

Probing Top-Quark–Electron Interactions at Future Colliders

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Top quark interactions offer a window into possible new high scale physics and many models of new physics predict that the top quark interactions will deviate significantly from those predicted by the standard model. We present an analysis of the experimental restrictions on anomalous 4-fermion $e^+e^-t\bar{t}$ operators that is accurate to next-to-leading order (NLO) in both the electroweak and QCD interactions within the standard model effective field theory framework. At NLO, there is sensitivity to an extended set of anomalous interactions beyond those probed at leading order. A comparison of current limits from electroweak precision observables, along with expected future limits from Drell-Yan and $t\bar{t}e^+e^-$ production at the high luminosity LHC, from deep inelastic scattering at the EIC, and from projected sensitivities at the future FCC-ee and CEPC machines demonstrates that each of these programs extends the precision understanding of the interactions of top quarks.

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Introduction and motivation—The top quark plays a special role in the standard model (SM). Because of its large mass, the couplings of the top quark to the Higgs boson and to longitudinal gauge bosons are much larger than those of the light quarks, suggesting that the top quark may be fundamentally different from the lighter fermions. Precision probes of top quark properties can thus help to elucidate questions of flavor in the quark sector and to determine whether there is new high scale physics affecting top quark interactions.

Limits on heavy new physics are often expressed in the framework of effective field theories (EFTs). If the unknown new physics is much heavier than the weak scale, EFTs offer a consistent way to compare the capabilities of different current and future colliders. By combining measurements from many sources, more stringent bounds are often obtained than are possible from a single experiment. In this Letter, we consider restrictions on operators involving the top quark in association with electrons from existing electroweak precision observables (EWPOs), neutral Drell-Yan and $pp \rightarrow t\bar{t}l^+l^-$ production at the high

luminosity LHC (HL-LHC), polarized deep inelastic scattering (DIS) at the future electron-ion collider (EIC) [1], and from future Z-pole measurements, Higgs-Z associated production, and top-pair production at the proposed FCC-ee and CEPC e^+e^- colliders [2–5]. For each of these experimental measurements, we present the limits on anomalous top quark-electron interactions and combine our results into a global fit [6]. We assume that the only anomalous interactions are 4-fermion operators with top quarks and leptons, and set all other non-SM interactions to zero.

Our Letter computes observables in the dimension-6 standard model effective field theory (SMEFT) and is accurate to next-to-leading order (NLO) in both the QCD and electroweak sectors. At NLO, there is sensitivity to new interactions that are not probed at lowest order (LO). Interactions with 4 light fermions are strongly restricted by current low energy data [8,9]. The two-fermion top-quark operators related to the vertices $t\bar{t}V$, $t\bar{t}W$, and $t\bar{t}H$, along with the four-fermion top-quark operators $q\bar{q}t\bar{t}$ are also stringently constrained [10–16]. In this Letter, we focus on the two-lepton–two-top-quark operators, which are currently only weakly constrained by the current LHC $pp \rightarrow t\bar{t}\ell^+\ell^-$ measurements [17,18].

One of the novel features of our Letter is that all relevant NLO electroweak corrections are included in the computations of observables. NLO QCD corrections can be automated [19,20], but electroweak corrections must be computed on a case by case basis in the SMEFT. The NLO electroweak contributions to Drell-Yan and DIS processes in the dimension-6 SMEFT from 4-fermion top-electron operators are presented here for the first time.

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SMEFT NLO calculations—The standard model effective field theory assumes an $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry and contains only the standard model particles. The Lagrangian is expanded around the SM Lagrangian,

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d,i} \frac{1}{\Lambda^{d-4}} C_i^d O_i^d, \quad (1)$$

where Λ is the scale of new physics and O_i^d are the gauge invariant operators of dimension d constructed out of SM particles and we restrict ourselves to dimension-6 operators. The coefficient functions C_i^d contain all of the information about potential new physics.

