities (production and decay)

Problems of Feynman-diagrammatic method:

- always only fixed order
- large logs not captured beyond the calculated order
**Method II:** EFT approach: Log resummation via RGE’s:


**Simple example for log resummation:**

SUSY mass scale: $M_{\text{SUSY}} = M_S \sim m_{\tilde{t}}$

Above $M_{\text{SUSY}}$: MSSM

Below $M_{\text{SUSY}}$: SM

**Relevant SM parameters:**

- quartic coupling $\lambda$
- top Yukawa coupling $h_t$ ($\alpha_t = h_t^2/(4\pi)$)
- strong coupling constant $g_s$ ($\alpha_s = g_s^2/(4\pi)$)

1. Take: $h_t(m_t), g_s(m_t)$
   
   SM RGEs for $h_t, g_s$: $h_t, g_s(m_t) \rightarrow h_t, g_s(M_S)$

2. Take $\lambda(M_S), h_t(M_S), g_s(M_S)$
   
   SM RGEs for $\lambda, h_t, g_s$: $\lambda, h_t, g_s(M_S) \rightarrow \lambda, h_t, g_s(m_t)$

3. Evaluate $M_h^2$
   
   $M_h^2 \sim 2\lambda(m_t)v^2$
Advantages of RGE log resummation:

- large logs taken into account to all orders
- calculation can easily be extended to very large scales

Problems of RGE log resummation:

- not all contributions at fixed order are captured
  → sub-leading logs more difficult
  → momentum dependence
- difficult (impossible?): include many different SUSY scales
- difficult (impossible?): control over Higgs boson self-energies
  → needed for other quantities (production and decay)
The best of both worlds:
to get the most precise prediction of $M_h$:

$$\Delta M_h^2 = (\Delta M_h^2)^{\text{RGE}}(X_t^{\overline{\text{MS}}}, M_S^{\overline{\text{MS}}}, \overline{m}_t) - (\Delta M_h^2)^{\text{FD,log}}(X_t, M_S, \overline{m}_t)$$

$$M_h^2 = (M_h^2)^{\text{FD}} + \Delta M_h^2$$

⇒ many technical aspects and complications . . .

⇒ combination of best FD result with resummed LL, NLL corrections for large $m_{\tilde{t}}$
⇒ most precise $M_h$ prediction for large $m_{\tilde{t}}$
⇒ first “hybrid code”: FeynHiggs 2.10.0

Codes on the market:

1.) Fixed order codes: good for all scales low
   - SuSpect
   - SPheno/SARAH
   - SoftSUSY/FlexibleSUSY
   - H3m

2.) EFT codes: good for all scales high
   - SusyHD
   - MhEFT
   - HSSUSY

3.) Hybrid codes: good always?!
   - FeynHiggs
   - FlexibleEFTHiggs
   - SPheno/SARAH

Obviously: quality depends on the details implemented
Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE's
- Inclusion of gluino mass scale in RGE's
- Inclusion of EW effects in RGE's
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc.
- “Two Higgs Doublet Model” below $M_S$
- Splitting in the scalar top sector
- ...
Possible & necessary refinements of the EFT calculation:

- Inclusion of EWino mass scale in RGE’s ⇒ included into FeynHiggs
- Inclusion of gluino mass scale in RGE’s ⇒ included into FeynHiggs
- Inclusion of EW effects in RGE’s ⇒ included into FeynHiggs
- Inclusion of 3-loop RGEs plus 2-loop thresholds etc. ⇒ included into FeynHiggs
- “Two Higgs Doublet Model” below $M_S$ ⇒ private version of FeynHiggs exists, other code: MhEFT
- Splitting in the scalar top sector ⇒ future work
- ...
Impact of precise $M_h$ calculation (I):

Impact of non-degenerate $\mathcal{O}(\alpha_t^2)$ threshold corr. in EFT part:

One scale $M_{\text{SUSY}}$, but large stop sector splitting, $\tan\beta = 10$:

$\Rightarrow$ important for large $X_t$ (more in a moment)
Impact of precise $M_h$ calculation (II):

Impact of pole mass determination improvements:
(ask me details over coffee!)

One scale $M_{\text{SUSY}}$, $\tan \beta = 10$:

$\Rightarrow$ calculation stabilized!
3. Improved predictions for MSSM scenarios

Are these improved calculations relevant?
Are they relevant in any “realistic” scenario?

Analysis in:
- CMSSM with stop co-annihilation
- sub-GUT models
- minimal Anomaly Mediation SUSY-breaking
- pMSSM11

Comparison of hybrid codes:

**FeynHiggs 2.10.0** – log-resummation with $M_S$
- $2L$ RGEs, $1L$ thresholds
- $m_t^{\overline{MS}}$ at NLO

**FeynHiggs 2.14.1** – log-resummation with $M_S$
- Inclusion of EWino mass scale in RGE’s
- Inclusion of gluino mass scale in RGE’s
- $3L$ RGEs, $2L$ thresholds
- $m_t^{\overline{MS}}$ at NNLO
- Inclusion of EW effects in RGE’s and $m_t^{\overline{MS}}$
3. A) Stop-coannihilation in the CMSSM:

\[ A_0 = 3m_0, \tan\beta = 5, \text{sgn}(\mu) > 0 \]
\[ A_0 = 3m_0, \tan\beta = 5, \text{sgn}(\mu) < 0 \]

⇒ clear impact of improved $M_{h}$ calculation
⇒ $\mathcal{O}(\alpha_t^2)$ non-degenerate threshold corr. crucial!
3. A) Stop-coannihilation in the CMSSM:

⇒ clear impact of improved $M_h$ calculation
⇒ refined allowed regions with new $M_h$
3. B) Sub-GUT models:

⇒ clear impact of improved $M_h$ calculation
⇒ enlarged allowed regions, better compatibility!
3. C) mAMSB:

⇒ clear impact of improved $M_h$ calculation
⇒ new allowed/disallowed regions!
3. D) pMSSM11:

⇒ clear impact of improved $M_h$ calculation
⇒ enlarged allowed regions, better compatibility!
4. Conclusions

- High precision predictions in BSM models for Higgs physics are needed! → to match experimental accuracy at the LHC and ILC/CLIC

- **FeynHiggs** provides these predictions for the MSSM (and beyond) (⇒ code adopted by the LHCHXSWG)
  ⇒ first and most developed “hybrid code” – necessary for high precision

- **CMSSM stop co-annihilation:**
  \( \mathcal{O}(\alpha_t^2) \) non-degenerate threshold corrections crucial
  ⇒ refined allowed regions

- **Sub-GUT models:** enlarged allowed regions, better compatibility!

- **mAMSB:** new allowed/disallowed regions!

- **pMSSM11:** enlarged allowed regions, better compatibility!

- Overall better compatibility with improved \( M_h \) calculation!
Higgs Days at Santander 2019
Theory meets Experiment
16.-20. September

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Further Questions?