# Probing the SMEFT quantum structure at future lepton colliders

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S. Di Vita, GD, C. Grojean, Z. Liu, G. Panico, M. Riembau, T. Vantalon, 1711.03978
GD, J. Gu, E. Vryonidou, C. Zhang, 1809.03520

with inputs from
GD, C.Grojean, J.Gu, K.Wang, 1704.02333
E. Vryonidou, C. Zhang, 1804.09766
GD, Martín Perelló, Marcel Vos, Cen Zhang, 1807.02121

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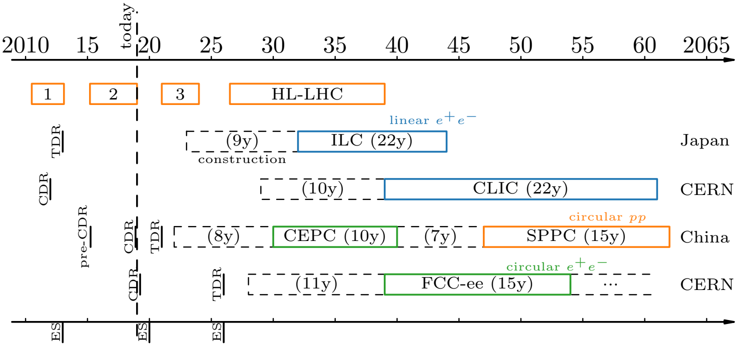
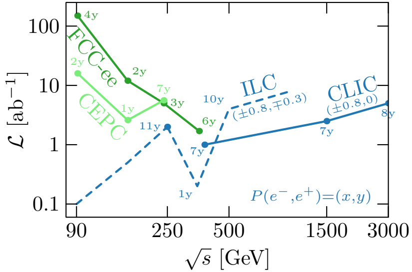
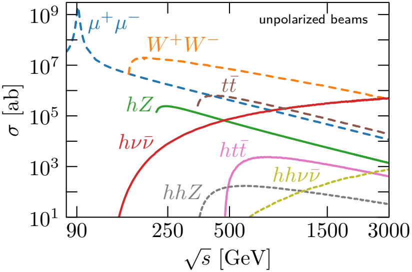
# Future lepton colliders

¡Timeline and run plans
subject to frequent updates!



High luminosities at the peak of $\sigma(e^+e^- \to hZ)$ and below will dramatically improve our knowledge of the Higgs and electroweak sectors.

...but...

Determining the trilinear Higgs self-coupling —constrained to order 100% at the HL-LHC— through Higgs pair production requires higher energies.

Much of the top electroweak sector will remain loosely constrained after the HL-LHC (order 10%) and $t\bar{t}, t\bar{t}h$ production also require higher energies.

...any improvement in the next 15-20 years?

High luminosities at the peak of $\sigma(e^+e^- \to hZ)$ and below will dramatically improve our knowledge of the Higgs and electroweak sectors.

For the Higgs trilinear and top EW couplings,

Q1. Could loop sensitivities and precision measurements at lower energies be exploited?

Q2. Could loosely constrained loop contributions *contaminate* precision measurements?

in a robust global SMEFT approach.

Much of the top electroweak sector will remain loosely constrained after the HL-LHC (order 10%) and $t\bar{t}$, $t\bar{t}h$ production also require higher energies.

...any improvement in the next 15-20 years?

# Probing the SMEFT quantum structure at future lepton colliders

- Tree-level Higgs and diboson
- Higgs trilinear loops
- Top electroweak loops

# Global Higgs and diboson tree-level SMEFT analysis

systematically parametrizes the theory space *above* the SM!

# Baseline setup

[GD, Grojean, Gu, Wang, '17]

- Higgs basis of dim-6 operators
- Higgs and diboson processes:

$$e^+e^- \to \quad hZ,\ W^+W^- \qquad \text{(incl. angular distributions)}$$
$$h\nu\bar{\nu},\ ht\bar{t},\ hhZ,\ hh\nu\bar{\nu}$$
$$h \to ZZ^*,\ WW^*,\ \gamma\gamma,\ \gamma Z,\ gg,\ b\bar{b},\ c\bar{c},\ \tau^+\tau^-,\ \mu^+\mu^-$$