The calculation of physical observables is both an expansion in powers of $(1/\Lambda)$ and in loops, $\sim(1/16\pi^2)$ [21]. We present $\mathcal{O}(1/16\pi^2\Lambda^2)$ NLO SMEFT results that are accurate to one loop in the QCD and electroweak interactions using the dimension-6 SMEFT. The NLO results include both virtual one-loop contributions and the real emission of photons and gluons and are performed with dimensional regularization in $D = 4 - 2\epsilon$ dimensions. As input parameters, we take $M_W = 80.369 \pm .013$ GeV, $M_Z = 91.1876 \pm .0021$ GeV, $G_F = 1.166\,378\,7(6) \times 10^{-5}/\text{GeV}^2$, $M_h = 125.10 \pm 0.14$ GeV, $M_t = 172.9 \pm 0.5$ GeV, and $\alpha_s(M_Z) = 0.1181 \pm 0.0011$. The CKM matrix is set to be diagonal and all fermions other than the top are assumed to be massless. We use a hybrid renormalization scheme: SM parameters are renormalized on shell, while coefficient functions, C_i^d are renormalized using $\overline{\text{MS}}$ [22].

Some of the processes we consider have been previously computed at NLO in the SMEFT: the NLO EWPOs [23–25] and $e^+e^- \rightarrow Zh$ cross section [26,27] are known analytically. The NLO results for all dimension-6 SMEFT contributions except from the 4-fermion interactions for Drell-Yan are known [28,29], while the 4-fermion results for Drell-Yan and DIS are new in this Letter.

We use FeynRules [30] routines to convert SMEFT R_ξ Feynman rules [31,32] into a FeynArts [33] model file, then using FeynCalc [34], we compute helicity amplitudes and reduce 1-loop integrals to Passarino-Veltman integrals which are evaluated using PACKAGE-X/FeynHelpers [35–37] and LoopTools [38]. We do not fix the gauge in the SMEFT Lagrangian and we verify the cancellation of ξ terms, in order to have a further check on our computations. To be consistent in the SMEFT expansion, our approach allows us to consider Feynman diagrams with at most a single SMEFT operator insertion. This ensures renormalizability by avoiding divergences that cannot be removed without introducing higher-dimension operators at leading order.

In this Letter, we present complete NLO SMEFT results including the effects of all two-electron-two-top operators

$$\mathcal{O}_{\ell q}^{(3),1133}, \quad \mathcal{O}_{\ell q}^{(1),1133}, \quad \mathcal{O}_{qe}^{3311}, \quad \mathcal{O}_{\ell u}^{1133}, \quad \mathcal{O}_{eu}^{1133}, \quad (2)$$

TABLE I. Dimension-6 operators containing 2 top quarks and 2 electrons that are considered in this Letter. ℓ_L is the first generation left-handed lepton doublet, $\ell_L^T = (\nu_{eL}, e_L)$, and $Q_L^T \equiv (t_L, b_L)$ is the third-generation left-handed quark doublet. e_R and t_R are the right-handed electron and top quark, respectively.

$\mathcal{O}_{\ell q}^{(3),1133} = (\bar{\ell}_L \gamma_\mu \tau^I \ell_L)(\bar{Q}_L \gamma^\mu \tau^I Q_L)$	
$\mathcal{O}_{\ell q}^{(1),1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_{\ell u}^{1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{t}_R \gamma^\mu t_R)$
$\mathcal{O}_{qe}^{3311} = (\bar{e}_R \gamma_\mu e_R)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_{eu}^{1133} = (\bar{e}_R \gamma_\mu e_R)(\bar{t}_R \gamma^\mu t_R)$

where the four indices in the superscript denote the flavor of the four fermions [39]. Please note that we still refer to it as an NLO electroweak correction when a top quark appears in the loop, even though such contributions are leading order for the corresponding operators. The operators we consider are identical to those of the top-centric model of [24]. The operators in the Warsaw basis [40] are defined in Table I and they contribute to the effective interactions $e^+e^-q\bar{q}$ (where q is a light quark) and e^+e^-Zh at NLO. We do not consider the chirality flipped scalar and tensor operators as they do not interfere with the SM contribution in the limit of massless leptons. Nevertheless, those operators can be important in some precise measurements of the SM suppressed processes [41]. Some sample Feynman diagrams are shown in Fig. 1. The DIS process is obtained by rotating the Feynman diagram on the left-hand side by 90° .

