Flavour constraints on MFV SMEFT

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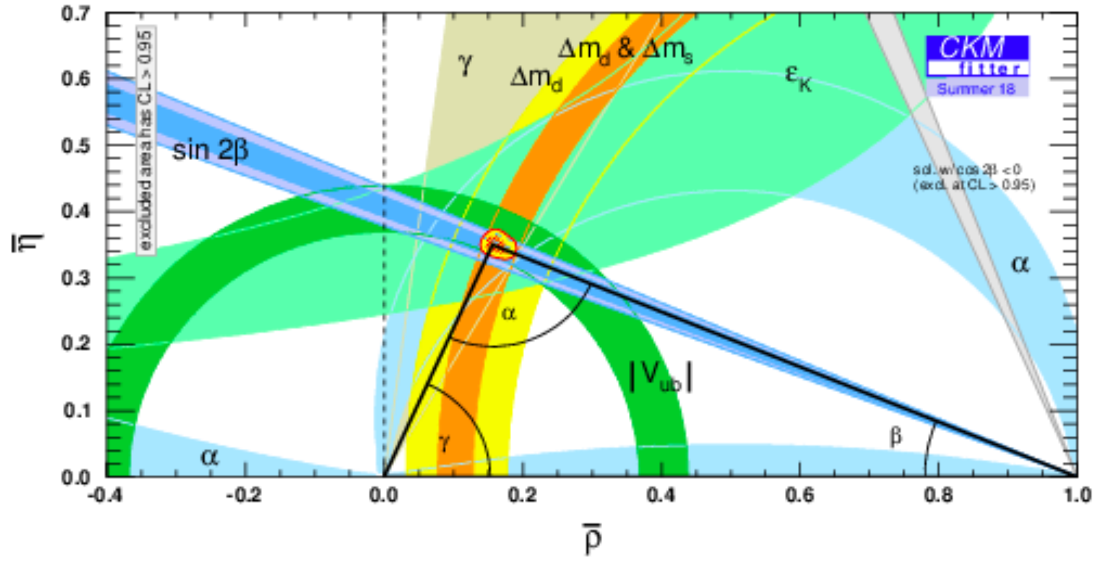
Two facets of flavor constraints

Flavour constraints do not give us much room for NP…

Model builders "use" MFV to escape from flavor constraints



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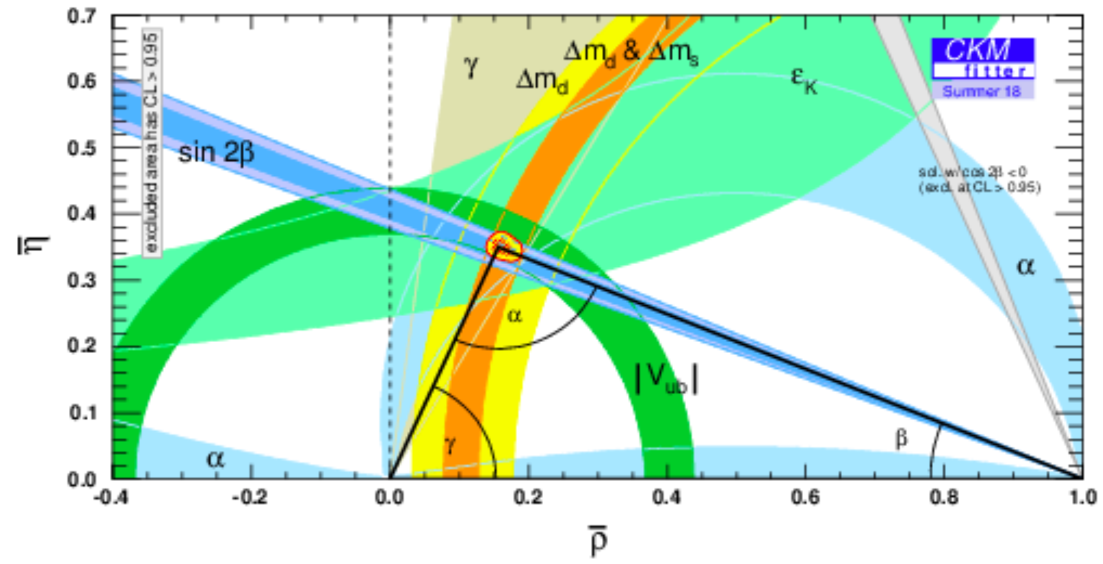

Model builders "use" MFV to escape from flavor constraints

Full one-loop matching from SMEFT to operators below weak scale mediating $d_i \to d_j \gamma$, $d_i \to d_j l^+ l^-$ and meson mixing

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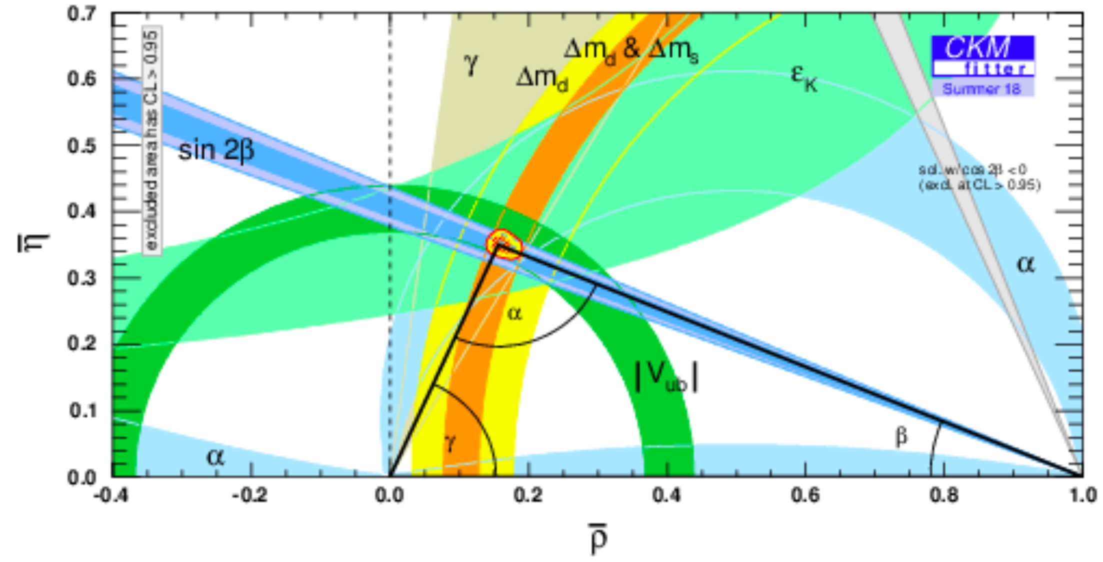
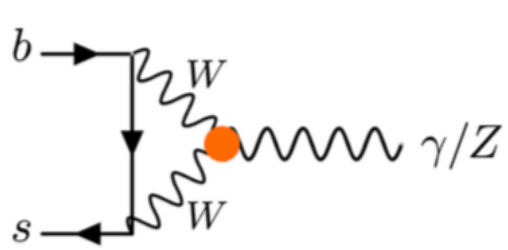


Full one-loop matching from SMEFT to operators below weak scale mediating $d_i \to d_j\gamma$, $d_i \to d_j l^+ l^-$ and meson mixing

One loop matching

“EW” WCs in the Flavour observables



What does flavor tell us about this WCs?

Can we improve the constraints?

SM (EFT) and its flavors

SM

only Yukawas break the flavor $U(3)^5$ symmetry

… FCNC only at loop level

BSM

Minimal Flavour Violation: *yukawas are the only source of this breaking*

SMEFT

too much flavor… $N_f = 1, 2, 3 \to 76,\ 582,\ 2499$

$U(3)^5$ flavour symmetry, only broken by quark Yukawa

… reduces to 59 (CP-even) ops.

