

Probing Top-quark Operators with Precision Electroweak Measurements

Yiming Liu

School of Physics, Beijing Institute of Technology

The Large Hadron Collider Physics Conference
Based on 2205.05655 with Yuhao Wang, Cen Zhang, Lei Zhang,
Jiayin Gu

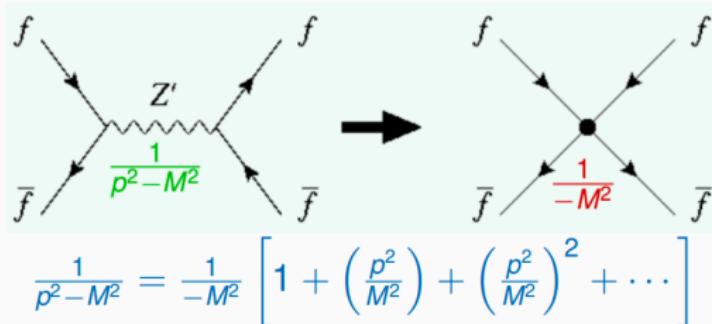


Motivation

- 1, At LEP1/2, low-energy precision measurements, and e^+e^- collider in the future, we can use loops to open up more possibilities. Loop factor suppression will be compensated for by the precision.
- 2, Our study is one of the many first steps towards a more complete loop-level SMEFT global analysis.



Theoretical framework



$$\mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)} + \dots$$



Theoretical framework

	X^3	φ^6 and $\varphi^4 D^2$	$\psi^2 \varphi^3$
Q_G	$f^{ABC} G_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	Q_{φ} $(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$ $(\varphi^\dagger \varphi) (\bar{L}_\mu \gamma^\mu \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_{\mu}^{A\nu} G_{\nu}^{B\rho} G_{\rho}^{C\mu}$	$Q_{\varphi \Box}$ $(\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi)$	$Q_{e\varphi}$ $(\varphi^\dagger \varphi) (\bar{q}_\mu u_\nu \bar{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$ $(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$	$Q_{e\varphi}$ $(\varphi^\dagger \varphi) (\bar{q}_\mu d_\nu \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$		
	$X^2 \varphi^2$	$\psi^2 X \varphi$	$\psi^2 \varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW} $(\bar{l}_\mu \sigma^{\mu\nu} e_\tau) \tau^I \varphi W_\nu^{I\mu}$	$Q_{\varphi \ell}^{(1)}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{l}_\mu \gamma^\mu l_\tau)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB} $(\bar{l}_\mu \sigma^{\mu\nu} e_\tau) \varphi B_{\mu\nu}$	$Q_{\varphi \ell}^{(3)}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu^I \varphi) (\bar{l}_\tau \tau^I \gamma^\mu l_\tau)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{I\mu}$	Q_{eG} $(\bar{q}_\mu \sigma^{\mu\nu} T^A u_\tau) \bar{\varphi} G_{\mu\nu}^A$	$Q_{e\varphi}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{e}_\mu \gamma^\mu e_\tau)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I W^{I\mu}$	Q_{eW} $(\bar{q}_\mu \sigma^{\mu\nu} u_\tau) \tau^I \bar{\varphi} W_\nu^{I\mu}$	$Q_{\varphi \ell}^{(1)}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{q}_\mu \gamma^\mu q_\tau)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{eB} $(\bar{q}_\mu \sigma^{\mu\nu} u_\tau) \bar{\varphi} B_{\mu\nu}$	$Q_{\varphi \ell}^{(3)}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu^I \varphi) (\bar{q}_\tau \tau^I \gamma^\mu q_\tau)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{eG} $(\bar{q}_\mu \sigma^{\mu\nu} T^A d_\tau) \varphi G_{\mu\nu}^A$	$Q_{e\varphi}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{u}_\tau \gamma^\mu u_\tau)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B^{\mu\nu}$	Q_{eW} $(\bar{q}_\mu \sigma^{\mu\nu} d_\tau) \tau^I \varphi W_\nu^{I\mu}$	$Q_{\varphi \ell}$ $(\varphi^\dagger \bar{l} \overset{\leftrightarrow}{D}_\mu \varphi) (\bar{d}_\tau \gamma^\mu d_\tau)$
$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I B^{\mu\nu}$	Q_{eB} $(\bar{q}_\mu \sigma^{\mu\nu} d_\tau) \varphi B_{\mu\nu}$	$Q_{\varphi \ell}$ $i(\bar{\tilde{l}} \gamma_\mu \varphi) (\bar{u}_\tau \gamma^\mu d_\tau)$

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{l}_\sigma \gamma^\mu l_\iota)$	Q_{ee}	$(\bar{e}_\mu \gamma_\nu e_\tau) (\bar{e}_\sigma \gamma^\mu e_\iota)$	Q_{le}	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{e}_\sigma \gamma^\mu e_\iota)$
$Q_{l\Box}^{(1)}$	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{q}_\sigma \gamma^\mu q_\iota)$	Q_{eu}	$(\bar{u}_\mu \gamma_\nu u_\tau) (\bar{u}_\sigma \gamma^\mu u_\iota)$	Q_{lu}	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{u}_\sigma \gamma^\mu u_\iota)$
$Q_{l\Box}^{(3)}$	$(\bar{q}_\mu \gamma_\nu \tau^I q_\tau) (\bar{q}_\sigma \gamma^\mu \tau^I q_\iota)$	Q_{dl}	$(\bar{d}_\mu \gamma_\nu d_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$	Q_{ld}	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$
$Q_{lq}^{(1)}$	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{q}_\sigma \gamma^\mu q_\iota)$	Q_{eu}	$(\bar{e}_\mu \gamma_\nu e_\tau) (\bar{u}_\sigma \gamma^\mu u_\iota)$	Q_{qe}	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{e}_\sigma \gamma^\mu e_\iota)$
$Q_{lq}^{(3)}$	$(\bar{l}_\mu \gamma_\nu l_\tau) (\bar{q}_\sigma \gamma^\mu \tau^I q_\iota)$	Q_{el}	$(\bar{e}_\mu \gamma_\nu e_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$	$Q_{lq}^{(1)}$	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{u}_\sigma \gamma^\mu u_\iota)$
$Q_{el}^{(1)}$	$(\bar{u}_\mu \gamma_\nu u_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$	$Q_{eu}^{(8)}$	$(\bar{u}_\mu \gamma_\nu T^A u_\tau) (\bar{d}_\sigma \gamma^\mu T^A d_\iota)$	$Q_{eu}^{(8)}$	$(\bar{u}_\mu \gamma_\nu T^A u_\tau) (\bar{u}_\sigma \gamma^\mu T^A u_\iota)$
$Q_{el}^{(8)}$	$(\bar{u}_\mu \gamma_\nu u_\tau) T^A (\bar{d}_\sigma \gamma^\mu d_\iota)$	$Q_{qd}^{(1)}$	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$	$Q_{qd}^{(1)}$	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$
		$Q_{el}^{(8)}$	$(\bar{u}_\mu \gamma_\nu T^A u_\tau) (\bar{d}_\sigma \gamma^\mu T^A d_\iota)$	$Q_{qd}^{(8)}$	$(\bar{q}_\mu \gamma_\nu q_\tau) (\bar{d}_\sigma \gamma^\mu d_\iota)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
Q_{loq}	$(\bar{l}_\mu^I e_\tau) (\bar{d}_\sigma q_\iota^F)$	Q_{loq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(\bar{d}_\mu^{\alpha I})^T C u_\nu^{\beta J}] [(\bar{q}_\lambda^{\gamma K})^T C l_\mu^h]$		
$Q_{loq}^{(1)}$	$(\bar{q}_\mu^I u_\tau) \varepsilon_{jk} (\bar{l}_\sigma^k d_\iota)$	Q_{qqn}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(\bar{q}_\mu^{\alpha I})^T C u_\nu^{\beta J}] [(\bar{u}_\lambda^{\gamma K})^T C e_\mu^h]$		
$Q_{loq}^{(3)}$	$(\bar{q}_\mu^I T^A u_\tau) \varepsilon_{jk} (\bar{l}_\sigma^k T^A d_\iota)$	Q_{qpp}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(\bar{q}_\mu^{\alpha I})^T C u_\nu^{\beta J}] [(\bar{u}_\lambda^{\gamma K})^T C e_\mu^h]$		
$Q_{loq}^{(1)}$	$(\bar{l}_\mu^I e_\tau) \varepsilon_{jk} (\bar{q}_\sigma^k u_\iota)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(\bar{q}_\mu^{\alpha I})^T C u_\nu^{\beta J}] [(\bar{u}_\lambda^{\gamma K})^T C l_\mu^h]$		
$Q_{loq}^{(3)}$	$(\bar{l}_\mu^I \sigma_{\mu\nu} e_\tau) \varepsilon_{jk} (\bar{q}_\sigma^k \sigma^{\mu\nu} u_\iota)$		$\varepsilon^{\alpha\beta\gamma} [(\bar{d}_\mu^{\alpha I})^T C u_\nu^{\beta J}] [(\bar{u}_\lambda^{\gamma K})^T C e_\mu^h]$		



