The interplay of EWPO and top interactions in SMEFT fits at Electroweak Interactions

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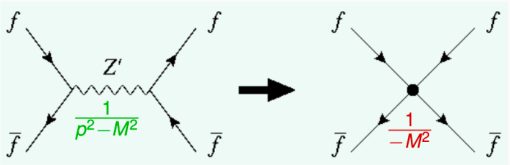
Based on 2205.05655 with Yuhao Wang, Cen Zhang, Lei Zhang, Jiayin Gu

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



$$\frac{1}{p^2-M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

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

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

[Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010]

Theoretical framework

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

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

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

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

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

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

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

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

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

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

$$Q^{(+)}_{\varphi Q} \equiv Q^{(1)}_{\varphi Q} + Q^{(3)}_{\varphi Q},$$
$$Q^{(+)}_{lQ} \equiv Q^{(1)}_{lQ} + Q^{(3)}_{lQ},$$
$$Q^{(-)}_{\varphi Q} \equiv Q^{(1)}_{\varphi Q} - Q^{(3)}_{\varphi Q},$$
$$Q^{(-)}_{lQ} \equiv Q^{(1)}_{lQ} - Q^{(3)}_{lQ},$$

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 $Br(W \to l\nu_l)$ Mass of W Boson M_W
$ee \to qq$	LEP/TRISTAN	Hadronic cross-section σ_{had} Ratio of cross-section R_f Forward-Backward Asymmetry for b/c A_{FB}^{f}
$ee \to ll$	LEP	cross-section σ_f Forward-Backward Asymmetry A_{FB}^{f} Differential cross-section $\frac{d\sigma_f}{dcos\theta}$
$ee \to WW$	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 flavorful effective theories.]

[Morad Aaboud, Georges Aad, Brad Abbott, Jalal Abdallah, O Abdinov, Baptiste Abeloos, Syed Haider Abidi, OS AbouZeid, Nadine L Abraham, Halina Abramowicz, et al. Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7 GeV$ 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 $\sqrt{s} = 58 GeV$]

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 $e^+e^- \to \bar{f}f(f \neq t), e^+e^- \to W^+W^-$.

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

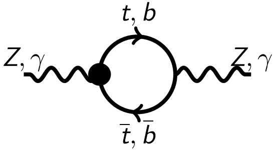
3, The third class are 4-fermion operators that directly contribute to the $e^+e^- \to \bar{f}f(f \neq t, b)$ and several low energy scattering processes at tree level.

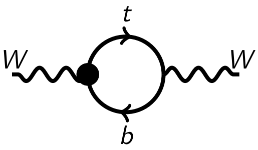
$$Q_{qe}, Q_{eu}, Q_{ed}, Q_{lq}^{(1)}, Q_{lq}^{(3)}, Q_{lu}, Q_{ld}, O_{ll}, Q_{ee}, Q_{le}$$

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

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

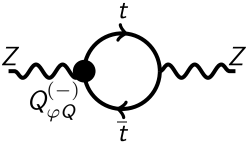
1, For observable without *Zbb* couplings, the nine operators modify the self-energies of W, Z, γ at loop-level, and therefore affect all measurements indirectly.





Example

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



Theoretical framework

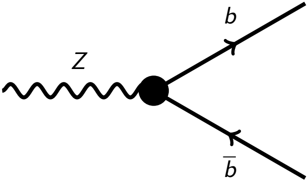
2, For observable with Zbb couplings, $Q_{\varphi Q}^{(+)}$, $Q_{\varphi b}$, Q_{bW}, Q_{bB} modify the $Z \to b\bar{b}$ measurements at tree-level.

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

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

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

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

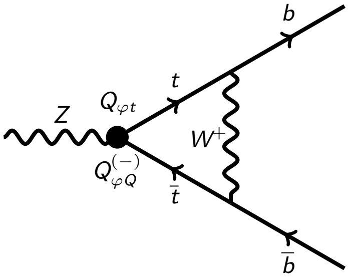


The first class operators associated with bottom quark!!!

