Top-quark EFT loops in Higgs processes at future lepton colliders

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Future lepton colliders

Timeline and run plans are indicative only!

To achieve “LEP precision” on the Higgs and top!
Observations

- Getting to $e^+e^- \rightarrow t\bar{t}$ energies may take many years.
- Individual HL-LHC sensitivities to top interactions are $\mathcal{O}(10\%)$ only. \cite{1σ, tZt}
- Higgs and di-boson are measured to $\mathcal{O}(0.1\%)$ at $\sqrt{s} \simeq 240$ GeV.
- Loop suppressions are $\mathcal{O}(1\%)$.

Questions

[inspired by Higgs trilinear discussions]

Q1: Can one get sensitivity to top interactions from Higgsstrahlung run?
Q2: Do top uncertainties impede precise Higgs measurements?

Answer ingredients

- Global tree-level EFT analysis of Higgs and diboson measurements
- Top EFT loop computations for Higgs, diboson, and $Z$-pole
- Global tree-level EFT analysis of $e^+e^- \rightarrow t\bar{t}$ (for comparison)
Global Higgs EFT analysis
Global Higgs EFT constraints

- importance of complementary measurements (different c.o.m. energies, polarizations, distributions)
- importance of diboson measurement precision (not studied much by exp. collaborations)
- order of magnitude improvement wrt LHC (especially on $\delta c_Z$, $\delta c_{ZZ}$, $\delta c_{Z\Box}$, $\delta y_b$, $\delta y_{\tau}$, $\lambda_Z$)
- LHC helps for $\bar{c}_{\gamma\gamma}$, $\delta y_{\mu}$, and $\delta y_t$ (below 500 GeV!)
Higgs self-coupling through loops

- NLO sensitivity (finite and gauge-invariant NLO EW subset)
- dominated by $e^+e^- \rightarrow hZ$ at threshold

$$\Sigma_{\text{NLO}}/\Sigma_{\text{NLO}}^{\text{SM}} \simeq 1 + (C_1 - 0.0031) \delta \kappa_\lambda + ...$$

→ few permil $hZ$ measurement naively implies a few 10% constraint
At the ILC, for instance

- individual $\Delta \chi^2 = 1$ limit (30%) much tighter than global ones (580, 130, 60%)
- 350 GeV run necessary to lift approximate degeneracies, without LHC

\[
\begin{align*}
\text{ILC} & \quad 2/\text{ab at 250 GeV} \\
& \quad +0.2/\text{ab at 350 GeV} \\
& \quad +1.5/\text{ab at 350 GeV}
\end{align*}
\]

- second LHC minimum already resolved by a 250 GeV run
- constraints dominated by lepton colliders for 1.5 ab$^{-1}$ at 350 GeV ($\sim 50\%$)
Global $e^+ e^- \rightarrow t \bar{t}$

EFT analysis
At CLIC, for instance

- in TeV$^{-2}$, $\Delta \chi^2 = 1$
- blobs: individual constraints
- gray numbers: global/individual ratios

[GD, Perello, Vos, Zhang ’18]

Two centre of mass energies are required to constrain all ten d.o.f. accessible linearly in resonant $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$. 

- statistically optimal observables
  - resonant $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$
  - $m_b/m_t \rightarrow 0$, analytical LO observable def.
  - effective stat. efficiencies determined with full sim. in semi-leptonic final state

CLIC-like scenario

- 1 ab$^{-1}$ at $\sqrt{s} = 380$ GeV
- 2.5 ab$^{-1}$ at $\sqrt{s} = 1.4$ TeV
- 5 ab$^{-1}$ at $\sqrt{s} = 3$ TeV

