Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

SFB 1258 Neutrinos Dark Matter Messengers

Technische Universität München

Associated Higgs Production at NNLO+PS with SMEFT contributions

Luc Schnell

IMPRS Colloquium
July 13, 2023

Source Image: amazon.de (no product placement).

1. Introduction

1.1 Associated Higgs Production (Vh)

1.2 Theoretical Predictions

1.3 SMEFT

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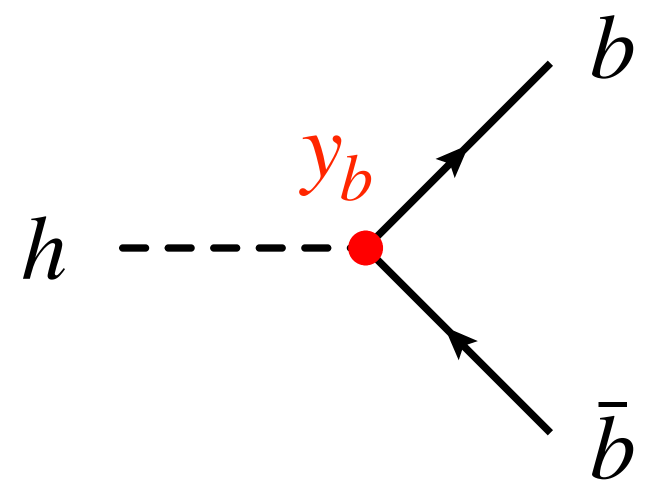
- **Goal:** 

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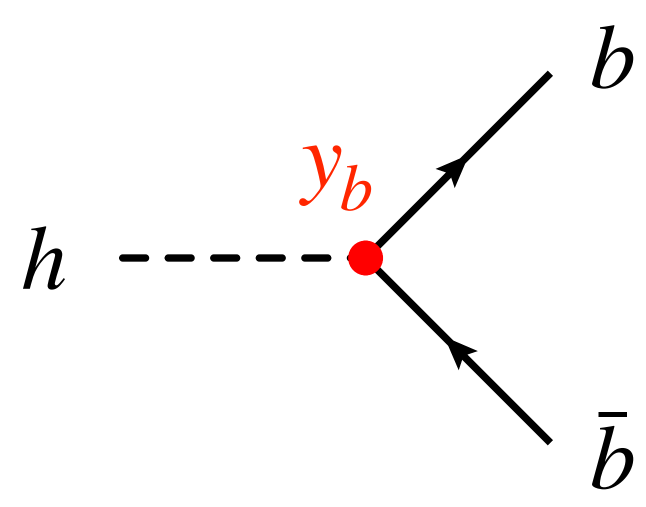

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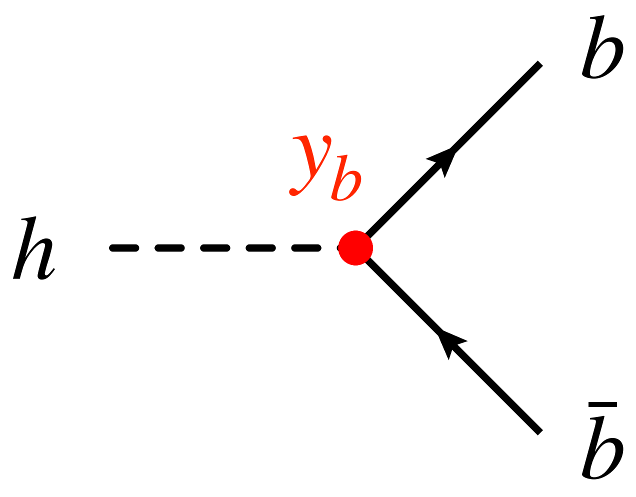

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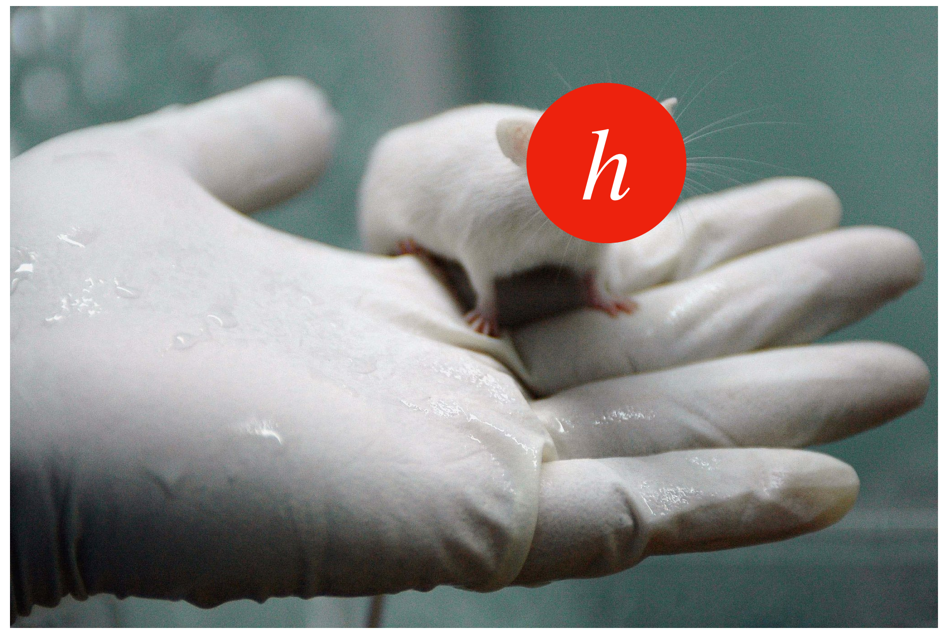

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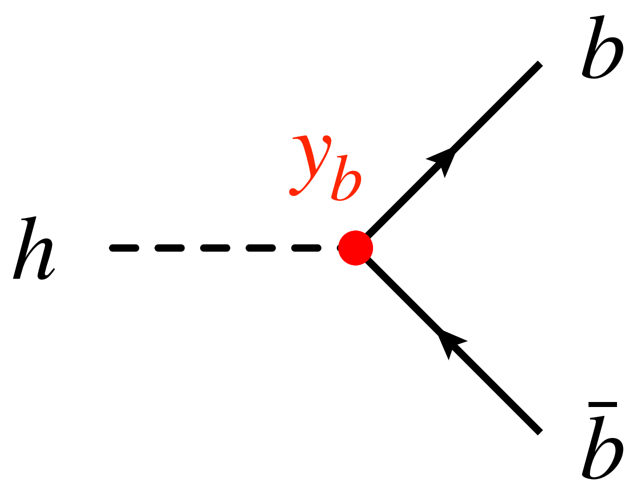
- **Goal:** 

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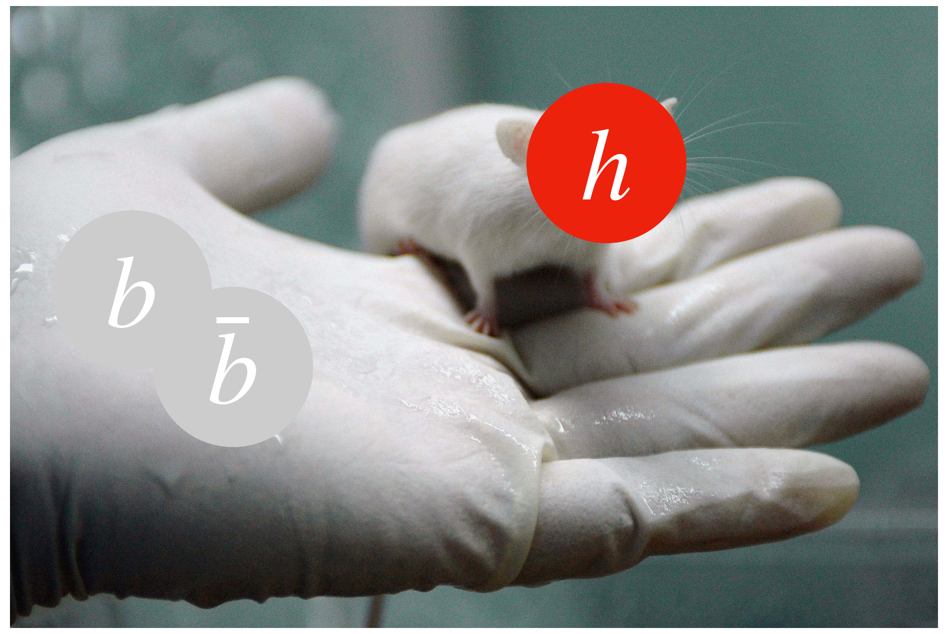

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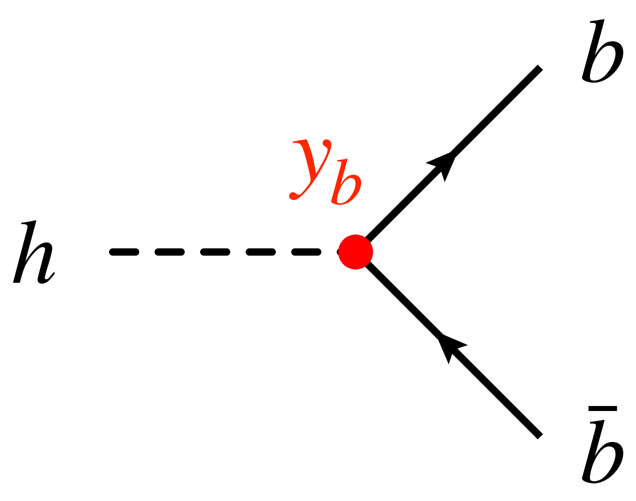
- **Goal:** 

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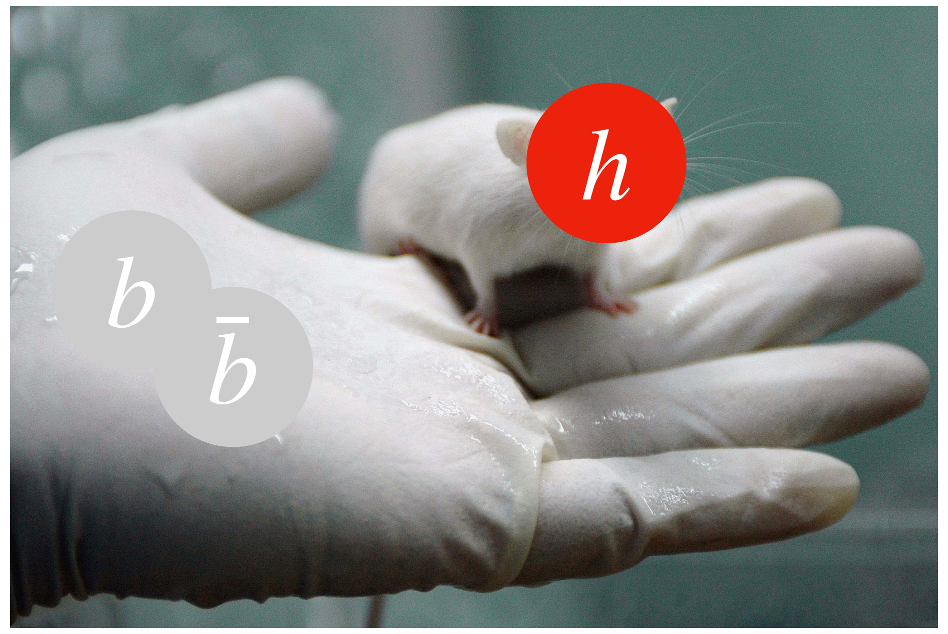

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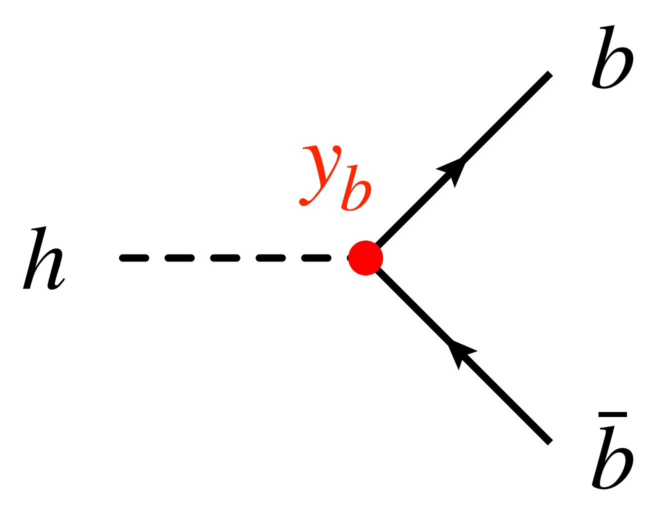

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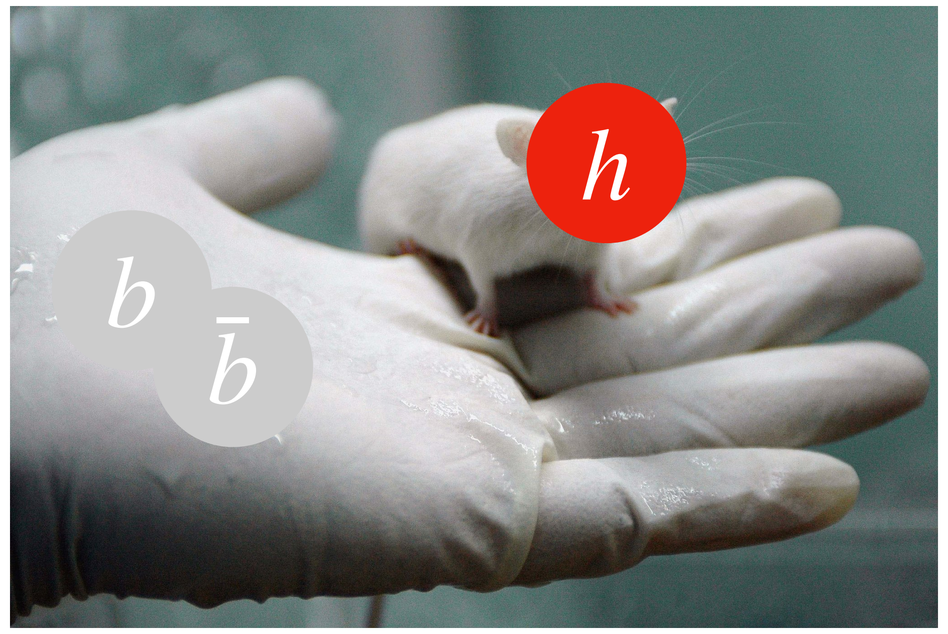

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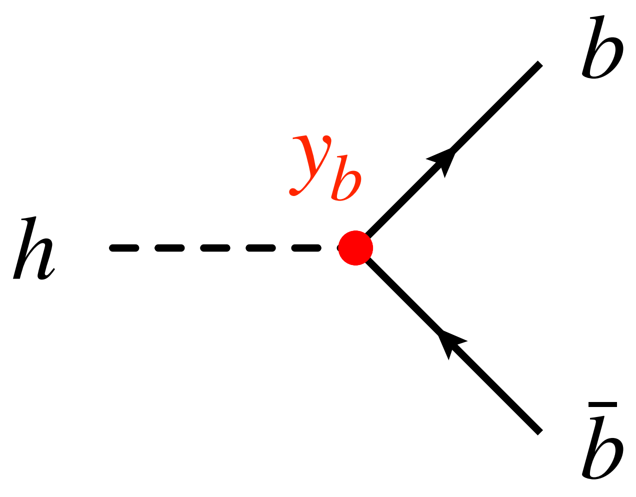
- **Goal:** 

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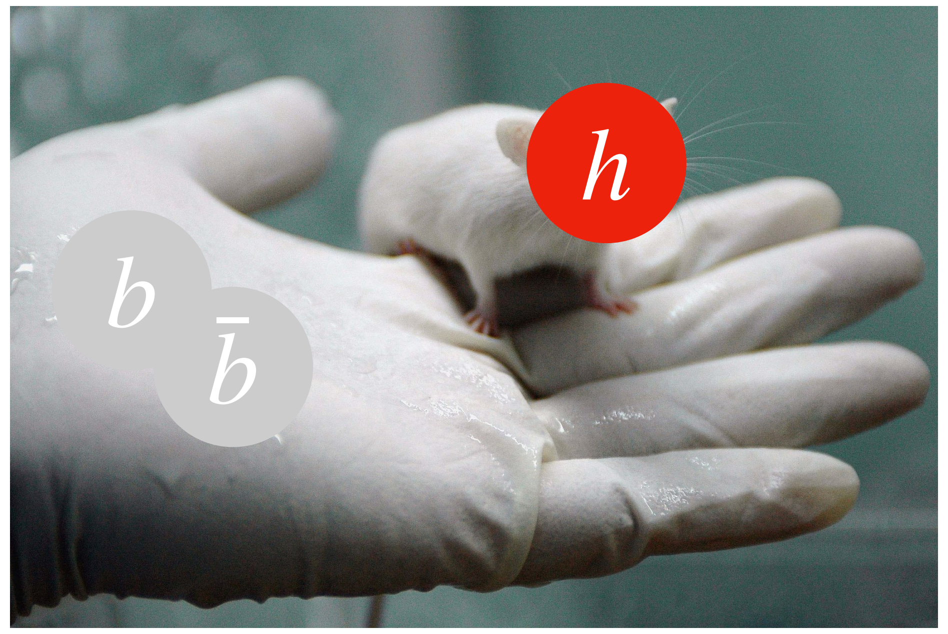

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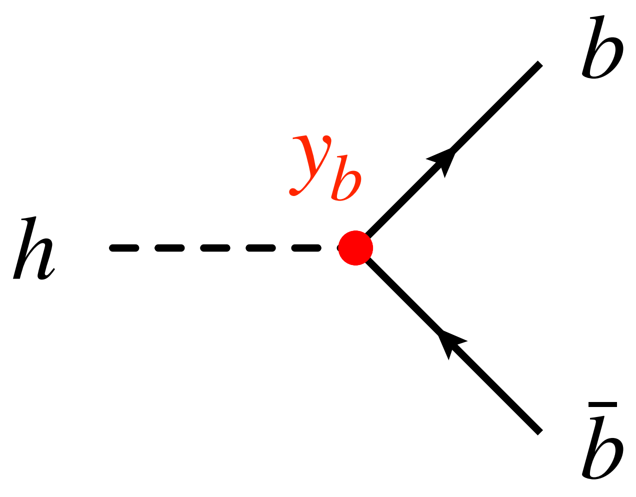

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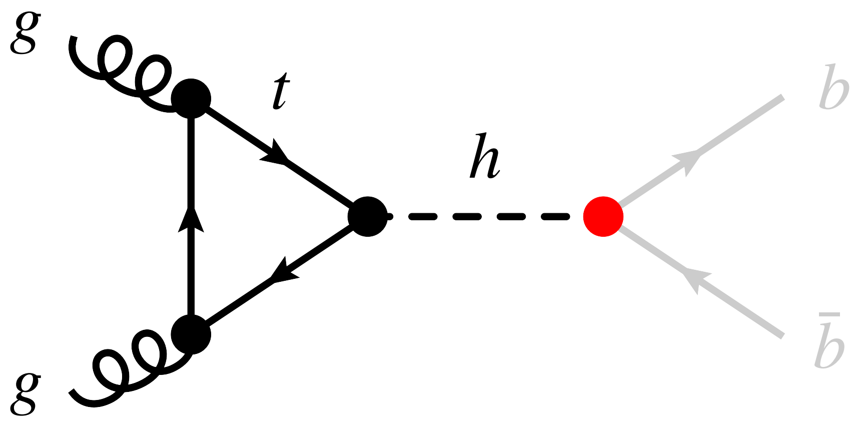

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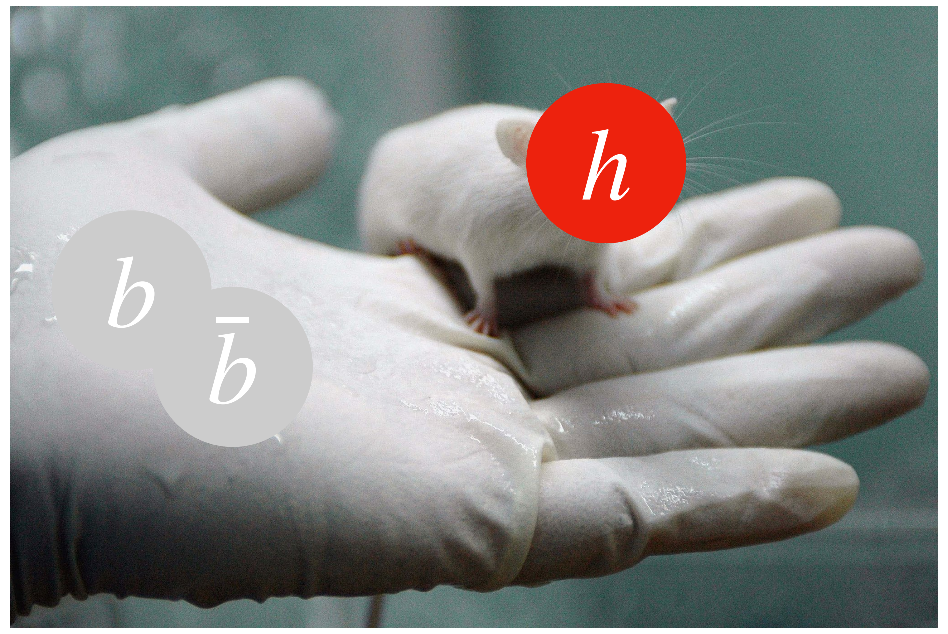

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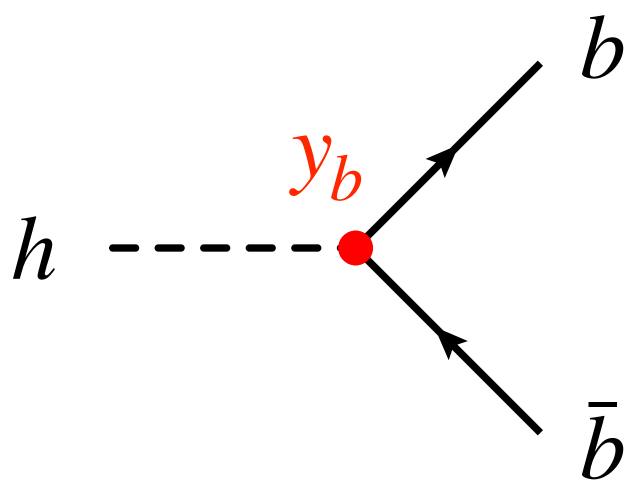
- **Goal:** 

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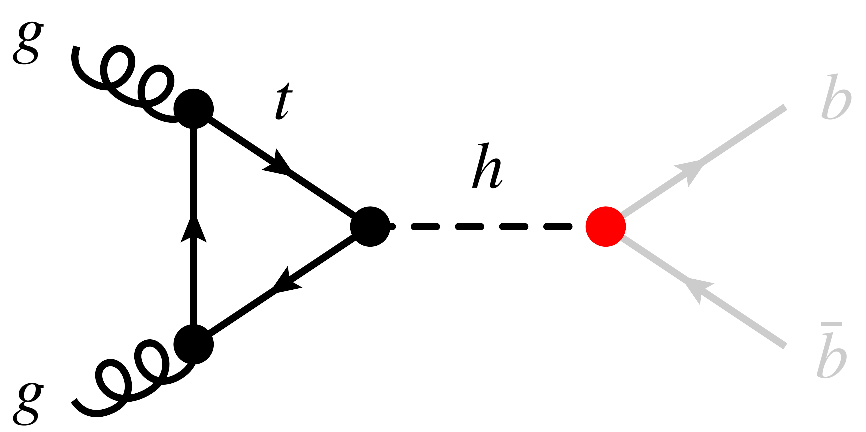

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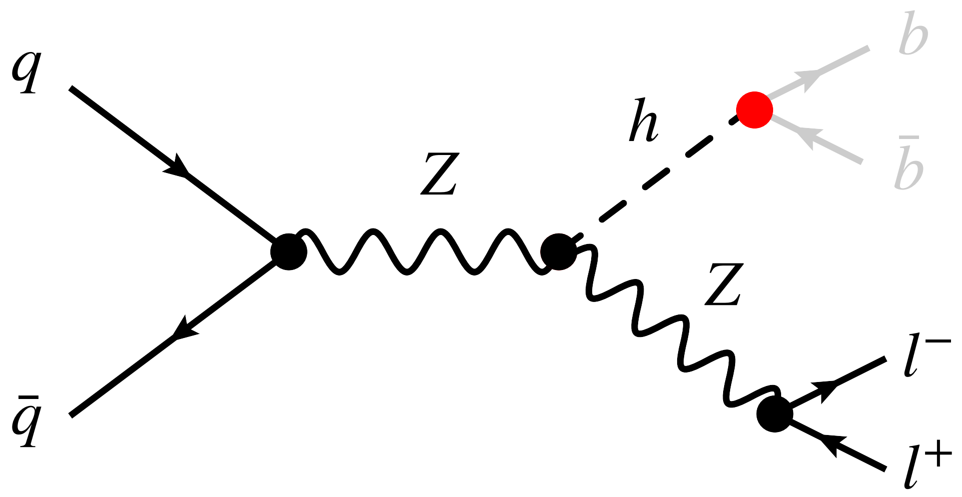

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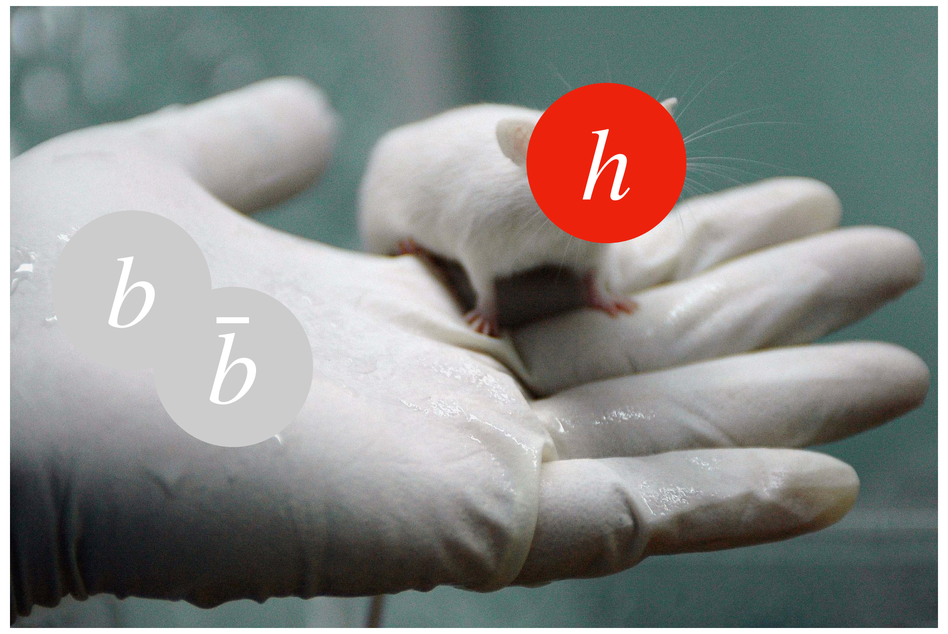

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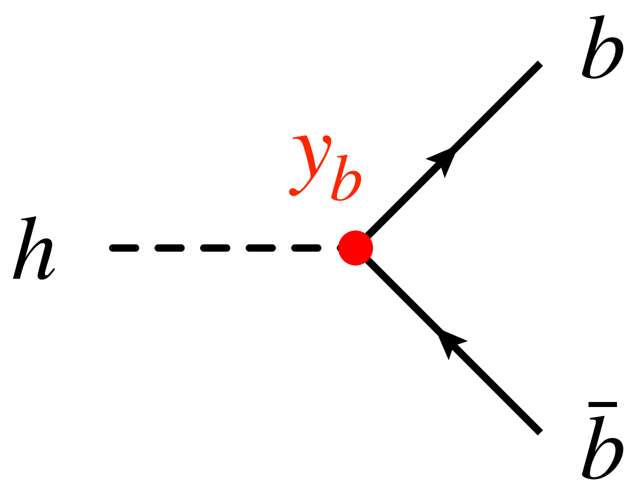
- **Goal:** 

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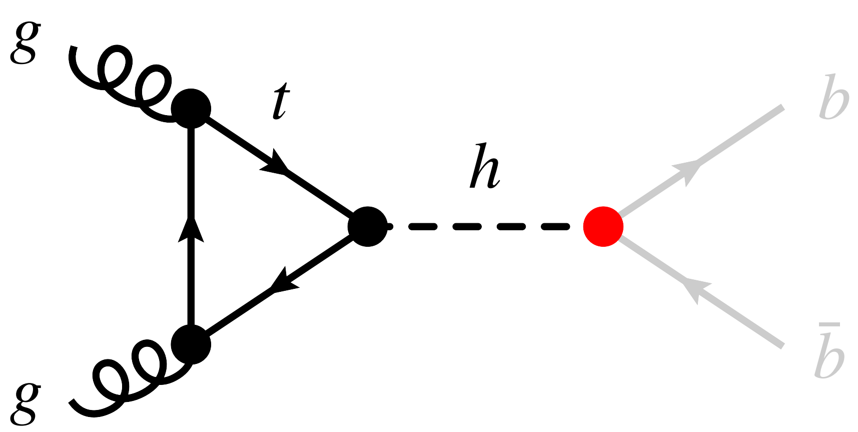

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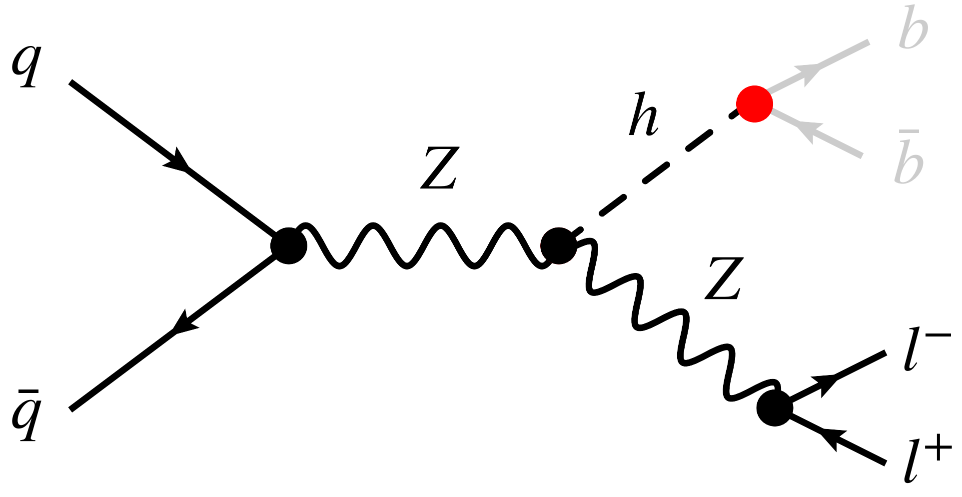

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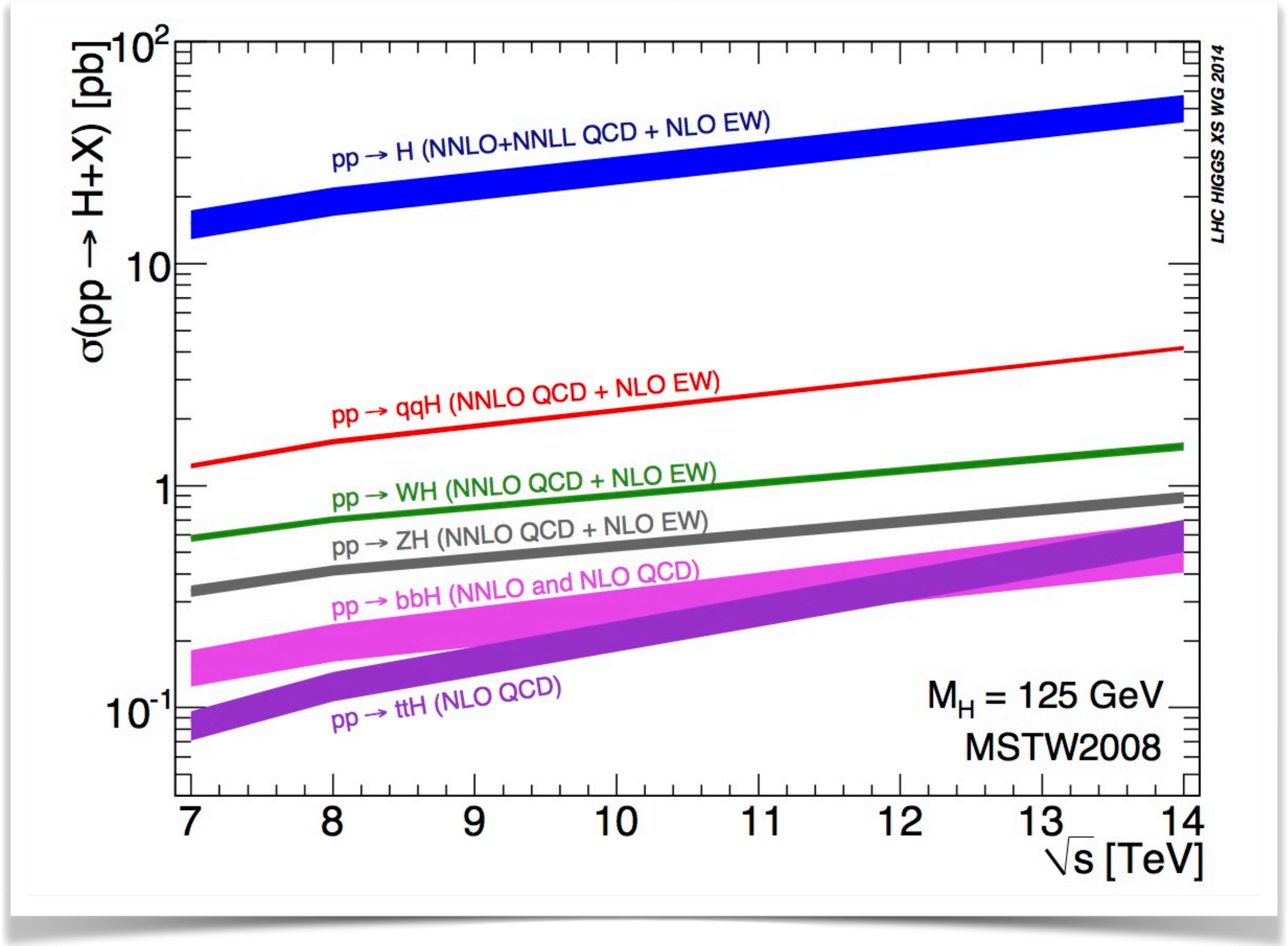

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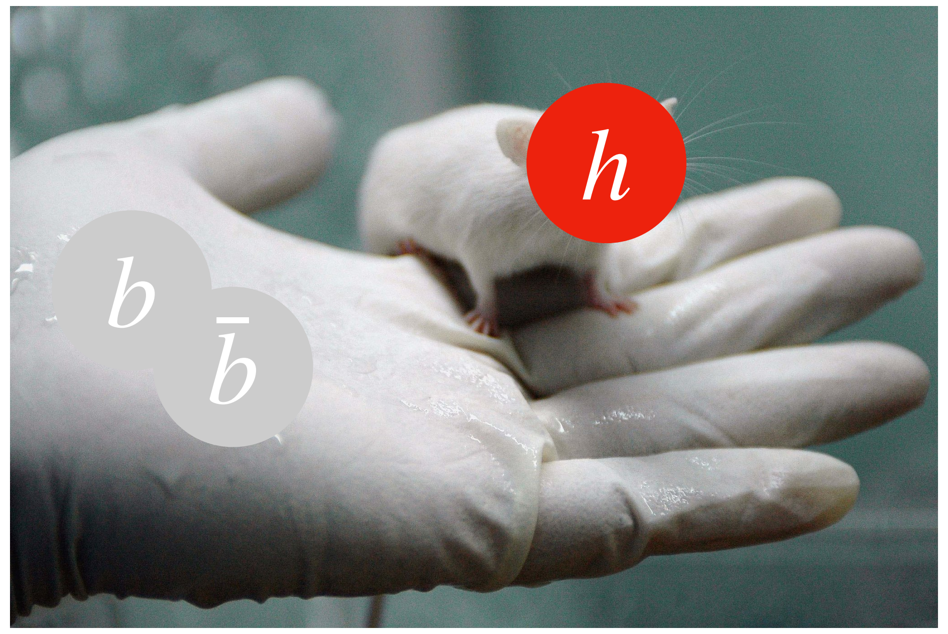

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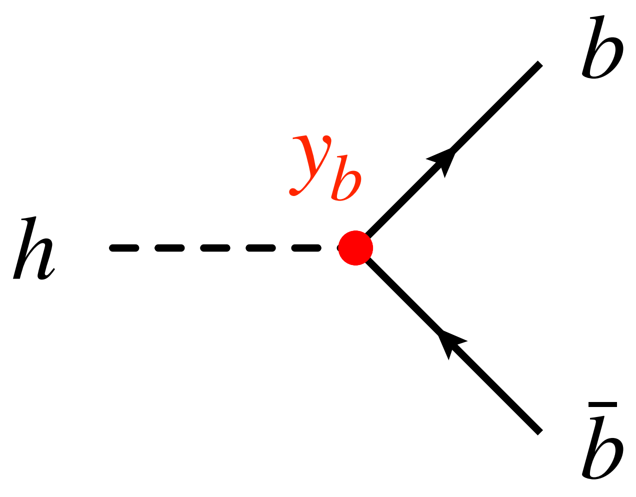

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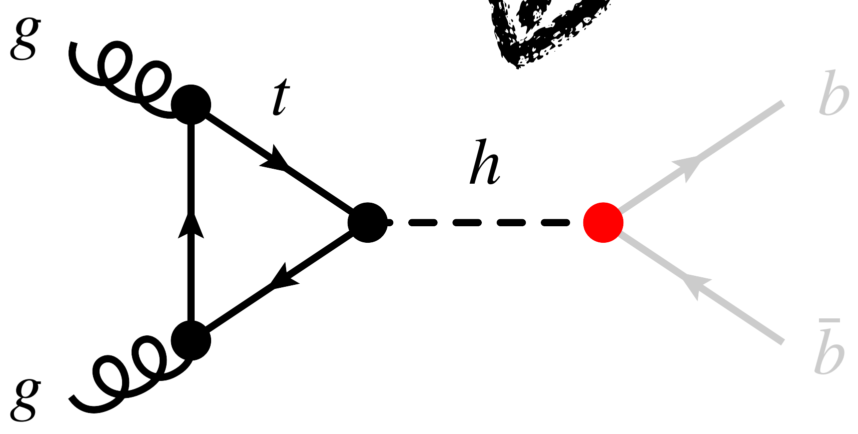

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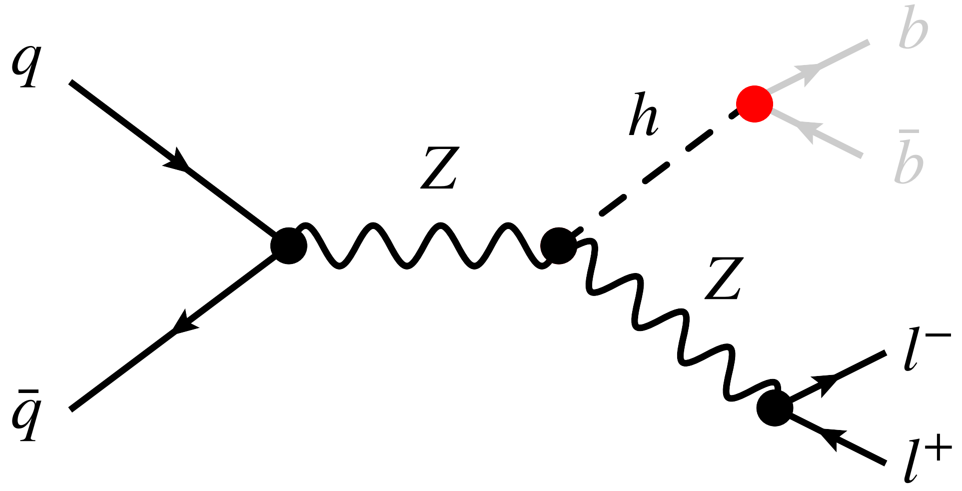

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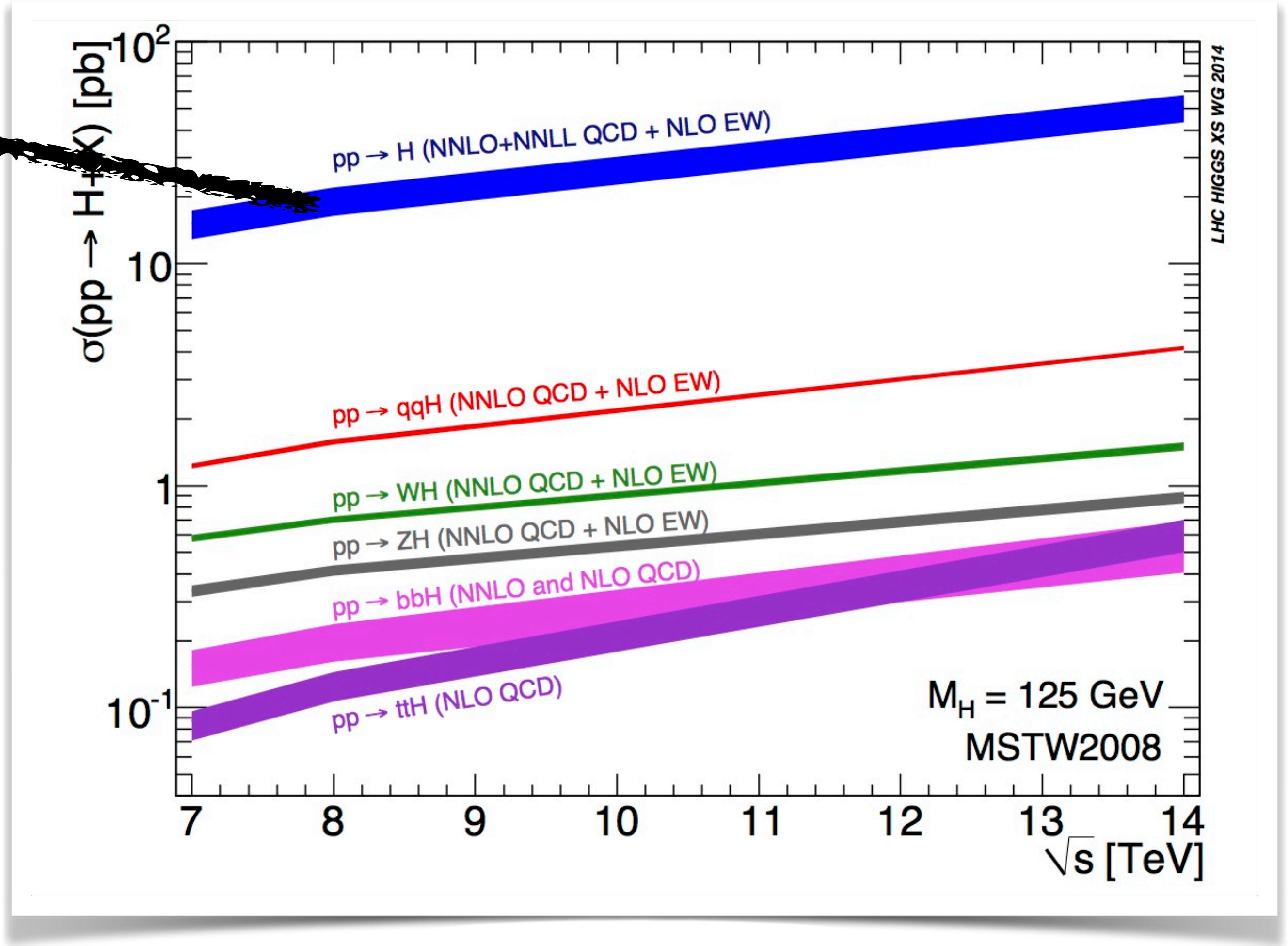

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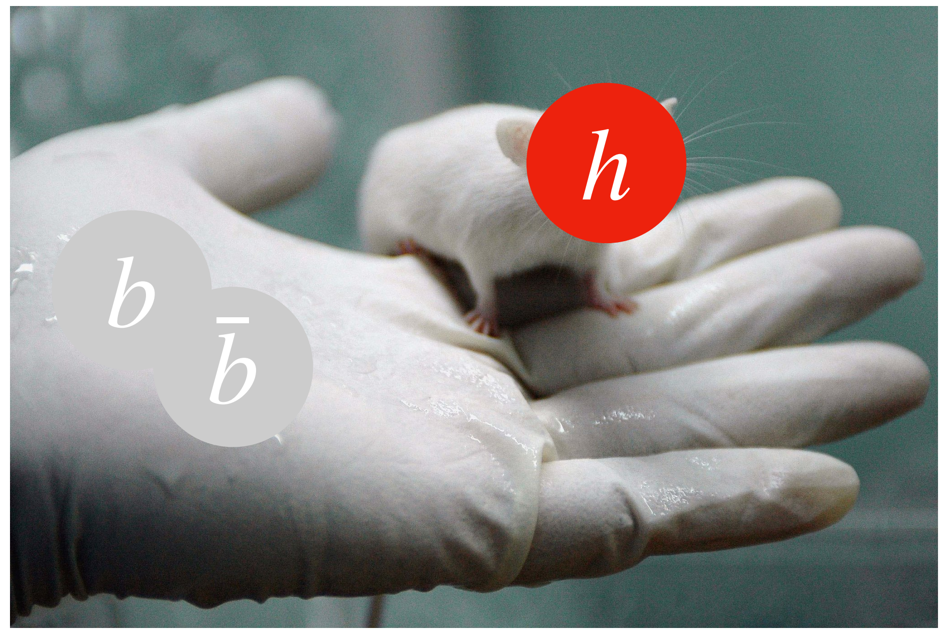

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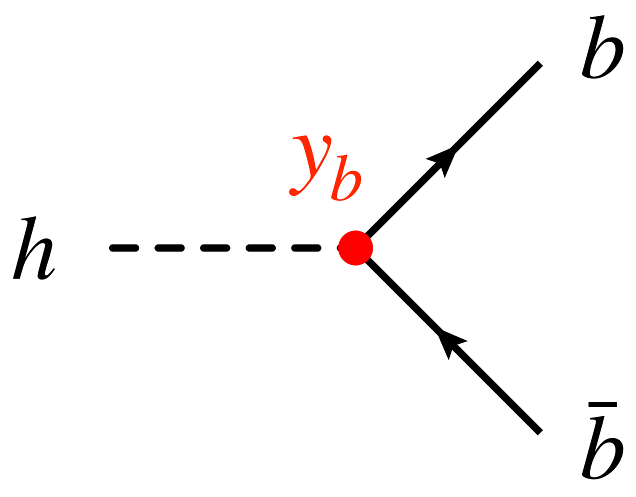

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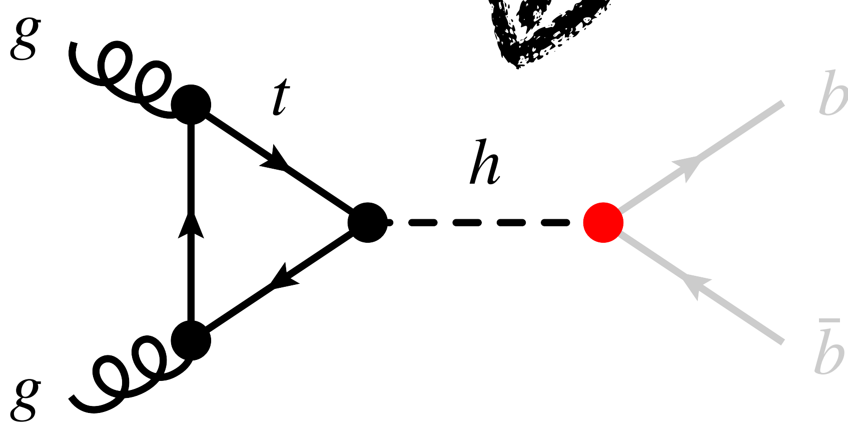

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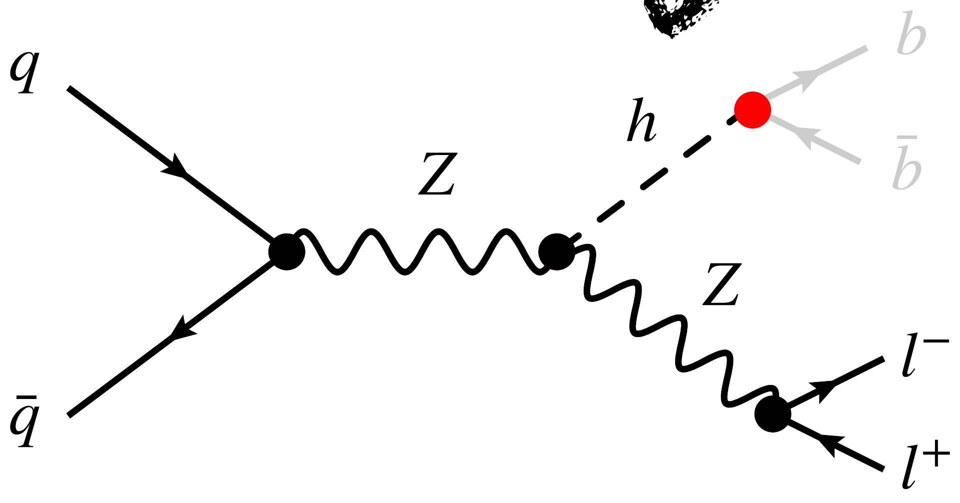

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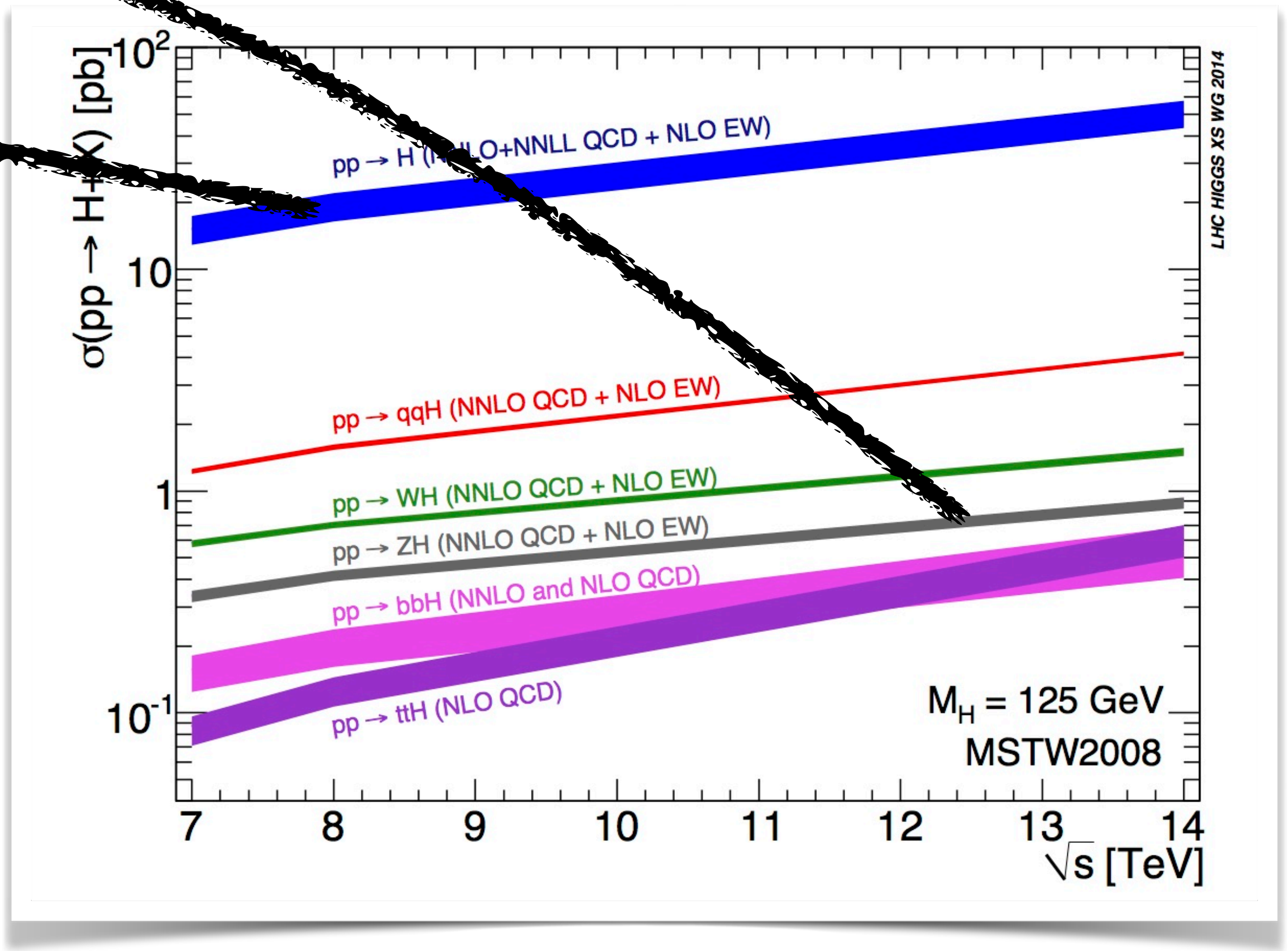

