The electro-weak couplings of the top quark
Precision today; prospects at the HL-LHC; comparison with e^+e^- colliders

Martín Perelló, Marcel Vos

IFIC, CSIC/UV, Valencia, Spain

CLIC week, CERN, 24 january 2019

Work in progress, preliminary results

Based on old work with Pöschl, Richard and I. García, more recent results with CLICdp and G. Durieux & C. Zhang, and ongoing work with S. Jung & J. Tian and others

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA
EXCELENCIA SEVERO OCHOA

The top quark

One of two SM particles to escape scrutiny at LEP

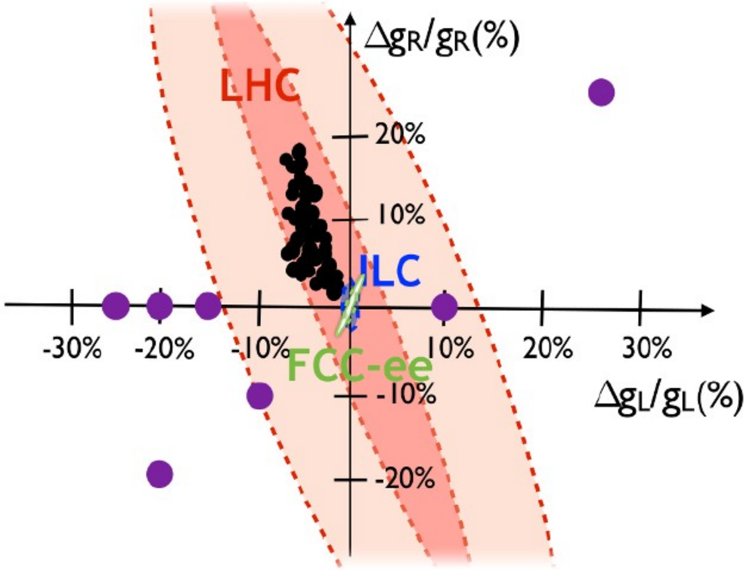
→ precise constraints on top (EW) couplings are missing

The SM particle with the closest connection to the Higgs

→ top Yukawa coupling is a key target of HEP

EW couplings of the top quark

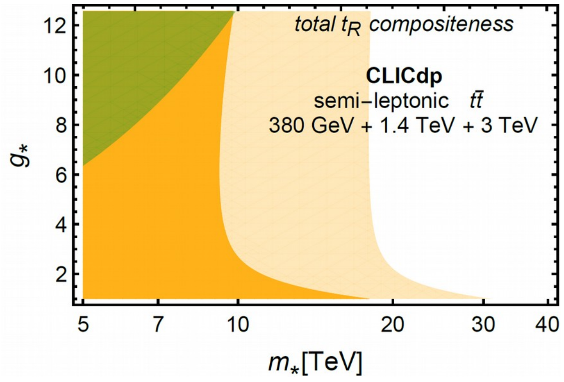
Large BSM family predicts sizeable deviations from SM prediction



- ● 5D models by several authors (A. Wulzer)
  Richard, arXiv:1403.2893

- ● 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)

Superseded by Durieux, Matsedonskiy?



marcel.vos@ific.uv.es

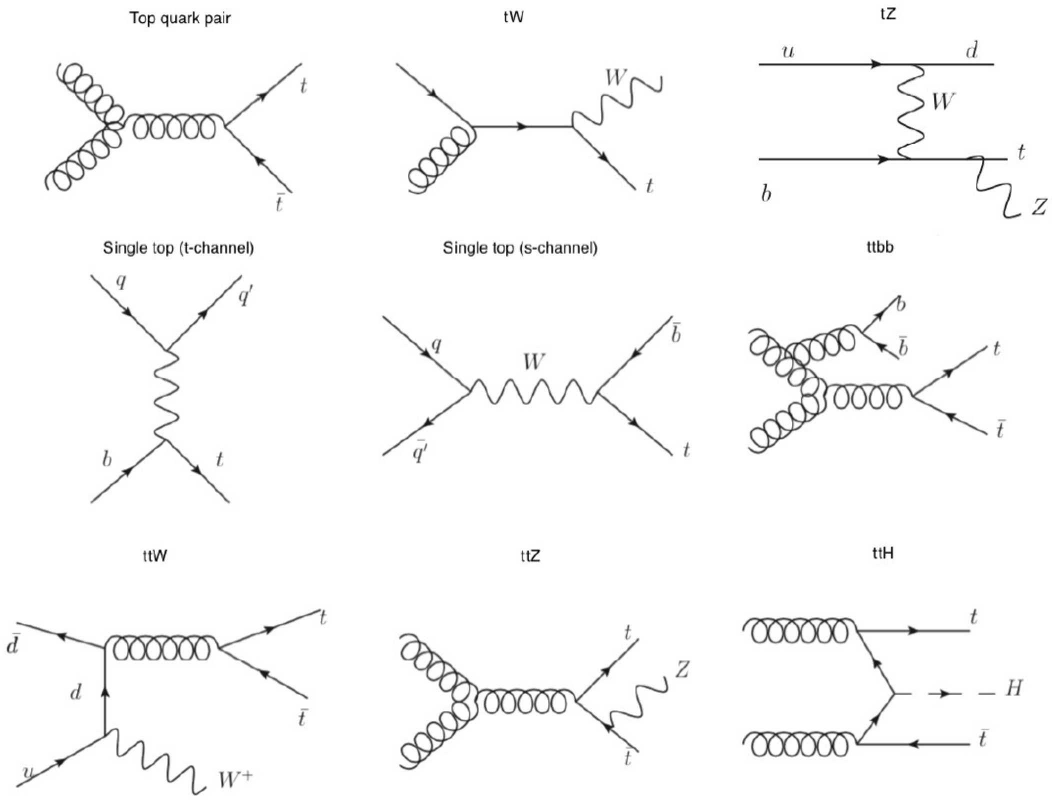
Top EW couplings at the LHC

Neutral current: ttZ, ttγ associated production (tZ, tγ)

→ processes “discovered”, cross section measurements 10-20%

Charged current: single top production, top decay observables

→ precision top physics at the LHC



Current status:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

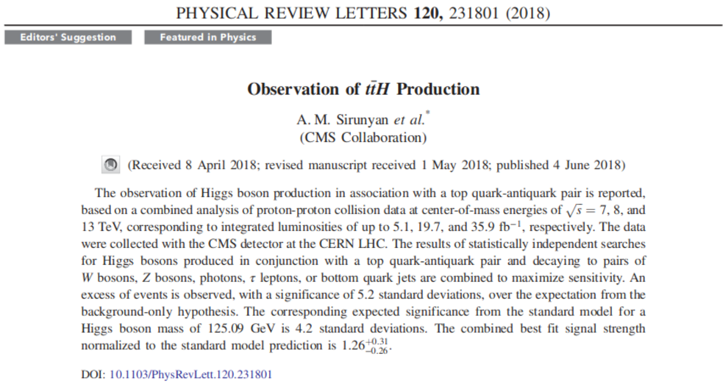
Prospect studies:

Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911
FCChh SM study, arXiv:1607.01831

LHC establishes $t\bar{t}$H production!

$t\bar{t}$H production observed in both ATLAS and CMS

Measurement of the top Yukawa coupling is competitive with indirect result



PHYSICAL REVIEW LETTERS **120,** 231801 (2018)

Editors' Suggestion　Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

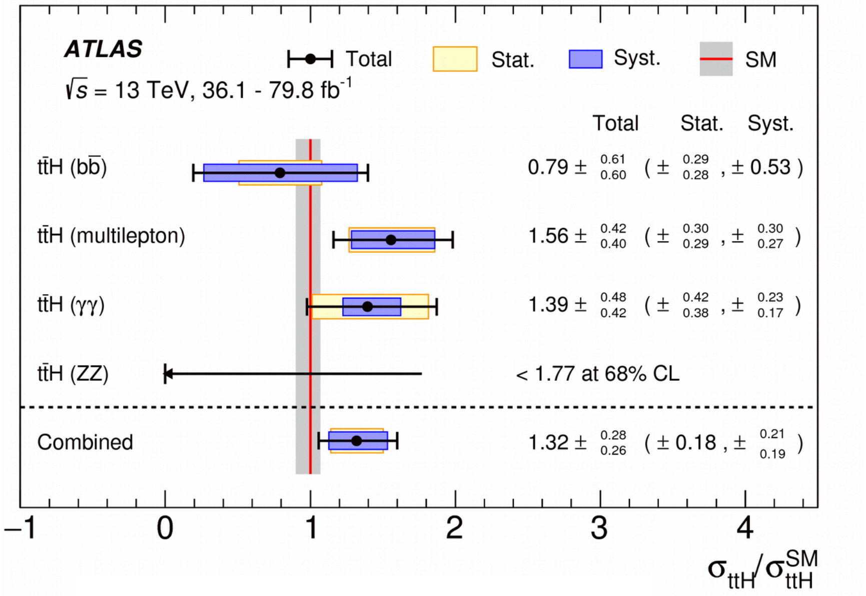
(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, and 35.9 fb^{-1}, respectively. The data were collected with the CMS detector at the CERN LHC. The results of statistically independent searches for Higgs bosons produced in conjunction with a top quark-antiquark pair and decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom quark jets are combined to maximize sensitivity. An excess of events is observed, with a significance of 5.2 standard deviations, over the expectation from the background-only hypothesis. The corresponding expected significance from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 standard deviations. The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-0.26}$.