Drell-Yan: NLO QCD-electroweak results for neutral Drell-Yan production including all contributing operators except for four-fermion operators are given in [28]. The four-fermion operators involving light quarks contribute at tree level [8] and are stringently limited from existing Drell-Yan measurements [42–44]. The four-fermion operators involving electrons and top quarks defined in Eq. (2) contribute at NLO and analytic results for the helicity amplitudes are presented here for the first time and documented in the Supplemental Material [45]. In the limit where the partonic center of mass energy $\hat{s} \gg m_t^2$, the NLO SMEFT contributions to the spin- and color-averaged partonic cross sections, $\hat{\sigma}_{\text{DY}}^{\text{NLO}}$, can be simplified,

$$\hat{\sigma}_{\text{DY}}^{\text{NLO}} = \frac{5G_F^2}{324\Lambda^2\pi^3} \sum_i X_{0,i} C_i + \frac{G_F^2}{162\Lambda^2\pi^3} \log(\hat{s}/m_t^2) \sum_i \left(\frac{m_t^2}{\hat{s}}\right)^{n_i} X_{1,i} C_i, \quad (3)$$

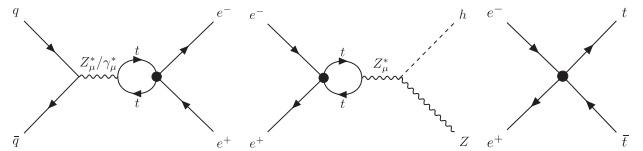


FIG. 1. Representative Feynman diagrams for the Drell-Yan process $q\bar{q} \rightarrow e^-e^+$ (left), associated Z boson-Higgs production (middle), and top-pair production (right).

TABLE II. The analytic expressions for the NLO SMEFT functions X_0 and X_1 in the high-energy limit of $q\bar{q} \rightarrow e^+e^-$. Here, we define $w \equiv M_W^2$, $z \equiv M_Z^2$.

Operators	$\mathcal{O}_{\ell q}^{(3),1133}$	$\mathcal{O}_{\ell q}^{(1),1133}$	$\mathcal{O}_{\ell u}^{1133}$	$\mathcal{O}_{qe}^{3311}$	$\mathcal{O}_{eu}^{1133}$
$\bar{u}u \rightarrow e^+e^-$ ($X_{0,i}$)	$[w(2w+z)/4]$	$-[(14w^2-31wz+17z^2)/36]$	$-[(14w^2-31wz+17z^2)/18]$	$-[17(w-z)^2/18]$	$-[17(w-z)^2/9]$
($X_{1,i}$)	$[3(88w^2-164wz+85z^2)/16]$	$-[(14w^2-31wz+17z^2)/2]$	$-[(32w^2-22wz+17z^2)/8]$	$-17(w-z)^2$	$-[(8w^2-25wz+17z^2)/4]$
$\bar{d}d \rightarrow e^+e^-$ ($X_{0,i}$)	$[w(4w-z)/4]$	$[(13wz-8w^2-5z^2)/36]$	$[(13wz-8w^2-5z^2)/18]$	$-5(w-z)^2/18]$	$-5(w-z)^2/9]$
($X_{1,i}$)	$[3(40w^2-56wz+25z^2)/16]$	$-[(8w^2-13wz+5z^2)/2]$	$-[(44w^2-22wz+5z^2)/8]$	$-5(w-z)^2$	$-[(14w^2-19wz+5z^2)/4]$