Theoretical framework

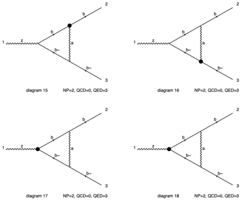
3, For observable with Zbb couplings, $Q_{\varphi Q}^{(-)}$, $Q_{\varphi t}$, Q_{tW}, Q_{tB} not only modify the self-energies of W, Z, γ at loop-level, but also modify the $Zb\bar{b}$ vertex at loop-level.

$$Q_{\varphi Q}^{(-)} = i\left(\phi^\dagger \tau^I D_\mu \phi\right)\left(\bar{Q}\gamma^\mu \tau^I Q\right)$$
$$Q_{\varphi t} = i\left(\phi^\dagger D_\mu \phi\right)\left(\bar{t}\gamma^\mu t\right)$$
$$Q_{\varphi tb} = i\left(\tilde{\phi}^\dagger D_\mu \phi\right)\left(\bar{t}\gamma^\mu b\right)$$
$$Q_{tW} = \left(\bar{q}\sigma^{\mu\nu}\tau^I t\right)\tilde{\phi} W^I_{\mu\nu}$$
$$Q_{tB} = \left(\bar{q}\sigma^{\mu\nu} t\right)\tilde{\phi} B_{\mu\nu}$$

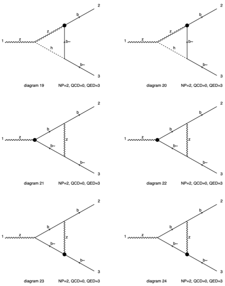


The first class operators associated with top quark!!!

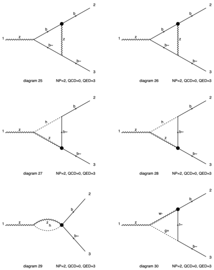
Theoretical framework



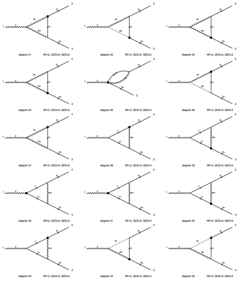
Diagrams made by MadGraph5_aMC@NLO



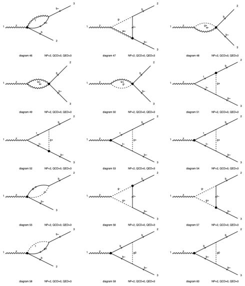
Diagrams made by MadGraph5_aMC@NLO



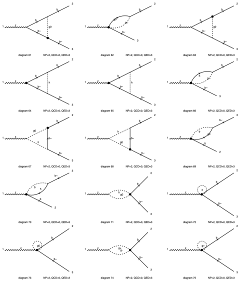
Diagrams made by MadGraph5_aMC@NLO



Diagrams made by MadGraph5_aMC@NLO



Diagrams made by MadGraph5_aMC@NLO



Diagrams made by MadGraph5_aMC@NLO

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 $\frac{c_{D\varphi W}}{\Lambda^2} iD^\mu \varphi^\dagger \sigma_a \varphi W^a_{\mu\nu}$:

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

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(tree level)

