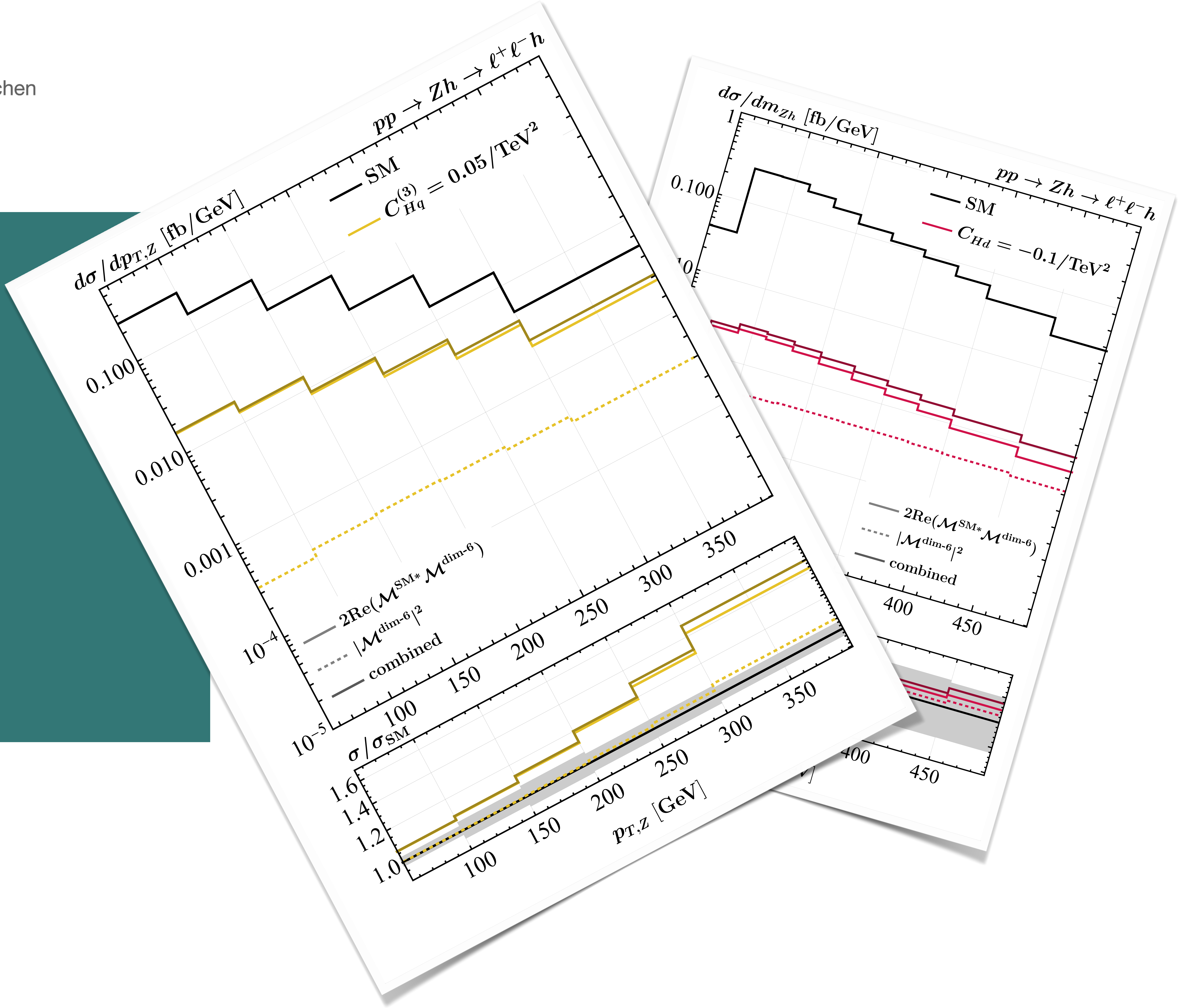
Reference: [2311.06107] (R. Gauld, U. Haisch, LS).

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
SFB 1258 Neutrinos Dark Matter Messengers
Technische Universität München

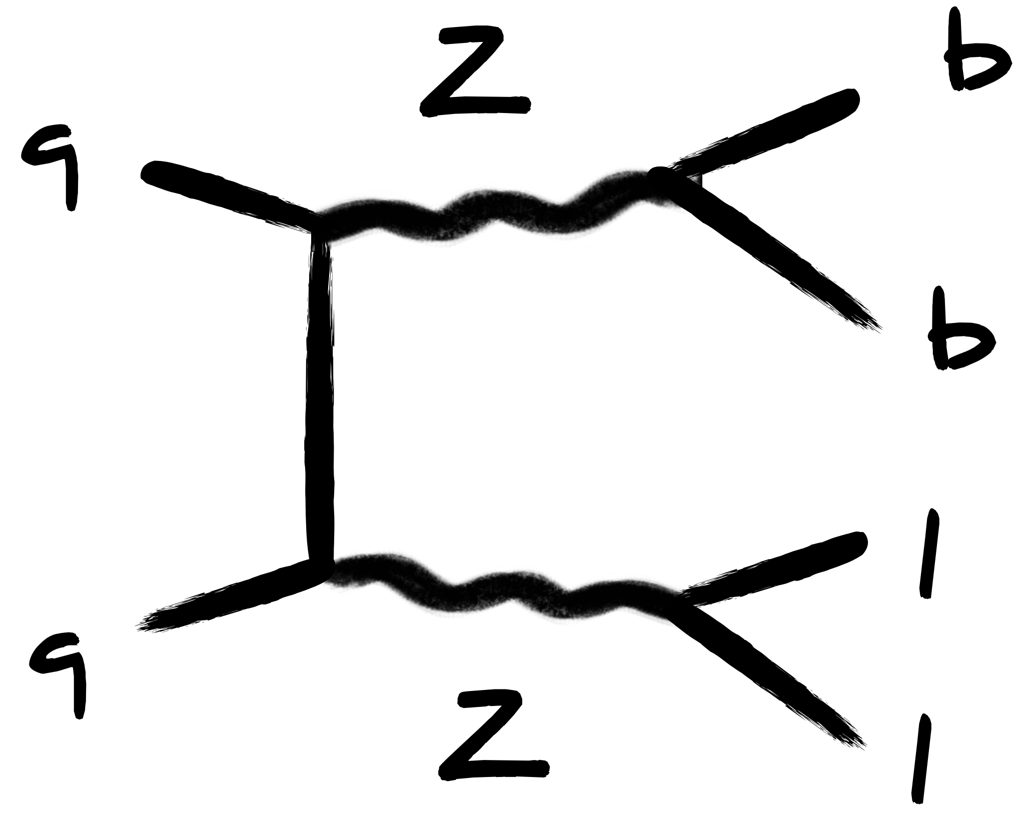
SMEFT at NNLO+PS: *Vh* production

Luc Schnell
EFT in Multiboson Production
June 10, 2024



Observation of h → b$\bar{b}$ @ LHC Run II

[ATLAS, 1808.08238]



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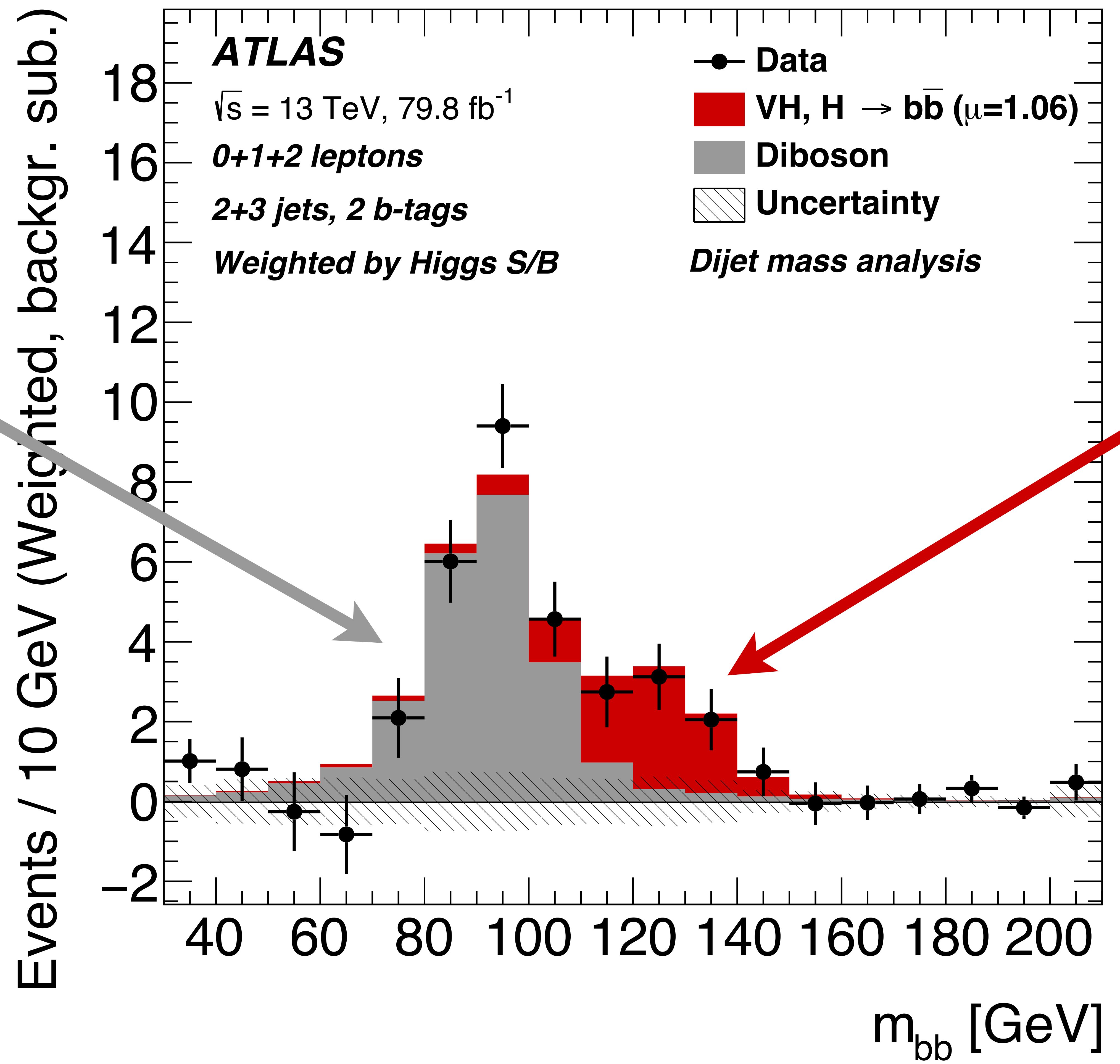
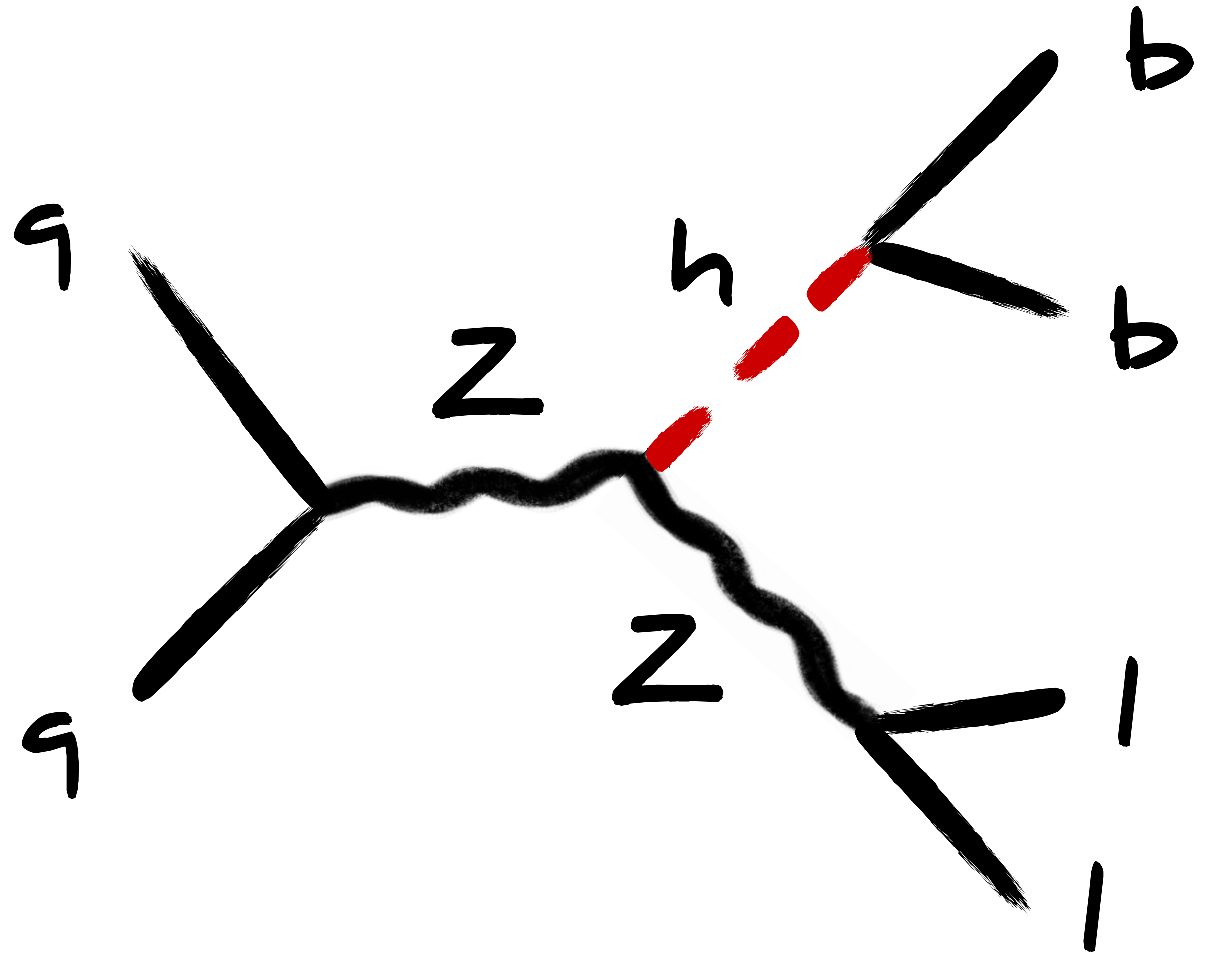


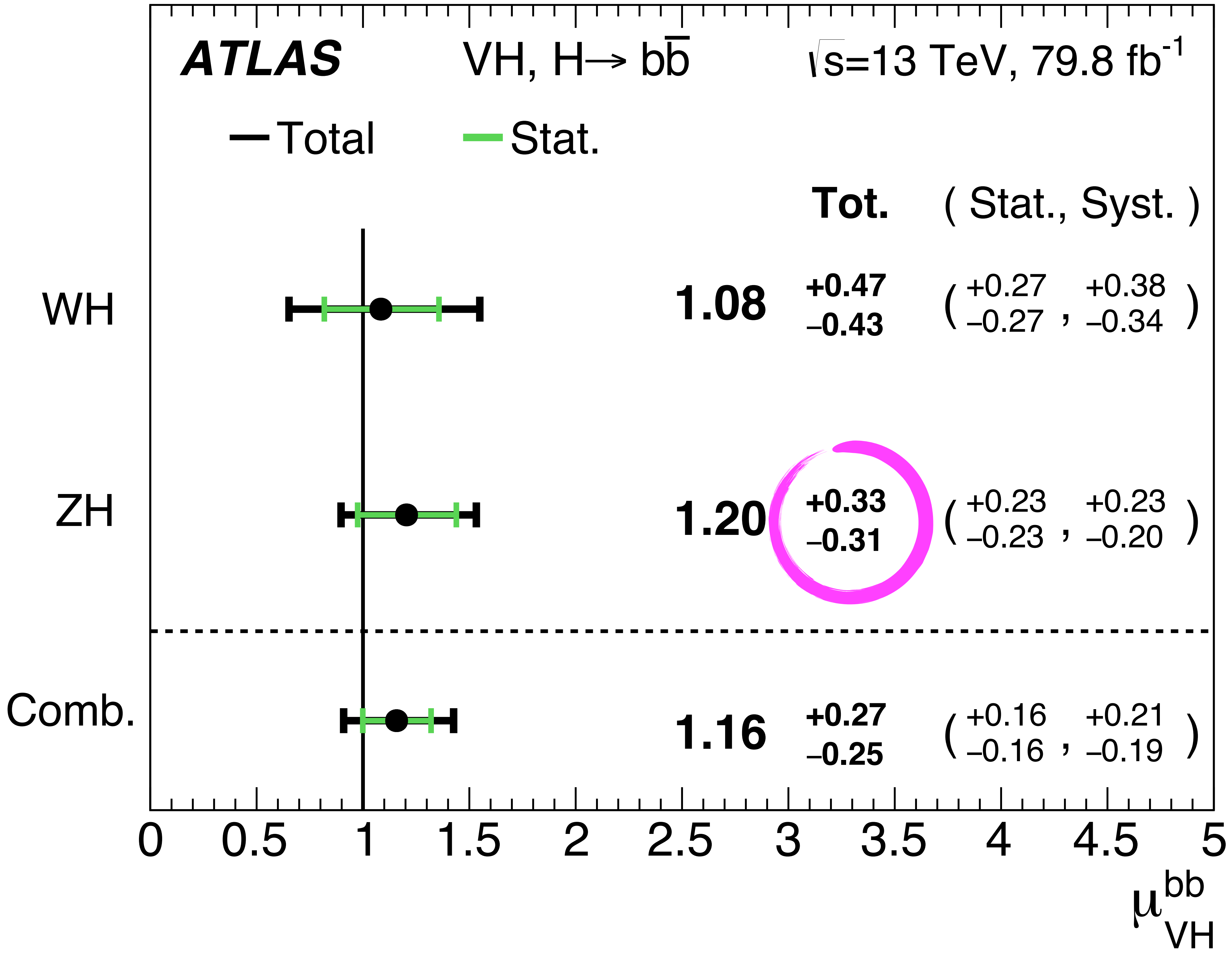


signal

[see also CMS, 1808.08242]

From 5σ to precision measurements

[ATLAS, 1808.08238]

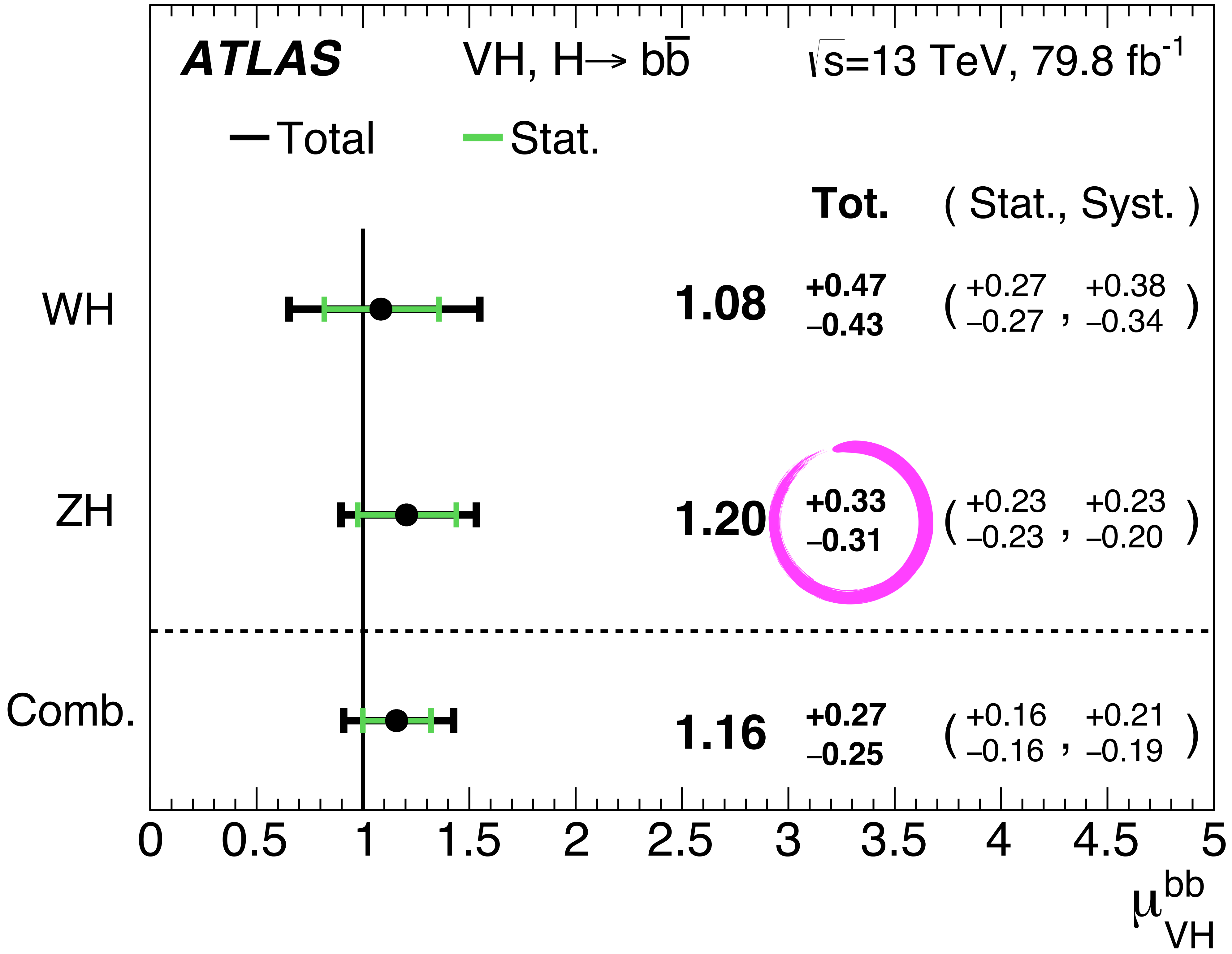


In LHC Run II, signal strength in Vh production found to be SM-like within 25%

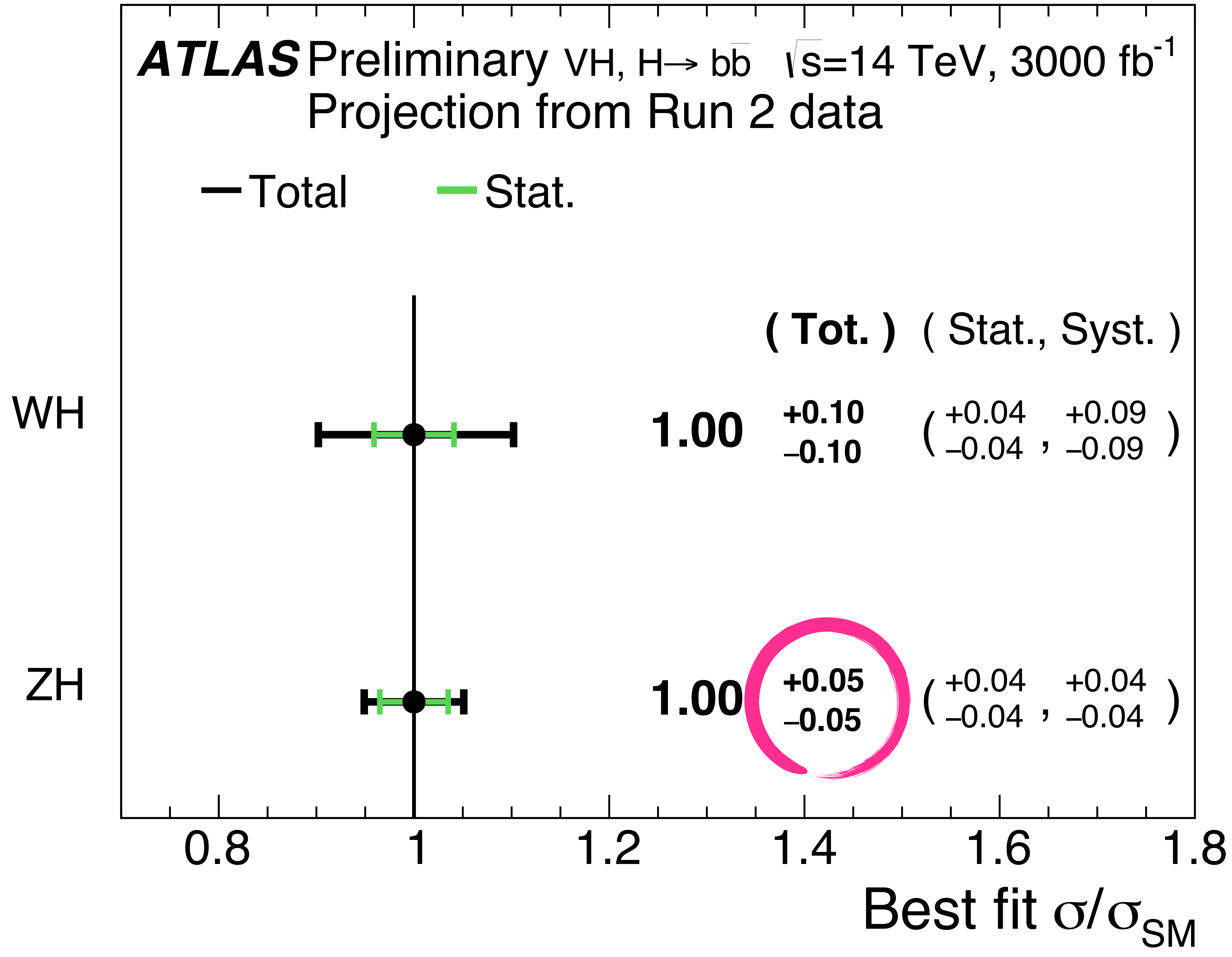
[see also CMS, 1808.08242]

From 5σ to precision measurements

[ATLAS, 1808.08238]



[ATL-PHYS-PUB-2018-054]

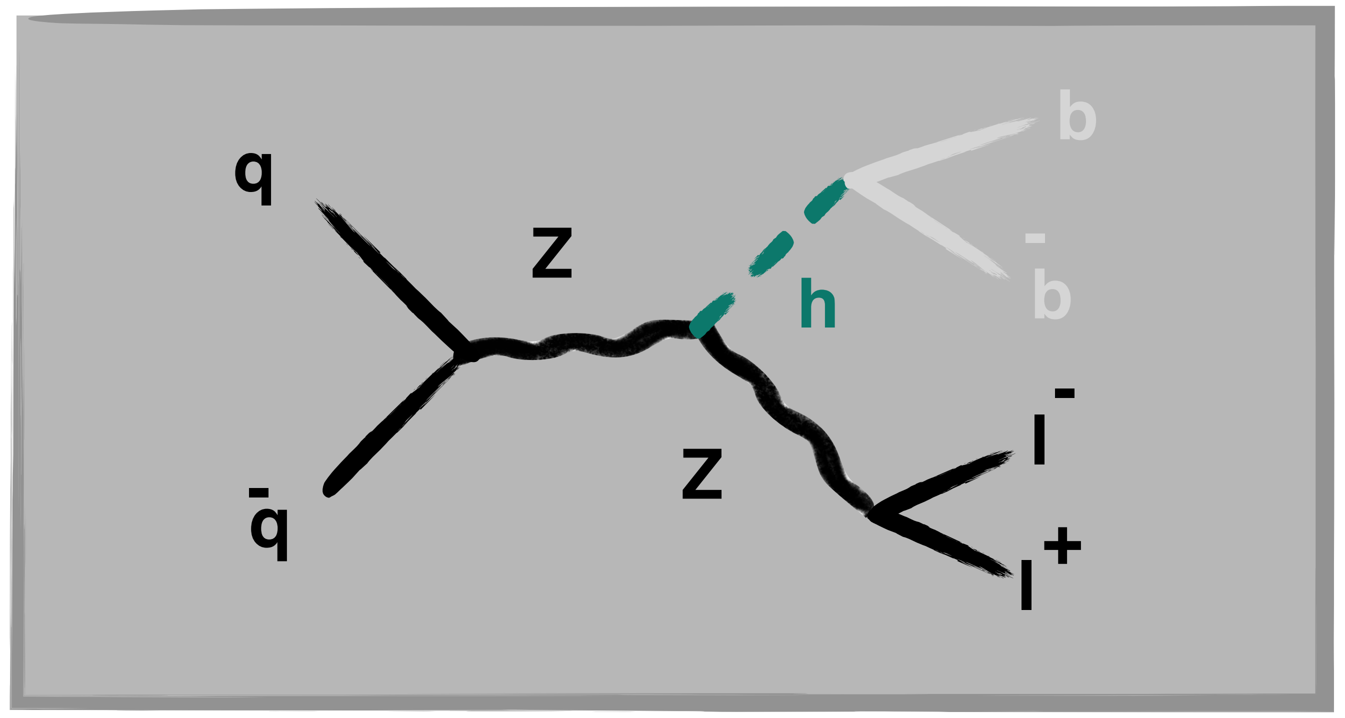


Ultimate accuracy projected to be 10% to 5% in Wh & Zh channel @ HL-LHC

[see also CMS, 1808.08242; CMS-PAS-FTR-18-011]

2. Anatomy of SMEFT Effects

2.1 Deviations from the SM



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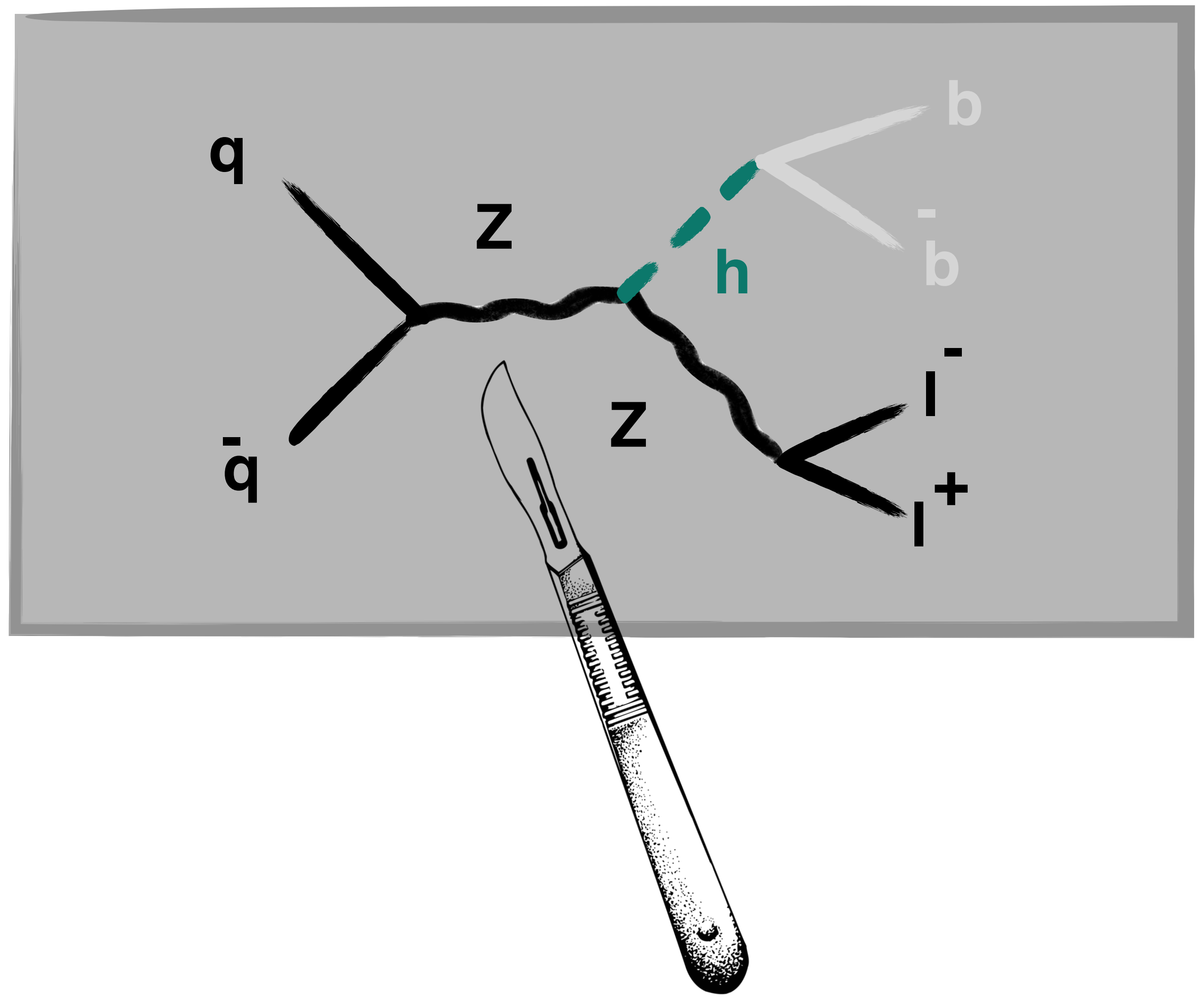

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QCD, Higgs operators: [2204.00663] (U. Haisch, D.J. Scott, M. Wiesemann, *et al.*)

$$Q_{bH} = y_b (H^\dagger H)\, \bar{q}_L b_R H \,,$$

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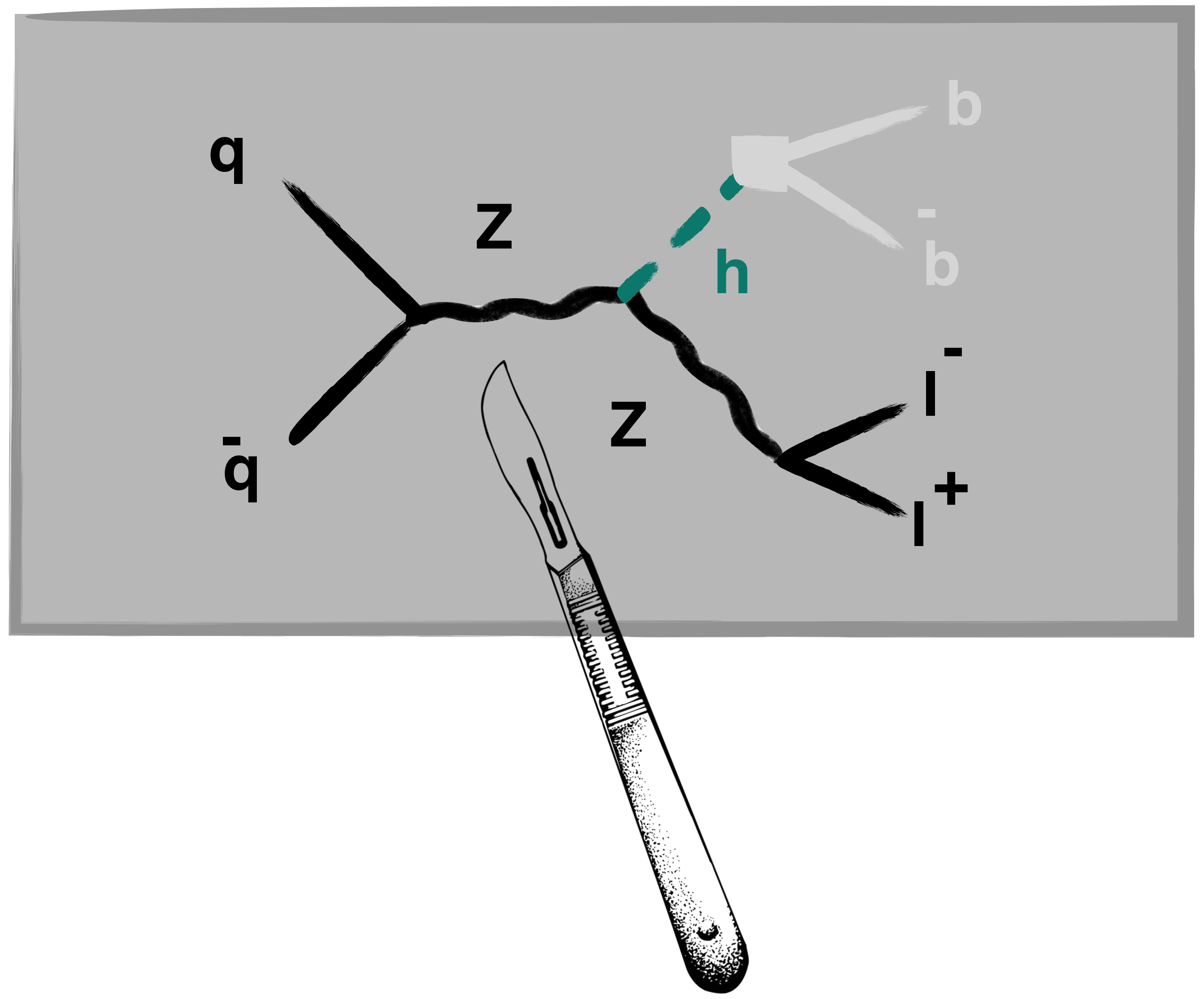

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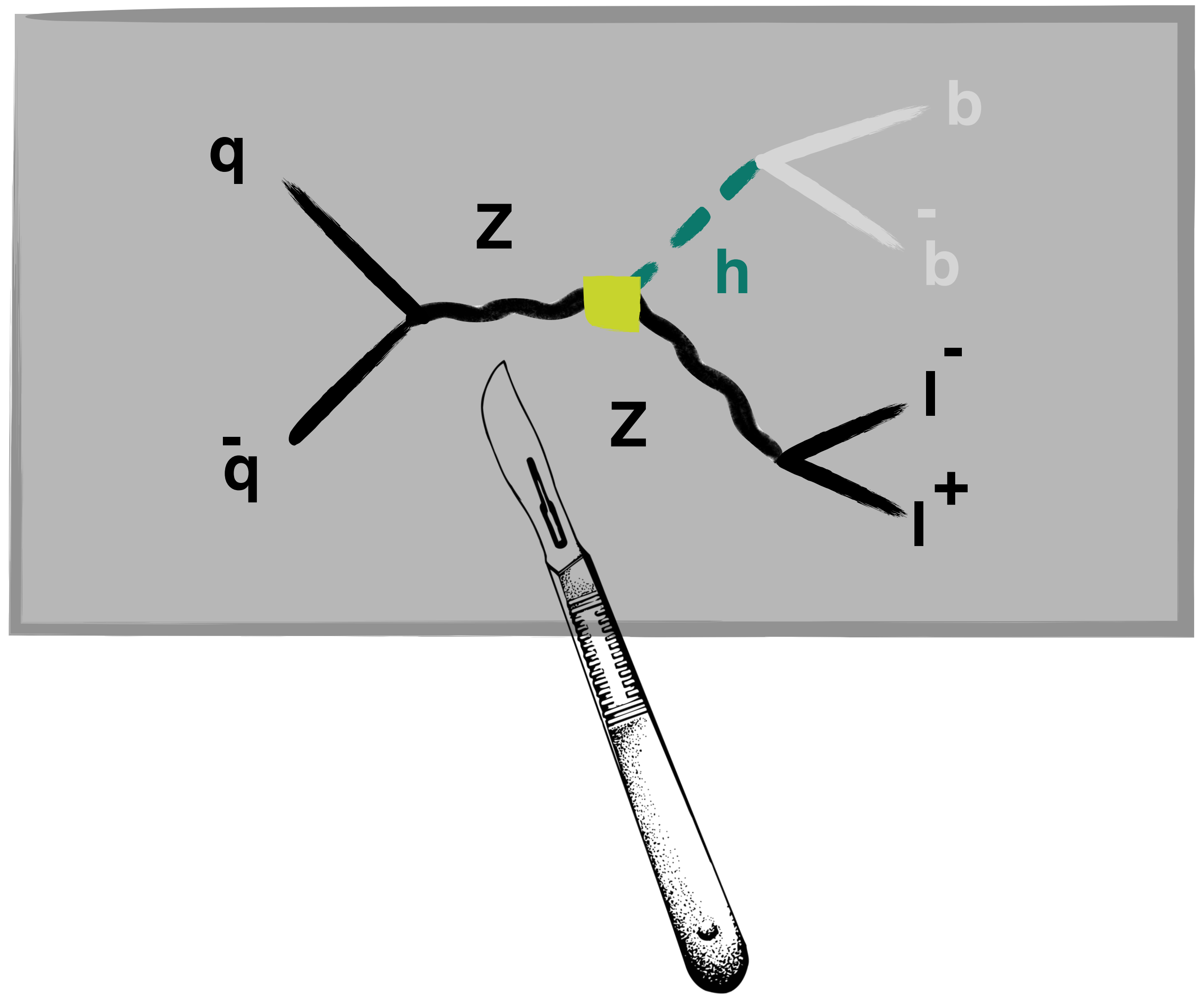

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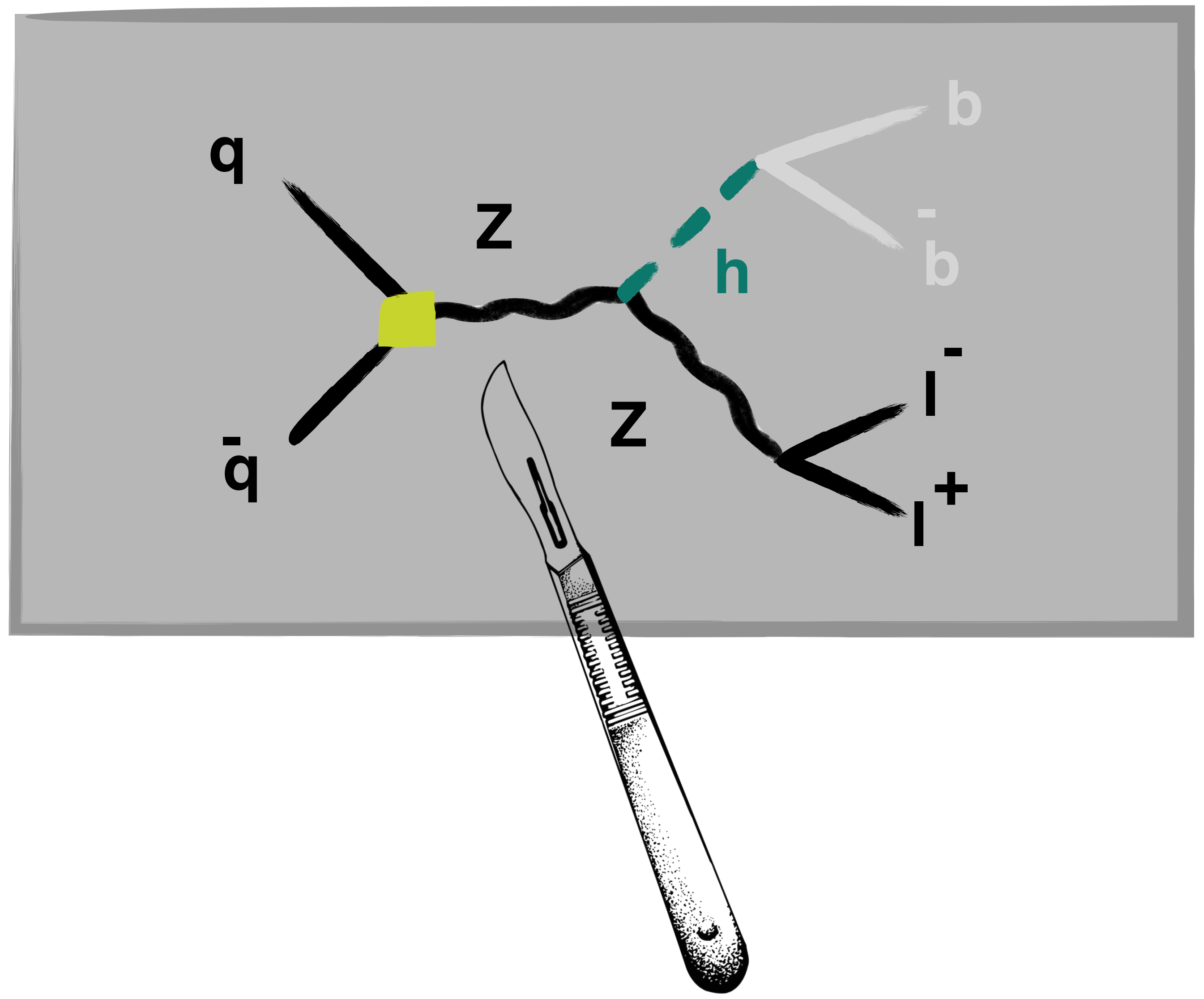

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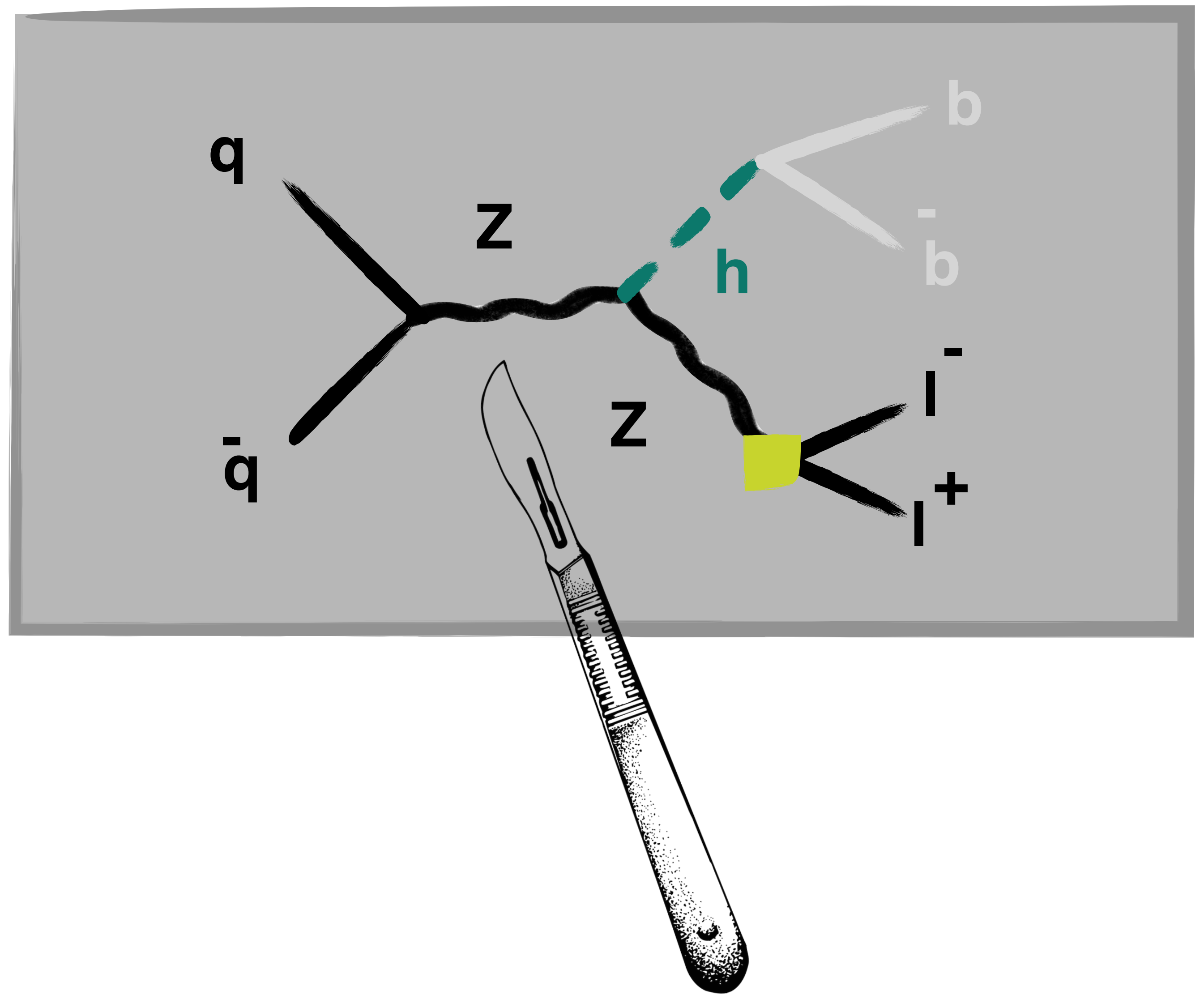

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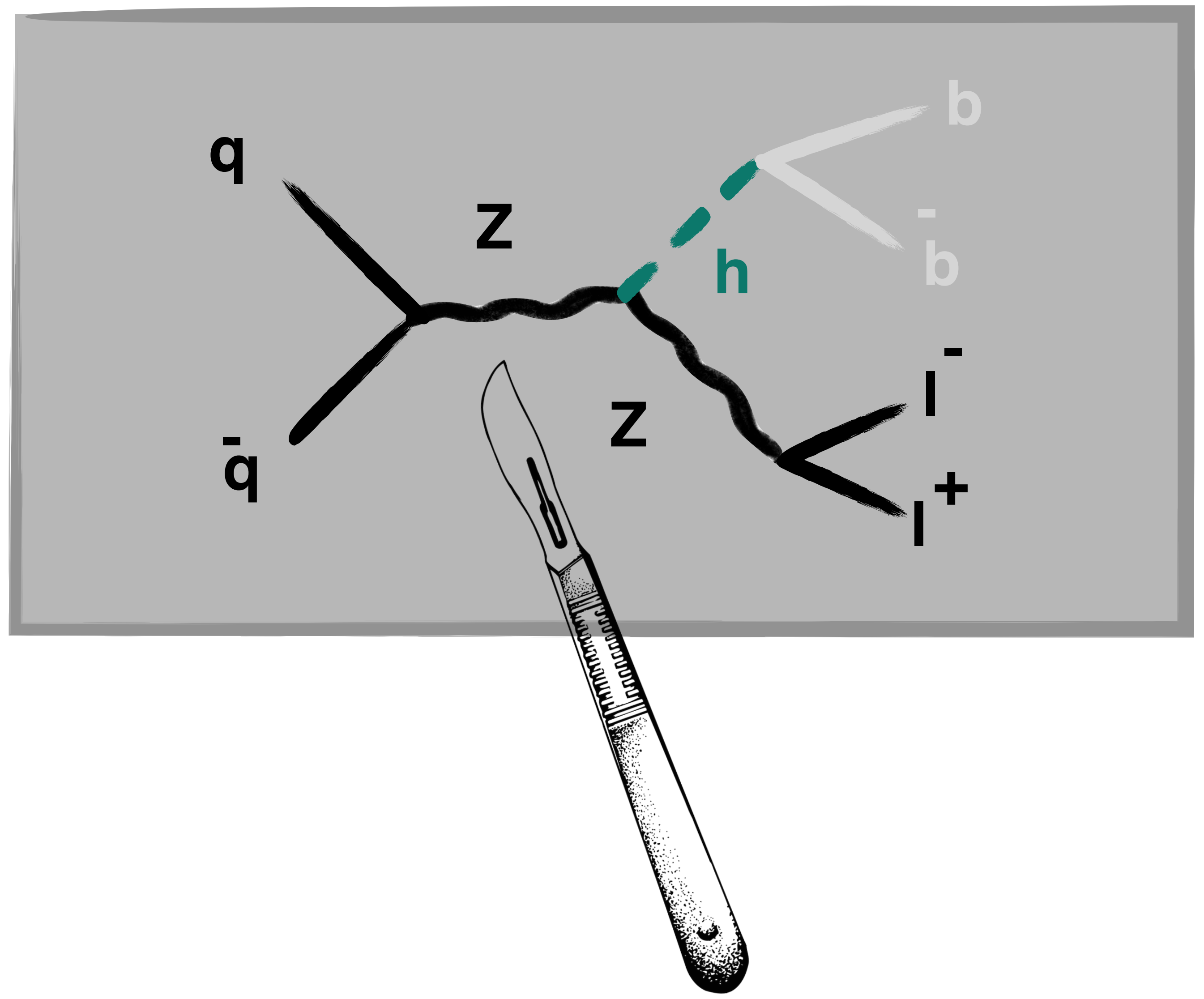

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Input scheme corrections: [2311.06107] (R. Gauld, U. Haisch, LS)

$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,,$ $\quad Q_{HD}$ $\quad Q_{\ell\ell}$

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LHC:

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

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ATLAS-CONF-2021-053 (ATLAS)
CMS-PAS-HIG-19-005 (CMS)

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

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hep-ex/0509008 (SLD et al.)

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ONF-2021-053 (ATLAS)
S-HIG-19-005 (CMS)

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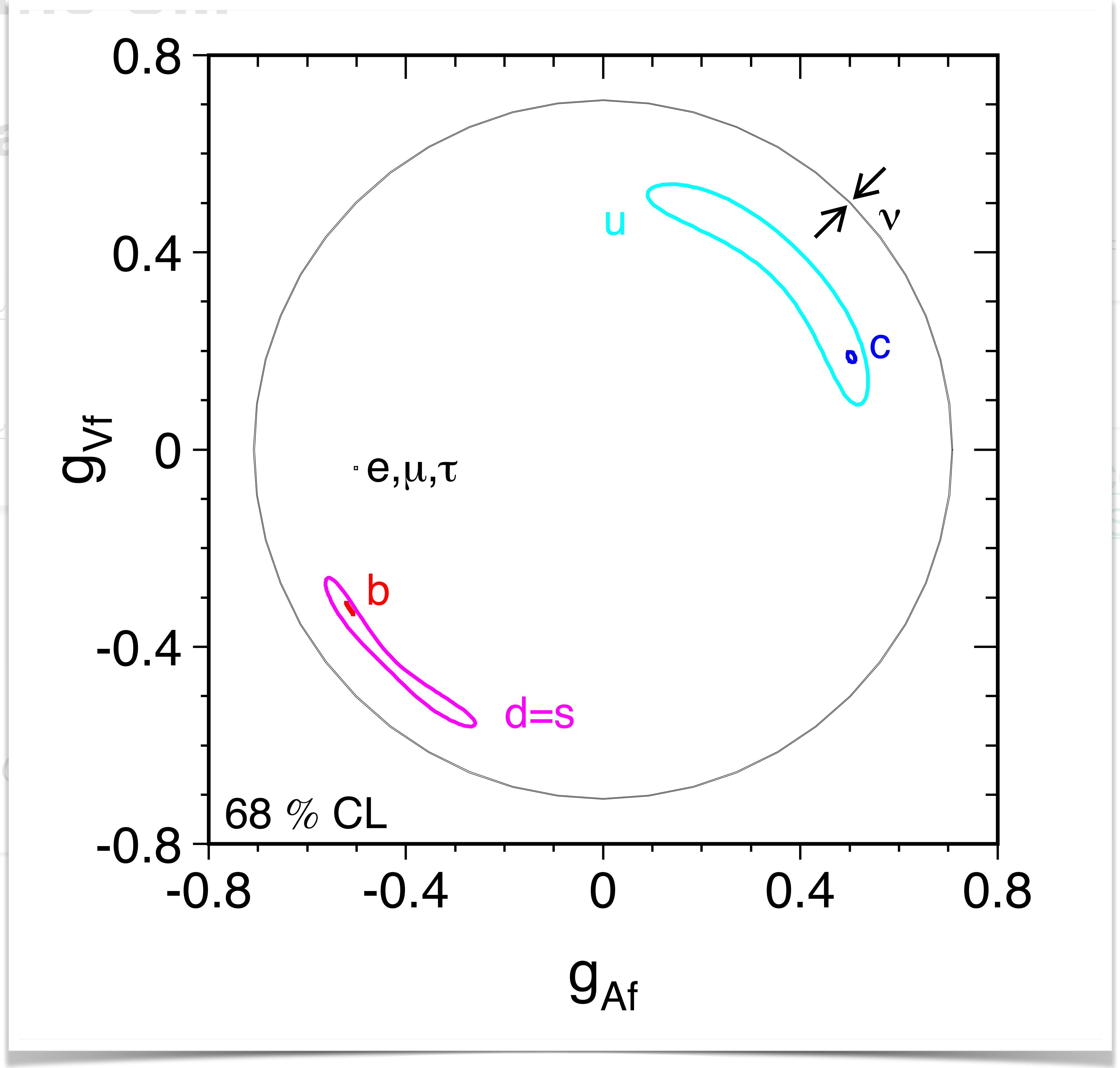

Source: hep-ex/0509008 (ALEPH, DELPHI, L3, OPAL, SLD, LEP EW Working Group, SLD EW and Heavy Flavour Groups)

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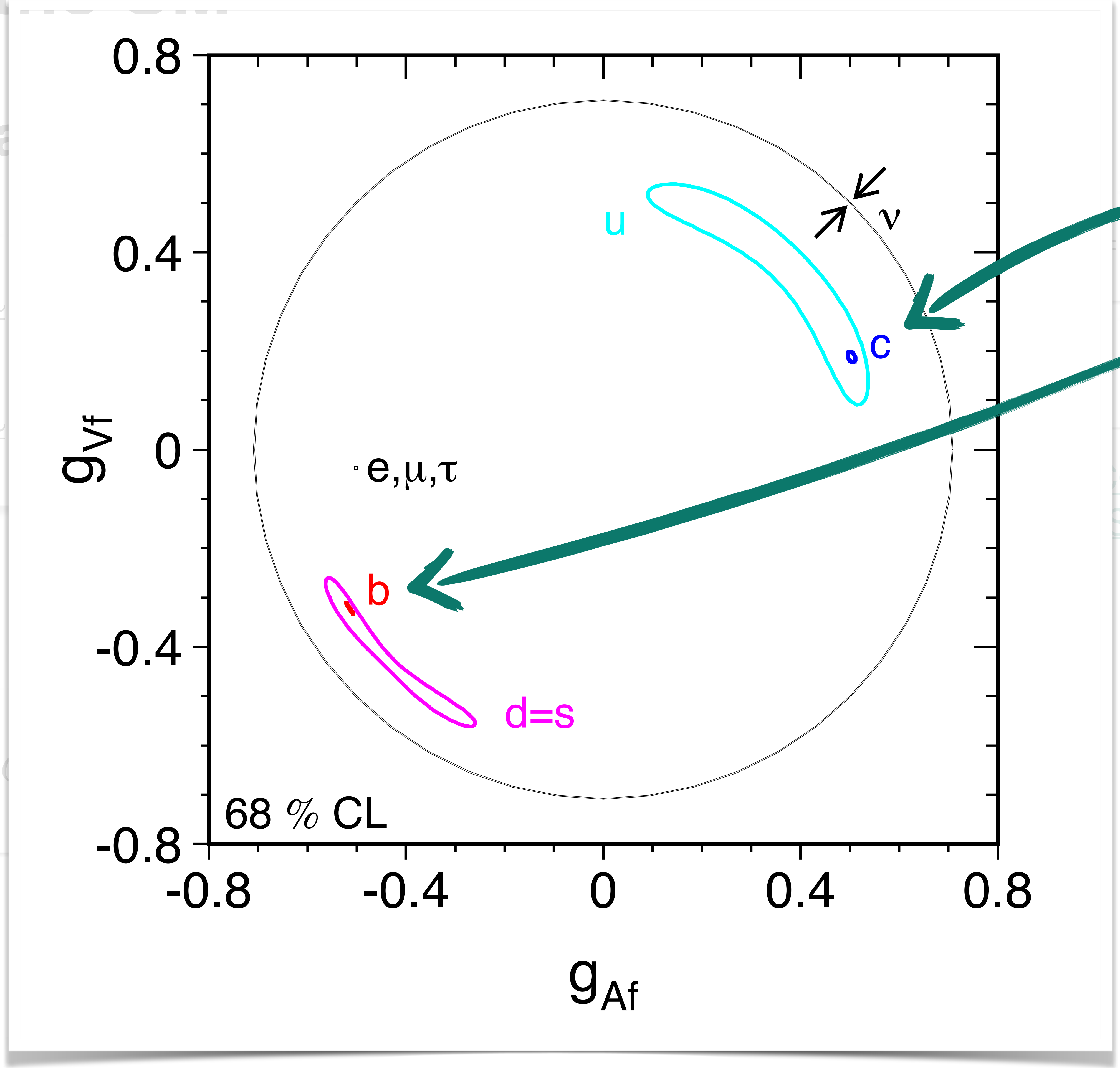

Better constraints from **forward-backward** asymmetry measurements.

