Recent (theoretical) changes

Henning Bahl

Max-Planck-Institut für Physik, München

3rd International `FeynHiggs` meeting
18.7.2018, Würzburg

Adapted 2L renormalization

Interpolation of EFT calculation for complex parameters

Non-degenerate threshold corrections

Implementation of finite field renormalization

$\tan\beta$ reparametrization

Uncertainty estimate

Adapted 2L renormalization

$$p^2 - m_A^2 + \hat{\Sigma}_{AA}(p^2) = 0$$

Expanding up to the two-loop level, we yield

$$M_A^2 = m_A^2 - \mathrm{Re}\left[\hat{\Sigma}^{(1)}_{AA}(m_A^2)\right] - \mathrm{Re}\left[\hat{\Sigma}^{(2)}_{AA}(m_A^2)\right] + \mathrm{Re}\left[\hat{\Sigma}^{(1)\prime}_{AA}(m_A^2)\hat{\Sigma}^{(1)}_{AA}(m_A^2)\right]$$

with

$$\hat{\Sigma}^{(i)}_{AA}(m_A^2) = \Sigma^{(i)}_{AA}(m_A^2) - \delta^{(i)} m_A^2$$

In order to make sure that input mass is equal to pole mass:

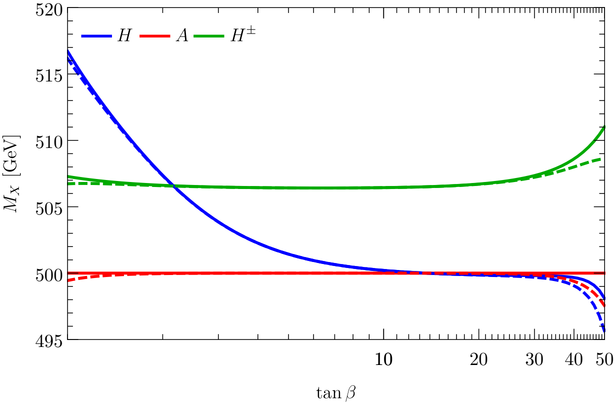
$$\delta^{(1)} m_A^2 = \mathrm{Re}\left[\Sigma^{(1)}_{AA}(m_A^2)\right],$$

$$\delta^{(2)} m_A^2 = \mathrm{Re}\left[\Sigma^{(2)}_{AA}(m_A^2)\right] + \mathrm{Im}\left[\Sigma^{(1)\prime}_{AA}(m_A^2)\right] \mathrm{Im}\left[\Sigma^{(1)}_{AA}(m_A^2)\right].$$

Adapted 2L renormalization - numerical impact

$M_A = 500$ GeV, $M_{\rm SUSY} = 800$ GeV, $X_t^{\rm OS} = 2 M_{\rm SUSY}$,

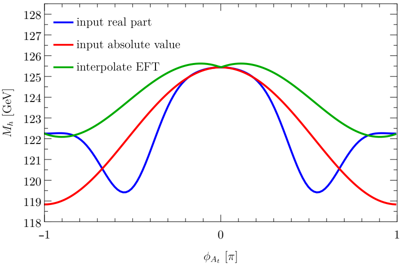
$M_1 = M_2 = M_3 = 500$ GeV, $\mu = -500$ GeV

