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

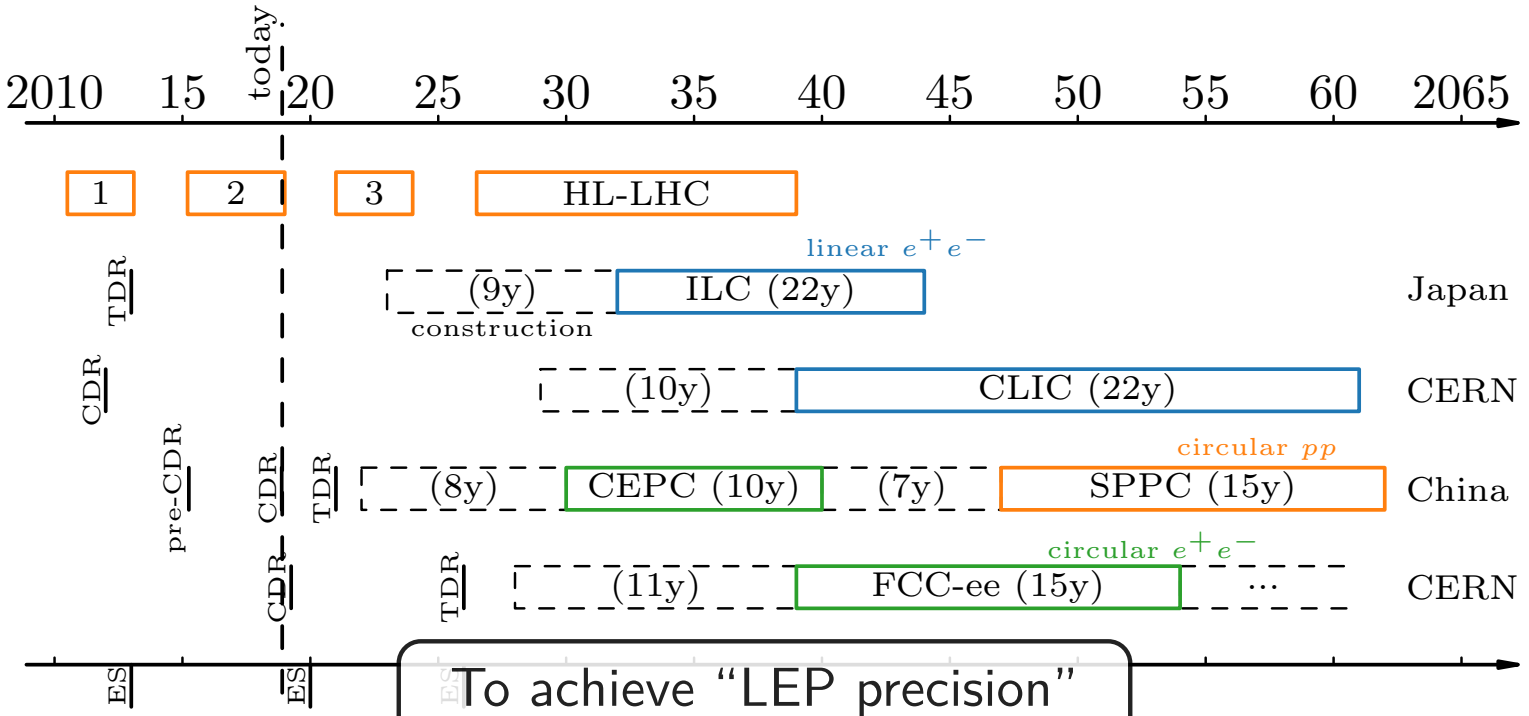
Gauthier Durieux
(Technion)

GD, Jiayin Gu, Eleni Vryonidou, Cen Zhang
[1809.03520]

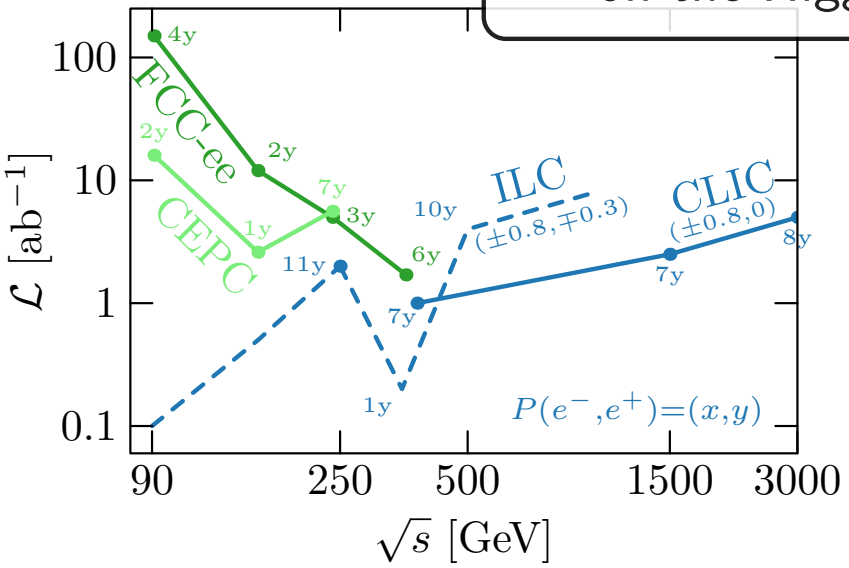
Tokyo, 29 November 2018
Higgs Couplings Workshop