DOI: 10.1103/PhysRevLett.120.231801

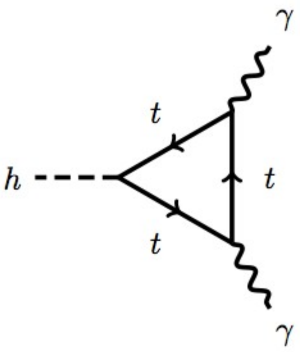
CMS, PRL 120, 231801 (2018)

ATLAS, PLB 784, 173-191 (2018)



indirect 8 TeV

Run I: $k_t = 1.43 \pm 0.23$

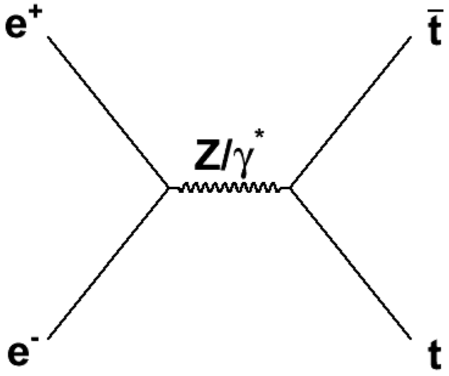


direct 13 TeV

CMS: $\mu_{ttH} = 1.26 \pm 0.3$

ATLAS: $\mu_{ttH} = 1.32 \pm 0.3$

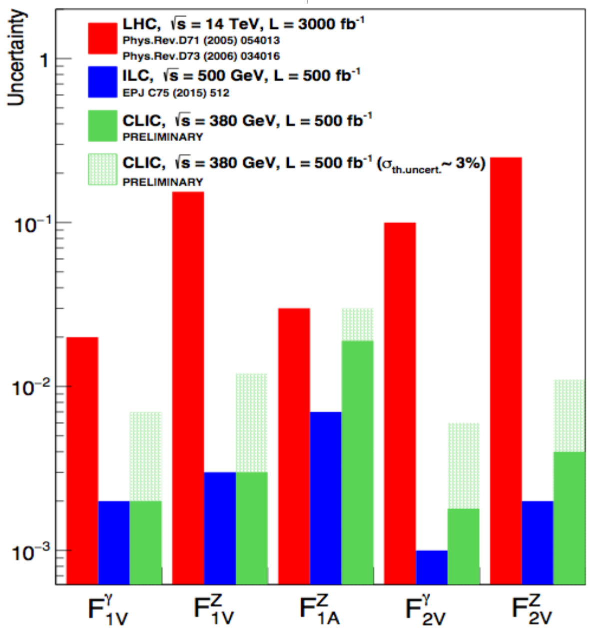
Top EW couplings at lepton colliders

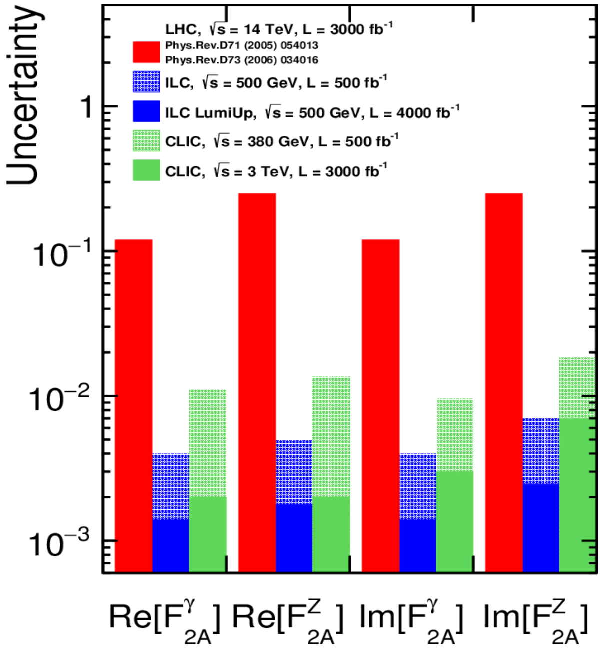


The best laboratory to test $\gamma t\bar{t}$ and $Zt\bar{t}$ vertices

FCC-ee, arXiv:1503.01325, 1509.09056
ILC di-lepton, arXiv:1503.04247

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





Prospects for HL-LHC/ILC500/CLIC380

arXiv:1307.8102, arXiv:1505.0620

EFT interpretation

Quantify BSM sensitivity in a model-agnostic way with limits on anomalous D6 operator coefficients in Effective Field Theory

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

EFT analyses “by sector” are becoming the standard interpretation for LHC analyses.

Very powerful benchmarking tool for future projects.

A linear collider can deliver the solid, and precise constraints that are crucial for a global SM EFT fit.

top EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

Circular
Collider
350+365

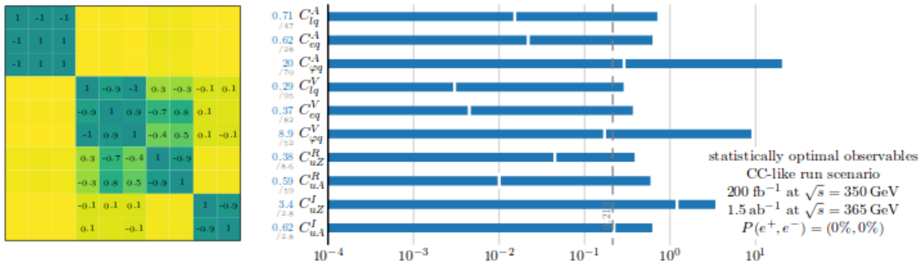


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

Sensitivity to four-fermion operators increases strongly with energy (see F. Riva, G. Durieux, this workshop)

