# EFT Perspective on Precision Higgs Couplings in Neutral Naturalness Models

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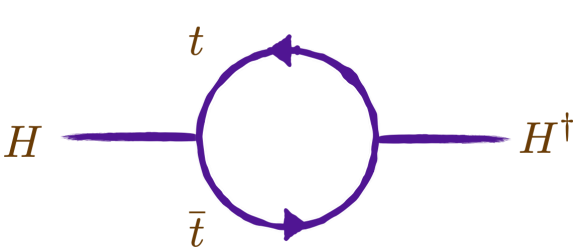
# Naturalness

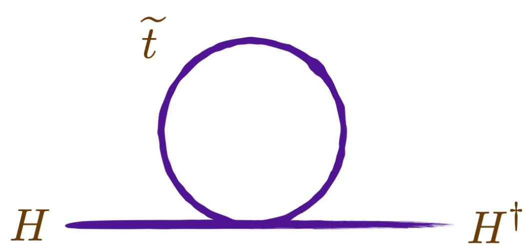
In EFTs, elementary scalars should have masses at the cutoff .

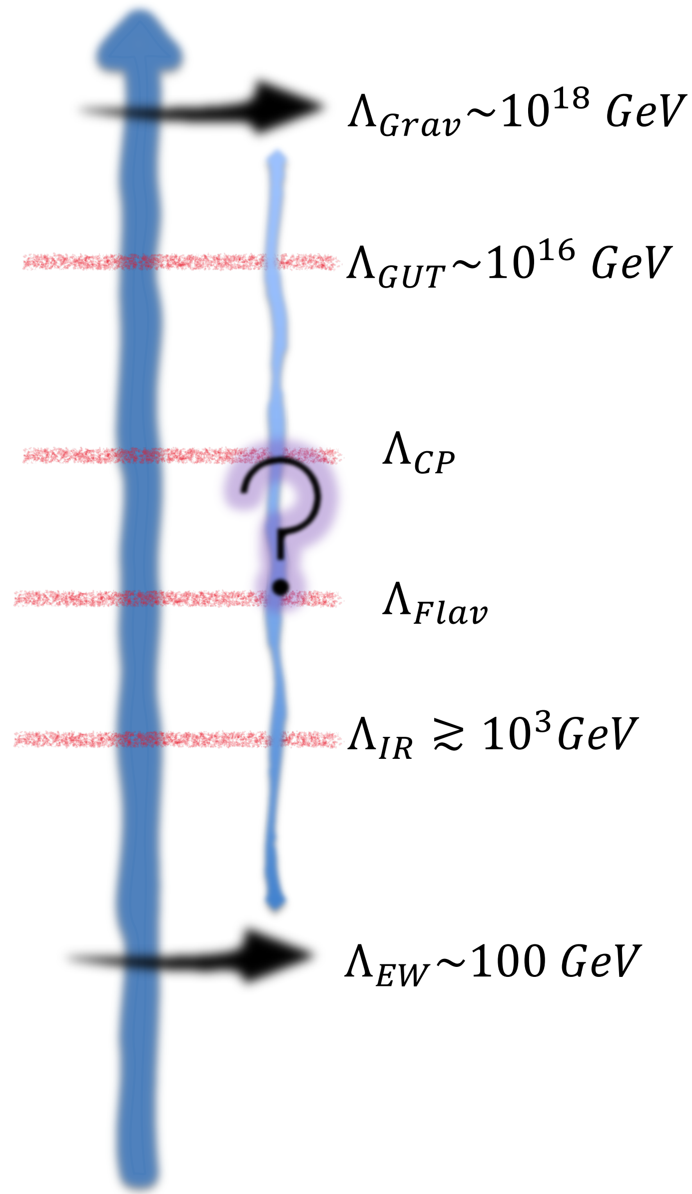
While in the SM, the mass of the observed Higgs is only 125 GeV, which is weird, maybe unnatural.

**SUSY** **CHM**

No colored partner particles has been discovered at the LHC



# Neutral Naturalness

Since 2005, a class of solutions to the Hierarchy Problem has emerged, in which the partners of the top quark are not charged under SM gauge .

A trigonometric parity ($Z_2$ $Symmetry$) ensures the Higgs potential gets rid of the quadratic divergences.

Bounds from direct colored production effectively vanish.

| Model | Coset |
|---|---|
| Twin Higgs (hep-ph0506256) | SO(8)/SO(7) |
| Brother Higgs (1709.05399, 1709.08636) | SO(6)/SO(5) |
| Minimal Neutral Naturalness (1810.01882) | SO(5)/SO(4) |

Some other models predicts colorless top partners:

| | Scalar Partner | Fermion Partner |
|---|---|---|
| **EW Charges** | Folded SUSY | Quirky Little Higgs |
| **No SM Charges** | Hyperbolic Higgs & Tripled Top | NN |

# Model Details

In order to render explicit the pNGB nature of the physical Higgs, we parameterize the multiplet $\mathcal{H}$ non-linearly in the fundamental representation of the corresponding global symmetry

$$\mathcal{H} = \left(f + \frac{\sigma}{\sqrt{2}}\right) e^{i\frac{\sqrt{2}\Pi_a T^{\hat{a}}}{f}} \Phi = \left(f + \frac{\sigma}{\sqrt{2}}\right) U\Phi$$

$$U = \left(\begin{array}{c|c} \mathbb{1}_{n\times n} - \left(1 - \cos\frac{|\Pi|}{f}\right)\frac{\Pi_i \Pi_j^\dagger}{|\Pi|^2} & \frac{\Pi_i}{|\Pi|}\sin\frac{|\Pi|}{f} \\ \hline -\frac{\Pi_j^\dagger}{|\Pi|}\sin\frac{|\Pi|}{f} & \cos\frac{|\Pi|}{f} \end{array}\right)$$

where $\sigma$ is the radial mode and $|\Pi| = \sqrt{\sum_{i=1}^{n} \Pi_i^2}$.

