Probing top-quark couplings indirectly at future colliders

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Outline

- EFT in top quark physics
- Precision top EFT at future lepton colliders
    - Calculation setup
    - Prospects for circular lepton colliders

SMEFT basics

- BSM? → New Interactions of SM particles

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

- 59(3045) operators at dim-6: Buchmuller, Wyler Nucl.Phys. B268 (1986) 621-653

  Grzadkowski et al arXiv:1008.4884

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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		

EFT for top quark interactions

SMEFT vs Anomalous couplings

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$\mathcal{L}_{ttZ} = e\bar{u}(p_t)\left[\gamma^\mu\left(C^Z_{1,V}+\gamma_5 C^Z_{1,A}\right)+\frac{i\sigma^{\mu\nu}q_\nu}{m_Z}\left(C^Z_{2,V}+i\gamma_5 C^Z_{2,A}\right)\right]v(p_{\bar{t}})Z_\mu$$

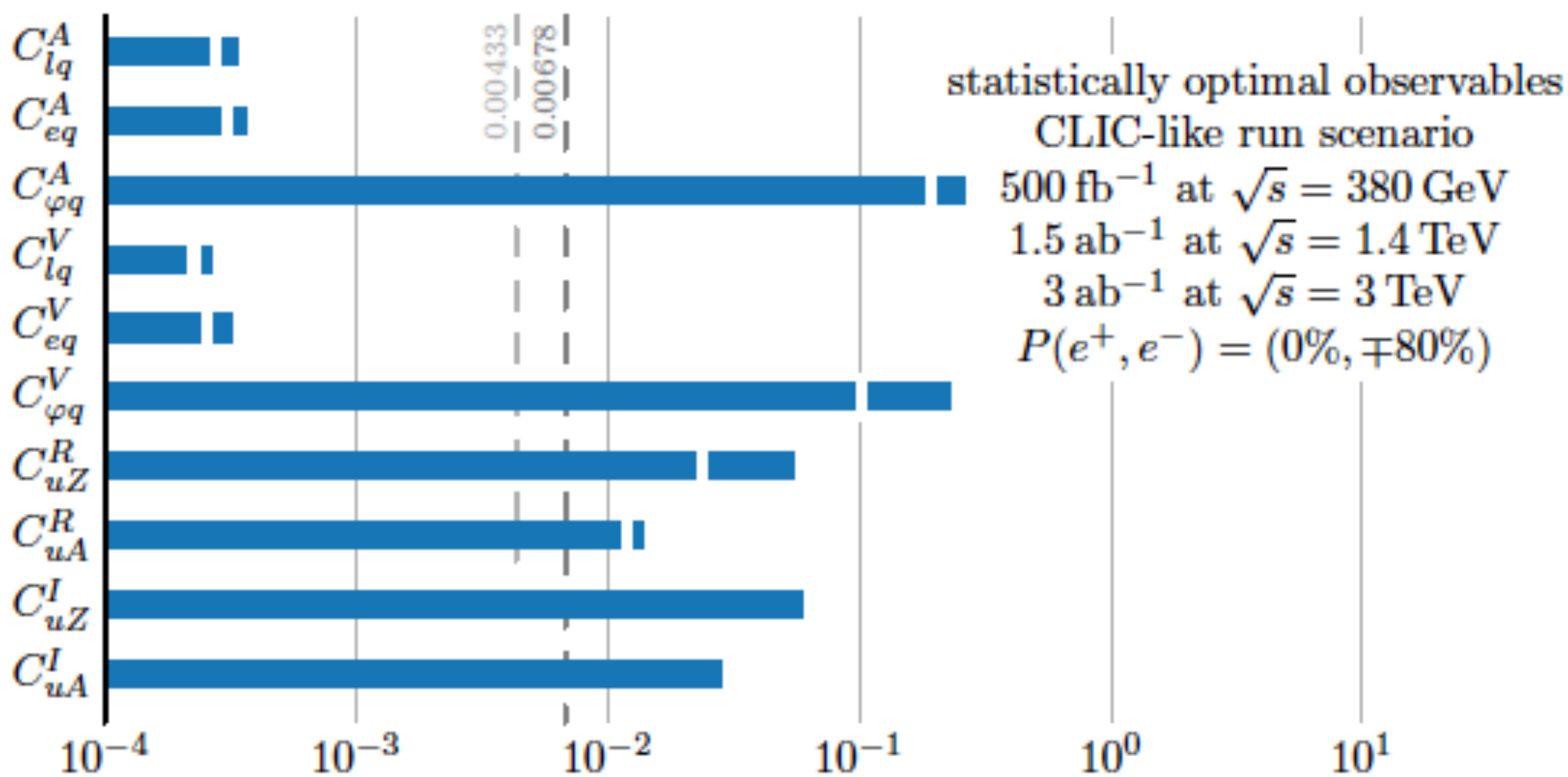
- SMEFT:
  - Gauge invariant ✔
  - Higher-order corrections: renormalisable order by order in 1/Λ ✔

$$\mathcal{O}(\alpha_s)+\mathcal{O}\left(\frac{1}{\Lambda^2}\right)+\mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right)+\cdots$$

