Towards automatizing Higgs decays in BSM models at one-loop in the decoupling renormalization scheme

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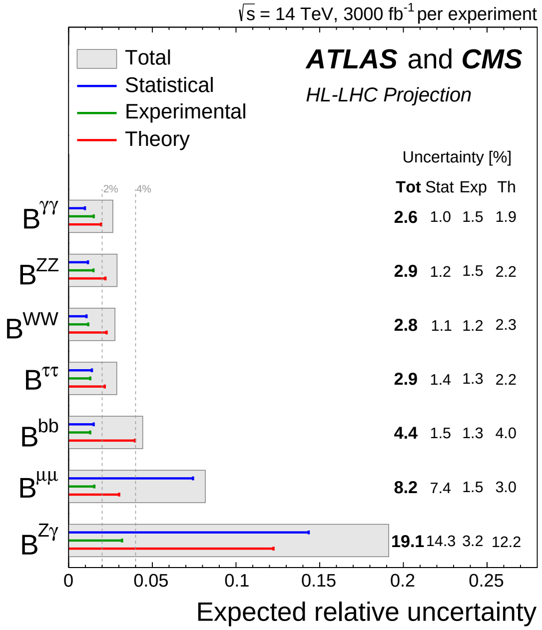
Why to study Higgs decays?

1. Measurements of the Higgs-sector become more precise

2. Extensions of the Higgs-sector solve a large variety of problems
→ from flavor problems to baryogenesis



There is great potential in tightly constraining BSM models through the Higgs-sector:
→ increasing experimental precision must be matched by theory
→ a large variety of models must be explored

Cepeda et. al.; Higgs Physics at the HL-LHC and HE-LHC; 1902.00134

How to organize higher order corrections?

Observables are connected to Greens functions to the Path integral

$$\langle T\left(\mathcal{O}(x_a)\mathcal{O}(x_b)\ldots\right)\rangle \propto \int \mathcal{D}[\Phi(x)]e^{iS[\Phi(x),\alpha]}\mathcal{O}(x_a)\mathcal{O}(x_b)\ldots$$

Couplings need to satisfy $\alpha \sim O(1)$ to evaluate this expression
→ perturbative expansion of the exponential

Higher order terms lead to an improvement of the prediction for observables
→ organized in terms of fixed loop expansion

The loop-corrections are not finite and need to be regularized and renormalized to get a meaningful prediction for observables

How to automatize these calculations?

By now the formal calculations are standard and many tools exist to calculate Feynman diagrams and observables

→ SARAH, FeynArts, FormCalc, LoopTools
→ HDECAY, 2HDECAY, FeynHiggs,...

A. Djouadi, J. Kalinowski, M. Spira; hep-ph/9704448
M. Krause, M. Mühlleitner, M. Spira; 1810.00768

Problem: Many of these Tools are very model specific

> Develop FlexibleSUSY and the extention FlexibleDecay to extend the available models for automatized high-precision calculation of model properties

FlexibleSUSY is a spectrum-generator generator:
→ it generates codes for a large models
→ state-of-the-art Higgs mass prediction

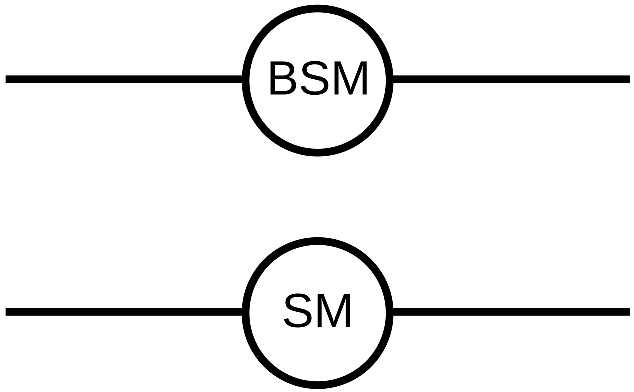
FlexibleDecay adds the ability to calculate Higgs decays:
→ higher order SM effects are taken into account
→ the BSM effects are renormalized in the decoupling renormalization scheme

Why to use the decoupling renormalization scheme?

