Precise Higgs mass calculations in supersymmetry

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RWTH Aachen

DESY theory workshop, 27.09.2017

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1. Supersymmetry and the Higgs sector
2. Higgs mass calculation in the MSSM
    - at fixed loop order
    - in an EFT
    - in a mixed approach
3. Summary

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Supersymmetry

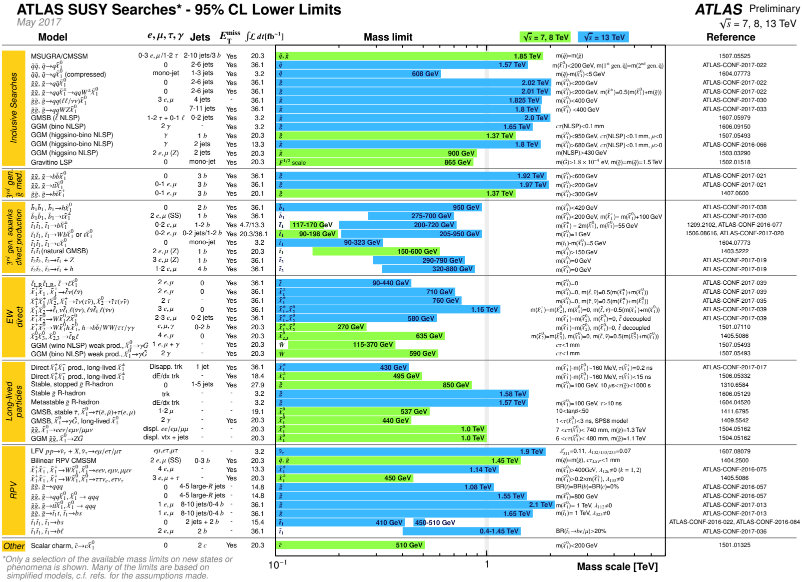
Still an attractive extension of the Standard Model!

Features:

- can predict the SM-like Higgs mass (see later)
- gauge coupling unification at $\sim 10^{16}$ GeV (due to extra matter)
- possible connection to super-gravity models and string theory (E_6SSM, MRSSM)
- can explain deviation of $(g-2)_\mu$
- can stabilize the electroweak vacuum (see later)

Problem: LHC has not found any SUSY particles so far $\Rightarrow$ SUSY particles are probably heavy

Current limits on SUSY particle masses



CP-even Higgs masses in the real MSSM

$(\mathrm{Im}\, H_d^0, \mathrm{Im}\, H_u^0) \xrightarrow{\beta} (G^0, A)$, $(\mathrm{Re}\, H_d^0, \mathrm{Re}\, H_u^0) \xrightarrow{\alpha} (h, H)$:

$$m^2_{h,H} = \frac{1}{2}\left[m_Z^2 + m_A^2 \mp \sqrt{(m_Z^2 + m_A^2)^2 - 4 m_Z^2 m_A^2 c_{2\beta}^2}\right]$$

If $m_A \gg m_Z \Rightarrow$

$$m_h^2 \approx m_Z^2 c_{2\beta}^2 \leq (91.2\,\mathrm{GeV})^2 \qquad \text{(tree-level)}$$

$\Rightarrow M_h \approx 125\,\mathrm{GeV}$ requires **large loop corrections**!

$$M_h^2 = m_h^2 + \Delta m_h^2 \qquad \Rightarrow \qquad \Delta m_h^2 \geq (85\,\mathrm{GeV})^2$$

Because of large loop corrections Δm_h^2:

$$\Delta M_h^{\mathrm{theo}} \gtrsim (1 \ldots 2)\,\mathrm{GeV} \quad \text{at least!}$$
$$\Delta M_h^{\mathrm{exp}} = 0.24\,\mathrm{GeV}$$ [PDG-2017]