  - Complete description-respecting SM symmetries ✔
  - Model Independent ✔

Top couplings at lepton colliders (1)

Above the top-pair or ttH threshold, top-gauge and top-Yukawa couplings can be probed by direct production of top pairs (+H)
e.g. CLIC



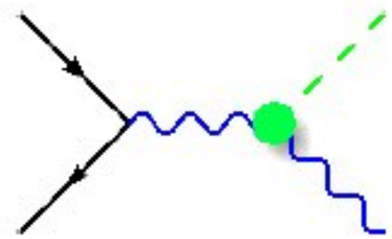
Durieux, Perello, Vos, Zhang arXiv:1807.02121

Top couplings at lepton colliders (2)

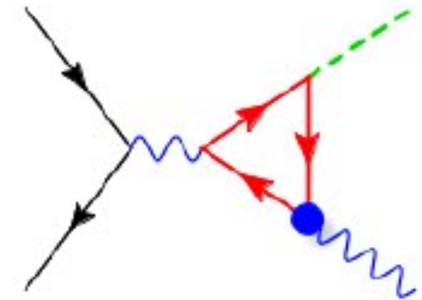
- What about colliders running below the direct production thresholds such as CEPC and FCC-ee?
- For future lepton colliders at energies below the top—anti-top (or ttH) threshold, can we determine the top-quark—gauge-boson/Higgs couplings with high precision?

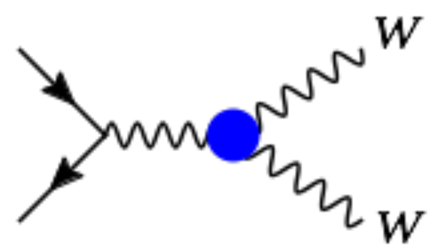
Going beyond direct probes

Are we measuring



or





or

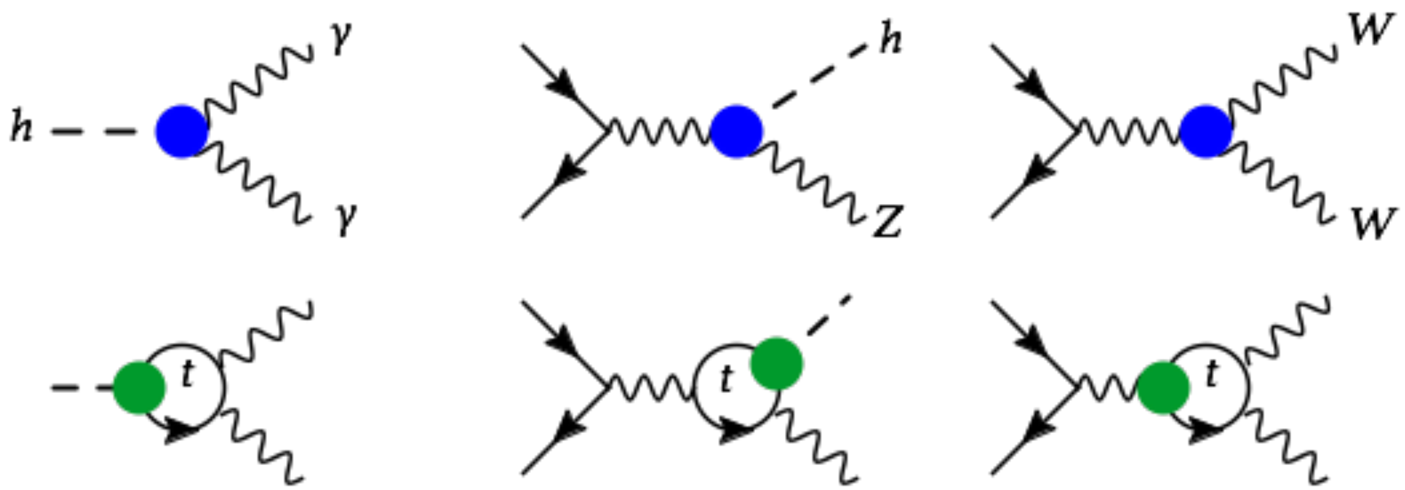
?

