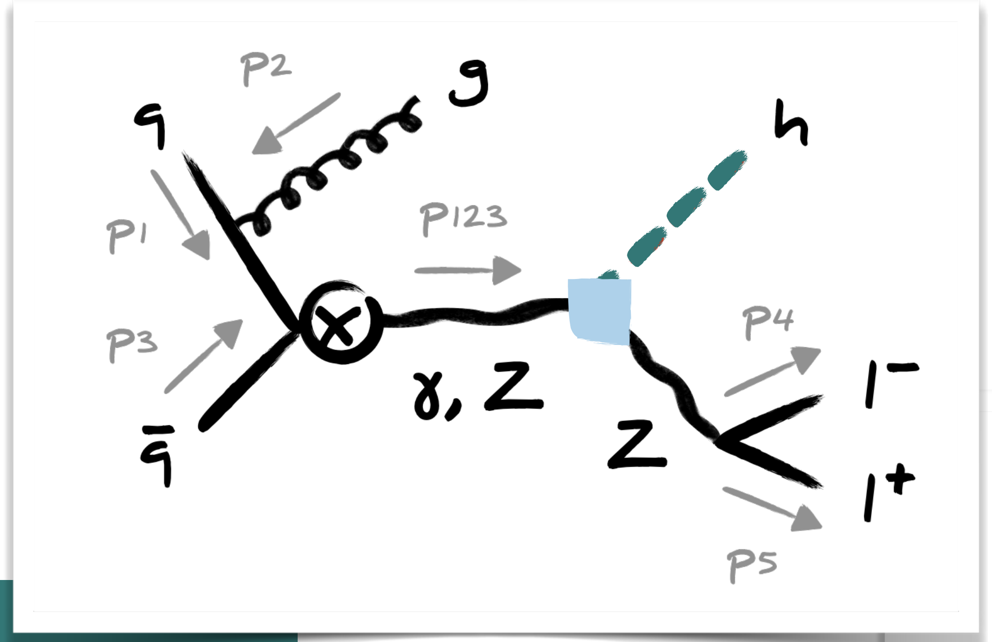
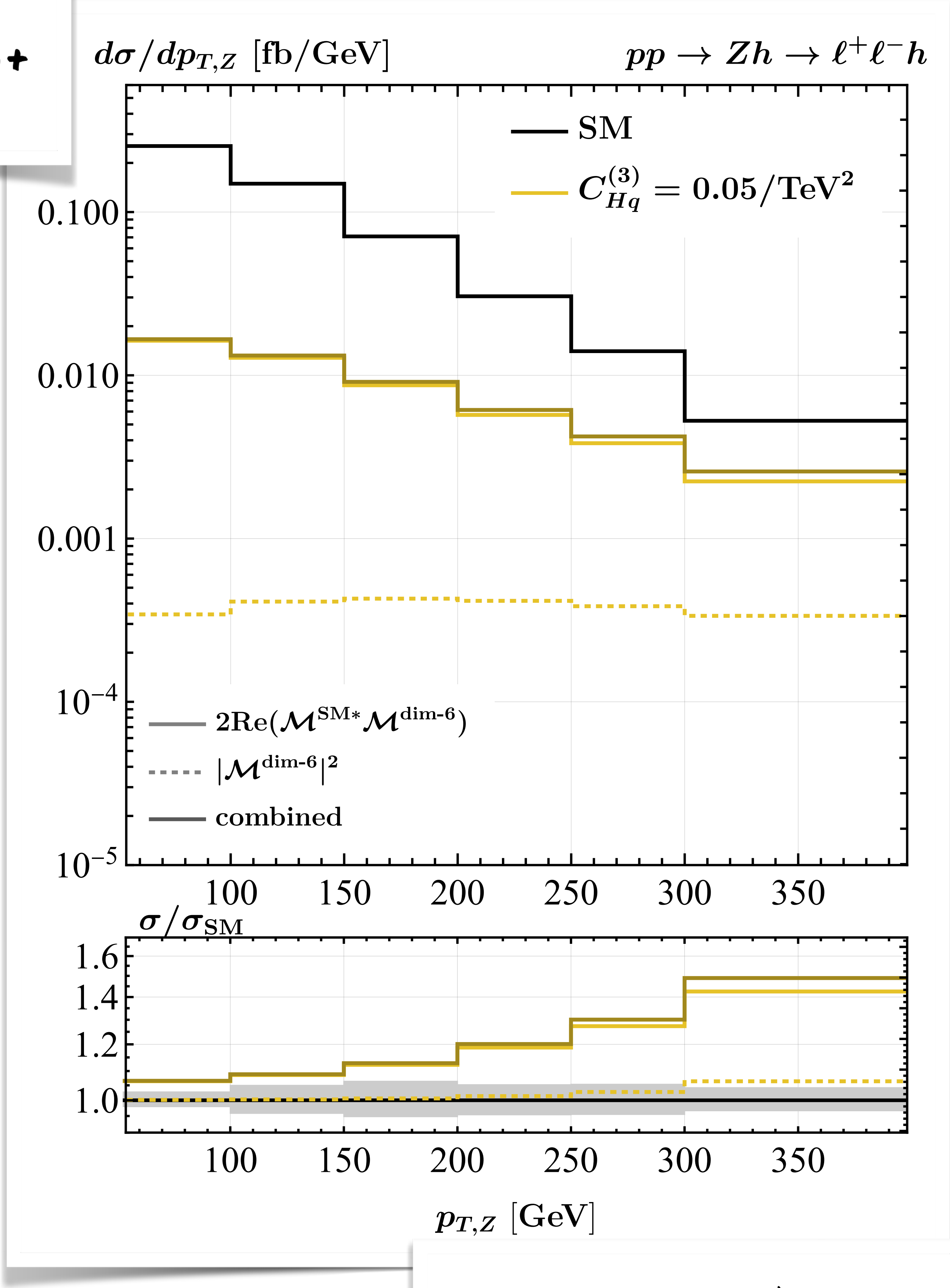
SMEFT at NNLO+PS: Vh production

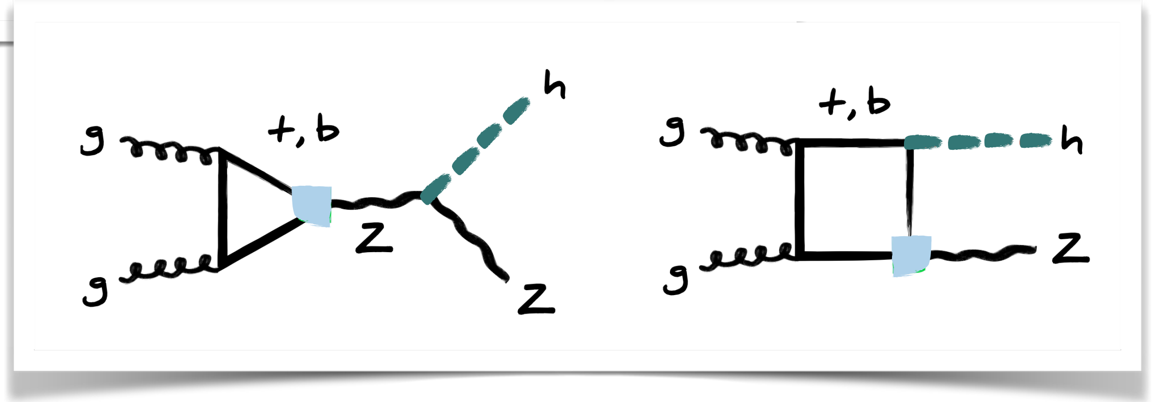
Luc Schnell

20th Workshop of the LHC Higgs Working Group

November 15, 2023







Based on:

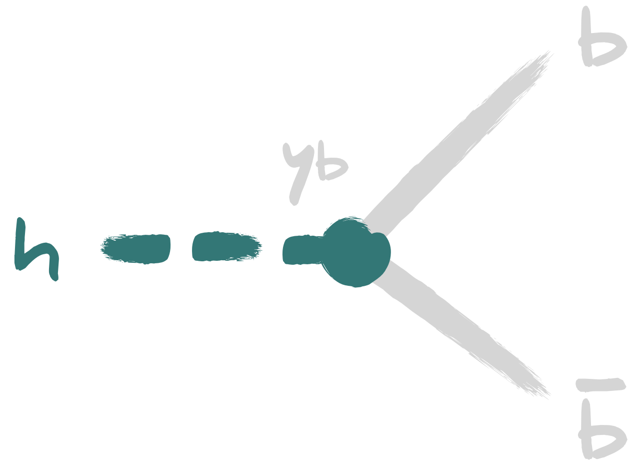
R. Gauld, U. Haisch, LS: *SMEFT at NNLO+PS: Vh production.* [2311.06107].

1. Introduction

1. Introduction

1.1 The importance of Higgsstrahlung

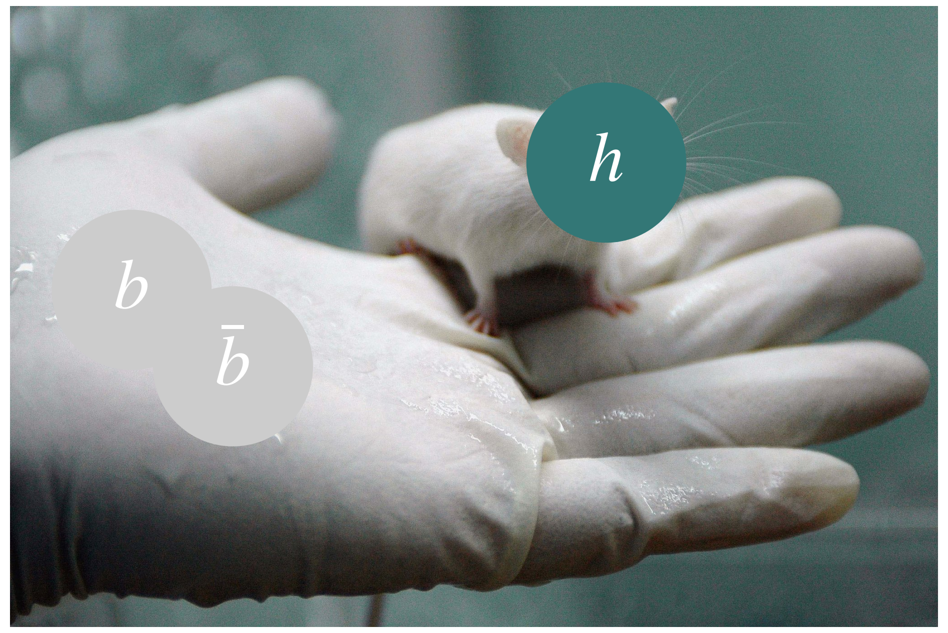
Goal:



Measure Higgs couplings (e.g. y_b) to appreciable precision.

SM: $y_b = \frac{\sqrt{2}\, m_b}{v}$ $\rightarrow$ any deviation is a clear sign for NP.

Currently: $\mu_{h \to b\bar{b}} = 1.01 \pm 0.20$ $\rightarrow$ HL-LHC is projected to push this down to ± 0.05 [1,2].



Source: nytimes.com.

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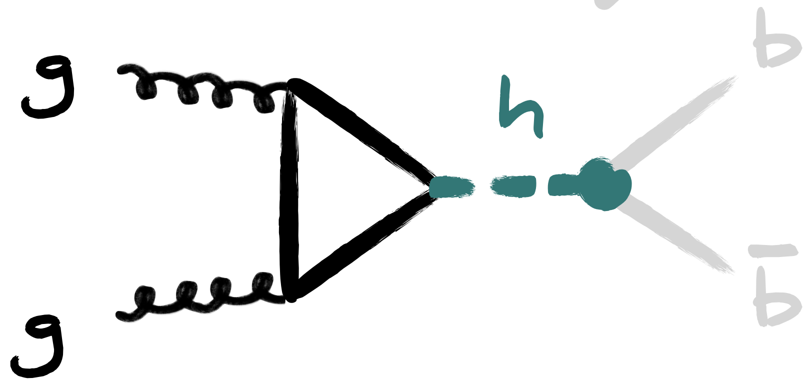
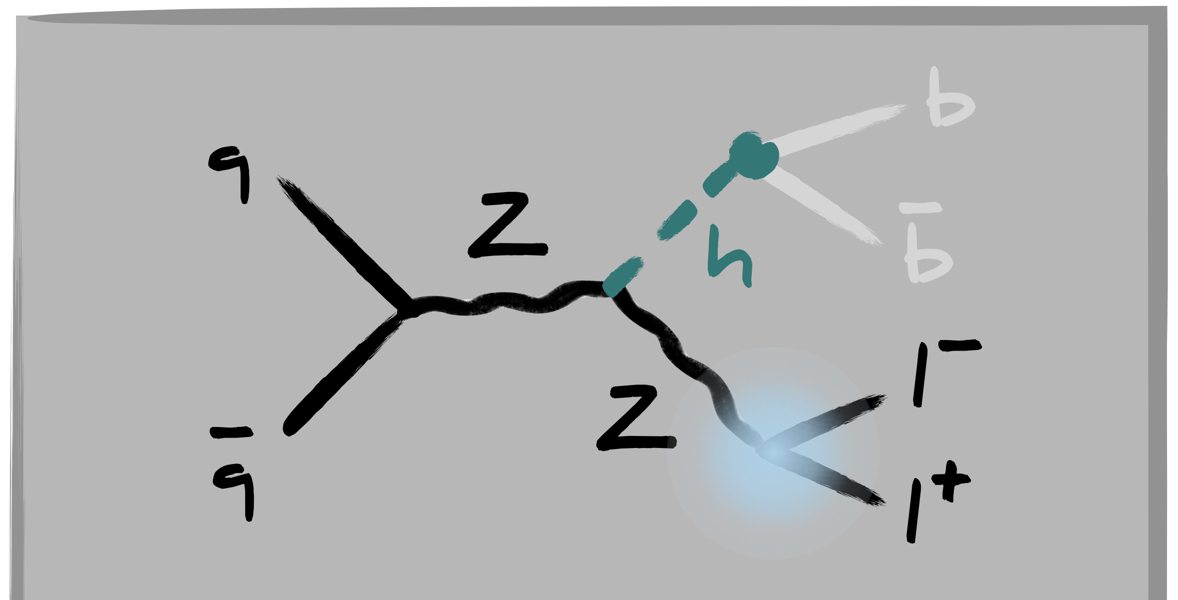
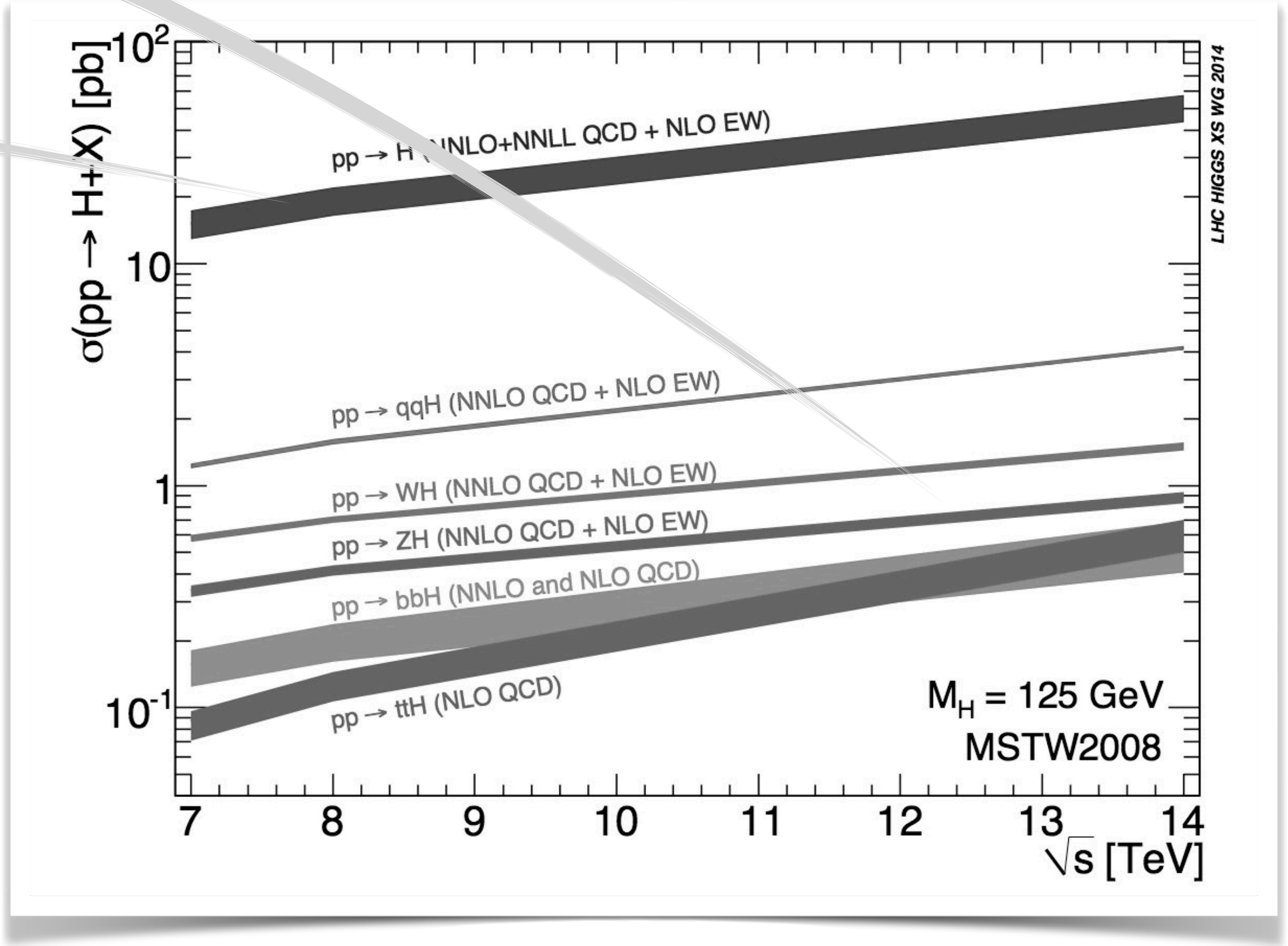


(ggF)



(Vh)



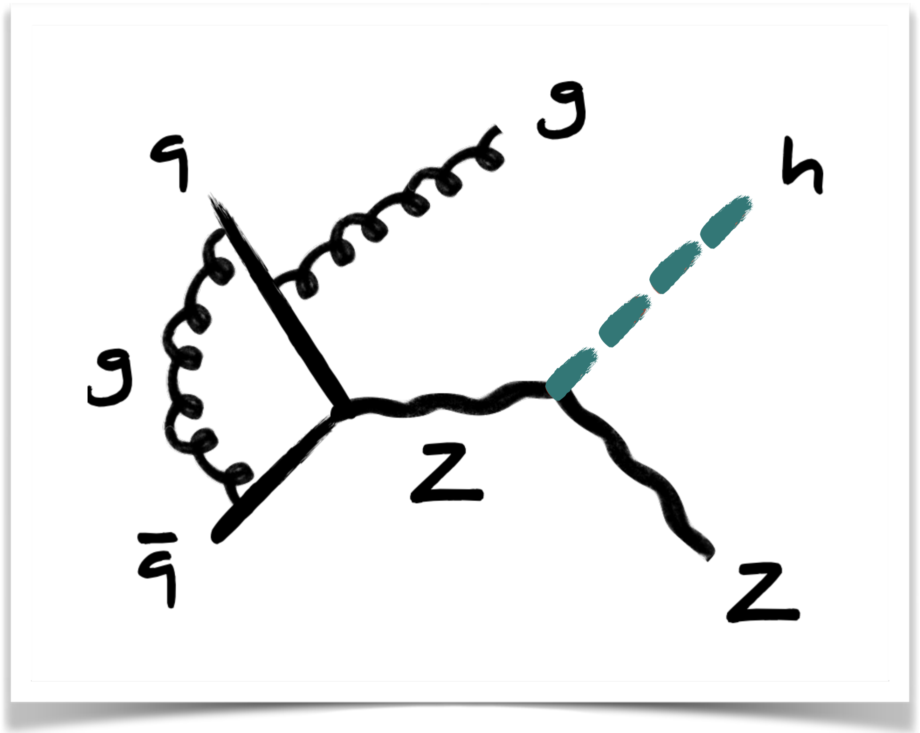
Source: LHC Higgs WG.

Sources: [1] ArXiv:1808.08238 (ATLAS), [2] ArXiv:1808.08242 (CMS).

1. Introduction

1.1 Theoretical predictions (SM)

In the SM, the higher-order QCD corrections to **Vh at NNLO+PS** are well-known [1,2,3].



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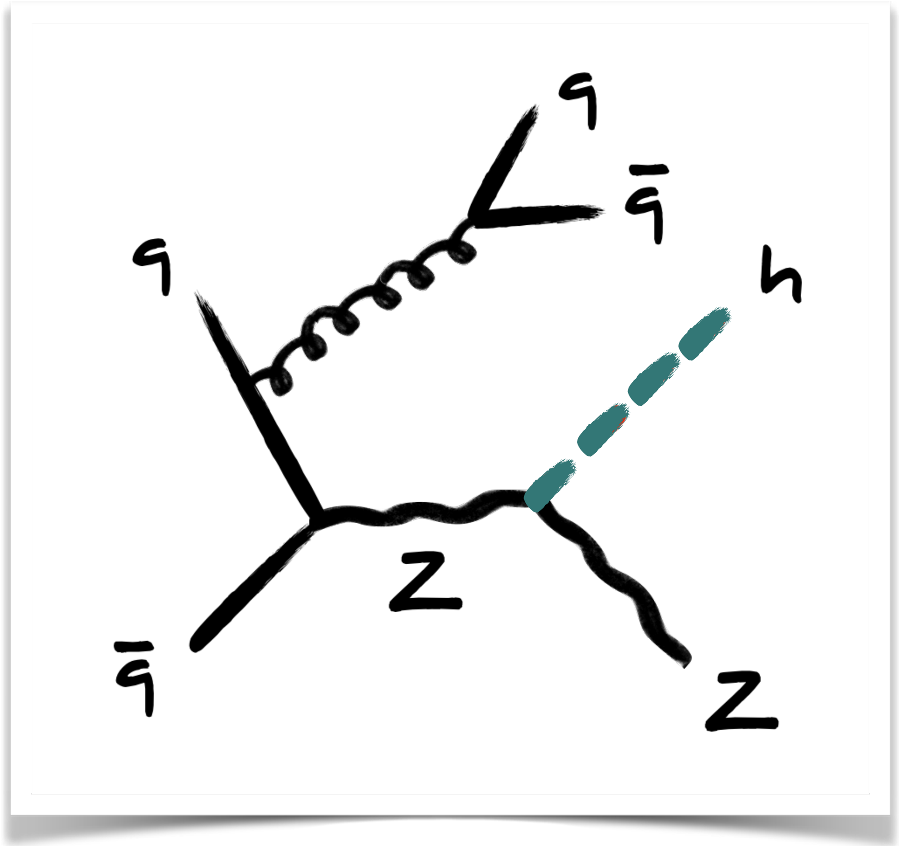

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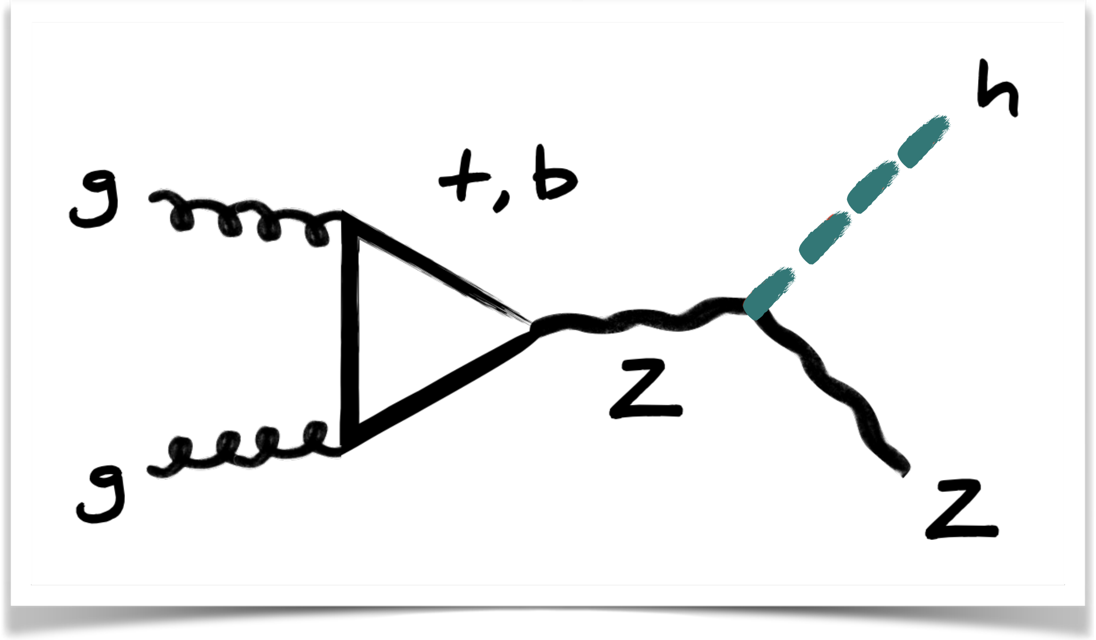


(A-type)

A dedicated Monte Carlo event generator has for example been made available in the **POWHEG MiNNLO$_{\mathbf{PS}}$** framework [4].

Sources: [1] DOI:10.1007/BF01679868 (G. Kramer, B. Lampe), [2] DOI:10.1016/0550-3213(91)90064-5 (R. Hamberg, W.L. van Neerven, T. Matsuura), [3] ArXiv:1112.1531 (T. Gehrmann, L. Tancredi), [4] ArXiv:2112.04168 (S. Zanoli, M. Chiesa, E. Re, M. Wiesemann, G. Zanderighi), [5] ArXiv:2209.06138 (J. Baglio, C. Duhr, B. Mistlberger, R. Szafron).

1. Introduction

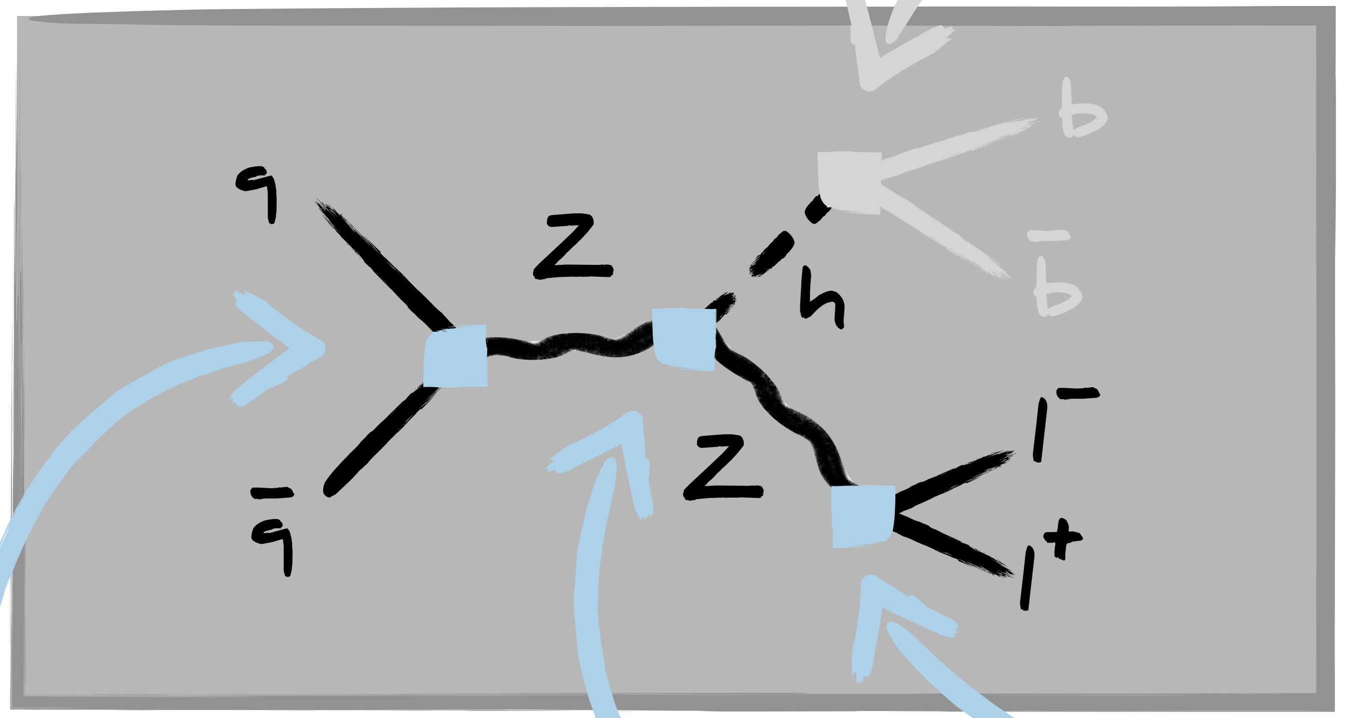
1.2 Theoretical predictions (BSM)

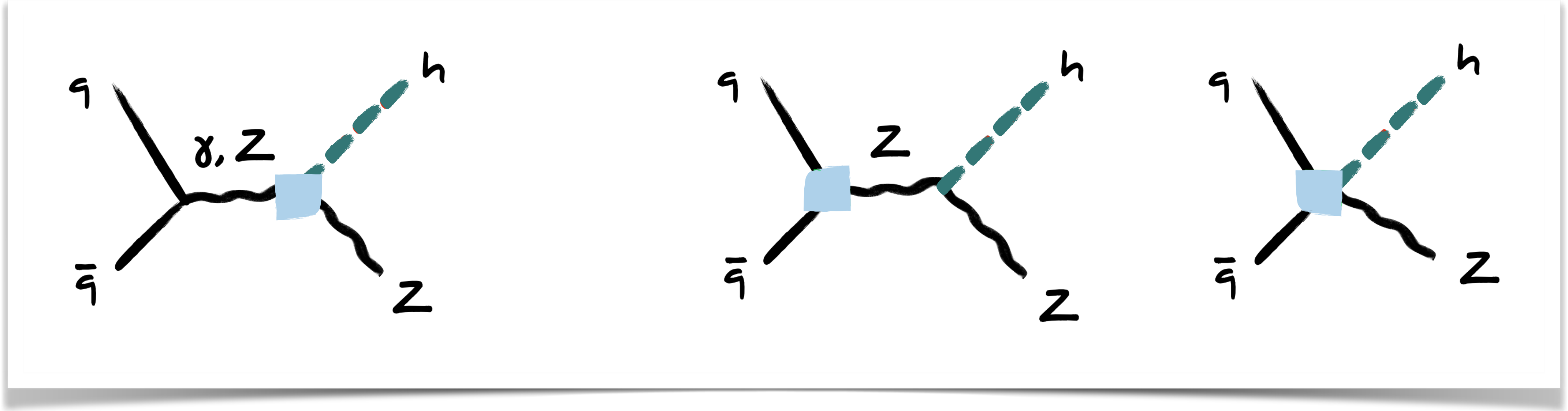
What about **new effects**?

QCD operators

$$Q_{bG} = \frac{g_s^3}{(4\pi)^2}\, y_b\, \bar{q}_L \sigma_{\mu\nu} T^a b_R H\, G^{a,\mu\nu}$$

Have **already been considered** in ref. [1].





$$Q_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$$

$$Q_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$$

V(h)qq

$$Q_{HW} = H^\dagger H\, W^a_{\mu\nu} W^{a,\mu\nu}$$

$$Q_{HWB} = H^\dagger \sigma^a H\, W^a_{\mu\nu} B^{\mu\nu}$$

VVh

$$Q_{H\ell}^{(3)} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{\ell}\gamma^\mu \tau^a \ell)$$

$$Q_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$$

V(h)ll

Sources: [1] ArXiv:2204.00663 (U. Haisch, D.J. Scott, M. Wiesemann, G. Zanderighi, S. Zanoli).

2. Details of the calculation

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2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?