Regularization and Renormalization are a standard procedure as well
→ many schemes available like OS, $\overline{\text{MS}}$,...

The most common scheme ($\overline{\text{MS}}$) suffers from large contributions due to the presence of the unknown BSM part
→ introduces large uncertainties
→ makes the whole calculation problematic

Idea: We separate the BSM effects from SM effects and hide them in SM renormalization constants
→ BSM contributions drop out in the decoupling limit



How to apply the decoupling scheme, theoretically?

We separate parameters in **SM-like** and BSM parameters

Renormalization conditions for SM-like parameters:

$$P_{\mathrm{BSM}}^{\mathrm{dec}} = P_{\mathrm{SM}}^{\overline{MS}}$$

Or in terms of renormalization constants

$$\delta P_{\mathrm{BSM}}^{\mathrm{dec}} = \delta P_{SM}^{\overline{MS}} + \delta P_{\mathrm{BSM}}^{\mathrm{OS}} - \delta P_{\mathrm{SM}}^{\mathrm{OS}}$$

The bare parameter of the BSM theory can be written in decoupling-and on-shell scheme

$$P_0 = P_{\mathrm{BSM}}^{\mathrm{dec}} + \delta P_{\mathrm{BSM}}^{\mathrm{dec}} \stackrel{!}{=} P_{\mathrm{BSM}}^{\mathrm{OS}} + \delta P_{\mathrm{BSM}}^{\mathrm{OS}}$$

The corresponding definition exists also in the SM

$$P_0 = P_{\mathrm{SM}}^{\overline{\mathrm{MS}}} + \delta P_{\mathrm{SM}}^{\overline{\mathrm{MS}}} \stackrel{!}{=} P_{\mathrm{SM}}^{\mathrm{OS}} + \delta P_{\mathrm{SM}}^{\mathrm{OS}}$$

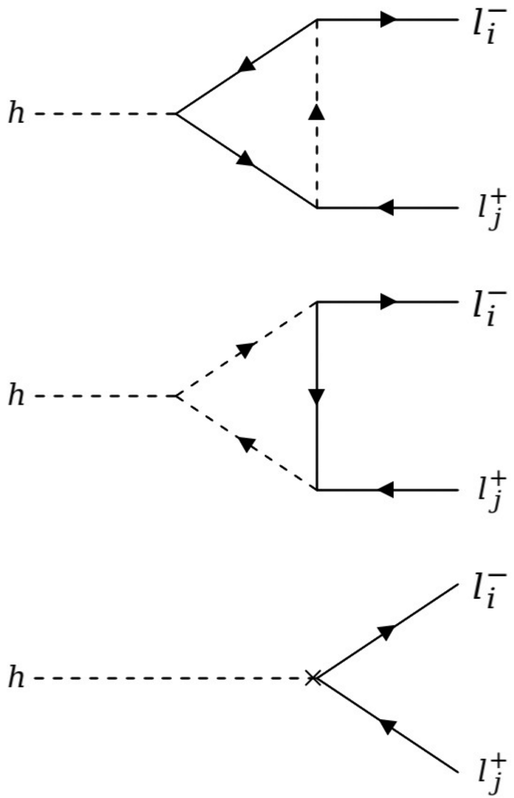
How to apply the decoupling scheme, practically?

Explore the S_1-Leptoquark model with ϕ the Leptoquark field transforming as $\left(3, 1, -\frac{1}{3}\right)$

$$\mathcal{L}_{Y\phi} = Y_{ij}^{LL}\,(Q^{C\,T}_{\;\;i} i\sigma^2 L_j)\phi^\dagger + Y_{ij}^{RR}\,q^C_{u\;i} l_j \phi^\dagger + \text{h.c.}$$

$$\mathcal{L}_{H\phi} = -g_{H\phi}(H^\dagger H)\phi^\dagger\phi$$

To properly predict decay properties in the decoupling scheme at one-loop we require the renormalization constants:
δm_i^l, δZ_{ij}^L, δZ_{ij}^R, δZ_H and δZ_v



How to calculate the triangle diagrams?

