The electro-weak couplings of the top quark: current constraints, prospects and impact in a combined top-Higgs EFT fit

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Beyond Standard Model

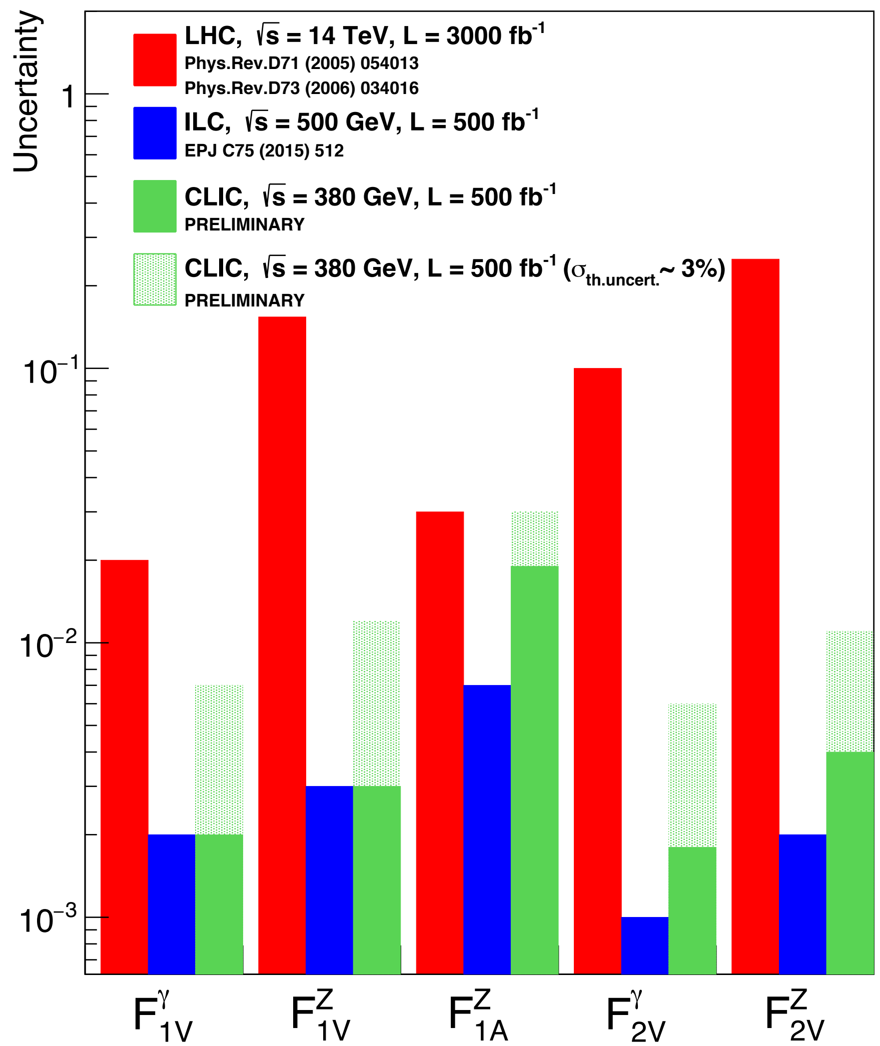
Done	To understand	Desires	Hints
Higgs boson - 2012	Dark Matter	GUT	B-anomalies
	Neutrino masses	Gravitation as a QFT	~~750 GeV~~
	Matter-Antimatter asymmetry		Solar axions (**Tritium?**)

Why study the **top quark**?

- **Some models BSM have strong couplings to the top quark** which provide a great sensitivity to high energy scales.
- Top quark precision measurements have never been done in a lepton collider. **Access to new observables.**
- This brings a great opportunity to provide a **bright window to new physics**.

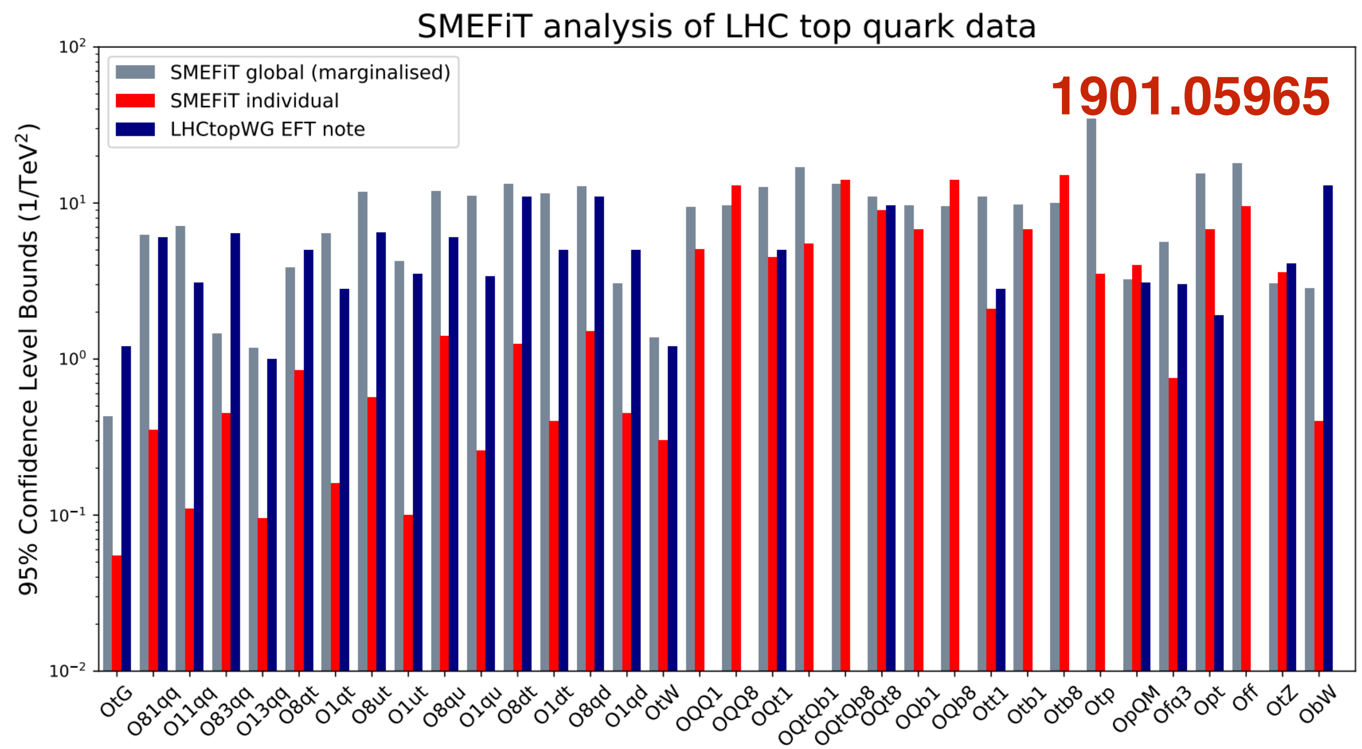
Top Quark couplings

Form-factors approach



$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu \left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$