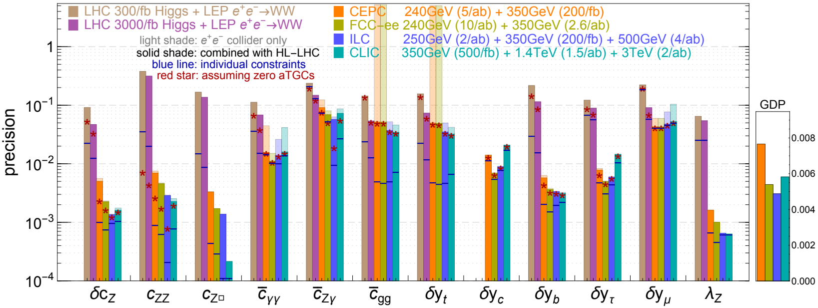
- flavour universality, relaxed to distinguish Yukawa's
- no CPV, EW parameters, dipole operators

$\longrightarrow$ 12 EFT d.o.f.: $\Gamma_{xy}/\Gamma_{xy}^{\text{SM}} \sim 1 \pm 2\bar{c}_{xy} + \ldots$

$$\delta c_Z\,,\quad c_{ZZ}\,,\quad c_{Z\Box}\,,$$
$$\bar{c}_{\gamma\gamma}\,,\quad \bar{c}_{Z\gamma}\,,\quad \bar{c}_{gg}\,,$$
$$\delta y_t\,,\quad \delta y_c\,,\quad \delta y_b\,,\quad \delta y_\tau\,,\quad \delta y_\mu\,,$$
$$\lambda_Z$$

# Global Higgs and diboson constraints

[GD, Grojean, Gu, Wang, '17]



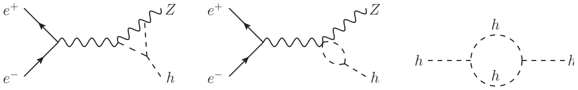

- importance of complementary measurements
  (different c.o.m. energies, polarizations, distributions)
- importance of diboson measurement precision
  (not studied much by exp. collaborations)
- order of magnitude improvement wrt LHC, and $\delta y_c$ constraint
  (especially on $\delta c_Z$, $\delta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

# Higgs trilinear loops

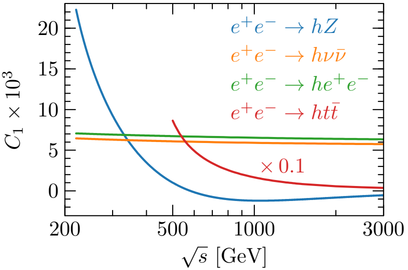
# Higgs trilinear (aka $\delta\kappa_\lambda$) loops

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

[McCullough '13]
[Gorbahn, Haisch '16]
[Degrassi et al. '16]
[Bizon et al. '16]
[Degrassi et al. '17]
[Kribs et al. '17]
[Maltoni et al. '17]
[Di Vita et al. '17]




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

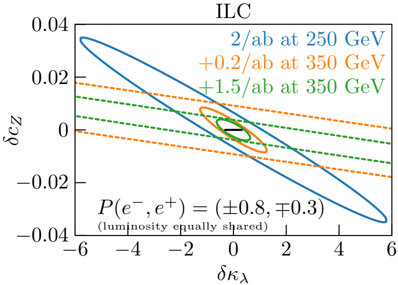


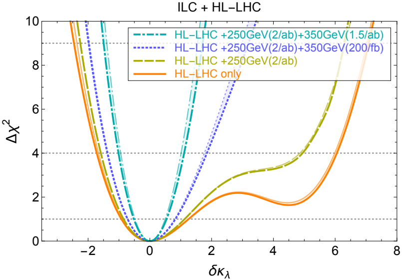

$\to$ few permil $hZ$ measurement naively implies a few 10% constraint

# Q1: Global trilinear loop sensitivity (at the ILC)

[Di Vita et al. '17]