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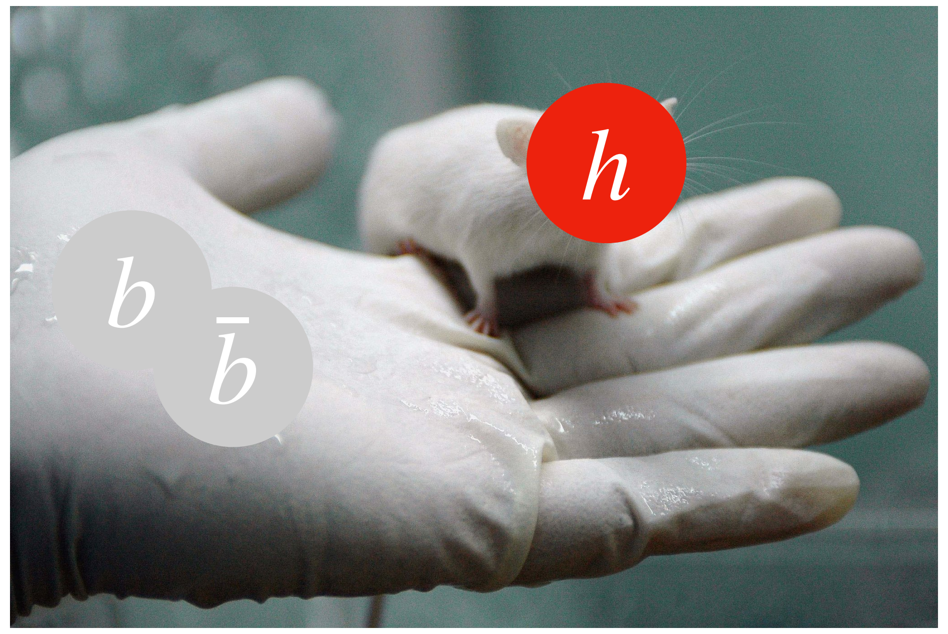

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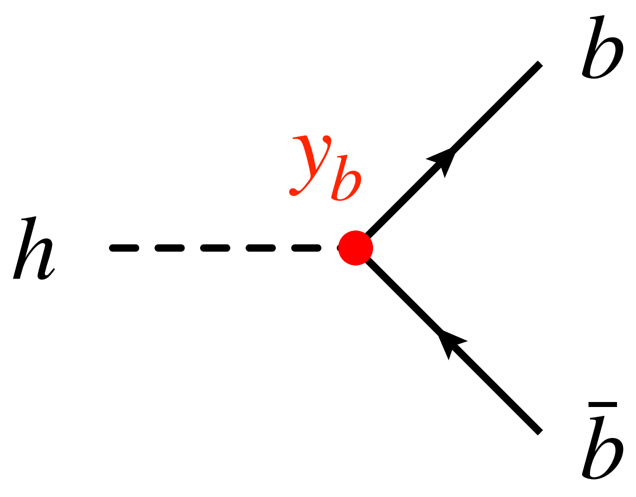

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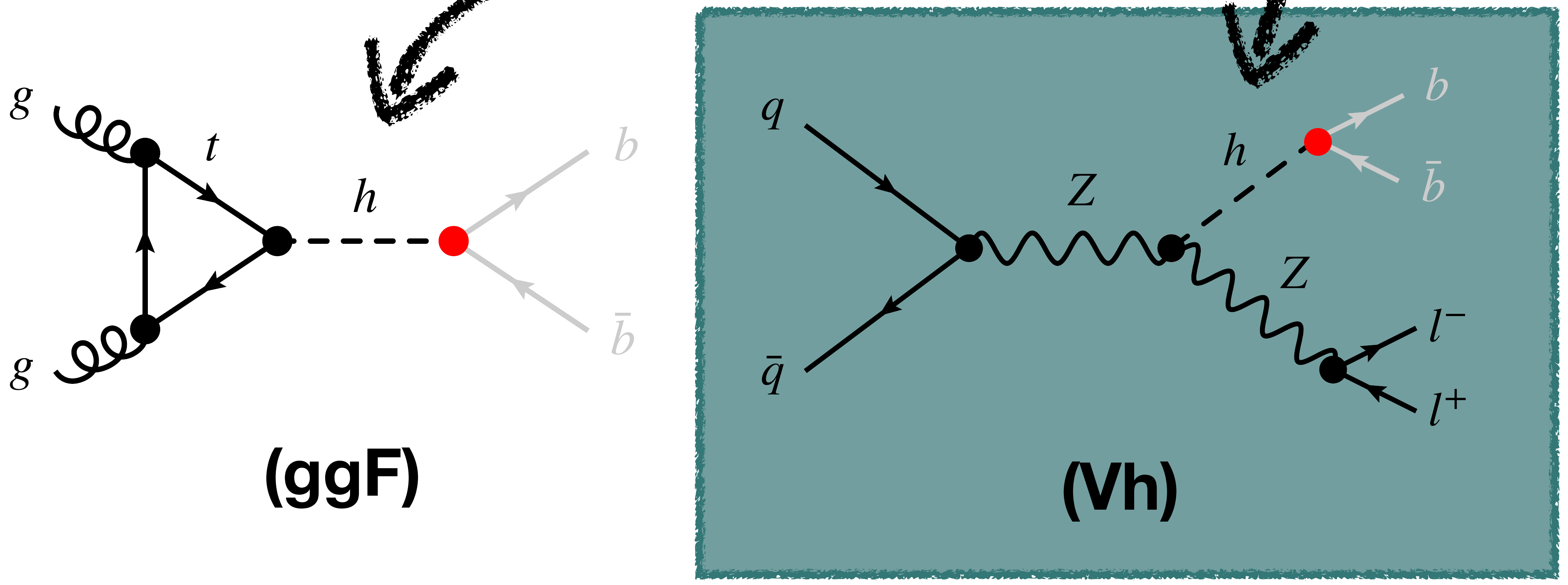

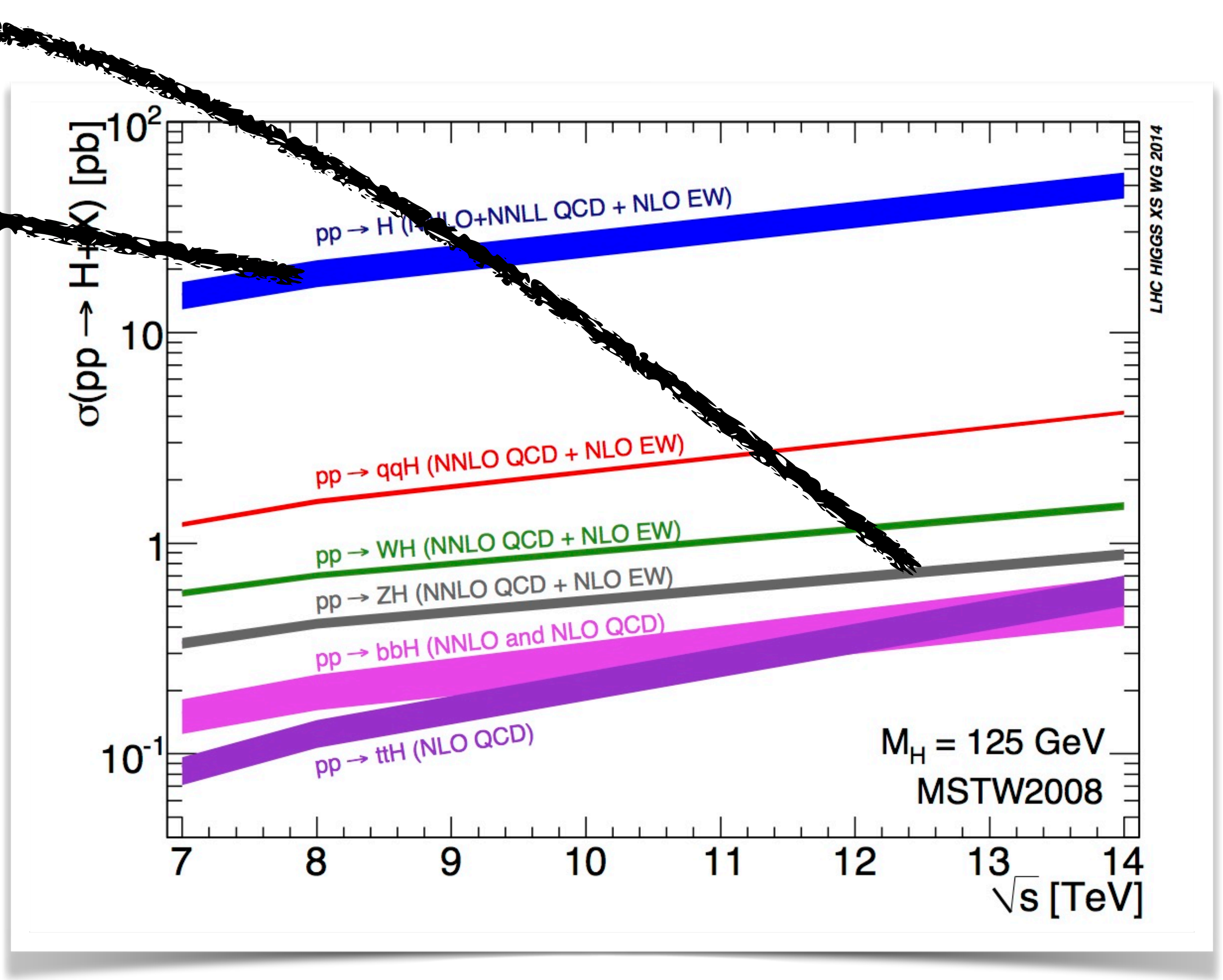

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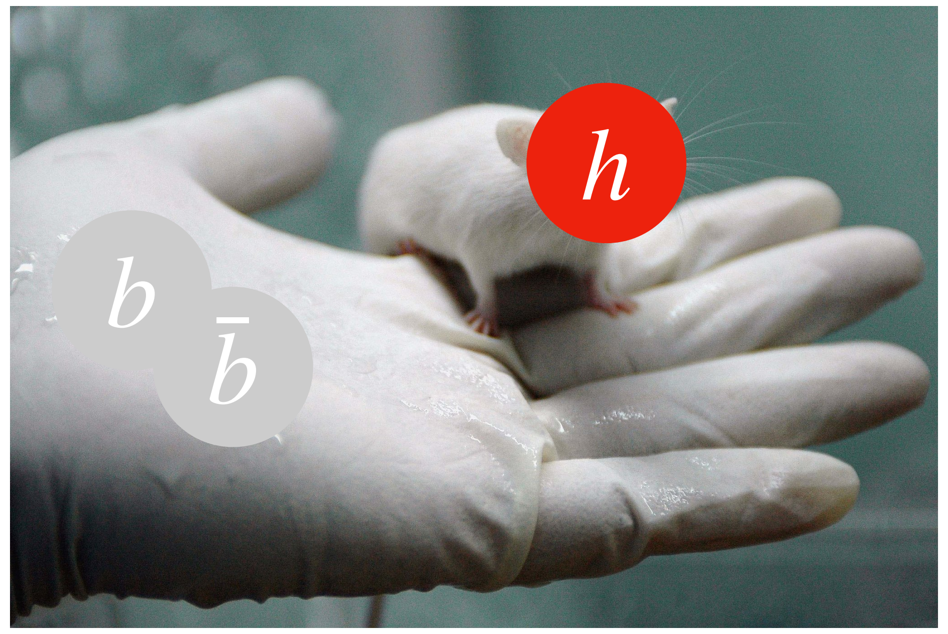

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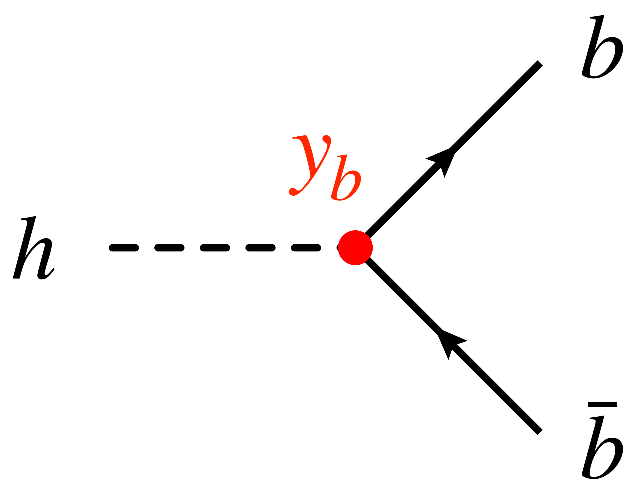
- **Goal:** 

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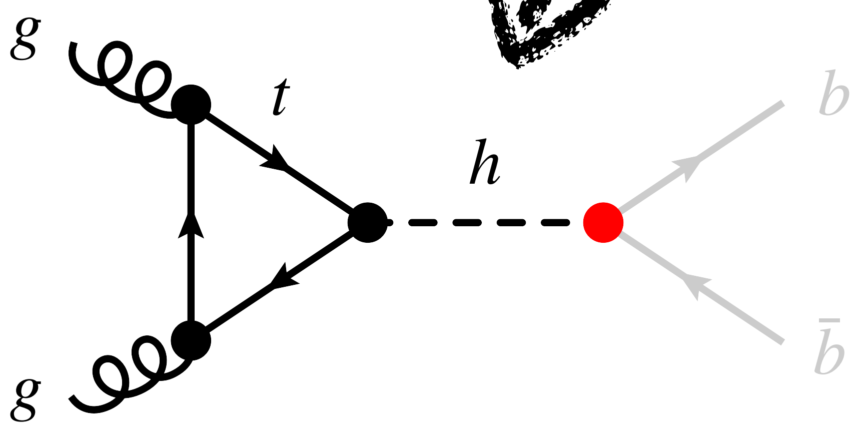

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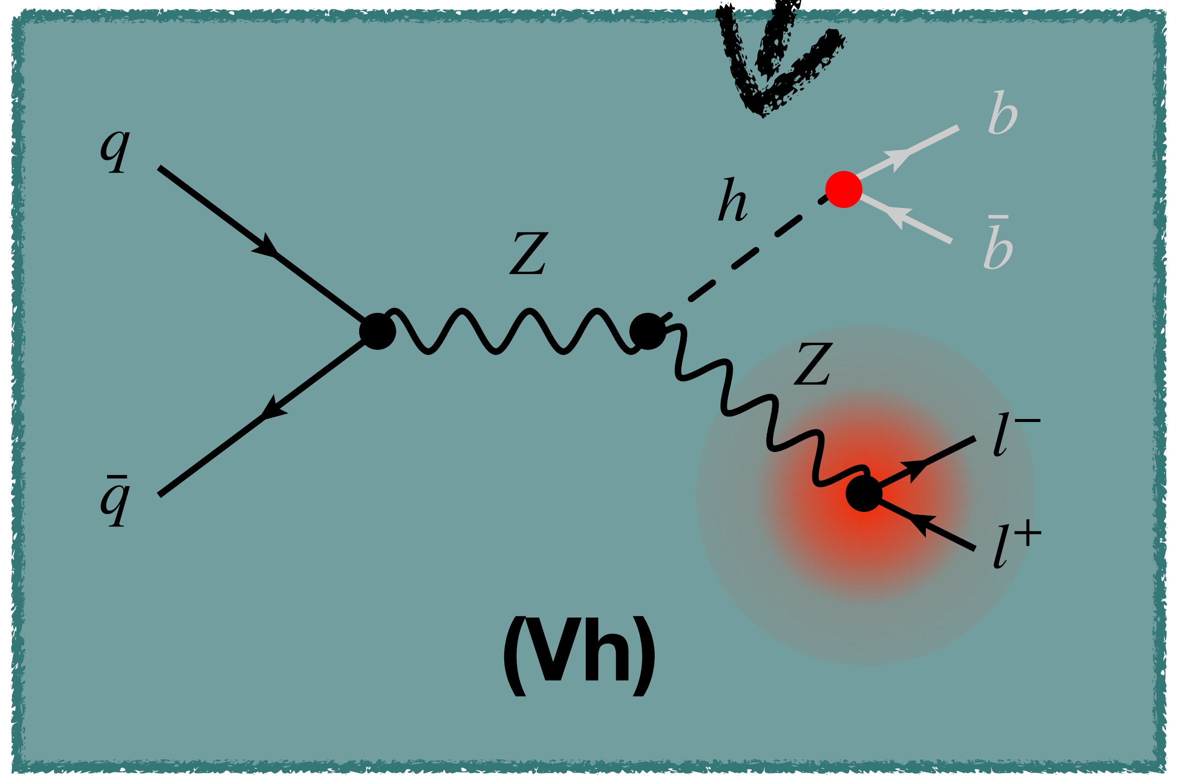

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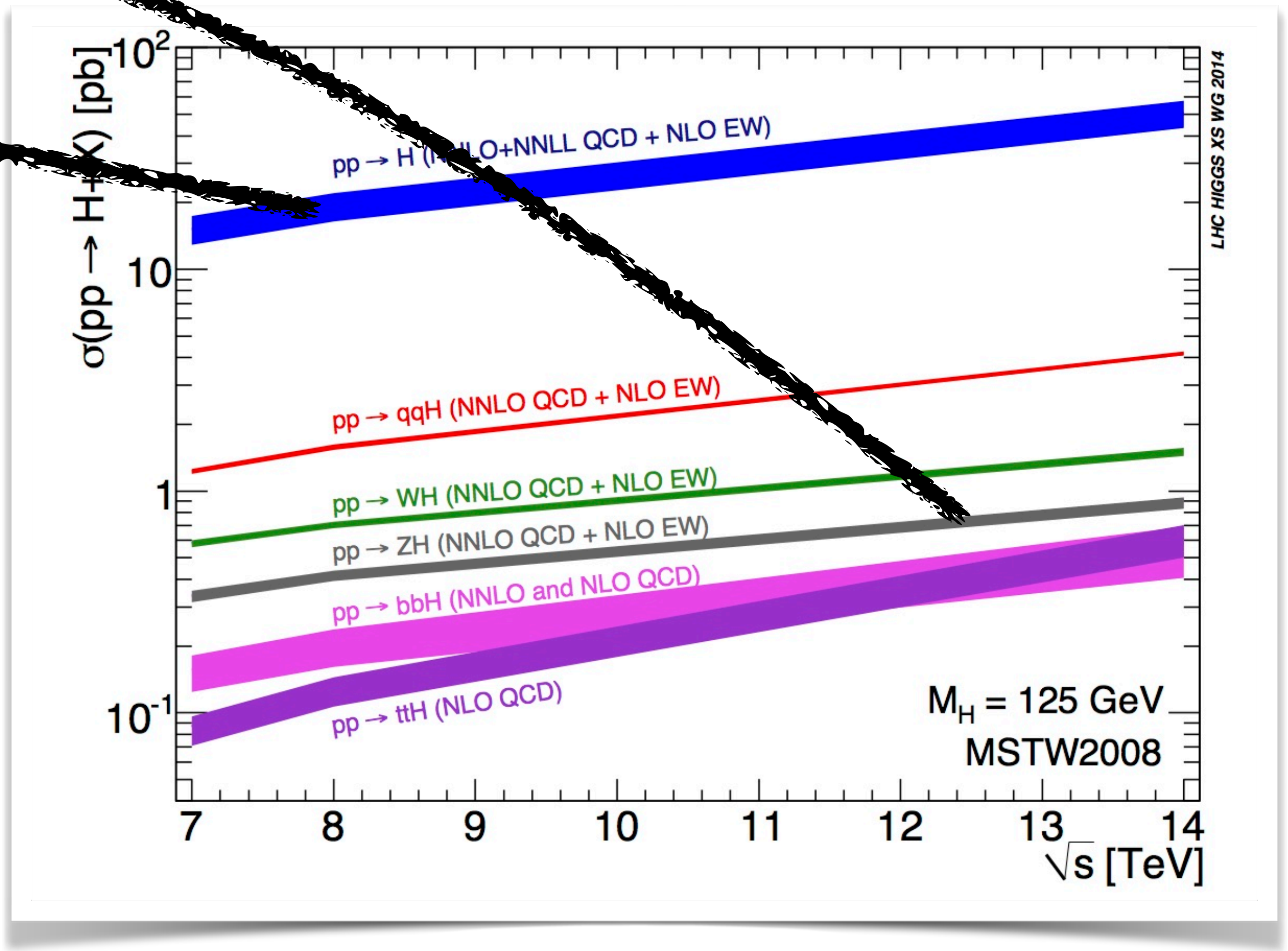

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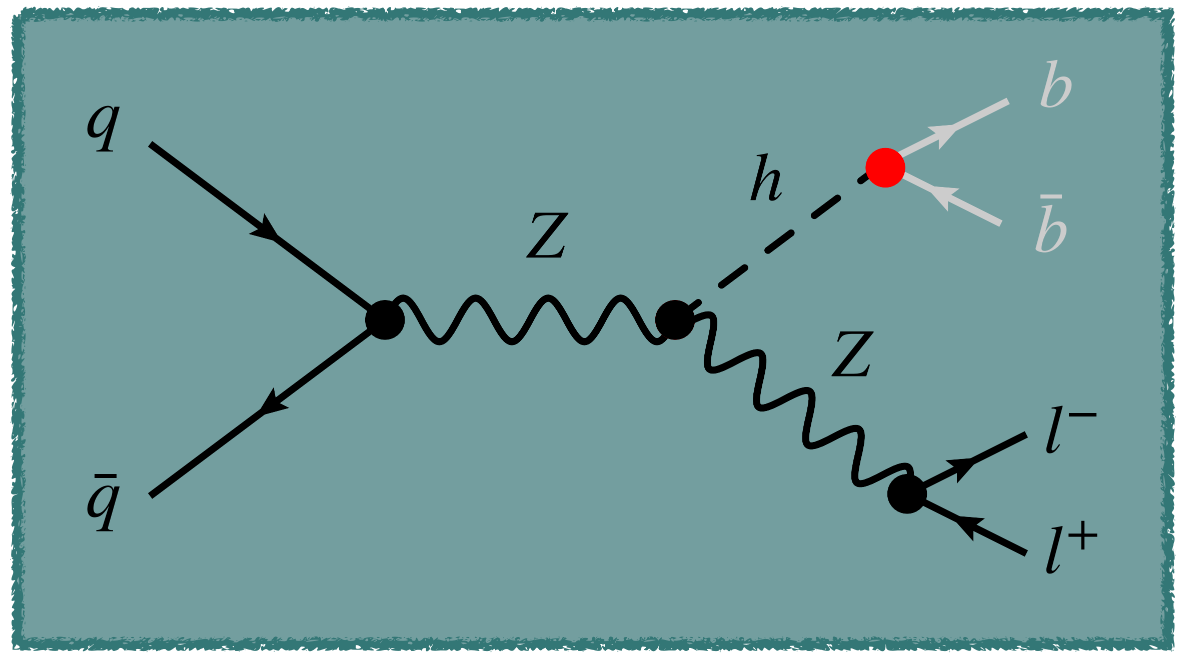

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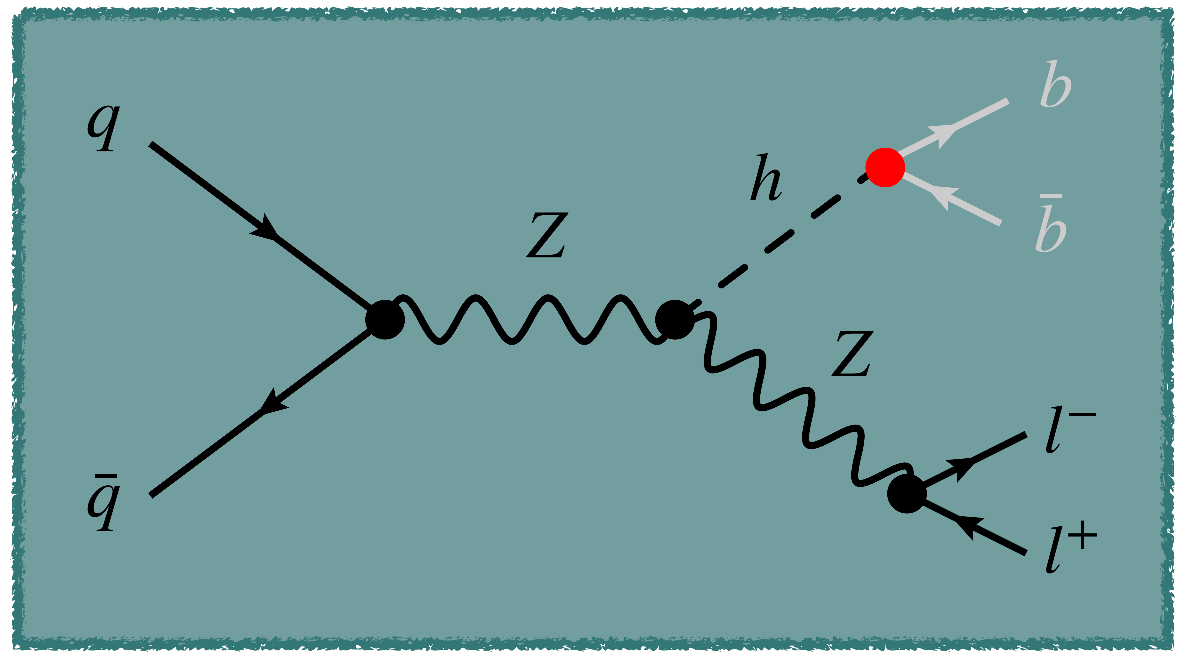

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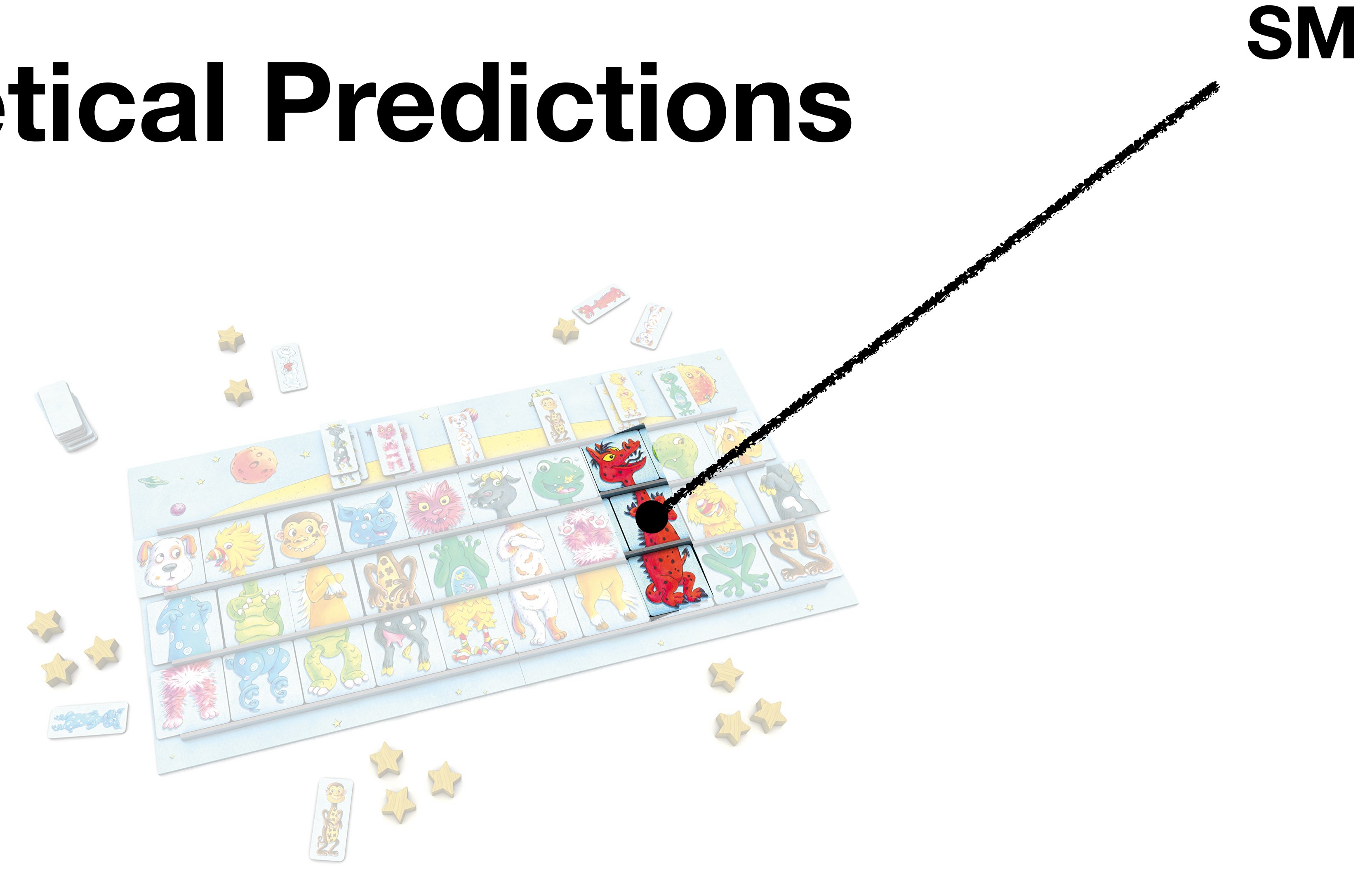

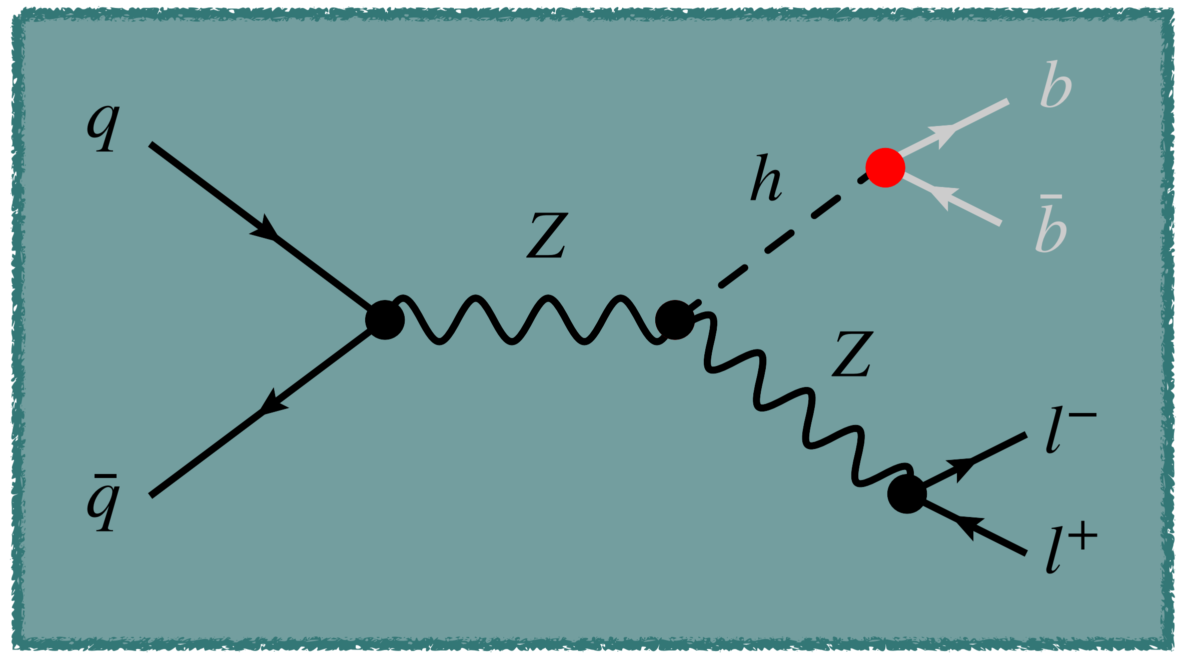

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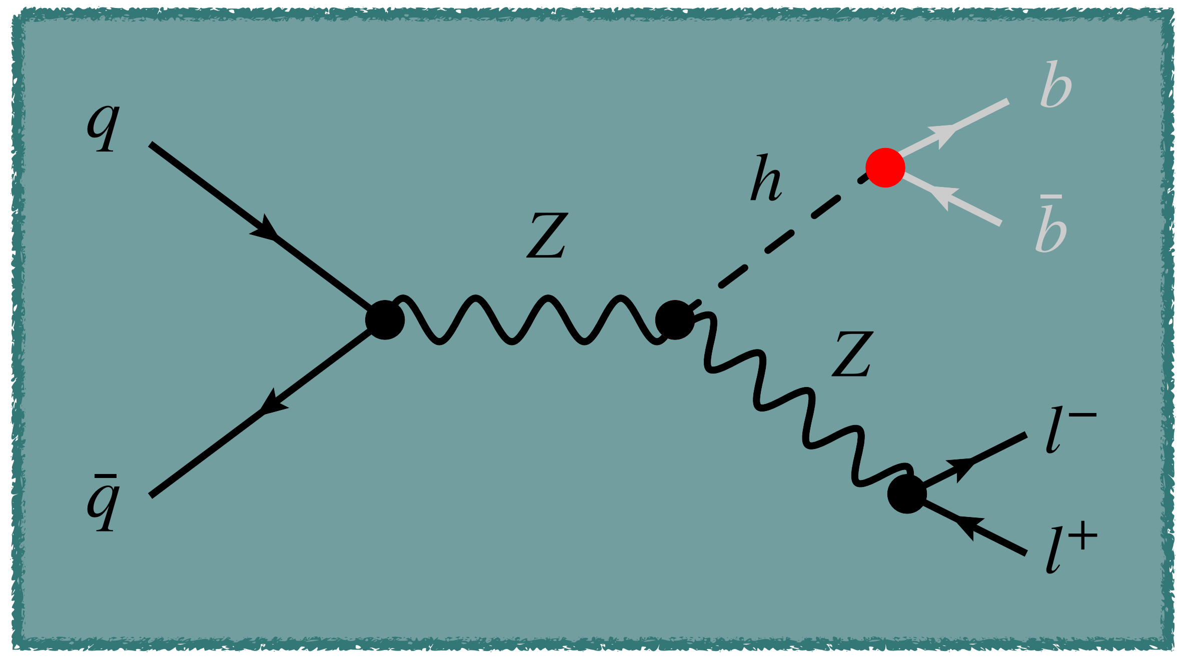

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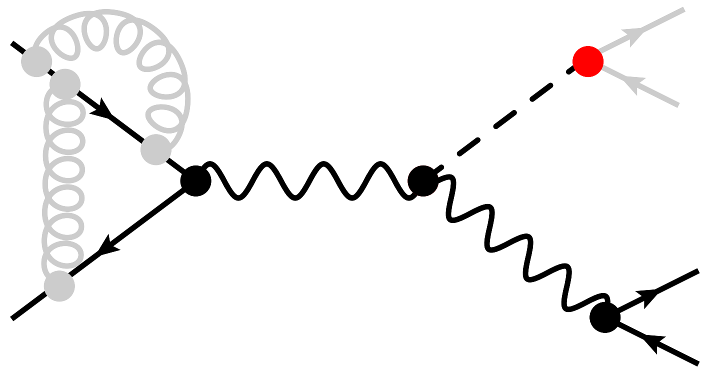
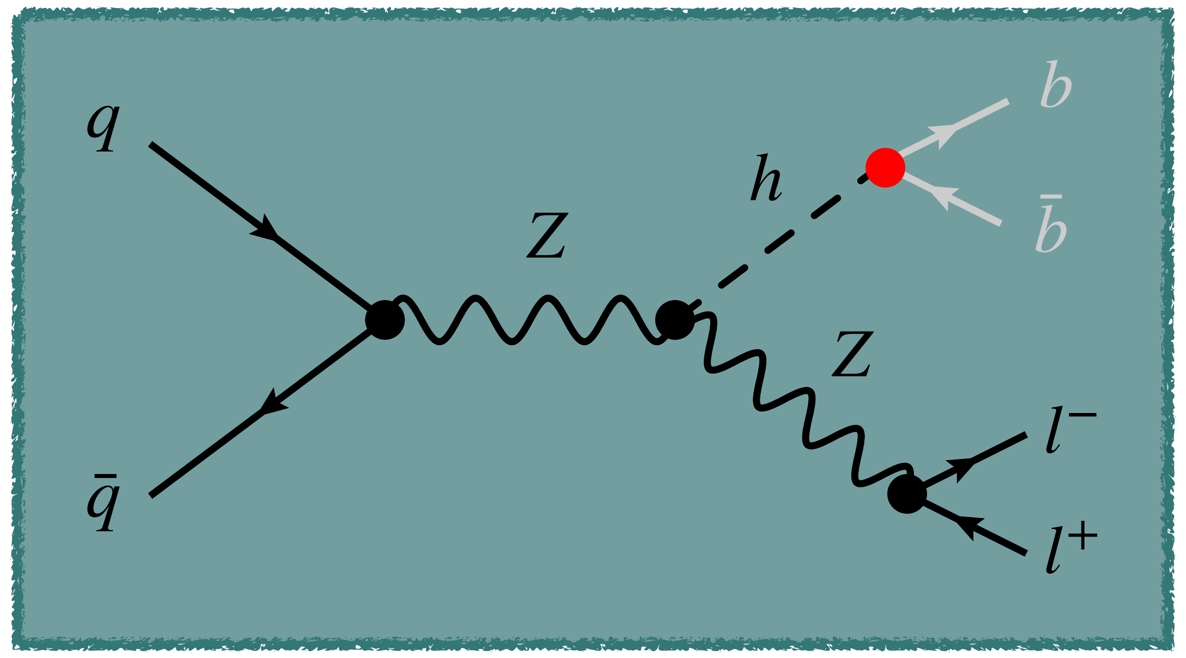


double virtual[1,2]



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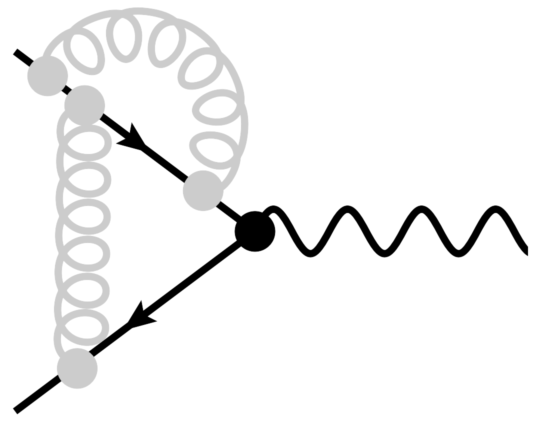

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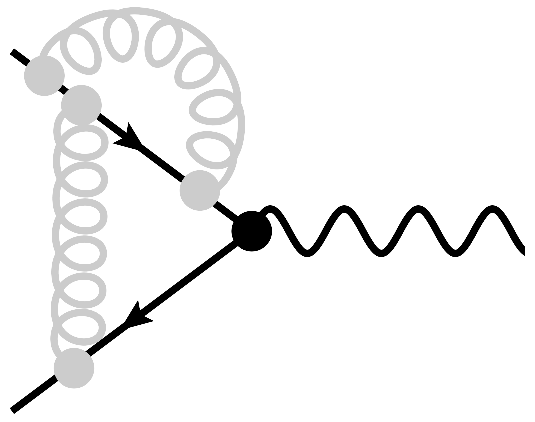

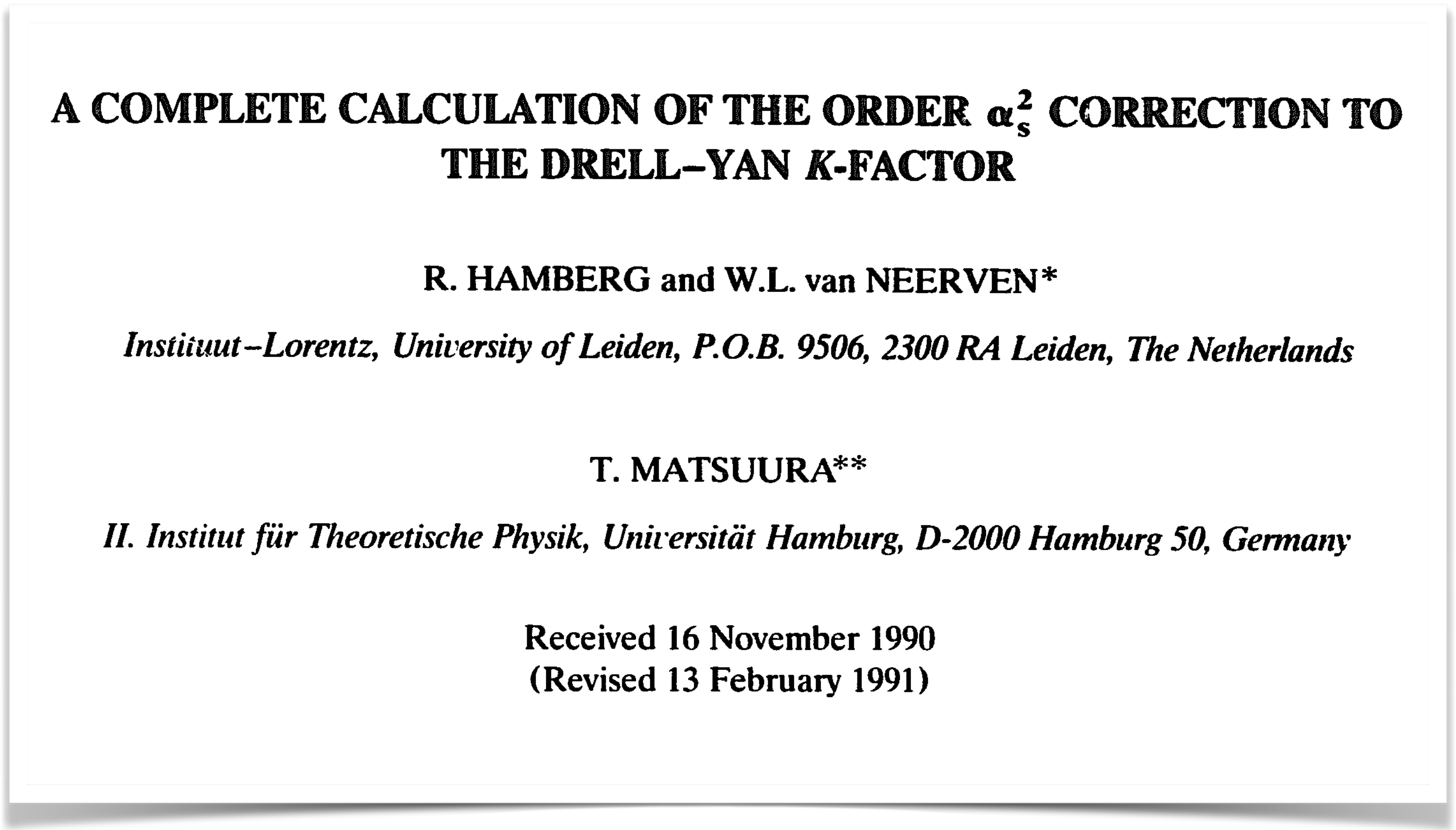

A COMPLETE CALCULATION OF THE ORDER α_s^2 CORRECTION TO THE DRELL–YAN *K*-FACTOR

R. HAMBERG and W.L. van NEERVEN*

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T. MATSUURA**

II. Institut für Theoretische Physik, Universität Hamburg, D-2000 Hamburg 50, Germany

Received 16 November 1990
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Source: DOI:10.1016/0550-3213(91)90064-5 (R. Hamberg et al.).

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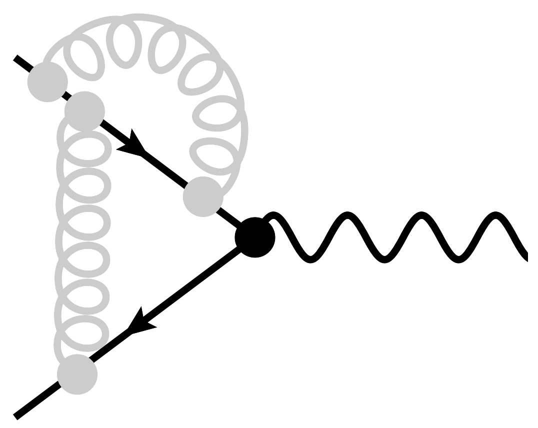

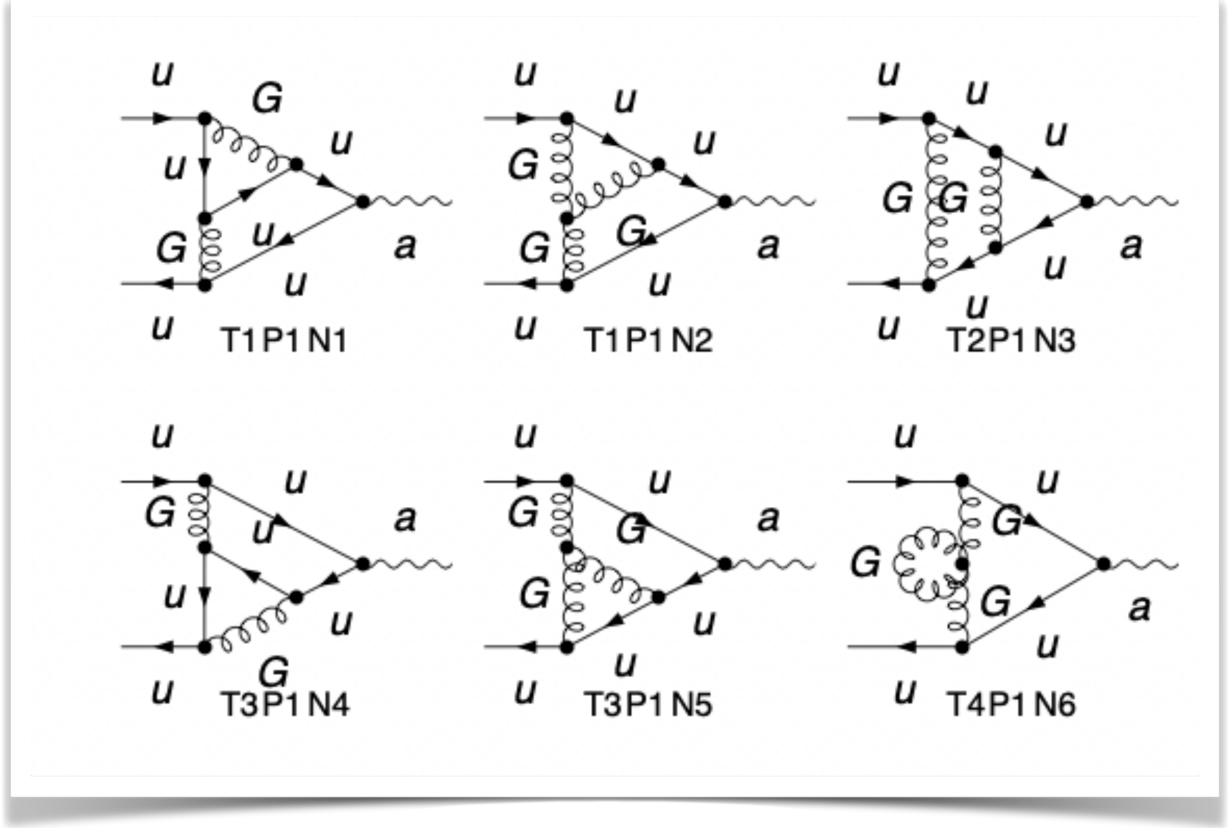

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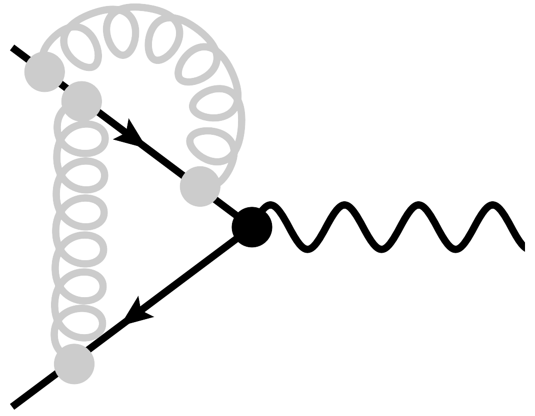

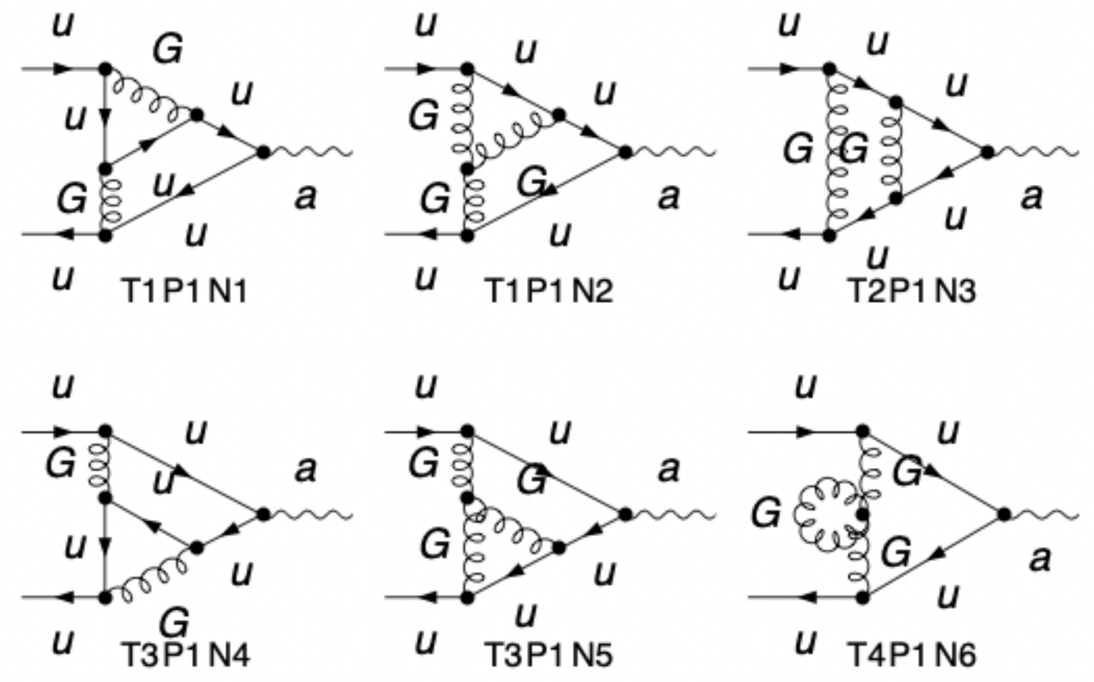

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FeynArts

FormCalc

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Master Integrals

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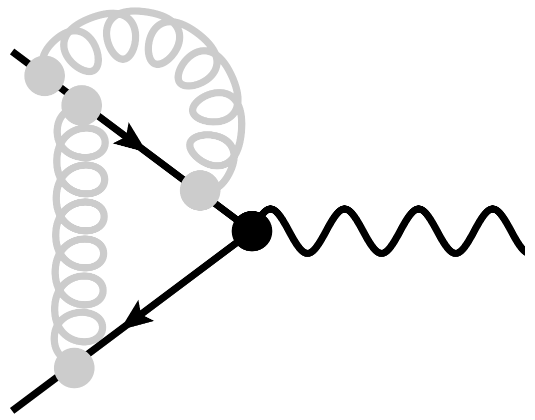

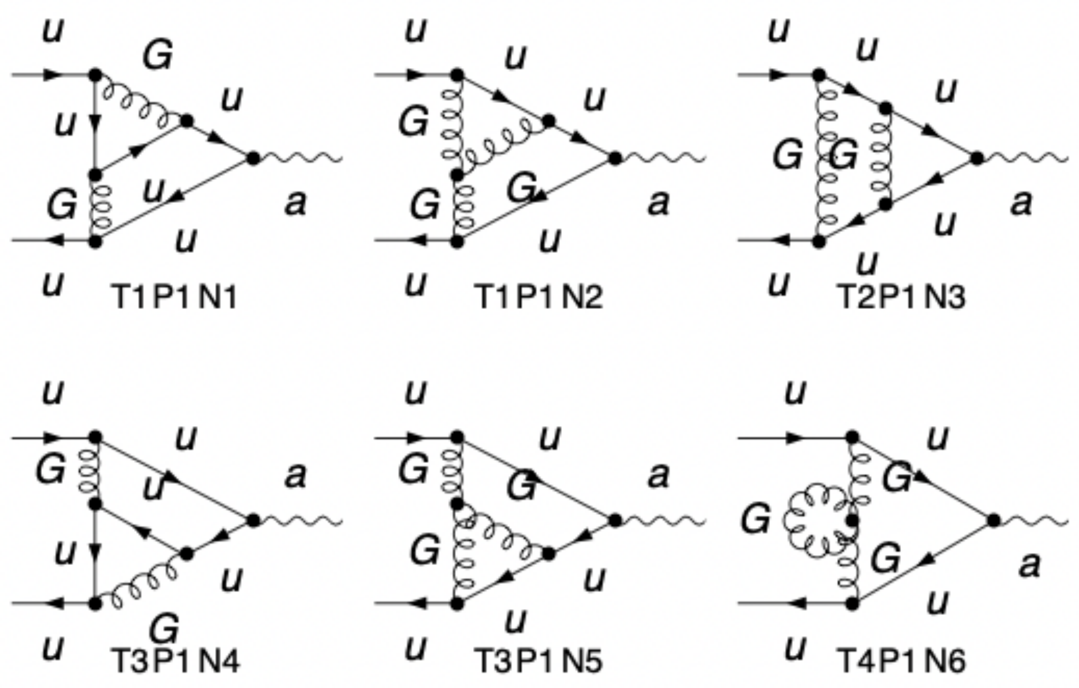

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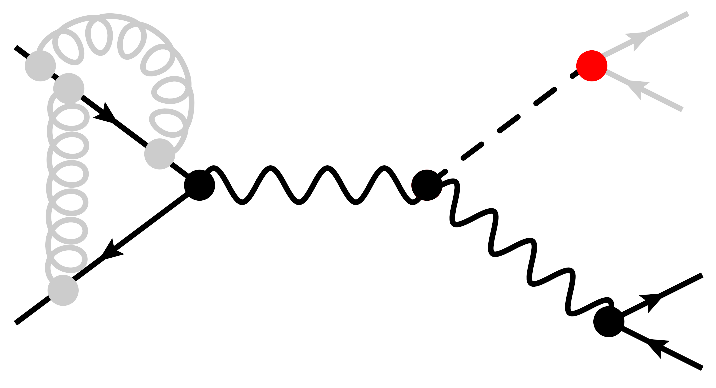