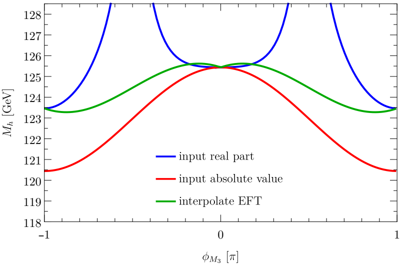


Solid: with “Im*Im” term; dasehd: without “Im*Im” term

EFT calculation in case of complex parameters

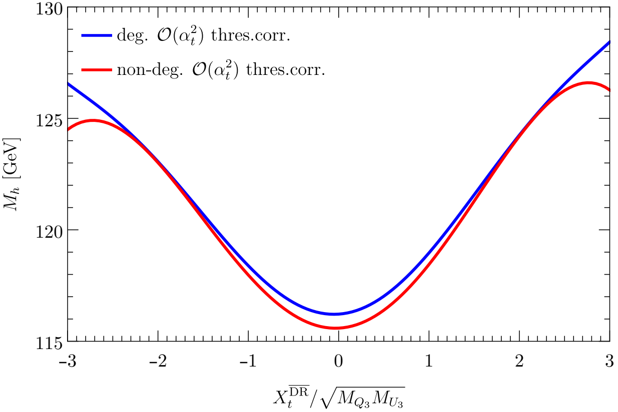
- So far EFT does not allow for complex input parameter
- But: interpolation built in
- interpolates in $\phi_{A_t}, \phi_{M_3}, \phi_\mu$





Non-degenerate threshold corrections

EFT now includes full 1L and 2L non-degenerate threshold corrections



Not yet in case of the THDM as EFT...

Finite field renormalization in the gauge eigenstate basis

$$\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} \to \mathbf{Z}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix} = \begin{pmatrix}\sqrt{Z_{11}} & \sqrt{Z_{12}}\\ \sqrt{Z_{21}} & \sqrt{Z_{22}}\end{pmatrix}\begin{pmatrix}\Phi_1\\ \Phi_2\end{pmatrix}$$

with

$$Z_{ij} = \delta_{ij} + \frac{1}{2}\delta Z_{ij} = \delta_{ij} + \frac{1}{2}\delta^{(1)} Z_{ij} + \frac{1}{2}\delta^{(2)} Z_{ij} + \ldots\ .$$

Requiring

$$\hat{\Sigma}_{ij} = \hat{\Sigma}_{ji}$$

implies

$$\mathbf{Z} = \mathbf{Z}^\dagger$$

Finite field renormalization in the mass eigenstate basis

$$\begin{aligned}
\delta Z_{hh} &= s_\alpha^2 \delta Z_{11} - s_\alpha c_\alpha \left(\delta Z_{12} + \delta Z_{21}\right) + c_\alpha^2 \delta Z_{22}, \\
\delta Z_{HH} &= c_\alpha^2 \delta Z_{11} + s_\alpha c_\alpha \left(\delta Z_{12} + \delta Z_{21}\right) + s_\alpha^2 \delta Z_{22}, \\
\delta Z_{hH} &= s_\alpha c_\alpha \left(\delta Z_{22} - \delta Z_{11}\right) + \frac{1}{2} c_{2\alpha} \left(\delta Z_{12} + \delta Z_{21}\right), \\
\delta Z_{AA} &= s_{\beta_n}^2 \delta Z_{11} - s_{\beta_n} c_{\beta_n} \left(\delta Z_{12} + \delta Z_{21}\right) + c_{\beta_n}^2 \delta Z_{22}, \\
\delta Z_{GG} &= c_{\beta_n}^2 \delta Z_{11} + s_{\beta_n} c_{\beta_n} \left(\delta Z_{12} + \delta Z_{21}\right) + s_{\beta_n}^2 \delta Z_{22}, \\
\delta Z_{AG} &= s_{\beta_n} c_{\beta_n} \left(\delta Z_{22} - \delta Z_{11}\right) + \frac{1}{2} c_{2\beta_n} \left(\delta Z_{12} + \delta Z_{21}\right), \\
\delta Z_{hA} &= \frac{i}{2} s_{\beta_n - \alpha} \left(\delta Z_{12} - \delta Z_{21}\right), \\
\delta Z_{hG} &= -\frac{i}{2} c_{\beta_n - \alpha} \left(\delta Z_{12} - \delta Z_{21}\right), \\
\delta Z_{HA} &= \frac{i}{2} c_{\beta_n - \alpha} \left(\delta Z_{12} - \delta Z_{21}\right), \\
\delta Z_{HG} &= \frac{i}{2} s_{\beta_n - \alpha} \left(\delta Z_{12} - \delta Z_{21}\right).
\end{aligned}$$