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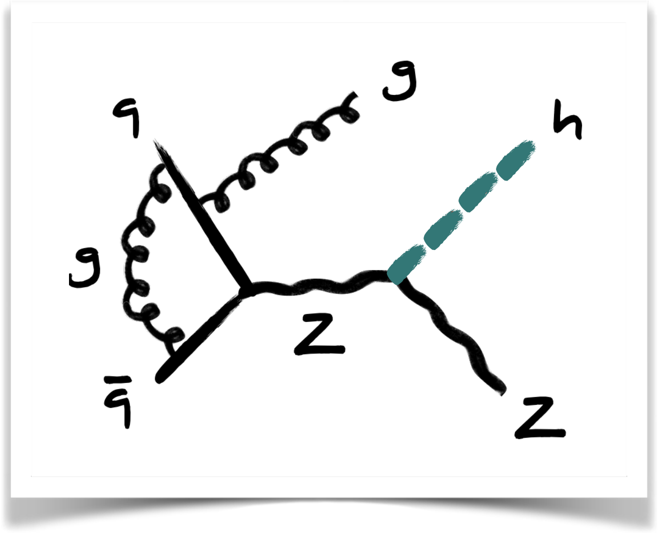

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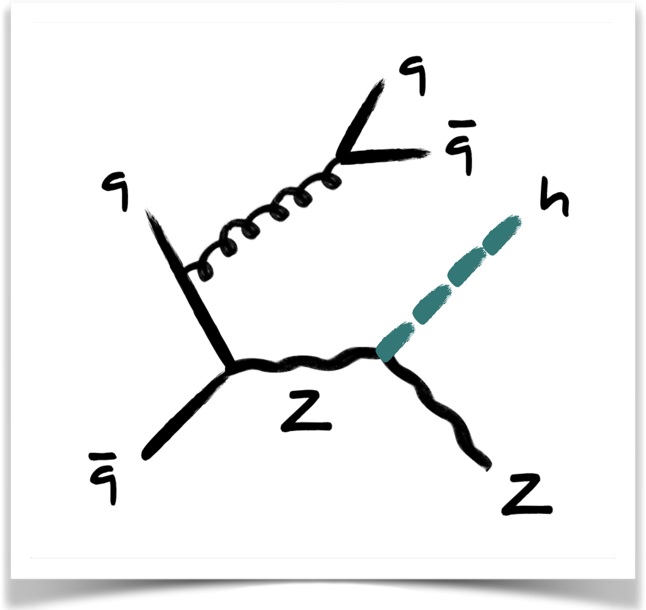

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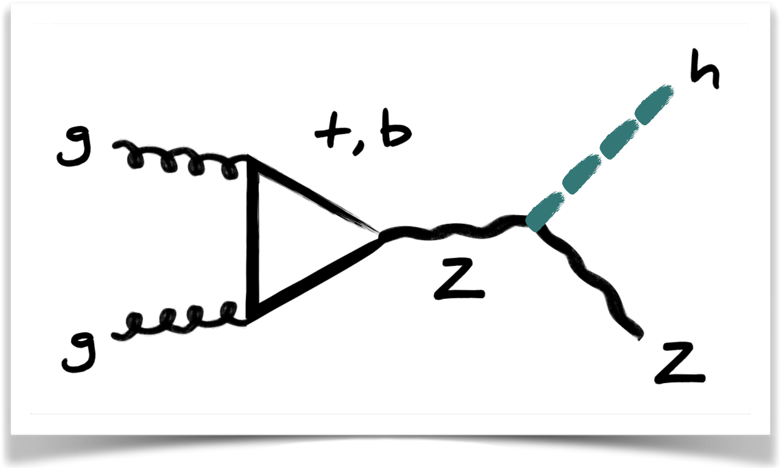

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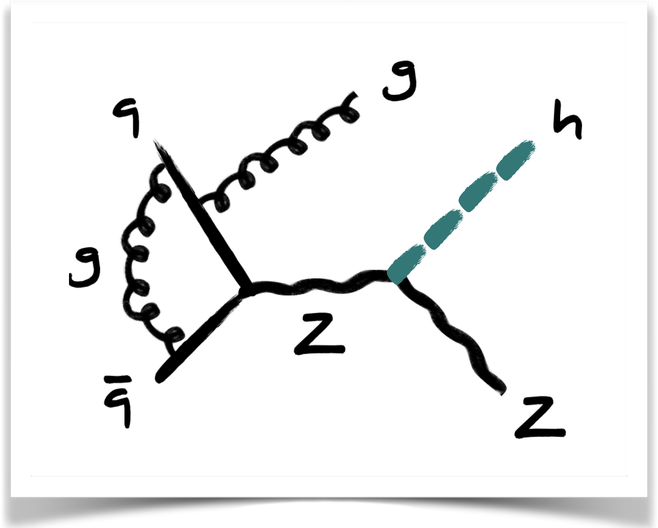

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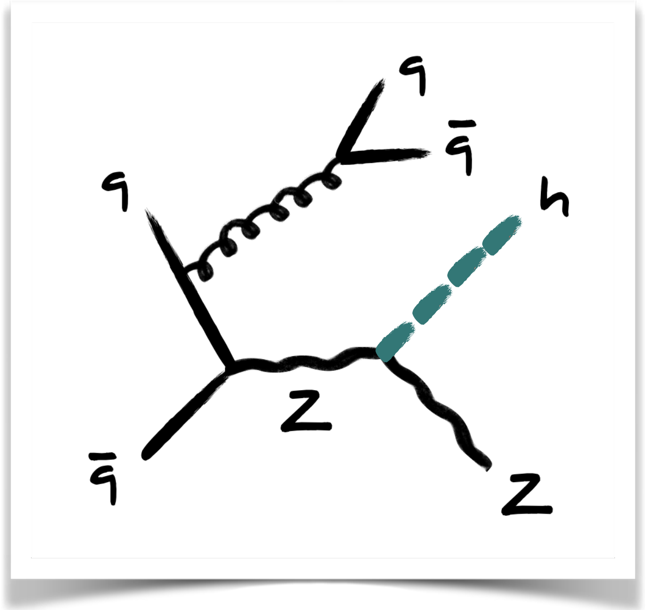

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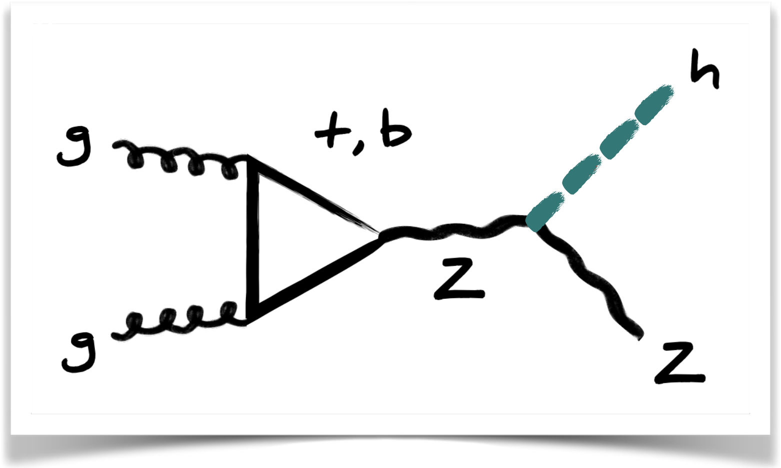

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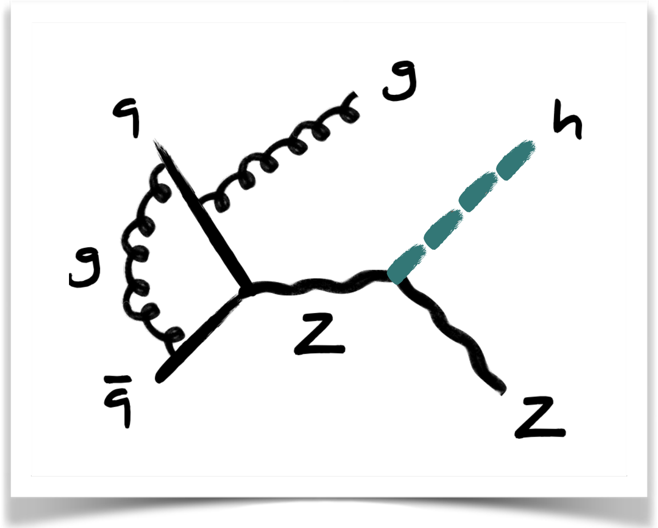

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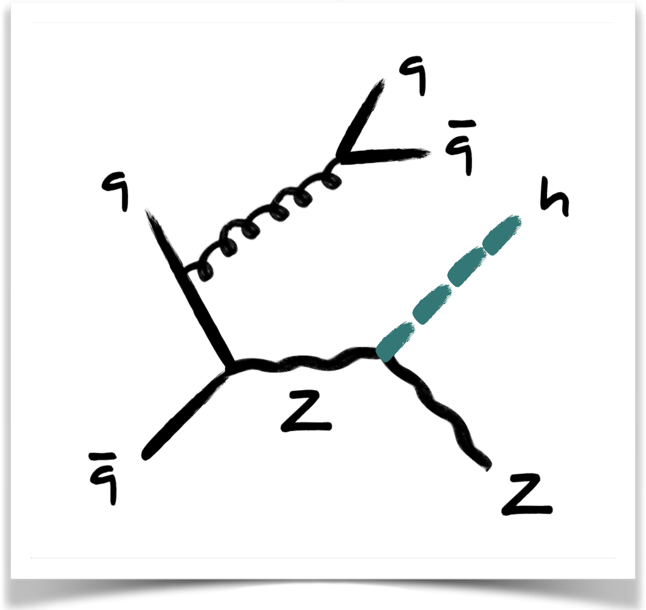

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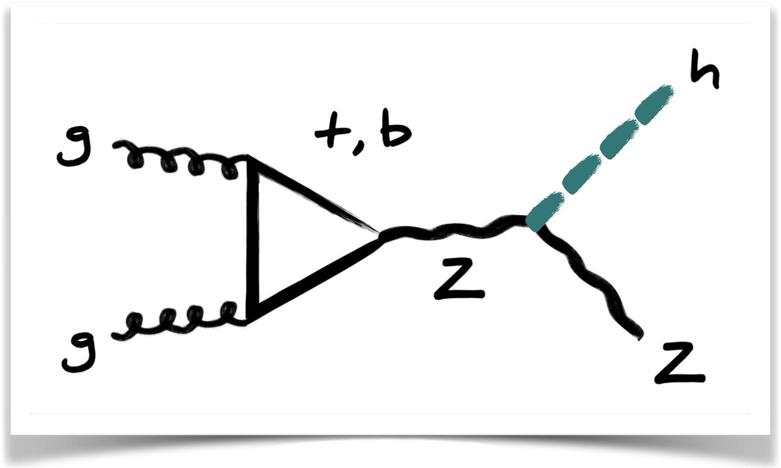

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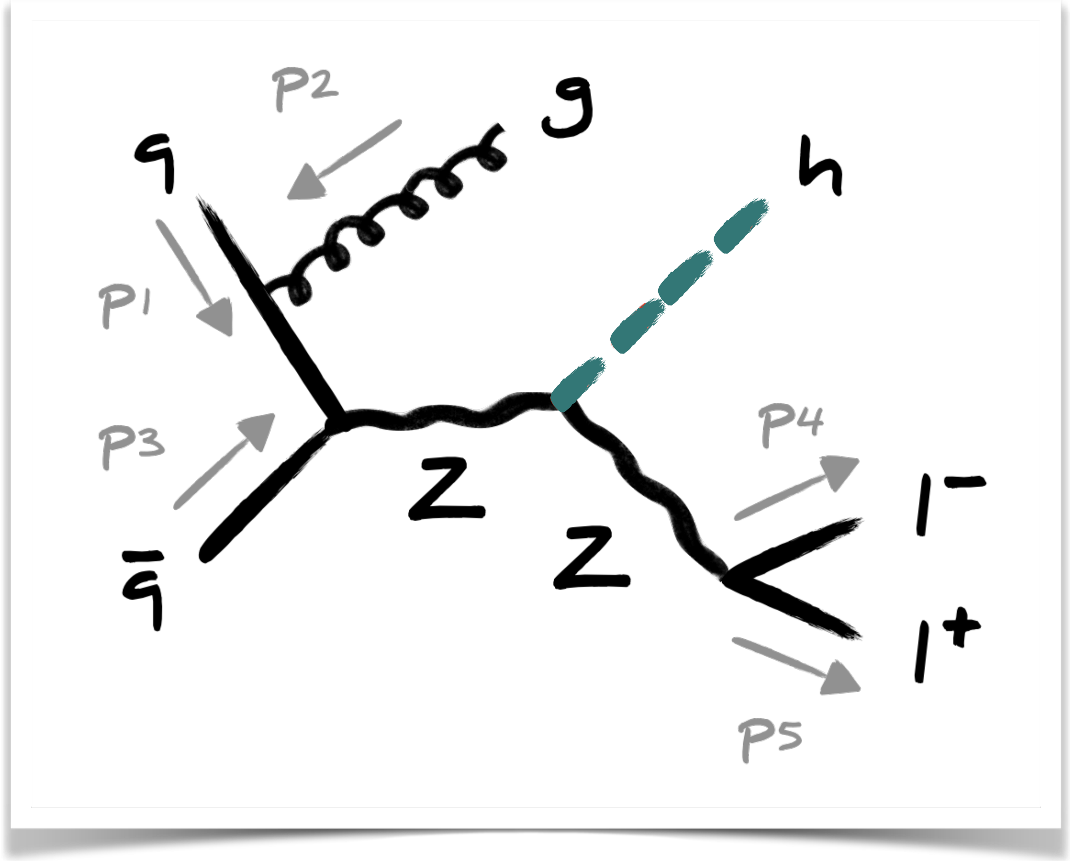

(B1g0Z)

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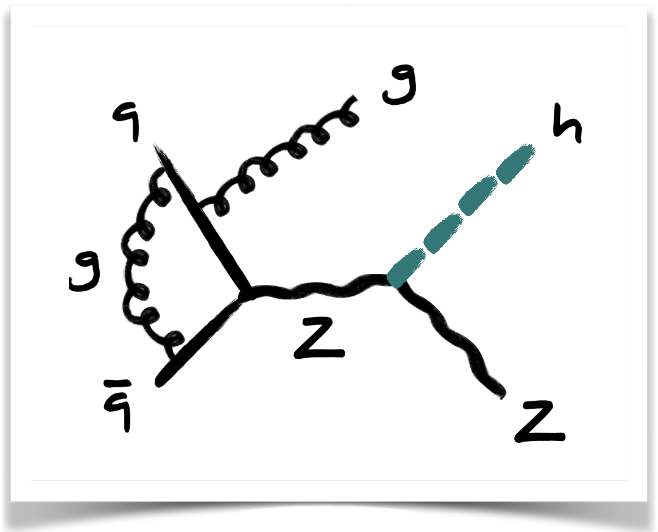

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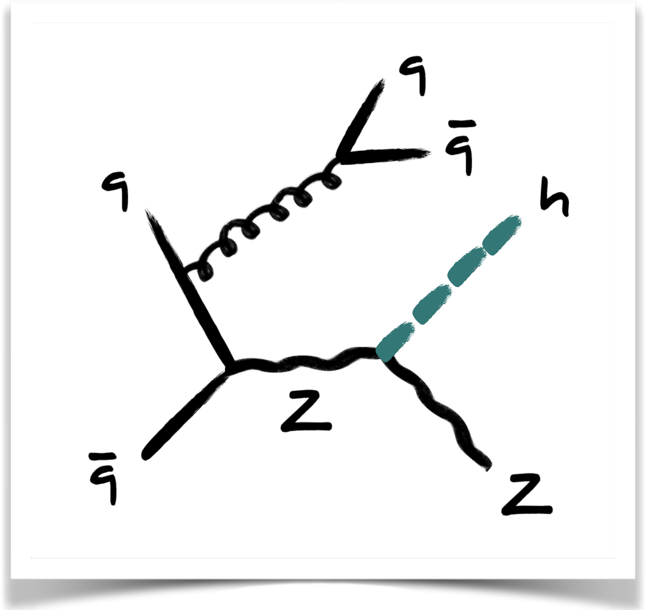

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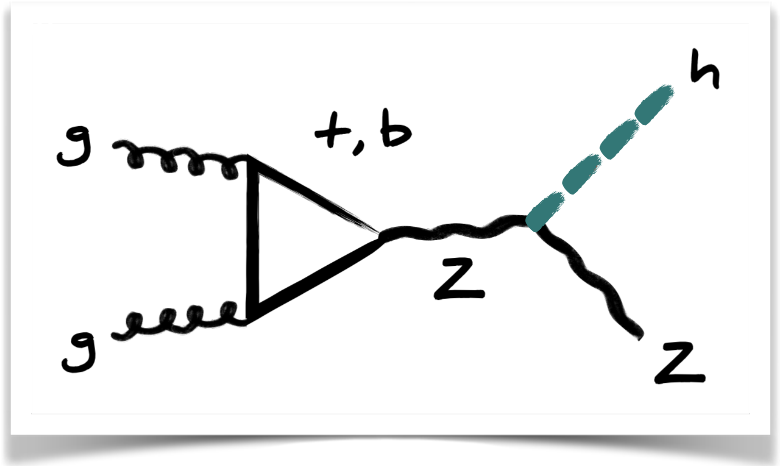

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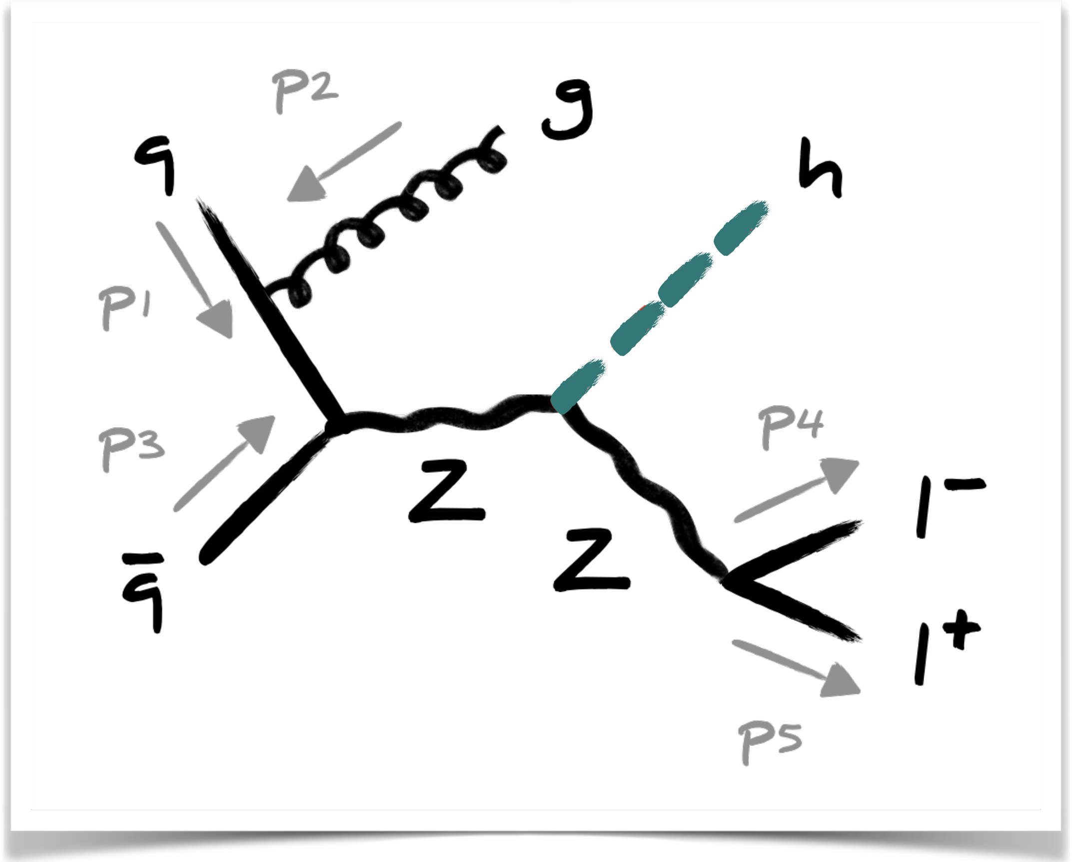
$$\mathcal{A}_{\mathrm{B1g0Z}}\left(1_q^-, 2_g^-, 3_{\bar{q}}^+; 4_\ell^-, 5_{\bar{\ell}}^+\right) = \frac{\langle 34\rangle}{\langle 12\rangle\langle 23\rangle}\left(\langle 13\rangle\,[51] + \langle 23\rangle\,[52]\right),$$



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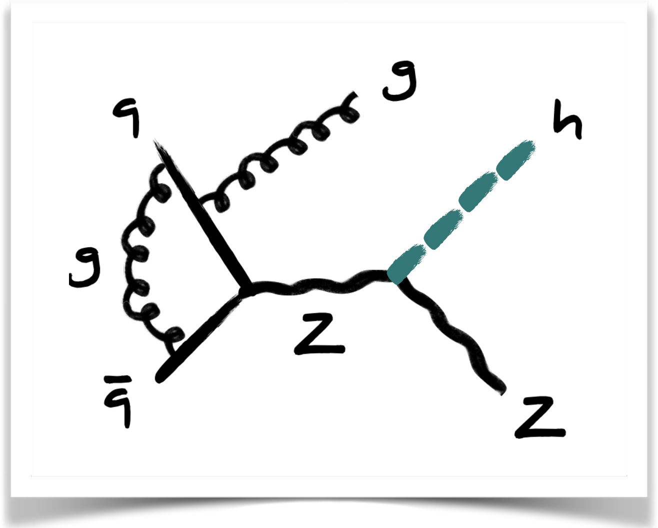

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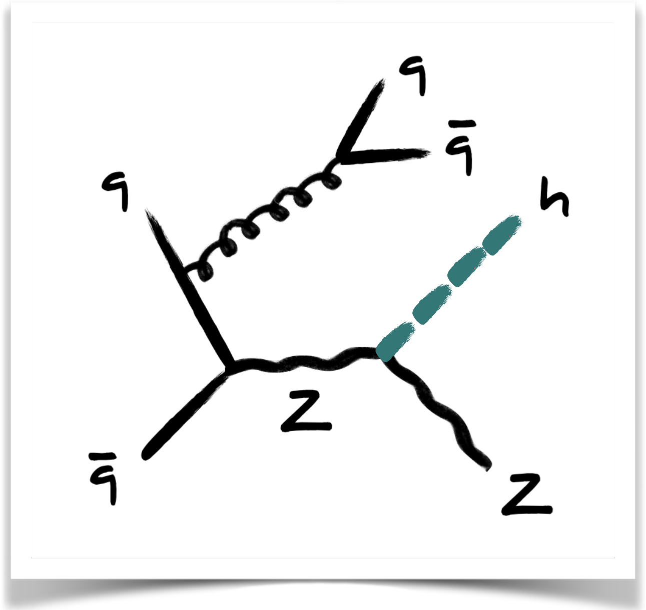

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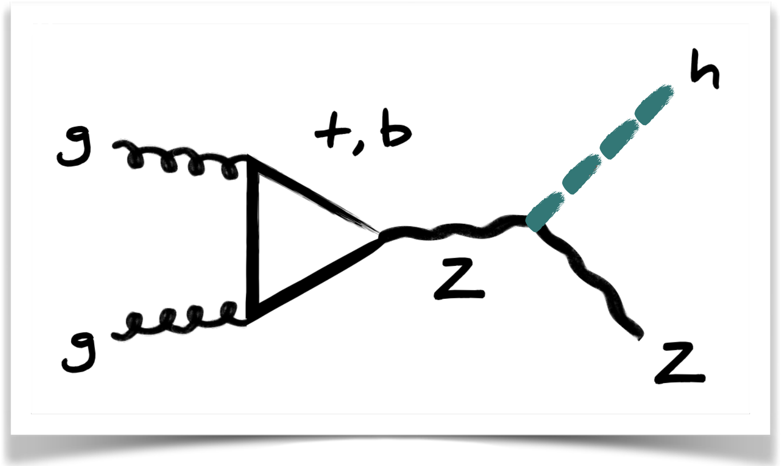

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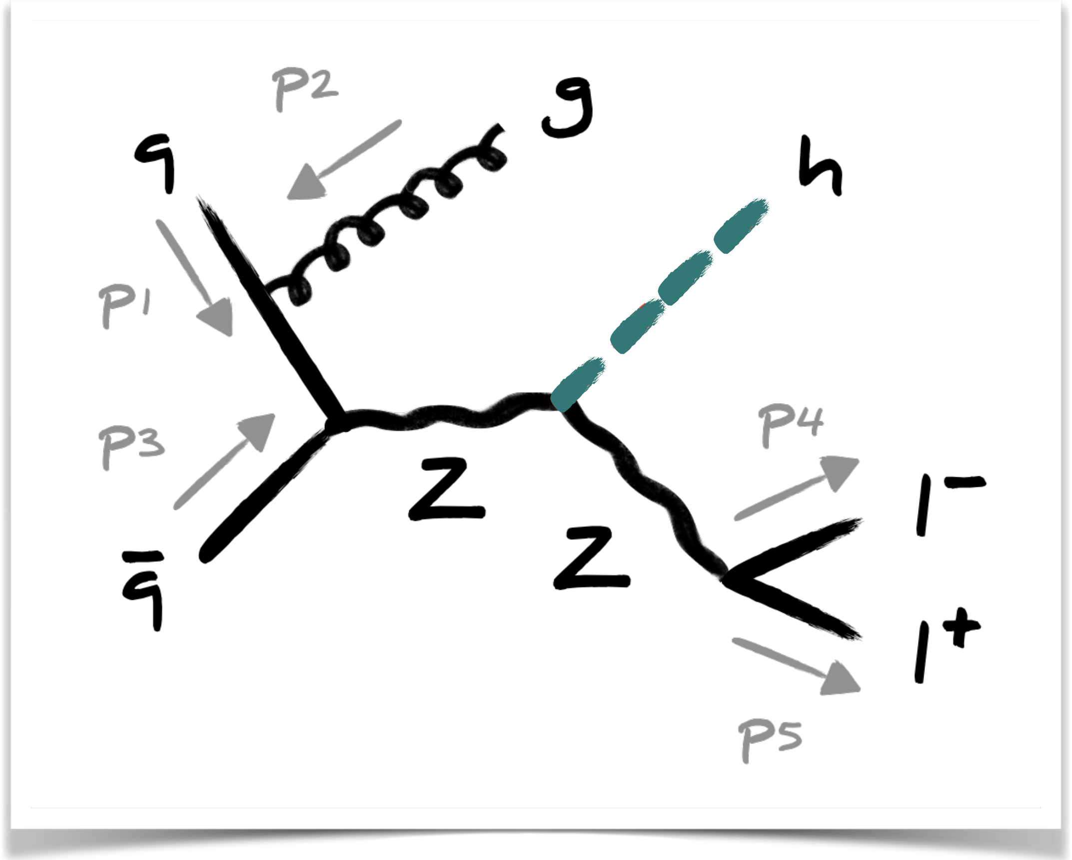

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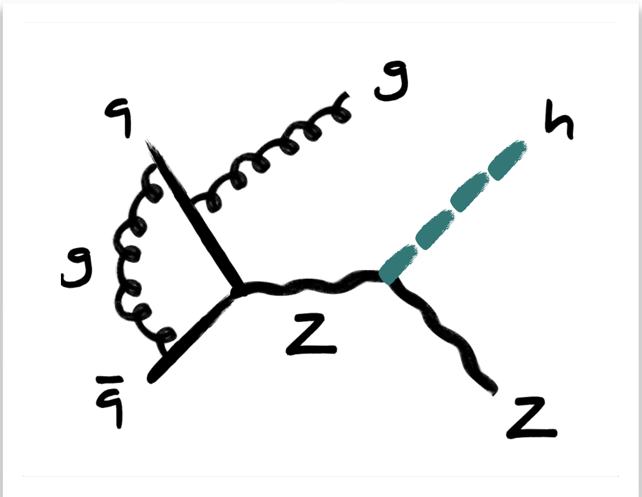

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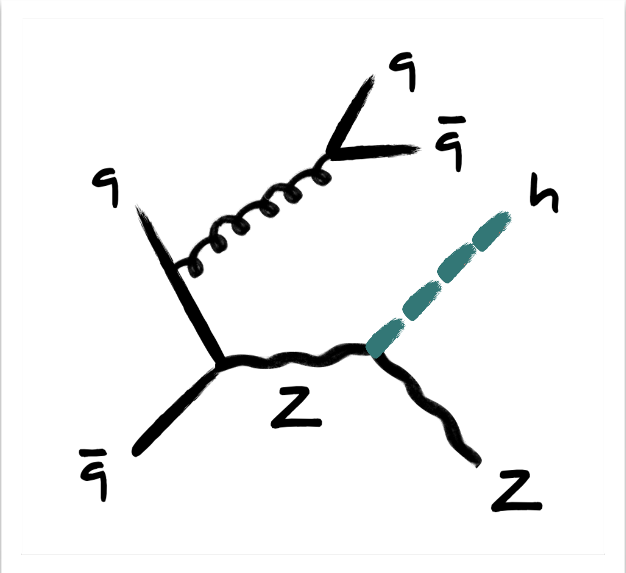

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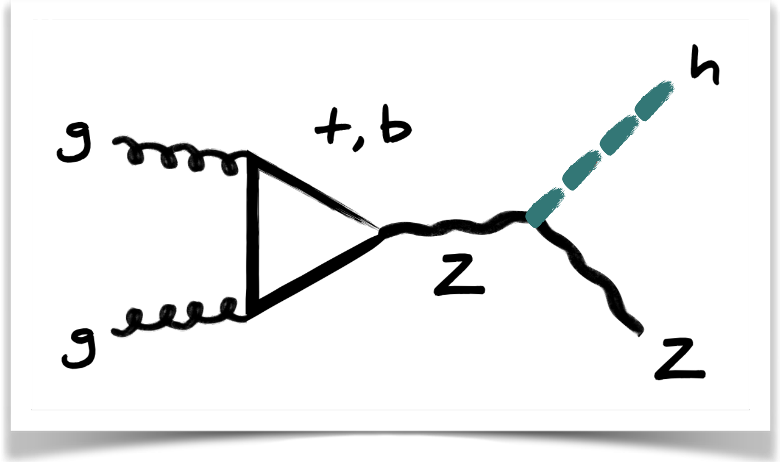

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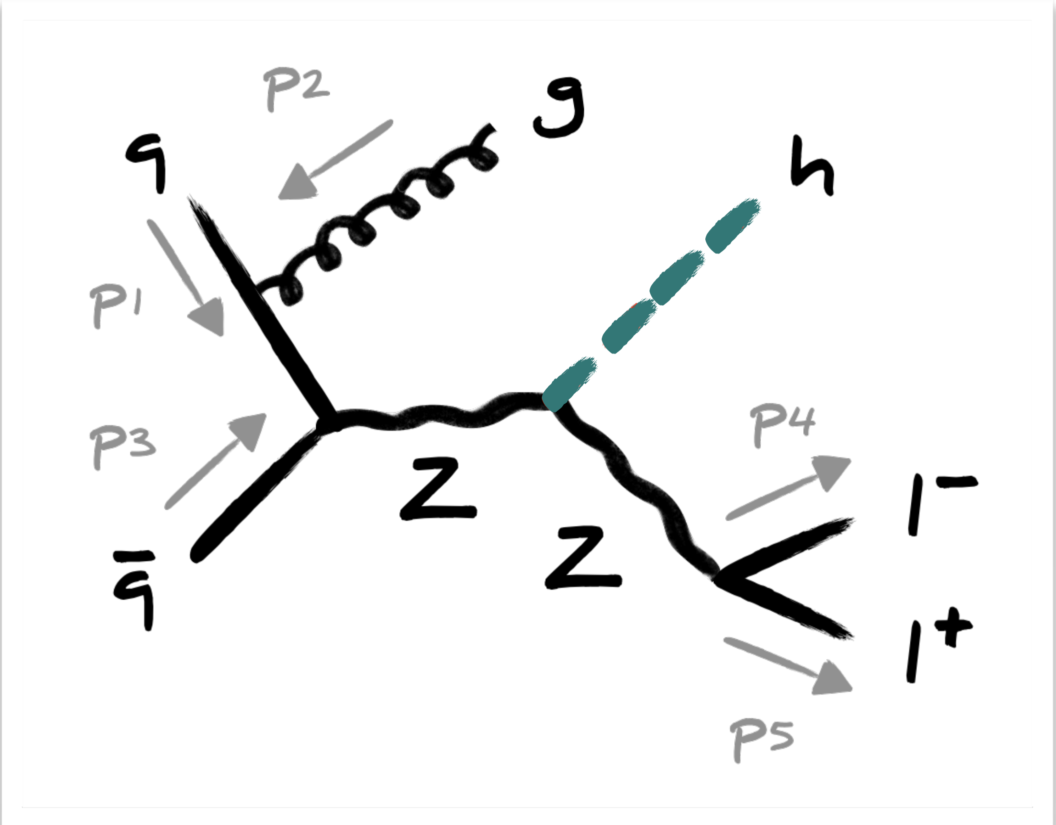

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$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A}\sum_{h_q,h_g,h_\ell=\pm}\left|\frac{g_{Zq}^{h_q}\,g_{Z\ell}^{h_\ell}\,g_{hZZ}}{D_Z(s_{123})\,D_Z(s_{45})}\,\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q},2_g^{h_g},3_{\bar{q}}^{-h_q};4_\ell^{h_\ell},5_{\bar{\ell}}^{-h_\ell}\right)\right|^2,$$

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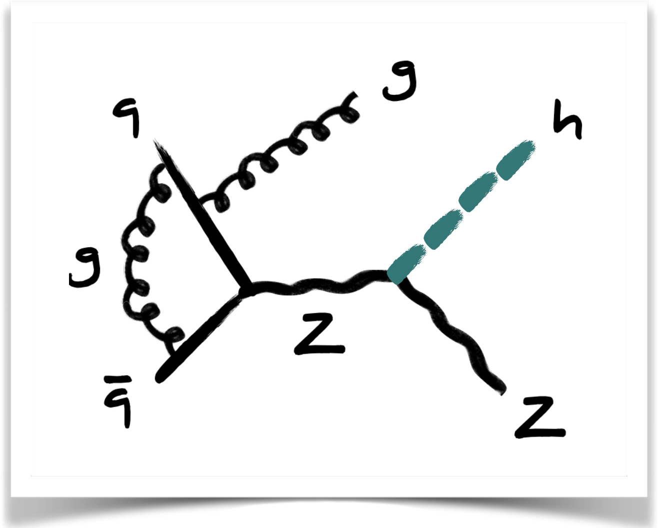

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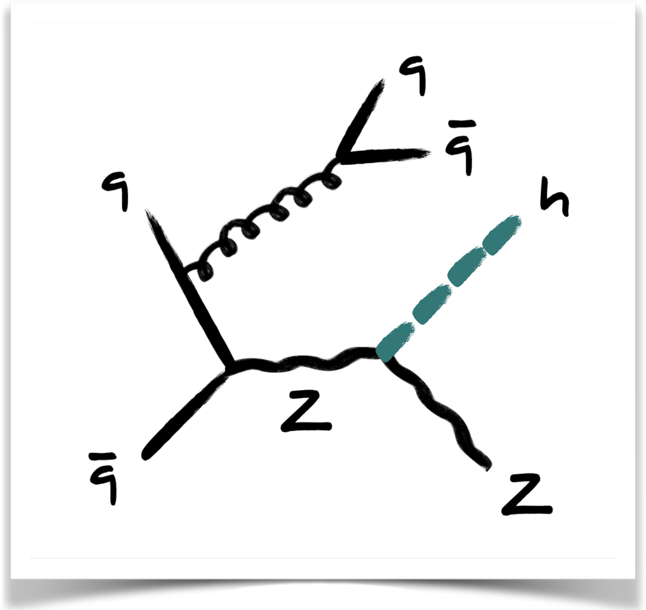

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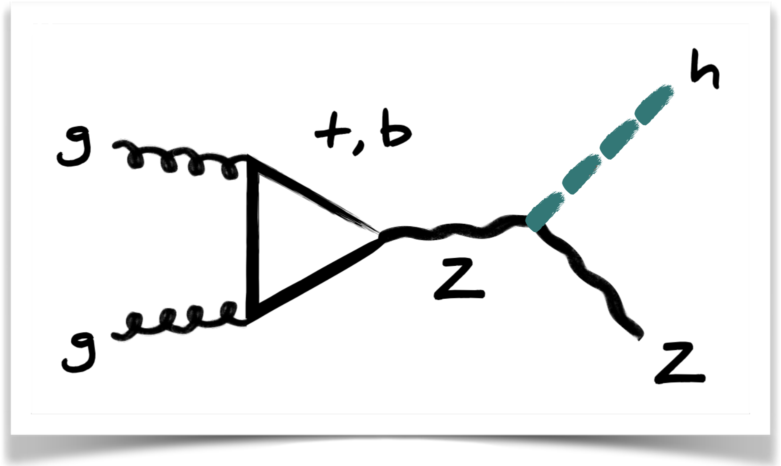

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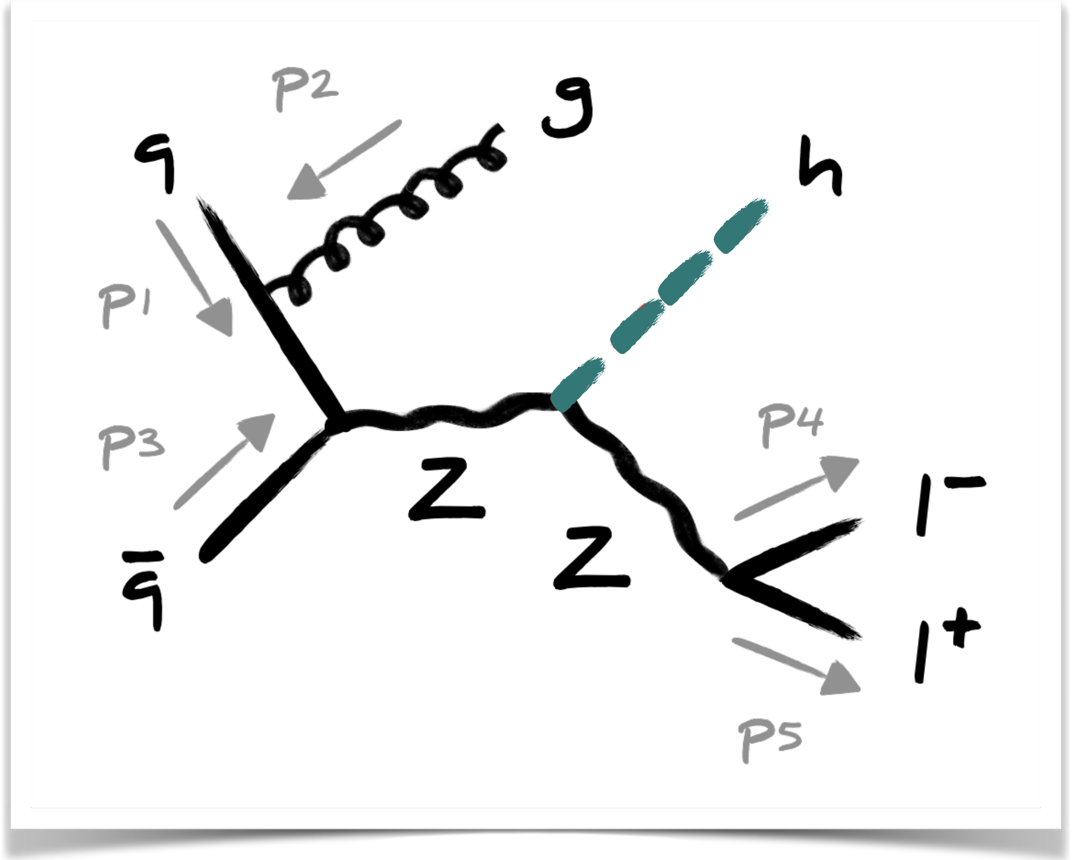