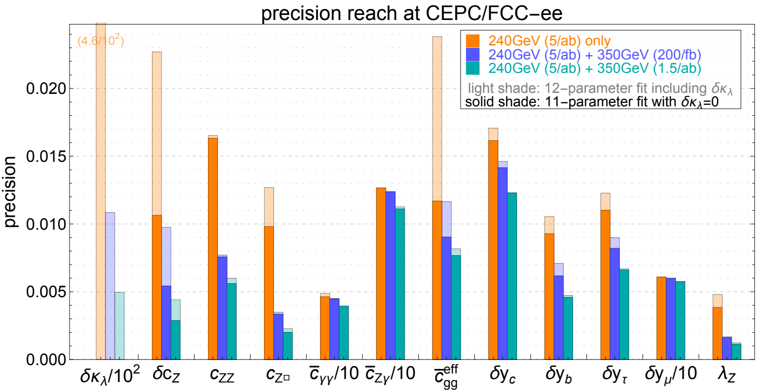
- individual $\Delta\chi^2$=1 limit (30%) much tighter than global ones (580, 130, 60%)
- 350 GeV run necessary to lift approximate degeneracies, without LHC




- 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%)

# Q2: Trilinear loop contamination (at the CEPC/FCC-ee)




- Two centre-of-mass energies are required to controle $\delta\kappa_\lambda$ uncertainties

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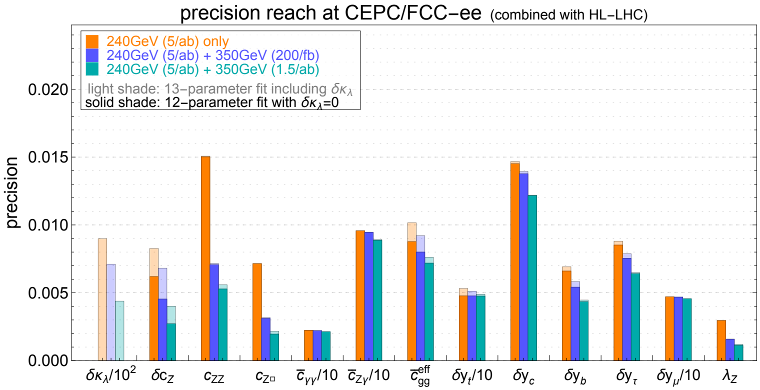
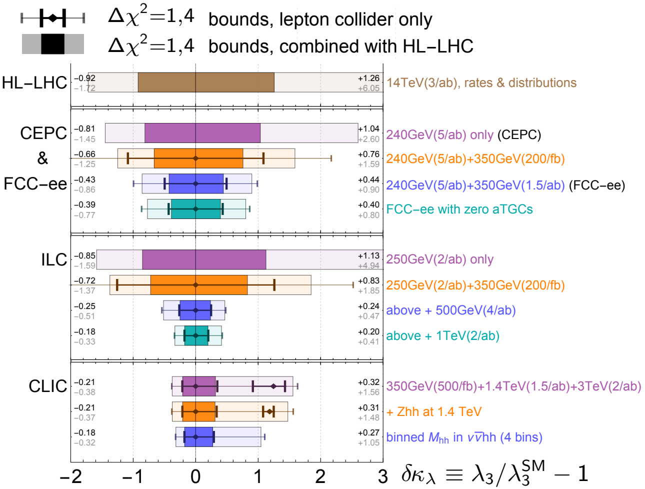



- Two centre-of-mass energies are required to controle $\delta\kappa_\lambda$ uncertainties or HL-LHC data.

# Compared to direct determinations




- robust indirect constraints at low energy require a global analysis

  $\sim$ 40% with 1.5 ab$^{-1}$ at 350 GeV

- best direct high-energy determinations

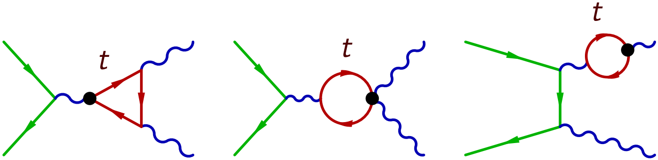
  $\sim$ 20% precision with 500 GeV + 1 TeV runs

# Top electroweak loops

# Top electroweak loops

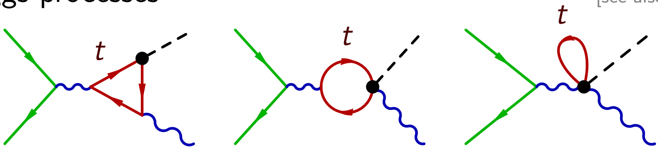
- At the $Z$ pole [Zhang, Greiner, Willenbrock '12]