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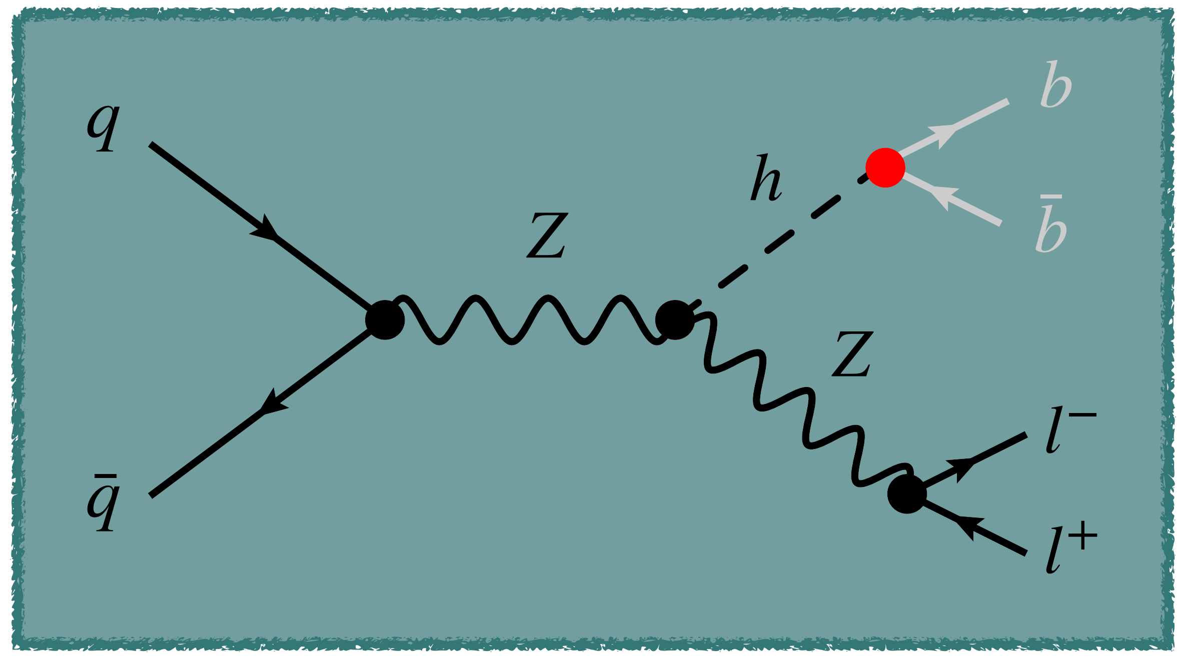

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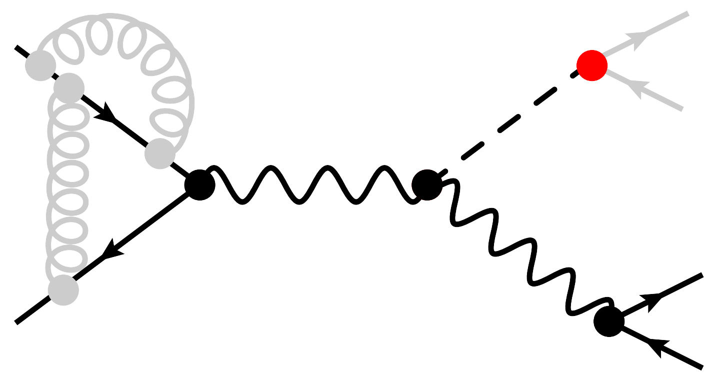

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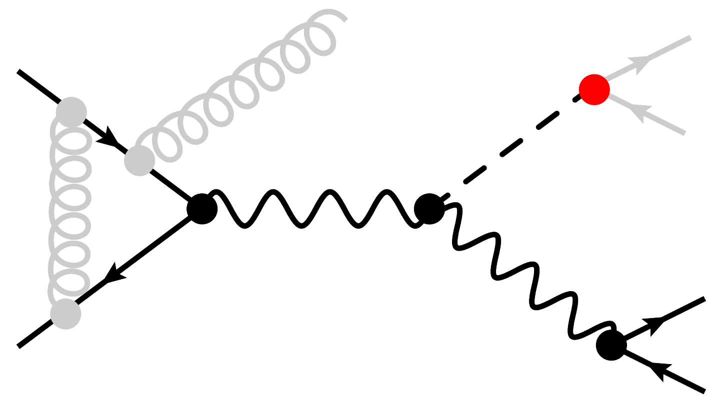

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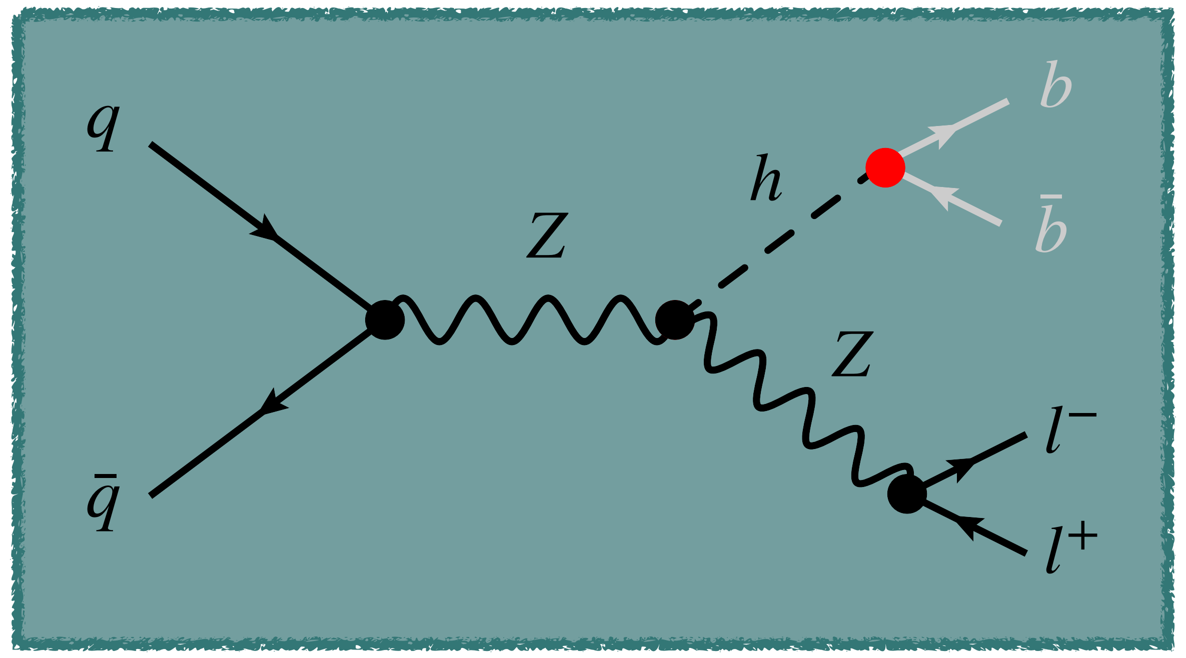

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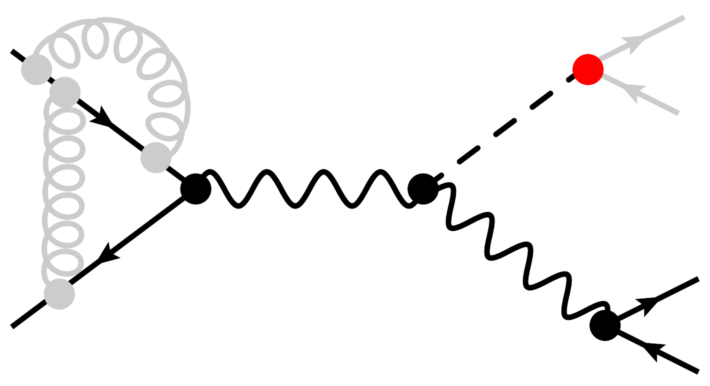

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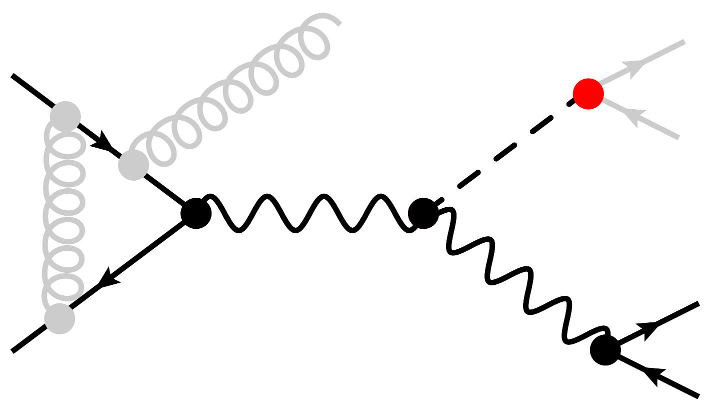

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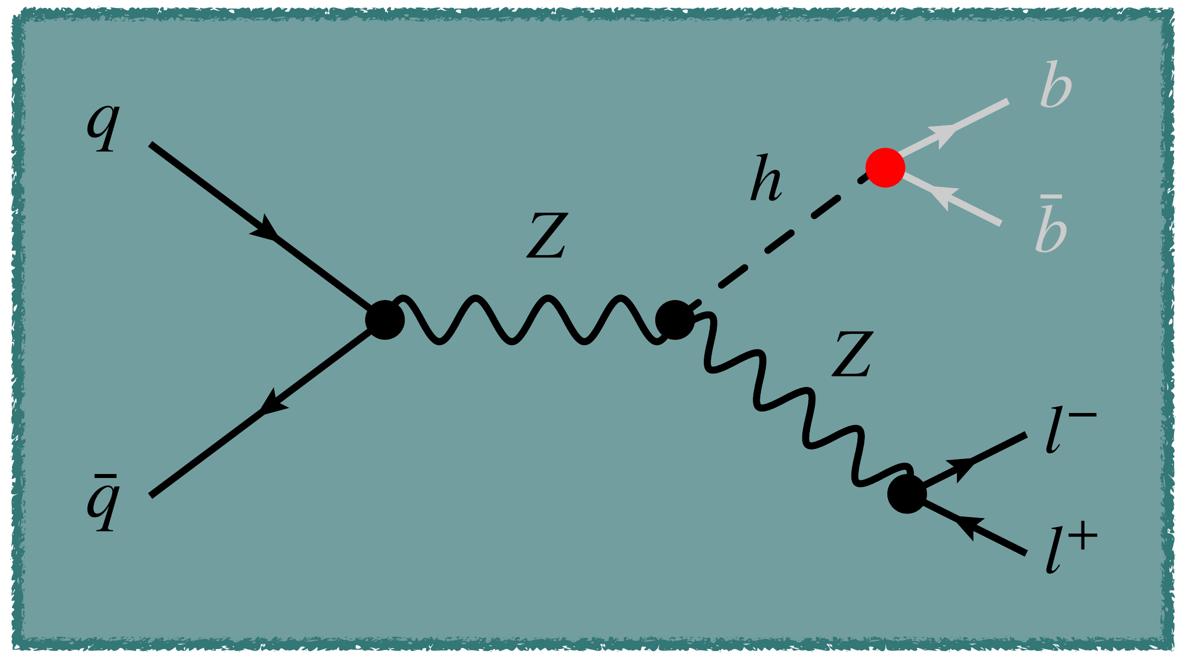

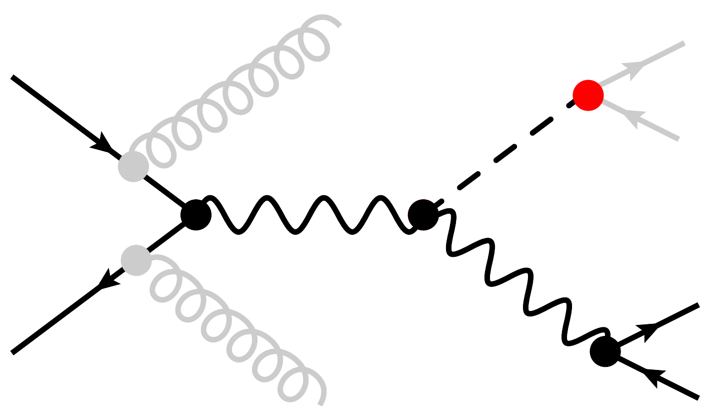

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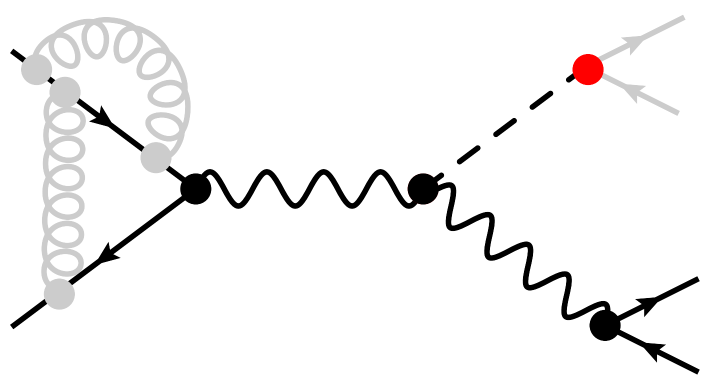
UV poles, IR poles



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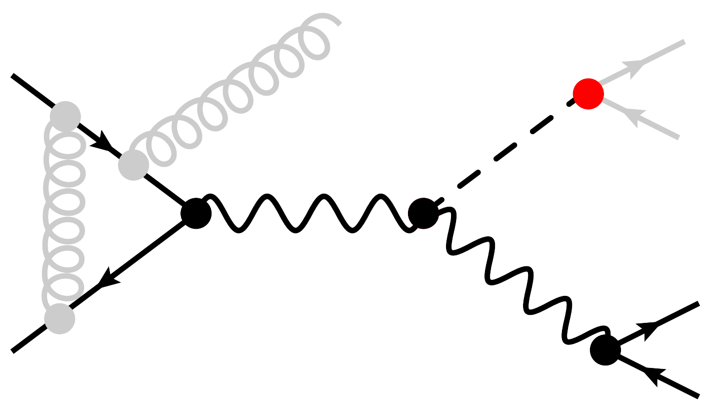

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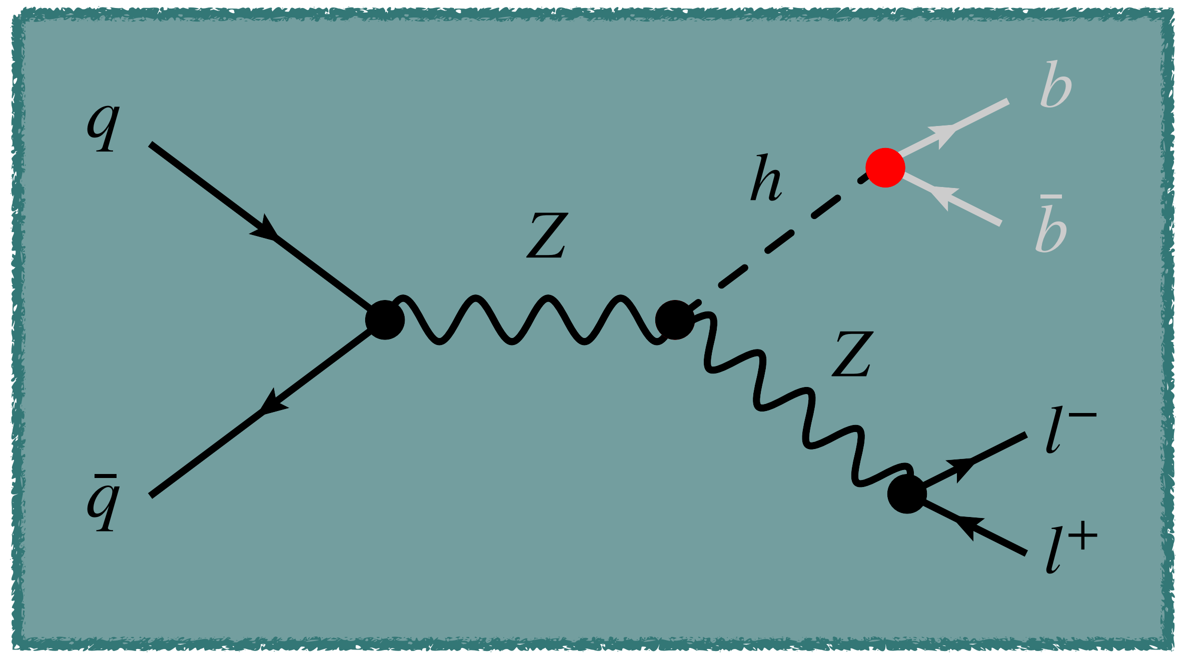

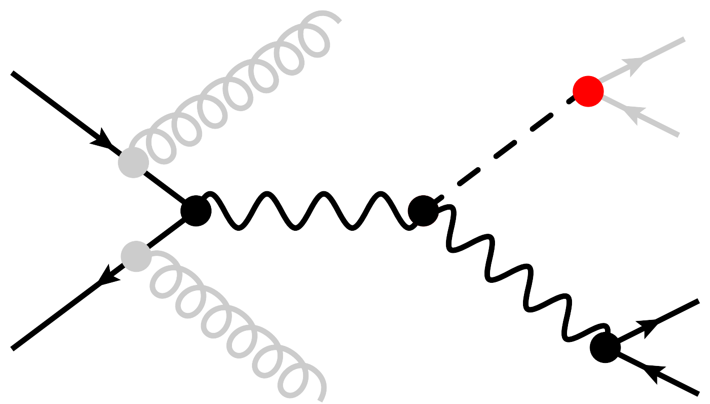

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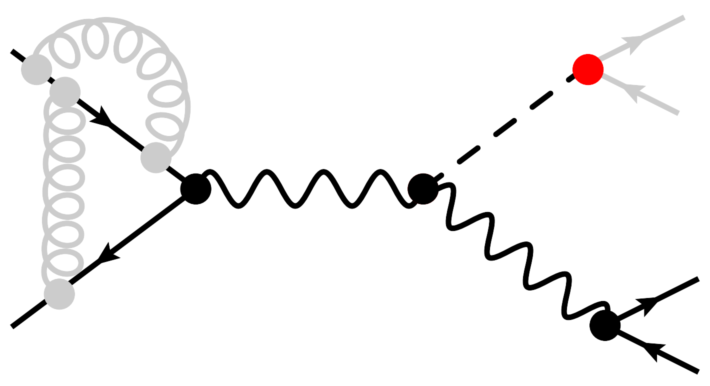

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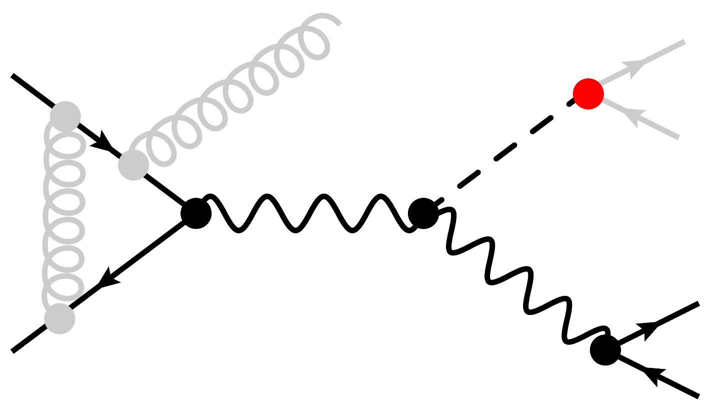

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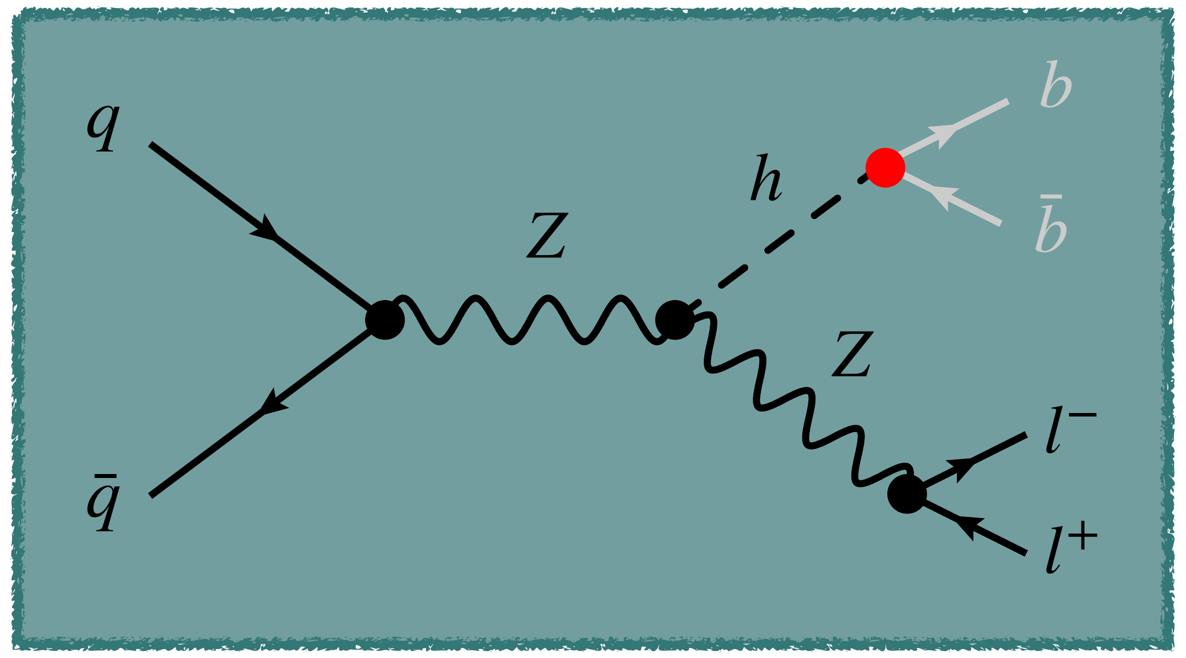

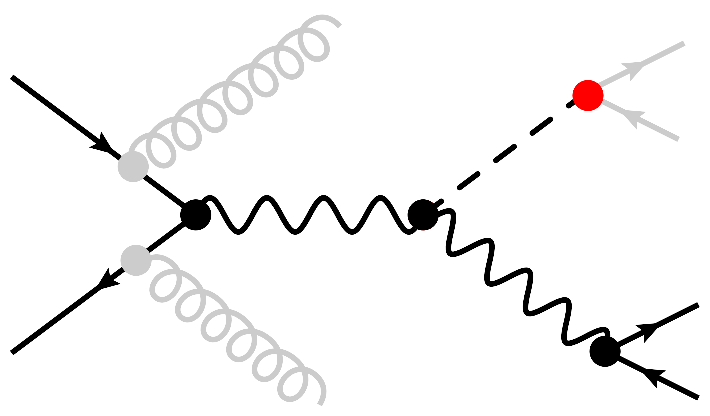

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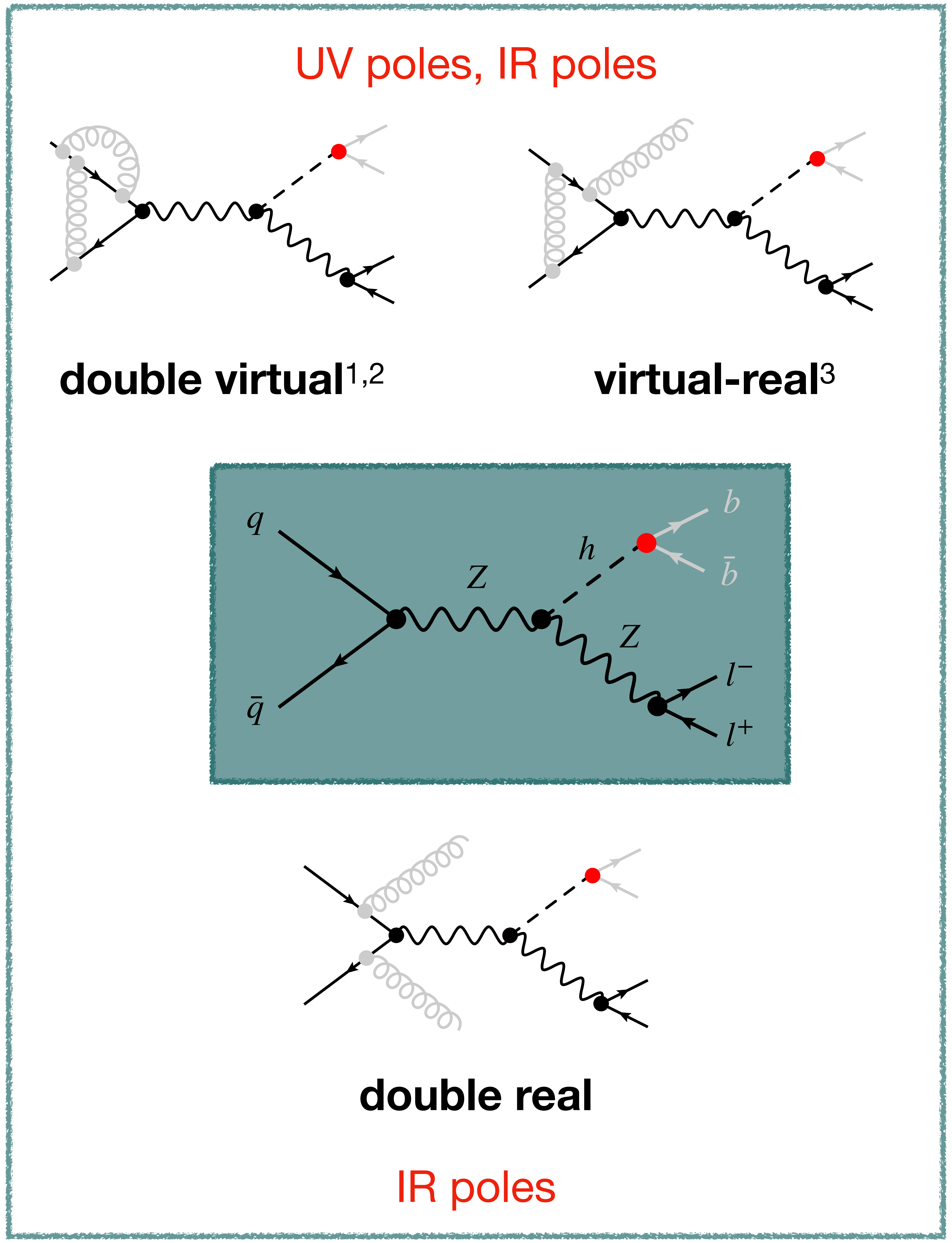

POWHEG MiNNLO$_{\text{PS}}$[4] code

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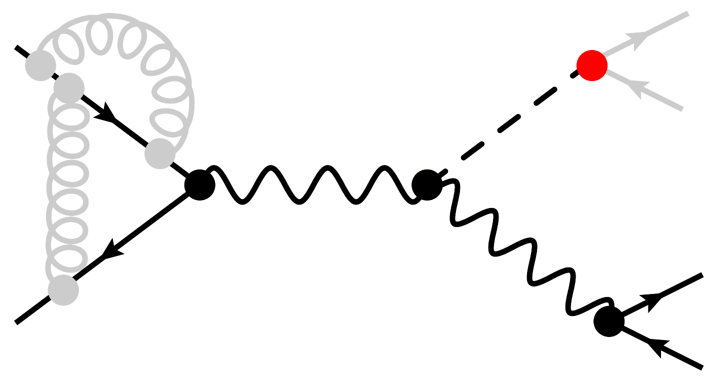

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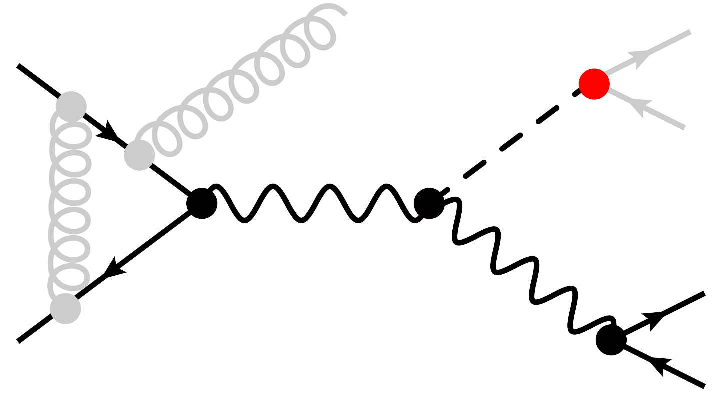

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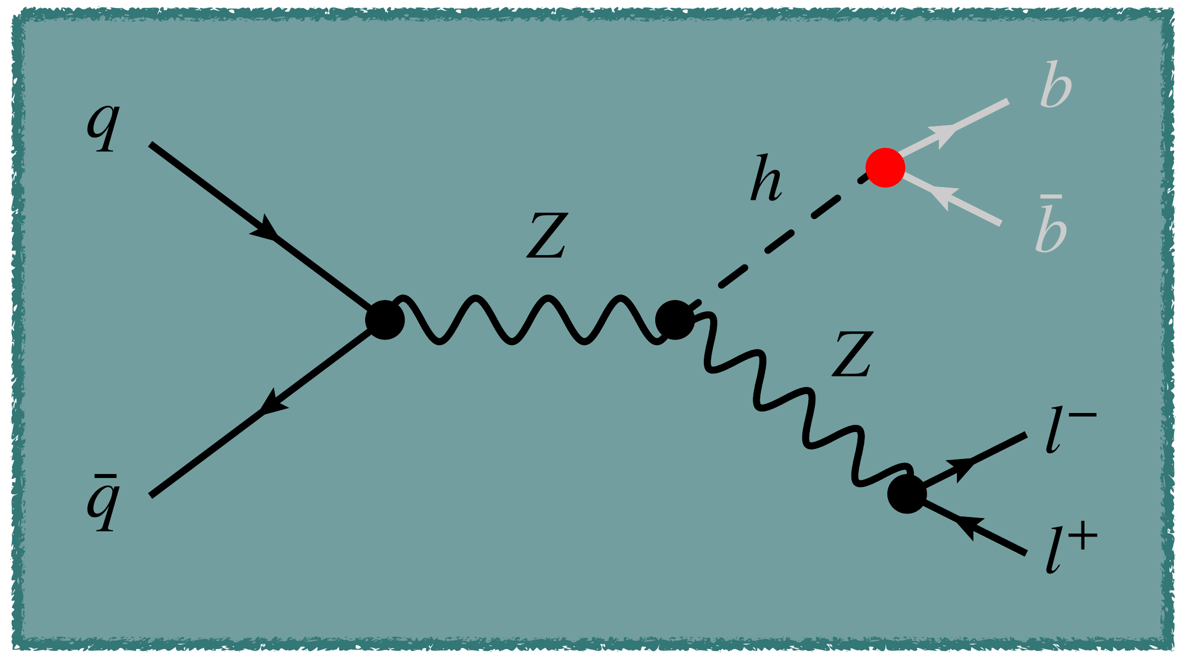

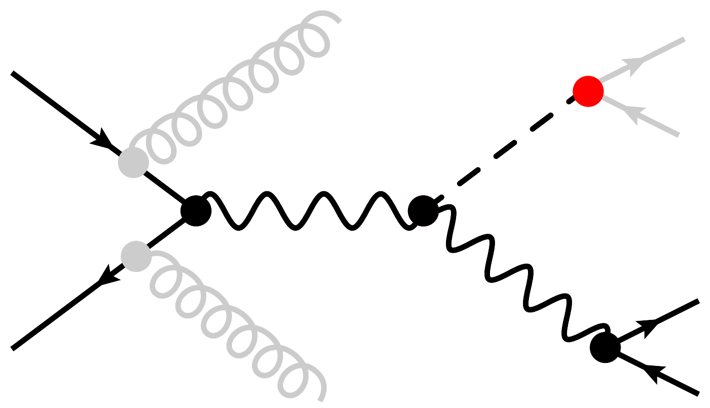

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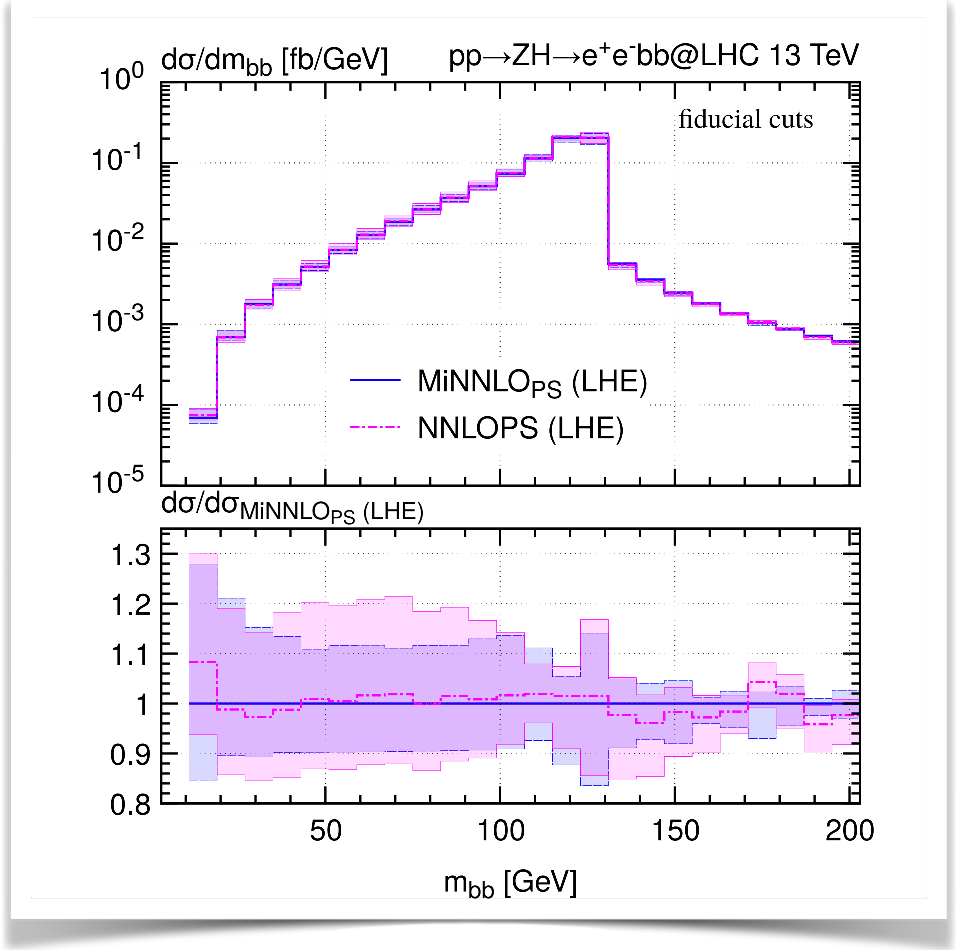

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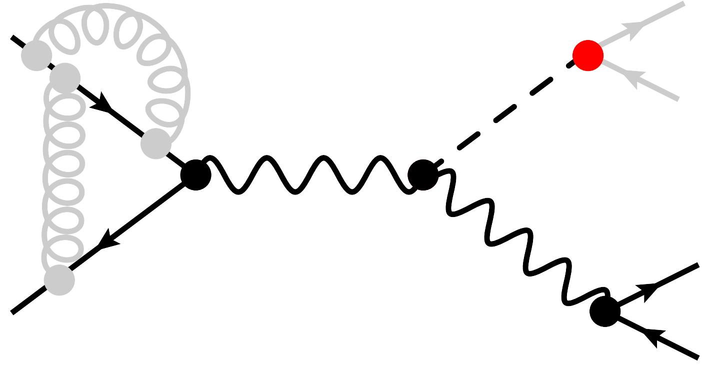

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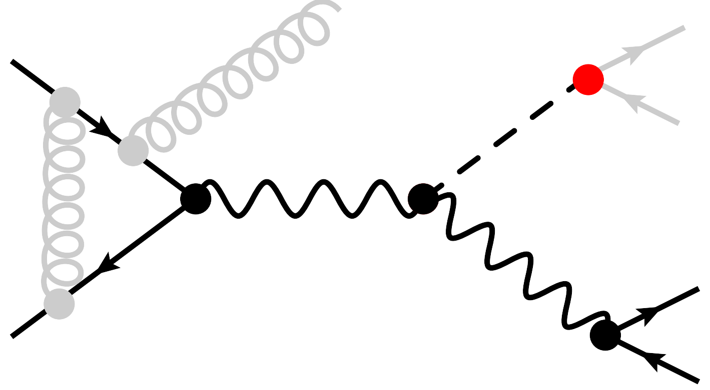

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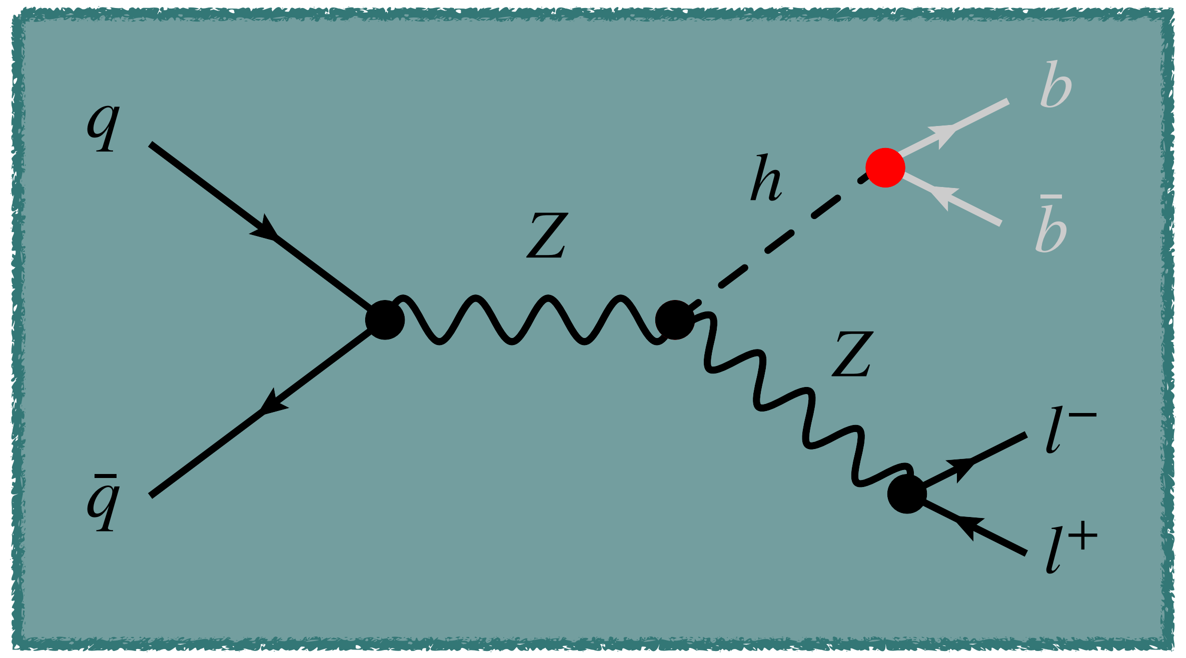

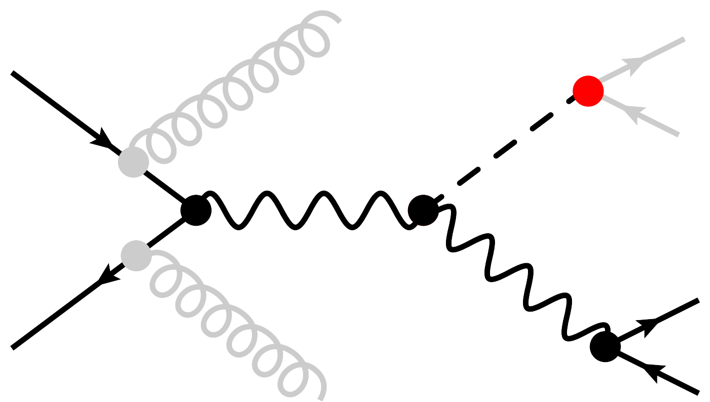

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1.3 SMEFT

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- What about **new effects**?

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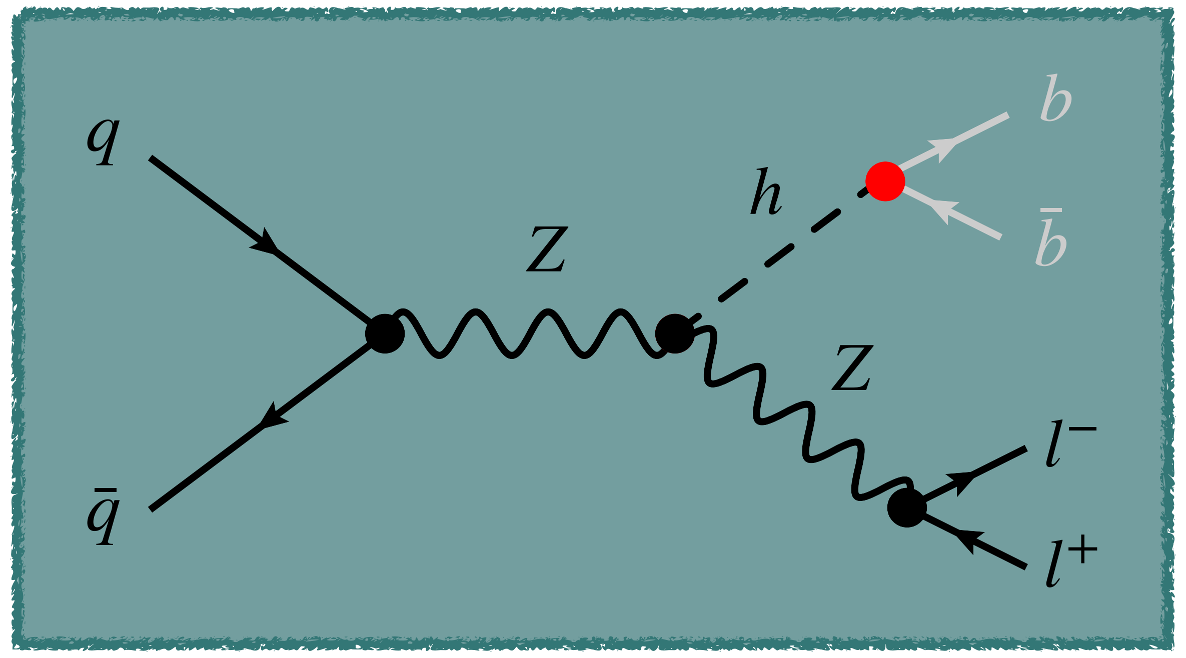

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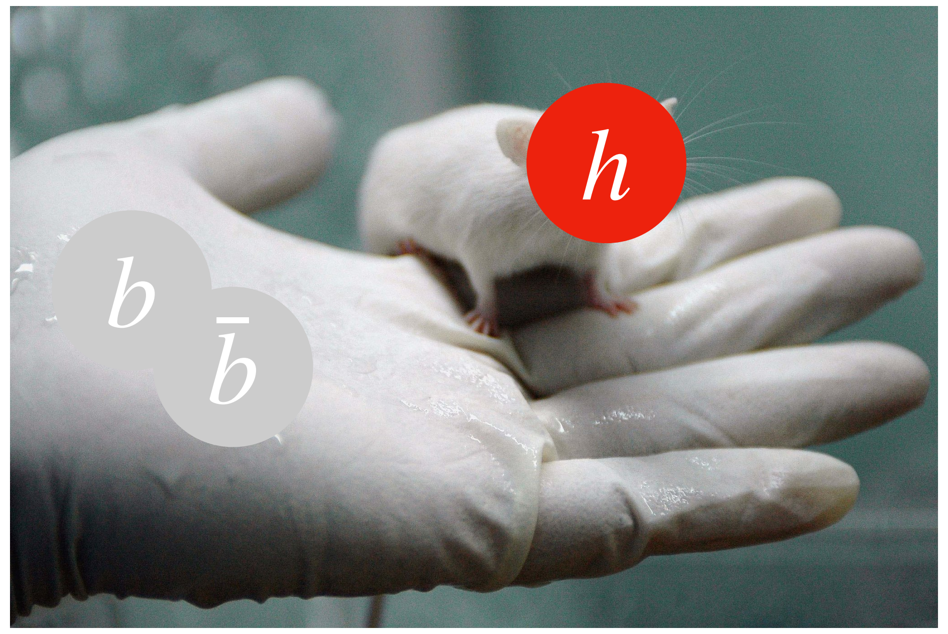

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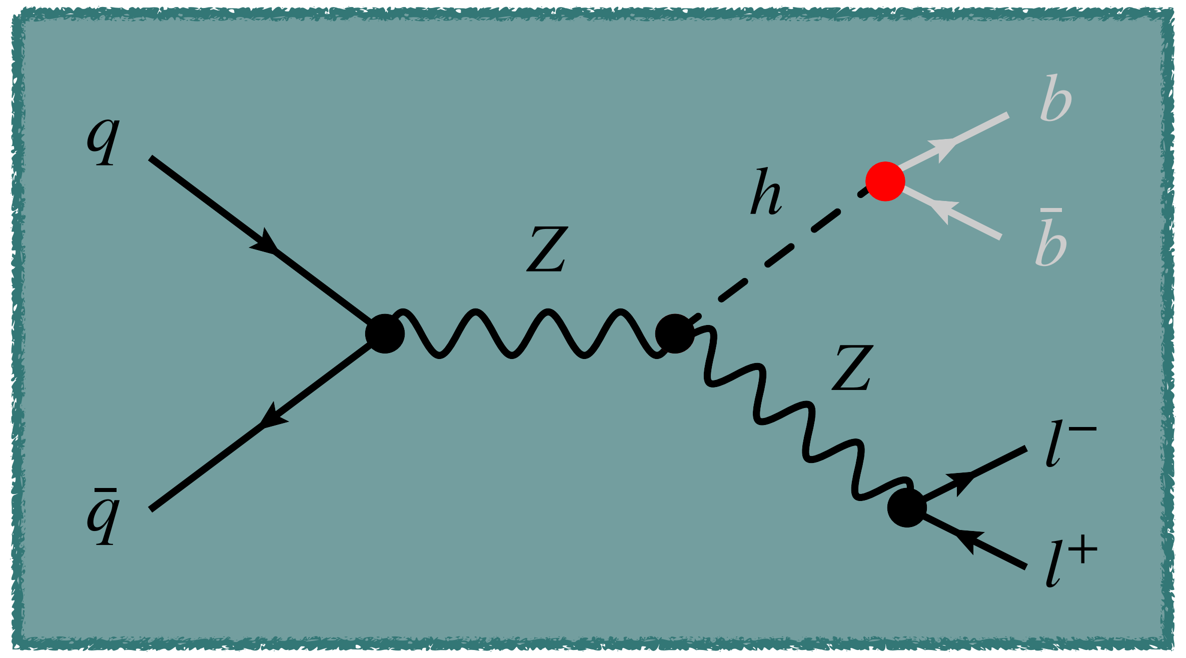

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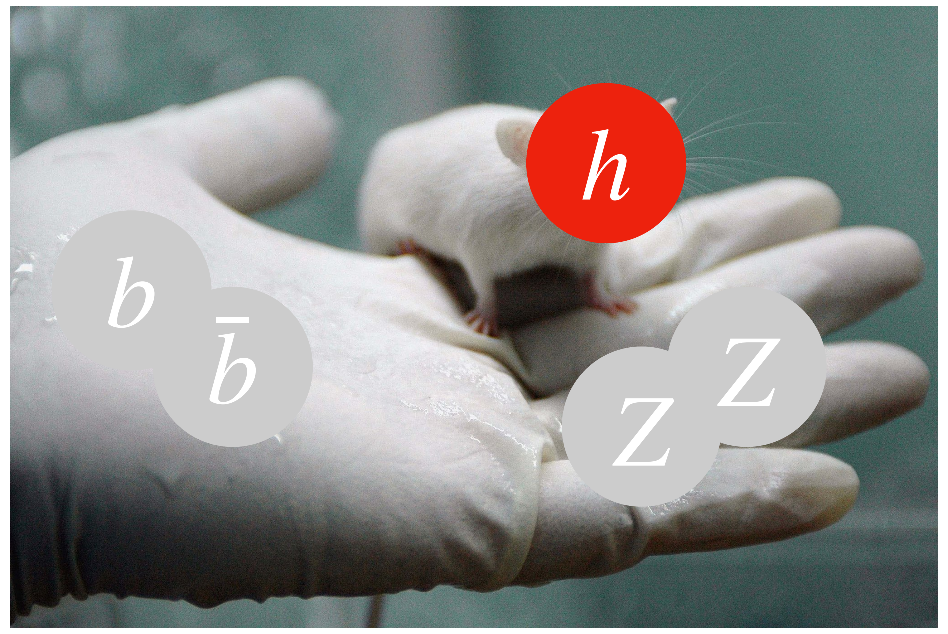

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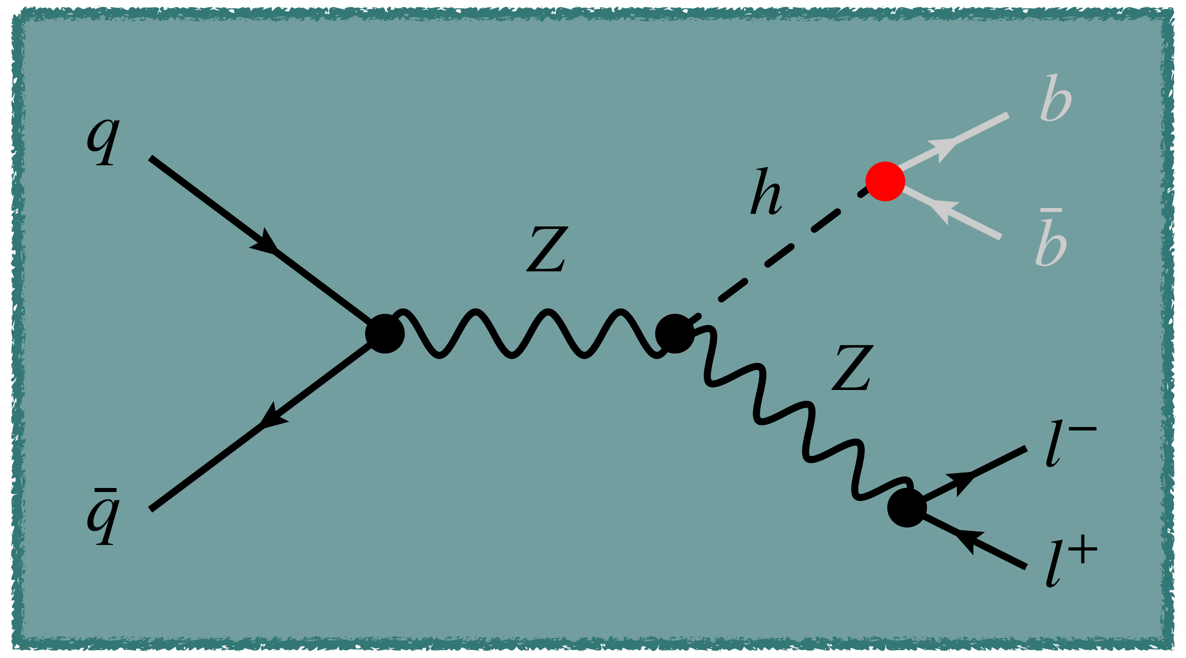

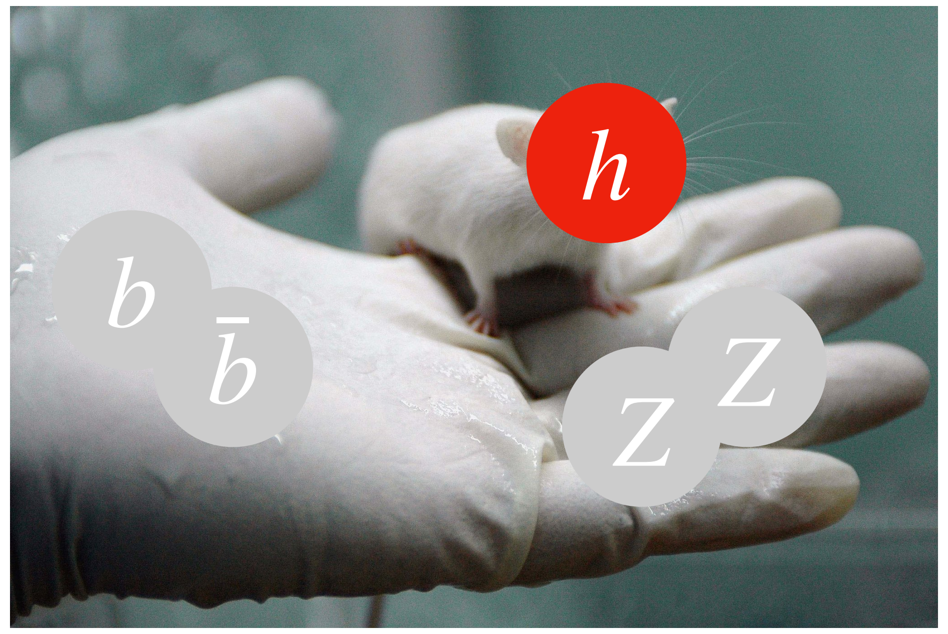

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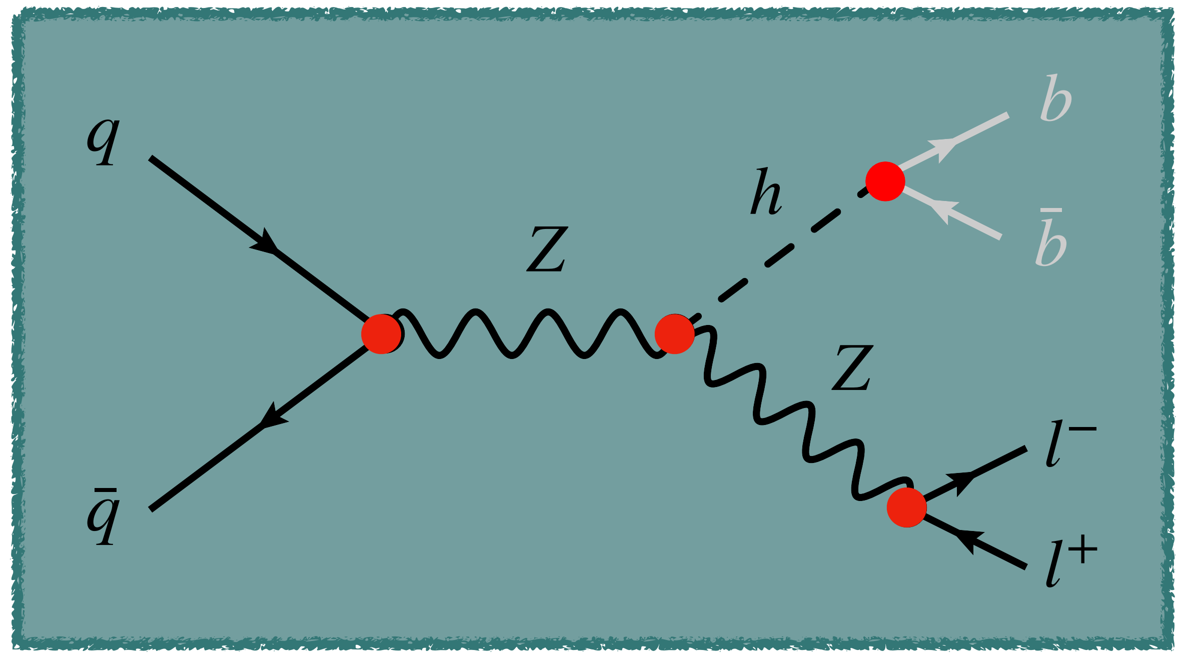