The physical Higgs doublet $H$ is identified as $H = \frac{1}{\sqrt{2}}(\Pi_2 + i\Pi_1, \Pi_4 - i\Pi_3)^T$

# Model Details

We express the Lagrangian of the scalar sector of these models as:

$$\mathcal{L}_S = (D_\mu \mathcal{H})^\dagger (D^\mu \mathcal{H}) - V_{sym}(\mathcal{H}) - V_{break}(\mathcal{H})$$

where the potentials $V_{sym}$ and $V_{break}$ respectively preserve and explicitly break the global symmetry and can be defined as

$$\mathcal{V}_{sym} = -\mu^2 |\mathcal{H}|^2 + \lambda |\mathcal{H}|^4 ,$$
$$\mathcal{V}_{break} = +\mathcal{H}^\dagger \mathbf{m}^2 \mathcal{H} + \left|\mathcal{H}^\dagger \boldsymbol{\delta} \mathcal{H}\right|^2$$

With

$$\mathbf{m}^2 = \begin{pmatrix} m^2 \mathbb{1}_{n\times n} & 0 \\ 0 & -m^2 \mathbb{1}_{p\times p} \end{pmatrix}, \quad \boldsymbol{\delta} = \begin{pmatrix} \sqrt{\delta} \mathbb{1}_{n\times n} & 0 \\ 0 & -i\sqrt{\delta} \mathbb{1}_{p\times p} \end{pmatrix}$$

And in general the relevant top sector Yukawa couplings can generally be written as

$$\mathcal{L}_F \supset \left(f + \frac{\sigma}{\sqrt{2}}\right) \left[\lambda_t \bar{\Psi}_L U \Psi_R + \tilde{\lambda}_t \bar{\tilde{\Psi}}_L U \tilde{\Psi}_R\right]$$

where the SM and Twin fermions are embedded as

$$\Psi_L = (-ib_L, -b_L, -it_L, t_L, 0, .., 0)^T ,$$
$$\Psi_R = (0, 0, 0, t_R, 0, .., 0)^T ,$$
$$\tilde{\Psi}_L = (0, ...0, \tilde{t}_L)^T ,$$
$$\tilde{\Psi}_L = (0, ...0, \tilde{t}_R)^T .$$

# EFT for Higgs doublet $H$

We then integrate out the radial mode $\sigma$ and derive all the couplings of the physical Higgs boson to SM and mirror quantum states

$$\mathcal{L}_S^{EFT} = |D^A H|^2 + \mu_H^2 |H|^2 - \lambda_H |H|^4 + \frac{c_H}{2f^2}\mathcal{O}_H + \frac{c_6}{f^2}\mathcal{O}_6$$

$$\mathcal{L}_F^{\rm EFT} \supset \left[\lambda_q(\bar{Q}_L H q_R + h.c.) + \tilde{\lambda}_q \bar{\tilde{q}}\tilde{q} f\left(1 - \frac{|H|^2}{2f^2} + \frac{|H|^2}{f^2}\left(\frac{4\delta f^2}{m_\sigma^2} - \frac{2m^2}{m_\sigma^2}\right)\right)\right]$$

where we define $\mathcal{O}_6 \equiv |H|^6\,, \quad \mathcal{O}_H \equiv (\partial_\mu |H|^2)^2$

$$\mu_H^2 = 2\delta f^2 - 2m^2\,, \qquad c_H = \frac{4m^2}{m_\sigma^2} + \frac{1}{2} - \frac{8\delta f^2}{m_\sigma^2}$$

$$\lambda_H = 2\delta + \frac{4m^4}{f^2 m_\sigma^2} - \frac{8\delta m^2}{m_\sigma^2} \qquad c_6 = \frac{16m^2}{45f^2} - \frac{16\delta}{45}$$

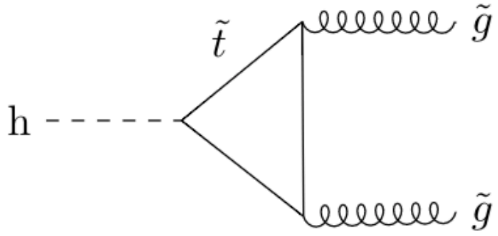
# EFT for Higgs doublet $H$

At low energies the Higgs potential receives important contributions from loops of light states, in particular from the top quark and its twin particles.

So we carry out RG improvement calculation to obtain the EW scale couplings and Higgs mass in order to compare to physical observables.