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→

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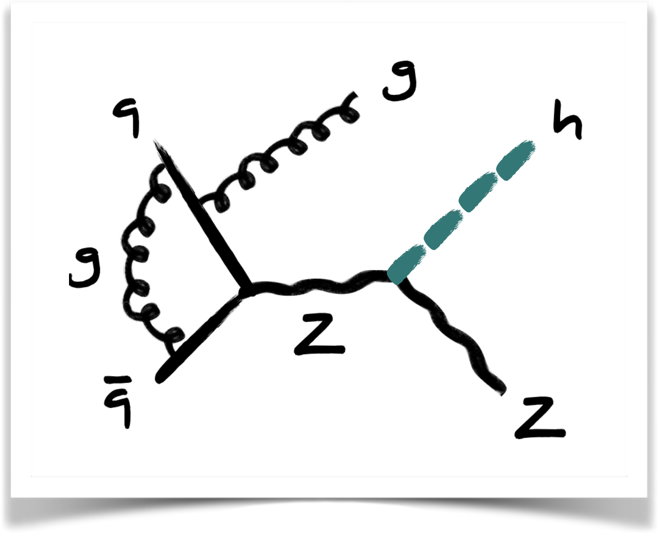

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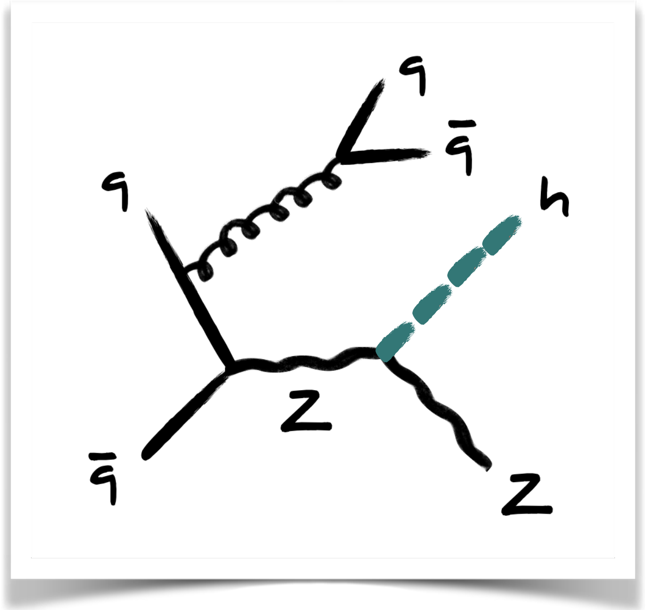

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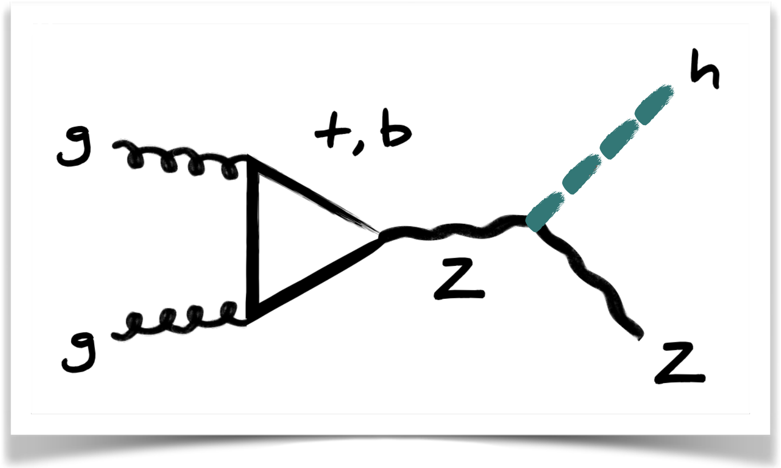

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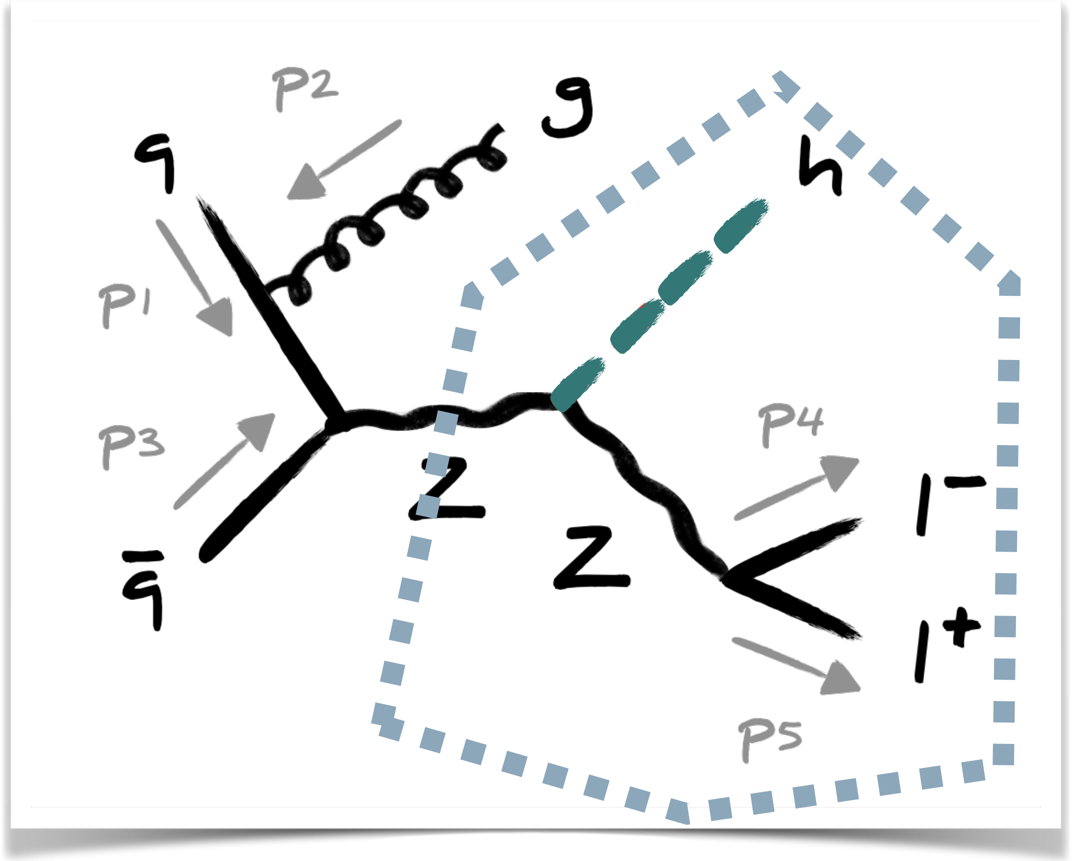

(B1g0Z)

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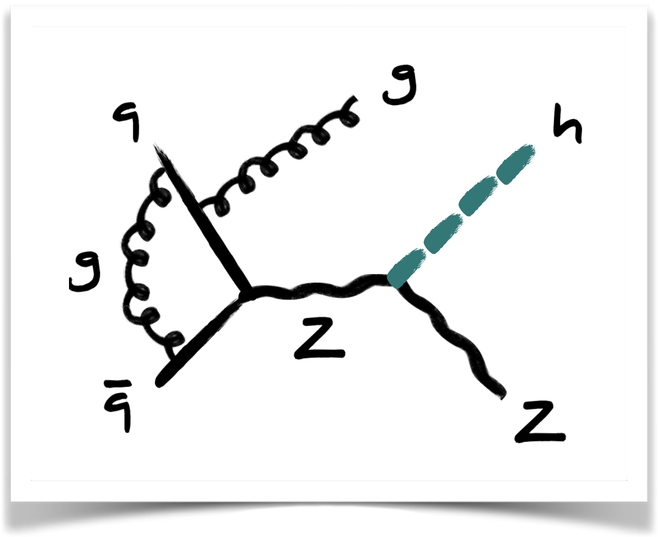

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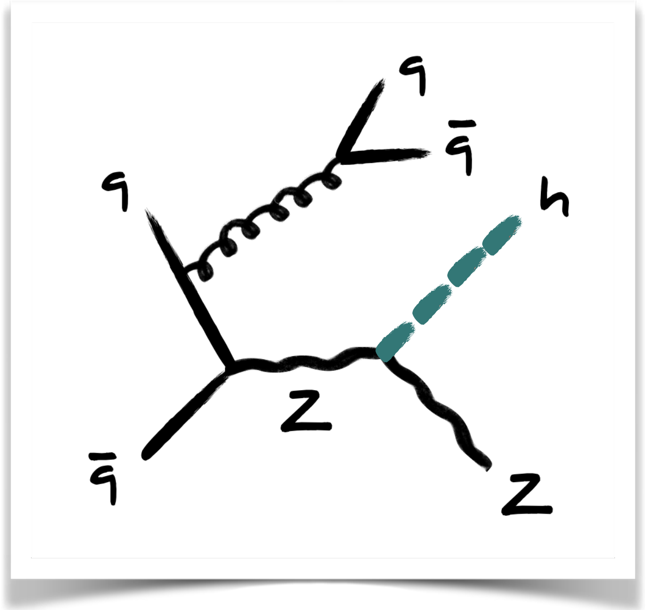

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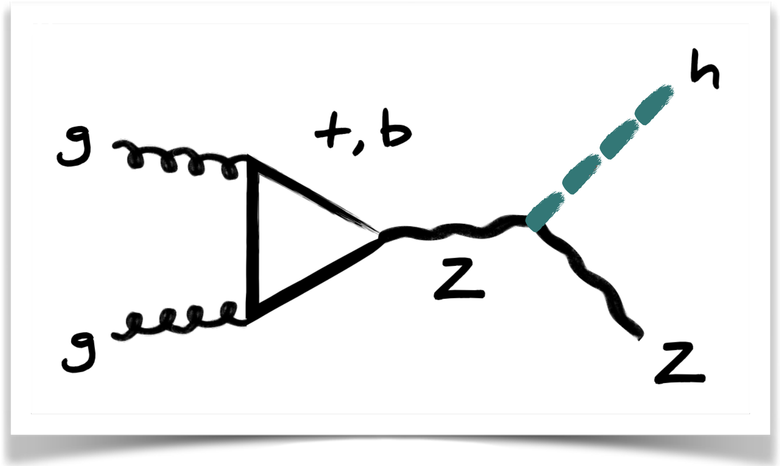
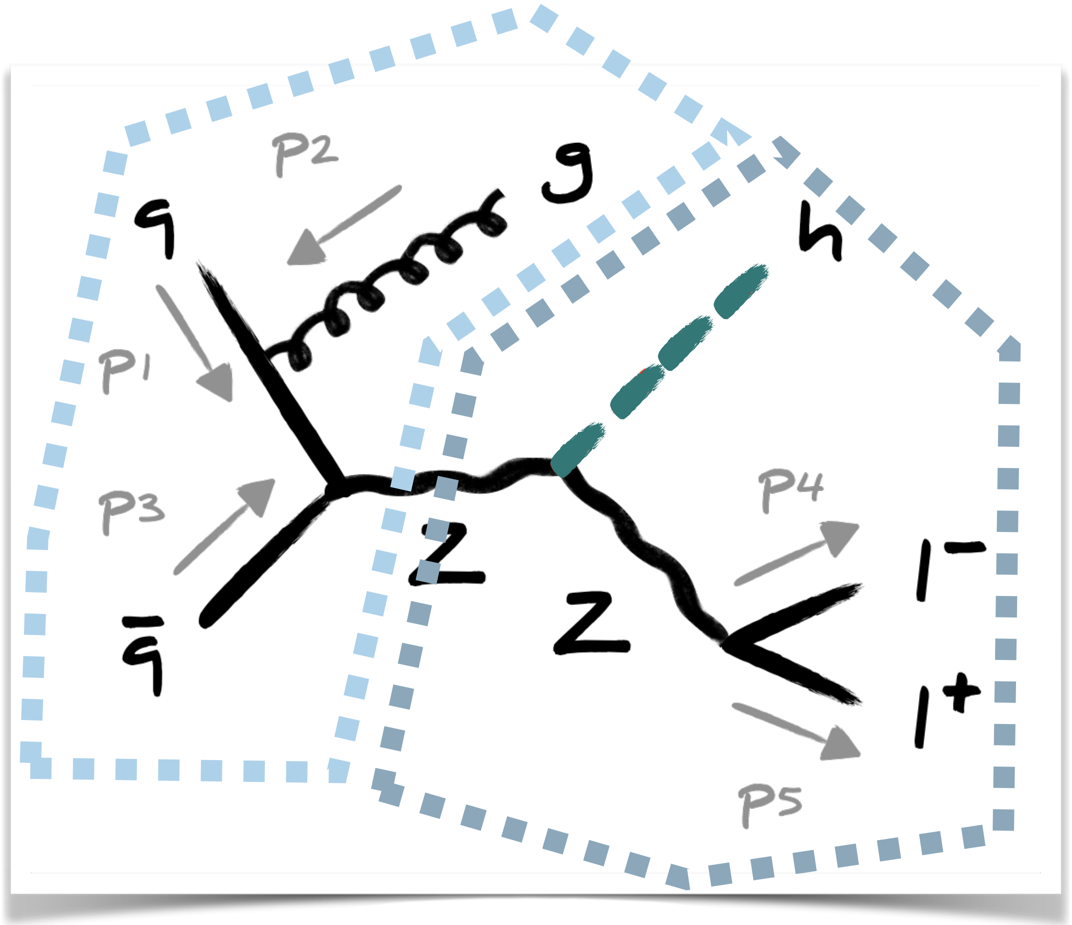


(A-type)



(B1g0Z)

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-,2_g^-,3_{\bar{q}}^+;4_\ell^-,5_{\bar{\ell}}^+\right)=\frac{\langle 34\rangle}{\langle 12\rangle\langle 23\rangle}\left(\langle 13\rangle[51]+\langle 23\rangle[52]\right),$$

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-,2_g^-,3_{\bar{q}}^+;4_\ell^-,5_{\bar{\ell}}^+\right)=\langle 4|\gamma_\mu|5]\,\mathcal{A}^\mu_{qgq}(1_q^-,2_g^-,3_{\bar{q}}^+)\,.$$

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-,2_g^+,3_{\bar{q}}^+;4_\ell^-,5_{\bar{\ell}}^+\right)=-\mathcal{A}_{\texttt{B1g0Z}}\left(3_q^-,2_g^-,1_{\bar{q}}^+;5_\ell^-,4_{\bar{\ell}}^+\right)^*,$$

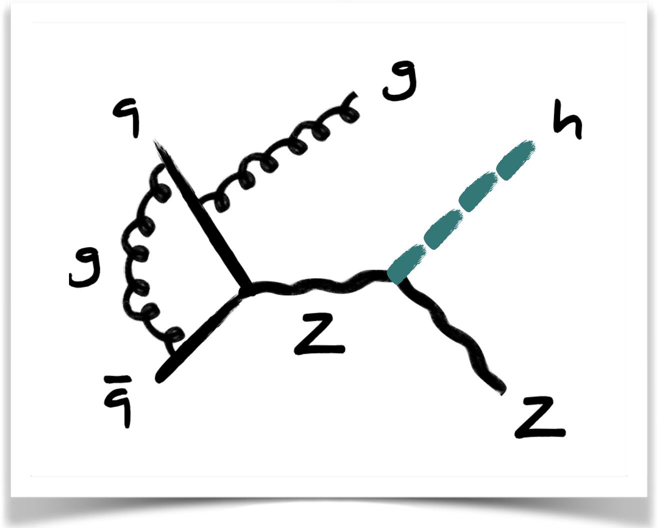
$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-,2_g^{h_g},3_{\bar{q}}^+;4_\ell^+,5_{\bar{\ell}}^-\right)=\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-,2_g^{h_g},3_{\bar{q}}^+;5_\ell^-,4_{\bar{\ell}}^+\right),$$

$$\texttt{B1g0Z}=\frac{8\pi\alpha_s C_F}{C_A}\sum_{h_q,h_g,h_\ell=\pm}\left|\frac{g_{Zq}^{h_q}\,g_{Z\ell}^{h_\ell}\,g_{hZZ}}{D_Z(s_{123})\,D_Z(s_{45})}\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q},2_g^{h_g},3_{\bar{q}}^{-h_q};4_\ell^{h_\ell},5_{\bar{\ell}}^{-h_\ell}\right)\right|^2,$$

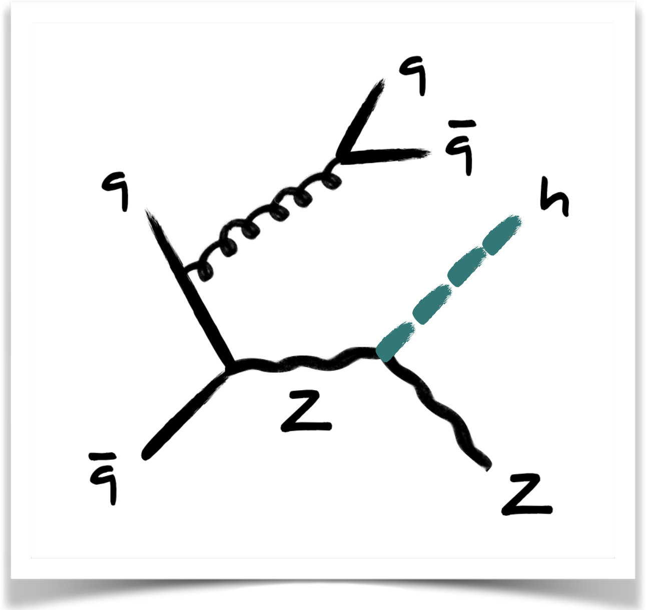
2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

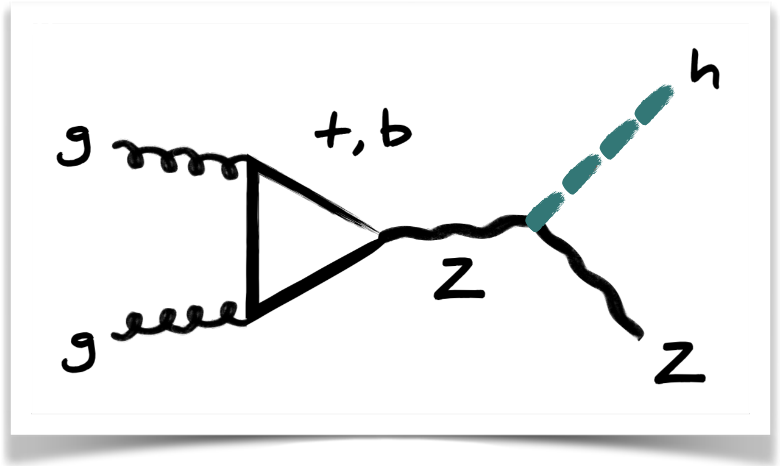
How can we calculate the relevant **SMEFT matrix elements**?



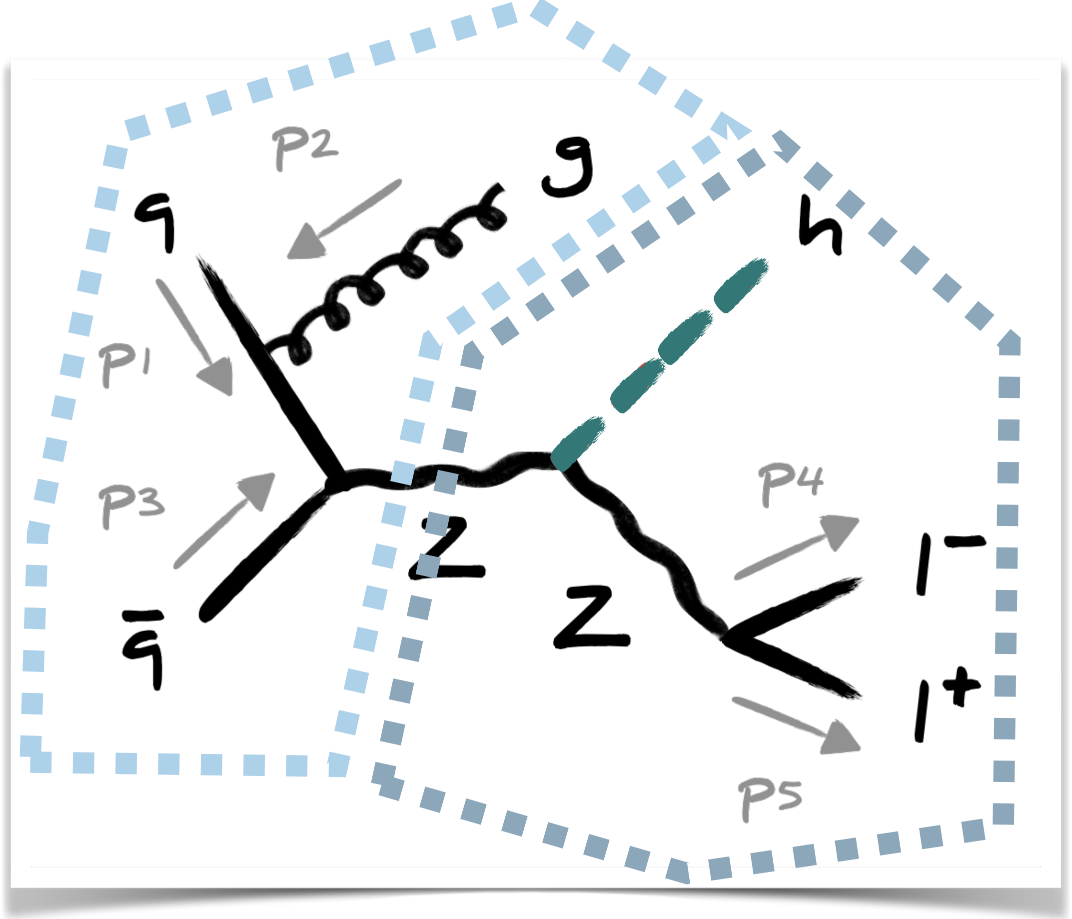
(B-type)



(C,D-type)



(A-type)



(B1g0Z)

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-, 2_g^-, 3_{\bar{q}}^+; 4_\ell^-, 5_{\bar{\ell}}^+\right) = \frac{\langle 34\rangle}{\langle 12\rangle\langle 23\rangle}\left(\langle 13\rangle\,[51] + \langle 23\rangle\,[52]\right),$$

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-, 2_g^-, 3_{\bar{q}}^+; 4_\ell^-, 5_{\bar{\ell}}^+\right) = \langle 4|\gamma_\mu|5]\,\mathcal{A}^\mu_{qgq}(1_q^-, 2_g^-, 3_{\bar{q}}^+).$$

$$\mathcal{A}^\mu_{qgq}(1_q^-, 2_g^-, 3_{\bar{q}}^+) = \frac{\langle 13\rangle\langle 3|\gamma^\mu|1] + \langle 23\rangle\langle 3|\gamma^\mu|2]}{2\langle 12\rangle\langle 23\rangle}.$$

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-, 2_g^+, 3_{\bar{q}}^+; 4_\ell^-, 5_{\bar{\ell}}^+\right) = -\mathcal{A}_{\texttt{B1g0Z}}\left(3_q^-, 2_g^-, 1_{\bar{q}}^+; 5_\ell^-, 4_{\bar{\ell}}^+\right)^*,$$

$$\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-, 2_g^{h_g}, 3_{\bar{q}}^+; 4_\ell^+, 5_{\bar{\ell}}^-\right) = \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^-, 2_g^{h_g}, 3_{\bar{q}}^+; 5_\ell^-, 4_{\bar{\ell}}^+\right),$$

$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A}\sum_{h_q,h_g,h_\ell=\pm}\left|\frac{g_{Zq}^{h_q}\,g_{Z\ell}^{h_\ell}\,g_{hZZ}}{D_Z(s_{123})\,D_Z(s_{45})}\mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right)\right|^2,$$

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

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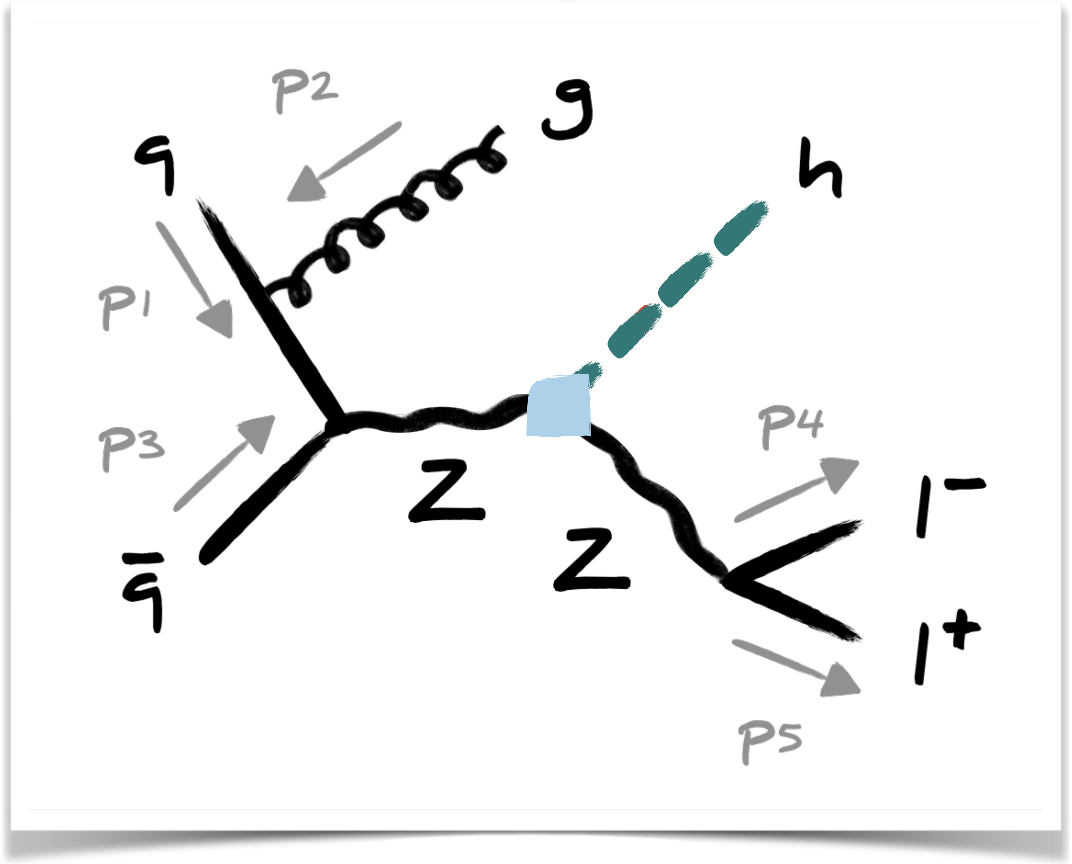

(B1g0Z)

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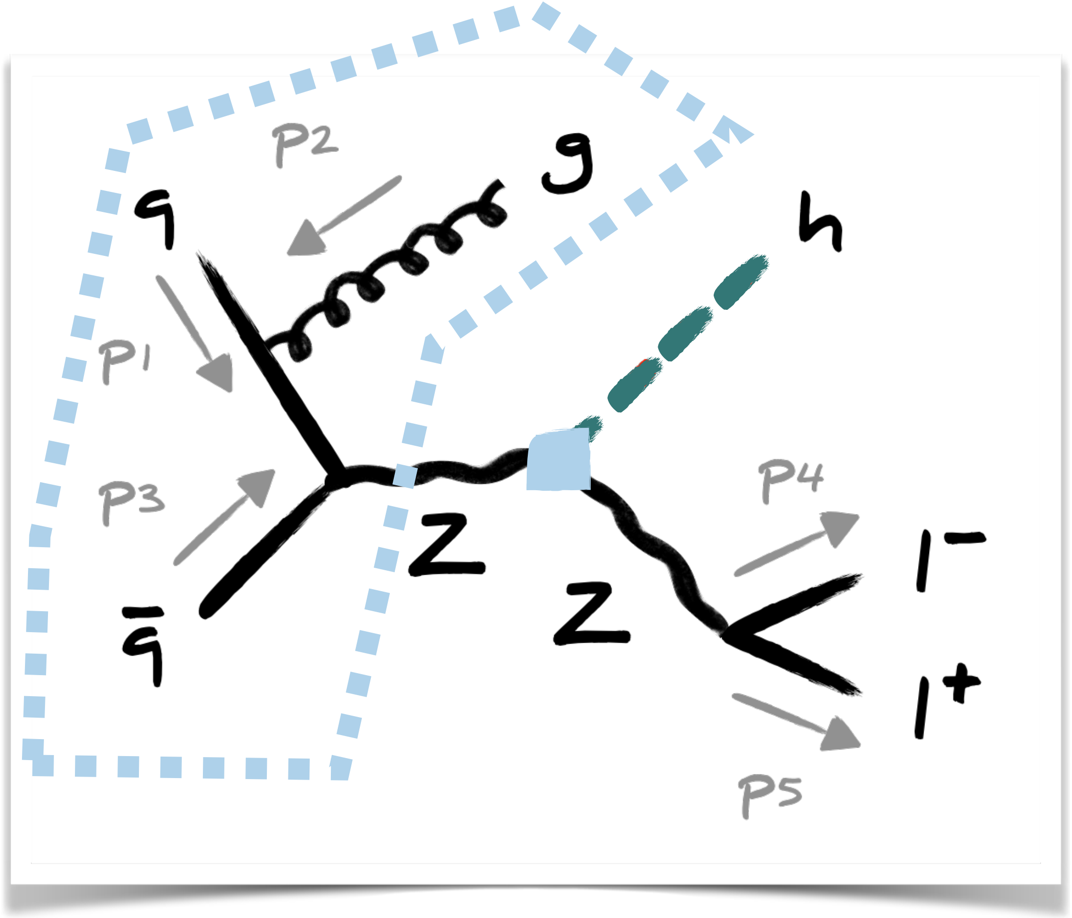

(B1g0Z)

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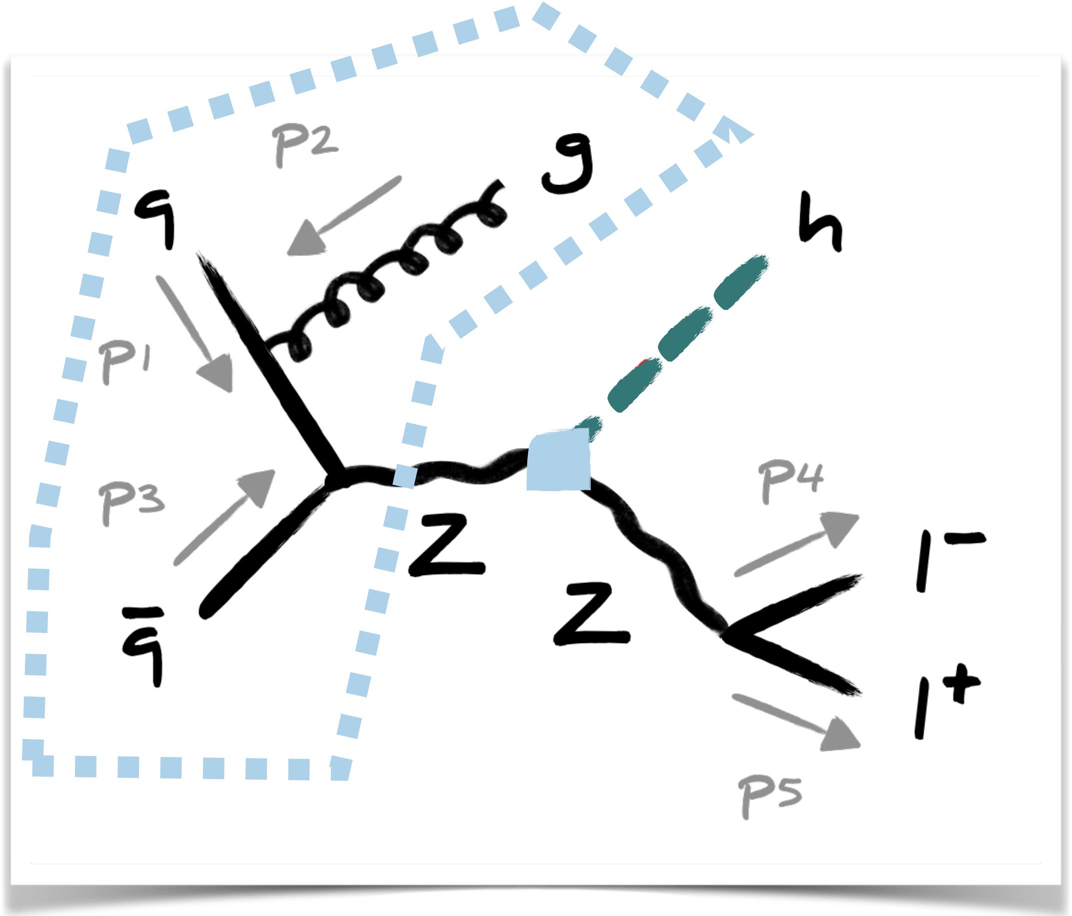

(B1g0Z)

$$\mathcal{A}^{\mu}_{qgq}(1_q^-, 2_g^-, 3_{\bar{q}}^+) = \frac{\langle 13\rangle\langle 3|\gamma^\mu|1] + \langle 23\rangle\langle 3|\gamma^\mu|2]}{2\langle 12\rangle\langle 23\rangle}\,.$$

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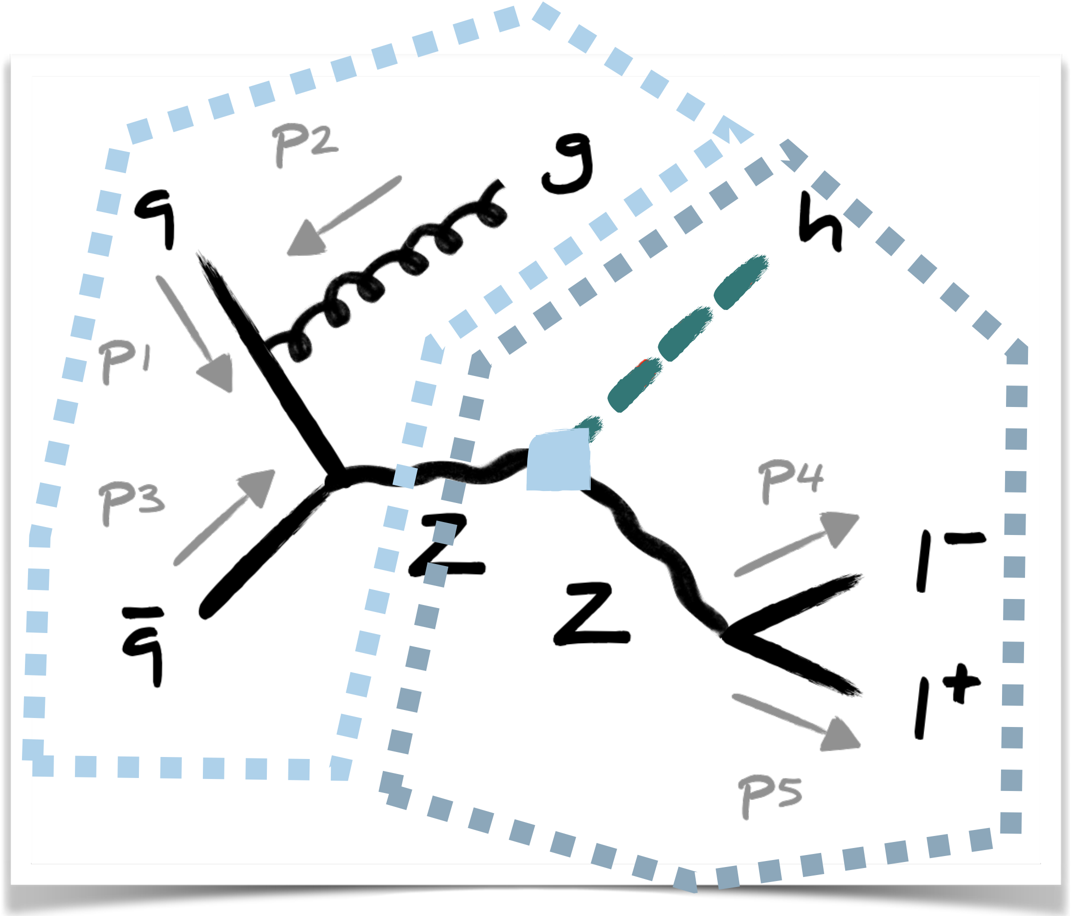