ILC500+
ILC1000

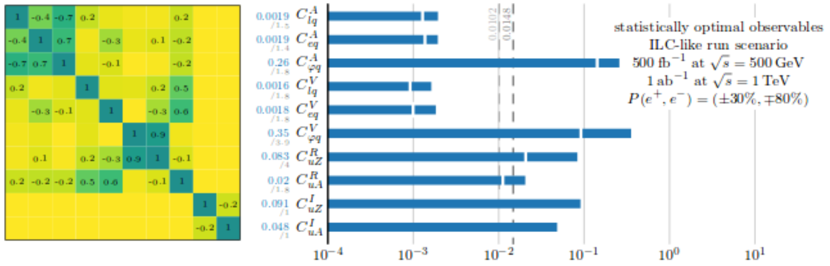


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

CLIC380+
CLIC1500+
CLIC3000

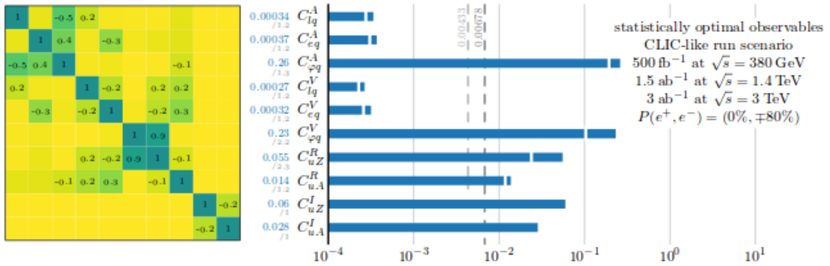


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

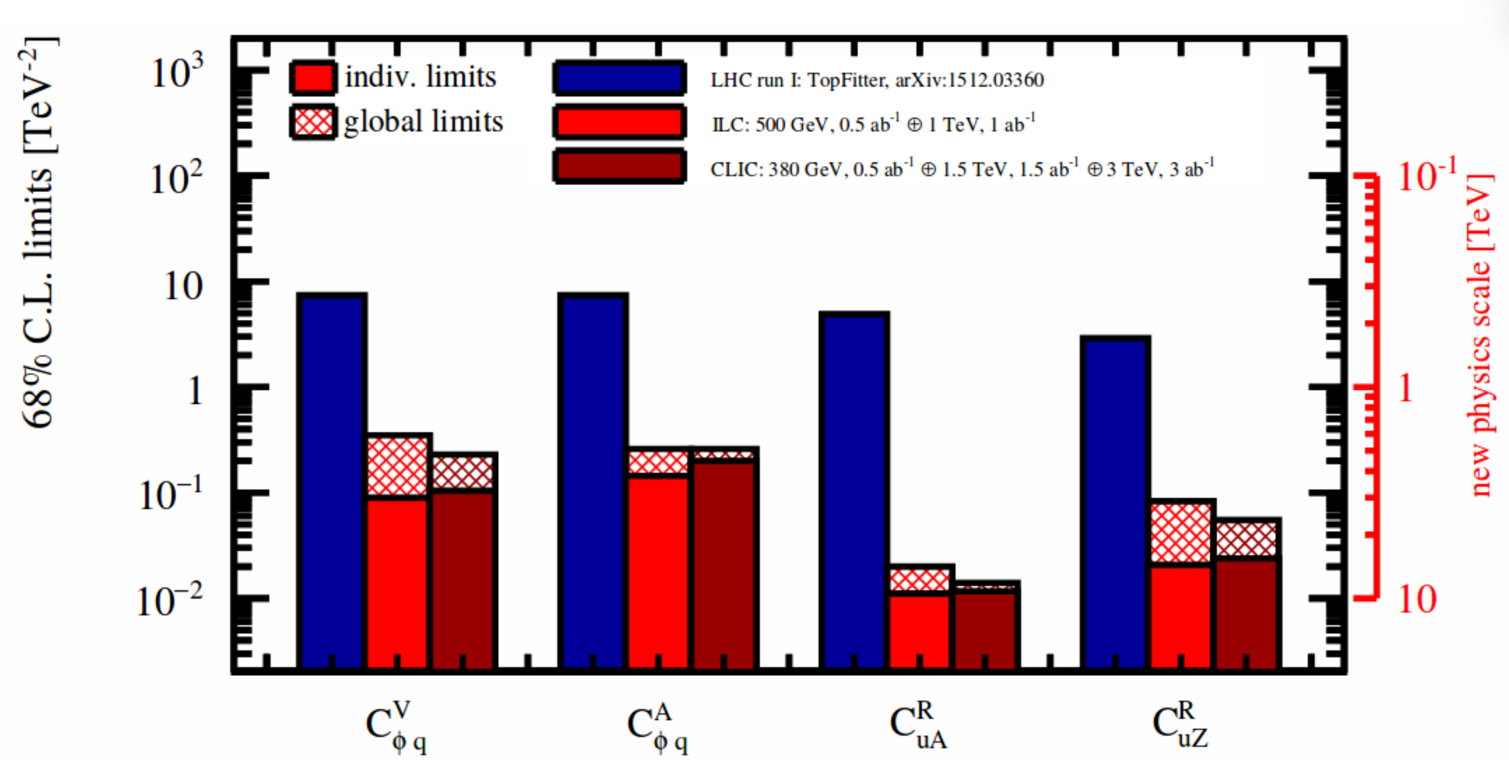
Warning: versions with old luminosity

marcel.vos@ific.uv.es

Top EFT fit at the LC

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441



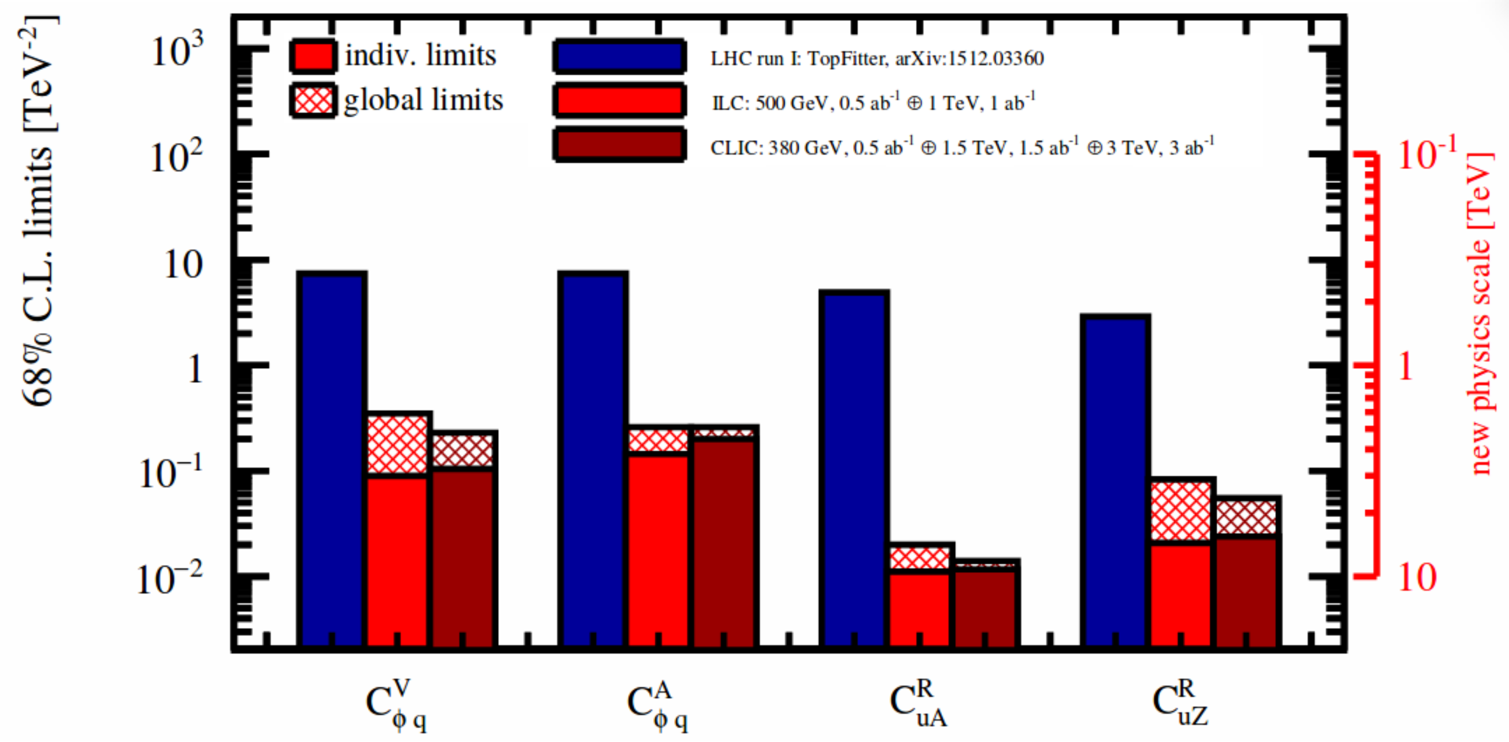
Two-fermion operator limits exceed HL-LHC prospects by two orders of magnitude

Constraints on 4-fermion operators cannot be compared trivially – left out

Top EFT fit at the LC

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441

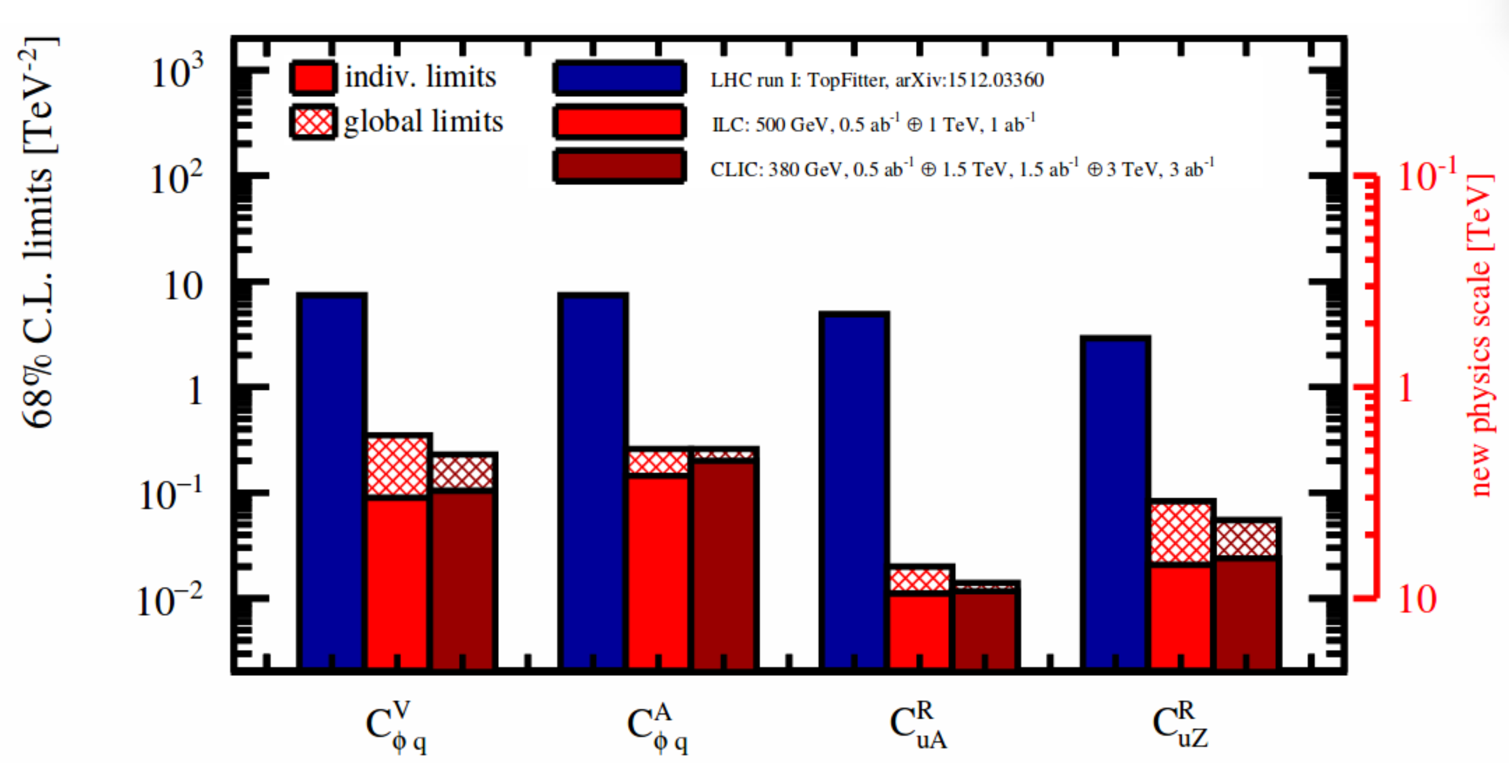


A reasonably simple plot to compare initial LC potential with LHC in one glance

marcel.vos@ific.uv.es

Top EFT fit at the LC

Durieux, Perello, Zhang, Vos, arXiv:1807.02121
CLICdp top paper, arXiv:1807.02441