$$B_{0;\mu;\mu\nu} = \frac{\tilde{\mu}^{4-D}}{i\pi^{\frac{D}{2}}} \int d^D k \frac{1; k_\mu; k_\mu k_\nu}{(k^2 - m_1^2)((k+k_1)^2 - m_2^2)}$$

$$C_{0;\mu;\mu\nu} = \frac{\tilde{\mu}^{4-D}}{i\pi^{\frac{D}{2}}} \int d^D k \frac{1; k_\mu; k_\mu k_\nu}{(k^2 - m_1^2)((k+k_1)^2 - m_2^2)((k+k_2)^2 - m_3^2)}$$

We can use the tensor structure and expand:

$$B^\mu = k_1^\mu B_1 \qquad C^\mu = k_1^\mu C_1 + k_2^\mu C_2$$

$$B^{\mu\nu} = \eta^{\mu\nu} B_{00} + k_1^\mu k_1^\nu B_{11} \qquad C^{\mu\nu} = \eta^{\mu\nu} C_{00} + (k_1^\mu k_2^\nu + k_2^\mu k_1^\nu) C_{12} + k_1^\mu k_1^\nu C_{11} + k_2^\mu k_2^\nu C_{22}$$

$$B_0(p, m_1, m_2) = \frac{1}{\epsilon} - \log\left(\frac{m_1^2}{\mu^2}\right) + 1 - \int_0^1 dx \log\left(1 + \frac{\overline{x}}{x}\alpha_1 - \overline{x}\beta_1\right) \qquad \alpha_1 = \frac{m_2^2}{m_1^2}, \beta_1 = \frac{p^2}{m_1^2}$$

From the triangle diagrams we get BSM contributions to form-factors

$$F^1_{Lij} = \frac{3m_{u_k}}{16\pi^2 v}\left\{\left[B_0\left(m^l_i, m_\phi, m_{u_k}\right) + 2m^2_{u_k} C_0(a) + m^2_\mu C_1(a) + m^2_H C_0(a)\right](Y^{RR\dagger})_{ik} Y^{LL}_{kj} + \cdots\right\}$$

$$F^2_{Lij} = \frac{3g_{H\phi}v}{16\pi^2}\left\{m_\mu[C_0(b) + C_1(b) + C_2(b)]\,(Y^{LL\dagger})_{ik} Y^{LL}_{kj} - m_\mu C_2(b)\,(Y^{RR\dagger})_{ik} Y^{RR}_{kj} + m_{u_k} C_0(b)\,(Y^{LL\dagger})_{ik} Y^{RR}_{kj}\right\}$$

The first diagram introduces divergences

Due to dimensional regularization

→ will be taken care of by choosing any appropriate renormalization scheme

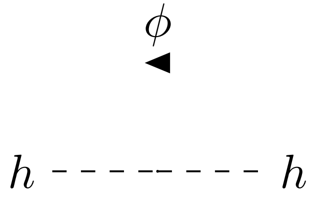
Due to a large Leptoquark mass

→ will be handled by using the decoupling renormalization scheme

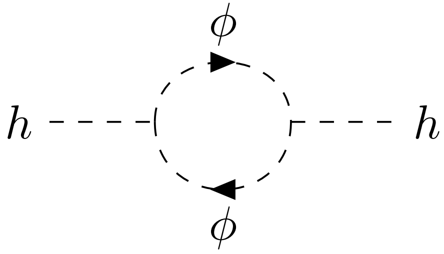
How to calculate the renormalization constants?

Generally the self-energies take the form

$$\Pi(p^2) = \Pi^{\text{BSM}}(p^2) + \Pi^{\text{SM}}(p^2) \longrightarrow \delta P^{\text{dec}}_{\text{BSM}} = \delta P^{\overline{MS}}_{SM} \boxed{+\, \delta P^{\text{OS}}_{\text{BSM}} - \delta P^{\text{OS}}_{\text{SM}}}$$