NLO EW in SMEFT may not be small:

$\mathcal{O}(\alpha_{EW}/\pi \cdot C_t/C_H)$ **instead of** $\mathcal{O}(\alpha_{EW}/\pi)$

Weak corrections can be important for unconstrained operators in particular in a precise lepton collider environment

Top-loops in Higgs and gauge boson production



Relevant top operators

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.$$ Top Yukawa

$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q), \qquad O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$

$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c., \qquad O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$

} Vector-like

$$O^{(+)}_{\varphi Q} \equiv \frac{1}{2}\left(O^{(1)}_{\varphi Q} + O^{(3)}_{\varphi Q}\right) \qquad O^{(-)}_{\varphi Q} \equiv \frac{1}{2}\left(O^{(1)}_{\varphi Q} - O^{(3)}_{\varphi Q}\right)$$

redefined for ttZ and bbZ

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

$$O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$

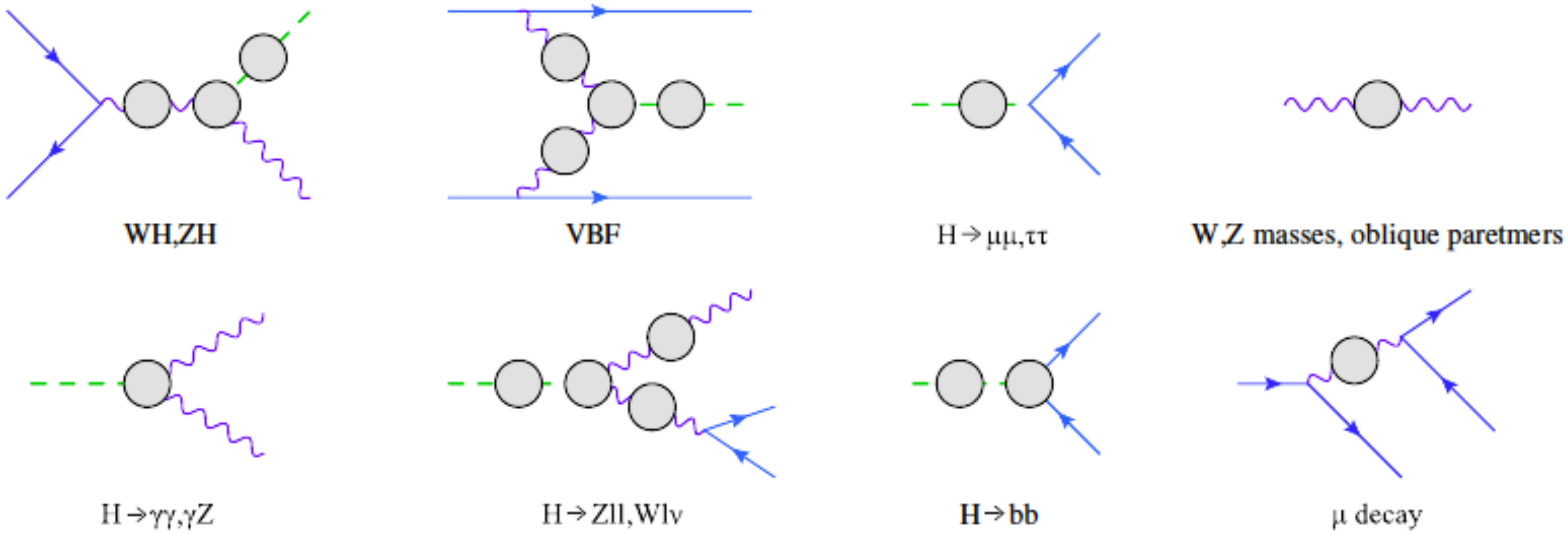
} Weak Dipoles

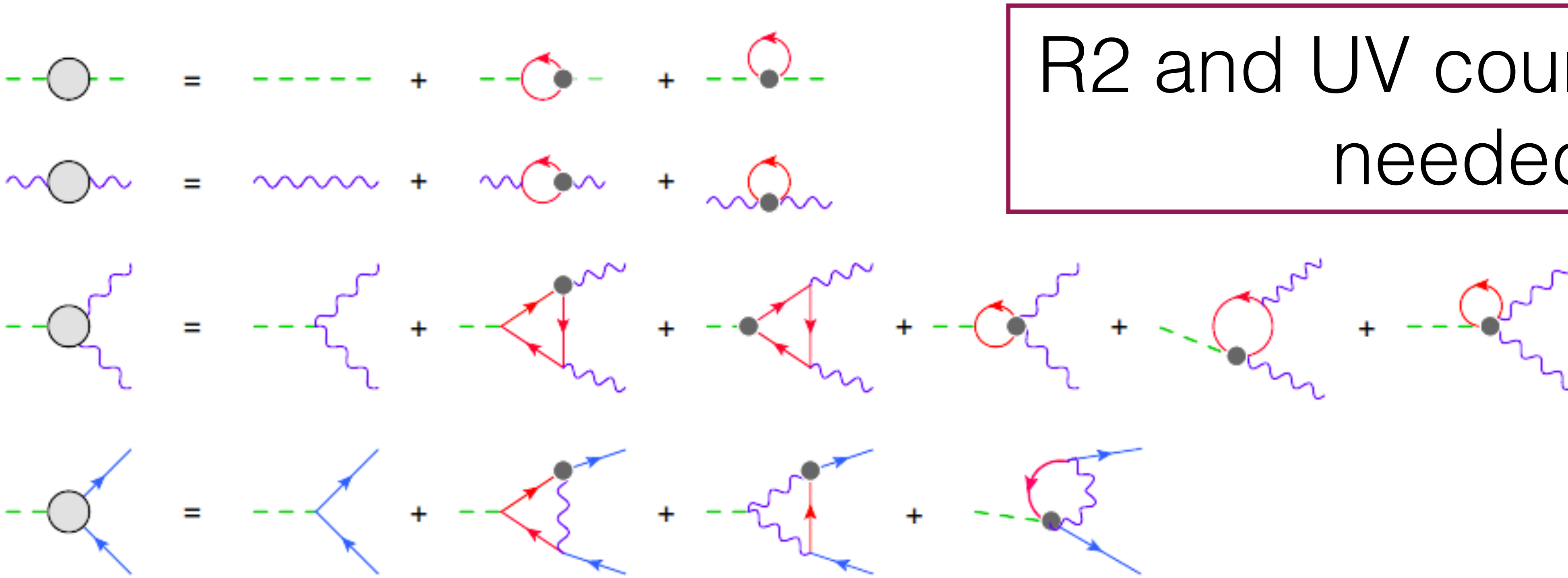
Why should we compute EW top loops?

