SMEFT NLO correction to Higgs decaying to fermion pairs implementation Sherpa

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Introduction

SMEFT: treat SM as a low-energy EFT of a UV complete theory, assuming

- $\Lambda_{NP} >> \Lambda_{EW}$, i.e. no new light particles
- $SU(3) \times SU(2) \times U(1)$ broken by vev of SU(2) doublet Higgs field.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}^{(6)}\,; \qquad \mathcal{L}^{(6)} = \sum_{i=1}^{59} C_i(\mu) Q_i(\mu)\,.$$

To calculate the decay rate:

$$\begin{aligned} |\mathcal{M}|^2 &= |\mathcal{M}_{\rm SM} + \mathcal{M}^{(6)}|^2 \\ &= |\mathcal{M}_{\rm SM}|^2 + 2\Re\left(\mathcal{M}^*_{\rm SM}\mathcal{M}^{(6)}\right) + |\mathcal{M}^{(6)}|^2 \end{aligned}$$

- For this discussion we will neglect term of order Λ_{NP}^{-4}
- Cross-term of order Λ_{NP}^{-2}

SMEFT NLO Landscape

A rapidly expanding field:

- A rapidly expanding field: Current calculations done on case-by-case basis: [Giardino, Dawson, Maltoni, Zhang, Trott, Petriello, Duhr, Schulze, Passarino, Signer, Pruna, Shepherd, Hartmann, Baglio, Lewis, Zhang, Boughezal, Degrande, Pecjak, Vryonidou, Mimasu, Deutschmann, Scott, Dedes, Suxho, Trifyllis, Gomez-Ambrosio, Durieux, Cullen, Gauld, Haisch, Zanderighi, Corbett . . .]
- Future is NLO automation as in SM (already available for QCD corrections [Degrande et al. arXiv:2008.11743])

Example: $h \to b\bar{b}$ SMEFT-NLO-QCD

- Operators involved:

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
Q_{dG}	$g_s(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$

- The subscripts p, r are flavour indices and q_p and d_r are left- and right-handed fields respectively.

JC, BP, and DS:[JHEP, vol. 08, p. 173, 2019]

$$\mathcal{L}_{\rm Yuk} = -\left[H^\dagger \overline{d}_r [Y_d]_{rs}\, q_s + h.c.\right] + \left[C^*_{\substack{dH\\sr}} (H^\dagger H) H^\dagger \overline{d}_r\, q_s + h.c.\right]$$

Operator C_{dH} gives correction to the Yukawa coupling $[Y_d]$.

Requiring that the kinetic terms are canonically normalised leads one to write the Higgs doublet in unitary gauge:

$$H(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ [1 + C_{H,\rm kin}]\, h(x) + v_T \end{pmatrix},$$

where

$$C_{H,\rm kin} \equiv \left(C_{H\Box} - \frac{1}{4} C_{HD}\right) v_T^2\,,$$

Feynman diagrams

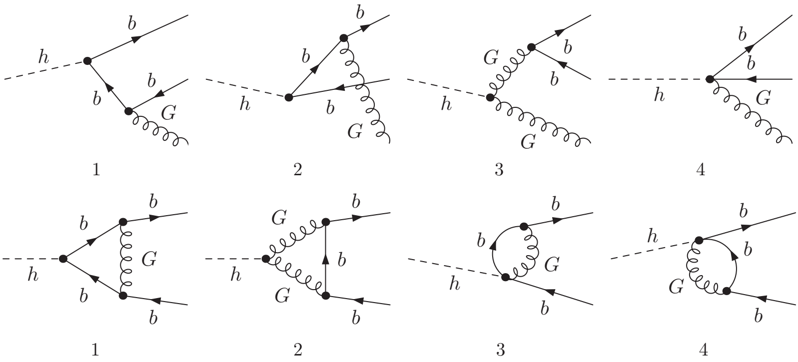

Figure 1: The real corrections labelled 3 and 4 are generated by Q_{HG} and Q_{bG} operators respectively. Similarly, the virtual corrections labelled 2 and $3, 4$ are generated by Q_{HG} and Q_{bG} operators respectively.