- In diboson production [GD, Gu, Vrionidou, Zhang '18]




differential in the production angle

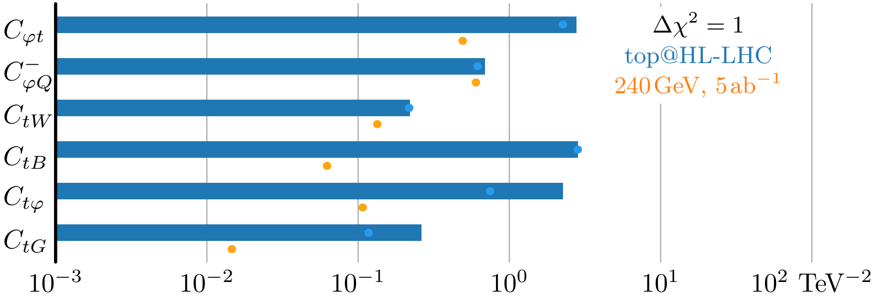
- In Higgs processes [Vrionidou, Zhang, '18] [see also Boselli et al '18]




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

(excluding four-fermion operators, no top loop included in $e^+e^- \to t\bar{t}$)

# Q1: Improvement on top operators (at the CEPC/FCC-ee)




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)

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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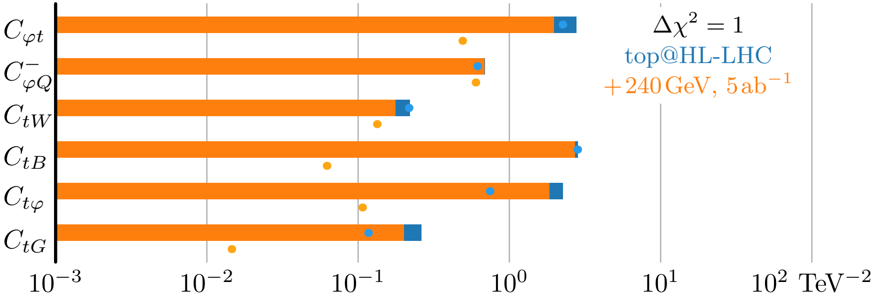


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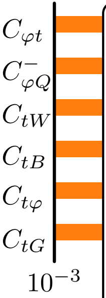
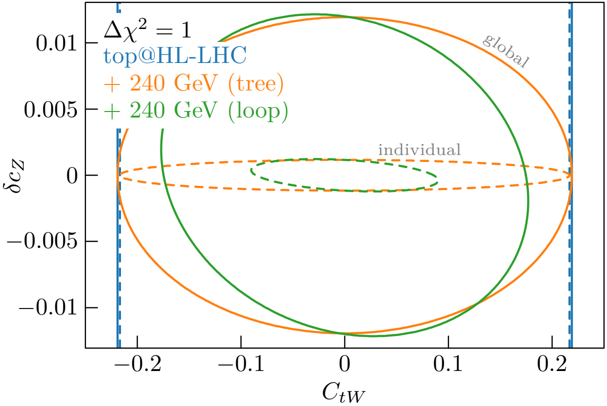



On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:




- extra parameter space covered thanks to loop sensitivity
- room for improvement between glo. and ind. constraints

$\mathrm{TeV}^{-2}$

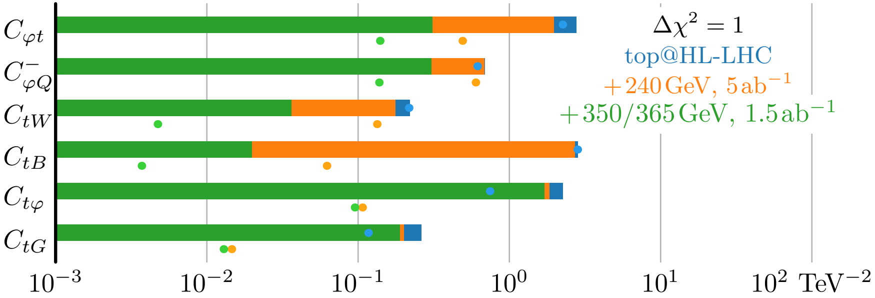
Individu

- com
- dom

Global c

- large
- still
- more differential distributions would help further

# Q1: Improvement on top operators (at the CEPC/FCC-ee)




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 $e^+e^- \to t\bar{t}$ would improve its impact on $C_{t\varphi}$ and $C_{tG}$