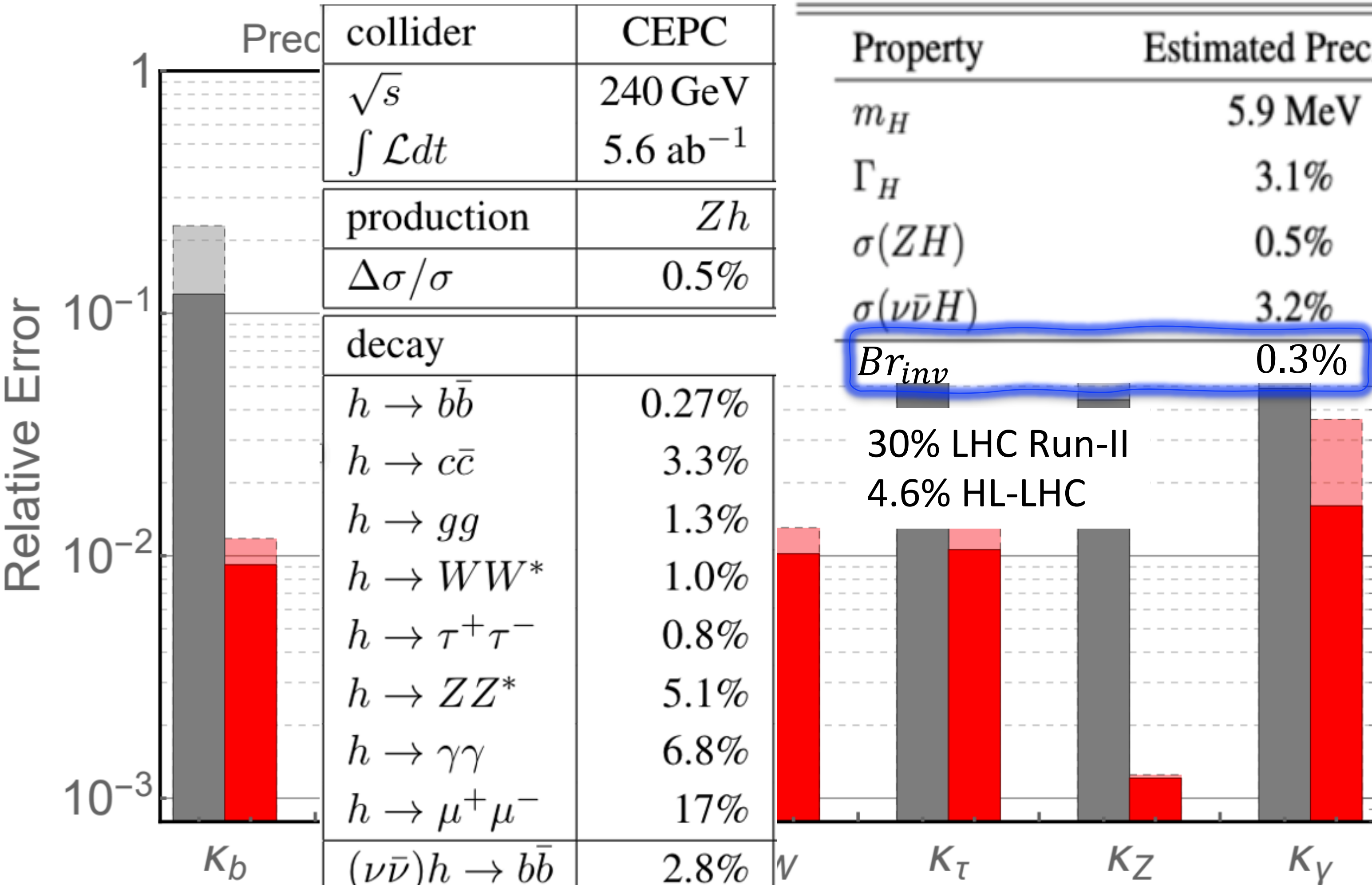
# Loop Induced Decay into Mirror Gluons

The decay of the Higgs boson into (mirror) gluons is mediated by loops involving heavy quarks




which is considered as invisible decay of Higgs in our study.

# Higgs Precision Measurements




| collider | CEPC |
|---|---|
| $\sqrt{s}$ | 240 GeV |
| $\int \mathcal{L}dt$ | 5.6 $\text{ab}^{-1}$ |
| production | $Zh$ |
| $\Delta\sigma/\sigma$ | 0.5% |
| decay | |
| $h \to b\bar{b}$ | 0.27% |
| $h \to c\bar{c}$ | 3.3% |
| $h \to gg$ | 1.3% |
| $h \to WW^*$ | 1.0% |
| $h \to \tau^+\tau^-$ | 0.8% |
| $h \to ZZ^*$ | 5.1% |
| $h \to \gamma\gamma$ | 6.8% |
| $h \to \mu^+\mu^-$ | 17% |
| $(\nu\bar{\nu})h \to b\bar{b}$ | 2.8% |

| Property | Estimated Precision |
|---|---|
| $m_H$ | 5.9 MeV |
| $\Gamma_H$ | 3.1% |
| $\sigma(ZH)$ | 0.5% |
| $\sigma(\nu\bar{\nu}H)$ | 3.2% |
| $Br_{inv}$ | 0.3% |

CEPC-CDR

# Global Fit strategy

Observables Experimental : $\mu_i$

$$\mu_i^{BSM} = \frac{(\sigma\times Br)_{BSM}}{(\sigma\times Br)_{SM}}$$

Fitting

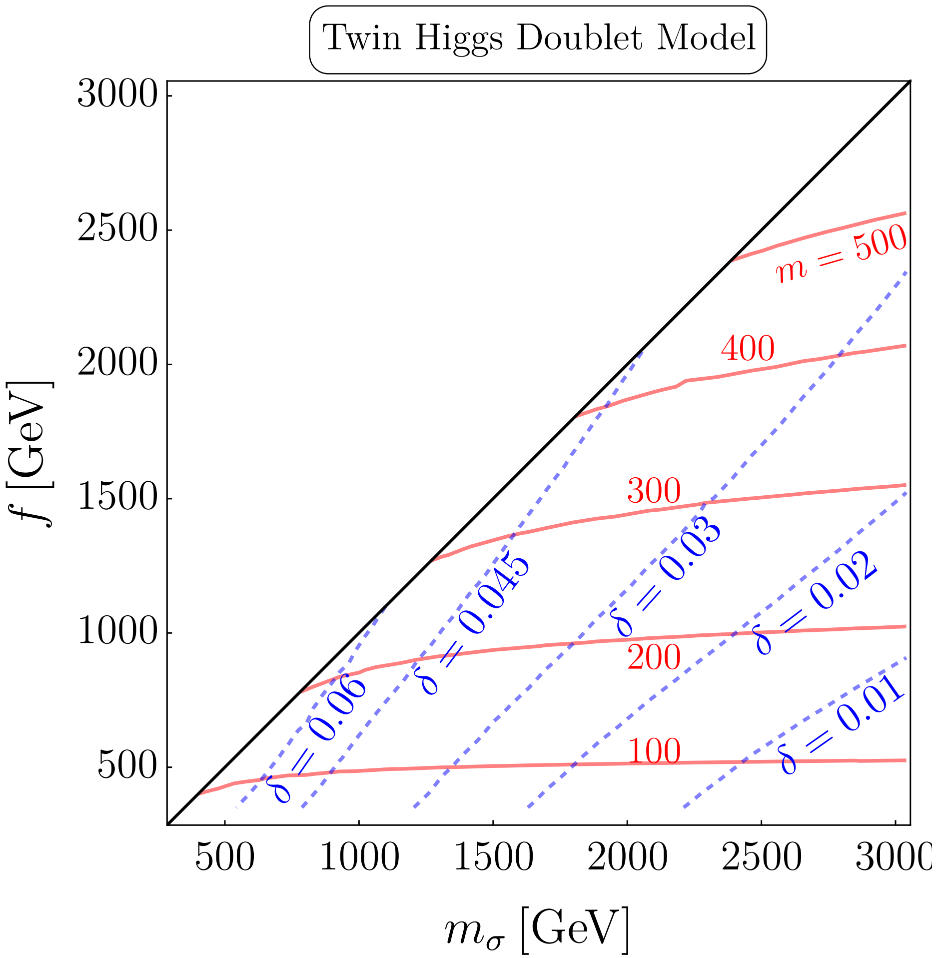
$\chi^2$ Fit:

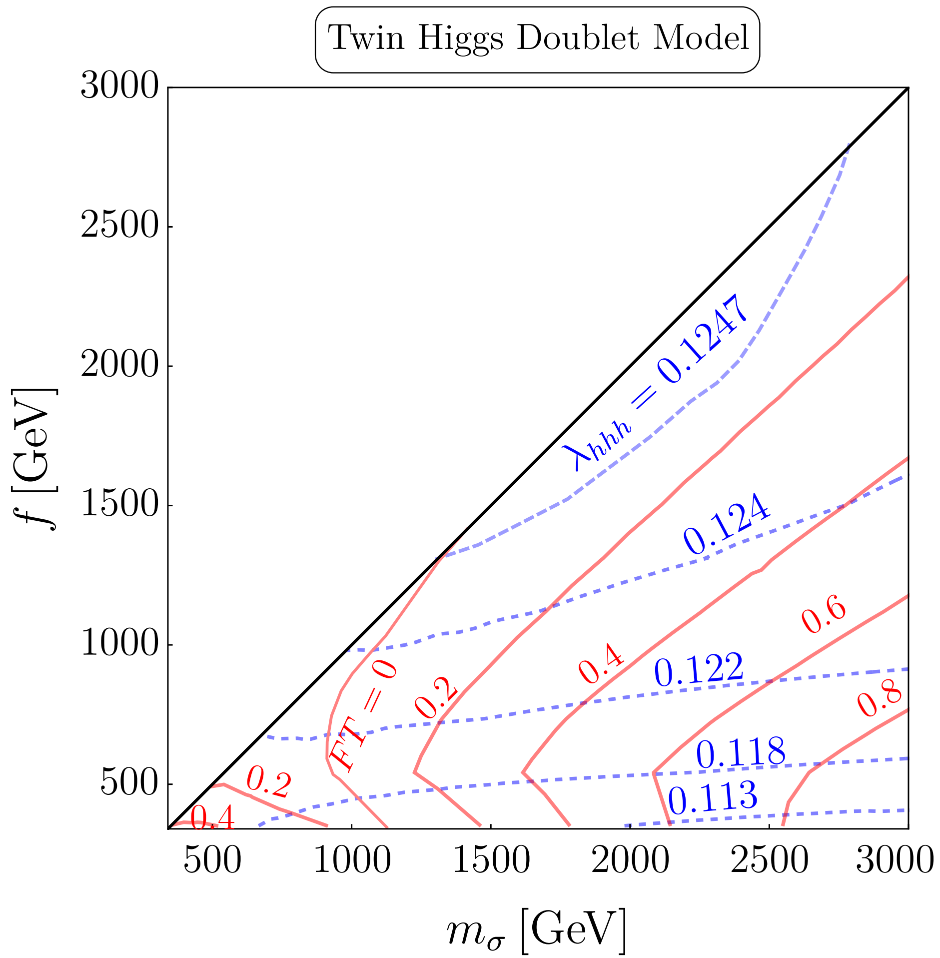
$$\chi^2 = \Sigma_i \frac{(\mu_i^{\rm BSM} - \mu_i^{\rm obs})^2}{\sigma_{\mu_i}^2} + \Sigma_i^{\rm Inv@BSM} \frac{({\rm Br}_i)^2}{\sigma_{\rm BR_i}^2}$$