SMEFT and its flavors

$$\boxed{U(3)^5 = U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R} \times U(3)_{L_L} \times U(3)_{e_R}}$$

$$Q_L \sim (3,1,1,1,1) \qquad u_R \sim (1,3,1,1,1) \qquad d_R \sim (1,1,3,1,1)$$

$$Y_u \sim (3,\bar{3},1,1,1) \qquad Y_d \sim (3,1,\bar{3},1,1)$$

SMEFT and its flavors

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$$Y_u \sim (3,\bar{3},1,1,1) \qquad Y_d \sim (3,1,\bar{3},1,1)$$

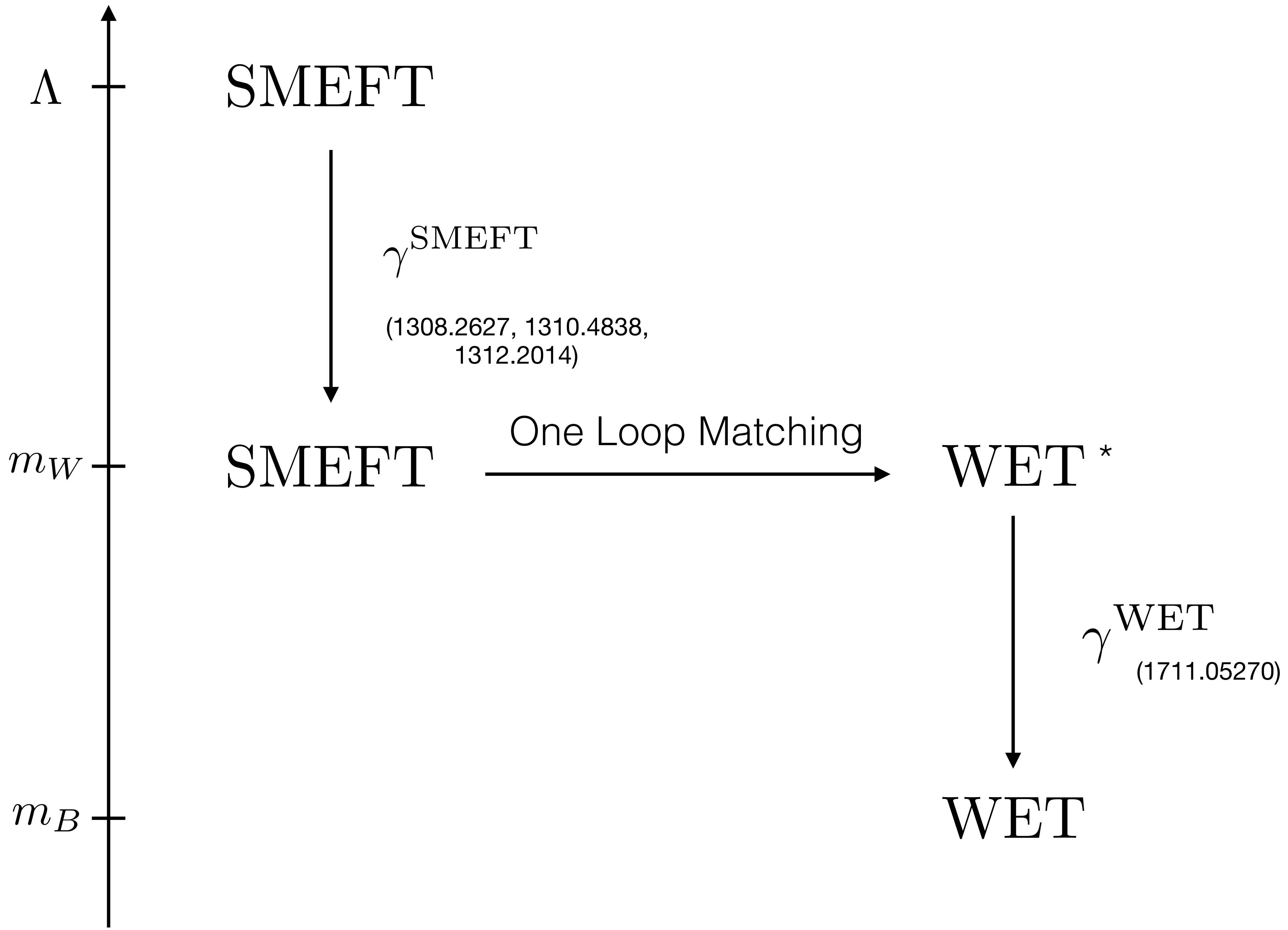
Transformation under $U(3)_Q \times U(3)_{u_R} \times U(3)_{d_R}$	Example	W.C	W.C. with only y_b, y_t nonzero
$(1,1,1)$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_i \gamma^\mu Q_j)$	$\propto \delta_{ij}$	$\propto \delta_{ij}$
$(\bar{3},3,1)$	$(\bar{Q}_i \sigma^{\mu\nu} u_j) B_{\mu\nu}$	$\propto (Y_u)_{ij}$	$\propto y_t \delta_{i3}\delta_{j3}$
$(\bar{3},1,3)$	$(\bar{Q}_i \sigma^{\mu\nu} d_j) B_{\mu\nu}$	$\propto (Y_d)_{ij}$	$\propto y_b V_{3i} \delta_{j3}$
$(1,\bar{3},3)$	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_i \gamma^\mu d_j)$	$\propto (Y_u^\dagger Y_d)_{ij}$	$\propto y_t y_b V_{33} \delta_{i3}\delta_{j3}$
$(8,3,3)$	$(\bar{Q}_i^\alpha u_j)\epsilon_{\alpha\beta}(\bar{Q}_k^\beta d_l)$	$\propto (Y_u)_{ij}(Y_d)_{kl}$	$\propto y_t y_b V_{3k} \delta_{i3}\delta_{j3}\delta_{l3}$

furthermore $\hat{Y}_u \approx (0,0,y_t)$ $\qquad \hat{Y}_d \approx (0,0,y_b)$

SMEFT

Ilaria’s talk

Match and Run!!



Goal: WET at mB as a linear combination of SMEFT in the UV

* also called LEFT

Weak Effective Theory

(aka Low-Energy Effective Field Theory - LEFT)

$$\mathcal{H}_{\text{eff}}^{|\Delta B|=|\Delta S|=1} = \frac{4\hat{G}_F}{\sqrt{2}}\left[-\frac{1}{(4\pi)^2}\hat{V}_{ts}^*\hat{V}_{tb}\sum_{i=3}^{10}C_i\mathcal{O}_i + \sum_{q=u,c}\hat{V}_{qs}^*\hat{V}_{qb}\left(C_1\mathcal{O}_1^q + C_2\mathcal{O}_2^q\right)\right]$$

Our Flavour assumption $U(3)^5 + Y_u, Y_d$

give us SM-like results

same CKM, no RH currents, GIM

$$\boxed{\begin{aligned}
\mathcal{O}_1^q &= (\bar{b}^\alpha\gamma_\mu P_L q^\beta)(\bar{q}^\beta\gamma^\mu P_L s^\alpha),\\
\mathcal{O}_2^q &= (\bar{b}^\alpha\gamma_\mu P_L q^\alpha)(\bar{q}^\beta\gamma^\mu P_L s^\beta),\\
\mathcal{O}_7 &= \hat{e}\hat{m}_b\,(\bar{s}\sigma^{\mu\nu}P_R b)\,F_{\mu\nu},\\
\mathcal{O}_8 &= \hat{g}_s\hat{m}_b\left(\bar{s}\sigma^{\mu\nu}T^A P_R b\right)G_{\mu\nu}^A,\\
\mathcal{O}_9 &= \hat{e}^2\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\ell\right),\\
\mathcal{O}_{10} &= \hat{e}^2\left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\gamma_5\ell\right).
\end{aligned}}$$

4 WET operators $\longrightarrow$ FCNC B mesons decays

same for ds

Related results

Some operators only…

Grzadkowski & Misiak, 0802.1413
Drobnak, Fajfer, Kamenik 1102.4347, 1109.2357
Bobeth & Haisch 1503.04829
Endo, Kitahara, Ueda 1811.04961

- focus on a particular vertex and few ops

Different flavour assumptions …

Aebischer, Crivellin, Fael & Greub, 1512.02830

- allows for tree level FCNC
- Loop level for only right-handed up type quarks

Recently, full one-loop matching

Denkes & Stoffer, 1908.05295

so far (first paper), only full symmetric…

$U(3)^5$

FCNC B decays

$b \to s\gamma$

$b \to s l^+ l^-$

$\mathrm{Meson\ mixing}$ … same for ds

SMEFT ops Groups: 1,2,3,4,7,8

$U(3)^5 + Y_u, Y_d$

FCNC B decays

$b \to s\gamma$

$b \to s l^+ l^-$

$\mathrm{Meson\ mixing}$ … same for ds

+

neutrino observables

$B \to V \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$ $K \to \pi\nu\bar{\nu}$

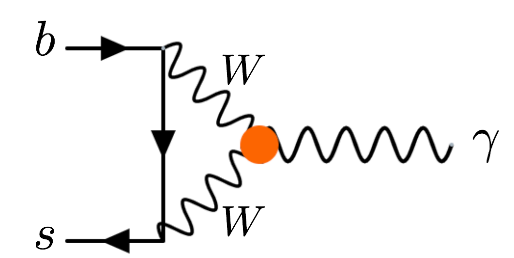
SMEFT ops Groups: same + 5,6,7,8

Operators for $U(3)^5$

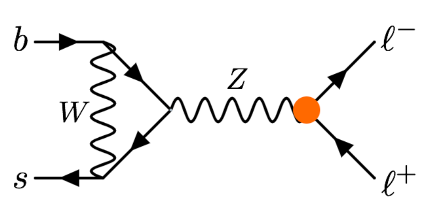
* via input parameters

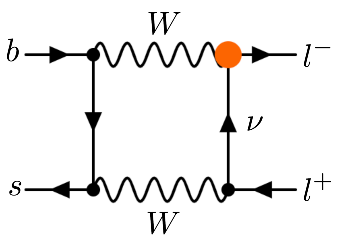
Group	Operators	$d_i \to d_j \gamma$	$d_i \to d_j\, l^+ l^-$	Meson mixing
1	Q_G	-	-	-
	Q_W	✔	✔	-
2	Q_H	-	-	-
3	$Q_{H\Box}$	-	-	-
	Q_{HD}	✔	✔	-
4	Q_{HG}	-	-	-
	Q_{HW}	-	-	-
	Q_{HB}	-	-	-
	Q_{HWB}	✔	✔	-
7	$Q_{H\ell}^{(1)}$	-	✔	-
	$Q_{H\ell}^{(3)}$	✔*	✔	✔*
	Q_{He}	-	✔	-
	$Q_{Hq}^{(1)}$	-	✔	-
	$Q_{Hq}^{(3)}$	✔	✔	✔
	Q_{Hu}	-	✔	-
	Q_{Hd}	-	-	-

