The golden couple of the SM:
top and Higgs at present and future colliders

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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

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The Higgs boson

In 2012, the LHC discovers a new, fundamental scalar

→ interactions tested so far compatible with a Higgs boson

With the discovery of the Higgs boson the SM is complete

→ focus shifting from searches to tests of SM internal consistency

The Higgs boson is a probe to physics beyond the SM

→ focus of HEP and this workshop

The top quark

The other SM particle 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

(see talks by Yandong Liu and Kaori Fuyuto at this workshop)

The top quark has a special role in SM extensions

→ light stop in SUSY, composite top in composite Higgs models

(see talks by Stefania de Curtis and Rikard Enberg later at this workshop)

Top and Higgs

The message of this talk:

A precise knowledge of the top quark is important for Higgs physics…

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Top and Higgs

The message of this talk:

Even if you think the top quark is boring you may be forced to understand it…

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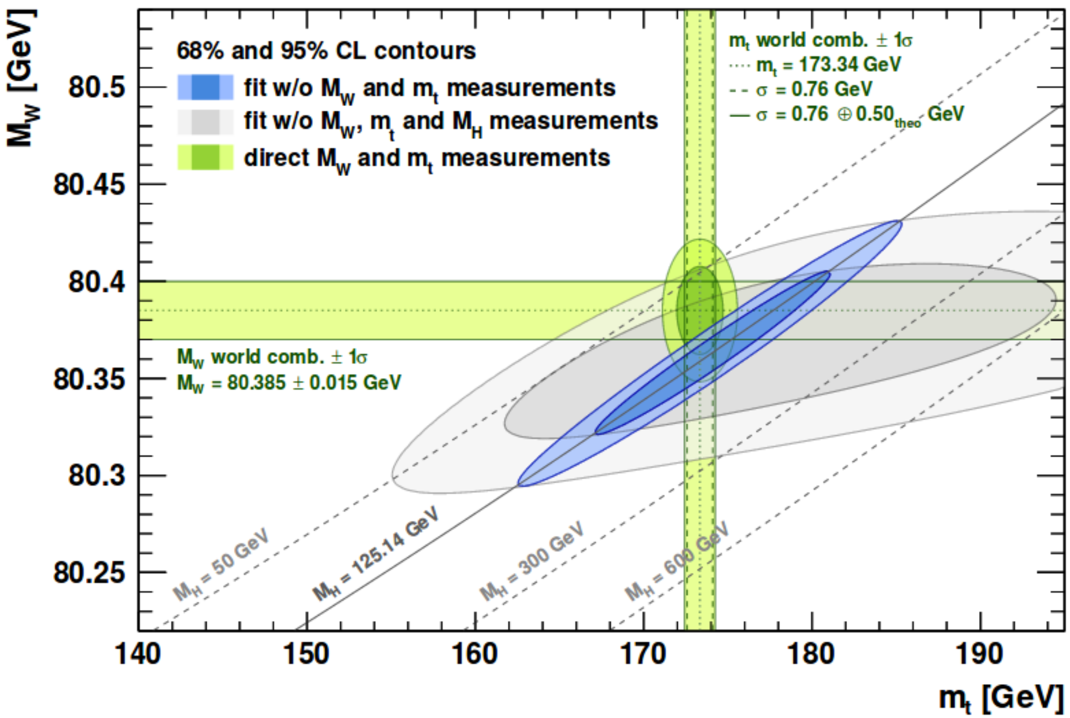
A well-known example: the EW fit



The Electroweak fit forms a stringent test of the internal consistency of the Standard Model

M. Baak et al., arXiv:1407.3792

Top mass may drive the Higgs potential at high scale negative

(But universe not likely to decay any time soon)

Buttazzo et al arXiv:1307.3536v4
V. Branchina at this workshop

Top mass at hadron colliders

Tev.+LHC top mass combination (2014): m_t = 173.3 ± 0.7 GeV (arXiv:1403.4427)

Baak et al. add 500 MeV theory uncertainty

Electroweak fit yields indirect
m_W = 80.354 ± 8 MeV

Error budget dominated by m_t

m_t: 5 MeV

m_Z: 2.5 MeV

m_H: 1 MeV

α_s: 2 MeV

Balance is important: must match the precision of several measurements to achieve the ultimate closure test of the Standard Model