Theoretical framework

$$Q_{\varphi Q}^{(3)} = i \left(\phi^\dagger \tau^I D_\mu \phi \right) \left(\bar{Q} \gamma^\mu \tau^I Q \right)$$

$$Q_{\varphi Q}^{(1)} = i \left(\phi^\dagger D_\mu \phi \right) \left(\bar{Q} \gamma^\mu Q \right)$$

$$Q_{\varphi t} = i \left(\phi^\dagger D_\mu \phi \right) \left(\bar{t} \gamma^\mu t \right)$$

$$Q_{\varphi b} = i \left(\phi^\dagger D_\mu \phi \right) \left(\bar{b} \gamma^\mu b \right)$$

$$Q_{\varphi tb} = i \left(\tilde{\phi}^\dagger D_\mu \phi \right) \left(\bar{t} \gamma^\mu b \right)$$

$$Q_{tW} = \left(\bar{q} \sigma^{\mu\nu} \tau^I t \right) \tilde{\phi} W'_{\mu\nu}$$

$$Q_{bW} = \left(\bar{q} \sigma^{\mu\nu} \tau^I b \right) \phi W'_{\mu\nu}$$

$$Q_{tB} = \left(\bar{q} \sigma^{\mu\nu} t \right) \tilde{\phi} B_{\mu\nu}$$

$$Q_{bB} = \left(\bar{q} \sigma^{\mu\nu} b \right) \phi B_{\mu\nu}$$

[Cen Zhang, Nicolas Greiner, Scott Willenbrock, 2012]



Theoretical framework

Impose a $U(2)_u \otimes U(2)_d \otimes U(2)_q \otimes U(3)_l \otimes U(3)_e$ flavor symmetry

$\psi^2 \varphi^3$	X^3	$\varphi^4 D^2$
$Q_{\varphi}^{ij} = (\varphi^\dagger \varphi) (\bar{q}_i u_j \tilde{\varphi})$ $Q_{d\varphi}^{ij} = (\varphi^\dagger \varphi) (\bar{q}_i d_j \varphi)$	$Q_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$
$\psi^2 \varphi^2 D$	$\psi^2 X \varphi$	$X^2 \varphi^2$
$Q_{\varphi e}^{ij(1)} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{l}_i \gamma^\mu l_j)$ $Q_{\varphi l}^{ij(3)} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{l}_i \tau^I \gamma^\mu l_j)$	$Q_{uW}^{ij} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi WB} = \varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$
$Q_{\varphi e}^{ij(2)} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{e}_i \gamma^\mu e_j)$ $Q_{\varphi q}^{ij(1)} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{q}_i \gamma^\mu q_j)$ $Q_{\varphi q}^{ij(3)} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{q}_i \tau^I \gamma^\mu q_j)$	$Q_{ub}^{ij} = (\bar{q}_i \sigma^{\mu\nu} u_j) \tilde{\varphi} B_{\mu\nu}$	$Q_{dW}^{ij} = (\bar{q}_i \sigma^{\mu\nu} d_j) \tau^I \varphi W_{\mu\nu}^I$ $Q_{dB}^{ij} = (\bar{q}_i \sigma^{\mu\nu} d_j) \varphi B_{\mu\nu}$
$Q_{\varphi u}^{ij} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{u}_i \gamma^\mu u_j)$ $Q_{\varphi d}^{ij} = \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{d}_i \gamma^\mu d_j)$ $Q_{\varphi ud}^{ij} = i(\bar{\varphi}^\dagger D_\mu \varphi) (\bar{u}_i \gamma^\mu d_j)$		
$(\bar{L}L)(\bar{L}L)$ $Q_{ll}^{prst} = (\bar{l}_p \gamma_\mu l_r) (\bar{l}_s \gamma^\mu l_t)$ $Q_{lq}^{prst(1)} = (\bar{l}_p \gamma_\mu l_r) (\bar{q}_s \gamma^\mu q_t)$ $Q_{lq}^{prst(3)} = (\bar{l}_p \gamma_\mu \tau^I l_r) (\bar{q}_s \gamma^\mu \tau^I q_t)$	$(\bar{R}R)(\bar{R}R)$ $Q_{ee}^{prst} = (\bar{e}_p \gamma_\mu e_r) (\bar{e}_s \gamma^\mu e_t)$ $Q_{eu}^{prst} = (\bar{e}_p \gamma_\mu e_r) (\bar{u}_s \gamma^\mu u_t)$ $Q_{ed}^{prst} = (\bar{e}_p \gamma_\mu e_r) (\bar{d}_s \gamma^\mu d_t)$	$(\bar{L}L)(\bar{R}R)$ $Q_{le}^{prst} = (\bar{l}_p \gamma_\mu l_r) (\bar{e}_s \gamma^\mu e_t)$ $Q_{lu}^{prst} = (\bar{l}_p \gamma_\mu l_r) (\bar{u}_s \gamma^\mu u_t)$ $Q_{ld}^{prst} = (\bar{l}_p \gamma_\mu l_r) (\bar{d}_s \gamma^\mu d_t)$ $Q_{qe}^{prst} = (\bar{q}_p \gamma_\mu q_r) (\bar{e}_s \gamma^\mu e_t)$

$$\begin{aligned} Q_{\varphi Q}^{(+)} &\equiv Q_{\varphi Q}^{(1)} + Q_{\varphi Q}^{(3)}, \\ Q_{IQ}^{(+)} &\equiv Q_{IQ}^{(1)} + Q_{IQ}^{(3)}, \\ Q_{\varphi Q}^{(-)} &\equiv Q_{\varphi Q}^{(1)} - Q_{\varphi Q}^{(3)}, \\ Q_{IQ}^{(-)} &\equiv Q_{IQ}^{(1)} - Q_{IQ}^{(3)}, \end{aligned}$$