Parameters in New Physics Models

$m_\sigma, f, m, \delta$ — Fixing $v, m_h$ → $m_\sigma, f$

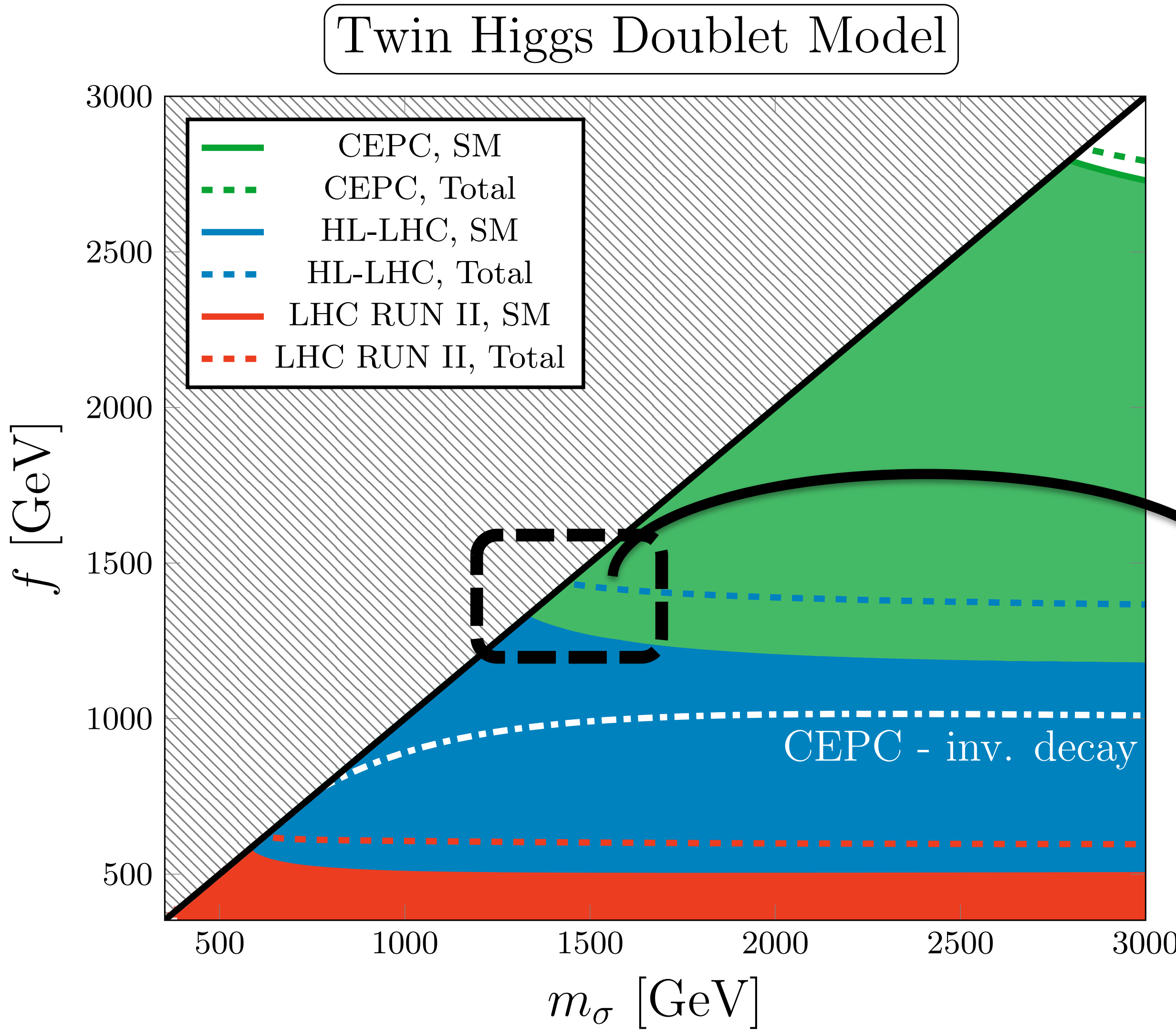
# Results




$$F.T. = \frac{|\delta f^2 - m^2|}{\max(\delta f^2, m^2)}$$

# Results



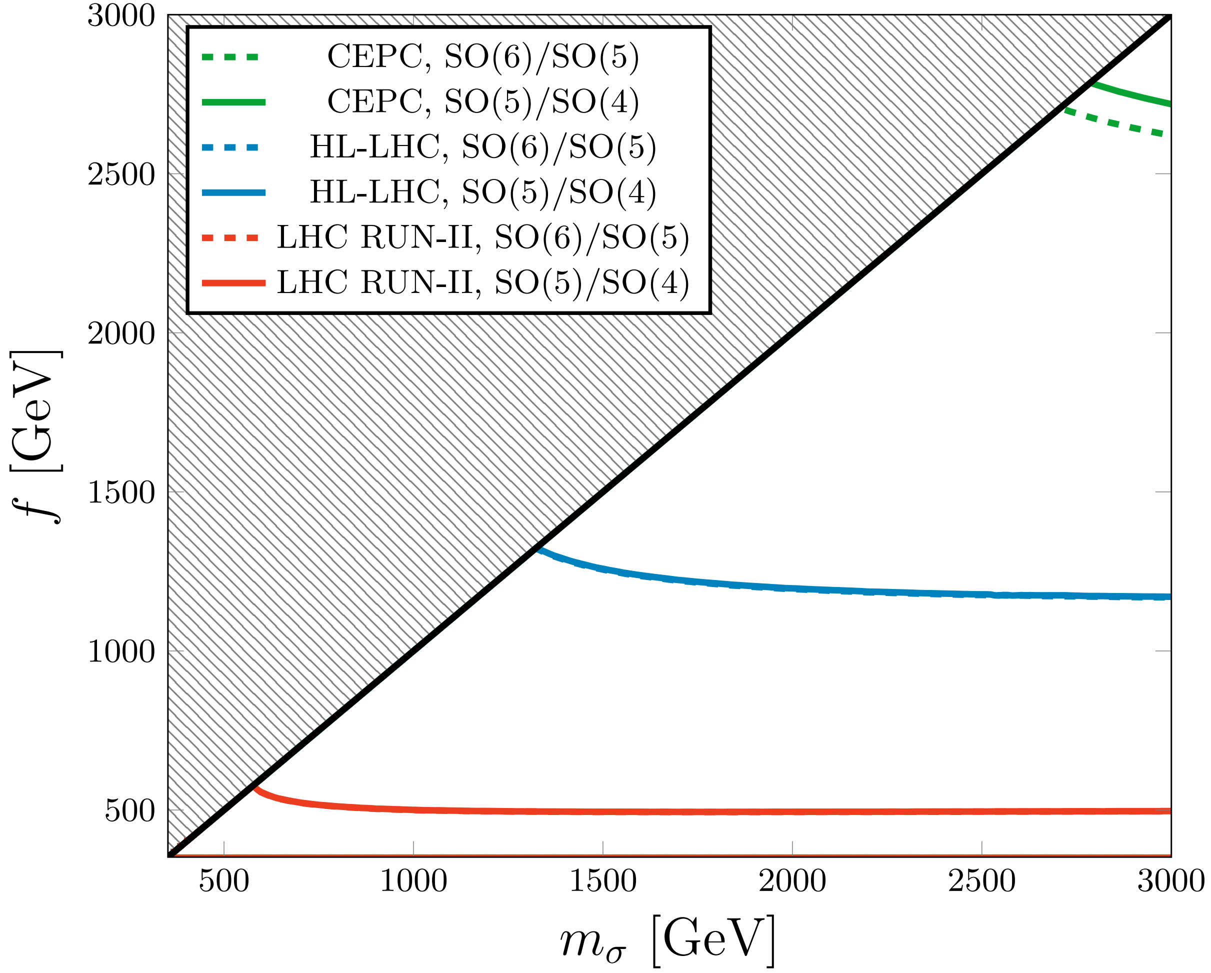