Purely bosonic

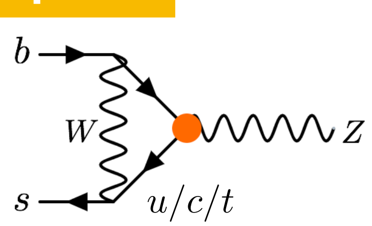


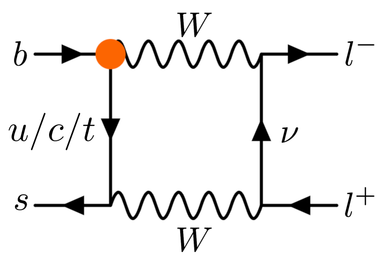
Higgs-lepton





Higgs-quark

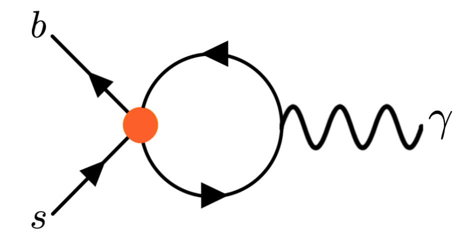


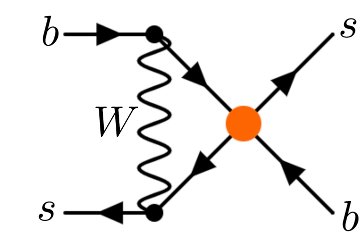


Operators for $U(3)^5$

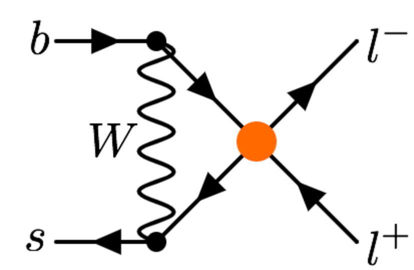
Group	Operators	$d_i \to d_j \gamma$	$d_i \to d_j l^+ l^-$	Meson mixing
8: $(\bar{L}L)(\bar{L}L)$	$Q_{\ell\ell}$	✔*	✔*	✔*
	$Q_{qq}^{(1)}$	-	✔	✔
	$Q_{qq}^{(3)}$	-	✔	✔
	$Q_{\ell q}^{(1)}$	-	✔	-
	$Q_{\ell q}^{(3)}$	-	✔	-
8: $(\bar{R}R)(\bar{R}R)$	Q_{ee}	-	-	-
	Q_{uu}	-	-	-
	Q_{dd}	-	-	-
	Q_{eu}	-	✔	-
	Q_{ed}	-	-	-
	$Q_{ud}^{(1)}$	-	-	-
	$Q_{ud}^{(8)}$	-	-	-
8: $(\bar{L}L)(\bar{R}R)$	$Q_{\ell e}$	-	-	-
	$Q_{\ell u}$	-	✔	-
	$Q_{\ell d}$	-	-	-
	Q_{qe}	-	✔	-
	$Q_{qu}^{(1)}$	-	-	-
	$Q_{qu}^{(8)}$	-	-	-
	$Q_{qd}^{(1)}$	-	-	-
	$Q_{qd}^{(8)}$	-	-	-

4 quarks





2 quarks 2 leptons



* via input parameters

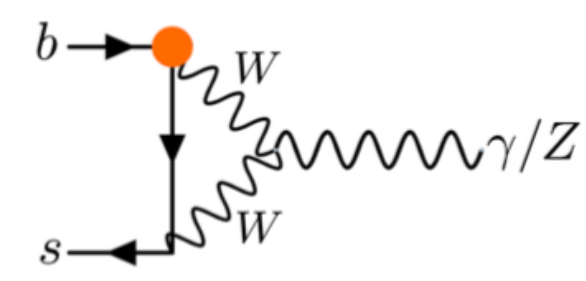
Operators for $U(3)^5 + Y_u, Y_d$

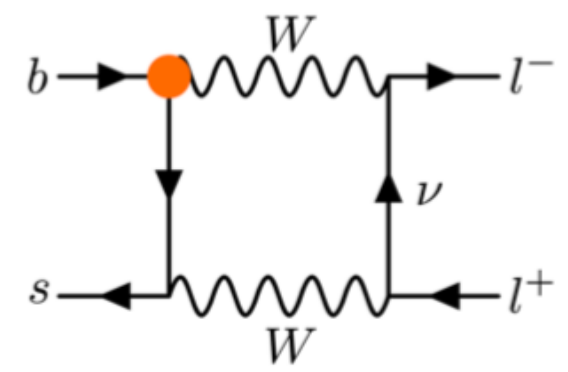
Same as before +

(which were forbidden previously)

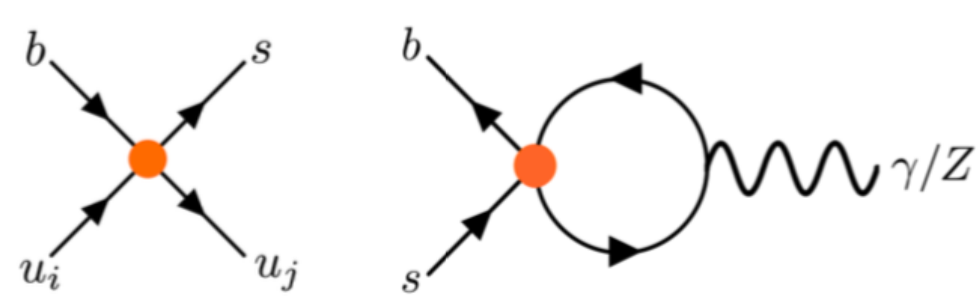
Group	Operators	$d_i \to d_j\gamma$	$d_i \to d_j l^+ l^-$	Meson mixing
5	$y_t Q_{uH}^{33}$	-	-	-
	$y_b Q_{dH}^{33}$	-	-	-
6	$y_t Q_{uG}^{33}$	✔	-	-
	$y_t Q_{uW}^{33}$	✔	✔	✔
	$y_t Q_{uB}^{33}$	✔	✔	-
	$y_b Q_{dG}^{33}$	-	-	-
	$y_b Q_{dW}^{33}$	✔	-	-
	$y_b Q_{dB}^{33}$	-	-	-
7	$y_b y_t V_{tb} Q_{Hud}$	✔	-	-
8: $(\bar{L}R)(\bar{R}L)$	$y_t y_b V_{tb} Q_{quqd}^{(1)3333}$	✔	-	-
	$y_t y_b V_{tb} Q_{quqd}^{(8)3333}$	✔	-	-

Higgs-quark and Gauge-quark





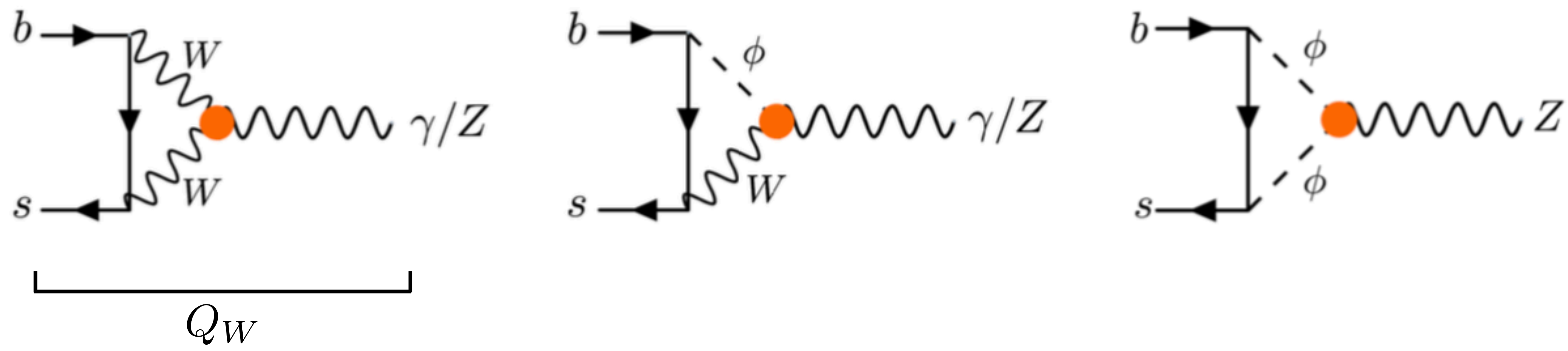
4 quarks



+ neutrinos

“EW” into C7

$$x_t \equiv \frac{m_t^2}{m_W^2}$$



$$C_7 = \frac{3}{2} g_2 v^2 C_W \left(-\frac{x_t^2 + x_t}{2(x_t - 1)^2} + \frac{x_t^2}{(x_t-1)^3} \log x_t \right)$$