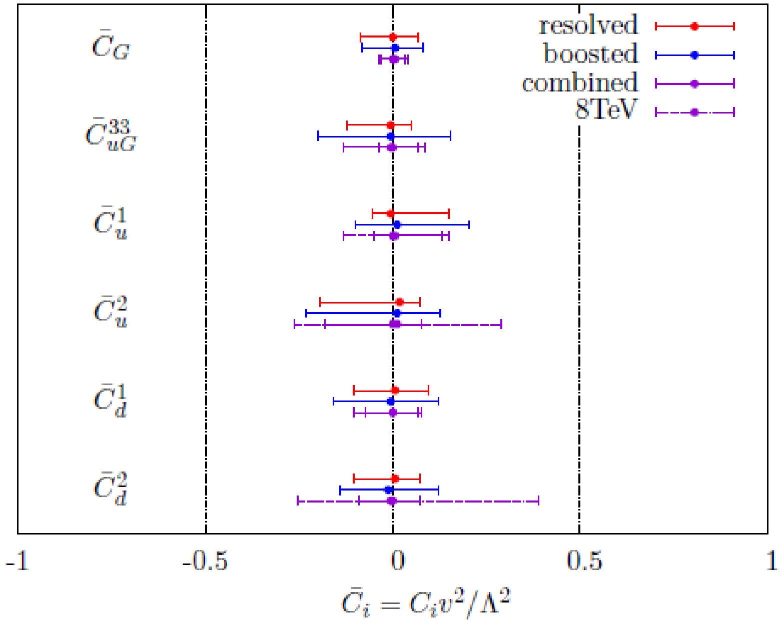
A reasonably simple plot to compare LC potential with LHC in one glance, however:

→ LHC is evolving
→ HL-LHC prospects are missing (and so are HE-LHC, SPPC, FCChh)
→ FCCee prospects are missing

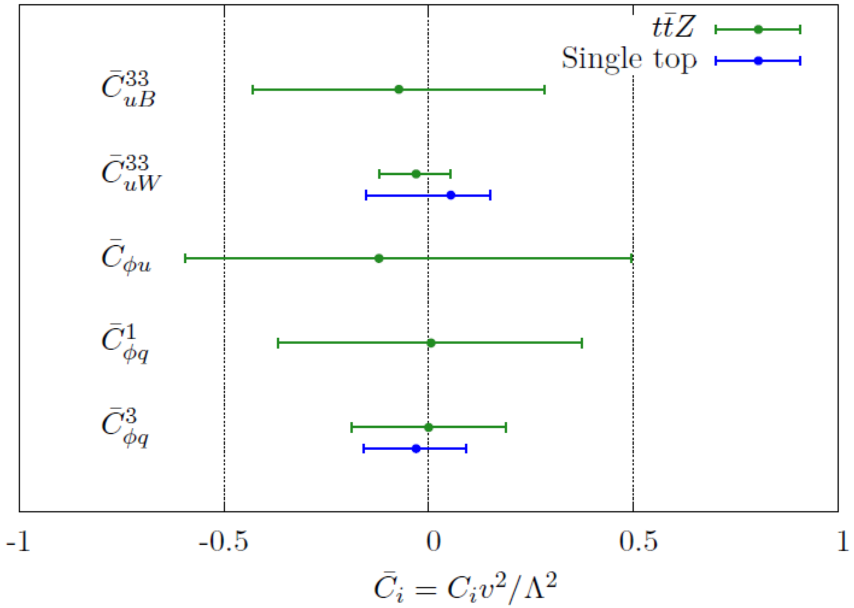
EFT constraints on top quark operators from the LHC

Very tight constraints on the QCD operators (ttg, ttqq)

First, weak limits on operators that affect top EW interactions



Differential cross section measurements
Englert et al., arXiv:1607.04304

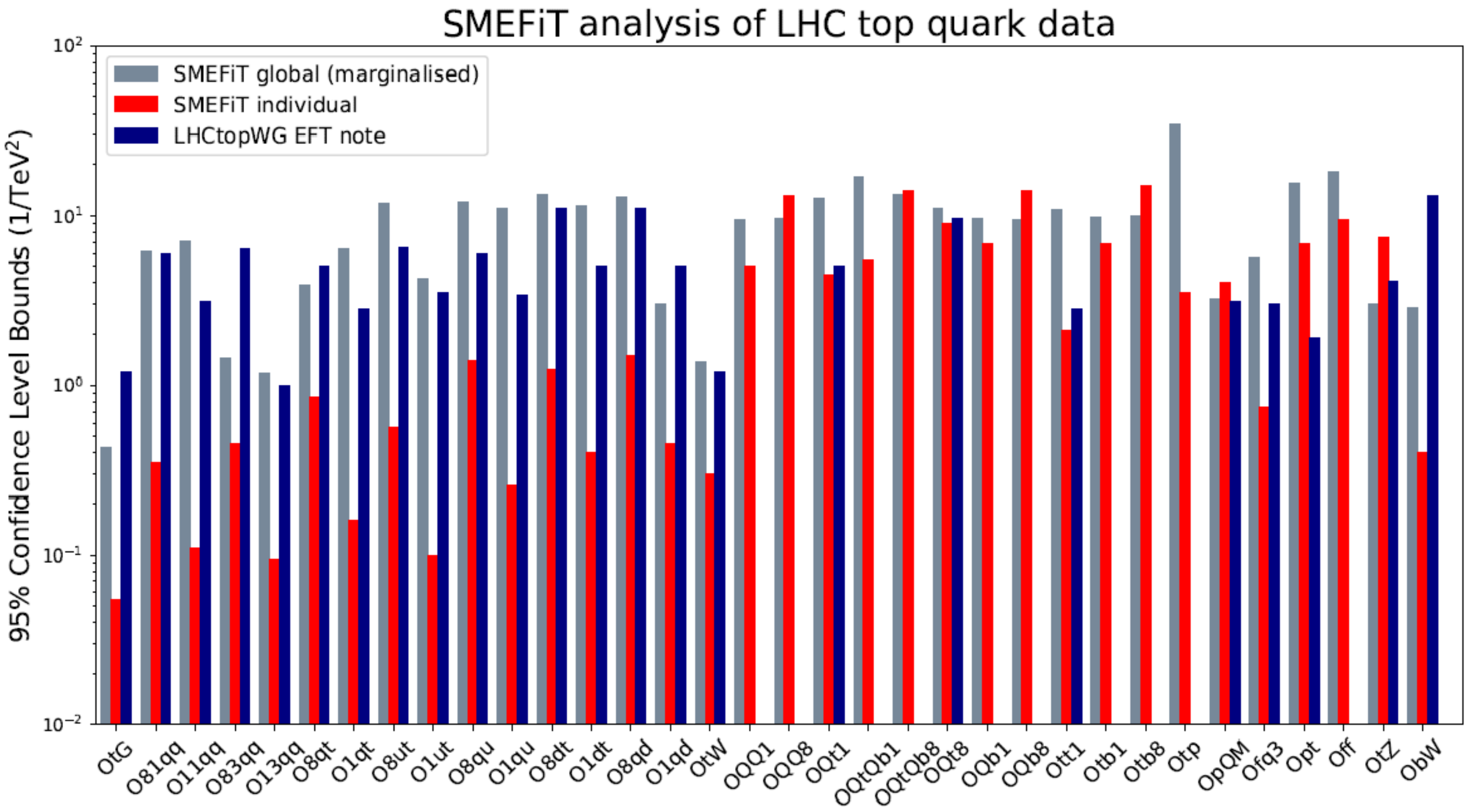


Rare associated production processes yield limits on top quark EW couplings
arXiv:1506.08845, arXiv:1512.03360

Further progress to come from the exploration of regions with enhanced sensitivity and new SM processes (ttH, ttZ, ttW, ttγ, tZ, tγ,...)

New: global fit to the top sector

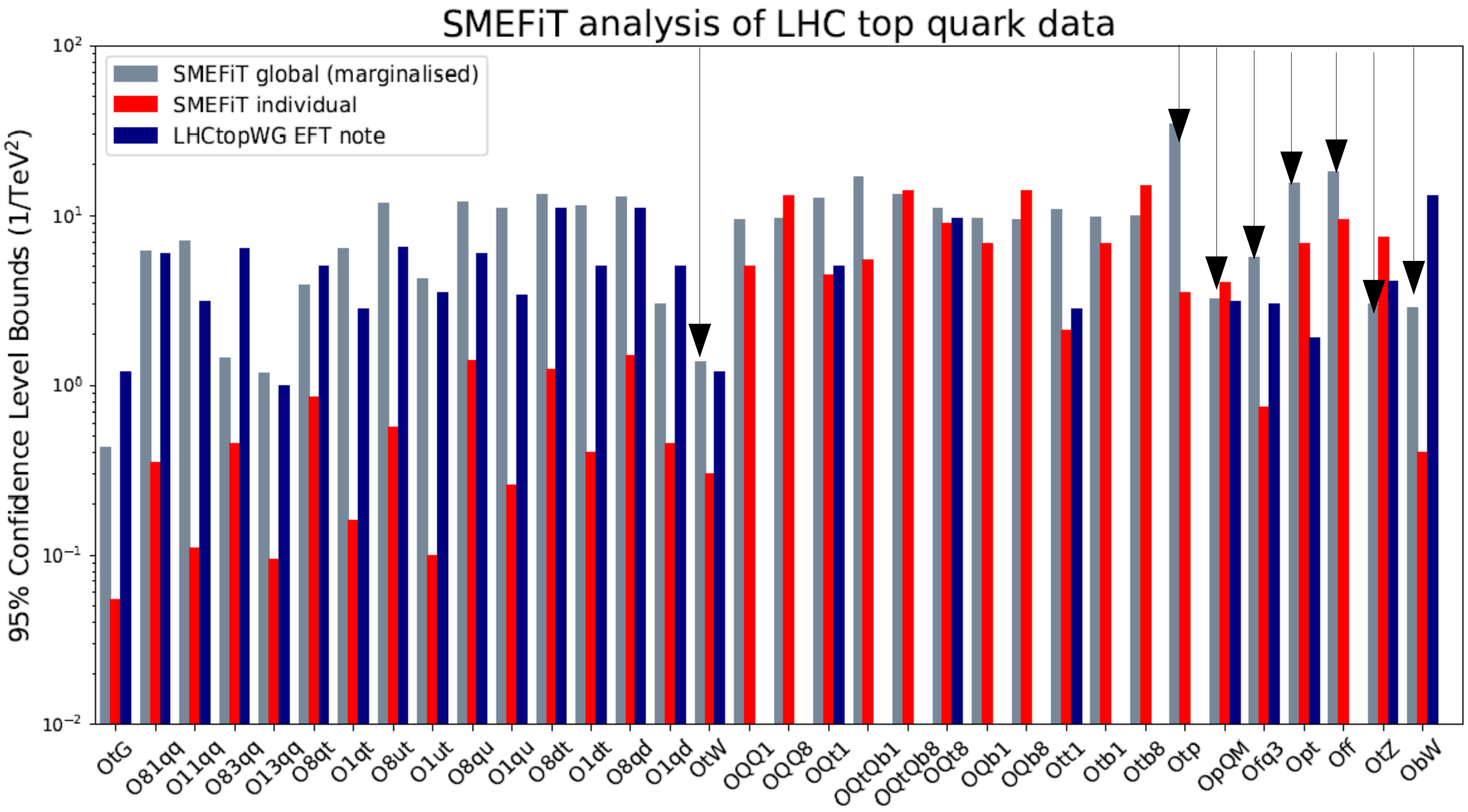
Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang, arXiv:1901.05965


SMEFiT analysis of LHC top quark data

34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD : very good individual limits ~0.1, global limits O(1)

New: global fit to the top sector

Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang, arXiv:1901.05965



34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)
Top QCD : very good individual limits ~0.1-1, global limits O(1-10)
Top EW : poorer individual limits, typically O(several), first global results!