(B1g0Z)

$$\mathcal{A}^{\mu}_{qgq}(1_q^-, 2_g^-, 3_{\bar{q}}^+) = \frac{\langle 13\rangle\langle 3|\gamma^\mu|1] + \langle 23\rangle\langle 3|\gamma^\mu|2]}{2\langle 12\rangle\langle 23\rangle} .$$

$$\mathcal{A}^{\mu}_{hZZ}(p_{123}, 4_\ell^-, 5_{\bar{\ell}}^+) = \frac{g_{Zq}^- g_{Z\ell}^-}{D_Z(s_{123})\, D_Z(s_{45})} \Big\{ \langle 4|\gamma^\mu|5] \left(g_{hZZ} + \delta g^{(2)}_{hZZ}\, (s_{123} + s_{34}) + \delta g^{(3)}_{hZZ} \right)$$
$$- \delta g^{(2)}_{hZZ}\, p^\mu_{123} \langle 4|\not{p}_{123}|5] - \frac{\delta g^{(1)}_{hZZ}}{2} \left(\langle 4|\gamma^\mu \not{p}_{123}|4\rangle[45] + \langle 45\rangle[5|\not{p}_{123}\gamma^\mu|5] \right) \Big\},$$

$$\mathcal{A}^{\mu}_{h\gamma Z}(p_{123}, 4_\ell^-, 5_{\bar{\ell}}^+) = \frac{g_{\gamma q}^- g_{Z\ell}^-}{s_{123}\, D(s_{45})} \Big\{ - \frac{\delta g^{(1)}_{h\gamma Z}}{2} \Big(\langle 4|\gamma^\mu|5] \left(\langle 4|\not{p}_{123}|4] + \langle 5|\not{p}_{123}|5] \right)$$
$$- 2\,(p^\mu_4 + p^\mu_5)\, \langle 4|\not{p}_{123}|5] \Big) + \delta g^{(2)}_{h\gamma Z} \left(\langle 4|\gamma^\mu|5]\, s_{123} - p^\mu_{123}\, \langle 4|\not{p}_{123}|5] \right) \Big\},$$

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

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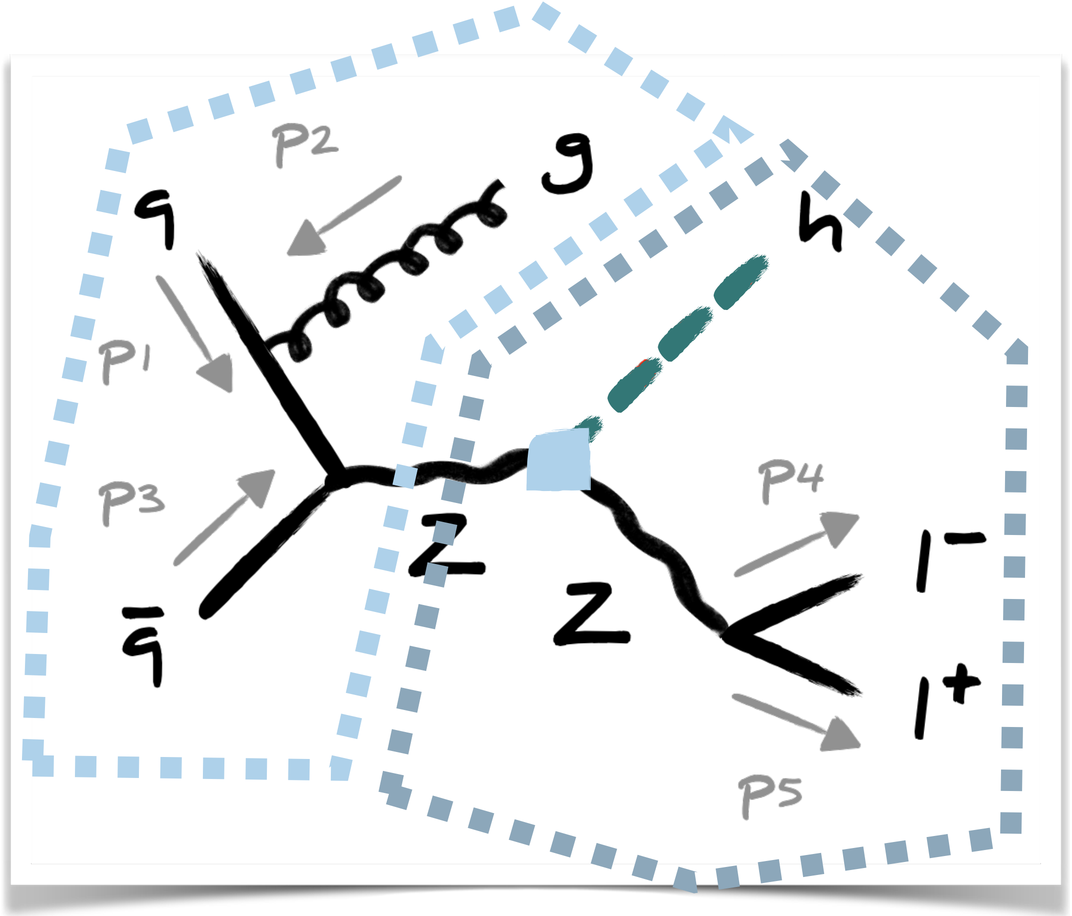

(B1g0Z)

$$\mathcal{A}^{\mu}_{qgq}(1^-_q, 2^-_g, 3^+_{\bar{q}}) = \frac{\langle 13\rangle\langle 3|\gamma^\mu|1] + \langle 23\rangle\langle 3|\gamma^\mu|2]}{2\langle 12\rangle\langle 23\rangle} \,.$$

$$\mathcal{A}^{\mu}_{hZZ}(p_{123}, 4^-_\ell, 5^+_{\bar{\ell}}) = \frac{g^-_{Zq}\, g^-_{Z\ell}}{D_Z(s_{123})\, D_Z(s_{45})} \Big\{ \langle 4|\gamma^\mu|5] \left(g_{hZZ} + \delta g^{(2)}_{hZZ}\,(s_{123}+s_{34}) + \delta g^{(3)}_{hZZ} \right) - \delta g^{(2)}_{hZZ}\, p^\mu_{123} \langle 4|\not{p}_{123}|5] - \frac{\delta g^{(1)}_{hZZ}}{2} \left(\langle 4|\gamma^\mu \not{p}_{123}|4\rangle [45] + \langle 45\rangle [5|\not{p}_{123}\gamma^\mu|5] \right) \Big\} \,,$$

$$\mathcal{A}^{\mu}_{h\gamma Z}(p_{123}, 4^-_\ell, 5^+_{\bar{\ell}}) = \frac{g^-_{\gamma q}\, g^-_{Z\ell}}{s_{123}\, D(s_{45})} \Big\{ -\frac{\delta g^{(1)}_{h\gamma Z}}{2} \Big(\langle 4|\gamma^\mu|5] \left(\langle 4|\not{p}_{123}|4] + \langle 5|\not{p}_{123}|5] \right) - 2\,(p^\mu_4 + p^\mu_5)\,\langle 4|\not{p}_{123}|5] \Big) + \delta g^{(2)}_{h\gamma Z} \left(\langle 4|\gamma^\mu|5]\, s_{123} - p^\mu_{123}\,\langle 4|\not{p}_{123}|5] \right) \Big\} \,,$$

$$\mathcal{A}_{qgq,\mu}\left(1^{h_q}_q, 2^{h_g}_g, 3^{-h_q}_{\bar{q}}\right) \left[\mathcal{A}^{\mu}_{hZZ}(p_{123}, 4^{h_\ell}_\ell, 5^{-h_\ell}_{\bar{\ell}}) + \mathcal{A}^{\mu}_{h\gamma Z}(p_{123}, 4^{h_\ell}_\ell, 5^{-h_\ell}_{\bar{\ell}}) \right] .$$

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?

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2.1 $q\bar{q}$-initiated contributions

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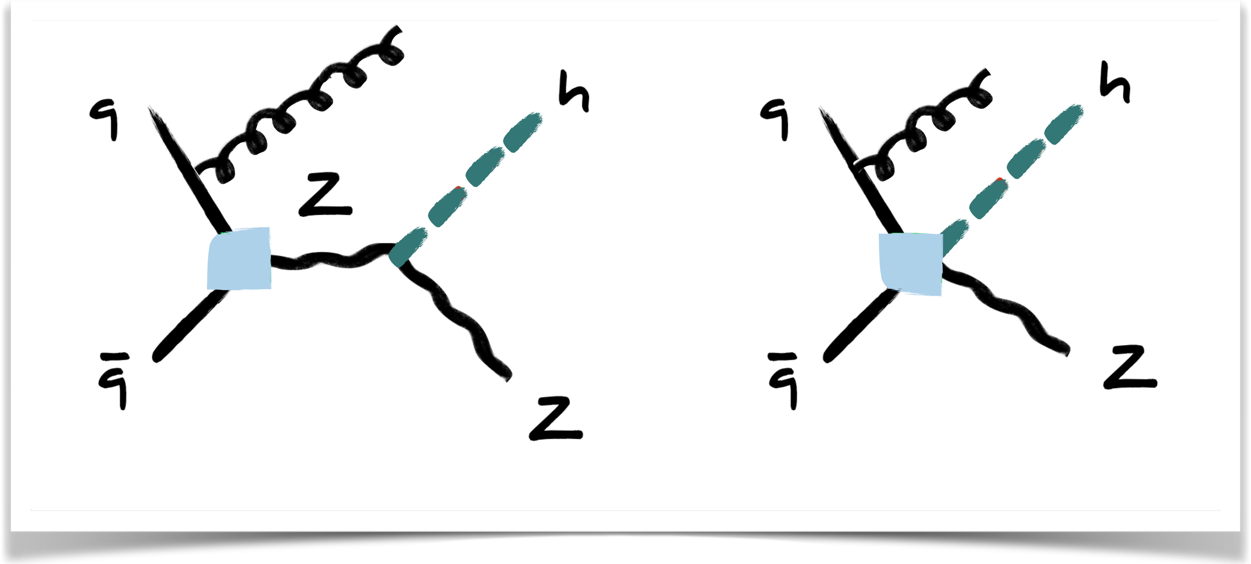

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

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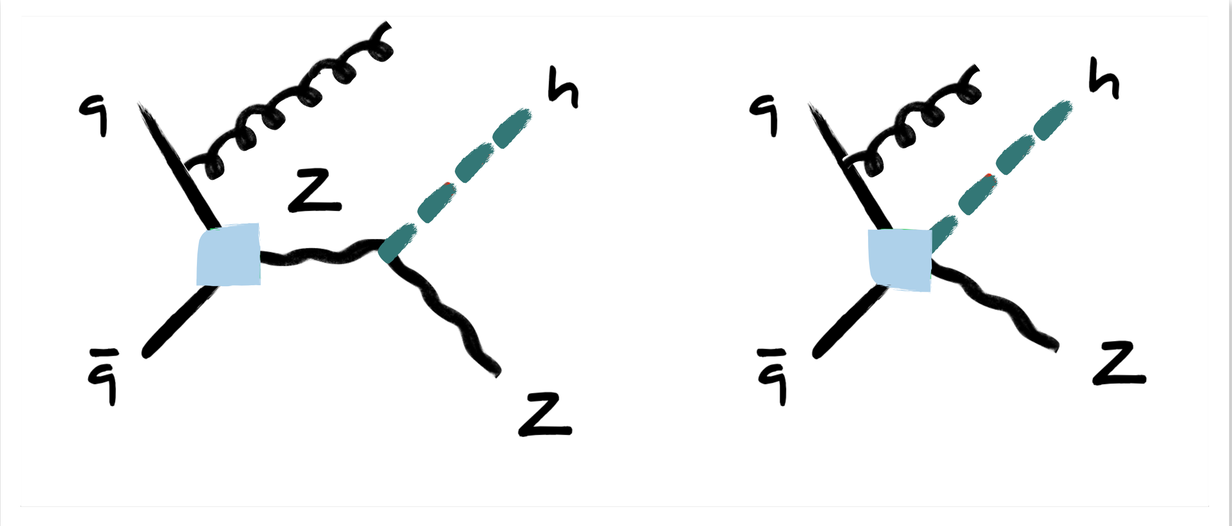

$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q} g_{Z\ell}^{h_\ell} g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}} \left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

2. Details of the calculation

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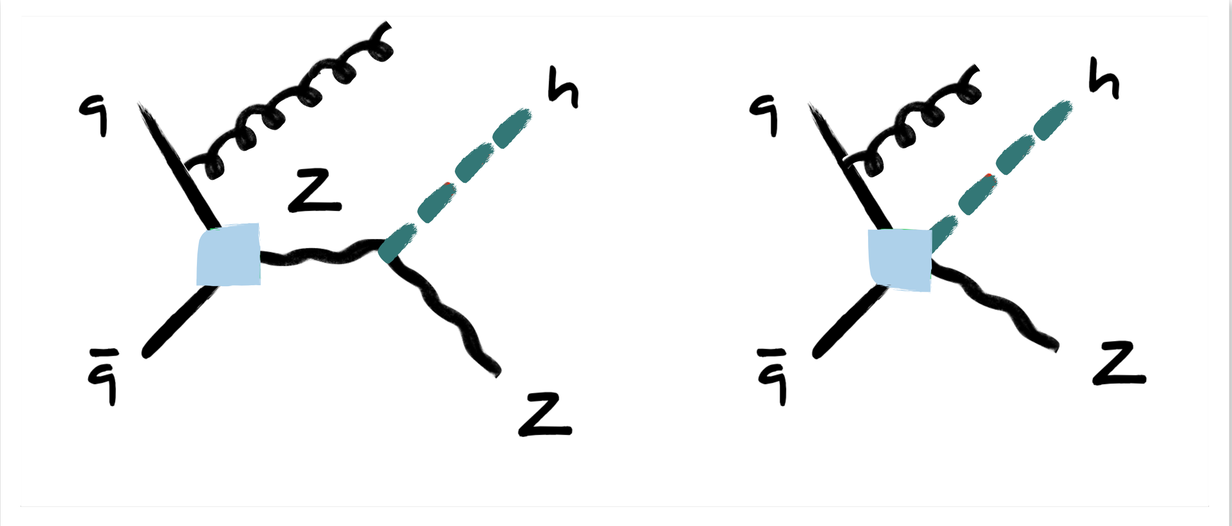


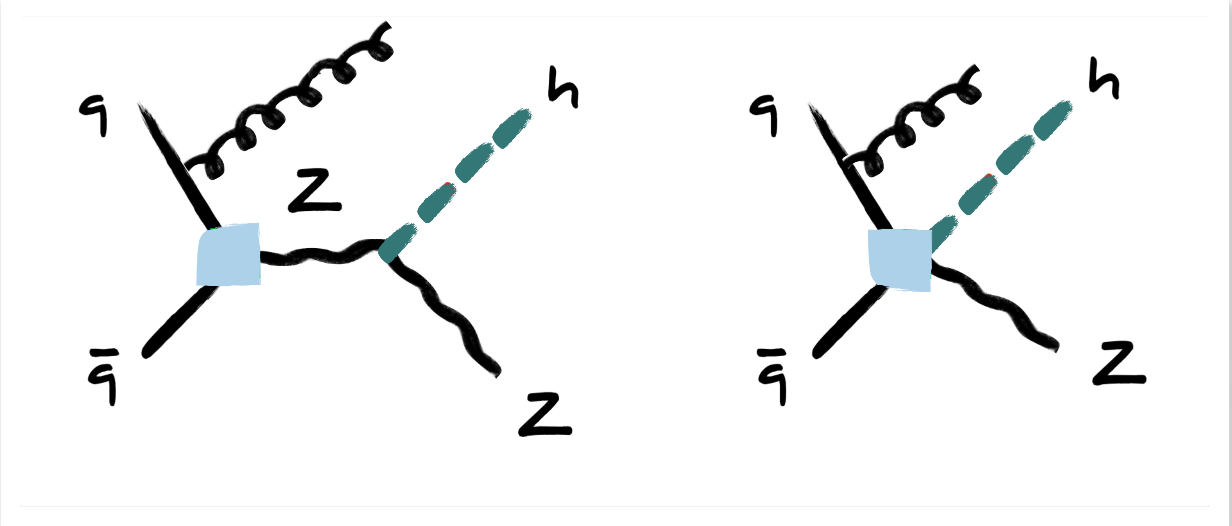
$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q}\, g_{Z\ell}^{h_\ell}\, g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

These contributions give **overall factors** to the SM amplitude.

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?



$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q} g_{Z\ell}^{h_\ell} g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2,$$

These contributions give **overall factors** to the SM amplitude.

$$g_{Zf}^{\pm} = \frac{g_1^2 Y_f^{\pm} - 2 g_2^2 T_f^{3\pm}}{2 g_+}$$

2. Details of the calculation

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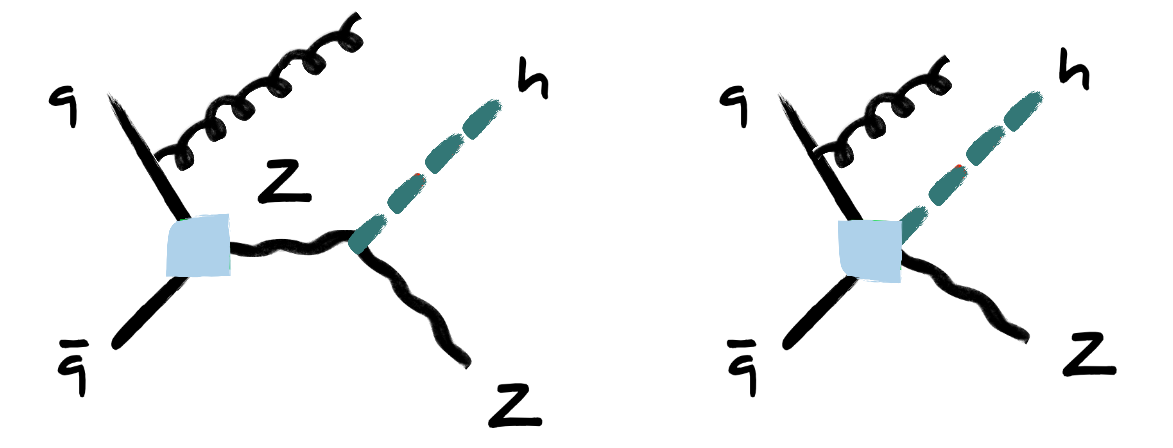


$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q}\, g_{Z\ell}^{h_\ell}\, g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

These contributions give **overall factors** to the SM amplitude.

$$g_{Zf}^{\pm} = \frac{g_1^2 Y_f^{\pm} - 2 g_2^2 T_f^{3\pm}}{2 g_+}$$

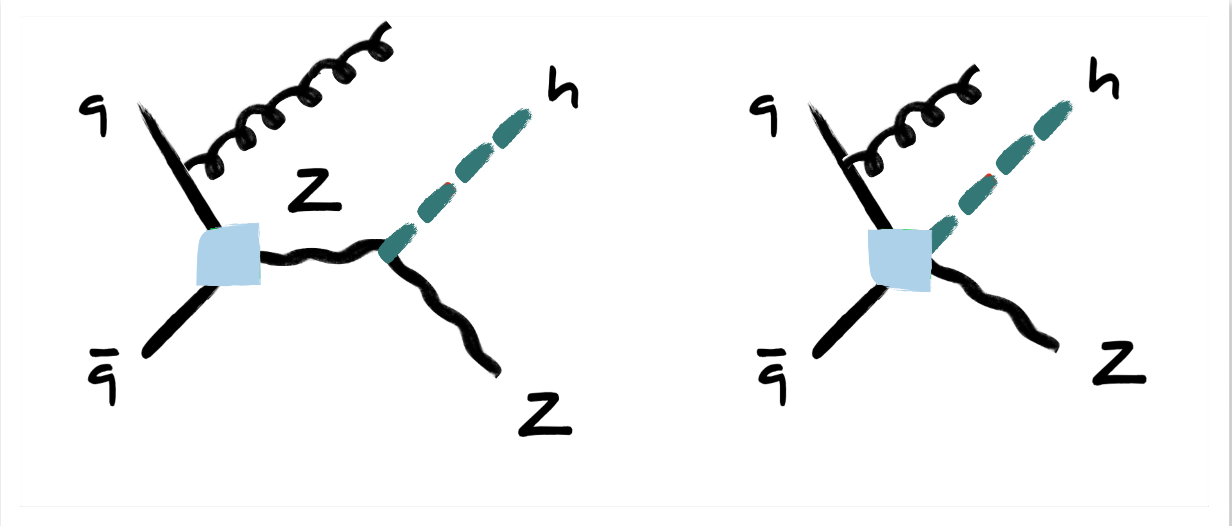
$$\delta g_{Zf}^{(0)\pm} = \frac{g_1^3 \delta g_1 Y_f^{\pm} - 2 g_2^3 \delta g_2 T_f^{3\pm} - g_1^2 g_2 \delta g_2 \left(Y_f^{\pm} + 4 T_f^{3\pm}\right) + 2 g_1 g_2^2 \delta g_1 \left(Y_f^{\pm} + T_f^{3\pm}\right)}{2\, {}^{3/2}\!\sqrt{g_+}} .$$

Input scheme corrections

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?



$$\mathtt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q} g_{Z\ell}^{h_\ell} g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\mathtt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

These contributions give **overall factors** to the SM amplitude.

$$g_{Zf}^{\pm} = \frac{g_1^2 Y_f^{\pm} - 2 g_2^2 T_f^{3\pm}}{2 g_+}$$

$$\delta g_{Zf}^{(0)\pm} = \frac{g_1^3 \delta g_1 Y_f^{\pm} - 2 g_2^3 \delta g_2 T_f^{3\pm} - g_1^2 g_2 \delta g_2 \left(Y_f^{\pm} + 4 T_f^{3\pm}\right) + 2 g_1 g_2^2 \delta g_1 \left(Y_f^{\pm} + T_f^{3\pm}\right)}{2\, \sqrt[3/2]{g_+}} .$$

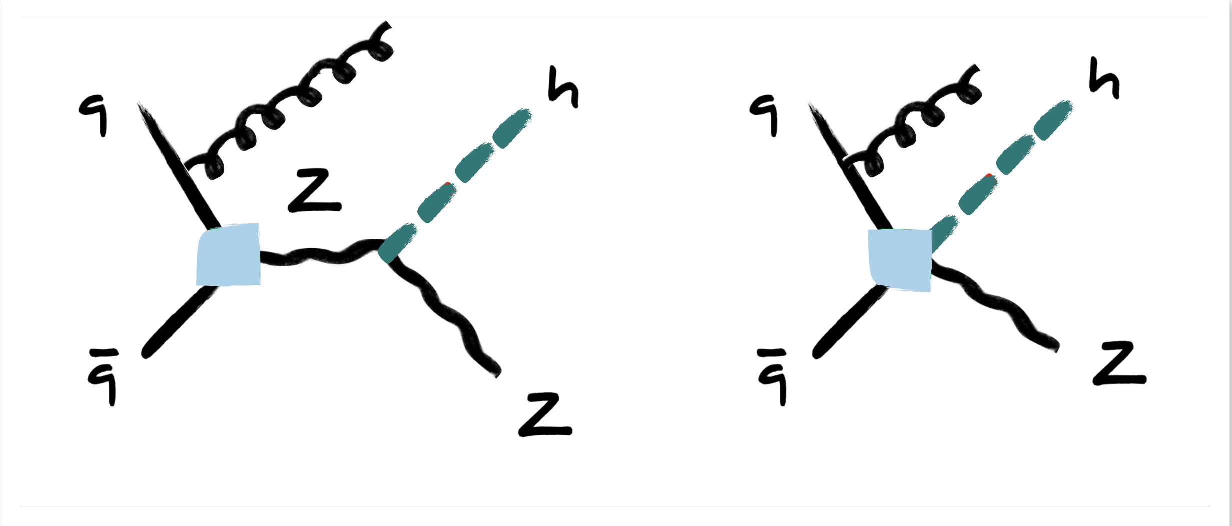
Input scheme corrections

α-scheme	α_μ-scheme	LEP-scheme
$\{G_F, m_Z, m_W\}$	$\{\alpha, m_Z, m_W\}$	$\{\alpha, G_F, m_Z\}$

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?



$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q} g_{Z\ell}^{h_\ell} g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}} \left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

These contributions give **overall factors** to the SM amplitude.

$$g_{Zf}^{\pm} = \frac{g_1^2 Y_f^{\pm} - 2 g_2^2 T_f^{3\pm}}{2 g_+}$$

$$\delta g_{Zd}^{(1)-} = \frac{v^2 g_+}{2}\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right), \qquad \delta g_{Zu}^{(1)-} = \frac{v^2 g_+}{2}\left(C_{Hq}^{(1)} - C_{Hq}^{(3)}\right),$$

Direct contributions

$$\delta g_{Zf}^{(0)\pm} = \frac{g_1^3 \delta g_1 Y_f^{\pm} - 2 g_2^3 \delta g_2 T_f^{3\pm} - g_1^2 g_2 \delta g_2 \left(Y_f^{\pm} + 4 T_f^{3\pm}\right) + 2 g_1 g_2^2 \delta g_1 \left(Y_f^{\pm} + T_f^{3\pm}\right)}{2\,{}^{3/2}\!\sqrt{g_+}} .$$

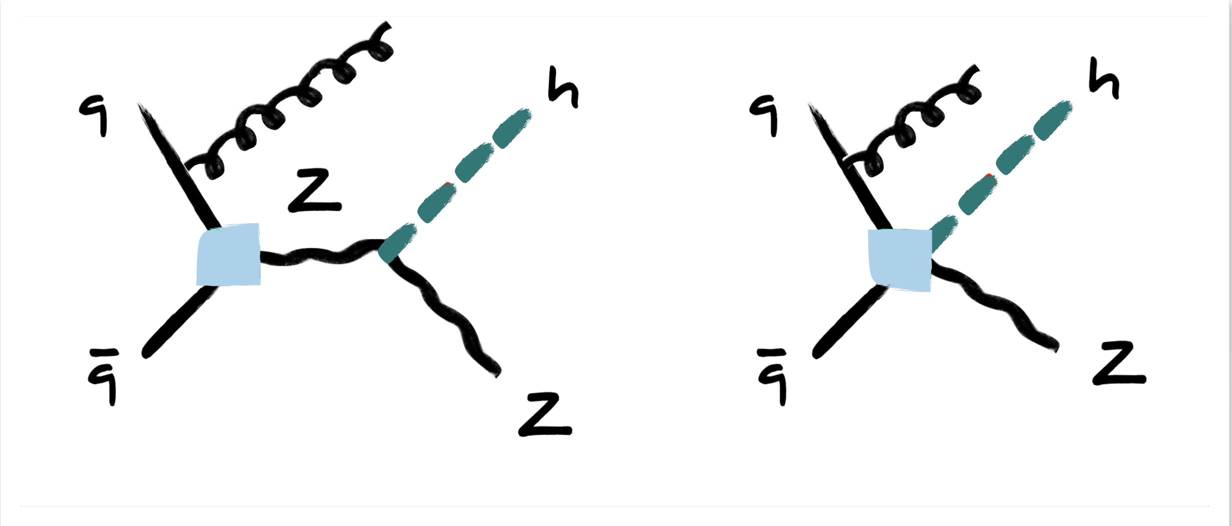
Input scheme corrections

α-scheme	α_μ-scheme	LEP-scheme
$\{G_F, m_Z, m_W\}$	$\{\alpha, m_Z, m_W\}$	$\{\alpha, G_F, m_Z\}$

2. Details of the calculation

2.1 $q\bar{q}$-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?



$$\texttt{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q} g_{Z\ell}^{h_\ell} g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2 ,$$

These contributions give **overall factors** to the SM amplitude.

$$g_{Zf}^{\pm} = \frac{g_1^2 Y_f^{\pm} - 2 g_2^2 T_f^{3\pm}}{2 g_+}$$

$$\delta g_{Zd}^{(1)-} = \frac{v^2 g_+}{2}\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right), \qquad \delta g_{Zu}^{(1)-} = \frac{v^2 g_+}{2}\left(C_{Hq}^{(1)} - C_{Hq}^{(3)}\right),$$

Direct contributions

$$\left(\frac{\delta g_{hZq}^{(1)h_q} g_{Z\ell}^{h_\ell}}{D_Z(s_{45})} + \frac{g_{Zq}^{h_q} \delta g_{hZ\ell}^{(1)h_\ell}}{D_Z(s_{123})} \right) \mathcal{A}_{\texttt{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right),$$

„**Quartic**“ contributions

$$\delta g_{Zf}^{(0)\pm} = \frac{g_1^3 \delta g_1 Y_f^{\pm} - 2 g_2^3 \delta g_2 T_f^{3\pm} - g_1^2 g_2 \delta g_2 \left(Y_f^{\pm} + 4 T_f^{3\pm}\right) + 2 g_1 g_2^2 \delta g_1 \left(Y_f^{\pm} + T_f^{3\pm}\right)}{2\, {}^{3/2}\!\sqrt{g_+}} .$$

Input scheme corrections

α-scheme	α_μ-scheme	LEP-scheme
$\{G_F, m_Z, m_W\}$	$\{\alpha, m_Z, m_W\}$	$\{\alpha, G_F, m_Z\}$

2. Details of the calculation

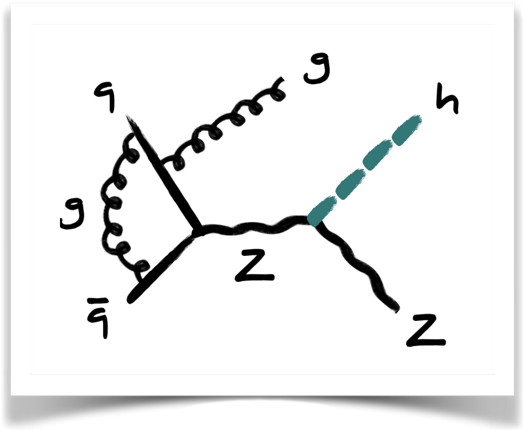
2.2 gg-initiated contributions

How can we calculate the relevant **SMEFT matrix elements**?

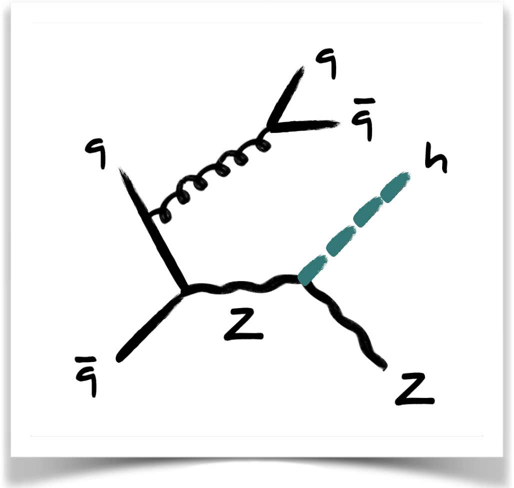
2. Details of the calculation

2.2 gg-initiated contributions

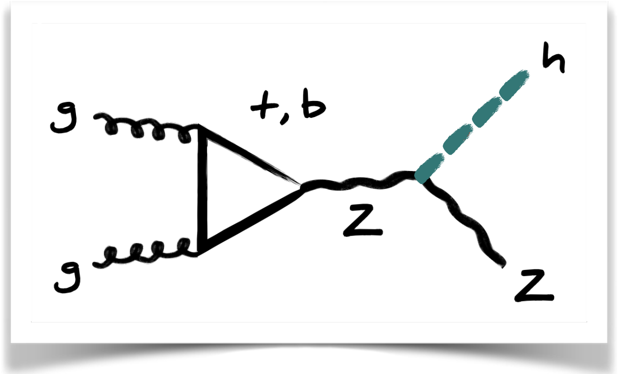
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



(C,D-type)

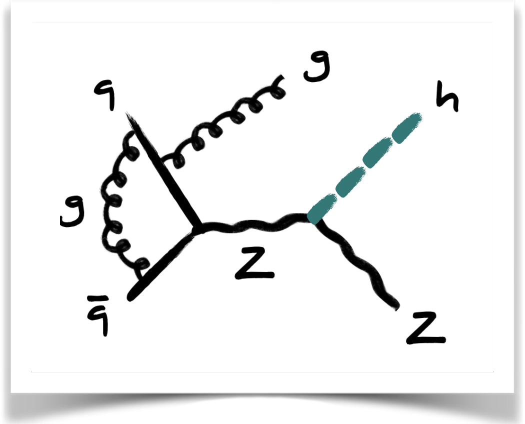


(A-type)

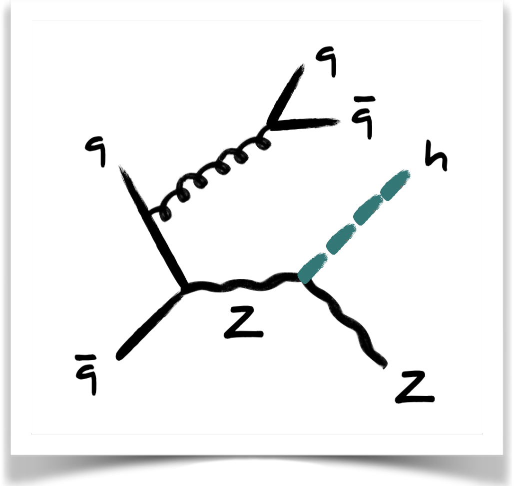
2. Details of the calculation

2.2 gg-initiated contributions

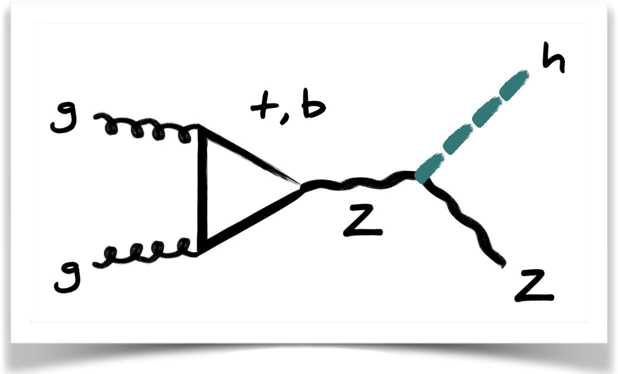
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



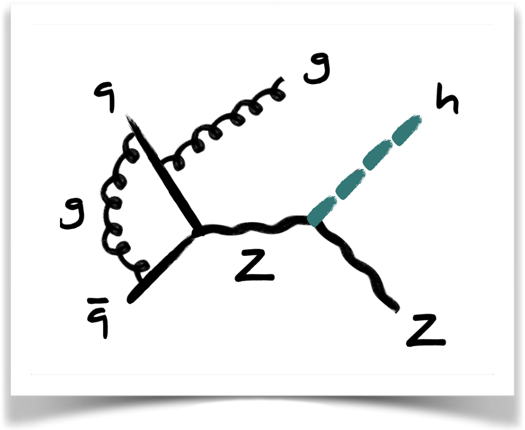
(C,D-type)



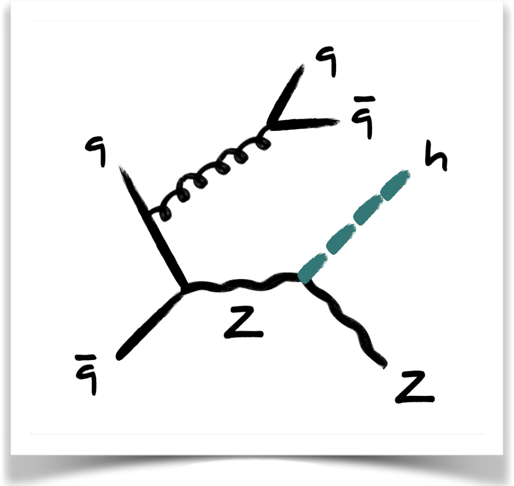
(A-type)

2. Details of the calculation

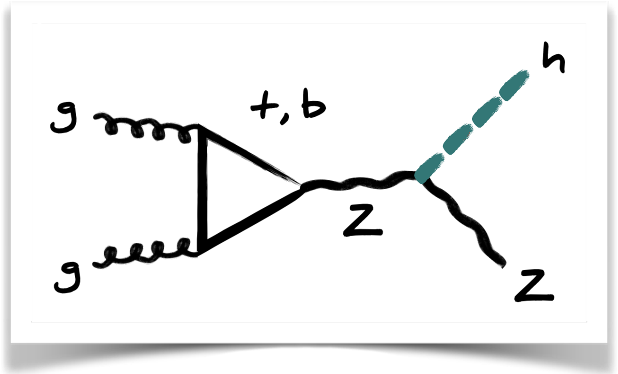
2.2 gg-initiated contributions



(B-type)

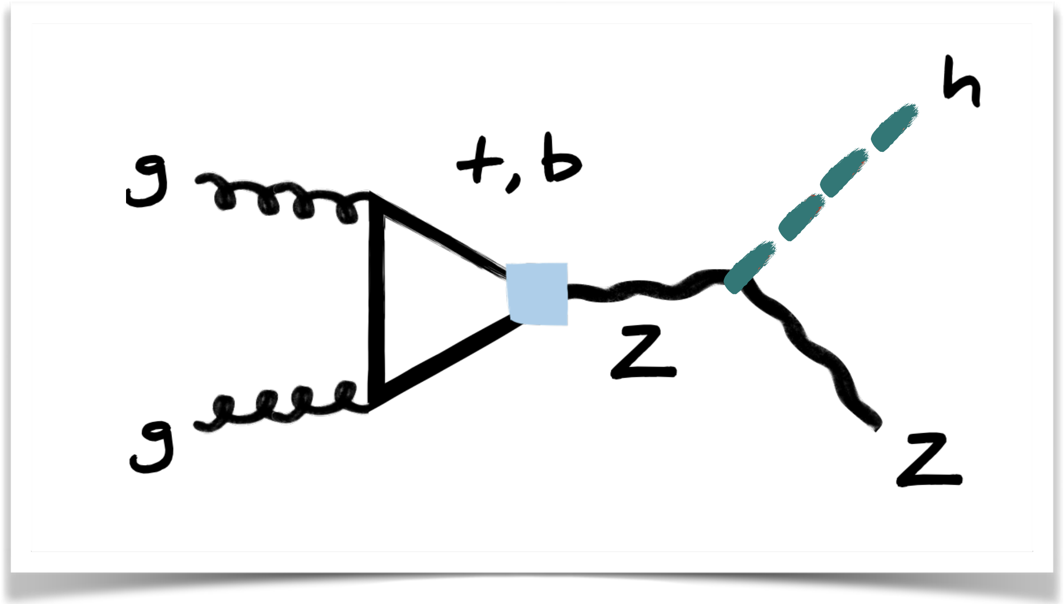


(C,D-type)



(A-type)

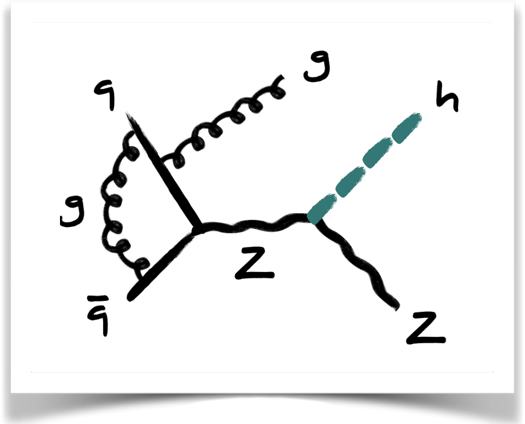
How can we calculate the relevant **SMEFT matrix elements**?