The differential decay rate to NLO is obtained by evaluating the expression

$$d\Gamma = \frac{d\phi_2}{2m_h}\sum\left|\mathcal{M}_{h\to b\bar{b}}\right|^2 + \frac{d\phi_3}{2m_h}\sum\left|\mathcal{M}_{h\to b\bar{b}g}\right|^2 .$$

The NLO decay rate in the SMEFT:

$$\Gamma = \Gamma^{(4,0)} + \Gamma^{(6,0)} + \Gamma^{(4,1)} + \Gamma^{(6,1)} ,$$

The tree-level decay amplitude for the process $h \to b\bar{b}$:

$$i\mathcal{M}^{(0)}(h \to b\bar{b}) = -i\bar{u}(p_b)\left(\mathcal{M}^{(0)}_{b,L}P_L + \mathcal{M}^{(0)*}_{b,L}P_R\right)v(p_{\bar{b}}) ,$$

where

$$\mathcal{M}^{(0)}_{b,L} = \frac{m_b}{v_T}\left[1 + C_{H,\text{kin}}\right] - \frac{v_T^2}{\sqrt{2}}C_{bH} .$$

JC, BP, and DS:[JHEP, vol. 08, p. 173, 2019]

We write the UV-renormalised 2-body contributions in the form

$$\frac{\left|\mathcal{M}_{h\to b\bar{b}}\right|^2}{M_2^{(4,0)}} = 1 + v_\sigma^2 K_2^{(6,0)} + \frac{1}{v_\sigma^2} K_{2,\text{weak}}^{(4,1))} + K_{2,\text{weak}}^{(6,1)}$$
$$+ \frac{C_F \alpha_s}{\pi} \left[K_2^{(4,1)} \left(1 + v_\sigma^2 K_2^{(6,0)}\right) + v_\sigma^2 K_2^{(6,1)} \right.$$
$$\left. - \frac{1}{\epsilon} \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left[1 + \frac{1+\beta^2}{2\beta} \ln x\right] \left(1 + v_\sigma^2 K_2^{(6,0)}\right) \right], \quad (1)$$

where

$$\beta = \sqrt{1 - \frac{4m_b^2}{m_H^2}}; \qquad x = \frac{1-\beta}{1+\beta}. \quad (2)$$

EW Input Scheme dependence

The calculation becomes more involved for the EW NLO corrections.

- Depending on the choice of input scheme, the WCs can differ.
- An input scheme is intrinsic part of the renormalisation procedure and a crucial step in any perturbative calculation.

$$\frac{1}{v_{T,0}^2} = \frac{1}{v_s^2}\left[1 - v_s^2 \Delta v_s^{(6,0,s)} - \frac{1}{v_s^2}\Delta v_s^{(4,1,s)} - \Delta v_s^{(6,1,s)}\right],$$

where, s = input scheme.
We discuss two of them and can see how the SMEFT correction differs.

AB, BP, and TS:[JHEP, vol. 04, p. 073, 2024]

EW Input Scheme dependence

$G\mu$-Scheme

Input parameters: $\{m_W, m_Z, G_F\}$

$$v_S \equiv v_\mu = \left(\sqrt{2}G_F\right)^{-\frac{1}{2}} ; \quad \Delta v_\mu^{(6,0,\mu)} = C_{\substack{HI\\11}}^{(3)} + C_{\substack{HI\\22}}^{(3)} - C_{\substack{ll\\1221}} ,$$

α-Scheme

Input parameters: $\{m_W, m_Z, \alpha\}$

$$v_S \equiv v_\alpha = \frac{2M_W s_w}{\sqrt{4\pi\alpha}}; \quad \Delta v_\alpha^{(6,0,\alpha)} = -2\frac{c_w}{s_w}\left[C_{HWB} + \frac{c_w}{4s_w}C_{HD}\right] ,$$

AB, BP, and TS:[JHEP, vol. 04, p. 073, 2024]

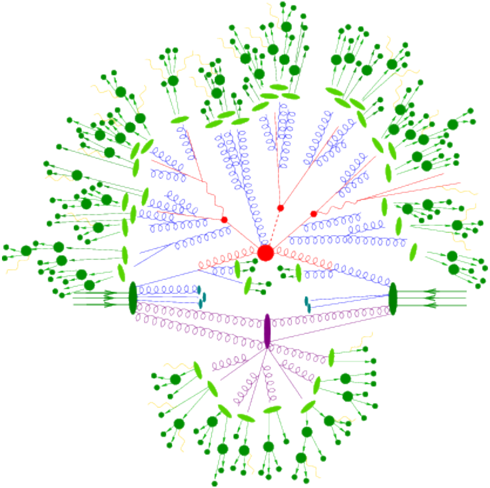

Figure 2: Pictorial representation of an event from SHERPA.

Image source: https://sherpa.hepforge.org/event.png

IR divergences

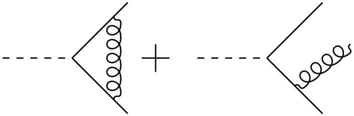

Figure 3: IR finite by KLM theorem

- In practice, for event generators we have to make them separately finite.
  - - Dipole subtraction.

$$\sigma^{\text{NLO}} = \int_{m+1} \left[d\sigma^R - d\sigma^A \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]$$

- Merging with production.

