The complex THDM as EFT in FeynHiggs

Henning Bahl

in collaboration with

N. Murphy & H. Rzehak

DESY, Hamburg

FeynHiggs online meeting

9.9.2020

Introduction

EFT calculation

Combination with fixed-order calculation

Results

Conclusions

Foundations

1. *Lee & Wagner, 1508.00576*
   $\rightarrow$ first calculation with THDM as EFT of the MSSM,
2. *HB & Hollik, 1805.00867*
   $\rightarrow$ improved THDM-EFT calculation,
   $\rightarrow$ combination with fixed-order calculation,
3. *Murphy & Rzehak, 1909.00726*
   $\rightarrow$ $\mathcal{CP}$ violating effects using complex THDM (cTHDM) as EFT.

$\Rightarrow$ Next step: incorporate cTHDM calculation into `FH` hybrid framework.

EFT hierarchies

Considered EFT tower

$$\text{MSSM} \xrightarrow{Q=M_{\text{SUSY}}} \text{cTHDM} \xrightarrow{Q=M_{H^\pm},} \text{SM}$$

- no separate thresholds for EWinos and/or gluino,
- RGE running using two-loop RGEs derived by [Murphy & Rzehak, 1909.00726].

cTHDM

Higgs potential

$$
\begin{aligned}
&V_{\mathrm{THDM}}(\Phi_1, \Phi_2) = \\
&= m_{11}^2\, \Phi_1^\dagger \Phi_1 + m_{22}^2\, \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right) \\
&+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
&+ \left(\frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \mathrm{h.c.} \right),
\end{aligned}
$$

with $\lambda_{5,6,7}$ and m_{12}^2 being potentially complex parameters.

Yukawa Lagrangian

$$
\mathcal{L}_{\mathrm{Yuk}} = -h_t \bar{t}_R \left(-i \Phi_2^T \sigma_2 \right) Q_L - h_t' \bar{t}_R \left(-i \Phi_1^T \sigma_2 \right) Q_L + \mathrm{h.c.}
$$

with h_t and h_t' being potentially complex parameters. The other Yukawa couplings are neglected.

Matching the SM and the cTHDM

Matching of quartic Higgs coupling λ:

$$\lambda(M_{H^\pm}) = \lambda_{\text{tree}} + \Delta\lambda_{\text{Re}} + \Delta\lambda_{\text{Im}} \quad \text{with}$$

$$\lambda_{\text{tree}} = \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \text{Re}\lambda_5) c_\beta^2 s_\beta^2 + 4\text{Re}\lambda_6 c_\beta^3 s_\beta + 4\text{Re}\lambda_7 c_\beta s_\beta^3,$$

$$\Delta_{\text{Re}}\lambda = -3k\Big((\text{Re}\lambda_6 + \text{Re}\lambda_7) c_{2\beta} + (\text{Re}\lambda_6 - \text{Re}\lambda_7) c_{4\beta} - \left(\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \text{Re}\lambda_5) c_{2\beta}\right) s_{2\beta}\Big)^2,$$

$$\Delta_{\text{Im}}\lambda = -3k\Big(\text{Im}\lambda_6 + \text{Im}\lambda_7 + (\text{Im}\lambda_6 - \text{Im}\lambda_7) c_{2\beta} + \text{Im}\lambda_5 s_{2\beta}\Big)^2.$$

Matching of SM top-Yukawa coupling y_t:

$$y_t(M_{H^\pm}) = \left|h_t s_\beta + h_t' c_\beta\right| \left(1 - \frac{3}{8} k \left|h_t c_\beta - h_t' s_\beta\right|^2\right).$$

Improvements w.r.t. [Murphy & Rzehak, 1909.00726]: One-loop corrections.

Matching the cTHDM and the MSSM

Tree-level relations:

$$\lambda_1 = \lambda_2 = \frac{1}{4}(g^2 + g_y^2),\ \lambda_3 = \frac{1}{4}(g^2 - g_y^2),\ \lambda_4 = -\frac{1}{2}g^2,\ \lambda_5 = \lambda_6 = \lambda_7 = 0,$$
$$h_t^{\text{THDM}} = h_t^{\text{MSSM}},\ (h_t')^{\text{THDM}} = 0$$

Loop corrections:

- full one-loop corrections (assuming degenerate soft SUSY-breaking masses),
- $\mathcal{O}(\alpha_t\alpha_s)$ threshold corrections for quartic couplings.