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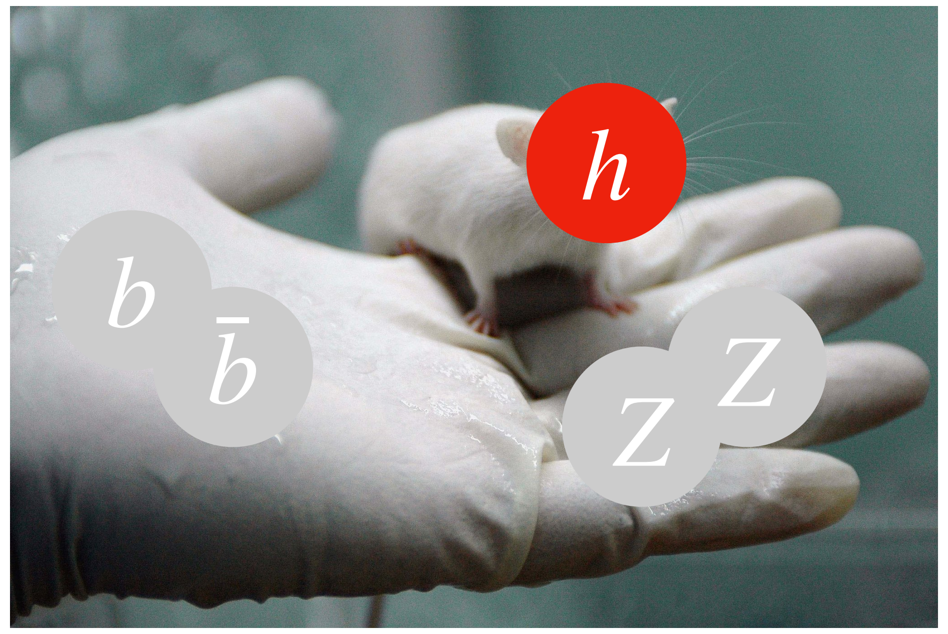

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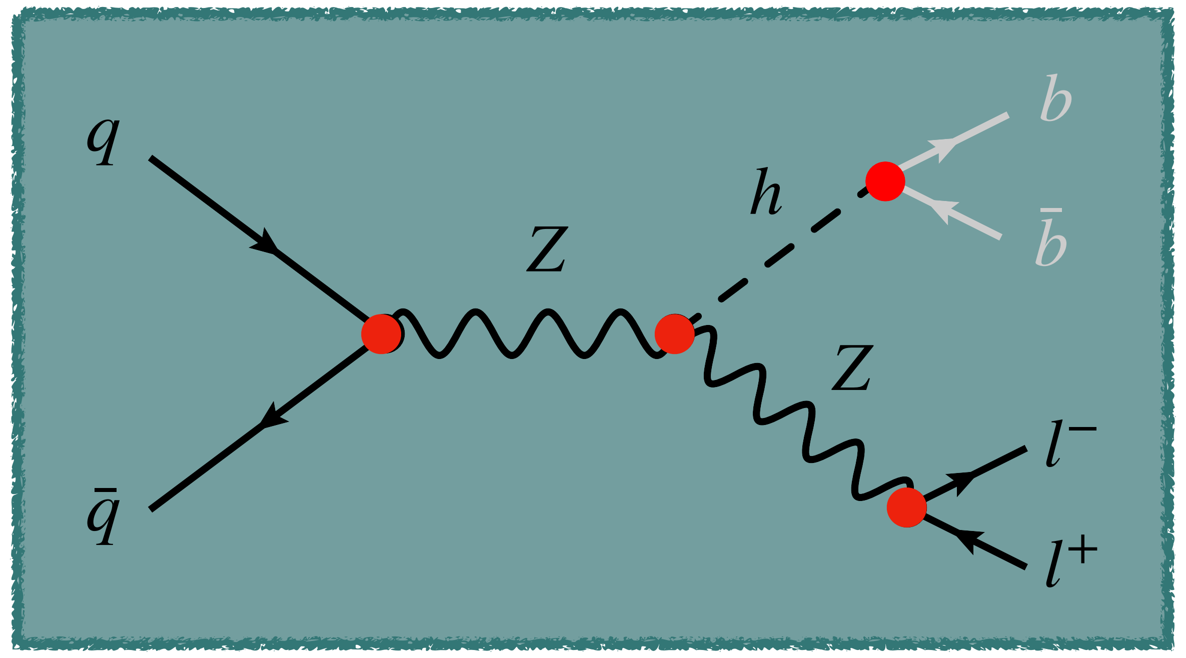

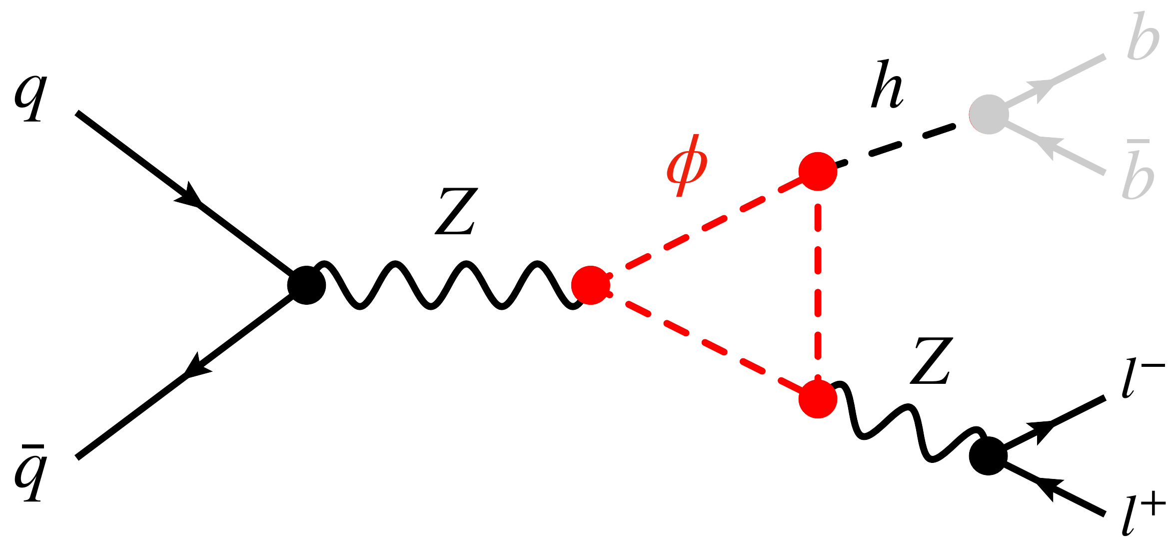

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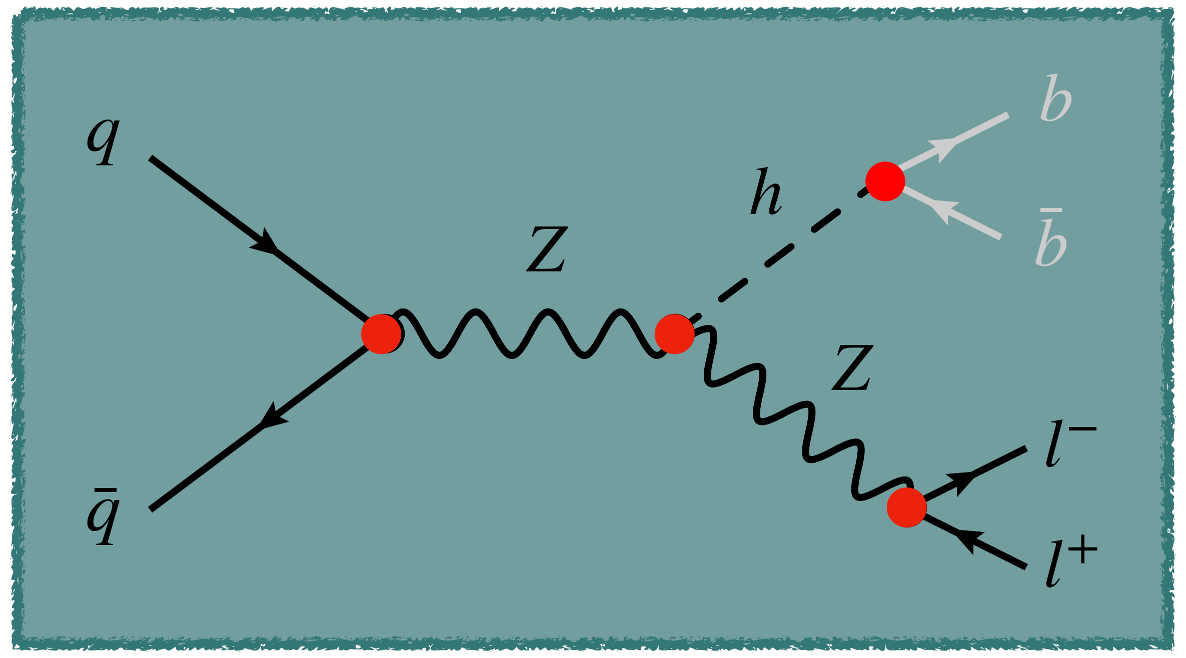

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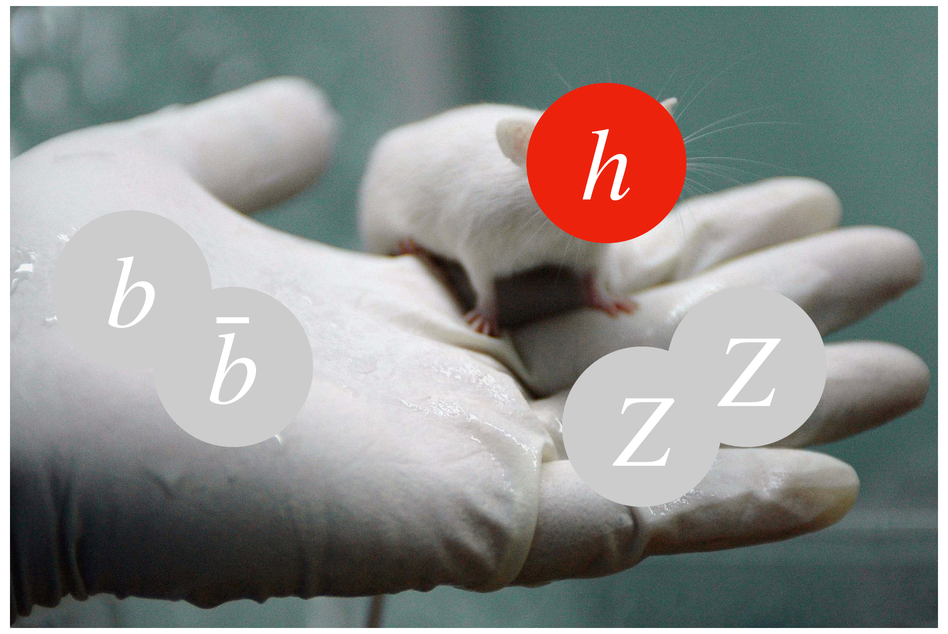

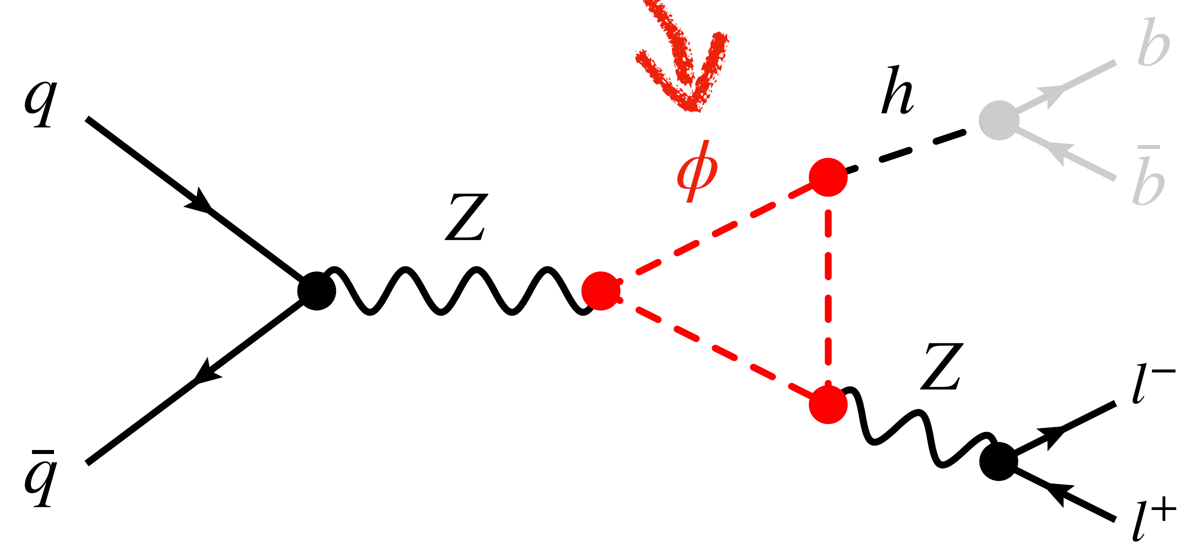

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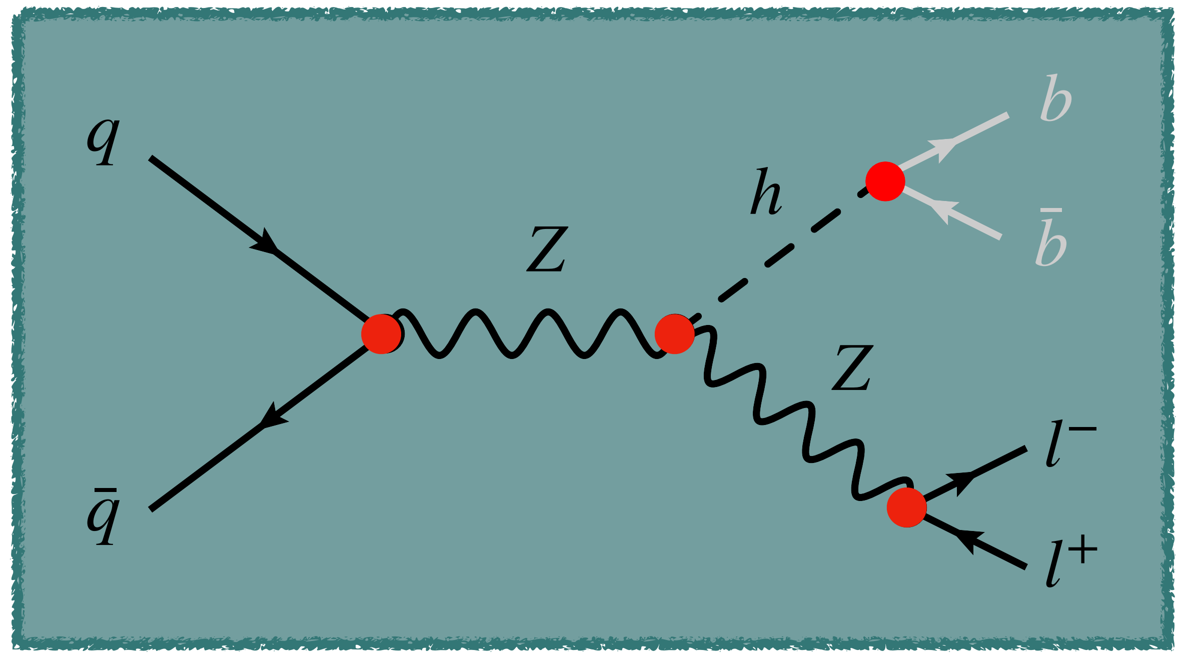

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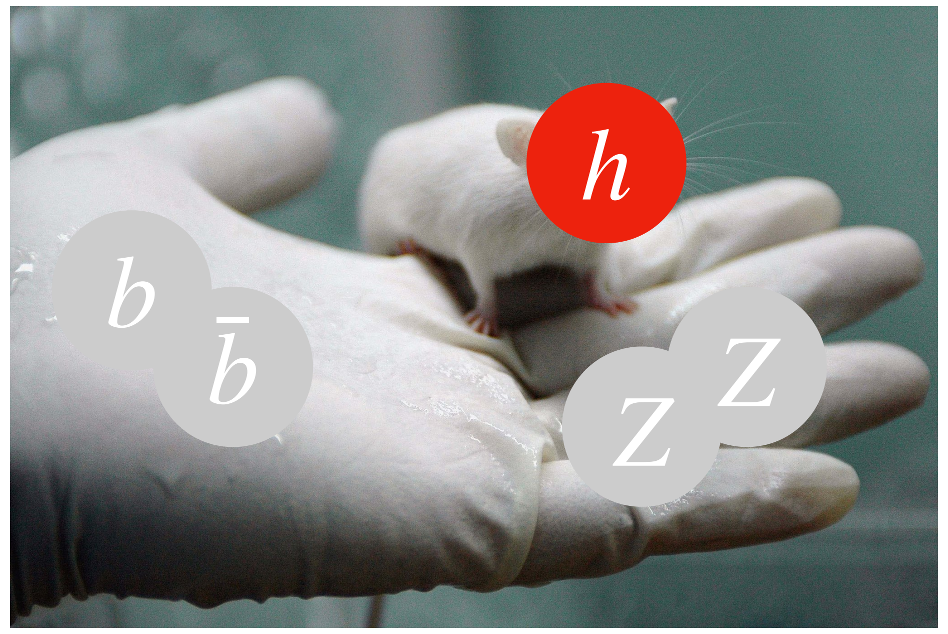

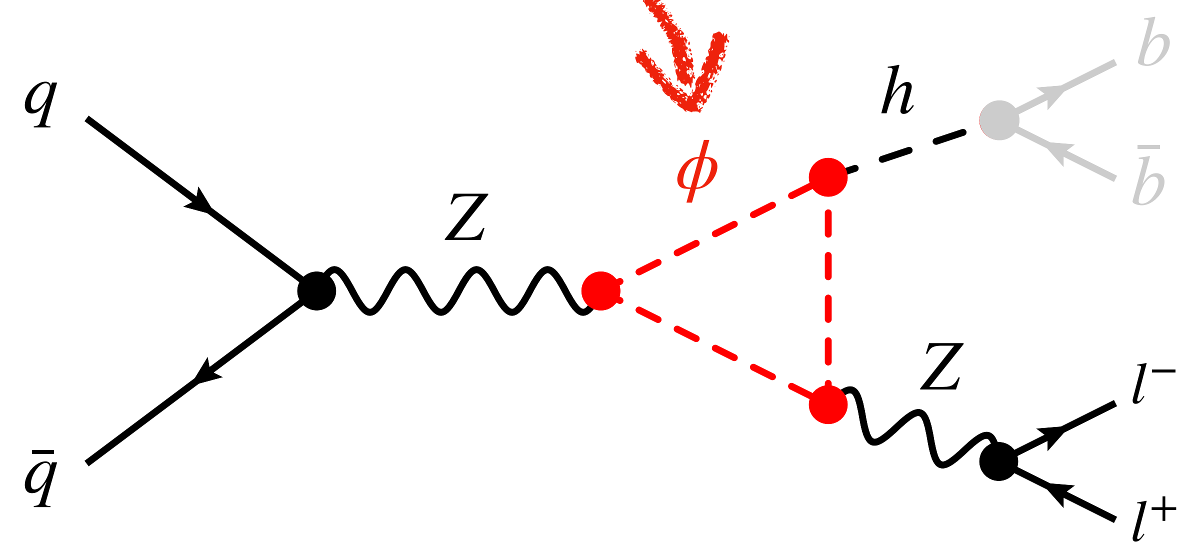

High scale $\Lambda_{UV} \sim M_\phi$

1. Introduction

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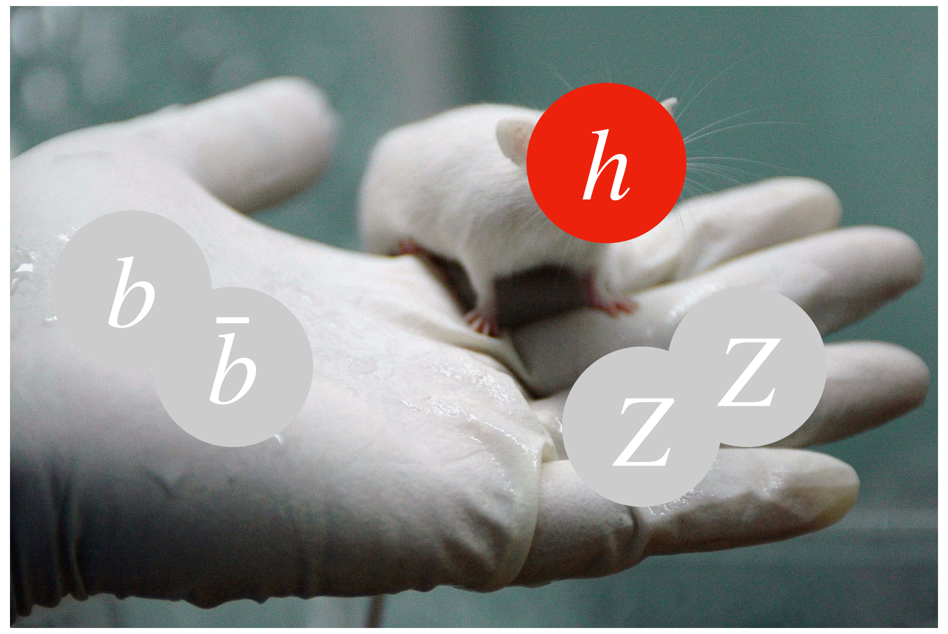

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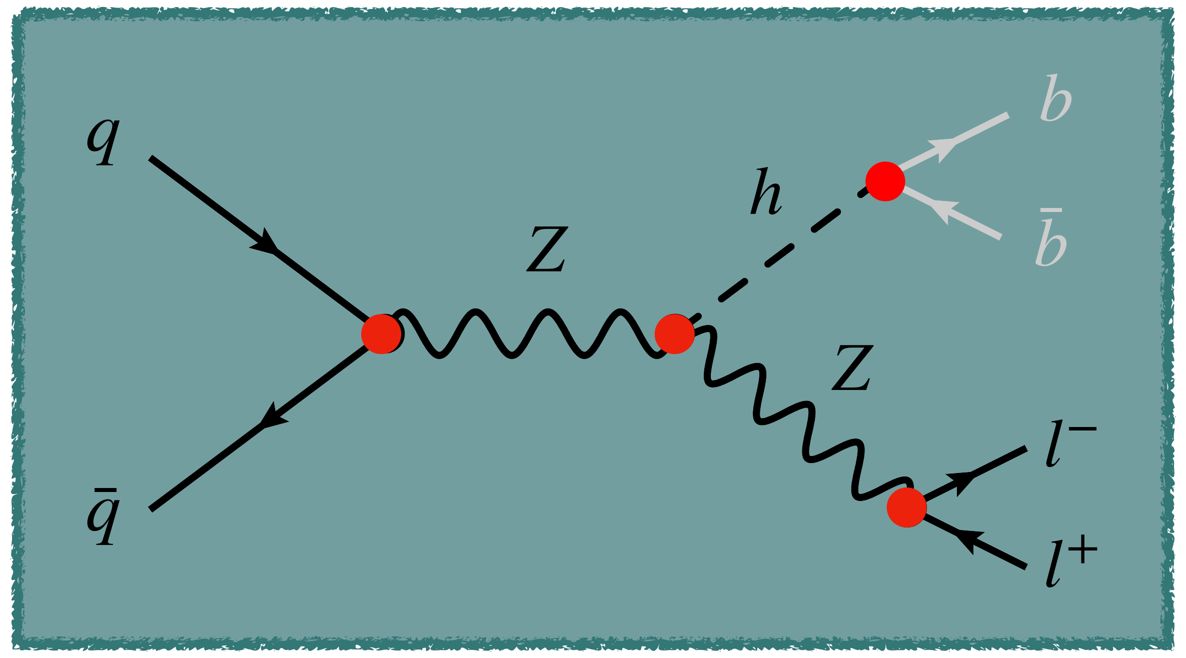

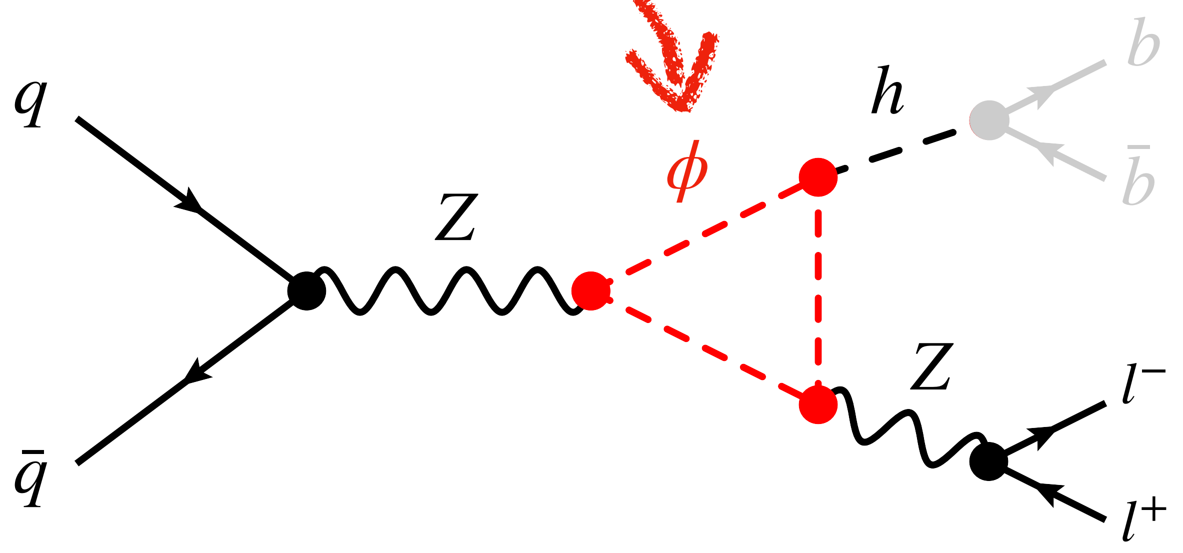

LHC scale Λ_{LHC}

High scale $\Lambda_{UV} \sim M_\phi$

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1.3 SMEFT

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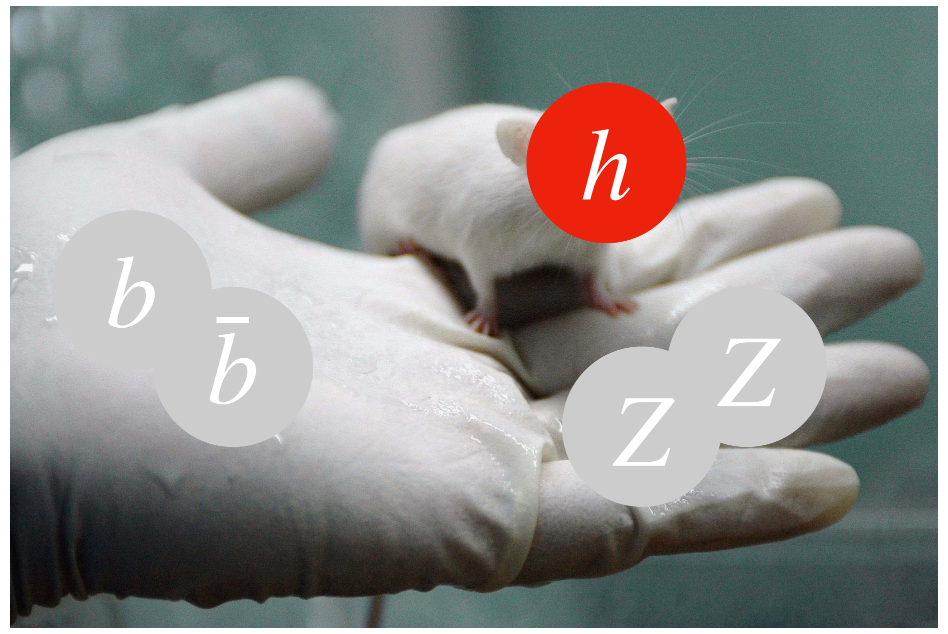

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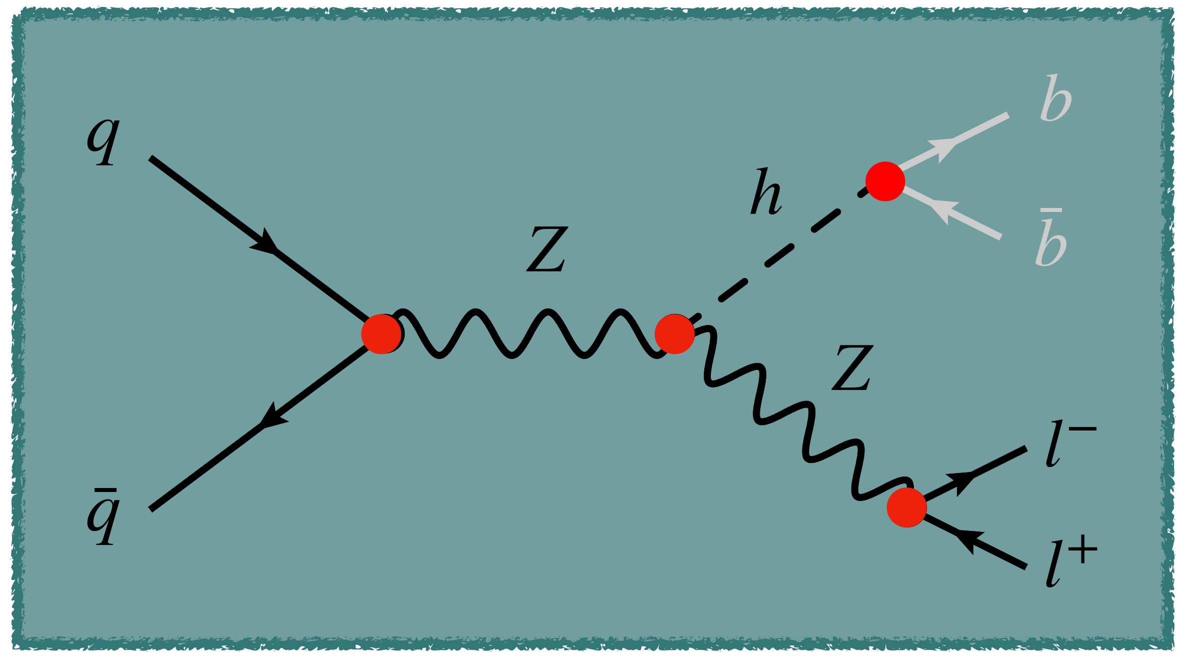

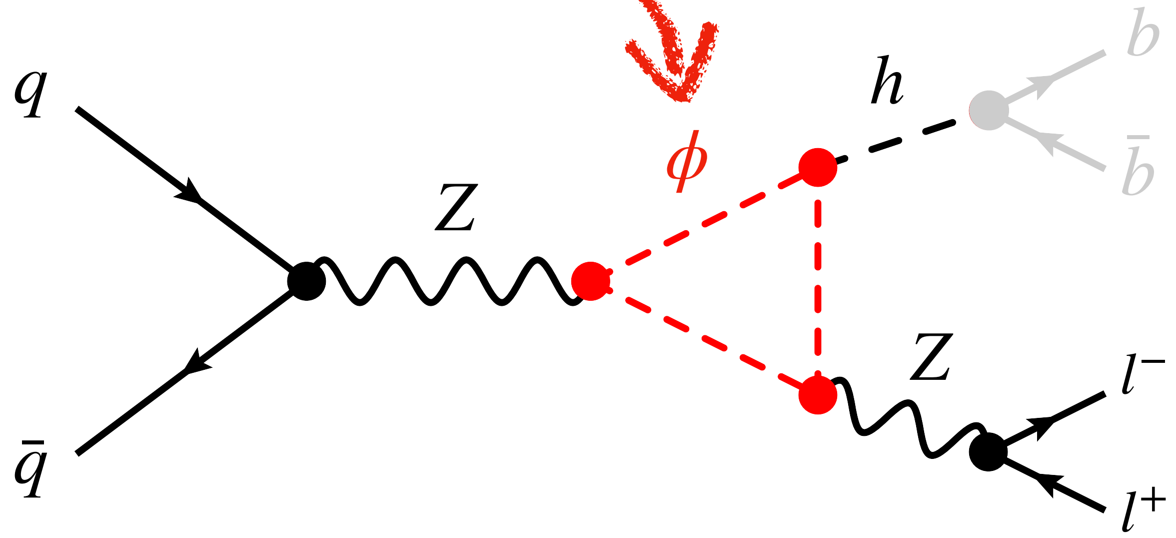

LHC scale Λ_{LHC}

High scale $\Lambda_{UV} \sim M_\phi$

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1. Introduction

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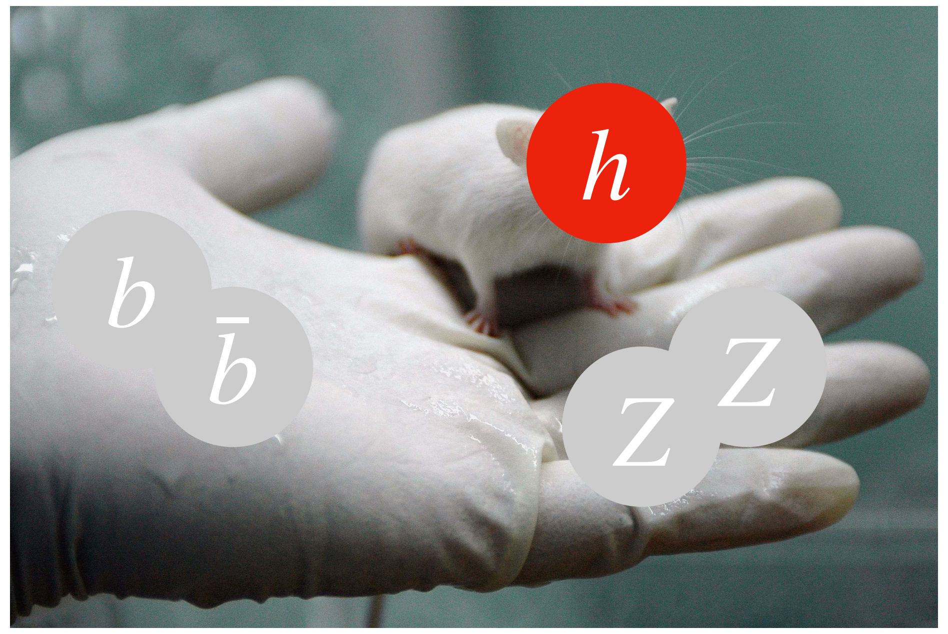

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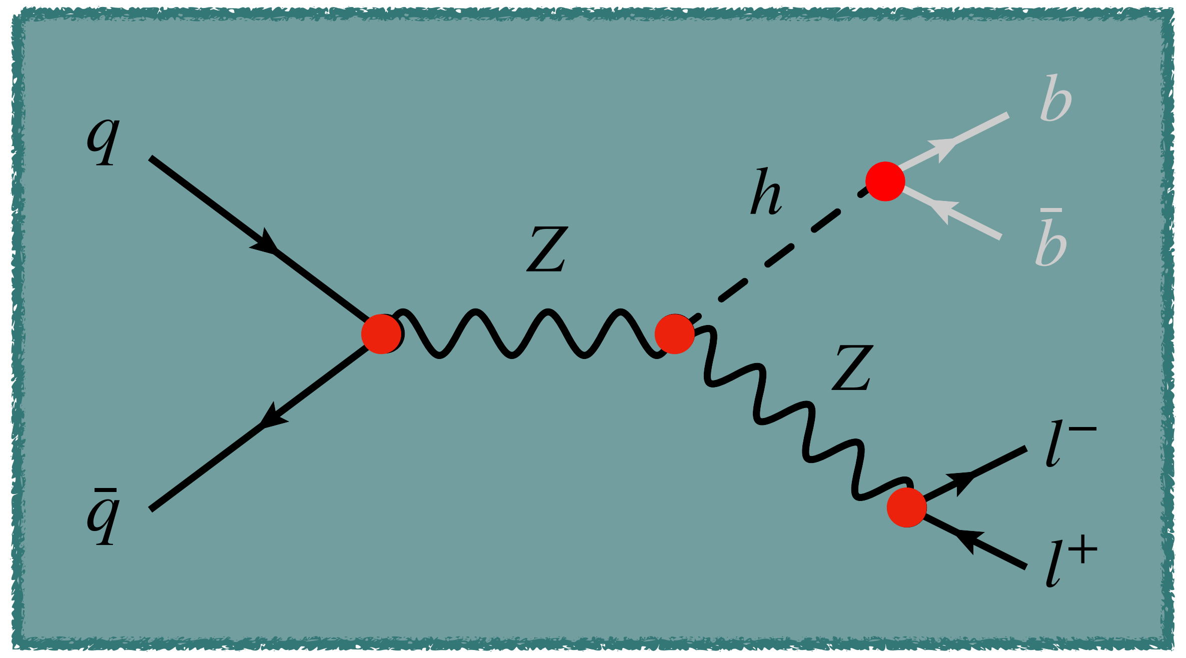

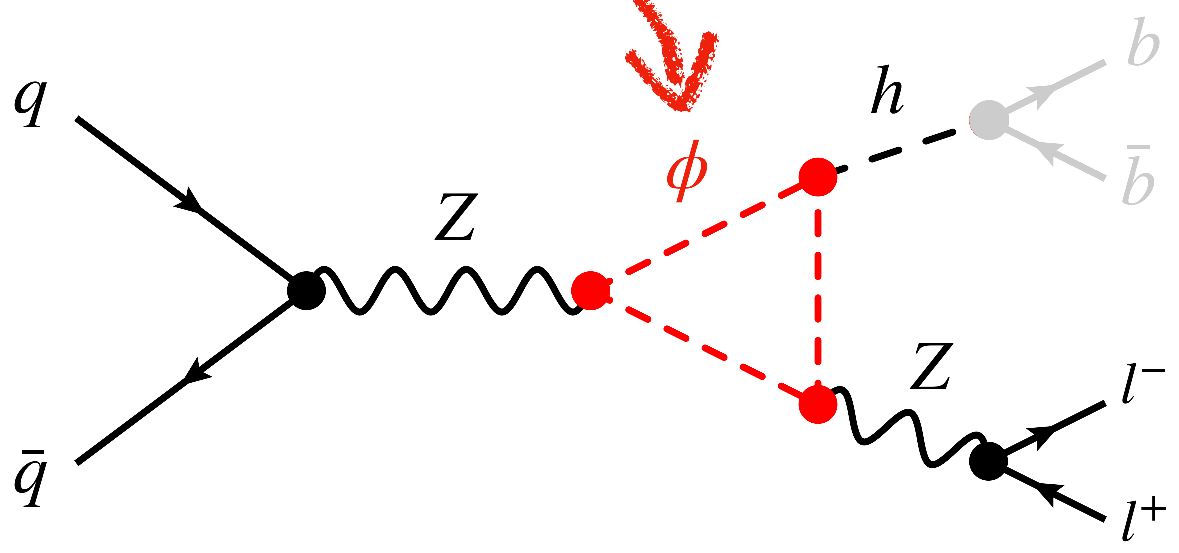

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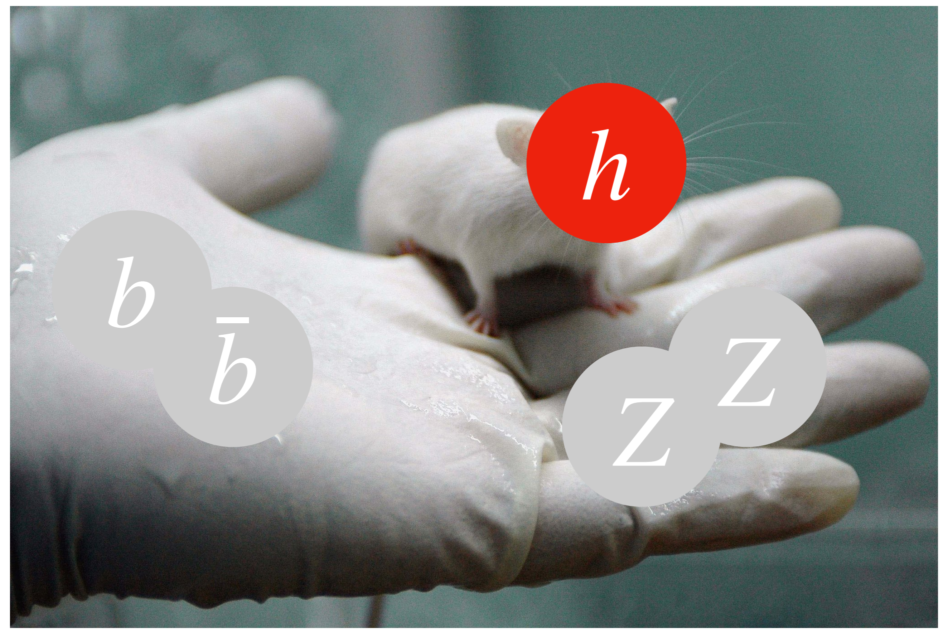

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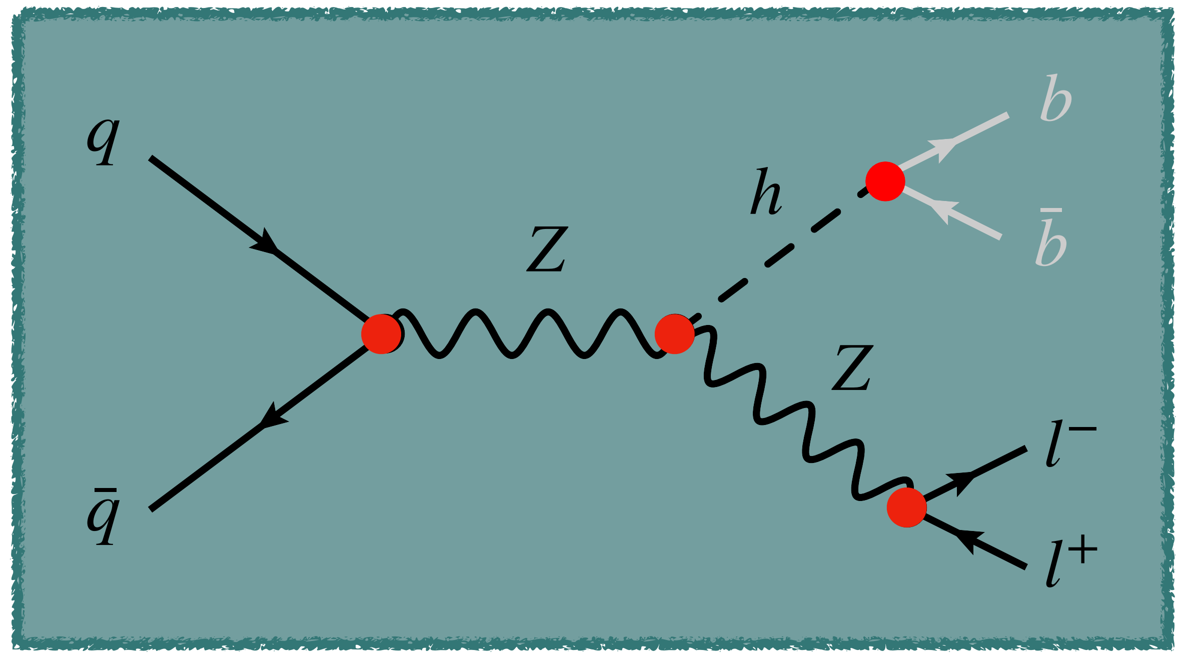

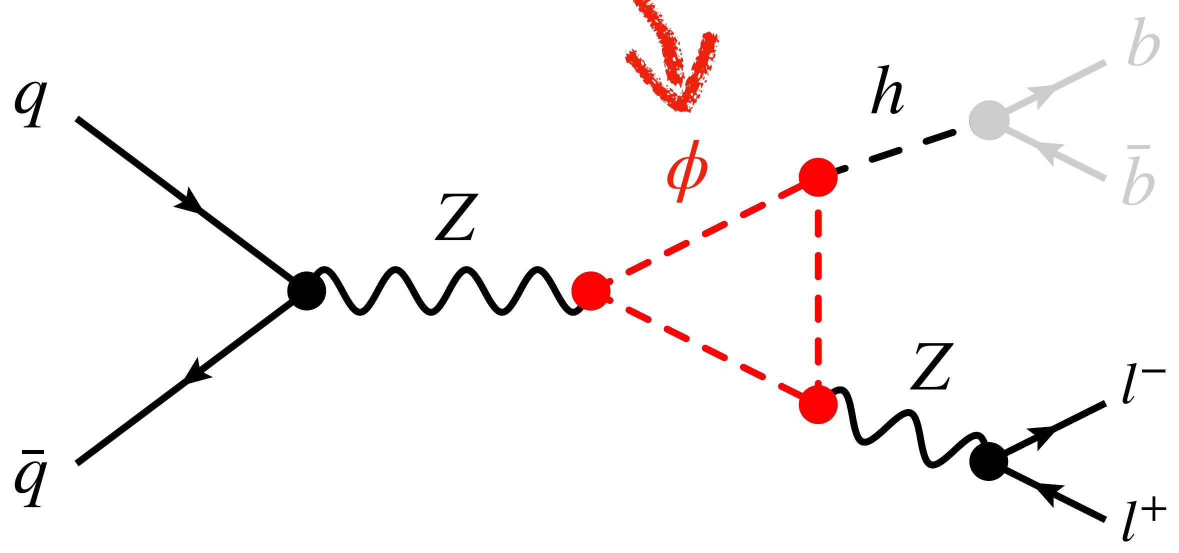

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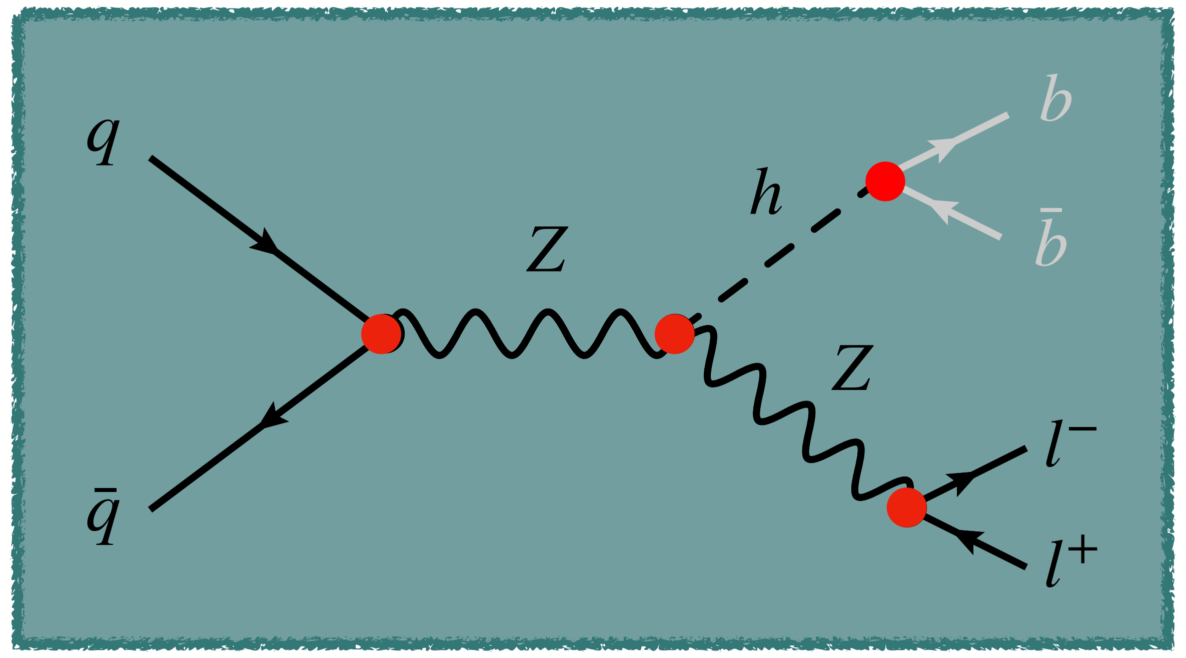

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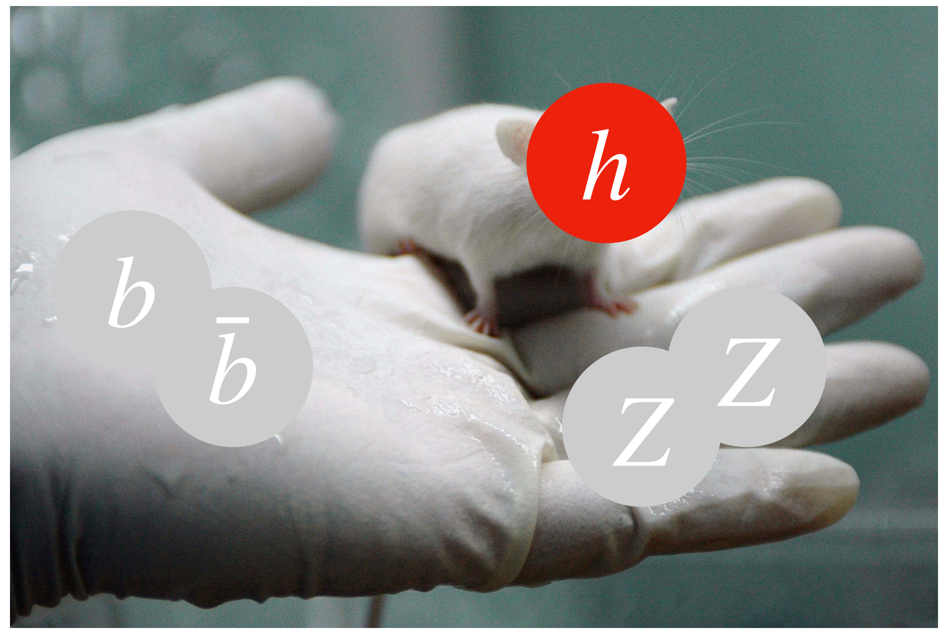

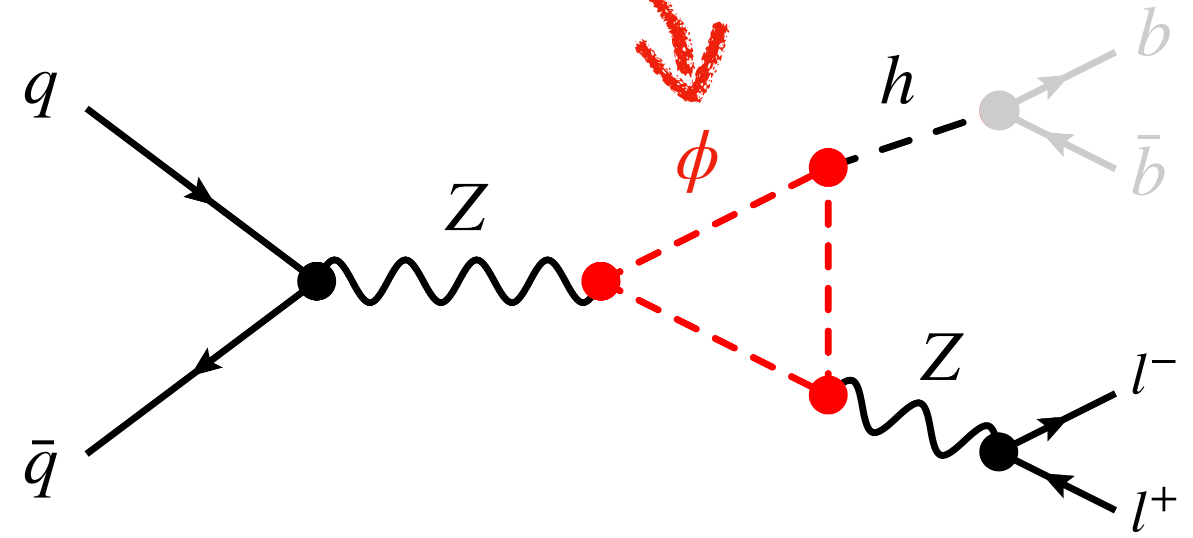

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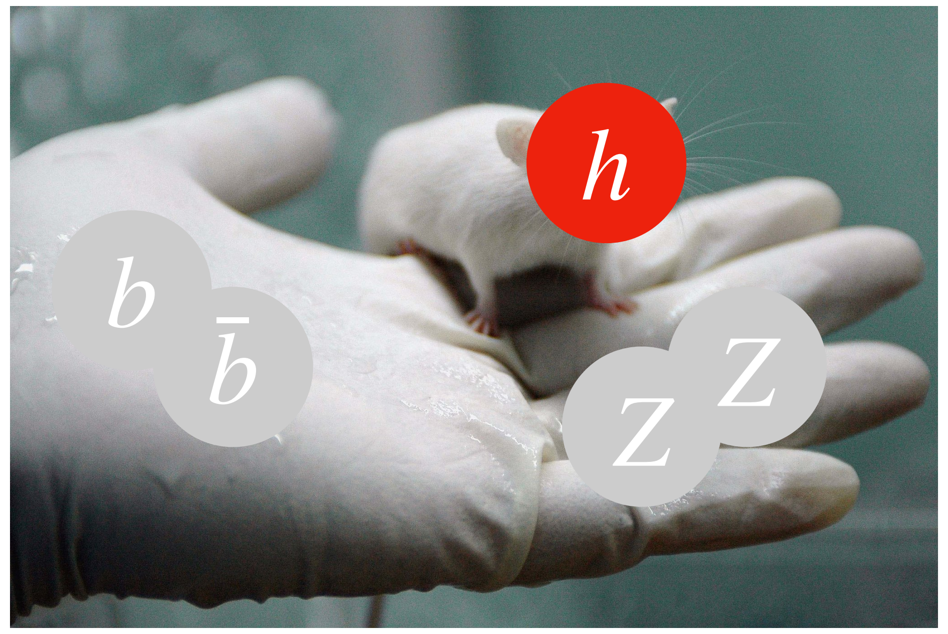