- Does the uncertainty on top-quark couplings affect the reach of precise measurements of Higgs couplings at the HL-LHC and future colliders?
- Can we extract meaningful constraints using one-loop contributions?
- For future lepton colliders at energies below the direct production threshold, can we determine the top-quark couplings with high precision?

The calculation

Higgs production and decay





R2 and UV counterterms needed

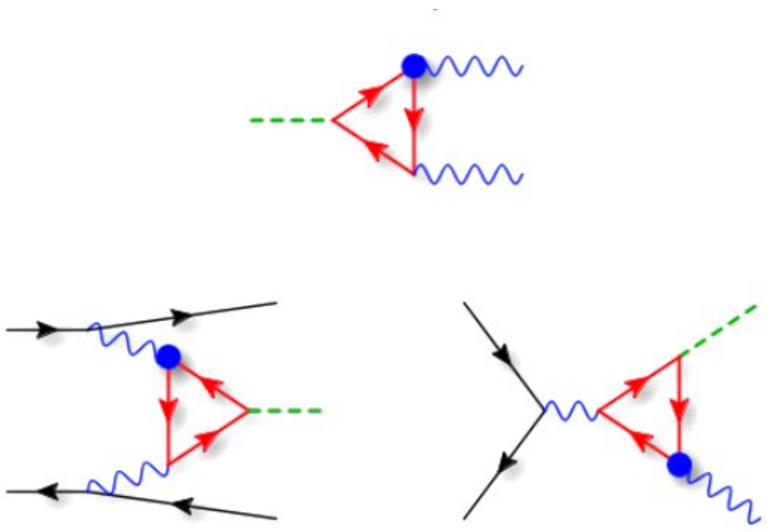
Automated within MG5_aMC@NLO: First step towards EFT@NLO EW (using event reweighting)

Renormalisation

- Dim-6 coefficients: MSbar renormalisation, except for $C_{\phi WB}$ and $C_{\phi D}$, which enter precision EW measurements.
- SM is renormalised in the MW, MZ and GF scheme.
- "Perfect precision EW measurements" would imply $C_{\phi WB} = C_{\phi D} = 0$ in a tree-level analysis.

- At one-loop level, top-quark operators will contribute to precision EW tests.
  - Use Z- and W-pole data to perform a global fit, which involves also all top operators at one loop.
  - The two tightest constraints are on two linear combinations of $C_{\phi WB}$, $C_{\phi D}$ and top-operator coefficients.
  - We adjust the counter-terms so that the top-operator couplings drop out from these combinations.
  - In this specific scheme, "perfect precision measurements" corresponds to exactly $C_{\phi WB} = C_{\phi D} = 0$.
  - One indirect constraint remains and can be combined to our global fit.

Impact of loops at the LHC



+

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\,(\varphi^\dagger\varphi) + h.c.,$$
$$O^{(3)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\gamma^\mu\tau^I Q),$$
$$O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.,$$
$$O_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu} + h.c.,$$
$$O_{\varphi t} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{t}\gamma^\mu t),$$
$$O^{(1)}_{\varphi Q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q),$$
$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c.,$$

+

Current direct constraints

Operator	Top Fitter	RHCC	$\sigma_{t\bar{t}H}$ [28]
$C_{\varphi tb}$		[-5.28,5.28]	
$C^{(3)}_{\varphi Q}$	[-2.59,1.50]		
$C^{(1)}_{\varphi Q}$	[-3.10,3.10]		
$C_{\varphi t}$	[-9.78,8.18]		
C_{tW}	[-2.49,2.49]		
C_{tB}	[-7.09,4.68]		
$C_{t\varphi}$			[-6.5,1.3]