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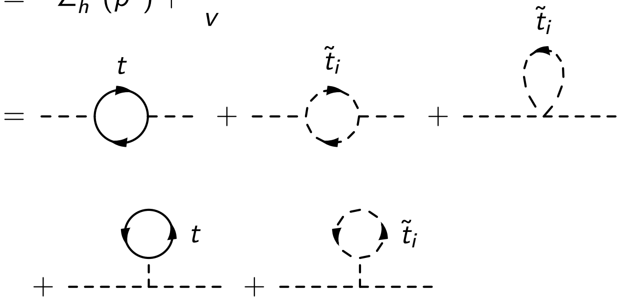
Fixed loop order calculation

Dominant contribution to M_h at the 1-loop level:

$$(\Delta m_h^2)^{1L} = -\Sigma_h^{1L}(p^2) + \frac{t_h^{1L}}{v}$$



$$\approx \frac{12 m_t^2 y_t^2}{(4\pi)^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12 M_S^4} \right) + O(p^2)$$

Summary of fixed loop order calculation

Typical order of magnitude of loop contributions (depends on parameter scenario):

$$\begin{aligned} M_h &= m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots \\ &\approx [91 + O(20\ldots30) + O(2\ldots4) + O(1\ldots2)]\,\text{GeV} \end{aligned}$$

Advantages:

- includes logarithmic, non-logarithmic and suppressed terms of the order $O(v^2/M_S^2)$ at fixed loop order
- precise prediction if $M_S \sim m_t$

Problem:

- large logarithmic corrections, if $M_S \gg m_t$
  $\Rightarrow$ slow convergence of perturbation series
  $\Rightarrow$ large theoretical uncertainty, (1–2 GeV, or more)
  $M_h^{\text{exp}} = (125.09 \pm 0.24)\,\text{GeV}$

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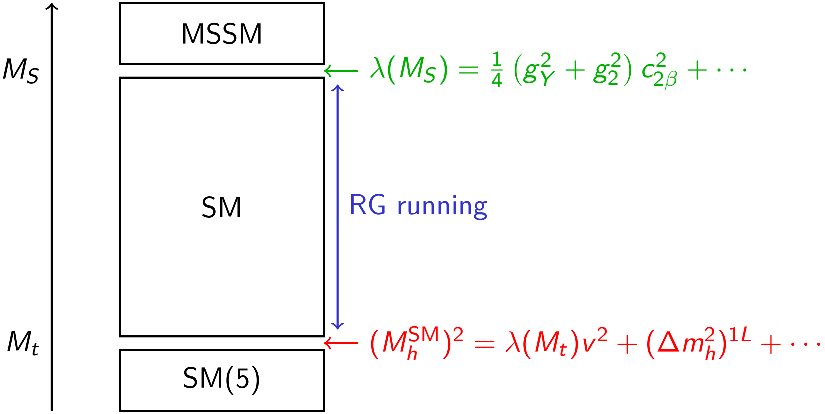
Higgs mass calculation in an EFT

Idea: Integrate out SUSY particles at M_S (expand in v^2/M_S^2)
$\Rightarrow \lambda(M_S)$ is fixed by the MSSM
$\Rightarrow$ effectively: separation of scales M_S and M_t.



Summary of EFT approach

Typical order of magnitude of loop contributions (depends on parameter scenario, here $X_t = 0$, $M_S = 20\,\text{TeV}$):

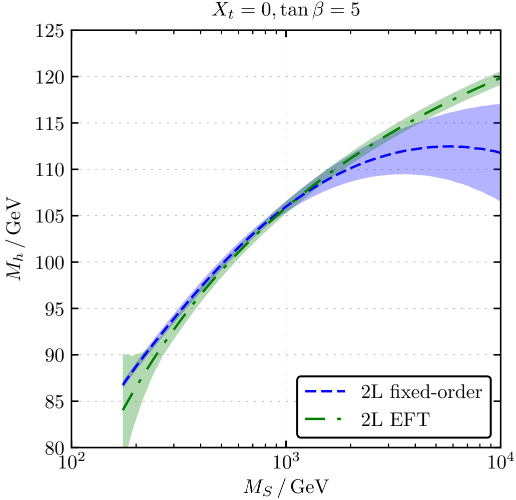
$$M_h = m_h + \Delta m_h^{1L} + \Delta m_h^{2L} + \Delta m_h^{3L} + \cdots$$
$$\approx [O(124) + O(0.5\ldots1) + O(0.1\ldots0.2) + O(0.02\ldots0.04)]\,\text{GeV}$$