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

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hep-ex/0509008 (SLD et al.)

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

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ATLAS-CONF-2021-053 (ATLAS)
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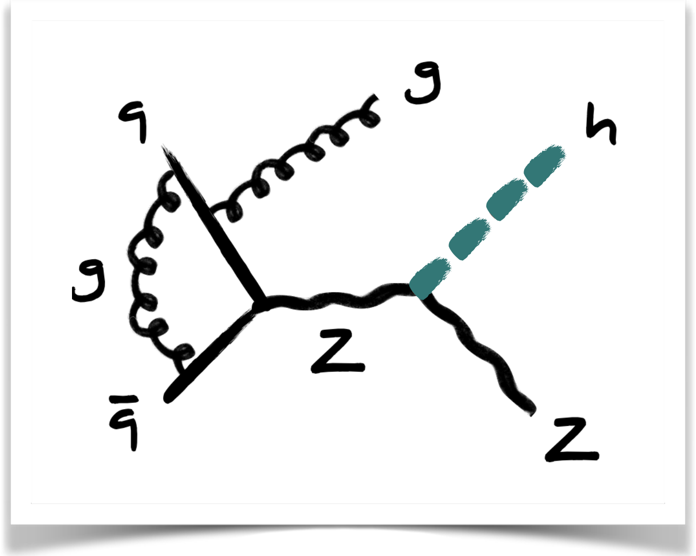

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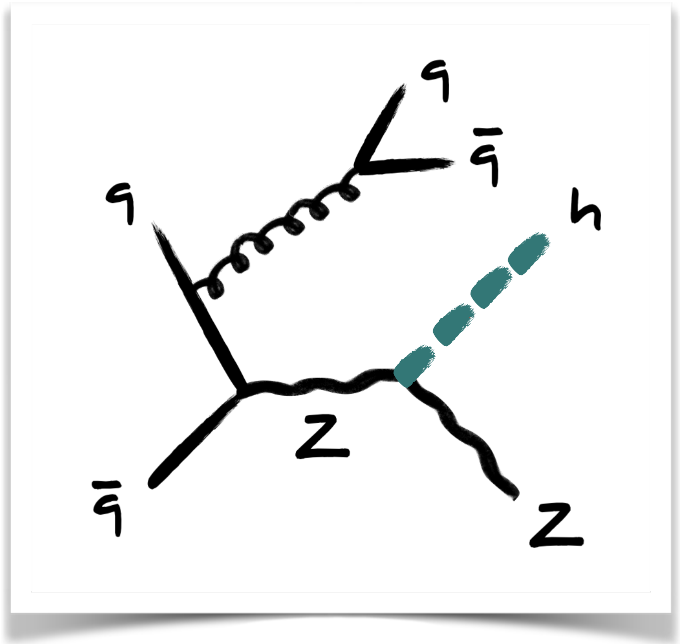

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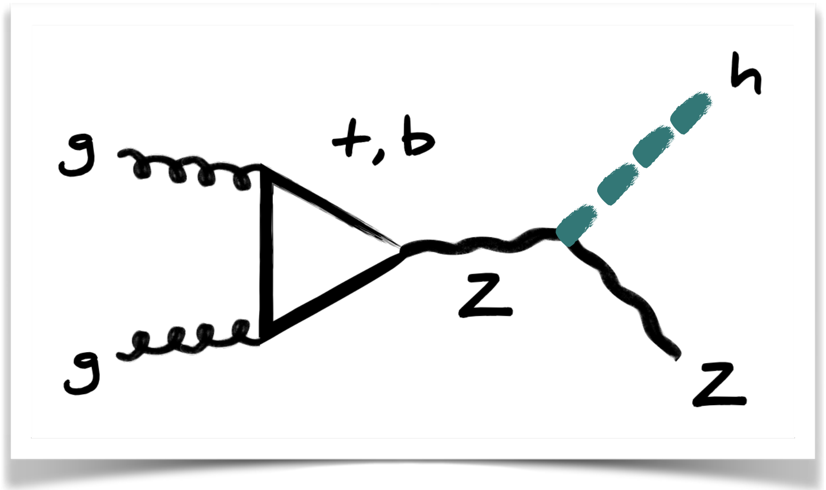

(A-type)

[1107.1164] (G. Ferrera, M. Grazzini, F. Tramontano)
[1601.00658] (J.M. Campbell, R.K. Ellis, C. Williams)
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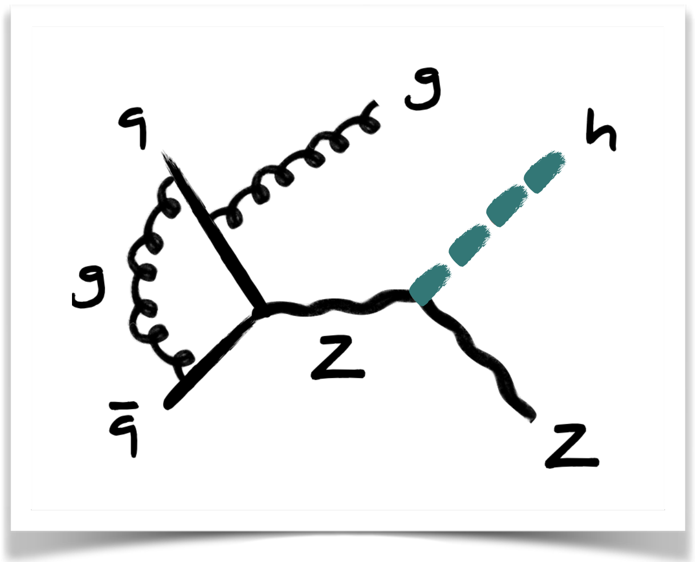

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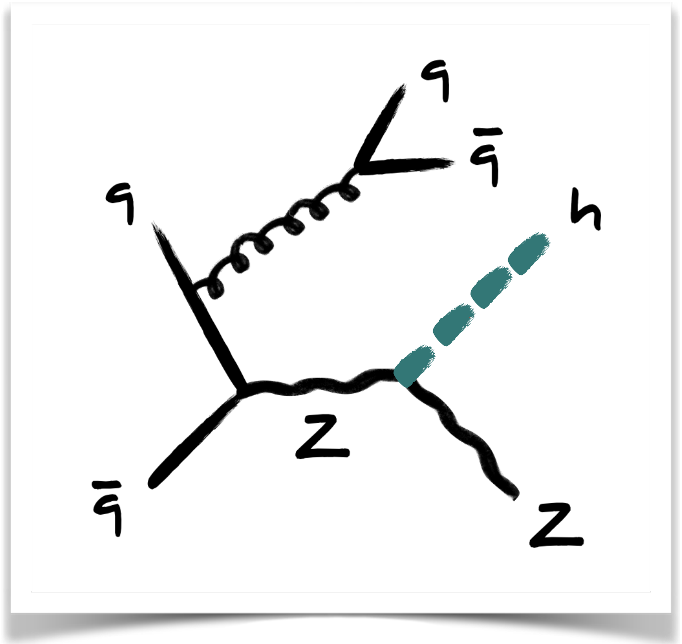

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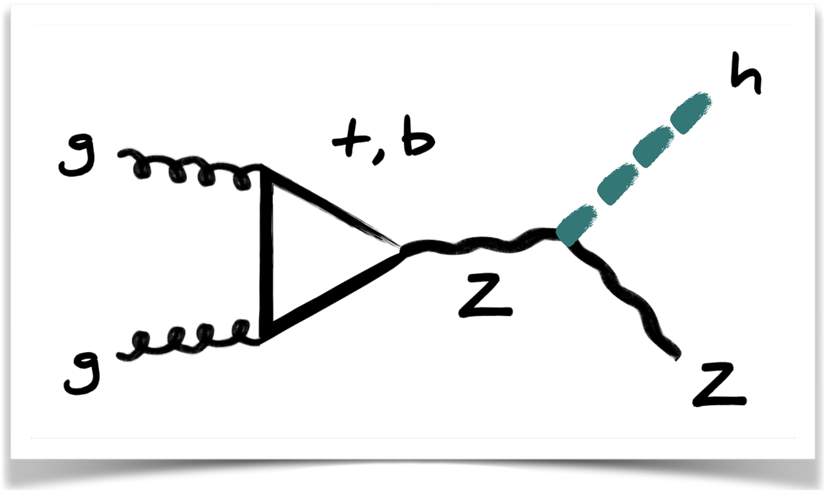

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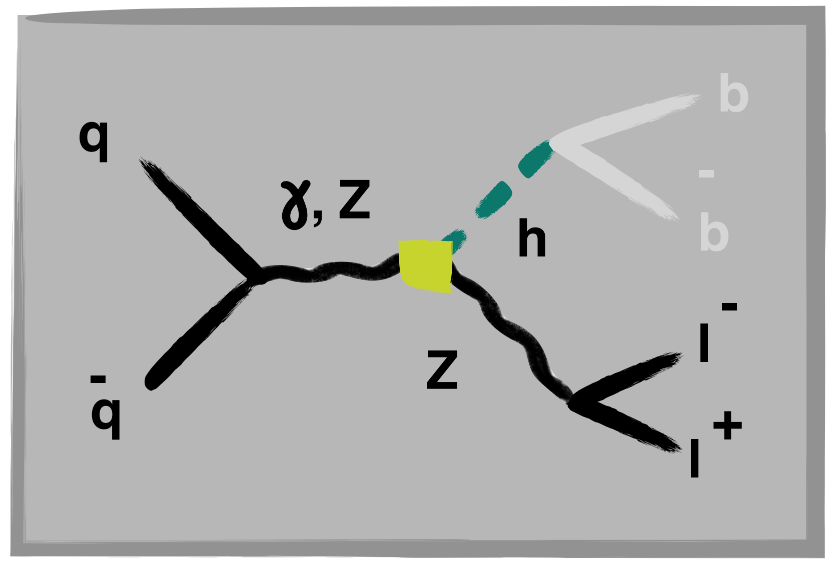
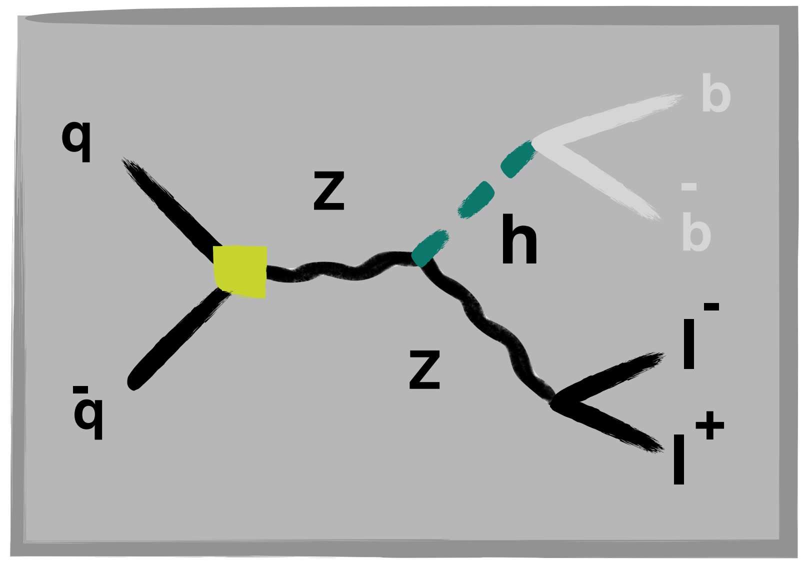
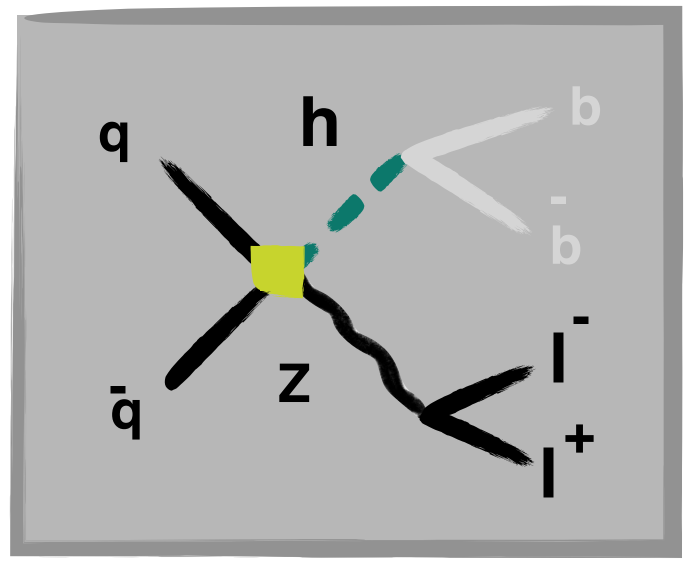
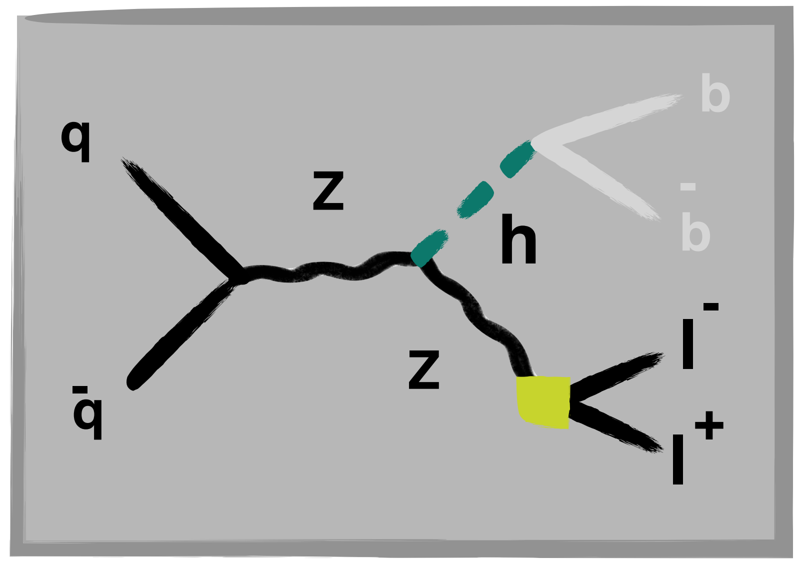
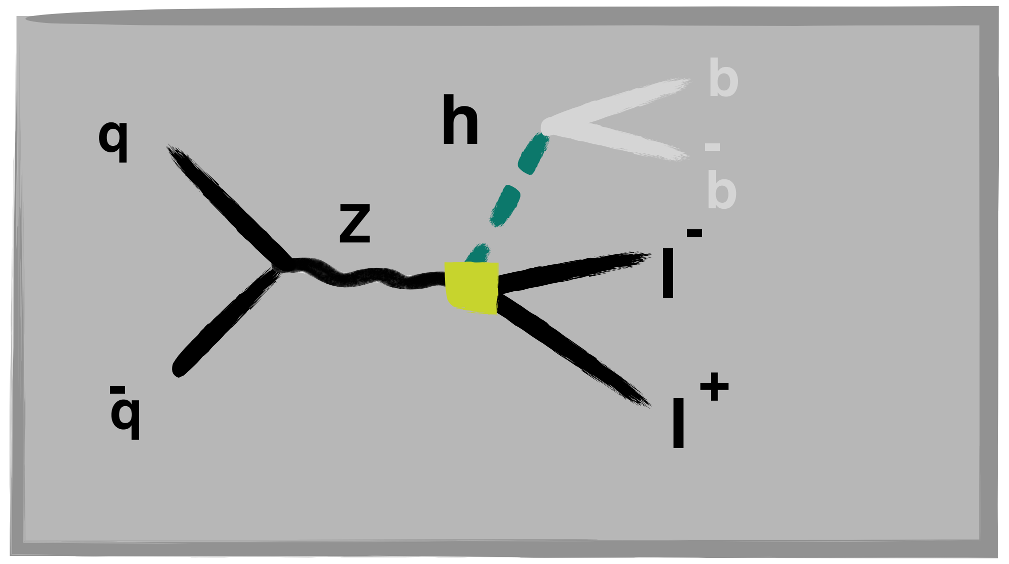
Our goal is to calculate the **NNLO+PS** corrections to these **SMEFT** contributions:











NLO:
[1512.02572] (K. Mimasu, V. Sanz, C. Williams)
[1609.04833] (C. Degrande, B. Fuks, K. Mawatari, *et al.*)
[1710.04143] (A. Greljo, G. Isidori, J.M. Lindert, *et al.*)
[1804.07407] (S. Alioli, W. Denkens, M. Girard, E. Mereghetti)

NNLO: [2204.00663] (U. Haisch, D.J. Scott, M. Wiesemann, *et al.*)

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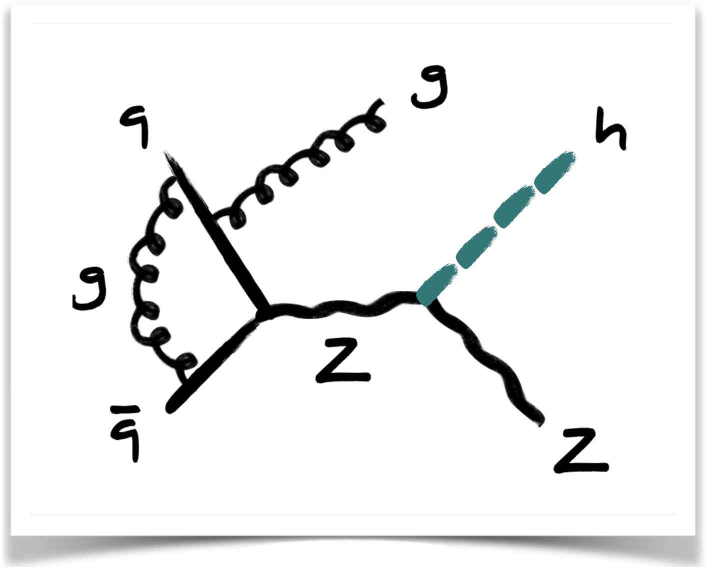

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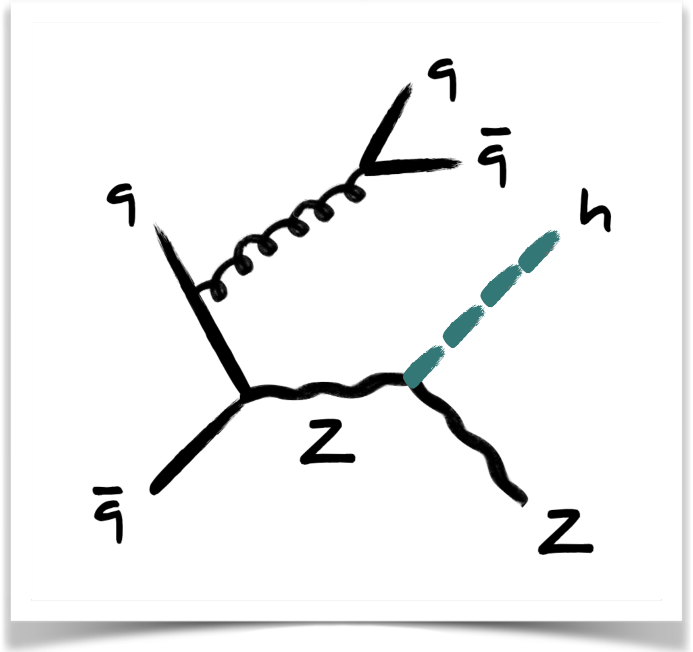

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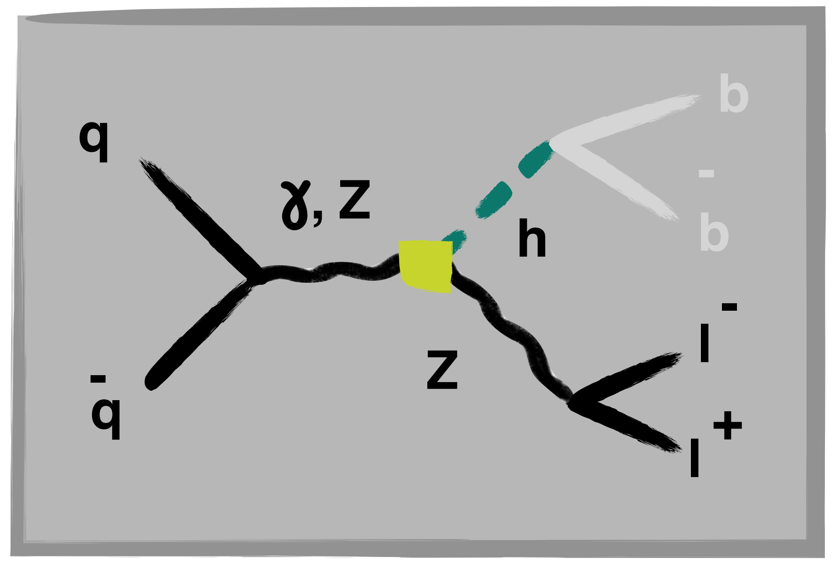
Diagram:



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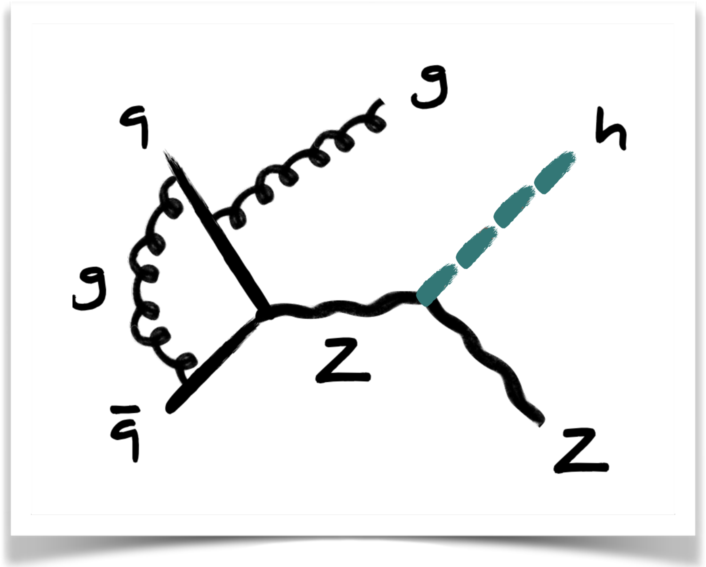

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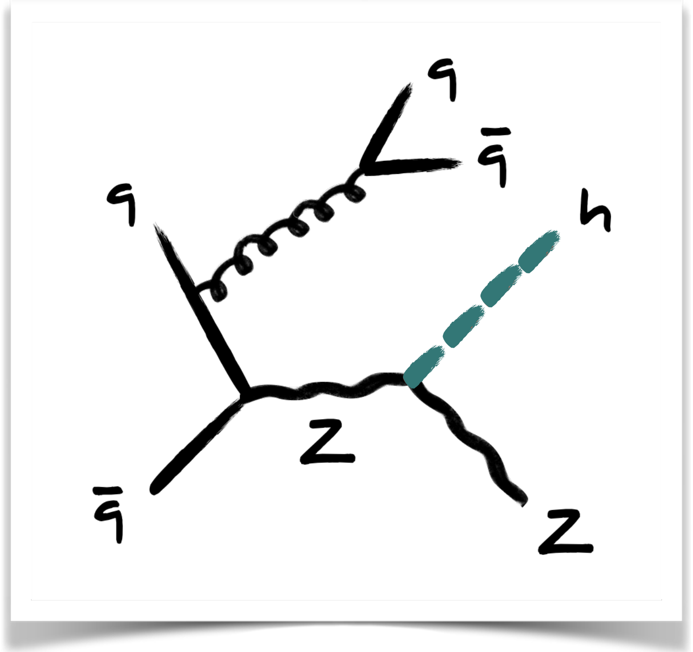

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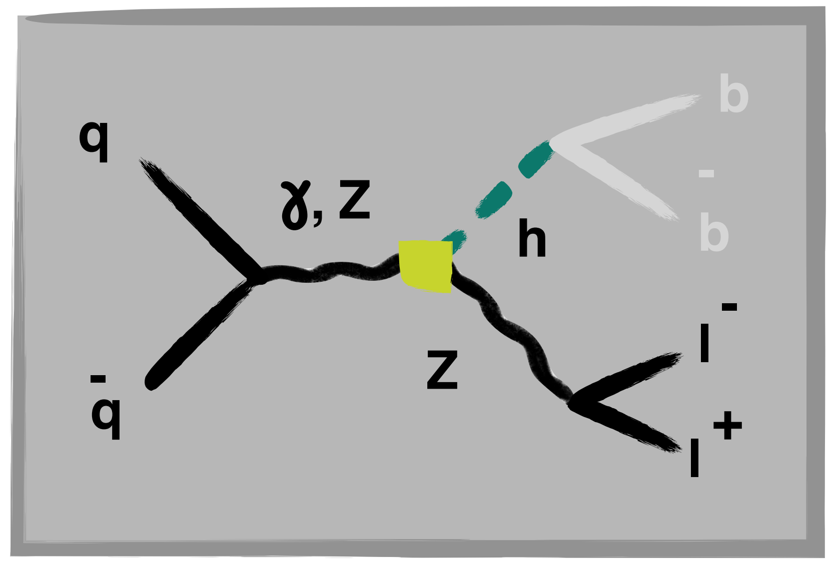

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[10.3929/ethz-b-000448848] (Thesis of I. Majer)
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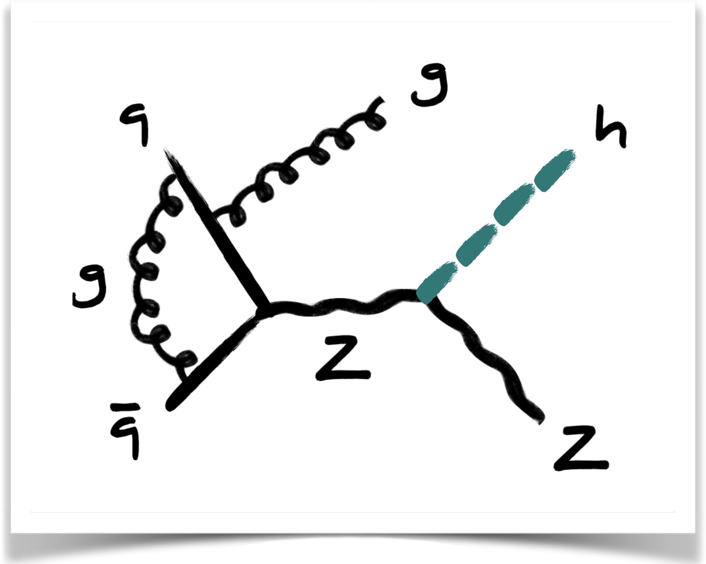

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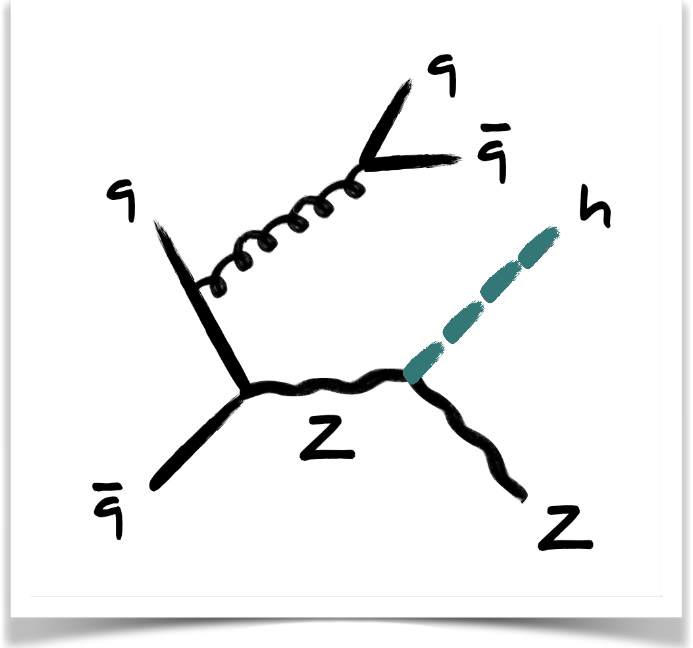

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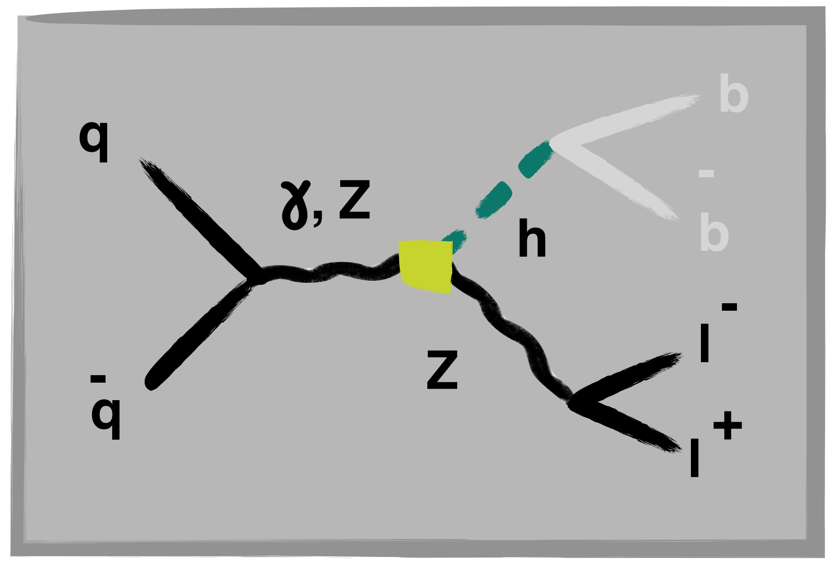

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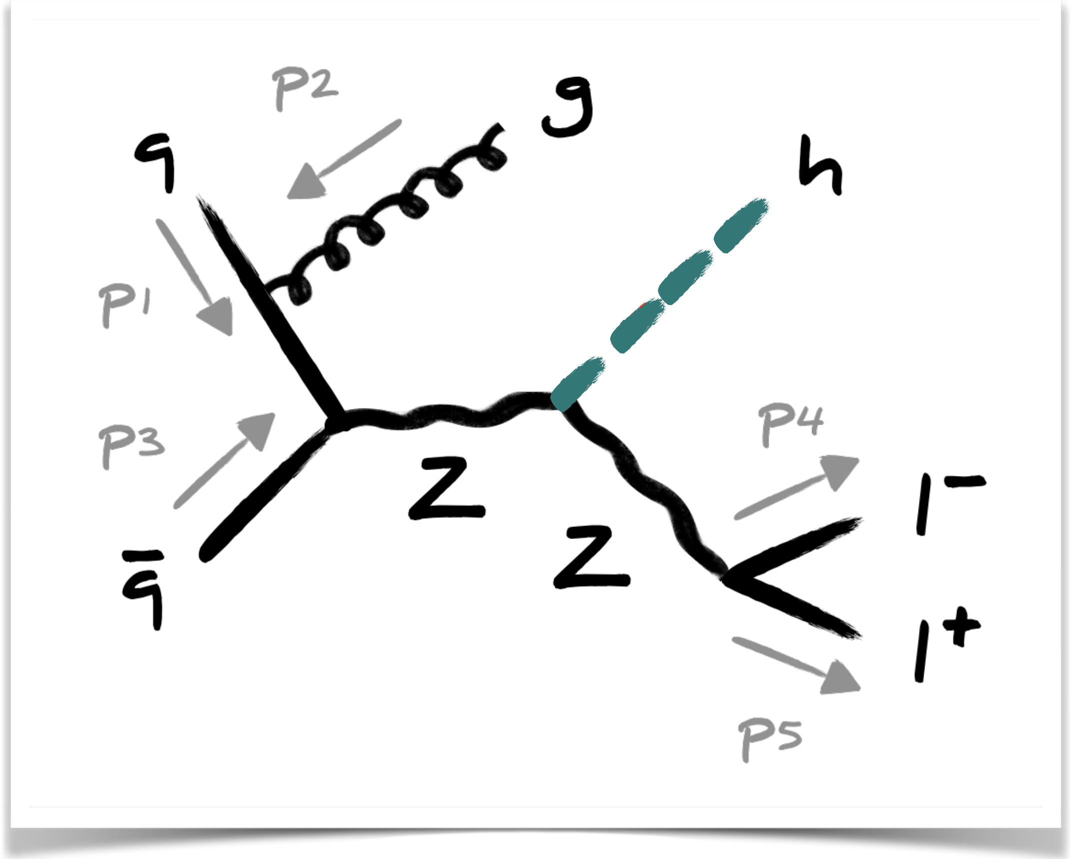

(B1g0Z)

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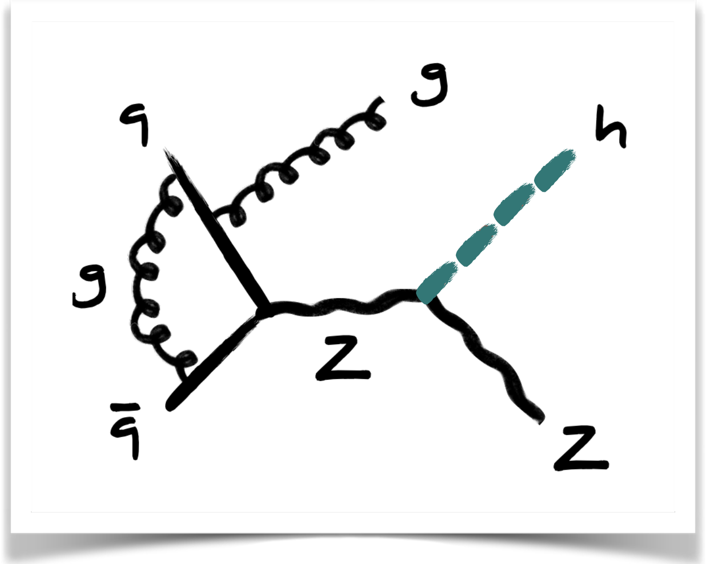

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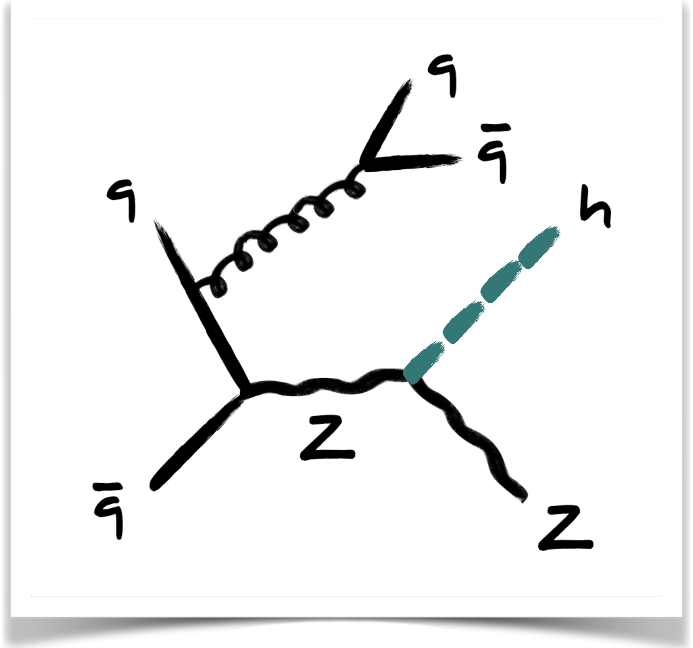

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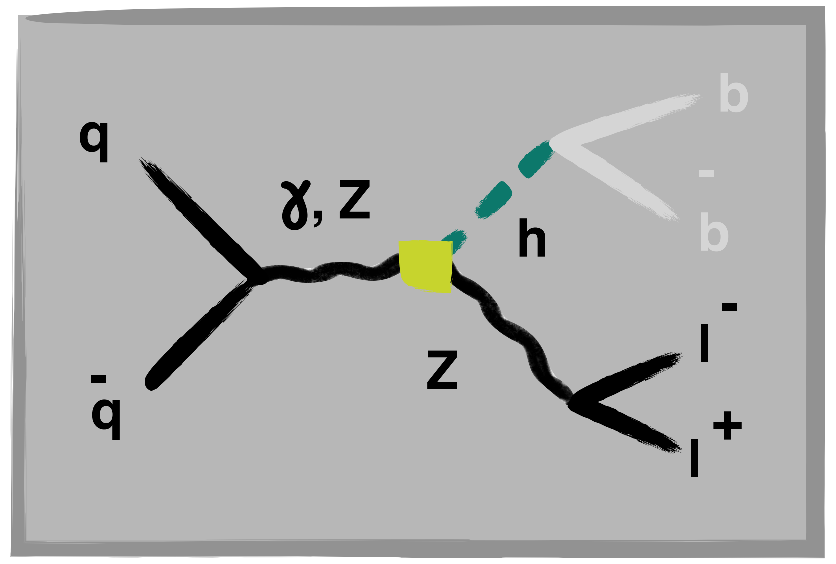

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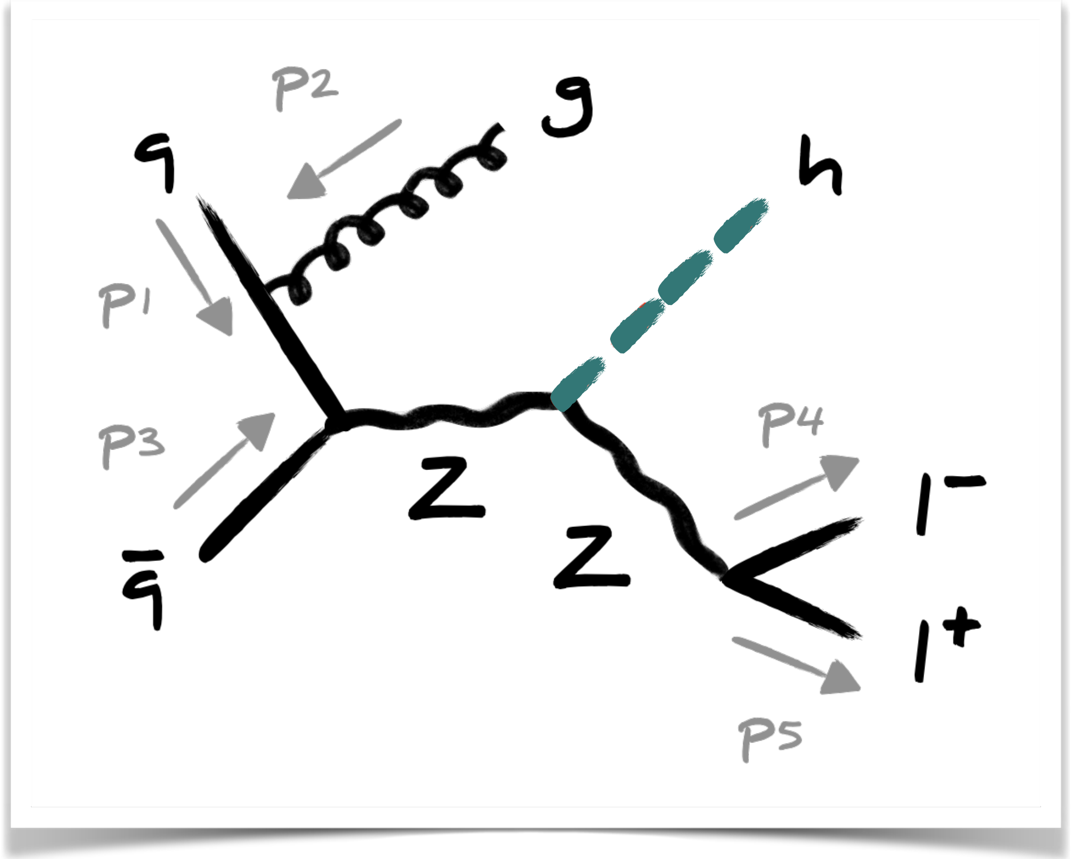

(B1g0Z)

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

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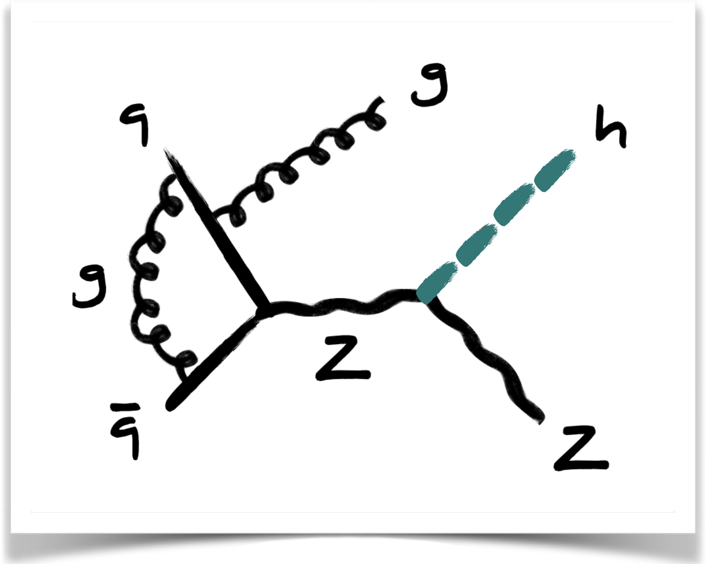

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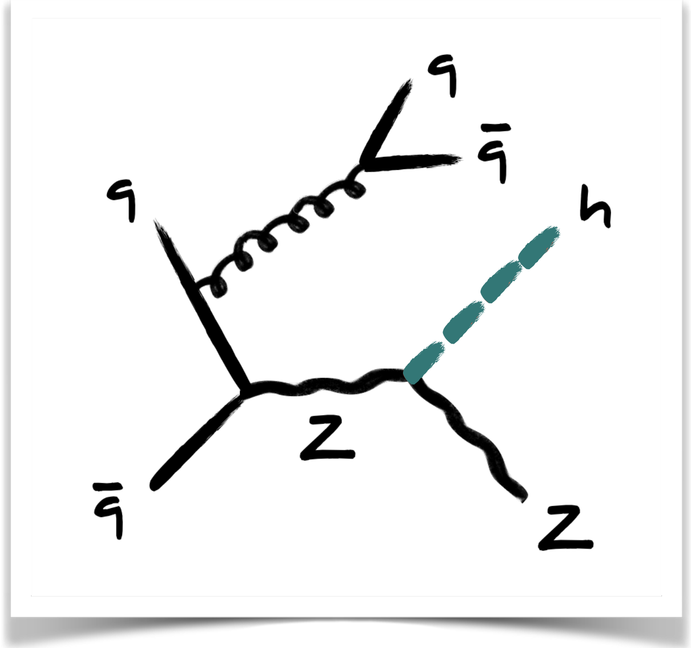

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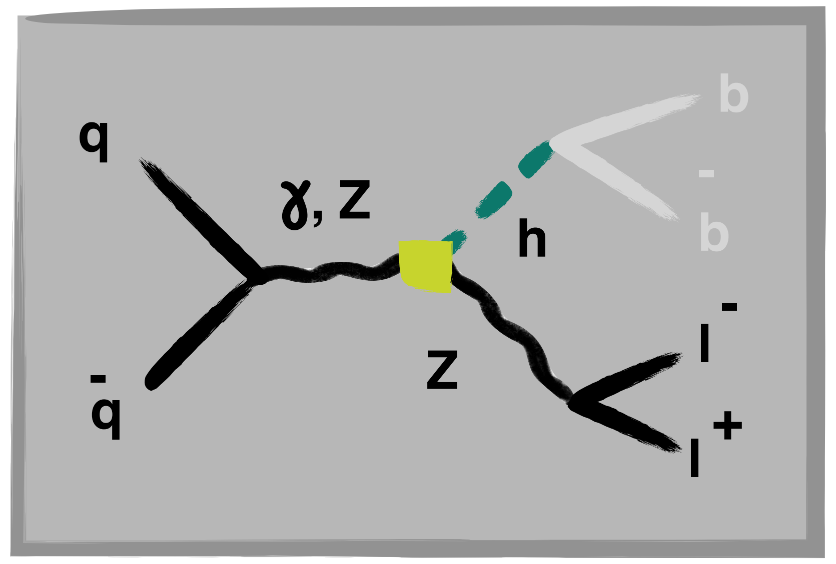

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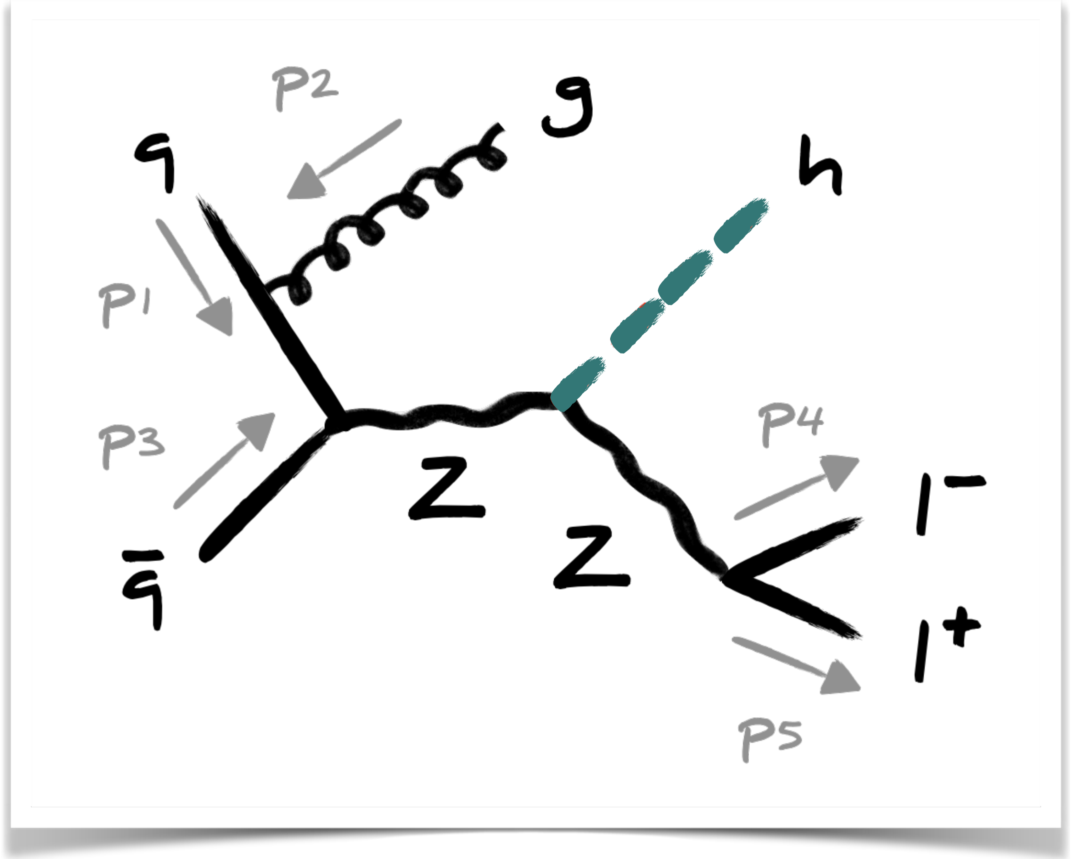


(B1g0Z)

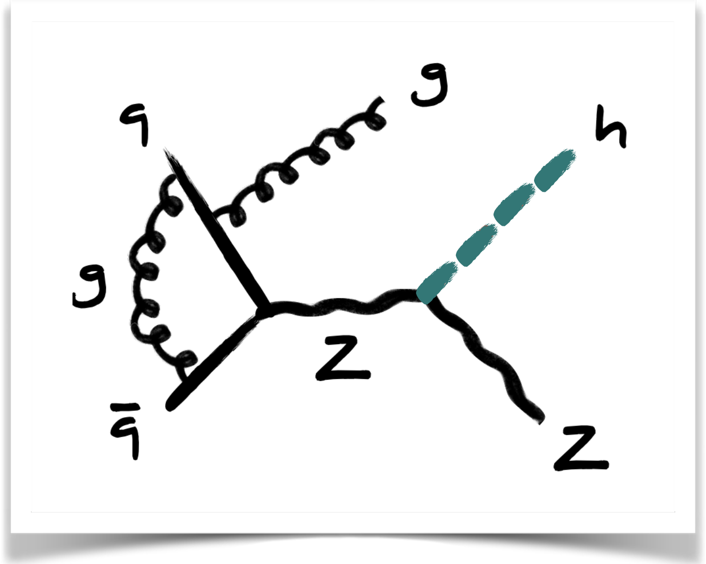
$$\mathrm{B1g0Z} = \frac{8\pi\alpha_s C_F}{C_A} \sum_{h_q,h_g,h_\ell=\pm} \left| \frac{g_{Zq}^{h_q}\, g_{Z\ell}^{h_\ell}\, g_{hZZ}}{D_Z(s_{123})\, D_Z(s_{45})} \mathcal{A}_{\mathrm{B1g0Z}}\left(1_q^{h_q}, 2_g^{h_g}, 3_{\bar{q}}^{-h_q}; 4_\ell^{h_\ell}, 5_{\bar{\ell}}^{-h_\ell}\right) \right|^2,$$

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

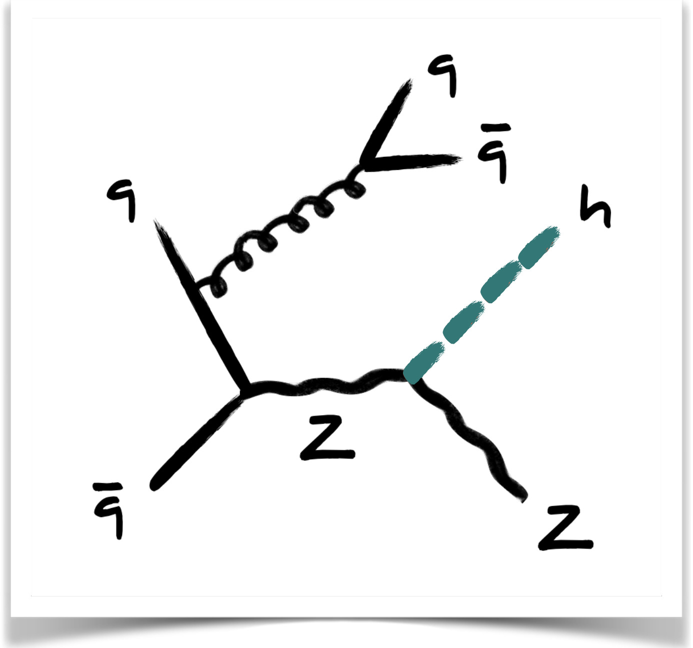
3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

Corrections:

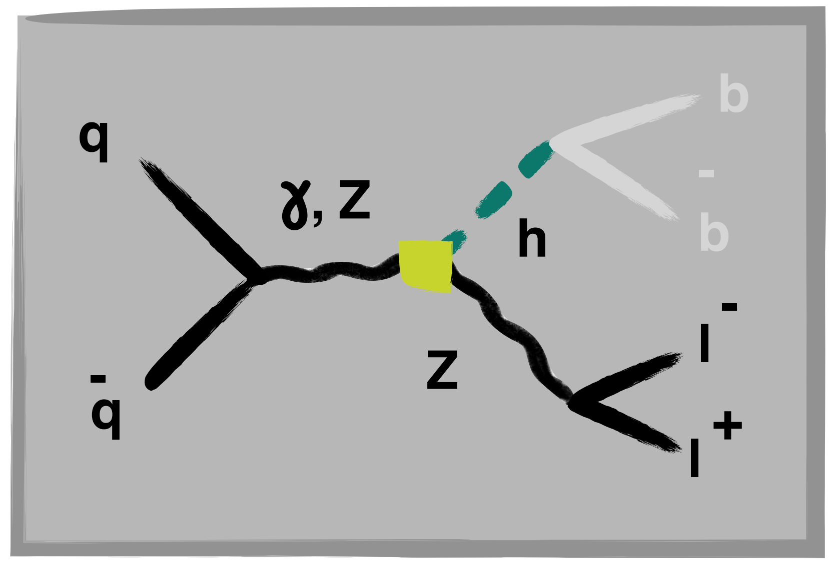


(B-type)



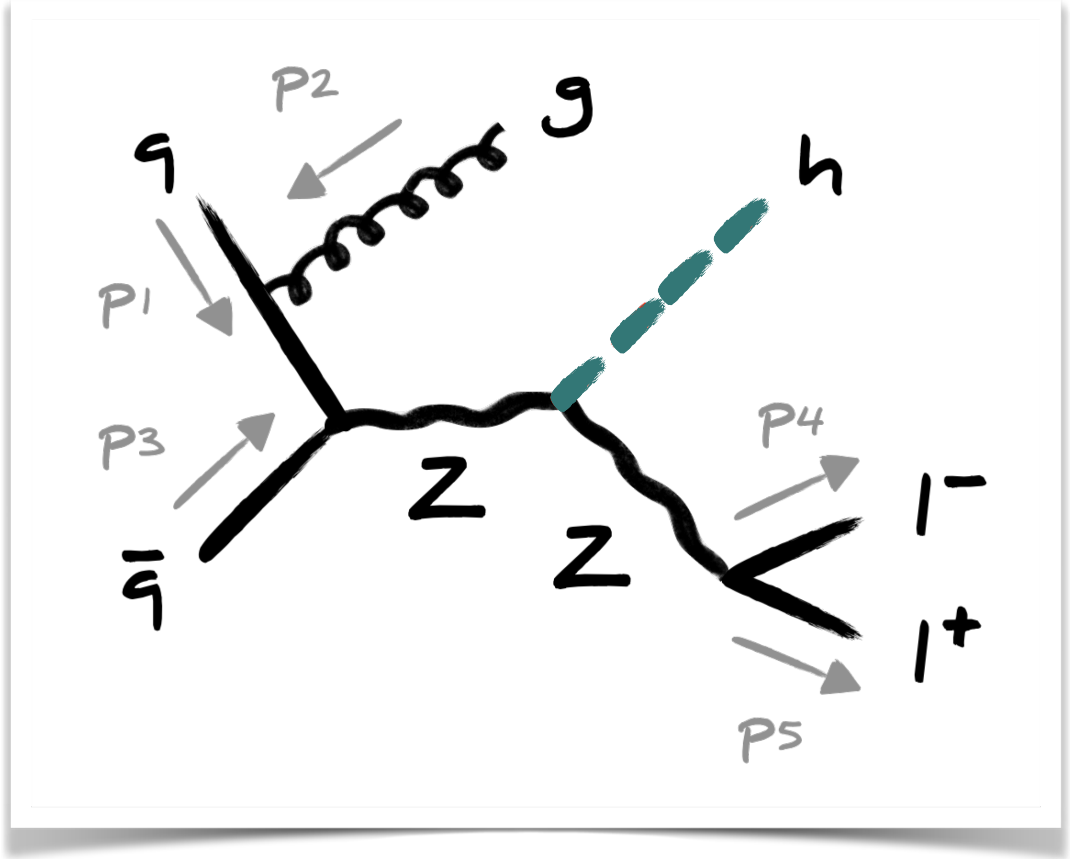
(C,D-type)

Diagram:



We start with the **SM spinor-helicity amplitudes**…

[10.3929/ethz-b-000448848] (Thesis of I. Majer)
[1112.1531] (T. Gehrmann, L. Tancredi)