Poor knowledge of top couplings leads to uncertainties on Higgs measurements at the LHC:

	$\gamma\gamma$	γZ	bb	WW*	ZZ*	$\tau\tau$	$\mu\mu$
gg	(-100%,1980%)	(-88%,200%)	(-40%,48%)	(-40%,47%)	(-40%,46%)	(-40%,48%)	(-40%,48%)
VBF	(-100%,1880%)	(-88%,170%)	(-6.1%,5.3%)	(-6.8%,6.7%)	(-8.8%,9.2%)	(-6.2%,5.9%)	(-6.2%,5.9%)
WH	(-100%,1880%)	(-88%,170%)	(-5.5%,4.2%)	(-6.1%,5.6%)	(-7.8%,7.9%)	(-5.8%,5.1%)	(-5.8%,5.1%)
ZH	(-100%,1880%)	(-87%,170%)	(-6.5%,5.9%)	(-7.1%,7.1%)	(-9.4%,9.9%)	(-6.8%,6.7%)	(-6.8%,6.7%)

loop-induced

tree-level

EV, Zhang arXiv:1804.09766

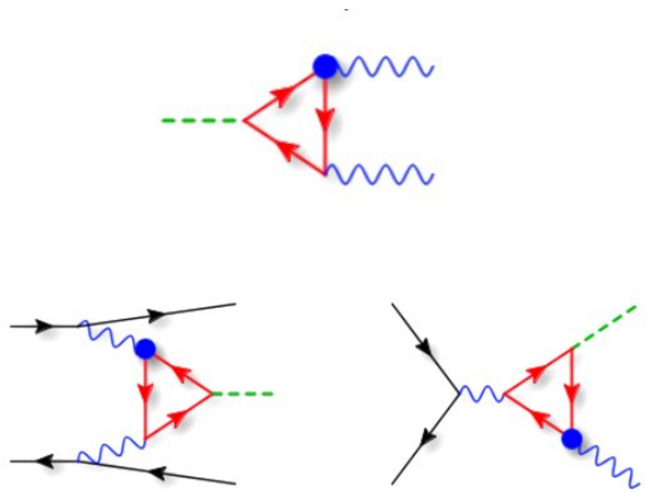
Indirect constraints at lepton colliders

At future colliders with runs below the ttbar threshold such as the CEPC, indirect (one-loop) constraints are the only source of info for top couplings

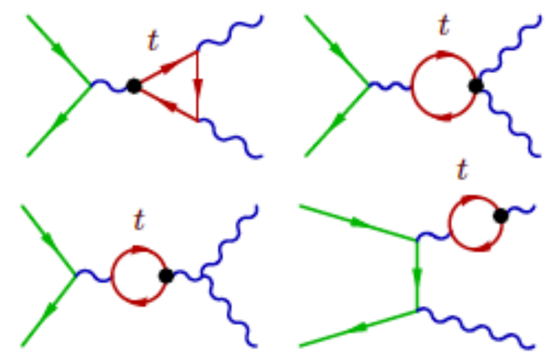
We consider:
Scenario 1: CEPC (240 GeV 5 ab^{-1})
Scenario 2: FCC-ee (350 GeV 0.2 ab^{-1} and 365 GeV 1.5 ab^{-1})