Advantages:

- large logarithmic fixed order loop corrections are avoided
- large logarithms $\propto \ln(M_S/M_t)$ are resummed to all orders

Disadvantage: usually terms $O(v^2/M_S^2)$ are neglected
$\Rightarrow$ imprecise when $v \sim M_S$
$\Rightarrow$ large theoretical uncertainty when $v \sim M_S$

Comparison of fixed-order and EFT approaches



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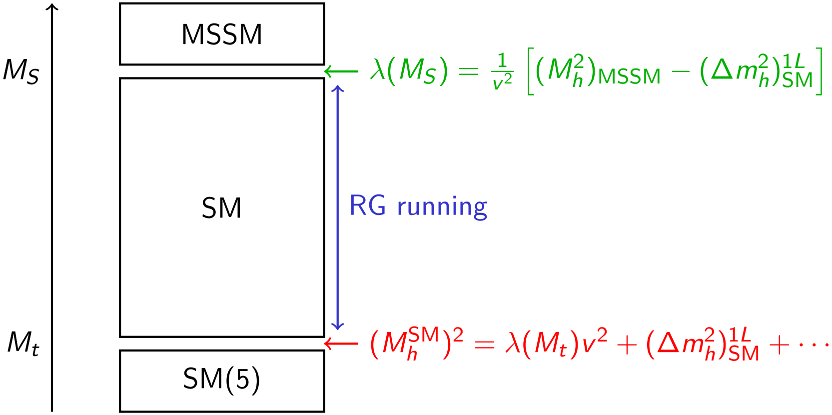
FlexibleEFTHiggs approach [arXiv:1609.00371]

Idea: Determine $\lambda(M_S)$ from the condition

$$(M_h^2)_{\text{SM}} \equiv \lambda(M_S)v^2 + (\Delta m_h^2)^{1L}_{\text{SM}} \stackrel{!}{=} (M_h^2)_{\text{MSSM}} \qquad \text{1L, } Q = M_S$$



Summary FlexibleEFTHiggs approach

$$(M_h^2)_{\text{SM}} = (M_h^2)_{\text{MSSM}} \qquad 1\text{L},\ Q = M_S$$

Advantages:

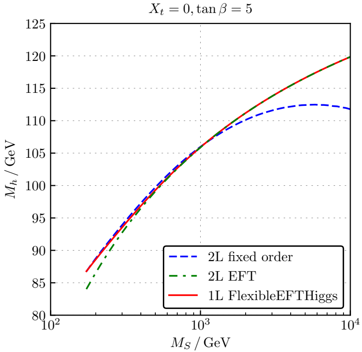
- large logarithms $\propto \ln(M_S/M_t)$ are resummed to all orders
- all suppressed terms $O(v^2/M_S^2)$ are incorporated in λ

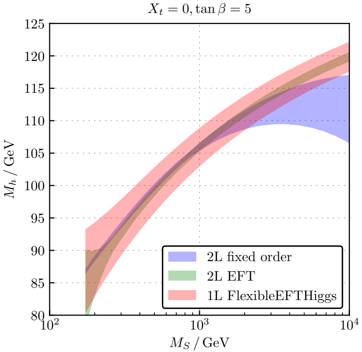
$\Rightarrow$ FlexibleEFTHiggs leads to a correct Higgs mass prediction at the full 1-loop level (including suppressed terms) with additional (N)LL resummation.