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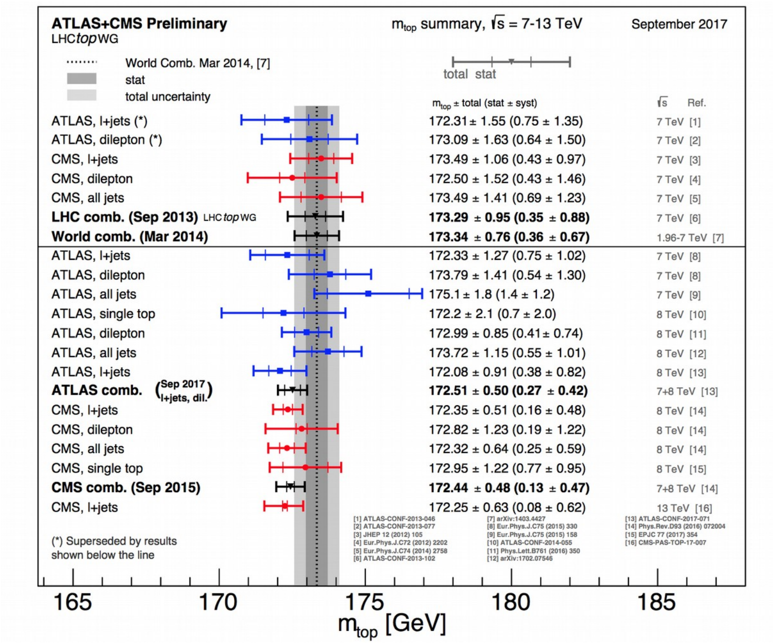
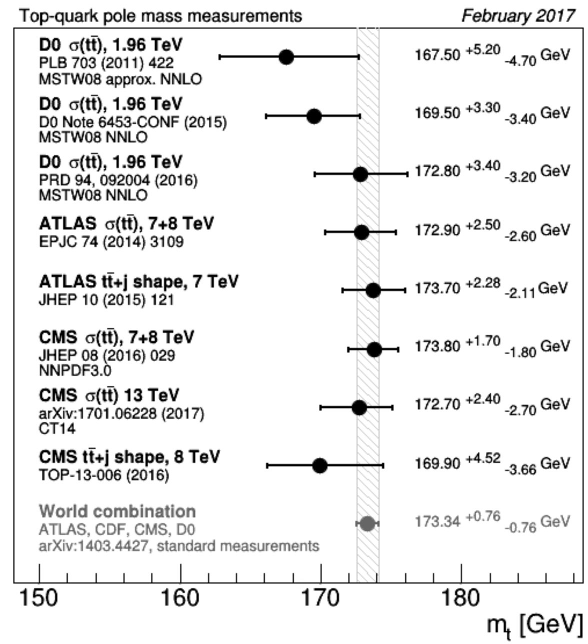
Top mass at hadron colliders

Direct mass



Pole mass



LHC 3 ab^{-1} prospects:

$\Delta m_t = \pm\, 0.2$ (exp.) $\pm$? GeV

(arXiv:1902.04070)

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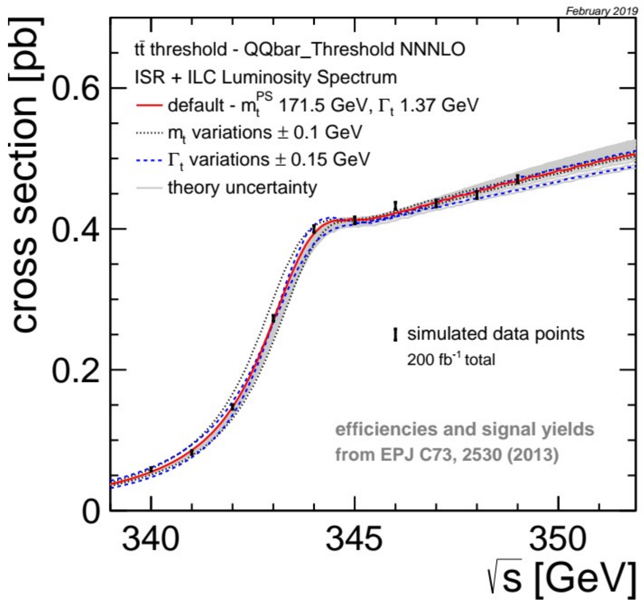
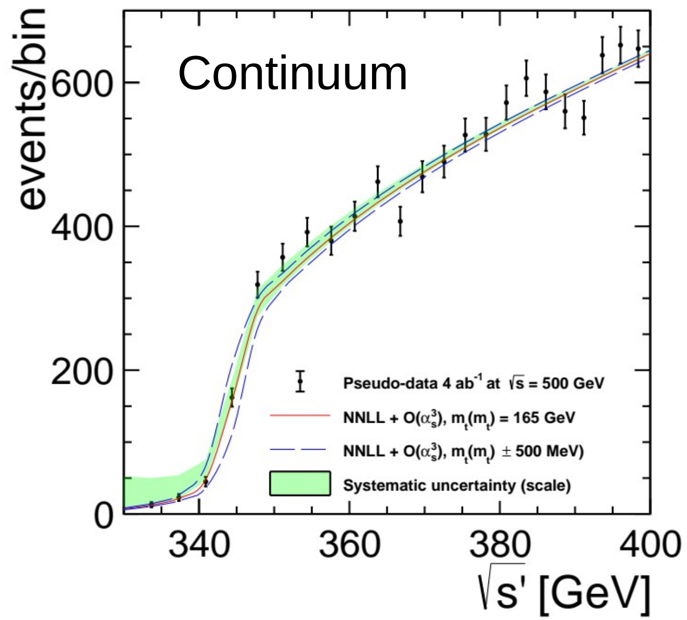
Top mass at e^+e^- colliders

Threshold scan: 50 MeV



Radiative: 100 MeV



A multi-parameter fit can extract a threshold mass with excellent precision

Statistical uncertainty:	~20 MeV	*200 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^{3}LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental syst:	25-50 MeV	*including LS, arXiv:1309.0372*