Implentation of finite field renormalization

@ 1L

- Generation of 1L self-energies automated → only have to change definition of counterterms

@ 2L

- Don't want to touch two-loop routines
  → add shifts induced by fin. field ren. separately
- worked out extension of 2L renormalization
- also need to take into account 1L subloop renormalization

Finite independent $\tan\beta$ counterterm

Introduce finite independent $\tan\beta$ counterterm

$$\delta^{(1)}t_\beta = \frac{1}{2}\left[t_\beta\left(\delta Z_{22} - \delta Z_{11}\right) + \frac{1}{2}(1-t_\beta^2)\left(\delta Z_{12} + \delta Z_{21}\right)\right] + \delta^{(1)}t_\beta\big|_{\text{fin}}$$

Fix $\delta^{(1)}t_\beta\big|_{\text{fin}}$ such that

$$\delta^{(1)}t_\beta = \frac{1}{2}\left[t_\beta\left(\delta Z_{22} - \delta Z_{11}\right) + \frac{1}{2}(1-t_\beta^2)\left(\delta Z_{12} + \delta Z_{21}\right)\right]_{\text{UV}}$$

Finite independent $\tan\beta$ counterterm???

$\tan\beta$ is a dependent quantity

$\rightarrow$ should not have an independent counterterm!

We can however always reparametrize $\tan\beta$:

$$M_h^2(t_\beta + \delta t_\beta) = M_h^2(t_\beta) + \left(\frac{d}{dt_\beta} M_h^2\right)\delta t_\beta + \ldots$$

Consequences of finite $\tan\beta$ counterterm

Also have to take into account shifts in α, β_n, β_c

$$\delta^{(1)} t_\alpha = \frac{2(M_A^4 - M_Z^4)c_\beta^2}{(m_H^2 - m_h^2)(m_H^2 - m_h^2 - (M_A^2 - M_Z^2)c_{2\beta})}\, \delta^{(1)} t_\beta\big|_{\text{fin}}$$

$$\delta^{(1)}\beta_n = \delta^{(1)}\beta_c = c_\beta^2\, \delta^{(1)} t_\beta\big|_{\text{fin}}$$

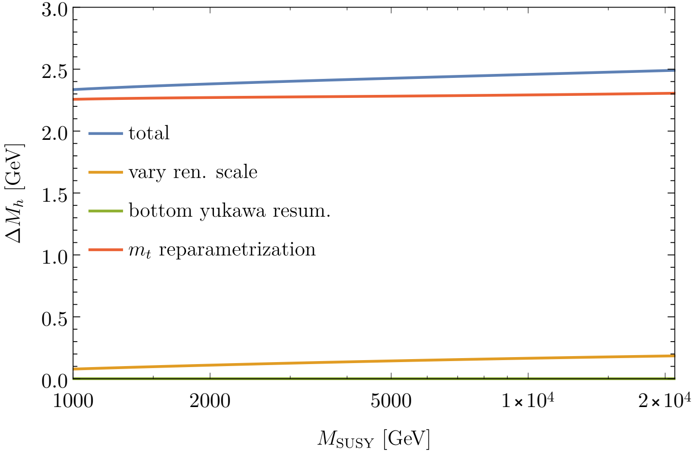
Futher induced counterterms

$$h \to h - k\,\delta^{(1)}\alpha\, H,$$
$$H \to H + k\,\delta^{(1)}\alpha\, h,$$
$$A \to A - k\,\delta^{(1)}\beta_n\, G,$$
$$G \to G + k\,\delta^{(1)}\beta_n\, A,$$
$$H^\pm \to H^\pm - k\,\delta^{(1)}\beta_c\, G^\pm,$$
$$G^\pm \to G^\pm + k\,\delta^{(1)}\beta_c\, H^\pm$$

Consequences of finite $\tan\beta$ counterterm

- Have to take into account induced shifts at 1L and 2L
- Allows to choose definition of $\tan\beta$
- What do we want?
  - $\tan\beta^{\text{MSSM}}(M_t)$
  - $\tan\beta^{\text{MSSM}}(M_{\text{SUSY}})$
  - $\tan\beta^{\text{THDM}}(M_A)$