Disadvantage:

- tricky to extend to 2-loop accuracy

Comparison of the three approaches





Summary

Supersymmetry is still viable, but LHC continuously excludes light SUSY scenarios

Approaches to calculate M_h:

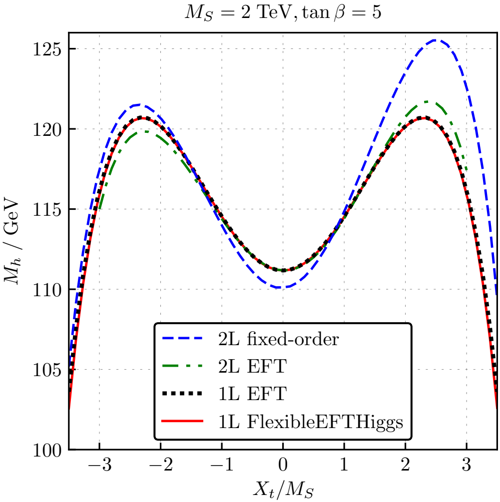
	low M_S $M_S \lesssim 2\,\text{TeV}$	high M_S $M_S \gtrsim 2\,\text{TeV}$
fixed-order	✓	✗
EFT	✗	✓
mixed (FlexibleEFTHiggs)	✓	✓

FlexibleEFTHiggs:

- full NLO + (N)LL resummation
- can be applied to **any** BSM model (SUSY or non-SUSY)
- can be easily automatized

Backup

Comparison of the three approaches



FlexibleEFTHiggs – EFT equivalence

Proof of equivalence: Start with matching condition:

$$
\begin{aligned}
(M_h^2)_{\text{SM}} &= (M_h^2)_{\text{MSSM}} \qquad 1\text{L}, \; Q = M_S \\
\lambda v^2 + (\Delta m_h^2)^{1L}_{\text{SM}} &= (M_h^2)_{\text{MSSM}}
\end{aligned}
$$

$\Rightarrow$

$$
\begin{aligned}
\lambda(M_S) &= \frac{1}{v^2}\left[(M_h^2)_{\text{MSSM}} - (\Delta m_h^2)^{1L}_{\text{SM}}\right] \\
&= \frac{1}{v^2}\left[(m_h^2)_{\text{MSSM}} + (\Delta m_h^2)^{1L}_{\text{MSSM}} - (\Delta m_h^2)^{1L}_{\text{SM}}\right]
\end{aligned}
$$

Now insert $(m_h^2)_{\text{MSSM}}$ and $(\Delta m_h^2)^{1L}_{\text{MSSM}}$ ...

FlexibleEFTHiggs – EFT equivalence

Inserting $(m_h^2)_{\text{MSSM}}$ and $(\Delta m_h^2)^{1L}_{\text{MSSM}}$ for $X_t = 0$:

$$\lambda(M_S) = \frac{1}{v^2}\Bigg[\frac{1}{4}(g_Y^2 + g_2^2)v^2 c_{2\beta}^2 + \frac{c_\alpha^2}{s_\beta^2}(\Delta m_h^2)^{1L}_{\text{SM}} - \frac{c_\alpha^2}{s_\beta^2}\frac{12(y_t^{\text{SM}})^2 m_t^2}{(4\pi)^2} B_0(m_h^2, M_S^2, M_S^2) - (\Delta m_h^2)^{1L}_{\text{SM}}\Bigg]$$

Now go to the decoupling limit $c_\alpha^2/s_\beta^2 \to 1$ ...