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→

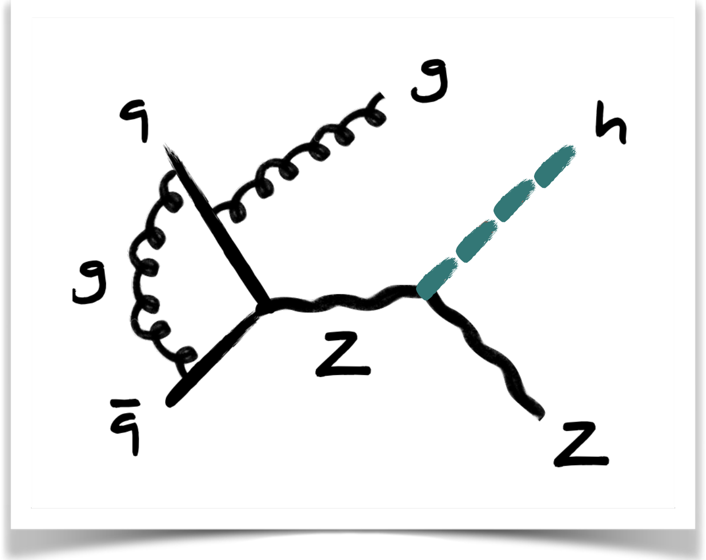
$$\langle 4|\gamma_\mu|5]\, \mathcal{A}^\mu_{qgq}(1_q^-, 2_g^-, 3_{\bar{q}}^+) .$$

SM full amplitude

3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

Corrections:



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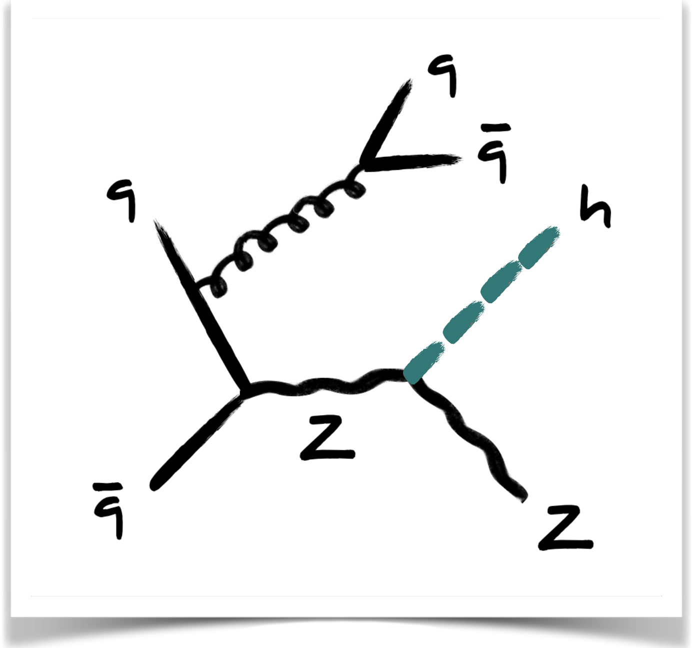

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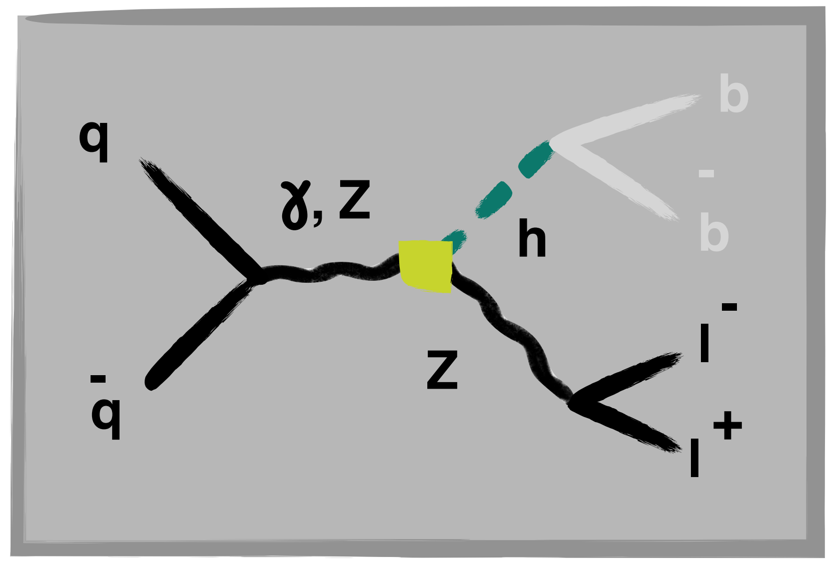
Diagram:



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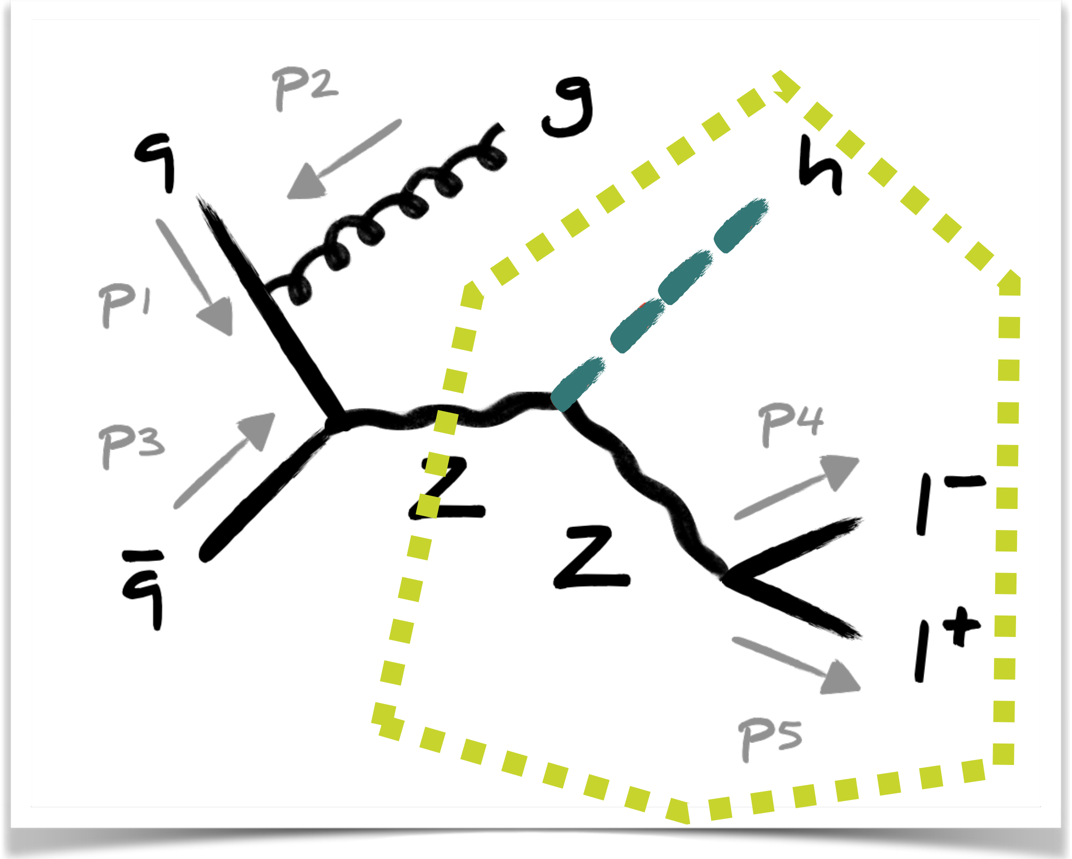

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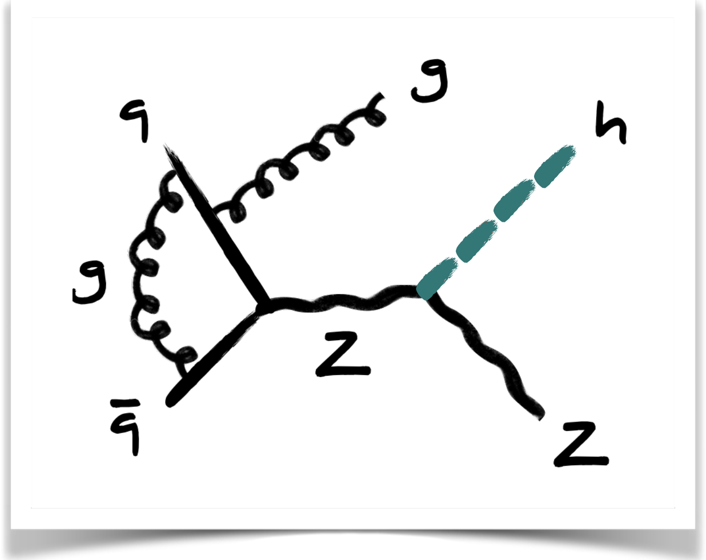
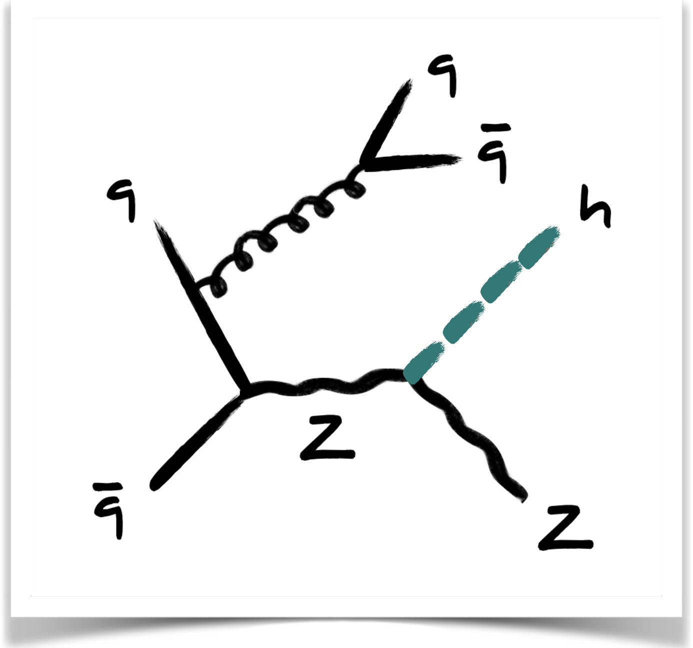
3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

Corrections:



(B-type)



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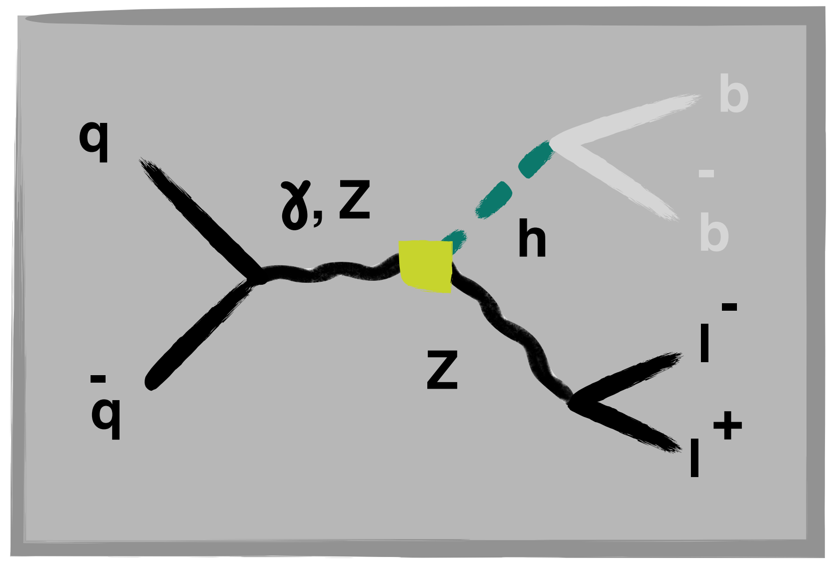

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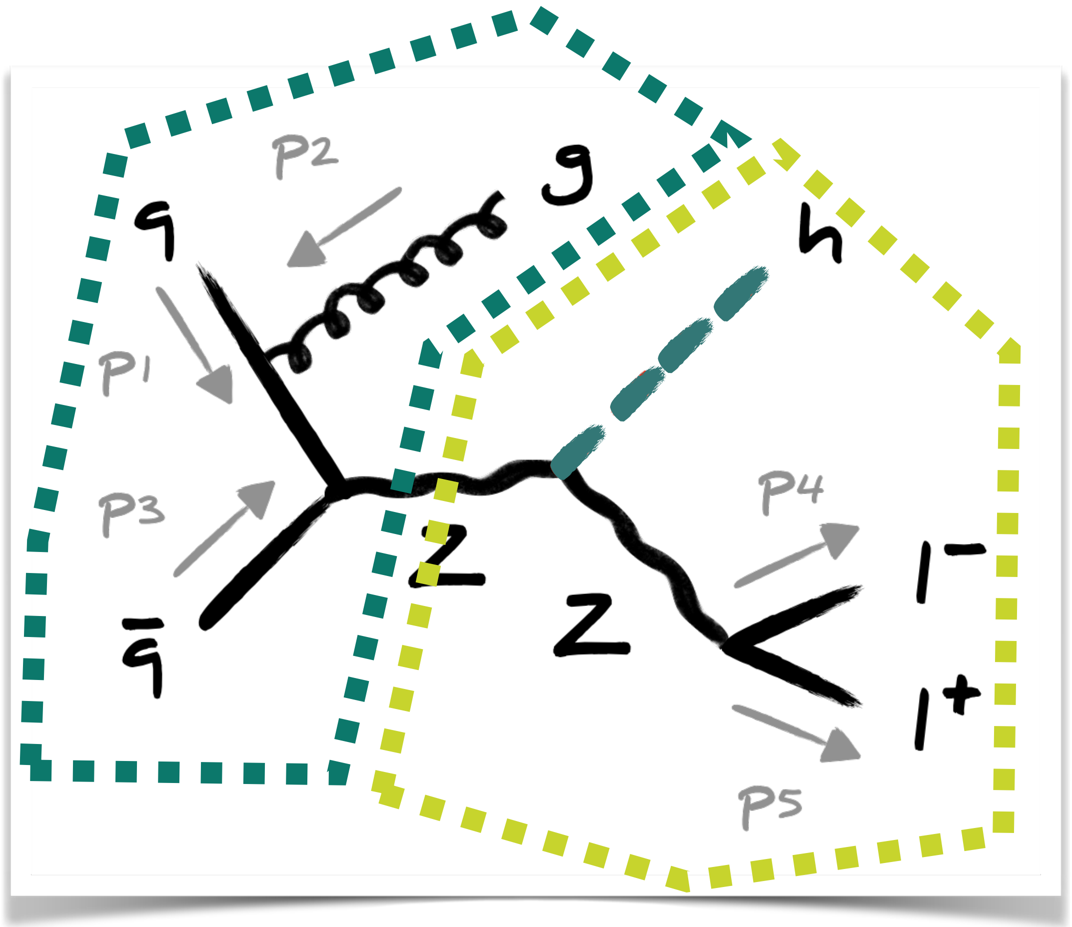

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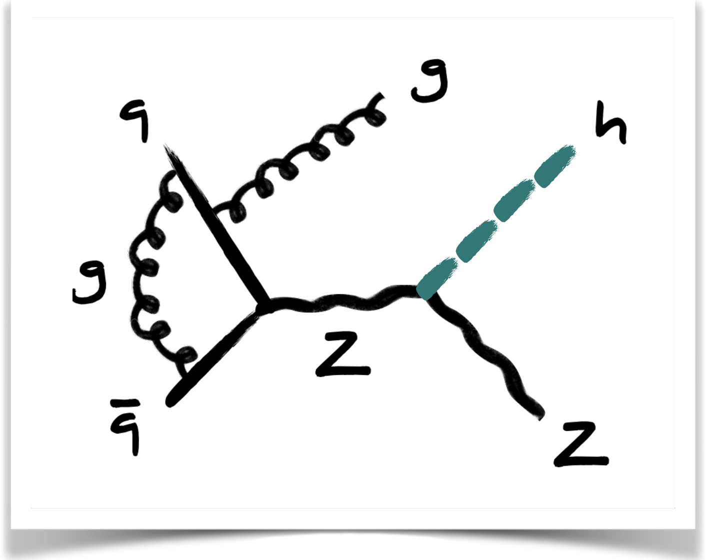
SM full amplitude

3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

Corrections:



(B-type)

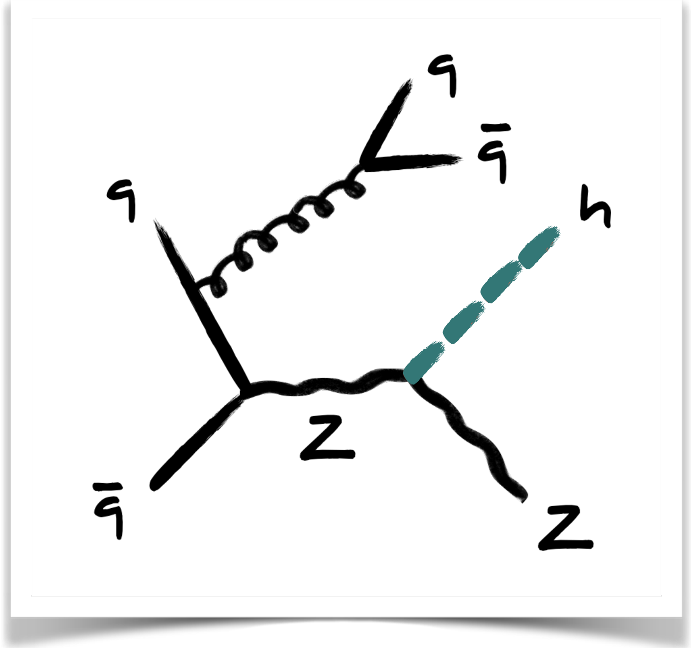


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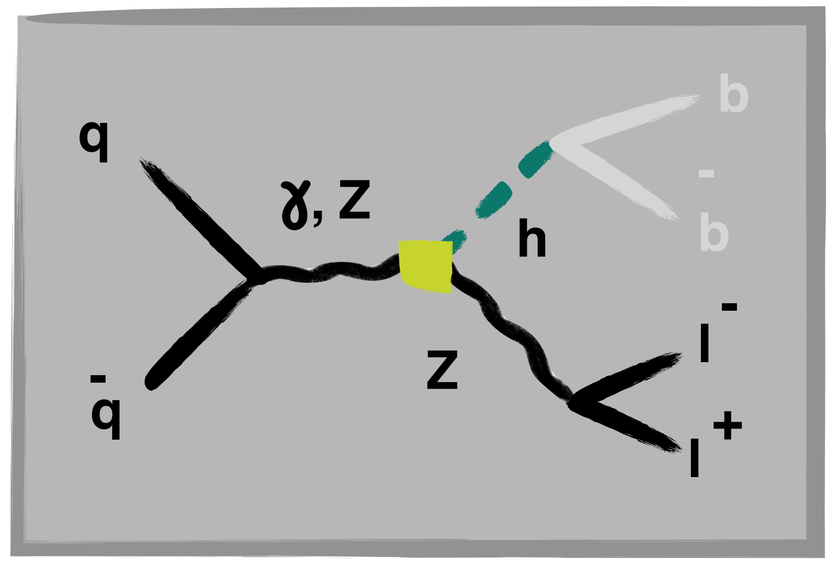
Diagram:



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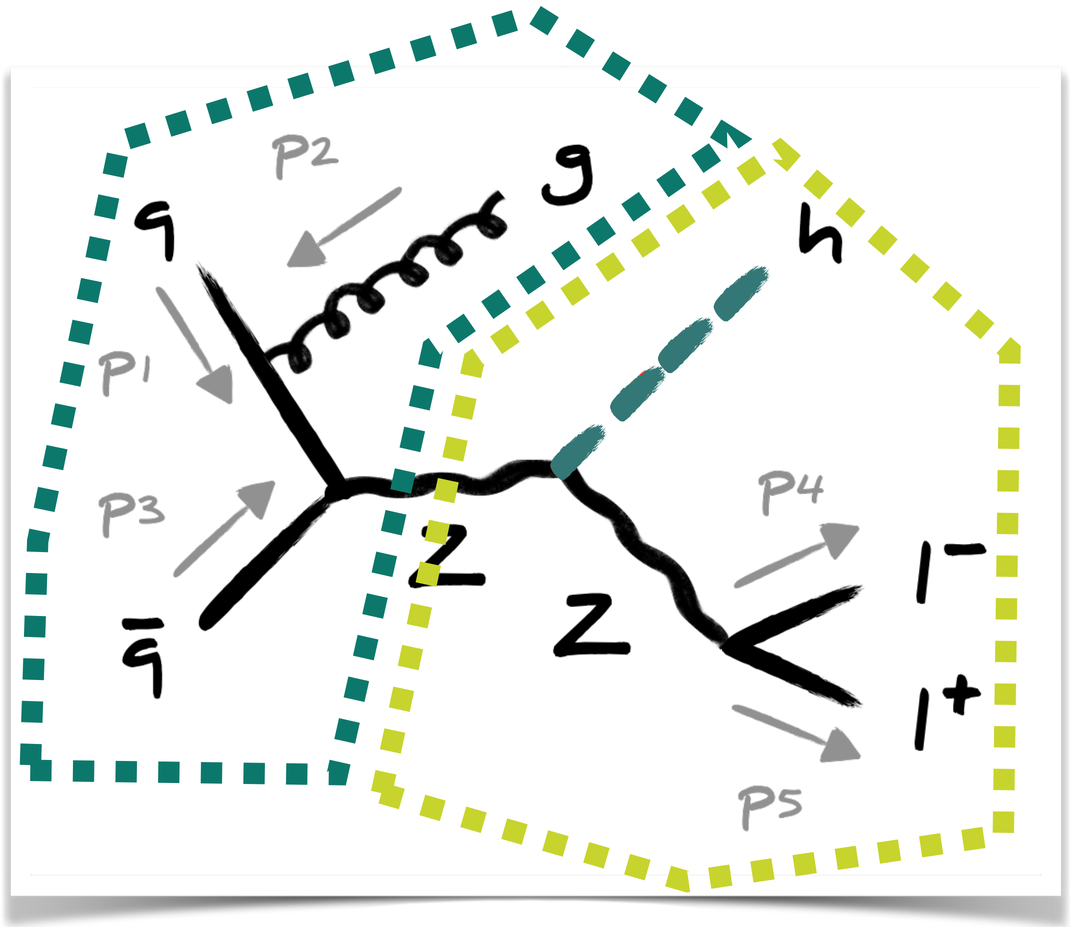

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SM full amplitude

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

SM initial state

3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

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… and contract the **new helicity structures**.

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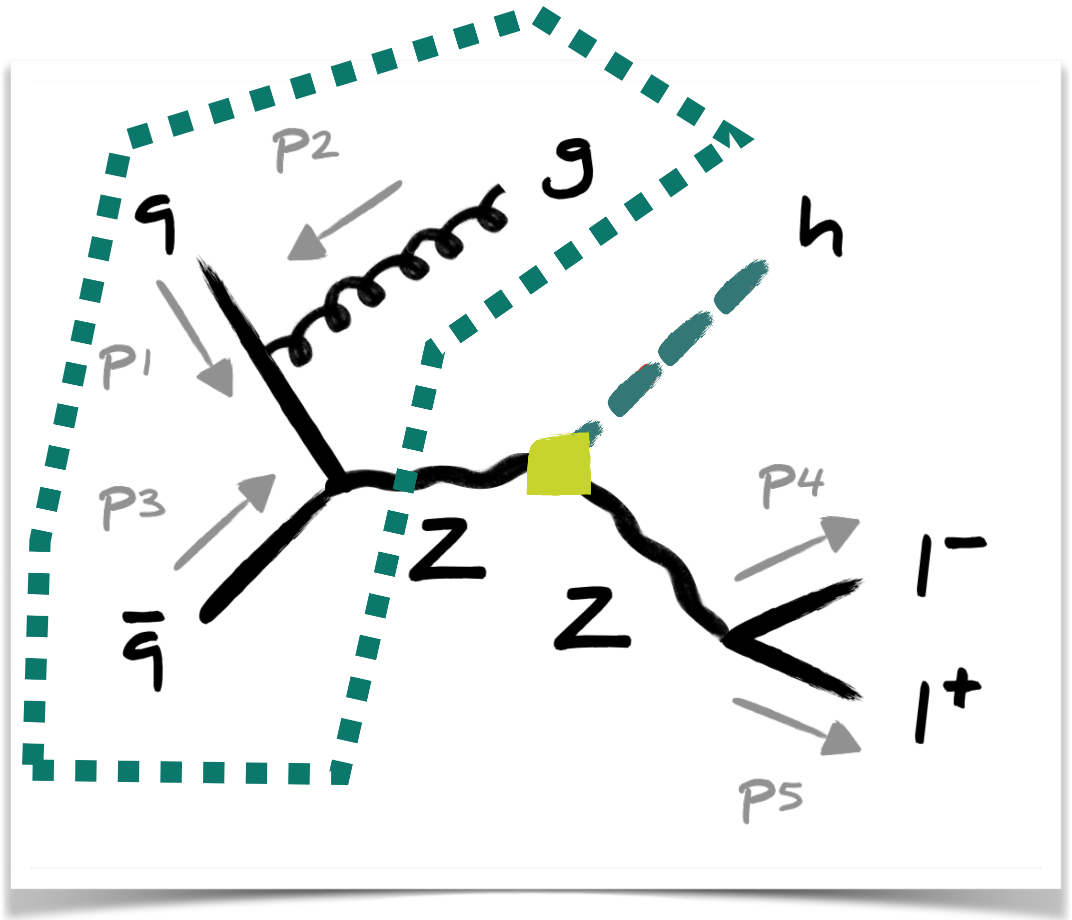
SM initial state



(B1g0Z)

3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

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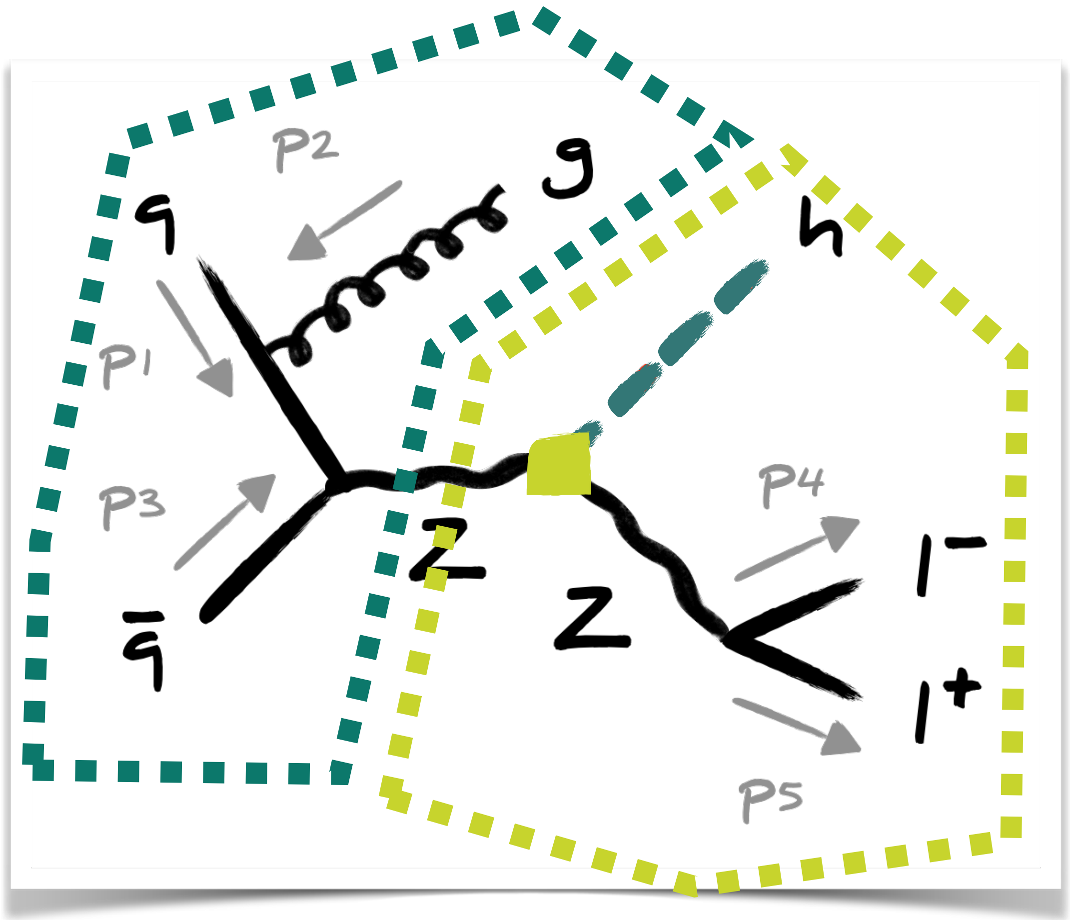


(B1g0Z)

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

SM initial state

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

$$\mathcal{A}^{\mu}_{h\gamma Z}(p_{123}, 4_\ell^-, 5_{\bar{\ell}}^+) = \frac{g^-_{\gamma q}\, g^-_{Z\ell}}{s_{123}\, D(s_{45})} \Bigg\{ - \frac{\delta g^{(1)}_{h\gamma Z}}{2} \Big(\langle 4|\gamma^\mu|5] \left(\langle 4|\not{p}_{123}|4] + \langle 5|\not{p}_{123}|5] \right) - 2\,(p_4^\mu + p_5^\mu)\, \langle 4|\not{p}_{123}|5] \Big) + \delta g^{(2)}_{h\gamma Z} \left(\langle 4|\gamma^\mu|5]\, s_{123} - p^\mu_{123}\, \langle 4|\not{p}_{123}|5] \right) \Bigg\},$$

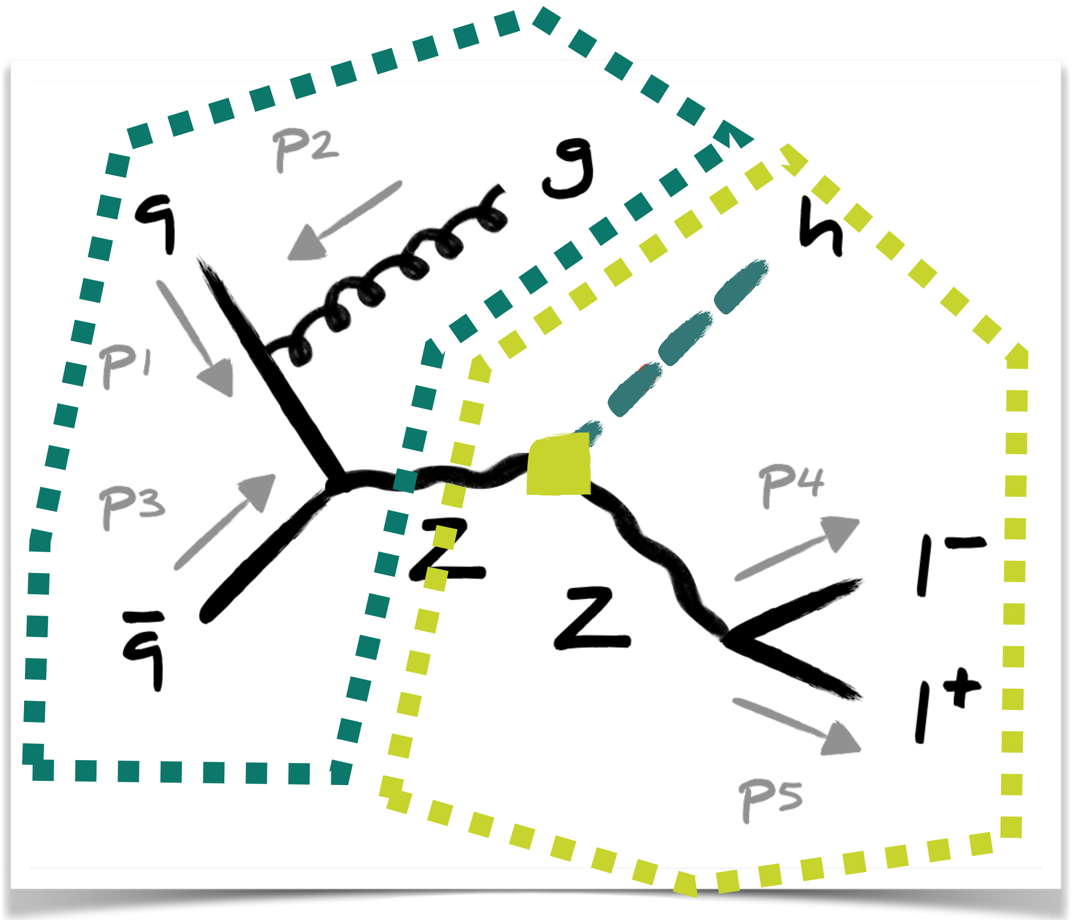
New helicity structures

[1512.02572] (K. Mimasu, *et al.*)

3. Higher-Order Corrections

3.2 $q\bar{q}$-initiated contributions

… and contract the **new helicity structures**.



(B1g0Z)

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SM initial state

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New helicity structures

[1512.02572] (K. Mimasu, *et al.*)

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

SMEFT full amplitude

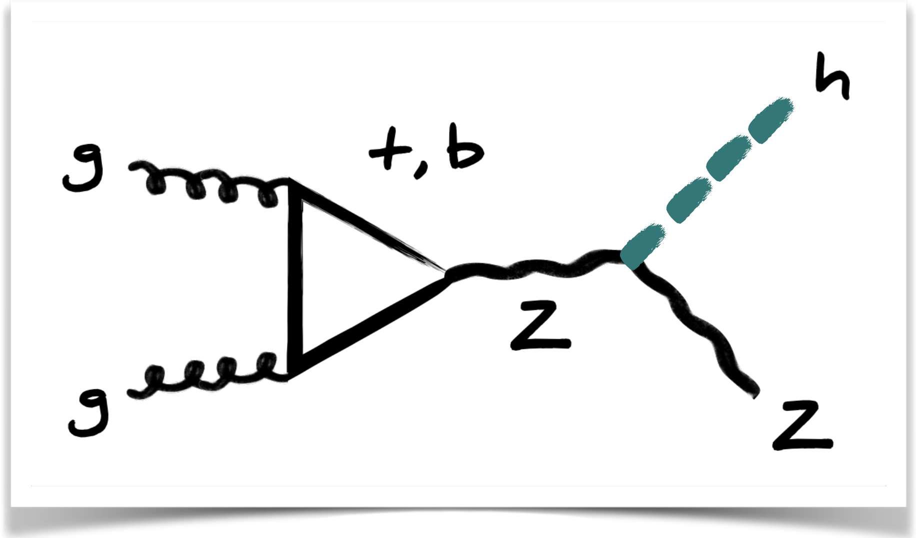
3. Higher-Order Corrections

3.3 gg-initiated contributions

3. Higher-Order Corrections

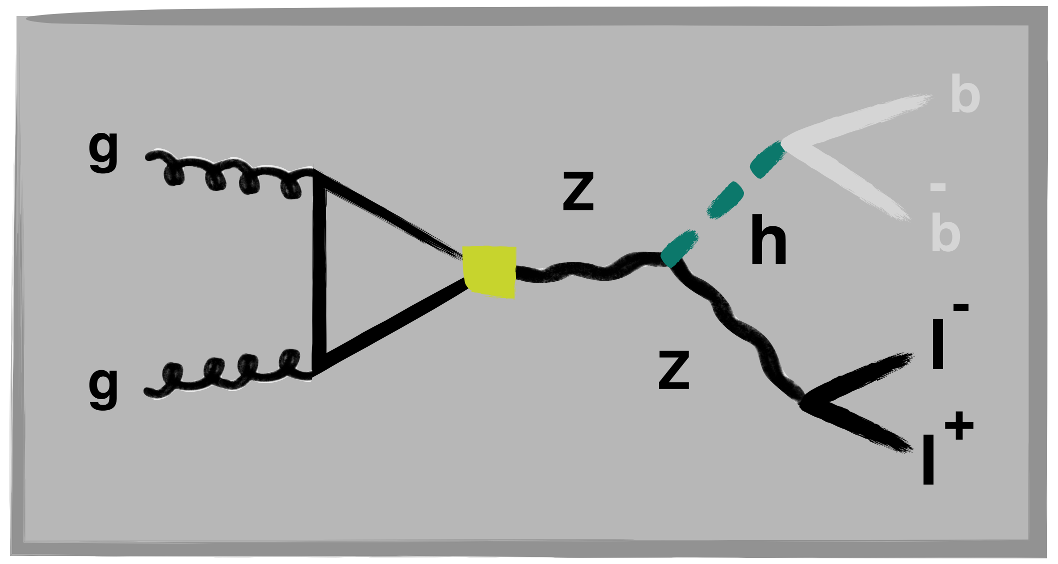
3.3 gg-initiated contributions

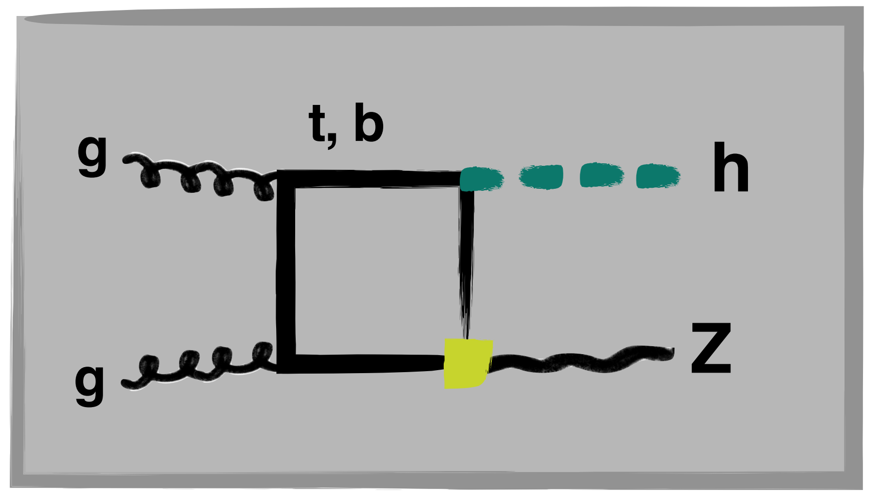
Corrections:

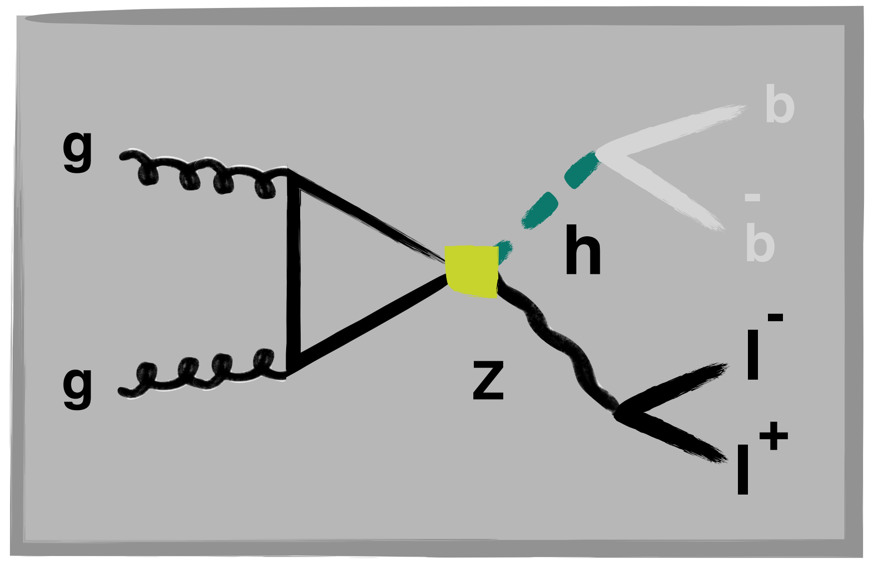


(A-type)

Diagrams:



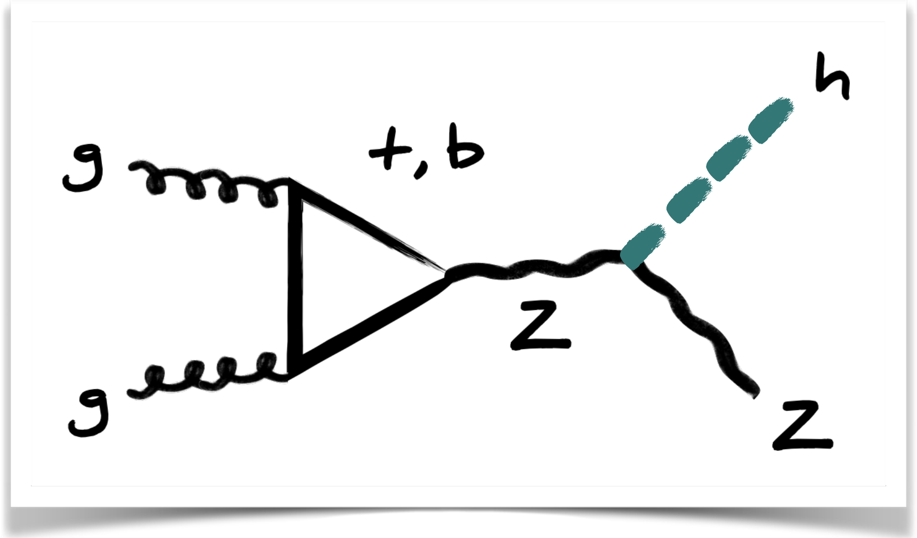




3. Higher-Order Corrections

3.3 gg-initiated contributions

Corrections:



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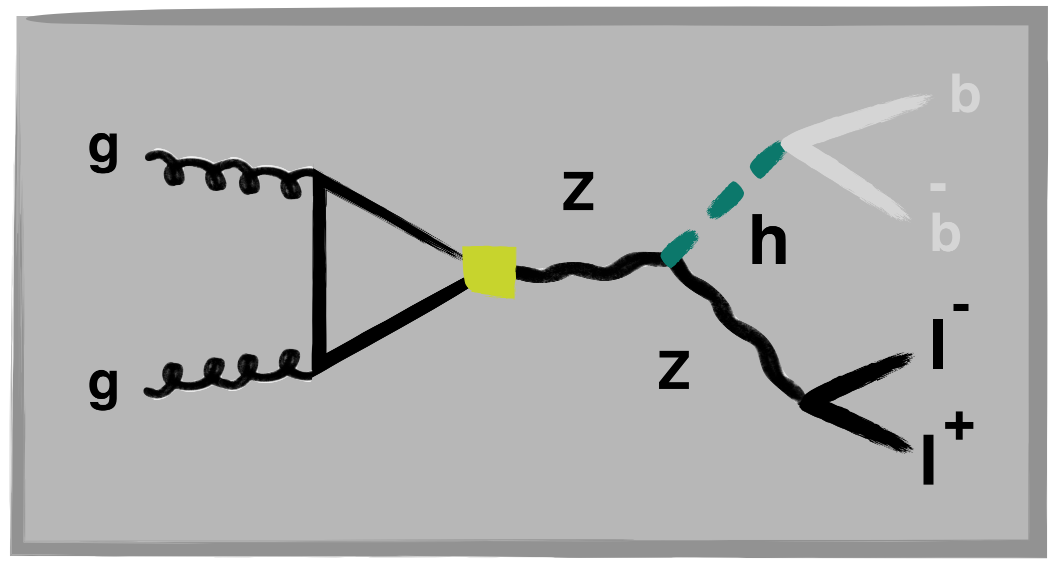
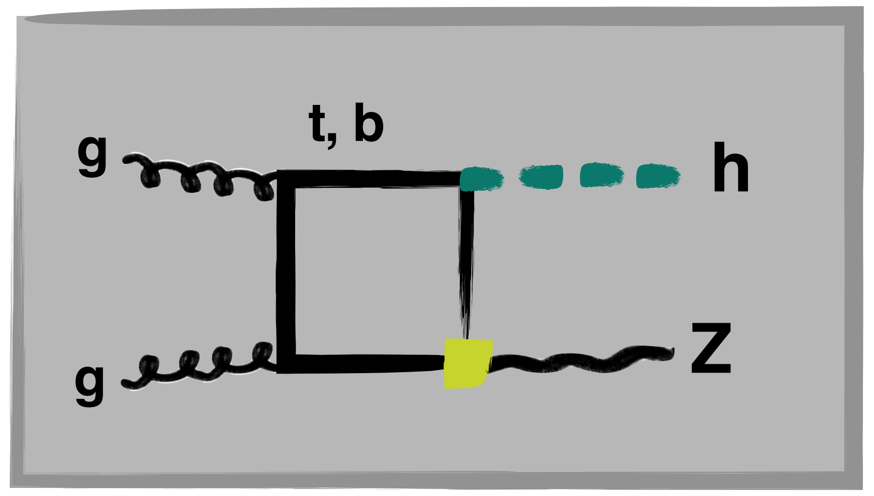
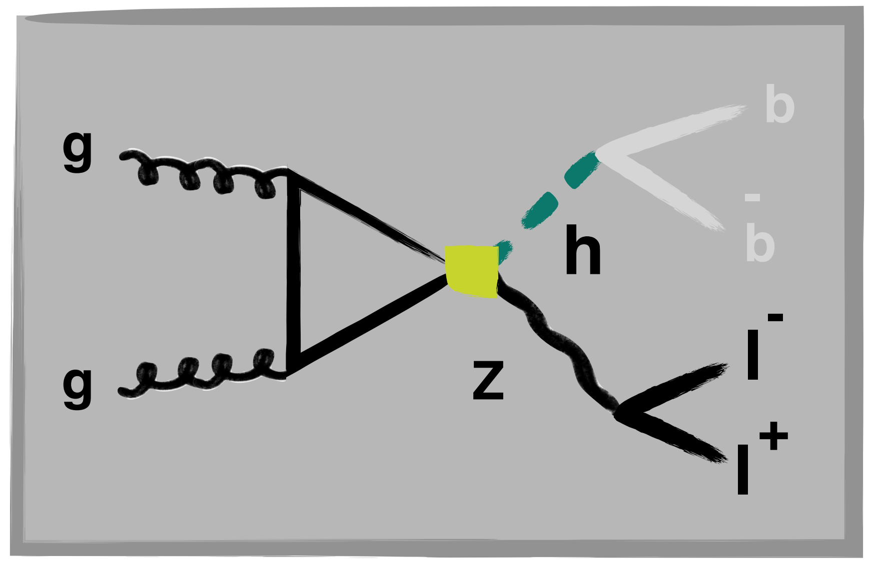




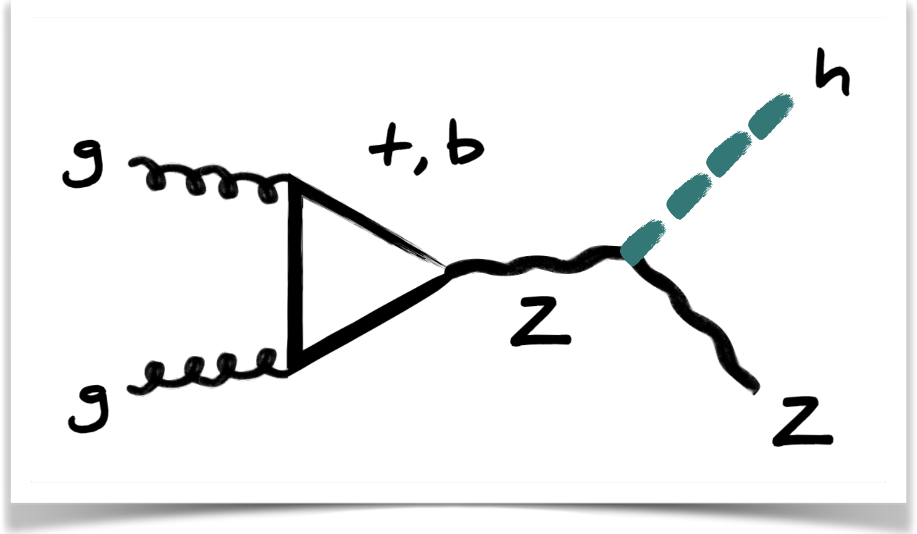


We start with the **SM spinor-helicity amplitudes…**

3. Higher-Order Corrections

3.3 gg-initiated contributions

Corrections:



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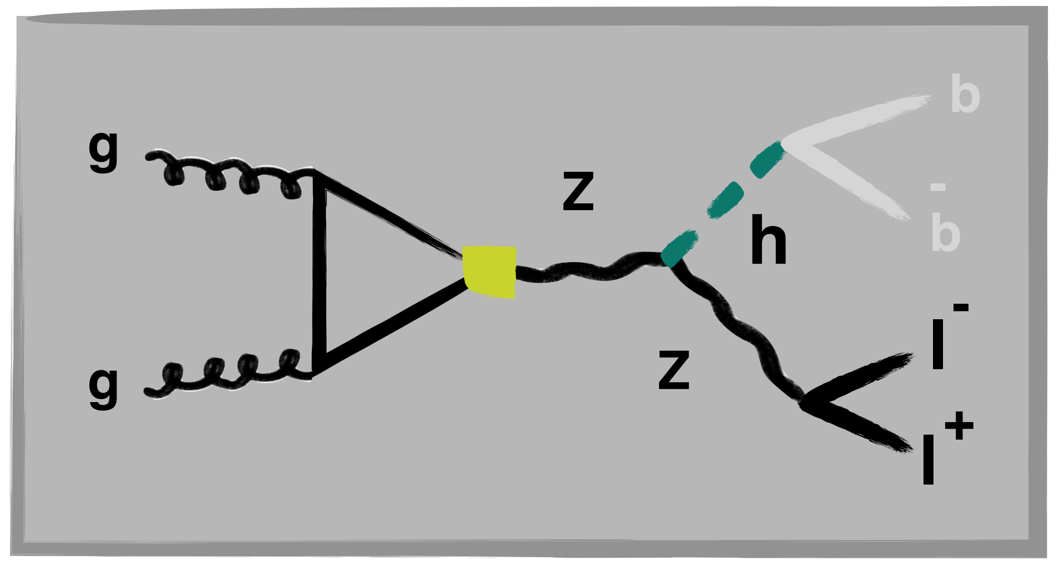

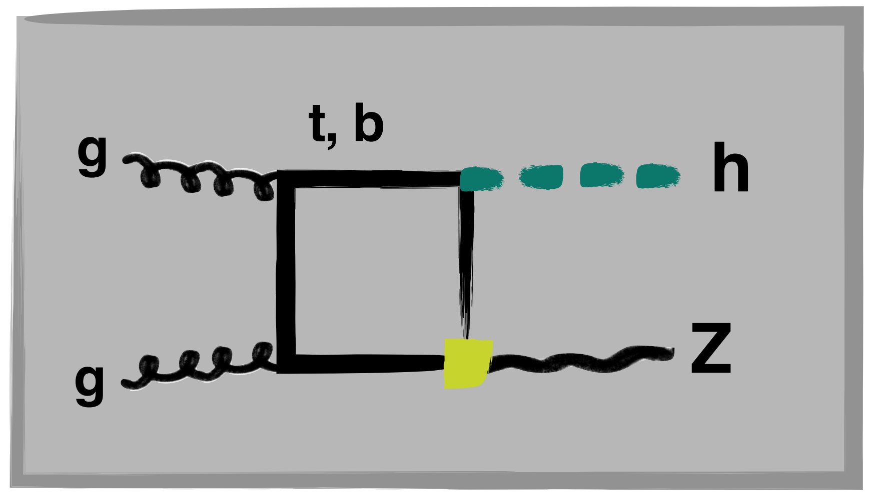

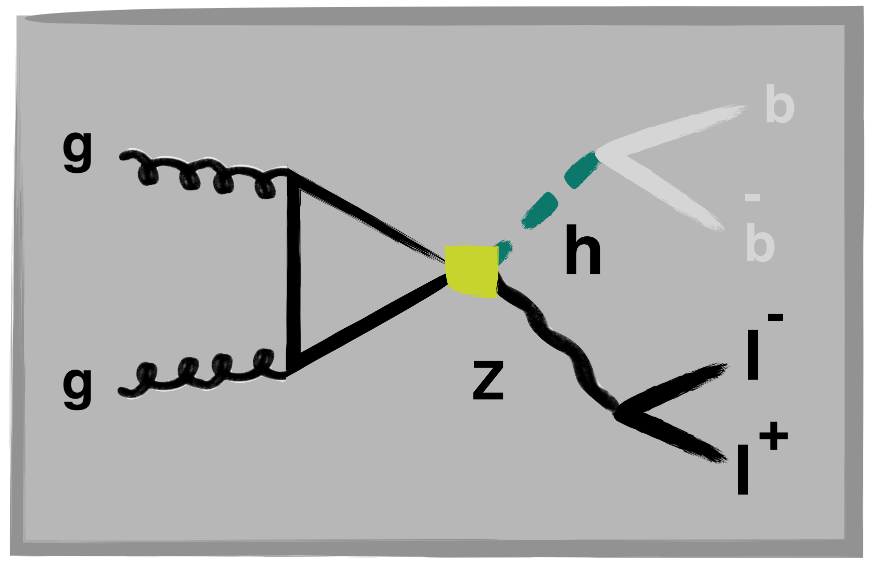

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$$\mathtt{A0g2Z} = \frac{\alpha_s^2}{8\pi^2\,(C_A^2-1)^2} \sum_{h_g,h_\ell=\pm} \left| \sum_{q=t,b} \left(\mathcal{A}^q_\triangle + \sum_{s=\pm} \frac{m_q^2}{m_Z^2}\, \mathcal{A}^{q,s}_\square \right) \right|^2 ,$$

with

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

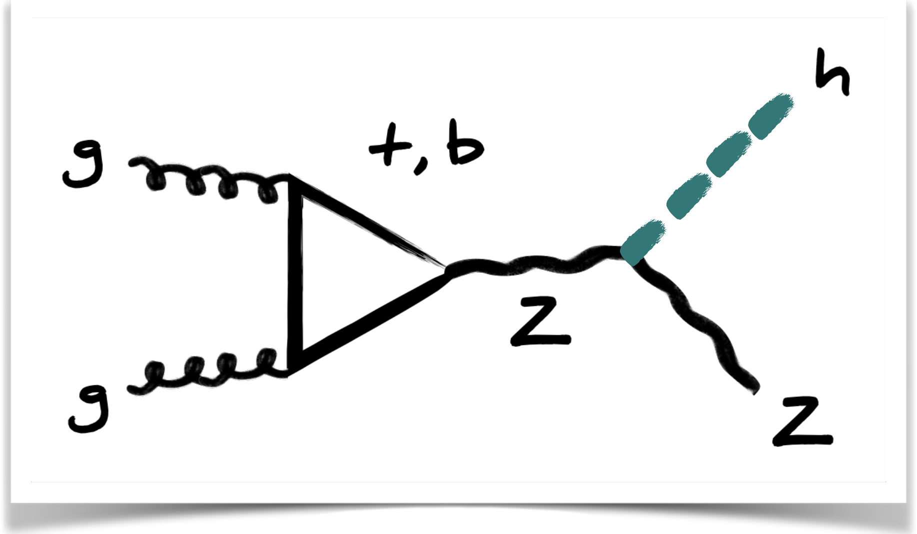
$$\mathcal{A}^q_{\mathtt{A0g2Z}\triangle}\left(1_g^+, 2_g^+, 3_\ell^-, 4_{\bar\ell}^+\right) = -\frac{2\,[21]\,\big([41]\,\langle 13\rangle + [42]\,\langle 23\rangle\big)}{\langle 12\rangle} \left(1 - \frac{s_{12}}{m_Z^2}\right)$$
$$\times\, m_q^2\, C_0(s_{12}, 0, 0, m_q, m_q, m_q)\,.$$

[1601.00658] (J.M. Campbell, R.K. Ellis, C. Williams)

3. Higher-Order Corrections

3.3 gg-initiated contributions

Corrections:



(A-type)