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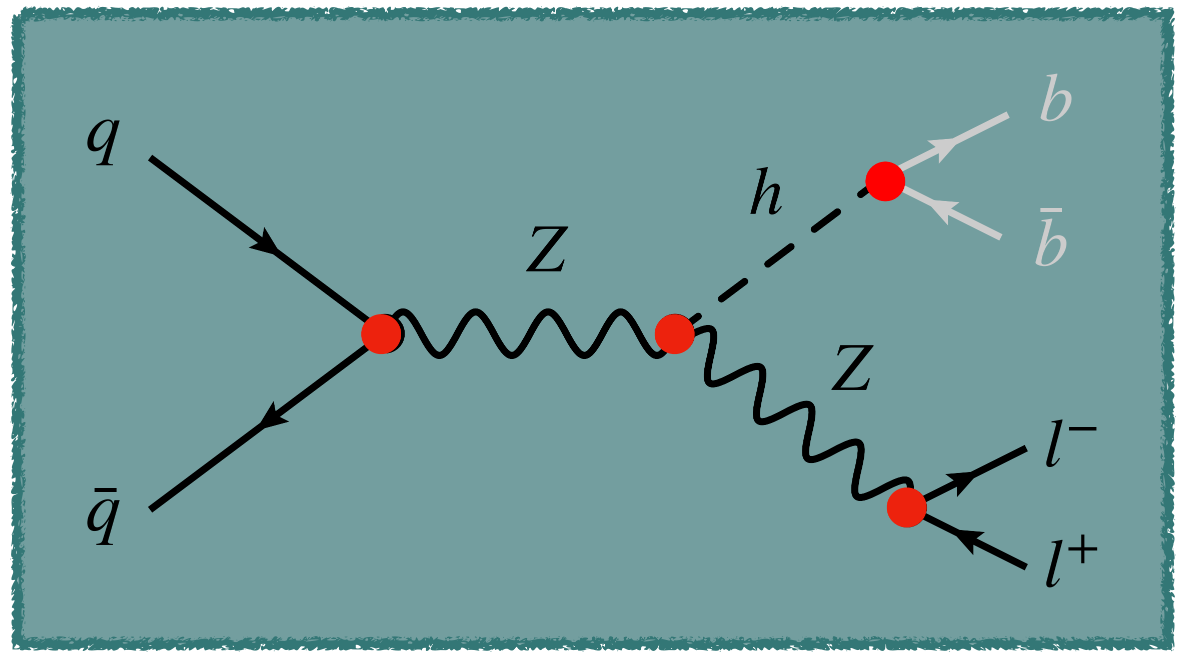

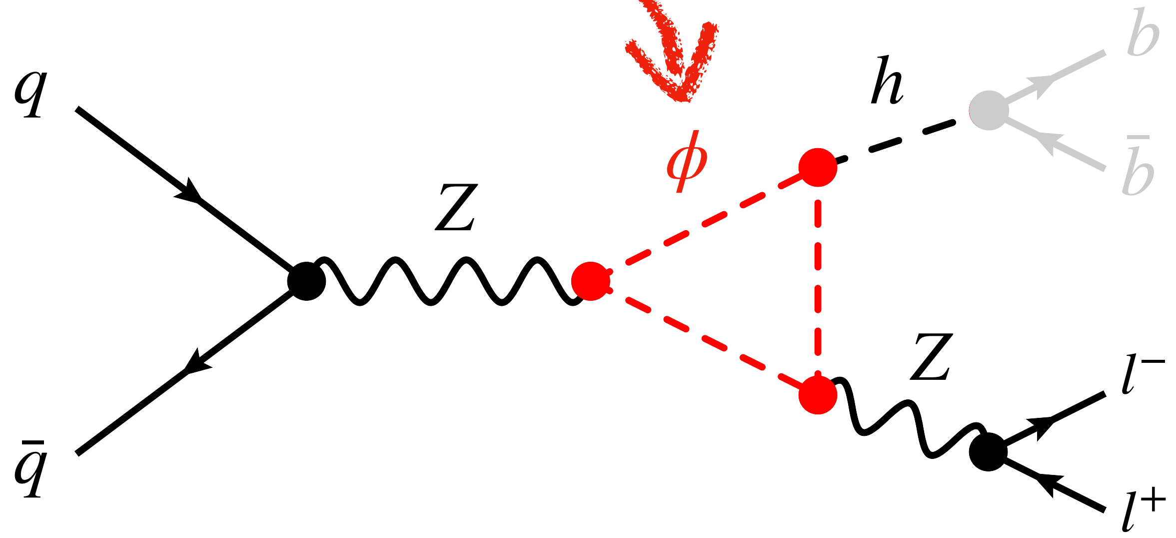

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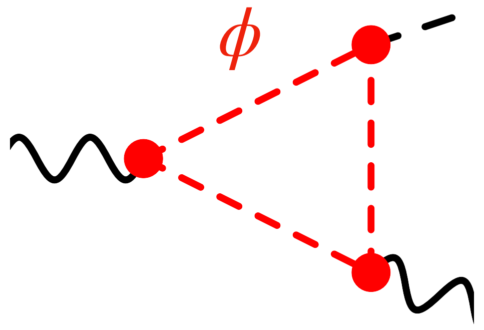

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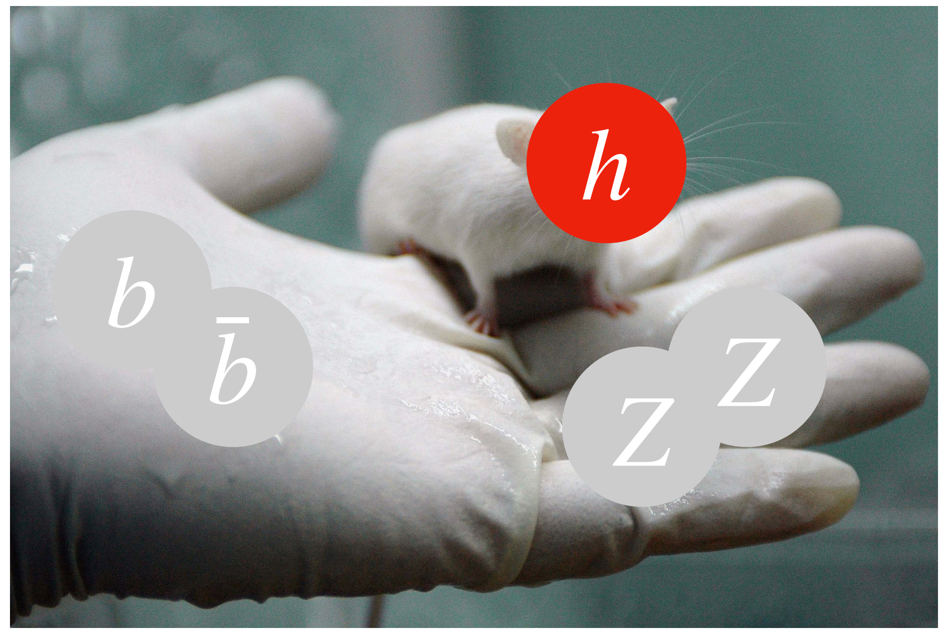

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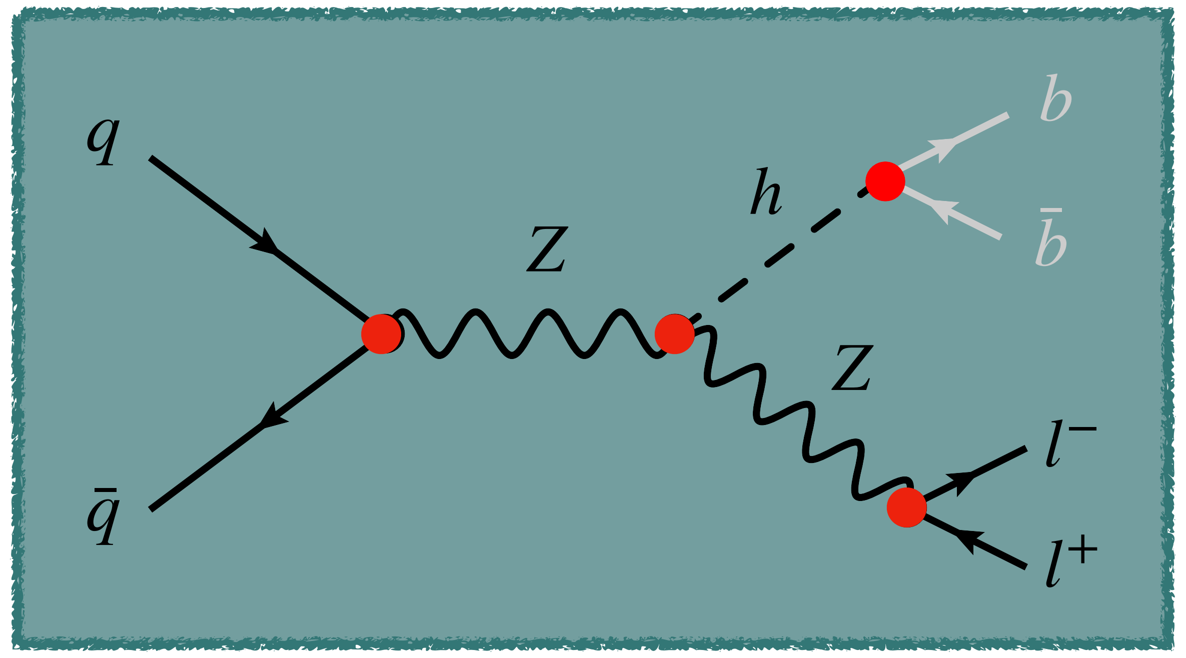

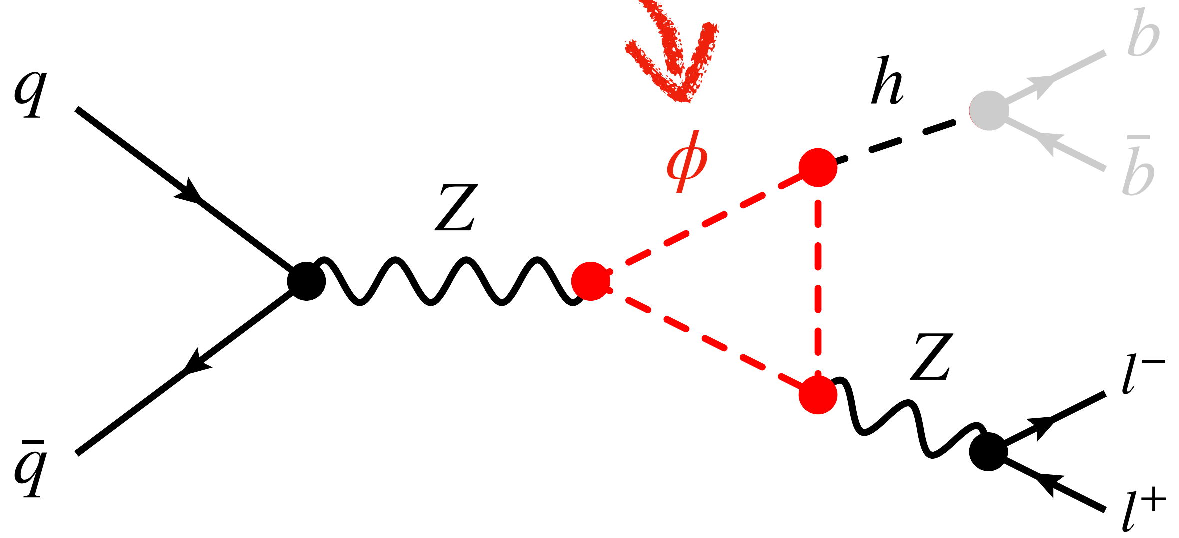

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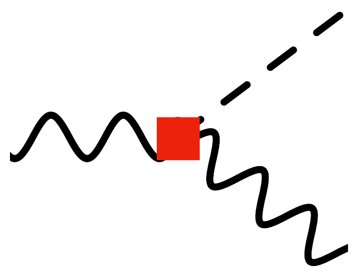

Anomalous coupling (SMEFT)

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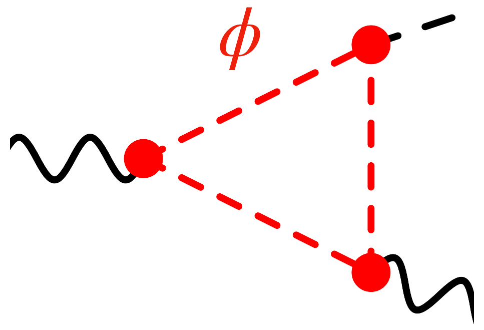

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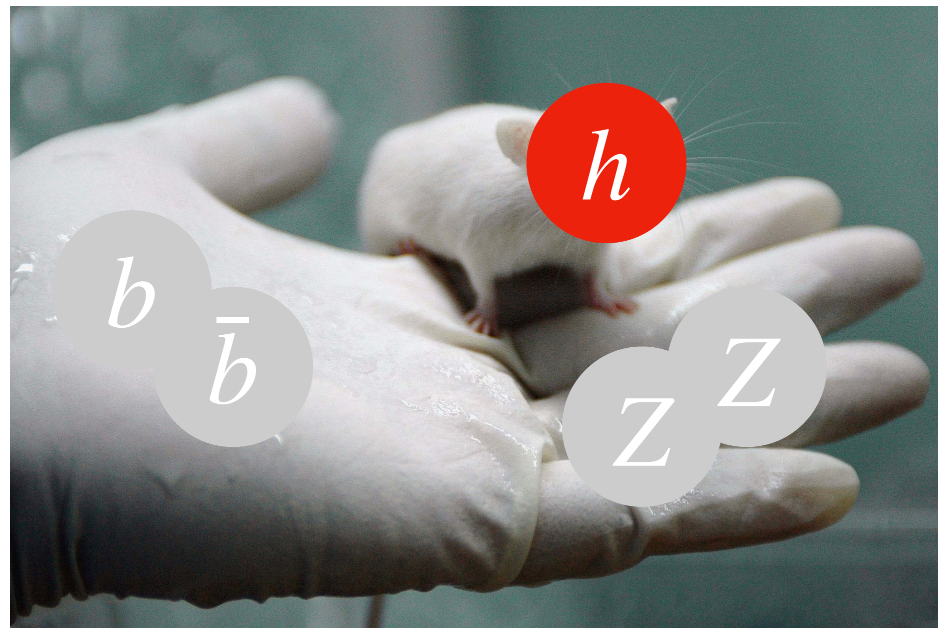
1.3 SMEFT



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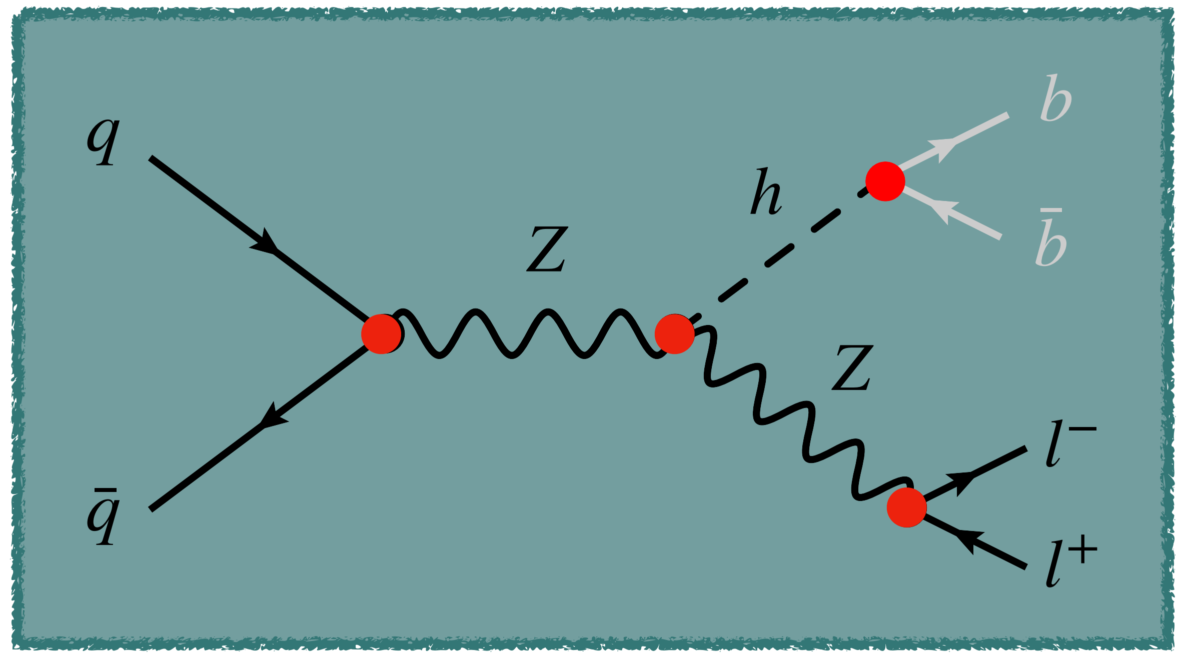

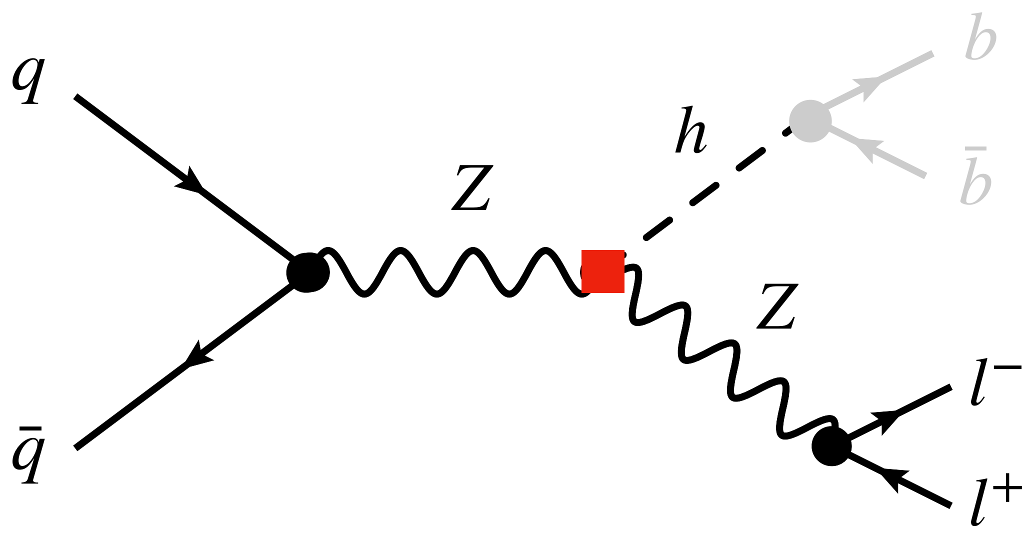

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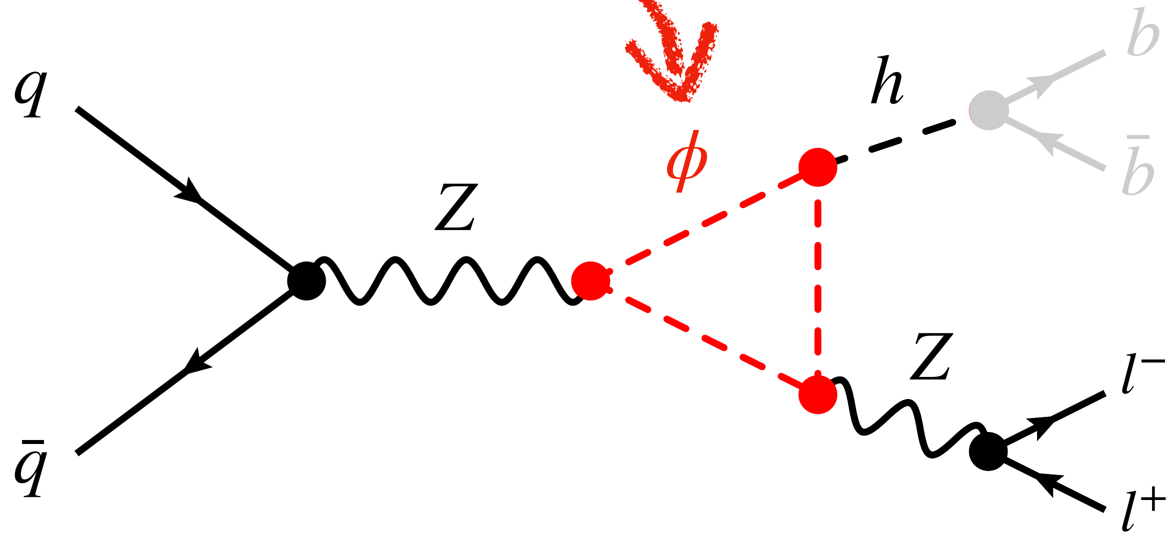

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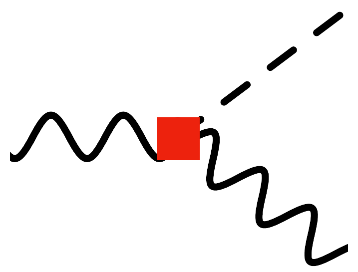

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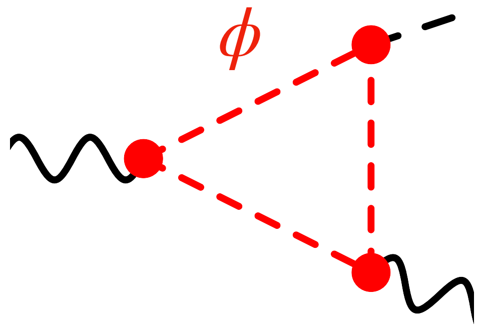

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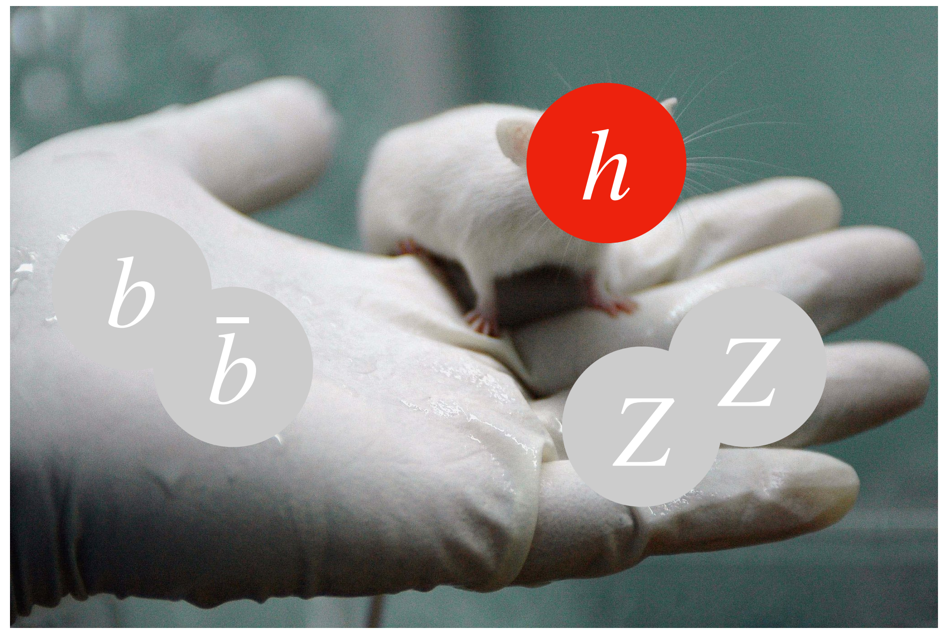

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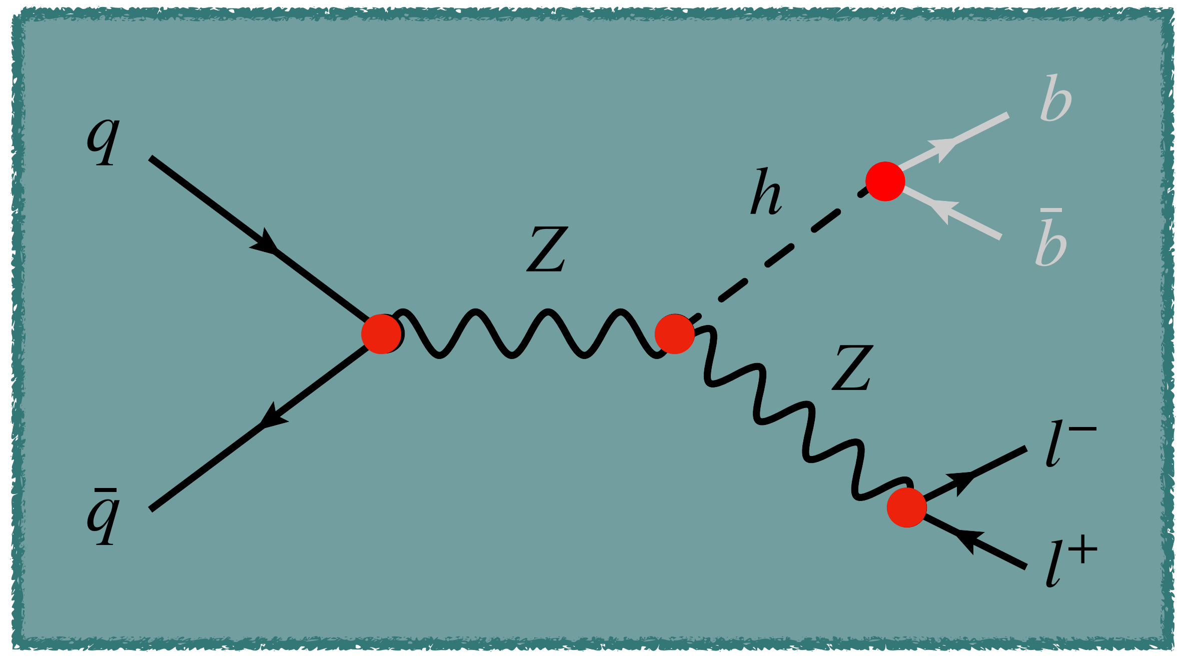

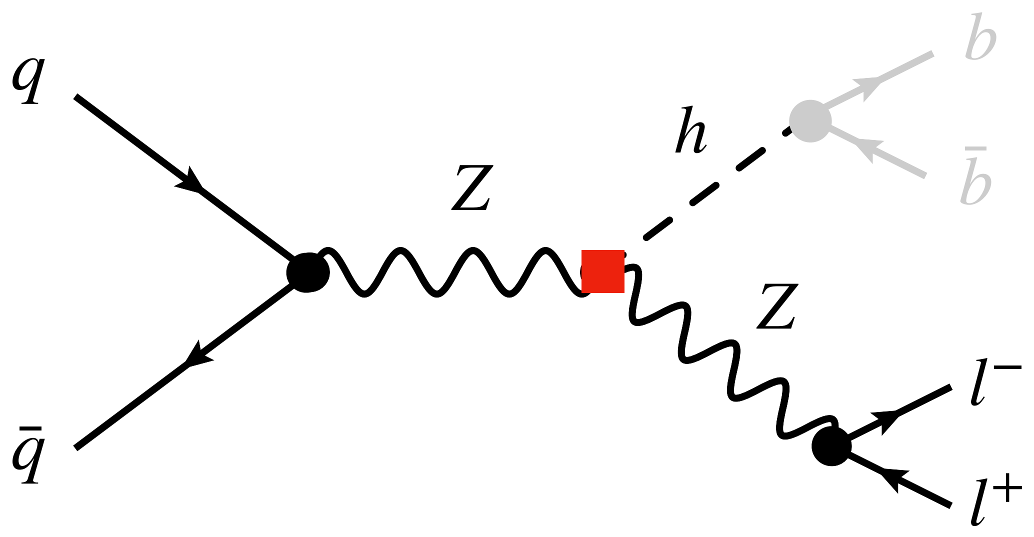

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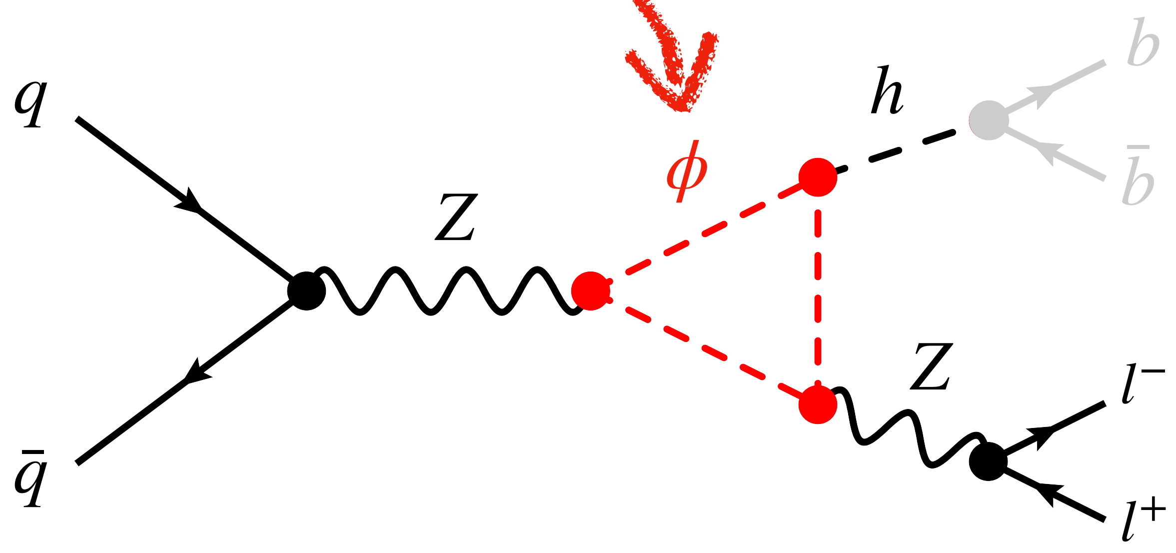

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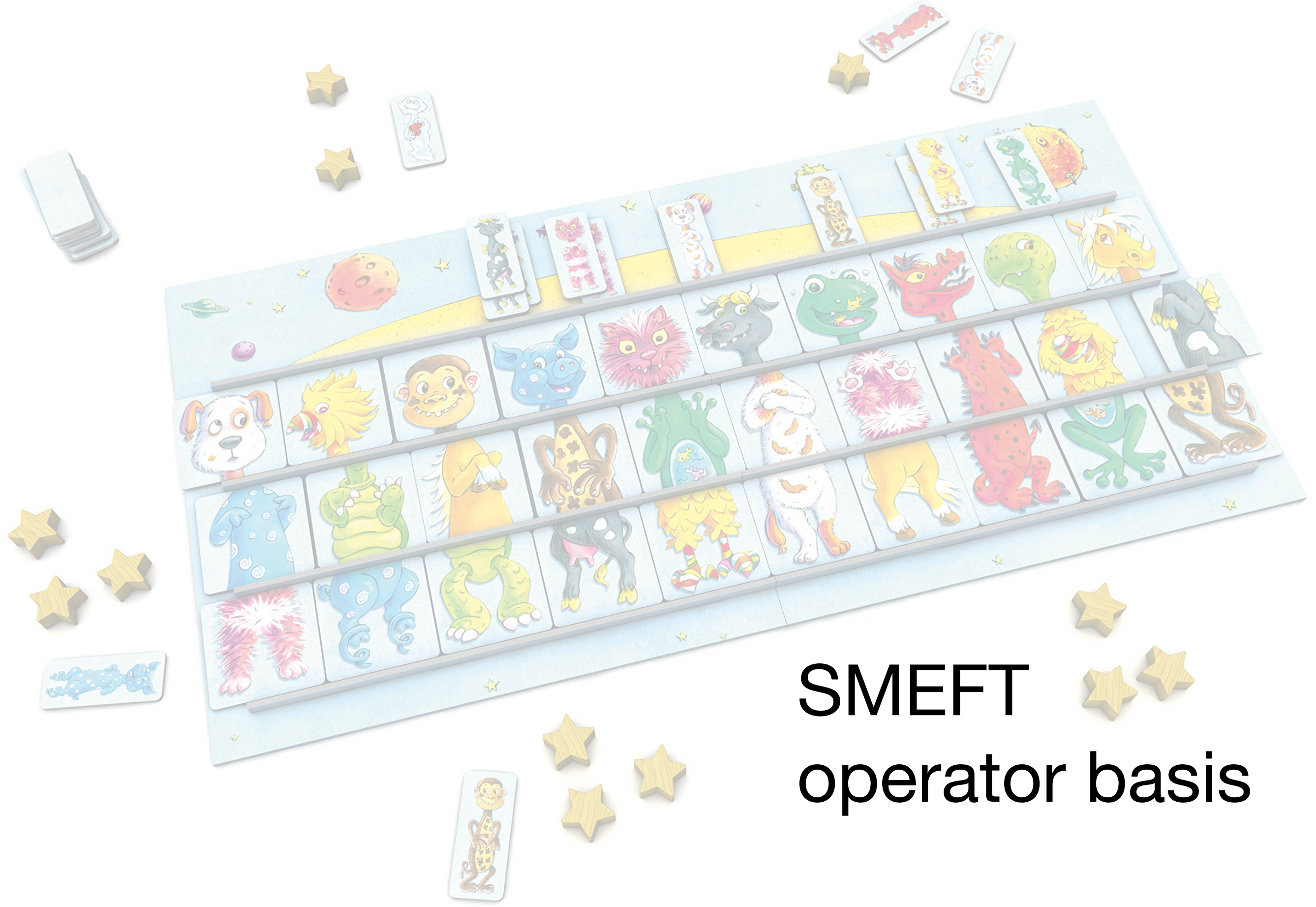
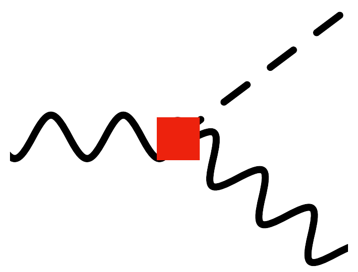


SMEFT
operator basis



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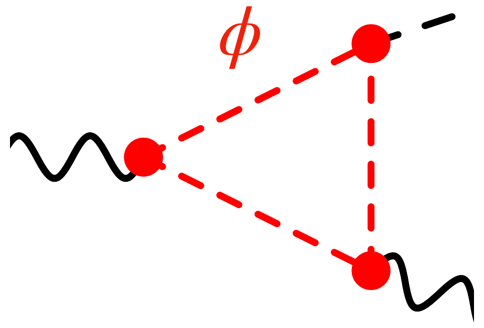

1. Introduction

1.3 SMEFT

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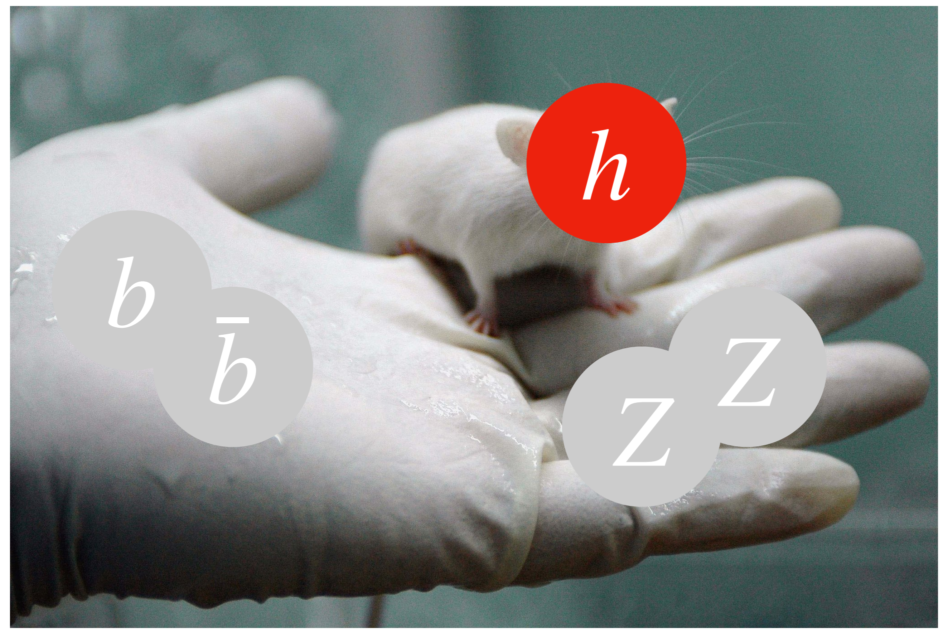

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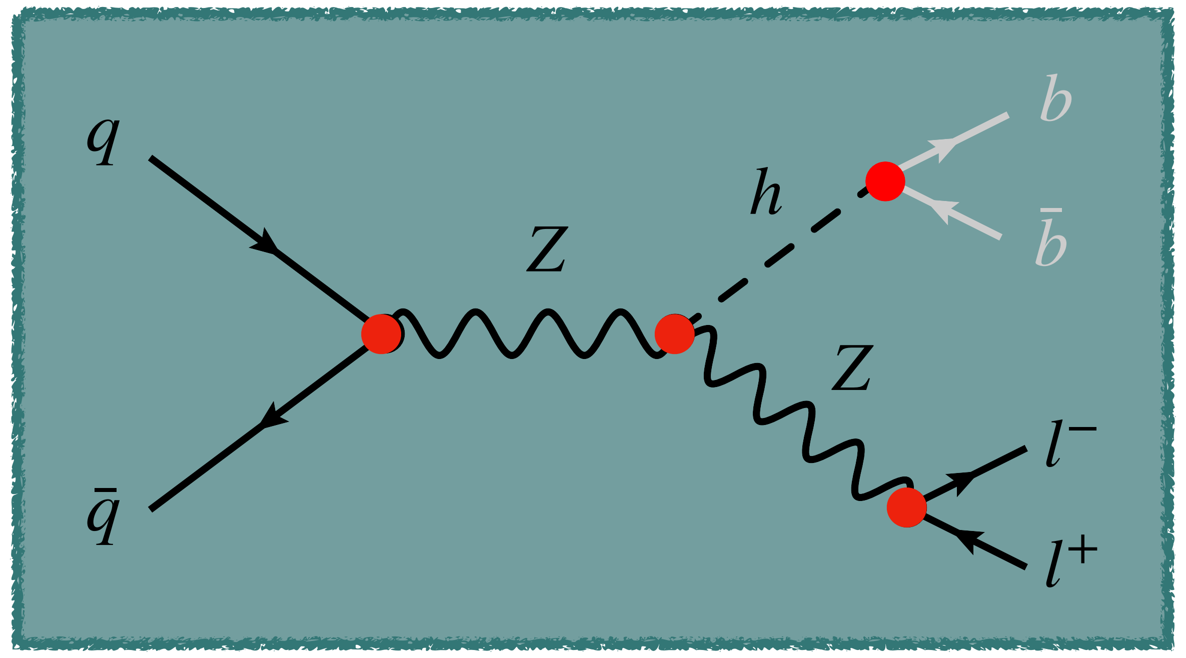

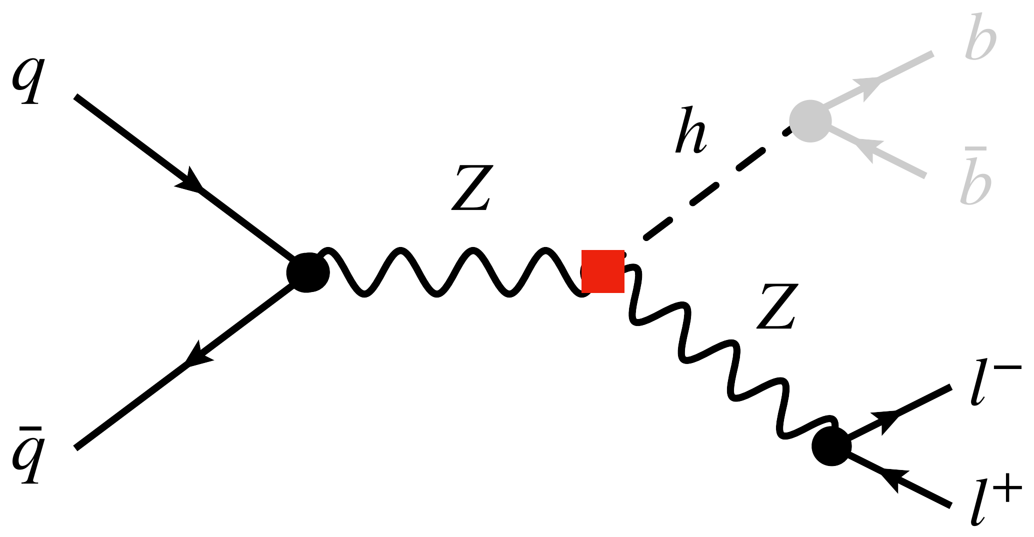

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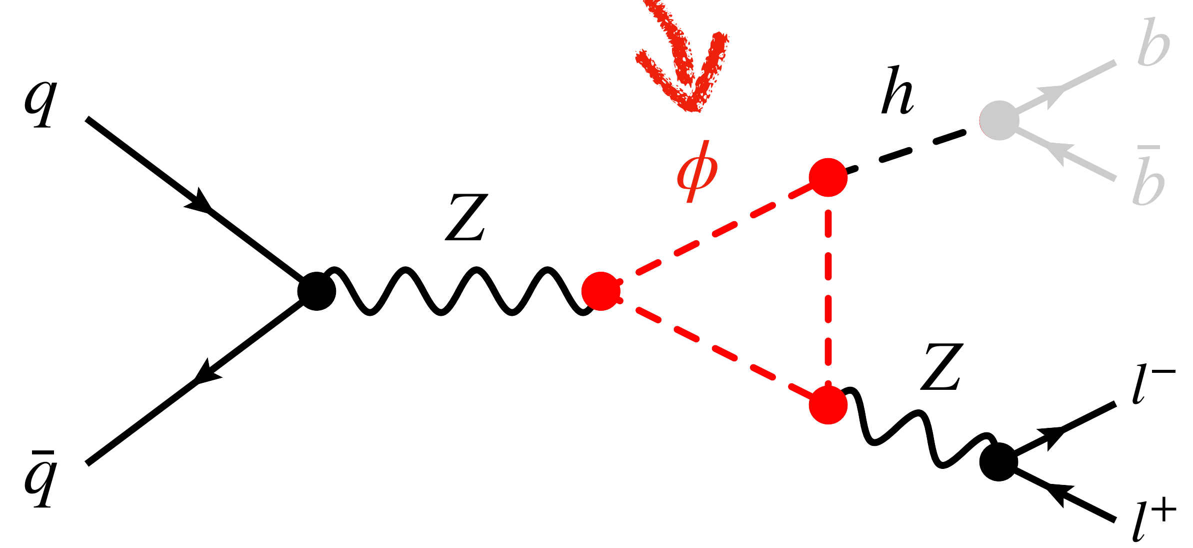

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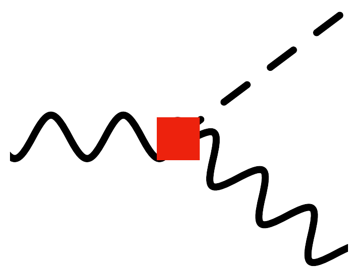

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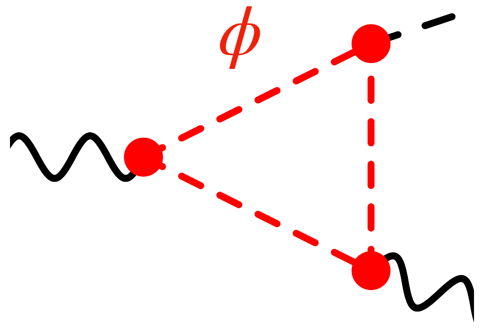

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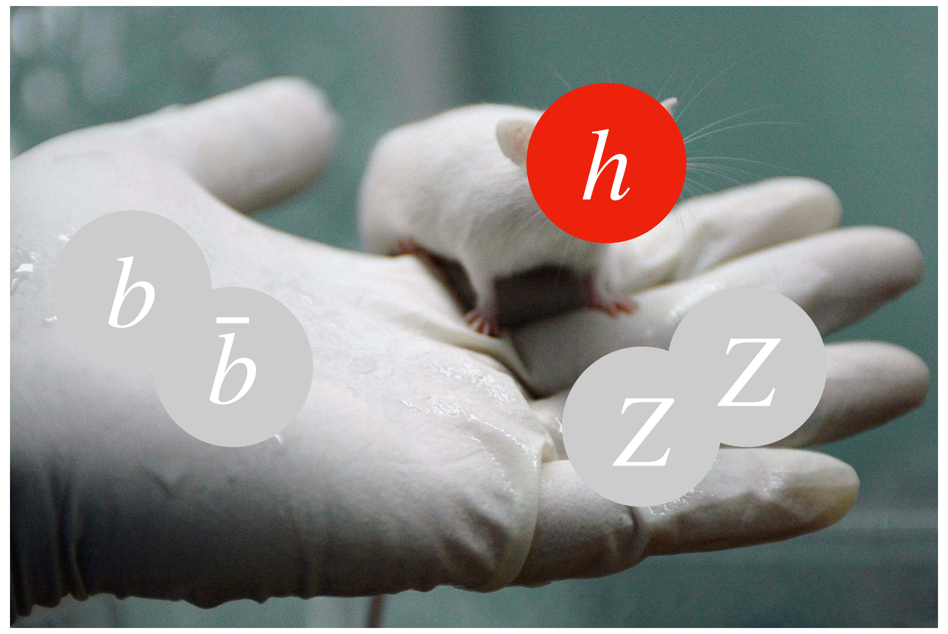
1.3 SMEFT



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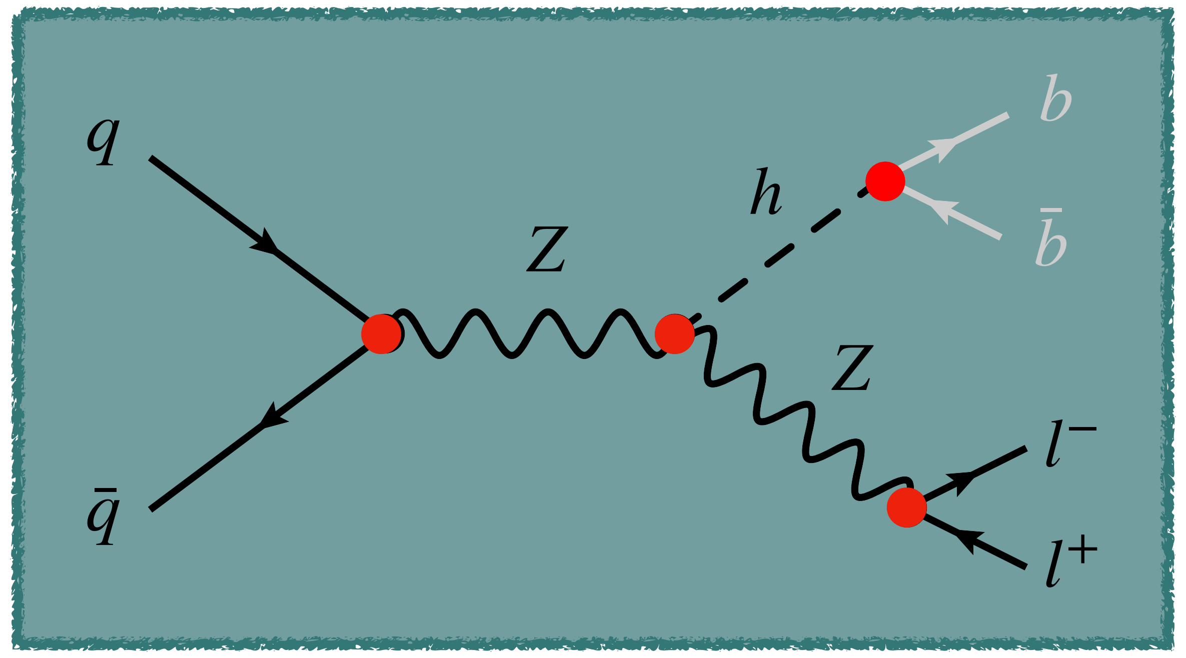

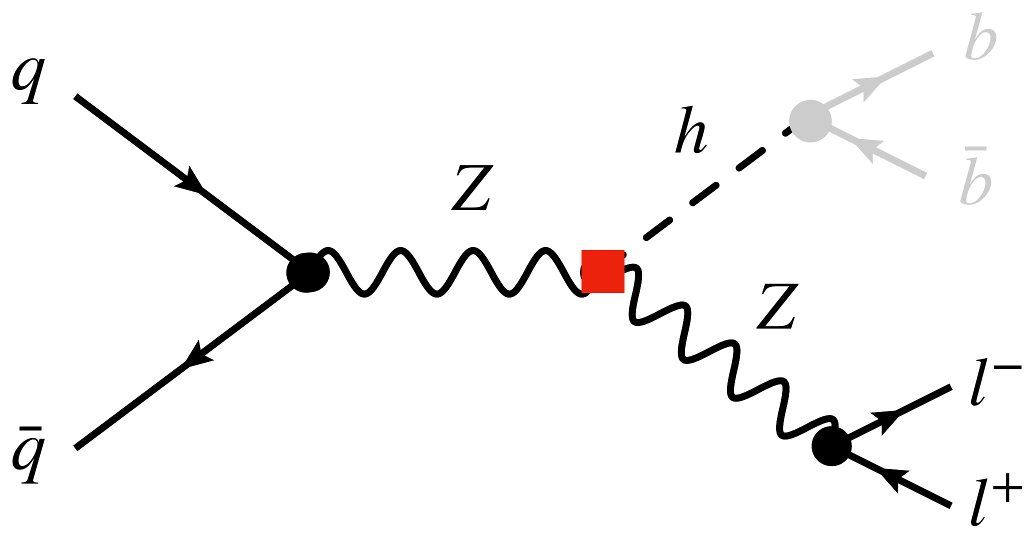

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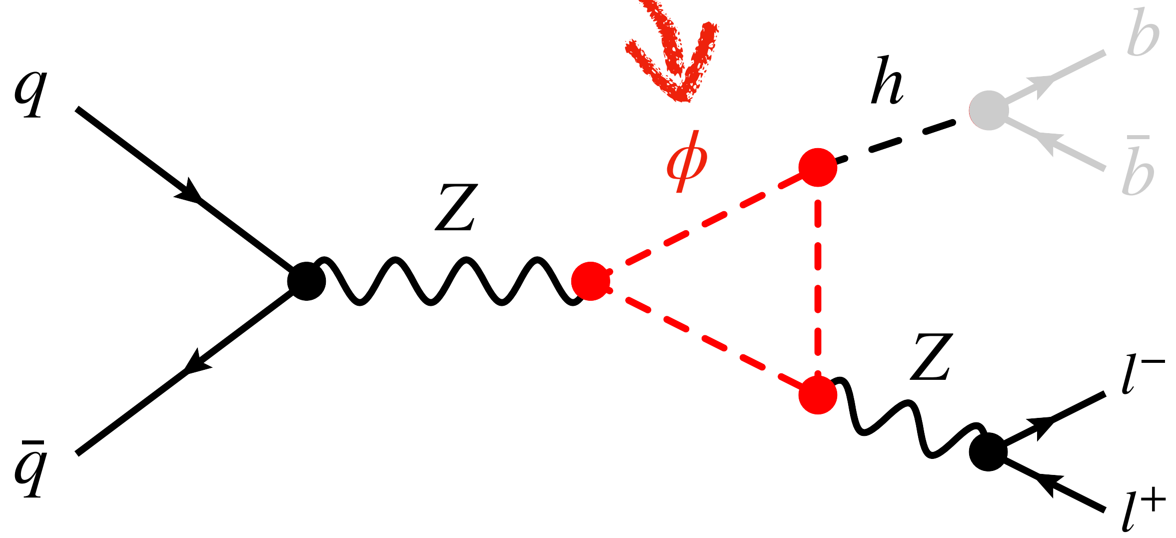