EFT approach

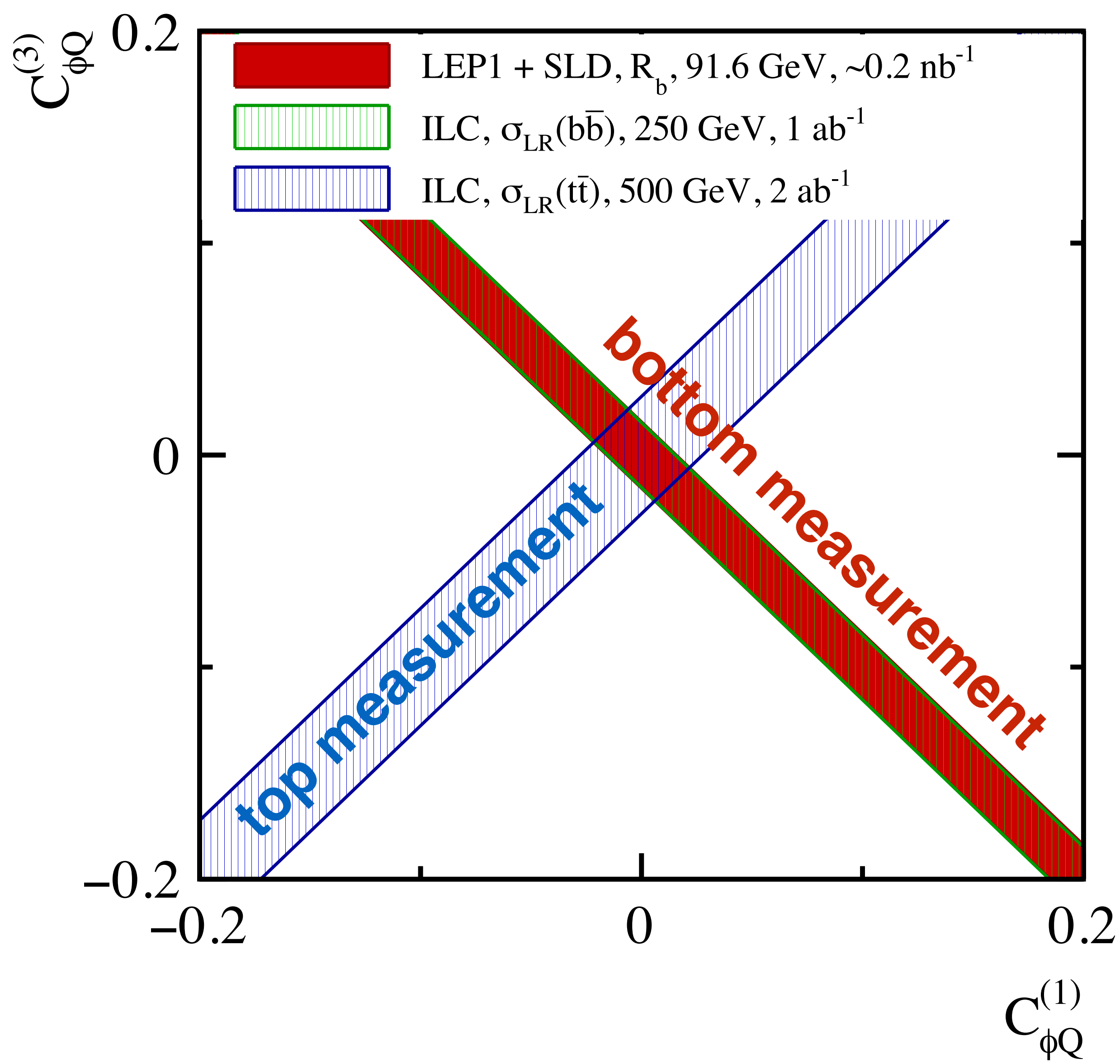


EFT:

- More fundamental representation
- Same operators for different processes
- Useful for benchmark studies

Motivation for a combined t- and b-quark fit

Complementarity between bb production (e.g. LEP measurements) and tt production (e.g. pp > ttZ)



Top and bottom quarks are in the same $SU(2)_L$ doublet

$$\delta g_L^t = -(C_{\varphi Q}^1 - C_{\varphi Q}^3) m_t^2/\Lambda^2$$

$$\delta g_L^b = -(C_{\varphi Q}^1 + C_{\varphi Q}^3) m_t^2/\Lambda^2$$

$$\delta g_R^t = -C_{\varphi u}\, m_t^2/\Lambda^2$$

$$\delta g_R^b = -C_{\varphi d}\, m_t^2/\Lambda^2$$

Top-quark operators

dim-6 EW 2-fermion operators

$$
\begin{array}{llll}
O^{1}_{\varphi Q} & \equiv \frac{y_t^2}{2} & \bar{q}\gamma^{\mu}q & \varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi, \\
O^{3}_{\varphi Q} & \equiv \frac{y_t^2}{2} & \bar{q}\tau^{I}\gamma^{\mu}q & \varphi^{\dagger} i\overleftrightarrow{D}^{I}_{\mu}\varphi, \\
O_{\varphi u} & \equiv \frac{y_t^2}{2} & \bar{u}\gamma^{\mu}u & \varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi, \\
O_{\varphi d} & \equiv \frac{y_t^2}{2} & \bar{d}\gamma^{\mu}d & \varphi^{\dagger} i\overleftrightarrow{D}_{\mu}\varphi, \\
O_{\varphi ud} & \equiv \frac{y_t^2}{2} & \bar{u}\gamma^{\mu}d & \varphi^{T}\epsilon i D_{\mu}\varphi, \\
O_{uW} & \equiv y_t g_W & \bar{q}\tau^{I}\sigma^{\mu\nu}u & \epsilon\varphi^{*}W^{I}_{\mu\nu}, \\
O_{dW} & \equiv y_t g_W & \bar{q}\tau^{I}\sigma^{\mu\nu}d & \varphi\, W^{I}_{\mu\nu}, \\
O_{uB} & \equiv y_t g_Y & \bar{q}\sigma^{\mu\nu}u & \epsilon\varphi^{*}B_{\mu\nu}, \\
O_{dB} & \equiv y_t g_Y & \bar{q}\sigma^{\mu\nu}d & \varphi\, B_{\mu\nu}, \\
O_{u\varphi} & \equiv & \bar{q}u & \epsilon\varphi^{*}\,\varphi^{\dagger}\varphi,
\end{array}
$$

Left- and right-handed couplings of the t- and b-quarks to the Z-boson

Charged current interaction

EW dipole operators

Top Yukawa

QCD operators excluded

LHC and LEP data

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

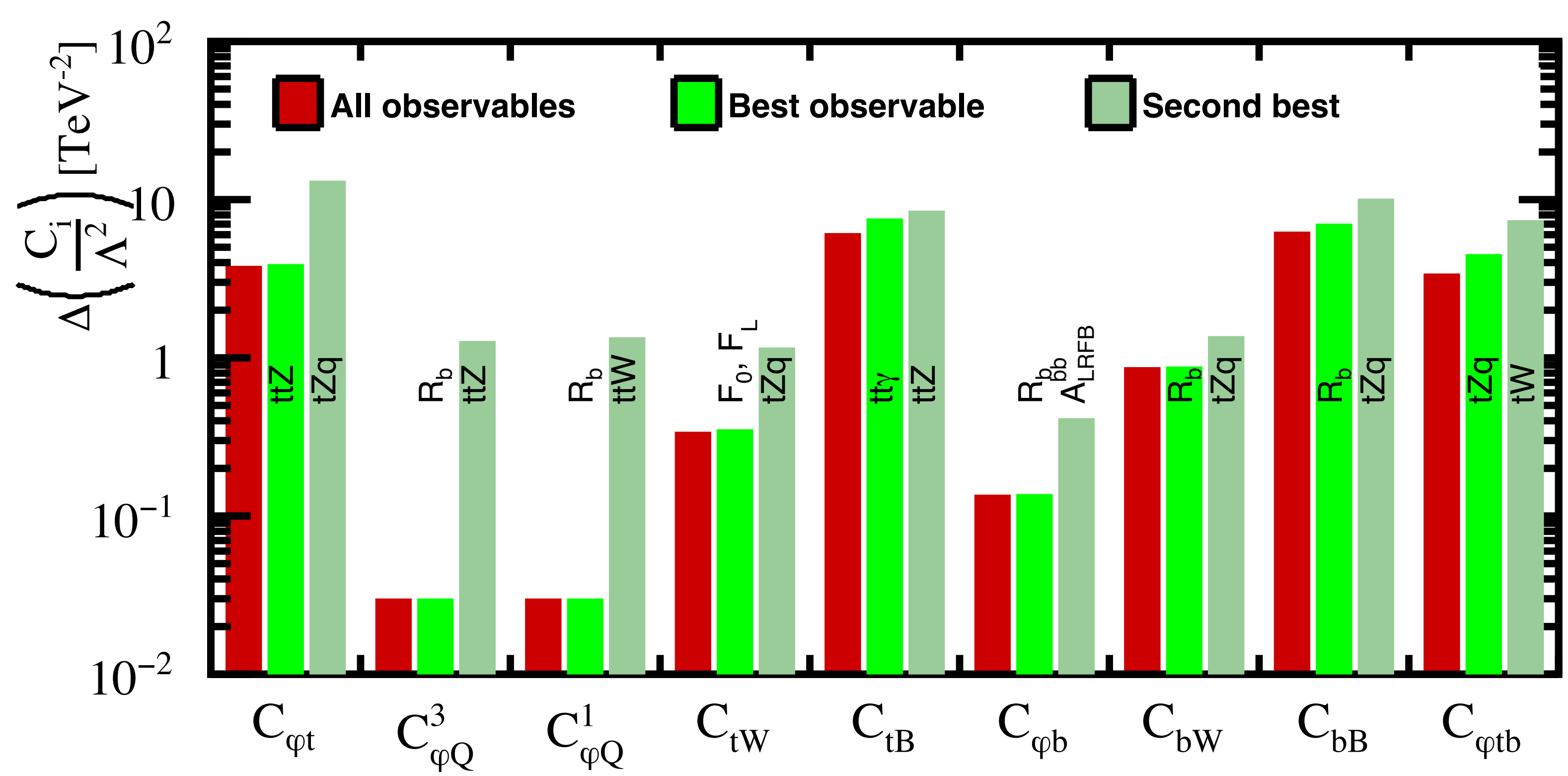
Process	observable	$\sqrt{s}$
$pp \to t\bar{t}H$	cross section	13 TeV
$pp \to t\bar{t}Z/W$	cross section	13 TeV
$pp \to t\bar{t}\gamma$	fid. x-sec.	13 TeV
single-top (t-ch)	cross section	13 TeV
single-top (Wt)	cross section	13 TeV
single-top (tZq)	cross section	13 TeV
$t \to W^+ b$	F_0, F_L	8 TeV
$e^- e^+ \to b\bar{b}$	R_b , A^{bb}_{FBLR}	$\sim$ 91 GeV

Observables with tree-level dependence to the dim-6 operators

Individual fit: 68% probability for each Wilson coefficient.