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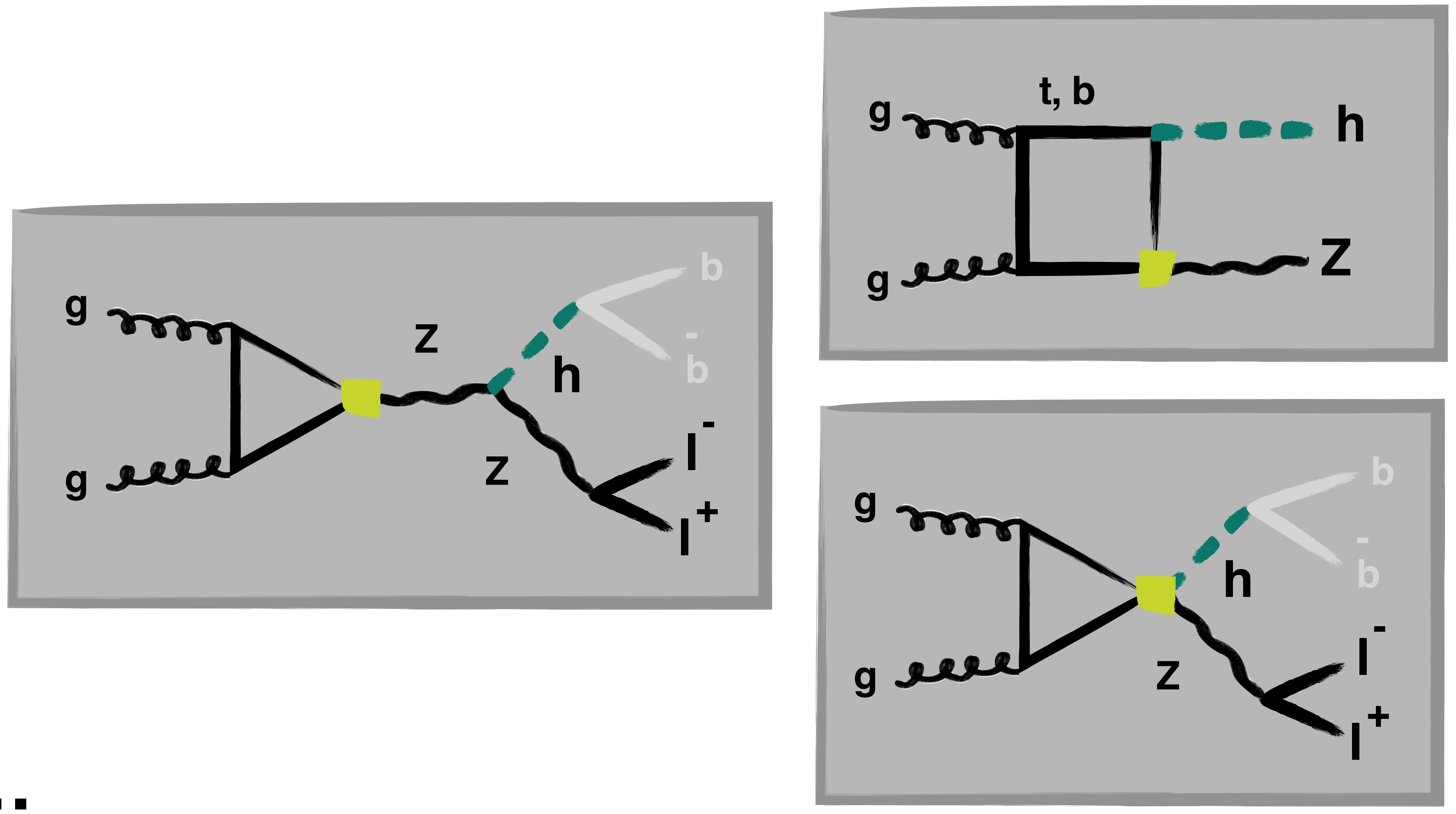

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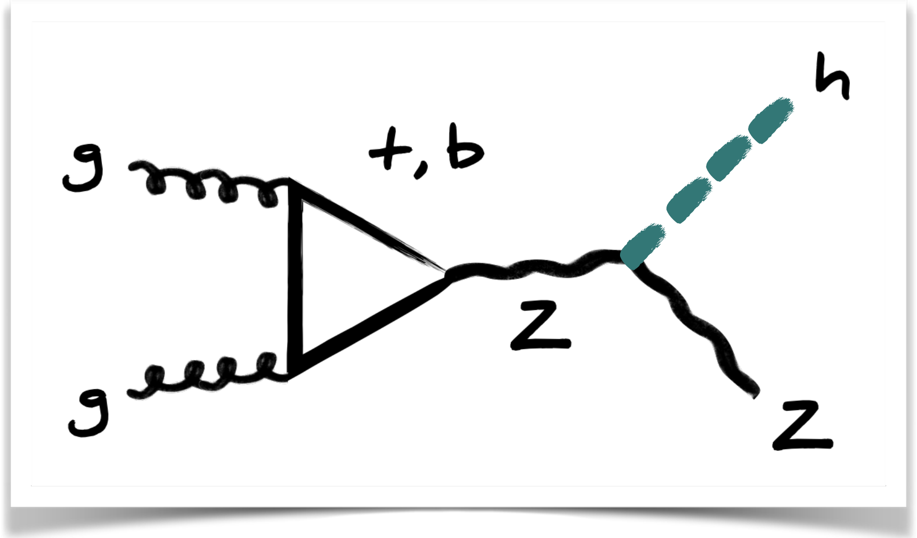
Longitudinal contribution

[1601.00658] (J.M. Campbell, R.K. Ellis, C. Williams)

3. Higher-Order Corrections

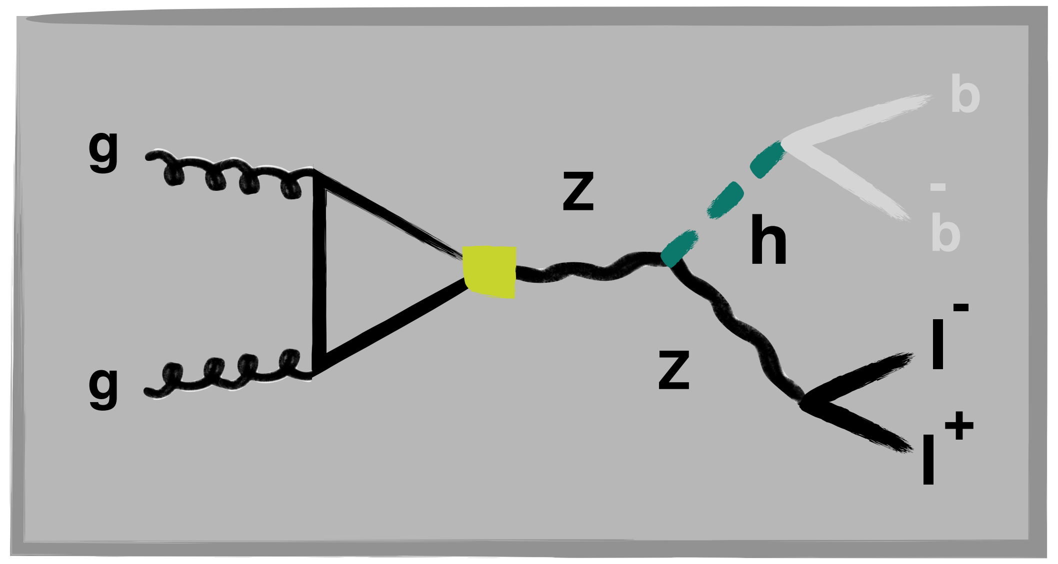
3.3 gg-initiated contributions

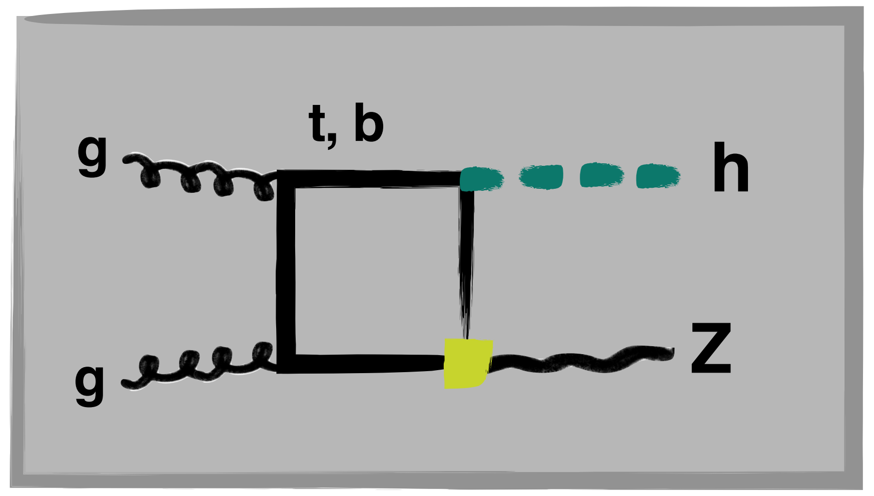
Corrections:

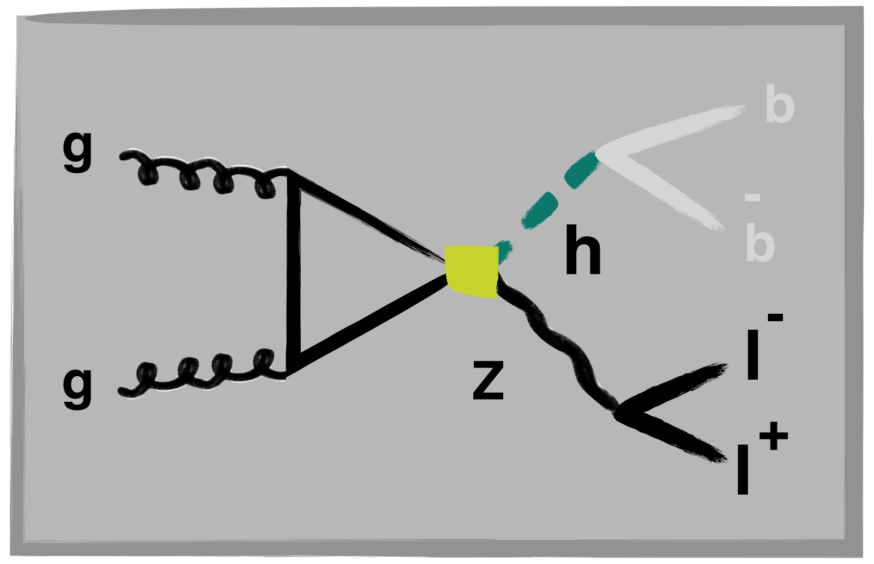


(A-type)

Diagrams:







We start with the **SM spinor-helicity amplitudes…**

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

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Only axial part contributes

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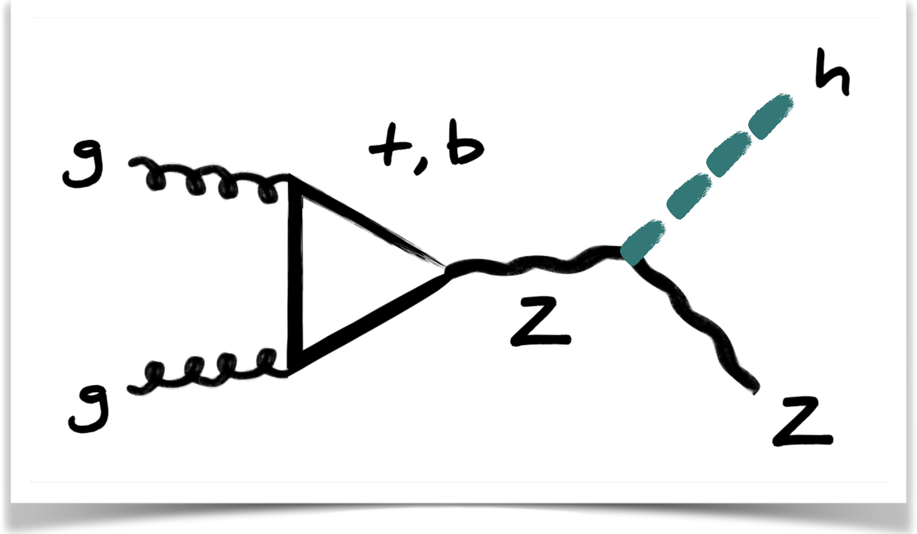
Longitudinal contribution

[1601.00658] (J.M. Campbell, R.K. Ellis, C. Williams)

3. Higher-Order Corrections

3.3 gg-initiated contributions

Corrections:



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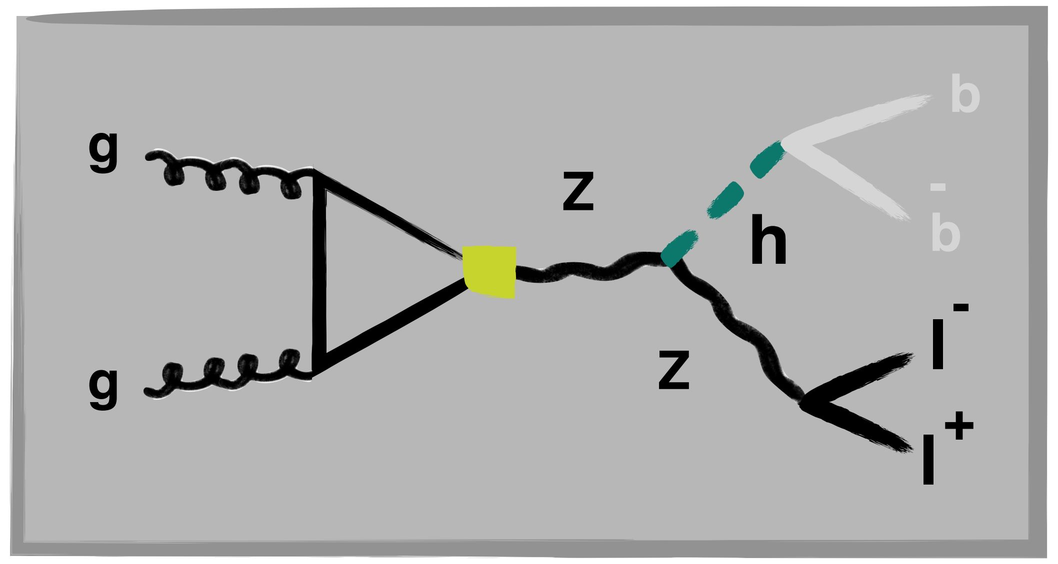

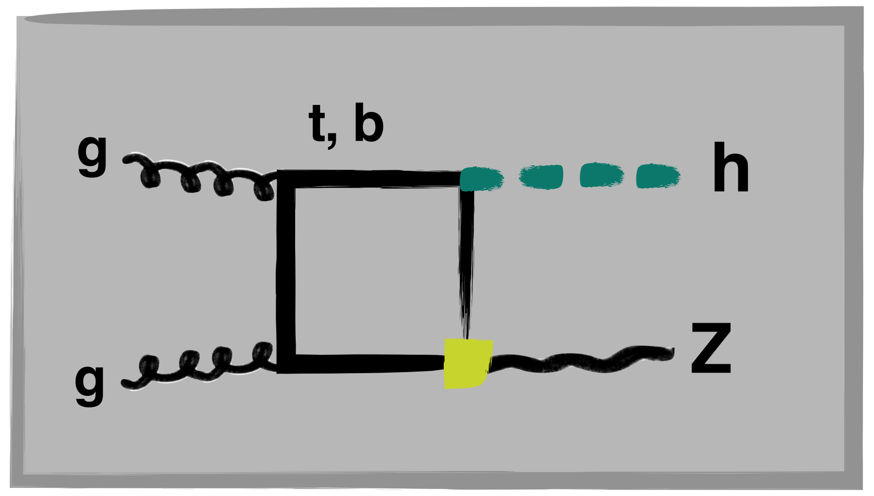

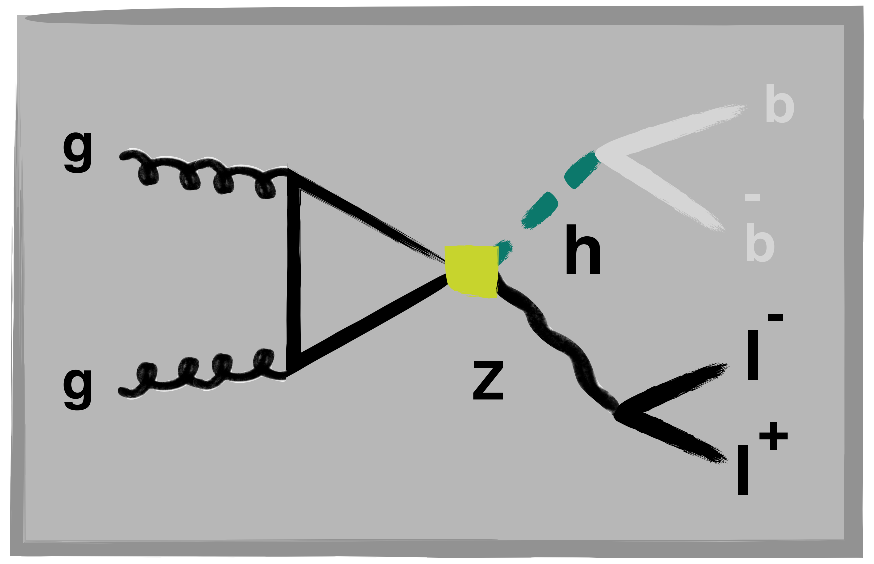

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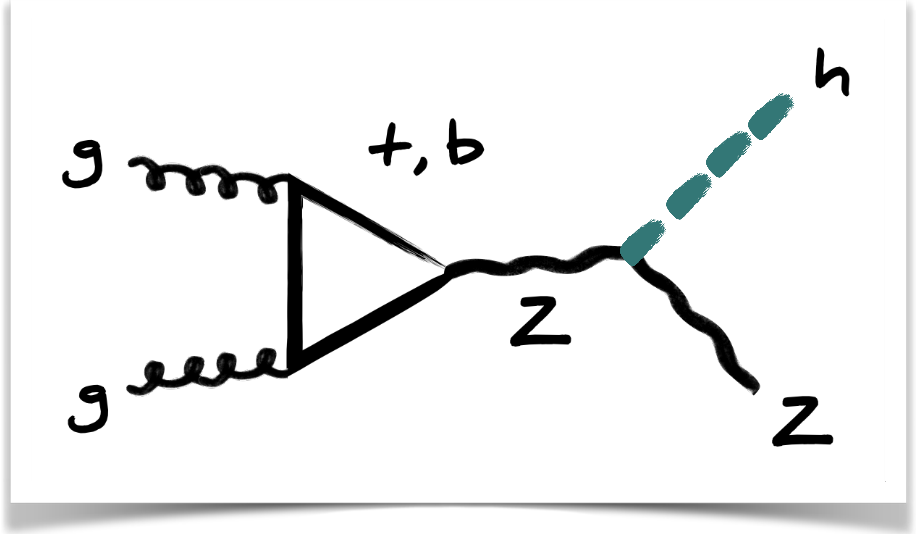

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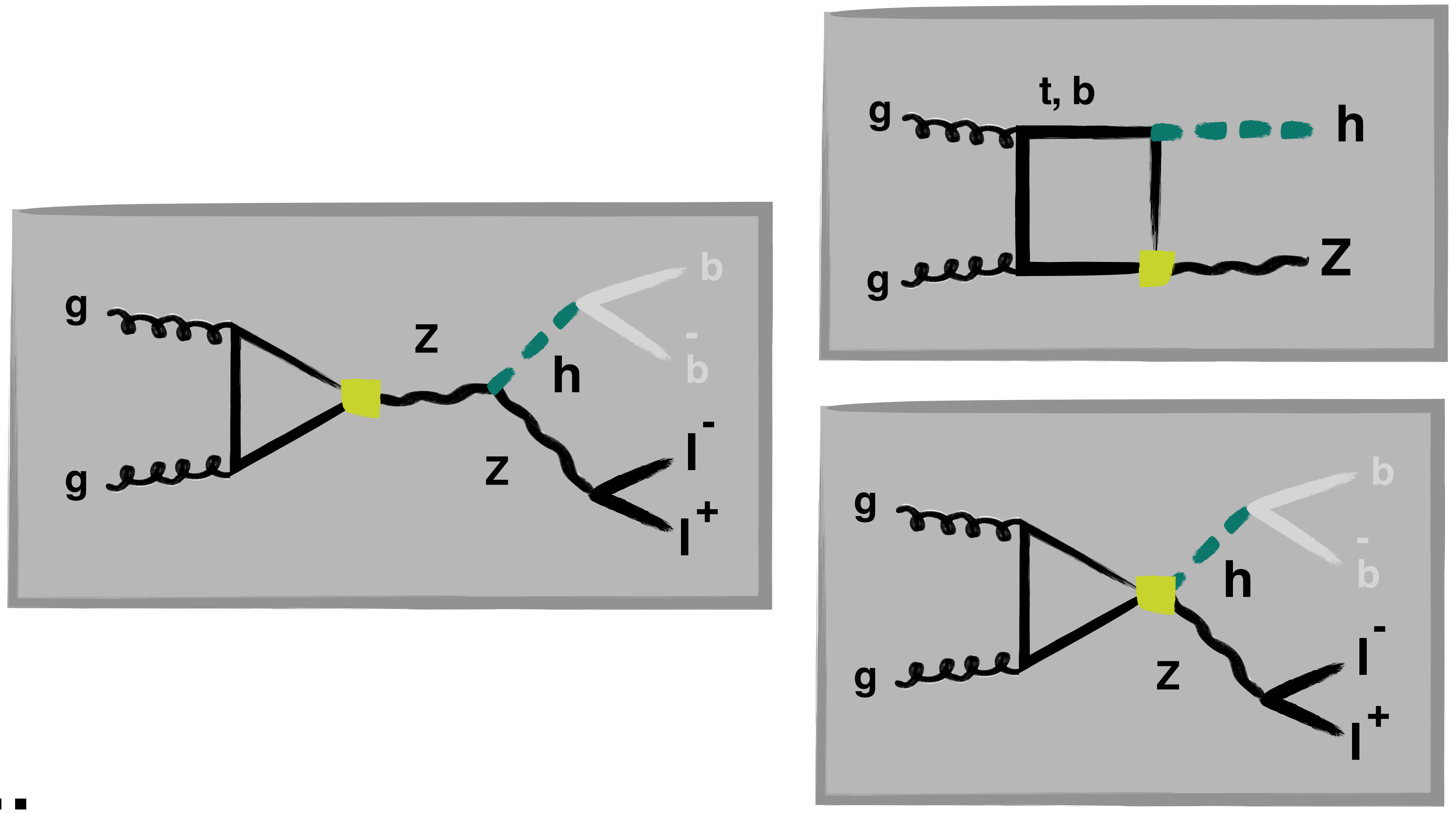

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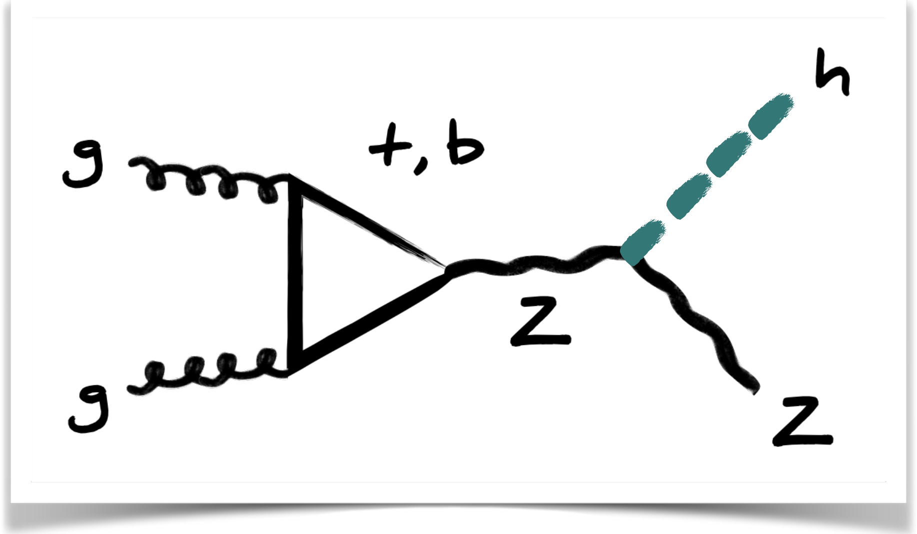

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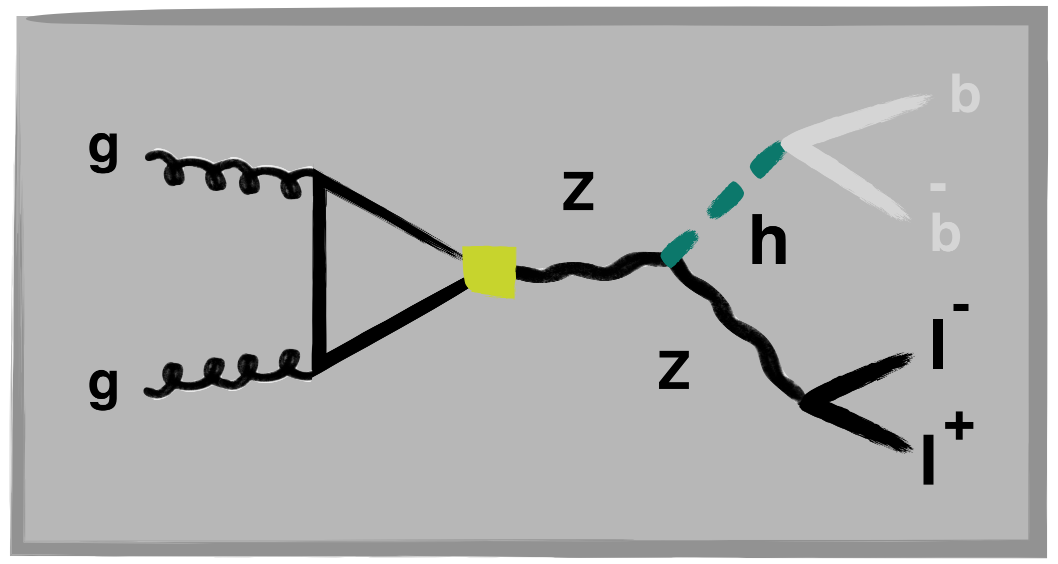

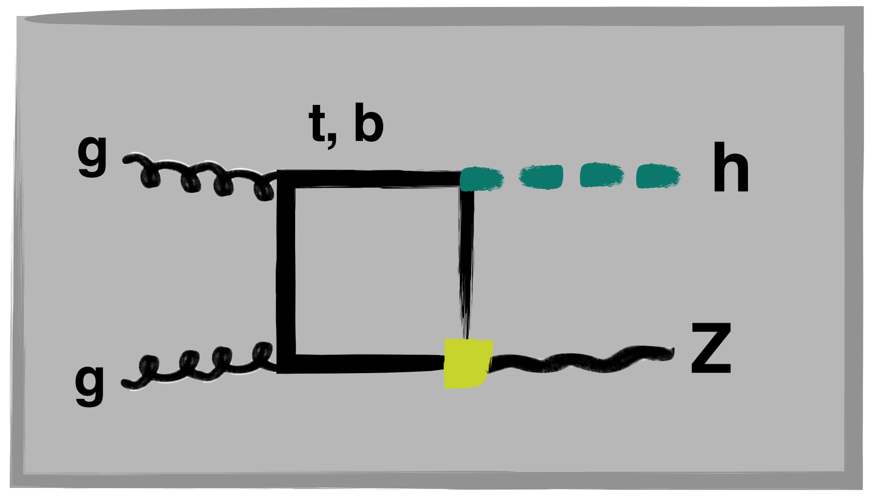

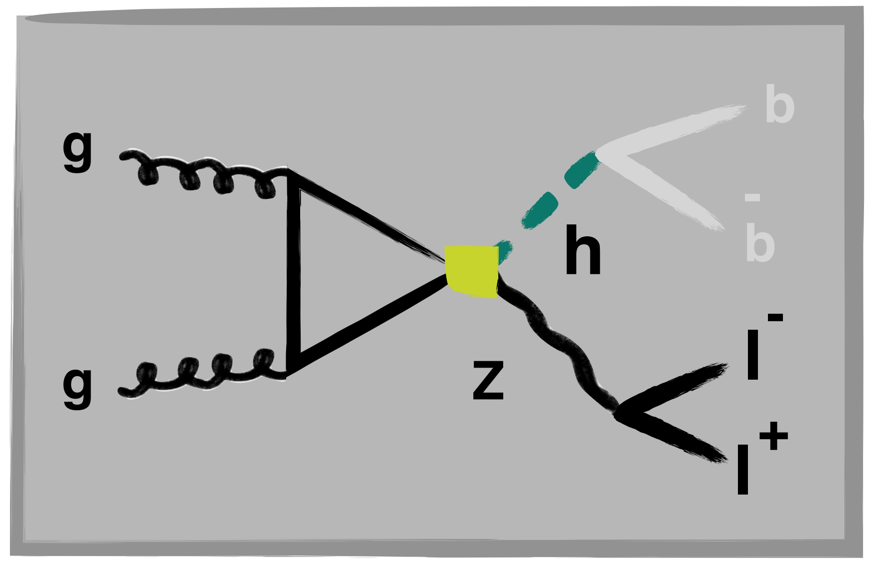

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$$(g_{Zt}^- - g_{Zt}^+) = -(g_{Zb}^- - g_{Zb}^+) ,$$

$$\sum_{q=t,b} (g_{Zq}^- - g_{Zq}^+)\, \mathcal{A}_{\mathtt{A0g2Z}\triangle}^q = (g_{Zt}^- - g_{Zt}^+) \left(\mathcal{A}_{\mathtt{A0g2Z}\triangle}^t - \mathcal{A}_{\mathtt{A0g2Z}\triangle}^b\right) ,$$

→ how does this work in the **SMEFT**?

3. Higher-Order Corrections

3.3 gg-initiated contributions

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Anomaly cancellation in the **SMEFT**:

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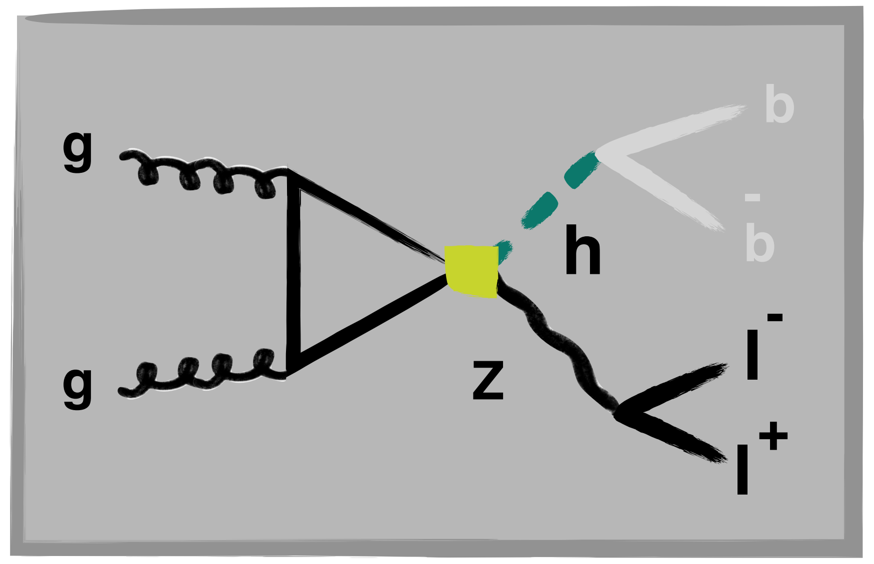

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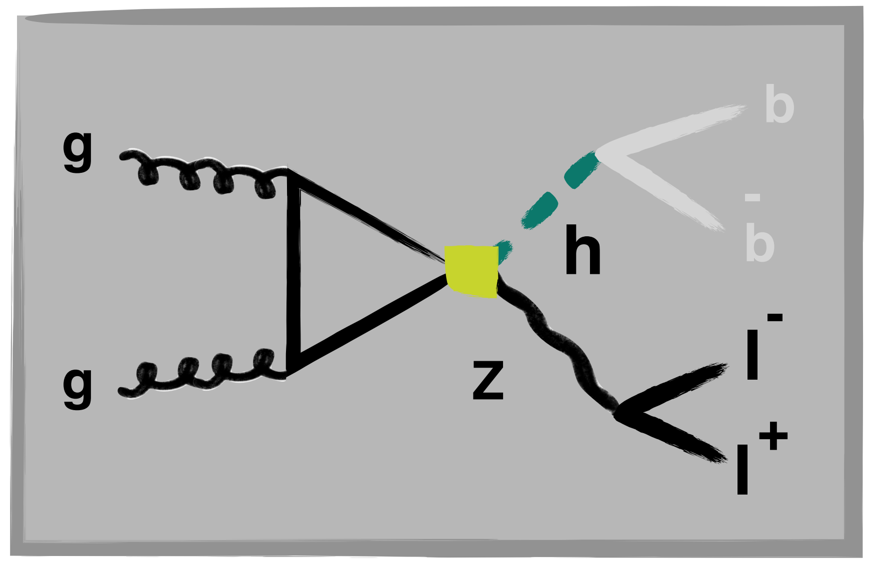

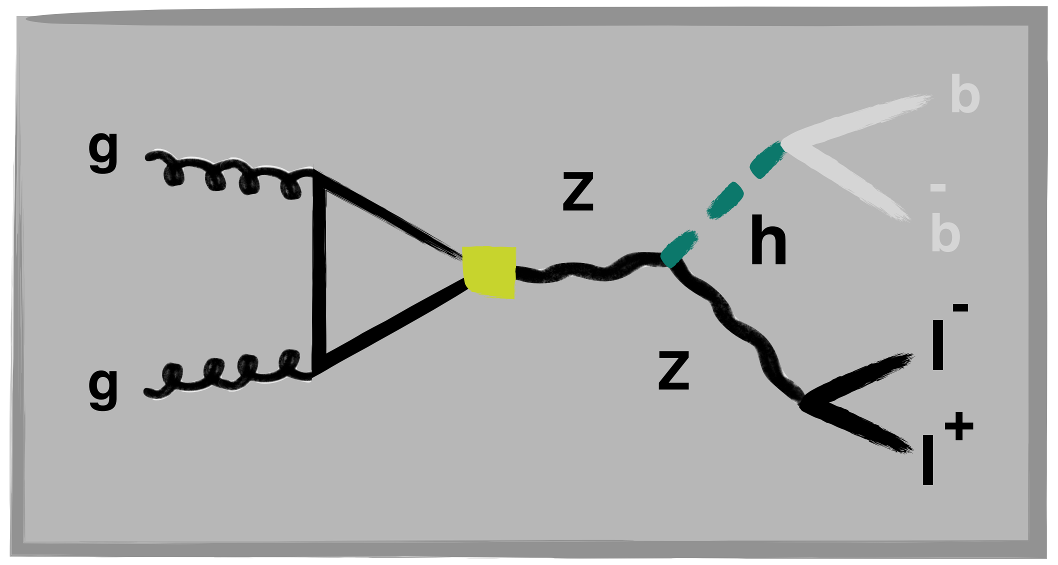

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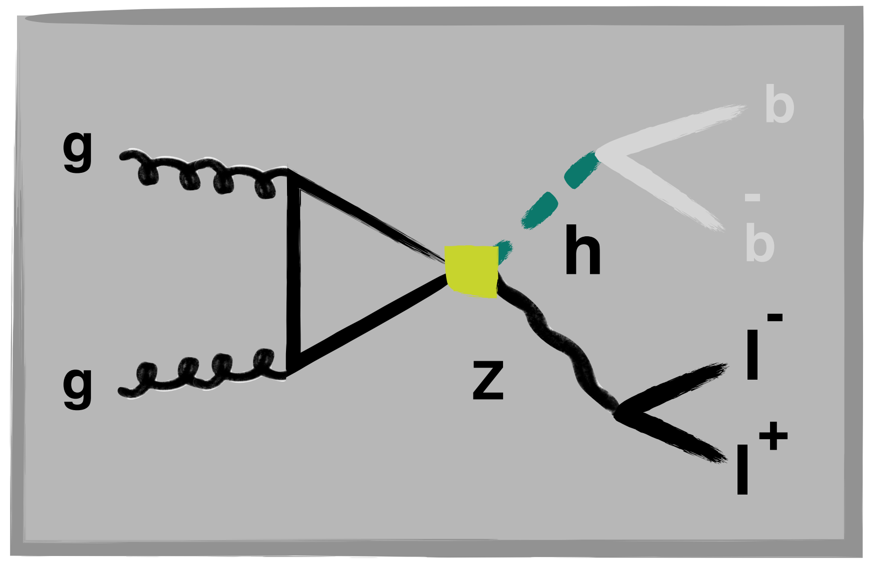
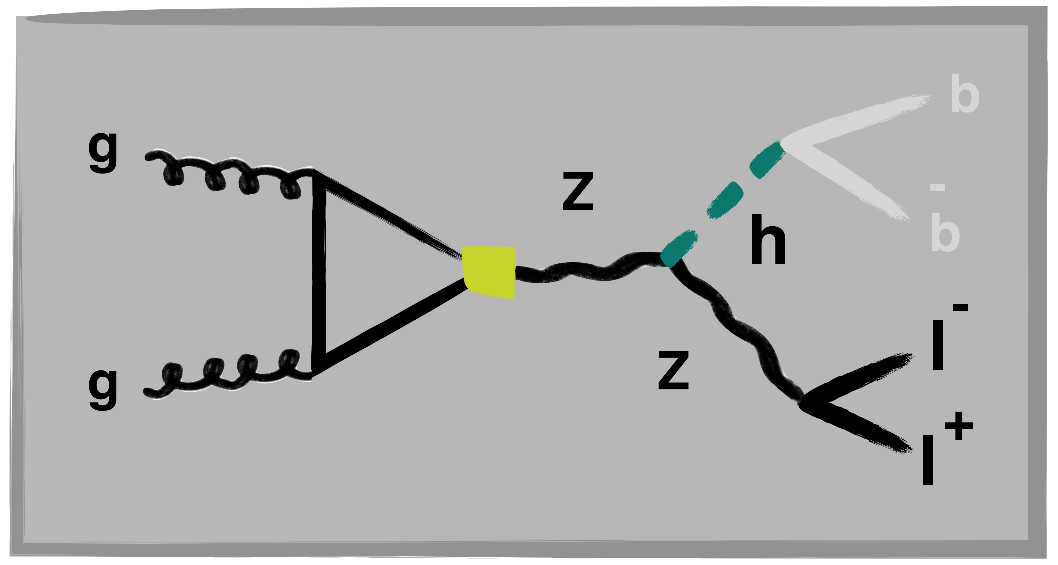


$$\frac{\left(\delta g^{(1)-}_{hZq} - \delta g^{(1)+}_{hZq}\right) g^{h_\ell}_{Z\ell}}{D_Z(s_{34})}$$

$$\frac{\mathcal{A}^q_{\mathtt{A0g2Z}\triangle}\left(1_g^{h_g}, 2_g^{h_g}, 3_\ell^{h_\ell}, 4_{\bar{\ell}}^{-h_\ell}\right)}{1-\frac{s_{12}}{m_Z^2}},$$



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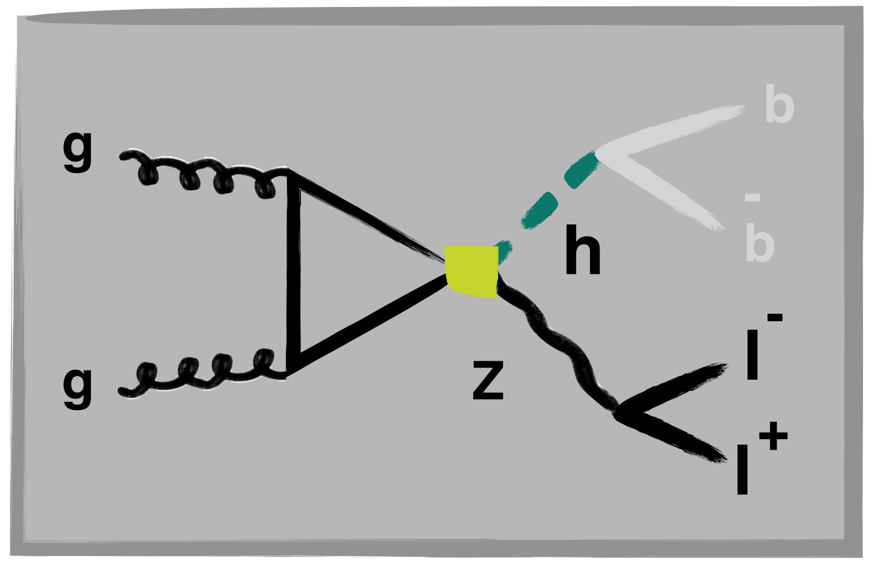

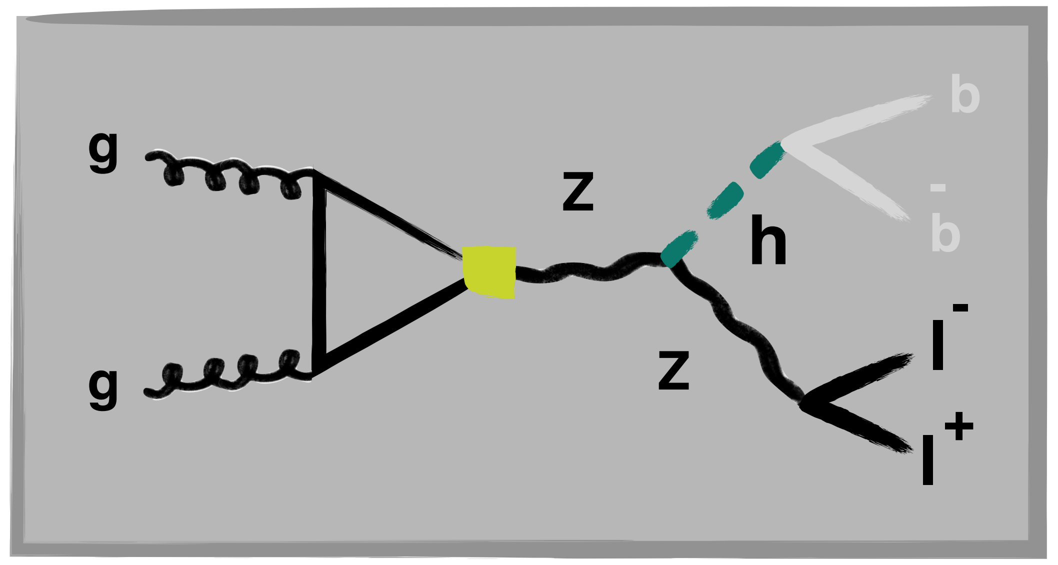

$$\frac{\left(\delta g^{(1)-}_{hZq} - \delta g^{(1)+}_{hZq}\right) g^{h_\ell}_{Z\ell}}{D_Z(s_{34})} \qquad \frac{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g}, 2_g^{h_g}, 3_\ell^{h_\ell}, 4_{\bar{\ell}}^{-h_\ell}\right)}{1-\frac{s_{12}}{m_Z^2}},$$

No longitudinal contribution
(massless leptons)

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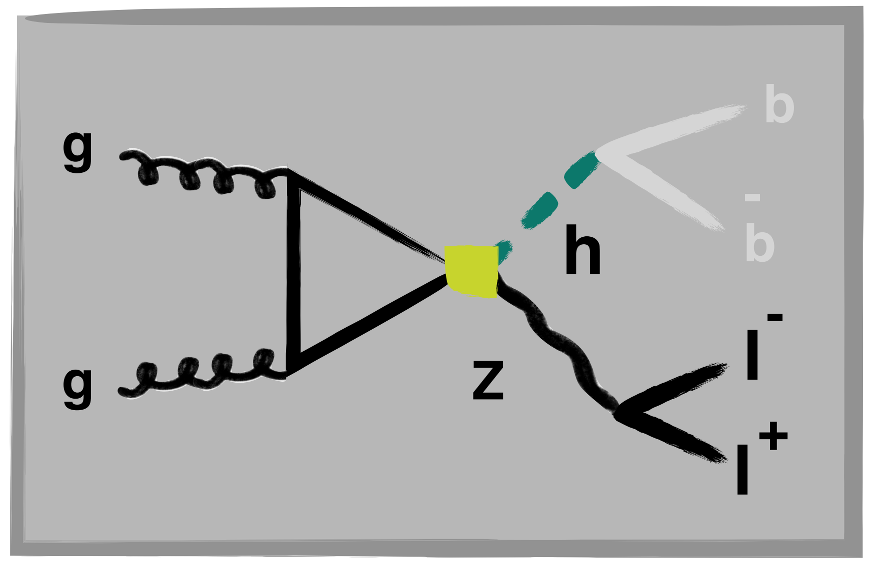

$$\frac{\left(\delta g^{(1)-}_{hZq} - \delta g^{(1)+}_{hZq}\right) g^{h_\ell}_{Z\ell}}{D_Z(s_{34})} \cdot \frac{\mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g}, 2_g^{h_g}, 3_\ell^{h_\ell}, 4_{\bar\ell}^{-h_\ell}\right)}{1 - \frac{s_{12}}{m_Z^2}},$$

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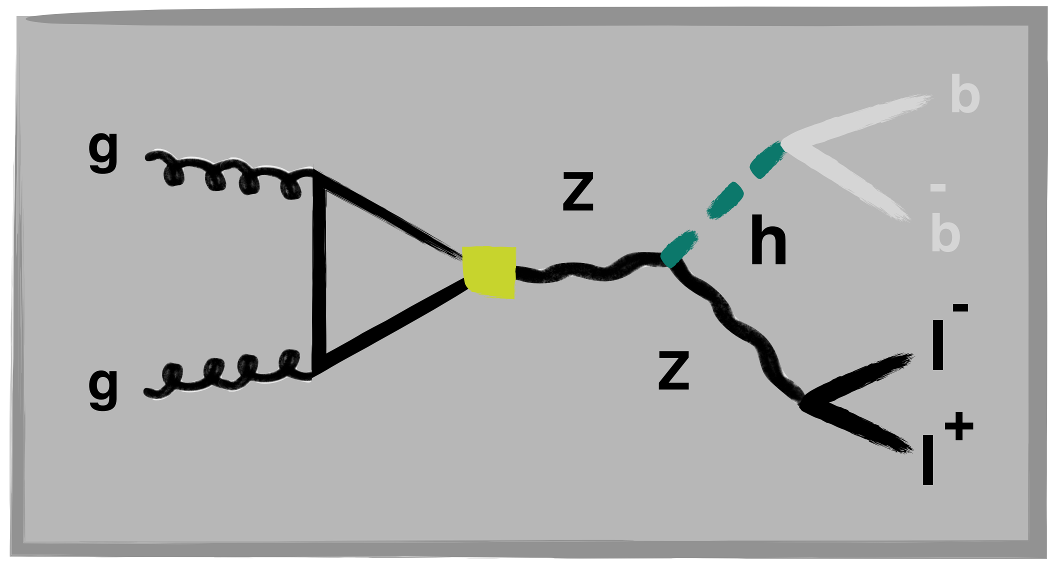

$$\frac{\left(\delta g^{(1)-}_{Zq} - \delta g^{(1)+}_{Zq}\right) g^{h_\ell}_{Z\ell}\, g_{hZZ}}{D_Z(s_{12}) D_Z(s_{34})} \; \mathcal{A}^q_{\texttt{A0g2Z}\triangle}\left(1_g^{h_g}, 2_g^{h_g}, 3_\ell^{h_\ell}, 4_{\bar\ell}^{-h_\ell}\right)$$

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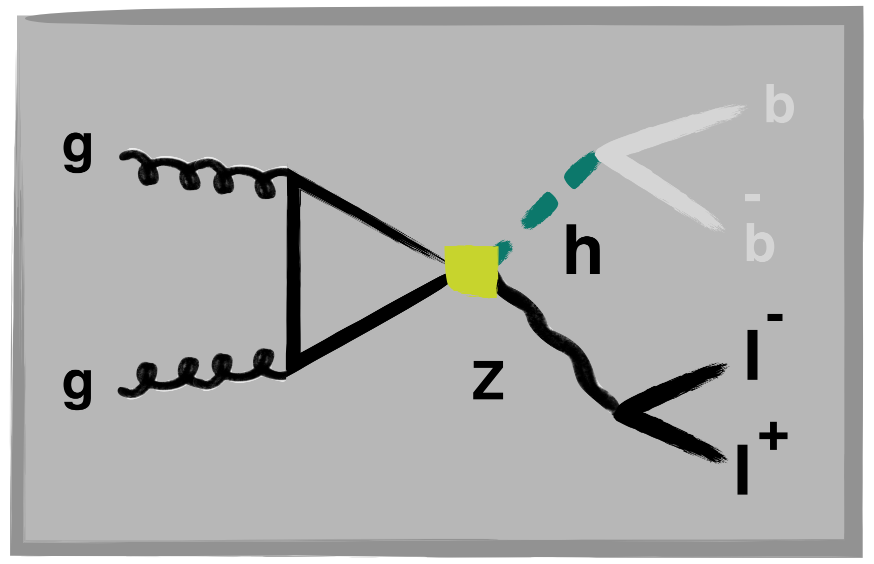

$$\frac{\left(\delta g_{hZq}^{(1)-} - \delta g_{hZq}^{(1)+}\right) g_{Z\ell}^{h_\ell}}{D_Z(s_{34})} \frac{\mathcal{A}^q_{\mathtt{A0g2Z}\triangle}\left(1_g^{h_g}, 2_g^{h_g}, 3_\ell^{h_\ell}, 4_{\bar\ell}^{-h_\ell}\right)}{1 - \frac{s_{12}}{m_Z^2}},$$

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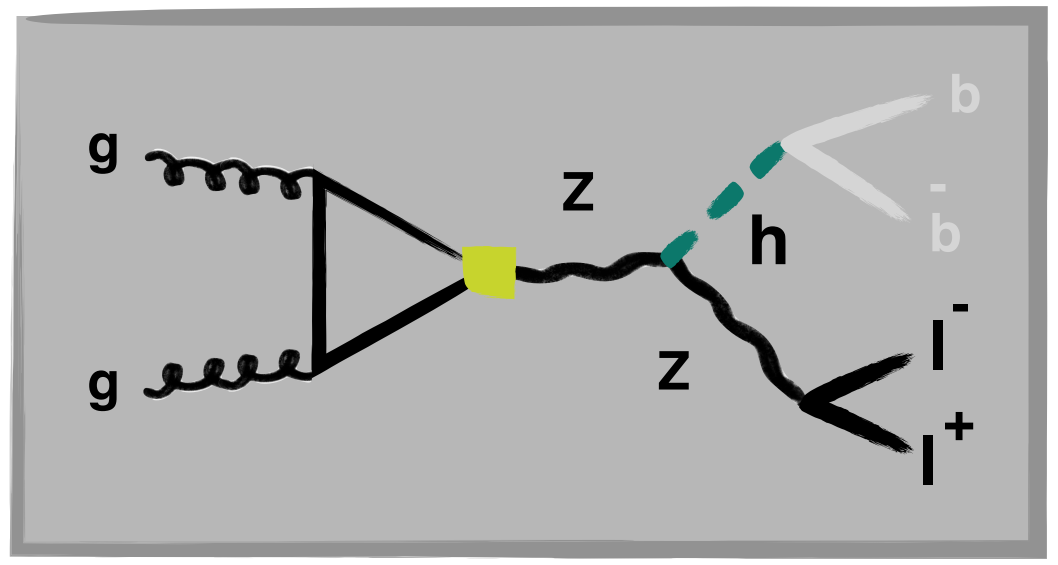

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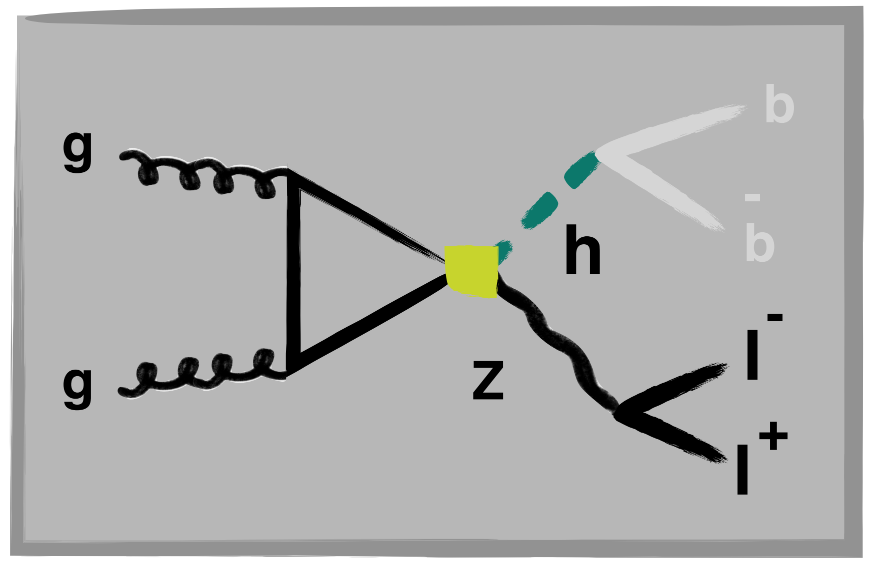

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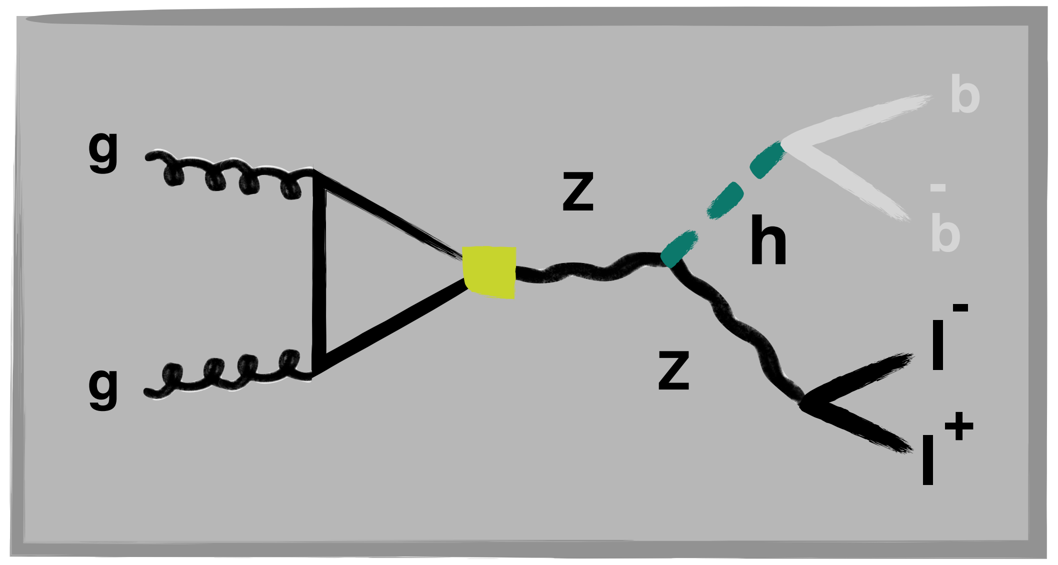

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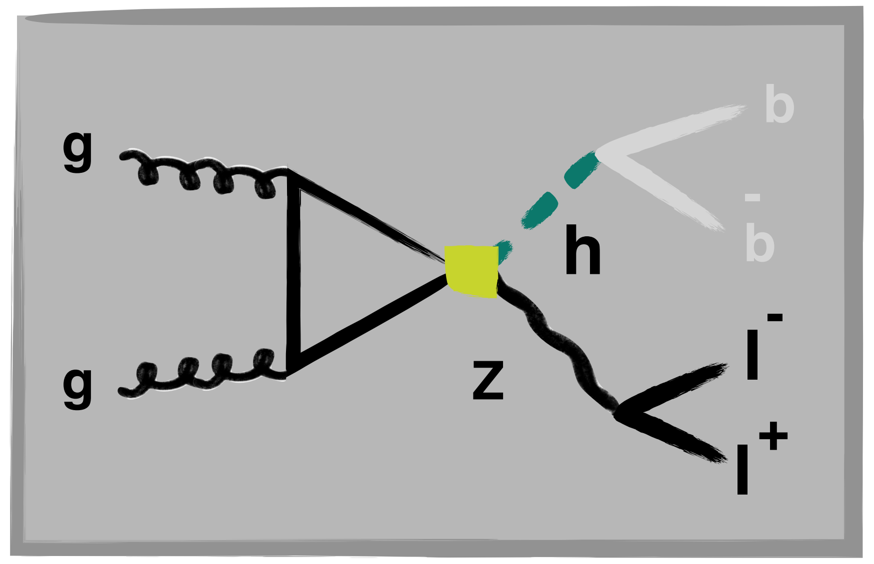

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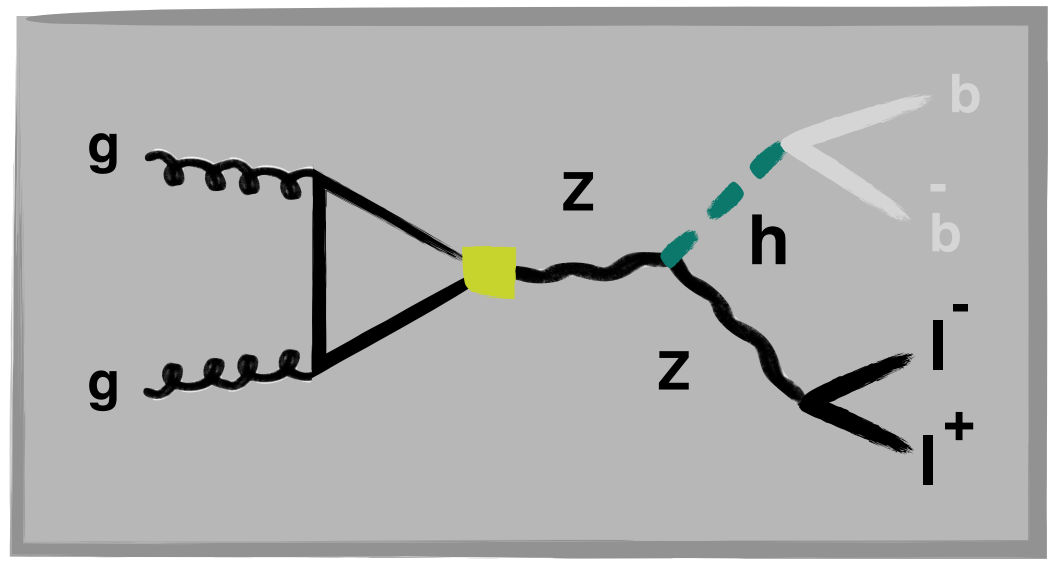

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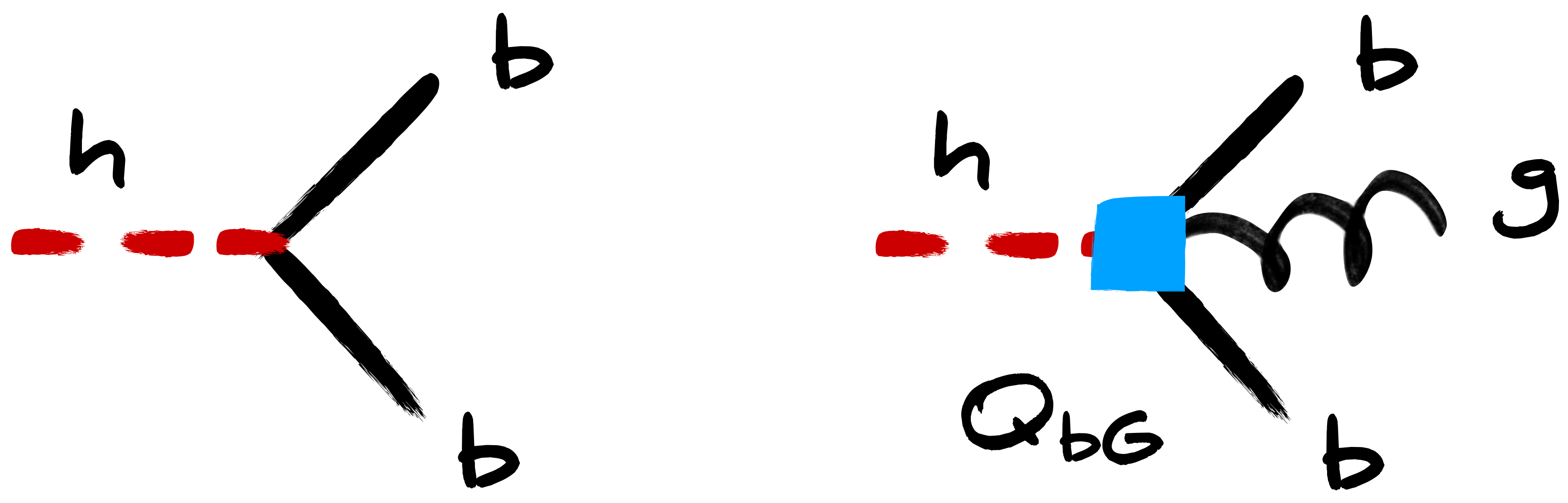
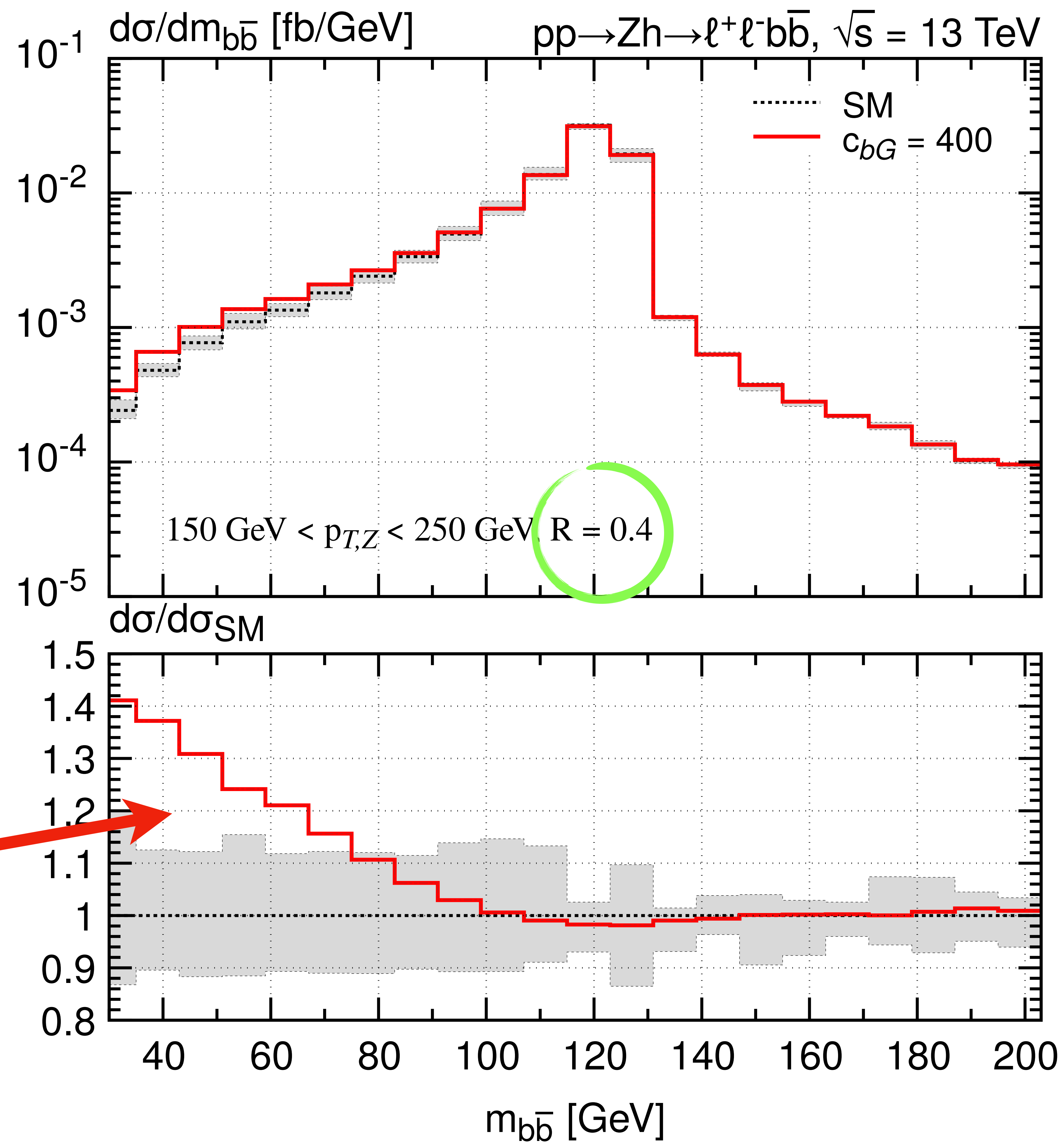
The SMEFT is **anomaly-free** (up to spurious “irrelevant” anomalies that can be subtracted).