A simpler fit

Identify an “isolated system” of top EW operators

$C_{t\phi}$ = modifies top Yukawa
$C^1_{\phi Q}$ = modifies left-handed coupling of top quark
$C^3_{\phi Q}$ = idem.
$C_{\phi t}$ = modifies right-handed coupling of top quark
C_{tW} = top dipole moment
C_{tB} = idem.
$C_{\phi b}$ = bottom quark
C_{dW} = bottom quark dipole

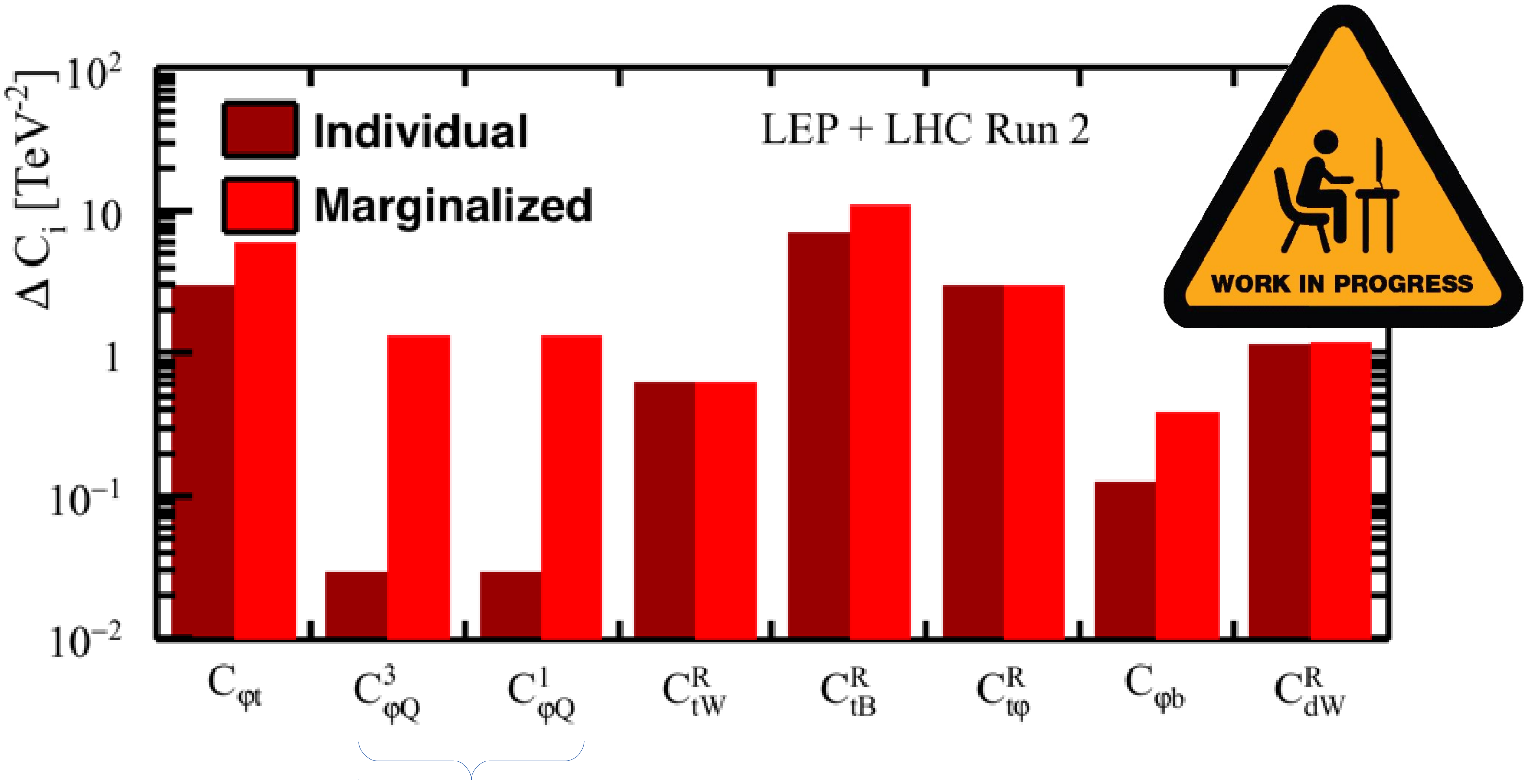
Shared with bottom quark
→ LEP constraints

Bottom quark operators: the prize to pay for including $e^+e^- \rightarrow b\bar{b}$ constraints

Does not include QCD operators, which are tightly constrained
Does not include $llt\bar{t}$ four-fermion operators, like (most) other analyses
Does not include CP-violating interactions, which can be constrained very well

Dedicated fit to top EW operators

Dedicated fit using only top EW operators [M. Perelló, M. Vos, preliminary]

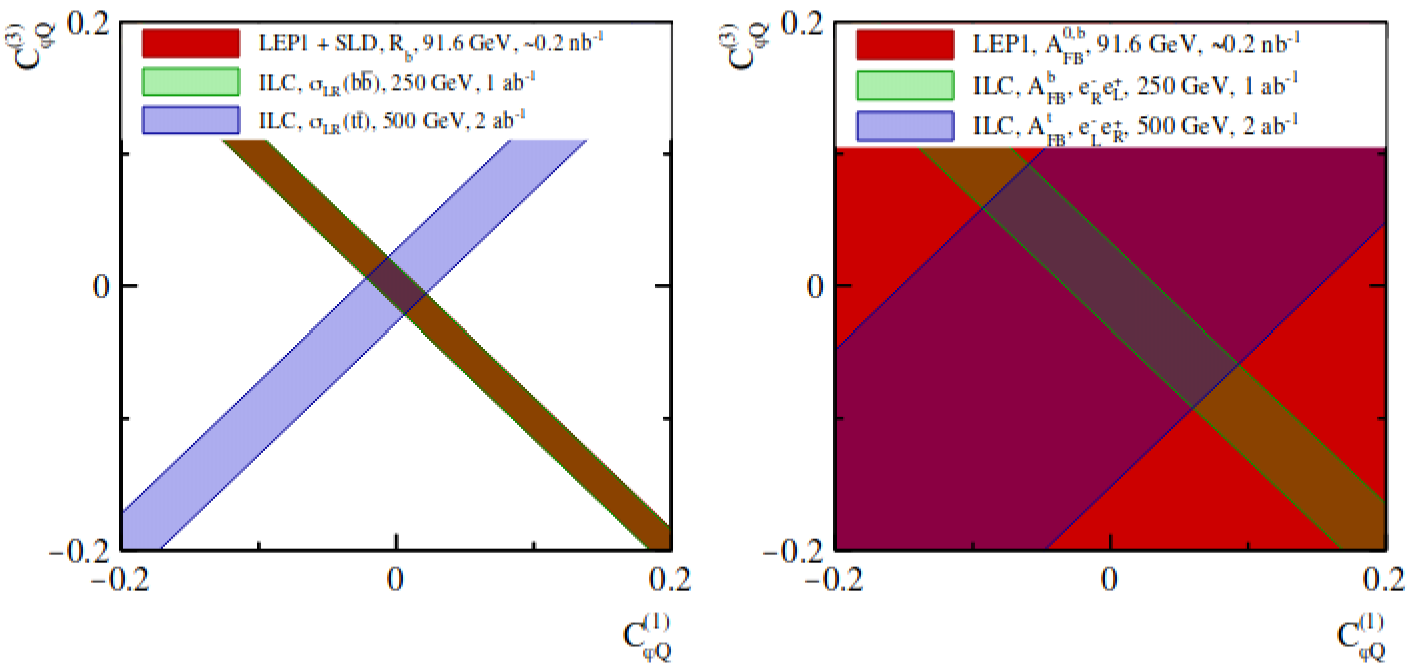


Tight constraint from LEP run I (R_b + asymmetries) on common operators (b, t)

For all other operators, global results are similar to individual limits

→ HepFit implementation with IFIC theory (A. Pich, A. Peñuelas, V. Miralles)