We observe a good interplay between the parameters and the chosen observables.

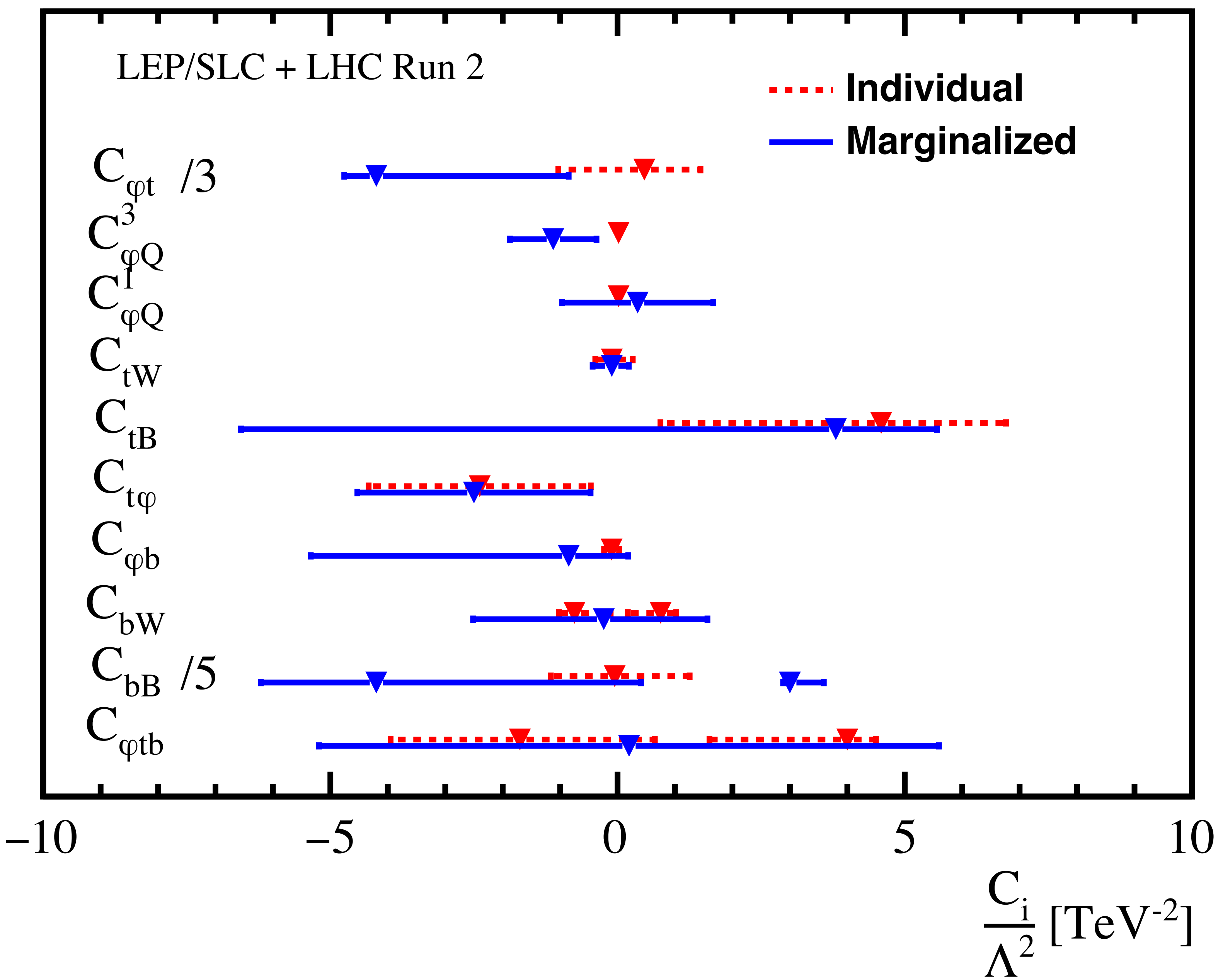
First time LHC provides good observables for an EW top fit



Current bounds: 10-parameter fit

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

Bayesian fit (HEPfit open source): 68% probability.



The fit yields robust results even when all operator coefficients are varied simultaneously.

Good fit for an EW couplings of the top and bottom quarks. All the coefficients are in agreement with the SM.

More robust than other fits based on a specific measurement.