Uncertainty estimate: different contributions for $\hat{X}_t^{\overline{\mathrm{DR}}} = \sqrt{6}$



Missing piece in FeynHiggs

No estimate of logarithmic uncertainty so far

$$\underbrace{g(M_{\text{SUSY}})^8}_{\text{estimated in EFT calc.}} = \underbrace{g(M_t)^8}_{\text{estimated in FH}} + \text{logs}$$

- $g(M_{\text{SUSY}})$ typically decreases with rising M_{SUSY}
- logarithms increase
- $g(M_t)$ stays constant

$\downarrow$

compensation between logarithms and non-logarithmic piece not taken into account in FeynHiggs

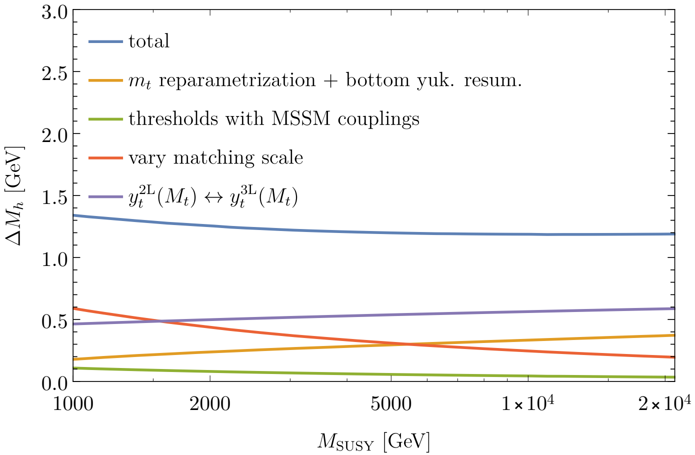
One idea under discussion:
Build upon uncertainty estimate of pure EFT calculation

Uncertainty based on EFT estimate

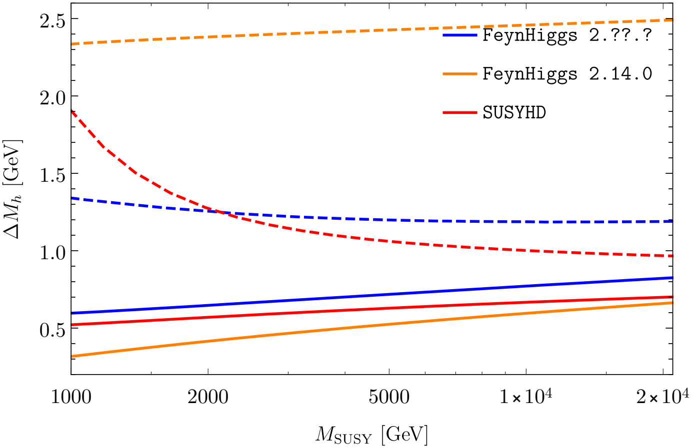
Estimate uncertainty in two step procedure:

1. uncertainty of EFT calculation
   - change between $y_t^{\overline{\text{MS}},2\text{L}} \leftrightarrow y_t^{\overline{\text{MS}},3\text{L}}$
   - variation of matching scale between $M_{\text{SUSY}}/2$ and $2M_{\text{SUSY}}$
   - reparametrization of threshold in terms of MSSM couplings
2. uncertainty of suppressed terms and SM contributions
   - change of renormalization scheme; switch between OS top mass and SM $\overline{\text{MS}}$ top mass
   - deactivating the resummation of bottom Yukawa coupling

Uncertainty based on EFT estimate for $\hat{X}_t^{\overline{\text{DR}}} = \sqrt{6}$



Comparison to SUSYHD



solid: $X_t^{\overline{\text{DR}}} = 0$; dashed: $X_t^{\overline{\text{DR}}}/M_{\text{SUSY}} = \sqrt{6}$