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

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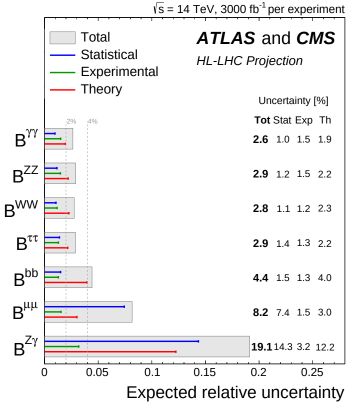
Why to study Higgs decays?

- Measurements of the Higgs sector are becoming more precise
- Extensions of the Higgs sector solve many problems
  - from flavor puzzles to baryogenesis

There is great potential in constraining BSM models through the Higgs sector:

- Increasing experimental precision must be matched by theory
- A wide variety of models must be explored



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

How to automatize these calculations?

Many tools exist to calculate Feynman diagrams and observables:

- SARAH, FeynArts, FormCalc, LoopTools
- HDECAY, 2HDECAY, FeynHiggs

Problem: many tools are very model specific

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

FlexibleSUSY is a spectrum-generator generator:

- Generates code for large classes of models
- Provides state-of-the-art Higgs mass predictions

FlexibleDecay adds the ability to calculate Higgs decays:

- Includes higher-order SM effects
- Renormalizes BSM effects in the decoupling scheme

Why to use the decoupling renormalization scheme?

Every precision calulation goes through Regularization and Renormaliztion

- many schemes available like OS, $\overline{\text{MS}}$,...

Motivation

The most common scheme ($\overline{\text{MS}}$) suffers from large contributions due to the precence of unknown BSM particles:

- introduces large uncertainties
- needs extra work to controll

Idea: separate BSM effects from SM effects

- Hide them in SM renormalization constants
- BSM contributions vanish in the decoupling limit

How to apply the decoupling scheme, theoretically?

Separate parameters into SM-equivalent and BSM parameters

Renormalization conditions for SM-equivalent parameters

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

Better approach for analytic calculations

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

Master Equation

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

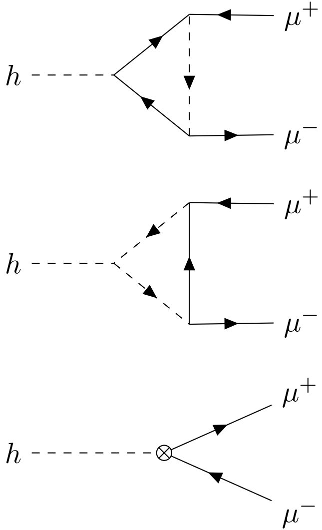
How to apply the decoupling scheme, practically?

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

$$\mathcal{L}_{Y\phi} = Y^{LL}_{ij}\,(\overline{Q^C}^T_i\, i\sigma^2 L_j)\phi^\dagger + Y^{RR}_{ij}\,\overline{q^C_u}_i l_j \phi^\dagger + \text{h.c.}$$

$$\mathcal{L}_{H\phi} = -g_{H\phi}(H^\dagger H)\,\mathrm{Tr}\left\{\phi^\dagger\phi\right\}$$

For proper predictions of Higgs decay properties in the decoupling scheme at one-loop we require the renormalization constants:
δm^l_i, δZ^L_{ij}, δZ^R_{ij}, δZ_H and δZ_v



Reminder of the B_0 function

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

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

The triangle diagrams result in

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

$B_0(m^l_i, m_\phi, m_{u_k})$ dictates the behaviour

Divergence due to regularization

- a suitable renormalization scheme takes care of the divergence

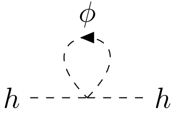
Logarithmic growth due to large Leptoquark masses

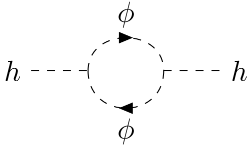
- the decoupling scheme will take care of this behaviour

How to calculate the renormalization constants?

Generally self-energies have the form

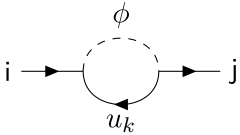
$$\Pi(p^2) = \Pi^{\mathsf{BSM}}(p^2) + \Pi^{\mathsf{SM}}(p^2)$$
$$\to \delta P^{\mathsf{dec}}_{\mathsf{BSM}} = \delta P^{\overline{MS}}_{SM} + \delta P^{\mathsf{OS}}_{\mathsf{BSM}} - \delta P^{\mathsf{OS}}_{\mathsf{SM}}$$



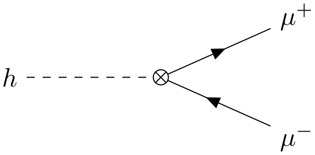


Beauty of this model: The SM contributions in the OS difference cancel

$$\delta Z^{\mathsf{L,dec}}_{ii} = \delta Z^{L,\overline{MS}}_{ii} + \frac{3}{16\pi^2}\left\{\left(Y^{LL\dagger}\right)_{ik} Y^{LL}_{ki} B_1(m^l_i, m_{u_k}, m_\phi) + \dots\right\}$$
$$\delta Z^{\mathsf{l,dec}}_{ii} = \delta Z^{R,\overline{MS}}_{ii} + \frac{3}{16\pi^2}\left\{\left(Y^{RR\dagger}\right)_{ik} Y^{RR}_{ki} B_1(m^l_i, m_{u_k}, m_\phi) + \dots\right\}$$
$$\delta Z^{\mathsf{m,dec}}_{ii} = \delta Z^{m,\overline{MS}}_{ii} + \frac{3 m_{u_k}}{32\pi^2} b^k_{ij} B_0(p, m_{u_k}, m_\phi) - \frac{3}{32\pi^2} a^k_{ii} B_1(m^l_i, m_{u_k}, m_\phi)$$