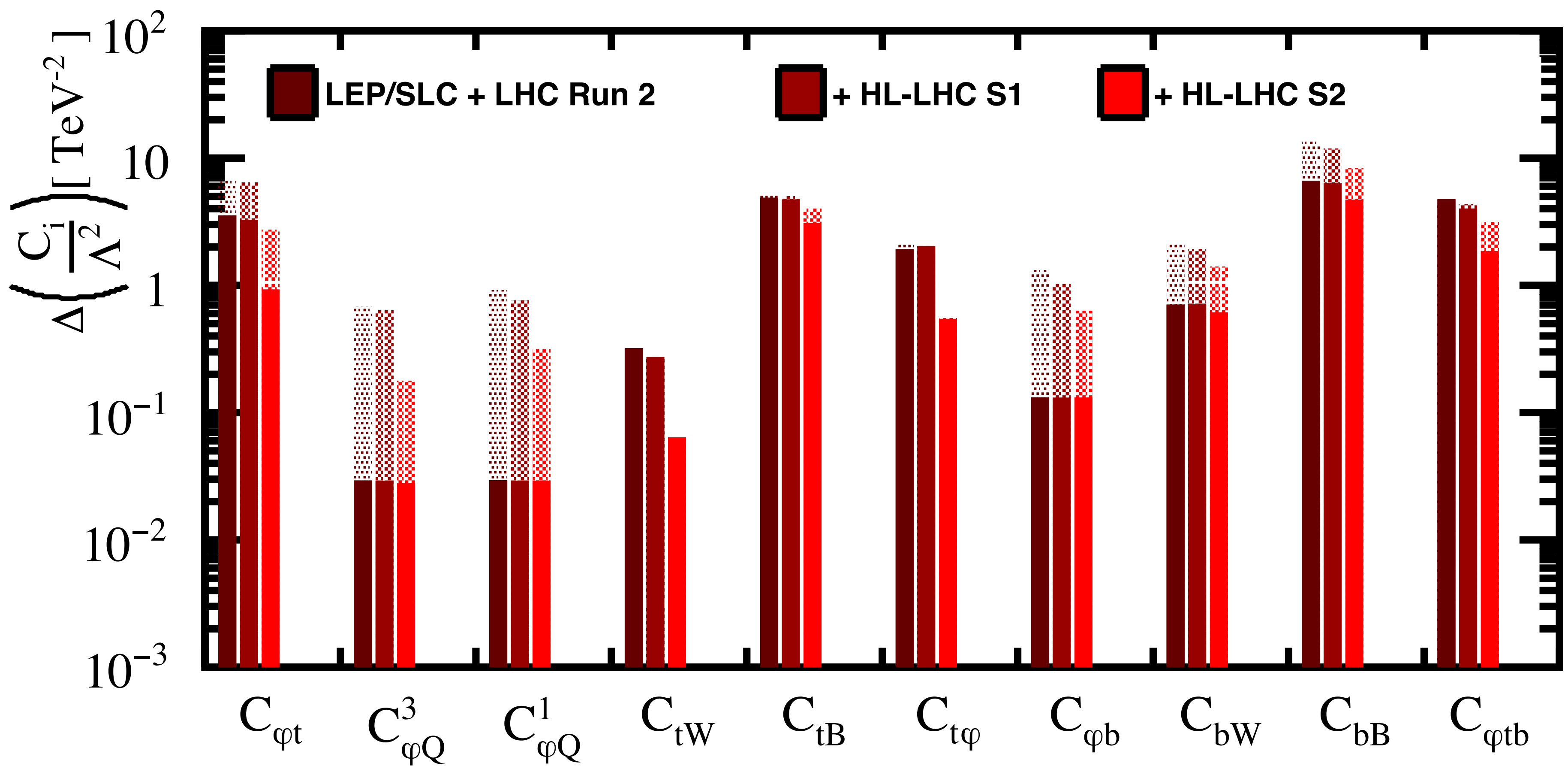
HL-LHC prospects

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

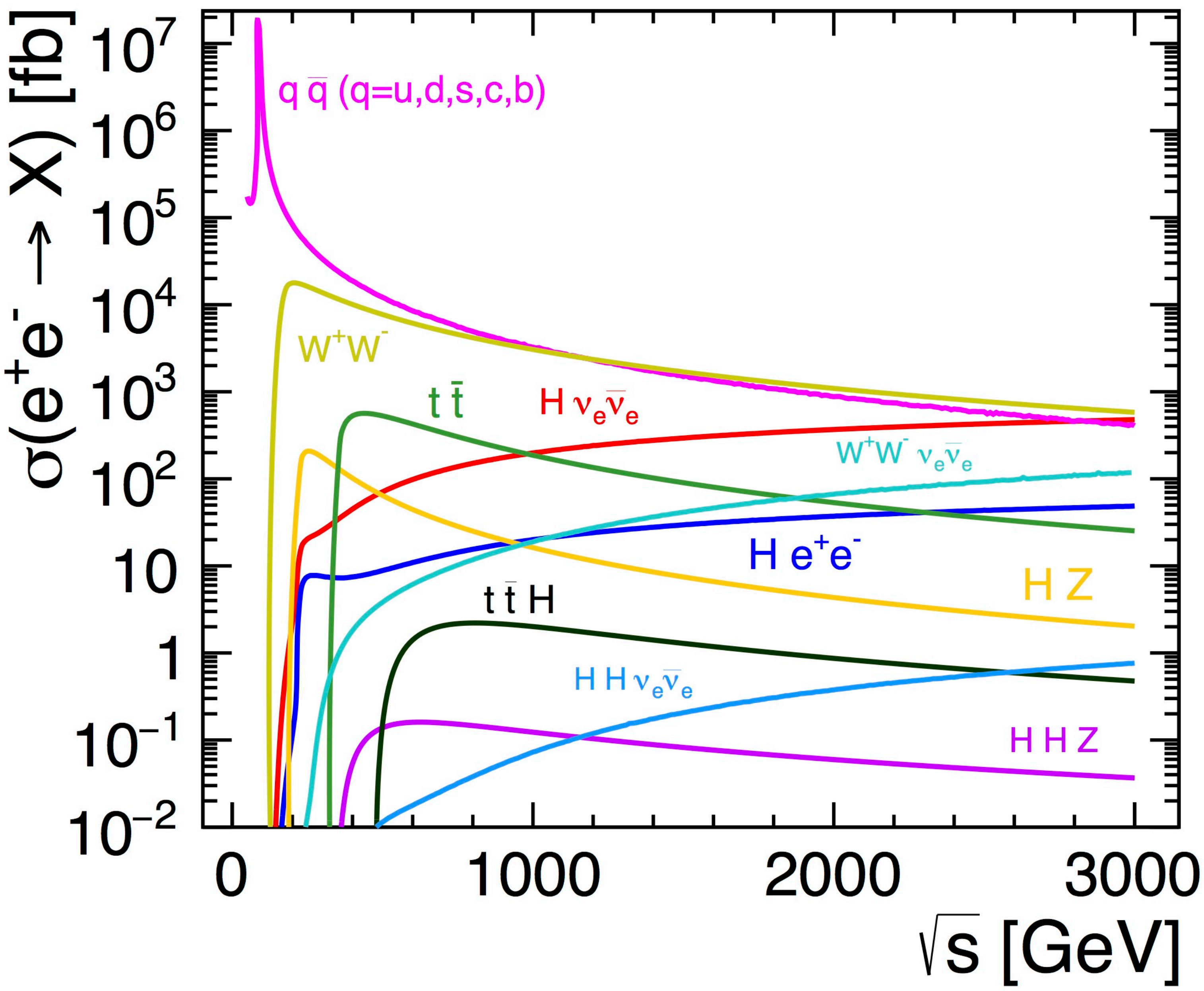
Inspired by Higgs chapter in the HL-LHC Yellow Report

2 scenarios for HL-LHC:

- S1: statistical uncertainty scaled with luminosity.
- S2: stat. and syst. scaled with $N^{-1/2}$, theory reduce by a factor 2.



Future electron-positron colliders



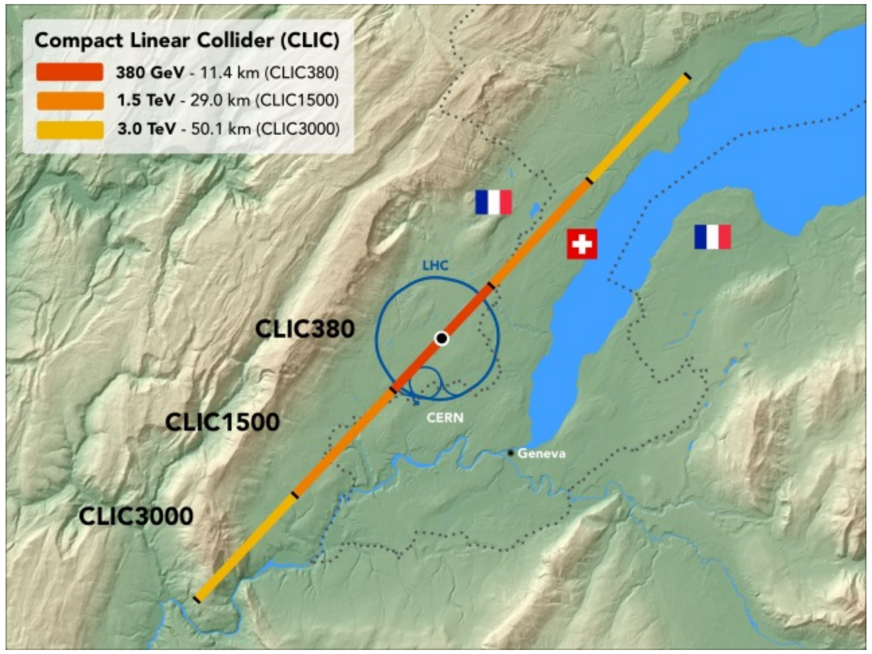
- We start to produce top pairs at ~350 GeV
- We can use bb measurements below 350 GeV

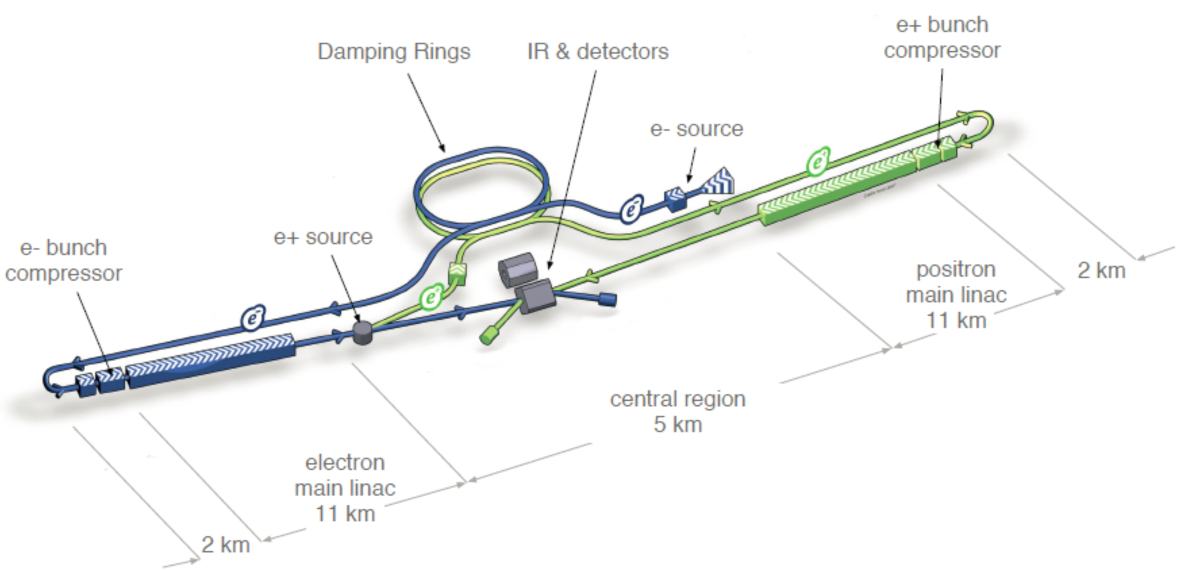
Future colliders

- **ILC in Japan**
  - linear electron-positron **@250 GeV** and possible upgrade to **500 GeV**
  - other energies: 91 GeV (Giga-Z) and **1 TeV**
  - 2 beam polarization configurations, **pol(e-,e+) = (±0.8, ∓ 0.3)**

