Corrections to Higgs Boson Masses in the MSSM

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content

Higgs mechanism

Standard Model:

- add complex $SU(2)$-field with non-trivial vacuum expectation value to the Lagrangian density:

$$\mathcal{L}_{\text{Higgs}} = \left(D^\mu \phi\right)^\dagger \left(D_\mu \phi\right) + \mu^2 \phi^\dagger \phi - \frac{\lambda}{4}\left(\phi^\dagger \phi\right)^2 + y_d \left(\psi_{\text{L}} \cdot \phi\right) \psi_{\text{R}}^d + y_u \left(\psi_{\text{L}} \cdot \phi^\dagger\right) \psi_{\text{R}}^u,$$

- explanation of fundamental particle's masses,
- restore unitarity,
- four degrees of freedom: 3 Goldstone bosons, 1 physical Higgs boson,
- two free parameters: μ, λ, corresponding to m_h and v,
- tree-level mass of the physical Higgs boson $m_h^2 = 2\mu^2 = \frac{\lambda v^2}{2}$.

Higgs mechanism

Supersymmetry:

- Lagrangian density composed of gauge terms, matter terms and the superpotential $\mathcal{W}$:

$$\mathcal{L}_{\text{SUSY}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{matter}} + \left(\int \mathrm{d}^2\theta \mathcal{W} + \text{h. c.} \right),$$

$$\mathcal{W} = c_i \Phi_i + \frac{1}{2} m_{ij} \Phi_i \Phi_j + \frac{1}{6} y_{ijk} \Phi_i \Phi_j \Phi_k,$$

- $\mathcal{W}$ must be analytic to preserve supersymmetry (Φ and $\Phi^\dagger$ together not allowed),
- at least two complex $SU(2)$-Higgs doublets necessary,

$$h_1 = \begin{pmatrix} \frac{1}{\sqrt{2}} \left(v_1 + \phi_1^0 - \mathrm{i}\gamma_1^0 \right) \\ -\phi_1^- \end{pmatrix} \quad \text{and} \quad h_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}} \left(v_2 + \phi_2^0 - \mathrm{i}\gamma_2^0 \right) \end{pmatrix},$$

- eight bosonic degrees of freedom: 3 Goldstone bosons, 5 physical Higgs bosons.

Higgs potential in the MSSM

- Higgs potential fixed by Lagrangian density:

$$V_{\text{Higgs}} = m_1^2 h_1^\dagger h_1 + m_2^2 h_2^\dagger h_2 - m_{12}^2 \left(h_1 \cdot h_2 + h_1^\dagger \cdot h_2^\dagger \right) + \frac{1}{8} \left(g_1^2 + g_2^2 \right) \left(h_2^\dagger h_2 - h_1^\dagger h_1 \right)^2 + \frac{1}{2} g_2^2 h_1^\dagger h_1 h_2^\dagger h_2,$$

- tree-level masses correlated:

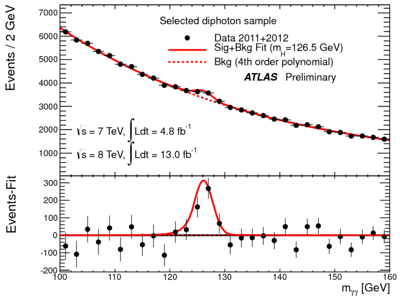
$$m_{H^0,h^0}^2 = \frac{1}{2} \left(m_{A^0}^2 + m_Z^2 \pm \sqrt{\left(m_{A^0}^2 + m_Z^2 \right)^2 - (2 m_Z m_{A^0} \cos 2\beta)^2} \right),$$

$$m_{H^\pm}^2 = m_{A^0}^2 + m_W^2,$$

- two free parameters: conventionally $\tan\beta = \frac{v_2}{v_1}$, m_{A^0},
- theoretical upper bound: $m_{h^0}^2 \leq (m_Z \cos 2\beta)^2$.

LHC discovery

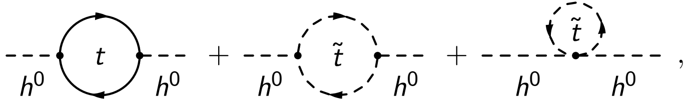
- 4th of July in 2012:
  ATLAS and CMS both declare the discovery of a new particle
- recent result:



[Fleischmann, Epiphany 2013],

- it is a boson with a mass of
  $(125.2 \pm 0.3(\text{stat}) \pm 0.6(\text{sys}))$ GeV, [Fleischmann, Epiphany 2013],
- it could be a Higgs particle.

- main contributions come from t and $\tilde{t}$ loops; order α_t, but proportional to m_t^4:

$\Sigma_{hh} =$ 

- additional parameters: $\mu, m_{\tilde{t}_\mathrm{R}}, m_{\tilde{q}_\mathrm{L}}, a_t$,
- mass contribution: ca. 40% of tree-level result,
- determination of the Higgs masses means finding the poles of the propagator matrix; in the real MSSM:

$$\begin{vmatrix} p^2 - m_{H^0}^2 + \hat{\Sigma}_{H^0 H^0}\left(p^2\right) & \hat{\Sigma}_{h^0 H^0}\left(p^2\right) \\ \hat{\Sigma}_{H^0 h^0}\left(p^2\right) & p^2 - m_{h^0}^2 + \hat{\Sigma}_{h^0 h^0}\left(p^2\right) \end{vmatrix} = 0,$$

- uncertainty of the calculation still too big.

two-loop corrections

most important parts:
corrections to m_t-enhanced one-loop contributions
in a gauge-less limit,

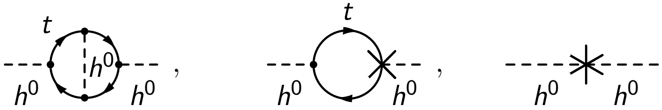
- corrections by gluons and gluinos already known,
  order $\alpha_t \alpha_s$ in an on-shell scheme,

  [Heinemeyer, Hollik, Rzehak, Weiglein, arXiv:hep-ph/0705.0746, 2007],
- corrections by Higgs and Higgsinos already known
  in the real MSSM in the effective potential approach,
  order α_t^2 in a $\overline{\text{DR}}$ scheme,

  [Brignole, Degrassi, Slavich, Zwirner, arXiv:hep-ph/0112177, 2002],
- corrections by Higgs and Higgsinos
  in the case of the complex MSSM: in process.