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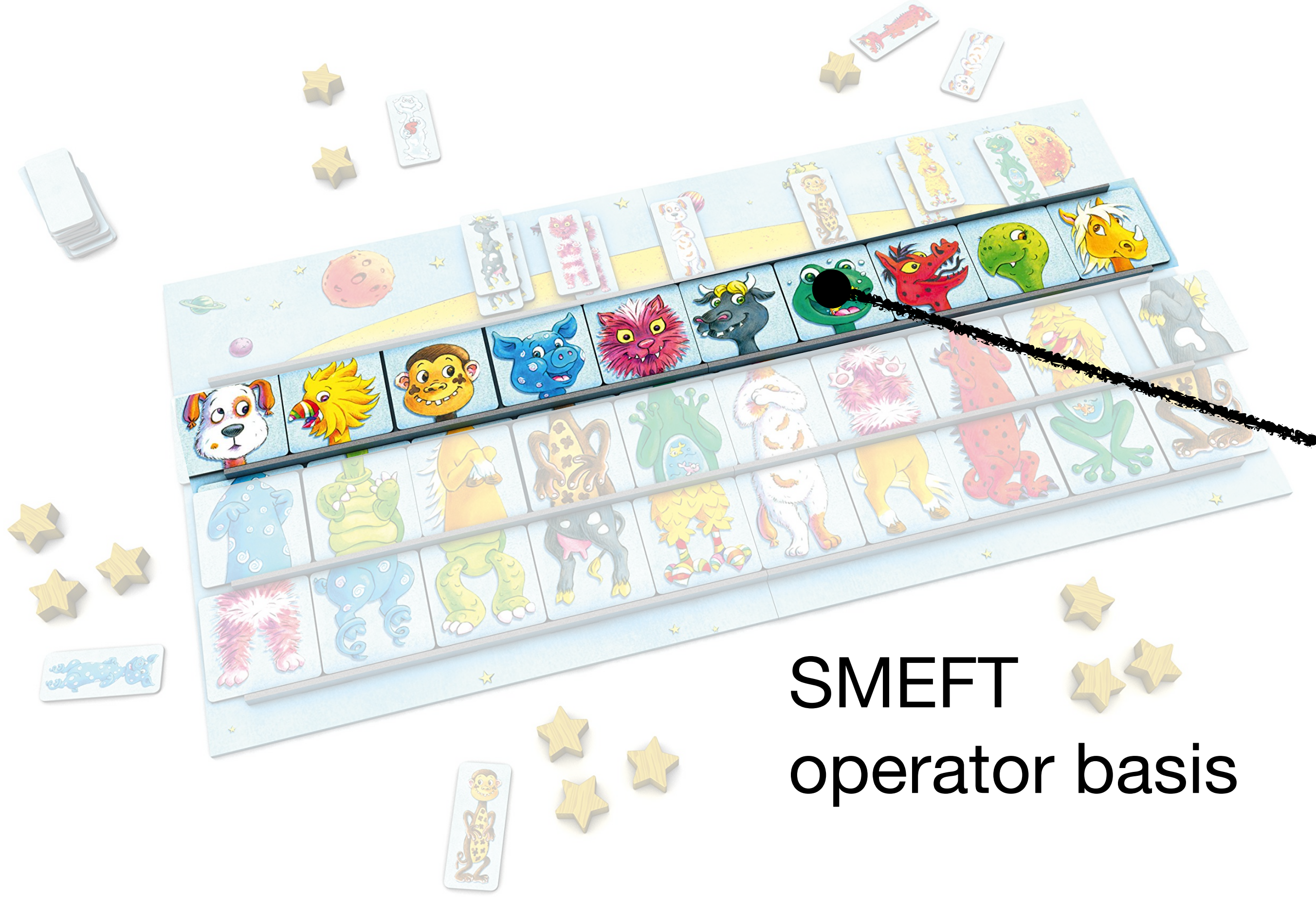

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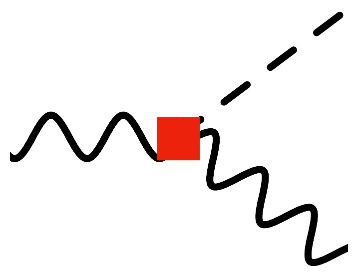

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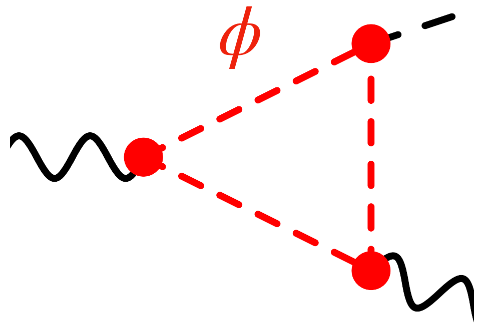

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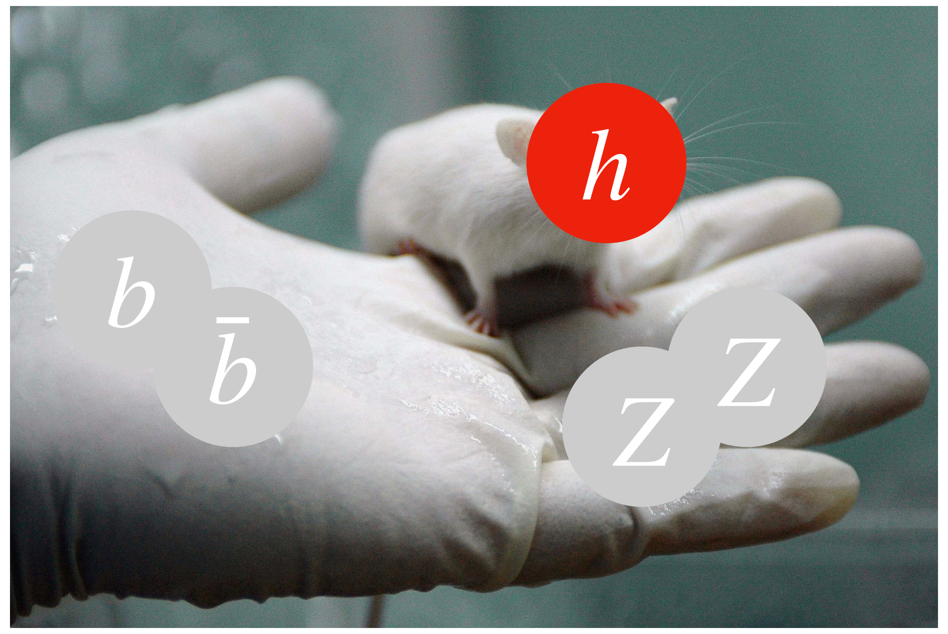

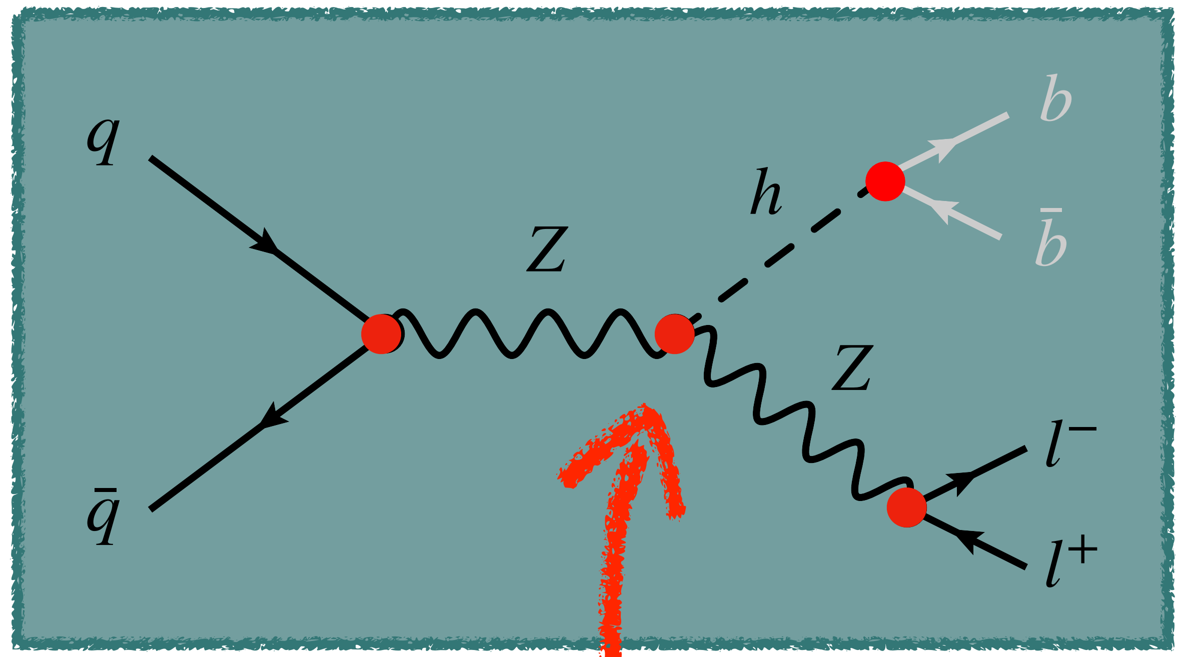

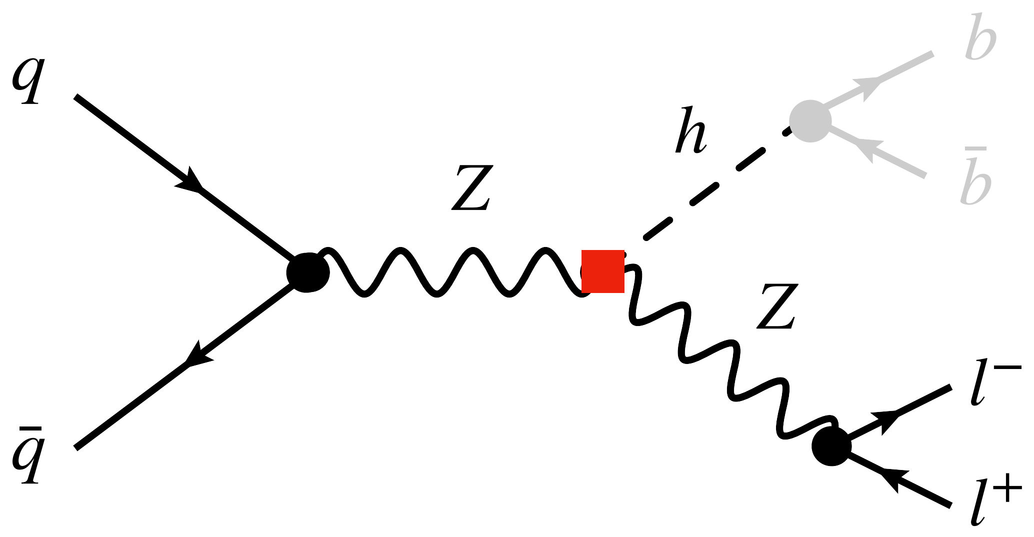

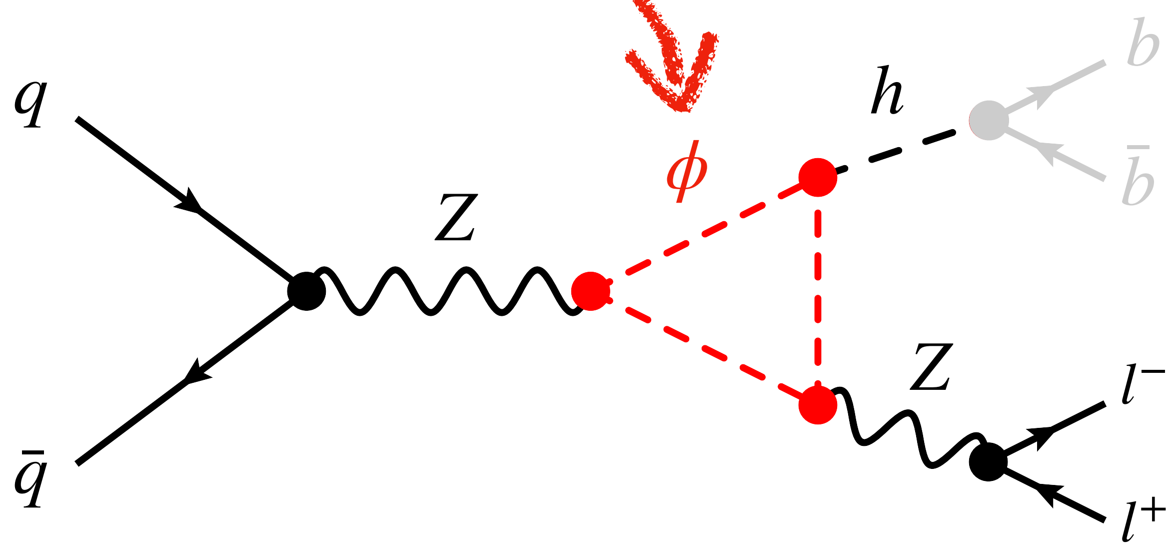

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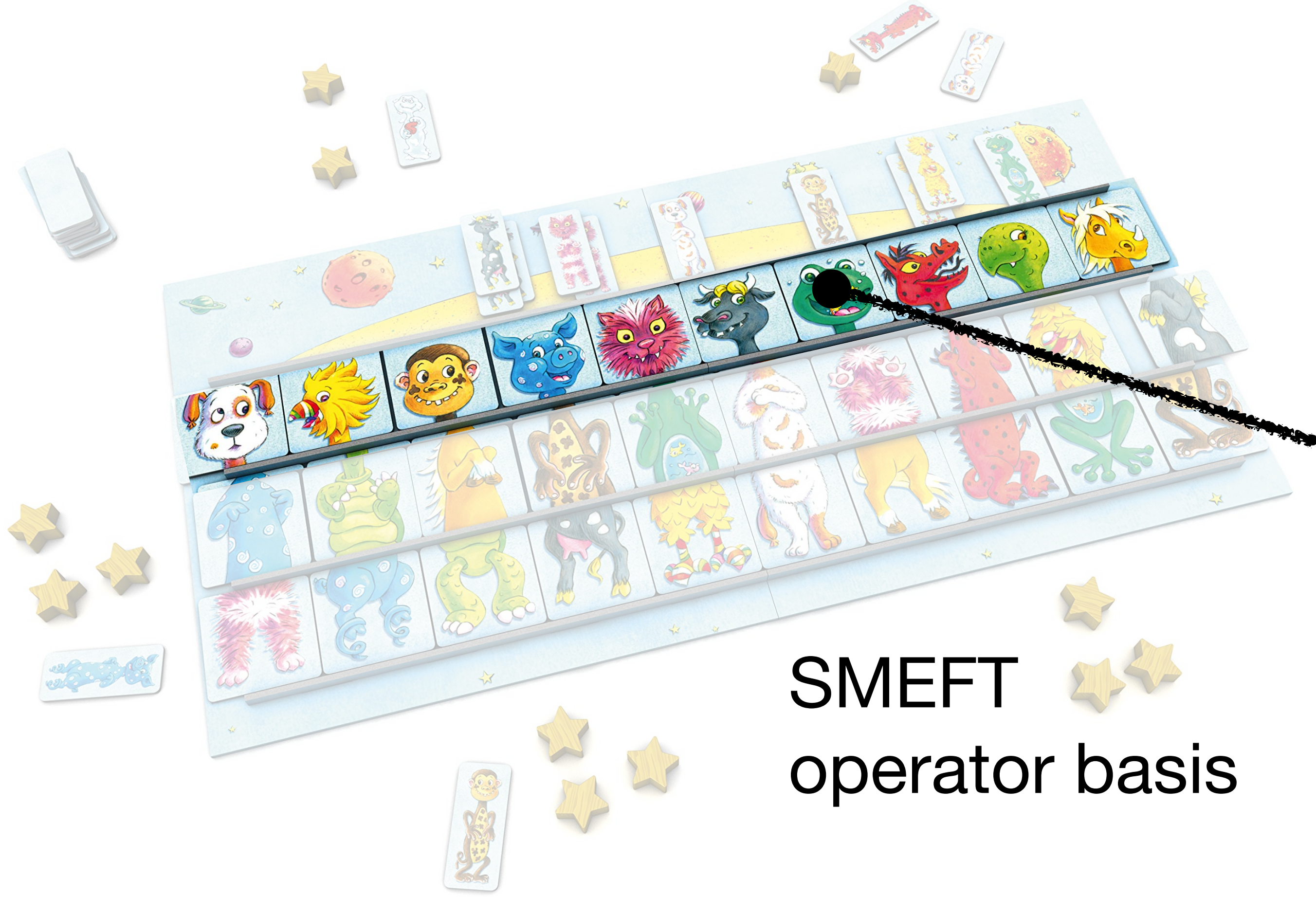

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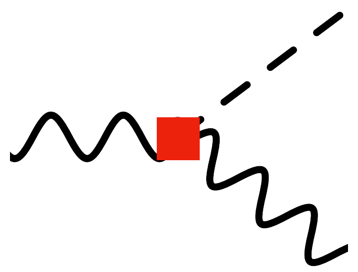

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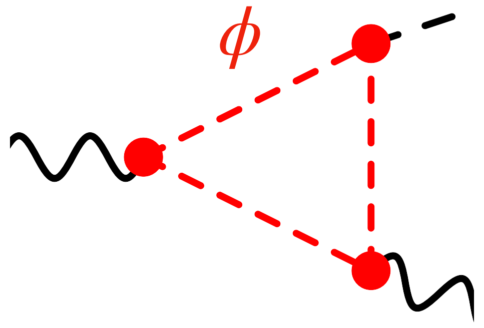

2. SMEFT Effects in Vh at NNLO+PS

2.1 QCD and Higgs Operators

2.2 EW Operators

2. SMEFT Effects in Vh at NNLO+PS

2.1 QCD and Higgs Operators

Sources: [1]ArXiv:2204.00663 (U. Haisch et al.).

2. SMEFT Effects in Vh at NNLO+PS

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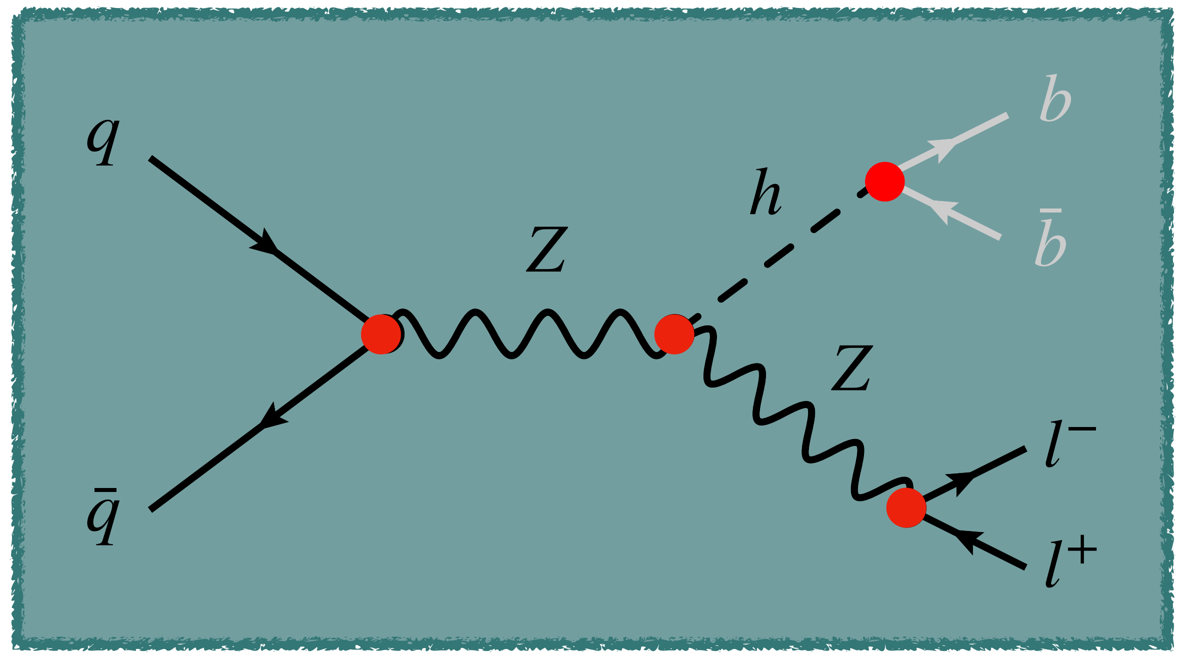

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$$Q_{bH} = y_b\,(H^\dagger H)\,\bar{q}_L b_R H\,, \qquad Q_{bG} = \frac{g_s^3}{(4\pi)^2}\,y_b\,\bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu}\,,$$

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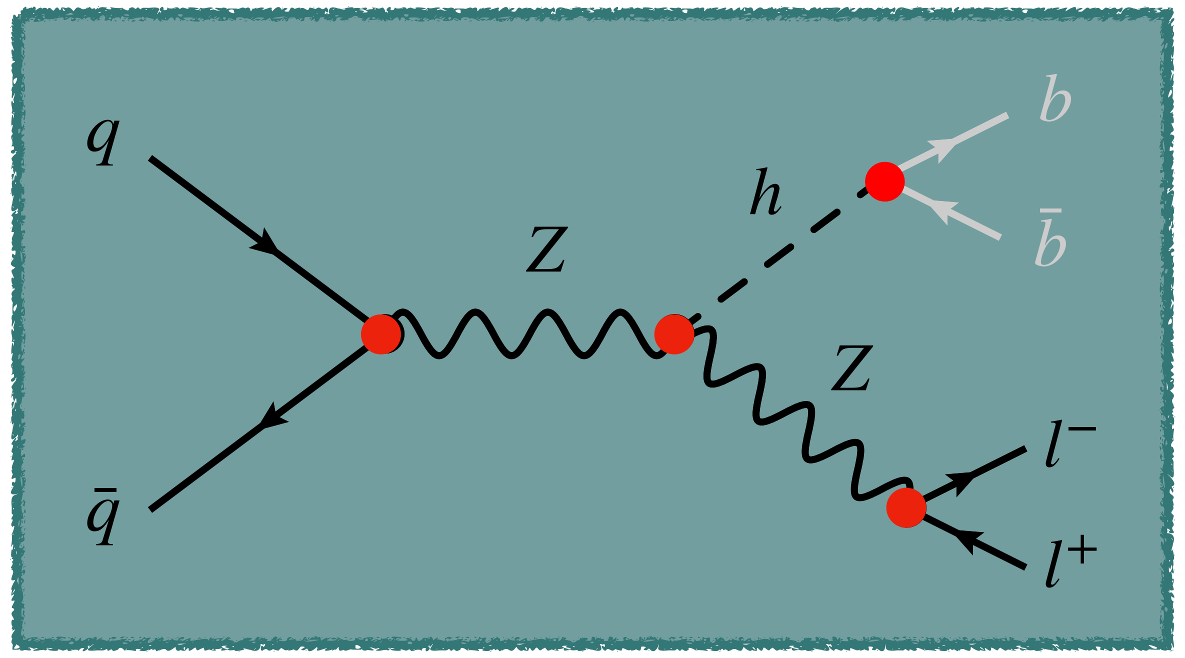

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2. SMEFT Effects in Vh at NNLO+PS

2.1 QCD and Higgs Operators

- Effects from **QCD and Higgs operators** have been implemented[1].

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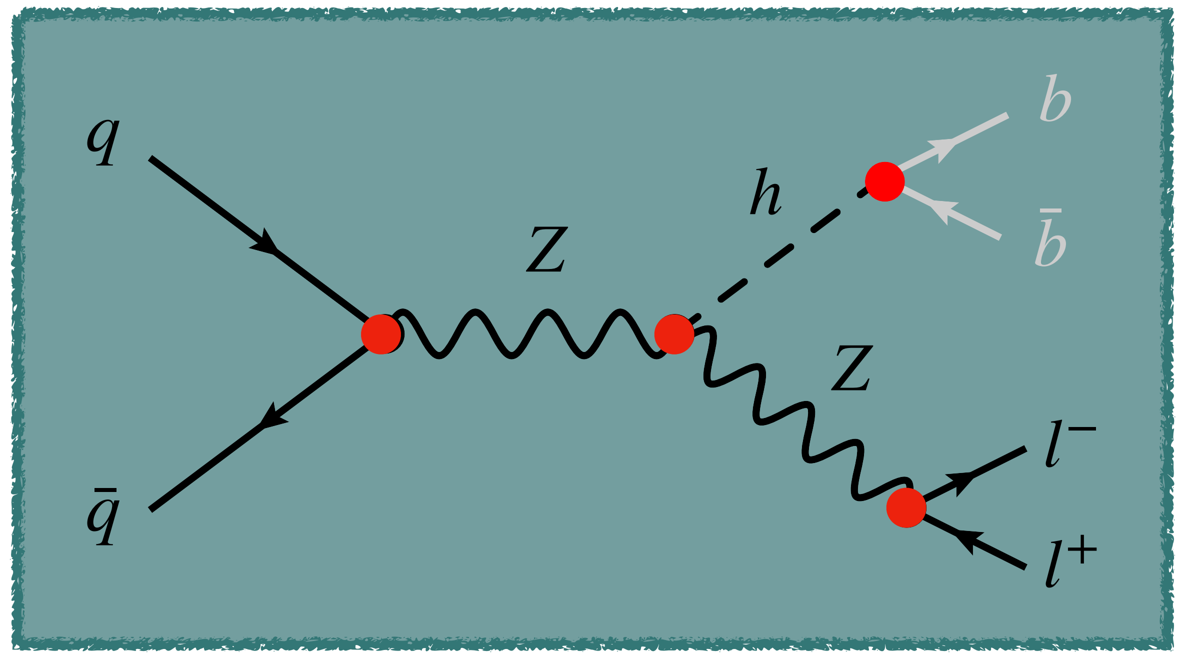

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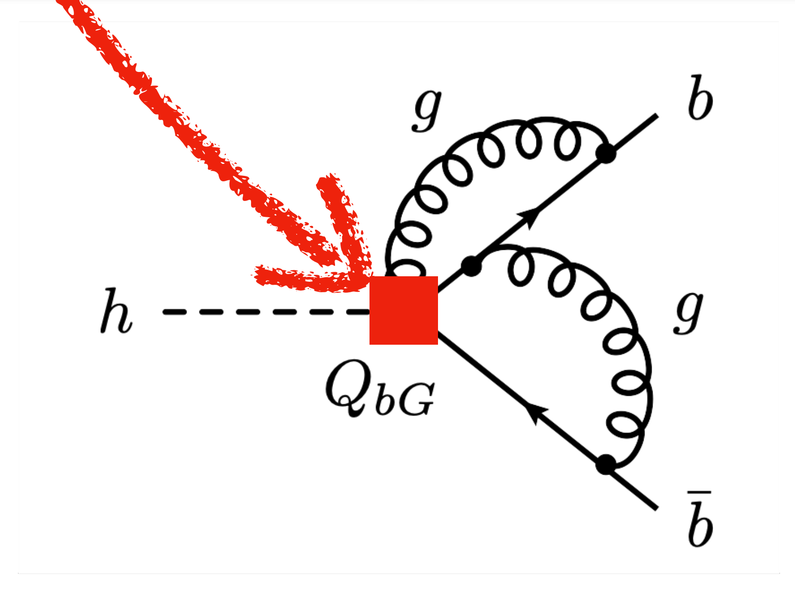

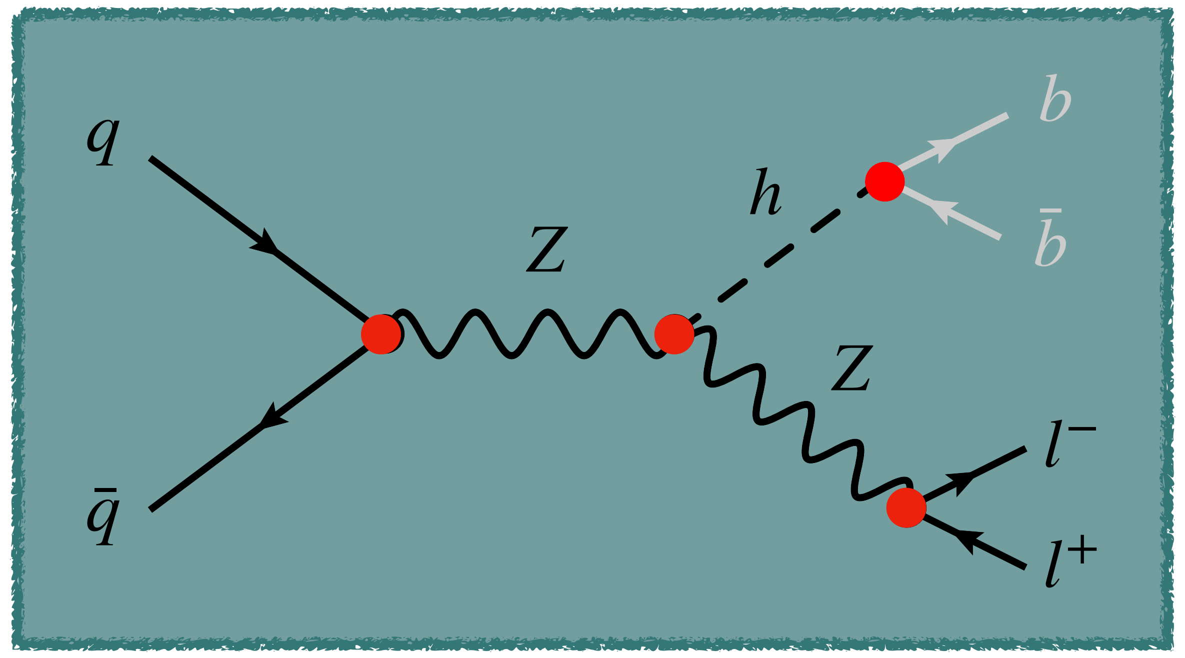

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2. SMEFT Effects in Vh at NNLO+PS

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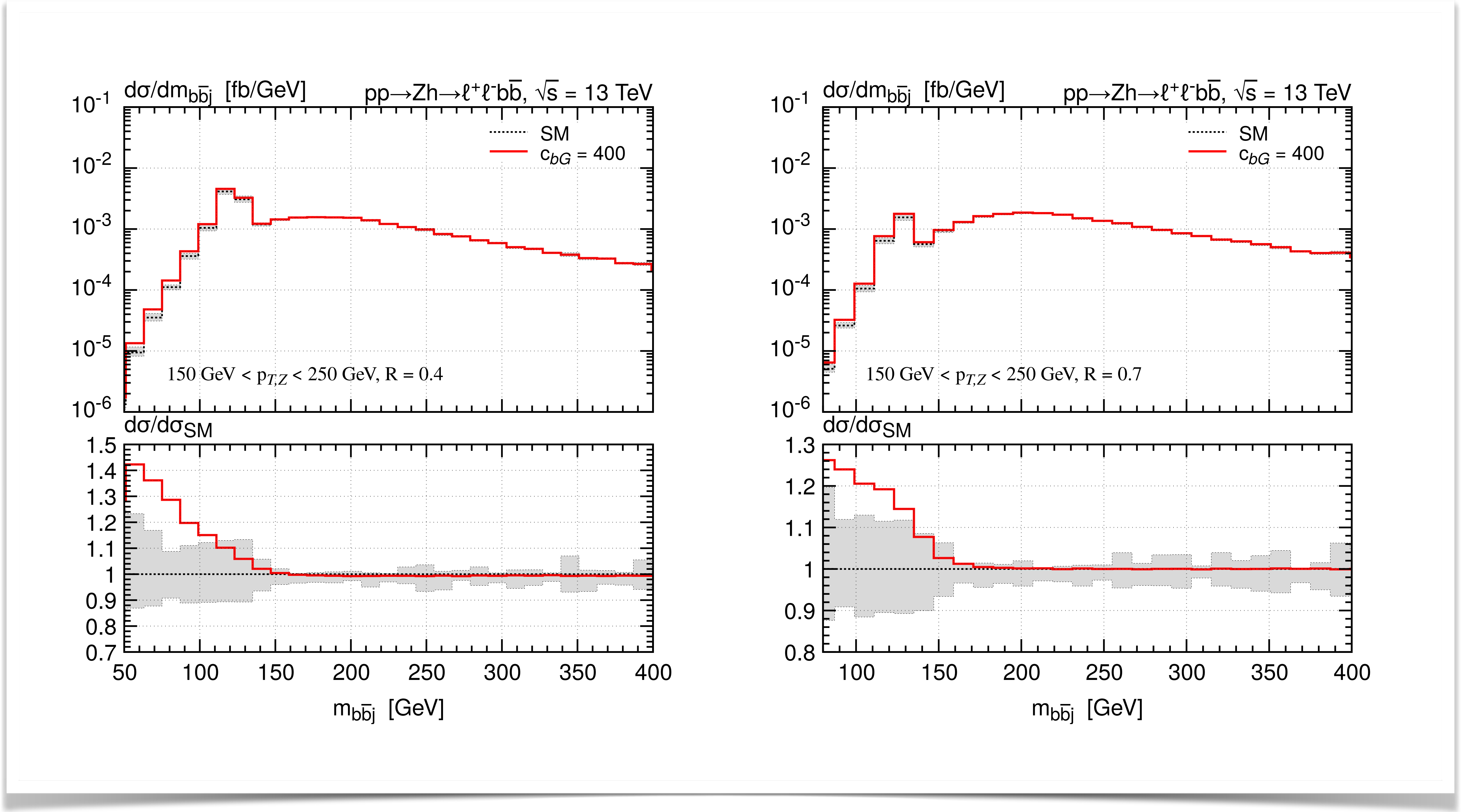

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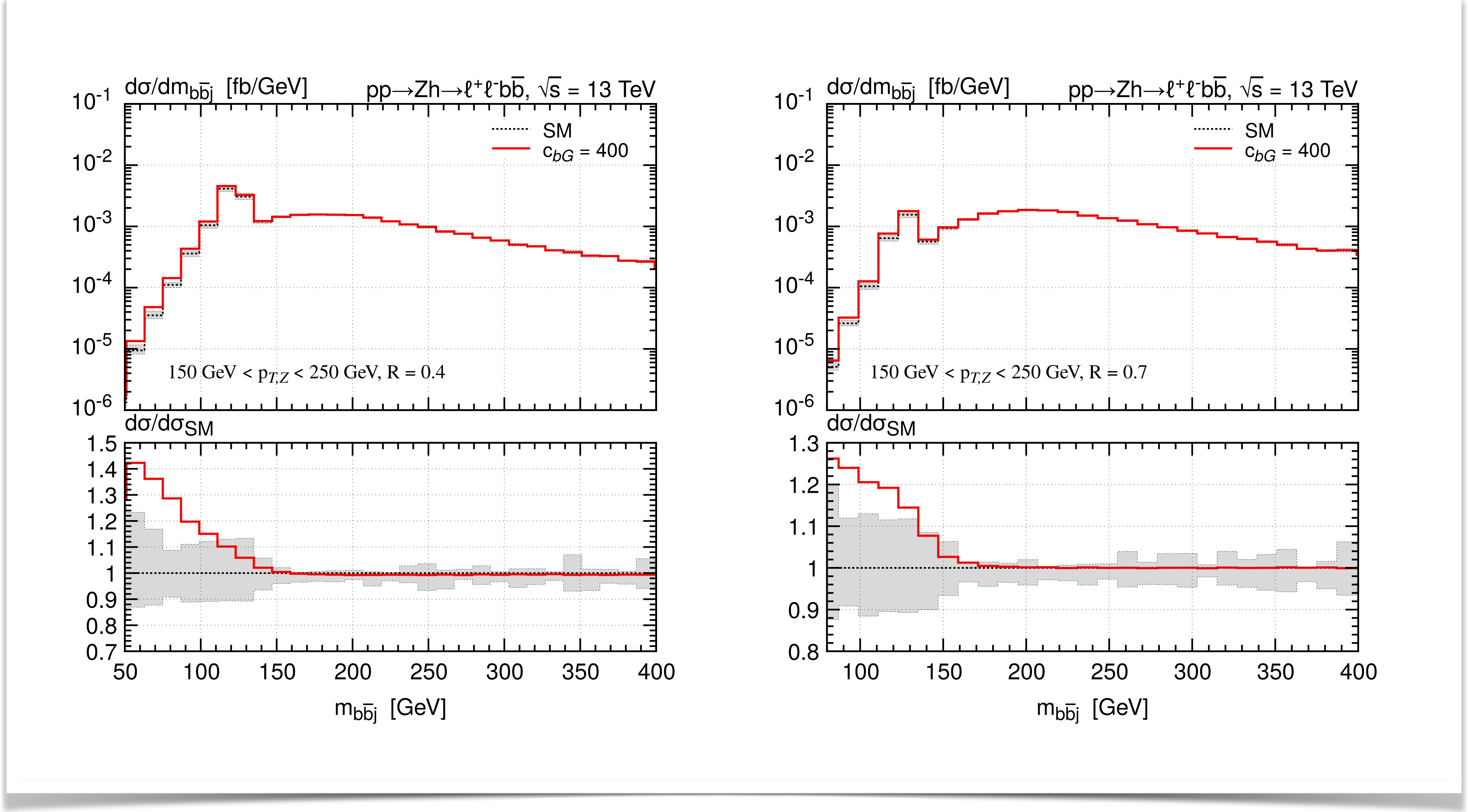

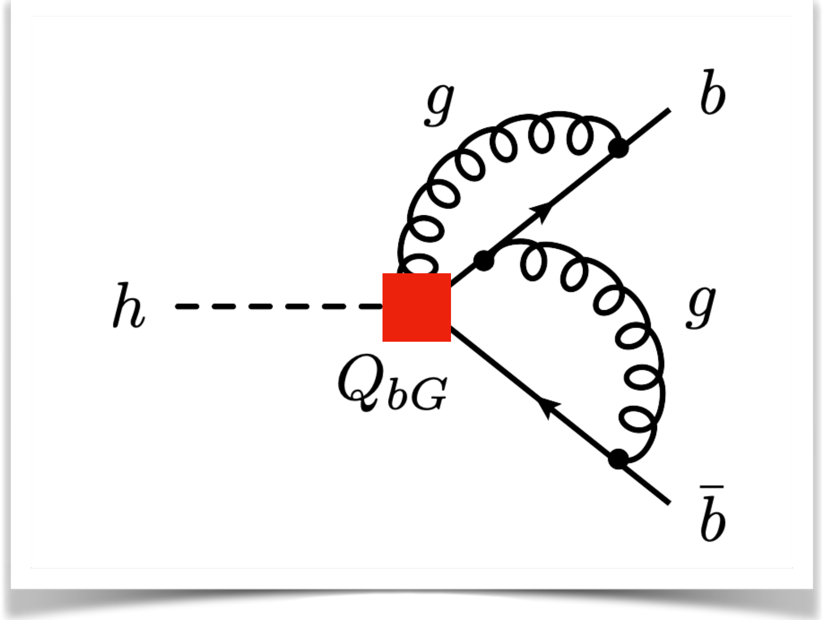

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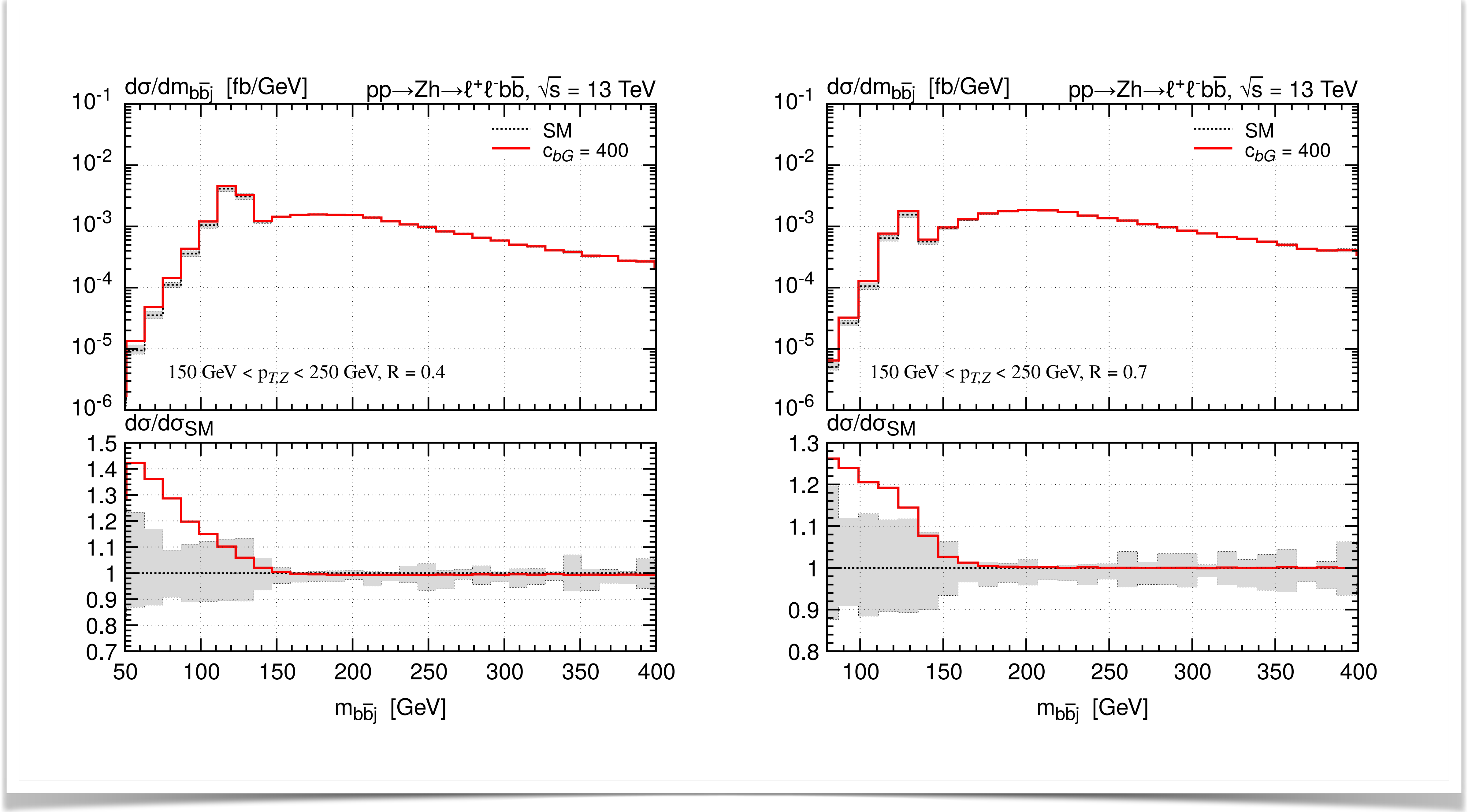

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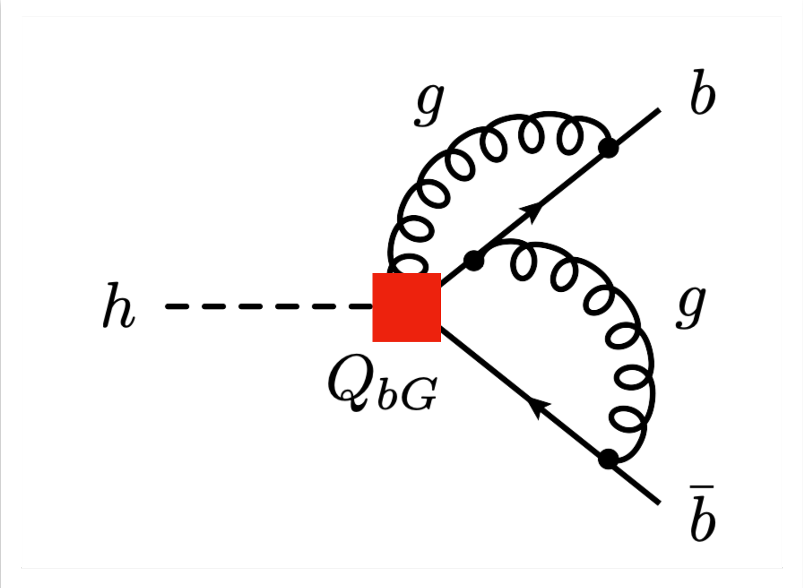

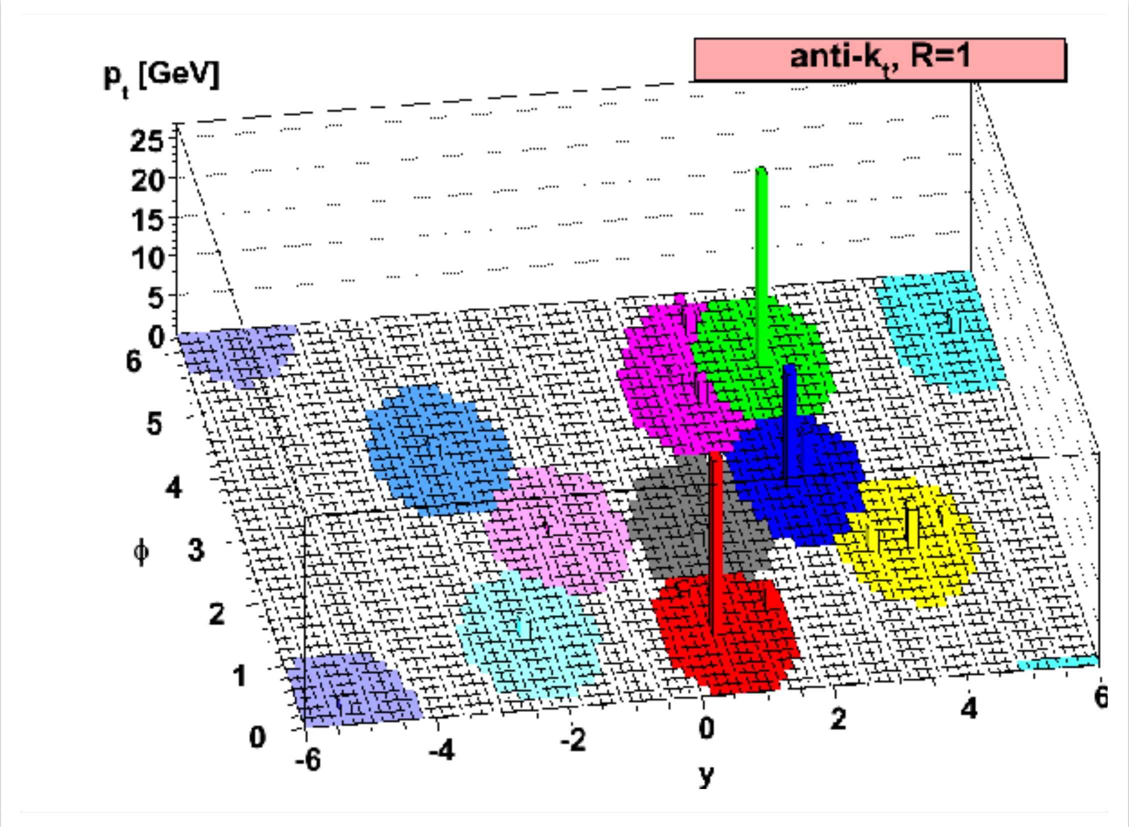

Source: ArXiv:0802.1189 (M. Cacciari et al.).