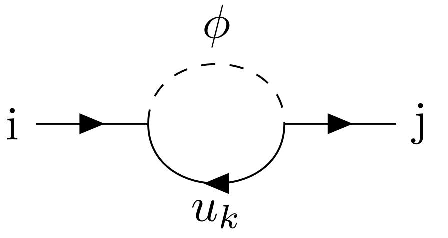
Beauty of this model: The SM contributions in the OS difference cancel, leaving only the BSM contributions



$$\delta Z^{\text{L,dec}}_{ii} = \delta Z^{L,\overline{MS}}_{ii} + \frac{3}{16\pi^2}\left\{(Y^{LL\dagger})_{ik} Y^{LL}_{ki} B_1(m^l_i, m_{u_k}, m_\phi) + \ldots\right\}$$

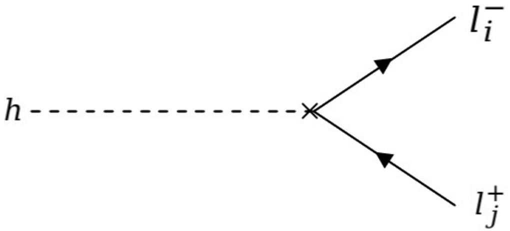
$$\delta Z^{\text{l,dec}}_{ii} = \delta Z^{R,\overline{MS}}_{ii} + \frac{3}{16\pi^2}\left\{(Y^{RR\dagger})_{ik} Y^{RR}_{ki} B_1(m^l_i, m_{u_k}, m_\phi) + \ldots\right\}$$

$$\delta Z^{\text{m,dec}}_{ii} = \delta Z^{m,\overline{MS}}_{ii} + \frac{3 m_{u_k}}{32\pi^2} b^k_{ij} B_0(p, m_{u_k}, m_\phi) - \frac{3}{32\pi^2} a^k_{ii} B_1(m^l_i, m_{u_k}, m_\phi)$$



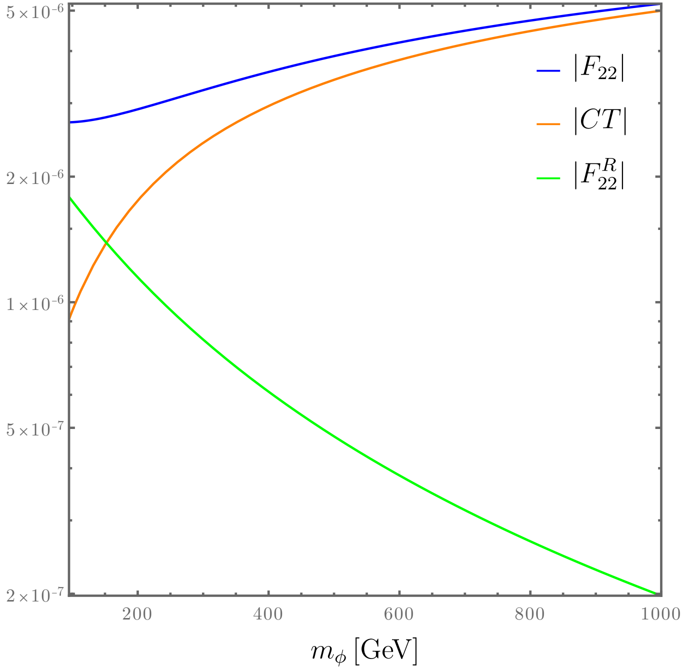
$$a^k_{ij} = (Y^{LL^\dagger} Y^{LL} + Y^{RR^\dagger} Y^{RR})_{ij}$$

$$b^k_{ij} = (Y^{LL^\dagger} Y^{RR} + Y^{RR^\dagger} Y^{LL})_{ij}$$



$$\supset -\frac{i}{v}\left\{\frac{1}{2}\left(m_i^l \delta Z_{ij}^{L,dec} + m_j^l \delta Z_{ij}^{l,dec\dagger}\right)P_L + m_i^l \delta Z^{m,dec} P_L + \dots\right\}$$

$$= -\frac{m_i^l}{2v}\left(\delta Z_{Lii}^{\overline{MS}} + \delta Z_{Rii}^{\overline{MS}}\right) - \frac{m_i^l}{2}\delta Z_{mii}^{\overline{MS}} \boxed{- \frac{3 m_{u_k}}{16\pi^2 v} b_{ii}^k B_0(m_i^l, m_{u_k}, m_\phi)} + \dots$$



The counter term removes all divergencies in the amplitude:
→ we get meaningful observables
→ Amplitudes show the decoupling behavior
→ delicate corrections are not spoiled by the BSM contributions

What about more complicated models?