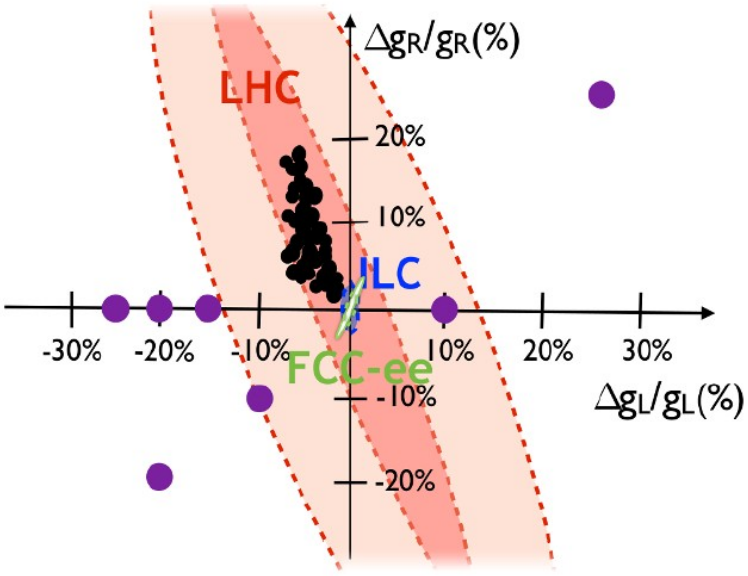
This threshold mass can be converted to the $\overline{\text{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

Top quark EW couplings

Large BSM family predicts sizeable deviations from SM

- 5D models by several authors (A. Wulzer)
  Richard, arXiv:1403.2893
- 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)



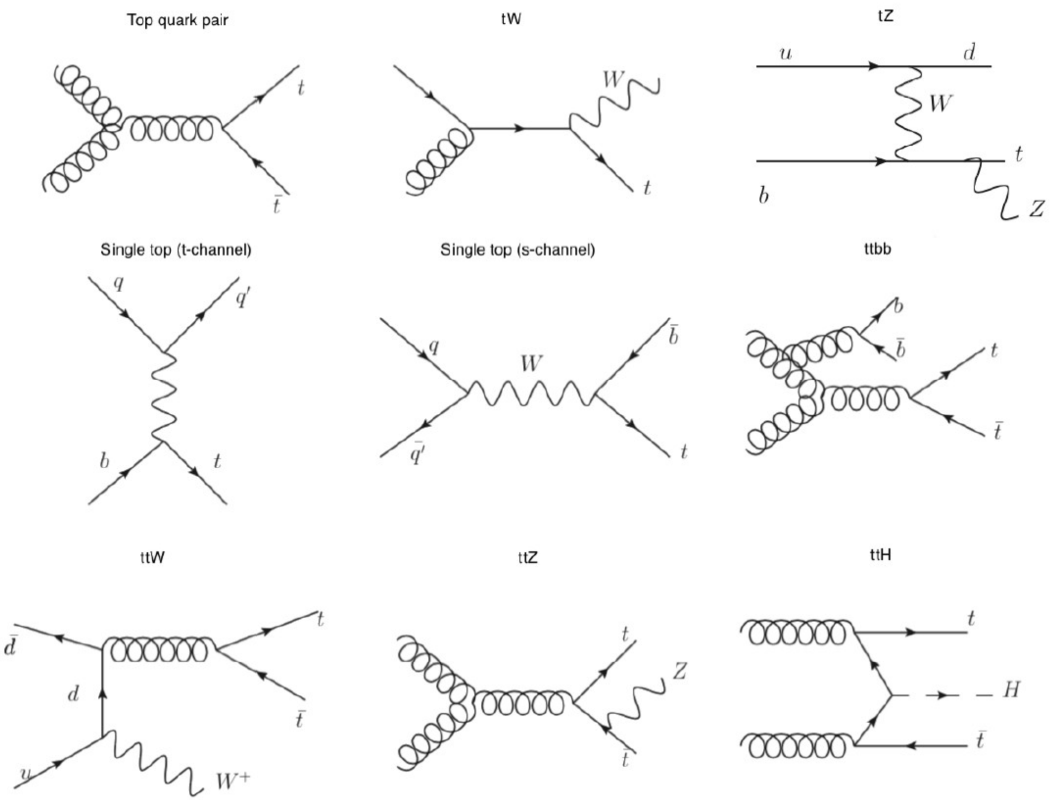
Top EW couplings at the LHC

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:

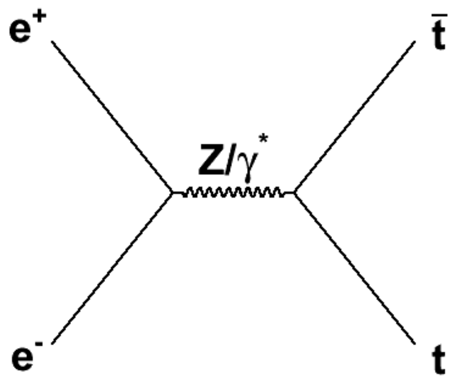
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