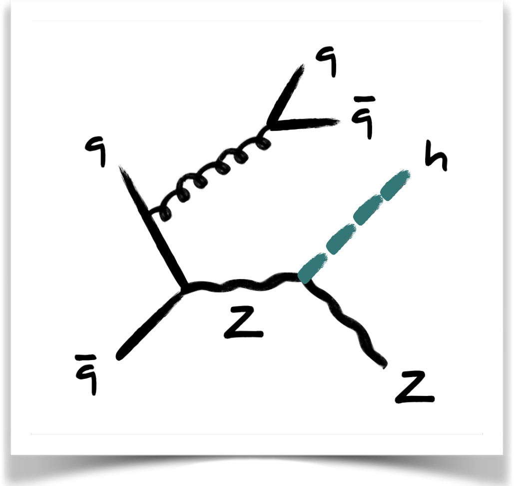
2. Details of the calculation

2.2 gg-initiated contributions

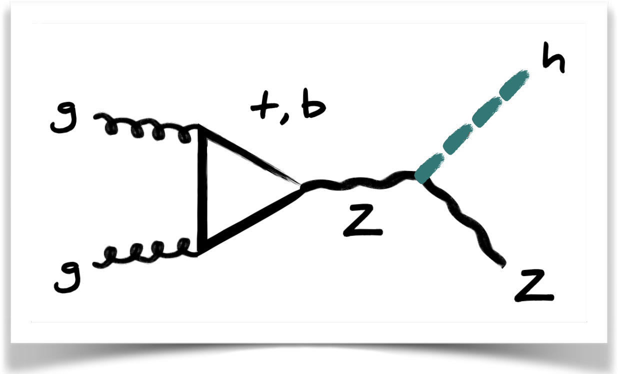
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)

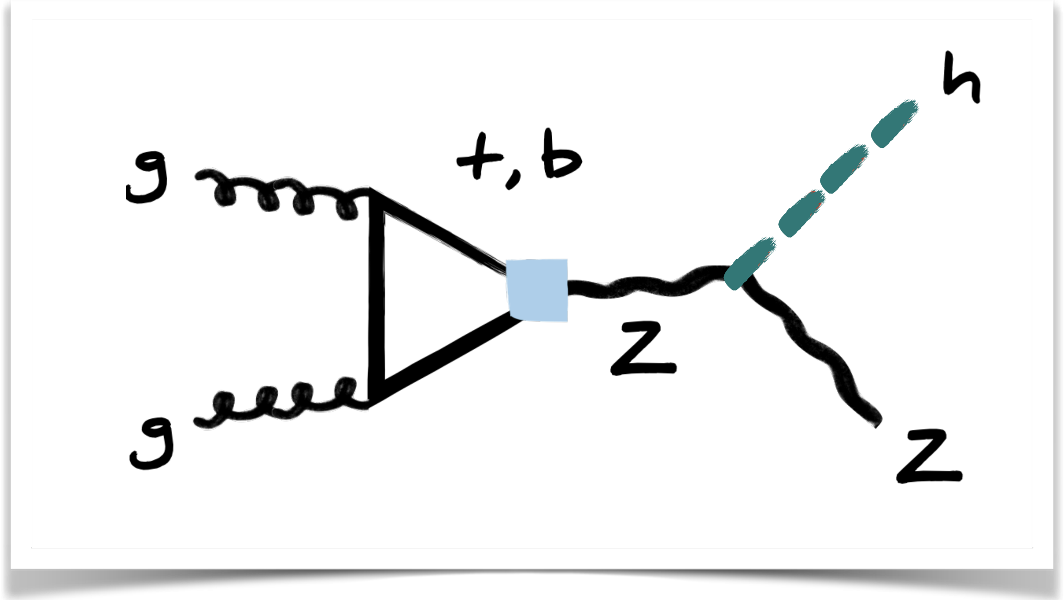


(C,D-type)



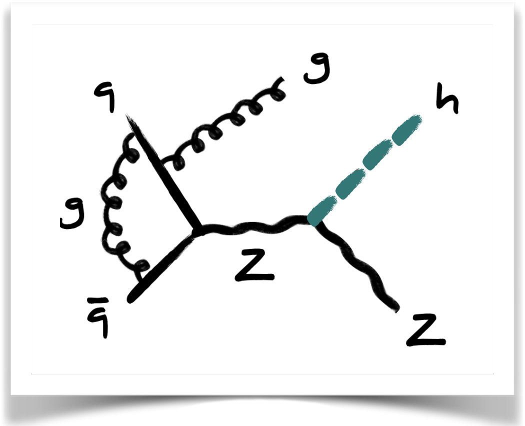
(A-type)

$$\mathcal{A}^{q}_{\texttt{A0g2Z}\triangle}\left(1^{+}_{g},2^{+}_{g},3^{-}_{\ell},4^{+}_{\bar{\ell}}\right) = -\frac{2\,[21]\,\left([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\right)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

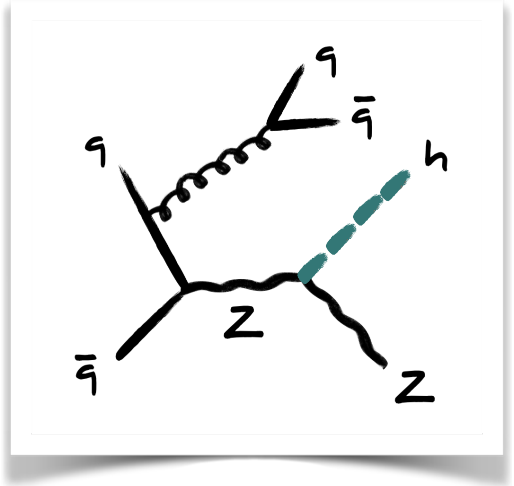


2. Details of the calculation

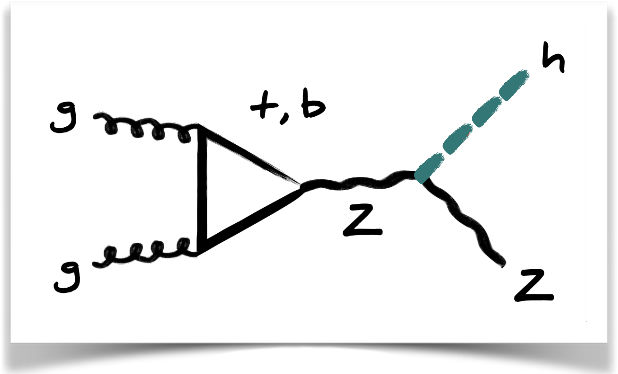
2.2 gg-initiated contributions



(B-type)



(C,D-type)



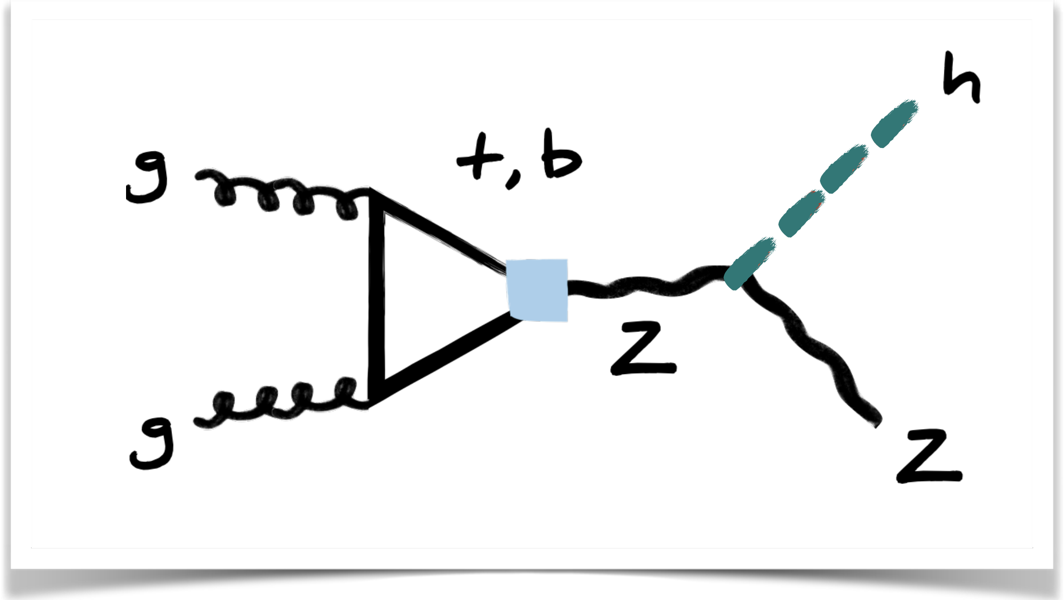
(A-type)

How can we calculate the relevant **SMEFT matrix elements**?

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_\ell^+\right) = -\frac{2\,[21]\,\left([41]\,\langle13\rangle+[42]\,\langle23\rangle\right)}{\langle12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^-,2_g^-,3_\ell^\mp,4_\ell^\pm\right) = -\overline{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,4_\ell^\mp,3_\ell^\pm\right)}\,,$$

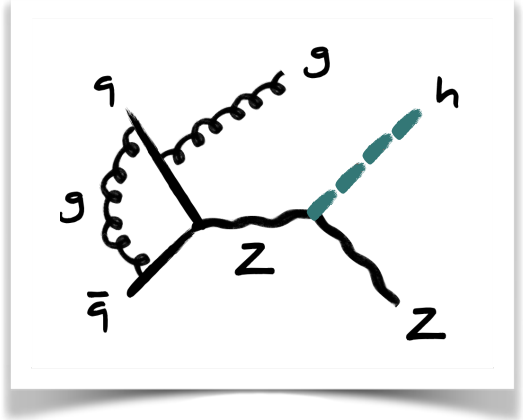
$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_\ell^-\right) = \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_\ell^+\right)\,,$$



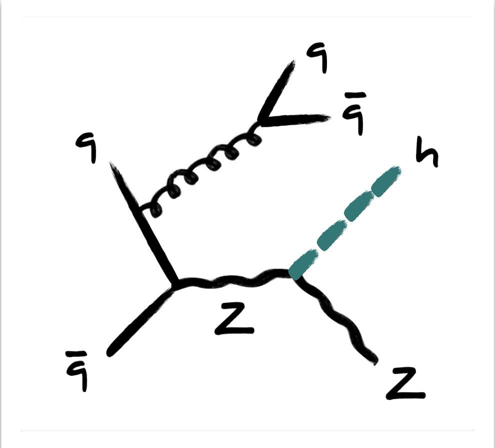
2. Details of the calculation

2.2 gg-initiated contributions

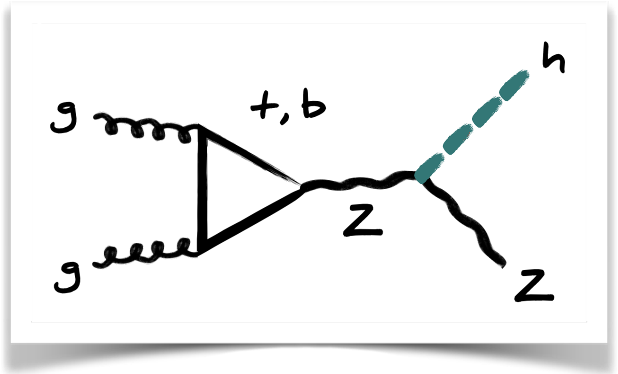
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



(C,D-type)

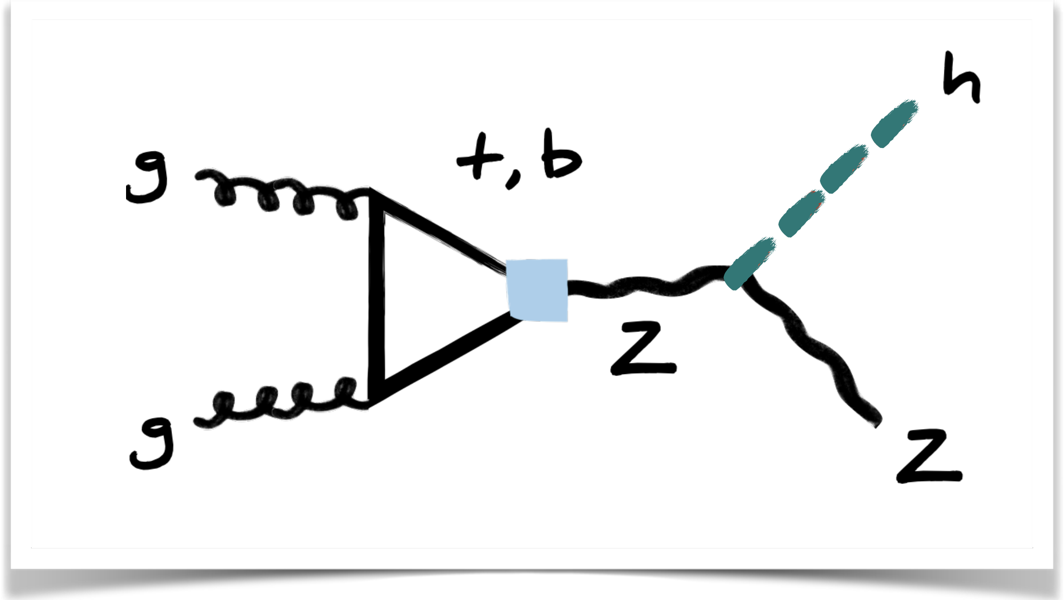


(A-type)

$$\mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^+,2_g^+,3_\ell^-,4_{\bar\ell}^+\right) = -\frac{2\,[21]\left([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\right)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^-,2_g^-,3_\ell^\mp,4_{\bar\ell}^\pm\right) = -\overline{\mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^+,2_g^+,4_\ell^\mp,3_{\bar\ell}^\pm\right)}\,,$$

$$\mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_{\bar\ell}^-\right) = \mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_{\bar\ell}^+\right)\,,$$



$$\mathtt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2}\sum_{h_g,h_\ell=\pm}\left|\sum_{q=t,b}\left(\mathcal{A}^q_\triangle + \sum_{s=\pm}\frac{m_q^2}{m_Z^2}\,\mathcal{A}^{q,s}_\square\right)\right|^2\,,$$

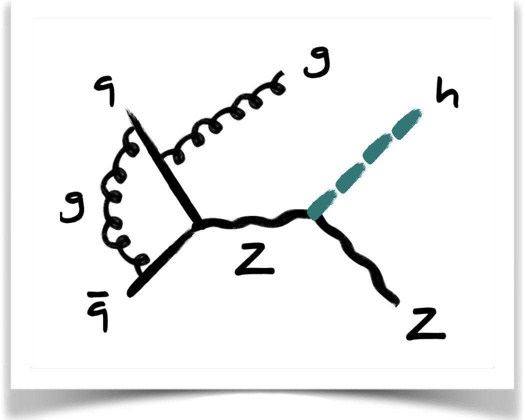
with

$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\mathtt{A0g2Z\triangle}}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_{\bar\ell}^{-h_\ell}\right)\,,$$

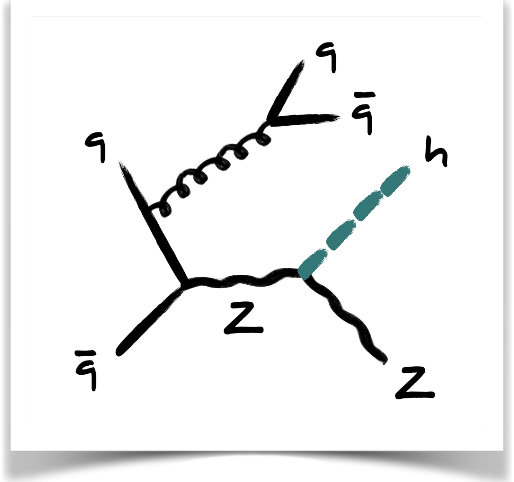
2. Details of the calculation

2.2 gg-initiated contributions

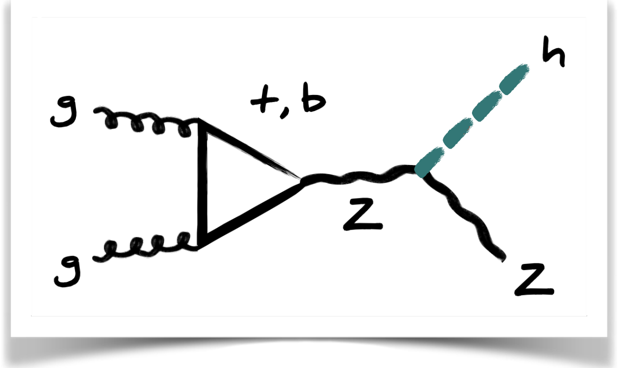
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



(C,D-type)

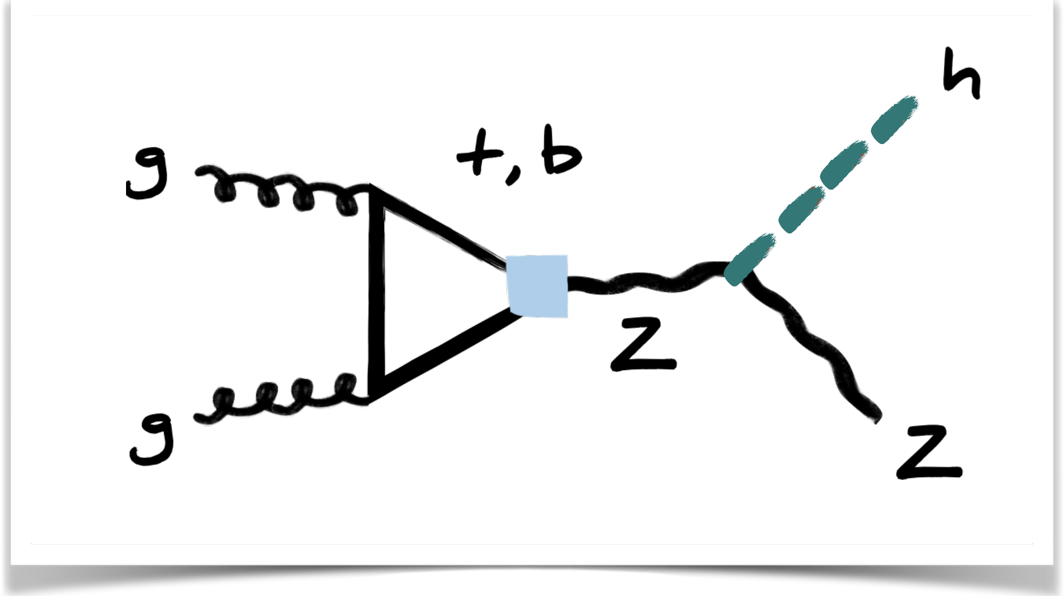


(A-type)

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_\ell^+\right) = -\frac{2\,[21]\,\left([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\right)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^-,2_g^-,3_\ell^\mp,4_\ell^\pm\right) = -\overline{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,4_\ell^\mp,3_\ell^\pm\right)}\,,$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_\ell^-\right) = \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_\ell^+\right)\,,$$



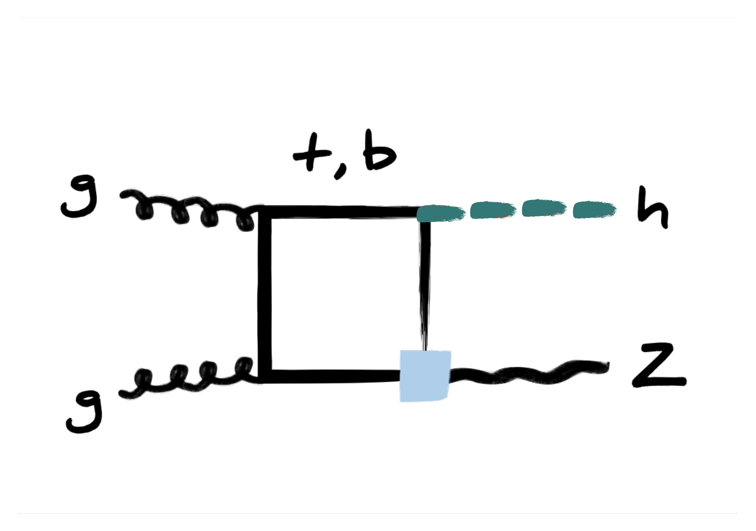
$$\texttt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2}\sum_{h_g,h_\ell=\pm}\left|\sum_{q=t,b}\left(\mathcal{A}^q_\triangle + \sum_{s=\pm}\frac{m_q^2}{m_Z^2}\,\mathcal{A}^{q,s}_\square\right)\right|^2\,,$$

with

$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_\ell^{-h_\ell}\right)\,,$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\square}\left(1_g^+,2_g^+,3_\ell^-,4_\ell^+\right)\,,$$

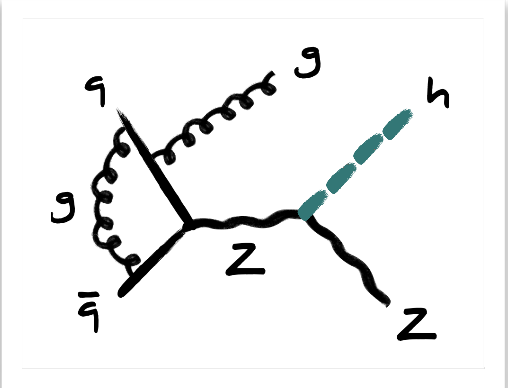
$$\mathcal{A}^q_{\texttt{A0g2Z}\square}\left(1_g^-,2_g^+,3_\ell^-,4_\ell^+\right)\,,$$



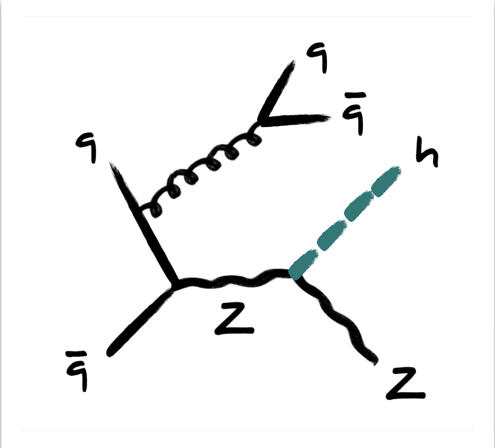
2. Details of the calculation

2.2 gg-initiated contributions

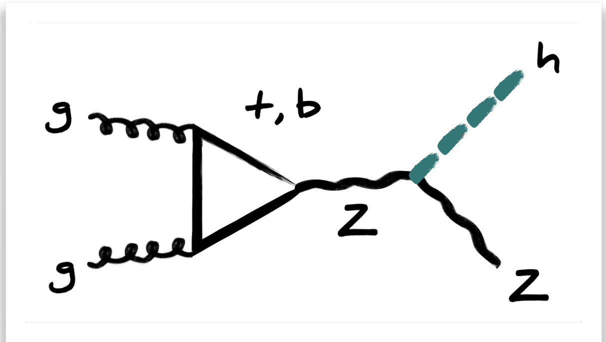
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



(C,D-type)

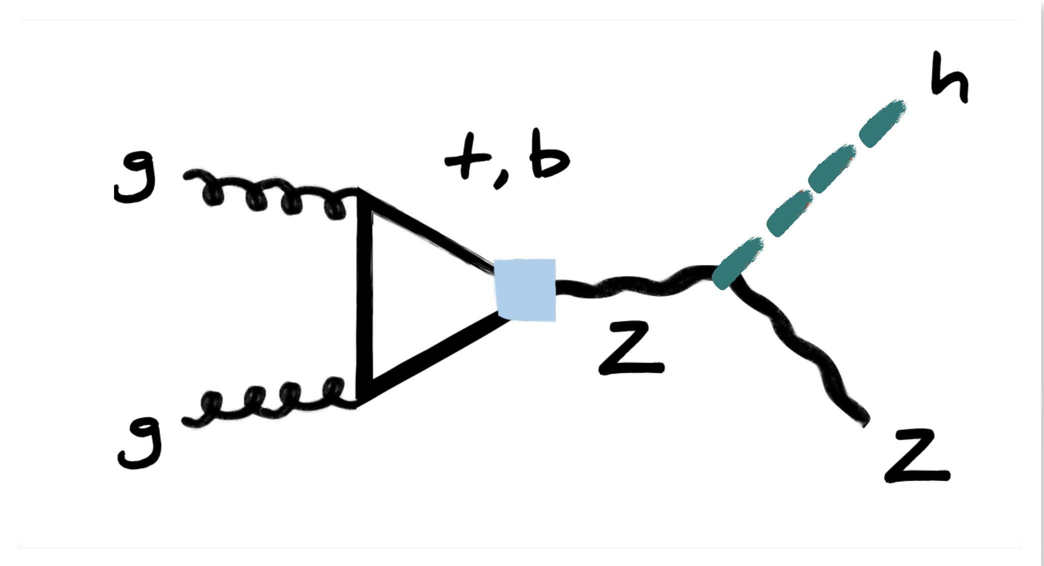


(A-type)

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_{\bar\ell}^+\right) = -\frac{2\,[21]\,\big([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\big)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^-,2_g^-,3_\ell^\mp,4_{\bar\ell}^\pm\right) = -\overline{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,4_\ell^\mp,3_{\bar\ell}^\pm\right)}\,,$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_{\bar\ell}^-\right) = \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_{\bar\ell}^+\right)\,,$$



$$\texttt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2}\sum_{h_g,h_\ell=\pm}\left|\sum_{q=t,b}\left(\mathcal{A}^q_\triangle + \sum_{s=\pm}\frac{m_q^2}{m_Z^2}\,\mathcal{A}^{q,s}_\square\right)\right|^2\,,$$

with

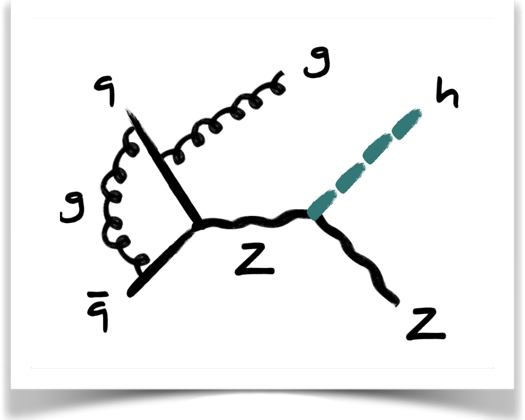
$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_{\bar\ell}^{-h_\ell}\right)\,,$$

Sources: [1] ArXiv:2012.13989 (F. Feruglio), [2] ArXiv:2012.07740 (Q. Bonnefoy, L. Di Luzio, Ch. Grojean, A. Paul, A.N. Rossia), ArXiv:1801.03505 (P.J. Fox, I. Low, Y. Zhang).

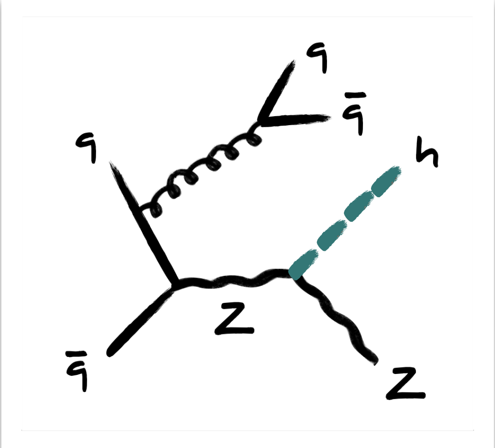
2. Details of the calculation

2.2 *gg*-initiated contributions

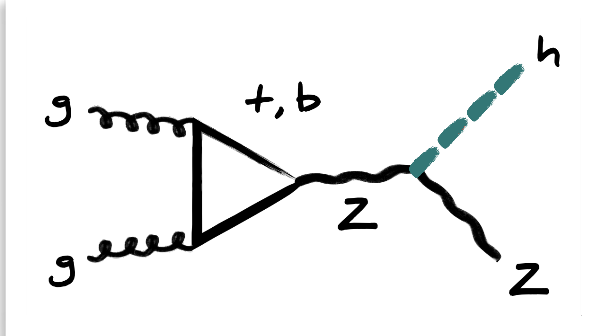
How can we calculate the relevant **SMEFT matrix elements**?



(B-type)



(C,D-type)



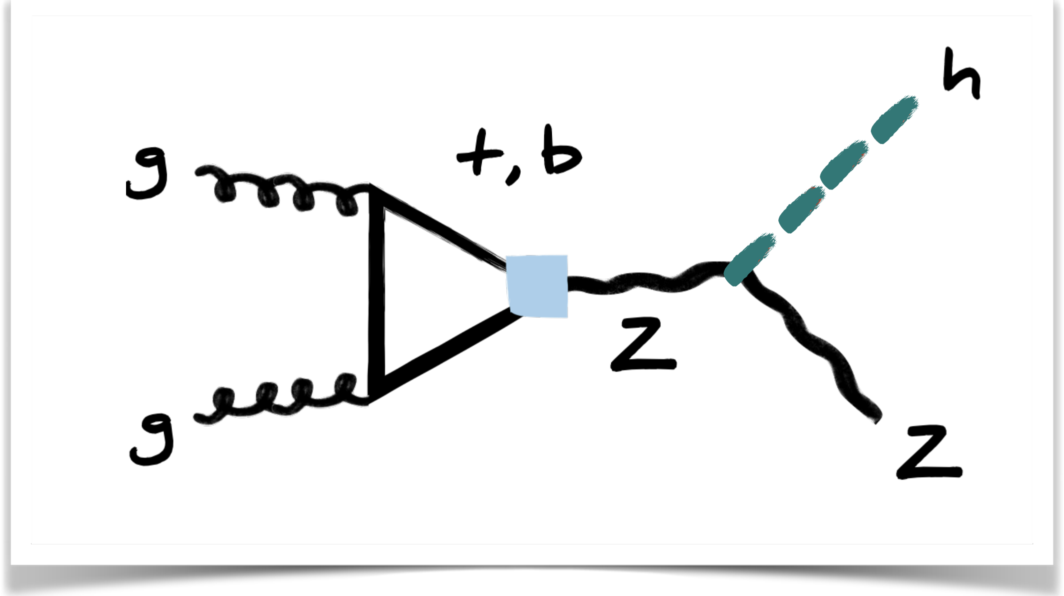
(A-type)

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_{\bar\ell}^+\right) = -\frac{2\,[21]\left([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\right)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^-,2_g^-,3_\ell^\mp,4_{\bar\ell}^\pm\right) = -\overline{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,4_\ell^\mp,3_{\bar\ell}^\pm\right)}\,,$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_{\bar\ell}^-\right) = \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_{\bar\ell}^+\right)\,,$$

The **axial current** contributes.
→ gauge anomalies?



$$\texttt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2}\sum_{h_g,h_\ell=\pm}\left|\sum_{q=t,b}\left(\mathcal{A}^q_\triangle + \sum_{s=\pm}\frac{m_q^2}{m_Z^2}\,\mathcal{A}^{q,s}_\square\right)\right|^2,$$

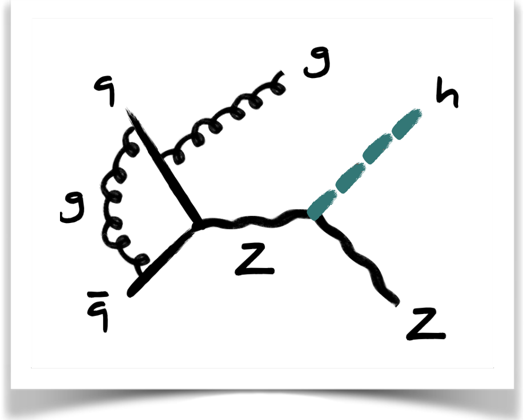
with

$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_{\bar\ell}^{-h_\ell}\right)\,,$$

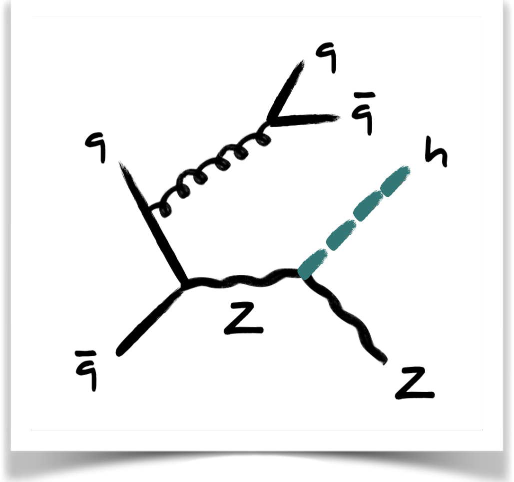
Sources: [1] ArXiv:2012.13989 (F. Feruglio), [2] ArXiv:2012.07740 (Q. Bonnefoy, L. Di Luzio, Ch. Grojean, A. Paul, A.N. Rossia), ArXiv:1801.03505 (P.J. Fox, I. Low, Y. Zhang).