$P(e^+, e^-) = (0\%, \mp 80\%), 80\%/20\%$ shared

[LCWS, 22 Oct. 2018]
Top loops & results
Top loops

- At the $Z$ pole
  
  - In diboson production

- In Higgs

  - Higgsstrahlung and $W$-fusion through reweighing in MG5/AMC@NLO
  
  - Higgs decays

(excluding four-fermion operators, no top loop included in $e^+e^- \rightarrow t\bar{t}$)
Q1: Improvement on top operators

$\Delta \chi^2 = 1$
top@HL-LHC
240 GeV, 5 ab$^{-1}$

Individual constraints (blobs)
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\phi}$)
- dominated by Higgs measurements (diboson improves with energy)

Global constraints (bars) (12 Higgs + 6 top op. floated)
- large flat directions with 240 GeV run alone (not shown)
- still improves the HL-LHC combination
- more differential distributions would help further
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On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:

- $\Delta \chi^2 = 1$
- $\text{top@HL-LHC}$
- $+ 240 \text{ GeV (tree)}$
- $+ 240 \text{ GeV (loop)}$

- extra parameter space covered thanks to loop sensitivity
- room for improvement between glo. and ind. constraints
Q1: Improvement on top operators

\[ \Delta \chi^2 = 1 \]

\[ \text{top@HL-LHC} + 240 \text{GeV}, 5 \text{ab}^{-1} + 350/365 \text{GeV}, 1.5 \text{ab}^{-1} \]

**Individual constraints (blobs)**
- competitive with the HL-LHC (e.g. on the top Yukawa \( C_{t\varphi} \))
- dominated by Higgs measurements (diboson improves with energy)
- loops in \( e^+ e^- \rightarrow t\bar{t} \) would improve its impact on \( C_{t\varphi} \) and \( C_{tG} \)

**Global constraints (bars) (12 Higgs + 6 top op. floated)**
- large flat directions with 240 GeV run alone (not shown)
- still improves the HL-LHC combination
- more differential distributions would help further
Q2: Contamination in Higgs operators

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. → 0

Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run ⊕ $e^+e^- \rightarrow t\bar{t}$: large $y_t$ contaminations in various coefficients
- Higgsstr. run ⊕ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run ⊕ $e^+e^- \rightarrow t\bar{t}$ ⊕ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only
Summary
Top-quark EFT loops in Higgs processes at future lepton colliders

The top and Higgs escaped the previous generation of lepton colliders and remain to be characterized to the level of EW gauge bosons.

We performed a global top+Higgs EFT analysis with one-loop contributions from top operators and tree-level contributions from Higgs ones.

**Q1:** More differential information could better exploit loop sensitivities to top operator in a Higgsstrahlung run.

**Q2:** Precise knowledge of the top quark is indispensable for precision Higgs coupling determination.

Outlook: more differential distributions, four-fermion and CP-odd operators, loops in $e^+e^- \rightarrow t\bar{t}$, polarized beams, full set of EWPO, $e^+e^- \rightarrow ZZ, Z\gamma, f\bar{f}, ...$
Backup
Global Higgs EFT setup

- employ the Higgs basis of dim-6 operators
- focus mostly on Higgs-related processes:
  \[ e^+ e^- \rightarrow hZ, \ W^+ W^- \] (incl. angular distributions)
  \[ h\nu\bar{\nu}, \ h\bar{t}t, \ hhZ, \ hh\nu\bar{\nu} \]
  \[ h \rightarrow ZZ^*, \ WW^*, \ \gamma\gamma, \ \gamma Z, \ gg, \ b\bar{b}, \ c\bar{c}, \ \tau^+\tau^-, \ \mu^+\mu^- \]
- only relax flavour universality to distinguish Yukawa's
- assume CPV, EW parameters, dipole operators are well constrained

\[ \rightarrow \ 13 \ EFT \ d.o.f.: \]

\[ \frac{\Gamma_{xy}}{\Gamma_{xy}^{SM}} \sim 1 \pm 2\bar{c}_{xy} + \ldots \]

\[ \delta c_Z, \ c_{ZZ}, \ c_{Z\Box}, \]

\[ \bar{c}_{\gamma\gamma}, \ \bar{c}_{Z\gamma}, \ \bar{c}_{gg}, \]

\[ \delta y_t, \ \delta y_c, \ \delta y_b, \ \delta y_{\tau}, \ \delta y_{\mu}, \]

\[ \lambda_Z, \delta\kappa\lambda \]
Up-sector SMEFT

Two-quark operators:

\[ \mathcal{L}_{\text{EFT}} = \sum_i \frac{C_i}{\Lambda^2} O_i \]