SC, SD, MS, and ZT [Nucl.Phys.B,vol.627, pp.189–265, 2002]

1. Introduction
2. Precision Calculation in SMEFT
3. Event Generator
4. **Discussion and Preliminary Results**
5. Conclusion

Validation: SHERPA Result

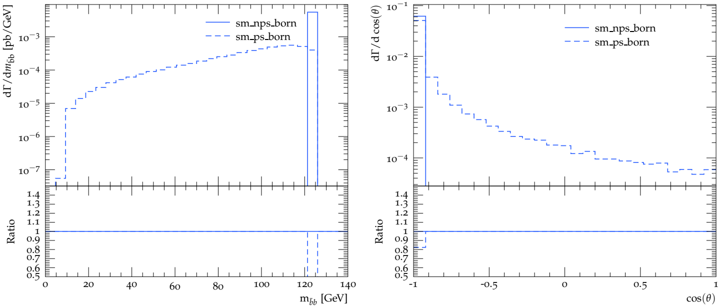

Figure 4: sm born level

Validation: SHERPA Result

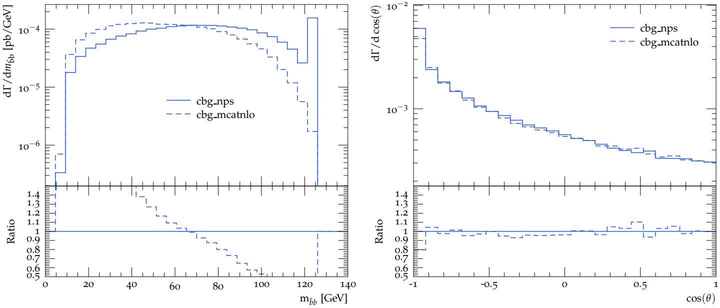

Figure 5: CbG

Validation: SHERPA Result

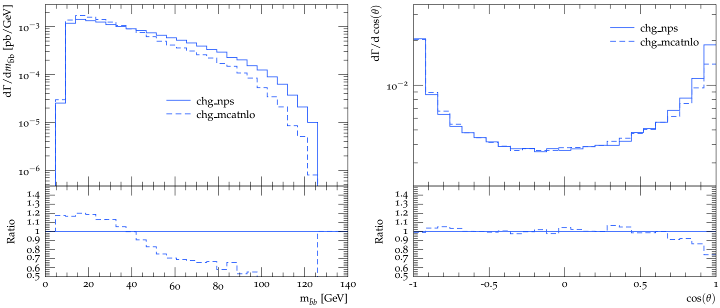

Figure 6: CHG

Validation: SHERPA Result

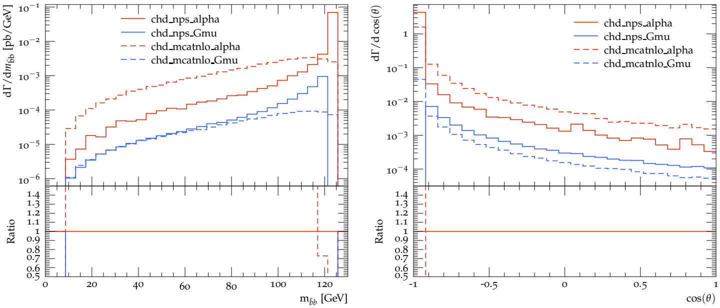

Figure 7: CHD

Validation: SHERPA Result with production

Process, $p\ p\ \rightarrow Z\ h\ \rightarrow \mu^+\mu^-\bar{b}b$.

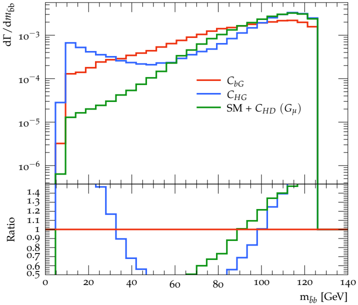

Figure 8: merged with production

Cuts: $m_{\mu^+\mu^-} \in (75, 100),\ p_T^{\mu} > 15,\ |\eta| < 2.5$

General: $h \to f\bar{f}; \quad f = b, c, \tau, \mu$

The QED and QCD corrections:

$$\Gamma^{(4,1)}_{f,(g,\gamma)} = \Gamma^{(4,0)}_{f} \left(\frac{\delta_{f,q} C_F \alpha_s + Q_f^2 \alpha}{\pi} \right) \left[\frac{17}{4} + \frac{3}{2} \ln\left(\frac{\mu^2}{m_H^2} \right) \right],$$