2. Details of the calculation

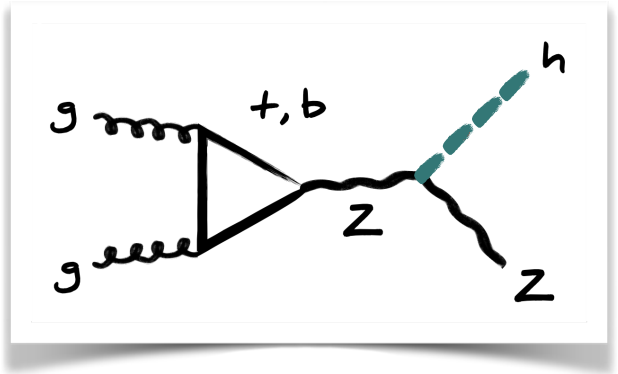
2.2 gg-initiated contributions



(B-type)



(C,D-type)



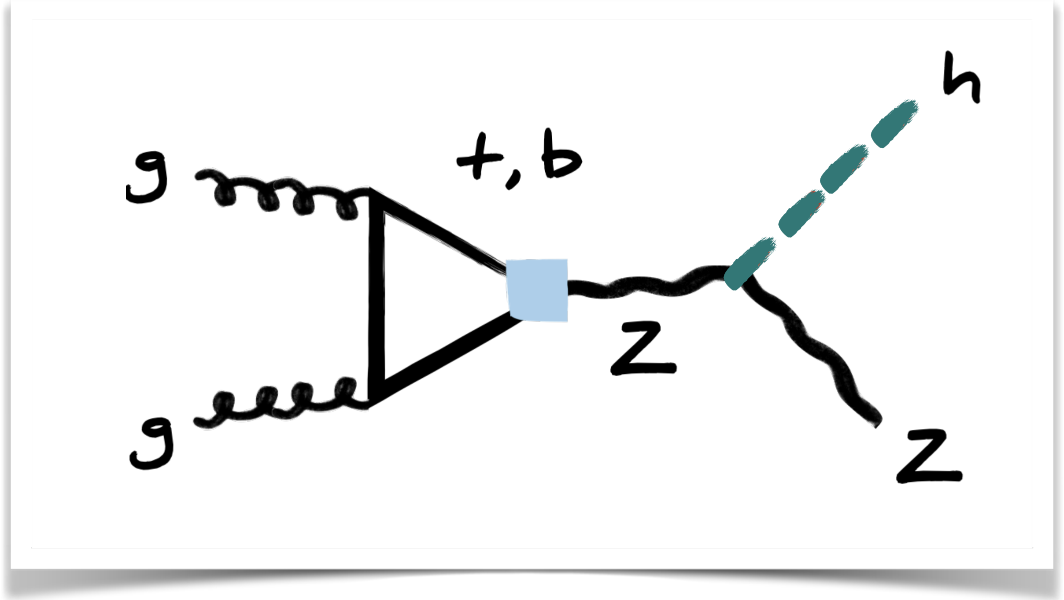
(A-type)

How can we calculate the relevant **SMEFT matrix elements**?

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_\ell^+\right) = -\frac{2\,[21]\,\big([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\big)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^-,2_g^-,3_\ell^\mp,4_\ell^\pm\right) = -\overline{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,4_\ell^\mp,3_\ell^\pm\right)}\,,$$

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,3_\ell^+,4_\ell^-\right) = \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^\pm,2_g^\pm,4_\ell^-,3_\ell^+\right)\,,$$



$$\texttt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2}\sum_{h_g,h_\ell=\pm}\left|\sum_{q=t,b}\left(\mathcal{A}^q_\triangle + \sum_{s=\pm}\frac{m_q^2}{m_Z^2}\,\mathcal{A}^{q,s}_\square\right)\right|^2\,,$$

with

$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_\ell^{-h_\ell}\right)\,,$$

The **axial current** contributes.
→ gauge anomalies?

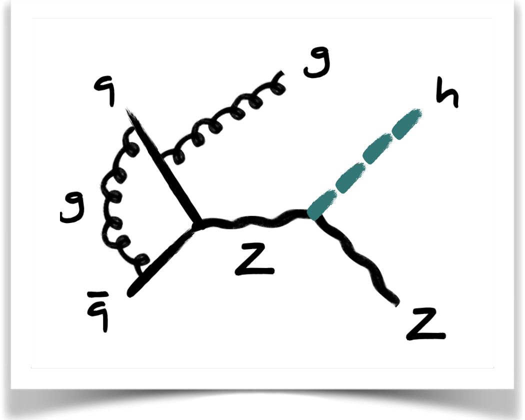
$$(g^-_{Zt}-g^+_{Zt}) = -(g^-_{Zb}-g^+_{Zb})\,,$$

Is required in the SM to cancel the **relevant anomalies** in the SM.

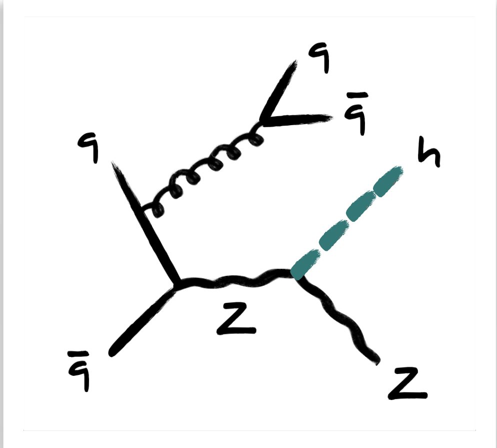
Sources: [1] ArXiv:2012.13989 (F. Feruglio), [2] ArXiv:2012.07740 (Q. Bonnefoy, L. Di Luzio, Ch. Grojean, A. Paul, A.N. Rossia), ArXiv:1801.03505 (P.J. Fox, I. Low, Y. Zhang).

2. Details of the calculation

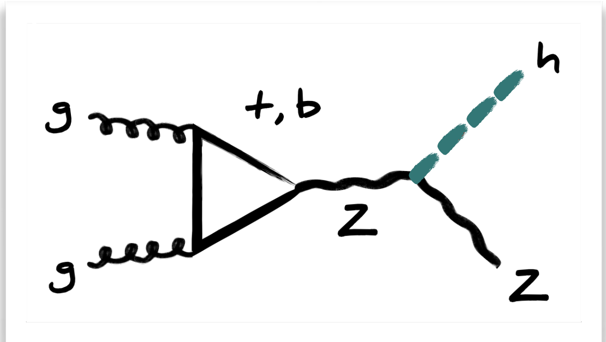
2.2 gg-initiated contributions



(B-type)



(C,D-type)



(A-type)

How can we calculate the relevant **SMEFT matrix elements**?

$$\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^+,2_g^+,3_\ell^-,4_\ell^+\right) = -\frac{2\,[21]\,\left([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\right)}{\langle 12\rangle}\left(1-\frac{s_{12}}{m_Z^2}\right) \times m_q^2\, C_0(s_{12},0,0,m_q,m_q,m_q)\,.$$

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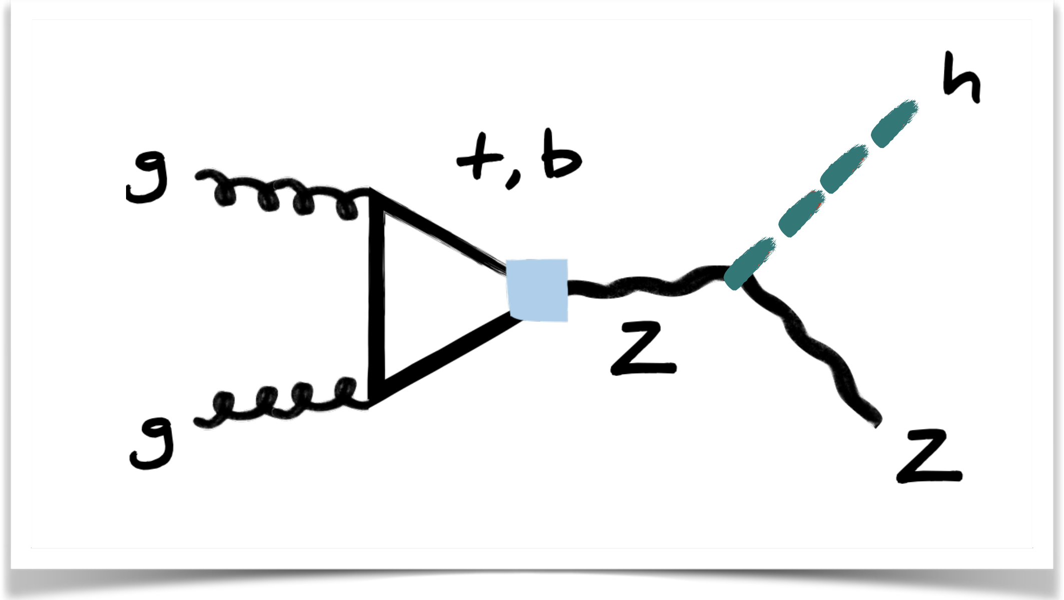

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$$\mathcal{A}^q_\triangle = \frac{(g^-_{Zq}-g^+_{Zq})\,g^{h_\ell}_{Z\ell}\,g_{hZZ}}{D_Z(s_{12})\,D_Z(s_{34})}\,\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g},2_g^{h_g},3_\ell^{h_\ell},4_\ell^{-h_\ell}\right)\,,$$

The **axial current** contributes.
→ gauge anomalies?

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Is required in the SM to cancel the **relevant anomalies** in the SM.
→ **how does this work in the SMEFT?**

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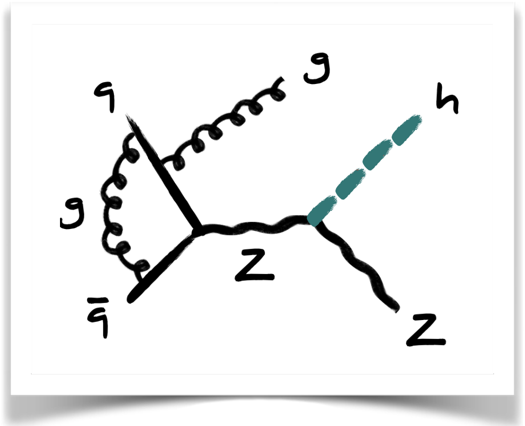
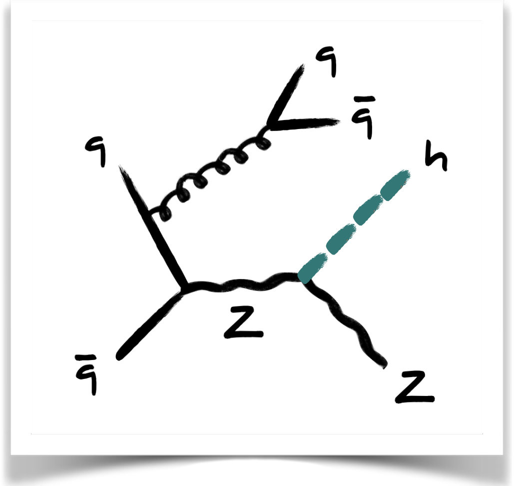
2. Details of the calculation

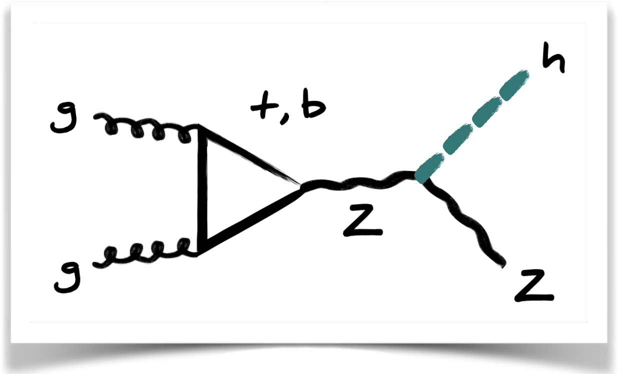
2.2 gg-initiated contributions



(B-type)



(C,D-type)



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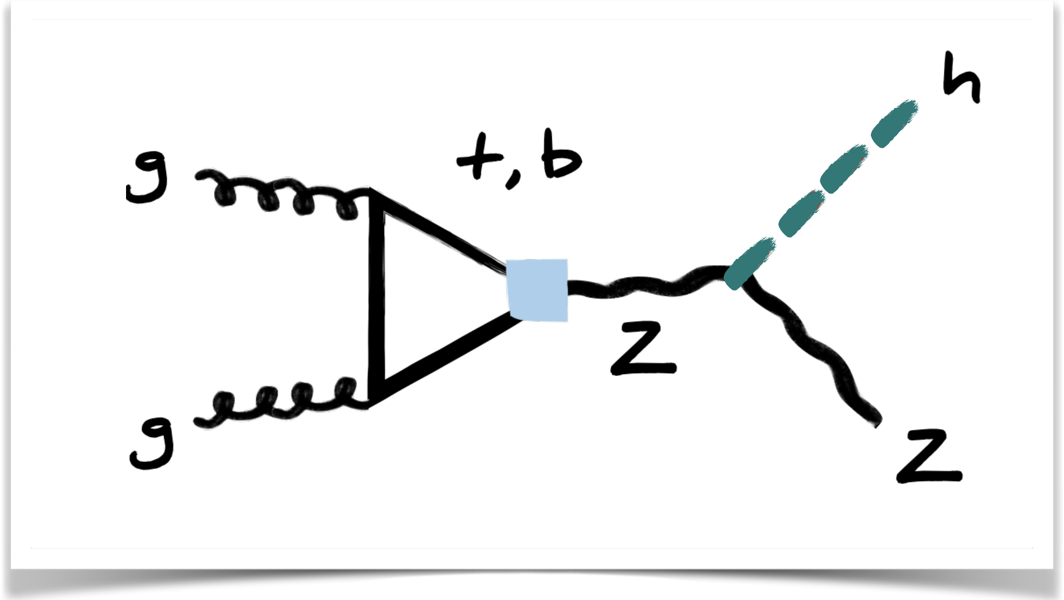

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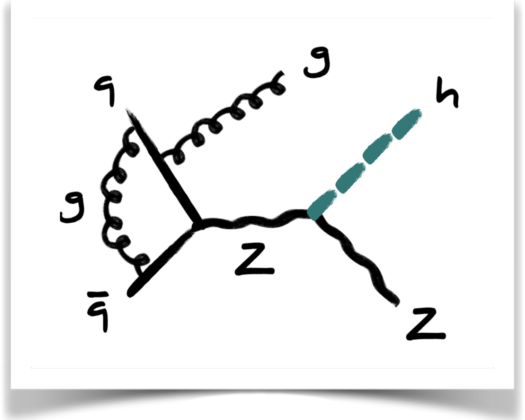

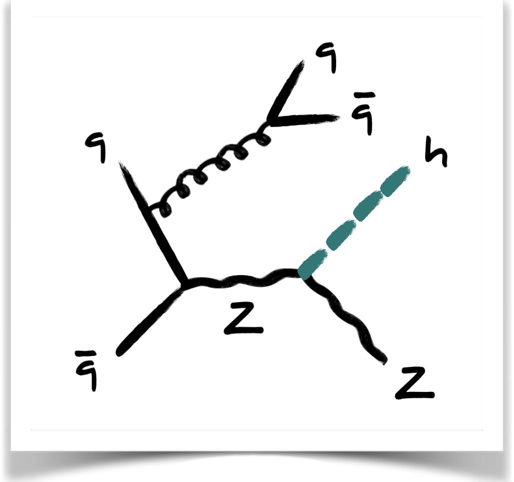

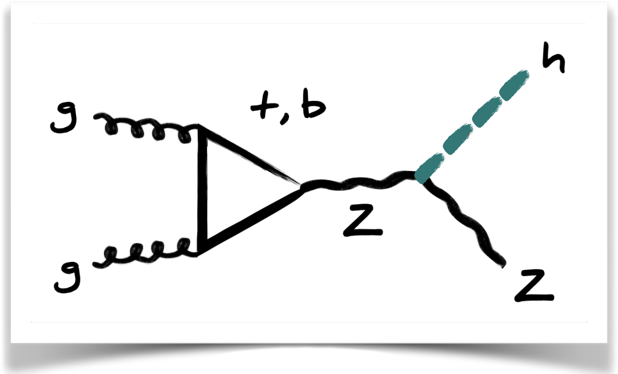

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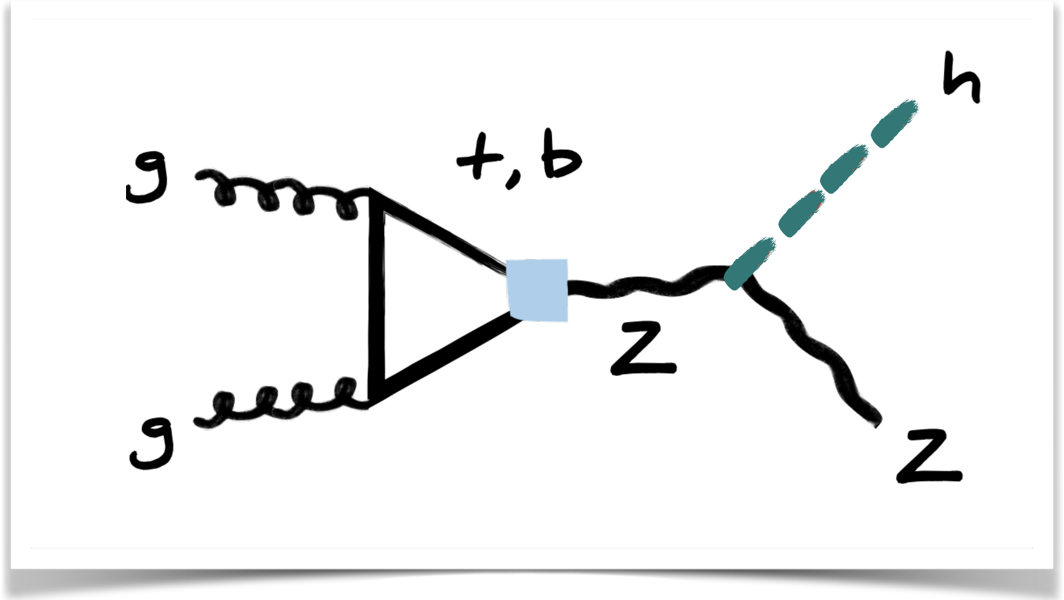

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Is required in the SM to cancel the **relevant anomalies** in the SM.
→ **how does this work in the SMEFT?**

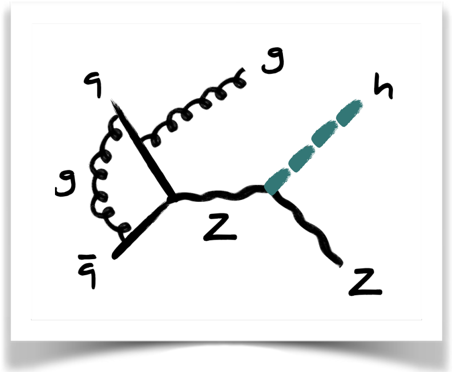
There are no relevant anomalies induced by the SMEFT operators.

The **irrelevant anomalies** (depending on the loop momentum routing scheme) can be cancelled with a local counterterm.

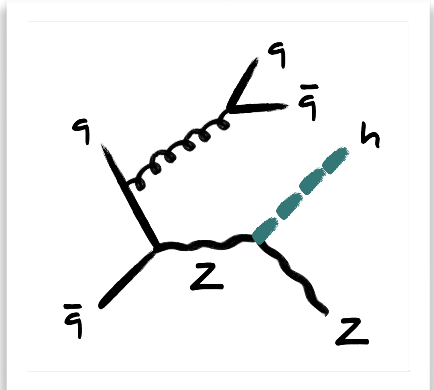
Sources: [1] ArXiv:2012.13989 (F. Feruglio), [2] ArXiv:2012.07740 (Q. Bonnefoy, L. Di Luzio, Ch. Grojean, A. Paul, A.N. Rossia), ArXiv:1801.03505 (P.J. Fox, I. Low, Y. Zhang).

2. Details of the calculation

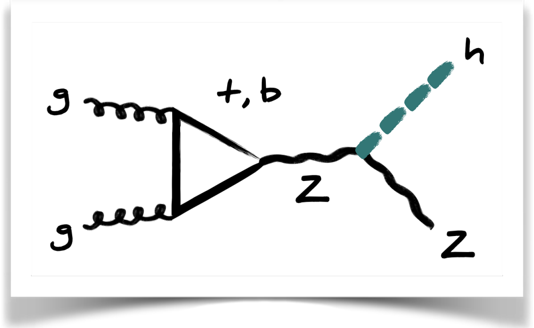
2.3 Matrix element library



(B-type)



(C,D-type)



(A-type)

We implemented all squared matrix elements in a **self-contained `Fortran` library**.

It includes the **spinor-helicity amplitudes for the dimension-four SM and dimension-six SMEFT contributions** as well as the definitions for the **couplings** and the **propagators** depending on the EW input scheme.

`B0g0V` `B1g0V` `B0g1V` `B1g1V` `B2g0V` `B0g2V`

`C0g0V` `D0g0V`

`A0g0V`

`B1g0V_colour` `B1g0V_spin`

$$2 s_b \mathcal{B}_{ij} = -N \sum_{\substack{\text{spins}\\ \text{colours}}} \mathcal{M}_{\{c_k\}} \left(\mathcal{M}^\dagger_{\{c_k\}}\right)_{\substack{c_i \to c_i' \\ c_j \to c_j'}} T^a_{c_i,c_i'} T^a_{c_j,c_j'} \, .$$

$$\mathcal{B}_j^{\mu\nu} = N \sum_{\{i\},s_j,s_j'} \mathcal{M}\left(\{i\}, s_j\right) \mathcal{M}^\dagger\left(\{i\}, s_j'\right) \left(\epsilon^\mu_{s_j}\right)^* \epsilon^\nu_{s_j'} \, ,$$

crossings event flavours

```
B1g0Z(i1,i2,i3,i4,i5,K,f1,f2)
```

Sources: [1] gitlab.com/lucschnell/vh-amplitudes (R. Gauld, U. Haisch, LS).

2. Details of the calculation

2.4 POWHEG event generator

We implemented the matrix element library in a **POWHEG MiNNLO$_{\mathrm{PS}}$ event generator**.

```
! ================================================
! Cuts
! ================================================
min_z_mass  10d0
max_z_mass  10000d0
min_h_mass  10d0
max_h_mass  10000d0
! ================================================

! ================================================
! Model parameters
! ================================================
! Input scheme
InputScheme 2   ! Input scheme. 0 = (Alpha, MZ, MW), 1 = (GF, MZ, MW), 2 = (Alpha, GF, MZ)

! Input parameters
mz 91.1876d0
Gfermi 1.1663788d-5
alpha 7.81549186d-3

mh 125.09d0
gh 4.1d-3
mt 172.5d0
mb 4.78d0

! Cutting-edge calculations for the SM
mw 80.361d0
gw 2.089d0
gz 2.4952d0

! Switches
SM          0     ! Switch (on/off). Whether to include the SM contribution or not.
Linear      1     ! Switch (on/off). Whether to include the linear NP corrections or not.
Quadratic   0     ! Switch (on/off). Whether to include the quadratic NP corrections or not.
```

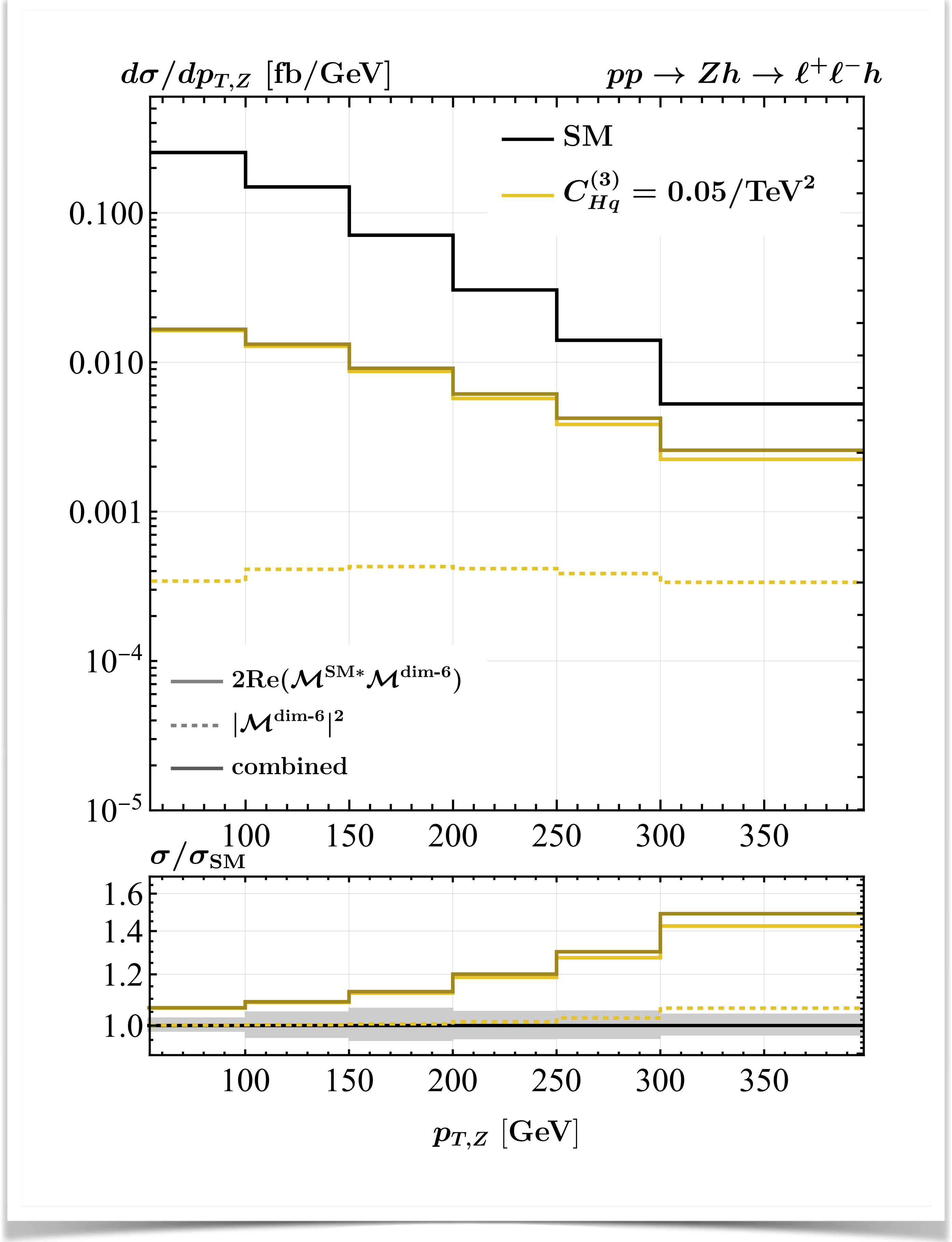
We will make it **available for download** on the POWHEG-BOX web page [1].

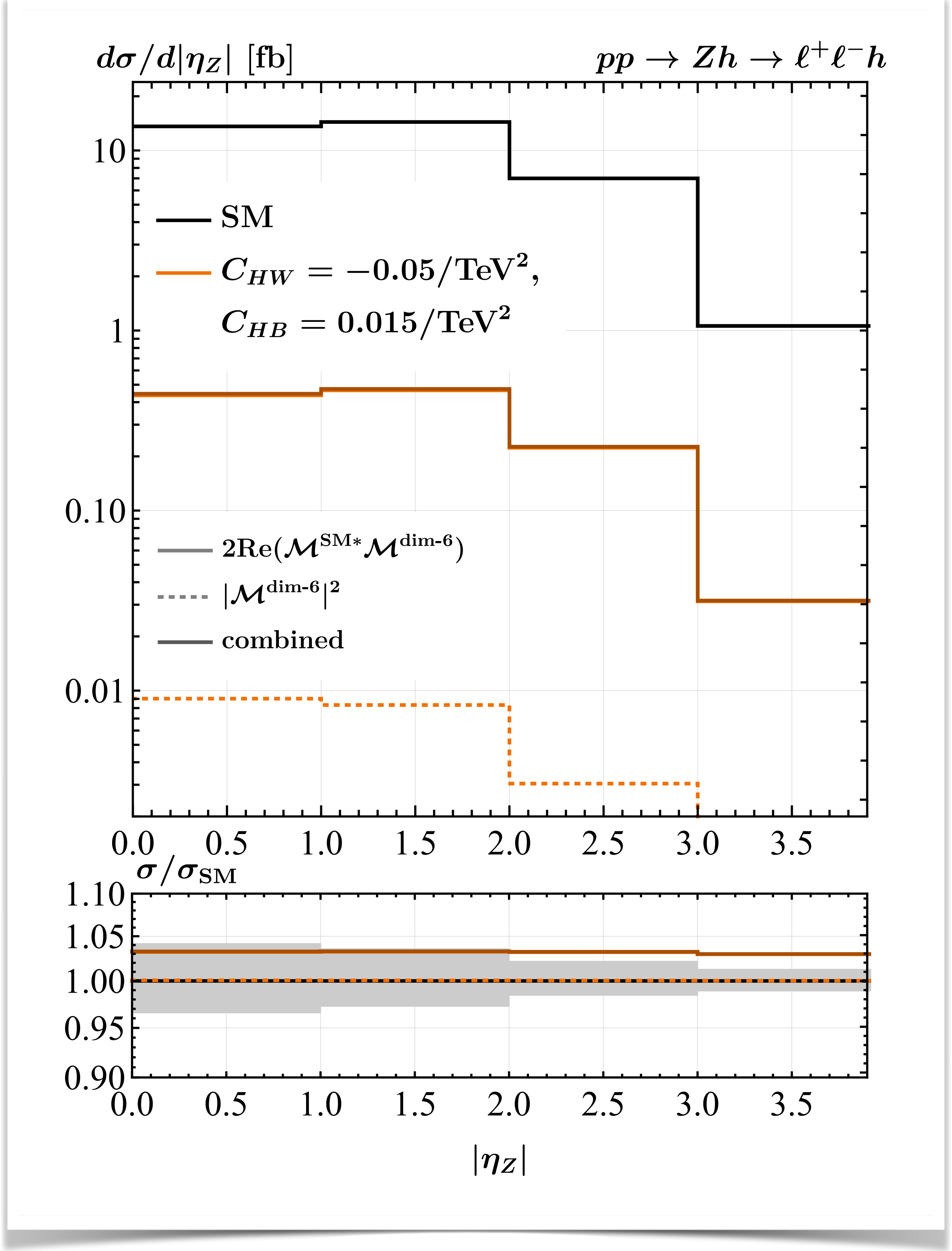
Sources: [1] powhegbox.mib.infn.it (S. Aioli, K. Hamilton, P. Nason, C. Oleari, E. Re. G. Zanderighi, T. Jezo).