Future Lepton Colliders

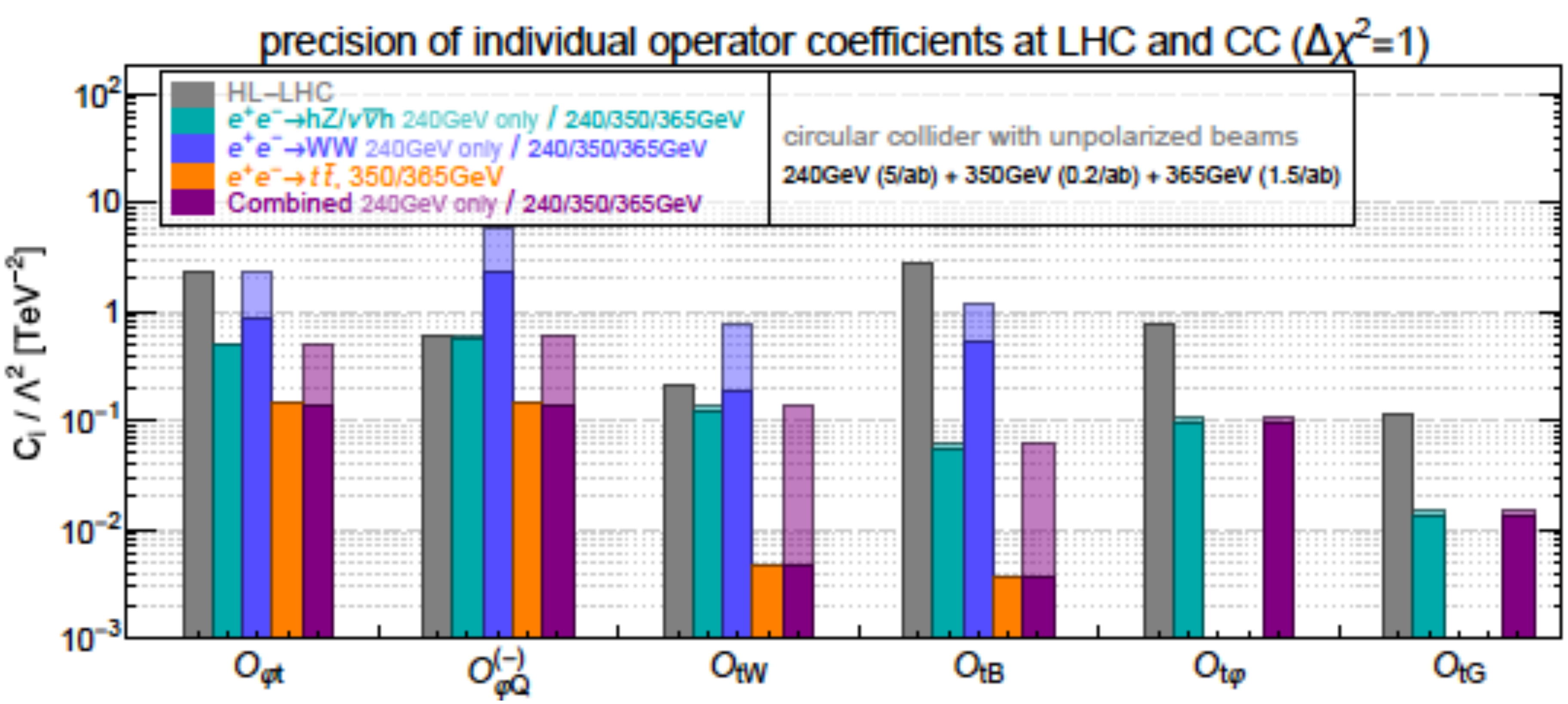
Future Circular Electron Positron Collider processes:



Higgs production and decay



WW production



Durieux, Gu, EV, Zhang arXiv:1809.03520

Individual bounds

Predictions:

- Higgs: ZH, WW fusion, all decay channels.
- Diboson Angular distributions
- Precision EW observables
- Top pair projections from Durieux, Perello, Vos, Zhang arXiv: 1807.02121

Global top-Higgs fit

12 SILH-like operators

$$O_{\varphi W} = \varphi^\dagger \varphi W^I_{\mu\nu} W^{I\mu\nu}, \qquad O_{\varphi B} = \varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu},$$
$$O_{\varphi\Box} = (\varphi^\dagger \varphi) \Box (\varphi^\dagger \varphi), \qquad O_W = i D^\mu \varphi^\dagger \tau^I D^\nu \varphi W^I_{\mu\nu},$$
$$O_B = i D^\mu \varphi^\dagger D^\nu \varphi B_{\mu\nu}, \qquad O_{b\varphi} = (\varphi^\dagger \varphi) \bar{Q} b \varphi + h.c.,$$
$$O_{\mu\varphi} = (\varphi^\dagger \varphi) \bar{l}_2 e_2 \varphi + h.c., \qquad O_{\tau\varphi} = (\varphi^\dagger \varphi) \bar{l}_3 e_3 \varphi + h.c.,$$
$$O_{t\varphi} = (\varphi^\dagger \varphi) \bar{Q} t \tilde{\varphi} + h.c., \qquad O_{c\varphi} = (\varphi^\dagger \varphi) \bar{q}_2 u_2 \tilde{\varphi} + h.c.,$$
$$O_{WWW} = \epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho, \qquad O_{\varphi G} = \varphi^\dagger \varphi G_{\mu\nu} G^{\mu\nu},$$

Fixed by EWPO

$$O_{\varphi WB} = \varphi^\dagger \tau^I \varphi W^I_{\mu\nu} B^{\mu\nu}, \qquad O_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$$