where i runs over the operators of Eq. (2) and C_i are the corresponding Wilson coefficients. $X_{0,i}$ and $X_{1,i}$ are functions of the weak boson masses and $n_i = 1$ for $\mathcal{O}_{\ell q}^{(3)}$ and $n_i = 2$ for the remaining operators. The results are given in Table II. The logarithmic terms are subdominant at the LHC due to the suppression of $(m_t^2/\hat{s})$ or $(m_t^2/\hat{s})^2$, and this is clear in Fig. 2, where we show the partonic SM cross sections (black curve) and the contributions from a representative SMEFT operator (solid red curve) as a function of $\sqrt{\hat{s}} = m_{\ell\ell}$. The contributions from the logarithmic and nonlogarithmic terms are shown by the dashed and dotted red curves, respectively. For illustration, we set $C_{\ell q}^{(3),1133} = 1$, and the remaining coefficients to zero. Similar features hold for the other operators. The overall positive (negative) sign in $X_{0,i}$ indicates a constructive (destructive) interference with the SM.

Electron ion collider (EIC): By interchanging the Mandelstam variables, $\hat{s} \leftrightarrow \hat{t}$, the NLO results for polarized electron-quark scattering at the future EIC are obtained from the Drell-Yan results. The EIC is able to produce an electron beam with $P_e = 70\%$ polarization and a systematic uncertainty $\lesssim 1\%$ [1] at $\sqrt{s} = 140$ GeV. To cancel the large SM photon contributions, we compute the left-right asymmetry

$$A_{LR} \equiv (\tilde{\sigma}_L - \tilde{\sigma}_R)/(\tilde{\sigma}_L + \tilde{\sigma}_R) \quad (4)$$

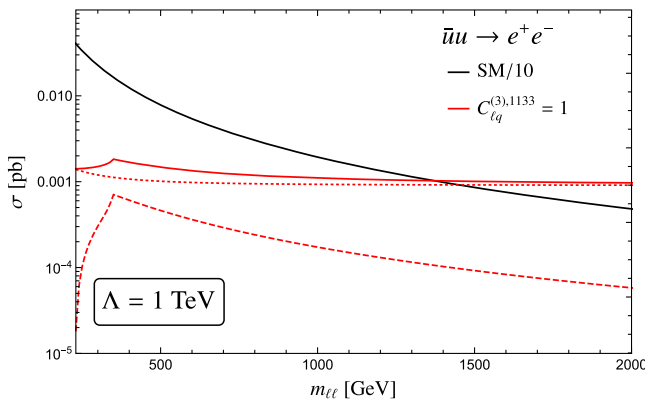


FIG. 2. The partonic Drell-Yan cross section as a function of $\sqrt{\hat{s}} = m_{\ell\ell}$, comparing the SM prediction (black) with the contribution from the operator $\mathcal{O}_{\ell q}^{(3),1133}$ (solid red). The contribution from $\mathcal{O}_{\ell q}^{(3),1133}$ is separated into logarithmic (dashed red) and nonlogarithmic (dotted red) terms.

as our observable at the EIC, where $\tilde{\sigma}_{L(R)} \equiv \sigma_{L(R)}(1 + P_e)/2 + \sigma_{R(L)}(1 - P_e)/2$, and $\sigma_{L(R)}$ is the hadronic cross section for the deep-inelastic scattering of a left (right)-handed electron.

Electroweak precision observables: The NLO SMEFT results for Z-pole observables were first computed in [23], and the results with an arbitrary flavor structure presented in [24,25]. We include the following Z-pole observables,

$$A_{\ell/b/s/c}, \quad R_{\ell/b/c}, \quad A_{\ell/b/s/c, \text{FB}}, \quad \sigma_h, \quad \Gamma_Z. \quad (5)$$

The running of the electromagnetic coupling from $q^2 = 0$ to $q^2 = M_Z^2$ and the W boson width, Γ_W , are additional precision observables that we include at NLO.

FCC-ee: The next run above the Z-pole at the FCC-ee is at the WW threshold ($\sqrt{s} = 162$ GeV). The first three operators listed in Eq. (2) involving the left-handed quark doublet can modify the cross section of $b\bar{b}$ pair production. At LO at $\sqrt{s} = 162$ GeV,

$$\begin{aligned} \sigma_{e^+e^- \rightarrow b\bar{b}}(\text{pb}) &= 5.97 - \{0.69C_{qe}^{3311} \\ &\quad - 1.96(C_{\ell q}^{(3),1133} + C_{\ell q}^{(1),1133})\} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2. \end{aligned} \quad (6)$$

The FCC-ee at $\sqrt{s} = 162$ GeV is expected to reach a precision of 2×10^{-4} on $\Delta R_b/R_b$ [46].