- **CLIC at CERN**
  - linear electron-positron **@380, 1500** and **3000 GeV**
  - 2 beam polarization configurations, **pol(e-,e+) = (±0.8, 0)**

- **FCC at CERN**
  - hadron circular collider @100TeV
  - possible electron-positron first stage at 91, 160, 240 and 365 GeV
  - appears in the European Strategy as the preferred future collider in Europe



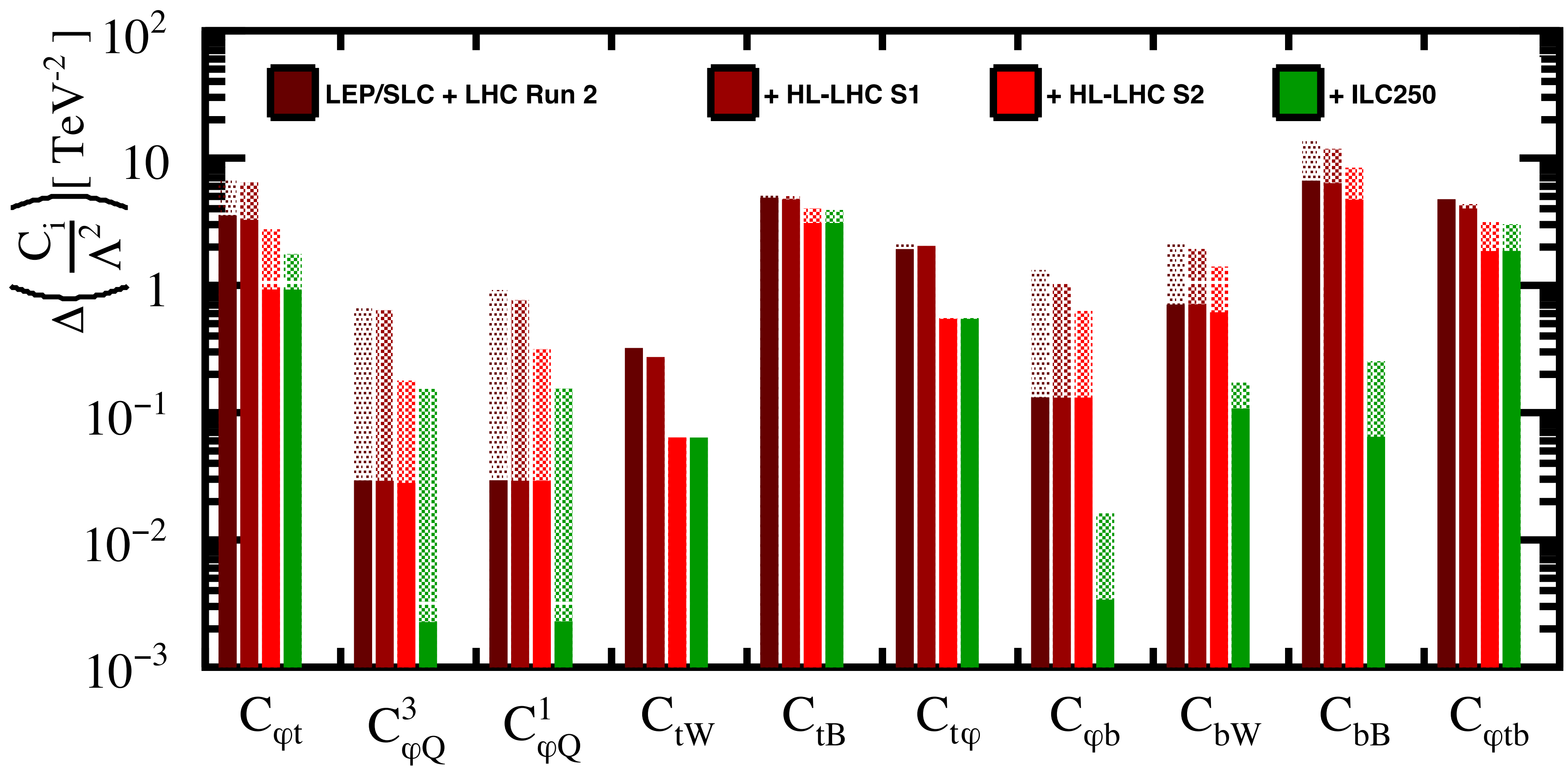


ILC250: bb production

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

Including **cross-section** and **Afb** from bb production with 2 polarizations…

- reduce substantially the individual limits in all b-quark operators
- in the global fit, **left-handed couplings barely improve** compared with LEP
- **right-couplings and dipole operators improve significantly** their bounds

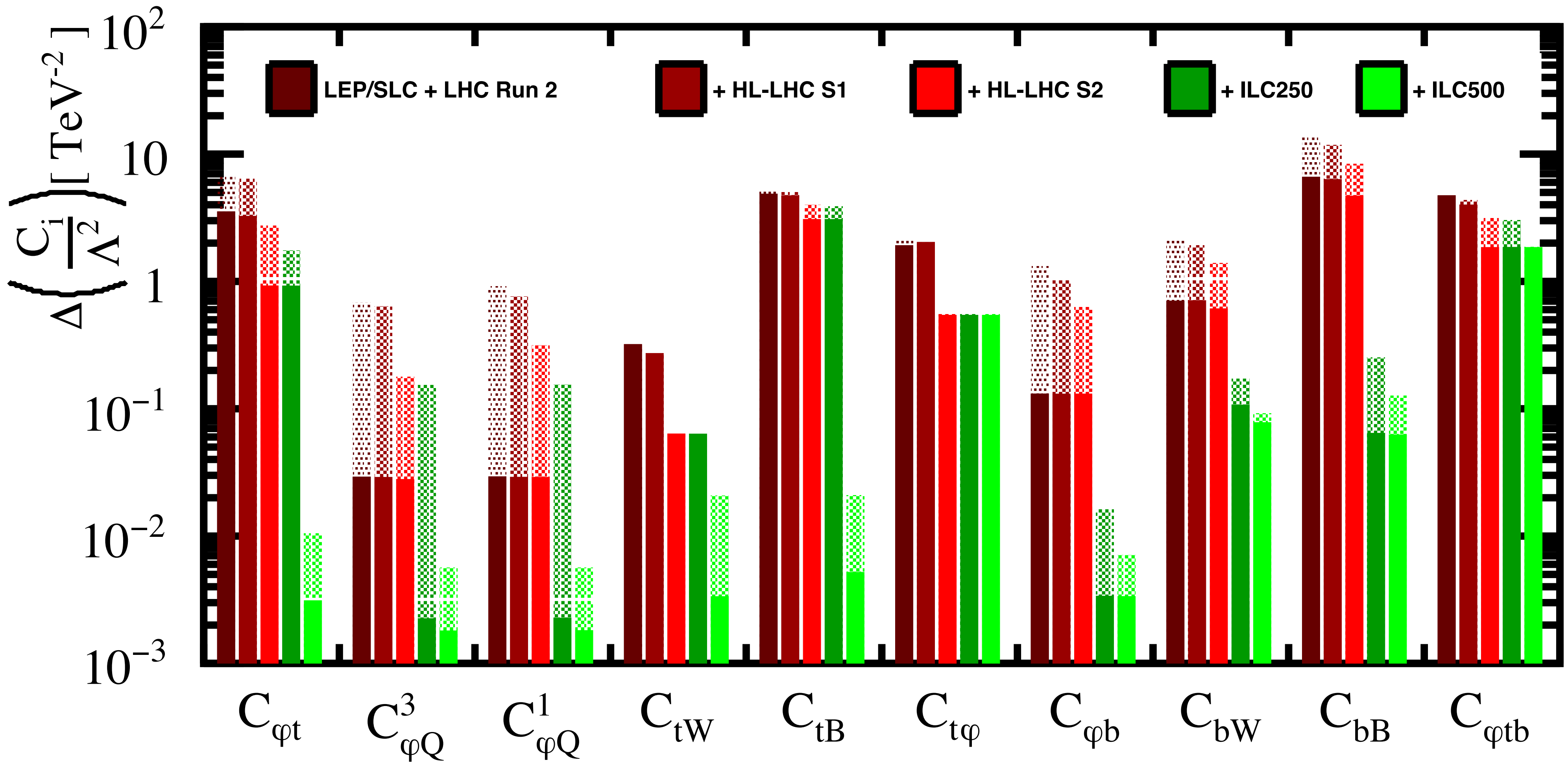


See A.Irles' talk on "Heavy quark production in high energy electron positron collisions"

ILC500: bb and tt production

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

- We include **cross-section and A_{fb} for bb** and **optimal observables for tt** production for **2 beam polarizations**.
- Bounds for top-quark operators are reduced 1-2 order of magnitude.