FlexibleEFTHiggs – EFT equivalence

In the decoupling limit $c_\alpha^2/s_\beta^2 \to 1$:

$$\begin{aligned}
\lambda(M_S) &= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 - 12\frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2} B_0(m_h^2, M_S^2, M_S^2) \\
&= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 - 12\frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2}\left[-\log\frac{M_S^2}{Q^2} + \frac{m_h^2}{6M_S^2} + O\left(\frac{m_h^4}{M_S^4}\right)\right] \\
&= \frac{1}{4}(g_Y^2 + g_2^2)c_{2\beta}^2 + 12\frac{m_t^2(y_t^{\text{SM}})^2}{(4\pi)^2 v^2}\left[\log\frac{M_S^2}{Q^2}\right] + O\left(\frac{v^2}{M_S^2}\right) \\
&= \lambda^{\text{EFT,tree}} + \Delta\lambda^{\text{EFT},1L} + O\left(\frac{v^2}{M_S^2}\right)
\end{aligned}$$

In the decoupling limit $\lambda(M_S)$ in the FlexibleEFTHiggs approach is equivalent to the EFT approach at 1-loop, up to suppressed terms $O(v^2/M_S^2)$

Higgs mass uncertainty estimate

fixed-order:

- $|M_h^{2L}(Q_{\text{pole}} = M_S/2) - M_h^{2L}(Q_{\text{pole}} = 2M_S)|$
- $|M_h^{2L}(y_t^{1L}) - M_h^{2L}(y_t^{2L})|$

EFT (SUSYHD):

- $|M_h^{2L}(Q_{\text{pole}} = M_t/2) - M_h^{2L}(Q_{\text{pole}} = 2M_t)|$
- $|M_h^{2L}(y_t^{2L}) - M_h^{2L}(y_t^{3L})|$
- $|M_h^{2L}(Q_{\text{match}} = M_S/2) - M_h^{2L}(Q_{\text{match}} = 2M_S)|$
- $|M_h^{2L} - M_h^{2L}(\lambda \to \lambda(1 + v^2/M_S^2))|$

FlexibleEFTHiggs:

- $|M_h^{2L}(Q_{\text{pole}} = M_t/2) - M_h^{2L}(Q_{\text{pole}} = 2M_t)|$
- $|M_h^{2L}(y_t^{2L}) - M_h^{2L}(y_t^{3L})|$
- $|M_h^{2L}(Q_{\text{match}} = M_S/2) - M_h^{2L}(Q_{\text{match}} = 2M_S)|$

Incorrect 2L logs in original FlexibleEFTHiggs-1L

Matching condition:

$$\lambda \leftarrow \frac{1}{v^2}\left[(m_h^{\text{SM}})^2 + (M_h^{\text{MSSM}})^2 - (M_h^{\text{SM}})^2\right]$$

Expansion of momentum iteration up to 1L level:

$$\lambda = \frac{1}{v^2}\left[(m_h^{\text{MSSM}})^2 + \Delta m_{h,\text{MSSM}}^2 - \Delta m_{h,\text{SM}}^2 + O(\hbar^2)\right]$$

with

$$\Delta m_{h,\text{MSSM}}^2 = -\Sigma_{\text{MSSM}}^{1L} + t_{\text{MSSM}}^{1L}/v_{\text{MSSM}}$$
$$\Delta m_{h,\text{SM}}^2 = -\Sigma_{\text{SM}}^{1L} + t_{\text{SM}}^{1L}/v_{\text{SM}}$$

Incorrect 2L logs in original FlexibleEFTHiggs-1L

Problem: $y_t^{\text{MSSM}} = y_t^{\text{SM}}/s_\beta[1 + O(\hbar)]$
$\Rightarrow$

$$\begin{aligned}
\Delta m^2_{h,\text{MSSM}} - \Delta m^2_{h,\text{SM}} &\propto \hbar\left[(y_t^{\text{MSSM}} s_\beta)^4 \log\frac{m_t}{M_S} - (y_t^{\text{SM}})^4 \log\frac{m_t}{M_S}\right] \\
&= \hbar\left[0 + \propto \hbar y_t^4 \log\frac{m_t}{M_S} + O(\hbar^2)\right] \\
&= O(\hbar^2 y_t^4 \log\frac{m_t}{M_S})
\end{aligned}$$

$\Rightarrow$
incorrect 2L logs remain in FlexibleEFTHiggs-1L