The four-fermion electron-top operators contribute to Higgstrahlung at NLO as depicted by the middle panel in Fig. 1, and the complete NLO SMEFT result for $\sigma(e^+e^- \rightarrow Zh)$ can be found in [26,27].

At $\sqrt{s} = 365$ GeV, the process $e^+e^- \rightarrow t\bar{t}$ becomes accessible and the electron-top four-fermion operators can be probed directly at LO as shown in the right panel of Fig. 1. The tree-level result at $\sqrt{s} = 365$ GeV is

$$\begin{aligned} \sigma_{e^+e^- \rightarrow t\bar{t}}(\text{pb}) &= 0.49 + \{0.60(C_{\ell q}^{(3),1133} - C_{\ell q}^{(1),1133}) \\ &\quad - 0.56C_{\ell u}^{1133} - 0.35C_{qe}^{3311} - 0.38C_{eu}^{1133}\} \\ &\quad \times \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2. \end{aligned} \quad (7)$$

The experimental uncertainty on the top-pair production cross section measurement at the FCC-ee with 2.7 ab^{-1} is expected to be 0.12% [47]. The theoretical uncertainty is

estimated as 1.2% by varying the top quark mass within ± 0.25 GeV. We also include the forward-backward asymmetry of top quarks A_{FB}^t , which can be calculated as

$$A_{\text{FB}}^t/10^3 = -88.3 + \{145.3(C_{\ell q}^{(1),1133} - C_{\ell q}^{(3),1133}) - 47.4C_{\ell u}^{1133} - 21.2C_{qe}^{3311} + 99.9C_{eu}^{1133}\} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2. \quad (8)$$

The uncertainty is set to be 0.0016 [48] including both systematic and statistical ones.

Numerical fits—We are now in a position to perform a fit in which all processes are computed to NLO QCD and NLO electroweak order. We emphasize that current global fits, while accurate to NLO QCD, typically do not include NLO electroweak corrections consistently. “Partial” NLO electroweak corrections were included in the global fits of [49,50], but the current calculation is the first to include NLO electroweak predictions for all observables, *albeit* for a restricted set of operators.

We begin by illustrating the effects of different data sets to constrain the top quark-electron operators of Eq. (2) using a χ^2 fit. In Fig. 3, we show the sensitivities of different future colliders to $C_{qe}^{3311}-C_{eu}^{1133}$ (upper panel) and $C_{\ell q}^{(3),1133}-C_{\ell q}^{(1),1133}$ (lower panel). All other coefficients are set to 0.

Future e^+e^- colliders will operate at various center-of-mass energies, ranging from the Z pole, the WW threshold ($\sqrt{s} = 162$ GeV) and the Zh threshold ($\sqrt{s} = 240$ GeV) to the top-pair threshold ($\sqrt{s} = 365$ GeV). The future FCC-ee and CEPC are projected to produce trillions of Z bosons at the Z-pole run, which will substantially improve the precision of Z-pole observables [51,52]. We do a χ^2 fit to EWPOs using the most precise theoretical results and the current experimental data, along with projections for the precision expected from FCC-ee Z-pole data. (The data used in the fit are given in the Supplemental Material.) The current limits from EWPOs are shown in Fig. 3 as the gray band, with the improvement from FCC-ee results in the purple band.

Higgstrahlung data have a different dependence on the top-quark electron operators from the EWPOs and the limit at $\sqrt{s} = 240$ GeV yields the green band [26,27,50]. At $\sqrt{s} = 365$ GeV, the Higgstrahlung results contribute to the fit, but the dominant contribution at this energy is from top quark pair production, which occurs at LO, shown as the dark blue band. (The results for CEPC are similar to those of FCC-ee. We do not include the ILC, as we have not optimized our Letter to include polarization effects relevant at the ILC.)