Top-Yukawa coupling

Durieux, Irles, Miralles, Peñuelas, Pöschl, MP, Vos, arXiv:1907.10619

We can study the top quark Yukawa coupling through **ttH production** at LHC and future electron-positron colliders

Assumed 13% uncertainty, limited by statistics

scenario	LHC Run 2 +LEP/SLC	HL-LHC S2 +LEP/SLC	ILC500	ILC550	ILC500 +ILC1000	CLIC1400
$\sqrt{s}$, $\int \mathcal{L}$	13 TeV, 36 fb^{-1}	14 TeV, 3 ab^{-1}	500 GeV, 4 ab^{-1}	550 GeV, 4 ab^{-1}	+1 TeV, +8 ab^{-1}	+2 ab^{-1}
68% probability interval for effective operator coefficient $C_{t\varphi}/\Lambda^2$ *[TeV^{-2}]*						
individual	$[-4.4, +0.0]$	$[-0.55, +0.55]$	$[-1.06, +1.06]$	$[-0.50, 0.50]$	$[-0.27, +0.27]$	**1807.02441 CLICdp Collaboration**
marginalized	$[-4.6, -0.2]$	$[-0.55, +0.55]$	$[-1.07, +1.07]$	$[-0.52, +0.52]$	$[-0.32, +0.32]$	
corresponding relative uncertainty on top-quark Yukawa coupling $\Delta y_t/y_t$ *[%]*						
individual	13.2	3.3	6.4	3.0	1.62	2.7
marginalized	13.2	3.3	6.4	3.1	1.96	

- ttH production provides a direct constraint for the top Yukawa coupling.
- The top-Yukawa coupling in the global fit is robust.
- The other operators that affect to ttH has to be controlled with other observables

Top quark Yukawa coupling

Boselli, Hunter, Mitov [1805.12027]:

"Prospects for determining the top quark Yukawa coupling at future electron-positron colliders"

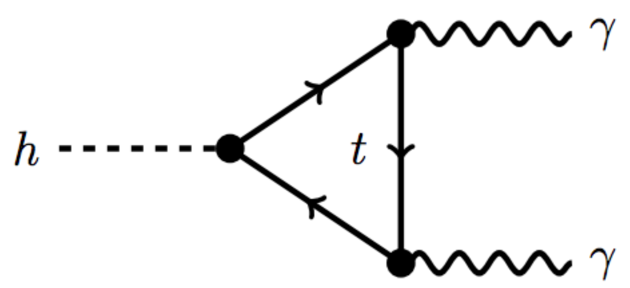
Collider	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	$h \to gg$	$h \to \gamma\gamma$	$h\gamma$	$t\bar{t}h$	total
FCC-ee	240	$1.0 \cdot 10^4$	0.7%	5.3%	10%	-	0.7%
	350	$2.6 \cdot 10^3$	1.3%	21%	19%	-	1.3%
CEPC	240	$5.0 \cdot 10^3$	0.6%	16%	14%	-	0.6%
CLIC	350	$5.0 \cdot 10^2$	2.6%	-	-	-	2.6%
	1400	$1.5 \cdot 10^3$	2.5%	27%	-	4.4%	2.2%
	3000	$2.0 \cdot 10^3$	2.2%	18%	-	7.3%	2.1%
ILC	250	$2.0 \cdot 10^3$	1.2%	21%	23%	-	1.2%
	500	$4.0 \cdot 10^3$	0.7%	10%	75%	5.0%	0.7%

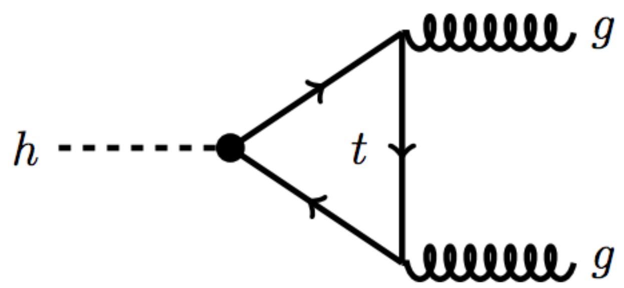
These are individual constraints for top-Yukawa from indirect constraints in Higgs decays.

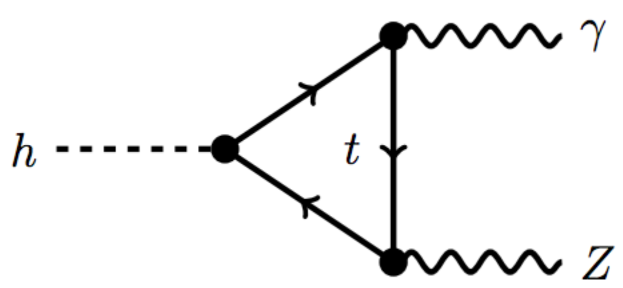
Top-Higgs fit

Jung, Lee, MP, Tian, Vos, arXiv:2006.14631

- Based on previous Higgs couplings fits arXiv:1708.09079 and arXiv:1708.08912







We perform global fits with an extended basis of **29 parameters**, including **both Higgs (22)** and **top (7) operators**, to the projections for the Higgs, top and electro-weak precision measurements at the International Linear Collider (ILC).

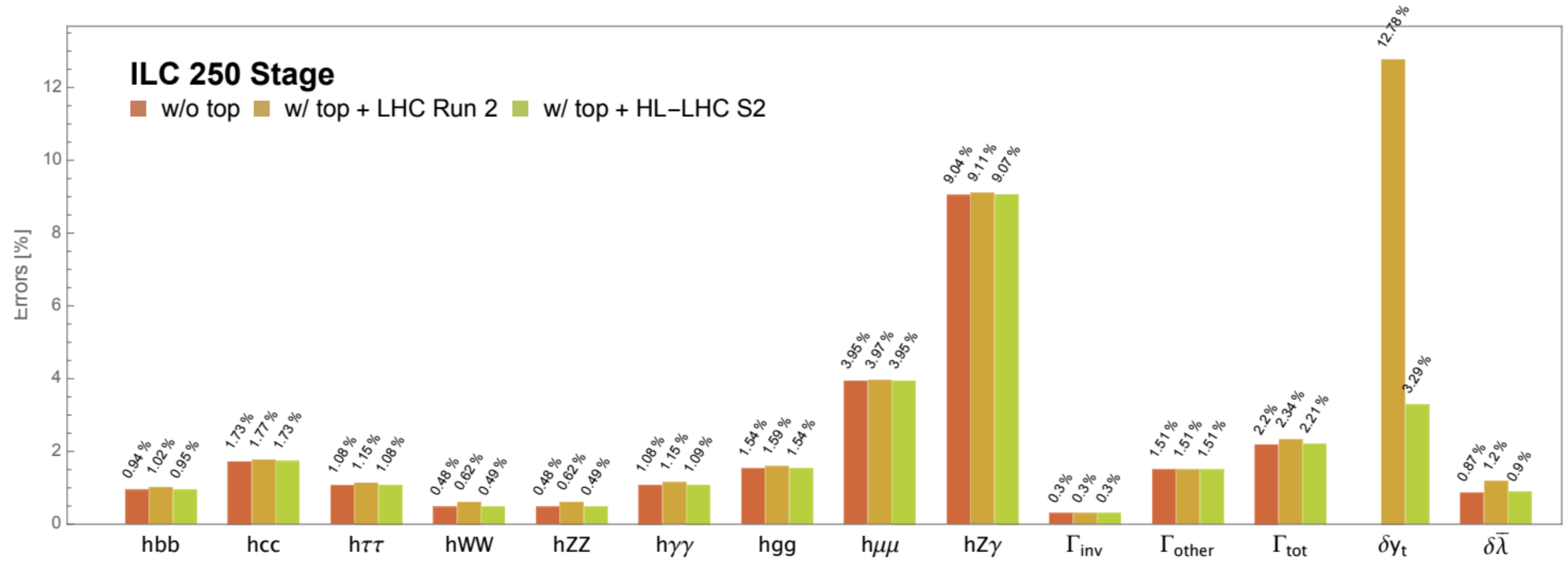
The leading contributions of operators involving top quarks arise mostly at one-loop suppressed order and can be captured by the renormalization group mixing with Higgs operators.