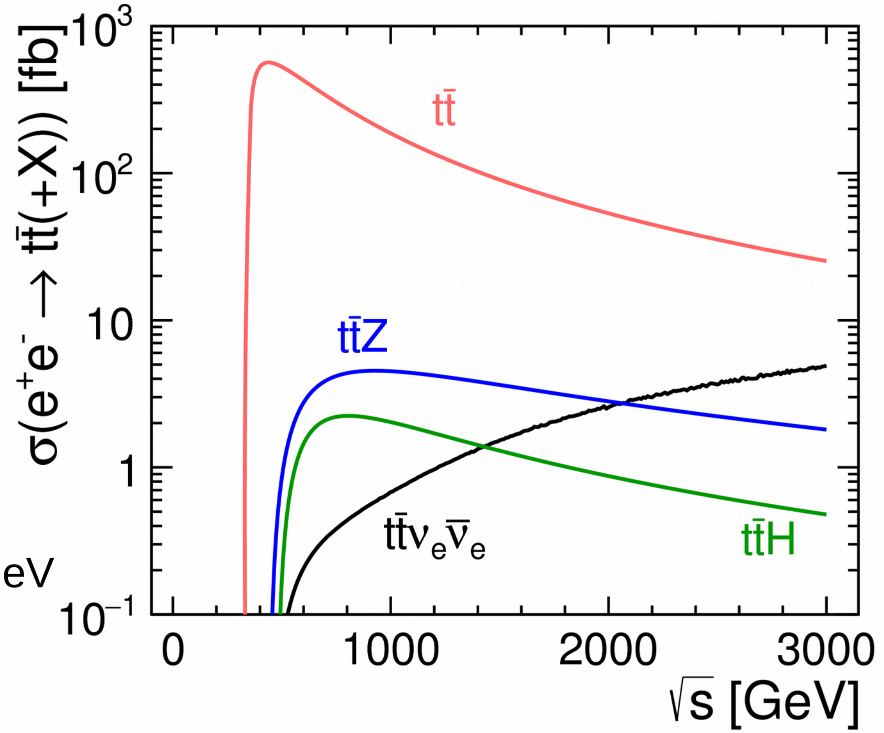
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Prospect studies:

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

Top quark production at e^+e^- colliders





$\sqrt{s} > 2\ m_t$, s-channel x-sec maximum ~420 GeV

VBF and ttH production accessible above 500 GeV

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

Measurements of cross-section, A_{FB} and CP-odd observables

Double the number of observables with LR and RL polarizations

Perform a simple fit of the form factors describing ttZ/γ vertex

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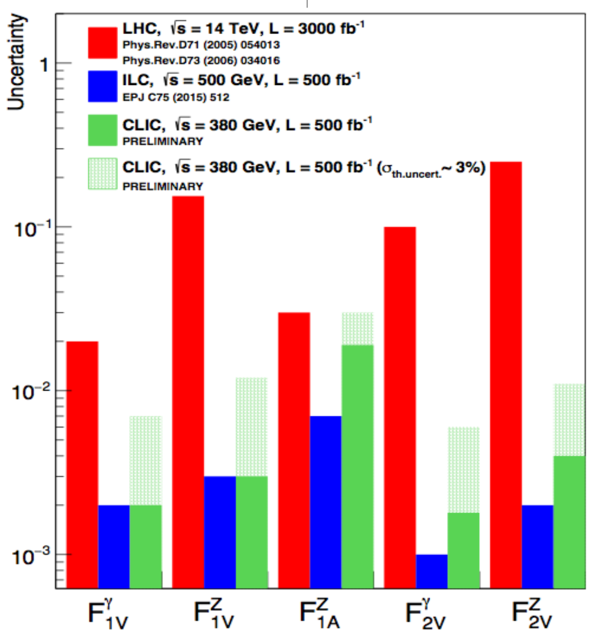
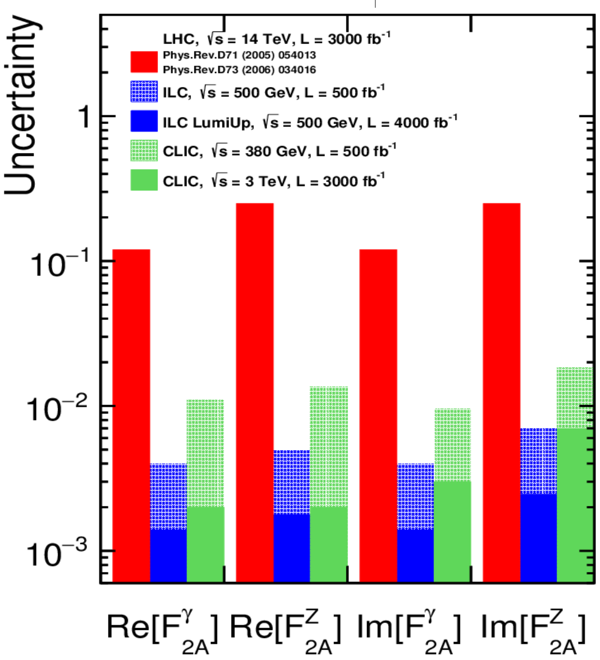
Top EW couplings at lepton colliders