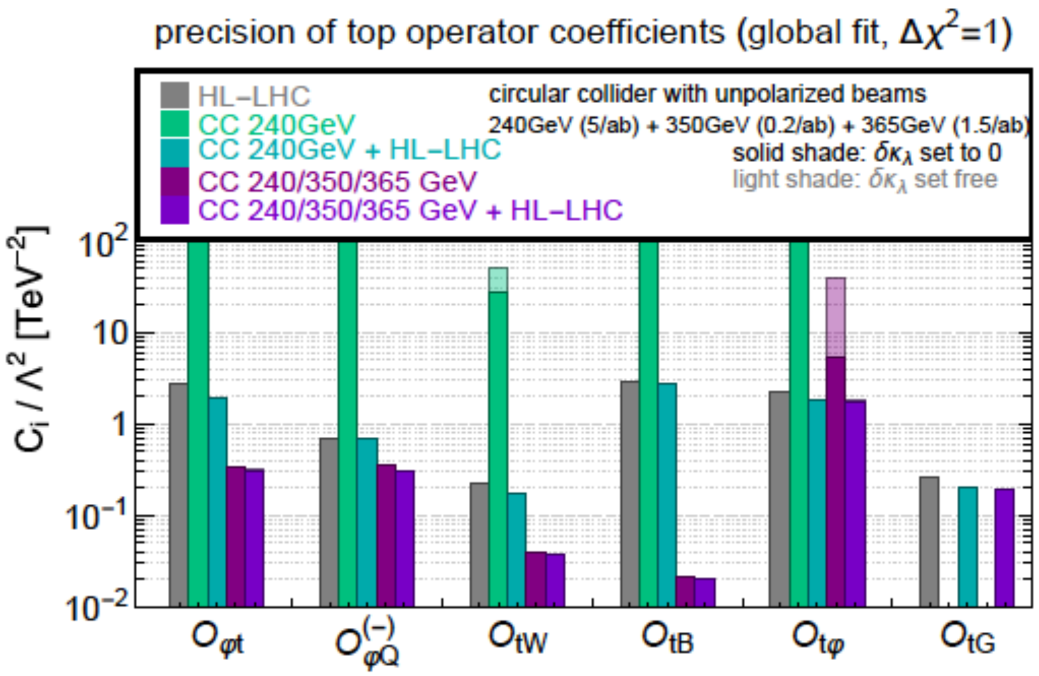
Triple Higgs coupling:

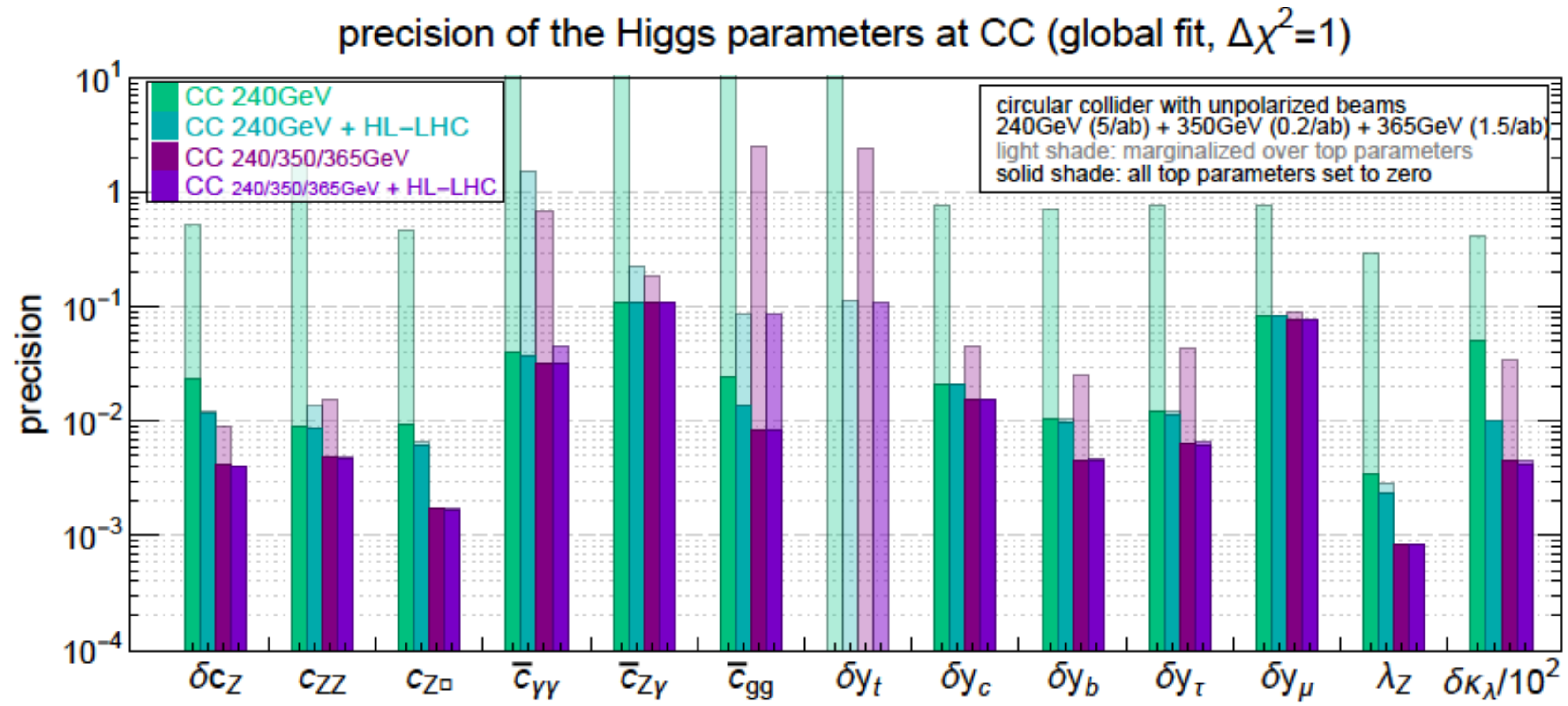
$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}, \qquad \lambda_3^{\rm SM} = \frac{m_h^2}{2v^2}$$