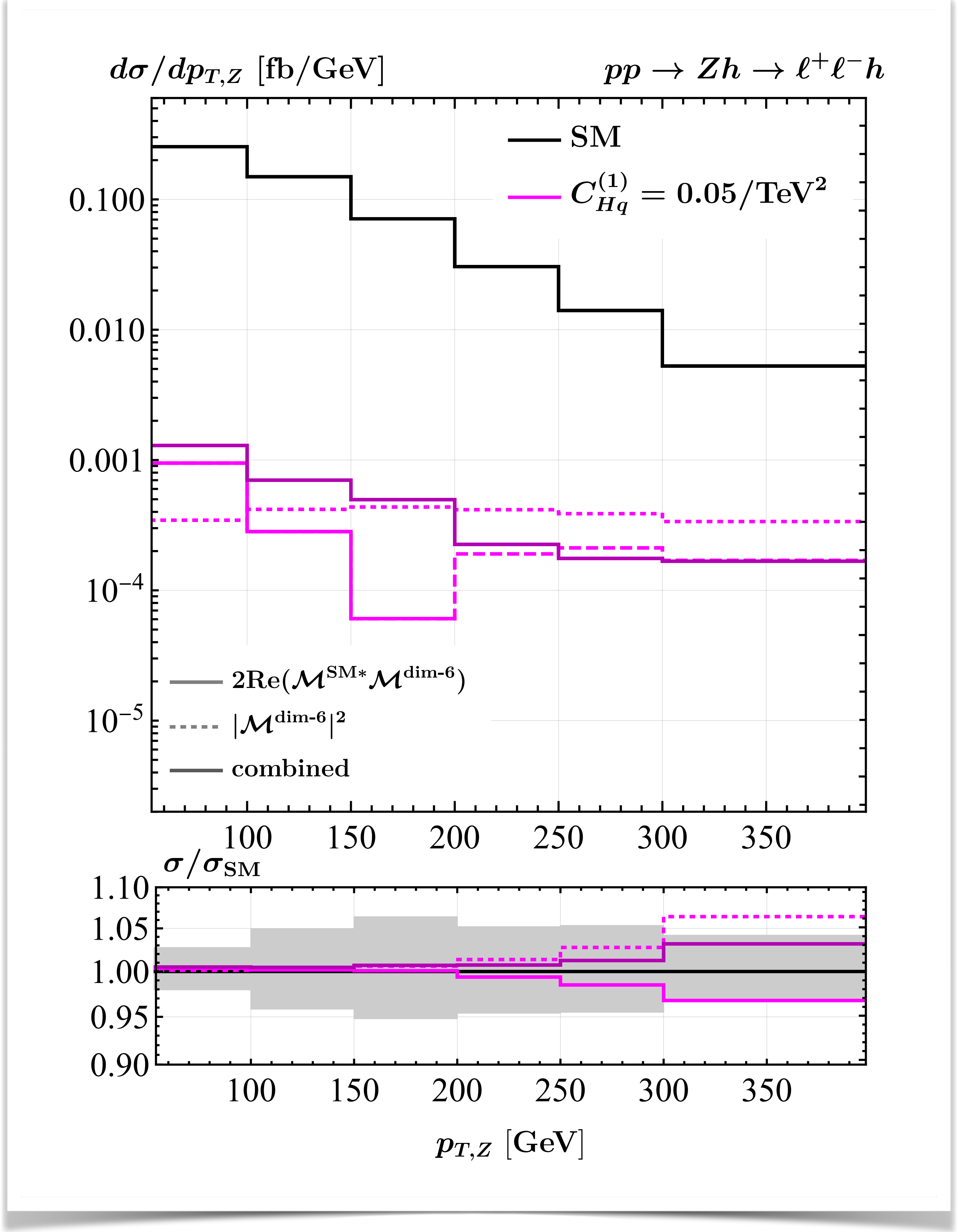
4. Results

4. Results

4.1 Spectra



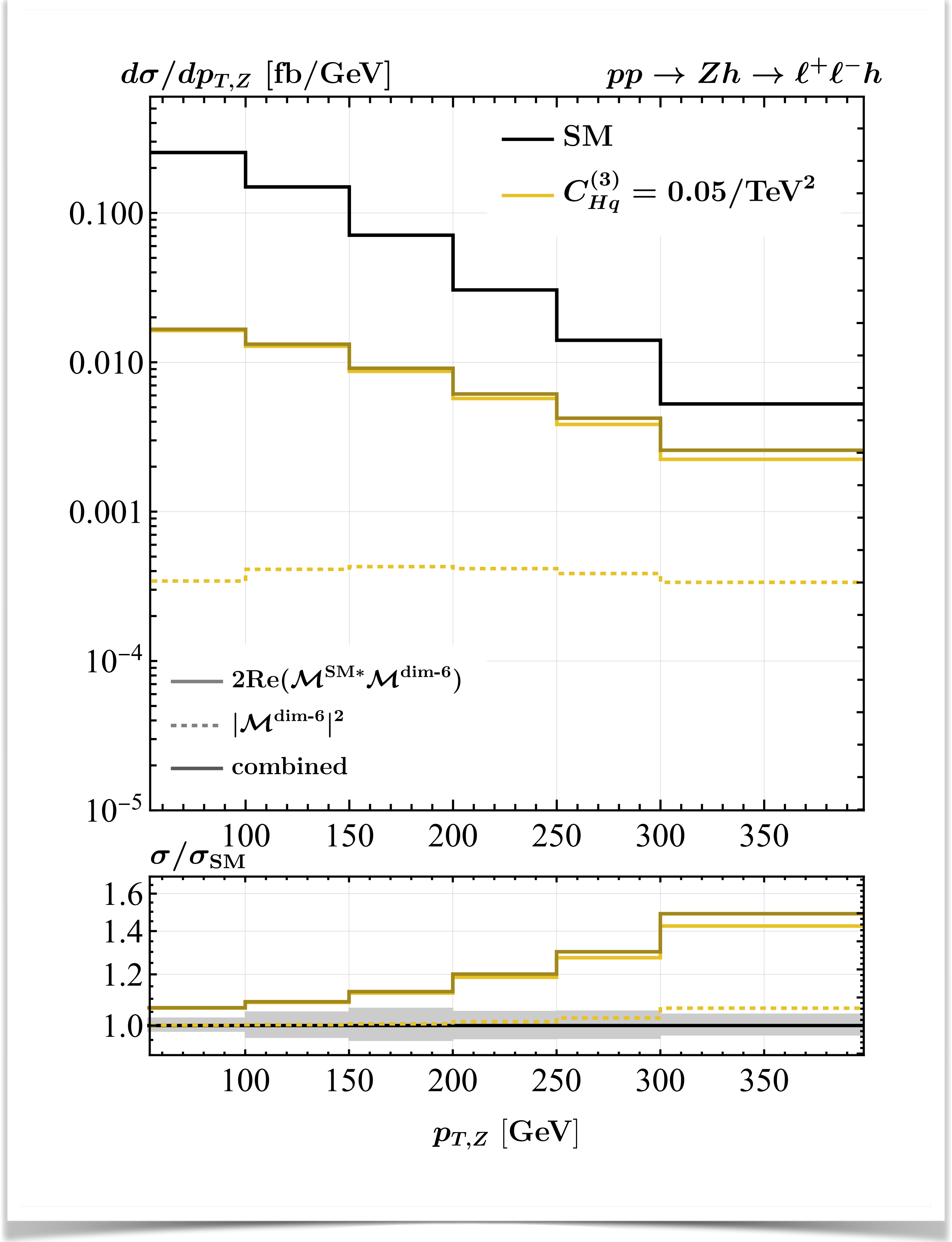


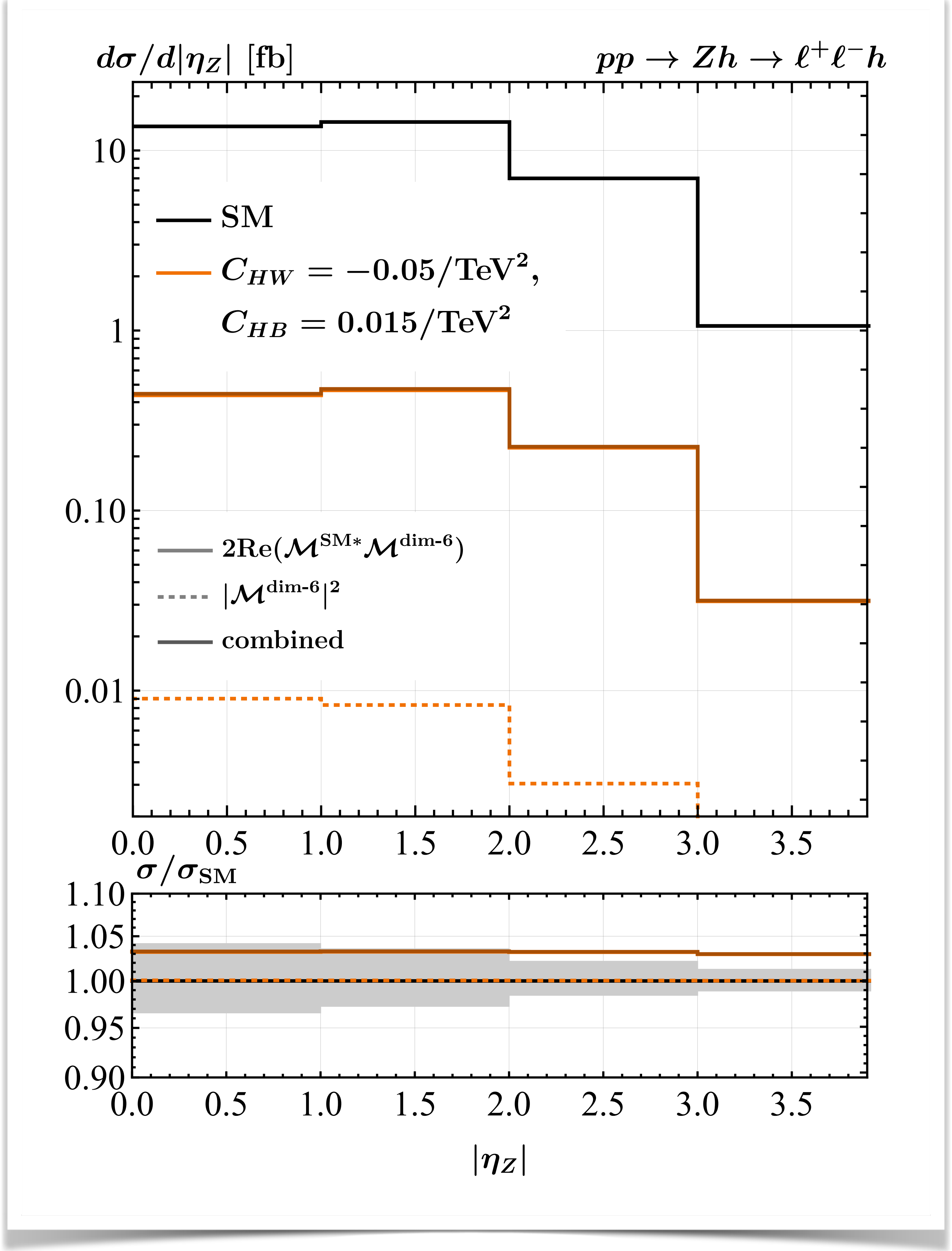


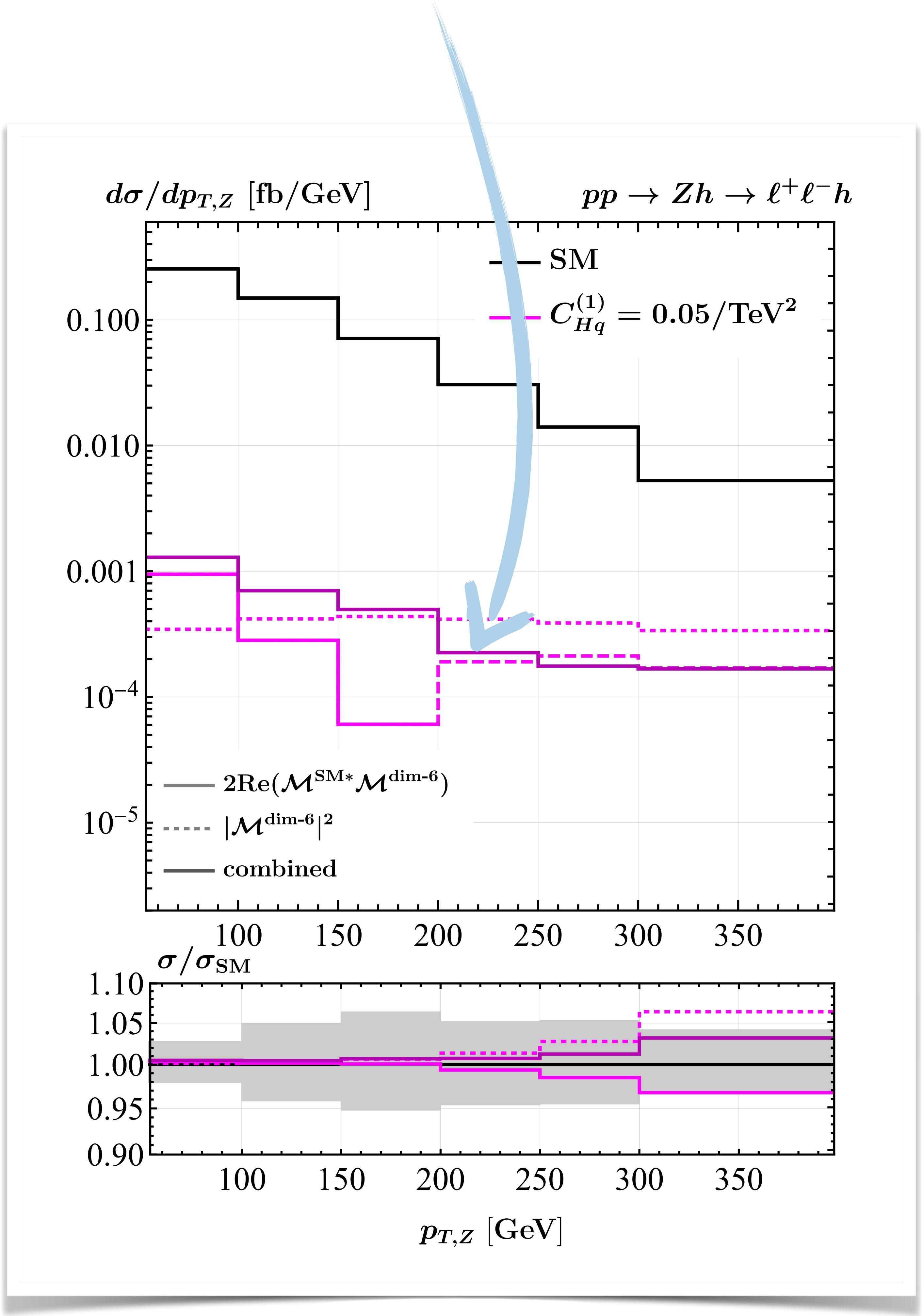
4. Results

4.1 Spectra

$g_{Zu}^{-} \sim \frac{1}{3}g_1^2 - g_2^2 \sim -0.38$ $\quad g_{Zd}^{-} \sim \frac{4}{3}g_1^2 + g_2^2 \sim 0.60$ $\quad \delta g_{Zu}^{(1)-} = \delta g_{Zd}^{(1)-} \sim C_{Hq}^{(1)}$

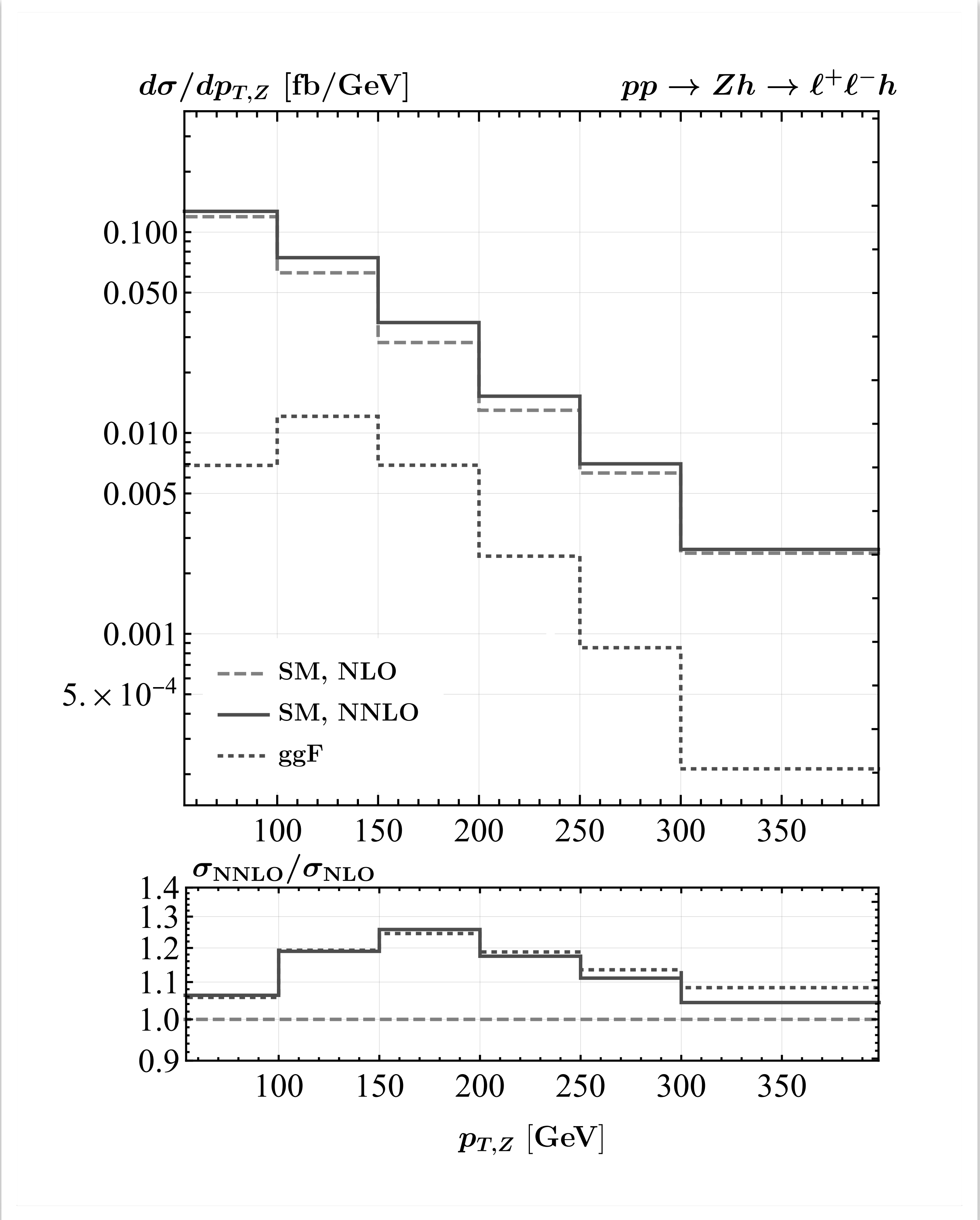


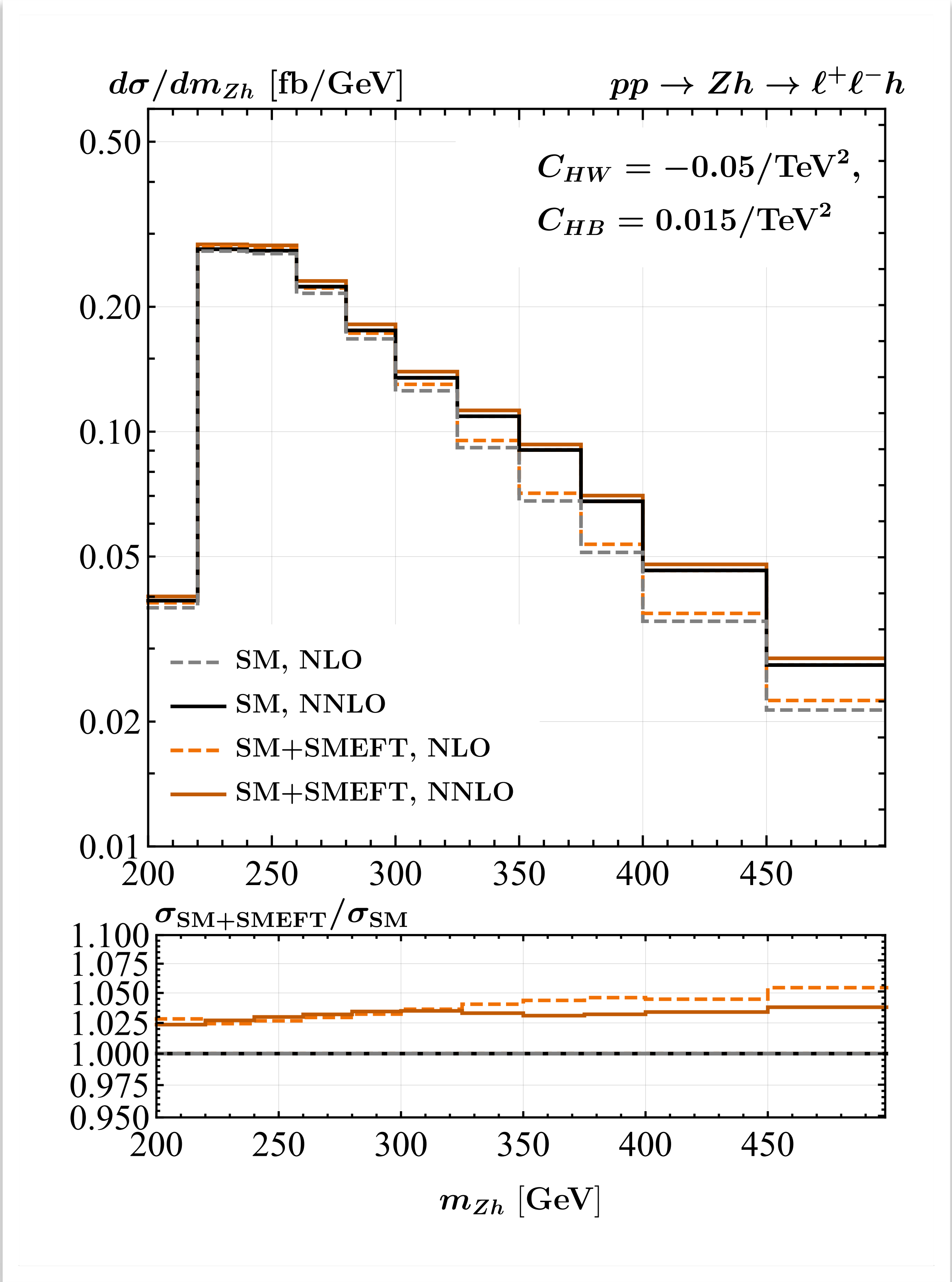


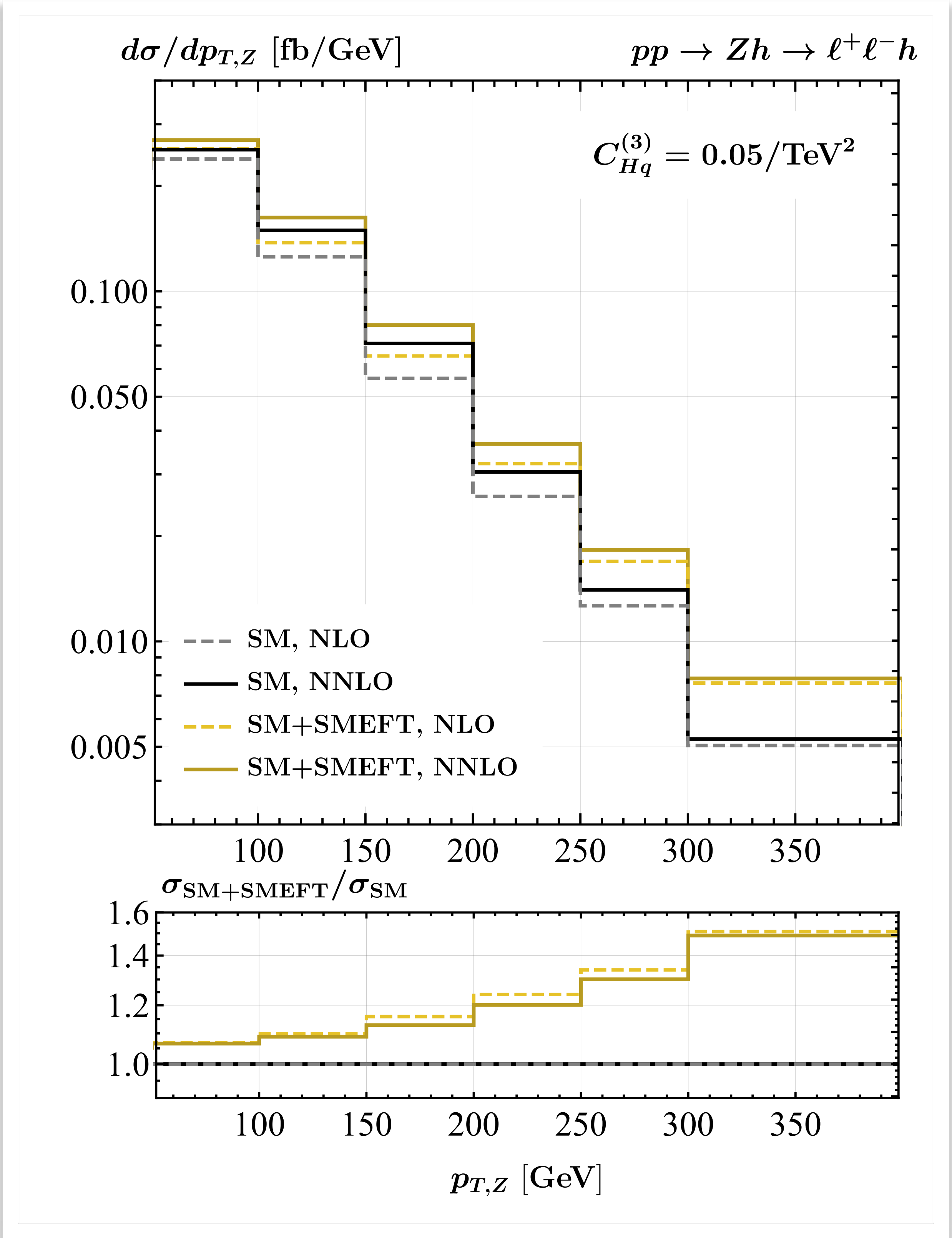


4. Results

4.2 NNLO vs NLO





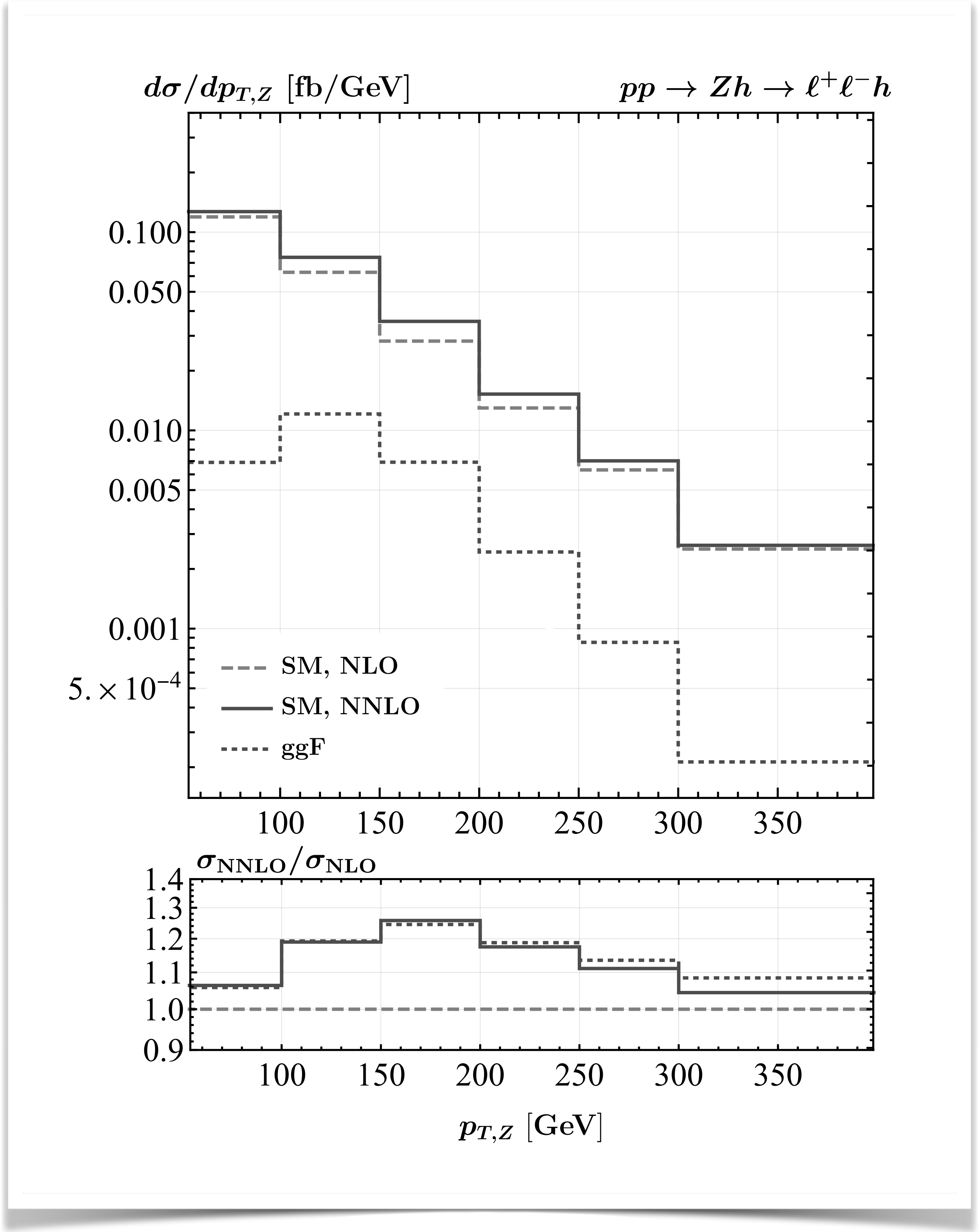


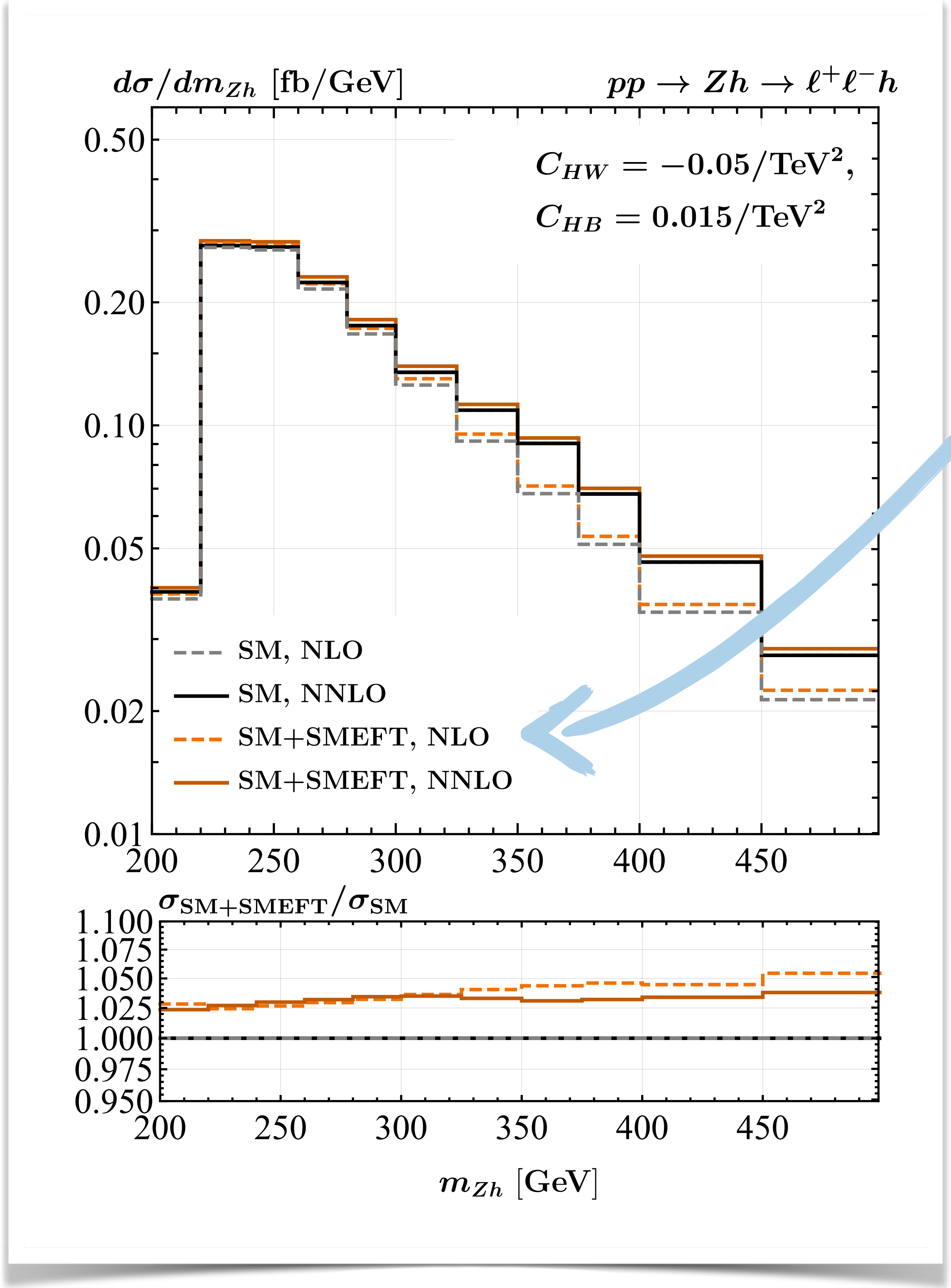
Sources: [1] ArXiv:1804.07407 (S. Alioli, W. Dekens, M. Girard, E. Mereghetti).

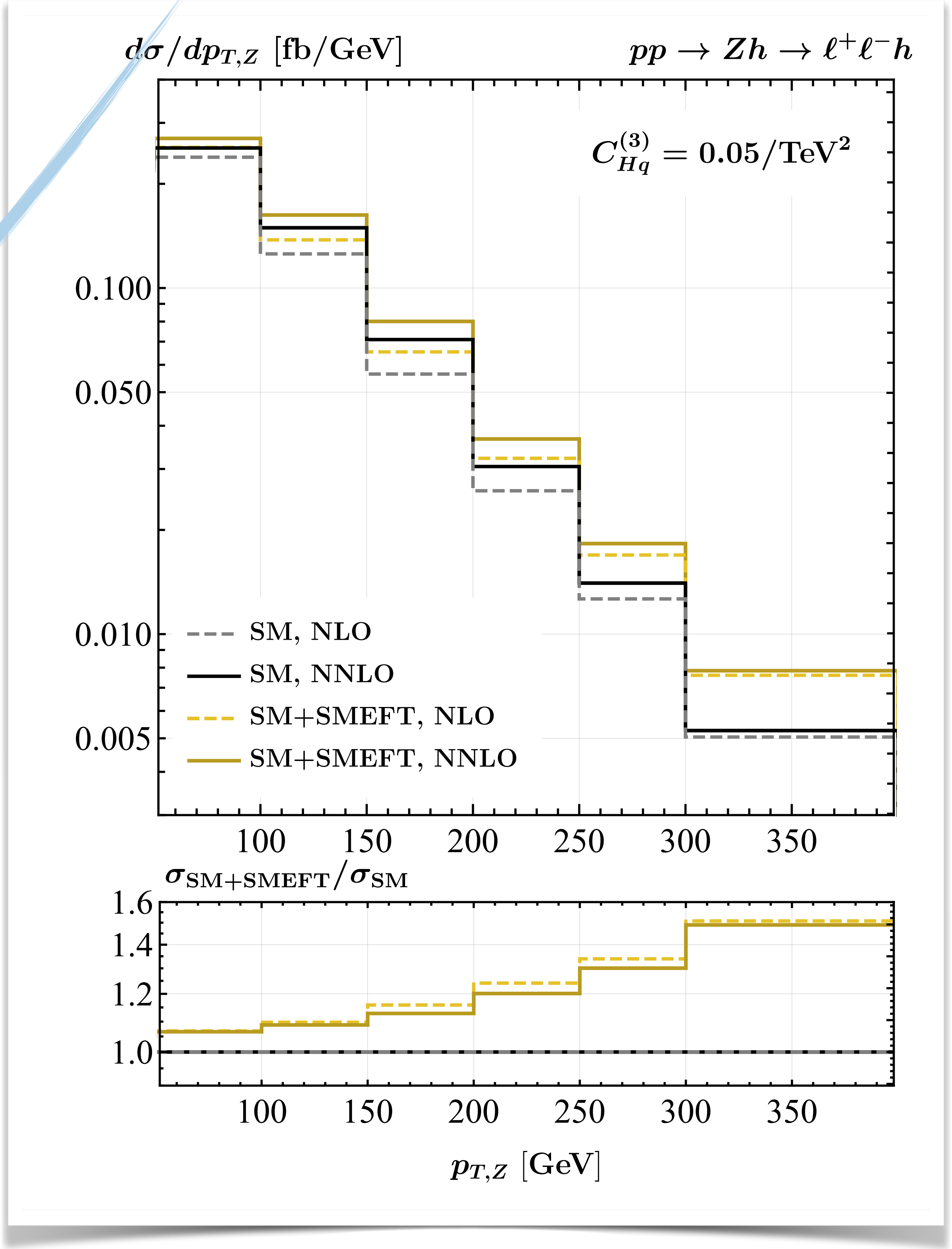
4. Results

4.2 NNLO vs NLO

From [1]: only $\left|M_{\text{dim-4}} + M_{\text{dim-6}}\right|^2$, no input scheme corrections.