$e^+e^- \to W^+W^-$

$e^+e^- \to l^+l^-$

low energy

Z,W−pole

low energy

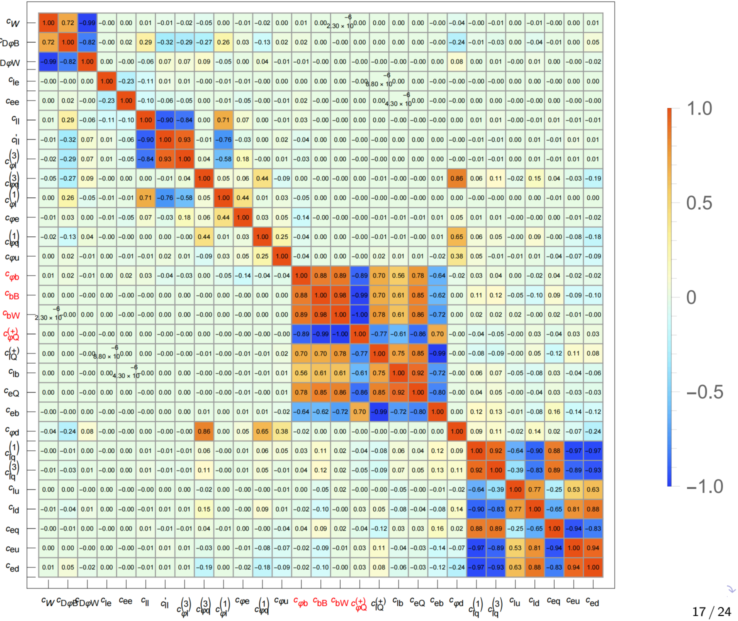
$e^+e^- \to b\tilde{b}$

off pole

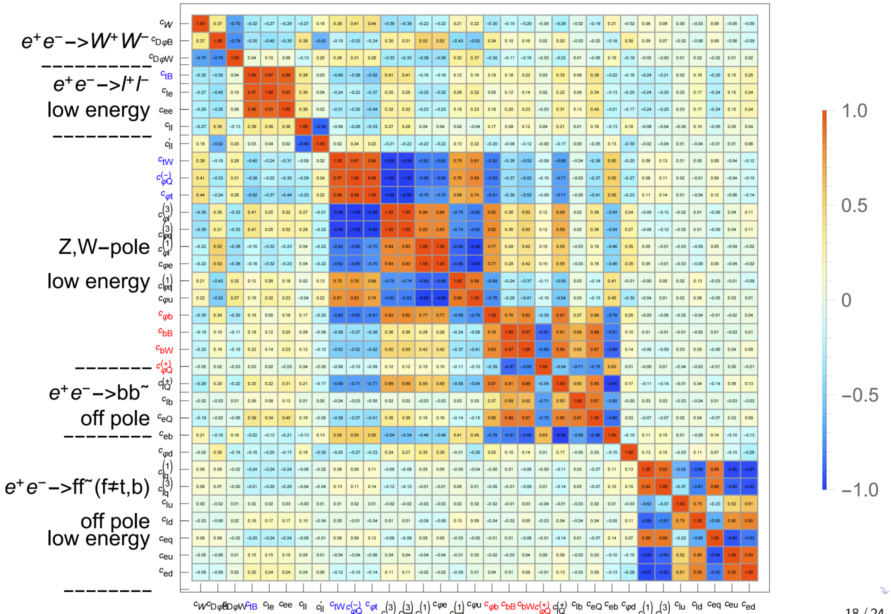
$e^+e^- \to f\tilde{f}\,(f \neq t,b)$

off pole

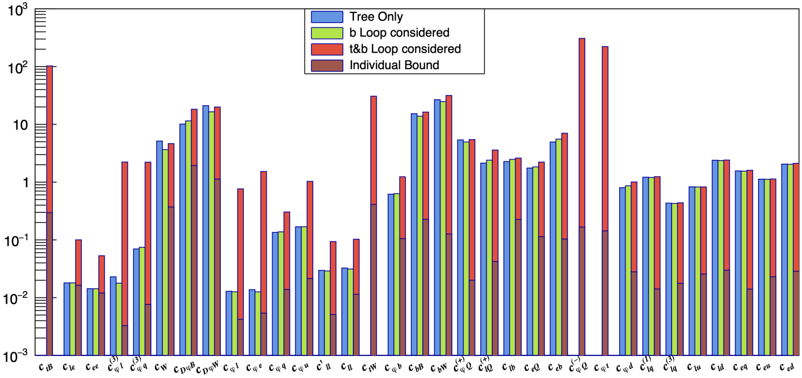
low energy



Results(tree level+loop level)



Results



Tree Only
b Loop considered
t&b Loop considered
Individual Bound
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
c_{tB} c_{le} c_{ee} $c^{(3)}_{\varphi l}$ $c^{(3)}_{\varphi q}$ c_W $c_{D\varphi B}$ $c_{D\varphi W}$ $c_{\varphi l}$ $c_{\varphi e}$ $c_{\varphi q}$ $c_{\varphi u}$ c'_{ll} c_{ll} c_{tW} $c_{\varphi b}$ c_{bB} c_{bW} $c^{(+)}_{\varphi Q}$ $c^{(+)}_{lQ}$ c_{lb} c_{eQ} c_{eb} $c^{(-)}_{\varphi Q}$ $c_{\varphi t}$ $c_{\varphi d}$ $c^{(1)}_{lq}$ $c^{(3)}_{lq}$ c_{lu} c_{ld} c_{eq} c_{eu} c_{ed}