Theoretical framework

	Experiment	Observables
Low Energy	CHARM/CDHS/ CCFR/NuTeV/ APV/QWEAK/ PVDIS	Effective Couplings
Z-pole	LEP/SLC	Total decay width Γ_Z Hadronic cross-section σ_{had} Ratio of decay width R_f Forward-Backward Asymmetry A_{FB}^f Polarized Asymmetry A_f
W-pole	LHC/Tevatron/ LEP/SLC	Total decay width Γ_W Branch Ratio of W Decay $Br(W \rightarrow l\nu_l)$ Mass of W Boson M_W
$ee \rightarrow qq$	LEP/TRISTAN	Hadronic cross-section σ_{had} Ratio of cross-section R_f Forward-Backward Asymmetry for b/c A_{FB}^f
$ee \rightarrow ll$	LEP	cross-section σ_f Forward-Backward Asymmetry A_{FB}^f Differential cross-section $\frac{d\sigma_f}{dcos\theta}$
$ee \rightarrow WW$	LEP	cross-section σ_{WW} Differential cross-section $\frac{d\sigma_{WW}}{dcos\theta}$

[J Erler and A Freitas. Electroweak model and constraints on new physics.] [D Geiregat, Gaston Wilquet, U Binder, H Burkard, U

Dore, W Flegel, H Grote, T Mouthuy, H Øverås, J Panman, et al.

First observation of neutrino trident production.]

[Aielet Efrati, Adam Falkowski, and Yotam Soreq. Electroweak constraints on flavor effective theories.]

[Morad Aaboud, Georges Aad, Brad Abbott, Jalal Abdallah, O Abdinov, Baptiste Abeoops, Syed Haider Abidi, OS AbouZeid, Nadine L Abraham, Halina Abramowicz, et al. Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7 \text{ GeV}$ with the ATLAS detector.]

[Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP.]

[A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model.]

[Measurement of the cross-section and forward-backward charge asymmetry for the b and c-quark in $e^+ e^-$ annihilation with inclusive muons at $\sqrt{s} = 58 \text{ GeV}$]



Theoretical framework

1, The first class involves the third generation quarks

$$Q_{\varphi Q}^{(1)}, Q_{\varphi Q}^{(3)}, Q_{\varphi t}, Q_{\varphi b}, Q_{\varphi \varphi}, Q_{tW}, Q_{tB}, Q_{bW}, Q_{bB}$$

2, The second class have tree-level contribution to
 $e^+ e^- \rightarrow f\bar{f}(f \neq t, b)$, $e^+ e^- \rightarrow W^+ W^-$.

$$Q_{\varphi Q}^{(1)}, Q_{\varphi Q}^{(3)}, Q_{\varphi u}, Q_{\varphi d}, Q_{\varphi l}^{(1)}, Q_{\varphi l}^{(3)}, Q_{\varphi e}, Q'_{ll}, Q_{\varphi D}, Q_{\varphi WB}, O_W$$

3, The third class are 4-fermion operators that directly contribute to
the $e^+ e^- \rightarrow f\bar{f}(f \neq t, b)$ and several low energy scattering processes
at tree level.

$$Q_{qe}, Q_{eu}, Q_{ed}, Q_{lq}^{(1)}, Q_{lq}^{(3)}, Q_{lu}, Q_{ld}, O_{ll}, Q_{ee}, Q_{le}$$

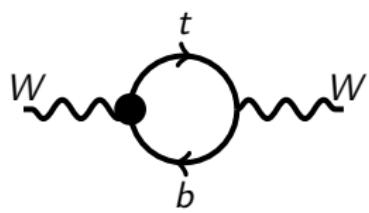
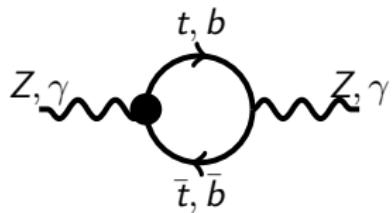
4, The fourth class are 4-fermion operators that directly contribute
to the $e^+ e^- \rightarrow b\bar{b}$ at tree level.

$$Q_{IQ}^{(1)}, Q_{IQ}^{(3)}, Q_{lb}, Q_{eQ}, Q_{eb}$$



Theoretical framework

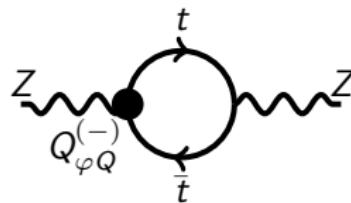
1, For observable without Zbb couplings, the nine operators modify the self-energies of W , Z , γ at loop-level, and therefore affect all measurements indirectly.



Theoretical framework

Example

$$\begin{aligned} Q_{\varphi Q}^{(-)} &= Q_{\varphi Q}^{(1)} - Q_{\varphi Q}^{(3)} \\ &= - \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^I \varphi \right) (\bar{q}_3 \tau^I \gamma^\mu q_3) + \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{q}_3 \gamma^\mu q_3) \\ &= - \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^1 \varphi \right) (\bar{q}_3 \tau^1 \gamma^\mu q_3) - \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^2 \varphi \right) (\bar{q}_3 \tau^2 \gamma^\mu q_3) \\ &\quad - \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu^3 \varphi \right) (\bar{q}_3 \tau^3 \gamma^\mu q_3) + \left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi \right) (\bar{q}_3 \gamma^\mu q_3) \\ &= \frac{-igv^2}{\sqrt{2}} W_\mu^+ (\bar{b} \gamma_\mu t) + \frac{igv^2}{\sqrt{2}} W_\mu^- (\bar{t} \gamma_\mu b) + \frac{igZ_\mu}{\cos \theta_W} v^2 \bar{t} \gamma_\mu t + \dots \end{aligned}$$



Theoretical framework

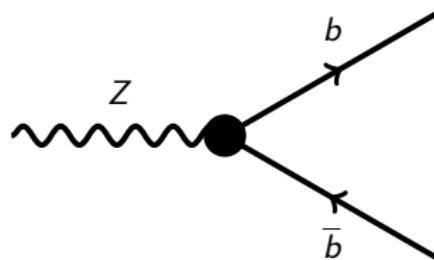
2, For observable with Zbb couplings, $Q_{\varphi Q}^{(+)}$, $Q_{\varphi b}$, Q_{bW} , Q_{bB} modify the $Z \rightarrow b\bar{b}$ measurements at tree-level.

$$Q_{\varphi Q}^{(+)} = i(\phi^\dagger D_\mu \phi)(\bar{Q}\gamma^\mu Q)$$

$$Q_{\varphi b} = i(\phi^\dagger D_\mu \phi)(\bar{b}\gamma^\mu b)$$

$$Q_{bW} = (\bar{q}\sigma^{\mu\nu}\tau^I b)\phi W_{\mu\nu}^I$$

$$Q_{bB} = (\bar{q}\sigma^{\mu\nu} b)\phi B_{\mu\nu}$$



Theoretical framework

3, For observable with Zbb couplings, $Q_{\varphi Q}^{(-)}$, $Q_{\varphi t}$, Q_{tW} , Q_{tB} not only modify the self-energies of W , Z , γ at loop-level, but also modify the Zbb vertex at loop-level.