**Precision@CEPC**

Invisible $f > 1.5$ TeV

Total $f > 2.7$ TeV

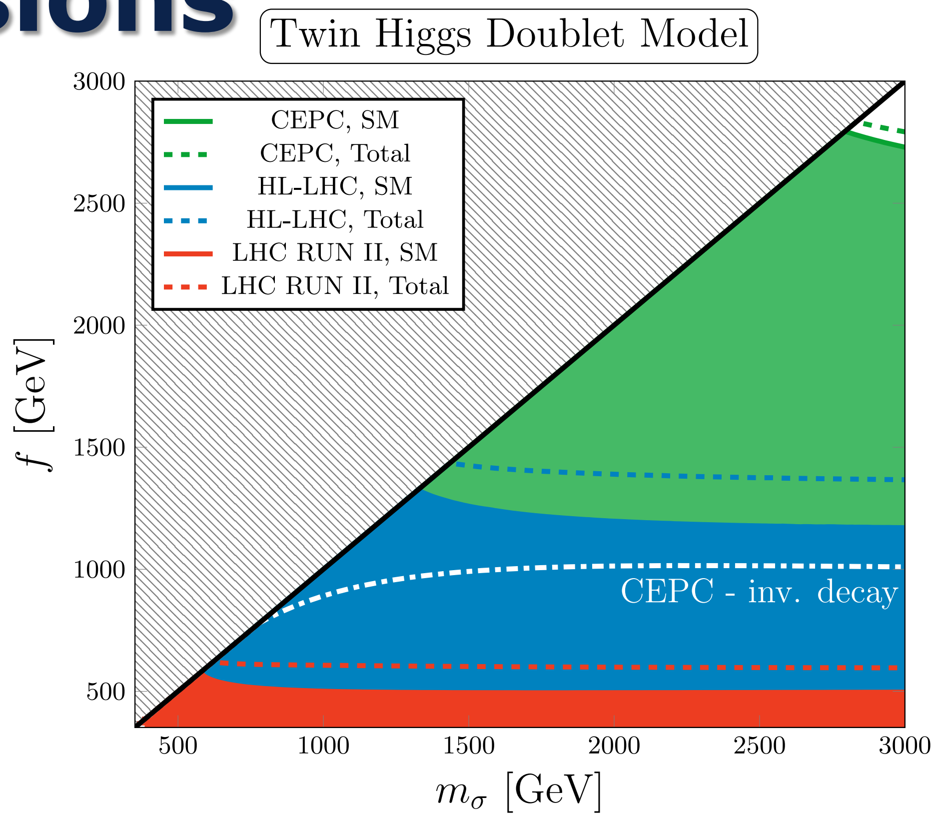
$$\kappa_i = \frac{g_{hii}^{BSM}}{g_{hii}^{SM}} \simeq 1 - c_H \frac{v^2}{2f^2} = 1 - \frac{v^2}{4f^2} - (1-2\delta)\frac{2v^2m^2}{f^2m_\sigma^2}$$