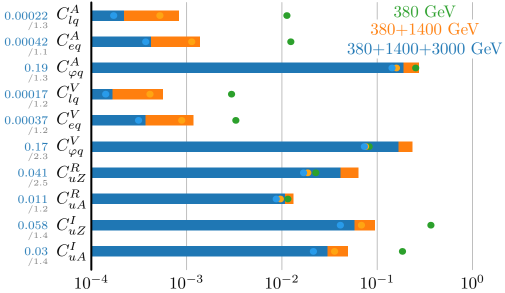
Global constraints (bars) (12 Higgs + 6 top op. floated)

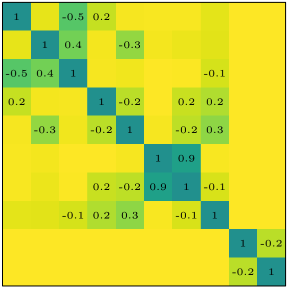
- large flat directions with 240 GeV run alone (not shown)
- still improves the HL-LHC combination
- more differential distributions would help further

# Direct determination (at CLIC)

[GD, Perello, Vos, Zhang '18]

from a global EFT analysis of $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$
using so-called *statistically optimal observables*
including simultaneously all linear top EFT contributions



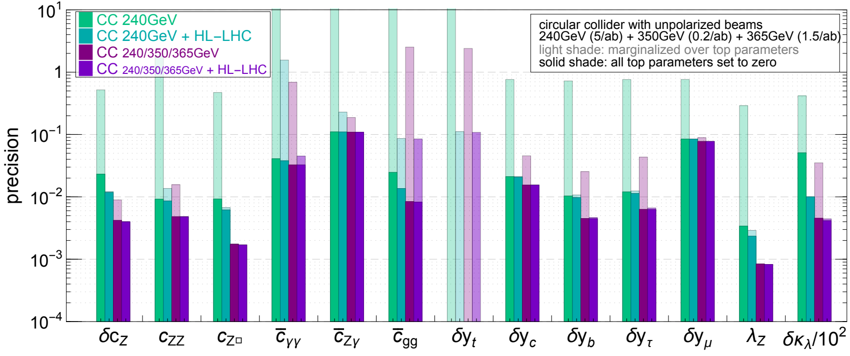



correlation matrix

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

# Q2: Contamination in Higgs operators

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\to 0$




Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large $y_t$ contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

# Summary

# Probing the SMEFT quantum structure at future lepton colliders

Precision measurements of Higgs processes at future lepton colliders will probe the quantum structure of the SM(EFT).

Indirect sensitivities and contaminations from loosely constrained couplings constitute opportunities and challenges.

trilinear

Q1. Runs at 240 and 350 GeV are necessary for an indirect determination of the trilinear Higgs self coupling.

Q2. A 240 GeV run needs to be combined with HL-LHC data to mitigate contaminations in single Higgs couplings.

top EW

Q1. Differential information will play a crucial role to indirectly constrain top electroweak couplings.

Q2. So far, $e^+e^- \to t\bar{t}$ measurements look indispensable to avoid large contaminations to single Higgs couplings.

# Backup

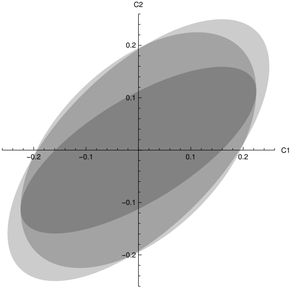
# Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space

(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small $C_i$, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the stat. opt. obs. are the average values of $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.




e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

# Up-sector SMEFT

[Grzadkowski et al '10]