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





Prospects for HL-LHC: *PRD71, 054013, PRD73, 034016*

Prospects for ILC/CLIC: *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

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

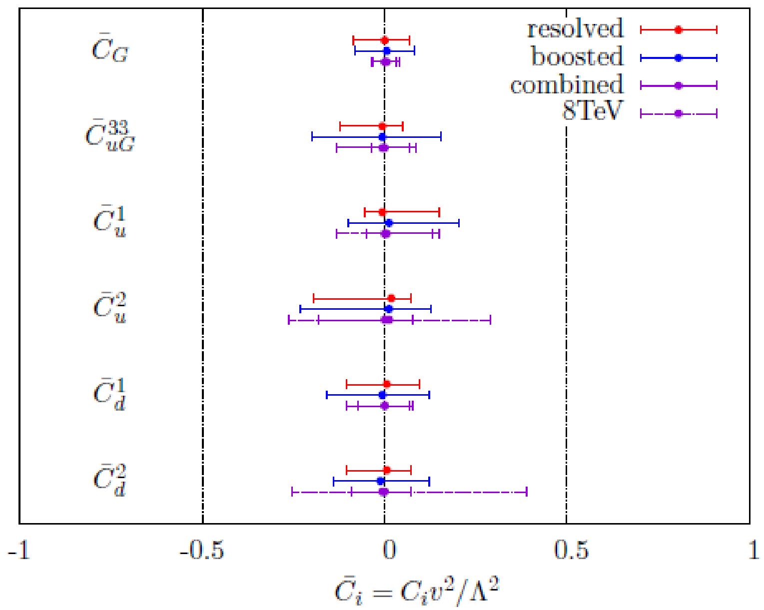
EFT analyses "by sector" are becoming the standard interpretation for LHC analyses.

Very powerful benchmarking tool for future projects.

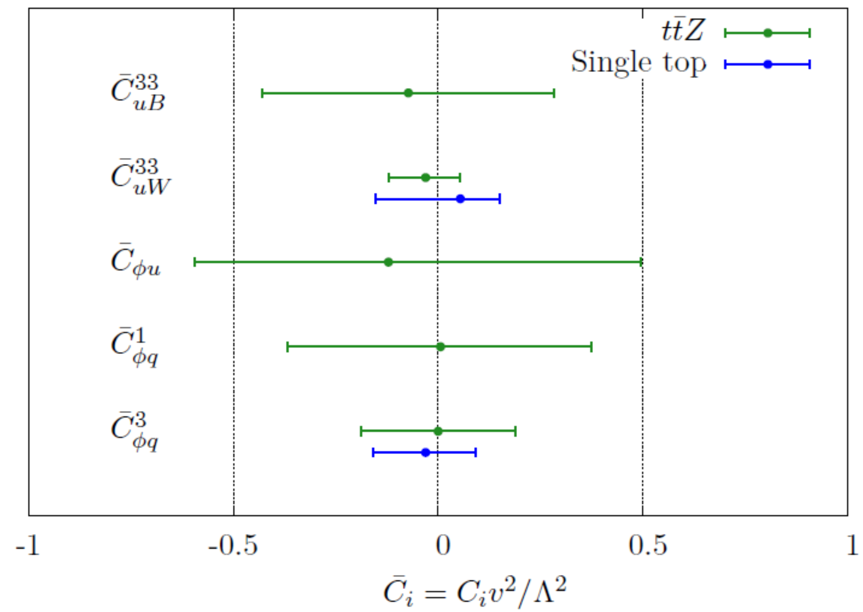
EFT constraints on top quark operators from the LHC