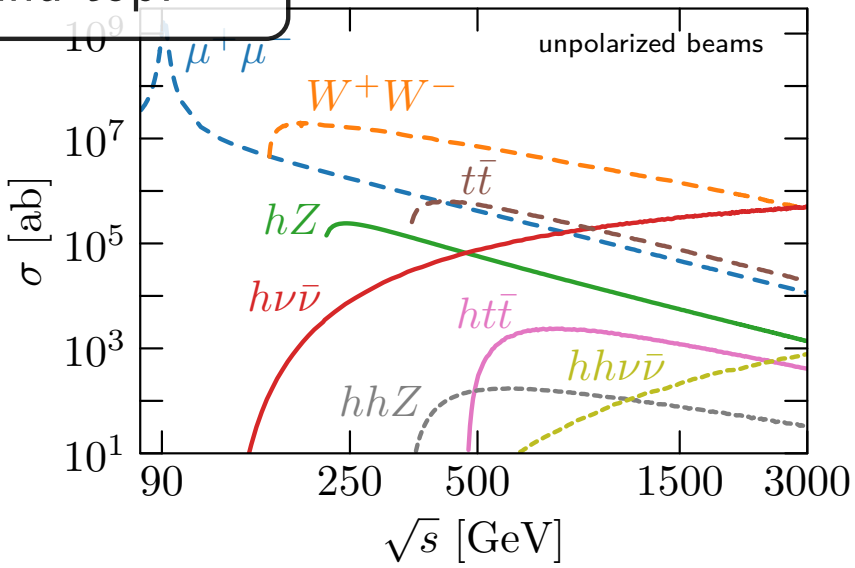
Future lepton colliders

¡Timeline and run plans are indicative only!



To achieve "LEP precision" on the Higgs and top!





Observations

- Getting to $e^+e^- \to t\,\bar{t}$ energies may take many years.
- Individual HL-LHC sensitivities to top interactions are $\mathcal{O}(10\%)$ only. [1σ, $\bar{t}\not{Z}t$]
- Higgs and di-boson are measured to $\mathcal{O}(0.1\%)$ at $\sqrt{s} \simeq 240\,\text{GeV}$.
- 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?

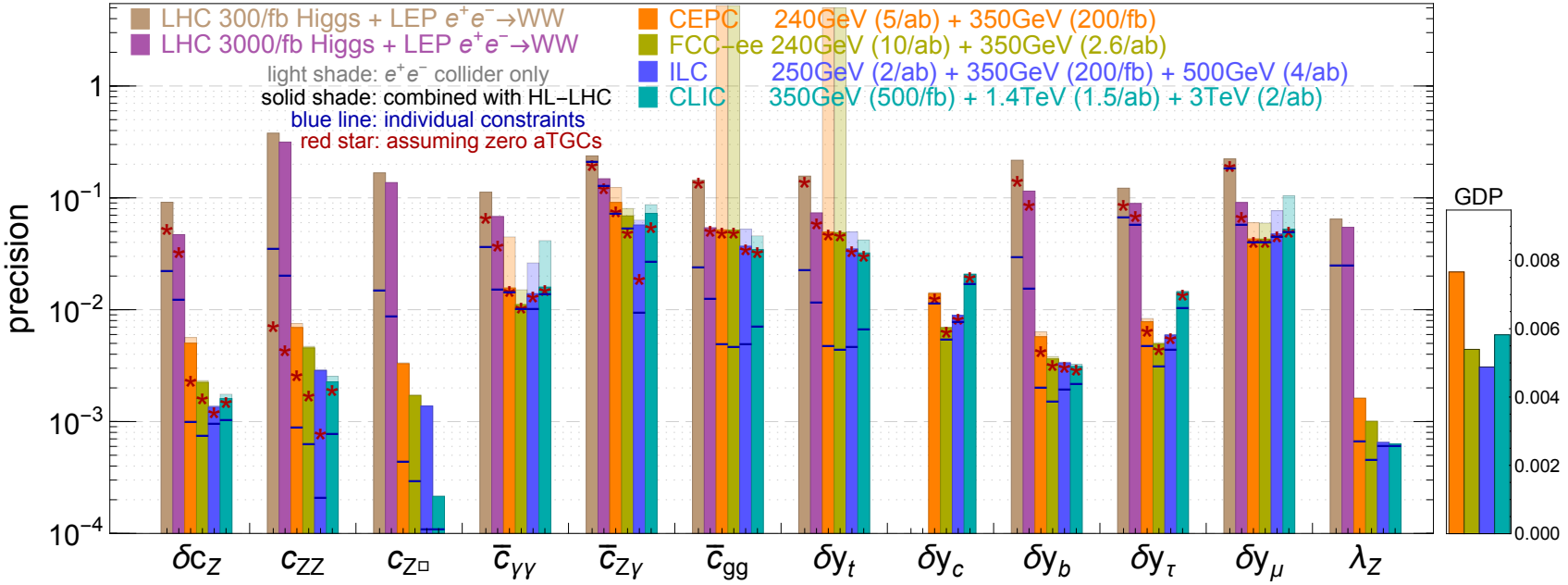
Answer ingredients

- 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 $e^+e^- \to t\,\bar{t}$ (for comparison)