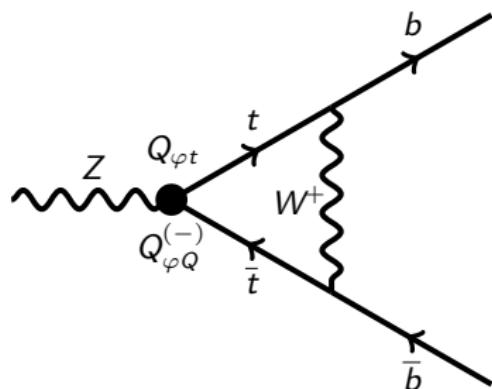
$$Q_{\varphi Q}^{(-)} = i \left(\phi^\dagger \tau^I D_\mu \phi \right) \left(\bar{Q} \gamma^\mu \tau^I Q \right)$$

$$Q_{\varphi t} = i \left(\phi^\dagger D_\mu \phi \right) (\bar{t} \gamma^\mu t)$$

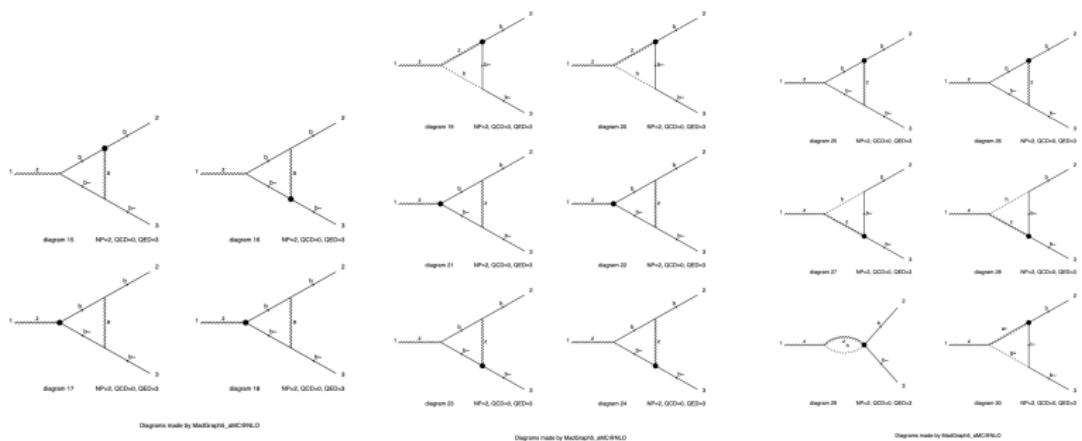
$$Q_{\varphi tb} = i \left(\tilde{\phi}^\dagger D_\mu \phi \right) (\bar{t} \gamma^\mu b)$$

$$Q_{tW} = \left(\bar{q} \sigma^{\mu\nu} \tau^I t \right) \tilde{\phi} W_{\mu\nu}^I$$

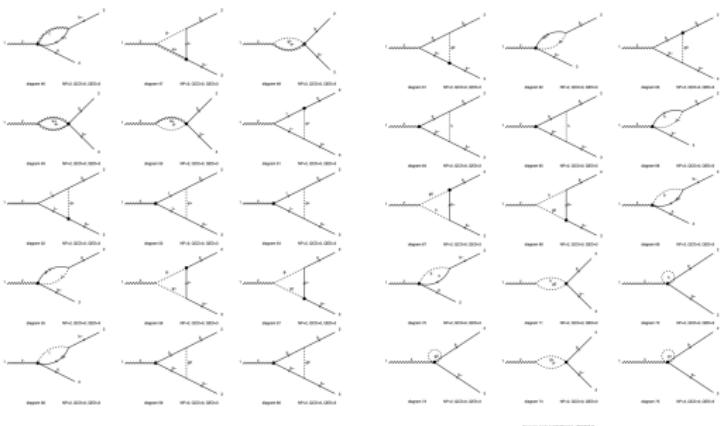
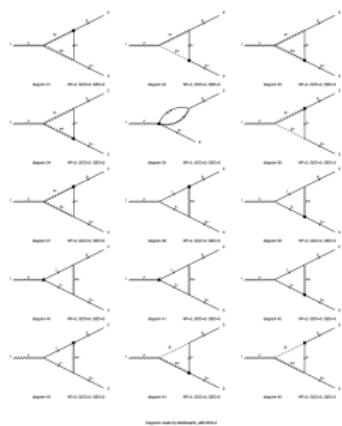
$$Q_{tB} = (\bar{q} \sigma^{\mu\nu} t) \tilde{\phi} B_{\mu\nu}$$



Theoretical framework



Theoretical framework



Theoretical framework

To better understand the impacts of the 3rd-generation-quark operators, we trade $\frac{c_{\varphi D}}{\Lambda^2} Q_{\varphi D}$ and $\frac{c_{\varphi WB}}{\Lambda^2} Q_{\varphi WB}$ in the Warsaw basis for $\frac{c_{D\varphi B}}{\Lambda^2} iD^\mu \varphi^\dagger D^\nu \varphi B_{\mu\nu}$ and $\frac{c_{D\varphi W}}{\Lambda^2} iD^\mu \varphi^\dagger \sigma_a \varphi W_{\mu\nu}^a$:

$$\begin{aligned} Q_{D\varphi B} &\equiv iD_\mu \phi^\dagger D_\nu \phi B^{\mu\nu} \\ &= -\frac{g'}{4} Q_{\varphi B} + \frac{g'}{2} \sum_\psi Y_\psi Q_{\varphi\psi}^{(1)} + \frac{g'}{4} Q_{\varphi\square} + g' Q_{\varphi D} - \frac{g}{4} Q_{\varphi WB} \\ Q_{D\varphi W} &\equiv iD_\mu \phi^\dagger \sigma_a D_\nu \phi W^{a\mu\nu} \\ &= \frac{g}{4} \sum_F Q_{\varphi F}^{(3)} + \frac{g}{4} \left(3Q_{\varphi\square} + 8\lambda_\phi Q_\varphi - 4\mu_\phi^2 (\phi^\dagger \phi)^2 \right) + \\ &\quad + \frac{g}{2} \left(y_{ij}^e (Q_{e\varphi})_{ij} + y_{ij}^d (Q_{d\varphi})_{ij} + y_{ij}^u (Q_{u\varphi})_{ij} + \text{h.c.} \right) \\ &\quad - \frac{g'}{4} Q_{\varphi WB} - \frac{g}{4} Q_{\varphi W}, \end{aligned}$$



Results

Operator	$C_{\varphi t}$	$C_{\varphi Q}^{(+)}$	$C_{\varphi Q}^{(-)}$	$C_{\varphi tb}$	C_{tW}	C_{tB}	$C_{t\varphi}$
$\mu_{EFT} = 125\text{GeV}$	2.5	1.3	3.2	9.3	0.2	0.07	0.9
$\mu_{EFT} = 1000\text{GeV}$	1.3	0.5	4.3	1.3	0.6	0.08	0.9
Current	2.3	5.1	1.2	5.3	0.06	0.145	3.9
Our results	0.286	0.04	0.336	14.8	0.822	0.592	—

[Ethier J J, Magni G, Maltoni F, et al. Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC]

[Alioli S, Cirigliano V, Dekens W, et al. Right-handed charged currents in the era of the Large Hadron Collider [J/OL].]