Order (1) 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

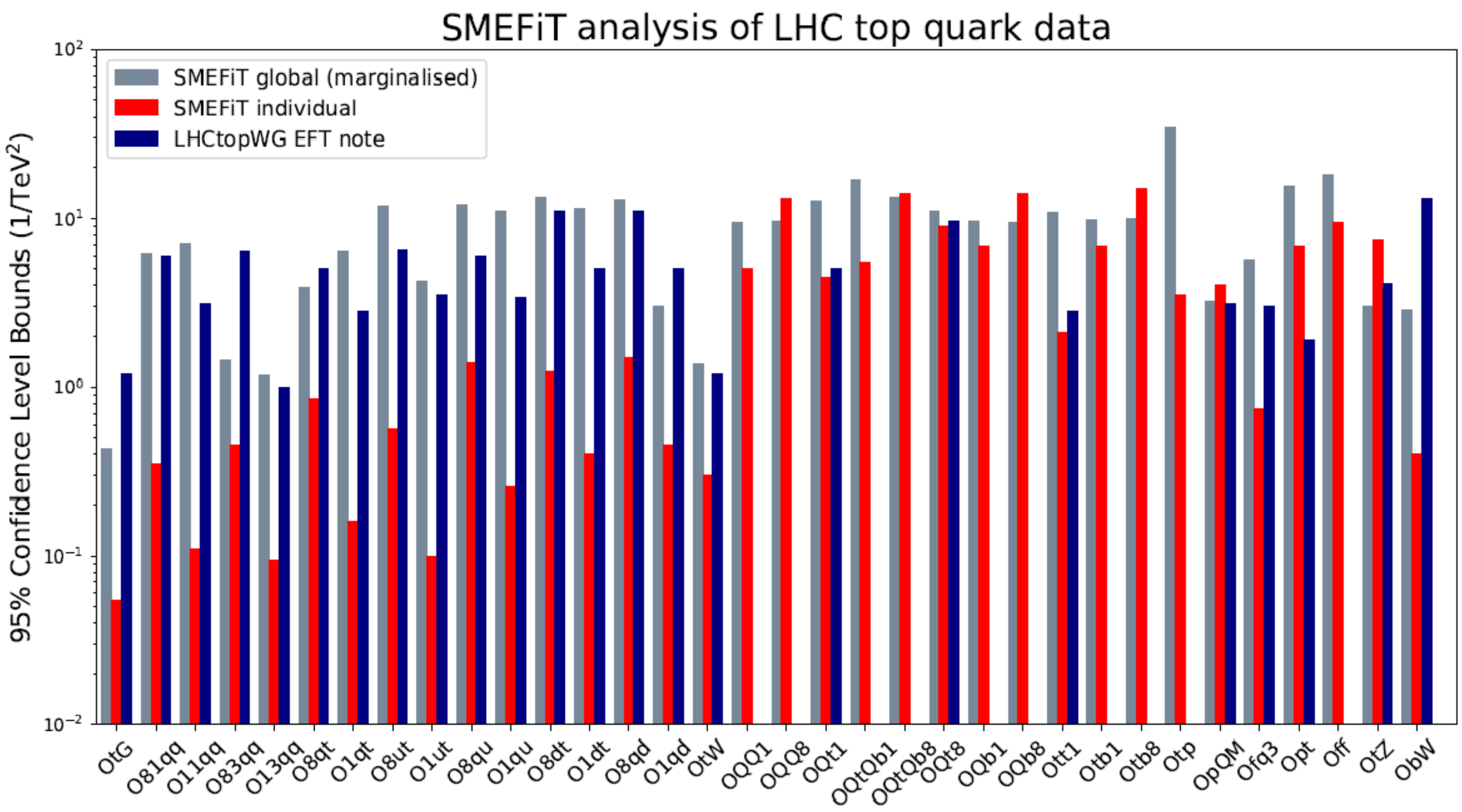


Rare associated production processes yield limits on top quark EW couplings
arXiv:1506.08845, arXiv:1512.03360

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

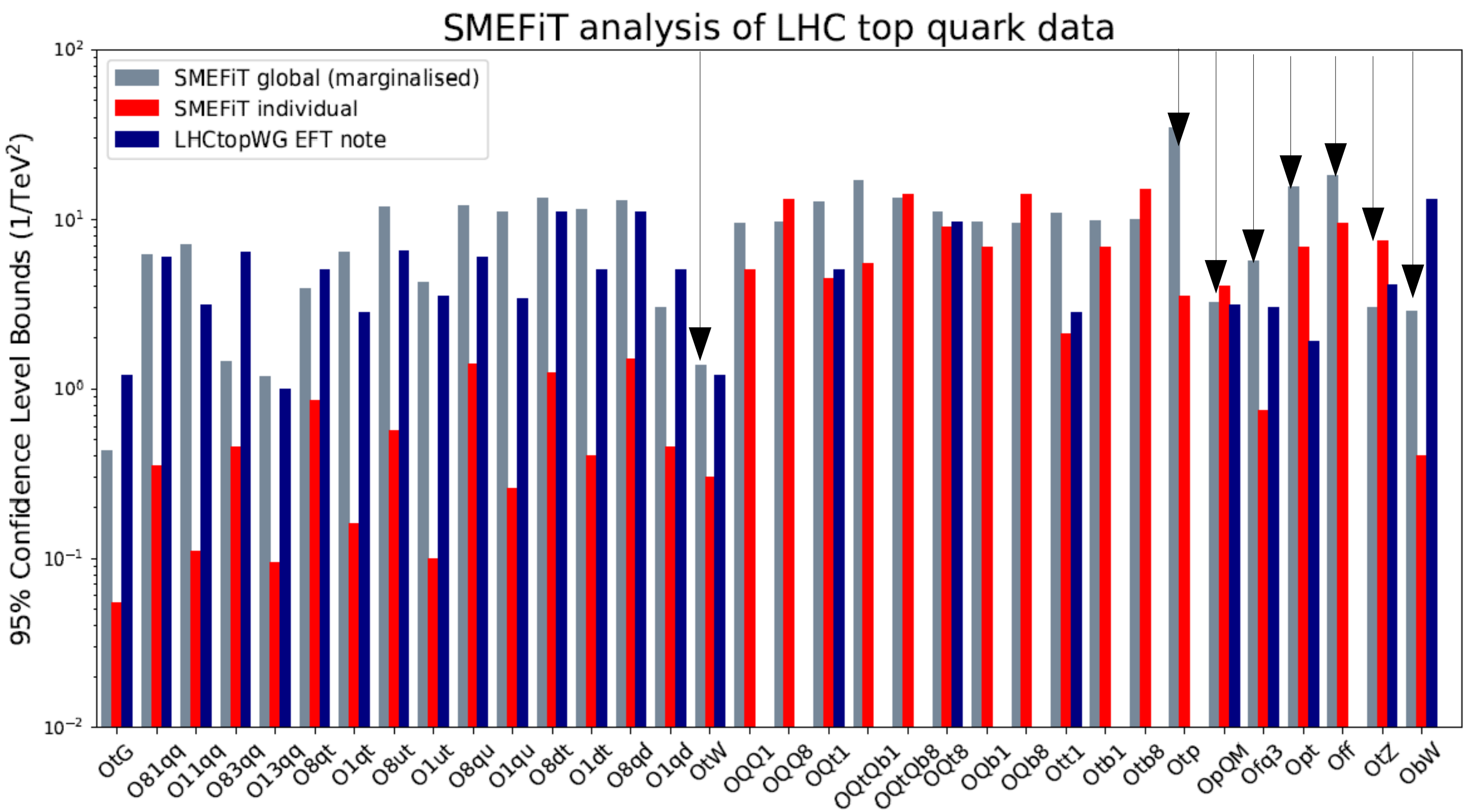
Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang, arXiv:1901.05965