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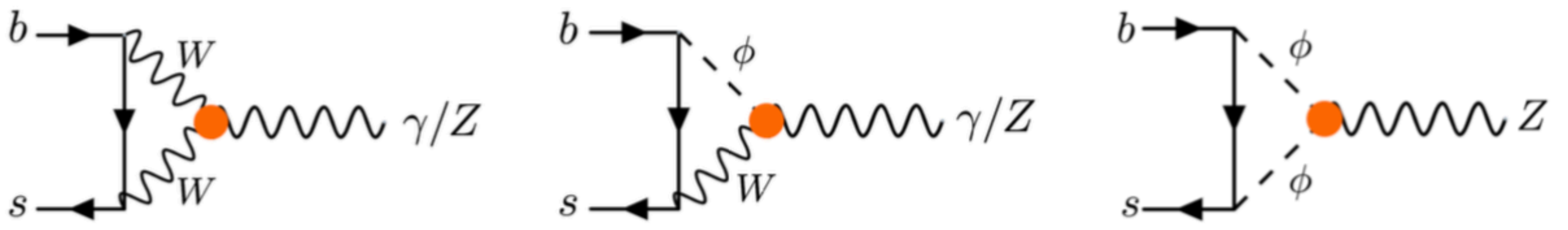

Q_{HD}

$$C_7 = \frac{1}{8}\frac{v^2}{s_\theta^2} C_{HD}(1 - s_\theta^2) D_0'(x_t)$$

Inami-Lim functions

$$D_0'(x_t) = \frac{8x_t^3 + 5x_t^2 - 7x_t}{12(x_t - 1)^3} + \frac{x_t^2(2 - 3x_t)}{2(1 - x_t)^4} \log x_t$$

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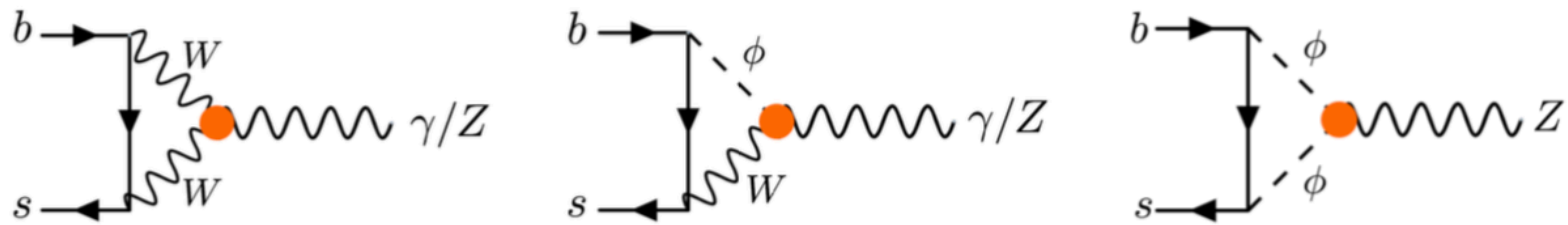
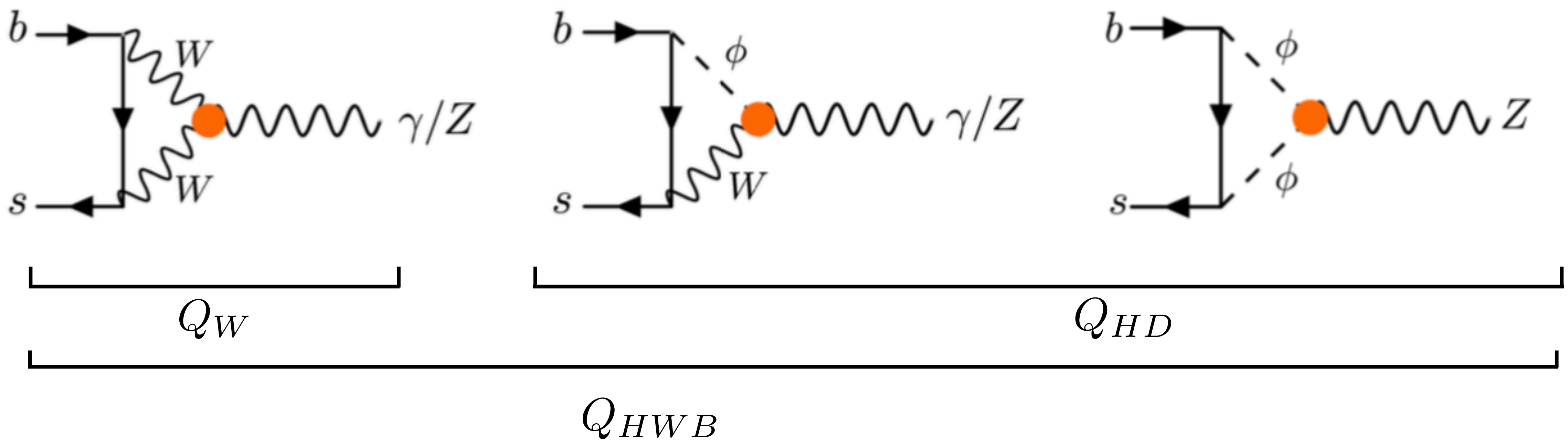


Q_{HWB}

$$C_7 = -v^2 C_{HWB} \frac{g_2}{g_1} \left(\frac{8x_t^2 - 7x_t + 5}{24(1-x_t)^3} + \frac{x_t(x_t^2 - x_t + 1)}{4(1-x_t)^4} \log x_t \right)$$

“EW” into C7

$$x_t \equiv \frac{m_t^2}{m_W^2}$$



$$C_7 = \frac{3}{2} g_2 v^2 C_W \left(-\frac{x_t^2 + x_t}{2(x_t - 1)^2} + \frac{x_t^2}{(x_t - 1)^3} \log x_t \right)$$

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$$C_7 = \frac{1}{8} \frac{v^2}{s_\theta^2} C_{HD}(1 - s_\theta^2) D_0'(x_t)$$

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Neutrinos

$$\mathcal{H} \supset -\frac{4G_F}{\sqrt{2}} \frac{1}{(4\pi)^2} \frac{e^2}{\sin^2\theta_W} V_{ts}^* V_{tb}\, C_L\, (s_L \gamma^\mu b_L)\, (\nu_L \gamma^\mu \nu_L)$$

SM result

$$C_L = C_0(x_t) - 4B_0(x_t)$$

$$B_0(x_t) = \frac{1}{4}\left[\frac{x_t}{1-x_t} + \frac{x_t}{(x_t-1)^2}\log x_t\right],$$

$$C_0(x_t) = \frac{x_t}{8}\left[\frac{x_t-6}{x_t-1} + \frac{3x_t+2}{(x_t-1)^2}\log x_t\right],$$

SMEFT result

$$\begin{aligned} C_L = {} & \frac{v^2}{\Lambda^2}\left(C_{Hl}^{(1)} + C_{Hq}^{(1)} - C_{Hu} + C_{lq}^{(1)} - C_{lu} + \frac{1}{2}C_{HD}\right) I(x_t) - \frac{v^2}{\Lambda^2} C_{lq}^{(3)} I^{lq}(x_t) \\ & + \frac{v^2}{\Lambda^2} C_{Hl}^{(3)} I_\nu^{Hl3}(x_t) + \frac{v^2}{\Lambda^2} C_{Hq}^{(3)} I_\nu^{Hq3}(x_t) + 2\frac{v^2}{\Lambda^2} C_{ll}' \left(C_0(x_t) - 4B_0(x_t)\right) \\ & + \sqrt{2} y_t \frac{m_t}{m_W} \frac{v^2}{\Lambda^2} C_{uW} I_\nu^{uW} \end{aligned}$$