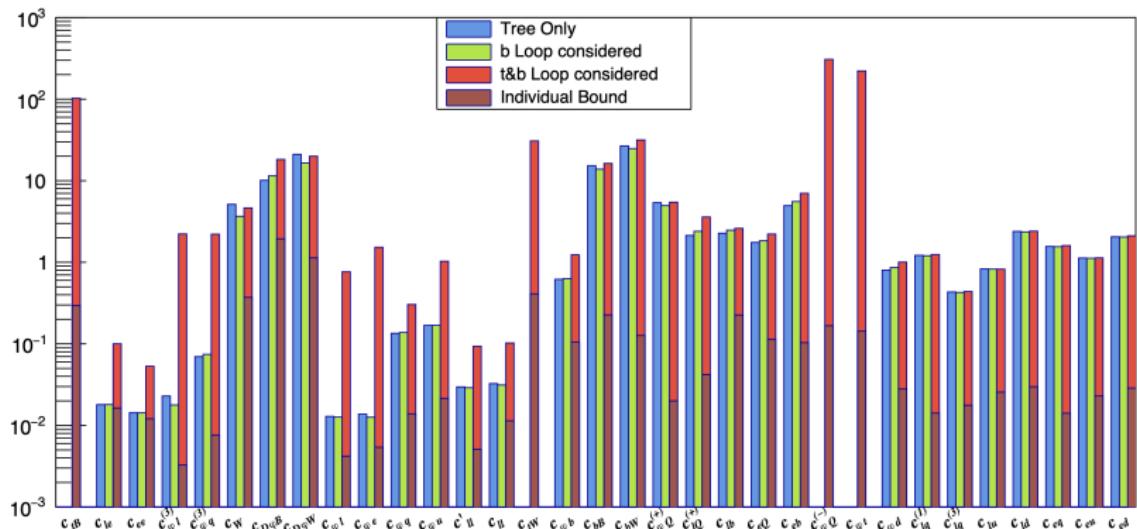
[Maltoni F, Vryonidou E, Zhang C. Higgs production in association with a top-antitop pair in the Standard Model Effective Field Theory at NLO in QCD [J/OL].]

[Buckley A, Englert C, Ferrando J, et al. Constraining top quark effective theory in the LHC Run II era [J/OL].]

[Vryonidou E, Zhang C. Dimension-six electroweak top-loop effects in Higgs production and decay]



Results



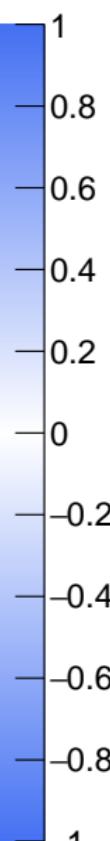
Results(tree level)