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!

top EFT fit at future colliders

CLIC top paper, arXiv:1807.02441

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

Circular Collider 350+365

Sensitivity to four-fermion operators increases strongly with energy

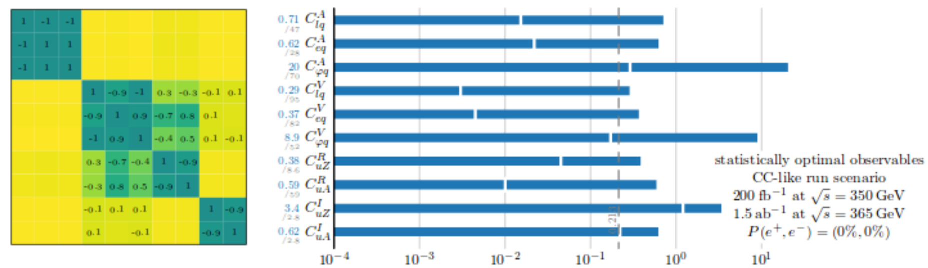


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

ILC500+ ILC1000

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

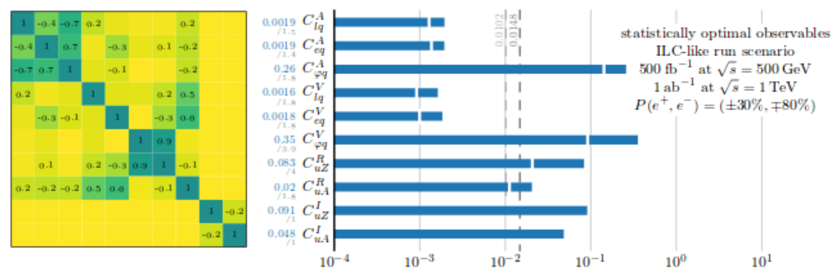


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

CLIC380+ CLIC1500+ CLIC3000

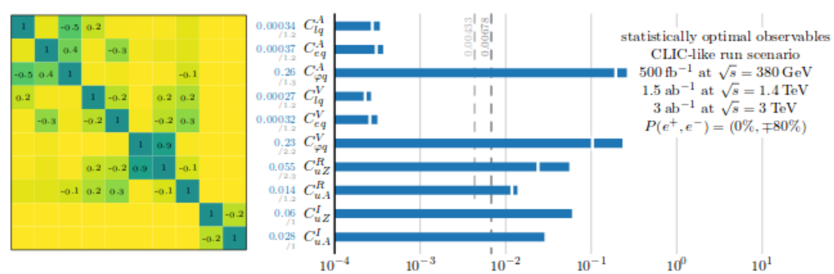


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