$\hat{m}_W$-scheme

neutrino observables

$B \to V \nu\bar{\nu}$

$K_L \to \pi^0 \nu\bar{\nu}$ $\quad K \to \pi\nu\bar{\nu}$

Our results are WET C's as a linear combination of SMEFT ops…

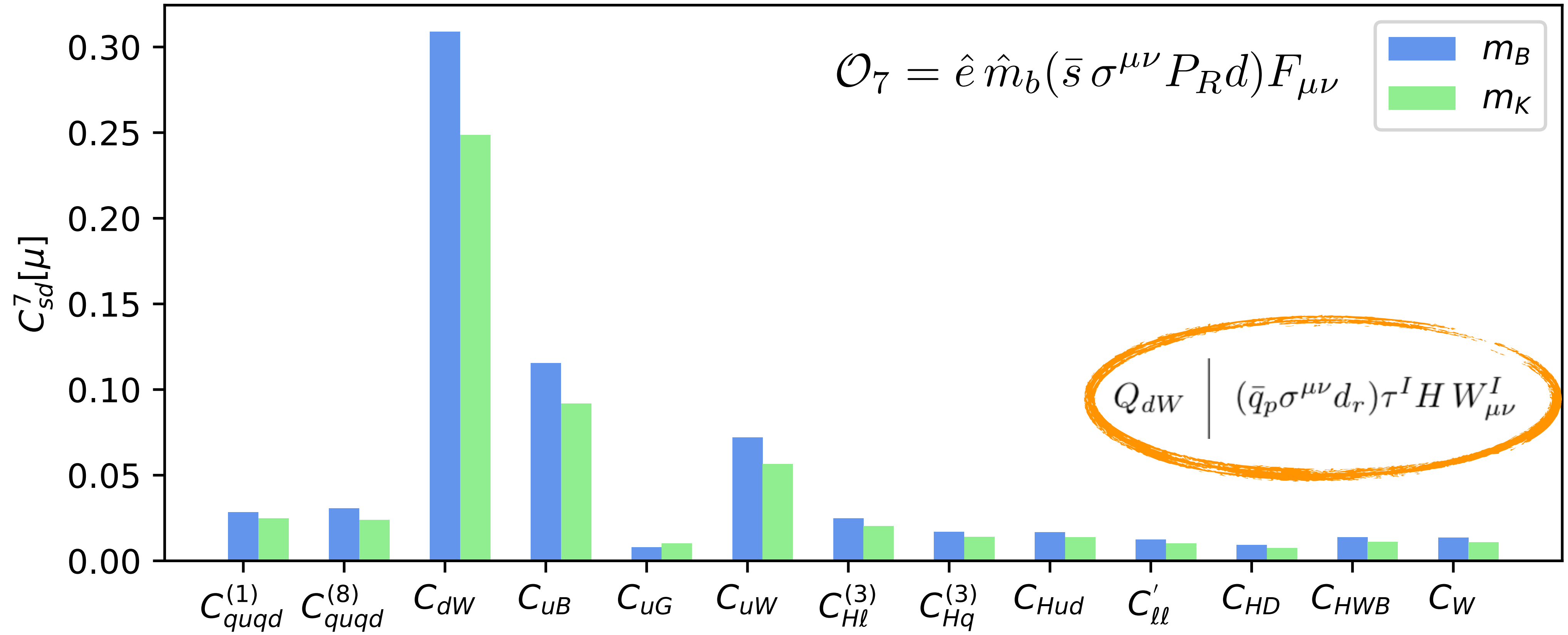
$$
\begin{aligned}
C_7(m_B) = \quad & - \quad (3450.15\, C^{(1)}_{quqd} - 3450.15\, C^{(8)}_{quqd}) \log \frac{m_W}{\Lambda} \\
& - \quad (225.32\, C_{dW} + 105.363\, C_{uB} + 11773.3\, C_{uG} - 56.3316\, C_{uW}) \log \frac{m_W}{\Lambda} + \\
& - \quad (12260.6\, C^{(1)}_{quqd} - 13291.\, C^{(8)}_{quqd}) \\
& - \quad (30.53\, C_{dW} - 33351.9\, C_{uB} - 2299.87\, C_{uG} + 5206.54\, C_{uW}) + \\
& + \quad 24839.6\, C^{(3)}_{H\ell} - 16910.8\, C^{(3)}_{Hq} - 16716.9\, C_{Hud} - 12419.8\, C'_{\ell\ell} \\
& + \quad 9342.61\, C_{HD} - 13866.9\, C_{HWB} - 13702.5\, C_W
\end{aligned}
$$

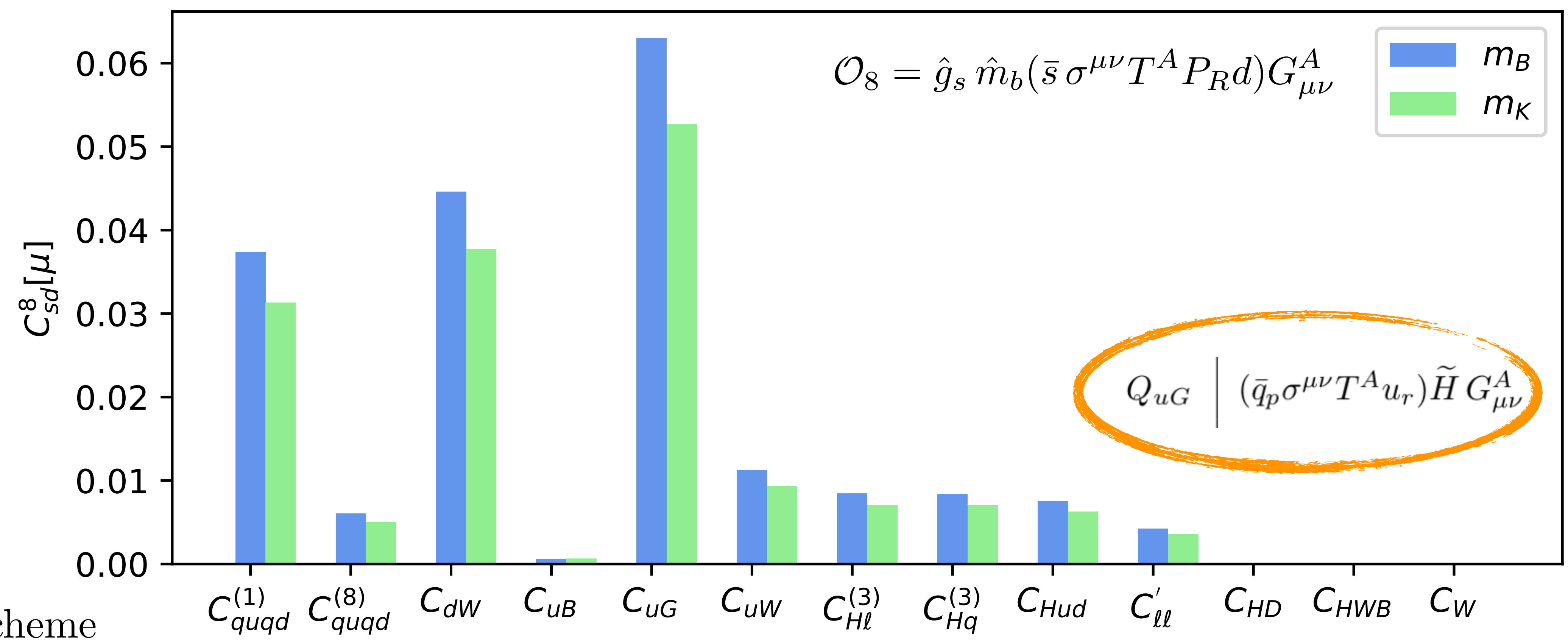
$$
\begin{aligned}
C_8(m_B) = \quad & - \quad (21310.7\, C^{(1)}_{quqd} - 3450.15\, C^{(8)}_{quqd}) \log \frac{m_W}{\Lambda} \\
& - \quad (618.4\, C_{dW} + 297.91\, C_{uB} + 32311.4\, C_{uG} - 154.6\, C_{uW}) \log \frac{m_W}{\Lambda} + \\
& - \quad (16175.5\, C^{(1)}_{quqd} - 2618.77\, C^{(8)}_{quqd}) \\
& + \quad (43060.7\, C_{dW} - 167.796\, C_{uB} - 18199.2\, C_{uG} + 11644.\, C_{uW}) + \\
& + \quad 8453.04\, C^{(3)}_{H\ell} - 8413.15\, C^{(3)}_{Hq} - 7492.09\, C_{Hud} - 4226.52\, C'_{\ell\ell} \\
& + \quad 47.0\, C_{HD} - 69.8\, C_{HWB} - 68.9\, C_W
\end{aligned}
$$