Global Higgs EFT analysis

Global Higgs EFT constraints

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

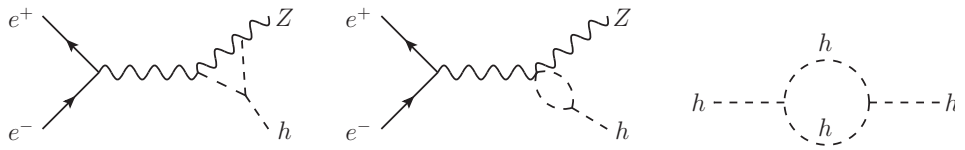


- importance of complementary measurements
  (different c.o.m. energies, polarizations, distributions)
- importance of diboson measurement precision
  (not studied much by exp. collaborations)
- order of magnitude improvement wrt LHC
  (especially on δc_Z, δc_{ZZ}, $\delta c_{Z\Box}$, δy_b, δy_τ, λ_Z)
- LHC helps for $\bar{c}_{\gamma\gamma}$, δy_μ, and δy_t (below 500 GeV!)

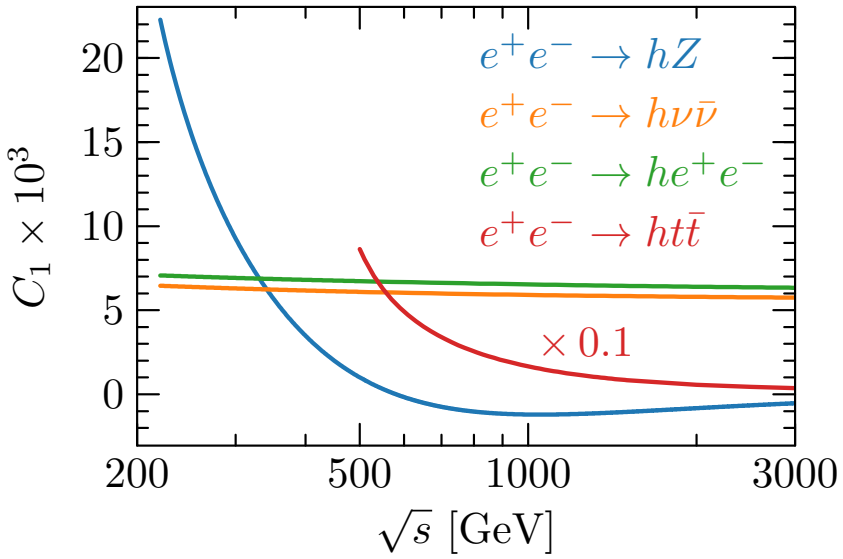
Higgs self-coupling through loops

- 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]



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

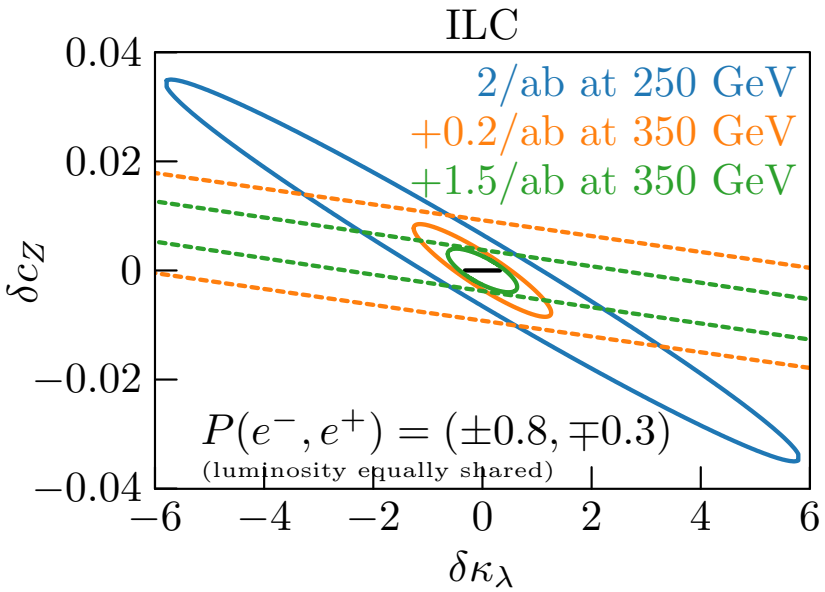


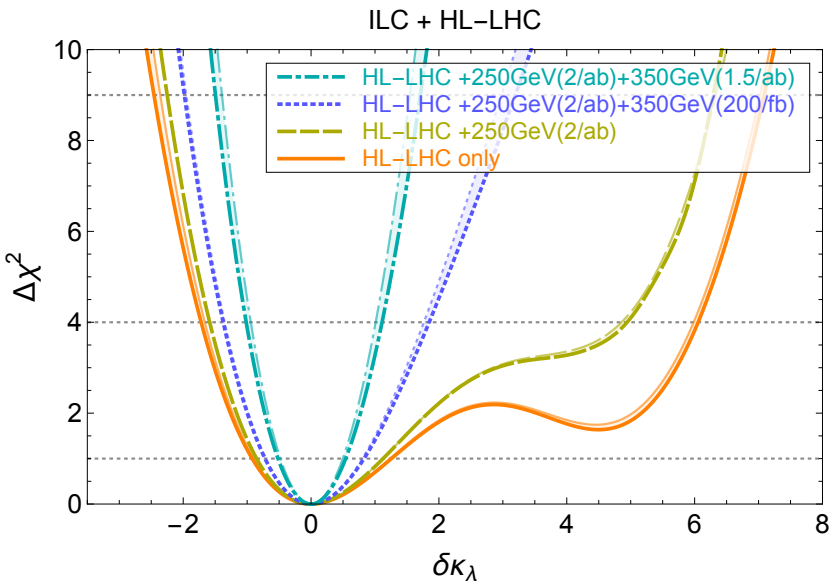
$\to$ few permil hZ measurement naively implies a few 10% constraint