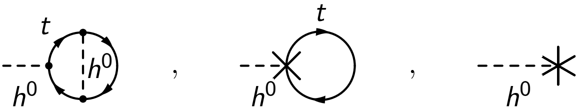
order α_t^2

- again: enhancement by additional m_t^2,
- Feynman-diagrammatic approach:



(two-loop), (one-loop) $\cdot$ $(\delta^{(1)})$, $(\delta^{(2)}) + (\delta^{(1)})^2$,
+(one-loop)^2

- $(\delta^{(2)}) + (\delta^{(1)})^2$ acquired by renormalizing the Higgs potential, additional Feynman-diagrams necessary:



extension by complex parameters

mixing of former CP-even and CP-odd Higgs possible:
$(h^0, H^0, A^0) \to (h_1, h_2, h_3)$,

- m_{A^0} not a useful input parameter anymore,
- (3×3)-propagator matrix, (at one-loop (5×5)),
- $m_{H^\pm}$ input parameter instead,
  also charged Higgs boson self energy has to be calculated,
- complex phases appear for A_t, μ and $m_{\tilde{g}}$,
  have to be renormalised.

procedure of calculation

- creation of Feynman-diagrams and amplitudes with FeynArts,
  [Hahn, arXiv:hep-ph/0012260, 2001],
- applying approximations,
- reducing one-loop diagrams to master integrals with FormCalc,
  [Hahn, arXiv:hep-ph/0901.1528, 2009],
- reducing two-loop diagrams to master integrals with TwoCalc,
  [Weiglein, Scharf, Böhm, arXiv:hep-ph/9310358, 1993],
- creating counterterms from the Higgs potential,
- applying renormalisation scheme,
- evaluating renormalisation constants with FeynArts and FormCalc,
- expanding master integrals, simplifying result.

applied approximations

(similar as for $\alpha_t \alpha_s$ corrections)

1. gauge-less limit: $g_1 = 0$, $g_2 = 0$,
   - only Yukawa-couplings left,
   - $m_W = 0$, $m_Z = 0$,
   - $m_{h^0} = 0$, $m_{G^0} = 0$, $m_{G^\pm} = 0$, $m_{H^0} = m_{H^\pm}$, $m_{A^0} = m_{H^\pm}$,
   - $m_{\tilde{\chi}_3^0} = -\mu$, $m_{\tilde{\chi}_4^0} = \mu$, $m_{\tilde{\chi}_2^\pm} = \mu$,
   - other Charginos and Neutralinos decouple,
   - Higgs mixing angle $\alpha = \beta - \frac{\pi}{2}$,
2. external momentum equal to zero,
   - only two-loop vacuum diagrams; known analytically,
   - renormalisation constants for genuine two-loop counterterms calculated at zero momentum,
3. bottom mass equal to zero,
   - no mixing in sbottom sector,
   - one sbottom (w. l. o. g. $\tilde{b}_2$) decouples,
   - $m^2_{\tilde{b}_1} = m^2_{\tilde{t}_1} - m^2_t$.

renormalisation scheme

required renormalisation constants:

1. at one-loop:
   - δm_t, $\delta m_{\tilde{t}_1}$ and $\delta m_{\tilde{t}_2}$ fixed by on-shell condition,
   - $\delta m_{\tilde{b}_1}$ dependent on top-stop-sector,
   - δA_t fixed by on-shell condition for mixing of stops,
   - $\delta\mu$ fixed by on-shell condition for $\tilde{\chi}_2^{\pm}$,
   - $\delta \tan\beta = \frac{\tan\beta}{2}(\delta Z_{H_2} - \delta Z_{H_1})\big|_{\text{div.}}$, $\overline{\text{DR}}$ scheme,
   - Higgs field renormalisation constants $\delta Z_{H_1}\big|_{\text{div.}}$ and $\delta Z_{H_2}\big|_{\text{div.}}$, $\overline{\text{DR}}$ scheme,
2. at one-loop and two-loop:
   - tadpoles $\delta t_{h^0}, \delta t_{H^0}, \delta t_{A^0}$ fixed by on-shell conditions,
   - $\delta m_{H^\pm}$ fixed by on-shell condition,
   - $\delta m_{h^0}, \delta m_{H^0}, \delta m_{A^0}$ and $\delta m_{h^0 H^0}, \delta m_{h^0 A^0}, \delta m_{H^0 A^0}$ dependent on tadpoles and $\delta m_{H^\pm}$.

status and outlook

current status:

- all Feynman-diagrams are generated and calculated,
- renormalisation at work,
- MSSM model file (e. g. for FeynArts) further improved,

outlook:

- numerical analysis,
- inclusion into FeynHiggs,

  [Hahn, Heinemeyer, Hollik, Rzehak, Weiglein, arXiv:hep-ph/1007.0956, 2010],
- investigate influence of external momentum.