$\hat{m}_W$-scheme

hard to tell something from here…

C7 and C8 - One Loop relative contributions from SMEFT



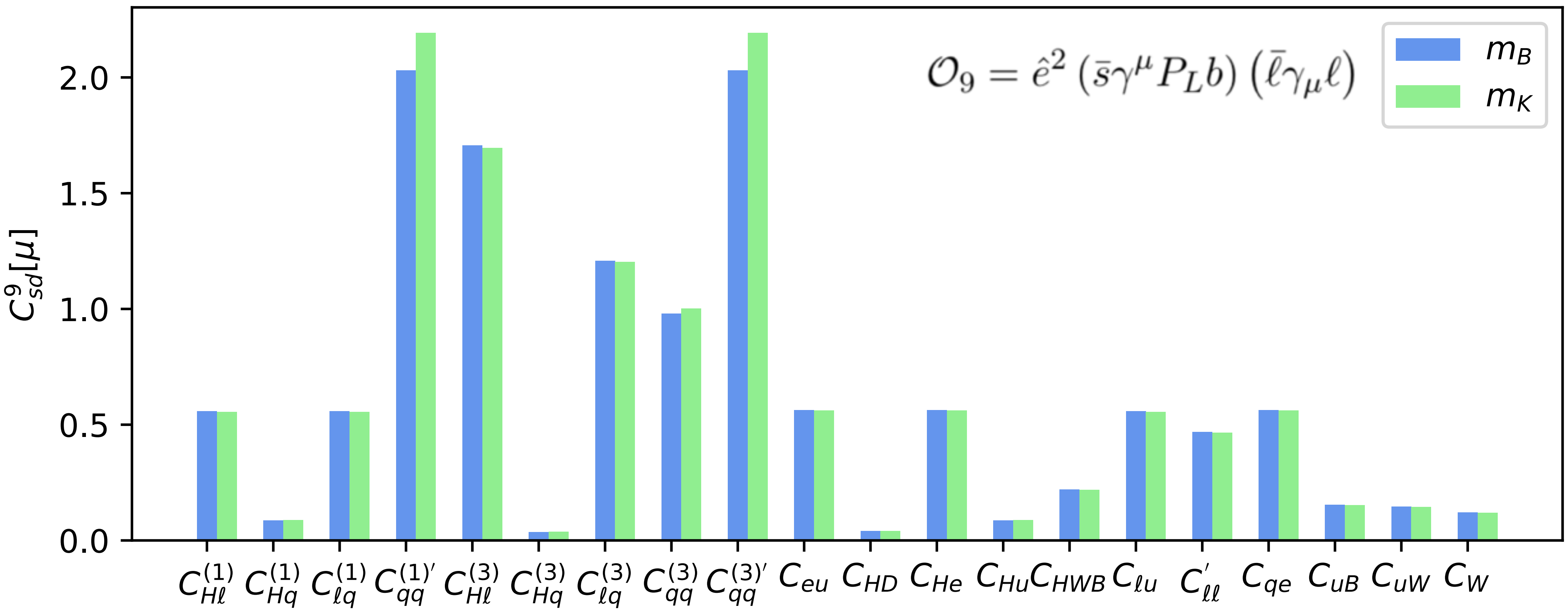


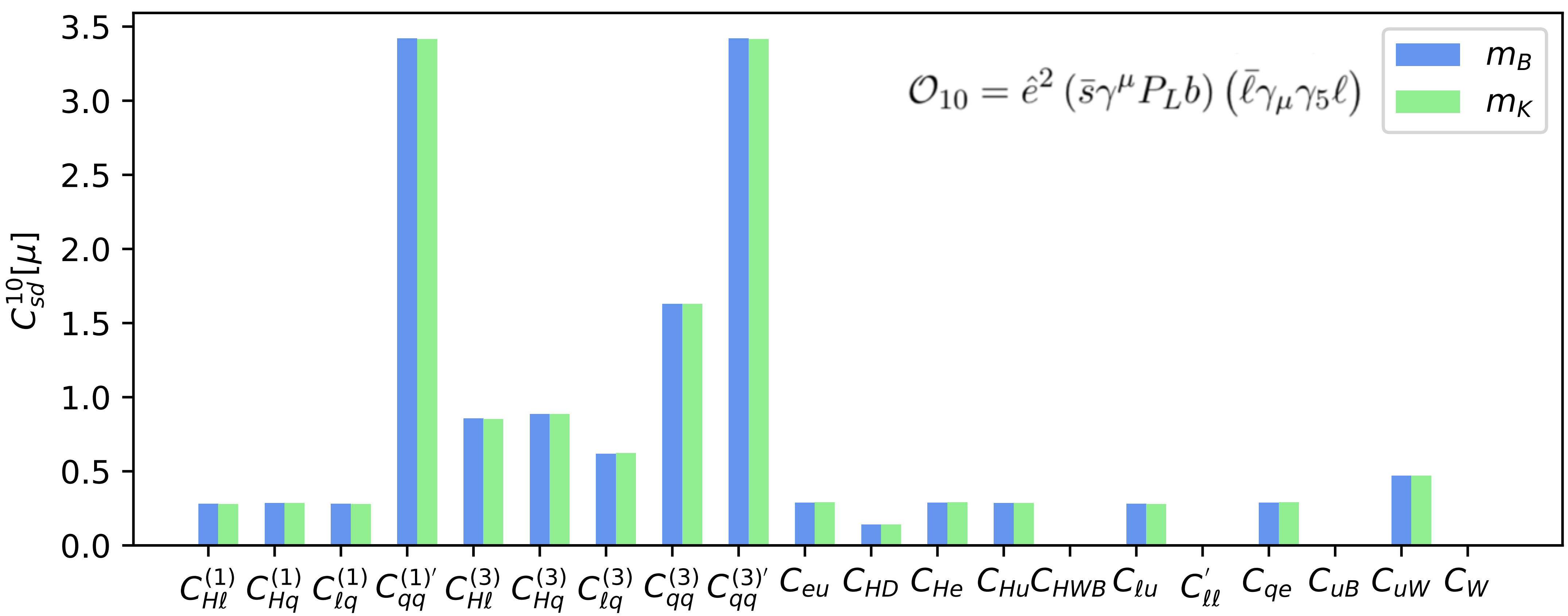
dipoles

$$\propto \frac{m_t}{m_W} y_t$$

$\hat{m}_W$-scheme

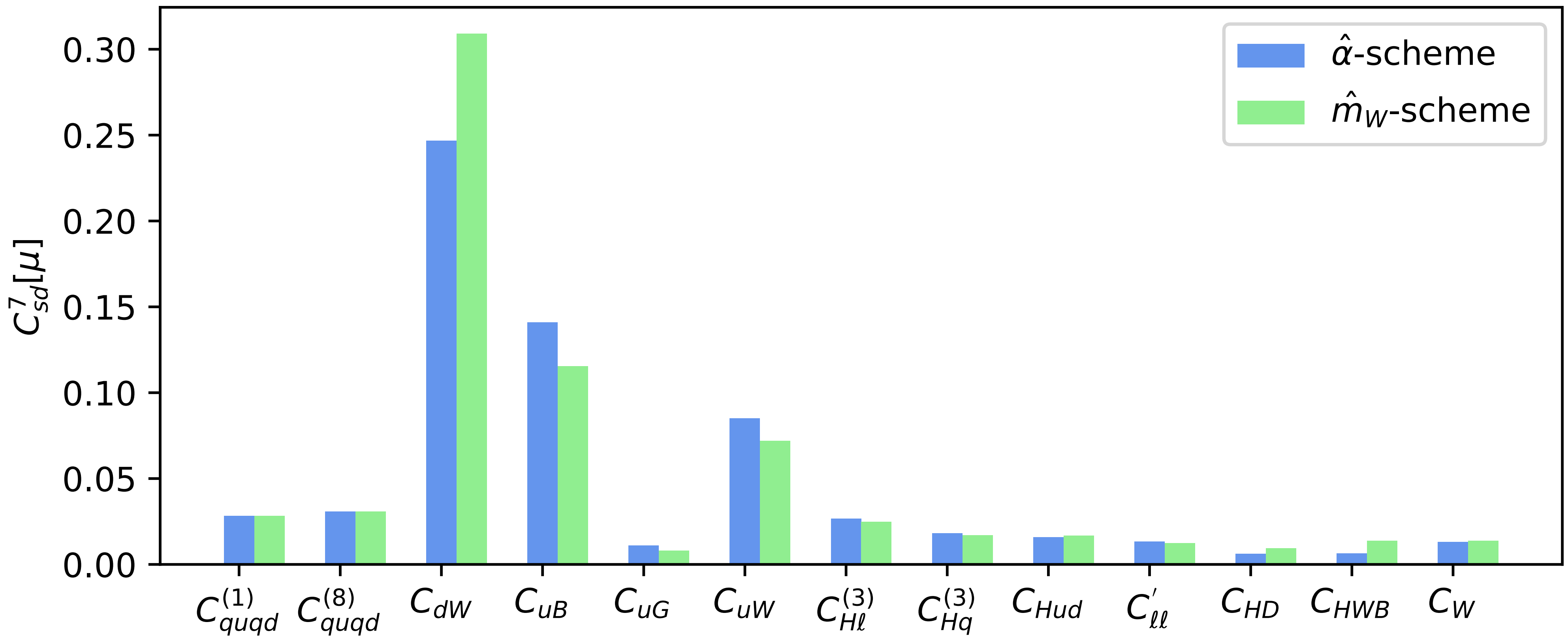
C9 and C10 - One Loop relative contributions from SMEFT





$\hat{m}_W$-scheme

Only C7 in both schemes



$\hat{\alpha}$-scheme

$$\{\underbrace{\hat{\alpha}, \hat{m}_Z, \hat{G}_F}, \underbrace{\hat{m}_t, \hat{m}_b, \hat{\alpha}_s, \hat{V}_{\text{CKM}}}\} \longrightarrow$$

Historically preferred due to LEP measurements

change the elctroweak parameters

unchanged, due to flavor symmetry

$\hat{m}_W$-scheme

$$\{\underbrace{\hat{m}_W, \hat{m}_Z, \hat{G}_F}, \underbrace{\hat{m}_t, \hat{m}_b, \hat{\alpha}_s, \hat{V}_{\text{CKM}}}\} \longrightarrow$$

- Simpler one loop expressions
- Avoid shifts in the W pole mass

EW + flavor constraints

The question we want to answer here is ….

… what flavor tells us about the know EW constraints?