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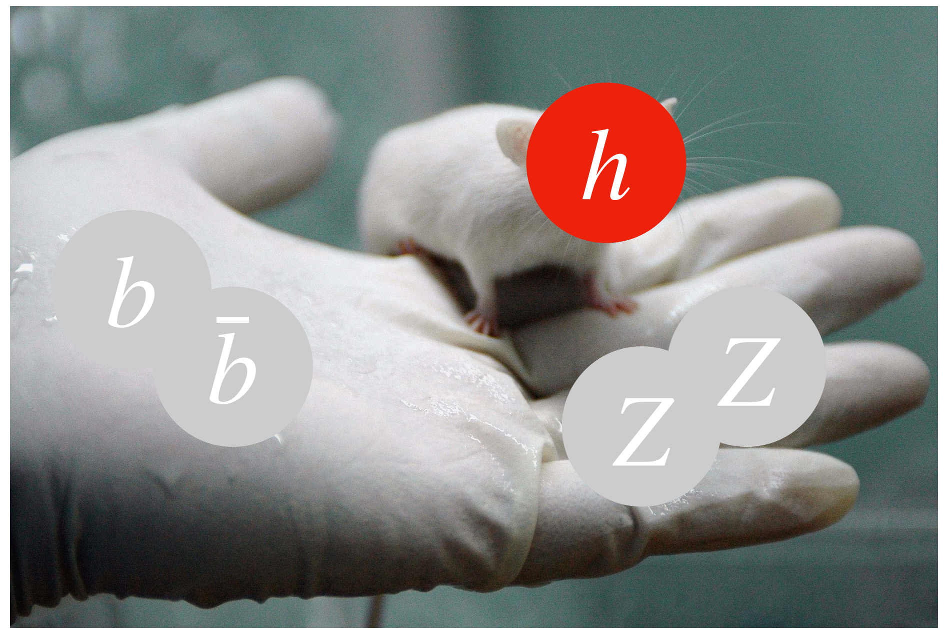

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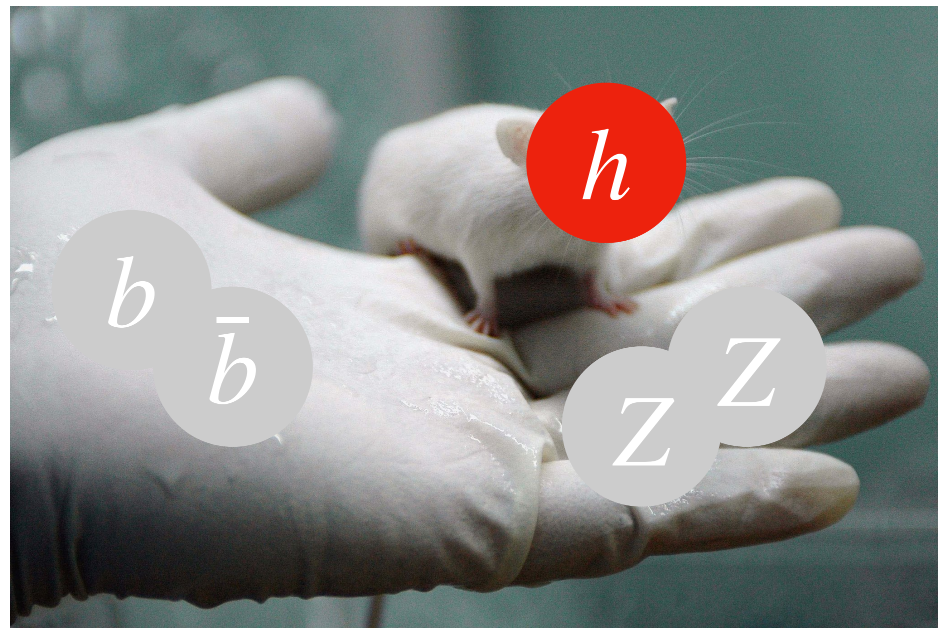

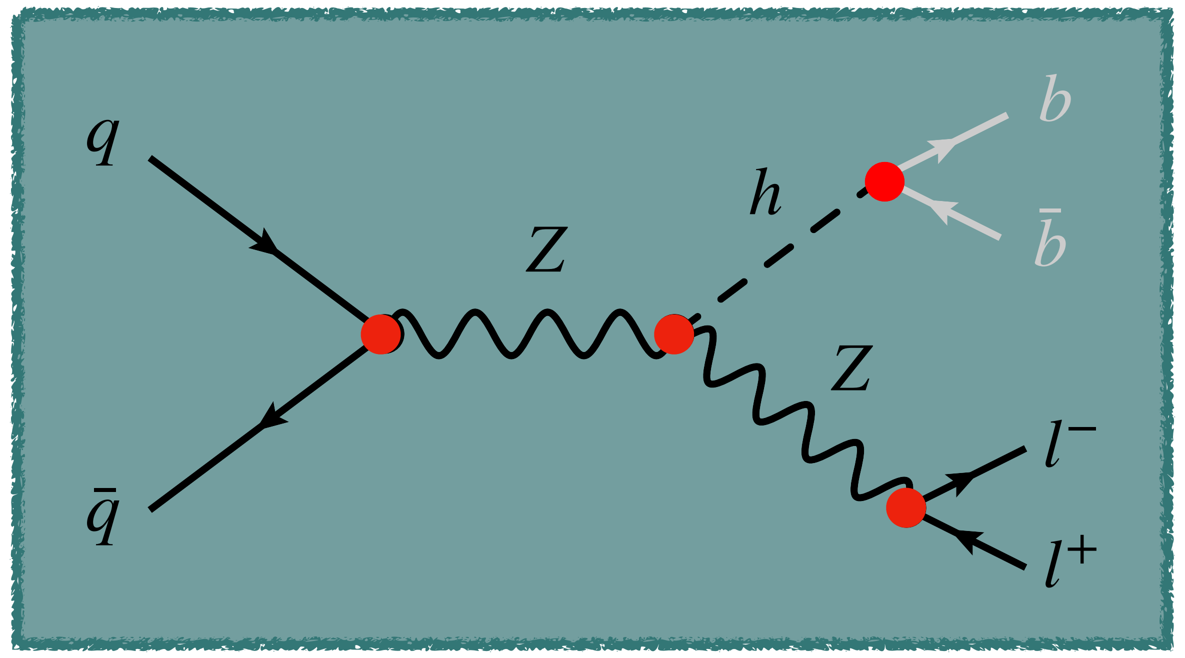

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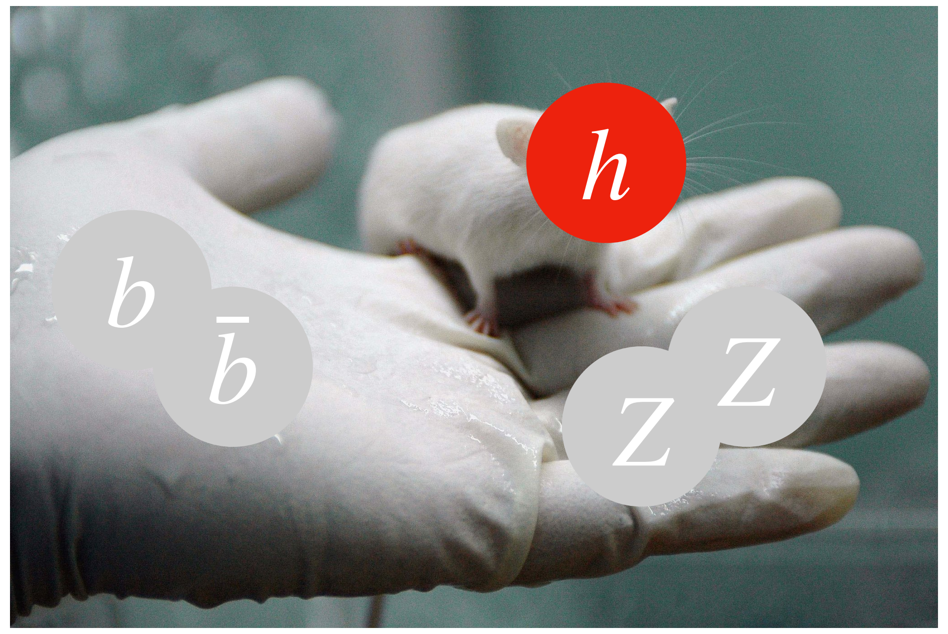

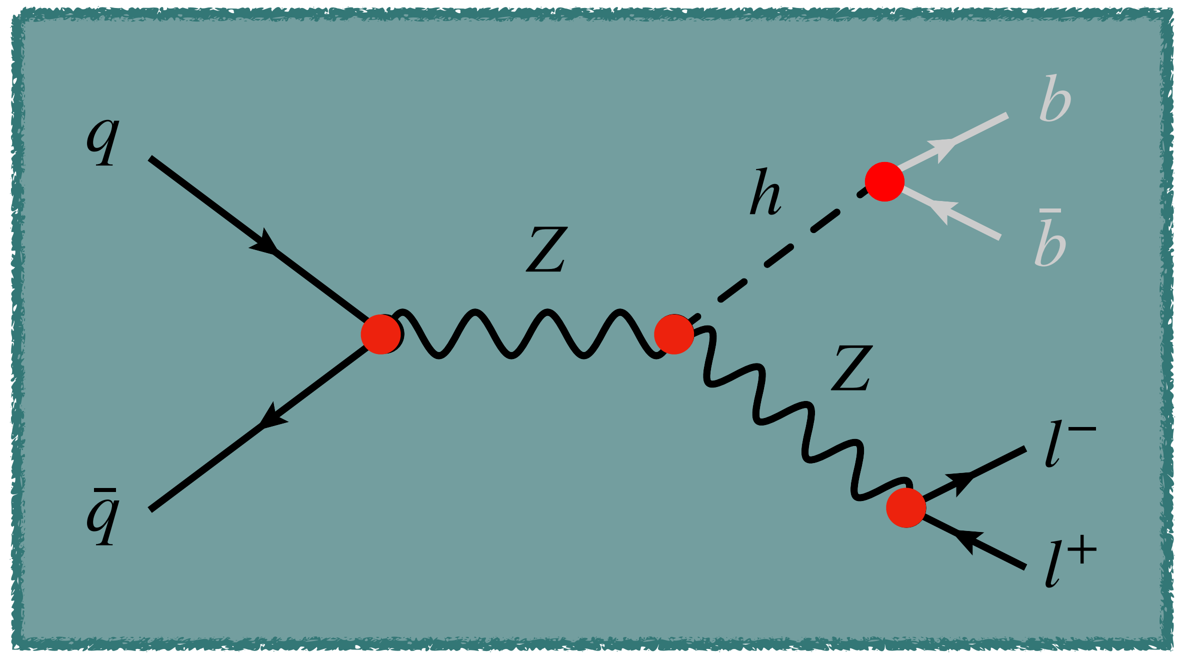

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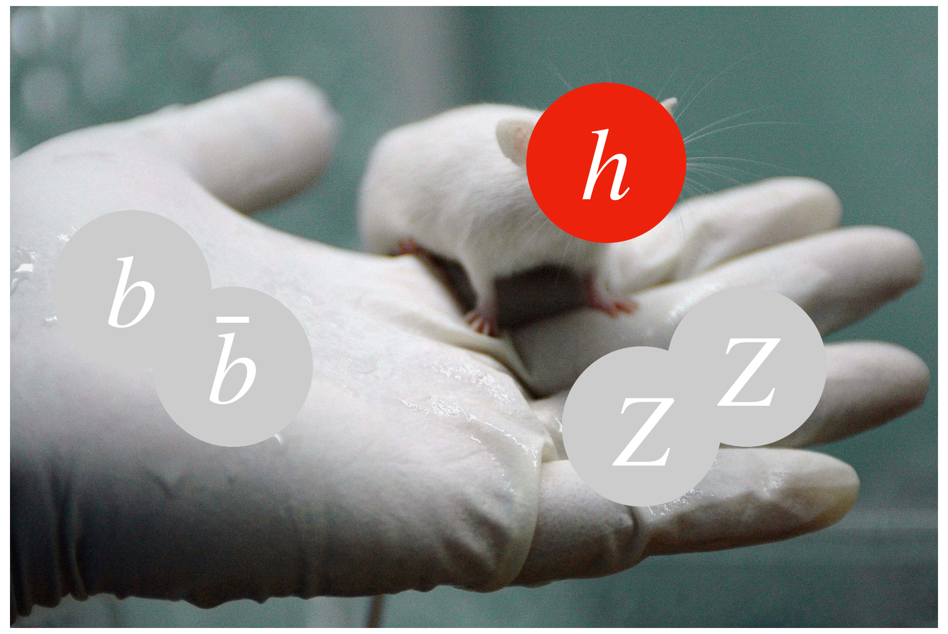

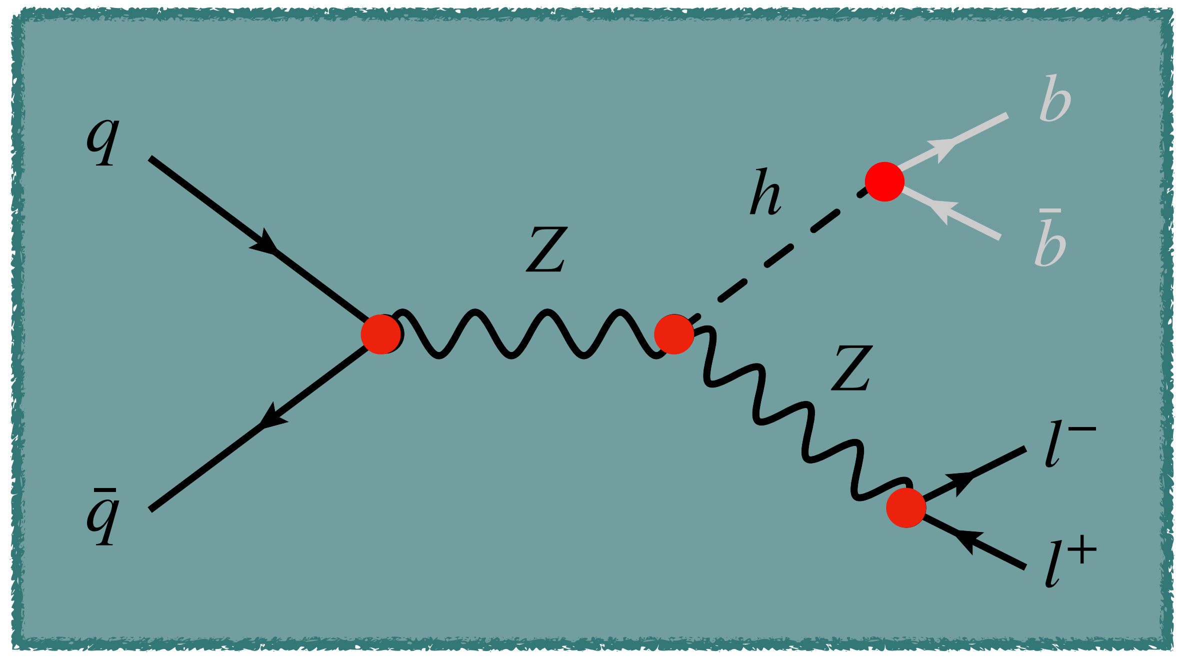

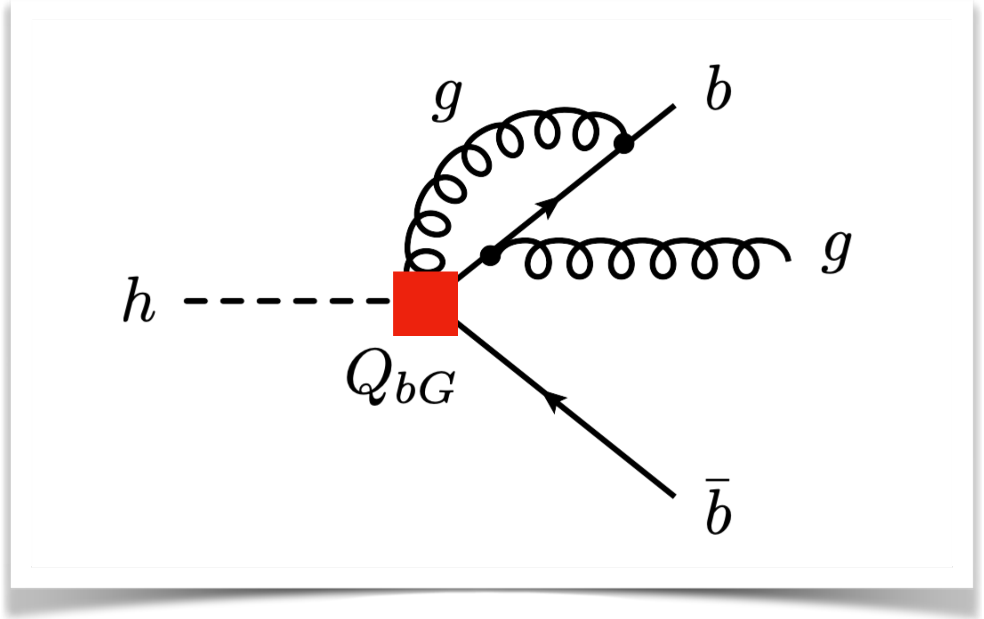

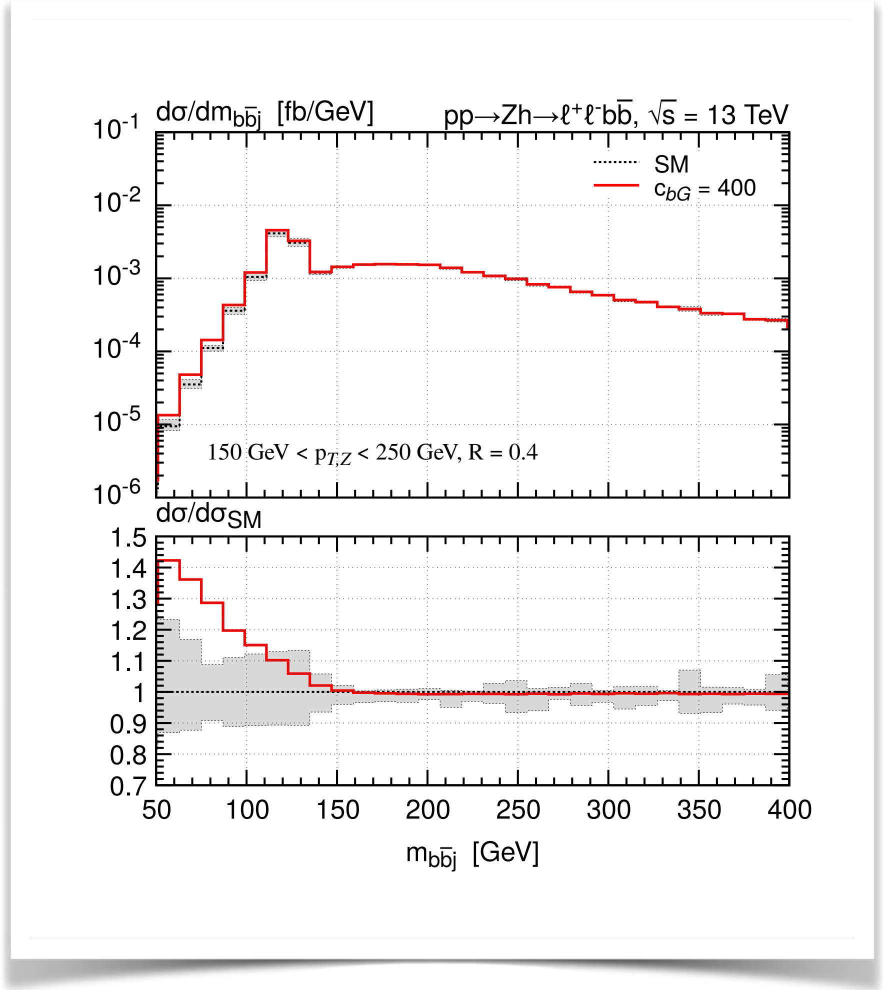

2. SMEFT Effects in Vh at NNLO+PS

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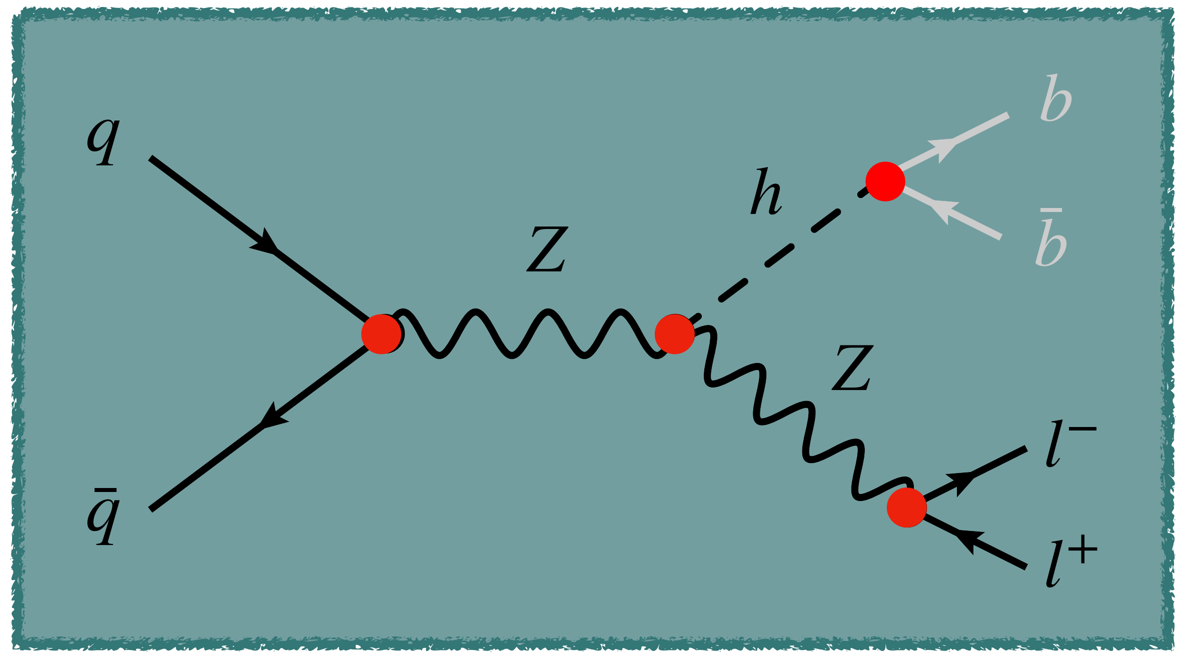

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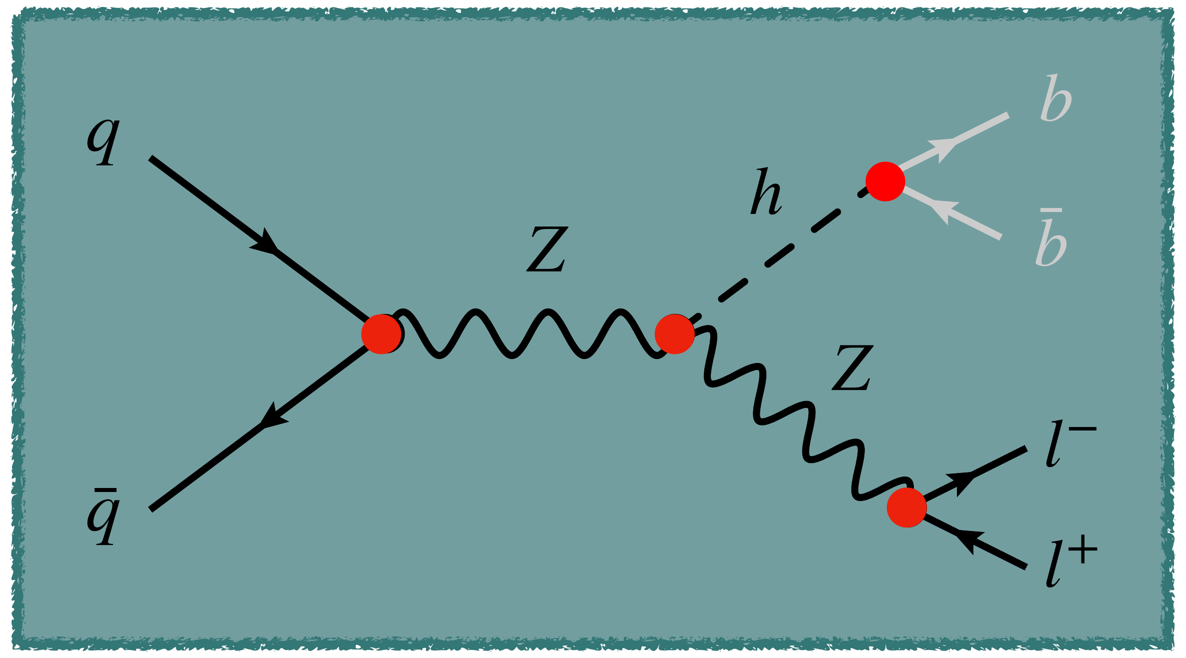
Source: ArXiv:1008.4884 (B. Grzadkowski et al.).



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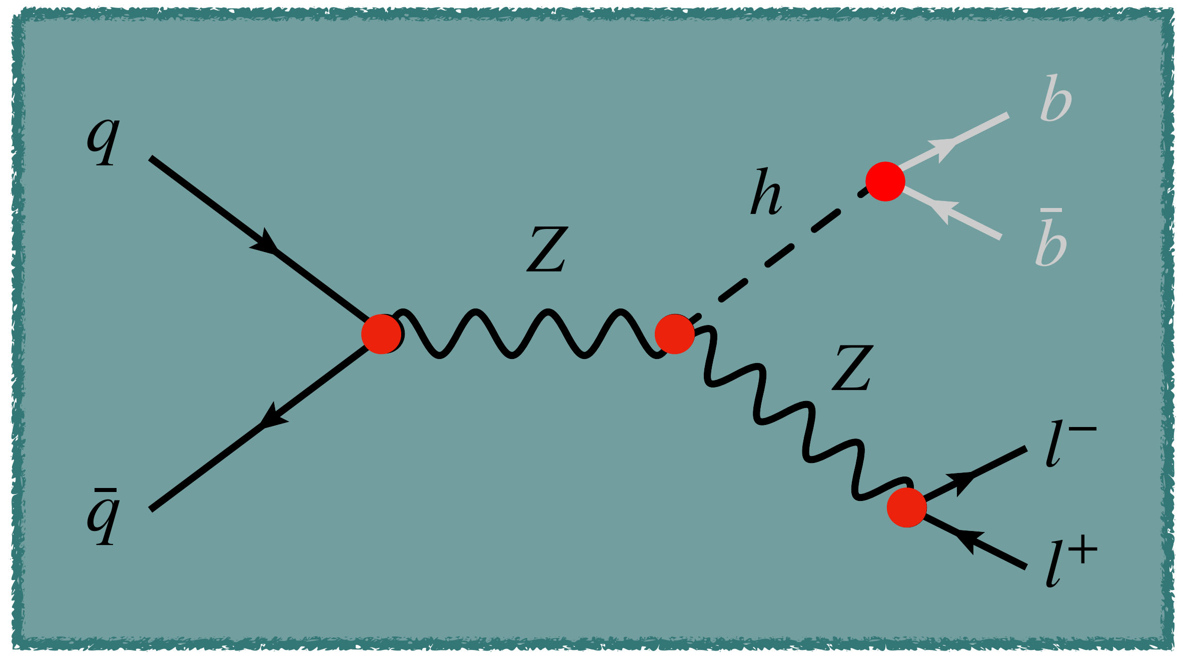

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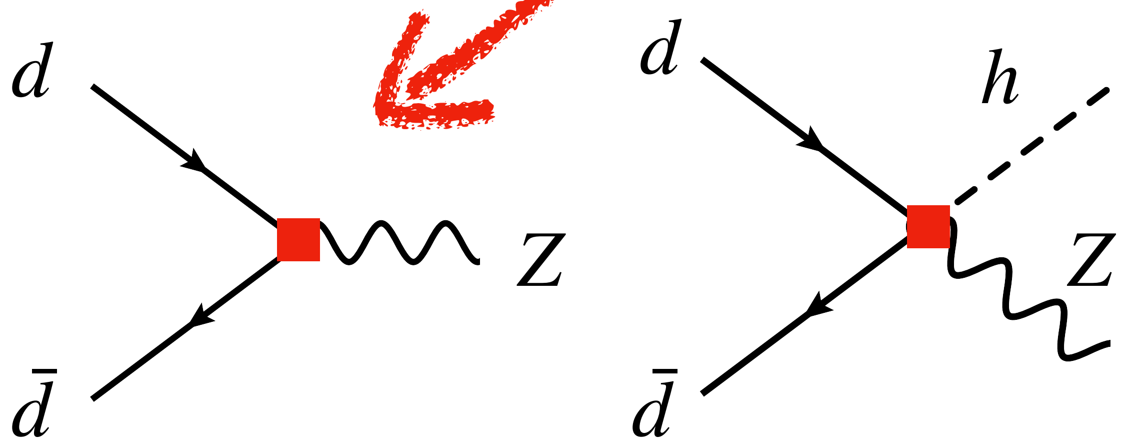

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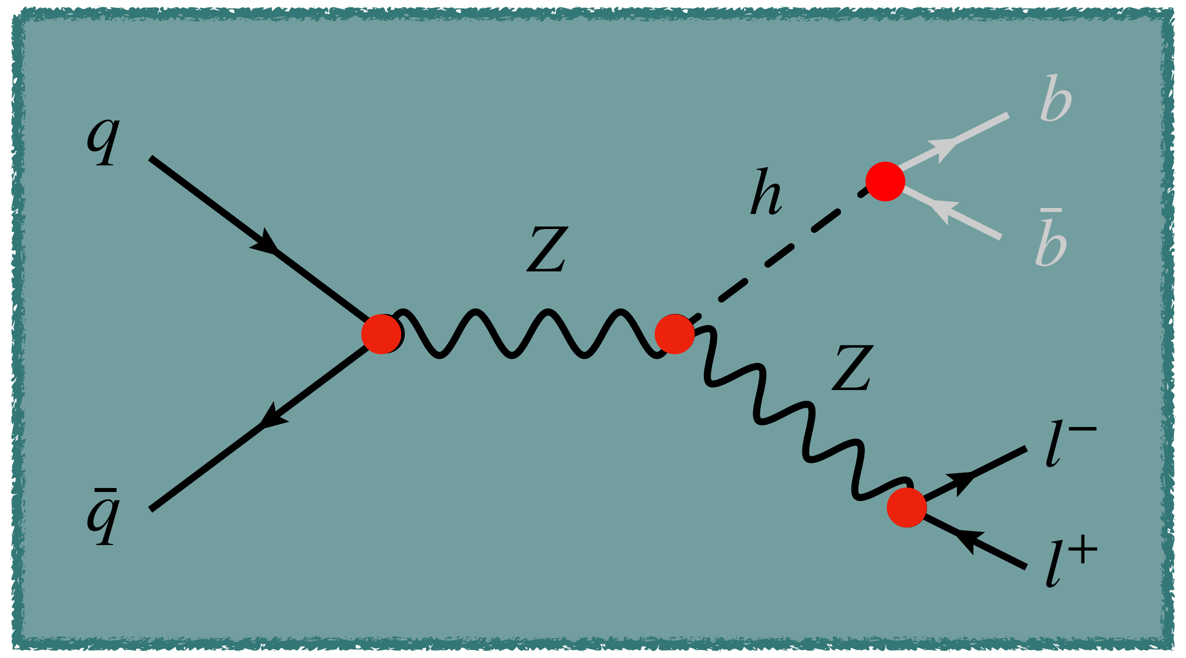

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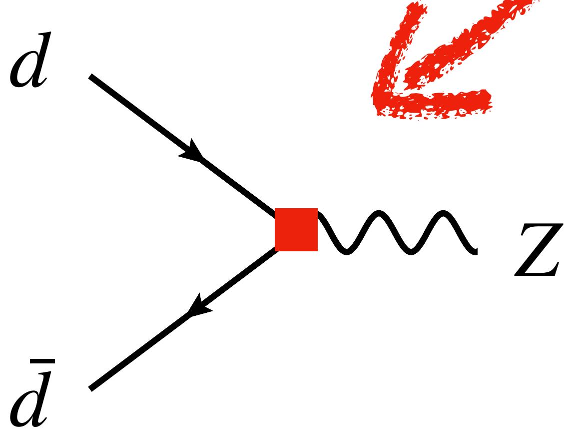

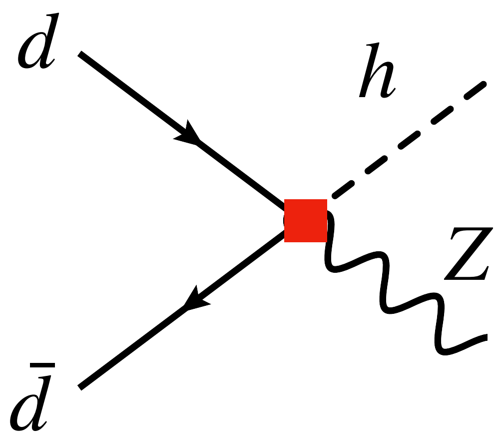

$$\left(\ldots\gamma^\mu P_L + \ldots\gamma^\mu P_R\right)$$

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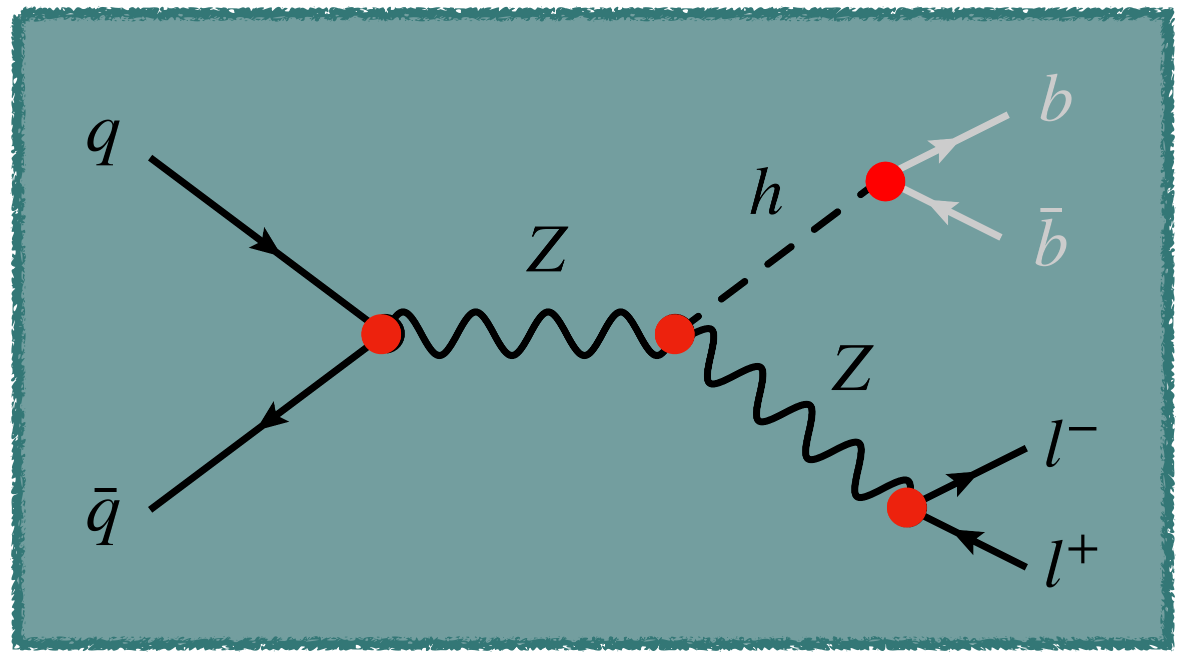

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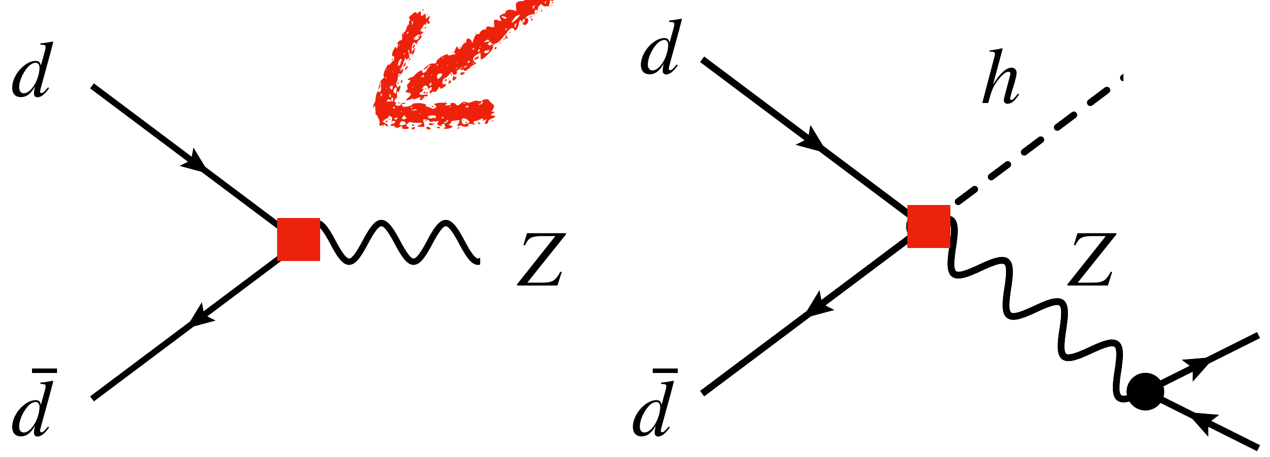

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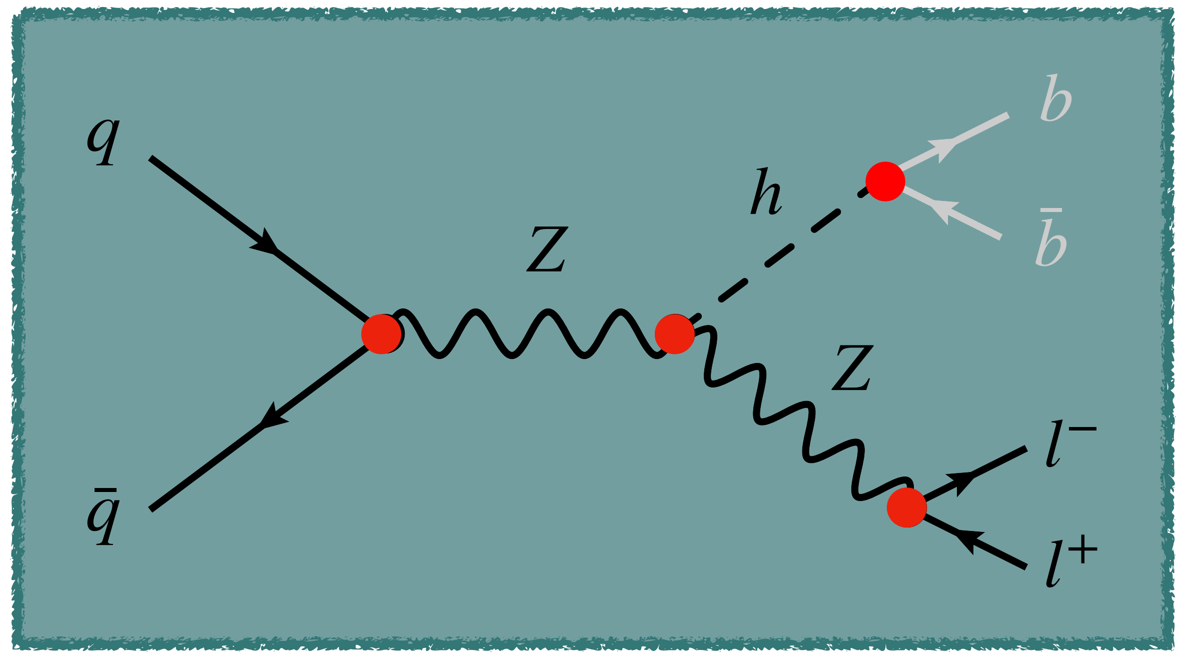

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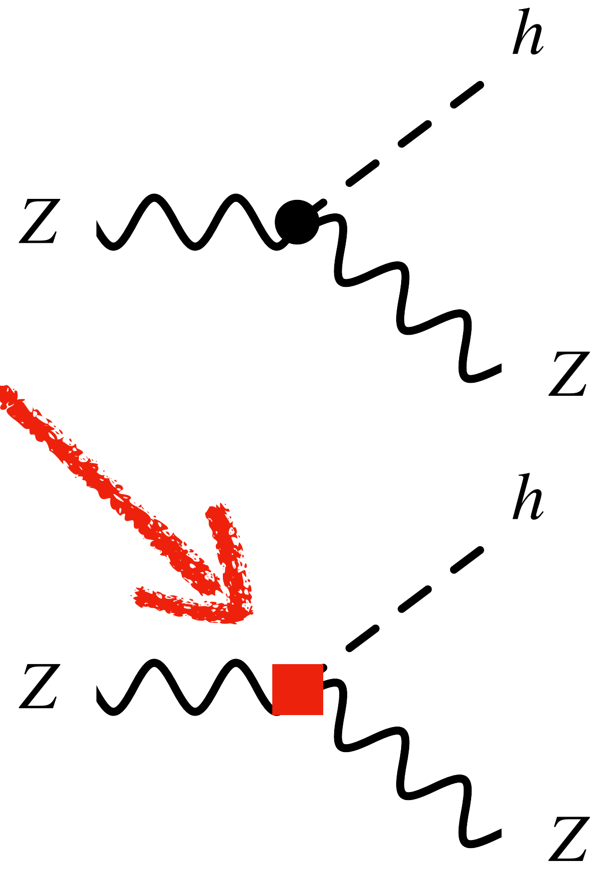

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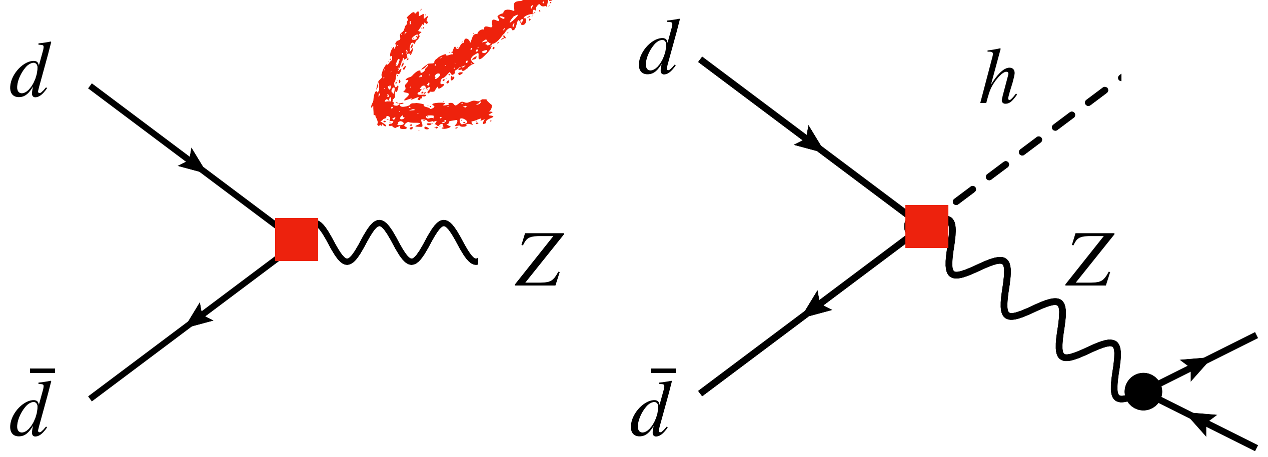

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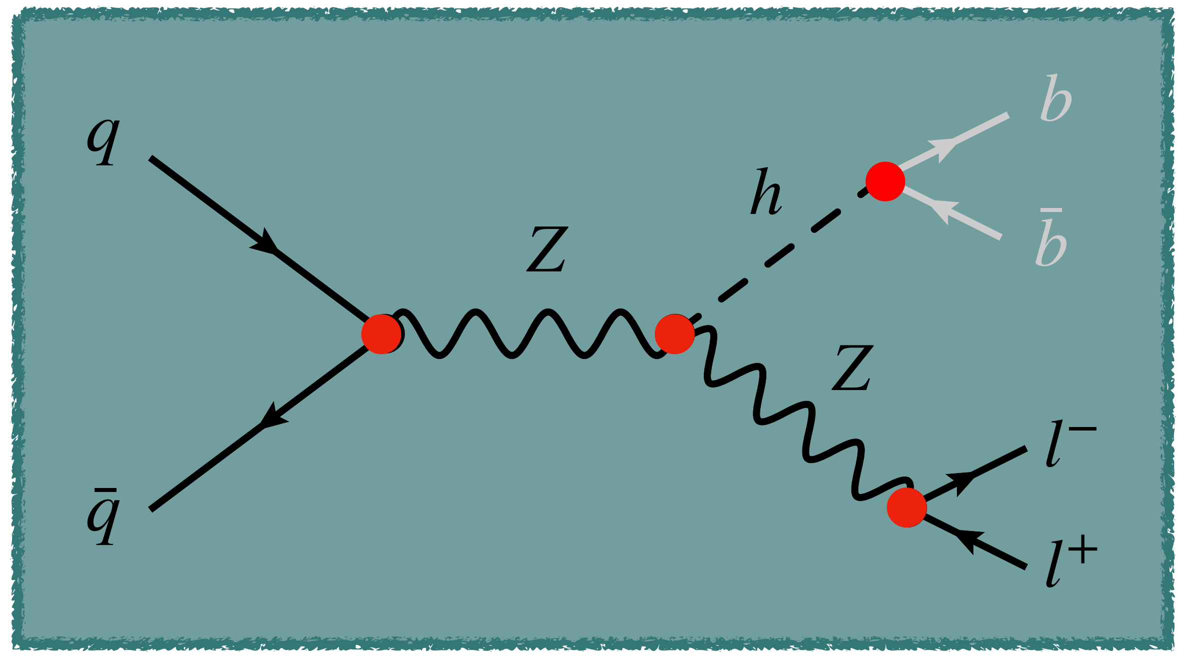

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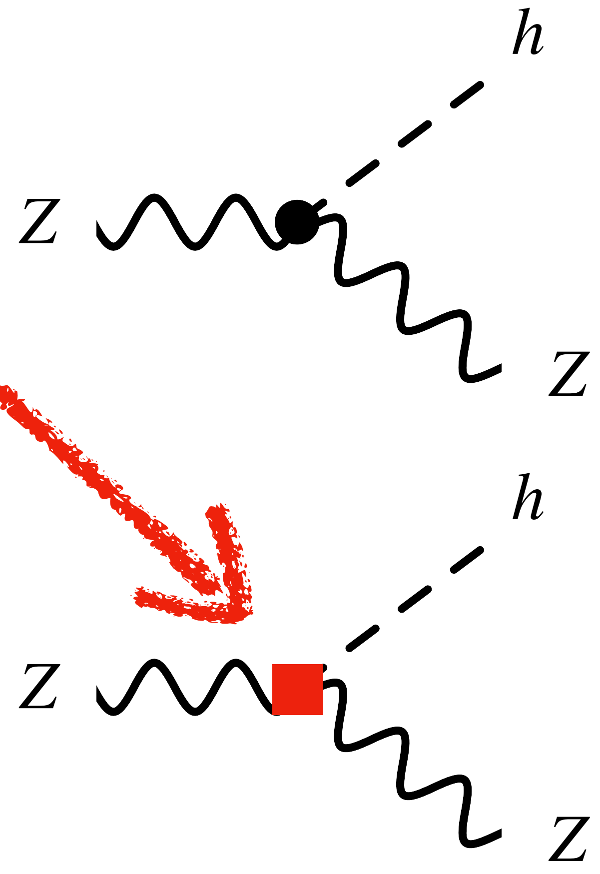
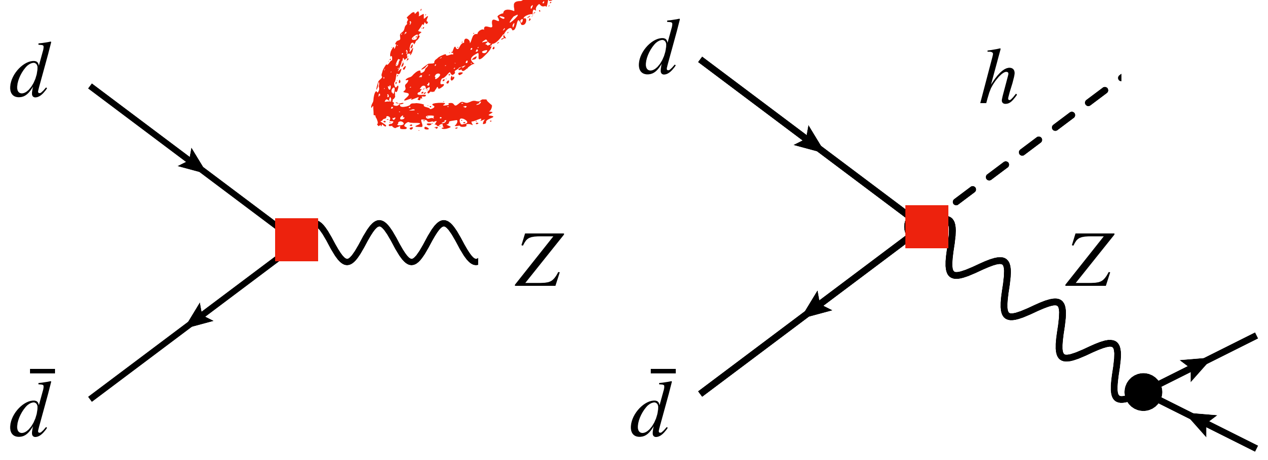


$\dots g^{\mu\nu}$

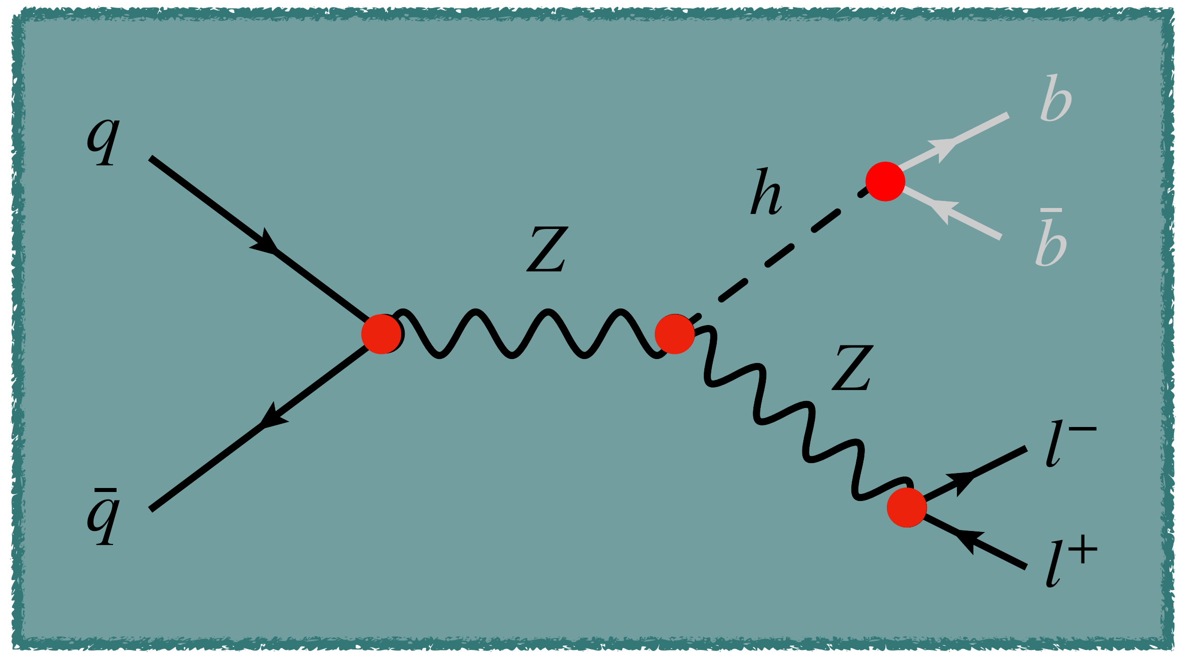
- **Fermion operators** factorize:



$$\left(\dots\gamma^\mu P_L + \dots\gamma^\mu P_R\right)$$

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

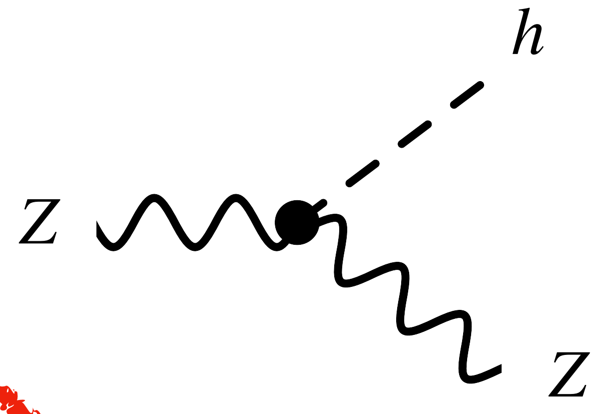


- We would like to extend the existing implementation to include **electroweak operators** as well.

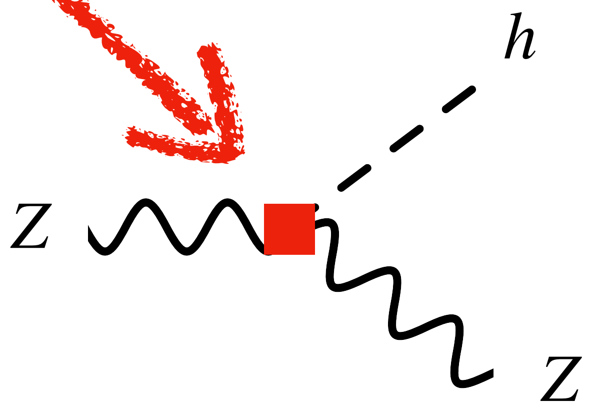
$$
\begin{aligned}
&Q_{HW} = H^\dagger H\, W^I_{\mu\nu} W^{I,\mu\nu}\,, \qquad Q_{HB} = H^\dagger H\, B_{\mu\nu} B^{\mu\nu}\,,\\
&Q_{HWB} = H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}\,,\\
&Q^{(1)}_{Hl} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{l}\gamma^\mu l)\,, \qquad Q^{(3)}_{Hl} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)(\bar{l}\tau^I\gamma^\mu l)\,,\\
&Q^{(1)}_{Hq} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{q}\gamma^\mu q)\,, \qquad Q^{(3)}_{Hq} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)(\bar{q}\tau^I\gamma^\mu q)\,,\\
&Q_{Hu} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{u}\gamma^\mu u)\,, \qquad Q_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{d}\gamma^\mu d)\,,\\
&Q_{He} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{e}\gamma^\mu e)\,,
\end{aligned}
$$

Source: ArXiv:1008.4884 (B. Grzadkowski et al.).