EFT: combined bottom-top fit



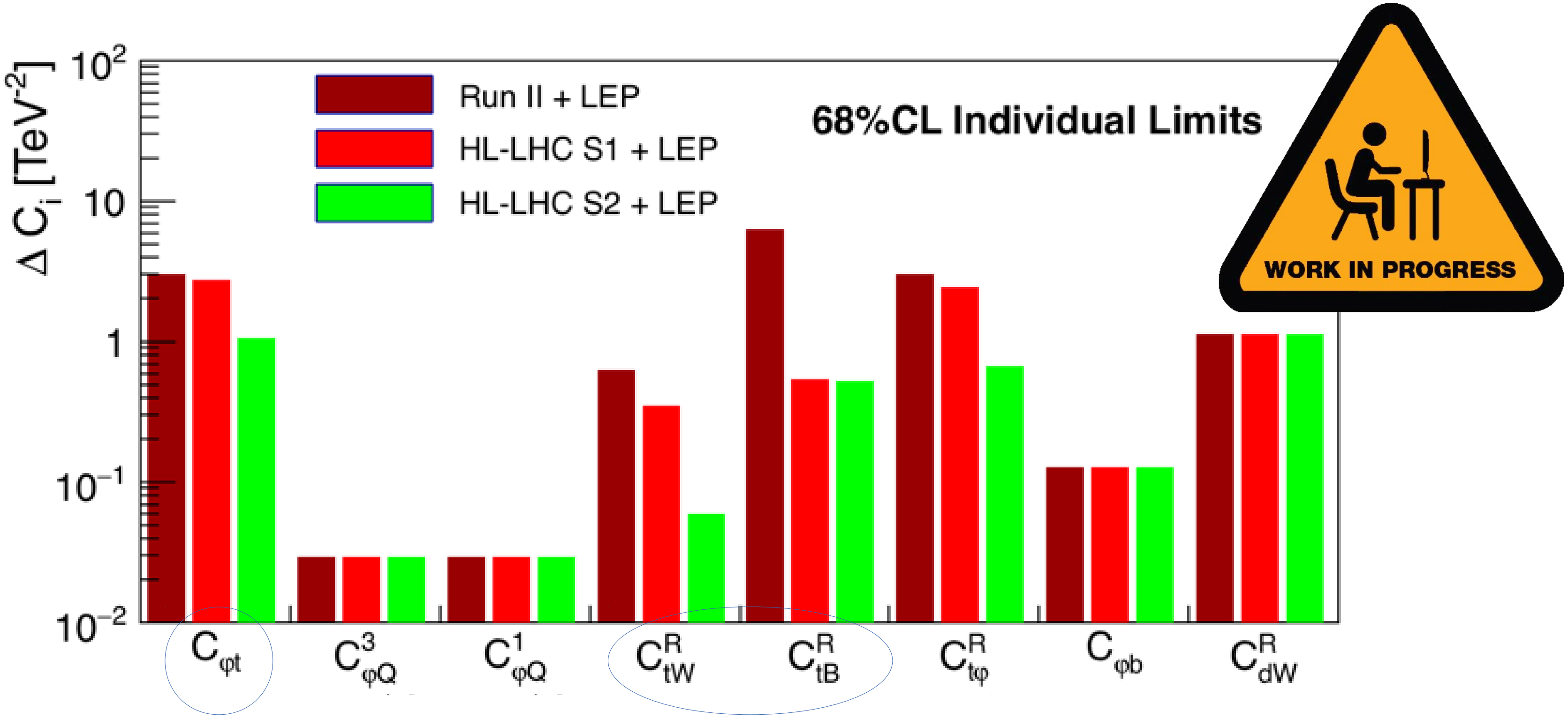
Bottom production provides an exactly complementary constraint

Other possibilities (top width, W polarization, $b\bar{b}Z$ production at LHC) provide complementary information, but of relatively poor precision.

marcel.vos@ific.uv.es

Dedicated fit to top EW operators: prospects

Dedicated fit using only top EW operators [M. Perelló, M. Vos, preliminary]



Individual limits expected to evolve with time:

- S1: reduce stat. uncertainty, but keep today's systematics
- S2: evolve exp. systematics with 1/sqrt(L), divide theory uncertainty by 2

To be superseded by more informed prospects from HL-LHC yellow report

Some limits saturate, but several important coefficients improve considerably

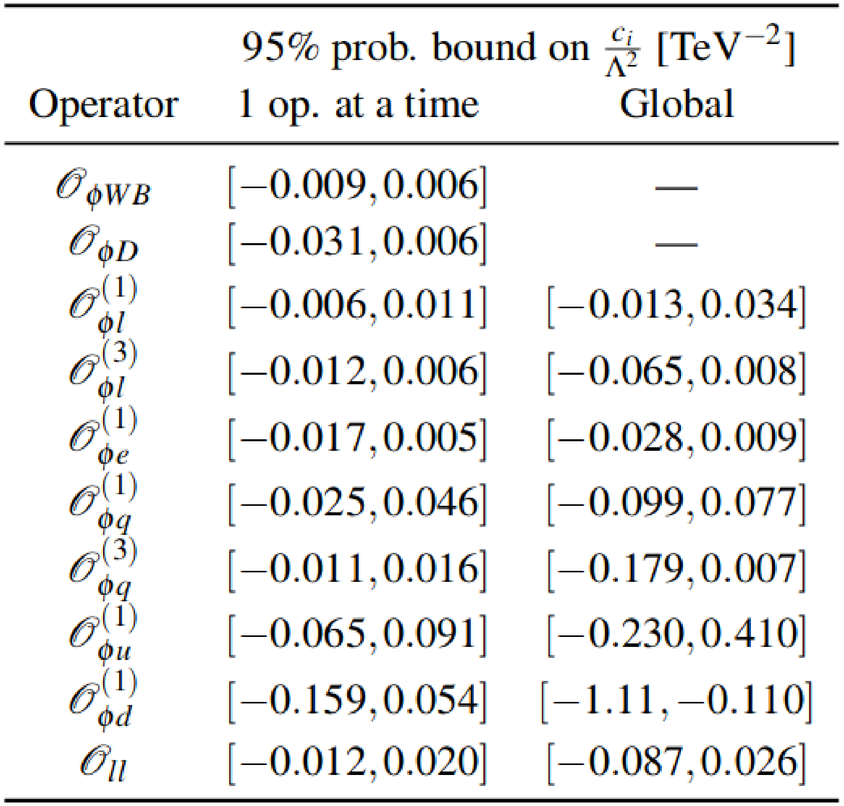
marcel.vos@ific.uv.es

Further EWPO constraints

In arXiv:1611.05343 de Blas et al. find very tight constraints on several operators from EW precision observables

The limits on the left-handed coupling are similar to ours (tree-level → R_b)

EWPO also provides very powerful limits on the right-handed coupling

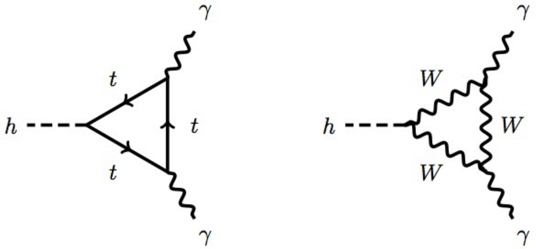


	95% prob. bound on $\frac{c_i}{\Lambda^2}$ [TeV^{-2}]	
Operator	1 op. at a time	Global
$\mathcal{O}_{\phi WB}$	$[-0.009, 0.006]$	—
$\mathcal{O}_{\phi D}$	$[-0.031, 0.006]$	—
$\mathcal{O}_{\phi l}^{(1)}$	$[-0.006, 0.011]$	$[-0.013, 0.034]$
$\mathcal{O}_{\phi l}^{(3)}$	$[-0.012, 0.006]$	$[-0.065, 0.008]$
$\mathcal{O}_{\phi e}^{(1)}$	$[-0.017, 0.005]$	$[-0.028, 0.009]$
$\mathcal{O}_{\phi q}^{(1)}$	$[-0.025, 0.046]$	$[-0.099, 0.077]$
$\mathcal{O}_{\phi q}^{(3)}$	$[-0.011, 0.016]$	$[-0.179, 0.007]$
$\mathcal{O}_{\phi u}^{(1)}$	$[-0.065, 0.091]$	$[-0.230, 0.410]$
$\mathcal{O}_{\phi d}^{(1)}$	$[-0.159, 0.054]$	$[-1.11, -0.110]$
$\mathcal{O}_{ll}$	$[-0.012, 0.020]$	$[-0.087, 0.026]$

Feeding into a global fit

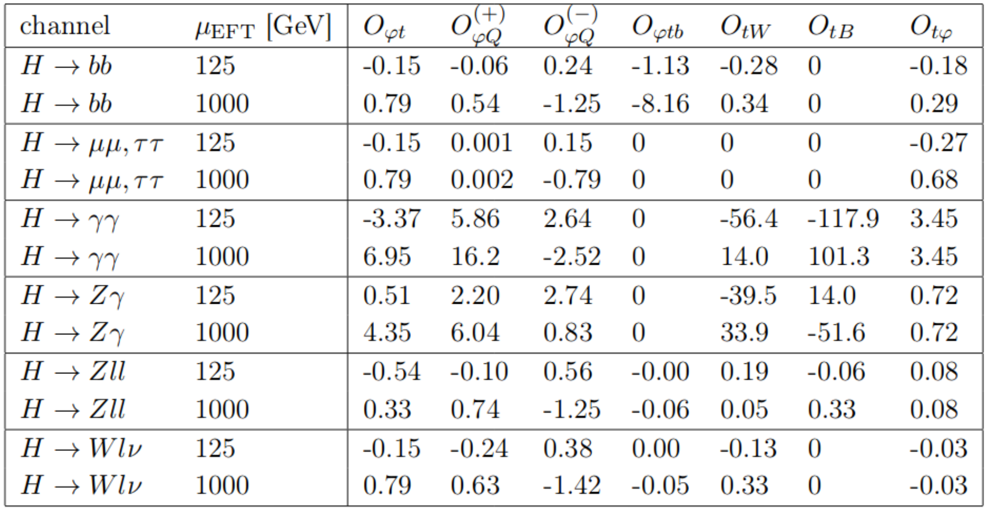
marcel.vos@ific.uv.es

A combined Higgs-top-EW EFT fit?