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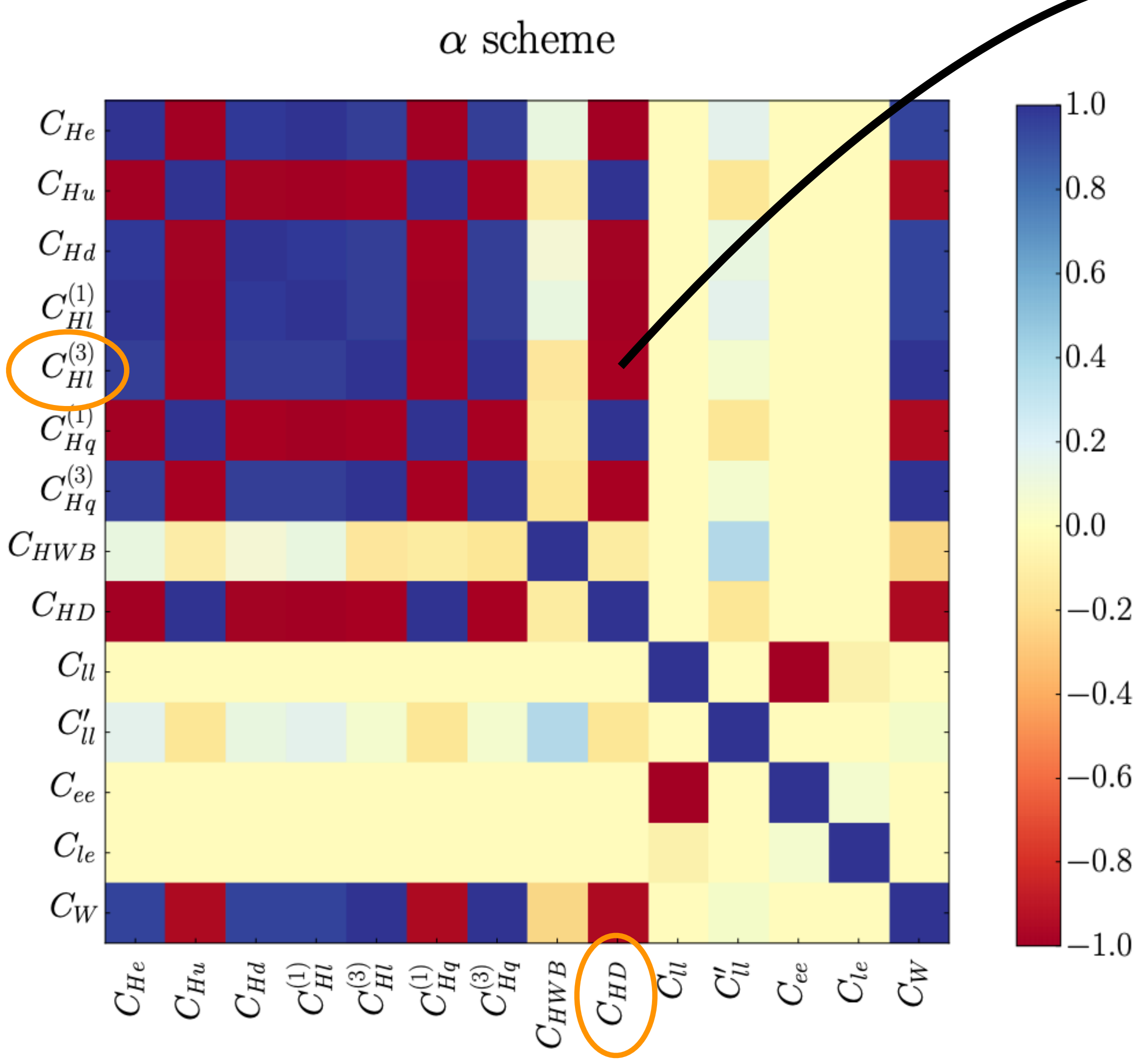
LEP I+II (WW data) fit



C_{HD} and $C_{H\ell}^{(3)}$

totally anti-correlated

Brivio and Trott, 2018

EW + flavor constraints

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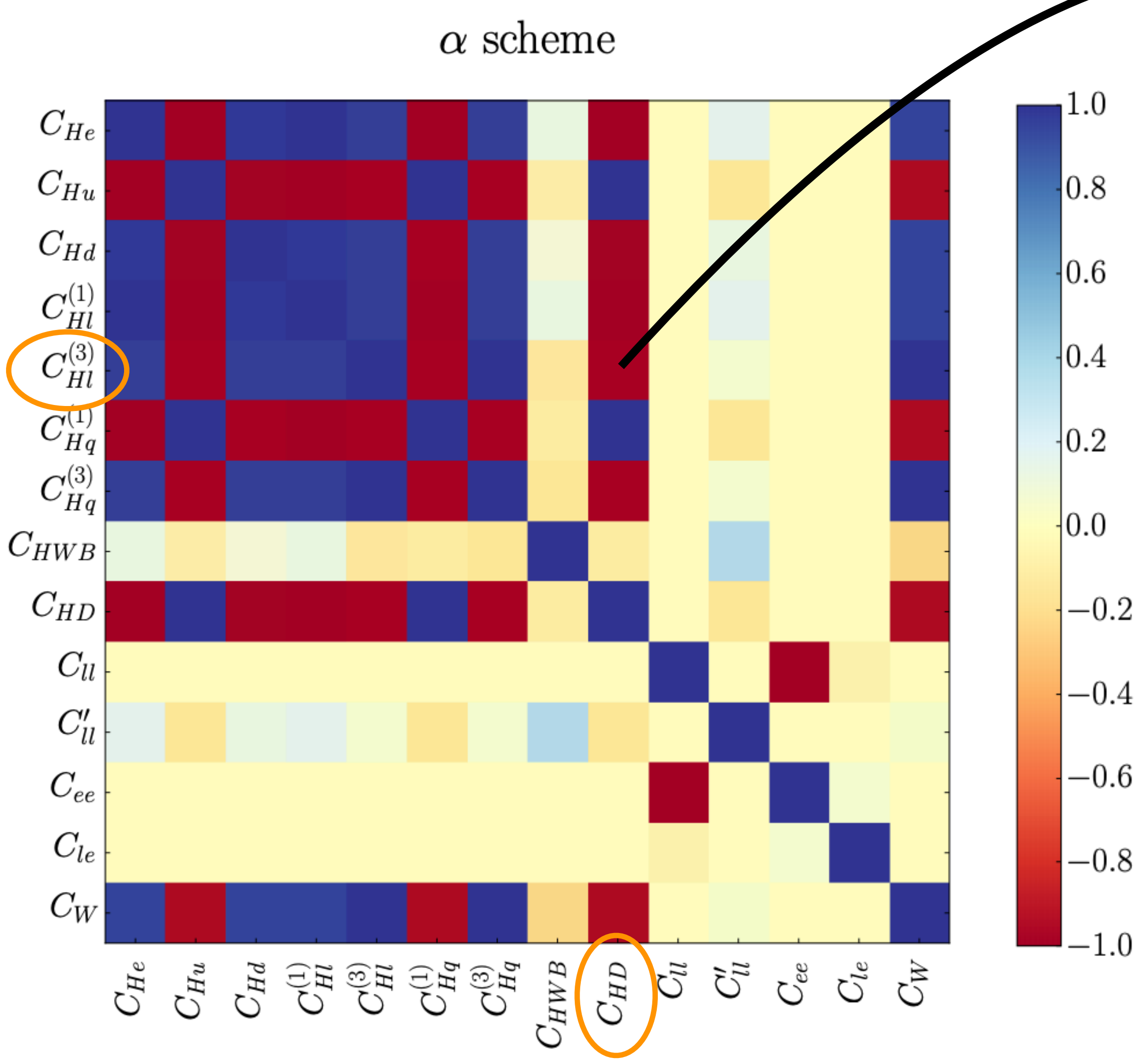


C_{HD} and $C_{H\ell}^{(3)}$

totally anti-correlated

but from one loop: $C_7 \propto C_{HD}, C_{H\ell}^{(3)}$

$$\mathcal{O}_7 = \hat{e}\hat{m}_b\,(\bar{s}\sigma^{\mu\nu}P_R b)\,F_{\mu\nu}\,;$$