Improvements w.r.t. [Murphy & Rzehak, 1909.00726]:

- purely electroweak contributions,
- $\mathcal{O}(\alpha_t\alpha_s)$ threshold corrections for quartic couplings.

$\mathcal{O}(\alpha_t\alpha_s)$ threshold corrections

SM to MSSM matching condition for SM Higgs self-coupling including full phase dependence already known.

$\Downarrow$

Use "Lee & Wagner trick" to distribute the correction to the λ_i.

Disadvantages:

- can not disentangle λ_3, λ_4 and λ_5,
- imaginary parts not accessible.

$\Rightarrow$ Ivan's talk.

Introduction

EFT calculation

Combination with fixed-order calculation

Results

Conclusions

Combination with fixed-order calculation I

Follows the recipe worked out in [HB & Hollik, 1805.00867].

Higgs two-point function:

$$\widehat{\Gamma}^{\text{hybrid}}_{hHA}(p^2) =$$
$$= i\left[p^2\mathbf{1} - \begin{pmatrix} m_h^2 & 0 & 0 \\ 0 & m_H^2 & 0 \\ 0 & 0 & m_A^2 \end{pmatrix} + \begin{pmatrix} \hat{\Sigma}^{\text{hybrid}}_{hh}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{hH}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{hA}(p^2) \\ \hat{\Sigma}^{\text{hybrid}}_{hH}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{HH}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{HA}(p^2) \\ \hat{\Sigma}^{\text{hybrid}}_{hA}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{HA}(p^2) & \hat{\Sigma}^{\text{hybrid}}_{AA}(p^2) \end{pmatrix}\right],$$

with

$$\hat{\Sigma}^{\text{hybrid}}_{ij}(p^2) = \hat{\Sigma}^{\text{FO}}_{ij}(p^2) + \Delta^{\text{EFT}}_{ij} - \Delta^{\text{sub}}_{ij},$$

Ingredients:

- fixed-order self-energies $\hat{\Sigma}^{\text{FO}}_{ij}(p^2)$,
- entries of cTHDM mass matrix Δ^{EFT}_{ij},
- subtraction terms Δ^{EFT}_{ij}.

Combination with fixed-order calculation II

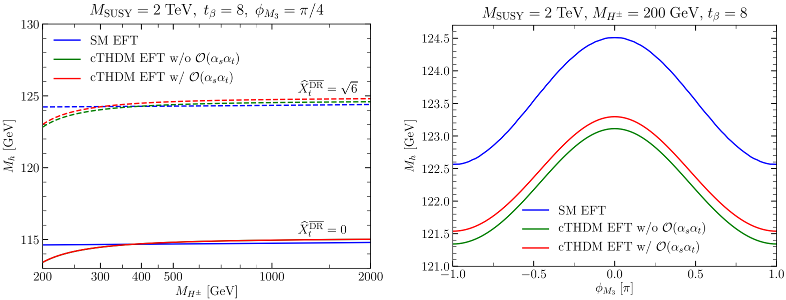
Important prerequisite

MSSM and cTHDM Higgs doublets must have the same normalization.

- [HB & Hollik, 1805.00867] $\rightarrow$ finite field renormalization for fixed-order calculation.
- [HB, 1812.06452] $\rightarrow$ extension to the $\mathcal{CP}$-violating case ("heavy-OS" scheme)

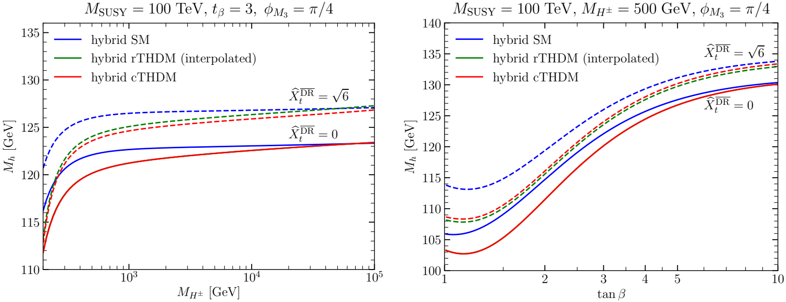
$\Rightarrow$ already implemented in FH, no extra work needed.