As in Durieux, Grojean, Gu, Wang arXiv:1704.02333

Weak loops in the EFT: Future colliders

Circular Electron Positron Collider, FCC-ee & HL-LHC: Top + Higgs Global Fit

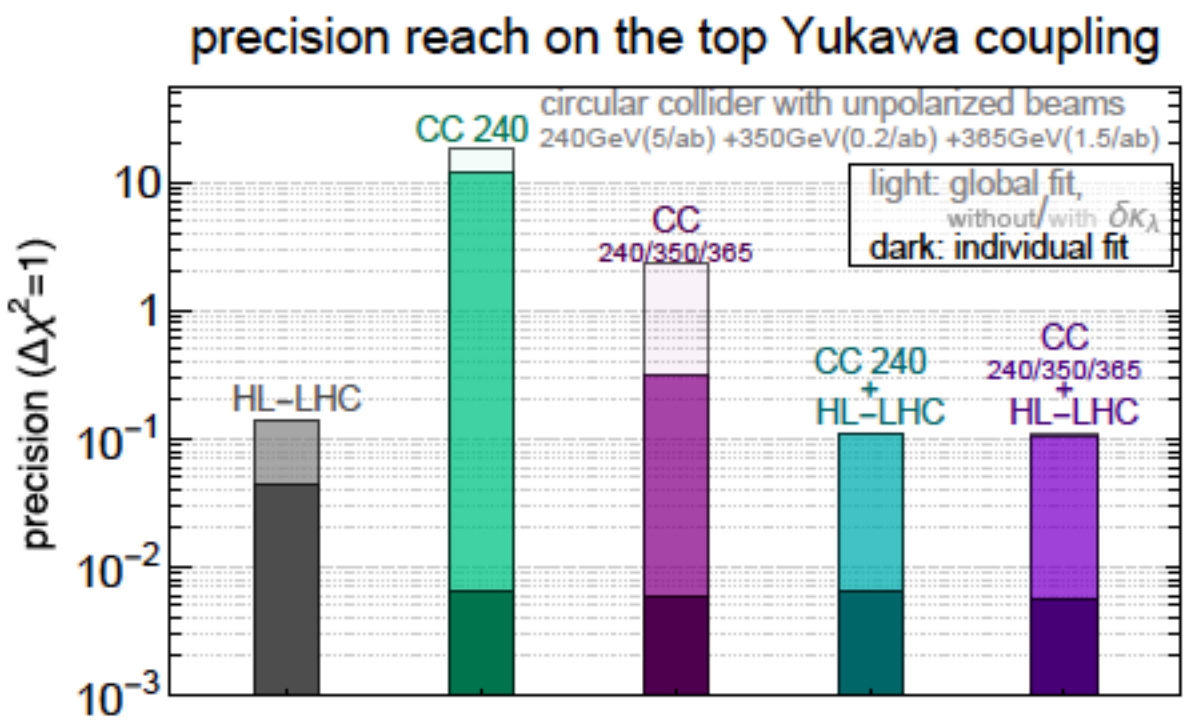




Important impact of unknown top-couplings on Higgs couplings at CEPC and FCC-ee.
The inclusion of top-couplings reduces the reach on most Higgs couplings by more than one order of magnitude.
This effect needs to be solved by runs above the top—anti-top threshold (FCC-ee) and combination with the HL-LHC.

Durieux, Gu, EV, Zhang arXiv:1809.03520

Yukawa coupling



- Large difference between individual and marginalised limit for indirect-only constraints
- Runs above the top—anti-top threshold will fix the top-gauge couplings: 32% precision can be reached on the Yukawa coupling from runs below the ttH threshold (FCC-ee)

Durieux, Gu, EV, Zhang arXiv:1809.03520

Outlook

- SMEFT is a consistent way to look for new interactions
- Higher-order corrections needed to match SM precision and experimental accuracy
- First steps towards electroweak corrections in the EFT
- Weak loops can be crucial for HL-LHC and future lepton colliders, progress towards computing them
- Results allow to indirectly probe top-couplings at e+e- colliders below the tt threshold at CEPC and ttH threshold at FCC-ee
- To precisely probe top and Higgs couplings a combination of the HL-LHC and e+e- runs above the threshold is needed

Thank you for your attention