→ Great advantage e.g. with respect to the κ framework.

[2012.13989] (F. Feruglio) [2012.07740] (Q. Bonnefoy, L. Di Luzio, Ch. Grojean, A. Paul, A.N. Rossia)

Phenomenology analysis

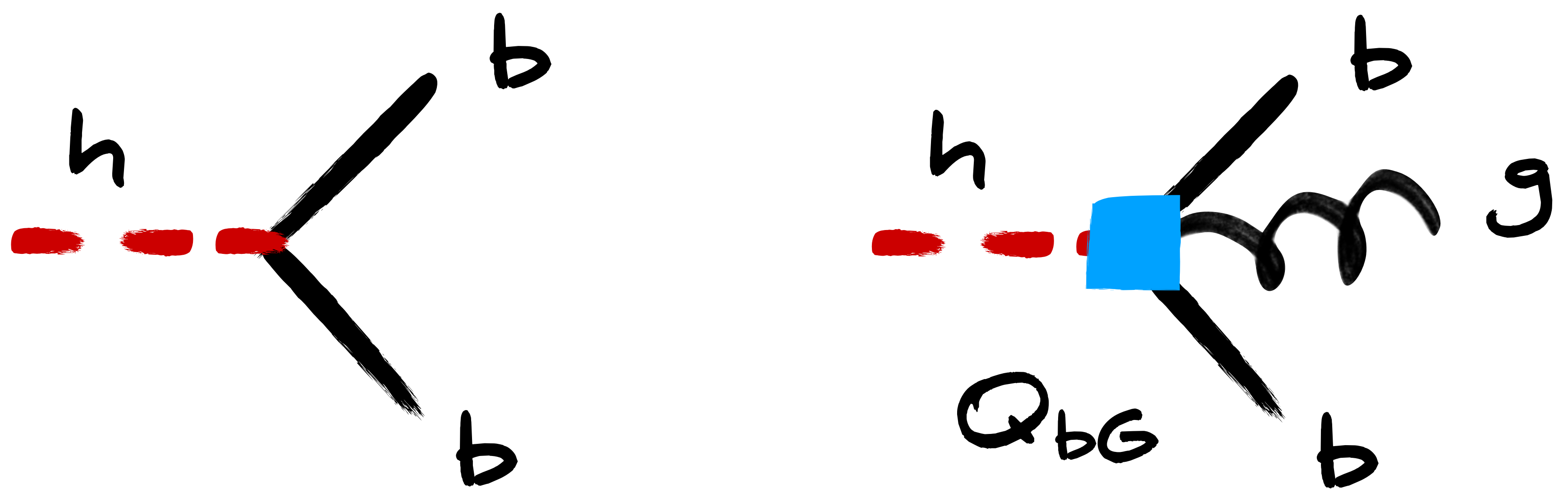


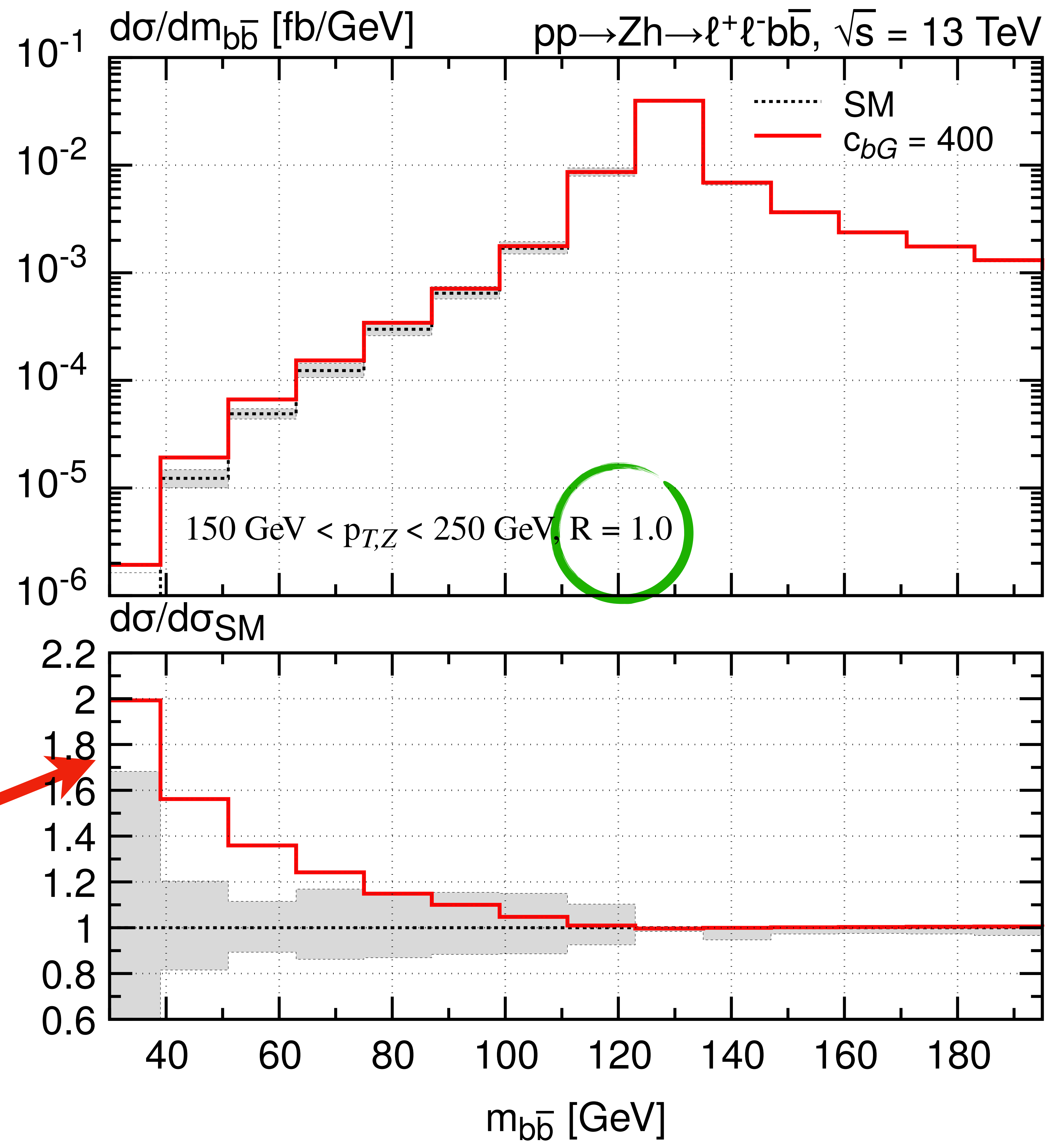


extra gluon emission in leading-order Q_{bG} contribution tends to reduce dibottom invariant mass relative to SM

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Phenomenology analysis





size of effect depends on radius parameter R used to reconstruct anti-k_t jets

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

4. Phenomenology

4.1 Matrix element library

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We implemented all squared matrix elements in a **Fortran library** using spinor helicity amplitudes…

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`C0g0V` `D0g0V`

`A0g0V`

`B1g0V_colour` `B1g0V_spin`

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

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

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`B1g0V_colour` `B1g0V_spin`

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

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

```
! ============================================================================
! Standard Model
! ============================================================================
! ( 1q-, 2g-, 3qb+; 4l-, 5lb+ )
! Particles before the ";" are incoming, after outgoing.
! This corresponds to the LL case.
complex(8) function B1g0V_Hel_SM_LL_minus(i1,i2,i3,i4,i5,K)
    integer, intent(in) :: i1,i2,i3,i4,i5
    type(Event_t), intent(in) :: K
    type(Constants_t) :: C

    ! Get Constants from K
    C = K%C

    ! The helicity amplitude
    B1g0V_Hel_SM_LL_minus = K%Za(i3,i4)/K%Za(i1,i2)/K%Za(i2,i3) &
      * (K%Za(i1,i3)*K%Zb(i5,i1)+K%Za(i2,i3)*K%Zb(i5,i2))

end function B1g0V_Hel_SM_LL_minus
! ============================================================================
```

4. Phenomenology

4.1 Matrix element library

We implemented all squared matrix elements in a **Fortran library** using spinor helicity amplitudes…