At the ILC, for instance

[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





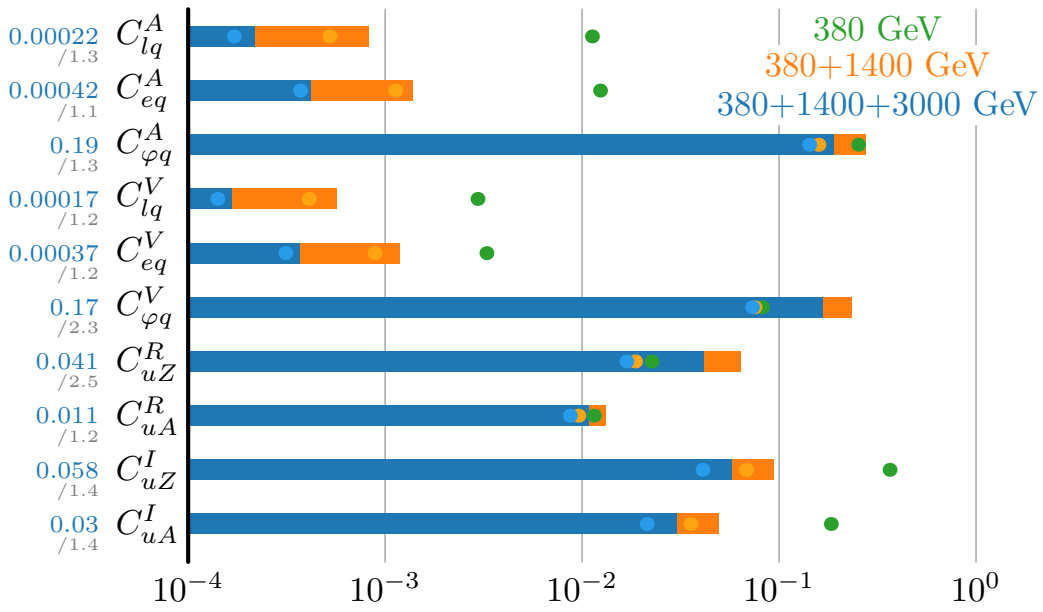
- second LHC minimum already resolved by a 250 GeV run
- constraints dominated by lepton colliders for 1.5 ab^{-1} at 350 GeV ($\sim$ 50%)

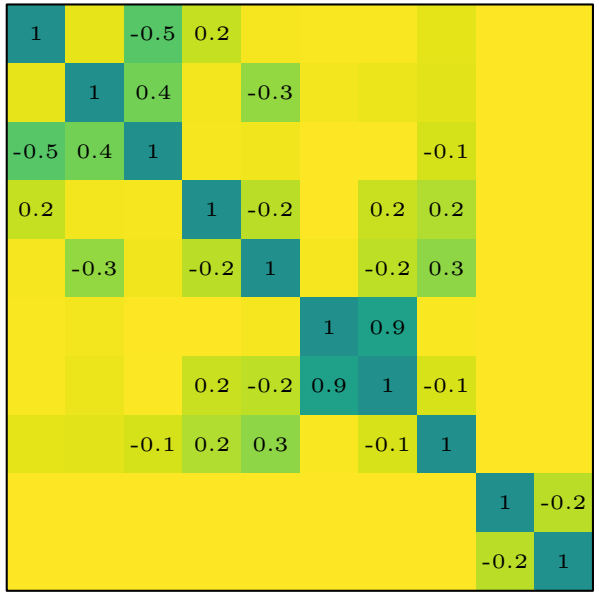
Global $e^+e^- \to t\,\bar{t}$ EFT analysis

At CLIC, for instance

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

[GD, Perello, Vos, Zhang '18]





correlation matrix

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

statistically optimal observables

resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytical LO observable def.

effective stat. efficiencies determined with full sim. in semi-leptonic final state

CLIC-like scenario [LCWS, 22 Oct. 2018]

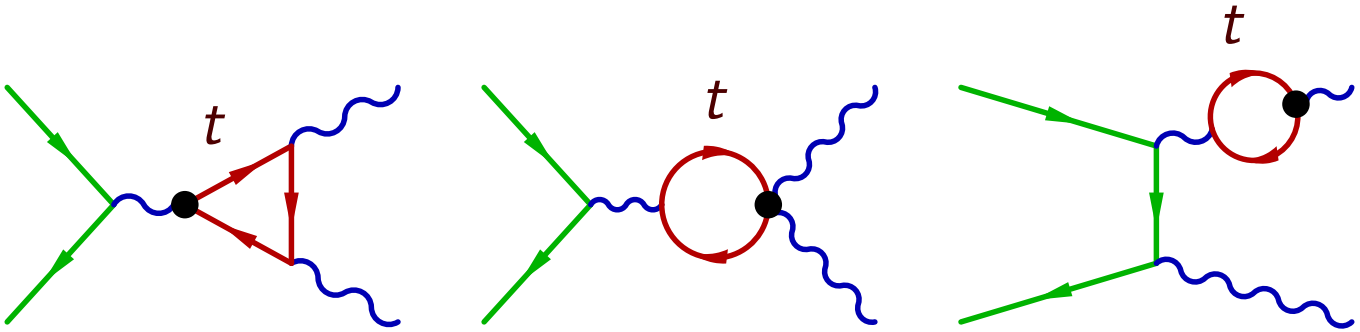
$1\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 380\,\mathrm{GeV}$
$2.5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 1.4\,\mathrm{TeV}$
$5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 3\,\mathrm{TeV}$