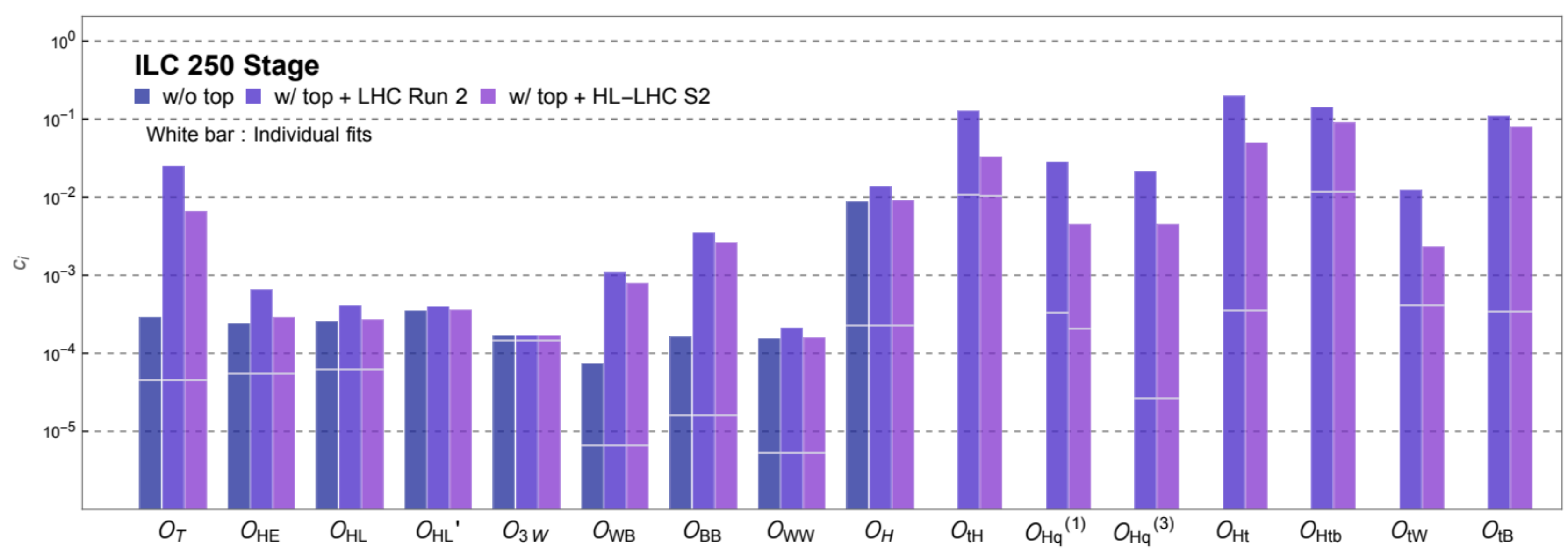
Top-Higgs fit @ILC250

Jung, Lee, MP, Tian, Vos, arXiv:2006.14631

The determination of the Higgs boson couplings at ILC250 is **degraded by the additional top-quark operators**.

We can recover the original bounds by the inclusion of precise measurements of top-quark EW couplings at the LHC.





The physical Higgs couplings are relatively robust, as the top mass is larger than the energy scale of EW processes.

Summary and conclusions

- A combined fit on the top and bottom quark EW couplings demonstrated to be robust using LEP/SLC and LHC Run 2 data
- Bounds from electron-positron colliders are 1-2 order of magnitude better than existing data. We increase the energy scale reached from 1 TeV to 100 TeV.
- To mitigate the effect of the adding top-quark operators in the Higgs boson fit, their contribution must be disentangled by including precise measurements of the top quark electro-weak couplings.

Statistically optimal observables

G. Durieux @TopLC 2017:

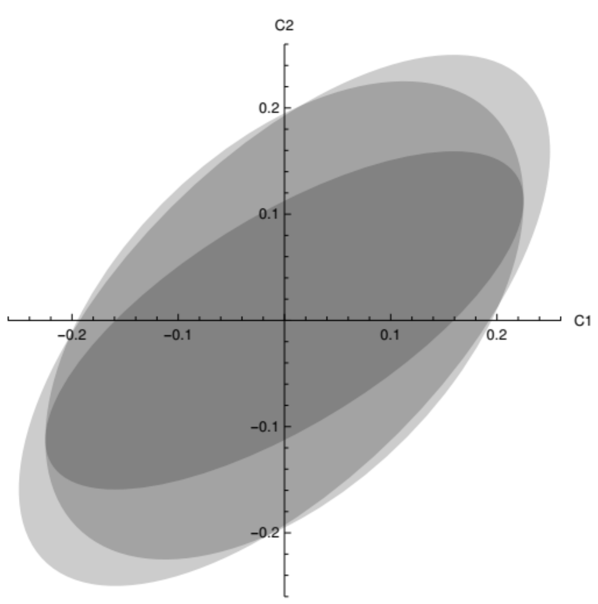
https://indico.cern.ch/event/595651/contributions/2573918/

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

Statistically optimal observables

minimize the one-sigma ellipsoid in EFT parameter space.
(*joint efficient* set of estimators, saturating the Rao-Cramér-Fréchet bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the statistically optimal set of observables is: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



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: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

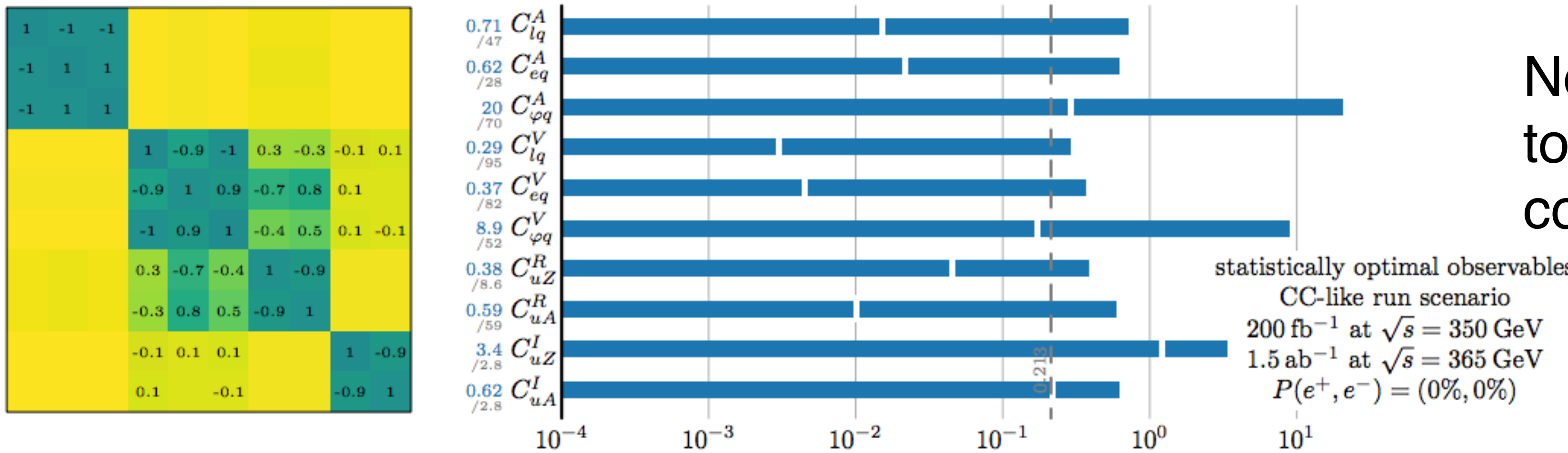
$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