B0g0V B1g0V B0g1V B1g1V B2g0V B0g2V

C0g0V D0g0V

A0g0V

B1g0V_colour B1g0V_spin

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

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end function B1g0V_Hel_SM_LL_minus
! ==========================================================================
```

B1g0Z amplitude we saw earlier

$\langle 13 \rangle$

4. Phenomenology

4.3 Spectra

4. Phenomenology

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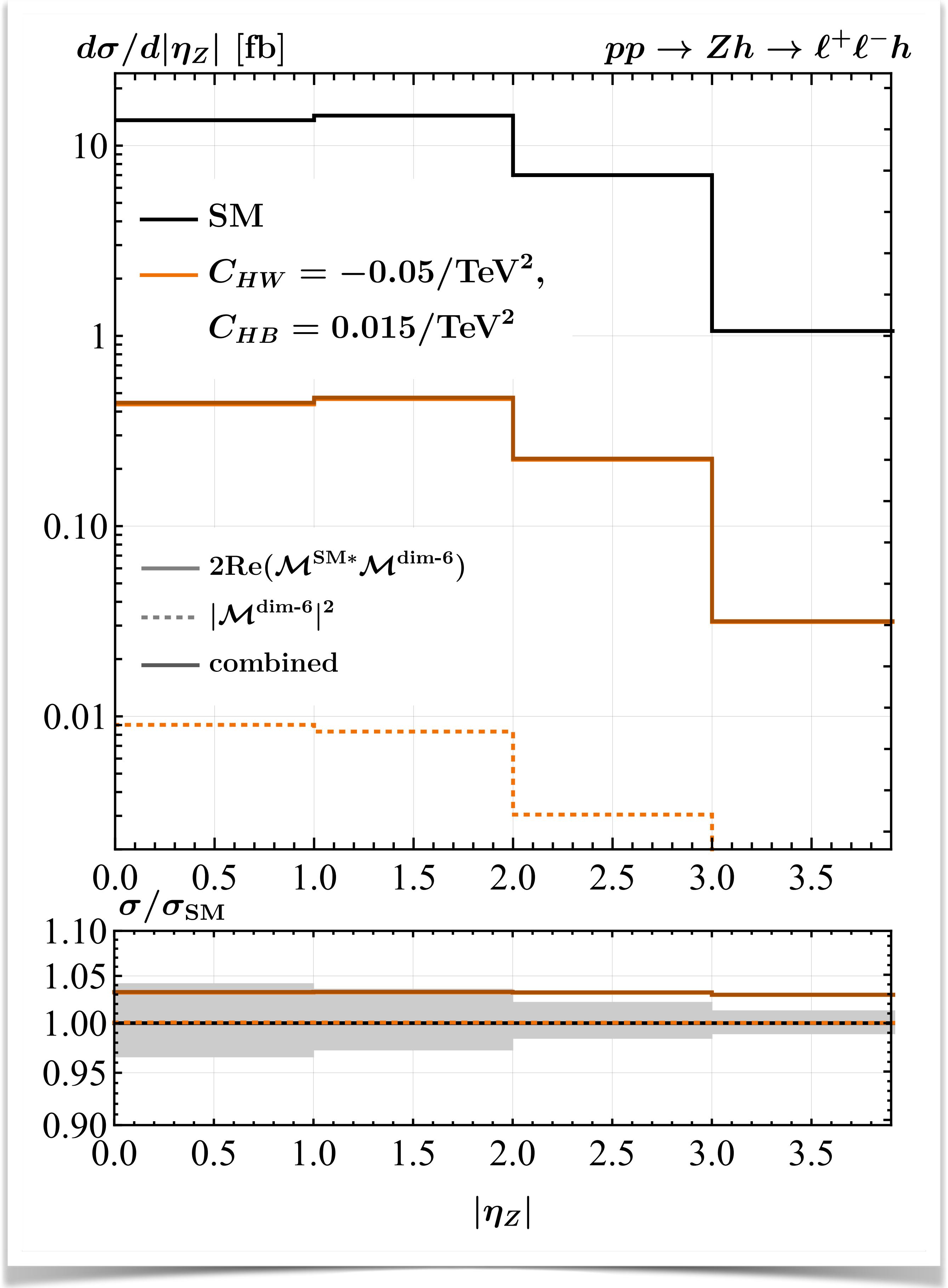
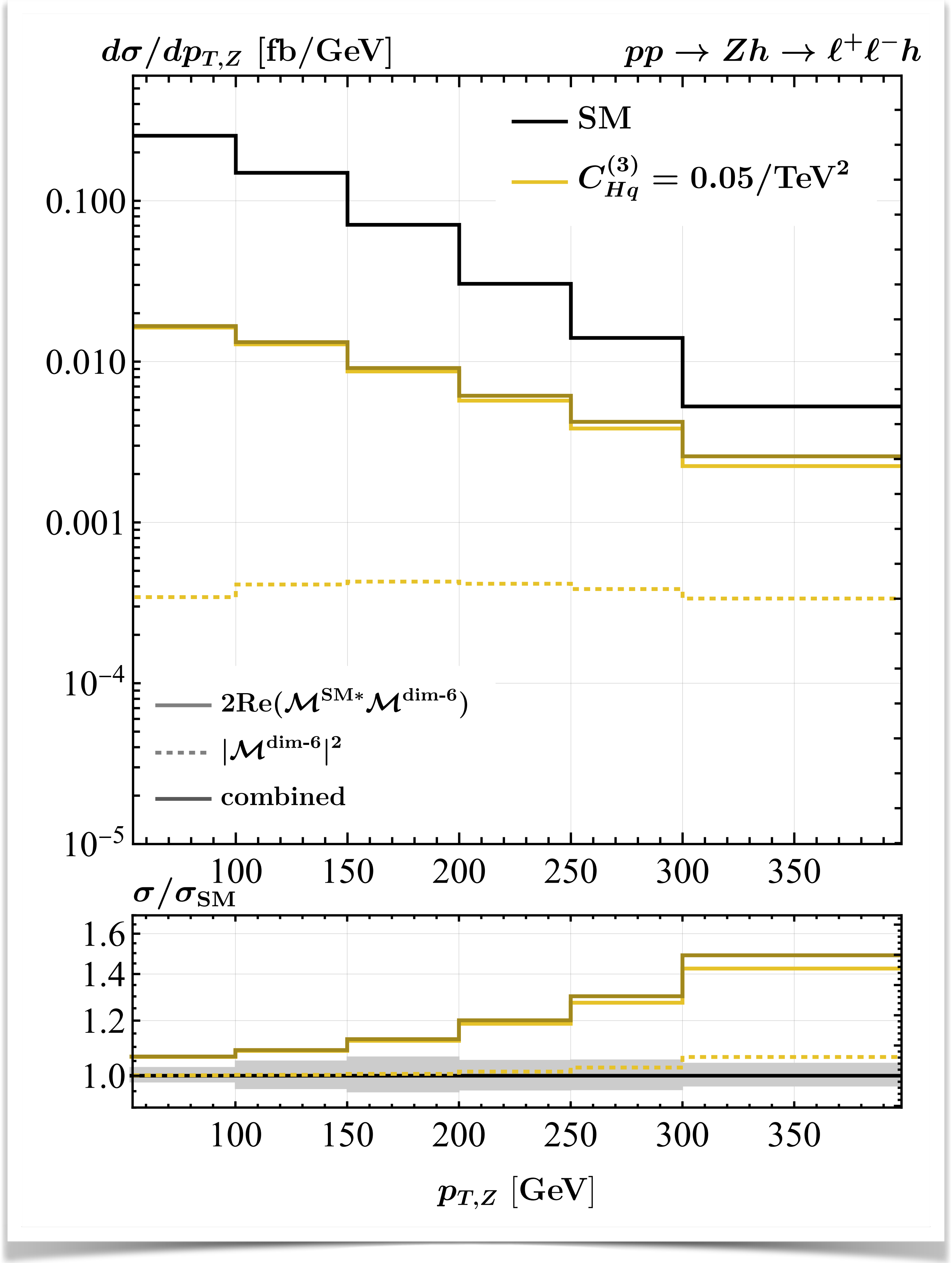
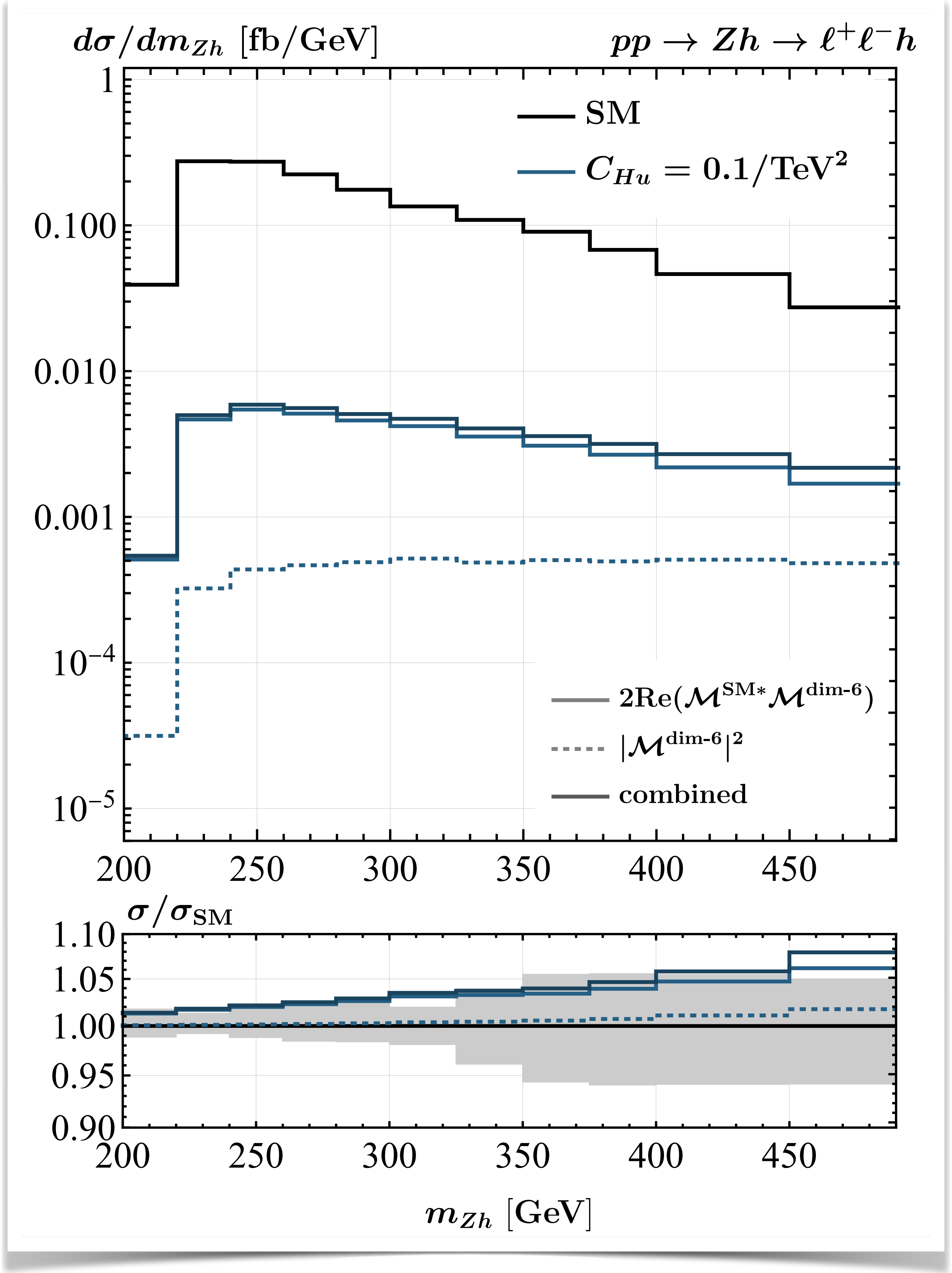




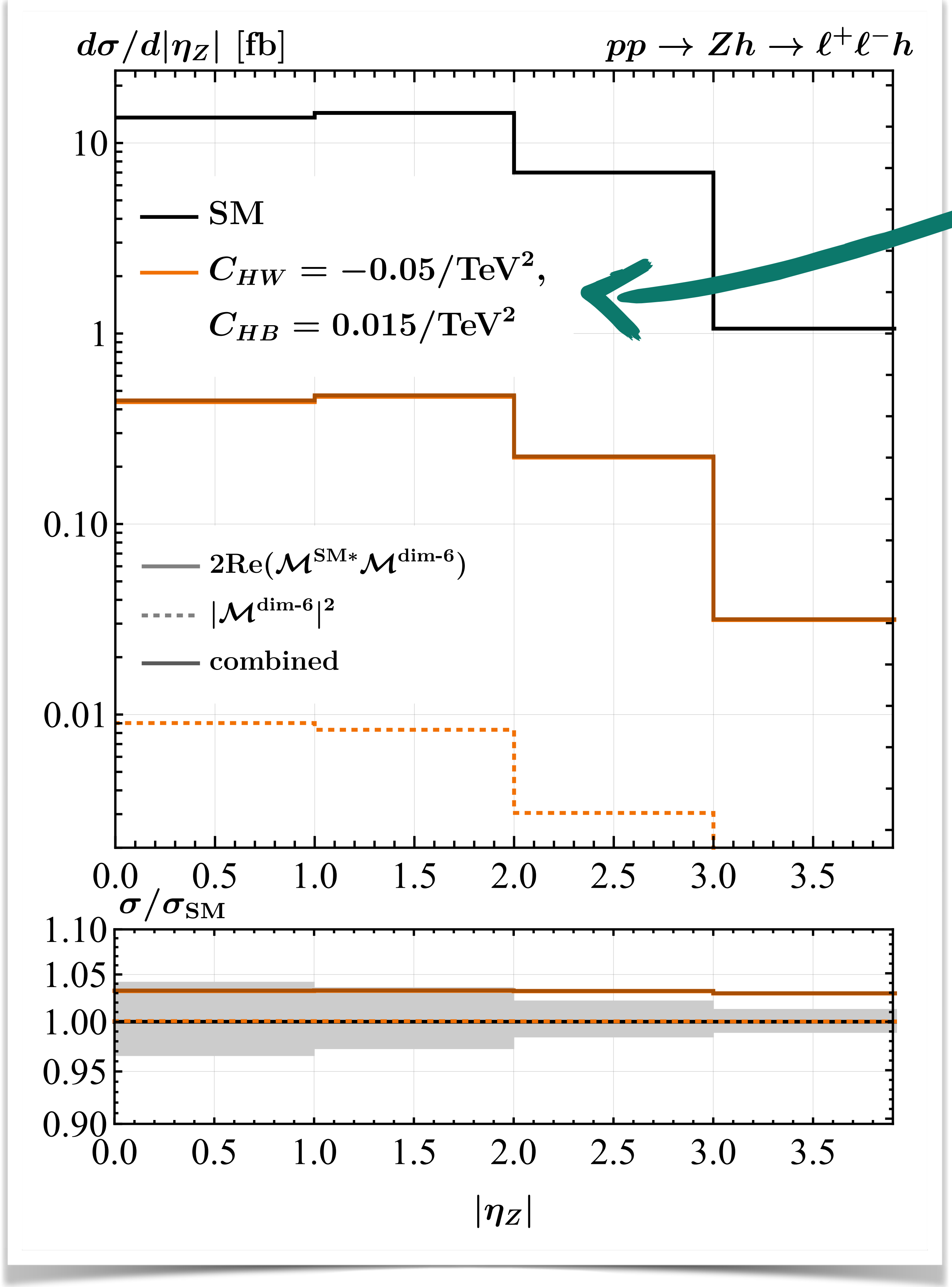


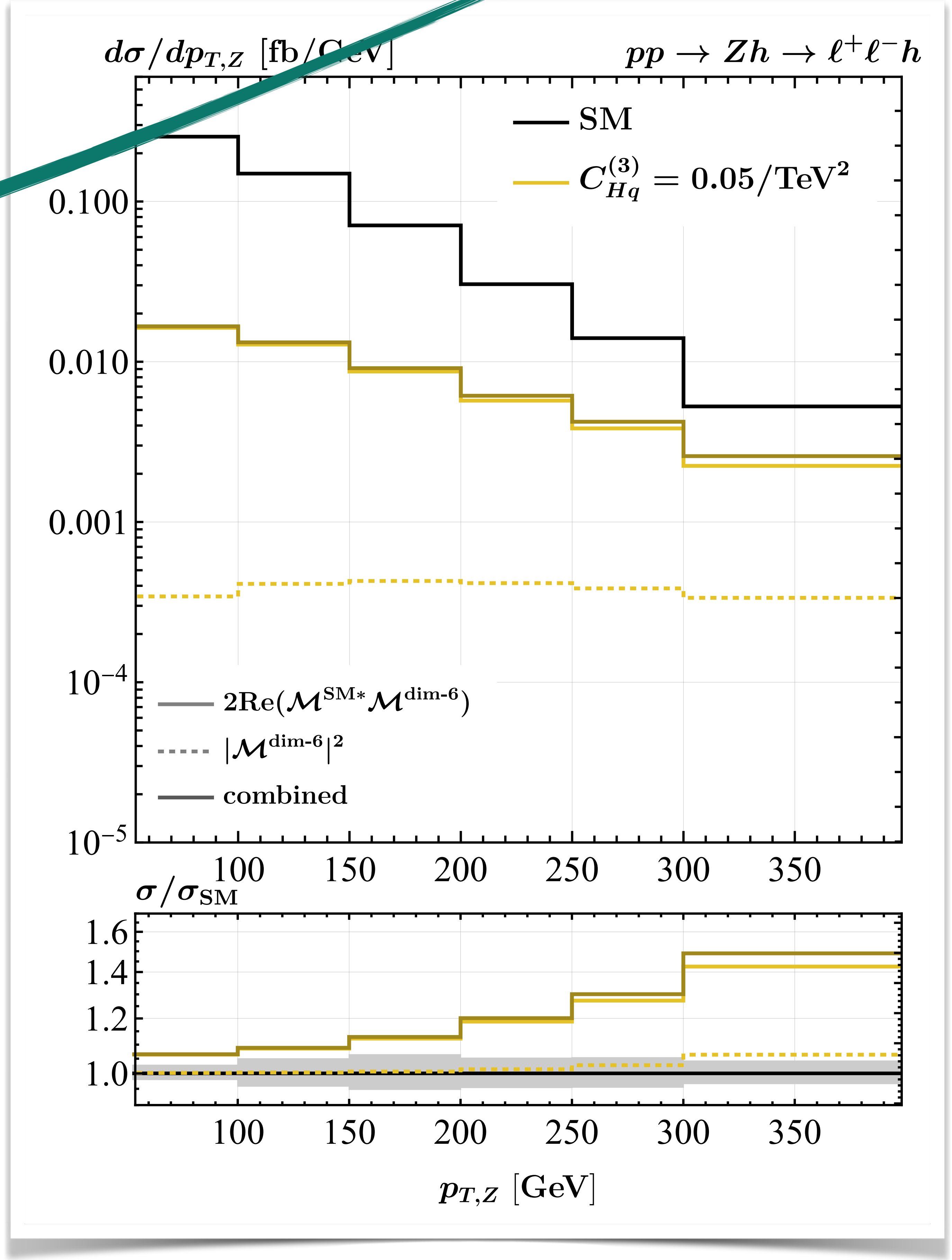
4. Phenomenology

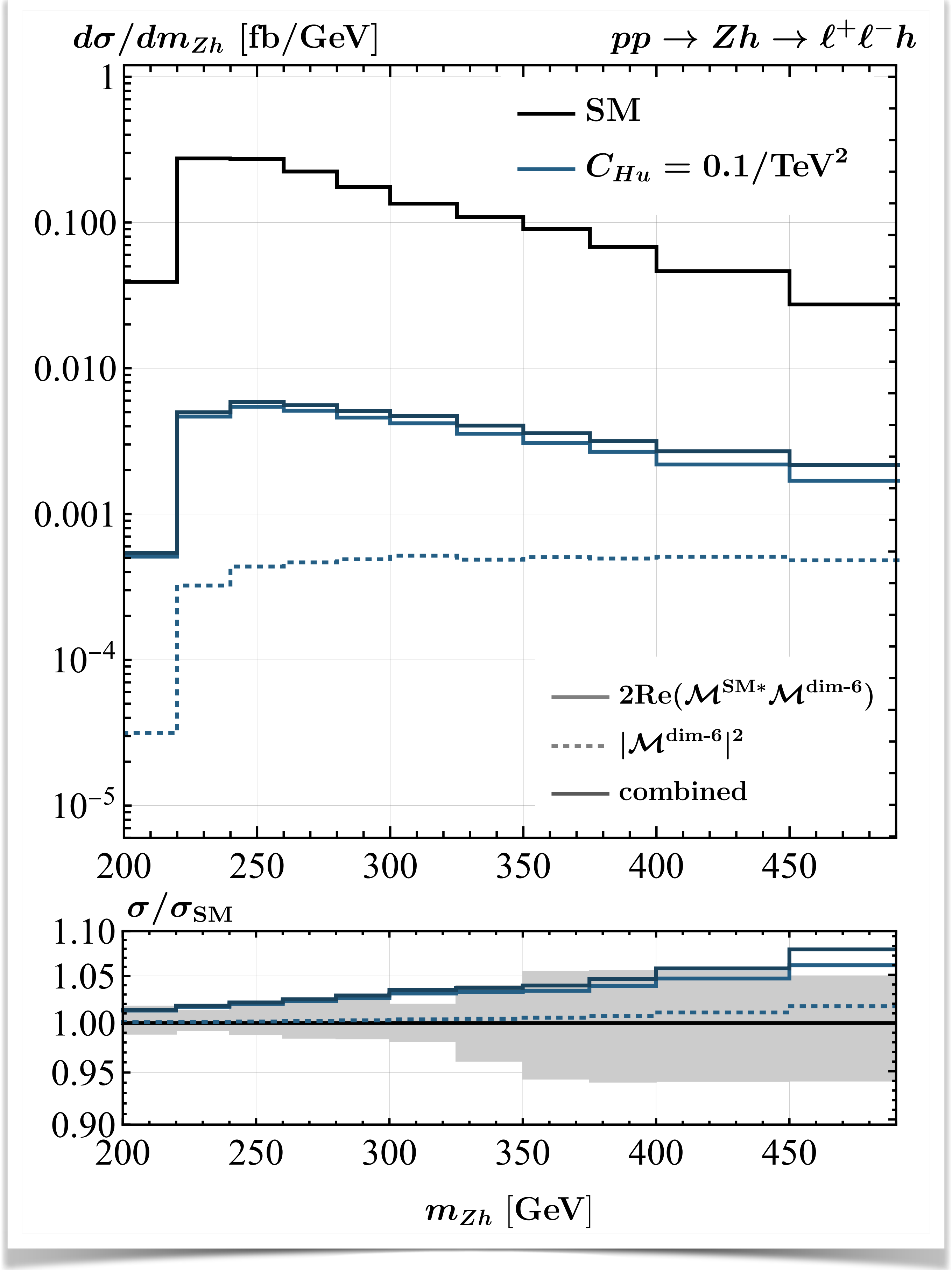
4.3 Spectra

[2311.06107] (R. Gauld, U. Haisch, LS)

Parameter benchmarks discussed in our paper.







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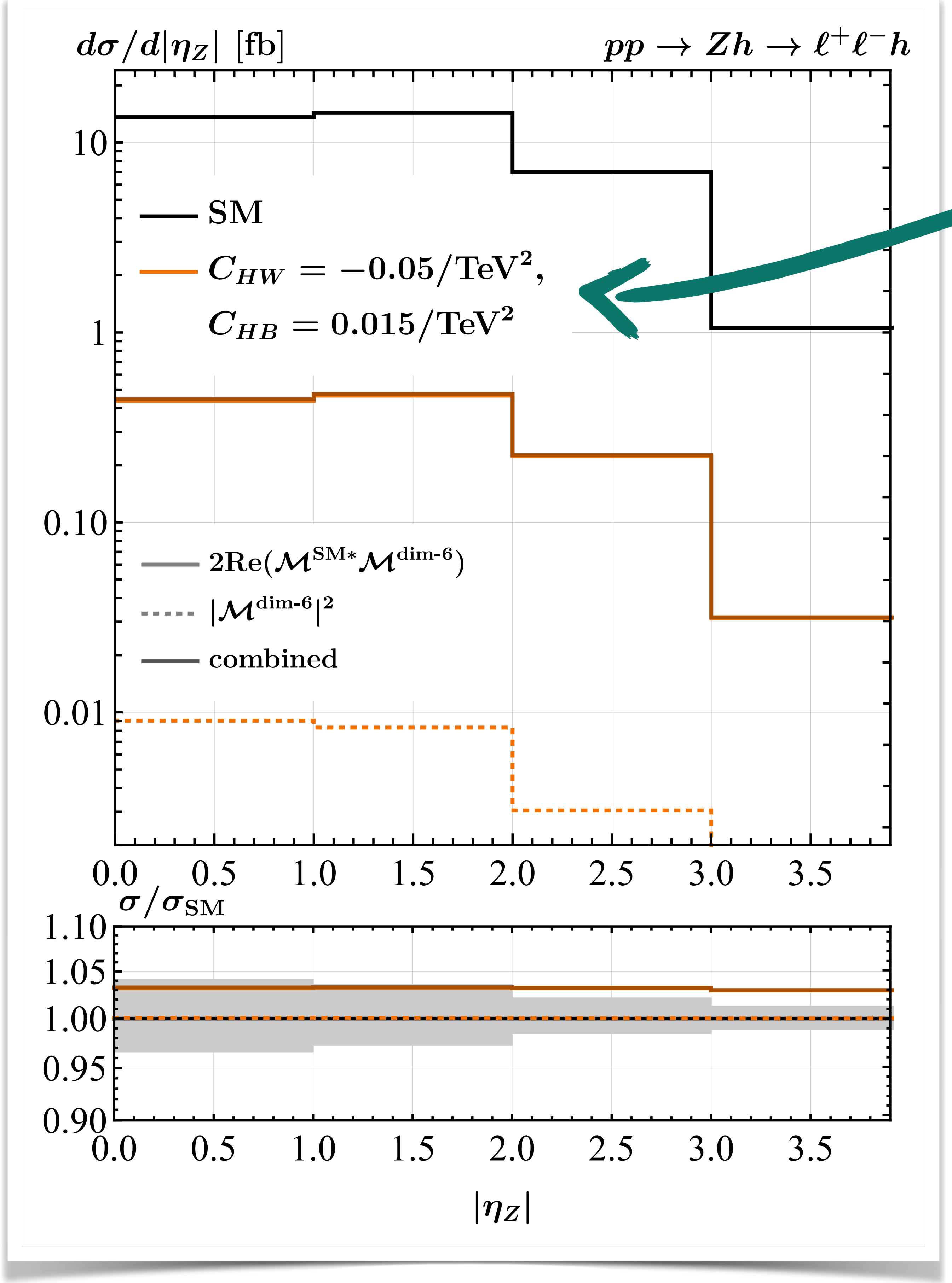

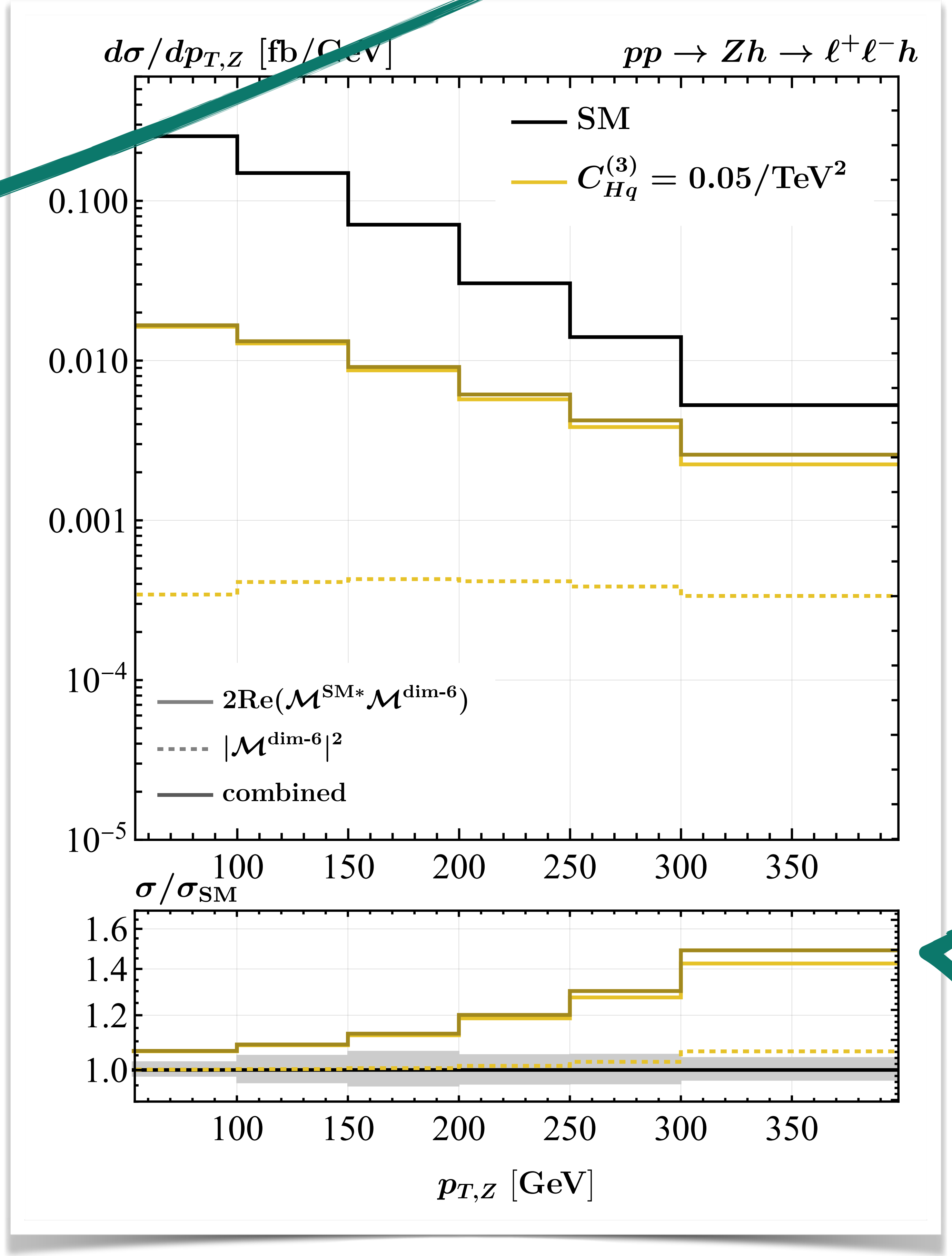

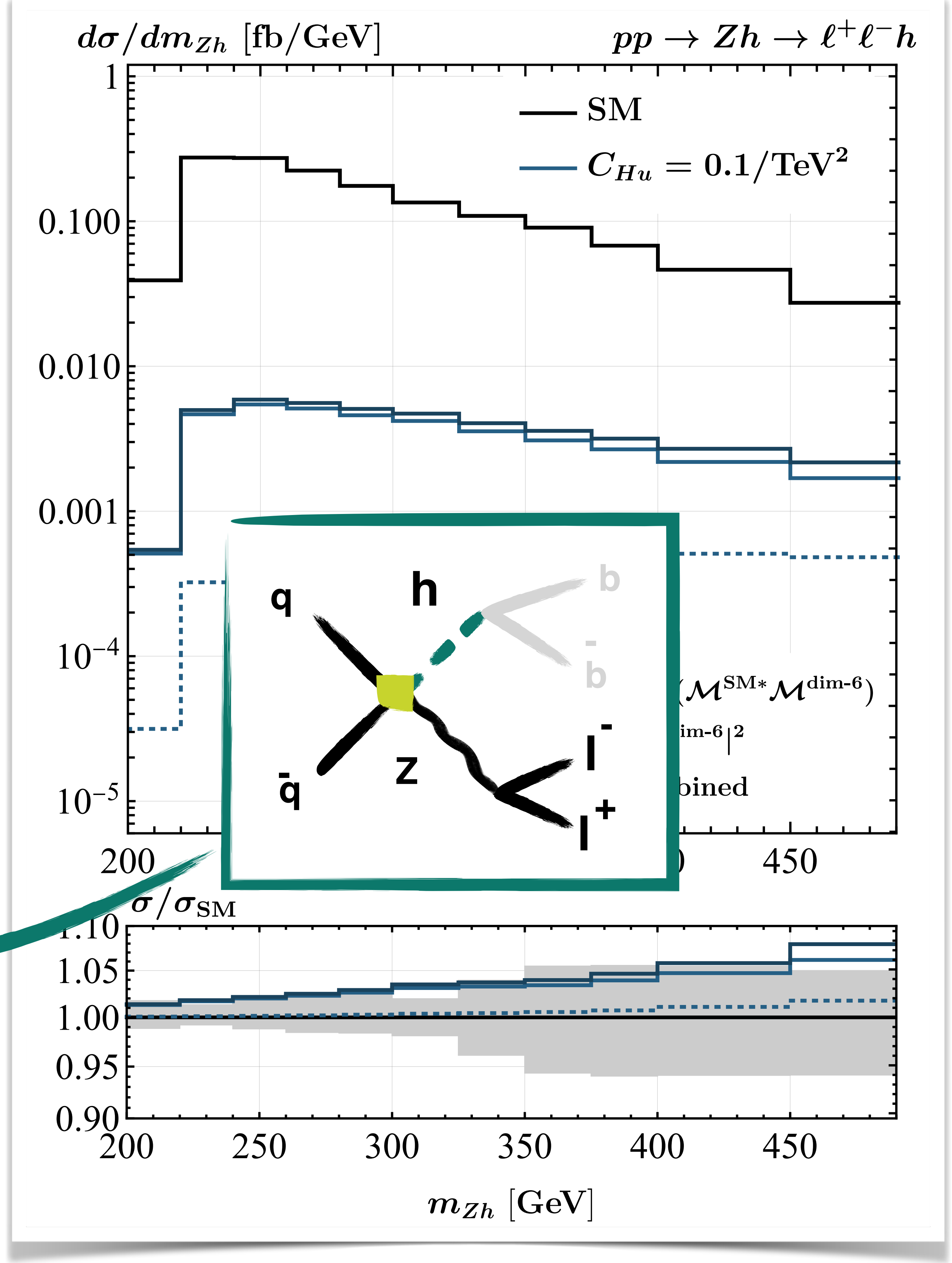

4. Phenomenology

4.4 NNLO vs NLO

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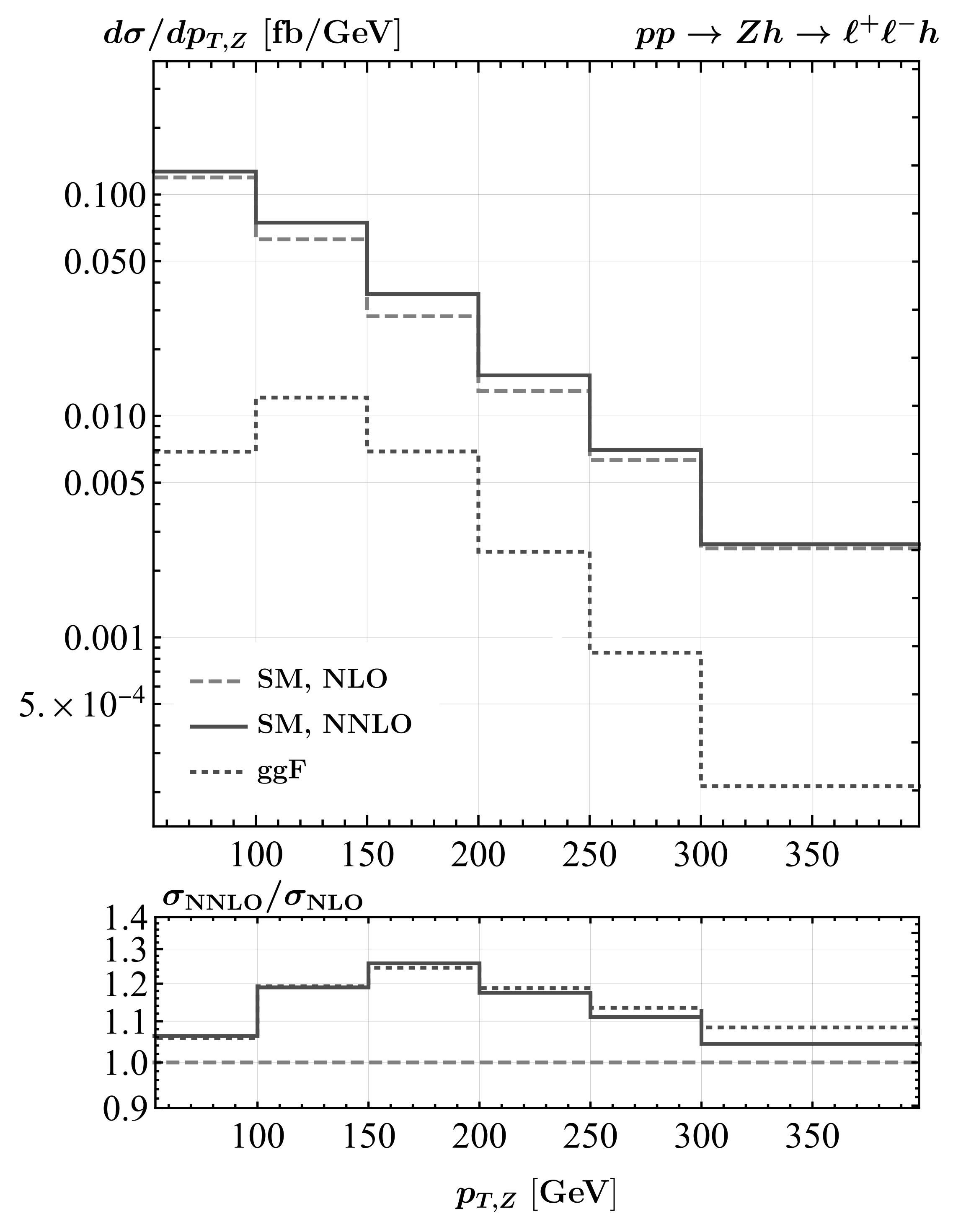
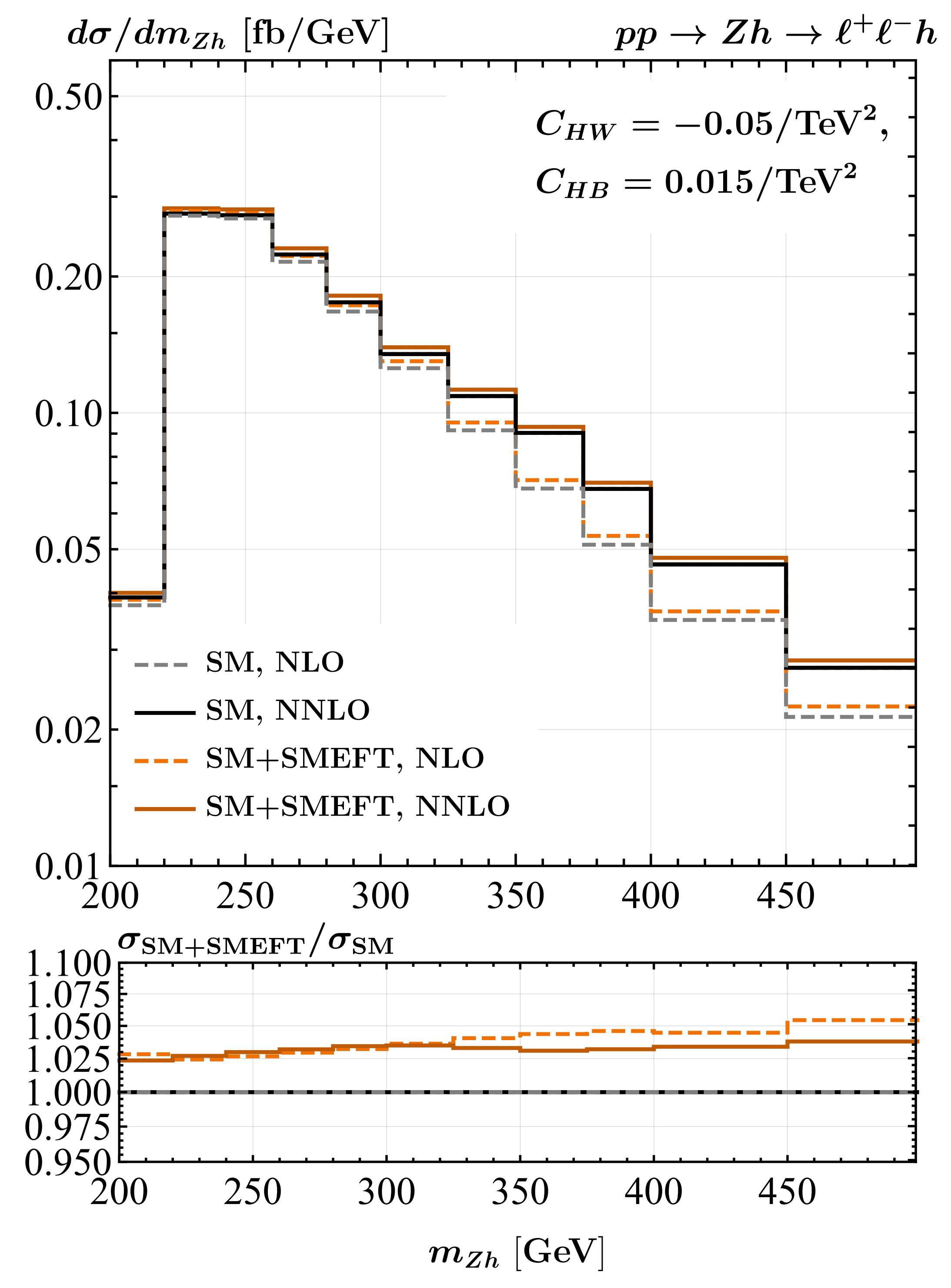
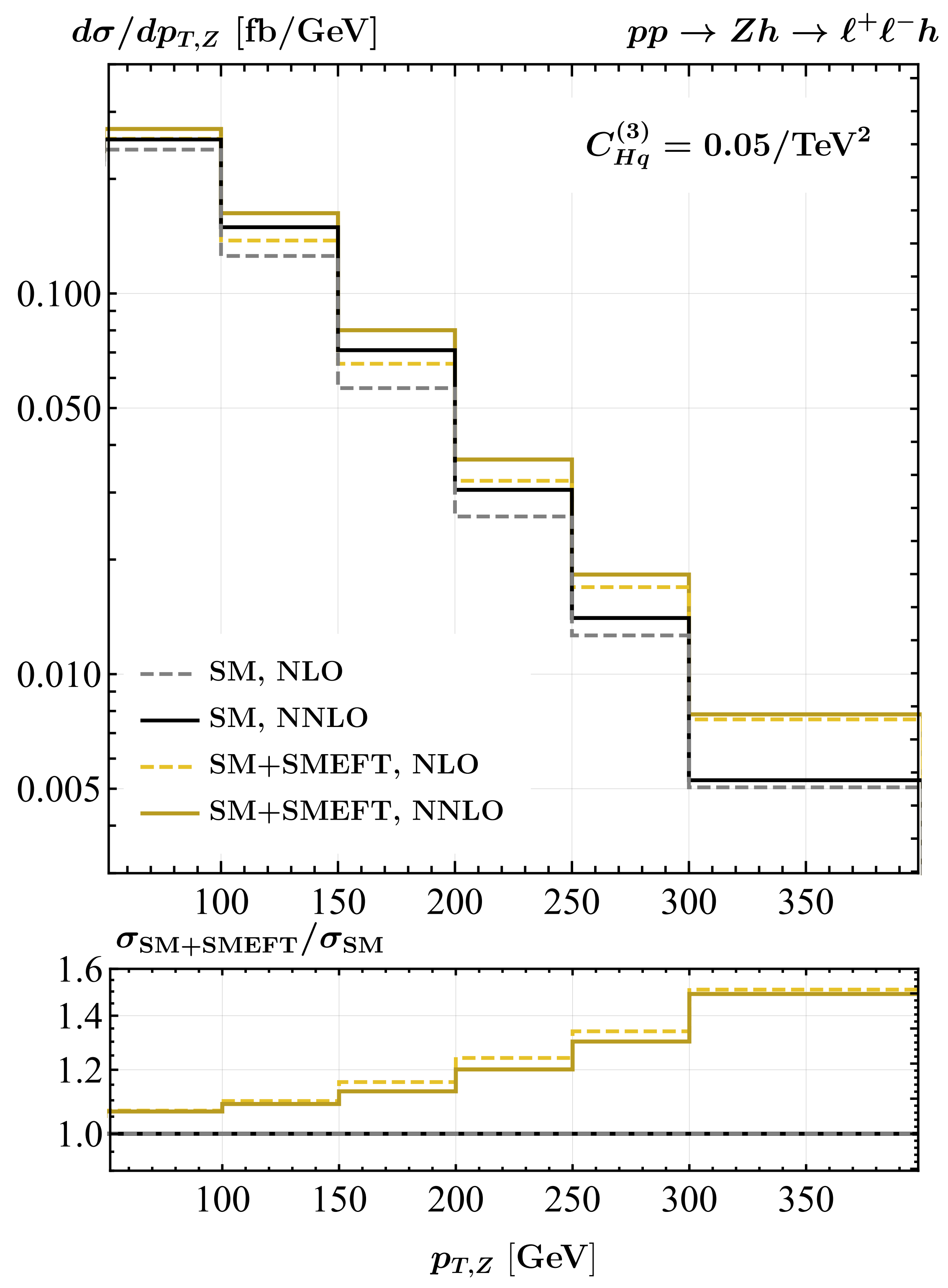




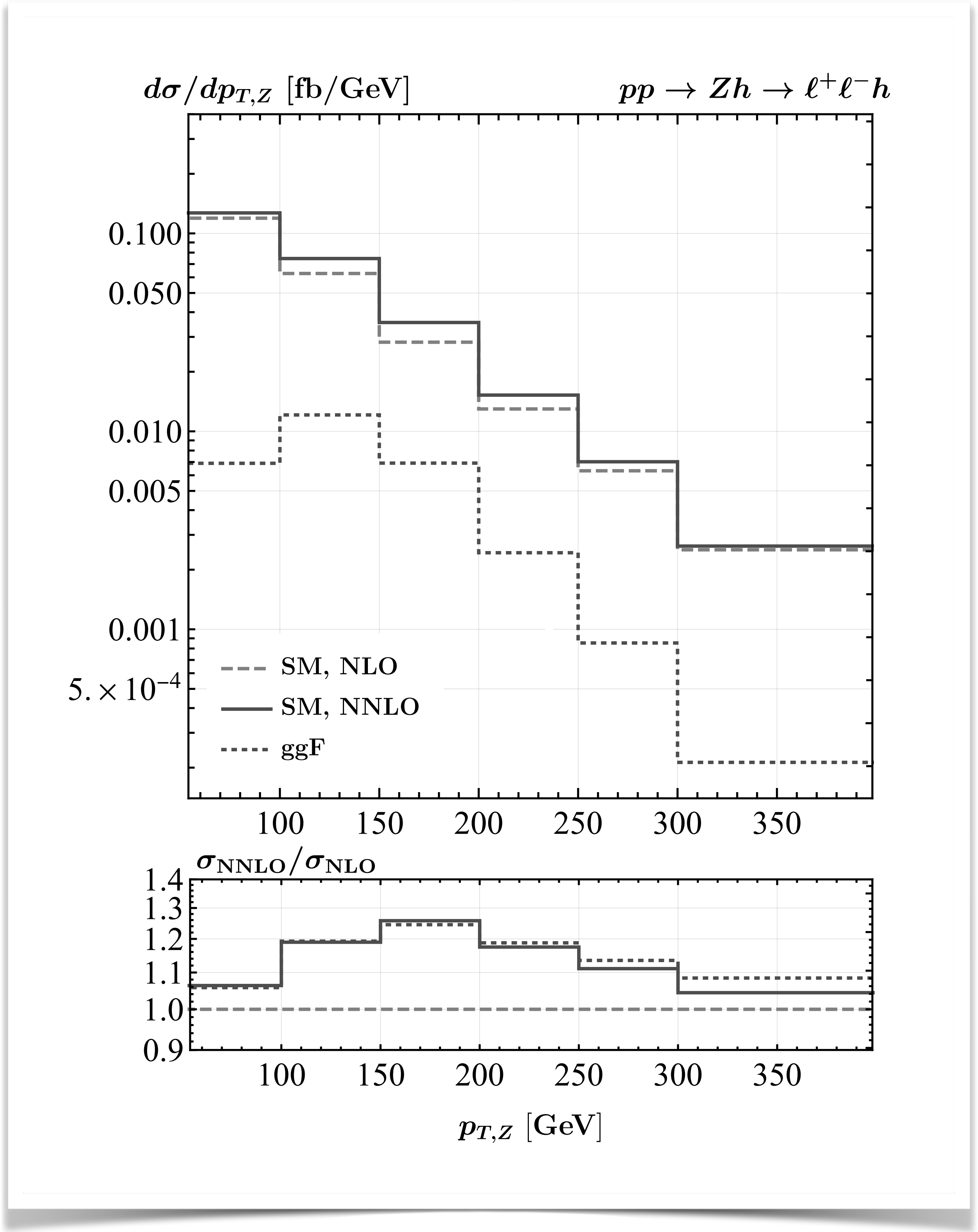


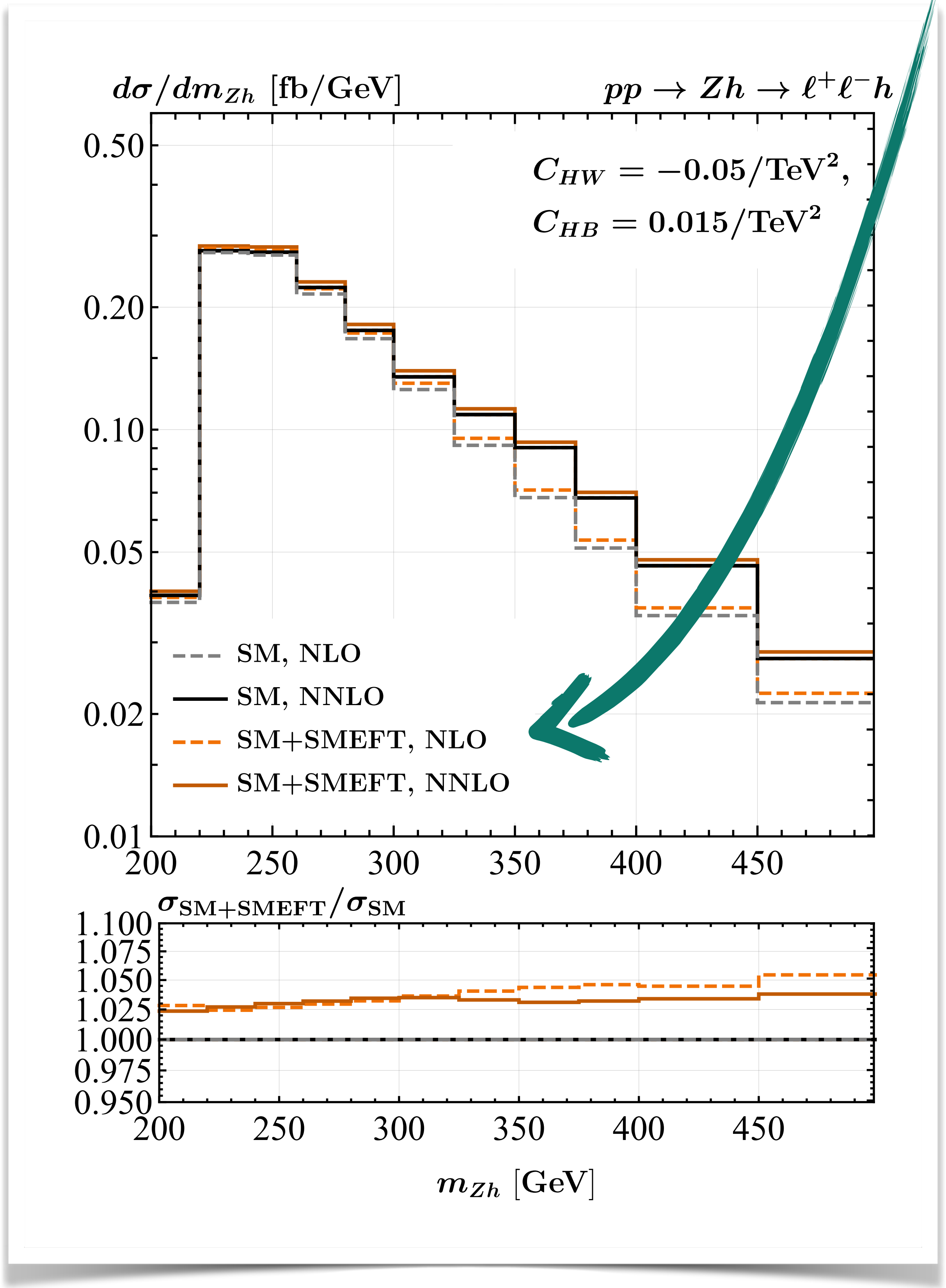
4. Phenomenology

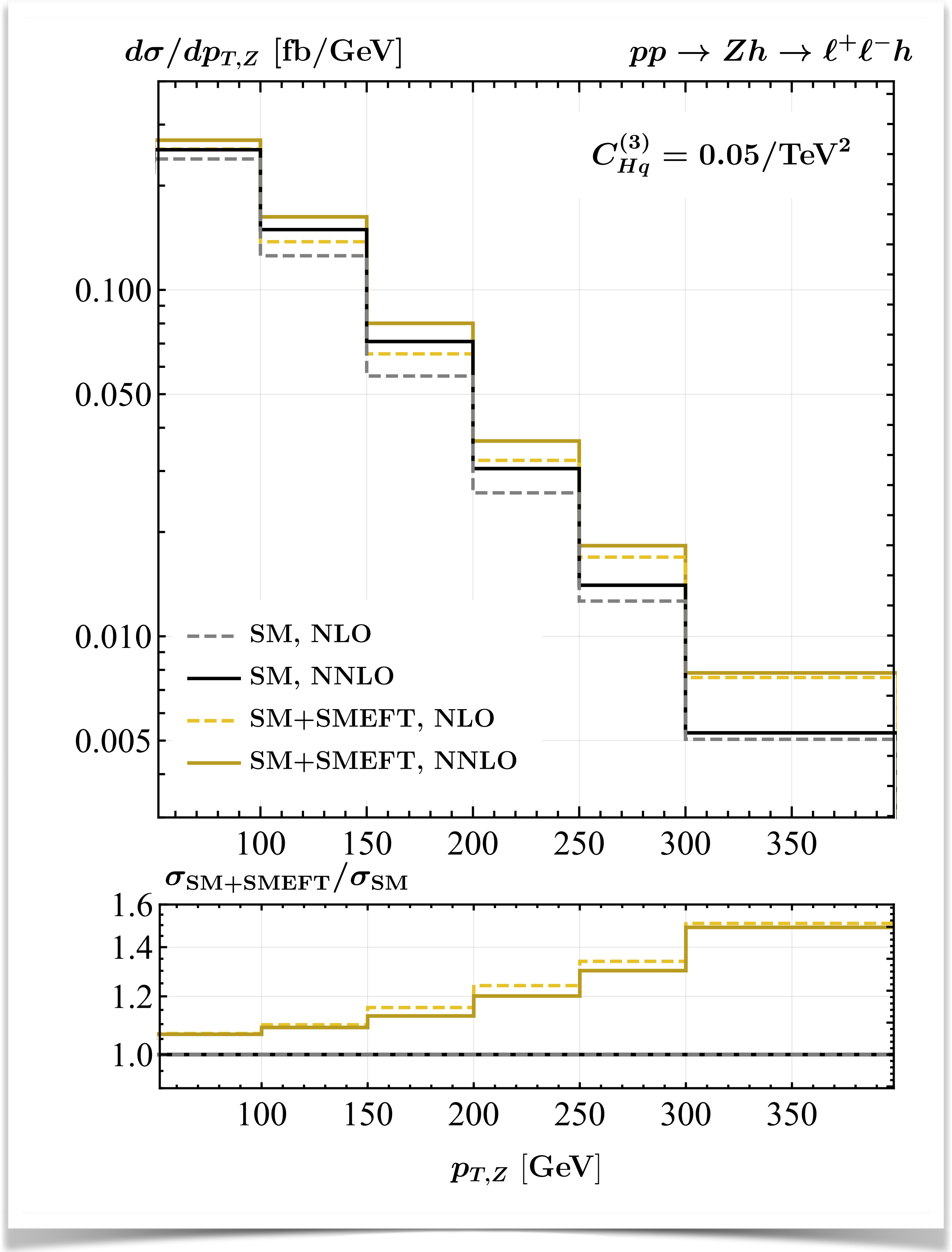
4.4 NNLO vs NLO

[1804.07407] (S. Alioli, W. Dekens, M. Girard, E. Mereghetti)

NLO+PS, $|M_{\text{dim-4}} + M_{\text{dim-6}}|^2$ only







4. Phenomenology

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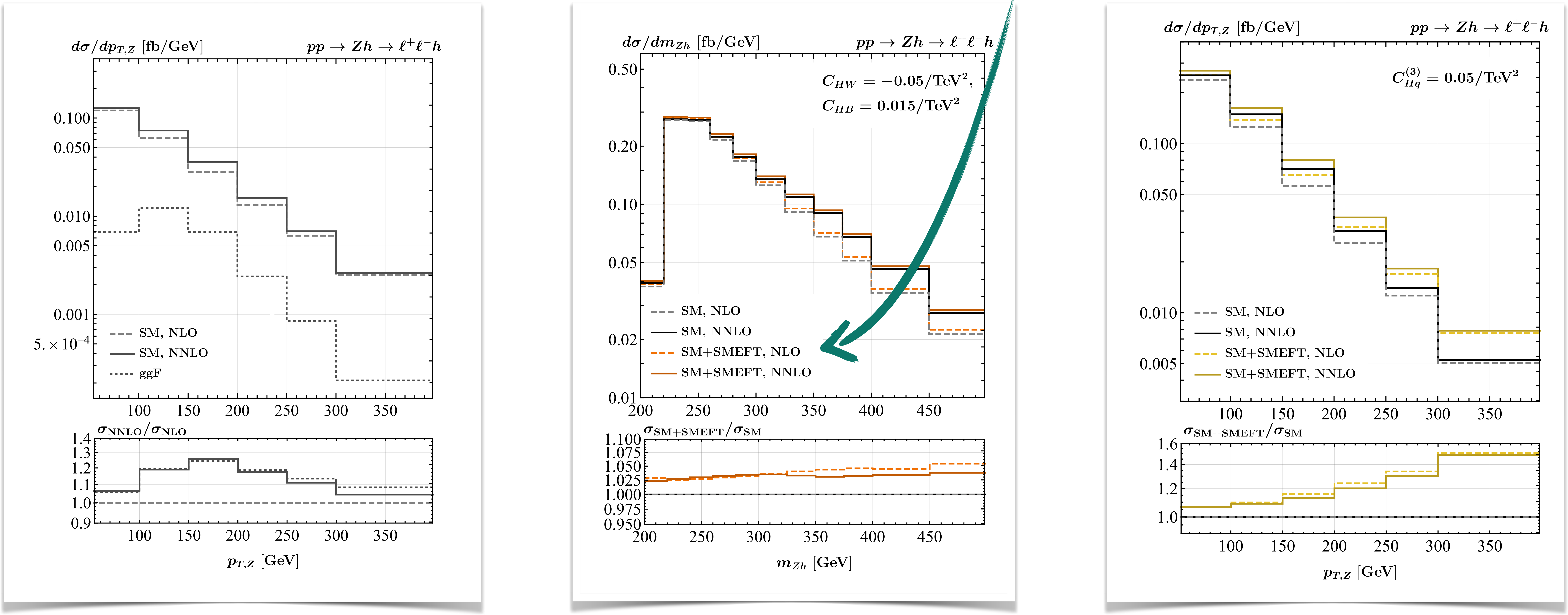

Our **NNLO+PS** code can do **SM**, **linear SMEFT**, **quadratic SMEFT** individually (+ input scheme corrections).

5. Conclusions

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

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- We calculated **SMEFT** contributions to $pp \to V(\to l^+l^-)h$ at **NNLO** and implemented them in an NNLO+PS accurate POWHEG MiNNLO$_{\text{PS}}$ event generator.

  $\to$ **useful tool for future Higgs characterisation studies at the LHC**

- In our calculation we encountered **interesting theoretical aspects**, including the un- and recontraction of spinor-helicity amplitudes and the cancellation of gauge anomalies in the SMEFT.

Backup

4. Phenomenology

4.2 POWHEG MiNNLO$_{PS}$ event generator

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[1908.06987] (P. Monni, E. Re. M. Wiesemann, G. Zanderighi)
[2006.04133] (P. Monni, E. Re. M. Wiesemann)

… and implemented the matrix elements in a **POWHEG MiNNLO$_{PS}$ NNLO+PS event generator**.

4. Phenomenology

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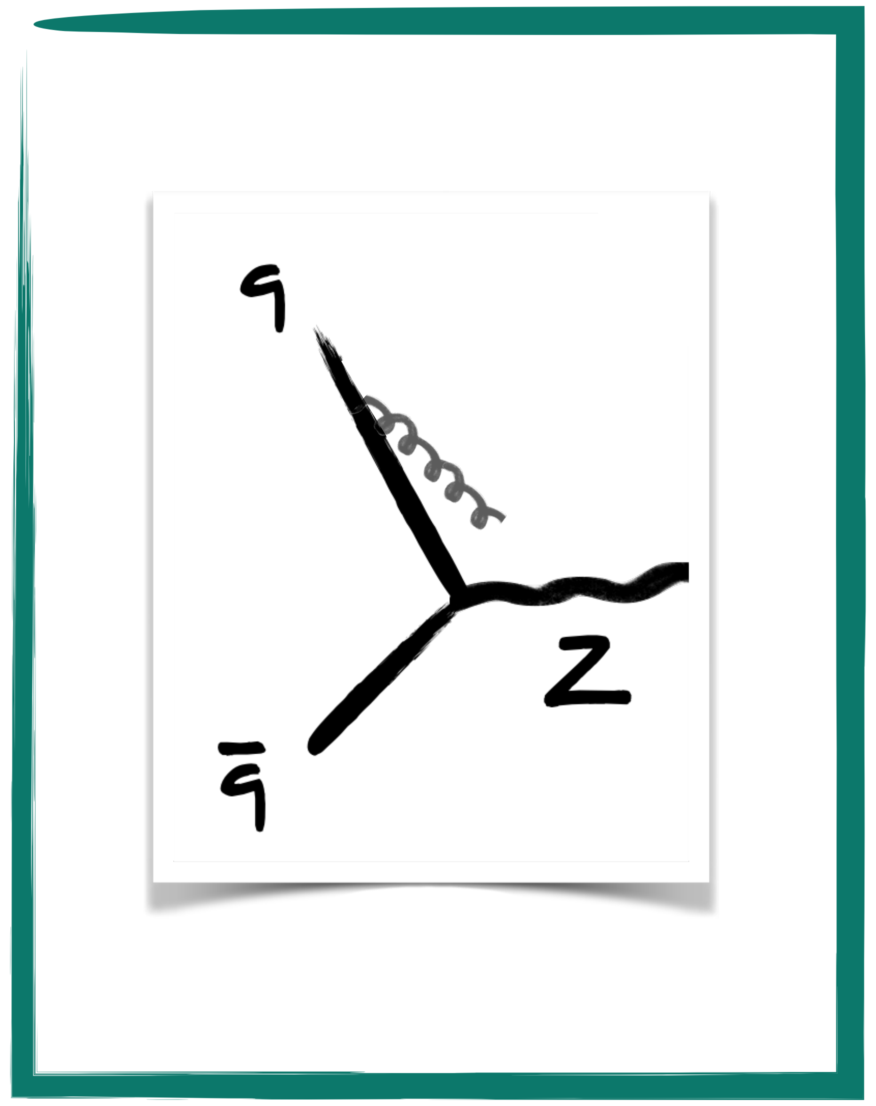

IR singularities

Deal with cases
where emitted parton
is soft or coll.

4. Phenomenology

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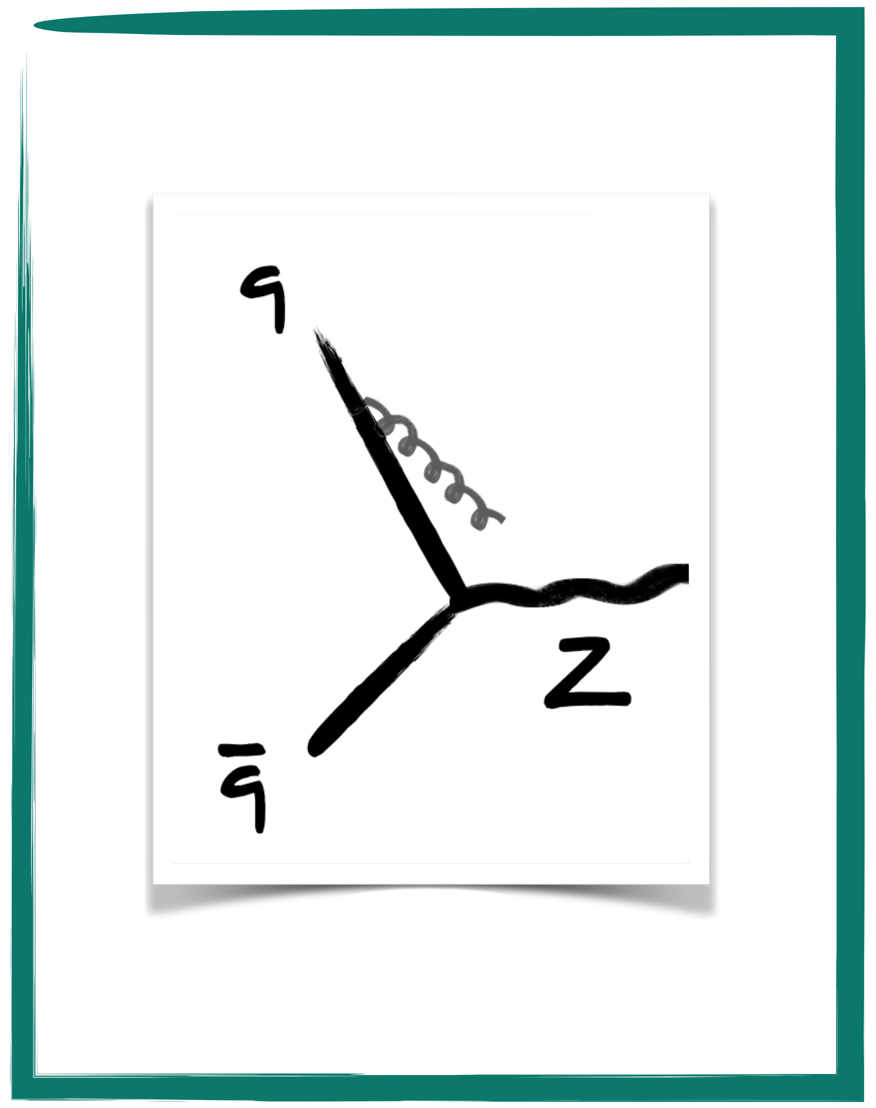

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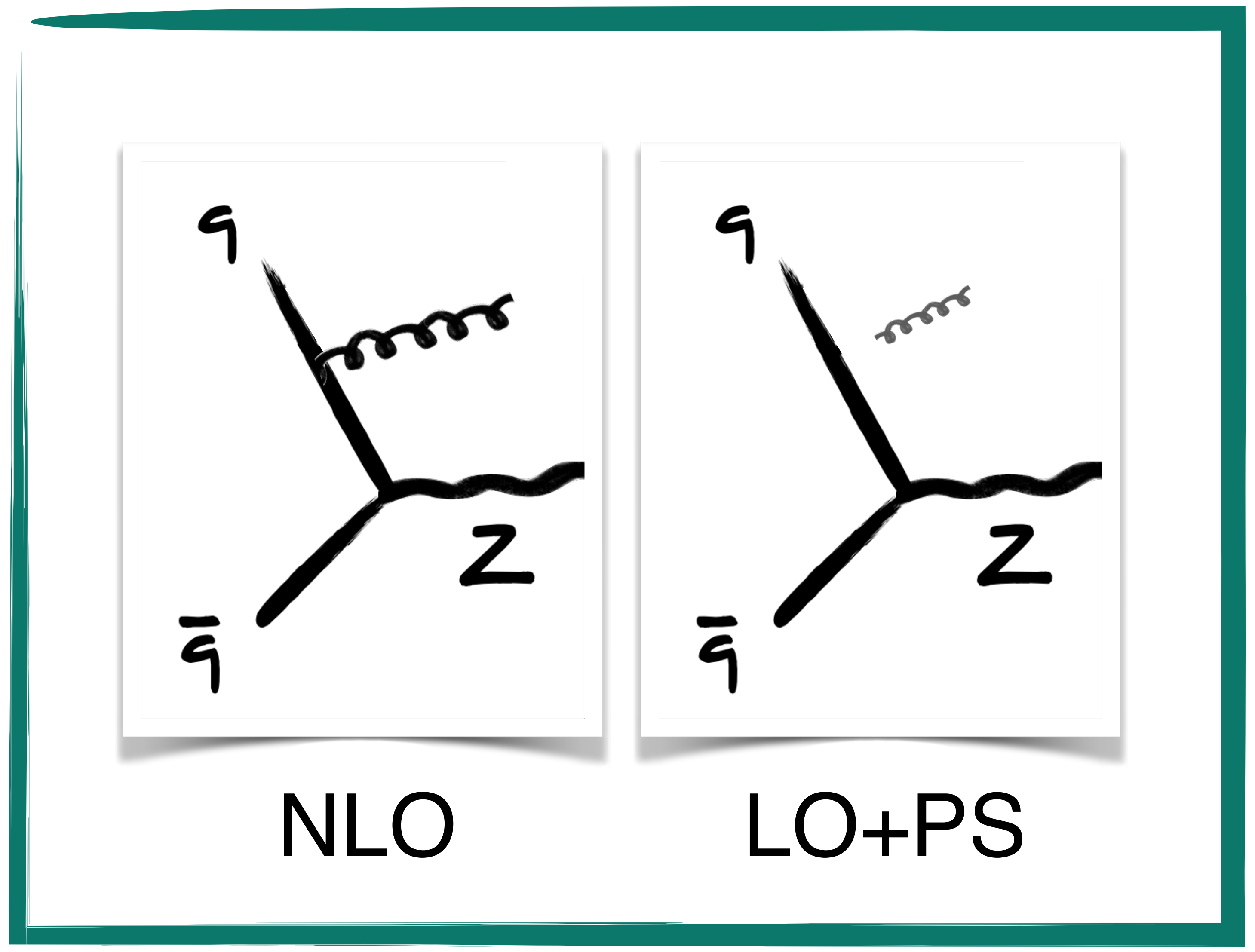

Matching

Avoid double counting between the full real and the approx. real from the PS.

4. Phenomenology

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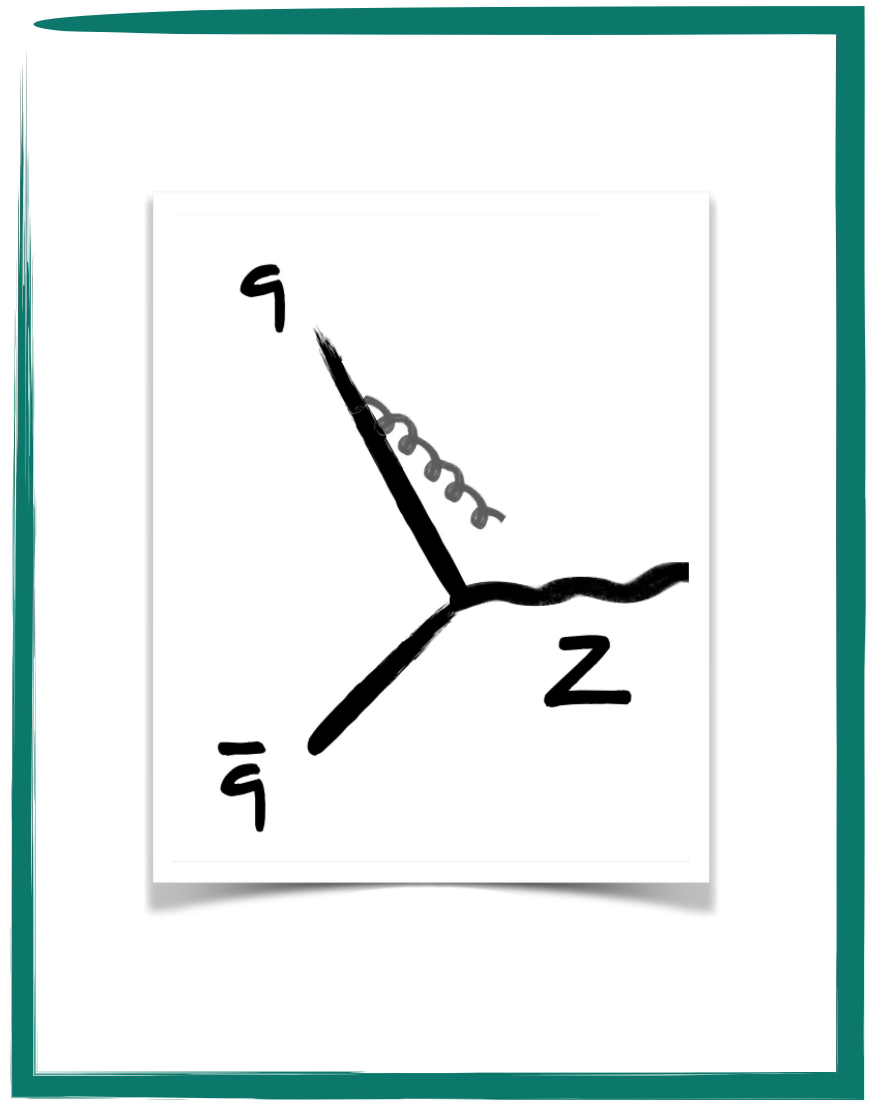

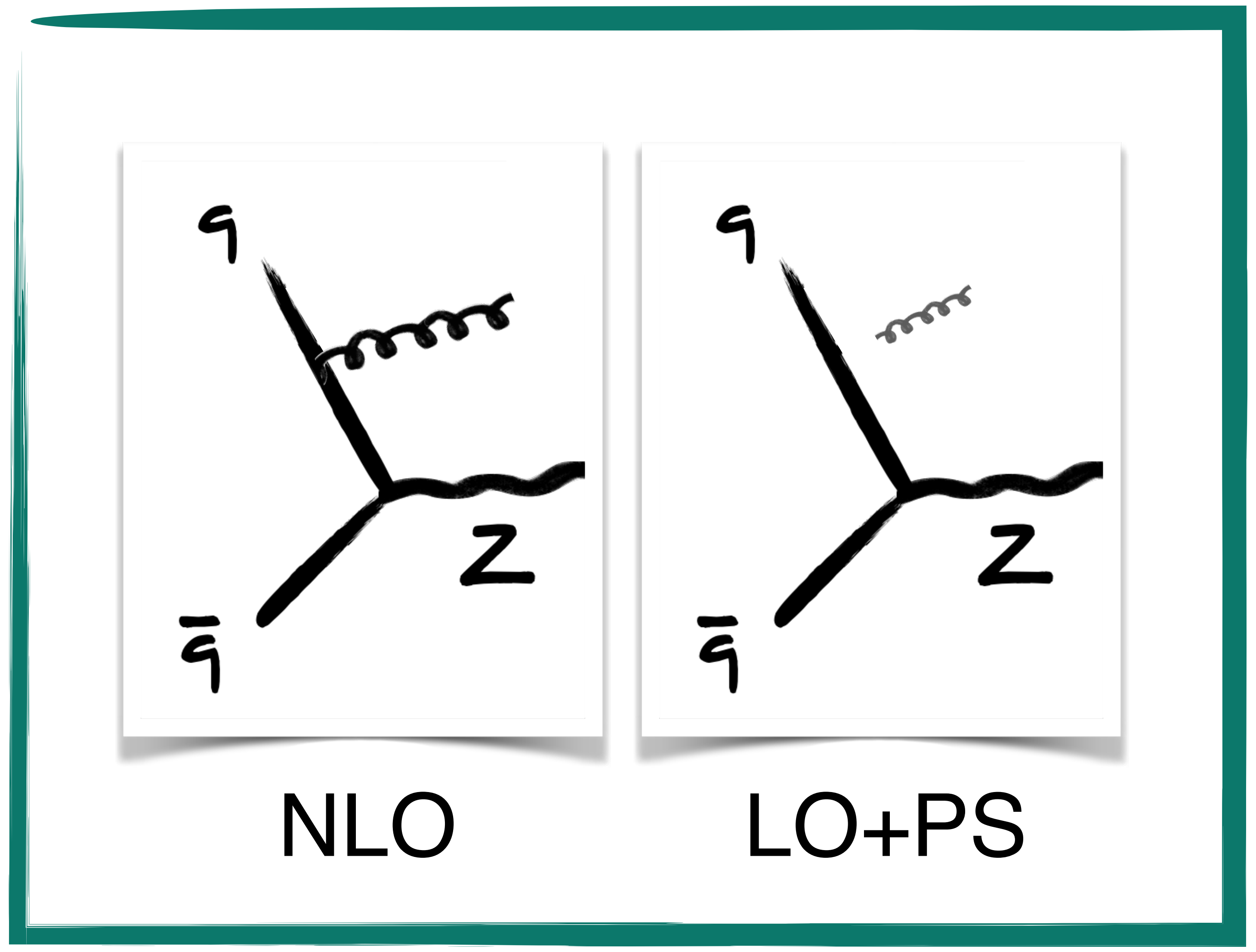

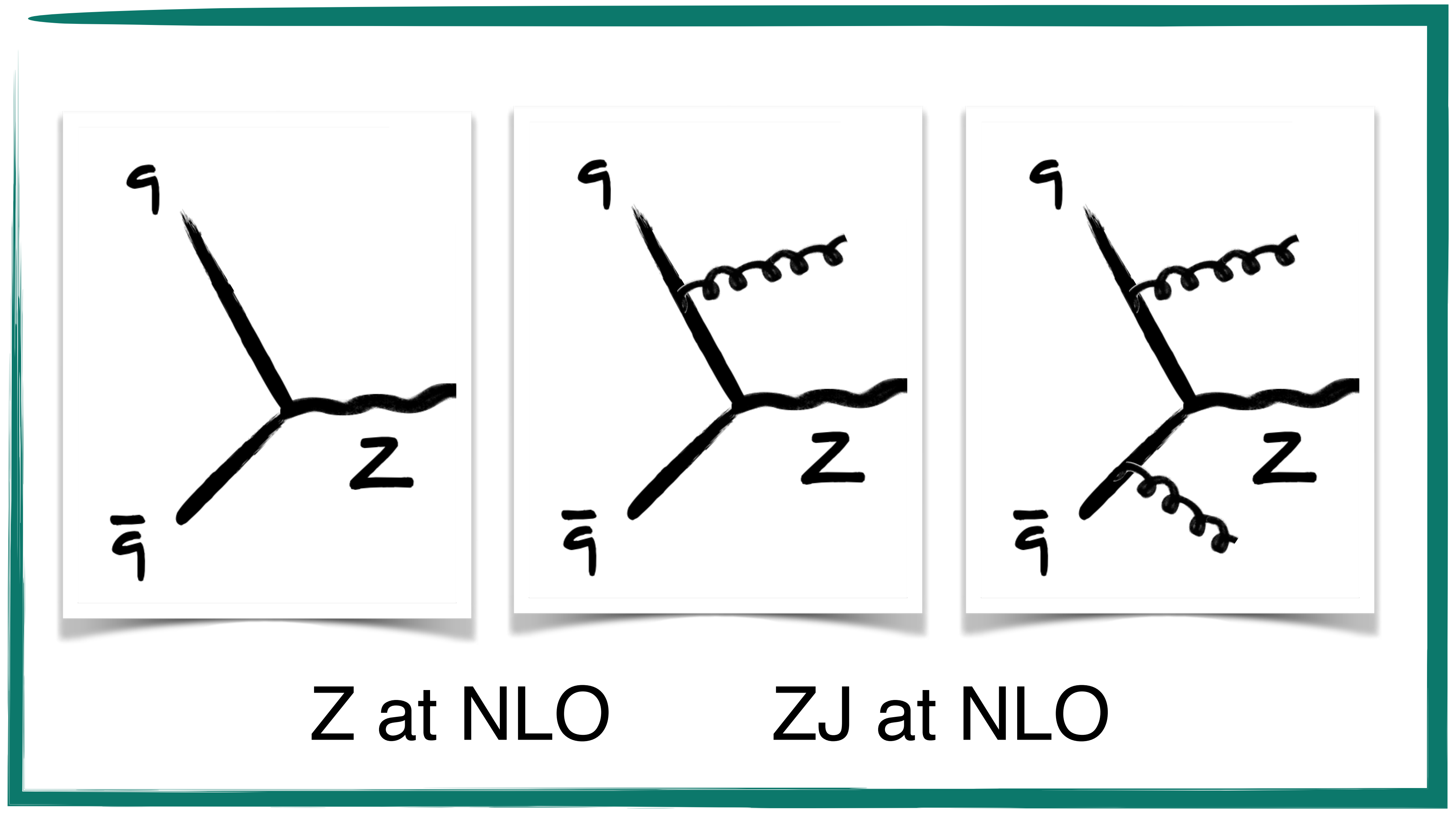

IR singularities

Deal with cases where emitted parton is soft or coll.

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Avoid double counting between the full real and the approx. real from the PS.

Merging

Combine Z at NLO with ZJ at NLO.

4. Phenomenology

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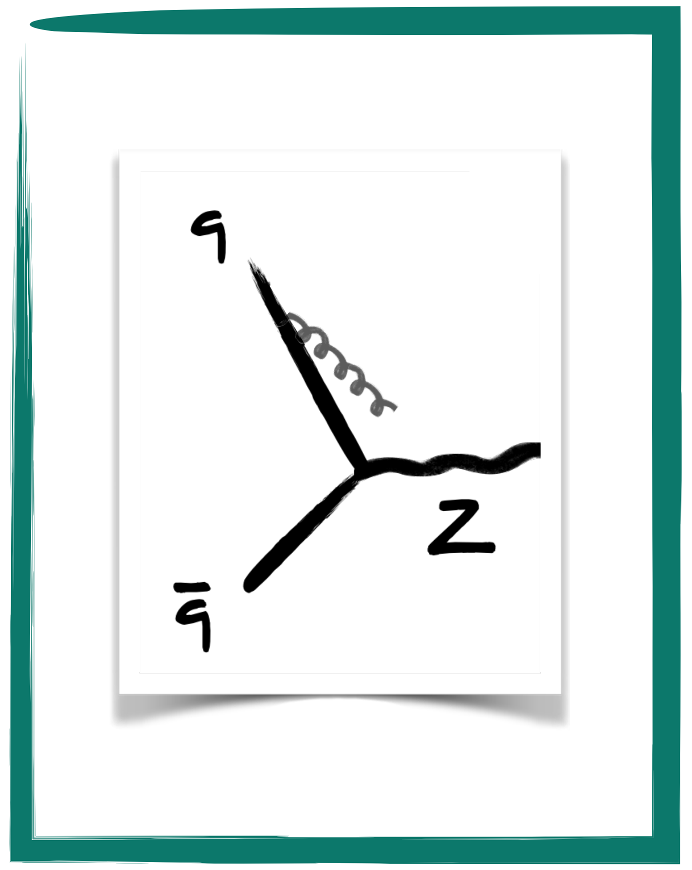
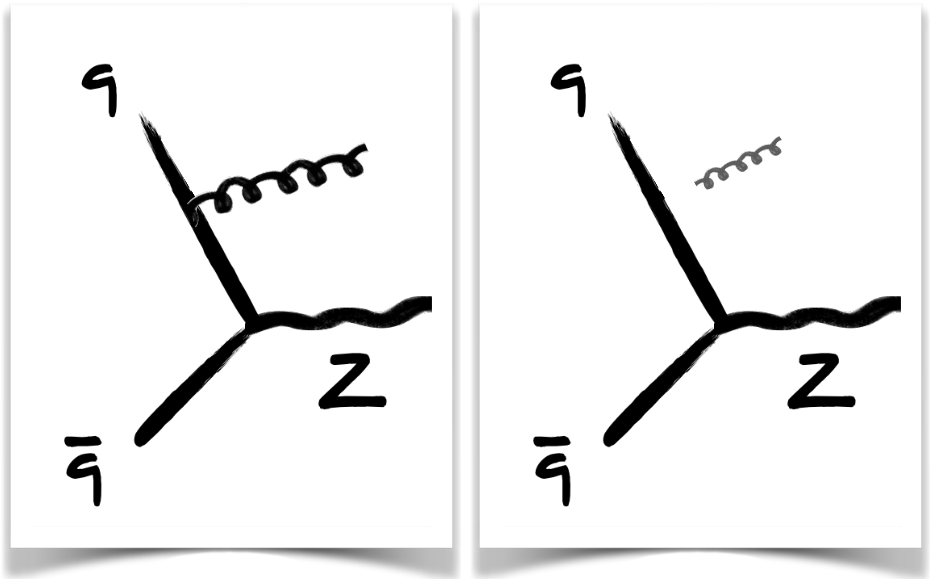
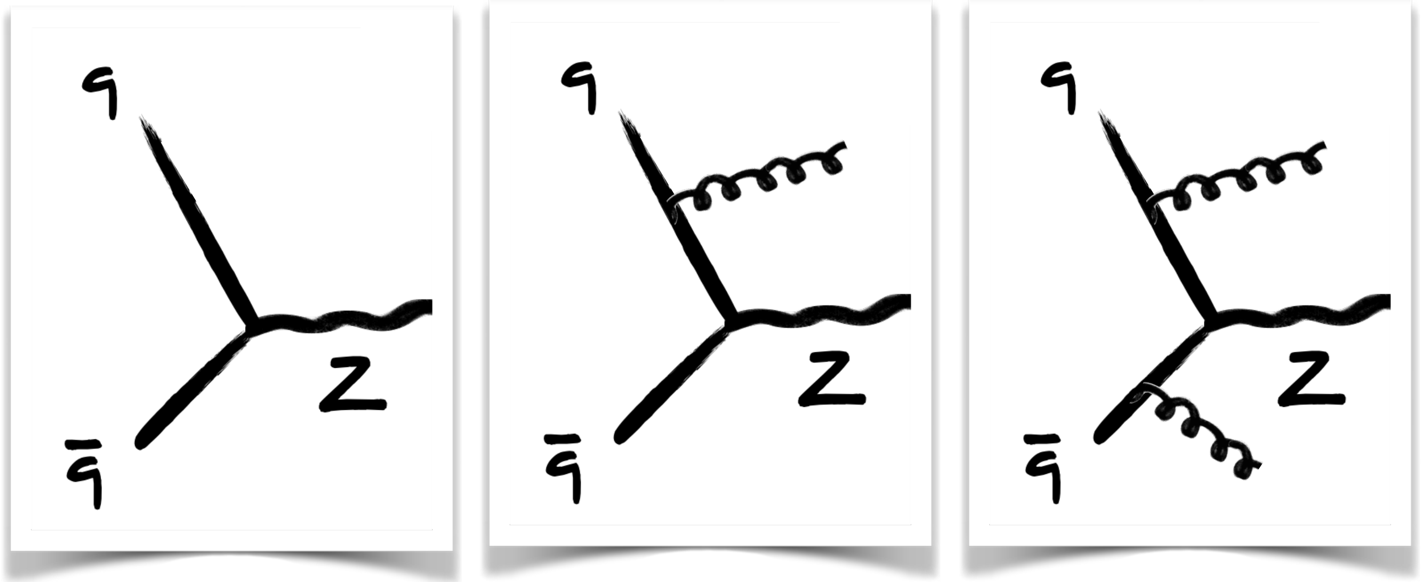




NLO LO+PS



Z at NLO ZJ at NLO

4. Phenomenology

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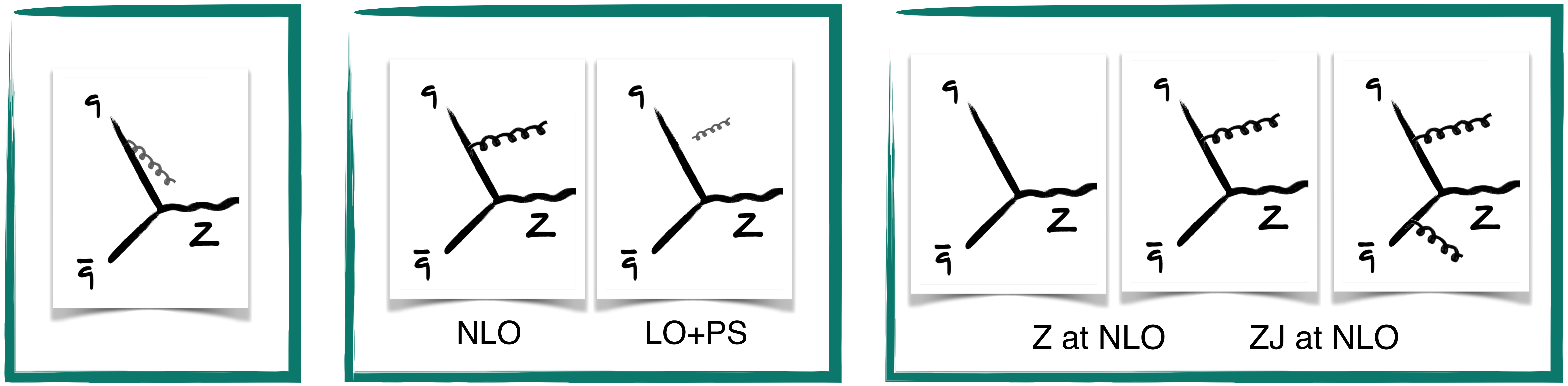
$$\langle \mathcal{O} \rangle_{\mathrm{NLO}} = \int d\mathbf{\Phi}_F \bar{B}(\mathbf{P}_F) \Big[\Delta_{\mathrm{pwg}}(\mathbf{P}_F, p_{T,\mathrm{pwg}}) \mathcal{O}(\mathbf{\Phi}_F) + \sum_\alpha \int_{p_{T,\mathrm{pwg}}} d\Phi_{\mathrm{rad}}^{(\alpha)} \frac{R^{(\alpha)}\left(\vec{\mathbf{P}}_{FJ}^{(\alpha)}\right)}{B(\mathbf{P}_F)} \Delta_{\mathrm{pwg}}\left(\mathbf{P}_F, q_{T,\mathrm{rad}}^{(\alpha)}\right) \mathcal{O}\left(\vec{\mathbf{\Phi}}_{FJ}^{(\alpha)}\right) \Big]$$

Master formula



Luc Schnell
EFT in Multiboson Production
June 2024

4. Phenomenology

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$$
\begin{aligned}
\bar{B}(\boldsymbol{P}_F) \equiv\ & B(\boldsymbol{P}_F) + V(\boldsymbol{P}_F) \\