Results

A simple example of the impact of the third-generation quark operators on EWPO

We focus only on $\mathbf{Z}$, $\mathbf{W}$ pole and low energy observables, which are mainly sensitive to non-derivative interactions between EW bosons and fermions:

$$
\begin{aligned}
\mathcal{L}_{\text{SMEFT}} \supset & -\frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{u}_L \gamma_\mu \left(V + \delta g_L^{Wq}\right) d_L + W_\mu^+ \bar{u}_R \gamma_\mu \delta g_R^{Wq} d_R + \text{ h.c. }\right) \\
& -\frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{\nu}_L \gamma_\mu \left(\mathbf{I} + \delta g_L^{We}\right) e_L + \text{ h.c. }\right) \\
& -\sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e,\nu} \bar{f}_L \gamma_\mu \left(\left(T_f^3 - s_\theta^2 Q_f\right) \mathbf{I} + \delta g_L^{Zf}\right) f_L\right] \\
& -\sqrt{g_L^2 + g_Y^2} Z_\mu \left[\sum_{f \in u,d,e} \bar{f}_R \gamma_\mu \left(-s_\theta^2 Q_f \mathbf{I} + \delta g_R^{Zf}\right) f_R\right]
\end{aligned}
$$

$$
\mathcal{L}_{\mathrm{SMEFT}} \supset \frac{g_L^2 v^2}{4}\left(1 + \delta m_w\right)^2 W_\mu^+ W_\mu^- + \frac{\left(g_L^2 + g_Y^2\right) v^2}{8} Z_\mu Z_\mu
$$

Results

$$\delta g_L^{Wf}(f=q,l), \delta g_L^{Zf}\left(f=u_L,d_L,e_L,\nu\right), \delta g_R^{Zf}\left(f=u_R,d_R,e_R\right), \delta m_w$$

$$c_{\varphi D}, c_{\varphi l}^{(3)}, c_{\varphi WB}, c_{\varphi l}^{(1)}, c_{\varphi e}, c_{\varphi q}^{(1)}, c_{\varphi q}^{(3)}, c_{\varphi u}, c_{\varphi d}, c'_{ll}$$

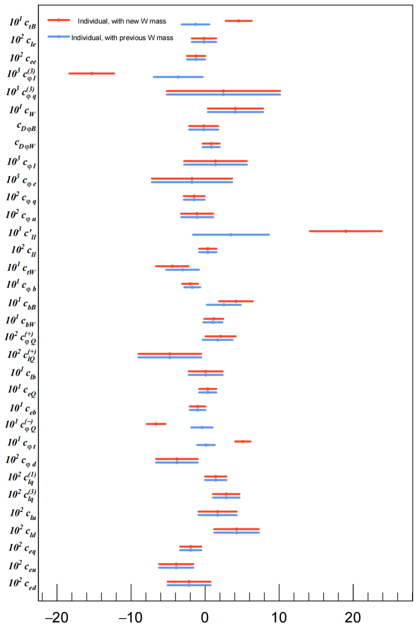
$$\delta g_L^{Z\nu} = \delta g_L^{Ze} + \delta g_L^{Wl}, \delta g_L^{Wq} = \delta g_L^{Zu} + \delta g_L^{Zd}$$

1). Under $U(3)^5$ flavor symmetry(without the effect of b-quark mass and loop).
Only 8 combinations can be constrained and their bounds are better than $\mathcal{O}(0.1)$ at 1σ.
2). Including b-quark mass.
There are two almost flat directions and their marginalized limits are at the level of $\mathcal{O}(1000-10000)$ at 1σ
3). Including the loop effects of $Q_{\varphi q}^{33(+)}$, $Q_{\varphi q}^{33(-)}$, $Q_{\varphi u}^{33}$, $Q_{\varphi d}^{33}$ and b-quark mass.
There are two almost flat directions, and their limits numerical value are in the order of $\mathcal{O}(10)$ at 1σ.