Scalar: \[ O_{u\varphi} \equiv \bar{q} u \varphi \varphi^\dag \varphi, \]
Vector: \[ O_{\varphi q}^1 \equiv \bar{q} \gamma^\mu q \varphi^\dag i\gamma^\mu \varphi \equiv O_{\varphi q}^+ + O_{\varphi q}^V - O_{\varphi q}^A, \]
\[ O_{\varphi q}^3 \equiv \bar{q} \gamma^\mu \tau^I q \varphi^\dag i\gamma^\mu \varphi \equiv O_{\varphi q}^+ - O_{\varphi q}^V + O_{\varphi q}^A \] (CC also)
\[ O_{\varphi u} \equiv \bar{u} \gamma^\mu u \varphi^\dag i\gamma^\mu \varphi \equiv O_{\varphi q}^V + O_{\varphi q}^A \] (CC only, \( m_b \) int.)
\[ O_{\varphi ud} \equiv \bar{u} \gamma^\mu d \varphi^\dag i\gamma^\mu \varphi, \]

Tensor: \[ O_{uB} \equiv \bar{q} \sigma^{\mu\nu} u \varphi g_Y B_{\mu\nu}, \]
\[ O_{uw} \equiv \bar{q} \sigma^{\mu\nu} \tau^I u \varphi g_W W_{\mu\nu}^{I}, \equiv O_{uA} - \tan \theta_W O_{uZ} \] (CC also)
\[ O_{d\bar{w}} \equiv \bar{q} \sigma^{\mu\nu} \tau^I d \varphi g_W W_{\mu\nu}^{I}, \]
\[ O_{ug} \equiv \bar{q} \sigma^{\mu\nu} T_A u \varphi g_s G_{\mu\nu}^{A}. \]

Two-quark–two-lepton operators:

Scalar: \[ O_{1 \text{equ}}^S \equiv \bar{1} e \varepsilon \bar{q} u, \]
\[ O_{1 \text{edq}} \equiv \bar{1} e \bar{d} q, \]
Vector: \[ O_{1q}^1 \equiv \bar{1} \gamma^\mu l \bar{q} \gamma^\mu q \equiv O_{lq}^+ + O_{lq}^V - O_{lq}^A, \]
\[ O_{1q}^3 \equiv \bar{1} \gamma^\mu \tau^I l \bar{q} \gamma^\mu \tau^I q \equiv O_{lq}^+ - O_{lq}^V + O_{lq}^A \] (CC also)
\[ O_{1u} \equiv \bar{1} \gamma^\mu l \bar{u} \gamma^\mu u \equiv O_{lq}^V + O_{lq}^A, \]
\[ O_{eq} \equiv \bar{e} \gamma^\mu e \bar{q} \gamma^\mu q \equiv O_{eq}^V - O_{eq}^A, \]
\[ O_{eu} \equiv \bar{e} \gamma^\mu e \bar{u} \gamma^\mu u \equiv O_{eq}^V + O_{eq}^A, \]

Tensor: \[ O_{1 \text{equ}}^T \equiv \bar{1} \sigma_{\mu\nu} e \varepsilon \bar{q} \sigma_{\mu\nu} u. \] (CC also, \( m_e \) int.)
Estimates used for HL-LHC top-quark measurement prospects, with theoretical uncertainties:

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<th>with th. unc.</th>
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