Two-quark operators:

$$\mathcal{L}_{\rm EFT} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

| | | | | |
|---|---|---|---|---|
| Scalar: | $O_{u\varphi} \equiv \bar{q}u\,\tilde{\varphi}\;\;\varphi^\dagger\varphi,$ | | | |
| Vector: | $O^1_{\varphi q} \equiv \bar{q}\gamma^\mu q\;\;\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi$ | $\equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q},$ | |
| | $O^3_{\varphi q} \equiv \bar{q}\gamma^\mu\tau^I q\;\;\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi$ | $\equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q}$ | (CC also) |
| | $O_{\varphi u} \equiv \bar{u}\gamma^\mu u\;\;\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi$ | $\equiv O^V_{\varphi q} + O^A_{\varphi q}$ | |
| | $O_{\varphi ud} \equiv \bar{u}\gamma^\mu d\;\;\tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu\varphi,$ | | (CC only, $m_b$ int.) |
| Tensor: | $O_{uB} \equiv \bar{q}\sigma^{\mu\nu}u\,\tilde{\varphi}\,g_Y B_{\mu\nu},$ | $\equiv O_{uA} - \tan\theta_W O_{uZ}$ | |
| | $O_{uW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I u\,\tilde{\varphi}\,g_W W^I_{\mu\nu},$ | $\equiv O_{uA} + \mathrm{cotan}\,\theta_W O_{uZ}$ | (CC also) |
| | $O_{dW} \equiv \bar{q}\sigma^{\mu\nu}\tau^I d\,\tilde{\varphi}\,g_W W^I_{\mu\nu},$ | | (CC only, $m_b$ int.) |
| | $O_{uG} \equiv \bar{q}\sigma^{\mu\nu}T^A u\,\tilde{\varphi}\,g_s G^A_{\mu\nu}.$ | | (NLO only) |

Two-quark–two-lepton operators:

| | | | |
|---|---|---|---|
| Scalar: | $O^S_{lequ} \equiv \bar{l}e\;\;\varepsilon\;\;\bar{q}u,$ | | (CC also, $m_e$ int.) |
| | $O_{ledq} \equiv \bar{l}e\;\;\bar{d}q,$ | | (CC only, $m_e$ int.) |
| Vector: | $O^1_{lq} \equiv \bar{l}\gamma_\mu l\;\;\bar{q}\gamma^\mu q$ | $\equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$ | |
| | $O^3_{lq} \equiv \bar{l}\gamma_\mu\tau^I l\;\;\bar{q}\gamma^\mu\tau^I q$ | $\equiv O^+_{lq} - O^V_{lq} + O^A_{lq},$ | (CC also) |
| | $O_{lu} \equiv \bar{l}\gamma_\mu l\;\;\bar{u}\gamma^\mu u$ | $\equiv O^V_{lq} + O^A_{lq},$ | |
| | $O_{eq} \equiv \bar{e}\gamma^\mu e\;\;\bar{q}\gamma_\mu q$ | $\equiv O^V_{eq} - O^A_{eq},$ | |
| | $O_{eu} \equiv \bar{e}\gamma_\mu e\;\;\bar{u}\gamma^\mu u$ | $\equiv O^V_{eq} + O^A_{eq},$ | |
| Tensor: | $O^T_{lequ} \equiv \bar{l}\sigma_{\mu\nu}e\;\;\varepsilon\;\;\bar{q}\sigma^{\mu\nu}u.$ | | (CC also, $m_e$ int.) |

# Top@HL-LHC

Estimates used for HL-LHC top-quark measurement prospects, with theoretical uncertainties:

| Channels | Uncertainties | |
|---|---|---|
| | without th. unc. | with th. unc. |
| $t\bar{t}$ | 4% [1] | 7% |
| Single top ($t$-ch.) | 4% [2] | 4% |
| $W$-helicity ($F_0$) | 3% [3] | 3% |
| $W$-helicity ($F_L$) | 5% [3] | 5% |
| $t\bar{t}Z$ | 10% | 15% |
| $t\bar{t}\gamma$ | 10% | 17% |
| $t\bar{t}h$ | 10% | 16% [4] |
| $gg \to h$ | 4% | 11% [4] |


[1] A. M. Sirunyan *et al.* (CMS), JHEP **09** (2017) 051, arXiv:1701.06228 [hep-ex].

[2] B. Schoenrock, E. Drueke, B. Alvarez Gonzalez, and R. Schwienhorst, in *Proceedings, 2013 Community Summer Study on the Future of U.S. Particle Physics: Snowmass on the Mississippi (CSS2013): Minneapolis, MN, USA, July 29-August 6, 2013*, arXiv:1308.6307 [hep-ex].

[3] M. Aaboud *et al.* (ATLAS), Eur. Phys. J. **C77** (2017) 264, arXiv:1612.02577 [hep-ex].

[4] ATLAS Collaboration, ATL-PHYS-PUB-2014-016 (2014).