Constraints on WET at low energy

.. set constraints on SMEFT WCs

Brivio and Trott, 2018

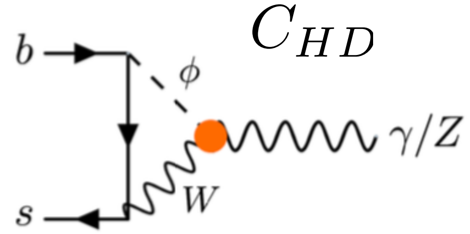
Flavour constraints

very naive example…

$b \to s\gamma$ observables

for $C_7 \propto C_{HD}, C_{H\ell}^{(3)}$

setting all other WCs to zero

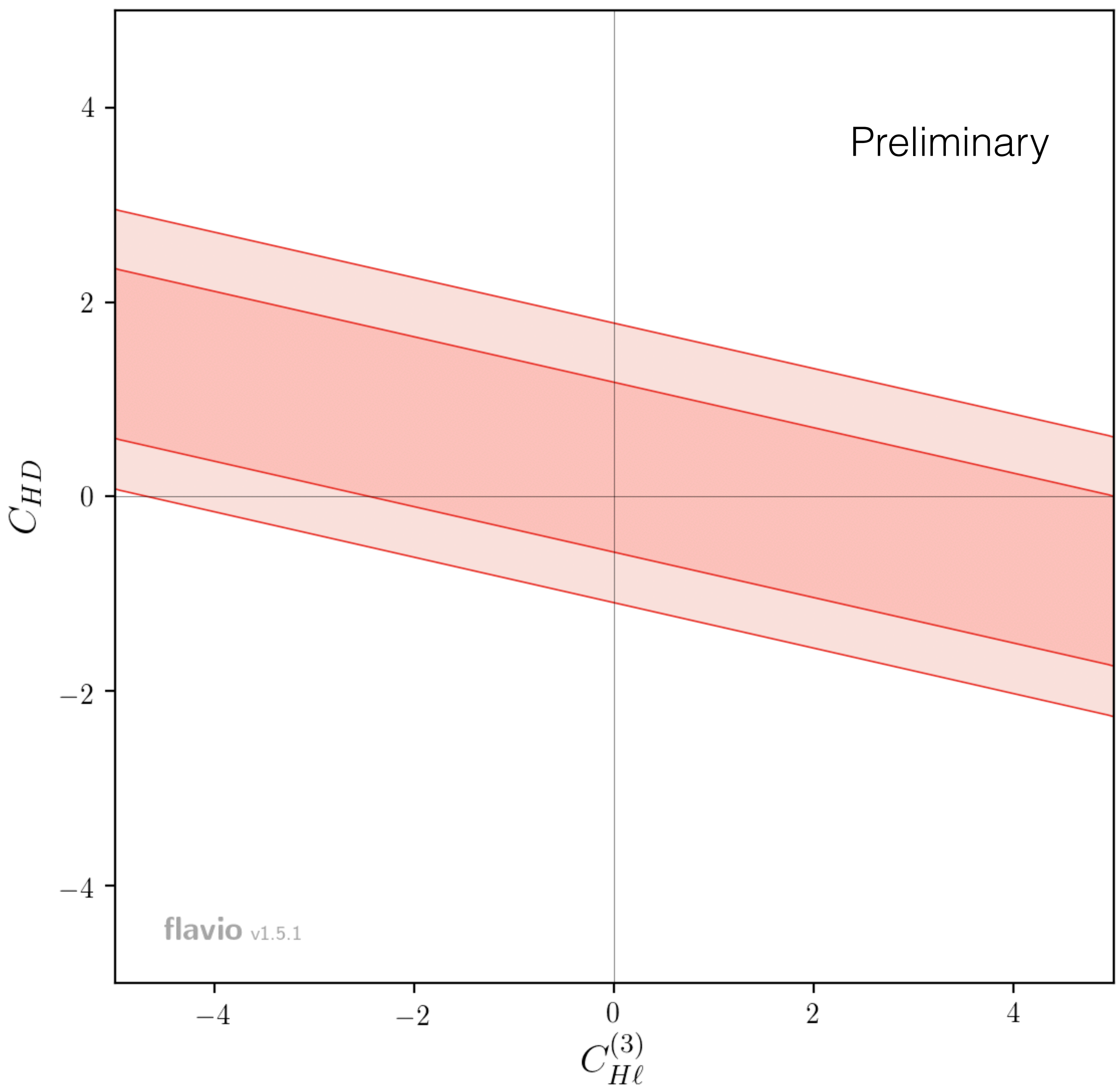


C_{HD}

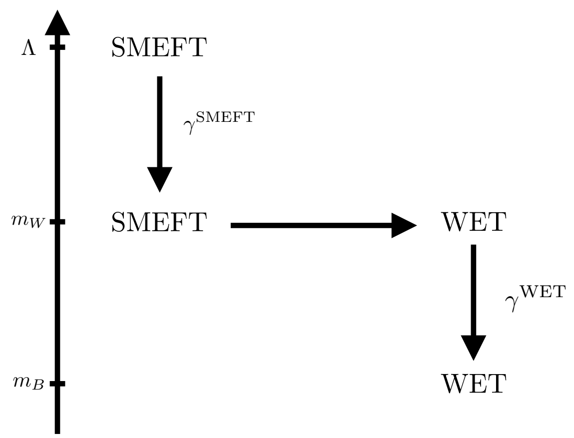
$C_{H\ell}^{(3)}$

and via input.

New constrained direction

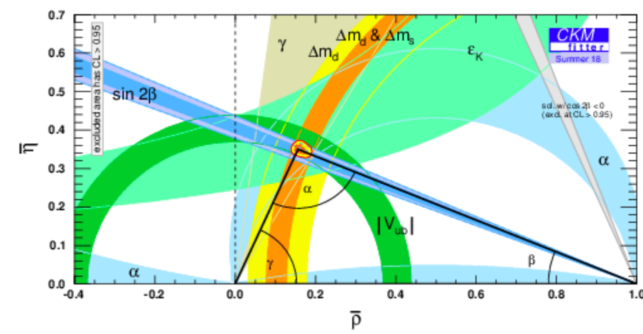


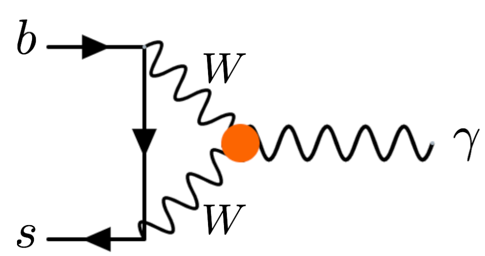
Conclusion + future..



- One loop matching between SMEFT and WET with Minimal Flavour Violation

- Flavour assumption is the "worst-case" scenario, which is a benchmark for other assumptions





- New constrain direction for EW observables and help to disentangle the correlation on the LEPI+II fits

- Work in progress: Putting together EW and Flavour constrains for all ops.

One loop matching → **New constraint direction for EW operators**

Thank you

Unterstützt von / Supported by

Back Up

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \mathrm{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \mathrm{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{\ell q}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{L}R) + \mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

$8: (\bar{L}R)(\bar{R}L) + \mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

Details of the calculation

- Used Feynman Rules from Dedes
- MS-bar dim-reg
- Compared with the literature:
  (Grzadkowski & Misiak 0802.1413, Drobnak, Fajfer, Kamenik 1102.4347 & 1109.2357, Bobeth & Haisch 1503.04829, Aebischer et al 1512.02830)
- Anomalous matrices: ((Alonso), Jenkins, Manohar & Trott 1308.2627, 1310.4838, 1312.2014)

Inami Lim functions

$$B_0(x_t) = \frac{1}{4}\left[\frac{x_t}{1-x_t} + \frac{x_t}{(x_t-1)^2}\log x_t\right],$$

$$C_0(x_t) = \frac{x_t}{8}\left[\frac{x_t-6}{x_t-1} + \frac{3x_t+2}{(x_t-1)^2}\log x_t\right],$$

$$D_0(x_t) = -\frac{4}{9}\log x_t + \frac{-19x_t^3+25x_t^2}{36(x_t-1)^3} + \frac{x_t^2(5x_t^2-2x_t-6)}{18(x_t-1)^4}\log x_t$$

$$D_0'(x_t) = \frac{8x_t^3+5x_t^2-7x_t}{12(x_t-1)^3} + \frac{x_t^2(2-3x_t)}{2(1-x_t)^4}\log x_t,$$

$$E_0'(x_t) = \frac{x_t(x_t^2-5x_t-2)}{4(x_t-1)^3} + \frac{3}{2}\frac{x_t^2}{(x_t-1)^4}\log x_t,$$

$$S_0(x_t) = \frac{4x_t-11x_t^2+x_t^3}{4(1-x_t)^2} - \frac{3x_t^3}{2(1-x_t)^3}\log x_t,$$

$$S_0(x_c) = x_c,$$

$$S_0(x_t,x_c) = x_c\left(\log\frac{x_t}{x_c} - \frac{3x_t}{4(1-x_t)} - \frac{3x_t^2}{4(1-x_t)^2}\log x_t\right)$$

Neutrinos

$$I(x_t) = \frac{x_t}{16}\left[-\log\frac{m_W^2}{\mu^2} + \frac{x_t-7}{2(1-x_t)} - \frac{x_t^2-2x_t+4}{(1-x_t)^2}\log x_t\right],$$

$$I^{lq}(x_t) = \frac{x_t}{16}\left[-\log\frac{m_W^2}{\mu^2} + \frac{1-7x_t}{2(1-x_t)} - \frac{x_t^2-2x_t+4}{(1-x_t)^2}\log x_t\right],$$

$$I_\nu^{Hl3}(x_t) = \frac{x_t}{16}\left[-\log\frac{m_W^2}{\mu^2} + \frac{9(1+x_t)}{2(1-x_t)} - \frac{x_t^2+10x_t-20}{(1-x_t)^2}\log x_t\right]$$

$$I_\nu^{Hq3}(x_t) = \frac{x_t}{16}\left[7\log\frac{m_W^2}{\mu^2} + \frac{x_t-31}{2(1-x_t)} + \frac{7x_t^2-2x_t-20}{(1-x_t)^2}\log x_t\right]$$

$$I_\nu^{uW}(x_t) = \frac{3}{4}\left[\frac{2-3x_t+x_t^2}{(1-x_t)^2} + \frac{x_t}{(1-x_t)^2}\log x_t\right].$$