We adopt the HL-LHC Drell-Yan projections in [53]. To ensure the validity of the EFT description, we restrict the Drell-Yan data to the 3 bins in the di-lepton invariant mass m_{ee} , which are [500,550], [550,650], and [650,800] GeV. The tree-level process $pp \rightarrow t\bar{t}e^+e^-$ is also included in our analysis. We follow [54] using the cross section measurements with four bins in m_{ee} , which are [100,120],

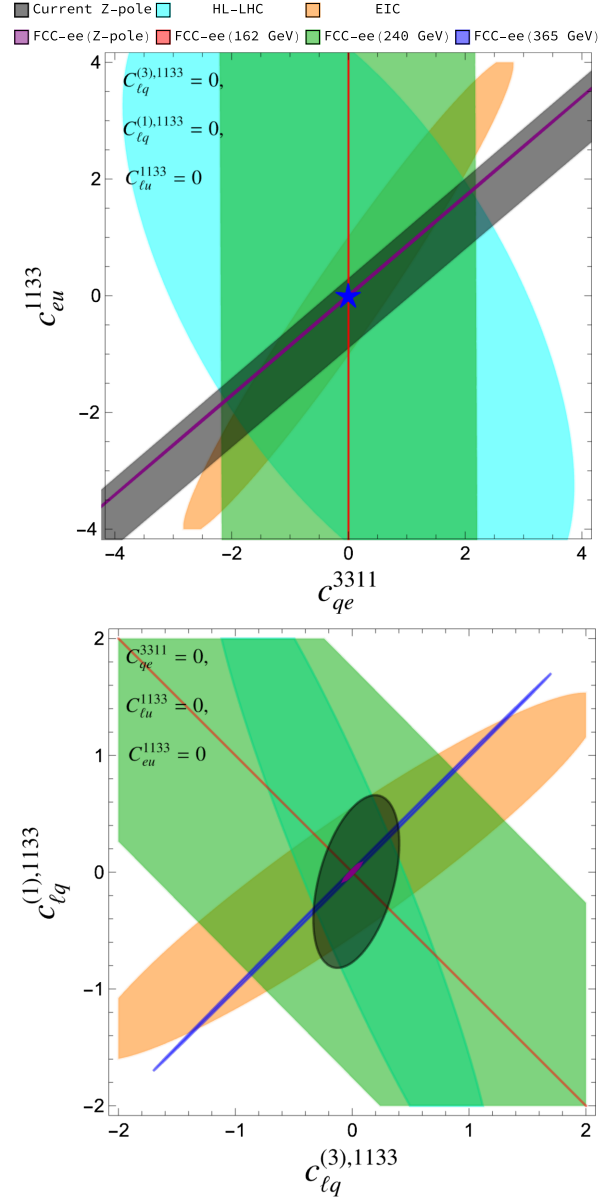


FIG. 3. The 2σ limits on $C_{qe}^{3311}-C_{eu}^{1133}$ (upper panel) and $C_{\ell q}^{(3),1133}-C_{\ell q}^{(1),1133}$ (lower panel) at current and future colliders. In the upper panel, the FCC-ee (365 GeV) projection appears as a dot at the origin (0,0). For clarity, we mark it with a blue star. All other operators are set to 0 and $\Lambda = 1$ TeV. The calculation does not include contributions of $\mathcal{O}(1/\Lambda^4)$.

[120,140], [140,180], and > 180 GeV with 3 ab^{-1} of data. Including both the NLO Drell-Yan and tree-level $pp \rightarrow t\bar{t}e^+e^-$ contributions can break the degeneracies in the fit, as shown by the cyan line in Fig. 3. We have verified that the NLO contributions from the Drell-Yan process are numerically comparable with and complementary to the $pp \rightarrow t\bar{t}e^+e^-$ contributions, even when considering only the low-mass $m_{\ell\ell}$ bins [45]. In the Drell-Yan contribution, the tree-level process $b\bar{b} \rightarrow e^+e^-$ is also included for the operators associated with the left-handed quark doublet.