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

Fits at different future scenarios

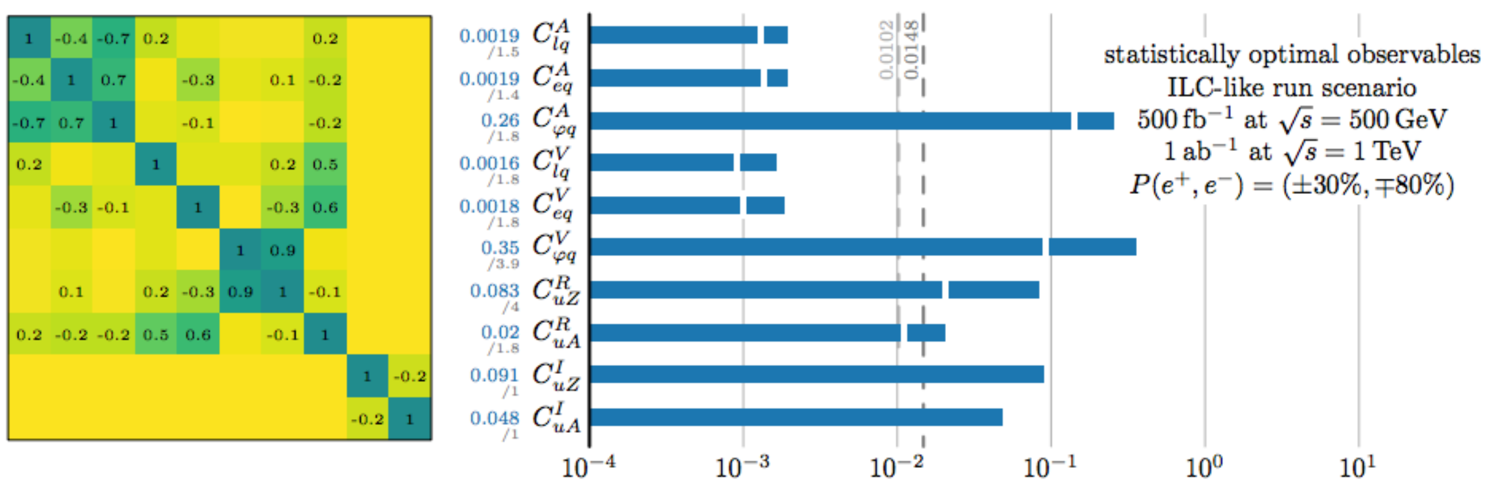
Durieux, MP, Vos, Zhang, arXiv:1807.02121

CC



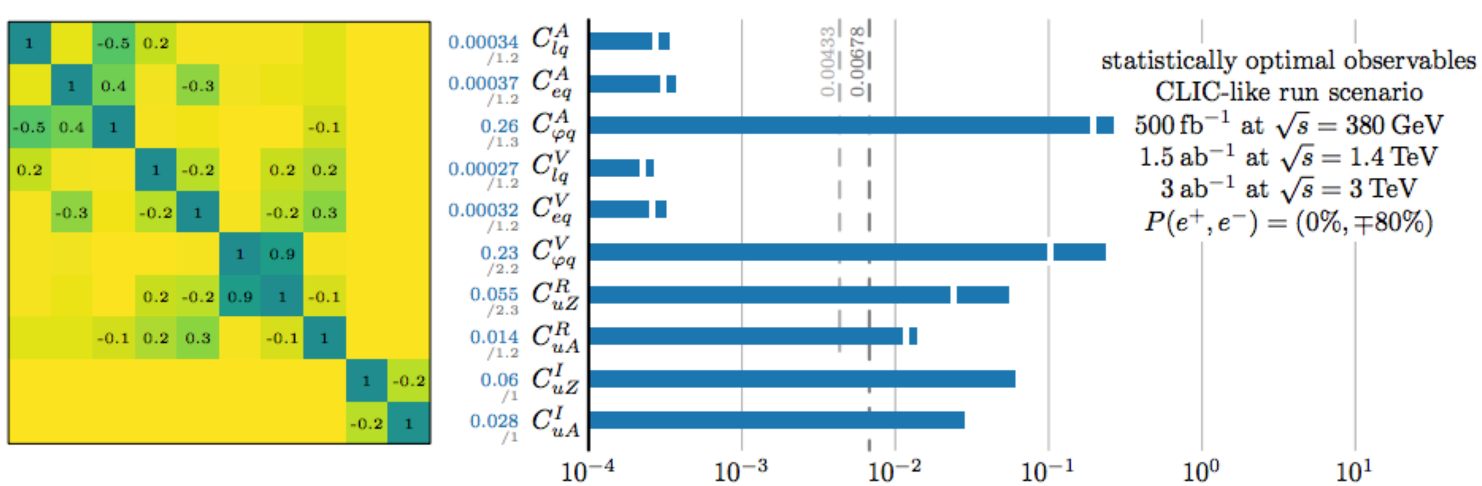
No high energy point with tops in a CC program, bad constraints

ILC

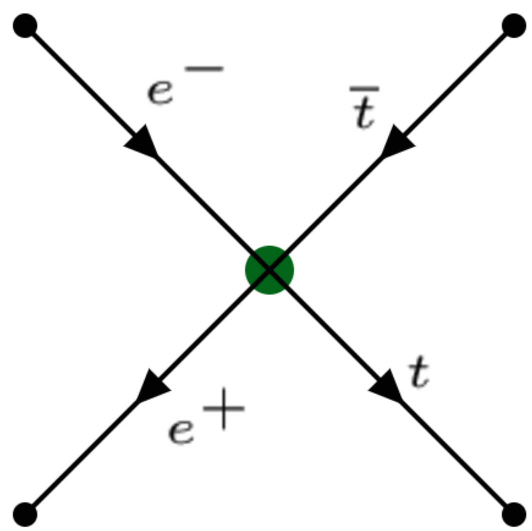


We need at least **2 energy points producing top quarks**, 1 at a high energy regime

CLIC



Including 2-lepton-2-quark operators



A complete top-bottom fit requires the inclusion of 2-lepton-2-quark operators. A total of **7 new operators** should be added.

$$
\begin{aligned}
O^1_{lq} &\equiv \tfrac{1}{2}\; \bar{q}\gamma_\mu q \;\; \bar{l}\gamma^\mu l,\\
O^3_{lq} &\equiv \tfrac{1}{2}\; \bar{q}\tau^I\gamma_\mu q \;\; \bar{l}\tau^I\gamma^\mu l,\\
O_{lu} &\equiv \tfrac{1}{2}\; \bar{u}\gamma_\mu u \;\; \bar{l}\gamma^\mu l,\\
O_{ld} &\equiv \tfrac{1}{2}\; \bar{d}\gamma_\mu d \;\; \bar{l}\gamma^\mu l,\\
O_{eq} &\equiv \tfrac{1}{2}\; \bar{q}\gamma_\mu q \;\; \bar{e}\gamma^\mu e,\\
O_{eu} &\equiv \tfrac{1}{2}\; \bar{u}\gamma_\mu u \;\; \bar{e}\gamma^\mu e,\\
O_{ed} &\equiv \tfrac{1}{2}\; \bar{d}\gamma_\mu d \;\; \bar{e}\gamma^\mu e,
\end{aligned}
$$

	10-parameter fit ILC250 + ILC500	17-parameter fit + ILC1000
$C_{\varphi t}/\Lambda^2$	0.01	0.09
$C^3_{\varphi Q}/\Lambda^2$	0.005	0.04
$C^1_{\varphi Q}/\Lambda^2$	0.005	0.04
C_{tW}/Λ^2	0.02	0.014
C_{tB}/Λ^2	0.02	0.015
$C_{t\varphi}/\Lambda^2$	0.54	0.54
$C_{\varphi b}/\Lambda^2$	0.007	0.008
C_{bW}/Λ^2	0.09	0.17
C_{bB}/Λ^2	0.13	0.17
$C_{\varphi tb}/\Lambda^2$	1.9	1.9
C_{eu}/Λ^2	—	0.0006
C_{ed}/Λ^2	—	0.0005
C_{eq}/Λ^2	—	0.0004
C_{lu}/Λ^2	—	0.0006
C_{ld}/Λ^2	—	0.0009
C^-_{lq}/Λ^2	—	0.0006
C^+_{lq}/Λ^2	—	0.0005

For 2-lepton-2-quark operators inclusion we need at least one more energy point with tt production at the ILC.

Impact of Λ-4 terms

Λ-4 terms are included in the fit

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

	Λ^{-2} and Λ^{-4} terms	Λ^{-2} term only
$C_{\varphi t}/\Lambda^2$	$(-16, -2.4)$	$(-2.1, +4.5)$
$C^3_{\varphi Q}/\Lambda^2$	$(-1.9, -0.4)$	$(-0.7, +0.5)$
$C^1_{\varphi Q}/\Lambda^2$	$(-1, +1.7)$	$(-0.6, +0.7)$
C_{tW}/Λ^2	$(-0.4, +0.2)$	$(-0.42, +0.24)$
C_{tB}/Λ^2	$(-6.8, +5.6)$	$(-9.6, +38.4)$
$C_{t\varphi}/\Lambda^2$	$(-4.6, -0.4)$	$(-4.42, 0)$
$C_{\varphi b}/\Lambda^2$	$(-5.4, +0.2)$	$(-0.6, +0.2)$
C_{bW}/Λ^2	$(-2.6, +2.1)$	—
C_{bB}/Λ^2	$(-31.2, +2.4)$, $(+14.4, +18)$	—
$C_{\varphi tb}/\Lambda^2$	$(-5.2, 5.6)$	—

} Interference with the SM is 0 due to mb->0 approximation

Without Λ-4 terms we cannot constrain the entire basis

dim-8 operators are not included