EFT calculation – impact of $\mathcal{O}(\alpha_t\alpha_s)$ threshold corrections



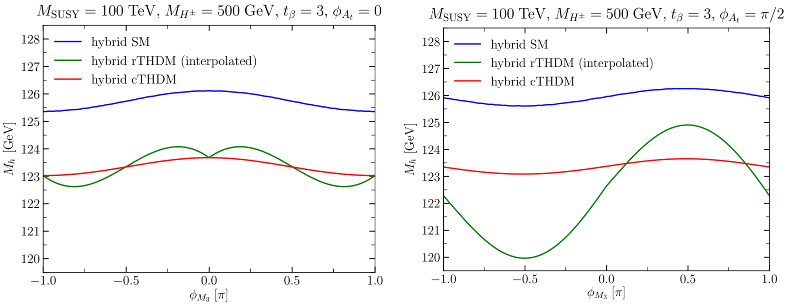
- impact of $\mathcal{O}(\alpha_t\alpha_s)$ threshold corrections even smaller for larger M_{SUSY},
- discrepancy between SM-EFT and THDM-EFT results for $M_{H^\pm} = M_{\text{SUSY}}$ mainly due to missing $\mathcal{O}(\alpha_t^2)$ threshold corrections ($\rightarrow$ Ivan's talk)

Hybrid calculation – comparison to SM-EFT calculation



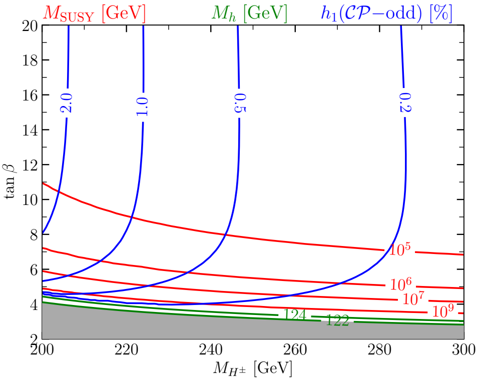
- Phase dependence smaller for larger $M_{\rm SUSY}$ where using the THDM as EFT is actually relevant.

Hybrid calculation – phase dependence



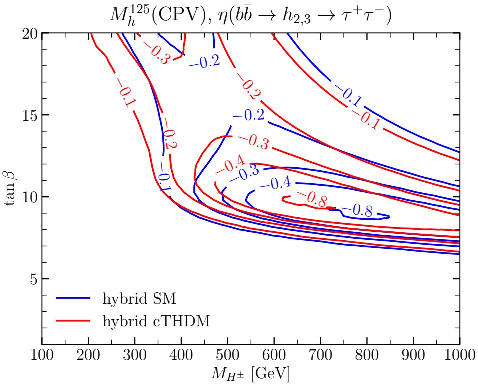
- Interpolation works less accurate if two phases are chosen non-zero.

Pheno application I – maximal $\mathcal{CP}$-odd component of h_{125}



- $M_{\rm SUSY}$ adjust at every point such that $M_h \sim 125$ GeV with upper limit $M_{\rm SUSY} = 10^16$ GeV
- gray area: $M_h < 122$ GeV
- $\mathcal{CP}$-odd component calculated by squaring 13-element of mixing matrix

Pheno application II – M_h^{125}(CPV) benchmark scenario



- interference between heavy Higgs bosons weakens $b\bar{b} \to h_{2,3} \to \tau^+\tau^-$ direct searches,
- quantified by interference factor $\eta = \eta_2^{IF} = \eta_3^{IF}$ defined via

$$\sigma(b\bar{b} \to h_{1,2,3} \to \tau^+\tau^-) = \sum_{a=1}^{3} \sigma(b\bar{b} \to h_a)(1 + \eta_a^{IF})\text{BR}(h_a \to \tau^+\tau^-)$$

Introduction

EFT calculation

Combination with fixed-order calculation

Results

Conclusions

Conclusions

- Incorporated cTHDM as EFT into FH,
- improved existing EFT calculation by adding more higher-order corrections,
- numerical impact relatively small.

Implementation in FH:

- working implementation exists,
- so far separate routines for rTHDM and cTHDM EFTs, since for cTHDM no light EWino/gluino thresholds implemented,
- still missing: routine to automatically choose between rTHDM and cTHDM EFTs.