Counter term and amplitudes

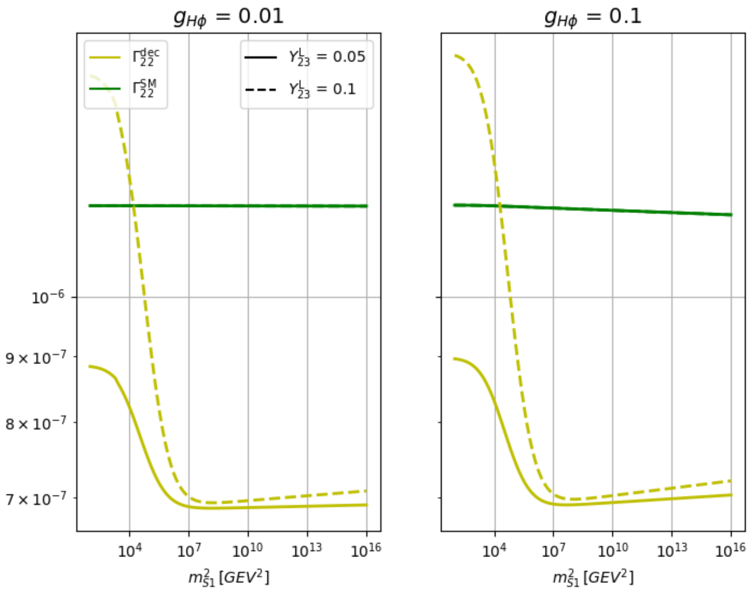


$$\supset \; -\frac{im_\mu}{v}\left\{\frac{1}{2}\left(\delta Z^L_{22}+\delta Z^{l\dagger}_{22}\right)P_L+\delta Z^{mL}_{\mu}P_L\right\}$$

$$= -\frac{m_\mu}{v}\left\{\frac{1}{2}\left(\delta Z^{\overline{MS}}_{L22}+\delta Z^{\overline{MS}}_{R22}\right)+\delta Z^{\overline{MS}}_{m22}\right\}-\frac{3m_{u_k}}{32\pi^2 v}b^k_{22}B_0(m_\mu,m_{u_k},m_\phi)+\dots$$

The counter term removes all divergencies in the amplitude:

- we get meaning full observables
- amplitudes show decoupling behaviour?
- delicate corrections are not spoiled by BSM corrections


$g_{H\phi} = 0.01$
$g_{H\phi} = 0.1$
Γ_{22}^{dec}
Γ_{22}^{SM}
$Y_{23}^{L} = 0.05$
$Y_{23}^{L} = 0.1$
10^{-6}
9×10^{-7}
8×10^{-7}
7×10^{-7}
10^{4} 10^{7} 10^{10} 10^{13} 10^{16}
$m_{S1}^2\,[GEV^2]$

What about more complicated models?

- We analyzed the HSESM and 2HDM
- Approach stays the same, but:
  - Different model structure compared to SM
  - Decoupling scheme renormalization constants become more complicated
- In these models:
  - Some terms remain the same
  - SM contributions do not cancel as in the leptoquark model

Summary & Outlook

The decoupling renormalization scheme

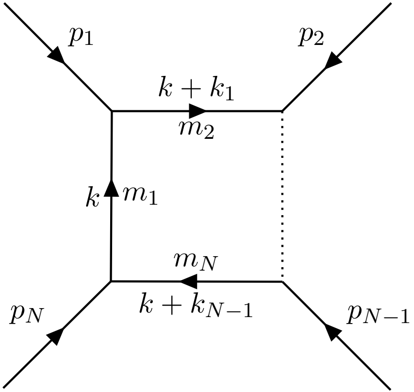
- is an interesting alternative to deal with BSM contributions,
- allows to take well known higher order SM corrections into account, and
- keeps large BSM corrections under control

Next steps:

- Make the scheme available in `FlexibleDecay`
- Compare with analytic calculations and other tools

Backup: Momentum conventions & PV-functions I

- Momentum conventions are taken from LoopTools
- From momentum conservation we obtain relations between external and internal momenta



From momentum conservation we also have:

$$k_1 = p_1$$
$$k_2 = p_1 + p_2$$
$$\vdots$$
$$k_{N-1} = \sum_{i=1}^{N-1} p_i$$

Backup: Momentum conventions & PV-functions II

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

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

Expand the integrals in the possible tensors and a corresponding scalar coefficient

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

$$B^{\mu\nu} = \eta^{\mu\nu} B_{00} + k_1^\mu k_1^\nu B_{11} \qquad B^{\mu\nu} = \eta^{\mu\nu} B_{00} + k_1^\mu k_1^\nu B_{11}$$

Backup: SM renormalization I

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

$$\updownarrow$$

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

Inverse Propagators for the Higgs and Fermions are

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

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: SM renormalization II

Applying the renormalization conditions yields

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

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

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

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

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