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

Top loops & results

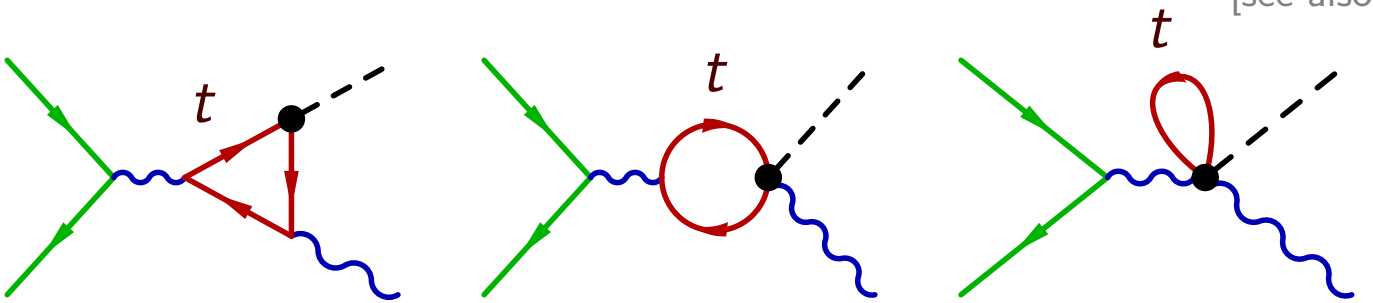
Top loops

- At the Z pole [Zhang, Greiner, Willenbrock '12]
- In diboson production [GD, Gu, Vrionidou, Zhang '18]



differential in the production angle

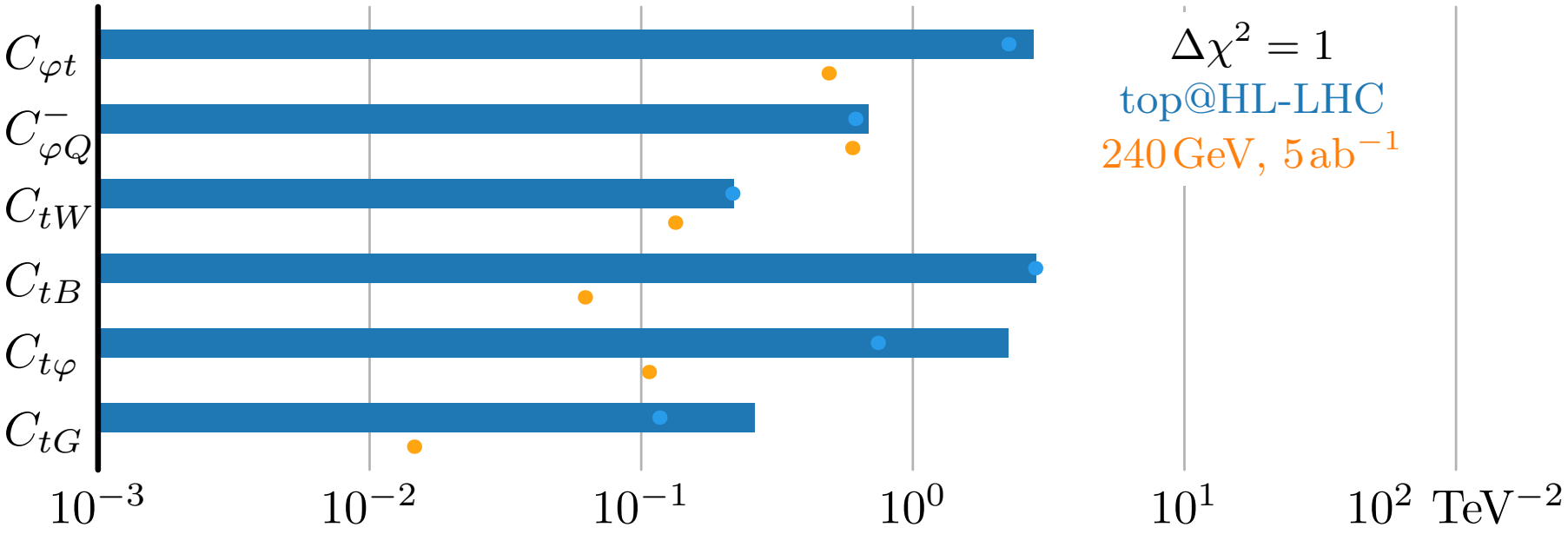
- In Higgs [Vrionidou, Zhang, '18] [see also Boselli et al '18]