# Results



CEPC, SO(6)/SO(5)
CEPC, SO(5)/SO(4)
HL-LHC, SO(6)/SO(5)
HL-LHC, SO(5)/SO(4)
LHC RUN-II, SO(6)/SO(5)
LHC RUN-II, SO(5)/SO(4)
$f$ [GeV]
$m_\sigma$ [GeV]
3000
2500
2000
1500
1000
500

# Conclusions

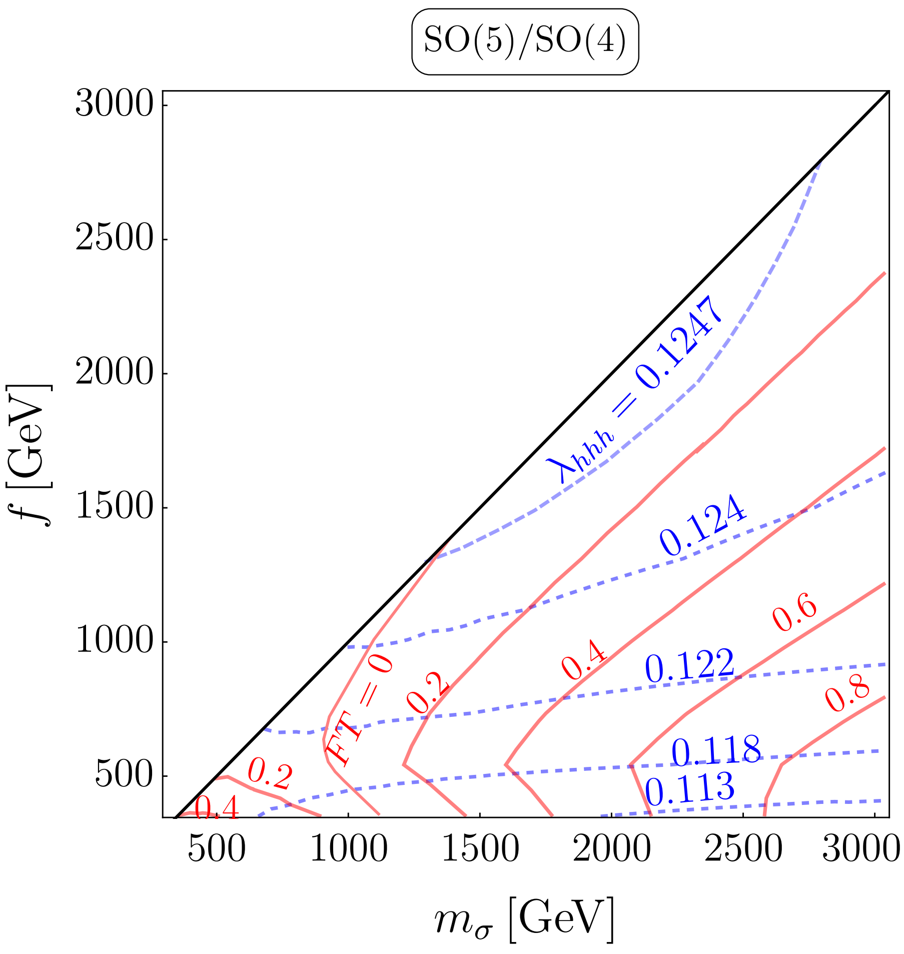


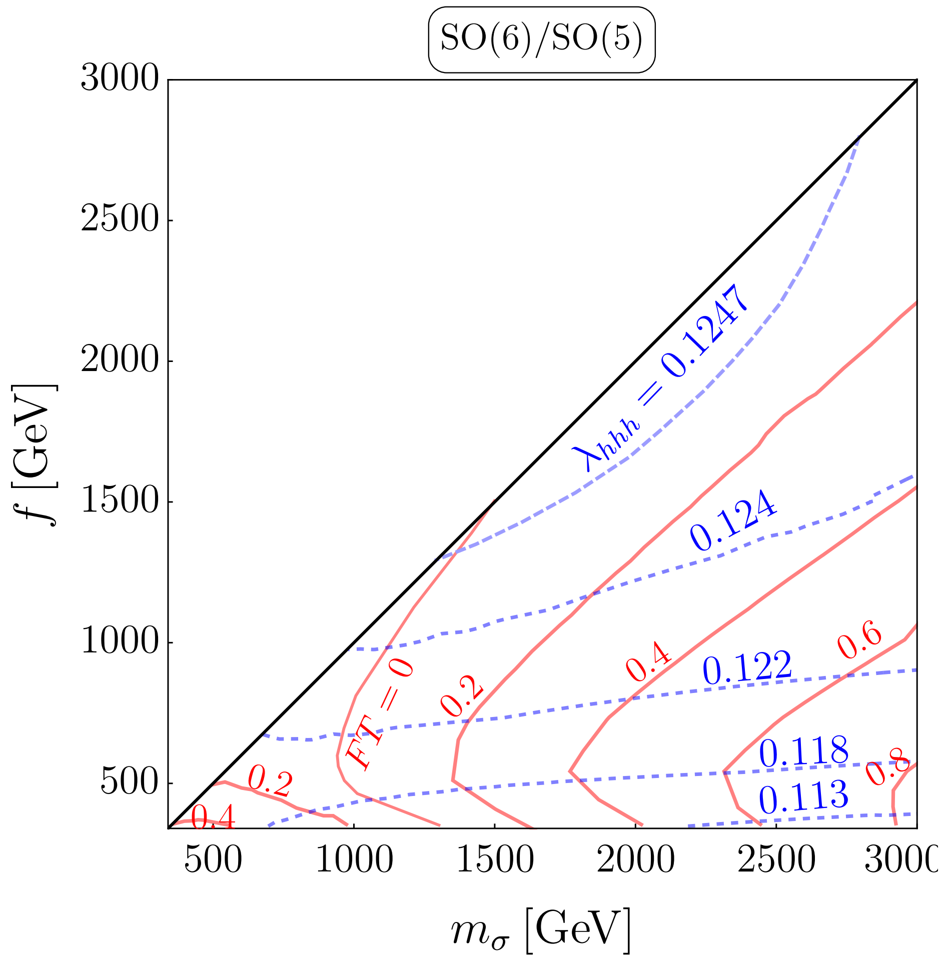

Neutral naturalness is an increasingly appealing paradigm.

While the new sector is SM neutral, it can be probed at the future lepton collider simply by Higgs couplings measurement.

# Backup Slides

# Results


SO(5)/SO(4)
$f$ [GeV]
$m_\sigma$ [GeV]
$\lambda_{hhh} = 0.1247$
0.124
0.122
0.118
0.113
$FT = 0$
0.2
0.4
0.6
0.8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$FT = 0$
0.2
0.4
0.6
0.8

# Nonlinear Parametrization

Coset structures for different models

$$\text{Twin Higgs (SU(4)/SU(3))} : \mathcal{H} = (f + \sigma/\sqrt{2})(\frac{H^T}{|H|}\sin\frac{|H|}{f}, 0, \cos(\frac{|H|}{f}))^T$$

$$\text{Twin Higgs (SO(8)/SO(7))} : \mathcal{H} = (f + \sigma/\sqrt{2})(\frac{\Pi_{i=1-4}}{|\Pi|}\sin\frac{|\Pi|}{f}, 0, 0, 0\cos(\frac{|\Pi|}{f}))^T$$

$$\text{SO(5)/SO(4)} : \mathcal{H} = (f + \sigma/\sqrt{2})(\frac{\Pi_{i=1-4}}{|\Pi|}\sin\frac{|\Pi|}{f}, \cos(\frac{|\Pi|}{f}))^T$$

$$\text{SO(6)/SO(5)} : \mathcal{H} = (f + \sigma/\sqrt{2})(\frac{\Pi_{i=1-4}}{|\Pi|}\sin\frac{|\Pi|}{f}, 0, \cos(\frac{|\Pi|}{f}))^T$$

# Nonlinear Parametrization

Goldstone Matrix for different cosets

| coset | U matrix |
|---|---|
| Twin Higgs (SU(4)/SU(3)) | $\begin{pmatrix} \mathbb{1} - \left(1 - \cos\frac{\lvert H\rvert}{f}\right)\frac{HH^\dagger}{\lvert H^2\rvert} & \begin{matrix}0\\0\end{matrix} & \frac{H}{\lvert H\rvert}\sin\frac{\lvert H\rvert}{f} \\ \hline 0 \quad\quad 0 & 0 & 0 \\ \hline -\frac{H^\dagger}{\lvert H\rvert}\sin\frac{\lvert H\rvert}{f} & 0 & \cos\frac{\lvert H\rvert}{f} \end{pmatrix}$ |
| Twin Higgs (SO(8)/SO(7)) | $\begin{pmatrix} \mathbb{1} - \left(1 - \cos\frac{\lvert\Pi\rvert}{f}\right)\frac{\Pi_i\Pi_j^\dagger}{\lvert\Pi^2\rvert} & 0_{4\times3} & \frac{\Pi_i}{\lvert\Pi\rvert}\sin\frac{\lvert\Pi\rvert}{f} \\ \hline 0_{3\times4} & 1_{3\times3} & 0_{3\times1} \\ \hline -\frac{\Pi_j^\dagger}{\lvert\Pi\rvert}\sin\frac{\lvert\Pi\rvert}{f} & 0 & \cos\frac{\lvert\Pi\rvert}{f} \end{pmatrix}$ |
| SO(5)/SO(4) | $\begin{pmatrix} \mathbb{1} - \left(1 - \cos\frac{\lvert\Pi\rvert}{f}\right)\frac{\Pi_i\Pi_j^\dagger}{\lvert\Pi\rvert^2} & \frac{\Pi_i}{\lvert\Pi\rvert}\sin\frac{\lvert\Pi\rvert}{f} \\ \hline -\frac{\Pi_j^\dagger}{\lvert H\rvert}\sin\frac{\lvert\Pi\rvert}{f} & \cos\frac{\lvert\Pi\rvert}{f} \end{pmatrix}$ |
| SO(6)/SO(5) | $\begin{pmatrix} \mathbb{1} - \left(1 - \cos\frac{\lvert\Pi\rvert}{f}\right)\frac{\Pi_i\Pi_j^\dagger}{\lvert\Pi^2\rvert} & 0_{4\times1} & \frac{\Pi_i}{\lvert\Pi\rvert}\sin\frac{\lvert\Pi\rvert}{f} \\ \hline 0_{1\times4} & 1 & 0 \\ \hline -\frac{\Pi_j^\dagger}{\lvert\Pi\rvert}\sin\frac{\lvert\Pi\rvert}{f} & 0 & \cos\frac{\lvert\Pi\rvert}{f} \end{pmatrix}$ |