The Higgs branching ratios depend on top EW couplings

NLO calculation of relation between Higgs observables and top EFT operator Wilson coefficients became available in 2018
Vryonidou & Zhang, arXiv:1804.09766



channel	μ_{EFT} [GeV]	$O_{\varphi t}$	$O_{\varphi Q}^{(+)}$	$O_{\varphi Q}^{(-)}$	$O_{\varphi tb}$	O_{tW}	O_{tB}	$O_{t\varphi}$
$H \to bb$	125	-0.15	-0.06	0.24	-1.13	-0.28	0	-0.18
$H \to bb$	1000	0.79	0.54	-1.25	-8.16	0.34	0	0.29
$H \to \mu\mu, \tau\tau$	125	-0.15	0.001	0.15	0	0	0	-0.27
$H \to \mu\mu, \tau\tau$	1000	0.79	0.002	-0.79	0	0	0	0.68
$H \to \gamma\gamma$	125	-3.37	5.86	2.64	0	-56.4	-117.9	3.45
$H \to \gamma\gamma$	1000	6.95	16.2	-2.52	0	14.0	101.3	3.45
$H \to Z\gamma$	125	0.51	2.20	2.74	0	-39.5	14.0	0.72
$H \to Z\gamma$	1000	4.35	6.04	0.83	0	33.9	-51.6	0.72
$H \to Zll$	125	-0.54	-0.10	0.56	-0.00	0.19	-0.06	0.08
$H \to Zll$	1000	0.33	0.74	-1.25	-0.06	0.05	0.33	0.08
$H \to Wl\nu$	125	-0.15	-0.24	0.38	0.00	-0.13	0	-0.03
$H \to Wl\nu$	1000	0.79	0.63	-1.42	-0.05	0.33	0	-0.03

Table 1. Percentage deviation μ_{ij} for decay channel i and operator j.

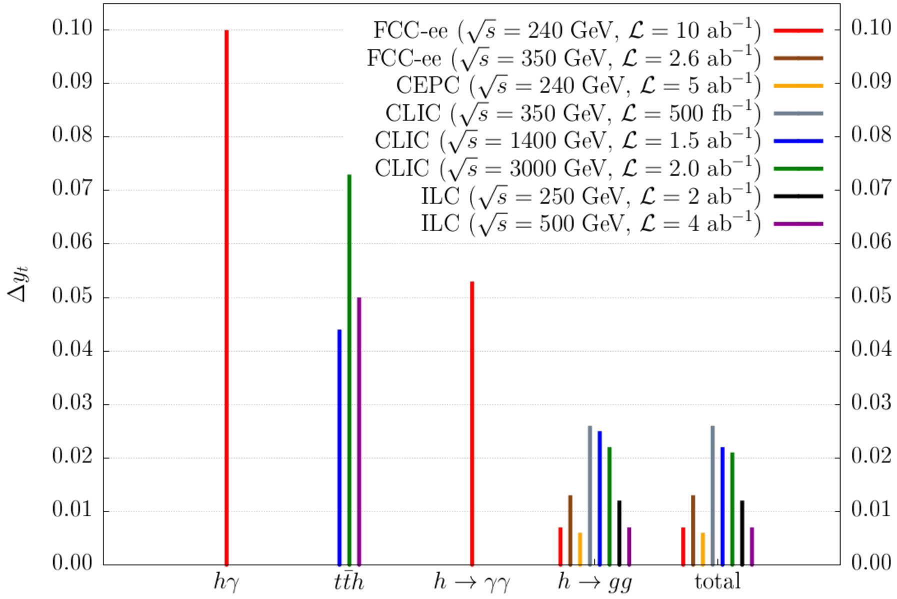
Coefficients are large /existing constraints are poor. Cannot ignore the top EW operators in a global EFT analysis. Especially pressing for a 250 GeV collider.
Durieux et al., arXiv:1809.03520

Example: indirect top Yukawa coupling

Mitov et al., arXiv:1805.12027

$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma^{\rm SM}_{h\to gg}} = 1 + 2\Delta y_t\,,$$

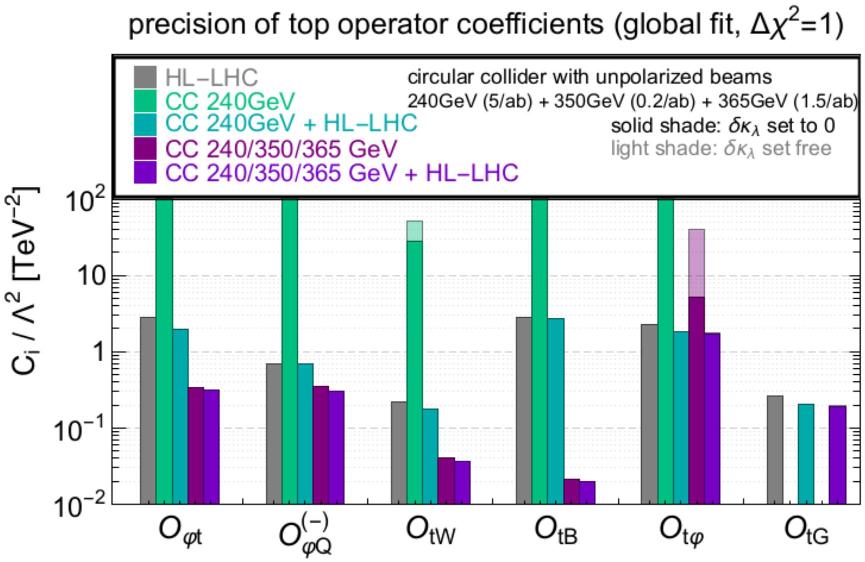
$$\mu_{h\to\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{\rm SM}_{h\to\gamma\gamma}} = 1 - 0.56\Delta y_t\,.$$



H → gg rate <u>at 250 GeV</u> yields a

1% precision on top Yukawa coupling in a one-parameter fit

S. Jung, J. Tian, M. Perelló:
H → $\gamma\gamma$ as powerful as H → gg



But… result for top Yukawa coupling is

not robust in a global analysis.

Durieux et al., arXiv:1809.03520

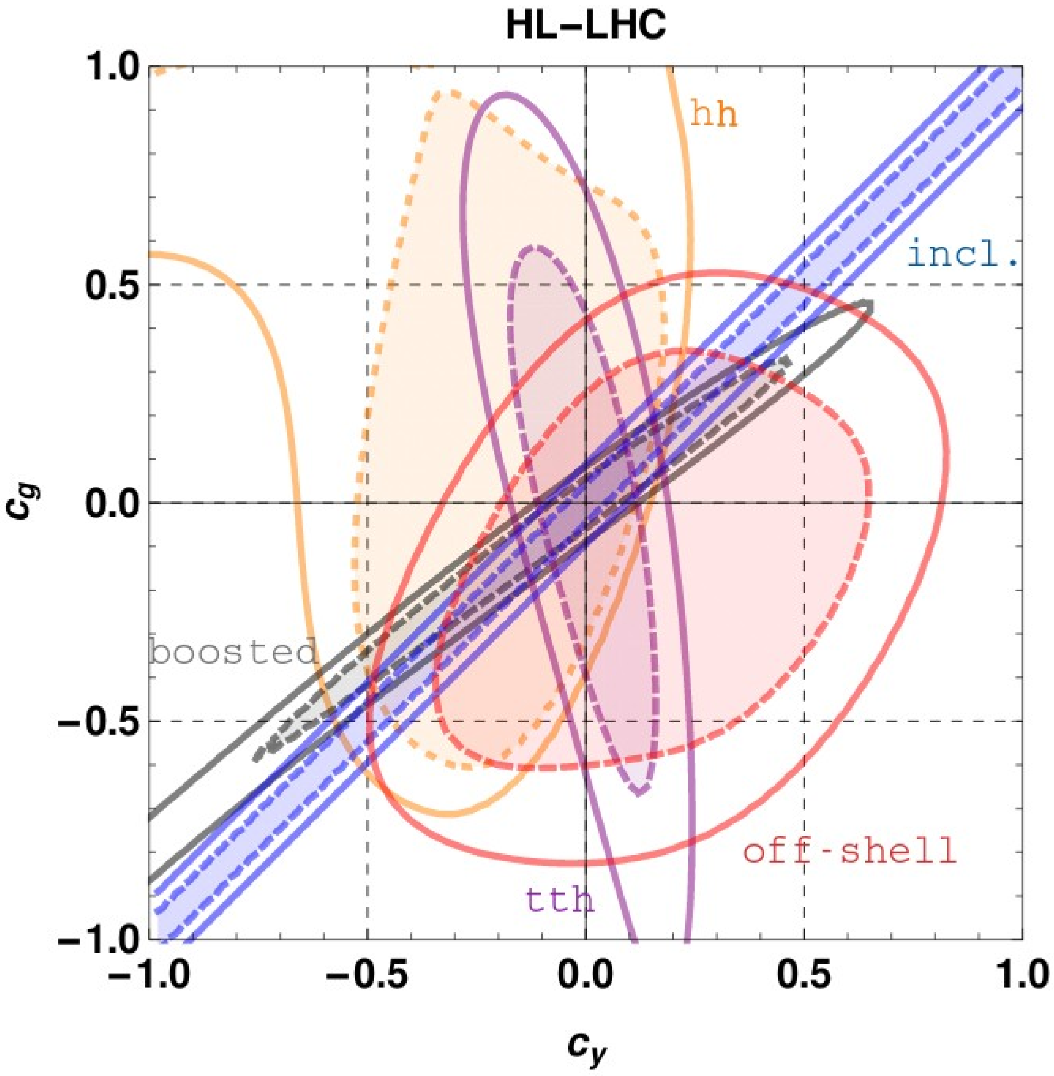
The top Yukawa coupling: global analysis at the LHC