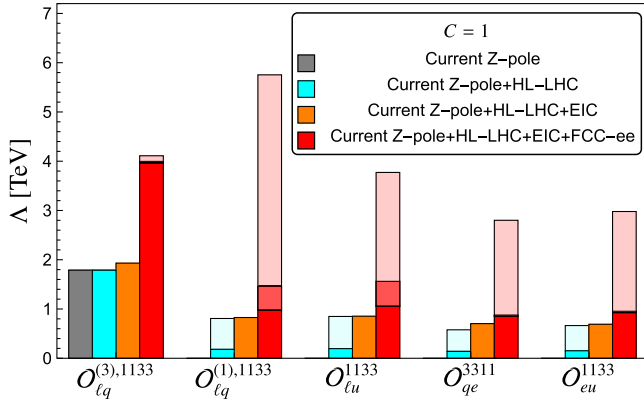


FIG. 4. The 2σ marginalized bounds on the scale Λ from a global fit to the 4-fermion operators considered in this Letter. The Wilson coefficients are set to 1. All contributions of $\mathcal{O}(1/\Lambda^4)$ are dropped. For the HL-LHC, we consider only including the tree-level process $pp \rightarrow t\bar{t}e^-e^+$ (cyan) and including both the tree-level and NLO Drell-Yan processes (light cyan). The FCC-ee projections consist of three components, corresponding to FCC-ee Z-pole, FCC-ee at WW threshold, and FCC-ee at $\sqrt{s} = 365$ GeV, shown in increasingly lighter shades of red. The contribution from FCC-ee at the WW threshold is indistinguishable from the Z-pole contribution for operators $\mathcal{O}_{\ell q}^{(3),1133}$, $\mathcal{O}_{\ell q}^{(1),1133}$, and $\mathcal{O}_{\ell e}^{1133}$. Higgstrahlung does not make an observable contribution to the FCC-ee bands.

We find that the sensitivity to $C_{\ell q}^{(3),1133}/C_{\ell q}^{(1),1133}$ is dominated by the one-loop (tree-level) contribution. For $C_{\ell q}^{(1),1133}$ there is a cancellation between the up- and down-type quark contributions at the NLO, as shown in Table II, while for $C_{\ell e}^{3311}$, the two contributions are comparable. The first new data after the HL-LHC will come from deep inelastic scattering at the EIC. We use 156 bins in the $x - Q^2$ plane with $Q^2 > 4$ GeV² and assume 500 fb⁻¹ integrated luminosity for each left-handed and right-handed electron beam mode leading to the sensitivity of the orange band. The renormalization or factorization scale is $\mu = \sqrt{Q^2}(m_{\ell\ell})$ for the DIS (Drell-Yan) process.

In Fig. 3, we see that by combining different observables at a variety of energies in a global SMEFT analysis, the

bounds can be significantly strengthened. However, the results from a fit to a single coefficient with the other operators marginalized over can give a quite different result from the single parameter fit, due to the presence of degeneracies. In Fig. 4, we present a marginalized fit to the operators of Eq. (2) meant to demonstrate a possible sequence in time of bounds on the new physics scale Λ (with the Wilson coefficients, C_i set to 1). With the current EWPO measurements, there is a limit of $\mathcal{O}(\sim 2$ TeV) for $C_{\ell q}^{(3)}$, but there are degeneracies among the remaining contributions which do not allow for a meaningful bound. Including the current bounds from the measurement of $pp \rightarrow t\bar{t}e^+e^-$ at the LHC [17,18] can break the degeneracies, but does not yield meaningful results as the constraints on C_i are beyond the perturbative limit at $\Lambda = 1$ TeV. Including the HL-LHC Drell-Yan and $pp \rightarrow t\bar{t}e^+e^-$ projections effectively breaks the degeneracies in the remaining four-fermion operators, as illustrated by the cyan bands in Fig. 4. The orange bands in Fig. 4 show the bounds after adding the EIC data. Finally, the results from the full FCC-ee program are shown as the red bands in Fig. 4.