- 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



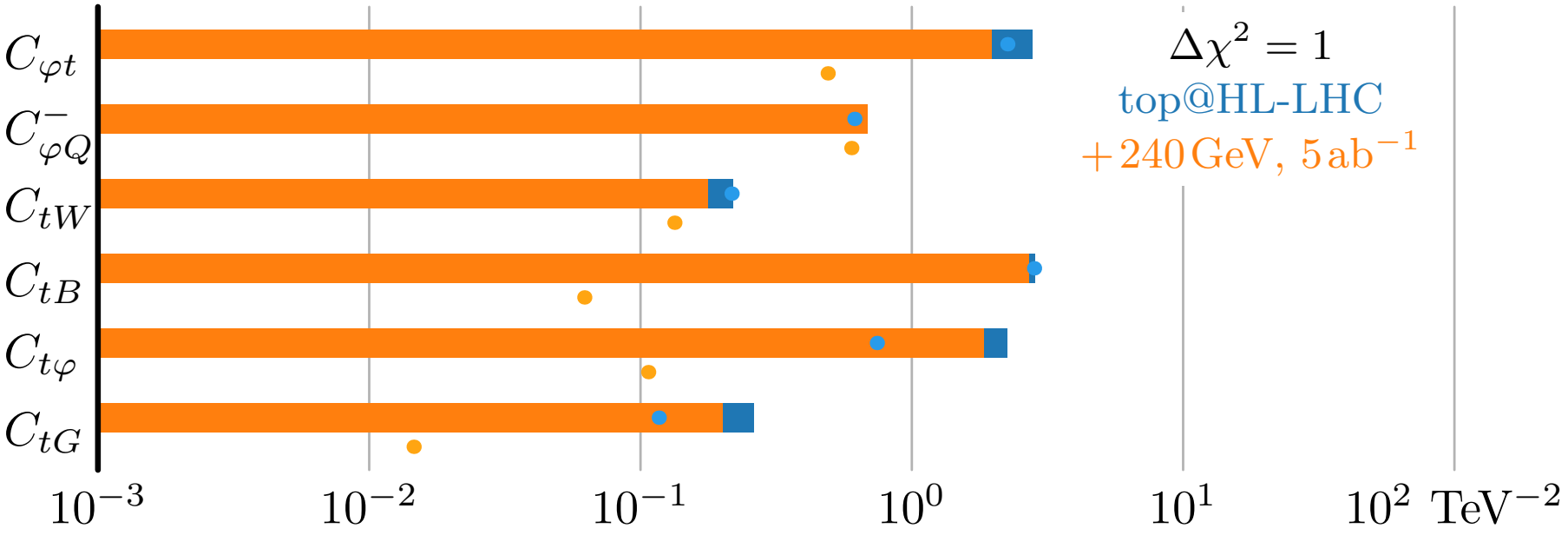
Individual constraints (blobs)

- 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

Q1: Improvement on top operators



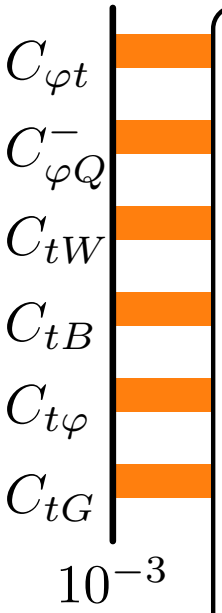
Individual constraints (blobs)