The indirect constraint on the top Yukawa coupling from top loops in gg → H (and H → γγ) is quite powerful

In a global EFT analysis it is very hard to distinguish the effect of a direct Hgg coupling (c_g) from that of the operator that modifies the top Yukawa coupling (c_y)

Direct measurement in $t\bar{t}$H is necessary in a global analysis

Azatov et al., arXiv:1608.00977



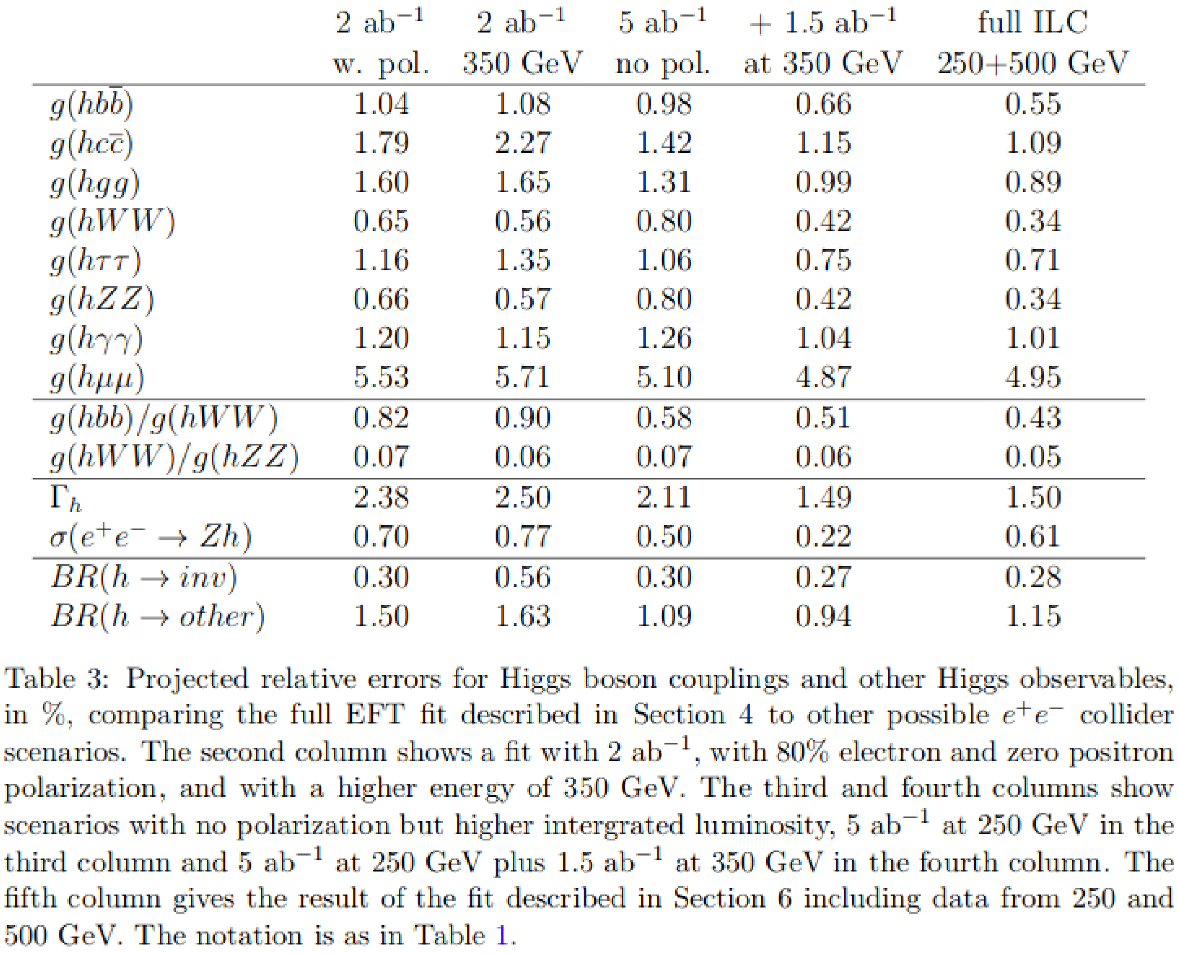
marcel.vos@ific.uv.es

Towards a global analysis

Linear collider fit of
the Higgs sector
arXiv:1708.08912

20 operator coefficients

EWPO + TGC + Higgs data

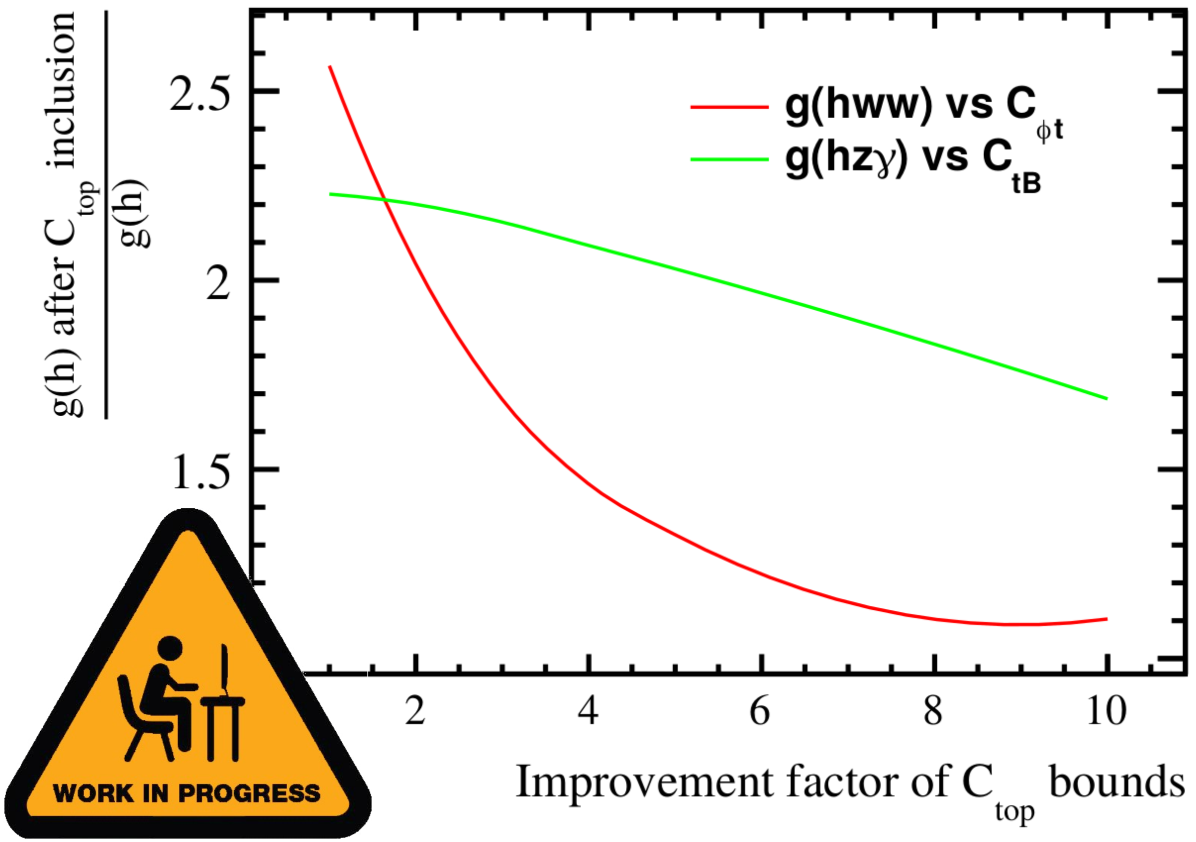


	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

Table 3: Projected relative errors for Higgs boson couplings and other Higgs observables, in %, comparing the full EFT fit described in Section 4 to other possible e^+e^- collider scenarios. The second column shows a fit with 2 ab^{-1}, with 80% electron and zero positron polarization, and with a higher energy of 350 GeV. The third and fourth columns show scenarios with no polarization but higher intergrated luminosity, 5 ab^{-1} at 250 GeV in the third column and 5 ab^{-1} at 250 GeV plus 1.5 ab^{-1} at 350 GeV in the fourth column. The fifth column gives the result of the fit described in Section 6 including data from 250 and 500 GeV. The notation is as in Table 1.

Adding top EW operators
(based partially on
Vryonidou & Zhang)
With S. Jung & J. Tian

Towards a global analysis: ILC250 + LEP + HL-LHC



Degradation of Higgs parameters due to inclusion of top parameters

Improvement of top operator limits wrt TopFitter results

Visualize the evolution for the worst combinations of Higgs and top parameters:

g(hWW) vs. $C_{\phi t}$ → factor 5 improvement restores fit to within 20% of previous result

g(hZγ) vs. C_{tB} → factor 10 is not enough

Future directions

Top quark EW couplings: future directions

Collect realistic LEP, LHC run 2 results + HL-LHC & ILC/CLIC prospects for relevant top physics measurements

→ *Dedicated top-EW fit on LEP+LHC run 2 close to final*
→ *Repeat on HL-LHC prospects from yellow report*
→ *Compare with ILC and CLIC prospects*

Merge EFT fits for EW precision + Higgs + top + ...

→ *work ongoing with Junping Tian and Sunghoon Jung*

Prepare comparison of global potential of future projects