Both the single-parameter and global-fit bounds on the Wilson coefficients (marginalized over the other 4 operators we consider) with $\Lambda = 1$ TeV are shown in Table III.

Conclusions—In this Letter, we studied the current and future constraints on dimension-6 4-fermion operators involving both electrons and top quarks in the SMEFT framework. The new feature of our Letter is that QCD and electroweak NLO contributions are included consistently.

In a global fit to the top-electron 4-fermion operators, current Z-pole observables impose a stringent constraint on the $SU(2)_L$ triplet 4-fermion operator $\mathcal{O}_{\ell q}^{(3),1133}$, with sensitivity reaching up to $\Lambda \sim 2$ TeV, while the other four top quark-electron operators are unconstrained due to degeneracies. Including the future HL-LHC tree-level $pp \rightarrow t\bar{t}e^+e^-$ projections breaks the degeneracies, leading to weak constraints. Adding the future NLO Drell-Yan measurements will significantly improve the limits on the Wilson coefficients of the four $SU(2)_L$ singlet 4-fermion operators by more than an order of magnitude, as shown in Table III. Finally, the FCC-ee Z-pole run is expected to

TABLE III. The 2σ allowed regions on the five four-fermion electron-top operators with $\Lambda = 1$ TeV. The global fit results are marginalized over the other two-electron-two-top-quark operators considered in this fit.

Observables		$C_{\ell q}^{(3),1133}$	$C_{\ell q}^{(1),1133}$	$C_{\ell u}^{1133}$	$C_{\ell e}^{3311}$	$C_{\ell e}^{1133}$
Current Z pole	Single parameter	[-0.21, 0.32]	[-0.65, 0.42]	[-0.36, 0.55]	[-0.31, 1.02]	[-0.87, 0.26]
	Global fit	[-0.29, 0.31]	...	...	...	...
Current Z pole + HL-LHC ($t\bar{t}e^-e^+$)	Single parameter	[-0.21, 0.32]	[-0.64, 0.42]	[-0.36, 0.55]	[-0.31, 1.02]	[-0.85, 0.26]
	Global fit	[-0.29, 0.31]	[-30.7, 24.6]	[-26.2, 20.9]	[-40.2, 51.4]	[-34.6, 43.4]
Current Z pole + HL-LHC	Single parameter	[-0.18, 0.25]	[-0.53, 0.37]	[-0.36, 0.54]	[-0.31, 0.97]	[-0.85, 0.26]
	Global fit	[-0.28, 0.31]	[-1.37, 1.53]	[-1.37, 1.39]	[-2.29, 3.00]	[-2.27, 2.21]
Current Z pole + HL-LHC + EIC	Single parameter	[-0.17, 0.23]	[-0.36, 0.28]	[-0.30, 0.43]	[-0.28, 0.57]	[-0.66, 0.26]
	Global fit	[-0.27, 0.24]	[-1.34, 1.46]	[-1.33, 1.38]	[-2.02, 1.88]	[-2.10, 1.46]
Current Z pole + HL-LHC + EIC + FCC-ee	Single parameter	[-0.0012, 0.0012]	[-0.0012, 0.0012]	[-0.0078, 0.0078]	[-0.0033, 0.0034]	[-0.016, 0.015]
	Global fit	[-0.058, 0.059]	[-0.029, 0.030]	[-0.070, 0.065]	[-0.12, 0.13]	[-0.11, 0.11]

reduce the experimental uncertainties on the Z-pole observables and has the potential to push the limit on Λ for the operator $\mathcal{O}_{\ell q}^{(3),1133}$ to 4 TeV. Nonetheless, it has very limited effects on the other four $SU(2)_L$ singlet operators due to degeneracies. The full FCC-ee program is needed to probe the electron-top 4-fermion operators at LO and to improve the limits on Λ for the four $SU(2)_L$ singlet operators by a factor of ~ 3 – 6 . We note that similar results can be obtained for CEPC.

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Data availability—The data that support the findings of this article are openly available [55].

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