# Nonlinear Parametrization

Covariant derivative in different models

| coset | $D_\mu^A$ | $D_\mu^B$ |
| --- | --- | --- |
| Twin Higgs (SU(4)/SU(3)) | $\partial_\mu \mathbb{1}_{2\times 2} - ig\frac{\sigma^\alpha}{2}W_\mu^\alpha - i\frac{g'}{2}B_\mu$ | $\partial_\mu \mathbb{1}_{2\times 2} - i\tilde{g}\frac{\sigma^\alpha}{2}\tilde{W}_\mu^\alpha - i\frac{\tilde{g}'}{2}\tilde{B}_\mu$ |
| Twin Higgs (SO(8)/SO(7)) | $\partial_\mu \mathbb{1}_{2\times 2} - igT_L W_\mu^\alpha - i\frac{g'}{2}B_\mu$ | $\partial_\mu \mathbb{1}_{2\times 2} - i\tilde{g}\tilde{T}_L\tilde{W}_\mu^\alpha - i\frac{\tilde{g}'}{2}\tilde{B}_\mu$ |
| SO(5)/SO(4) | $\partial_\mu \mathbb{1}_{4\times 4} - igt_L^\alpha W_\mu^\alpha - ig't_R^3 B_\mu$ | $\partial_\mu \mathbb{1}_{1\times 1}$ |
| SO(6)/SO(5) | $\partial_\mu \mathbb{1}_{4\times 4} - igt_L^\alpha W_\mu^\alpha - ig't_R^3 B_\mu$ | $\partial_\mu \mathbb{1}_{2\times 2} - ig_1\frac{\sigma^2}{\sqrt{2}}B'_\mu$ |

# RG Improvement of the Higgs Potential and Couplings

The RG-improved Higgs effective potential is obtained by solving the one-loop β-function of the vacuum energy in the background of the Higgs field.

$$\frac{dV_f(H_c,t)}{dt} = \frac{3}{16\pi^2}\left[M_t(H_c,t)^4 + M_{\tilde{t}}(H_c,t)^4\right]$$

$$V_s(H_c,t) = -\frac{1}{64\pi^2}\Big[M_H(H_c)\Big]^4 t = -\frac{1}{64\pi^2}\Big[-\frac{1}{2}\mu_H^2 + \frac{3}{2}\lambda_H h_c^2 - \frac{15c_6}{8f^2}h_c^4\Big]^2 t$$

$$V_g(H_c,t) = -\frac{3}{64\pi^2}\left[2M_W(H_c)^4 + M_Z(H_c)^4 + 3M_{\tilde{W}}(H_c)^4\right]t$$

where

$$M_t(H_c,t) = \lambda_t(H_c,t), \quad M_{\tilde{t}}(H_c,t) = \tilde{\lambda}_t(H_c,t)f\left[1-(1-\frac{8\delta f^2}{m_\sigma^2}+\frac{4m^2}{m_\sigma^2})\frac{H_c^2}{2f^2}\right]$$

The total improved effective potential is

$$V^{\rm RGE}(H_c,t) = V_s(H_c,t) + V_g(H_c,t) + V_f(H_c,t)$$

# RG Improvement of the Higgs Potential and Couplings

The loop correction to the filed strength of the Higgs doublet renders the kinetic terms in the non-canonical

$$|D_\mu^A H_c|^2 \to Z_{H_c} |D_\mu^A H_c|^2, \quad Z_{H_c} = 1 + \frac{3\lambda_t^2}{(4\pi)^2} t$$

In our calculation, $\lambda_t(m_\sigma)$ and $g_S(m_\sigma)$ are computed from $\lambda_t(m_t)$ and $g_S(m_t)$ using two-loop and one-loop fixed-order formulae, respectively

$$\lambda_t(m_\sigma) = \lambda_t(m_t) \left[ 1 - \left( \frac{g_S(m_t)^2}{4\pi^2} - \frac{9\lambda_t(m_t)^2}{64\pi^2} \right) \log \frac{m_\sigma^2}{m_t^2} + \frac{22 g_S(m_t)^4}{(4\pi)^4} \log^2 \frac{m_\sigma^2}{m_t^2} \right],$$

$$g_S(m_\sigma) = g_S \left[ 1 - \frac{7 g_S(m_t)^2}{32\pi^2} \log \frac{m_\sigma^2}{m_t^2} \right].$$

# RG Improvement of the Higgs Potential and Couplings

The EW scale EFT is given as

$$\mathcal{L}_S^{\rm EFT,EW} = |D_\mu^A H_c|^2 + V^{\rm RGE}(H_c/\sqrt{Z_{H_c}}) + \frac{c_H}{2f^2 Z_{H_c}^2}\mathcal{O}_H + \frac{c_6}{f^2 Z_{H_c}^3}\mathcal{O}_6\,,$$

$$\mathcal{L}_F^{\rm EFT,EW} \supset \lambda_q(H_c,t)\left(\frac{\bar{Q}_L H_c q_R}{\sqrt{Z_{H_c}}} + h.c.\right) + \tilde{\lambda}_q(H_c,t)\bar{\tilde{q}}\tilde{q}f\left[1 - \frac{|H_c|^2}{2f^2 Z_{H_c}}\left(1 - \frac{8\delta f^2}{m_\sigma^2} + \frac{4m^2}{m_\sigma^2}\right)\right]\,.$$

The mass of the mirror fermion $\tilde{b}$ and $\tilde{\tau}$ is

$$m_q = \frac{\lambda_q v}{\sqrt{2Z_{H_c}}}\,, \quad \tilde{m}_q = \tilde{\lambda}_q\left[f - \frac{v^2}{2Z_{H_c}}\left(\frac{1}{2f} + \frac{2m^2}{fm_\sigma^2} - \frac{4\delta f}{m_\sigma^2}\right)\right]$$

the Yukawa couplings become

$$\mathcal{L}_{hff} \supset \tilde{\lambda}_q^{\rm eff} h\bar{\tilde{q}}\tilde{q} + \lambda_q^{\rm eff} h(\bar{q}_L q_R + h.c.)$$

$$\tilde{\lambda}_q^{\rm eff} \equiv -\frac{\tilde{\lambda}_q v}{2Z_{H_c}\sqrt{Z_h}}\left[\frac{1}{f} + \frac{4m^2}{fm_\sigma^2} - \frac{8\delta f}{m_\sigma^2}\right]\,, \text{ and } \lambda_q^{\rm eff} \equiv \frac{\lambda_q}{\sqrt{2Z_h Z_{H_c}}}$$

the coupling of the physical Higgs boson to vector bosons is given by

$$\mathcal{L}_{hVV} = \frac{h}{\sqrt{Z_h}v}\left[\frac{g^2v^2}{2}W_\mu^+ W^{\mu,-} + \frac{(g^2+g'^2)v^2}{4}Z_\mu Z^\mu\right] + \text{mirror terms}$$

with $\quad Z_h = 1 + \dfrac{c_H}{Z_{H_c}^2}\dfrac{v^2}{f^2}$