	c_{ee}	c_{ee}	$c_{q\bar{q}}^{(3)}$	$c_{q\bar{q}}^{(3)}$	c_W	$c_{D\bar{q}B\bar{q}D\bar{q}W}$	$c_{q\bar{q}}$	$c_{q\bar{q}\epsilon}$	$c_{q\bar{q}q}$	$c_{q\bar{q}u}$	$c_{q\bar{q}d}$	c_{ll}	c_{ll}	$c_{q\bar{b}b}$	$c_{b\bar{b}b}$	$c_{b\bar{b}Q}$	$c_{q\bar{Q}}^{(4)}$	$c_{l\bar{Q}}$	c_{lb}	c_{lQ}	c_{sb}	c_{qd}	$c_{lq}^{(I)}$	$c_{lq}^{(3)}$	c_{lu}	c_{lf}	c_{eq}	c_{eu}	c_{ed}		
c_{le}	1	-0.23	0.0001	-0.0002	-0.013	-0.00e+00	0.01	0.001	-0.0074	-0.0038	0.0007	0.002	-0.005	-0.0012	-0.0017	-0.0017	-0.0017	0.0015	-0.0008	-0.0013	0.0012	-0.0011	-0.0011	0.00032	-0.00049	-0.00087	0.0007	0.002			
c_{et}	-0.23	1	-0.0001	0.018	0.0007	0.0015	-0.008	0.0078	0.0077	-0.0044	-0.018	-0.042	-0.13	0.16	0.31	0.18	-0.14	0.17	0.078	0.12	-0.18	-0.00083	-0.008	-0.008	0.048	0.073	-0.007	0.007	0.009		
$c_{q\bar{q}}^{(3)}$	0.00021	-0.0001	1	0.19	-0.008	-0.29	0.87	-0.008	0.8	-0.0087	-0.018	0.89	-0.76	0.83	0.87	0.8	-0.82	0.87	0.8	0.81	-0.82	0.81	0.81	-0.81	0.81	-0.81	0.81	-0.81	-0.81		
$c_{q\bar{q}}^{(3)}$	-0.0003	0.018	0.19	1	-0.003	-0.28	0.1	0.14	0.21	0.13	-0.09	0.069	-0.056	0.18	0.21	0.18	-0.2	0.11	0.12	0.17	-0.28	0.01	0.11	0.10	-0.098	0.009	0.001	-0.019	-0.31		
c_W	-0.012	0.0037	-0.009	-0.003	1	0.72	-0.00	0.0008	-0.0008	-0.0008	-0.0009	-0.019	0.02	-0.027	-0.027	-0.027	-0.027	-0.027	0.024	-0.014	-0.013	-0.02	0.011	-0.041	-0.0009	-0.012	0.0010	-0.001	0.0008	0.011	
$c_{D\bar{q}B\bar{q}}$	-0.00-08	0.019	-0.00	-0.00	0.00	1	-0.00	0.01	0.01	-0.02	-0.12	0.01	-0.032	0.03	-0.030	-0.030	-0.030	-0.030	-0.030	-0.030	-0.030	-0.030	0.011	-0.001	-0.001	-0.018	0.017	0.000	0.000	-0.000	-0.000
$c_{D\bar{q}W}$	0.01	-0.008	0.01	0.1	-0.00	-0.00	1	0.00	0.000	0.000	-0.000	0.070	-0.07	0.005	0.003	0.003	0.003	0.003	-0.001	0.017	0.019	0.008	-0.014	0.002	0.013	0.018	-0.008	0.000	-0.000		
$c_{q\bar{l}l}$	0.0011	0.0078	-0.008	0.14	-0.0009	0.01	-0.03	1	0.007	0.0001	0.012	0.03	0.04	0.27	0.38	0.39	-0.36	0.21	0.23	0.3	-0.17	0.0003	0.007	0.008	-0.049	-0.007	0.009	-0.077	-0.005		
$c_{q\bar{e}e}$	-0.0014	-0.0070	0.01	0.11	-0.004	-0.02	0.009	0.01	0.014	0.014	0.022	0.22	-0.18	0.47	0.59	0.83	-0.85	0.26	0.41	0.55	-0.3	0.022	0.17	0.10	-0.006	-0.17	0.14	-0.10	-0.17		
$c_{q\bar{q}q}$	-0.0003	-0.0044	-0.0004	0.01	-0.021	-0.12	0.042	0.0000	0.014	1	0.00	-0.0000	-0.0000	-0.002	-0.014	-0.013	0.012	-0.017	-0.010	-0.010	0.013	0.008	0.00	-0.0010	-0.0002	-0.0007	-0.019	-0.18			
$c_{q\bar{u}u}$	0.0007	-0.018	-0.018	-0.00	0.0048	0.00	-0.008	0.012	0.014	0.02	1	0.0044	0.0005	-0.006	-0.003	-0.003	-0.003	-0.010	-0.011	-0.011	-0.002	0.000	0.002	-0.0001	0.017	-0.008	-0.005	-0.000			
$c_{l\bar{l}l}$	0.0002	-0.043	0.001	0.000	-0.018	-0.02	0.075	-0.53	0.22	-0.0000	0.0044	1	-0.01	0.21	0.31	0.27	-0.26	0.16	0.19	0.24	-0.13	-0.002	0.008	0.000	-0.04	-0.007	0.002	-0.008	-0.005		
$c_{l\bar{g}g}$	-0.005	-0.13	0.78	-0.004	0.00	0.00	0.00	-0.07	0.04	-0.18	0.0004	0.0005	-0.01	1	-0.06	-0.32	-0.31	0.02	-0.22	-0.2	-0.37	0.19	0.0001	-0.008	-0.003	0.018	0.002	-0.006	0.000		
$c_{q\bar{b}b}$	-0.0012	0.15	0.55	0.10	-0.001	-0.008	0.025	0.27	0.47	-0.002	-0.006	0.21	-0.05	1	0.00	0.00	-0.005	0.005	0.005	0.00	0.00	0.004	0.004	-0.0017	-0.0007	0.0046	-0.003	-0.002			
$c_{b\bar{b}b}$	-0.0017	0.11	0.07	0.21	-0.005	-0.006	0.030	0.38	0.00	-0.014	-0.003	0.31	-0.32	0.00	1	0.00	-0.00	0.00	0.00	0.00	0.00	0.0004	0.11	0.11	-0.05	-0.1	0.1	-0.1			
$c_{b\bar{b}W}$	-0.0017	0.15	0.6	0.19	-0.003	-0.005	0.03	0.38	0.00	-0.013	-0.003	0.37	-0.31	0.00	0.00	1	-0.01	0.00	0.00	-0.02	0.00	0.0004	0.024	0.021	0.012	-0.0001	0.009	-0.02	-0.0002		
$c_{q\bar{Q}}^{(4)}$	0.0007	-0.14	0.02	-0.2	0.028	0.032	-0.001	-0.28	-0.00	0.012	0.032	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	1	-0.078	-0.081	-0.07	0.0203	-0.0008	-0.0043	0.0208	-0.0008	0.0208	0.0203			
$c_{l\bar{Q}}^{(4)}$	-0.0013	0.17	0.27	0.11	-0.014	-0.027	0.017	0.21	0.38	-0.017	-0.008	0.18	-0.22	0.07	0.07	1	0.00	0.00	0.00	0.00	0.0003	-0.027	-0.031	-0.0001	0.007	-0.11	0.000	0.0001			
c_{lb}	-0.0002	0.079	0.4	0.12	-0.018	-0.023	0.019	0.22	0.41	-0.018	-0.011	0.18	-0.2	0.06	0.01	0.01	-0.01	0.078	0.00	0.00	0.00	0.0006	-0.026	0.008	0.0006	-0.027	0.000	-0.008			
c_{eQ}	-0.0013	0.12	0.06	0.17	-0.00	-0.004	0.038	0.3	0.00	-0.018	-0.003	0.00	-0.07	0.08	0.08	0.08	0.08	0.00	1	-0.08	-0.0006	0.007	-0.003	-0.000	0.003	-0.007	-0.007				
c_{eb}	0.0012	-0.18	-0.03	-0.00	0.011	0.021	-0.014	-0.21	-0.01	0.010	0.021	-0.12	0.08	-0.04	-0.03	-0.03	-0.03	-0.02	0.00	-0.00	0.00	0.0008	0.11	0.12	-0.0021	-0.007	0.10	-0.13	-0.12		
c_{qd}	-0.0004	-0.0003	-0.0002	0.01	-0.001	-0.001	0.0003	0.002	0.003	0.003	0.000	-0.002	0.0001	-0.003	-0.003	-0.003	-0.003	-0.003	0.0001	-0.002	-0.002	0.0001	0.008	0.008	0.000	-0.002	-0.002	-0.002			
$c_{lq}^{(I)}$	-0.0011	-0.004	0.10	0.11	-0.000	-0.007	0.013	0.007	0.10	0.000	0.000	0.011	0.12	0.00	-0.000	-0.000	-0.000	-0.000	0.000	0.000	0.000	1	0.00	0.00	-0.00	-0.00	-0.00	-0.00			
$c_{lq}^{(3)}$	-0.0010	-0.008	0.10	0.10	-0.012	-0.002	0.016	0.008	0.10	0.00	-0.018	0.000	0.000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	0.00	0.00	-0.00	-0.00	-0.00	-0.00		
c_{lu}	0.0003	0.047	-0.00	-0.00	0.0043	0.012	-0.008	0.000	0.000	0.000	0.000	-0.007	0.001	0.017	0.017	0.017	0.017	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
c_{eq}	-0.00007	-0.047	0.13	0.000	-0.000	-0.018	0.000	0.000	0.000	0.000	0.000	-0.007	-0.008	0.001	-0.005	0.004	0.01	0.008	-0.0045	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000			
c_{eu}	0.00007	0.057	-0.14	-0.004	0.000	0.017	-0.000	-0.007	-0.15	-0.079	-0.005	0.000	0.000	-0.1	-0.082	0.009	0.005	-0.040	-0.007	-0.13	-0.072	-0.000	0.000	0.000	0.000	0.000	0.000	0.000			
c_{ed}	0.002	0.008	-0.15	-0.24	0.015	0.005	-0.006	-0.17	-0.10	-0.005	-0.005	0.000	-0.000	-0.000	-0.1	-0.000	0.001	0.00	-0.004	-0.007	-0.12	-0.024	-0.007	-0.003	0.000	0.000	0.000	0.000	0.000		