- 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

Q1: Improvement on top operators



TeV^{-2}

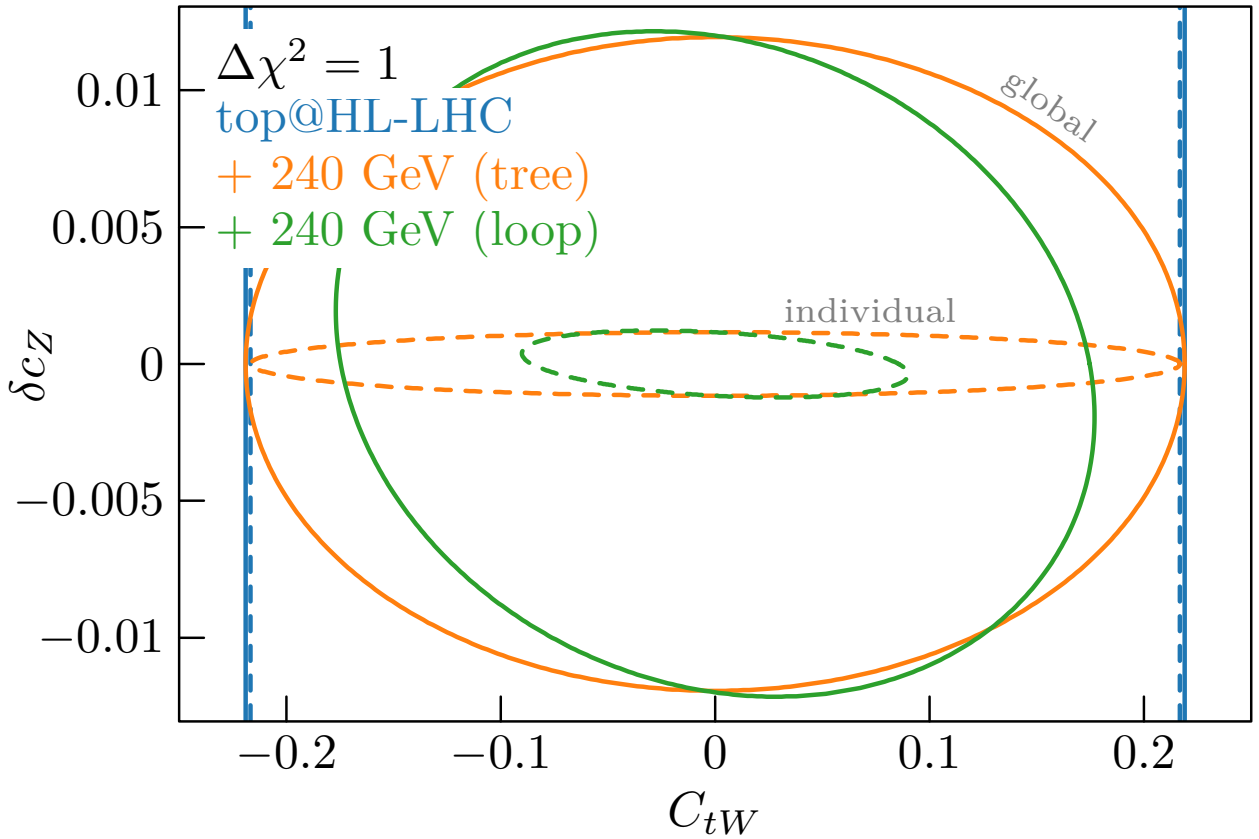
Individu

- com
- dom

Global c

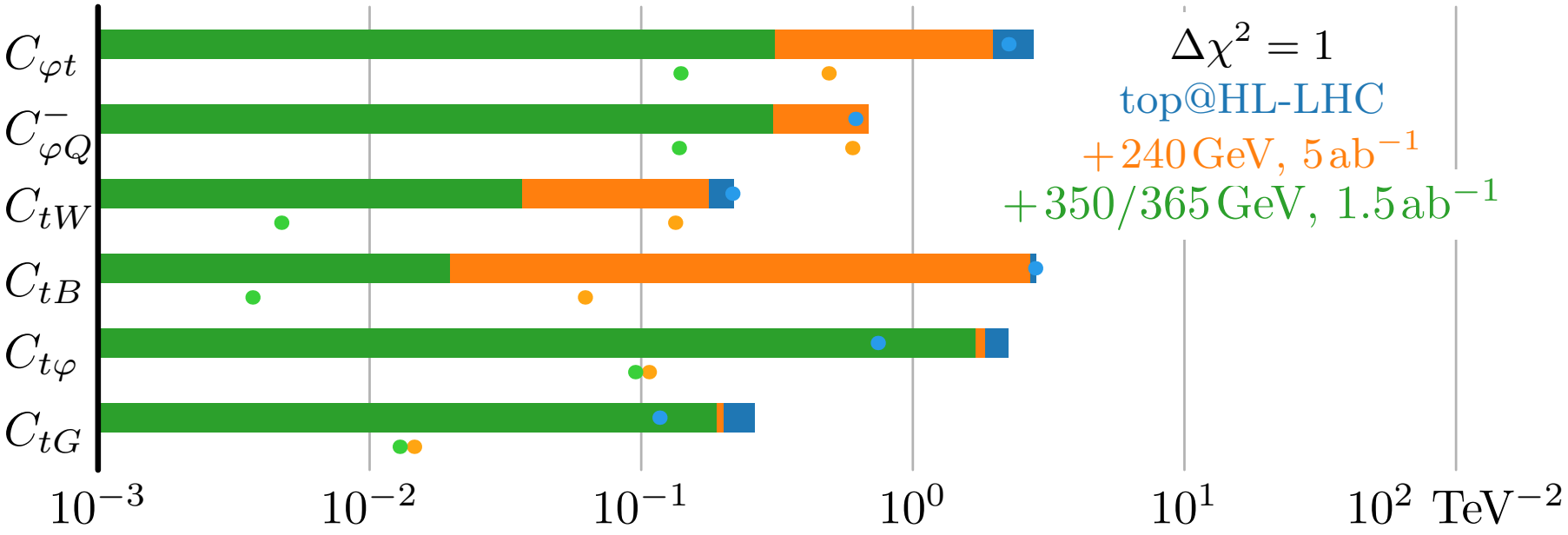
- large
- still
- more differential distributions would help further

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

Q1: Improvement on top operators



Individual constraints (blobs)