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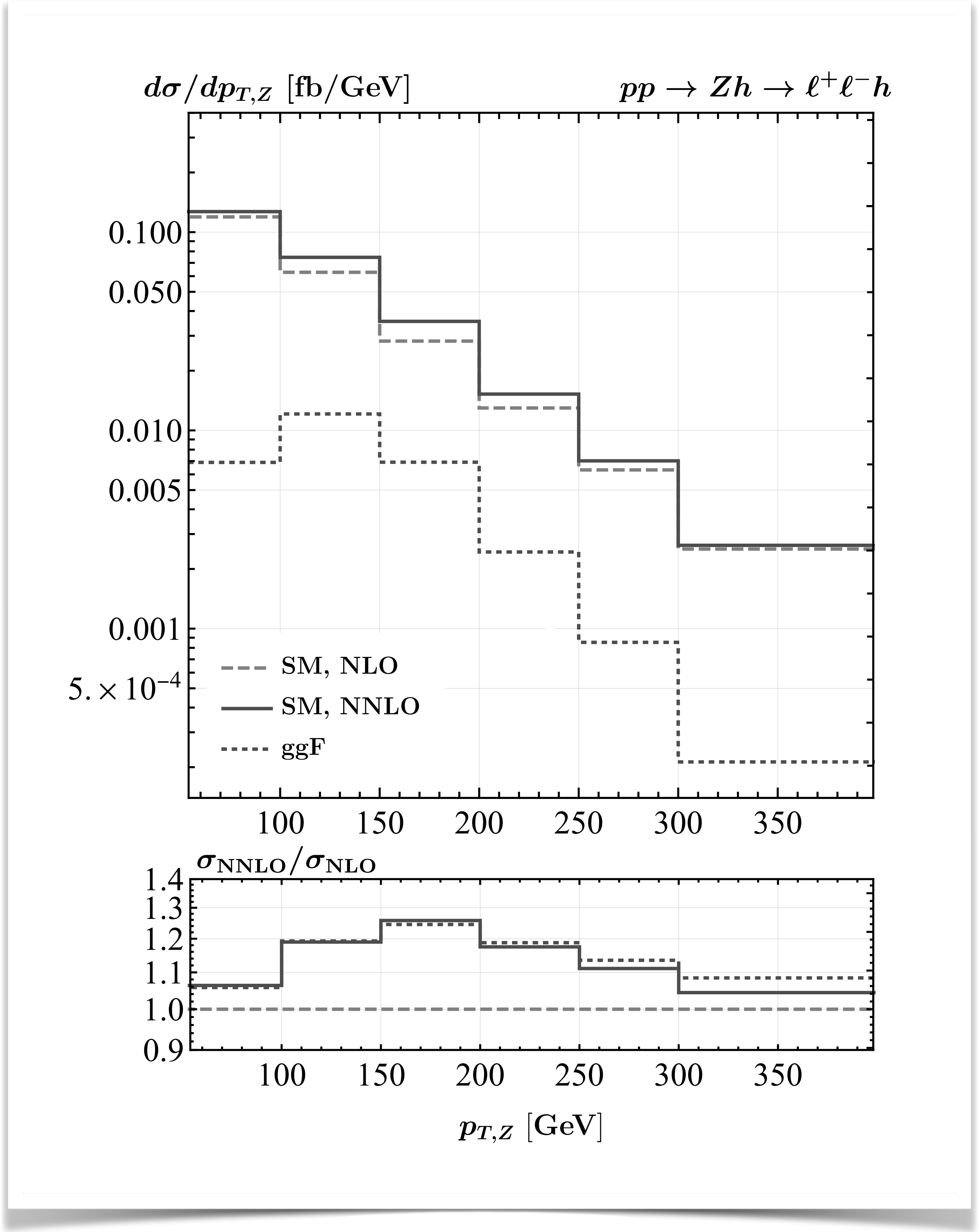

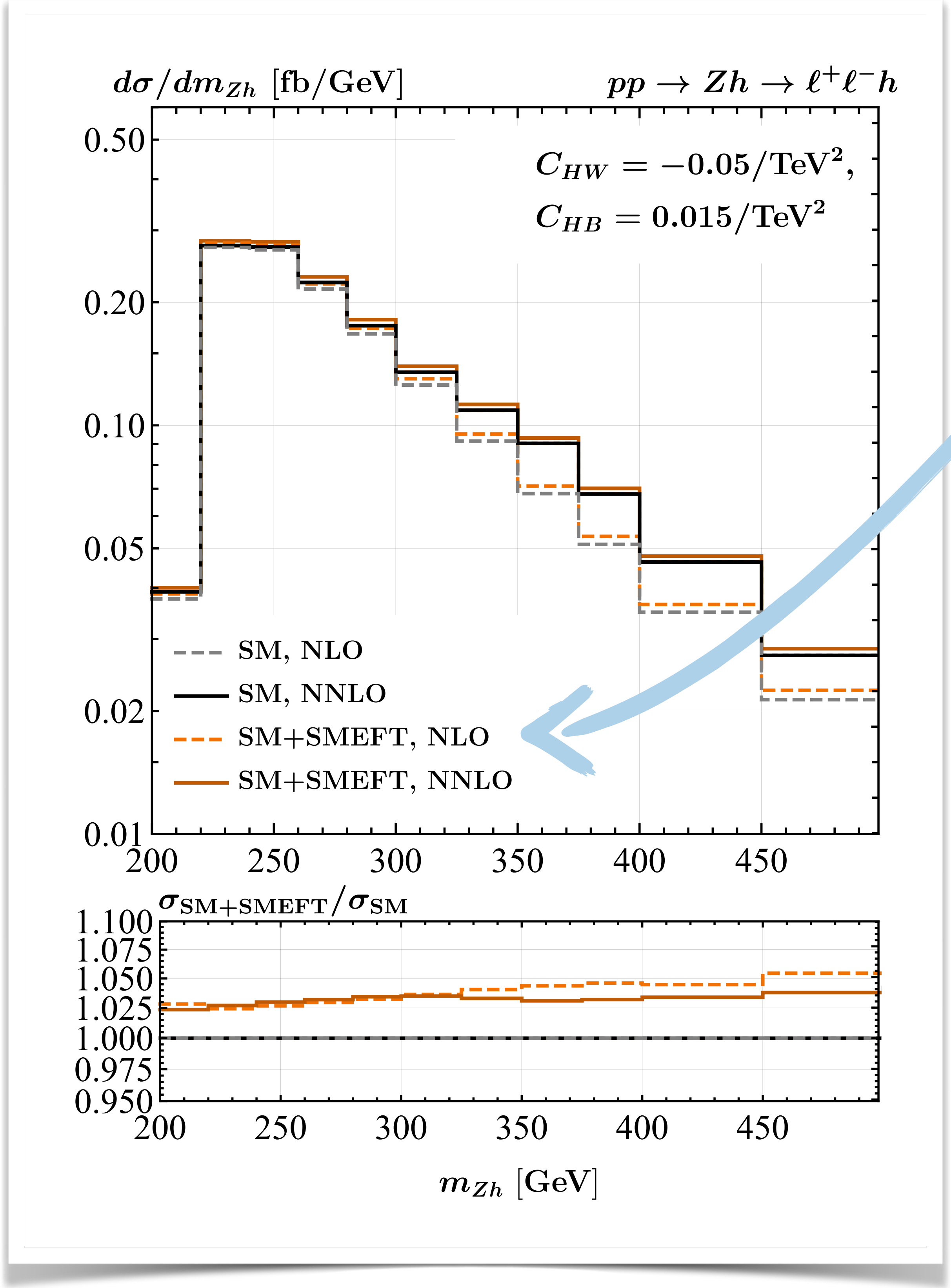

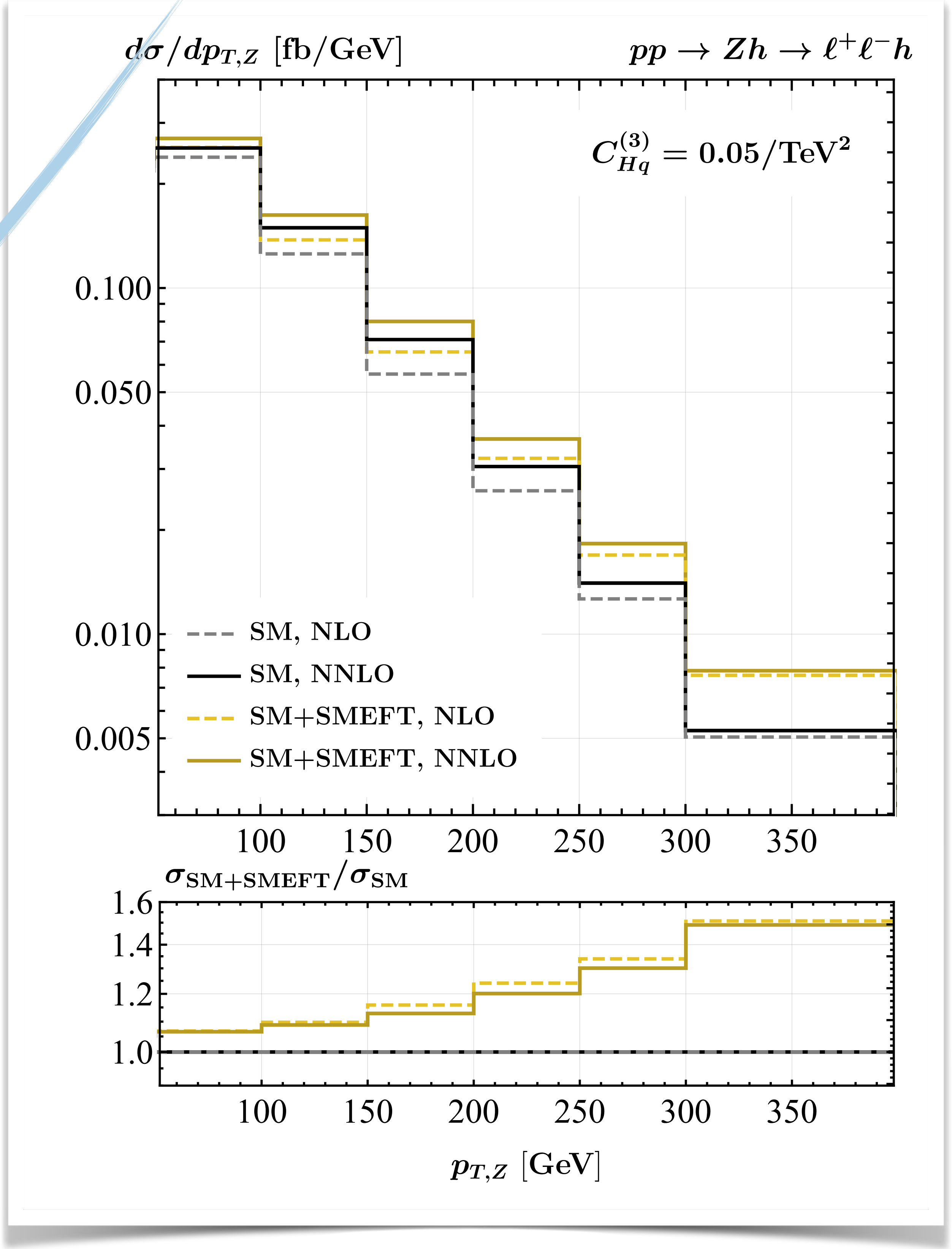

Our code can do $\left|M_{\text{dim-4}}\right|^2$, $2\text{Re}\left\{M^{\dagger}_{\text{dim-4}}M_{\text{dim-6}}\right\}$, $\left|M_{\text{dim-6}}\right|^2$ individually, for all three input schemes.

Sources: [1] ArXiv:1804.07407 (S. Alioli, W. Dekens, M. Girard, E. Mereghetti).

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  → **essential tool for future Higgs characterisation studies at the LHC**

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  → **essential tool for future Higgs characterisation studies at the LHC**

- Higher-order SMEFT calculations come with **interesting theoretical aspects**, including the „recycling“ of SM spinor-helicity amplitudes and the treatment of gauge anomalies.

Thank you for your attention!

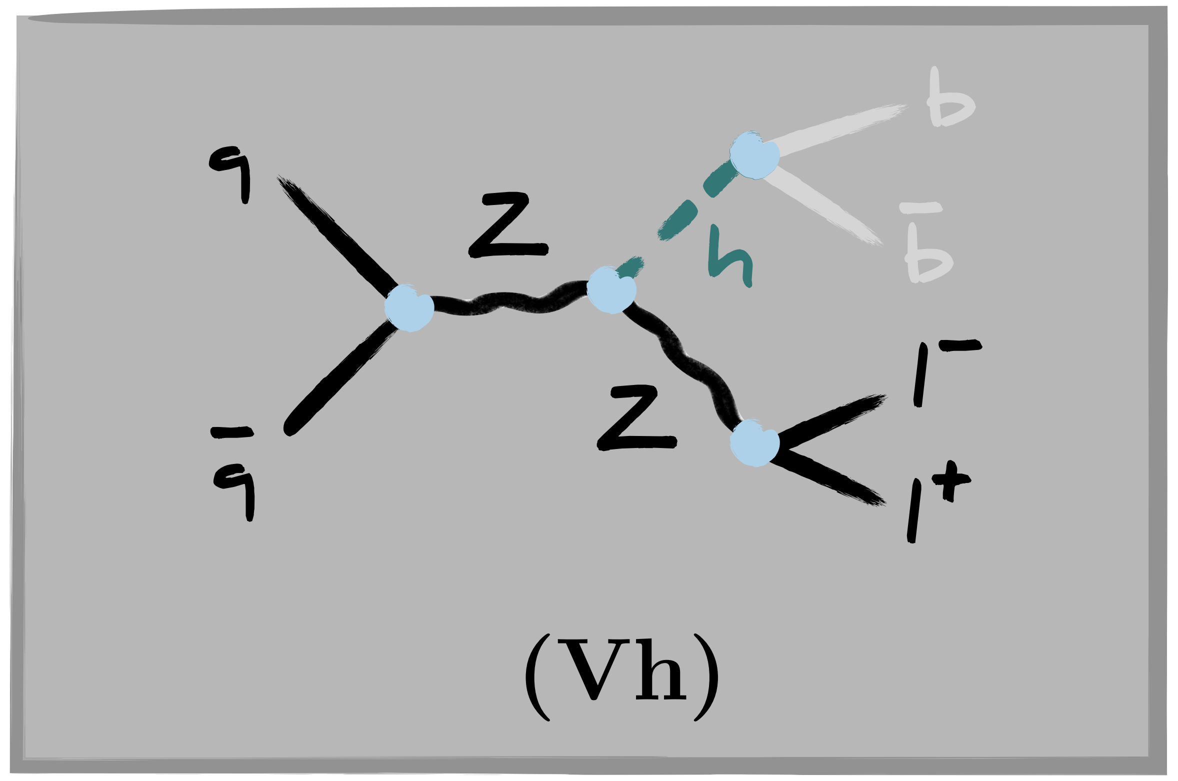
Source Image: cds.cern.ch.

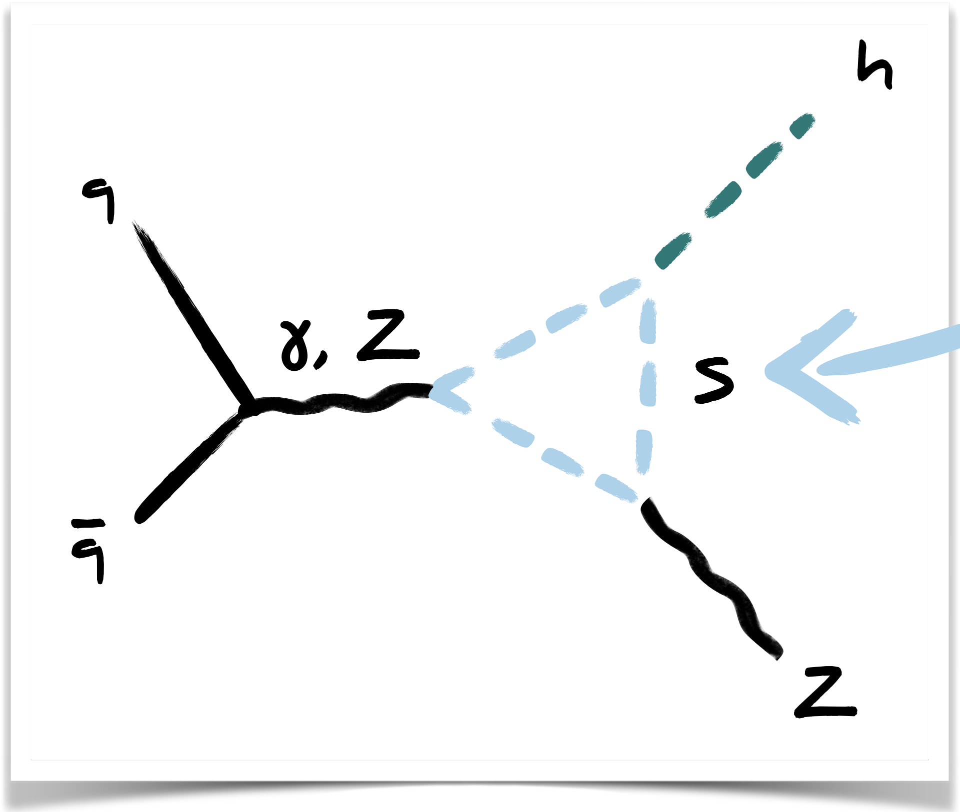
Introduction

Theoretical predictions (BSM)

What about **new effects**?

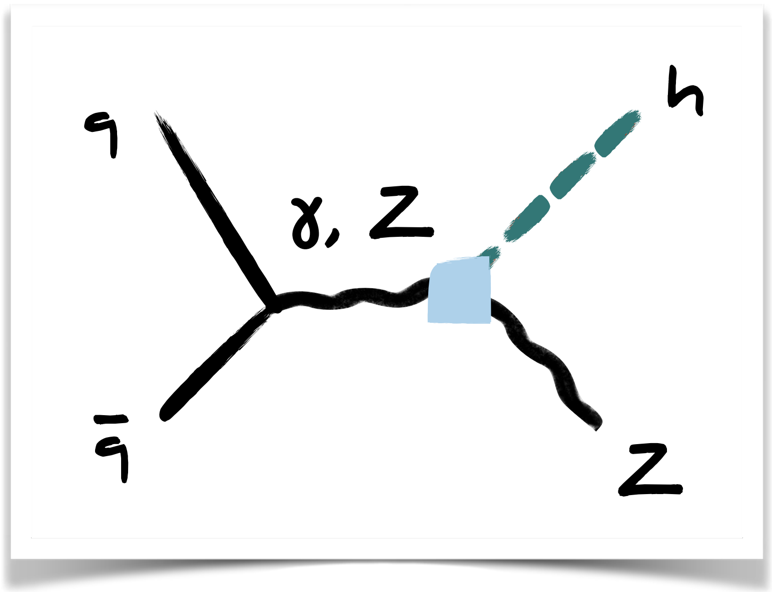
Has to be **heavy**, otherwise we would have produced it resonantly.





High scale $\Lambda_{UV} \sim M_S$

$$\int \frac{dk^D}{(2\pi)^D} \frac{\dots}{((p+k)^2 - M_S^2)\ \dots}$$



LHC scale Λ_{LHC}

$$\int \frac{dk^D}{(2\pi)^D} \frac{\dots}{((\not{p} + k)^2 - M_S^2)\ \dots} \sim \underbrace{\int \frac{dk^D}{(2\pi)^D} \frac{\dots}{(k^2 - M_S^2)\ \dots}}_{\text{independent of kinematics}}$$

The SMEFT allows us to study the **indirect contributions** from high-scale BSM physics in a (largely) **model-independent way**.

Anatomy of SMEFT effects

Current constraints

What are the **current constraints** on these types of SMEFT operators?

V(h)qq: $C_{Hq}^{(1)}, C_{Hq}^{(3)}, C_{Hu}, C_{Hd}$

$$\delta g_L^{\psi} = \frac{g_2}{c_w}\frac{v^2}{\Lambda^2}\left[g_{T_\psi^3} T_\psi^3 - g_{Q_\psi} Q_\psi - \frac{1}{2}\left(C_{H\psi_L}^{(1)} - 2T_\psi^3 C_{H\psi_L}^{(3)}\right)\right],$$

V(h)ll: $C_{Hl}^{(1)}, C_{Hl}^{(3)}, C_{He}$

VVh: C_{HB}, C_{HW} C_{HWB}

$$\delta\kappa_{\gamma\gamma} \simeq \frac{1}{g_{h\gamma\gamma}}\frac{v^2}{\Lambda^2}\left[c_w^2 C_{HB} + s_w^2 C_{HW} - c_w s_w C_{HWB}\right],$$

$$\delta\kappa_{\gamma Z} \simeq -\frac{1}{g_{h\gamma Z}}\frac{v^2}{\Lambda^2}\left[2c_w s_w (C_{HB} - C_{HW}) + (c_w^2 - s_w^2) C_{HWB}\right],$$

LEP/SLD:

$$\delta g_L^u \in [0.2, 6.8]\cdot 10^{-2},$$

$$\delta g_L^e \in [-7.1, 2.0]\cdot 10^{-4},$$

$$\frac{C_{Hq}^{(3)}}{\Lambda^2} \in [-0.9, 2.8]\ \text{TeV}^{-2},$$

$$\frac{C_{H\ell}^{(3)}}{\Lambda^2} \in [-3.6, 1.0]\cdot 10^{-2}\ \text{TeV}^{-2},$$

LHC:

$$\mu_{\text{ggF}}^{\gamma\gamma} = 1.05 \pm 0.09,$$

$$\mu_{\text{ggF}}^{\gamma Z} = 2.2 \pm 0.7$$

$$C_{HB} \simeq -\frac{s_w^2}{c_w^2} C_{HW}$$

$$C_{HB} = 0.015,$$

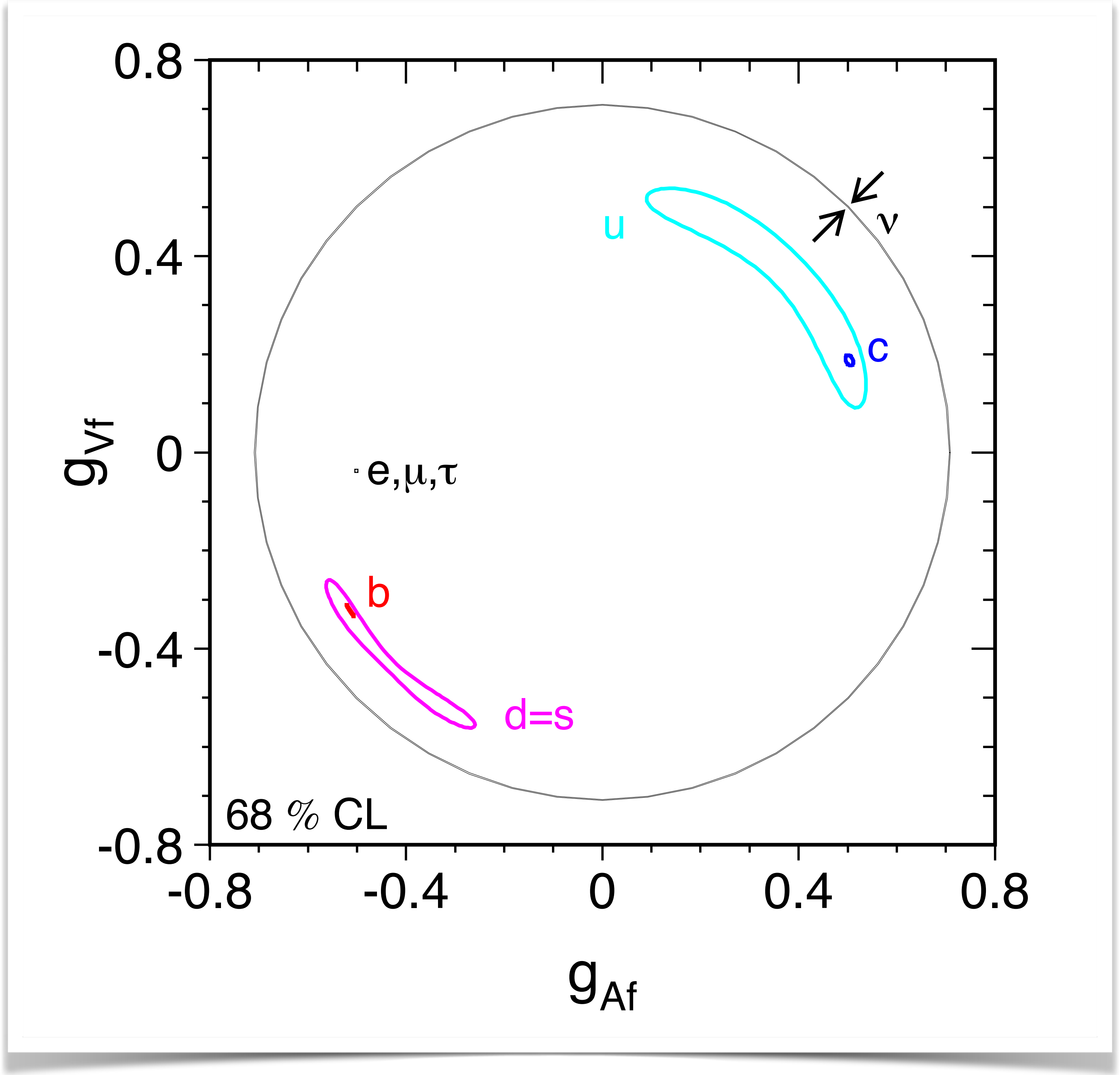
$$C_{HW} = -0.05,$$

Sources: [1] 10.1093/ptep/ptac097 (PDG), [2] hep-ex/0509008 (SLD et al.), [3] ATLAS-CONF-2021-053 (ATLAS), [4] CMS-PAS-HIG-19-005 (CMS), [5] ArXiv:2309.03501 (ATLAS and CMS)

Anatomy of SMEFT Effects

Current constraints

***Z* couplings to lighter quark generations are less constrained** than couplings to heavier quark generations:



Source: hep-ex/0509008 (ALEPH, DELPHI, L3, OPAL, SLD, LEP EW Working Group, SLD EW and Heavy Flavour Groups)

Anatomy of SMEFT Effects

Input scheme corrections

Input scheme corrections:

$$Q_{\ell\ell} = (\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma^\mu \ell)$$

$$Q_{HD} = (H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$$

$$G_F = \frac{1}{\sqrt{2}v^2}\left(1 + \frac{\delta G_F}{G_F}\right),$$

$$\frac{\delta G_F}{G_F} = v^2 \left([C_{H\ell}^{(3)}]_{\mu\mu} + [C_{H\ell}^{(3)}]_{ee} - \frac{1}{2}[C_{\ell\ell}]_{\mu e e \mu} - \frac{1}{2}[C_{\ell\ell}]_{e \mu \mu e} \right) + \mathcal{O}(\Lambda^{-4}),$$

Source: ArXiv:1812.08163 (S. Descotes-Genon, A. Falkowski, M. Fedele, M. González-Alonso, J. Virto)

Let us consider the situation in the **LEP input scheme** $\{\alpha, G_F, M_Z\}$:

Input scheme corr.:

$$\frac{\delta m_W}{m_W} = -\frac{c_w s_w}{2(c_w^2 - s_w^2)}\frac{v^2}{\Lambda^2}\left[2C_{HWB} + \frac{s_w}{c_w}\left(2C_{H\ell}^{(3)} - C_{\ell\ell}\right) + \frac{c_w}{2 s_w} C_{HD}\right]$$

$$\frac{\delta m_W}{m_W} \in [-0.9, 5.6]\cdot 10^{-4},$$

$$\frac{C_{HWB}}{\Lambda^2} \in [-1.2, 0.2]\cdot 10^{-2}\,\text{TeV}^{-2},$$

Details of the calculation

The POWHEG method

$$\sigma_{\rm NLO} = \int d\mathbf{\Phi}_n \, \mathcal{L} \left[\mathcal{B}(\mathbf{\Phi}_n) + \mathcal{V}_{\rm b}(\mathbf{\Phi}_n)\right] + \int d\mathbf{\Phi}_{n+1} \, \mathcal{L} \, \mathcal{R}(\mathbf{\Phi}_{n+1}) + \int d\mathbf{\Phi}_{n,\oplus} \, \mathcal{L} \, \mathcal{G}_{\oplus,\rm b}(\mathbf{\Phi}_{n,\oplus}) + \int d\mathbf{\Phi}_{n,\ominus} \, \mathcal{L} \, \mathcal{G}_{\ominus,\rm b}(\mathbf{\Phi}_{n,\ominus}) \, ,$$

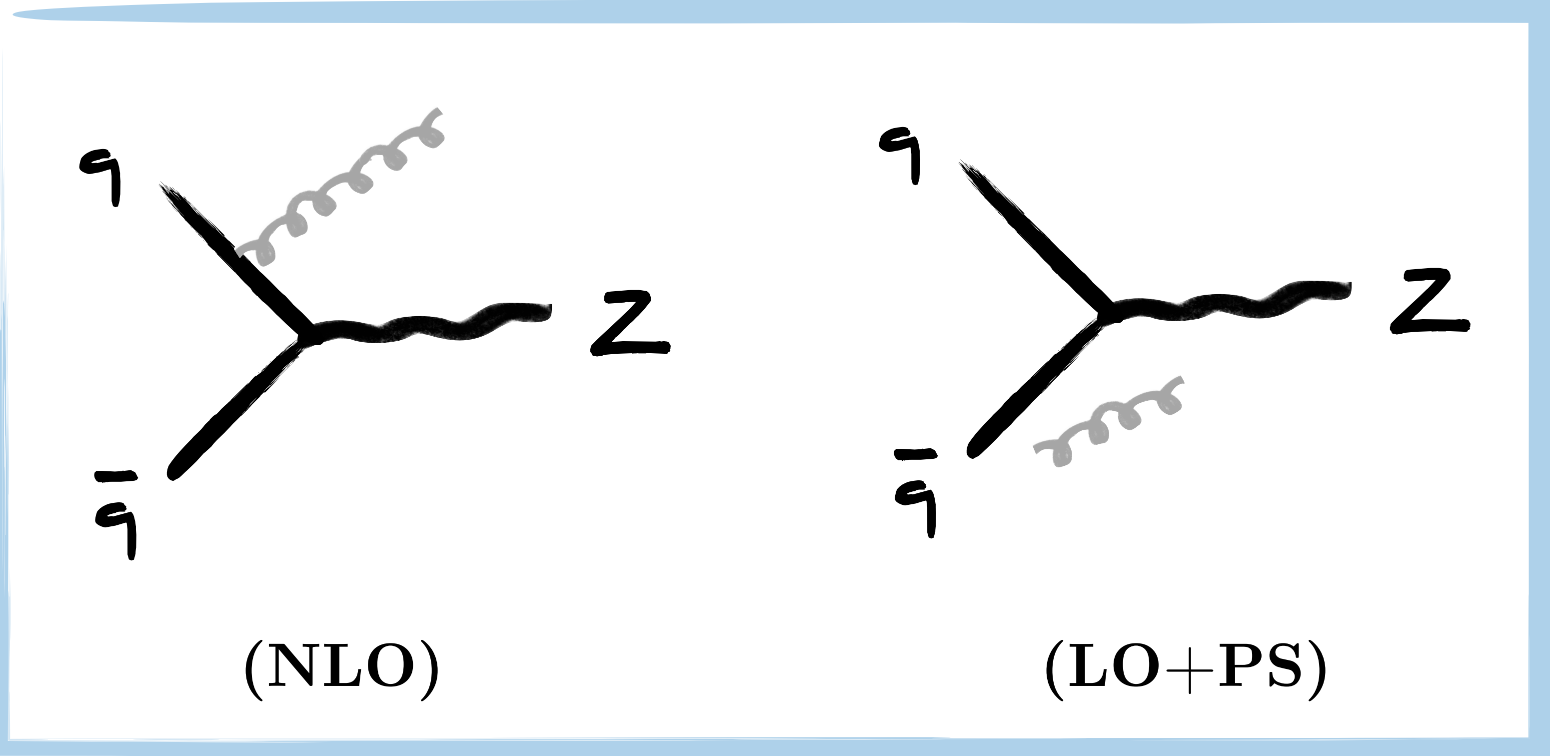
→ how to deal with IR singularities?

Soft/collinear divergences

Subtraction:

$$\begin{aligned}\langle O \rangle = &\int d\mathbf{\Phi}_n \, \mathcal{L} \, O_n(\mathbf{\Phi}_n) \left[\mathcal{B}(\mathbf{\Phi}_n) + \mathcal{V}_{\rm b}(\mathbf{\Phi}_n)\right] \\ &+ \int d\mathbf{\Phi}_{n+1} \left\{ \mathcal{L} \, O_{n+1}(\mathbf{\Phi}_{n+1}) \, \mathcal{R}(\mathbf{\Phi}_{n+1}) - \sum_\alpha \left[\tilde{\mathcal{L}} \, O_n(\bar{\mathbf{\Phi}}_n) \, \mathcal{C}(\mathbf{\Phi}_{n+1})\right]_\alpha \right\} \\ &+ \sum_{\alpha \in \{\rm FSC, S\}} \left[\int d\bar{\mathbf{\Phi}}_n \, \tilde{\mathcal{L}} \, O_n(\bar{\mathbf{\Phi}}_n) \, \bar{\mathcal{C}}(\bar{\mathbf{\Phi}}_n)\right]_\alpha + \sum_{\alpha \in \{\rm ISC_\oplus\}} \left[\int d\mathbf{\Phi}_{n,\oplus} \, \tilde{\mathcal{L}} \, O_n(\bar{\mathbf{\Phi}}_n) \, \bar{\mathcal{C}}(\mathbf{\Phi}_{n,\oplus})\right]_\alpha \\ &+ \int d\mathbf{\Phi}_{n,\oplus} \, \tilde{\mathcal{L}} \, O_n(\bar{\mathbf{\Phi}}_n) \, \mathcal{G}_{\oplus,\rm b}(\mathbf{\Phi}_{n,\oplus}) + \int d\mathbf{\Phi}_{n,\ominus} \, \tilde{\mathcal{L}} \, O_n(\bar{\mathbf{\Phi}}_n) \, \mathcal{G}_{\ominus,\rm b}(\mathbf{\Phi}_{n,\ominus}) \, .\end{aligned}$$

→ inclusive NLO



→ how to avoid **double counting**?

Sudakov form factor:

$$\Delta(\mathbf{\Phi}_n, p_{\rm T}) = \exp\left\{ -\int \frac{\left[d\Phi_{\rm rad} \, R(\mathbf{\Phi}_{n+1}) \, \theta(k_{\rm T}(\mathbf{\Phi}_{n+1}) - p_{\rm T})\right]^{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n}}{B(\mathbf{\Phi}_n)} \right\} .$$

$$d\sigma = \bar{B}(\mathbf{\Phi}_n) \, d\mathbf{\Phi}_n \left\{ \Delta(\mathbf{\Phi}_n, p_{\rm T}^{\rm min}) + \Delta(\mathbf{\Phi}_n, k_{\rm T}(\mathbf{\Phi}_{n+1})) \frac{R(\mathbf{\Phi}_{n+1})}{B(\mathbf{\Phi}_n)} d\Phi_{\rm rad} \right\}_{\bar{\mathbf{\Phi}}_n = \mathbf{\Phi}_n} ,$$

→ exclusive NLO above $p_T^{\rm min}$

→ **parton shower** for radiation below $p_T^{\rm min}$

Sources: [1] ArXiv:0709.2092 (S. Frixione, P. Nason, C. Oleari).

Details of the calculation

The **POWHEG** method

In practice, what one has to implement is

- **Flavour structure** for Vhj and Vhjj
- Vhj **phase space**

- **Born** matrix element (Vh)
- **Virtual**
- **Double virtual**

- **Real** (Vhj)
- **Colour-correlated** real
- **Spin-correlated** real

- **Virtual-real** (Vhj)
- **Double real** (Vhjj)

POWHEG-BOX for Vhj

$$2s_b\mathcal{B}_{ij} = -N \sum_{\substack{\text{spins}\\ \text{colours}}} \mathcal{M}_{\{c_k\}} \left(\mathcal{M}^\dagger_{\{c_k\}}\right)_{\substack{c_i\to c_i'\\ c_j\to c_j'}} T^a_{c_i,c_i'}\, T^a_{c_j,c_j'}\,.$$

$$\mathcal{B}_j^{\mu\nu} = N \sum_{\{i\},s_j,s_j'} \mathcal{M}\left(\{i\},s_j\right) \mathcal{M}^\dagger\left(\{i\},s_j'\right) \left(\epsilon^\mu_{s_j}\right)^* \epsilon^\nu_{s_j'}\,,$$

Sources: [1] ArXiv:0709.2092 (S. Frixione, P. Nason, C. Oleari).

Results

Event generator

Generation-level **cuts**

Input scheme

SM parameters

Switches for different contributions

SMEFT operators

```
! ================================================
! Cuts
! ================================================
min_z_mass  10d0
max_z_mass  10000d0
min_h_mass  10d0
max_h_mass  10000d0
! ================================================

! ================================================
! Model parameters
! ================================================
! Input scheme
InputScheme 2   ! Input scheme. 0 = (Alpha, MZ, MW), 1 = (GF, MZ, MW), 2 = (Alpha, GF, MZ)

! Input parameters
mz 91.1876d0
Gfermi 1.1663788d-5
alpha 7.81549186d-3

mh 125.09d0
gh 4.1d-3
mt 172.5d0
mb 4.78d0

! Cutting-edge calculations for the SM
mw 80.361d0
gw 2.089d0
gz 2.4952d0

! Switches
SM          0     ! Switch (on/off). Whether to include the SM contribution or not.
Linear      1     ! Switch (on/off). Whether to include the linear NP corrections or not.
Quadratic   0     ! Switch (on/off). Whether to include the quadratic NP corrections or not.


! Anomalous couplings
Anomalous   0     ! Switch (on/off)
ghzz1       0d0   ! Anomalous coupling
ghzz2       0d0   ! Anomalous coupling
ghzz3       0d0   ! Anomalous coupling
ghaz1       0d0   ! Anomalous coupling
ghaz2       0d0   ! Anomalous coupling


! SMEFT
SMEFTScale       1000d0   ! Scale of SMEFT operators

Warsaw              1     ! Switch (on/off)
CHe                 0d0  ! SMEFT coefficient
CHl1                0d0   ! SMEFT coefficient
CHl3                0d0   ! SMEFT coefficient
CHq1                0.05d0   ! SMEFT coefficient
CHq3                0d0   ! SMEFT coefficient
CHu                 0d0   ! SMEFT coefficient
CHd                 0d0   ! SMEFT coefficient

CHB                 0d0   ! SMEFT coefficient
CHW                 0d0   ! SMEFT coefficient
CHWB                0d0   ! SMEFT coefficient


! Linear combinations of SMEFT operators
WarsawRotated       0     ! Switch (on/off)
CHA                 0d0   ! SMEFT coefficient (sw2*CHW + cw2*CHB)
CHZ                 0d0   ! SMEFT coefficient (cw2*CHW - sw2*CHB)
! ================================================
```

Our code will be available for download on the POWHEG-BOX web page.