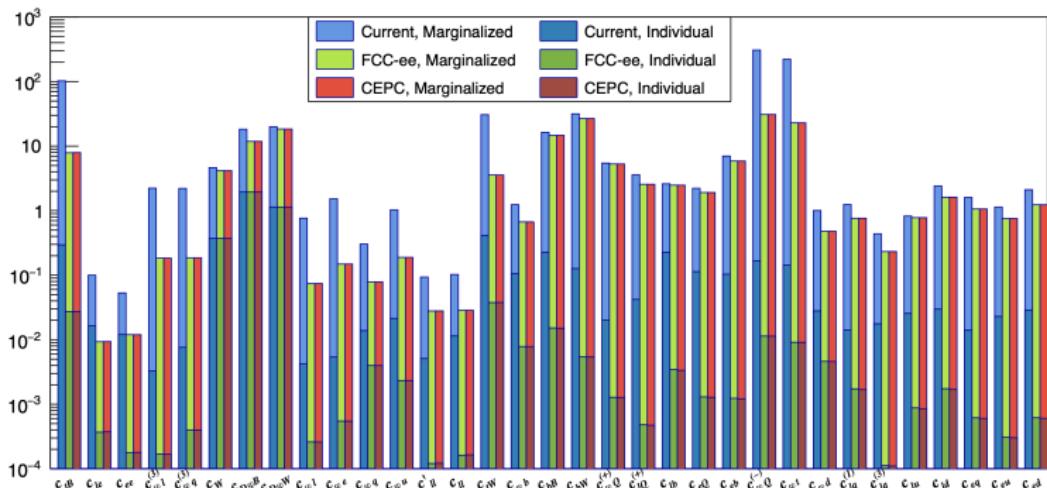


Results(tree level+loop level)