& + \sum_{\alpha} \int d\Phi_{\text{rad}}^{(\alpha)} \left(R^{(\alpha)}\left(\vec{\boldsymbol{P}}_{FJ}^{(\alpha)}\right) - C^{(\alpha)}\left(\vec{\boldsymbol{P}}_{FJ}^{(\alpha)}\right)\right) \\
& + \sum_{\alpha_\oplus} \int \frac{dz}{z} G_{\oplus}^{(\alpha_\oplus)}\left(\{\boldsymbol{P}_F, z\}\right) + \sum_{\alpha_\ominus} \int \frac{dz}{z} G_{\ominus}^{(\alpha_\ominus)}\left(\{\boldsymbol{P}_F, z\}\right) .
\end{aligned}
$$

$$
\begin{aligned}
\langle \mathcal{O} \rangle_{\text{NLO}} = \int d\boldsymbol{\Phi}_F \bar{B}(\boldsymbol{P}_F) \Bigg[& \Delta_{\text{pwg}}(\boldsymbol{P}_F, p_{T,\text{pwg}}) \mathcal{O}(\boldsymbol{\Phi}_F) \\
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\end{aligned}
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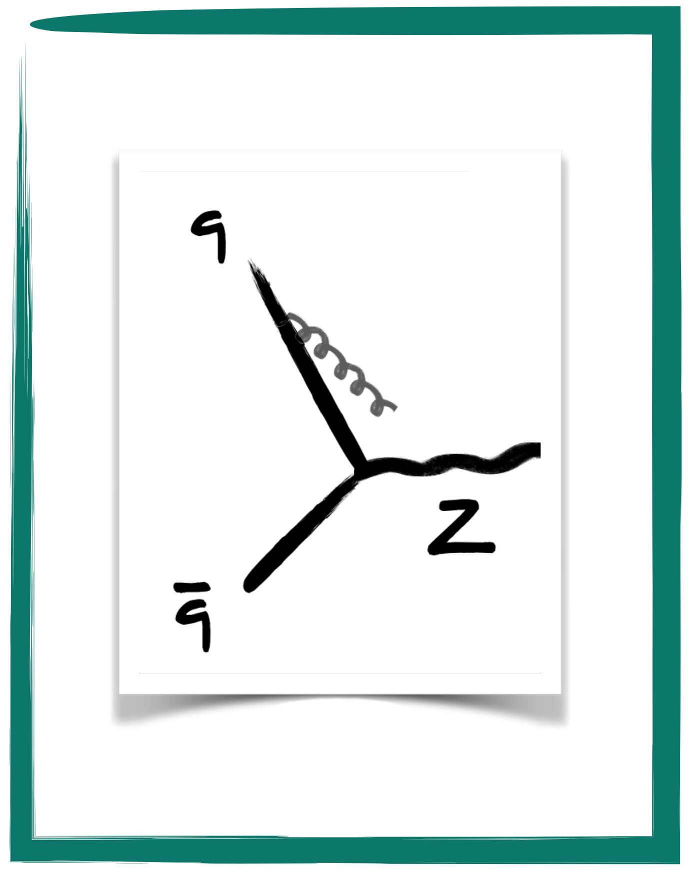
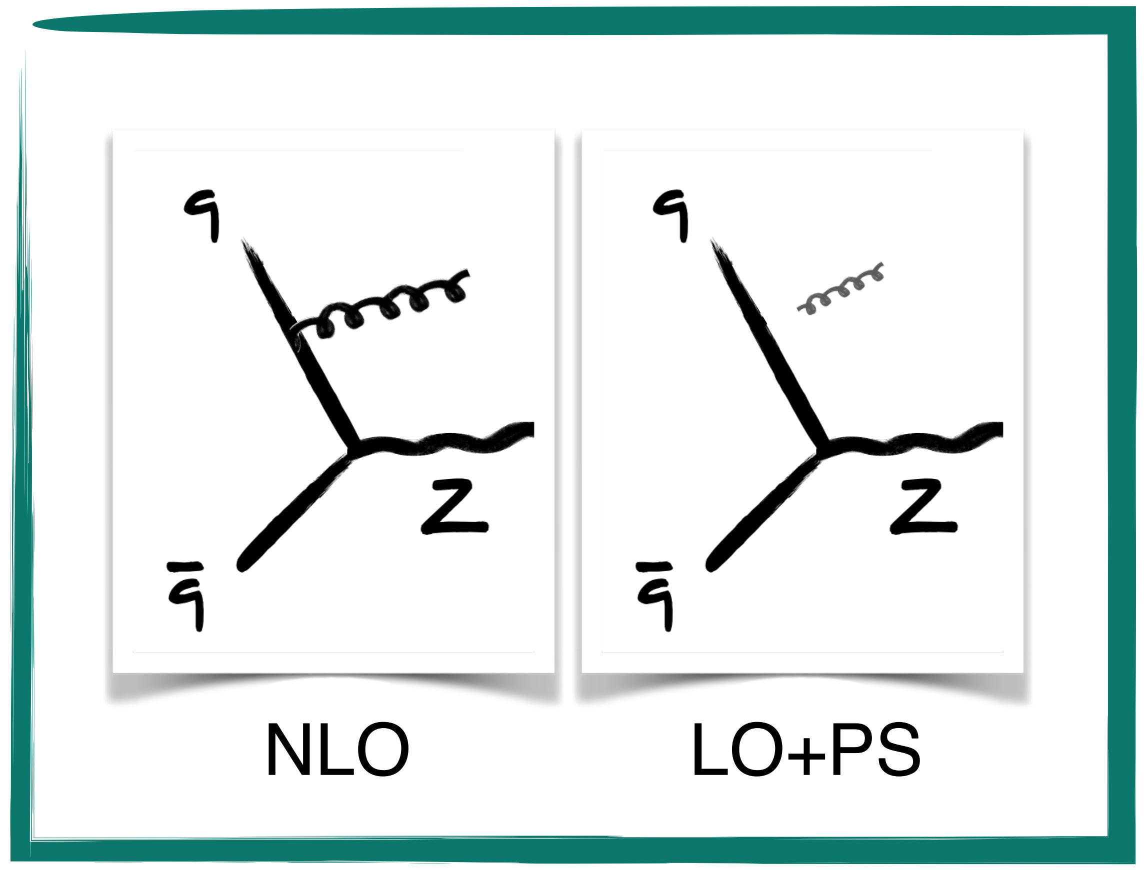
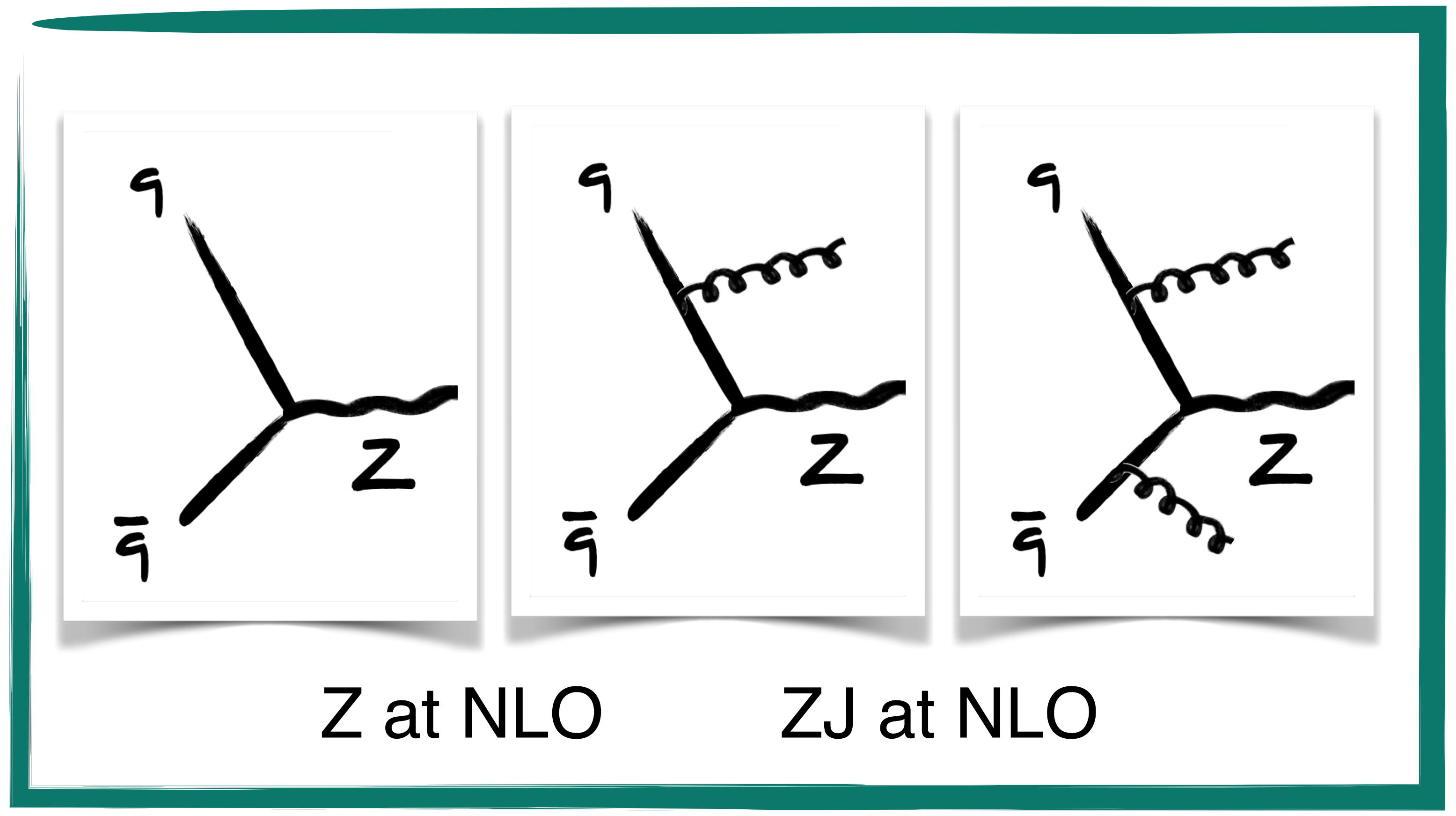
Master formula







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\end{aligned}
$$

Subtraction counterterms.

$$
\begin{aligned}
\langle \mathcal{O} \rangle_{\text{NLO}} = \int d\boldsymbol{\Phi}_F \bar{B}(\boldsymbol{P}_F) \Bigg[\Delta_{\text{pwg}}(\boldsymbol{P}_F, p_{T,\text{pwg}}) \mathcal{O}(\boldsymbol{\Phi}_F) \\
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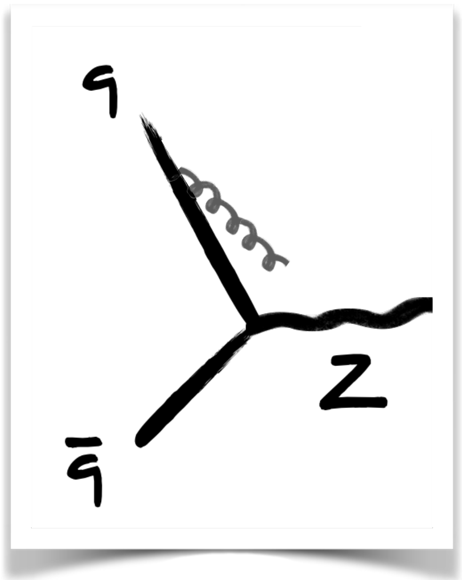
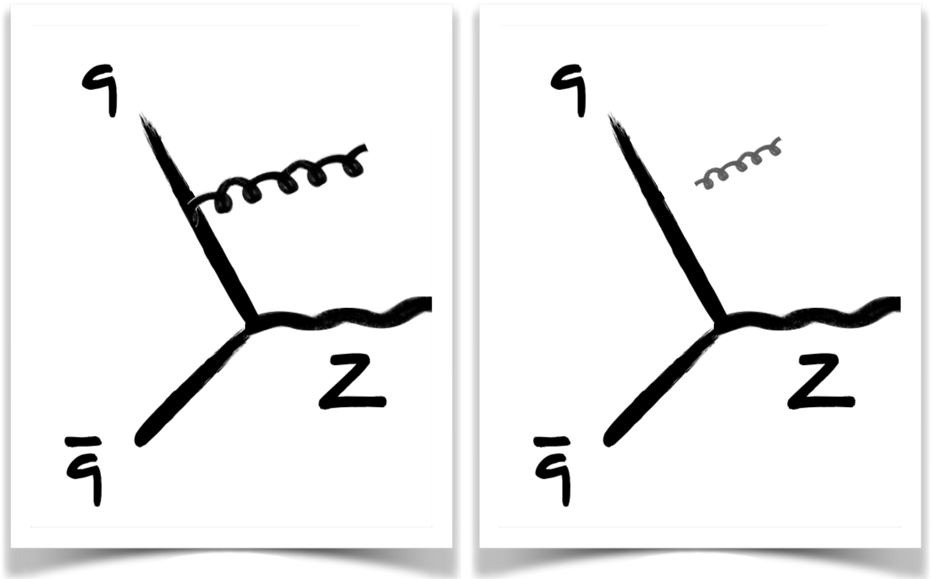
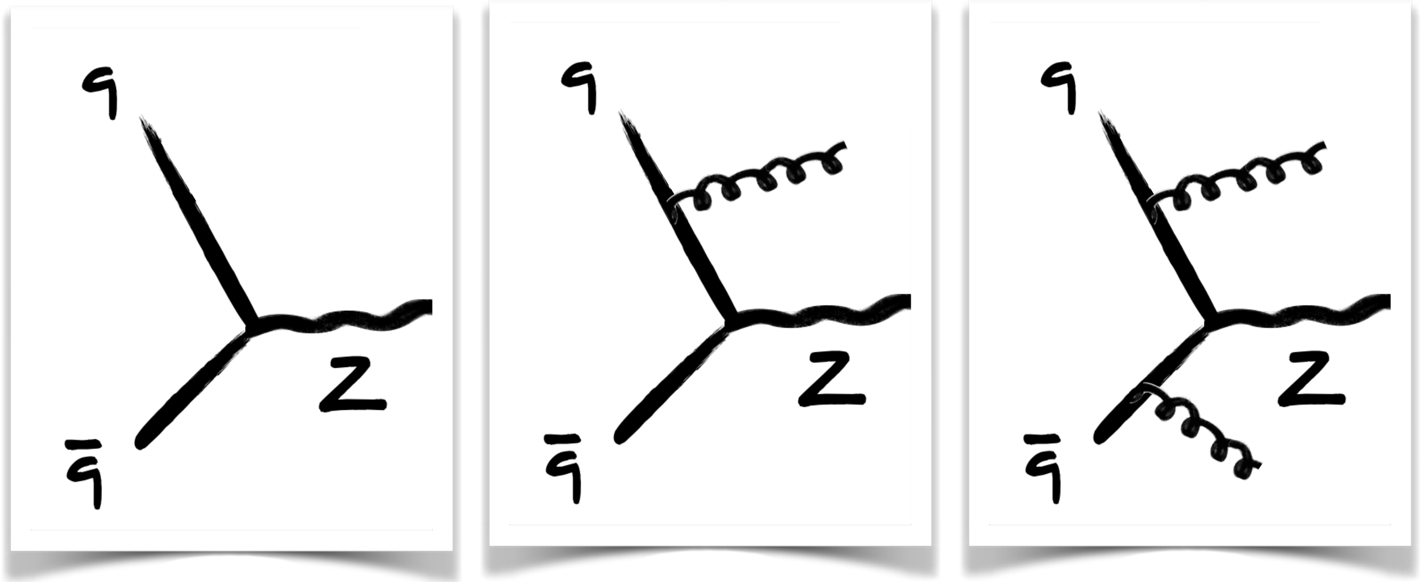




NLO LO+PS



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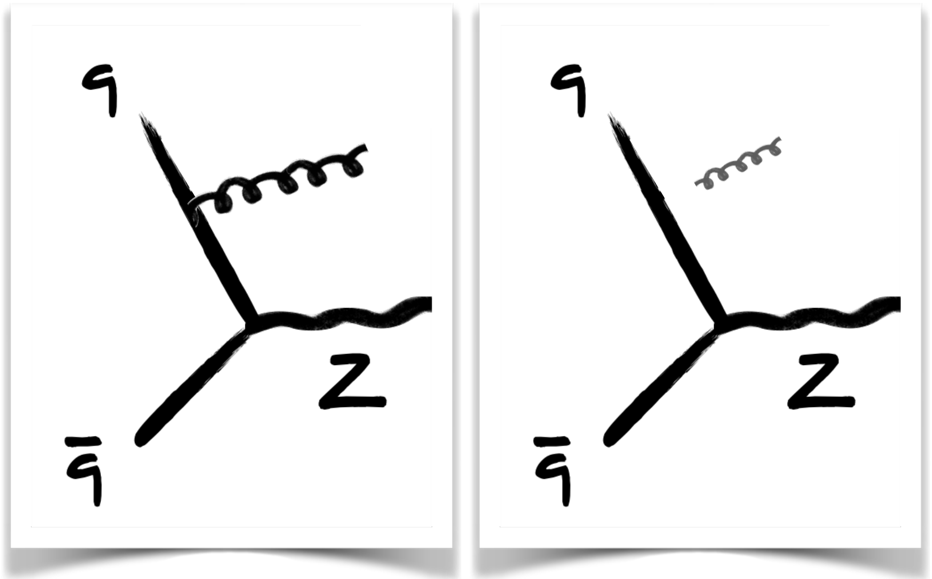

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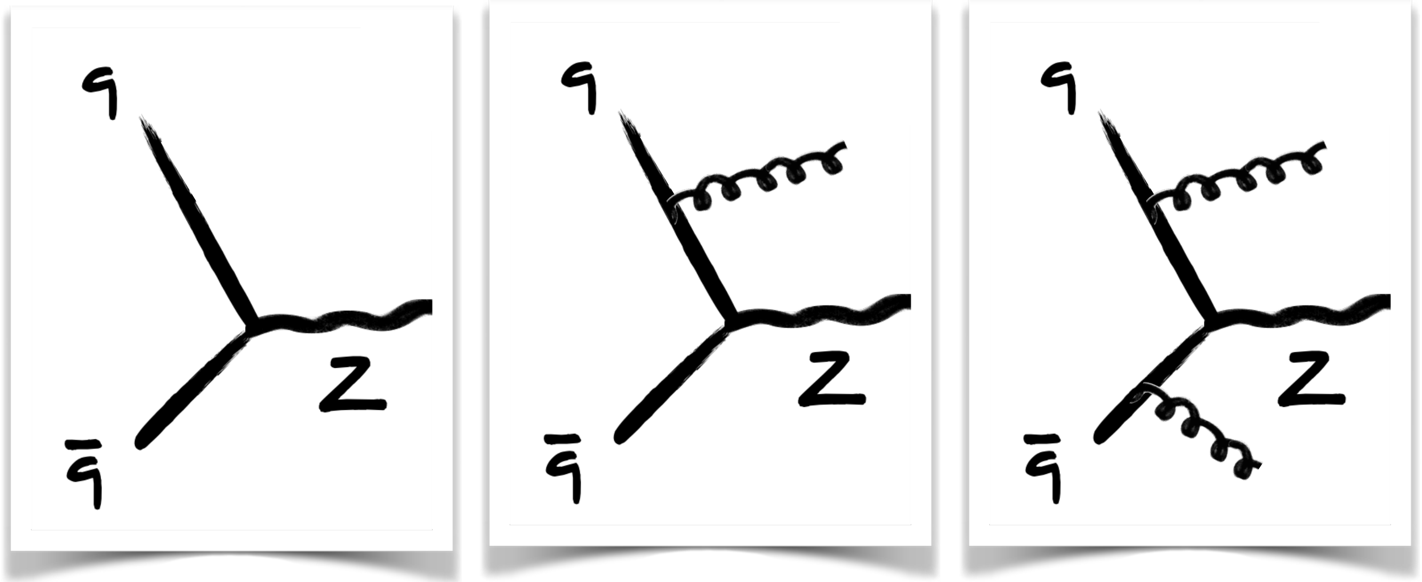

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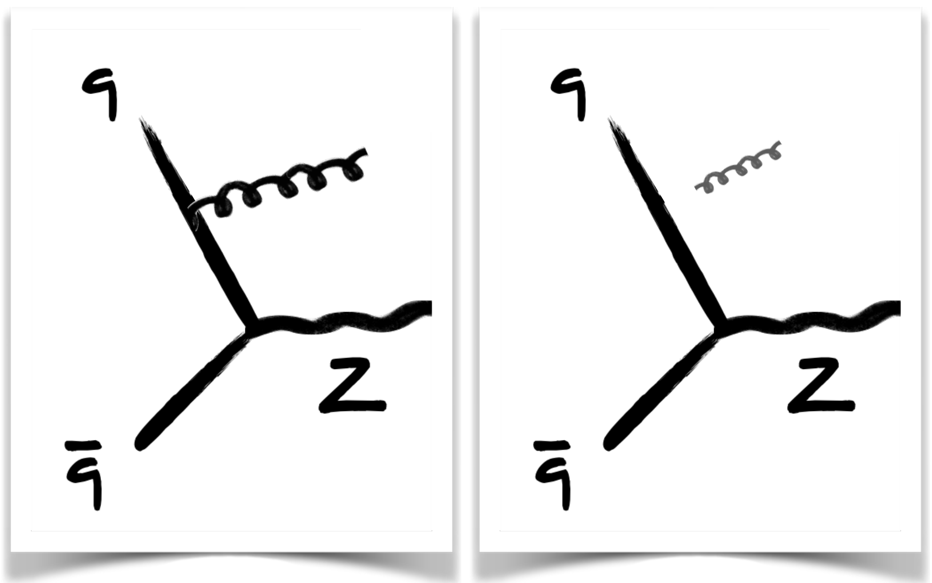
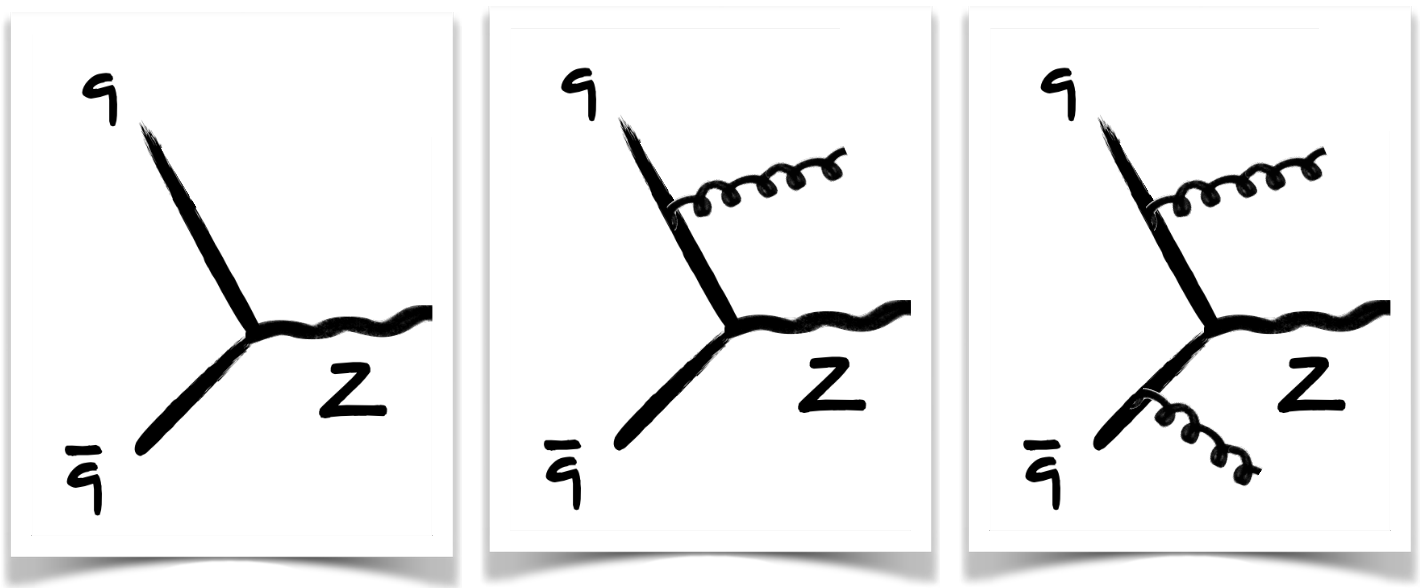
Master formula

Sudakov form factor includes hardest emission at full NLO accuracy.
→ only use PS below p_T^{min}



NLO LO+PS



Z at NLO ZJ at NLO

4. Phenomenology

4.2 POWHEG MiNNLO$_{\text{PS}}$ event generator

… and implemented the matrix elements in a **POWHEG MiNNLO$_{\text{PS}}$ NNLO+PS event generator**.

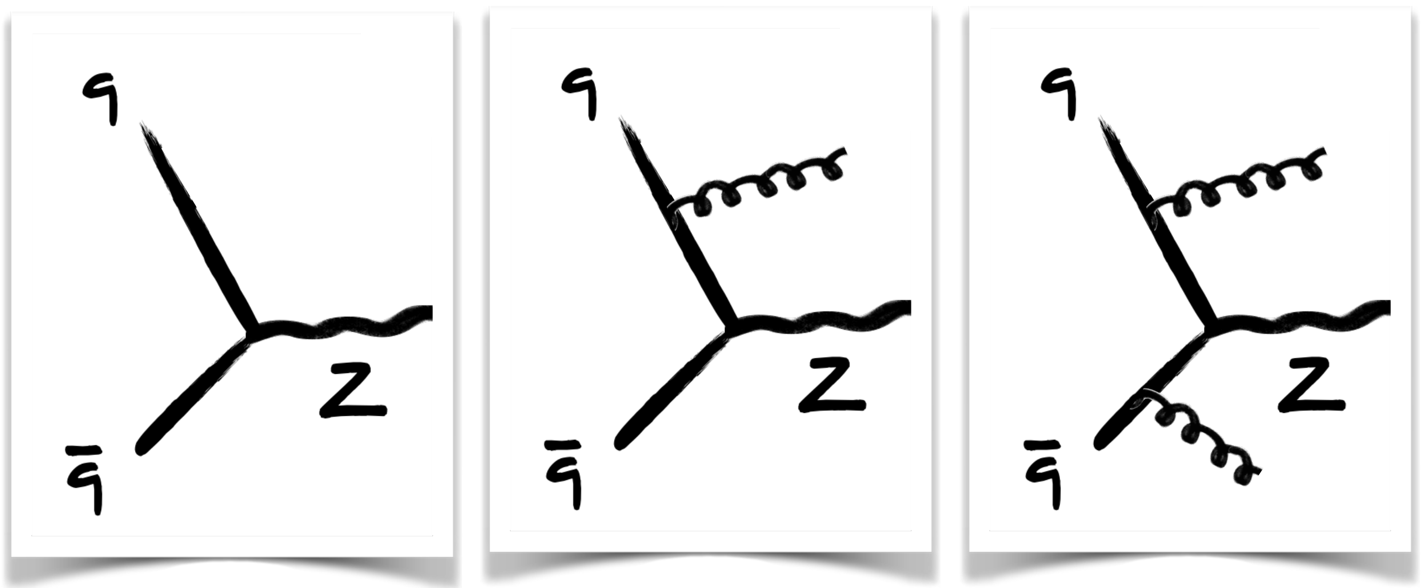
$$\bar{B}(\boldsymbol{P}_F) \equiv B(\boldsymbol{P}_F) + V(\boldsymbol{P}_F) + \sum_{\alpha} \int d\Phi_{\text{rad}}^{(\alpha)} \left(R^{(\alpha)} (\vec{\boldsymbol{P}}_{FJ}^{(\alpha)}) - C^{(\alpha)} (\vec{\boldsymbol{P}}_{FJ}^{(\alpha)}) \right) + \sum_{\alpha_\oplus} \int \frac{dz}{z} G_\oplus^{(\alpha_\oplus)} (\{\boldsymbol{P}_F, z\}) + \sum_{\alpha_\ominus} \int \frac{dz}{z} G_\ominus^{(\alpha_\ominus)} (\{\boldsymbol{P}_F, z\}) .$$

Subtraction counterterms.

$$\langle \mathcal{O} \rangle_{\text{NLO}} = \int d\boldsymbol{\Phi}_F \bar{B}(\boldsymbol{P}_F) \Bigg[\Delta_{\text{pwg}}(\boldsymbol{P}_F, p_{T,\text{pwg}}) \mathcal{O}(\boldsymbol{\Phi}_F) + \sum_{\alpha} \int_{p_{T,\text{pwg}}} d\Phi_{\text{rad}}^{(\alpha)} \frac{R^{(\alpha)} \left(\vec{\boldsymbol{P}}_{FJ}^{(\alpha)} \right)}{B(\boldsymbol{P}_F)} \Delta_{\text{pwg}} \left(\boldsymbol{P}_F, q_{T,\text{rad}}^{(\alpha)} \right) \mathcal{O} \left(\vec{\boldsymbol{\Phi}}_{FJ}^{(\alpha)} \right) \Bigg]$$

Master formula

Sudakov form factor includes hardest emission at full NLO accuracy.
→ only use PS below p_T^{min}



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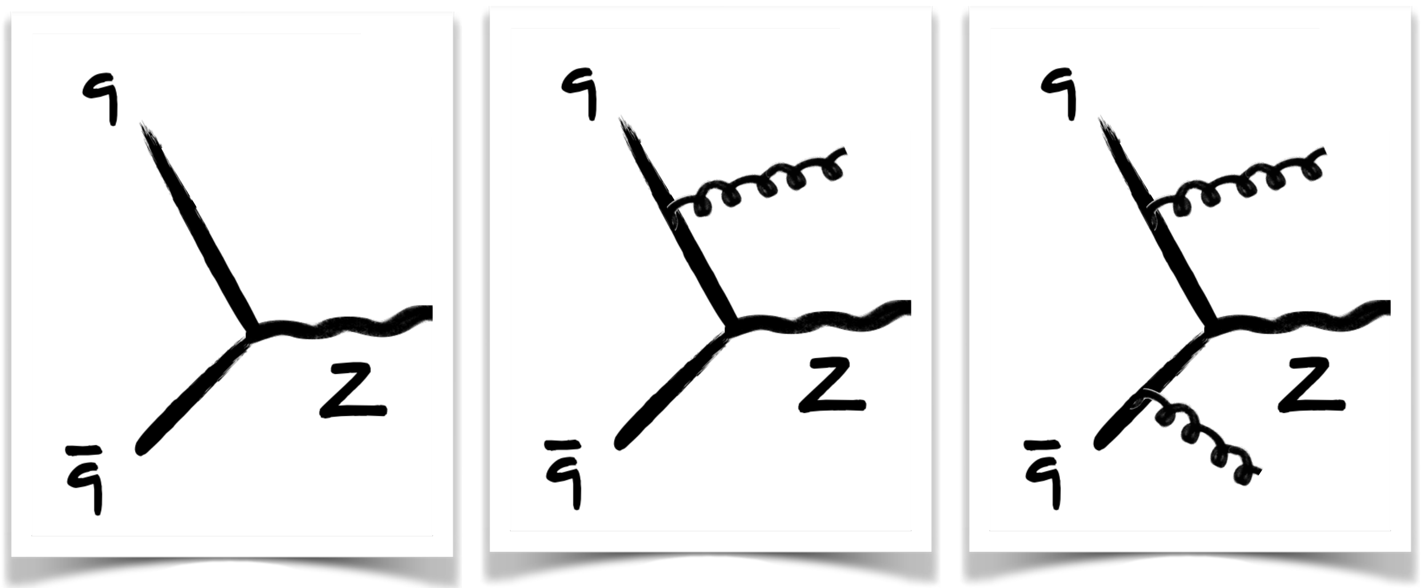
Subtraction counterterms.

Add (N)NLO terms to retain (N)NLO accuracy when emitted parton has small p_T.

$$\langle \mathcal{O} \rangle_{\rm NLO} = \int d\boldsymbol{\Phi}_F \bar{B}(\boldsymbol{P}_F) \Big[\Delta_{\rm pwg}(\boldsymbol{P}_F, p_{T,\rm pwg}) \mathcal{O}(\boldsymbol{\Phi}_F) + \sum_{\alpha} \int_{p_{T,\rm pwg}} d\Phi^{(\alpha)}_{\rm rad} \frac{R^{(\alpha)}\left(\vec{\boldsymbol{P}}^{(\alpha)}_{FJ}\right)}{B(\boldsymbol{P}_F)} \Delta_{\rm pwg}\left(\boldsymbol{P}_F, q^{(\alpha)}_{T,\rm rad}\right) \mathcal{O}\left(\vec{\boldsymbol{\Phi}}^{(\alpha)}_{FJ}\right) \Big]$$

Sudakov form factor includes hardest emission at full NLO accuracy.
→ only use PS below $p_T^{\rm min}$

Master formula for Vhj



Z at NLO ZJ at NLO

4. Phenomenology

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… and implemented the matrix elements in a **POWHEG MiNNLO$_{\text{PS}}$ NNLO+PS event generator**.

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Subtraction counterterms.

Add (N)NLO terms to retain (N)NLO accuracy when emitted parton has small p_T.

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Master formula for Vhj

Sudakov form factor includes hardest emission at full NLO accuracy.
→ only use PS below p_T^{min}

4. Phenomenology

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Master formula for Vhj

Sudakov form factor includes hardest emission at full NLO accuracy.
→ only use PS below p_T^{min}