We analyzed the HSESM and 2HDM:
→ the approach stays the same
→ due to the different structure to the SM the decoupling scheme renormalization constants take a much more difficult form

$$\delta P_{\mathrm{BSM}}^{\mathrm{dec}} = \delta P_{SM}^{\overline{MS}} + \delta P_{\mathrm{BSM}}^{\mathrm{OS}} - \delta P_{\mathrm{SM}}^{\mathrm{OS}}$$

This term stays the same

Contrary to the previous model the SM contribution do not cancel

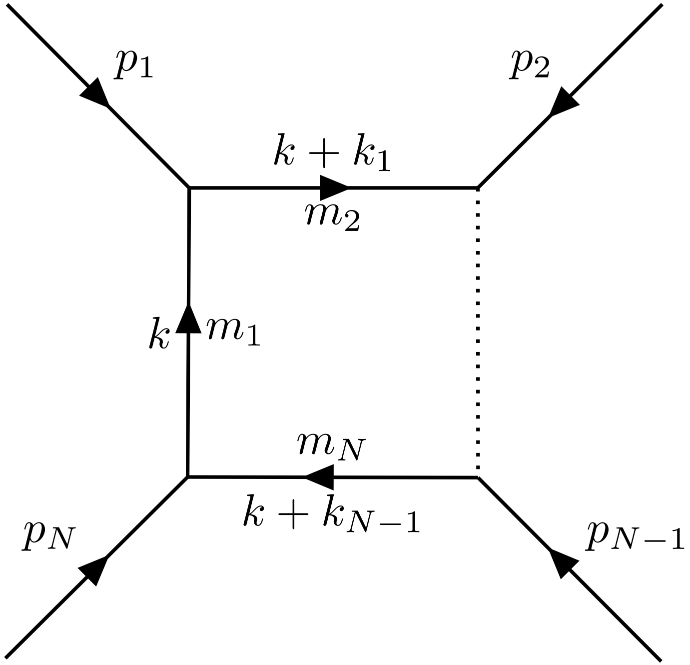
Summary & Outlook

- Higgs decays are a important to constrain and test BSM models
- FlexibleSUSY provides a framework to analyze many models
- The decoupling renormalization scheme does not spoil higher order corrections with large BSM contributions

- The presented renormalization scheme must be implemented in FlexibleDecay
- Compare with analytic calculation and other tools
- Use FlexibleDecay for phenomenological explorations of Higgs properties

Backup: Momentum conventions

The momentum conventions along the calculations are taken over from LoopTools.



From Momentum conservation we get:

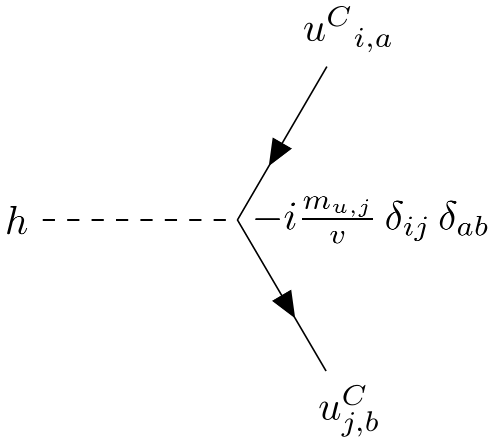
$$k_1 = p_1$$

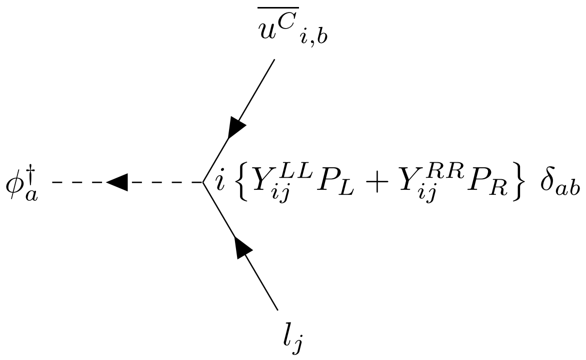
$$k_2 = p_1 + p_2$$

$$k_{N-1} = \sum_{i=1}^{N-1} p_i$$

T. Hahn; LoopTools 2.15 User's Guide

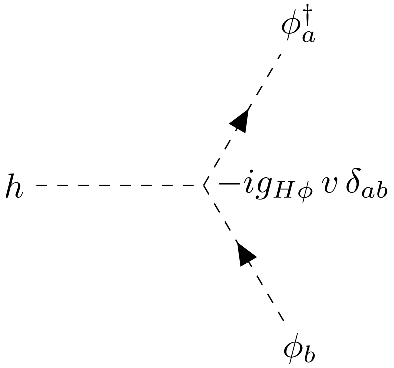
Backup: Feynman rules for the leptoquark model

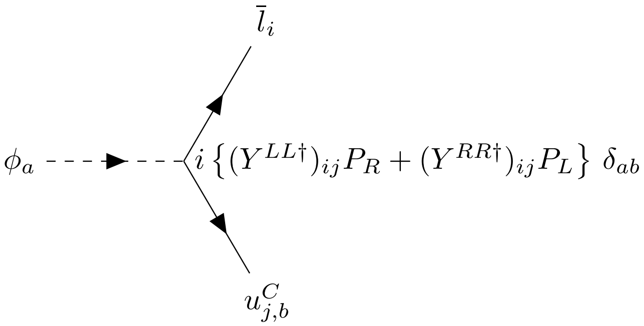




$$Y^{LL}_{ij}\,({Q^C}^T_i\, i\sigma^2 L_j)\phi^\dagger + Y^{RR}_{ij}\, {q_u^C}_i l_j \phi^\dagger + \mathrm{h.c.}$$

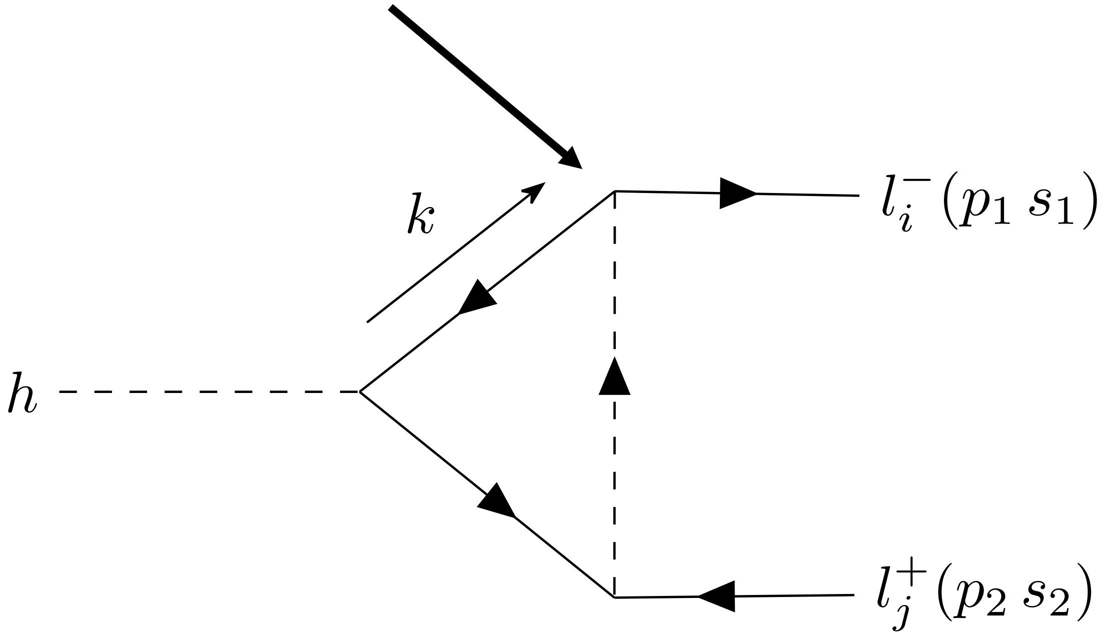
$$-g_{H\phi}(H^\dagger H)\phi^\dagger\phi$$