	c_{dR}	c_{eR}	$c_{\nu R}$	$c_{qI}^{(j)}$	$c_{qQ}^{(j)}$	c_W	c_{DqR}	c_{BqR}	c_{qI}	$c_{\bar{q}F}$	$c_{\bar{q}Q}$	c_{qF}	c_{qQ}	c_{qU}	$c'_{\bar{q}}$	c_{ll}	c_{lW}	c_{qb}	c_{bb}	c_{bw}	$c_{\bar{q}Q}^{(+)}$	$c_{\bar{q}Q}^{(-)}$	c_{lb}	c_{cQ}	c_{cb}	$c_{\bar{q}Q}^{(j)}$	c_{qI}	c_{qJ}	$c_{lq}^{(j)}$	$c_{lq}^{(j)}$	c_{lu}	c_{ld}	c_{eq}	c_{eu}	c_{ed}
c_{dR}	-1	0.07	0.06	0.04	0.4	-0.3	-0.33	0.026	-0.18	-0.16	0.13	0.15	0.087	0.37	-0.4	0.19	0.18	0.21	0.027	0.33	0.087	0.28	-0.21	-0.38	-0.02	0.77	-0.35	-0.21	-0.2	0.026	0.17	-0.25	0.15	0.35	
c_{eR}	0.07	1	0.03	0.26	0.26	-0.26	-0.4	0.086	-0.22	-0.22	0.27	0.23	0.048	0.27	-0.26	0.048	0.12	0.12	0.022	0.22	0.085	0.24	-0.12	-0.22	-0.27	-0.21	-0.22	-0.2	0.026	0.17	-0.25	0.15	0.34		
$c_{\nu R}$	0.08	0.03	1	0.22	0.22	-0.26	-0.23	0.020	-0.24	-0.24	0.18	0.24	0.027	0.38	-0.32	0.10	0.2	0.22	0.029	0.31	0.12	0.8	-0.27	-0.2	-0.61	-0.78	-0.20	-0.31	-0.22	0.026	0.17	-0.25	0.15	0.34	
$c_{qI}^{(j)}$	0.4	0.35	0.32	1	1	-0.28	0.2	-0.33	0.03	0.03	-0.76	-0.82	-0.2	0.27	0.086	0.02	0.3	0.8	0.12	0.089	0.02	0.28	-0.36	-1	0.89	0.24	-0.092	-0.13	-0.12	-0.12	0.026	0.17	-0.25	0.15	0.34
$c_{qQ}^{(j)}$	0.4	0.35	0.32	1	1	-0.28	0.2	-0.33	0.03	0.03	-0.76	-0.82	-0.21	0.28	0.086	0.02	0.3	0.8	0.12	0.089	0.02	0.28	-0.36	-1	0.89	0.27	-0.089	-0.12	-0.13	-0.13	0.026	0.17	-0.25	0.15	0.34
c_W	0.3	-0.26	-0.26	-0.26	-0.26	1	0.07	-0.23	-0.23	0.22	0.22	0.18	-0.26	0.28	-0.2	-0.2	-0.2	-0.089	-0.29	-0.22	0.21	0.07	0.66	-0.023	0.78	0.02	-0.013	-0.02	0.01	-0.007	-0.007	-0.007	-0.006	-0.006	
c_{DqR}	0.18	-0.4	-0.25	0.2	0.2	0.3	0.3	0.37	0.52	0.52	-0.32	-0.32	-0.32	0.38	-0.19	0.33	0.088	0.18	0.077	0.2	-0.021	-0.019	0.3	0.85	0.088	-0.017	-0.012	0.008	-0.003	-0.004	-0.004	-0.004	-0.004		
c_{DqW}	0.021	0.005	0.020	-0.2	-0.2	0.2	0.2	-0.7	-0.7	-0.7	1	-0.37	-0.27	0.21	0.2	-0.14	0.28	-0.2	-0.1	-0.16	0.023	-0.22	-0.009	-0.009	0.1	0.32	0.28	-0.17	-0.014	0.014	0.01	0.01	-0.01	0.01	-0.011
c_{qI}	-0.18	-0.33	-0.24	0.03	0.03	-0.23	0.02	-0.37	1	1	-0.89	-0.89	-0.22	0.022	-0.02	-0.77	0.23	0.61	0.1	0.35	-0.027	0.78	-0.6	-0.84	-0.76	0.33	0.032	-0.171	-0.225	-0.038	-0.047	-0.036	-0.036		
$c_{q\bar{e}}$	-0.18	-0.33	-0.24	0.03	0.03	-0.23	0.02	-0.37	1	1	-0.89	-0.89	-0.22	0.021	-0.02	-0.77	0.23	0.61	0.1	0.35	-0.027	0.78	-0.6	-0.84	-0.76	0.33	0.032	-0.171	-0.225	-0.038	-0.047	-0.036	-0.036		
$c_{q\bar{q}}$	0.13	0.27	0.19	-0.75	-0.71	0.22	-0.23	0.21	-0.88	-0.88	1	0.80	0.13	0.021	0.75	-0.88	-0.24	-0.36	-0.1	0.89	0.83	-0.14	0.4	0.75	0.87	-0.003	-0.018	0.016	0.12	-0.023	-0.023				
$c_{q\bar{u}}$	0.18	0.23	0.24	-0.82	-0.82	0.22	-0.22	0.26	-0.88	-0.88	0.86	1	0.22	-0.034	0.8	-0.78	-0.27	-0.4	-0.1	0.64	0.62	0.003	0.21	0.007	0.002	0.022	0.022	0.034	0.034	0.034	0.034				
$c_{\bar{q}I}$	0.007	0.007	-0.2	-0.21	0.18	-0.82	0.2	-0.22	-0.22	0.18	0.22	1	-0.03	0.012	-0.2	-0.072	-0.17	-0.038	-0.16	0.0088	-0.048	0.13	0.26	0.21	-0.3	-0.021	-0.001	0.001	-0.028	0.017	-0.006				
$c_{\bar{q}B}$	0.37	0.37	0.36	0.27	0.29	-0.26	0.39	-0.16	0.032	0.021	0.021	-0.034	0.039	1	-0.088	0.16	0.16	0.12	0.041	0.21	0.094	0.1	-0.13	-0.29	-0.33	0.18	-0.082	-0.001	0.009	0.11	-0.001	0.003			
$c_{\bar{q}W}$	-0.8	-0.34	-0.31	-0.95	-0.95	0.38	-0.19	0.28	-0.82	-0.82	0.75	0.8	0.012	-0.086	1	-0.12	-0.26	-0.21	0.001	0.039	-0.043	-0.28	0.84	0.97	0.96	-0.18	0.001	0.13	0.011	-0.024	0.006	-0.008	-0.13		
$c_{\bar{q}b}$	0.19	0.069	0.19	0.02	0.02	-0.2	-0.22	-0.2	0.77	0.77	-0.88	-0.76	-0.2	0.18	0.18	0.82	1	0.75	0.82	-0.29	0.00	0.27	0.88	-0.82	0.2	0.24	-0.001	-0.009	-0.021	-0.012	0.073	0.04			
$c_{\bar{q}B}$	0.18	0.12	0.26	0.33	0.13	-0.1	-0.11	0.26	0.28	0.28	-0.072	0.072	0.001	-0.28	0.7	1	0.37	0.87	0.1	0.89	0.82	0.00	0.209	0.011	-0.011	-0.001	-0.011	-0.011	-0.011	-0.011	-0.011	-0.011			
$c_{\bar{q}W}$	0.32	0.13	0.22	0.22	0.22	-0.2	-0.16	-0.16	0.42	0.42	-0.36	-0.36	-0.11	-0.12	-0.32	0.87	0.87	1	-0.89	0.82	0.87	-0.09	-0.32	0.82	0.14	-0.005	-0.004	0.023	0.009	0.038	0.091				
$c_{\bar{q}Q}^{(+)}$	0.038	0.022	-0.03	0.10	0.11	-0.047	0.016	-0.011	0.006	0.005	-0.039	-0.037	-0.023	0.039	-0.086	-0.038	-0.036	-0.036	-0.03	1	-0.54	-0.7	-0.75	0.6	0.086	-0.087	0.0073	-0.0023	-0.0026	-0.002	-0.011	0.0052	-0.0048		
$c_{\bar{q}Q}^{(-)}$	0.33	0.32	0.21	0.09	0.09	0.29	0.2	-0.22	0.05	0.05	-0.69	-0.64	-0.16	0.76	-0.21	-0.089	0.065	0.035	0.034	1	0.6	0.26	-0.06	-0.71	-0.71	0.17	-0.11	-0.13	-0.11	-0.011	0.003	0.14	0.09	0.13	
$c_{\bar{q}B}$	0.009	0.004	0.12	0.022	0.022	-0.024	-0.02	0.069	-0.025	-0.025	0.027	0.029	0.001	0.01	-0.069	0.27	0.28	0.02	-0.7	0.61	1	0.07	-0.08	0.034	-0.002	0.003	0.022	0.026	-0.023	0.028	0.009	-0.021	-0.028		
$c_{\bar{q}cQ}$	0.38	0.34	0.36	0.26	0.35	-0.18	-0.21	-0.071	0.16	0.16	-0.14	-0.13	-0.008	0.16	-0.38	0.66	0.66	0.07	-0.75	0.65	0.67	1	-0.06	-0.27	0.065	1	0.36	-0.27	0.065	0.12	0.073	-0.023	-0.023		
$c_{\bar{q}cb}$	-0.38	-0.32	-0.3	-0.6	-0.6	-0.66	-0.23	0.26	-0.75	-0.74	-0.67	-0.67	0.047	0.72	-0.31	-0.33	0.06	-0.28	-0.02	0.002	0.71	-0.009	-0.61	0.06	0.065	-0.007	0.023	-0.047	-0.11	-0.009	-0.009				
$c_{\bar{q}Q}$	0.32	-0.37	-0.37	-0.6	-0.6	-0.66	-0.23	0.26	-0.75	-0.74	-0.67	-0.67	0.047	0.72	-0.31	-0.33	0.06	-0.28	-0.02	0.002	0.71	-0.009	-0.61	0.06	0.065	-0.007	0.023	-0.047	-0.11	-0.009	-0.009				
$c_{\bar{q}I}$	-0.17	-0.21	-0.24	-0.24	-0.24	-0.071	0.071	-0.001	-0.001	-0.001	-0.02	-0.02	0.002	-0.002	-0.002	-0.007	0.007	-0.007	0.007	-0.007	0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007				
$c_{\bar{q}I}^{(j)}$	0.32	-0.24	-0.24	-0.24	-0.24	-0.071	0.071	-0.001	-0.001	-0.001	-0.02	-0.02	0.002	-0.002	-0.002	-0.007	0.007	-0.007	0.007	-0.007	0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007	-0.007					
$c_{\bar{q}I}^{(j)}$	0.31	-0.2	-0.2	-0.1	-0.12	0.082	0.089	0.0077	-0.011	-0.011	0.005	0.01	-0.007	-0.001	0.13	-0.049	-0.011	-0.008	0.003	-0.19	0.027	-0.077	0.15	0.12	0.13	0.13	0.13	-0.27	-0.11	0.089	-0.089	-0.089			
$c_{\bar{q}I_q}$	0.021	0.025	0.006	-0.01	-0.011	-0.002	-0.017	0.0096	-0.023	-0.023	0.013	0.021	0.0095	-0.0094	-0.02	-0.009	0.002	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004	-0.004				
$c_{\bar{q}I_u}$	0.017	0.18	0.17	0.015	0.021	-0.023	-0.001	-0.008	-0.008	0.12	0.005	-0.006	0.11	-0.037	-0.029	-0.02	-0.049	-0.029	0.017	-0.004	-0.006	-0.005	-0.004	0.11	-0.03	-0.01	-0.01	-0.01	0.01	-0.005					
$c_{\bar{q}ld}$	0.17	0.18	0.17	0.015	0.021	-0.023	-0.001	-0.008	-0.008	0.12	0.005	-0.006	0.11	-0.037	-0.029	-0.02	-0.049	-0.029	0.017	-0.004	-0.006	-0.005	-0.004	0.11	-0.03	-0.01	-0.01	-0.01	0.01	-0.005					
$c_{\bar{q}eq}$	0.13	-0.23	-0.24	-0.008	-0.007	0.008	-0.011	0.007	0.008	-0.023	-0.023	0.023	0.009	-0.005	-0.005	-0.008	-0.012	-0.004	0.004	0.004	-0.011	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008					
$c_{\bar{q}eu}$	0.13	0.13	0.13	0.008	0.008	-0.003	0.01	-0.007	-0.007	-0.013	-0.02	0.02	0.004	-0.004	-0.007	-0.008	0.013	-0.028	0.006	-0.11	-0.14	-0.28	-0.07	-0.03	-0.03	-0.03	-0.03	0.01	0.01	-0.005					
$c_{\bar{q}cd}$	0.33	0.34	0.34	0.12	0.11	-0.001	-0.004	0.011	-0.018	-0.019	-0.023	-0.023	0.004	-0.004	-0.007	-0.008	0.013	-0.028	0.006	-0.11	-0.14	-0.28	-0.07	-0.03	-0.03	-0.03	-0.03	0.01	0.01	-0.005					



Results



Conclusions

- 1 The outstanding precision of these measurements (especially at future lepton colliders) could be sensitive to many important loop contributions of the new physics.
- 2 The tree-level contributions of the bottom dipole operators to the electroweak processes are non-negligible.
- 3 Our study is one of the many first steps towards a more complete loop-level SMEFT global analysis, for which many improvements are still needed.



Thank you for your attention!