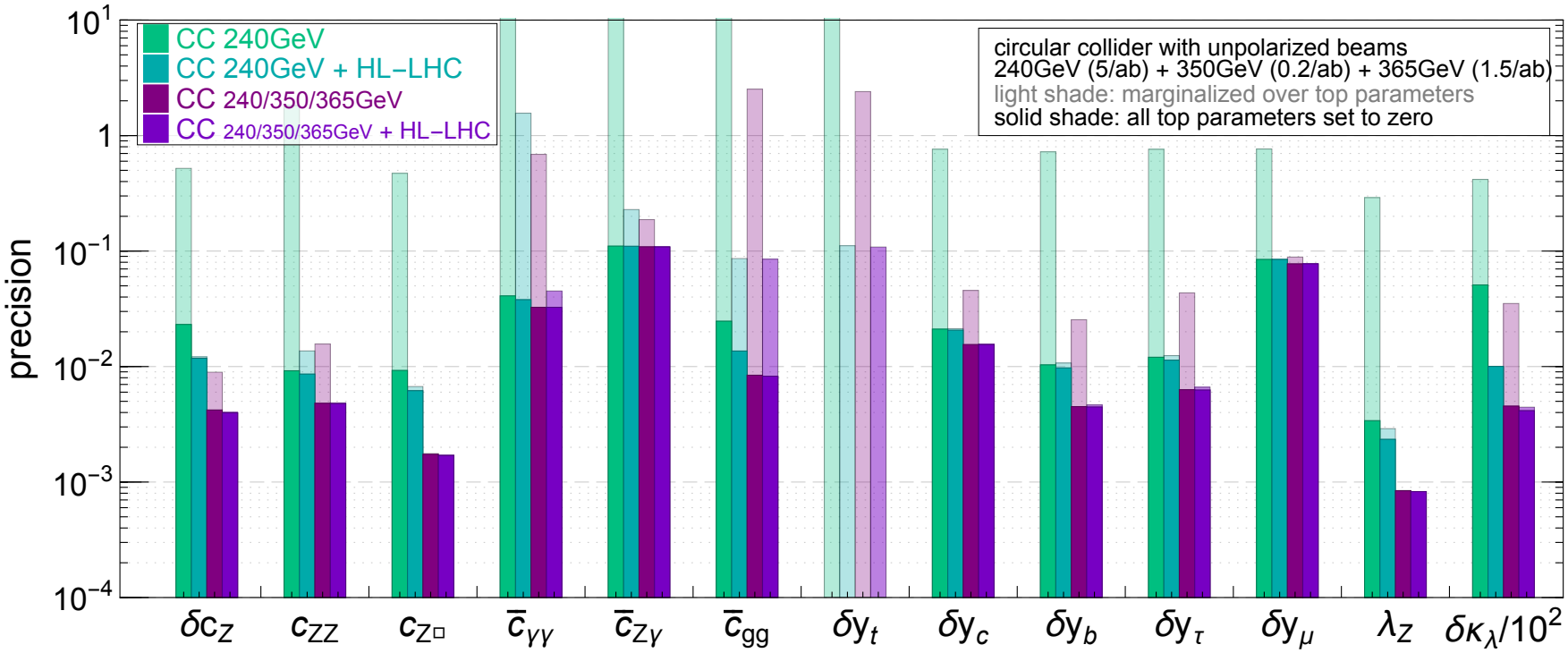
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)
- loops in $e^+e^- \to t\bar{t}$ would improve its impact on $C_{t\varphi}$ and C_{tG}

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

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 $\oplus$ $e^+e^- \to t\bar{t}$: 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

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 $e^+e^- \to t\,\bar{t}$, polarized beams, full set of EWPO, $e^+e^- \to ZZ, Z\gamma, f\bar{f}$, ...

Backup

Global Higgs EFT setup

- employ the Higgs basis of dim-6 operators
- focus mostly on Higgs-related processes:

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

- only relax flavour universality to distinguish Yukawa's
- assume CPV, EW parameters, dipole operators are well constrained

$\longrightarrow$ 13 EFT d.o.f.:

$\Gamma_{xy}/\Gamma_{xy}^{\rm SM} \sim 1 \pm 2\bar{c}_{xy} + \ldots$

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

Up-sector SMEFT

[Grzadkowski et al '10]

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

Two-quark operators:

Scalar:	$O_{u\varphi}$	$\equiv \bar{q} u \, \tilde{\varphi} \quad \varphi^\dagger \varphi,$		
Vector:	$O^1_{\varphi q}$	$\equiv \bar{q}\gamma^\mu q \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi$	$\equiv O^+_{\varphi q} + O^V_{\varphi q} - O^A_{\varphi q},$	
	$O^3_{\varphi q}$	$\equiv \bar{q}\gamma^\mu \tau^I q \quad \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi$	$\equiv O^+_{\varphi q} - O^V_{\varphi q} + O^A_{\varphi q}$	(CC also)
	$O_{\varphi u}$	$\equiv \bar{u}\gamma^\mu u \quad \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi$	$\equiv O^V_{\varphi q} + O^A_{\varphi q}$	
	$O_{\varphi ud}$	$\equiv \bar{u}\gamma^\mu d \quad \tilde{\varphi}^\dagger i\overleftrightarrow{D}_\mu \varphi,$		(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}	$\equiv \bar{q}\sigma^{\mu\nu}\tau^I u \, \tilde{\varphi} \, g_W W^I_{\mu\nu},$	$\equiv O_{uA} + \text{cotan}\,\theta_W O_{uZ}$	(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}	$\equiv \bar{l} e \quad \bar{d} q,$		(CC only, m_e int.)
Vector:	O^1_{lq}	$\equiv \bar{l}\gamma_\mu l \quad \bar{q}\gamma^\mu q$	$\equiv O^+_{lq} + O^V_{lq} - O^A_{lq},$	
	O^3_{lq}	$\equiv \bar{l}\gamma_\mu \tau^I l \quad \bar{q}\gamma^\mu \tau^I q$	$\equiv O^+_{lq} - O^V_{lq} + O^A_{lq},$	(CC also)
	O_{lu}	$\equiv \bar{l}\gamma_\mu l \quad \bar{u}\gamma^\mu u$	$\equiv O^V_{lq} + O^A_{lq},$	
	O_{eq}	$\equiv \bar{e}\gamma^\mu e \quad \bar{q}\gamma_\mu q$	$\equiv O^V_{eq} - O^A_{eq},$	
	O_{eu}	$\equiv \bar{e}\gamma_\mu e \quad \bar{u}\gamma^\mu u$	$\equiv O^V_{eq} + O^A_{eq},$	
Tensor:	O^T_{lequ}	$\equiv \bar{l}\sigma_{\mu\nu} e \quad \varepsilon \quad \bar{q}\sigma^{\mu\nu} u.$		(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).