Backup: Structure of triangle diagrams

Coupling contains left and right projectors



$$= \overline{u}_i(p_1)\,\{F_L\,P_L + F_R\,P_R\}\,v_j(p_2)$$

Backup: Renormalization of the SM

$$e_0 = Z_e e$$
$$m_{W0}^2 = Z_{mW} m_W^2$$
$$m_{Z0}^2 = Z_{mZ} m_Z^2$$
$$m_{H0}^2 = Z_{mH} m_H^2$$
$$m_{f0,ij} = \tilde{Z}_{mf,ik} m_{f,kj}$$

$$\Updownarrow$$

$$\delta e = \delta Z_e e$$
$$\delta m_W^2 = \delta Z_{mW} m_W^2$$
$$\delta m_Z^2 = \delta Z_{mZ} m_Z^2$$
$$\delta m_H^2 = \delta Z_{mH} m_H^2$$
$$\delta m_{f,ij} = \delta \tilde{Z}_{mf,ik} m_{f,kj}$$

Inverse Propagators for the Higgs and Fermions are

$$\hat{\Gamma}^H(p) = i\left(p^2 - m_H^2\right) + i\hat{\Pi}_H(p^2)$$
$$\hat{\Gamma}_{ij}^F(p) = i\left(p - m_i^f\right)\delta_{ij} + i\left\{p\left[\hat{\Sigma}_{1ij}^{\mathrm{L}}(p^2)P_L + \hat{\Sigma}_{1ij}^{\mathrm{R}}(p^2)P_R\right] + \hat{\Sigma}_{2ij}^{\mathrm{L}}(p^2)P_L + \hat{\Sigma}_{2ij}^{\mathrm{R}}(p^2)P_R\right\}$$

And the corresponding renormalization conditions become

$$\hat{\Pi}_H(p^2 = m_H^2) = 0 \qquad \left.\frac{\partial\hat{\Pi}_H(p^2)}{\partial p^2}\right|_{p^2=m_H^2} = 0$$

$$\left.\hat{\Sigma}_{ij}(p)u_j(p)\right|_{p^2=m_j^{l2}} = 0 \qquad \left.u_i(p)\hat{\Sigma}_{ij}(p)\right|_{p^2=m_i^{l2}} = 0$$

$$\left.\frac{p + m_i^l}{p^2 - m_i^{l2}}\hat{\Sigma}_{ii}(p)u_i(p)\right|_{p^2=m_i^{l2}} = 0 \qquad \left.u_i(p)\hat{\Sigma}_{ii}(p)\frac{p + m_i^l}{p^2 - m_i^{l2}}\right|_{p^2=m_i^{l2}} = 0$$

Backup: Higgs-and Fermion renormalization constants

Applying the renormalization conditions yields

$$\delta Z_H = -\frac{\partial \Pi_H^{\mathrm{BSM}}(p^2)}{\partial p^2}\Big|_{p^2=m_H^2}$$

$$\delta Z_{mH} = \frac{\Pi_H^{\mathrm{BSM}}(m_H^2)}{m_H^2}$$

$$\delta Z_{ii}^L = -\Sigma_{1ii}^L(m_i^{l2}) - m_i^l \frac{\partial}{\partial p^2}(m_i^l(\Sigma_{1ii}^L(p^2) + \Sigma_{1ii}^R(p^2)) + \Sigma_{2ii}^L(p^2) + \Sigma_{2ii}^R(p^2))$$

$$\delta Z_{ii}^l = -\Sigma_{1ii}^R(m_i^{l2}) - m_i^l \frac{\partial}{\partial p^2}(m_i^l(\Sigma_{1ii}^L(p^2) + \Sigma_{1ii}^R(p^2)) + \Sigma_{2ii}^L(p^2) + \Sigma_{2ii}^R(p^2))$$

$$\delta Z_{ii}^{\mathrm{m}} = \frac{1}{2}(\Sigma_{1ii}^L(m_i^{l2}) + \Sigma_{1ii}^R(m_i^{l2}) + \Sigma_{2ii}^L(m_i^{l2}) + \Sigma_{2ii}^R(m_i^{l2}))$$