- **Gauge operators** do not factorize:

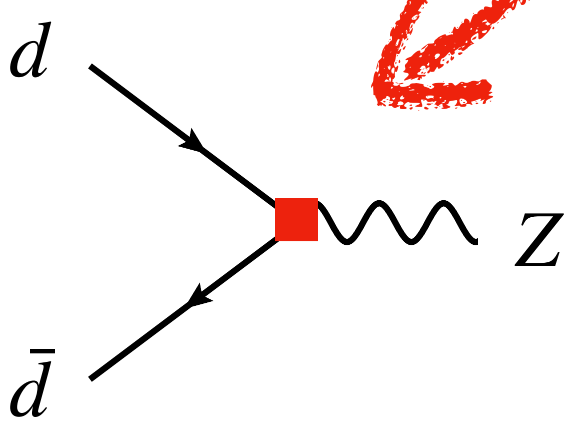


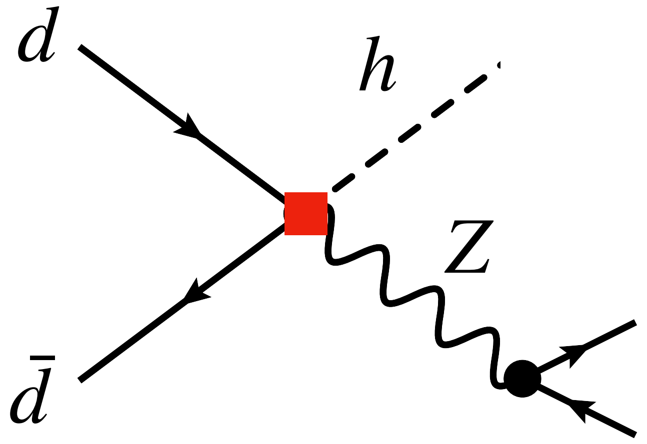
$$\ldots g^{\mu\nu}$$



$$\ldots g^{\mu\nu} + \ldots p_1^\mu p_2^\nu + \ldots \left(p_1^\mu p_1^\nu + p_2^\mu p_2^\nu\right)$$

- **Fermion operators** factorize:





$$\left(\ldots\gamma^\mu P_L + \ldots\gamma^\mu P_R\right)$$

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

2. SMEFT Effects in Vh at NNLO+PS

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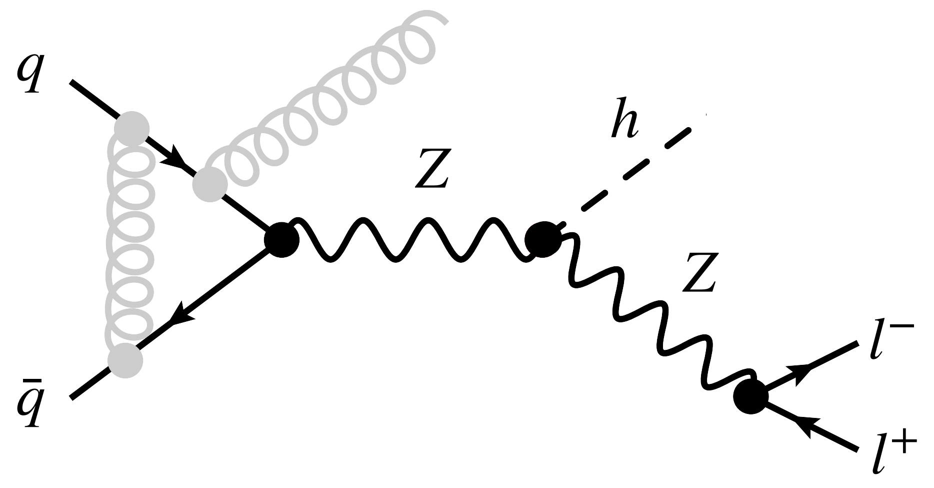
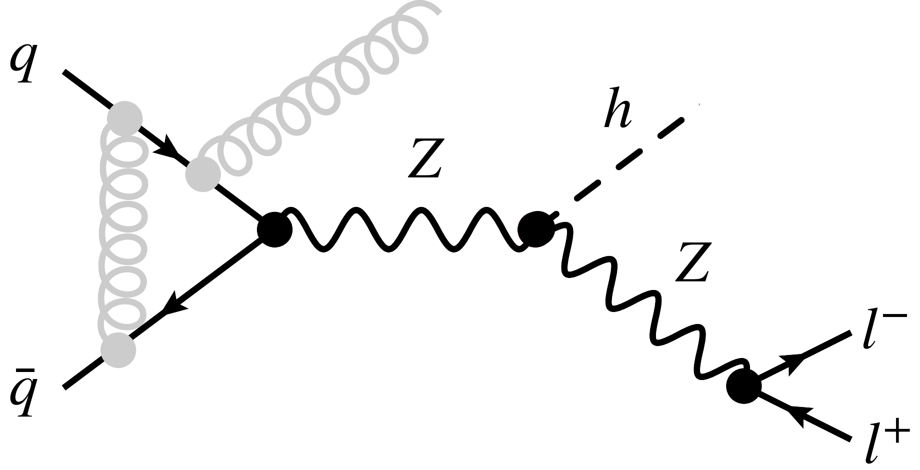
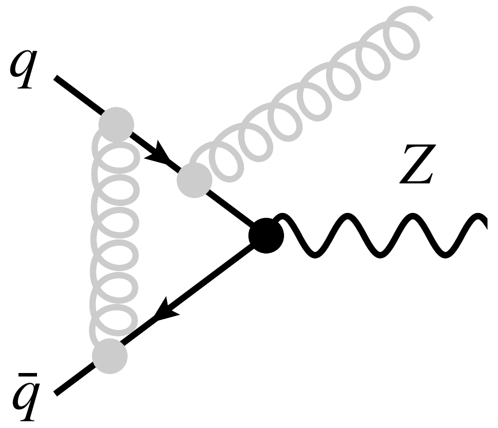


2. SMEFT Effects in Vh at NNLO+PS

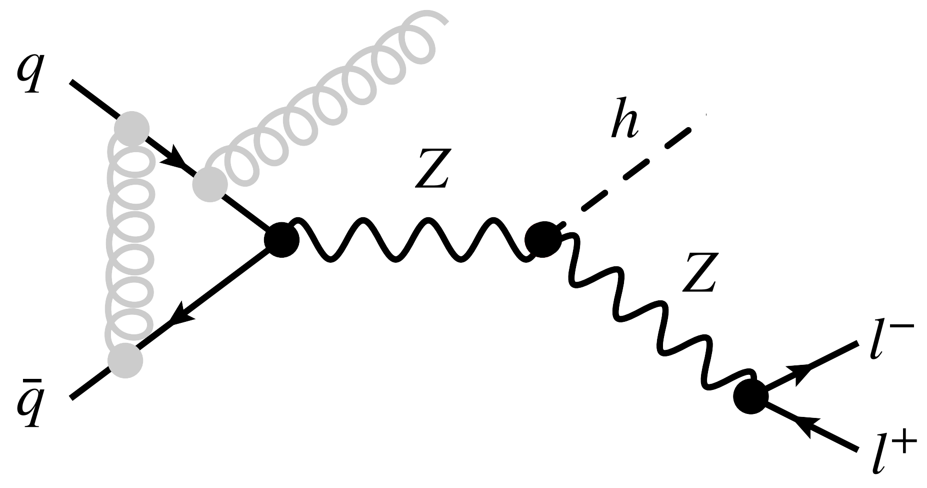
2.2 EW Operators

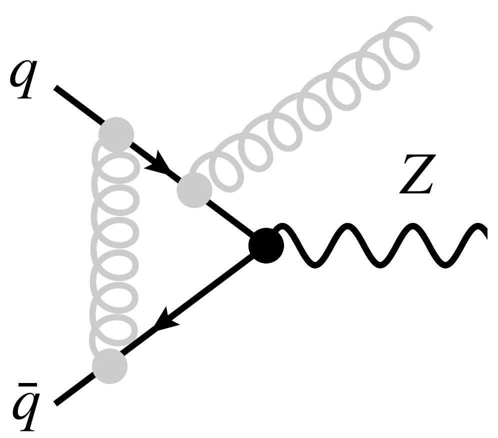


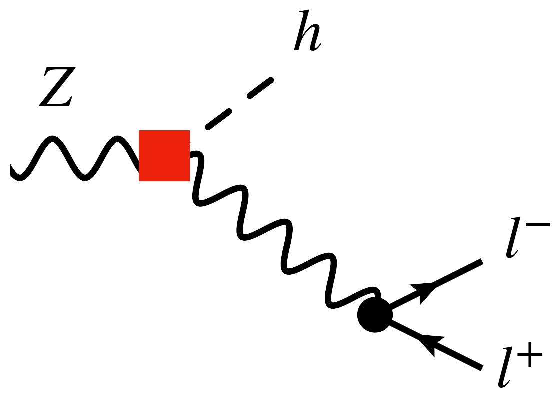


2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

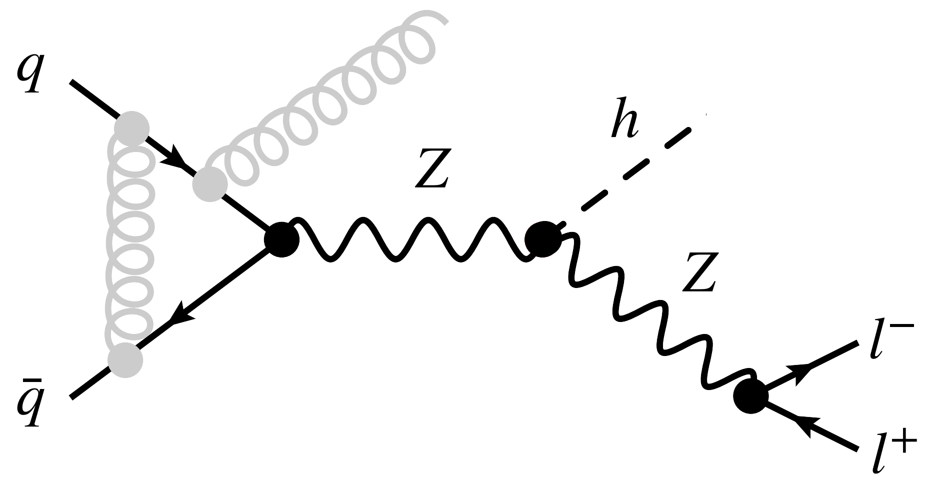


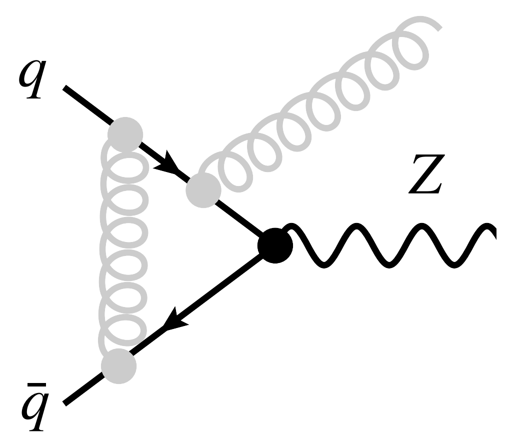


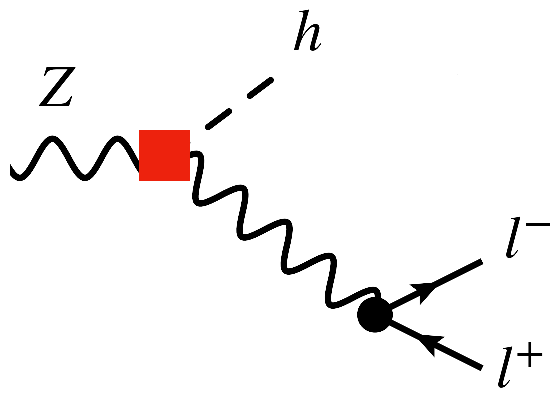


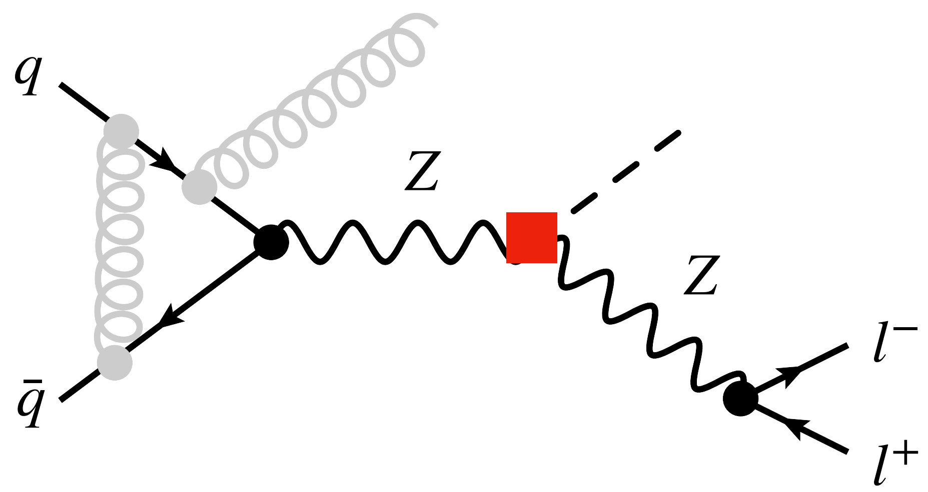
2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators



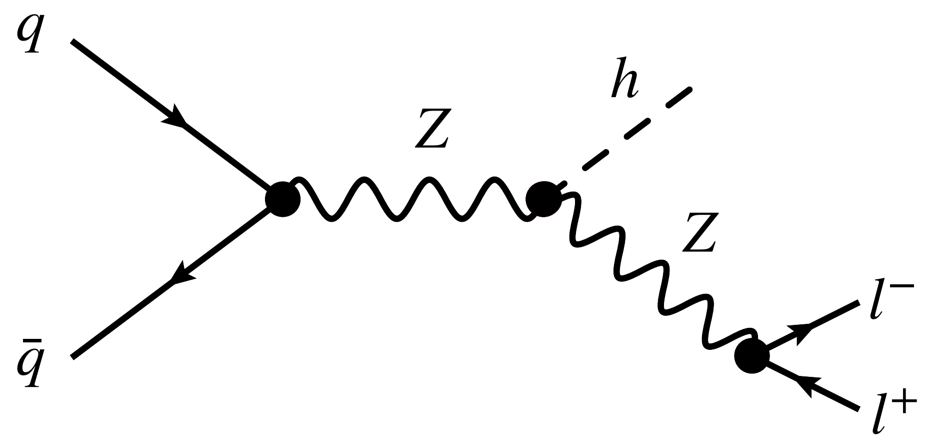


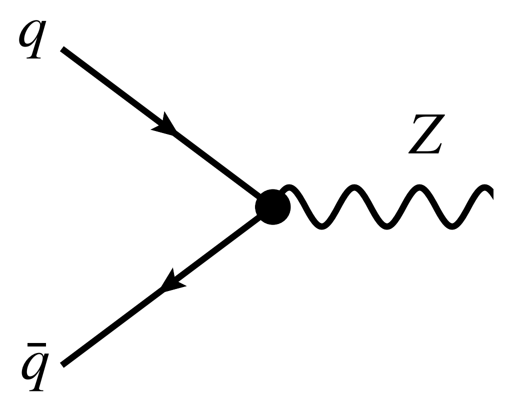


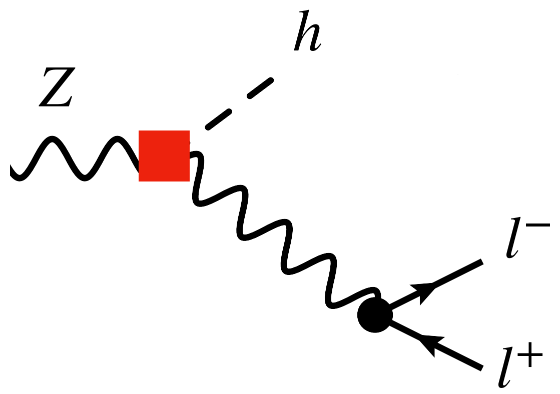


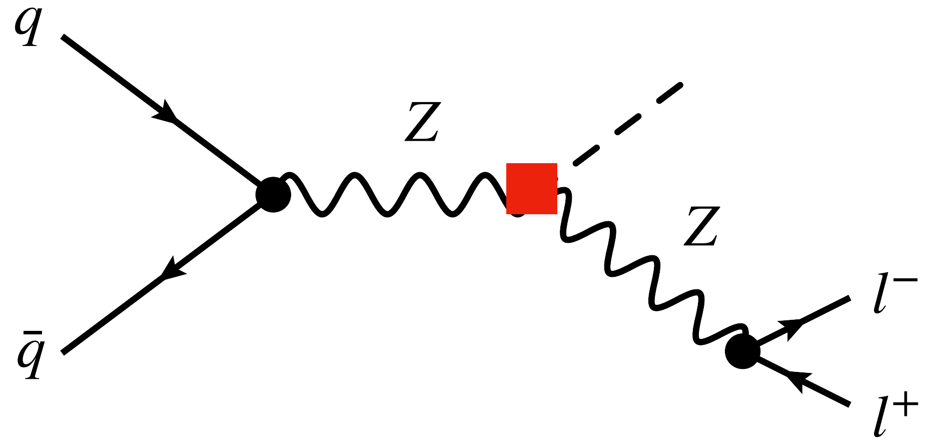
2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators



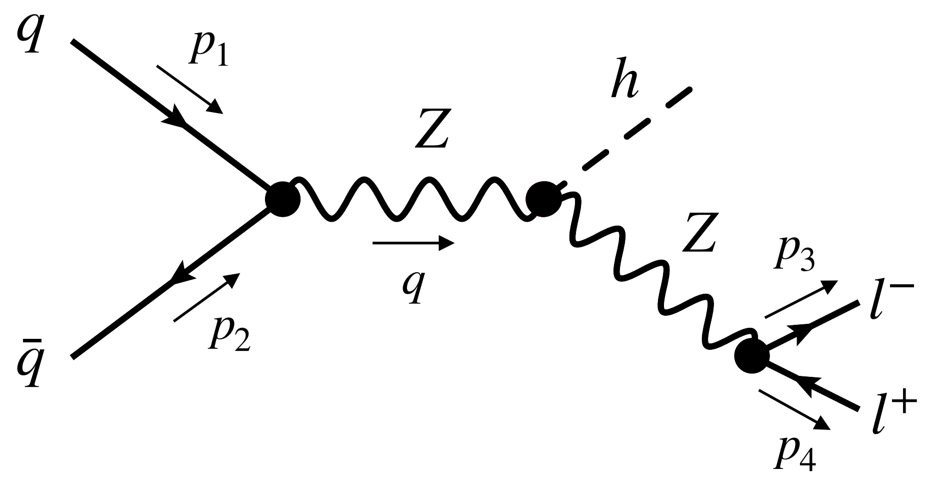


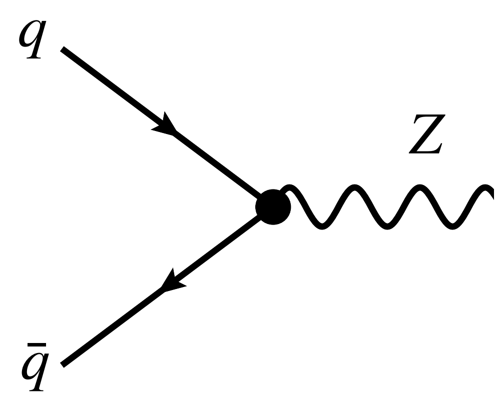


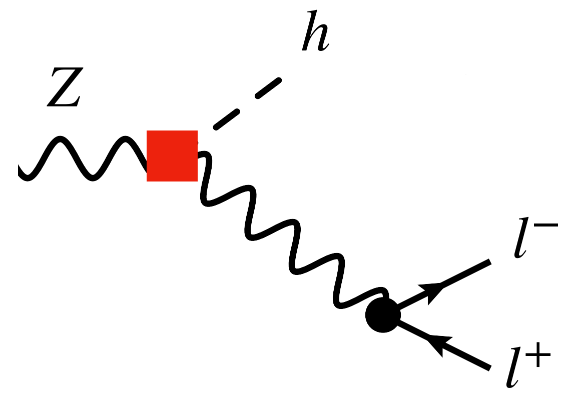


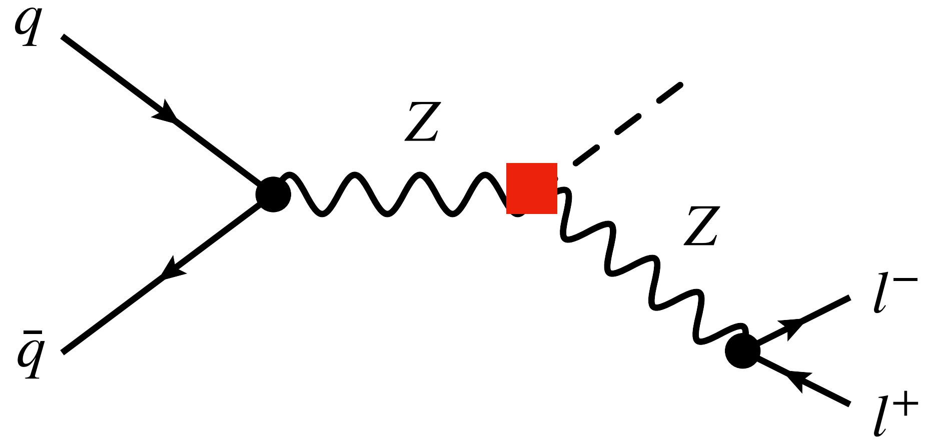
2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators





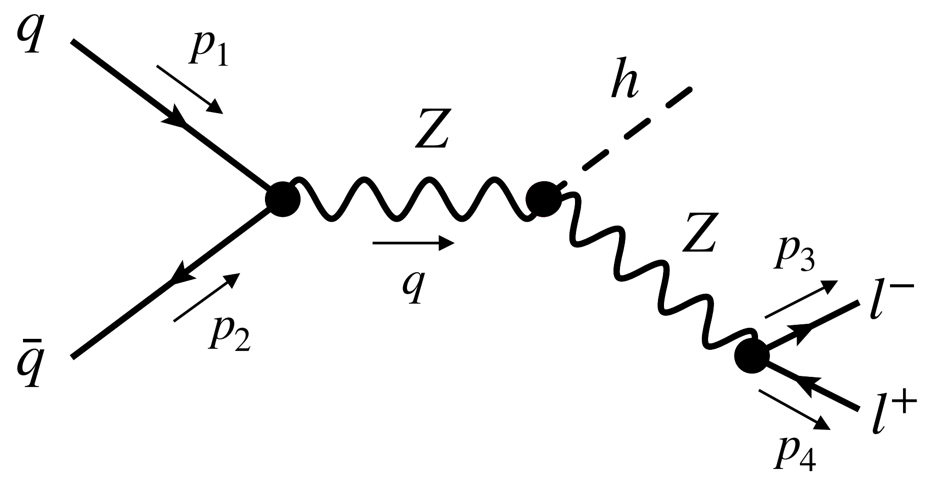


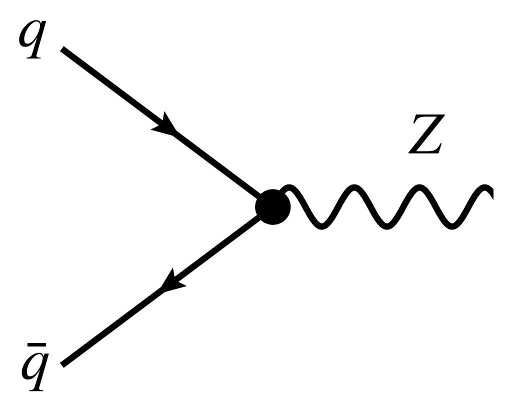


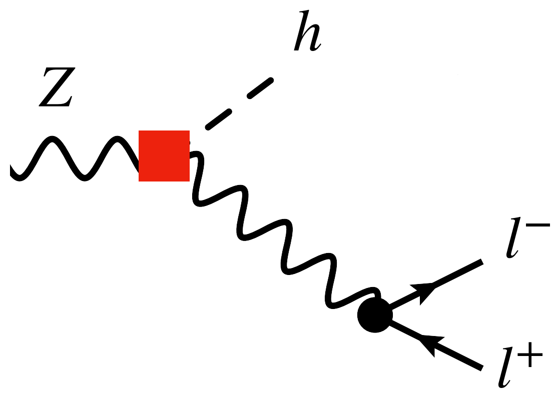
2. SMEFT Effects in Vh at NNLO+PS

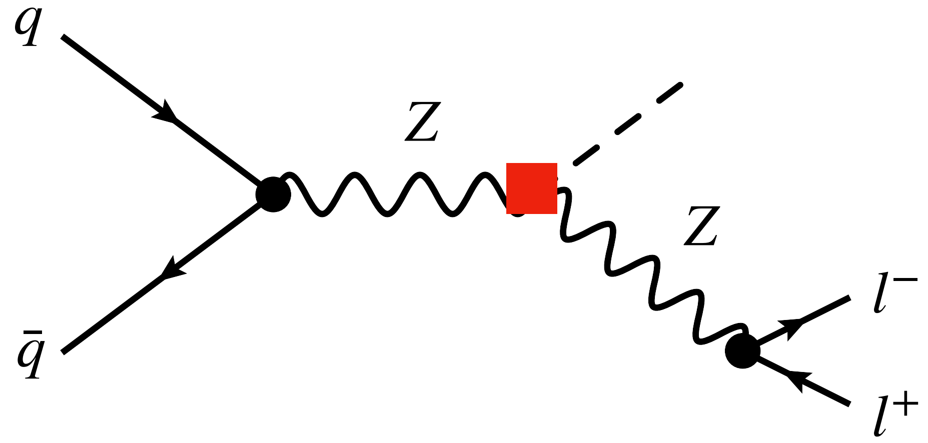
2.2 EW Operators







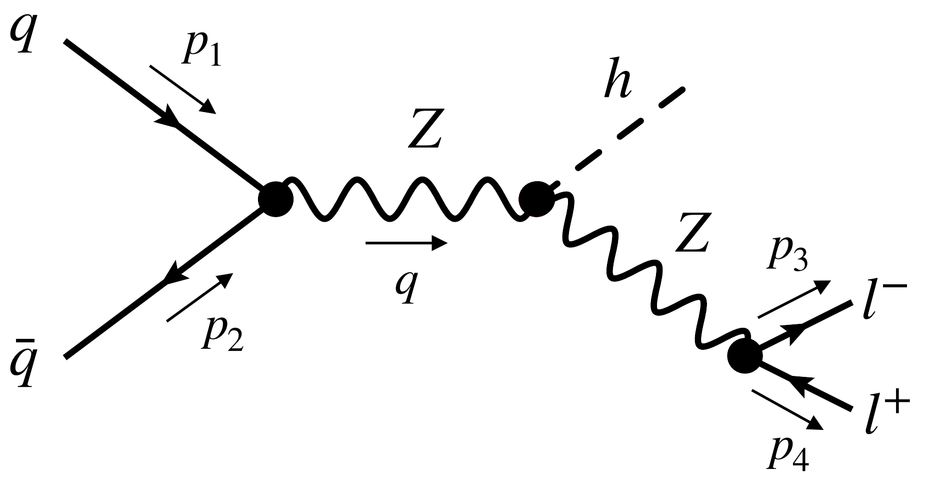


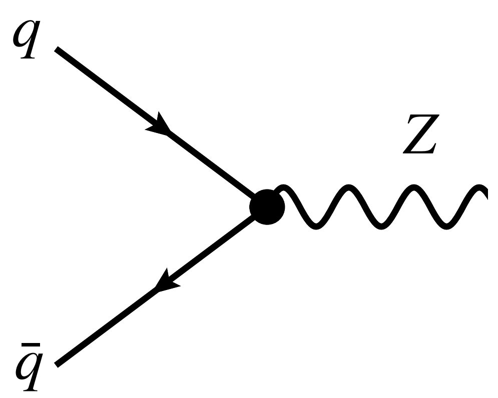
$$\frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)}\left(\frac{gM_Z}{c_w}\right)\langle 23\rangle[41]$$

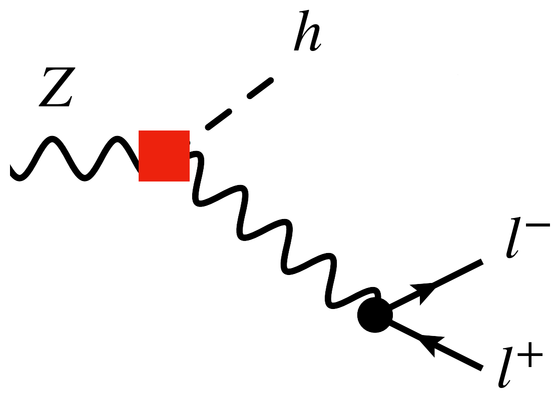
2. SMEFT Effects in Vh at NNLO+PS

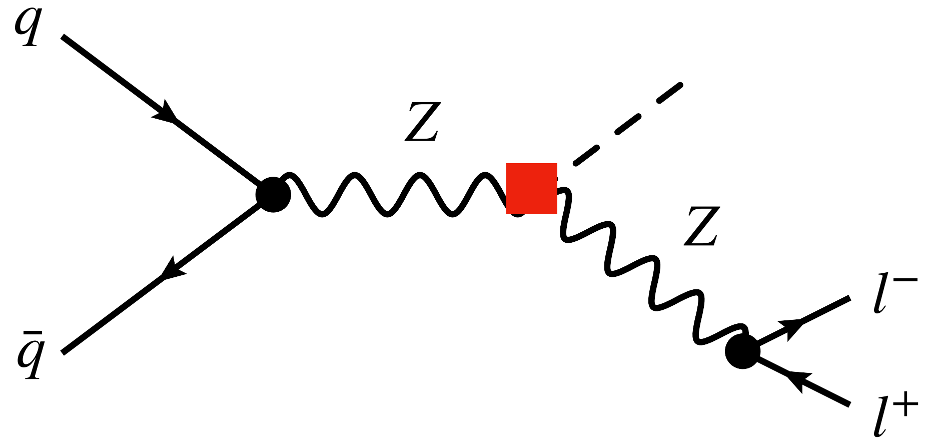
2.2 EW Operators







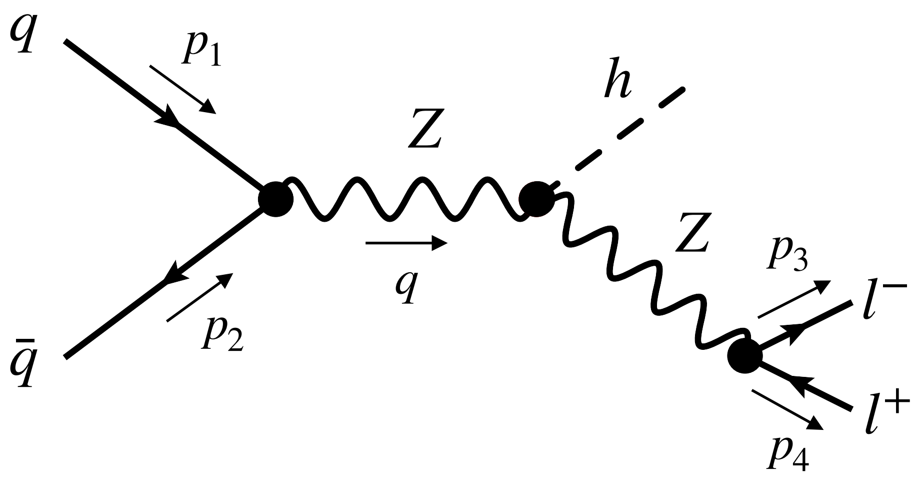


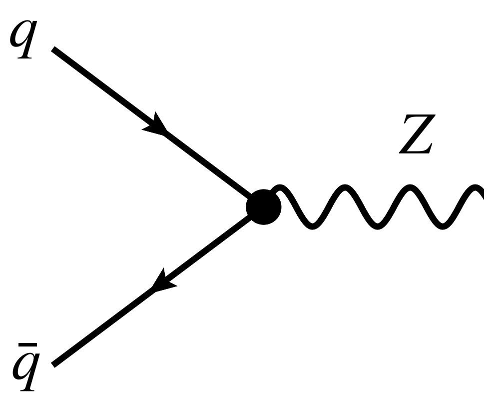
$$\frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)}\left(\frac{gM_Z}{c_w}\right)\langle 23\rangle[41]$$

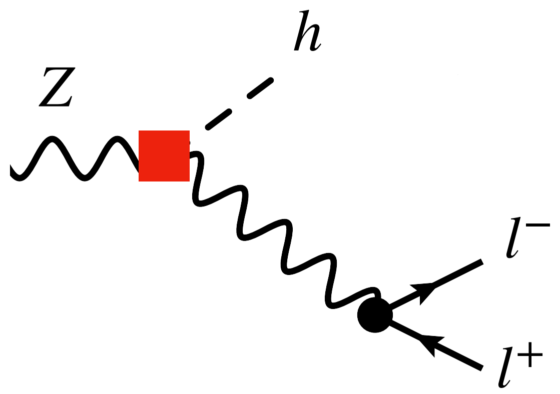
$$\langle 23\rangle[41] = \frac{1}{2}\,\langle 3|\gamma^\mu|4]\langle 1|\gamma_\mu|2]$$

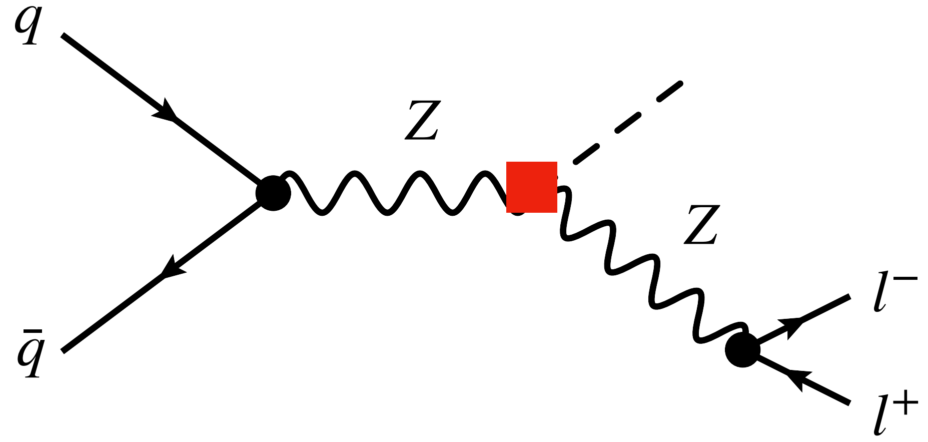
2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators









$$\frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)} \left(\frac{g M_Z}{c_w}\right) \langle 23\rangle[41]$$

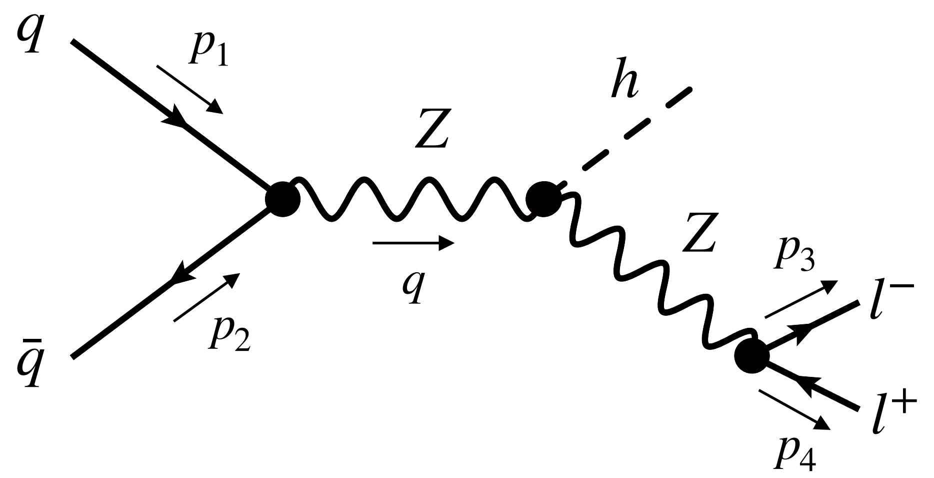
$$\langle 1|\gamma_\mu|2]$$

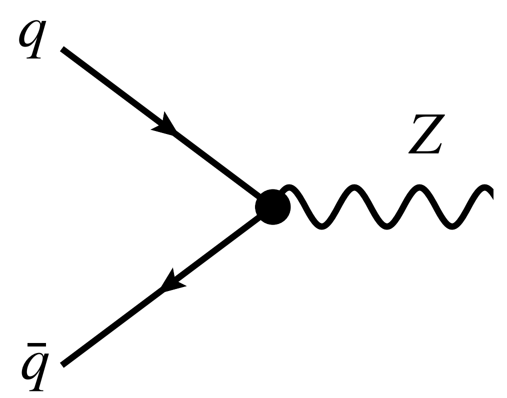
$$\langle 23\rangle[41] = \frac{1}{2}\langle 3|\gamma^\mu|4]\langle 1|\gamma_\mu|2]$$

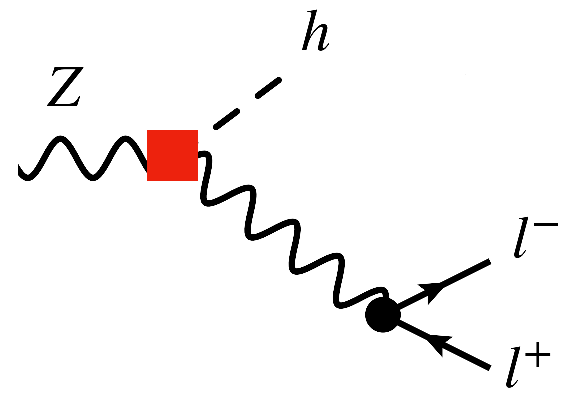
2. SMEFT Effects in Vh at NNLO+PS

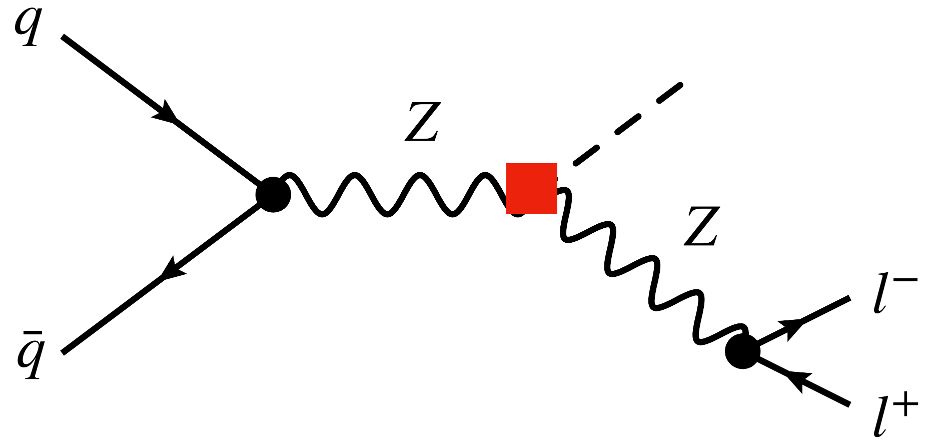
2.2 EW Operators









$$\frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)}\left(\frac{gM_Z}{c_w}\right)\langle 23\rangle[41]$$

$$\langle 1|\gamma_\mu|2]$$

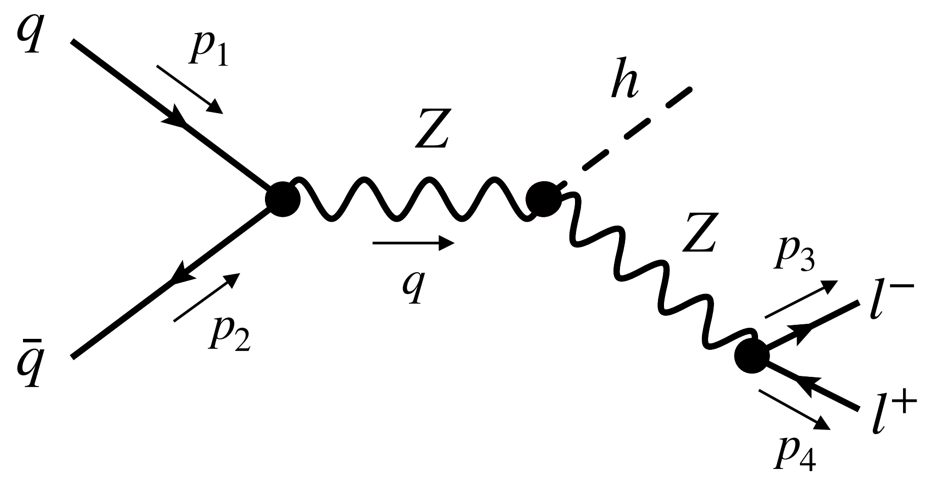
$$\langle 3|\gamma^\mu q|3\rangle[34] + \langle 34\rangle[4|q\gamma^\mu|4]$$

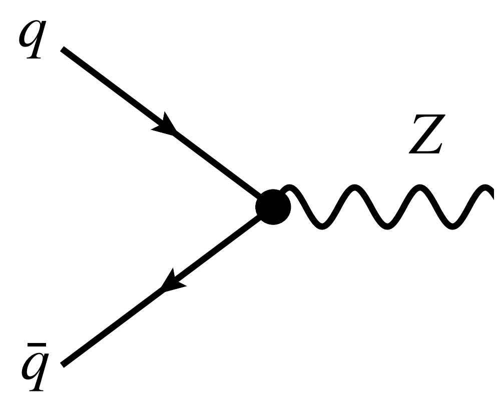
$$\langle 23\rangle[41] = \frac{1}{2}\,\langle 3|\gamma^\mu|4]\langle 1|\gamma_\mu|2]$$

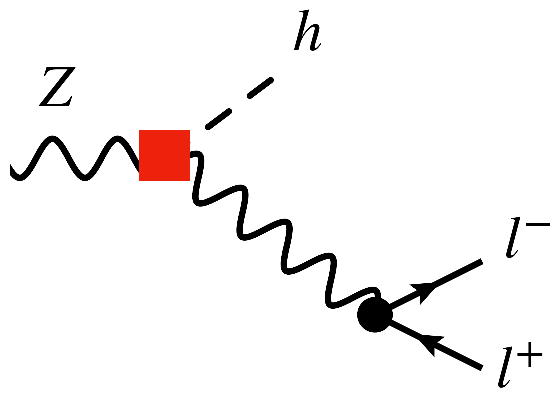
2. SMEFT Effects in Vh at NNLO+PS

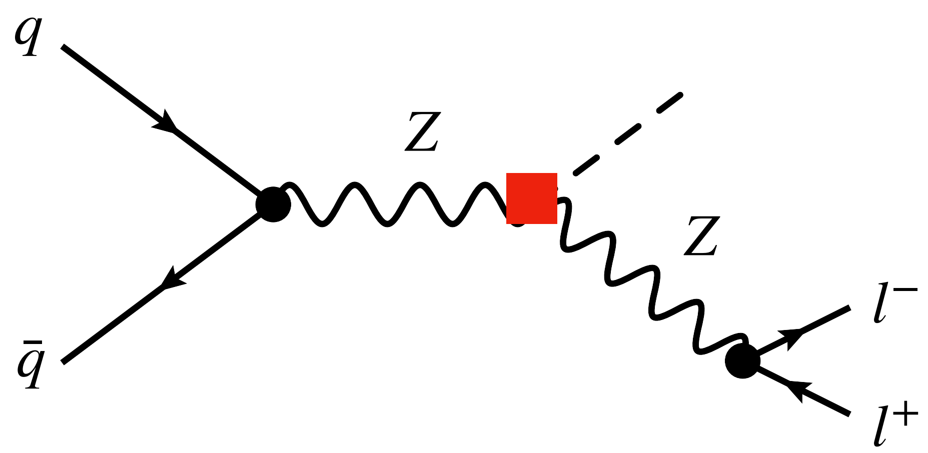
2.2 EW Operators









$$\frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)}\left(\frac{gM_Z}{c_w}\right)\langle 23\rangle[41]$$

$$\langle 1|\gamma_\mu|2]$$

$$\langle 3|\gamma^\mu q|3\rangle[34] + \langle 34\rangle[4|q\gamma^\mu|4]$$

$$\sim \frac{i g^Z_{q_L} g^Z_{l_L}}{\left(s_{12}-M_Z^2\right)\left(s_{34}-M_Z^2\right)}\left(-\langle 12\rangle\langle 34\rangle[41]^2 + \langle 23\rangle^2[21][43]\right)$$

$$\langle 23\rangle[41] = \frac{1}{2}\langle 3|\gamma^\mu|4]\langle 1|\gamma_\mu|2]$$

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

2. SMEFT Effects in Vh at NNLO+PS

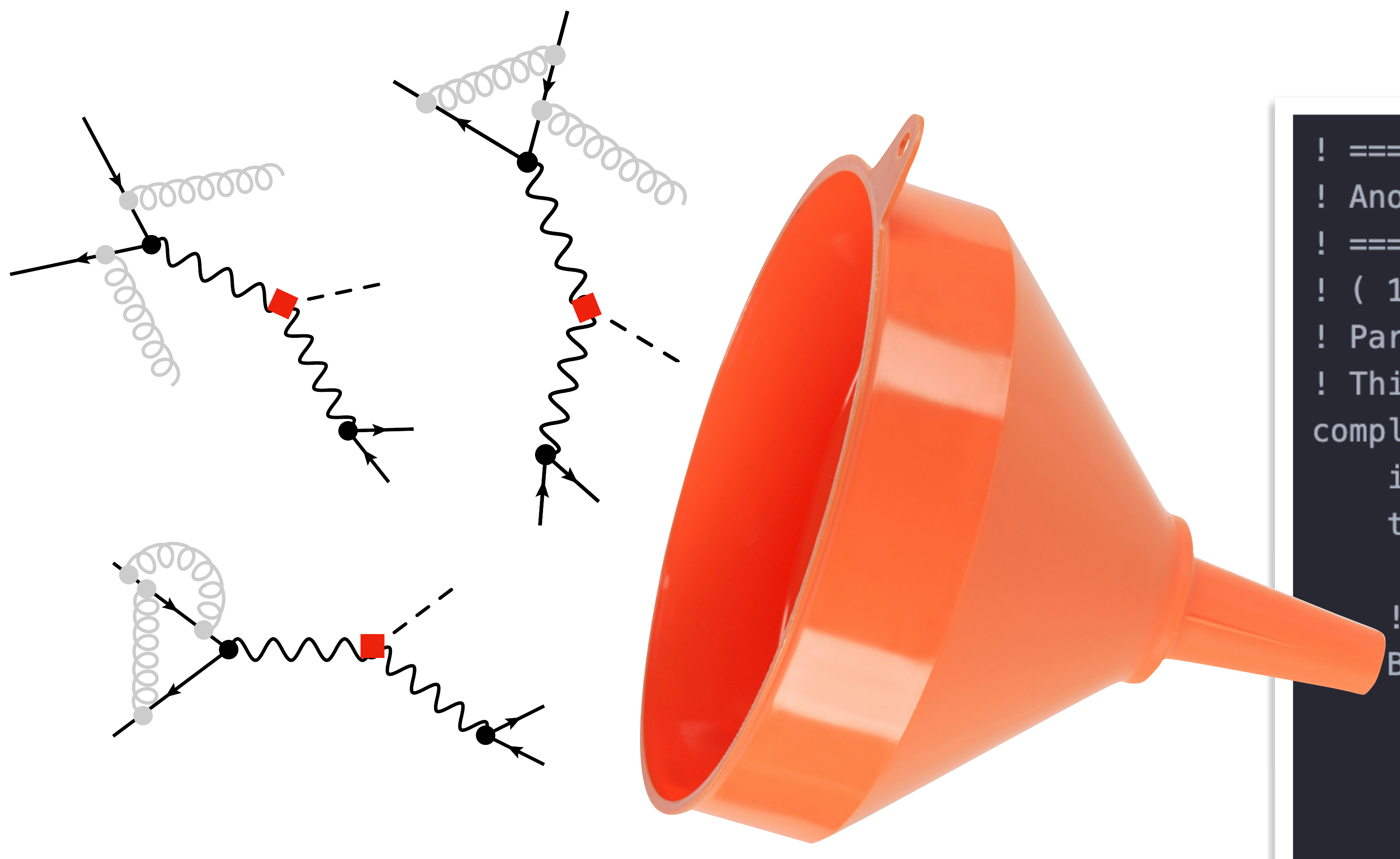
2.2 EW Operators

- **Fortran** implementation…

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

- **Fortran** implementation…

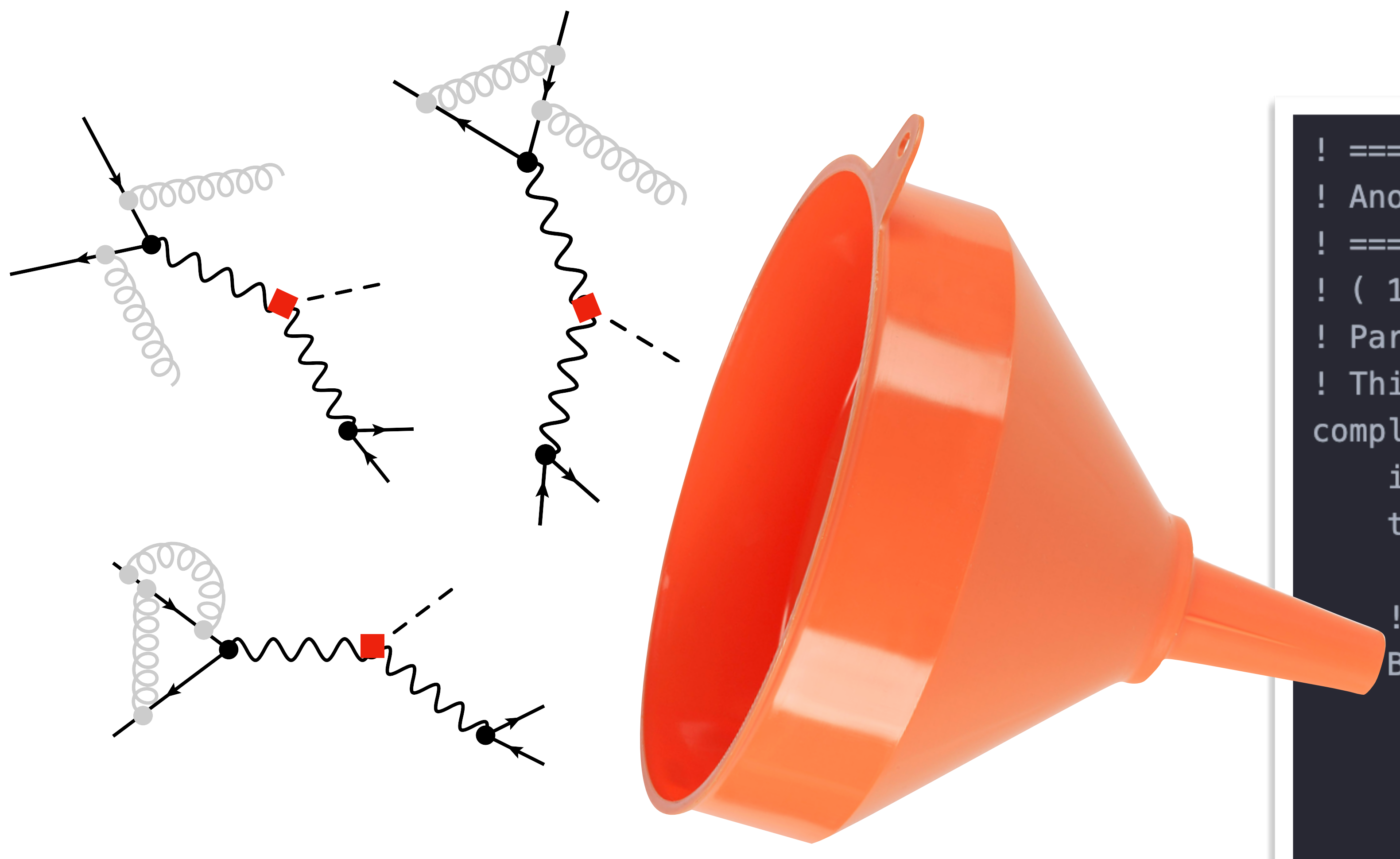


```fortran
! ===========================================================================
! Anomalous couplings (ghzz1)
! ===========================================================================
! ( 1q-, 2qb+; 3l-, 4lb+ )
! Particles before the ";" are incoming, after outgoing.
! This corresponds to the LL case.
complex(8) function B0g0Z_Hel_ghzz1_LL(i1,i2,i3,i4,K)
    integer, intent(in) :: i1,i2,i3,i4
    type(Event_t), intent(in) :: K

    ! The helicity amplitude
    B0g0Z_Hel_ghzz1_LL = -(K%Za(i1,i2)*K%Za(i3,i4) &
                        * pow(K%Zb(i4,i1),2) &
                        + pow(K%Za(i2,i3),2) &
                        * K%Zb(i2,i1)*K%Zb(i4,i3))

end function B0g0Z_Hel_ghzz1_LL
! ===========================================================================
```

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

- **Fortran** implementation…



```
! =========================================================================
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    ! The helicity amplitude
    B0g0Z_Hel_ghzz1_LL = -(K%Za(i1,i2)*K%Za(i3,i4) &
                         * pow(K%Zb(i4,i1),2) &
                         + pow(K%Za(i2,i3),2) &
                         * K%Zb(i2,i1)*K%Zb(i4,i3))

end function B0g0Z_Hel_ghzz1_LL
! =========================================================================
```
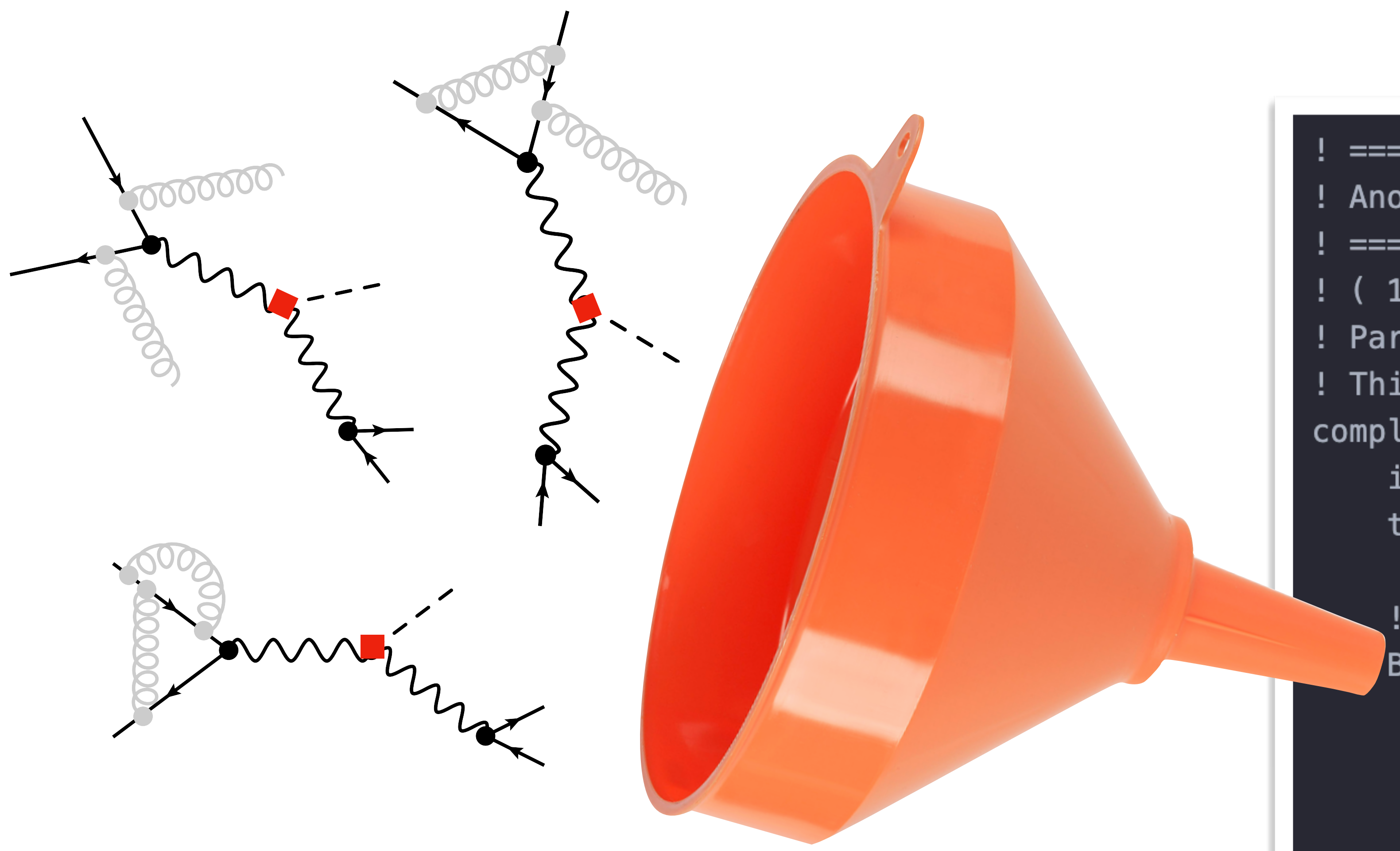

```
---------------------------------
         Checks Virtual
---------------------------------
Ratio Virtual (ours/existing):   0.99999999999971267
---------------------------------
     Checks correlated Born
---------------------------------
i, j:           1           1
Ratio:     1.0000000008927112
i, j:           1           2
Ratio:     1.0000000008927112
i, j:           1           6
Ratio:     1.0000000008927112
mu, nu:           1           1
Ratio:     1.0000000347233580
mu, nu:           1           2
Ratio:    0.99999999037223986
mu, nu:           2           1
Ratio:    0.99999999037223986
mu, nu:           2           2
Ratio:     1.0000000309149535
i, j:           2           1
Ratio:     1.0000000008927112
i, j:           2           2
Ratio:     1.0000000008927110
i, j:           2           6
Ratio:     1.0000000008927112
i, j:           6           1
Ratio:     1.0000000008927112
i, j:           6           2
Ratio:     1.0000000008927112
i, j:           6           6
Ratio:     1.0000000008927110
---------------------------------
          Checks Born
---------------------------------
Ratio Born (ours/existing):    1.0000000008927110
```

2. SMEFT Effects in Vh at NNLO+PS

2.2 EW Operators

- **Fortran** implementation…



```
! ==========================================================================
! Anomalous couplings (ghzz1)
! ==========================================================================
! ( 1q-, 2qb+; 3l-, 4lb+ )
! Particles before the ";" are incoming, after outgoing.
! This corresponds to the LL case.
complex(8) function B0g0Z_Hel_ghzz1_LL(i1,i2,i3,i4,K)
    integer, intent(in) :: i1,i2,i3,i4
    type(Event_t), intent(in) :: K

    ! The helicity amplitude
    B0g0Z_Hel_ghzz1_LL = -(K%Za(i1,i2)*K%Za(i3,i4) &
                        * pow(K%Zb(i4,i1),2) &
                        + pow(K%Za(i2,i3),2) &
                        * K%Zb(i2,i1)*K%Zb(i4,i3))

end function B0g0Z_Hel_ghzz1_LL
! ==========================================================================
```

```
--------------------------------
         Checks Virtual
--------------------------------
Ratio Virtual (ours/existing):   0.99999999999971267
--------------------------------
     Checks correlated Born
--------------------------------
i, j:             1            1
Ratio:    1.0000000008927112
i, j:             1            2
Ratio:    1.0000000008927112
i, j:             1            6
Ratio:    1.0000000008927112
mu, nu:             1            1
Ratio:    1.0000000347233580
mu, nu:             1            2
Ratio:   0.99999999037223986
mu, nu:             2            1
Ratio:   0.99999999037223986
mu, nu:             2            2
Ratio:    1.0000000309149535
i, j:             2            1
Ratio:    1.0000000008927112
i, j:             2            2
Ratio:    1.0000000008927110
i, j:             2            6
Ratio:    1.0000000008927112
i, j:             6            1
Ratio:    1.0000000008927112
i, j:             6            2
Ratio:    1.0000000008927112
i, j:             6            6
Ratio:    1.0000000008927110
--------------------------------
          Checks Born
--------------------------------
Ratio Born (ours/existing):    1.0000000008927110
```

- **Next step:** generate phenomenology plots.

3. Conclusions

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- Using spinor-helicity amplitudes, the electroweak **SM helicity structure can be replaced by new helicity structures** without having to recompute the QCD corrections.

Thank you for your attention!