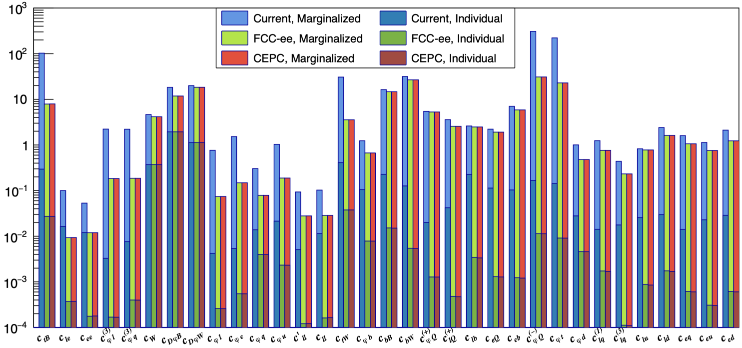
Results

	Z pole	W pole	ee→ WW	ee→ qq	ee→ ll	low energy
c_{tB}	0.80	0.18	0.01	0.00	0.00	0.01
c_{le}	0.00	0.00	0.00	0.00	1.00	0.00
c_{ee}	0.00	0.00	0.00	0.00	0.71	0.29
$c_{\varphi l}^{(3)}$	0.66	0.31	0.01	0.00	0.00	0.02
$c_{\varphi q}^{(3)}$	0.97	0.01	0.01	0.00	0.00	0.01
c_W	0.00	0.00	1.00	0.00	0.00	0.00
$c_{D\varphi B}$	0.00	0.00	1.00	0.00	0.00	0.00
$c_{D\varphi W}$	0.00	0.00	1.00	0.00	0.00	0.00
$c_{\varphi l}$	0.99	0.00	0.00	0.00	0.00	0.00
$c_{\varphi e}$	0.99	0.00	0.00	0.00	0.00	0.01
$c_{\varphi q}$	0.05	0.00	0.00	0.00	0.00	0.95
$c_{\varphi u}$	0.33	0.00	0.00	0.00	0.00	0.67
c'_{ll}	0.57	0.18	0.03	0.01	0.17	0.03
c_{ll}	0.00	0.00	0.00	0.00	0.73	0.27
c_{tW}	0.98	0.01	0.00	0.00	0.00	0.01
$c_{\varphi b}$	0.99	0.00	0.00	0.01	0.00	0.00
c_{bB}	0.96	0.01	0.00	0.03	0.00	0.00
c_{bW}	0.97	0.00	0.00	0.03	0.00	0.00
$c_{\varphi Q}^{(+)}$	0.99	0.00	0.00	0.01	0.00	0.00
$c_{lQ}^{(+)}$	0.00	0.00	0.00	1.00	0.00	0.00
c_{lb}	0.00	0.00	0.00	1.00	0.00	0.00
c_{eQ}	0.00	0.00	0.00	1.00	0.00	0.00
c_{eb}	0.00	0.00	0.00	1.00	0.00	0.00
$c_{\varphi Q}^{(-)}$	0.44	0.53	0.01	0.00	0.00	0.00
$c_{\varphi t}$	0.49	0.48	0.02	0.00	0.00	0.00
$c_{\varphi d}$	0.14	0.00	0.00	0.00	0.00	0.86
$c_{lq}^{(1)}$	0.00	0.00	0.00	0.01	0.00	0.99
$c_{lq}^{(3)}$	0.00	0.00	0.00	0.93	0.00	0.07
c_{lu}	0.00	0.00	0.00	0.05	0.00	0.95
c_{ld}	0.00	0.00	0.00	0.02	0.00	0.98
c_{eq}	0.00	0.00	0.00	0.02	0.00	0.98
c_{eu}	0.00	0.00	0.00	0.23	0.00	0.77
c_{ed}	0.00	0.00	0.00	0.09	0.00	0.91

$$f_i = \frac{\frac{\partial^2 \chi_i^2}{\partial c_j^2}}{\frac{\partial^2 \chi_{all}^2}{\partial c_j^2}}$$



Results



Current, Marginalized
Current, Individual
FCC-ee, Marginalized
FCC-ee, Individual
CEPC, Marginalized
CEPC, Individual
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4

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.