```
! Switches
SM          0
Linear      1
Quadratic   0
```

```
! Input scheme
InputScheme 2
```

```
! SMEFT
SMEFTScale        1000d0   ! Scale of SMEFT operators

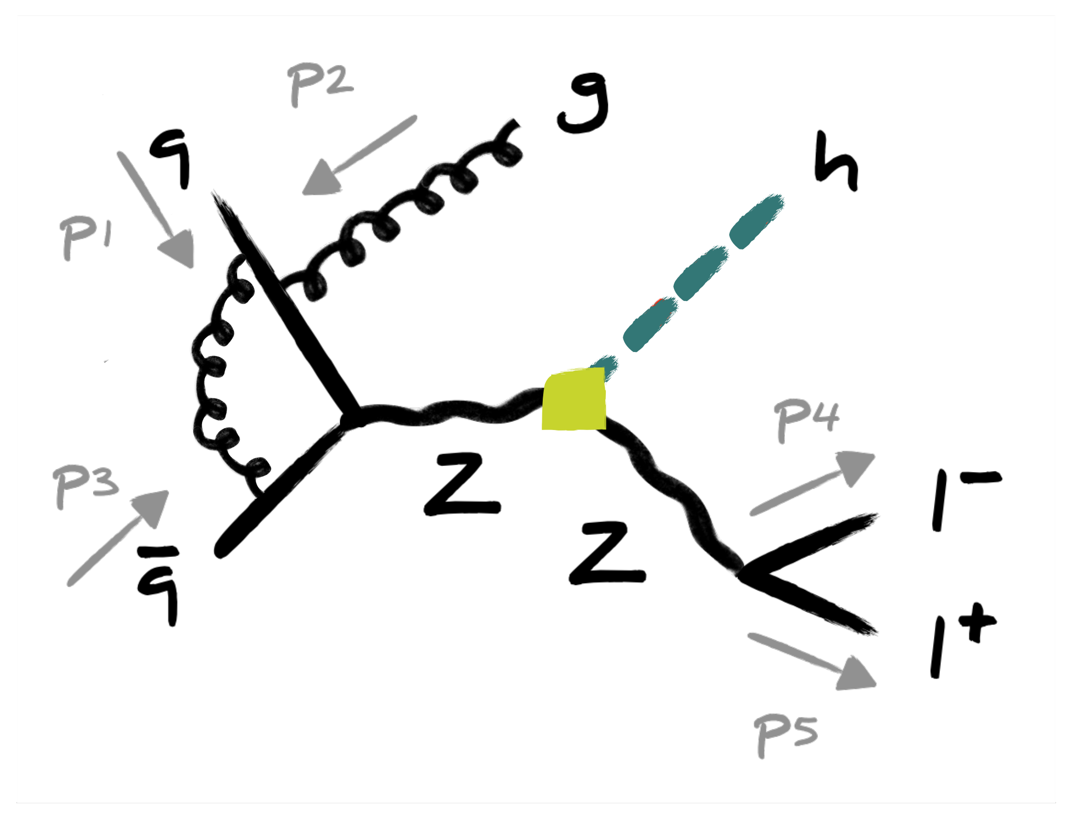
Warsaw               1      ! Switch (on/off)
CHe                  0d0  ! SMEFT coefficient
CHl1                 0d0    ! SMEFT coefficient
CHl3                 0d0    ! SMEFT coefficient
CHq1                 0.05d0    ! SMEFT coefficient
```

The code will be released on the **POWHEG webpage**!

Higher-Order Corrections

$q\bar{q}$-initiated contributions

… and **repeat**.



(B1g1Z)

[1112.1531] (T. Gehrmann, L. Tancredi)

$$\mathcal{A}_{\mathtt{B1g1Z}} = \alpha \mathcal{A}_\alpha + \beta \mathcal{A}_\beta + \gamma \mathcal{A}_\gamma \,.$$

Loop coefficients:

$$\Omega = I^{(1)}(\epsilon)\, \Omega^{(0)} + \Omega^{(1),\,\mathrm{finite}} \,,$$

with $\Omega = \alpha, \beta, \gamma$

$$\Omega^{(1),\,\mathrm{finite}} = C_A\, \Omega_1^{(1),\,\mathrm{finite}} + \frac{1}{C_A}\, \Omega_2^{(1),\,\mathrm{finite}} + \beta_0\, \Omega_3^{(1),\,\mathrm{finite}} \,,$$

(same as in the **SM**)

Helicity amplitudes:

$$\mathcal{A}_{\mathrm{nc}} = \langle 13 \rangle [21] \frac{\langle 14 \rangle [51] + \langle 24 \rangle [52] + \langle 34 \rangle [53]}{2 s_{123} \langle 12 \rangle} \,.$$

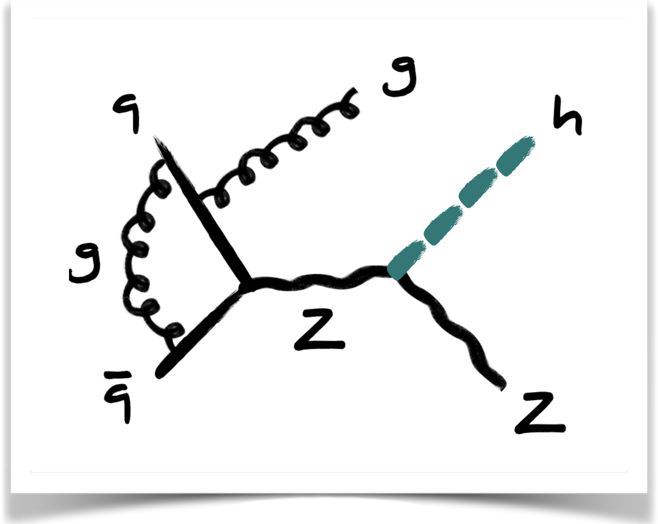
(add contribution, since momentum is carried away by the Higgs and therefore $p_1 + p_2 + p_3 \neq p_4 + p_5$)

Obtain **SMEFT spinor-helicity amplitudes** by un- and recontracting the SM initial-state amplitude.

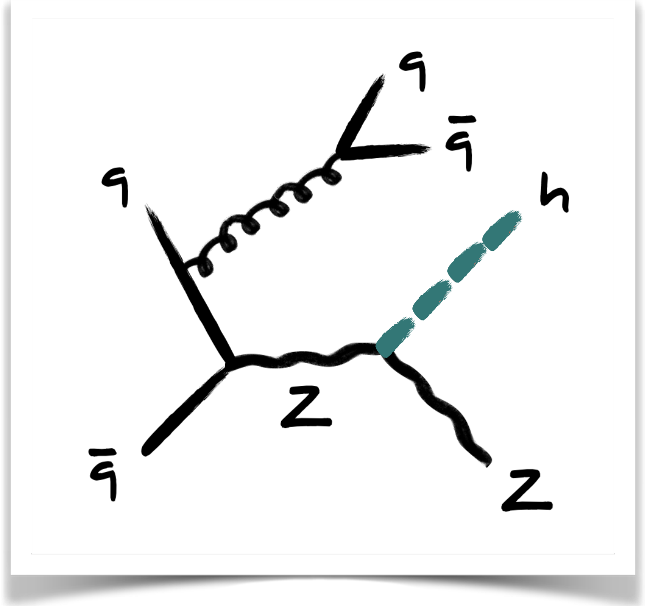
Interesting Aspects of the Calculation

$q\bar{q}$-initiated contributions

Corrections:

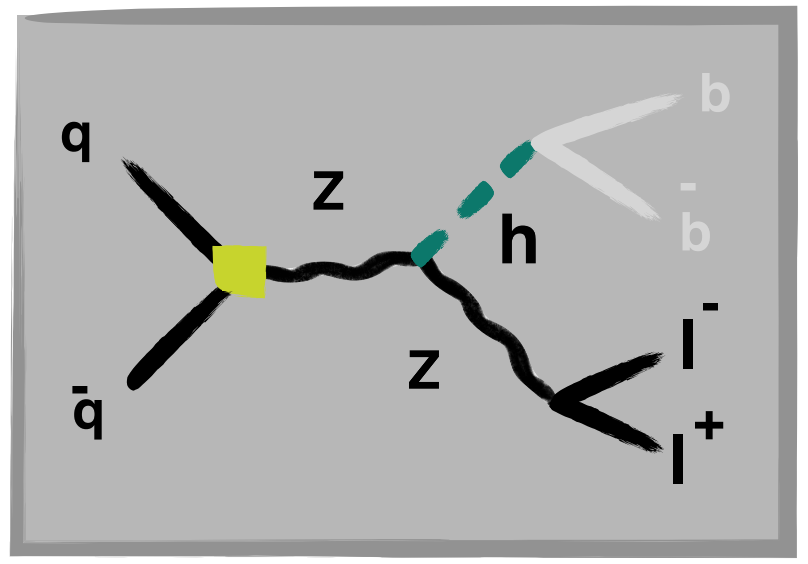


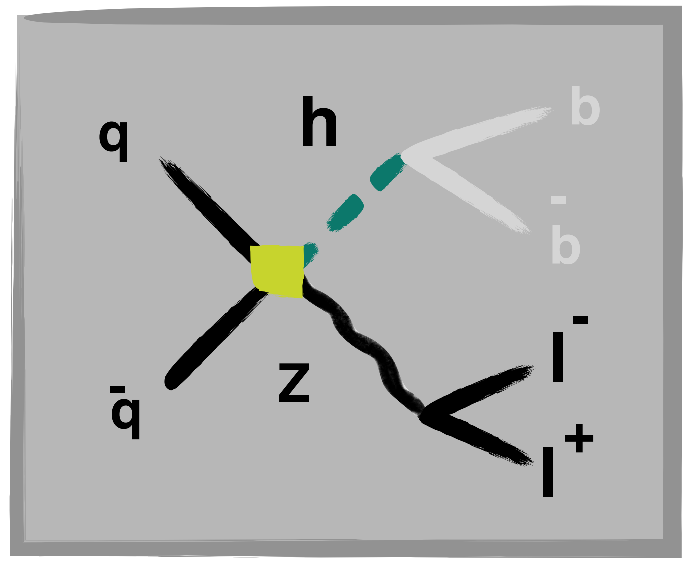
(B-type)



(C,D-type)

Diagrams:





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

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

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

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

(+ input scheme corrections)

Details of the calculation

The POWHEG method

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

→ how to deal with IR singularities?

Soft/collinear divergences

$$\langle \mathcal{O} \rangle_{\text{NLO}} = \int d\boldsymbol{\Phi}_F \bar{B}(\boldsymbol{P}_F) \Bigg[\Delta_{\text{pwg}}(\boldsymbol{P}_F, p_{T,\text{pwg}}) \mathcal{O}(\boldsymbol{\Phi}_F) + \sum_\alpha \int_{p_{T,\text{pwg}}} d\Phi^{(\alpha)}_{\text{rad}} \frac{R^{(\alpha)}\left(\vec{\boldsymbol{P}}^{(\alpha)}_{FJ}\right)}{B(\boldsymbol{P}_F)} \Delta_{\text{pwg}}\left(\boldsymbol{P}_F, q^{(\alpha)}_{T,\text{rad}}\right) \mathcal{O}\left(\vec{\boldsymbol{\Phi}}^{(\alpha)}_{FJ}\right) \Bigg]$$

Master formula

Subtraction:

$$\bar{B}(\boldsymbol{P}_F) \equiv B(\boldsymbol{P}_F) + V(\boldsymbol{P}_F) + \sum_\alpha \int d\Phi^{(\alpha)}_{\text{rad}} \left(R^{(\alpha)}\left(\vec{\boldsymbol{P}}^{(\alpha)}_{FJ}\right) - C^{(\alpha)}\left(\vec{\boldsymbol{P}}^{(\alpha)}_{FJ}\right)\right) + \sum_{\alpha_\oplus} \int \frac{dz}{z} G^{(\alpha_\oplus)}_\oplus\left(\{\boldsymbol{P}_F, z\}\right) + \sum_{\alpha_\ominus} \int \frac{dz}{z} G^{(\alpha_\ominus)}_\ominus\left(\{\boldsymbol{P}_F, z\}\right) .$$

→ **inclusive** (N)NLO

Sudakov form factor:

$$\Delta_{\text{pwg}}(\boldsymbol{P}_F, p_{T,\text{pwg}}) \equiv \exp\left[-\sum_\alpha \int d\Phi^{(\alpha)}_{\text{rad}} \frac{R^{(\alpha)}\left(\vec{\boldsymbol{P}}^{(\alpha)}_{FJ}\right) \theta\left(q^{(\alpha)}_{T,\text{rad}} - p_{T,\text{pwg}}\right)}{B(\boldsymbol{P}_F)}\right] ,$$

→ **exclusive** above p_T^{min}

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

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

Operators considered in our work

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

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

$$Q_{HG} = \frac{g_s^2}{(4\pi)^2}\,(H^\dagger H)\,G^a_{\mu\nu}\,G^{a,\mu\nu} \qquad Q_{3G} = \frac{g_s^3}{(4\pi)^2}\,f^{abc}\,G^{a,\nu}_{\mu}\,G^{b,\sigma}_{\nu}\,G^{c,\mu}_{\sigma}$$

Operators normalised such that Wilson coefficients are expected to be of O(1) in UV-complete weakly-coupled BSM models

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Factorisable contributions

Since operators $Q_{H\Box}$, Q_{HD} & Q_{bH} do not contain a gluon, associated SMEFT effects factorise to all orders in strong coupling constant. SMEFT results can be obtained from SM matrix elements by following simple replacement:

$$y_b^2 \to y_b^2 \left\{ 1 + \frac{2v^2}{\Lambda^2} \left[C_{H\Box} - \frac{C_{HD}}{4} - \mathrm{Re}\left(C_{bH}\right) \right] \right\}$$

corrections due to Higgs wave function

correction due to Yukawa operator

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Factorisable contributions

For example in case of partial h → b$\bar{\text{b}}$ decay rate factorisable corrections are:

$$\Gamma(h \to b\bar{b})^{\text{fac}}_{\text{SMEFT}} = \frac{3y_b^2 m_h}{16\pi}\left\{1 + \frac{2v^2}{\Lambda^2}\left[C_{H\Box} - \frac{C_{HD}}{4} - \text{Re}\left(C_{bH}\right)\right]\right\}$$

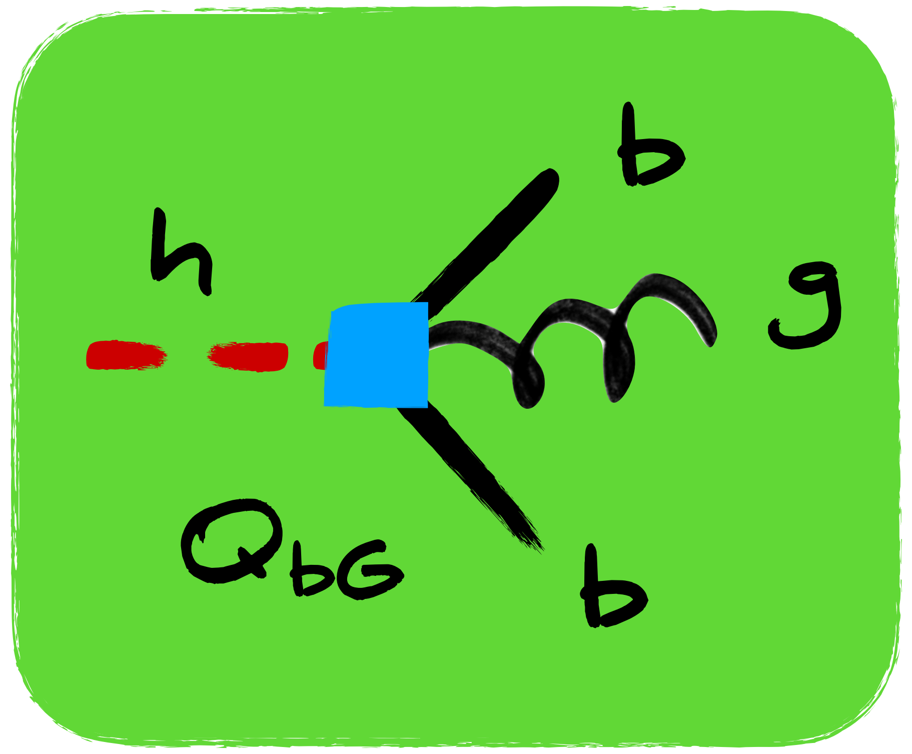
$$\times\left[1 + \frac{\alpha_s}{\pi}\,5.67 + \left(\frac{\alpha_s}{\pi}\right)^2 29.15\right]$$

NLO & NNLO QCD correction in SM

[in principle extension to N^{4}LO possible using SM results given in Baikov et al., hep-ph/0511063; Herzog et al., 1707.01044]

Non-factorisable contributions

Dominant non-factorisable corrections arise from dipole operator Q_{bG}:

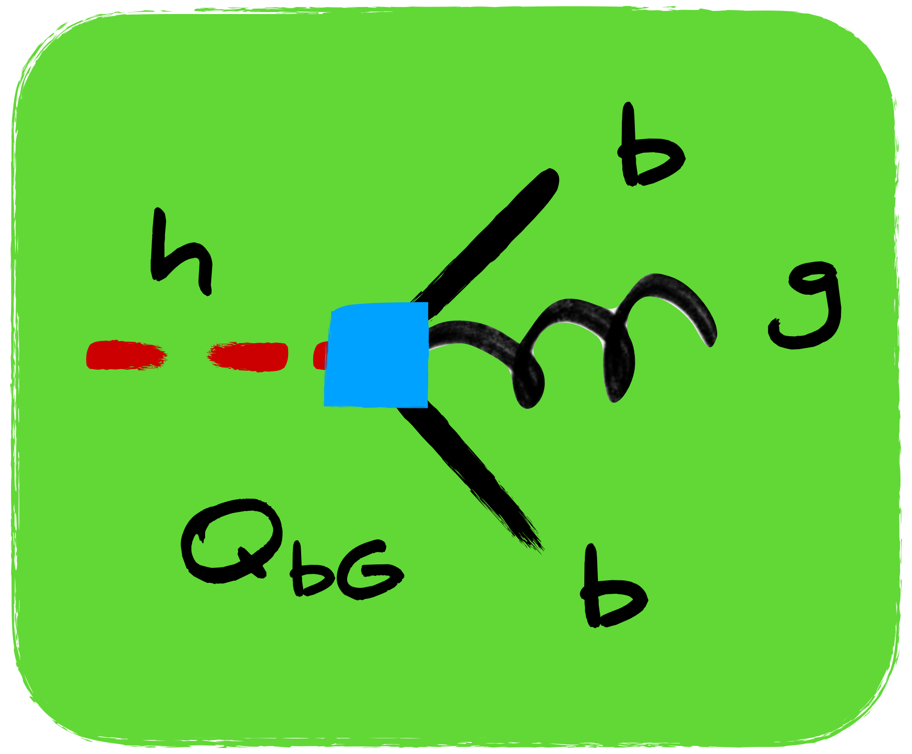


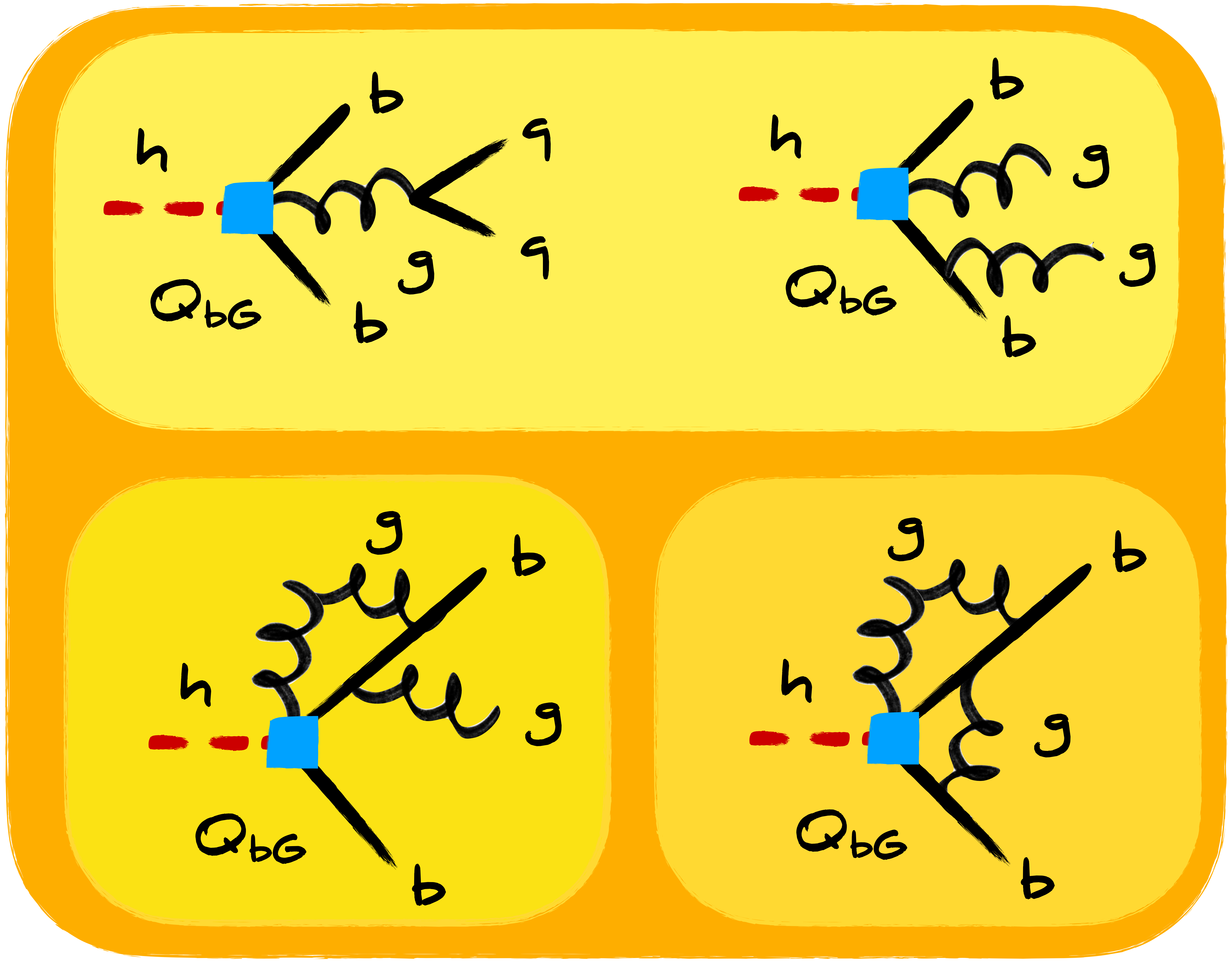
leading contribution from interference of $h \to b\bar{b}g$ amplitude in SMEFT & SM

[Gauld, Pecjak & Scott, 1607.06354]

Non-factorisable contributions

Dominant non-factorisable corrections arise from dipole operator Q_{bG}:

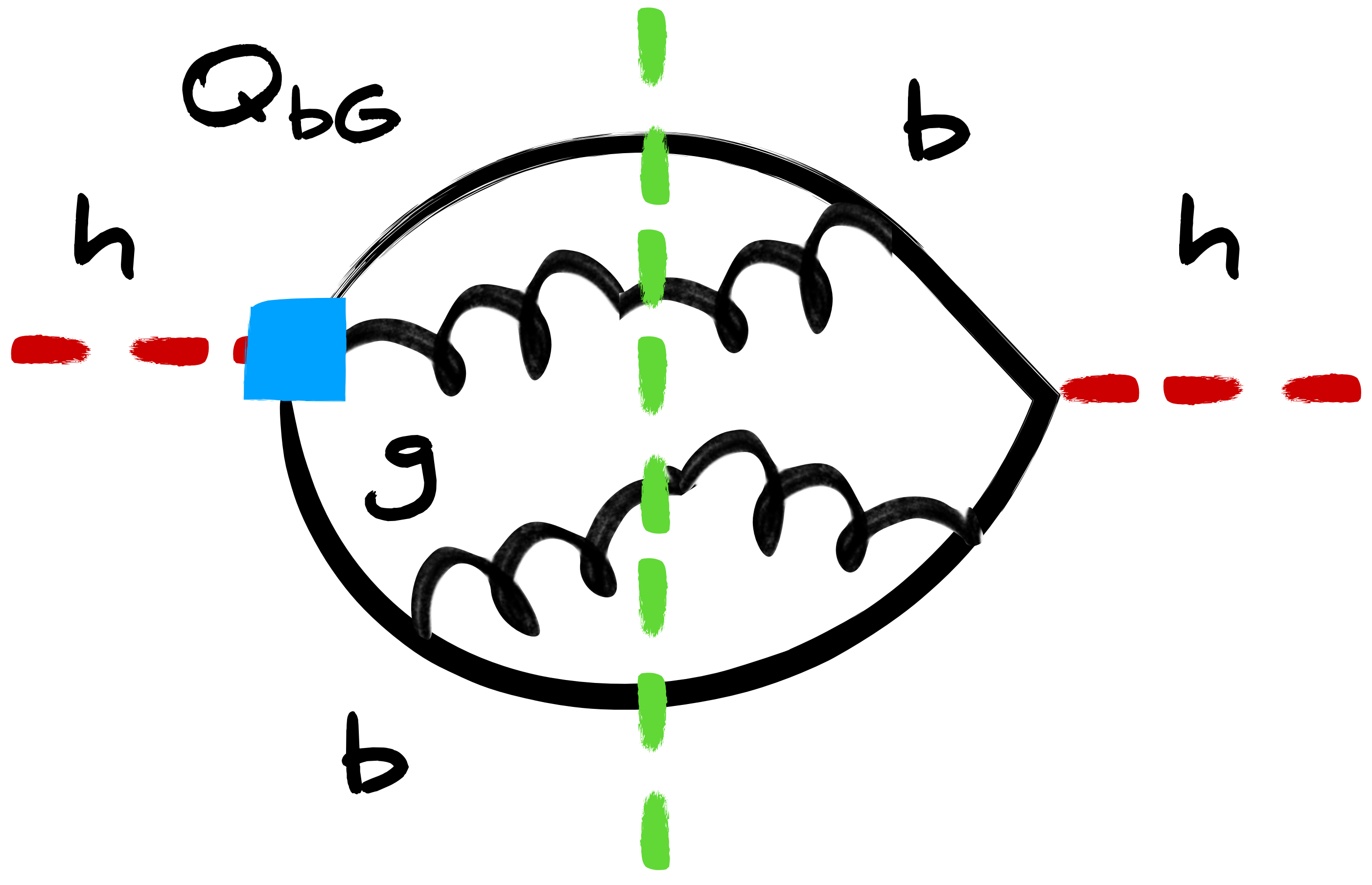




beyond leading order, double real, 1-loop single real & 2-loop virtual contributions

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Non-factorisable contributions



$$
\begin{aligned}
f_{b\bar{b}gg}(p_1,p_2,p_3,p_4) &= \frac{4y_{24}^2}{y_{23}y_{34}y_{234}} + \frac{y_{13}^2 y_{24}^2}{2y_{14}y_{23}y_{34}y_{134}y_{234}} + \frac{(10\ldots}{\ldots} \\
&+ \frac{(4y_{24}+19y_{34}-4)\,y_{24}}{y_{23}y_{134}y_{234}} + \frac{(4y_{14}(y_{23}+2)+y_{13}(12y_{24}+7))\ldots}{2y_{34}y_{134}y_{234}\ldots} \\
&- \frac{2y_{34}^2}{y_{13}y_{14}y_{134}} + \frac{y_{34}^2(y_{23}+y_{24}+y_{34}-1)}{y_{13}y_{14}y_{23}y_{134}} + \frac{y_{34}^2(y_{23}+3y_{24}+\ldots}{y_{13}y_{14}y_{134}y_{23}\ldots} \\
&+ \frac{18y_{34}+2y_{24}(4y_{13}+2y_{23}+2y_{24}+2y_{34}+19)-3}{2y_{134}y_{234}} + \frac{12y_{14}\ldots}{\ldots} \\
&+ \frac{2y_{14}y_{24}(2y_{24}+3y_{34}-1)+y_{34}(3y_{34}^2+(9y_{24}-2)\,y_{34}+4(\ldots}{y_{13}y_{23}y_{134}y_{234}\ldots}
\end{aligned}
$$

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Non-factorisable contributions

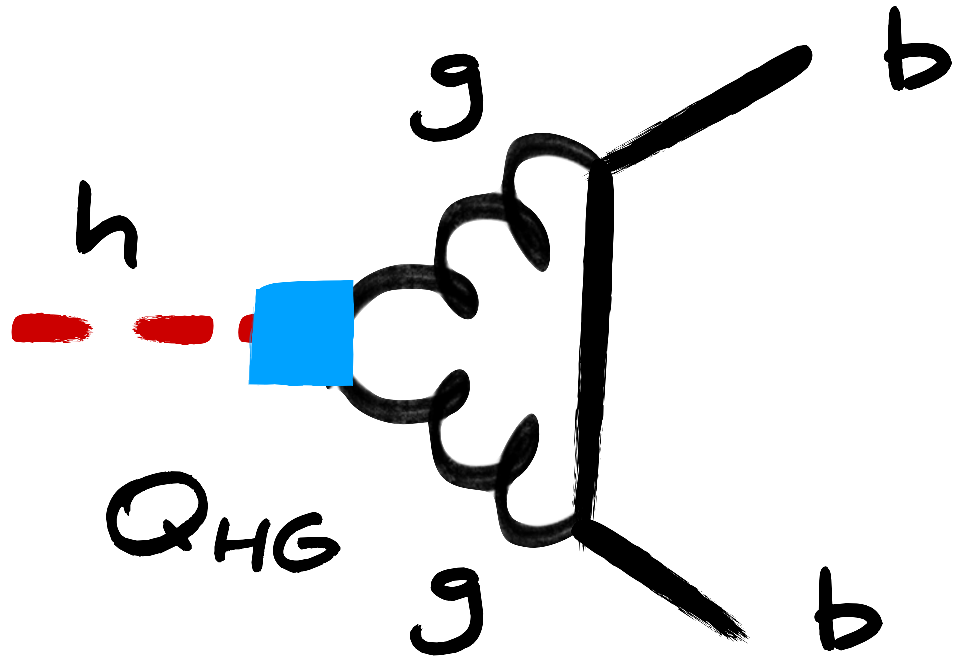
Q_{bG} corrections implemented into POWHEG-BOX. Possible to obtain realistic exclusive description of $pp \to Zh \to l^+l^-b\bar{b}$ production with NNLO accuracy using MiNLO′ & $\text{MiNNLO}_{\text{PS}}$ methods. Applying code to Higgs decay leads to:

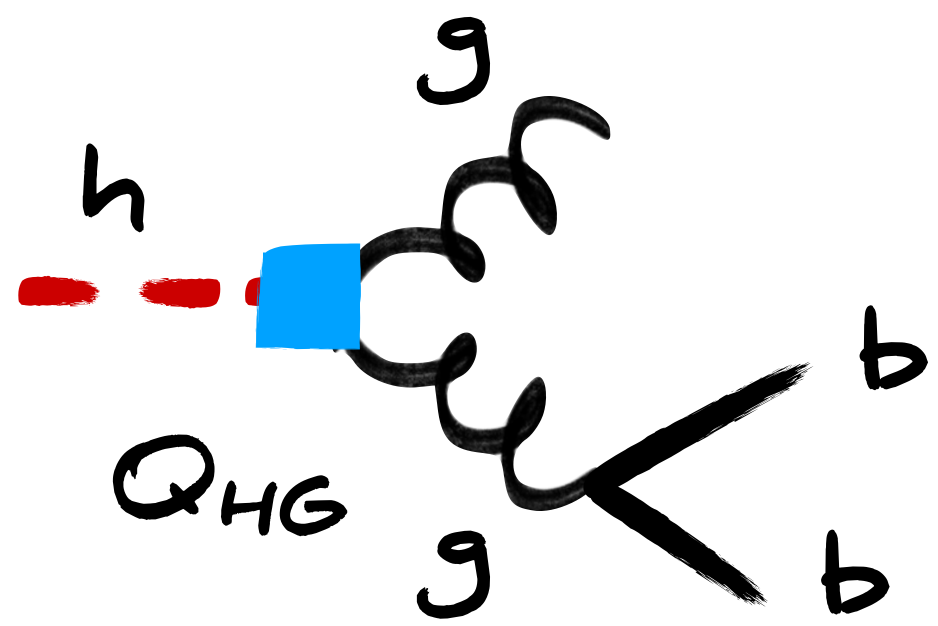
$$\Gamma(h \to b\bar{b})^{\text{non}}_{\text{SMEFT}} = \frac{3y_b^2 m_h}{16\pi} \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{3v^2} \left[1 + \frac{\alpha_s}{\pi} 17.32\right] \frac{v^2}{\Lambda^2} \text{Re}\left(C_{bG}\right)$$

new term represents
a 60% correction

[see MiNNLO talks on Tuesday morning; UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Contributions from Q_{HG}





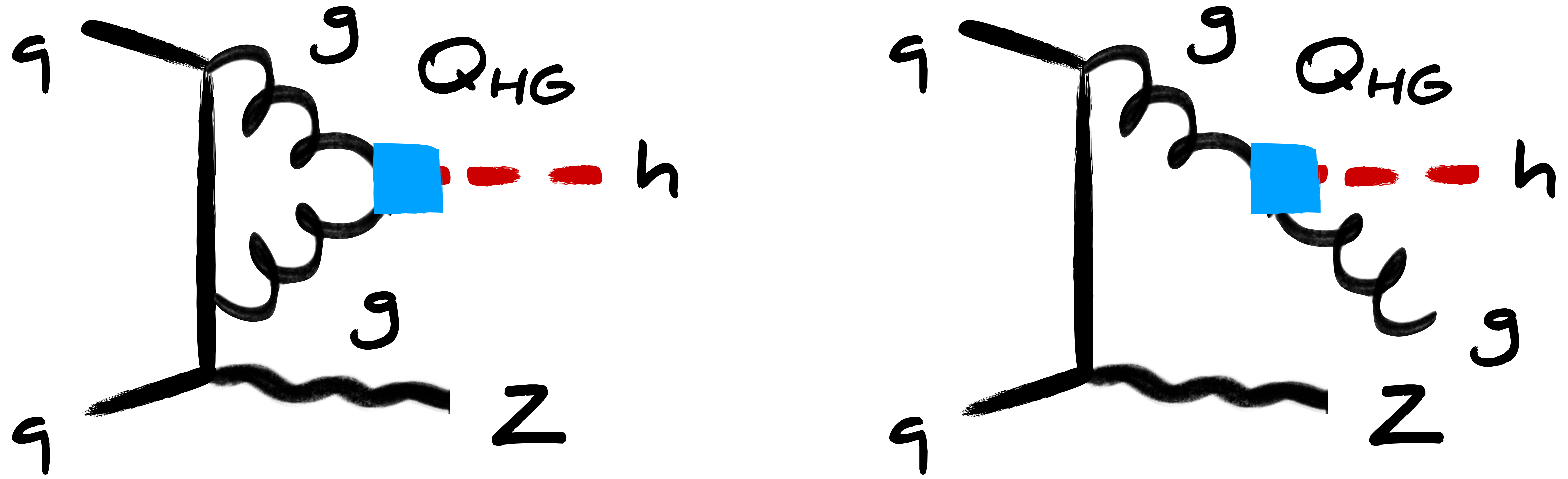
$$c_{HG} = \frac{v^2}{\Lambda^2} C_{HG} \in [-0.09, 0.06]$$

[Ellis et al., 2012.02779]

$$\frac{\Gamma(h \to b\bar{b})^{HG}_{\rm SMEFT}}{\Gamma(h \to b\bar{b})^{\rm LO}_{\rm SM}} = \left(\frac{\alpha_s}{\pi}\right)^2 \left[\frac{19}{3} - 2\zeta_2 + \frac{1}{3}\ln^2\left(\frac{m_b^2}{m_h^2}\right)\right] c_{HG} \in [-2.7, 1.7] \cdot 10^{-3}$$

[Gauld, Pecjak & Scott, 1607.06354; UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Contributions from Q_{HG}



$$c_{HG} = \frac{v^2}{\Lambda^2} C_{HG} \in [-0.09, 0.06]$$

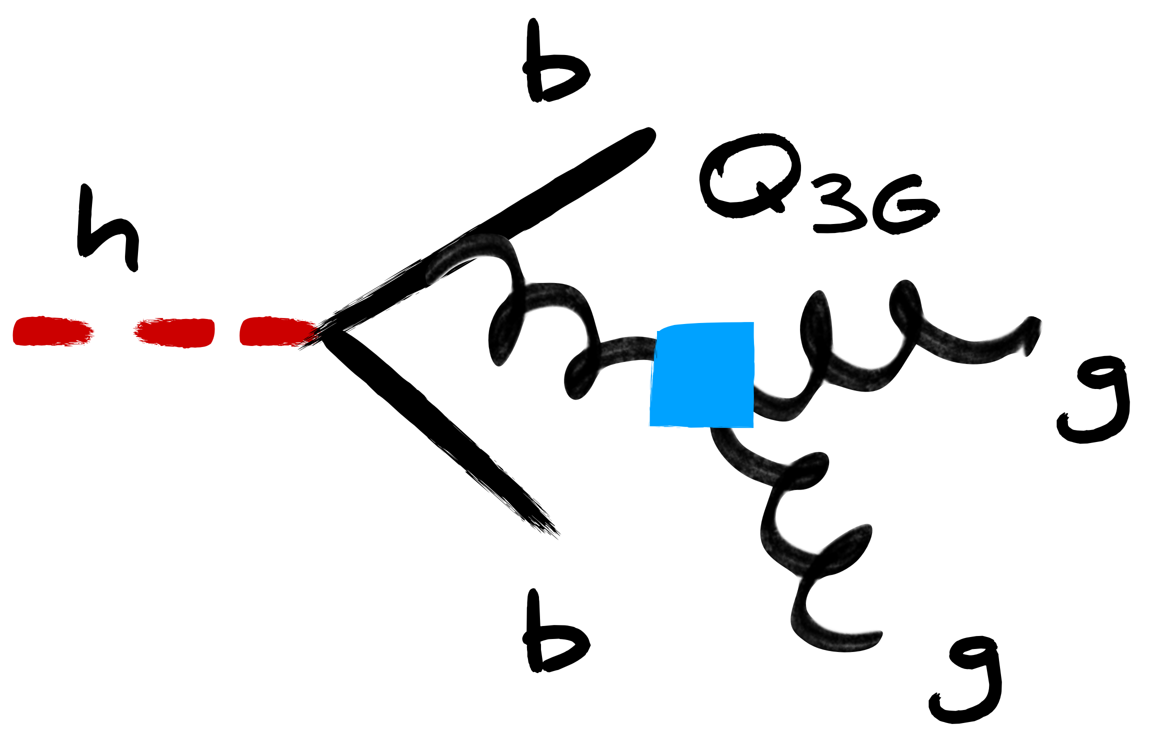
[Ellis et al., 2012.02779]

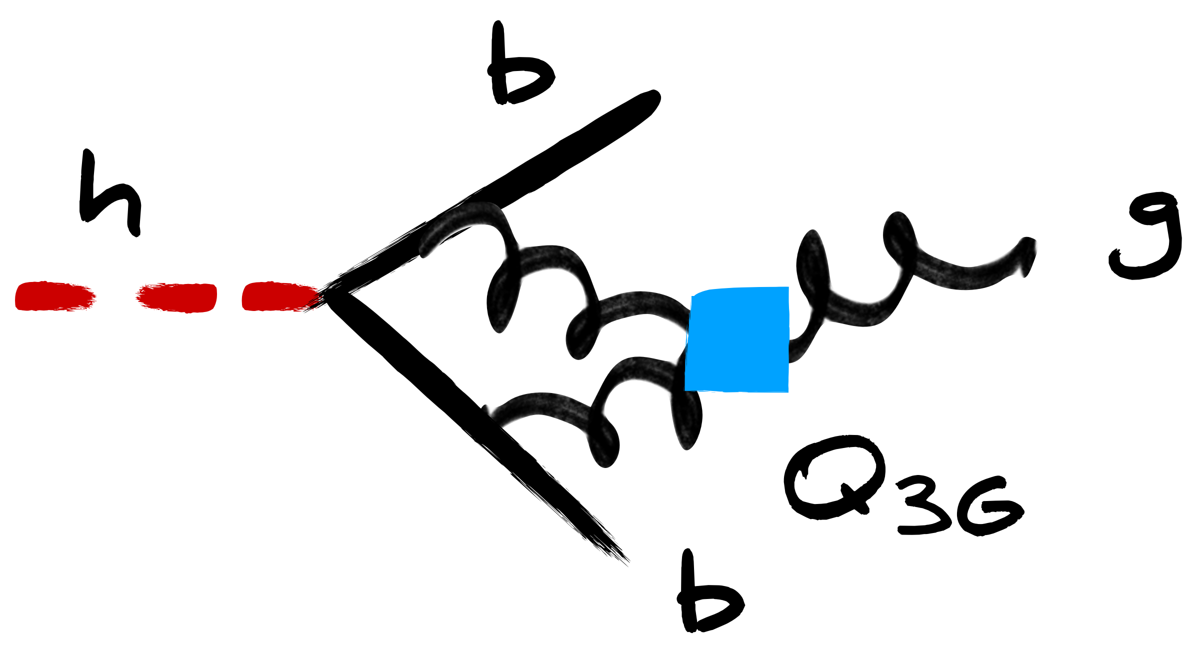
$$\frac{\sigma(pp \to hZ)^{HG}_{\rm SMEFT}}{\sigma(pp \to hZ)^{\rm LO}_{\rm SM}} = 3 \left(\frac{\alpha_s}{\pi}\right)^2 \delta \, c_{HG} \in [-3.9, 2.4] \cdot 10^{-3}$$

numerically, one has δ = 10.7

[Brein, Harlander, Wiesemann & Zirke, 1111.0761; UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Contributions from Q_{3G}





$$c_{3G} = \frac{v^2}{\Lambda^2} C_{3G} \in [-12.5, -4.1]$$

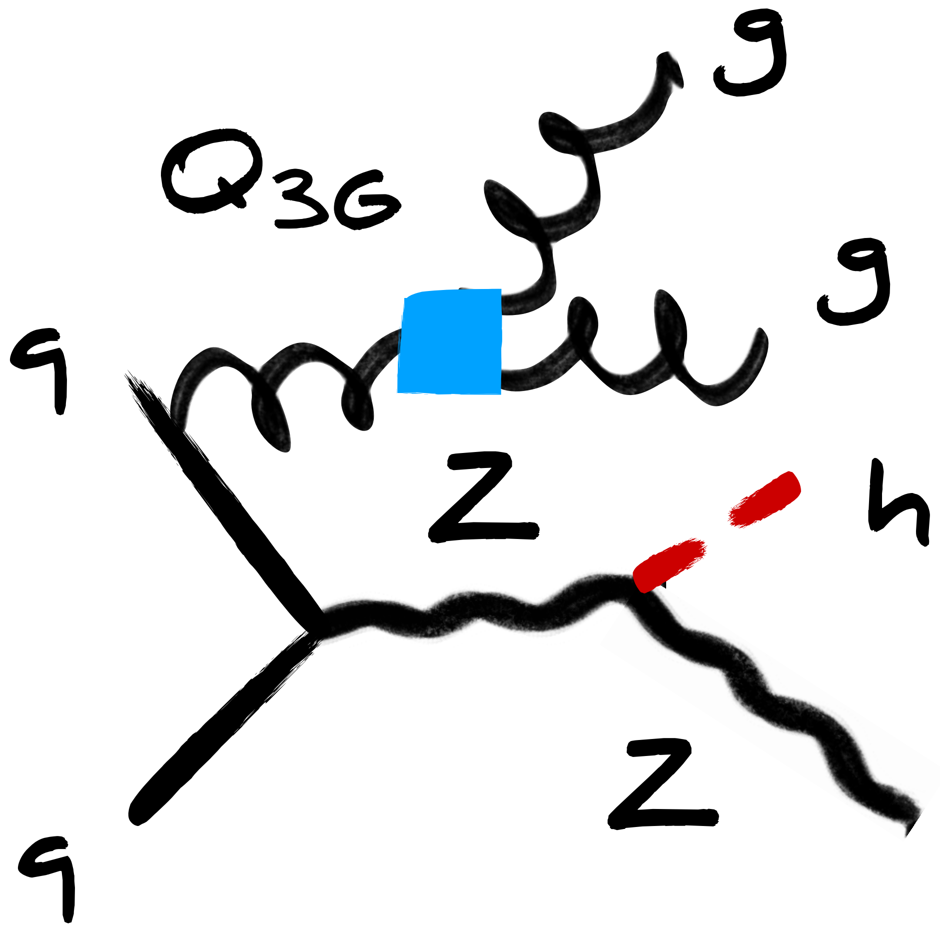
[Ellis et al., 2012.02779]

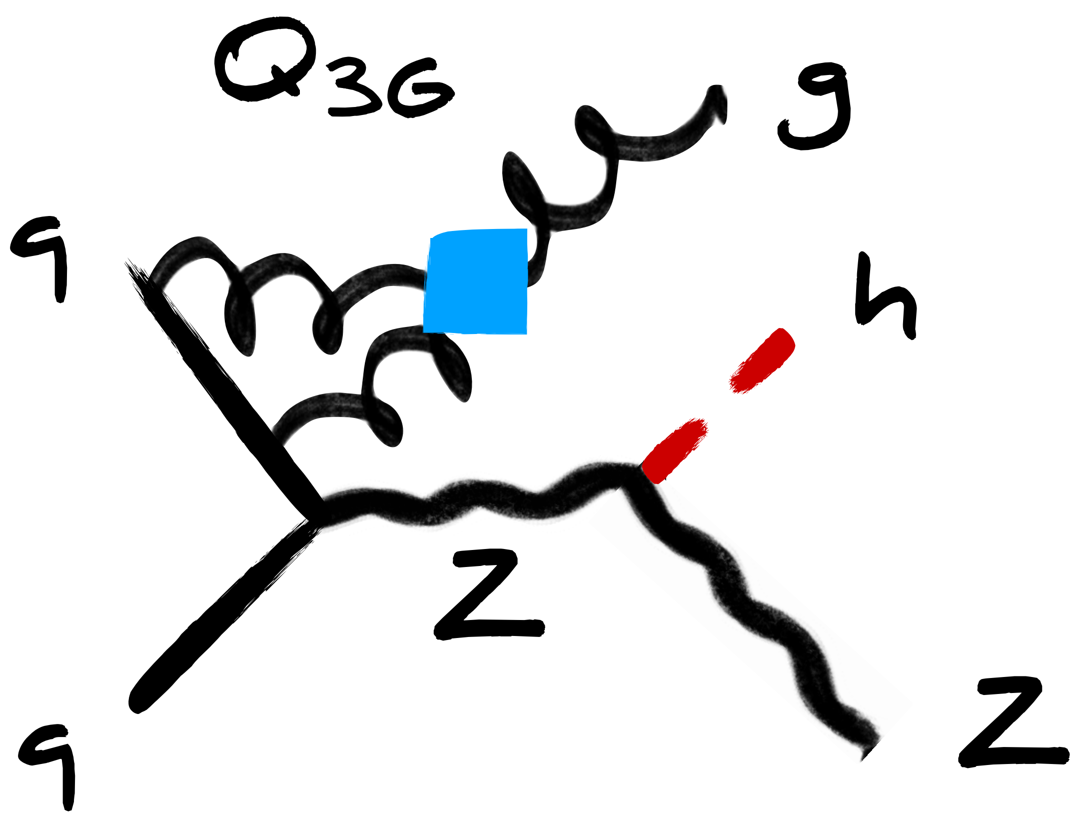
$$\frac{\Gamma(h \to b\bar{b})^{3G}_{\rm SMEFT}}{\Gamma(h \to b\bar{b})^{\rm LO}_{\rm SM}} = N^{\rm dec}_{3G} \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{v^2} c_{3G} \in [-0.3, -0.1] \cdot 10^{-3}$$

explicit calculation gives $N^{\rm dec}_{3G} = 2.23$

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Contributions from Q_{3G}





$$c_{3G} = \frac{v^2}{\Lambda^2} C_{3G} \in [-12.5, -4.1]$$

[Ellis et al., 2012.02779]

$$\frac{\sigma(pp \to hZ)^{3G}_{\rm SMEFT}}{\sigma(pp \to hZ)^{\rm LO}_{\rm SM}} = N^{\rm prod}_{3G} \left(\frac{\alpha_s}{\pi}\right)^3 c_{3G} \in [-5.8, -1.9] \cdot 10^{-3}$$

quoted number corresponds to $N^{\rm prod}_{3G} = 10$

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Phenomenology analysis

We have seen that QCD corrections associated to operators other than $Q_{H\Box}$, Q_{HD}, Q_{bH} & Q_{bG} do not exceed level of a few permille

Maximal size of factorisable corrections to partial $h \to b\bar{b}$ decay rate can be derived from global fits of SMEFT Wilson coefficients:

$$\frac{\Gamma(h \to b\bar{b})^{\mathrm{N^3LO}}_{\mathrm{SMEFT}}}{\Gamma(h \to b\bar{b})^{\mathrm{N^3LO}}_{\mathrm{SM}}} - 1 \ \in \ [-39, 26]\% \quad \text{for} \quad c_{bH} = \frac{v^2}{\Lambda^2}\mathrm{Re}(C_{bH}) \in [-0.13, 0.20]$$

[Ellis et al., 2012.02779]

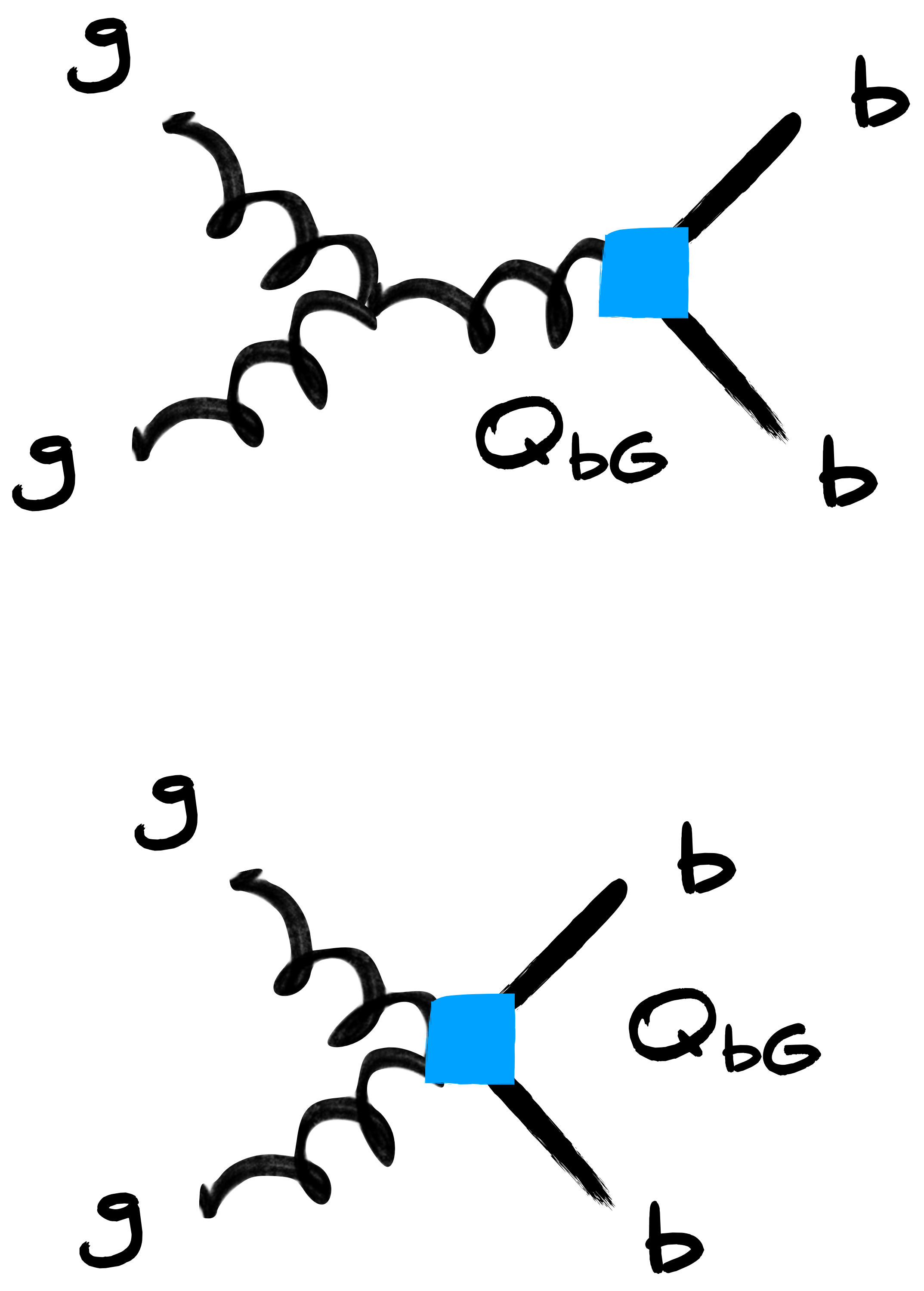
Interlude: bounds on dipole operator Q_{bG}

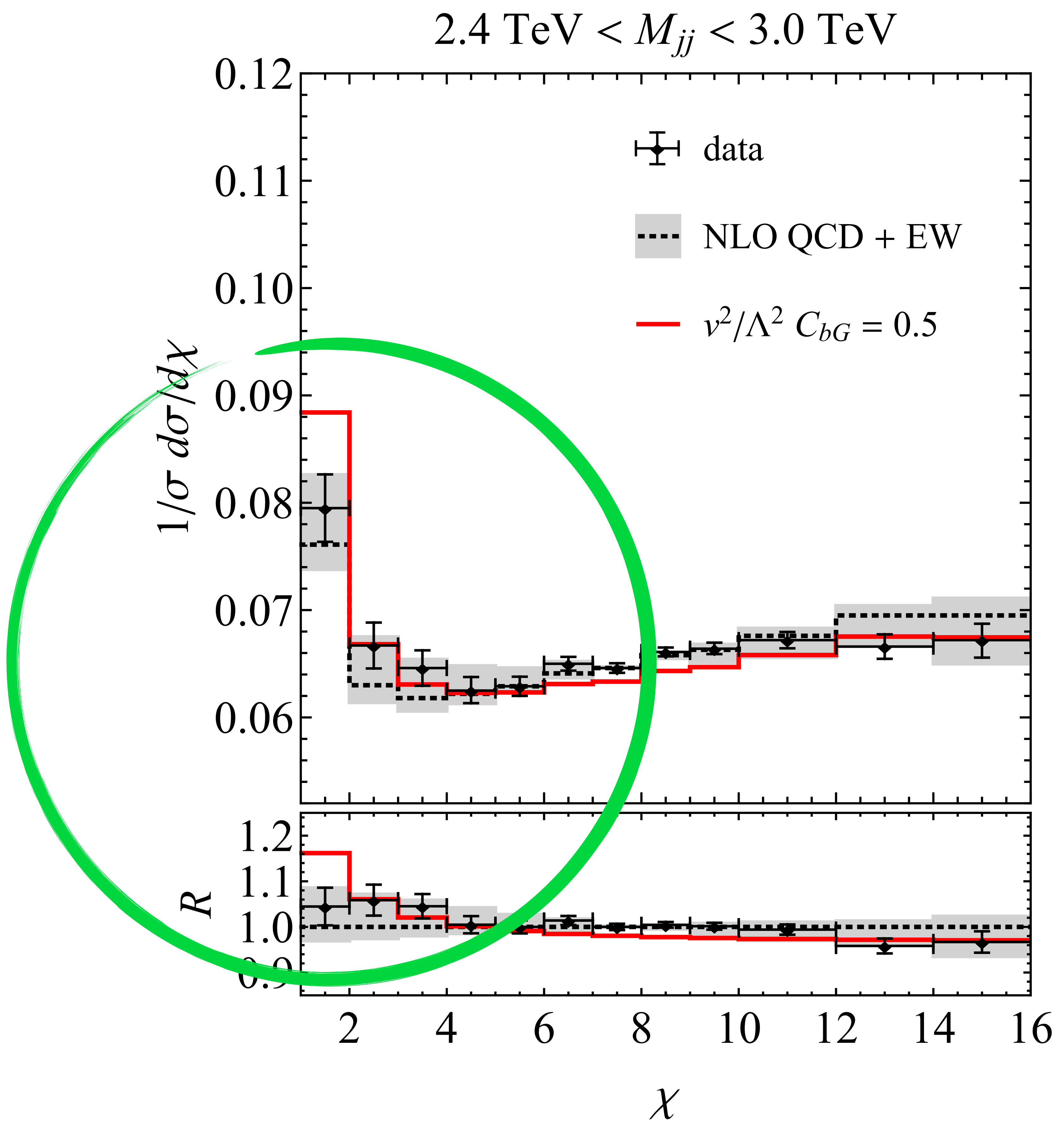
Observable	Wilson coefficient	95% CL bound
Dijet angular distributions	$\lvert c_{bG} \rvert$	2864
Two b-tagged jets	$\lvert c_{bG} \rvert$	152
Z-boson production with two b-jets	$\lvert c_{bG} \rvert$	438
Searches for neutron electric dipole moment	$\lvert \mathrm{Im}\left(c_{bG}\right) \rvert$	0.05

Due to chirality-flipping nature of Q_{bG} no interference between SMEFT & SM amplitudes for $m_b = 0$. Resulting LHC bounds on $|c_{bG}|$ thus very weak. $|\mathrm{Im}(c_{bG})|$ instead severely constrained by neutron electric dipole moment

[UH & Koole, 2106.01289]

Bounds on dipole-type operator Q_{bG}

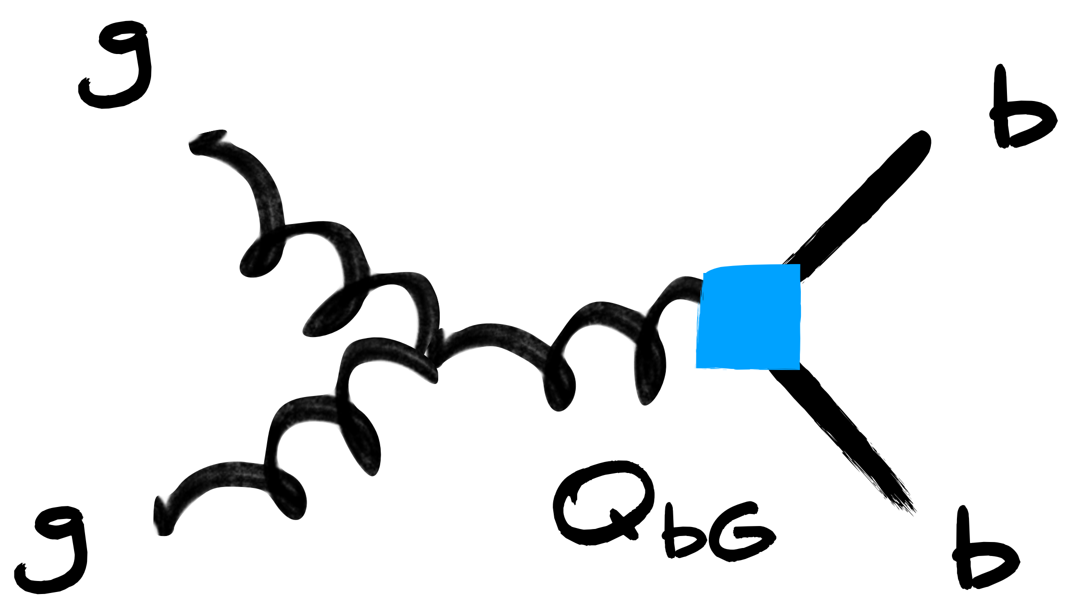


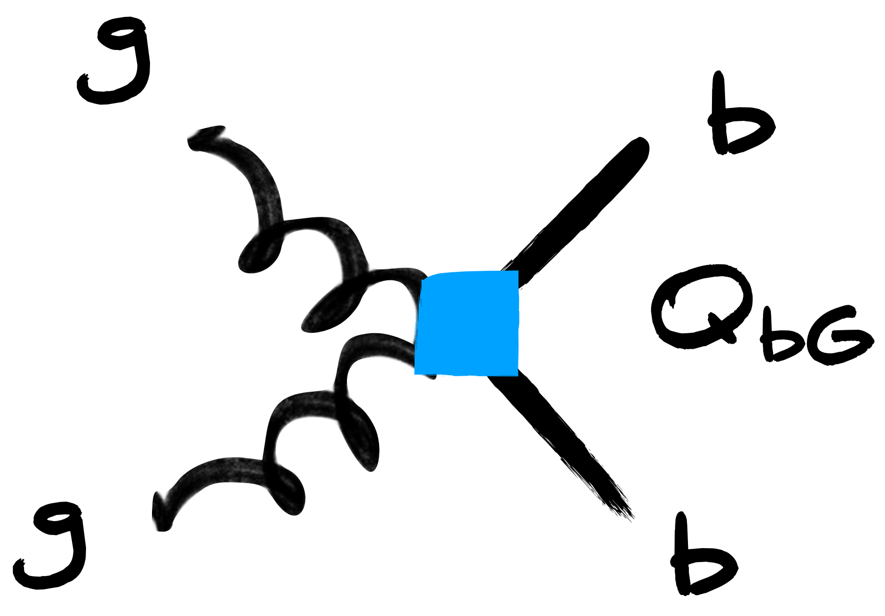


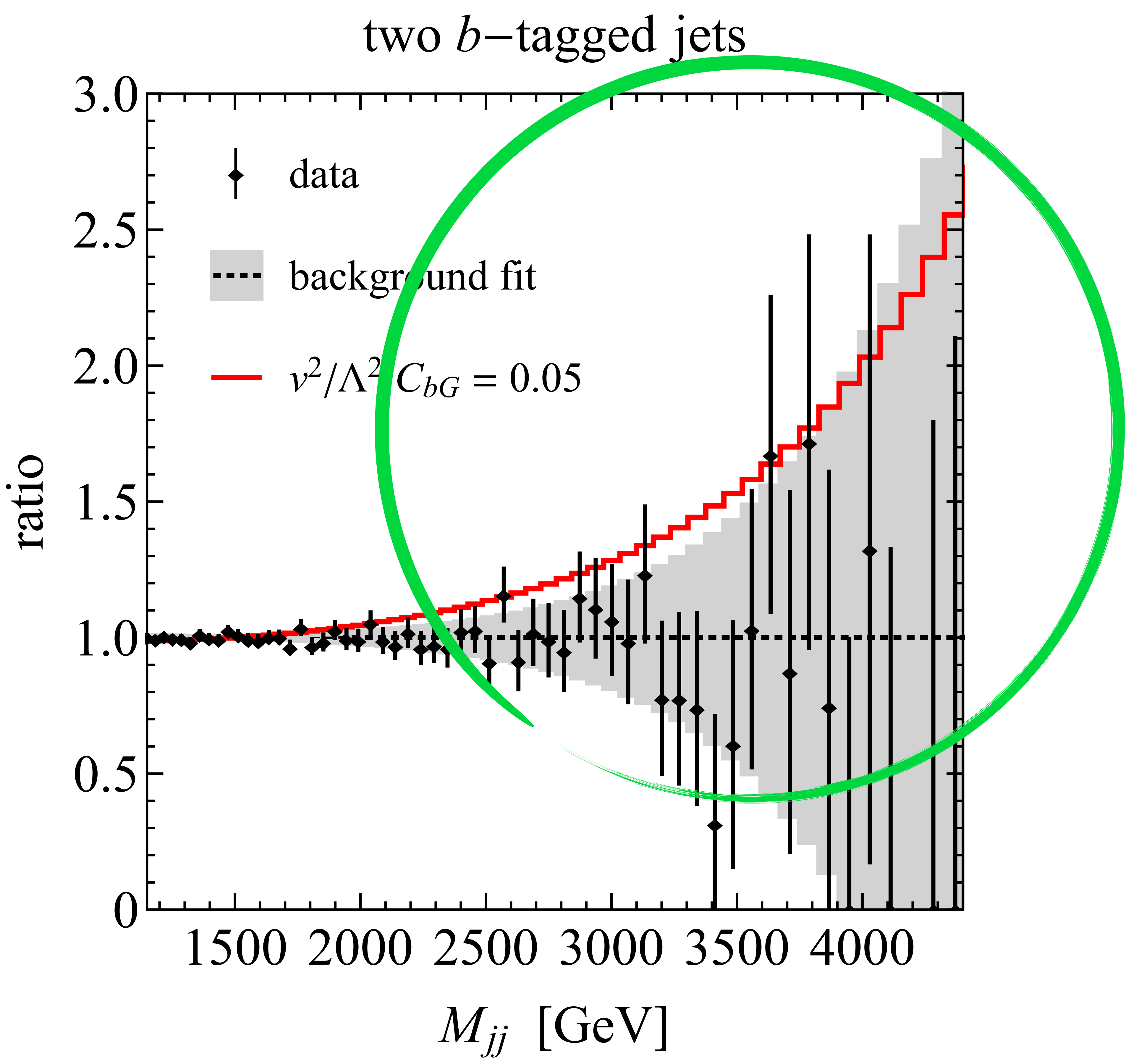
Q_{bG} contributions lead to an enhanced activity of high-energy jets in central region

[UH & Koole, 2106.01289]

Bounds on dipole-type operator Q_{bG}



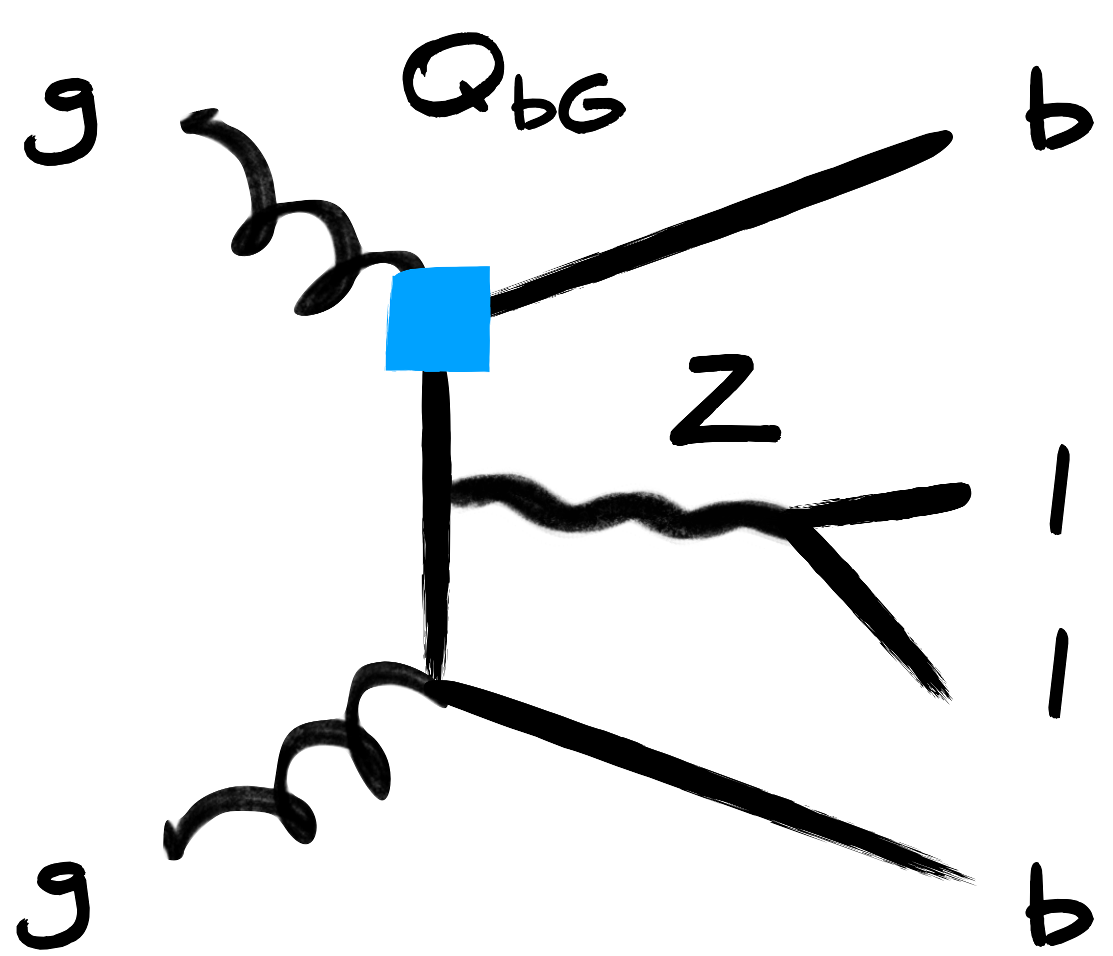


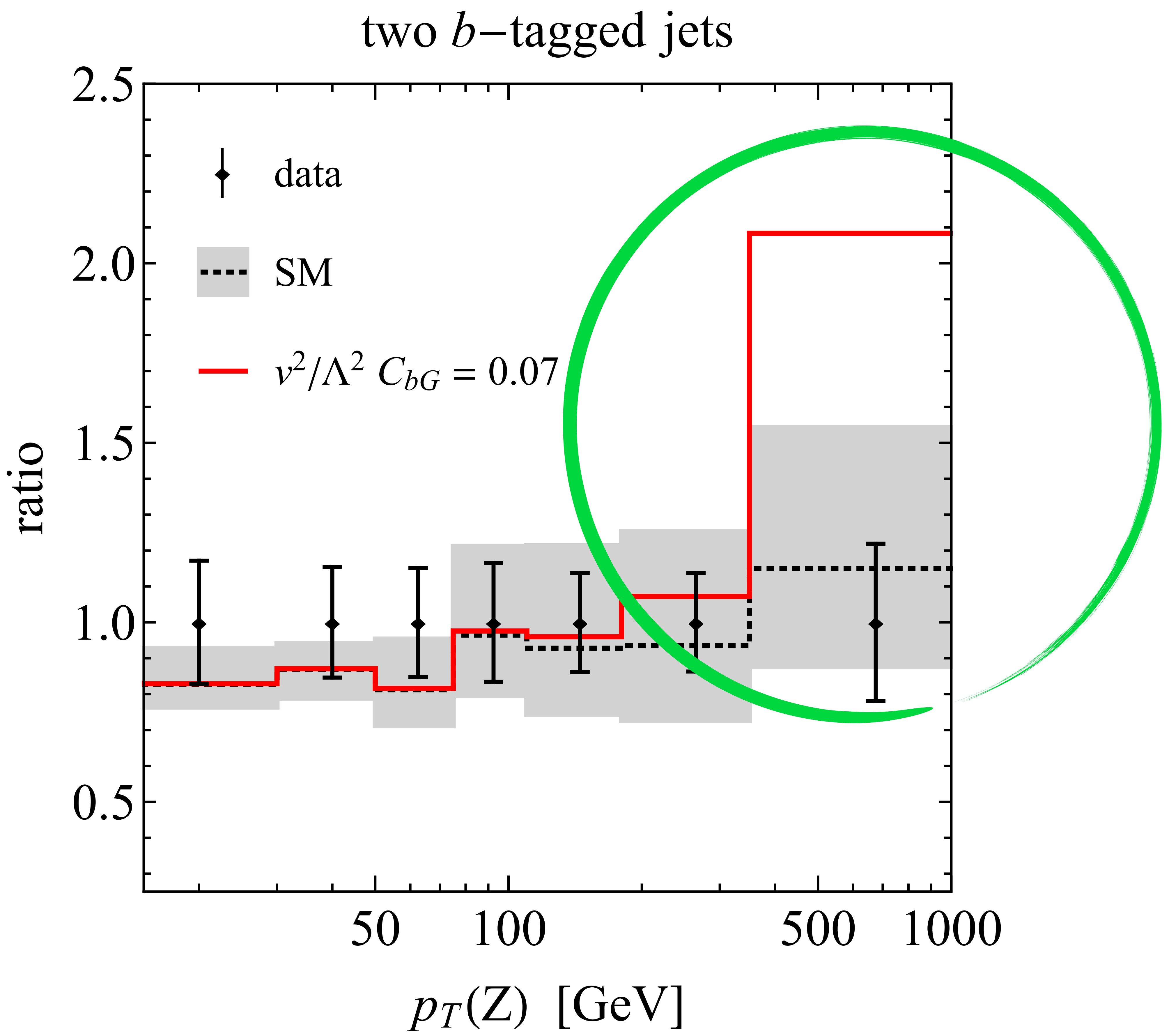


Q_{bG} contributions lead to an enhancement of rate for high dijet invariant masses

[UH & Koole, 2106.01289]

Bounds on dipole-type operator Q_{bG}





Q_{bG} effects grow with transverse momentum & lead to more events at high p_T(Z)

[UH & Koole, 2106.01289]

Phenomenology analysis

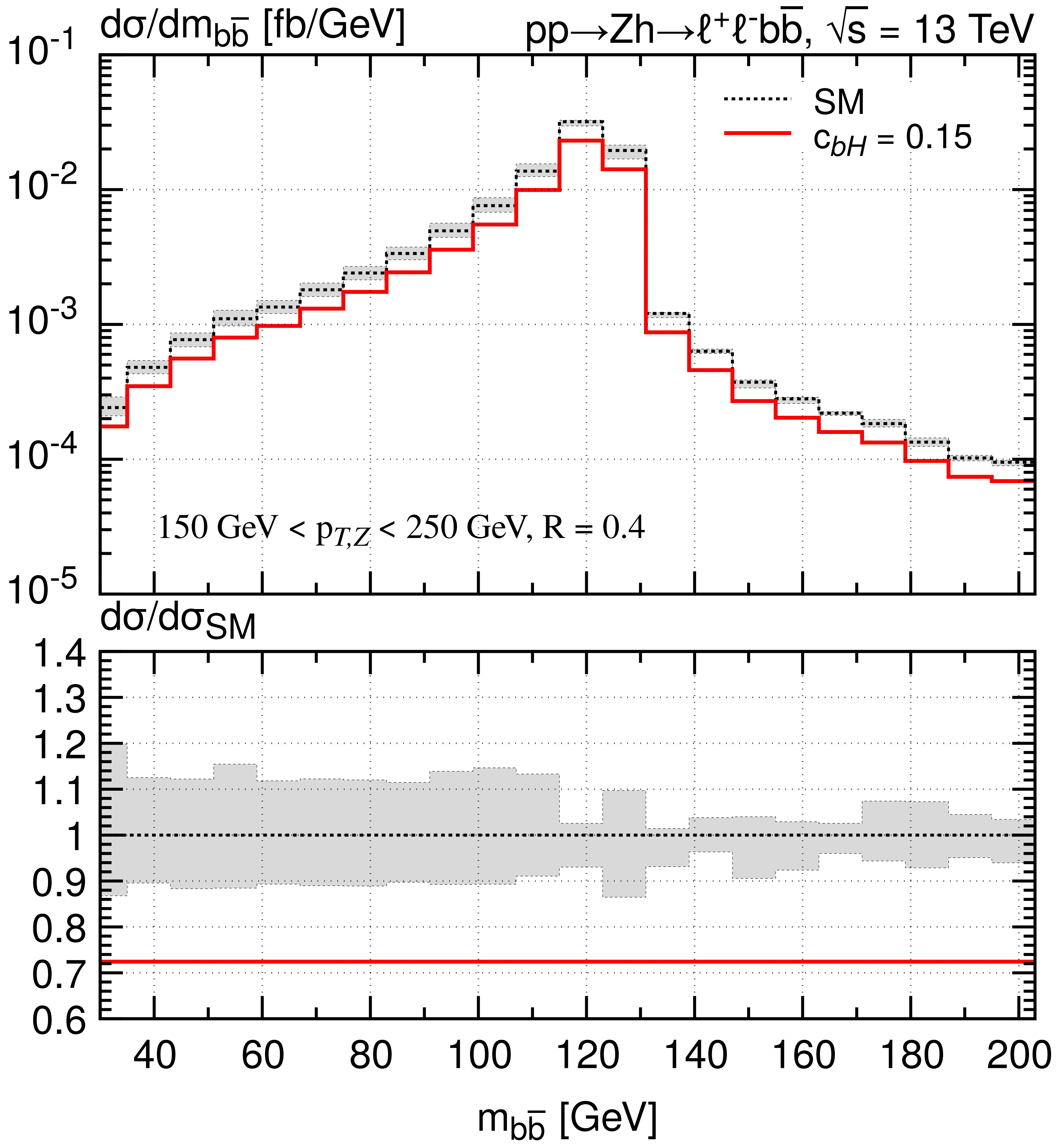
Despite large Wilson coefficient of Q_{bG} possible size of non-factorisable contributions to partial $h \to b\bar{b}$ decay rate smaller than that of factorisable ones by a factor of O(5):

$$\frac{\Gamma(h \to b\bar{b})^{\mathrm{N^3LO}}_{\mathrm{SMEFT}}}{\Gamma(h \to b\bar{b})^{\mathrm{N^3LO}}_{\mathrm{SM}}} - 1 \in [-6.3, 6.3]\% \text{ for } c_{bG} = \frac{v^2}{\Lambda^2}\mathrm{Re}(C_{bG}) \in [-438, 438]$$

But non-factorisable contributions lead to non-trivial modifications of spectra in $pp \to Zh \to l^+l^-b\bar{b}$ production

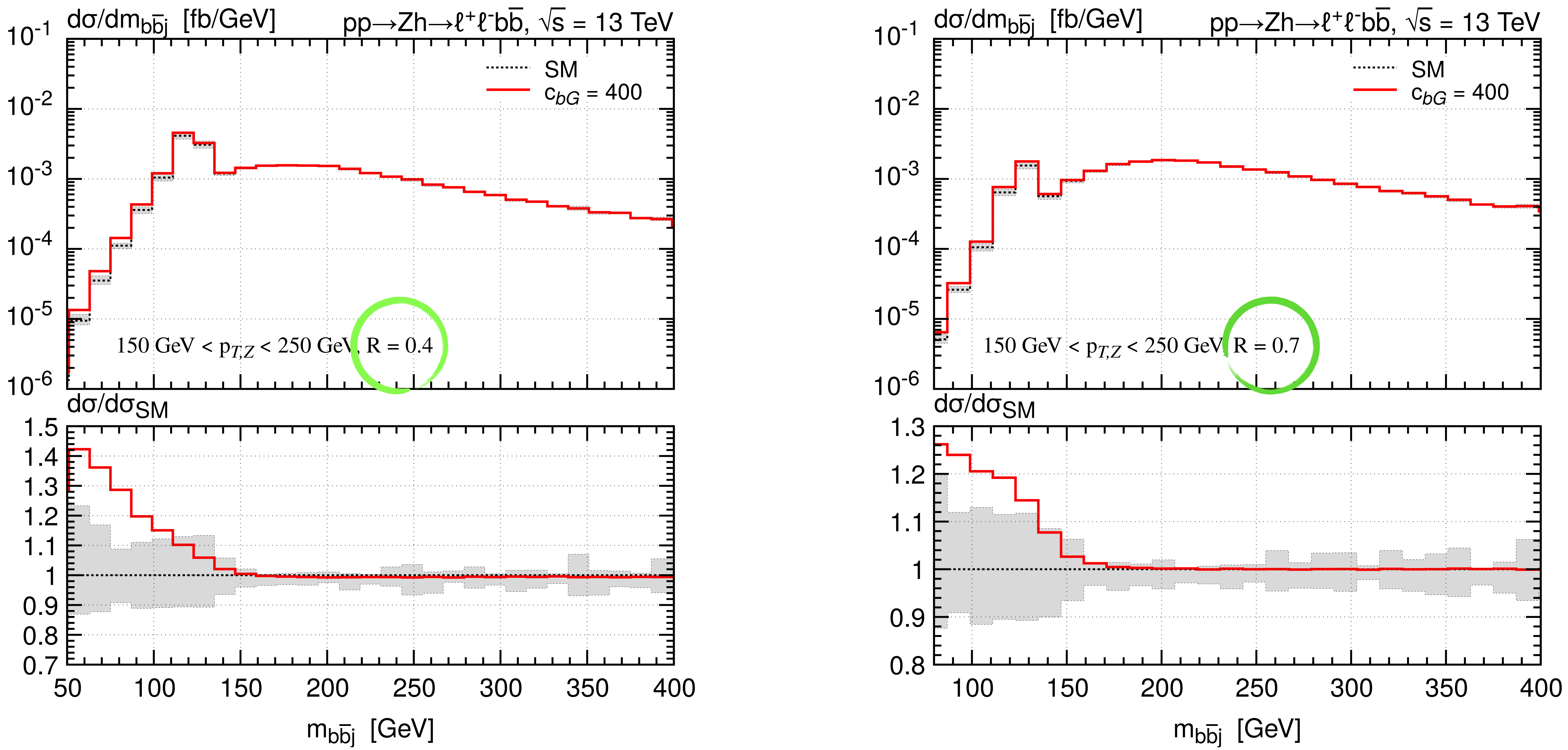
Phenomenology analysis

factorisable contributions just lead to a constant shift, i.e. a K-factor, in all pp → Zh → $l^+l^-b\bar{b}$ distributions



[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Phenomenology analysis



Also 3-jet invariant mass reduced on average. Effects again R-dependent

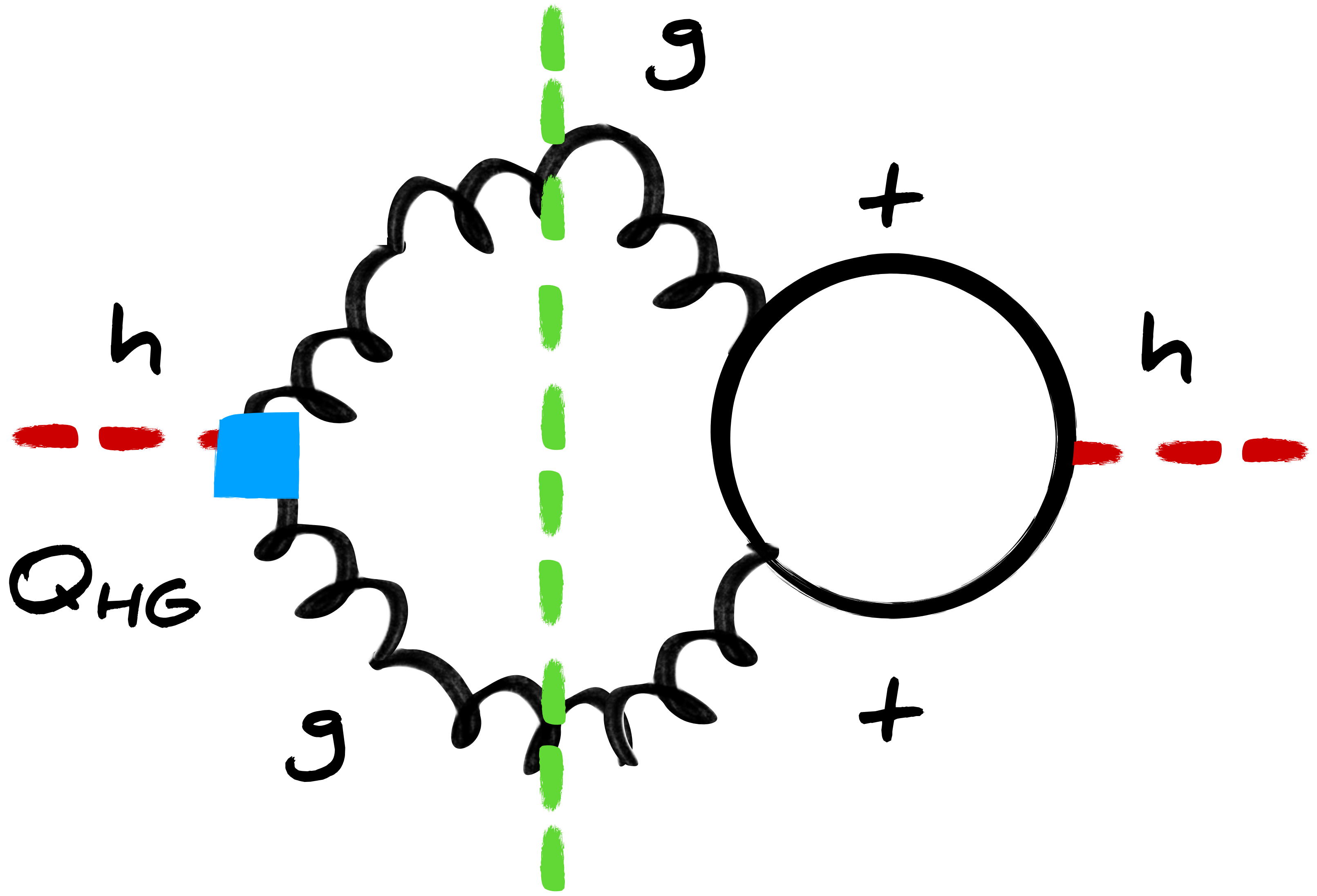
[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

SMEFT corrections to total Higgs width

$$\Gamma_h^{\mathrm{SMEFT}} = (1 + 2c_{\mathrm{kin}}) \Big[\Gamma_h^{\mathrm{SM}} - (2\Delta c_{bH} - K_{bG}\,\Delta_{\mathrm{non}}\,c_{bG})\,\Gamma(h \to b\bar{b})^{\mathrm{LO}}_{\mathrm{SM}}$$

$$+ 6\,K_{HG}\,c_{HG}\,\Gamma(h \to gg)^{\mathrm{LO}}_{\mathrm{SM}} \Big]$$

$$K_{HG} = 1.844$$



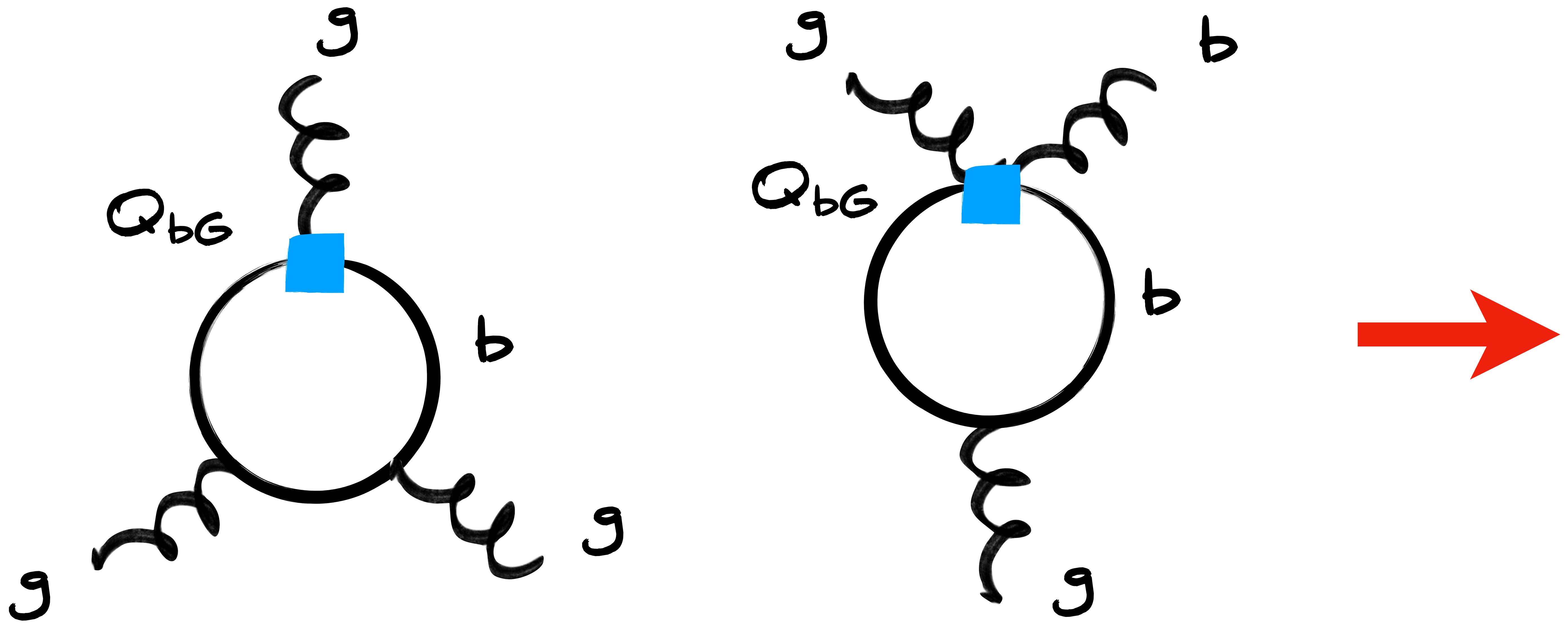
[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Event selections

In our differential analysis we select events with two charged leptons (electrons or muons) to explore the $Zh \to \ell^+\ell^- b\bar{b}$ signature. The leptons are required to have a transverse momentum of $p_{T,\ell} > 15\,\text{GeV}$ and a pseudorapidity of $|\eta_\ell| < 2.5$. The invariant mass of the dilepton pair is restricted to $m_{\ell^+\ell^-} \in [75, 105]\,\text{GeV}$. The events are furthermore required to have at least two b-jets, which are reconstructed using the anti-k_t algorithm [65] as implemented in `FastJet` [66]. We impose transverse momentum cuts of $p_{T,b} > 25\,\text{GeV}$ and a rapidity threshold of $|\eta_b| < 2.5$ on the b-jets. The definition of potential additional jets use the same thresholds as those of the b-jets. The dominant background processes are $Z+$jets, $t\bar{t}$, single-top and diboson production. The latter three types of backgrounds can be substantially reduced by requiring large values of $p_{T,Z}$ [67]. Hence, to improve the signal-to-background ratio we impose $p_{T,Z} \in [150, 250]\,\text{GeV}$. Notice that this $p_{T,Z}$ requirement corresponds to the second resolved $p_{T,Z}$ bin as recommended in the stage 1.2 simplified template cross sections (STXS) framework [68–70] which is also implemented in the latest ATLAS LHC Run II measurements of the $pp \to Zh \to \ell^+\ell^- b\bar{b}$ process [71, 72]. We will also comment on how our results are modified if the other two resolved regions, i.e. $p_{T,Z} \in [75, 150]\,\text{GeV}$ and $p_{T,Z} > 250\,\text{GeV}$, are considered.

[UH, Scott, Wiesemann, Zanderighi & Zanoli, 2204.00663]

Bounds on dipole-type operator Q_{bG}



$$f^{abc}\, G^{a}_{\mu\sigma}\, G^{b,\sigma}_{\nu}\, \widetilde{G}^{c,\mu\nu}$$

1-loop threshold corrections involving Q_{bG} generate CP-violating Weinberg operator.

This operator leads to a non-zero neutron electric dipole moment at hadronic scale

[UH & Koole, 2106.01289]