$$\Gamma^{(6,1)}_{f,(g,\gamma)} = \Gamma^{(6,0)}_{f} \frac{\Gamma^{(4,1)}_{f,(g,\gamma)}}{\Gamma^{(4,0)}_{f}} + \frac{\bar{v}^2}{\pi} \Gamma^{(4,0)}_{f} \left\{ \frac{m_H^2}{\sqrt{2} \bar{v} m_f} \left(\delta_{f,q} \frac{C_F}{g_s} \alpha_s C_{fG} + \frac{Q_f}{\bar{e}} \alpha \left(C_{fB} \hat{c}_w + 2 T_f^3 C_{fW} \hat{s}_w \right) \right) + \left(\delta_{f,q} C_F \alpha_s C_{HG} + Q_f^2 \alpha\, c_{h\gamma\gamma} \right) \times \left[19 - \pi^2 + \ln^2\left(\frac{\overline{m}_f^2}{m_H^2} \right) + 6 \ln\left(\frac{\mu^2}{m_H^2} \right) \right] + c_{h\gamma Z}\, v_f\, Q_f \alpha\, F_{h\gamma Z}\left(\frac{M_Z^2}{m_H^2}, \frac{\mu^2}{m_H^2}, \frac{\overline{m}_f^2}{m_H^2} \right) \right\},$$

JC and BP:[JHEP, vol. 11, p. 079, 2020.]

General: $h \to f\bar{f}$; $\quad f = b, c, \tau, \mu$

where $v_f = (T_f^3 - 2Q_f \hat{s}_w^2)/(2\hat{s}_w \hat{c}_w)$ is the vector coupling of f to the Z-boson, T_f^3 is the weak isospin of fermion f (i.e. $T_\tau^3 = -\frac{1}{2}$ and $T_c^3 = \frac{1}{2}$), $\delta_{f,q} = 1$ if f is a quark and $\delta_{f,q} = 0$ if f is a lepton, $C_F = (N_c^2 - 1)/(2N_c)$ with $N_c = 3$.
The combinations of Wilson coefficients are:

$$
\begin{aligned}
c_{h\gamma\gamma} &= C_{HB}\hat{c}_w^2 + C_{HW}\hat{s}_w^2 - C_{HWB}\hat{c}_w\hat{s}_w \,, \\
c_{h\gamma Z} &= 2(C_{HB} - C_{HW})\hat{c}_w\hat{s}_w + C_{HWB}(\hat{c}_w^2 - \hat{s}_w^2) \,.
\end{aligned}
$$

$$
F_{h\gamma Z}\left(z, \hat{\mu}^2, 0\right) = -12 + 4z - \frac{4}{3}\pi^2\bar{z}^2 + \left(3 + 2z + 2\bar{z}^2\ln(\bar{z})\right)\ln(z) + 4\bar{z}^2\mathrm{Li}_2(z) - 6\ln(\hat{\mu}^2) \,,
$$

where $\bar{z} = 1 - z$.

JC and BP:[JHEP, vol. 11, p. 079, 2020.]

Conclusion

- Substantial progress has been made in NLO-SMEFT calculations over the past few years.
- For some processes it has been already implemented in MADGRAPH.
- We are currently implementing SMEFT-NLO (QCD & EW) Higgs decaying to fermion pair processes in SHERPA.
- Some of the cross-check and validation have been performed.

Future Plan

- We are planning to implement the same in case of the Drell-Yan process.

Suggestions for any other interesting processes are welcome!

Thanks for listening.

Backup

The differential decay rate to NLO is obtained by evaluating the expression

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where

$$\mathcal{M}^{(0)}_{b,L} = \frac{m_b}{v_T}\left[1 + C_{H,\mathrm{kin}}\right] - \frac{v_T^2}{\sqrt{2}} C_{bH} .$$

JC, BP, and DS:[JHEP, vol. 08, p. 173, 2019]

Renormalisation

The counterterm amplitude can be constructed, and is generally written as

$$\mathcal{M}^{\mathrm{C.T.}}(h \to b\bar{b}) = -\bar{u}(p_b)\left(\delta\mathcal{M}_L P_L + \delta\mathcal{M}_L^* P_R\right) v(p_{\bar{b}})\,.$$

The expression for the (real) SM counterterm is

$$\delta\mathcal{M}_L^{(4)} = \frac{m_b}{v_T}\left(\frac{\delta m_b^{(4)}}{m_b} + \delta Z_b^{(4)}\right)\,,$$

and the corresponding dimension-6 counterterm is

$$\delta\mathcal{M}_L^{(6)} = \left(\frac{m_b}{v_T} C_{H,\mathrm{kin}}\right)\left(\frac{\delta m_b^{(4)}}{m_b} + \delta Z_b^{(4)}\right) - \frac{v_T^2}{\sqrt{2}}\left(\delta C_{bH} + C_{bH}\delta Z_b^{(4)}\right) + \cdots$$

JC, BP, and DS:[JHEP, vol. 08, p. 173, 2019]