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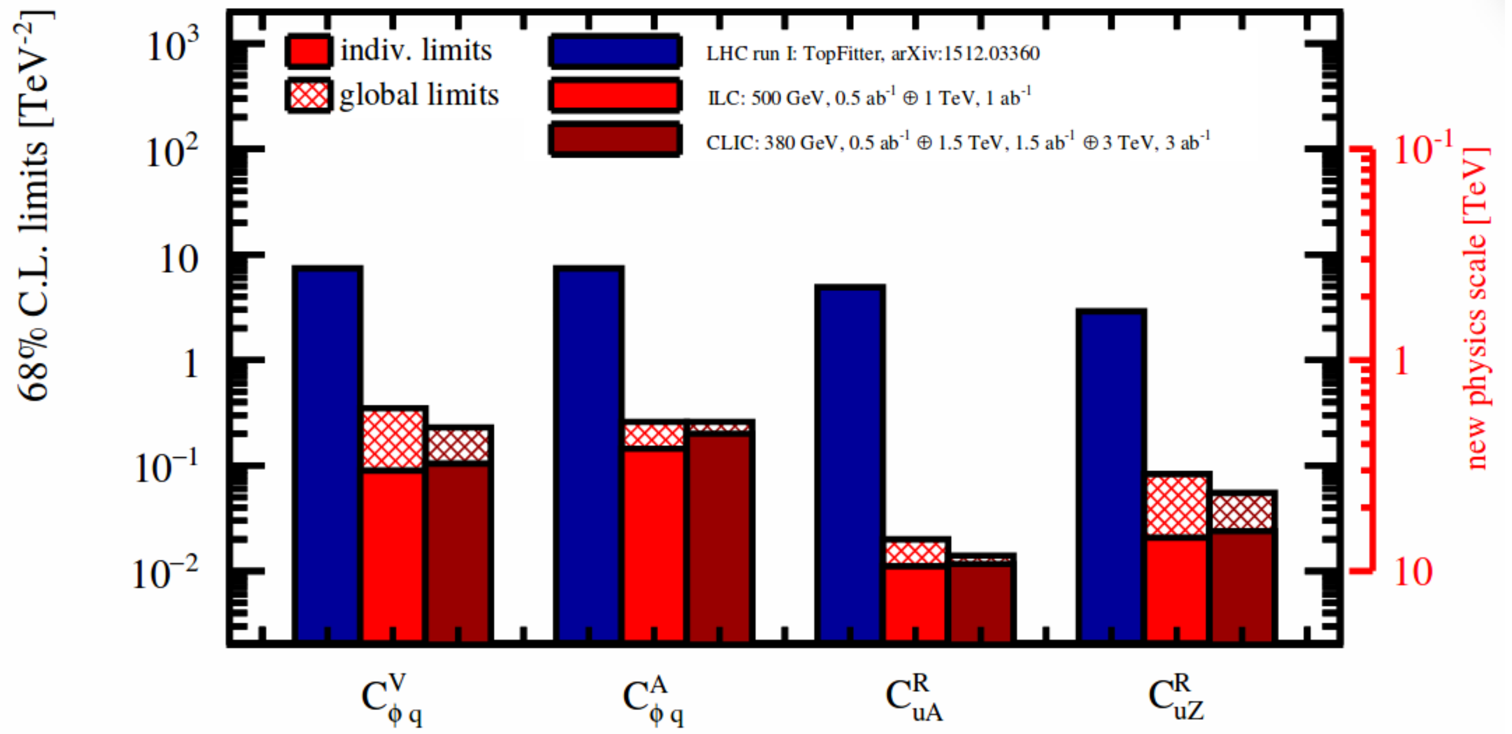
Top EFT fit at the LC

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



Two-fermion operators:

LC prospects exceed LHC run 2 by two orders of magnitude

Four-fermion operators:

LC limits on eett operators can compete with hadron collider limits on qqtt

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.

Shared with bottom quark → LEP constraints

$C_{\phi t}$ = 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

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

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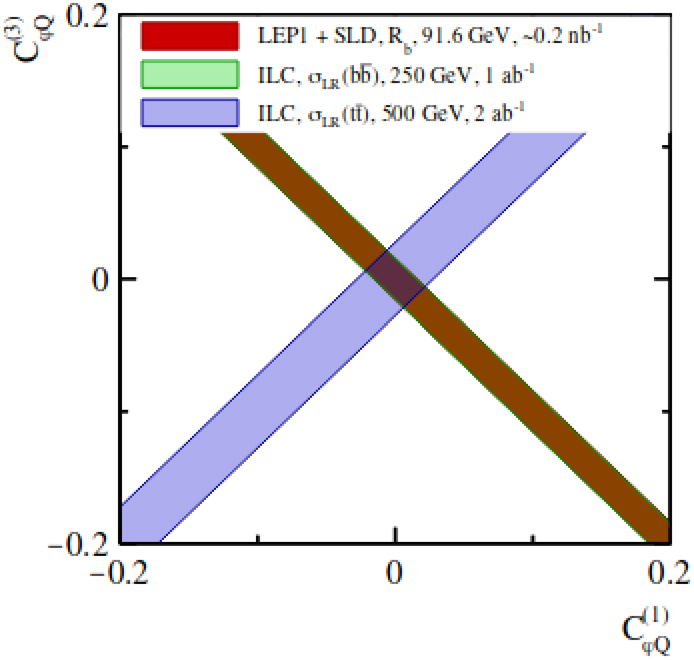
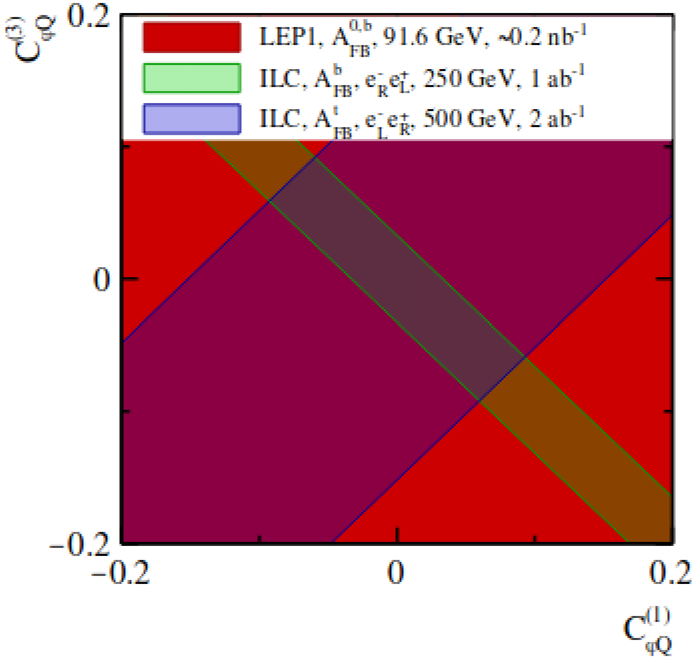
EFT: combined bottom-top fit



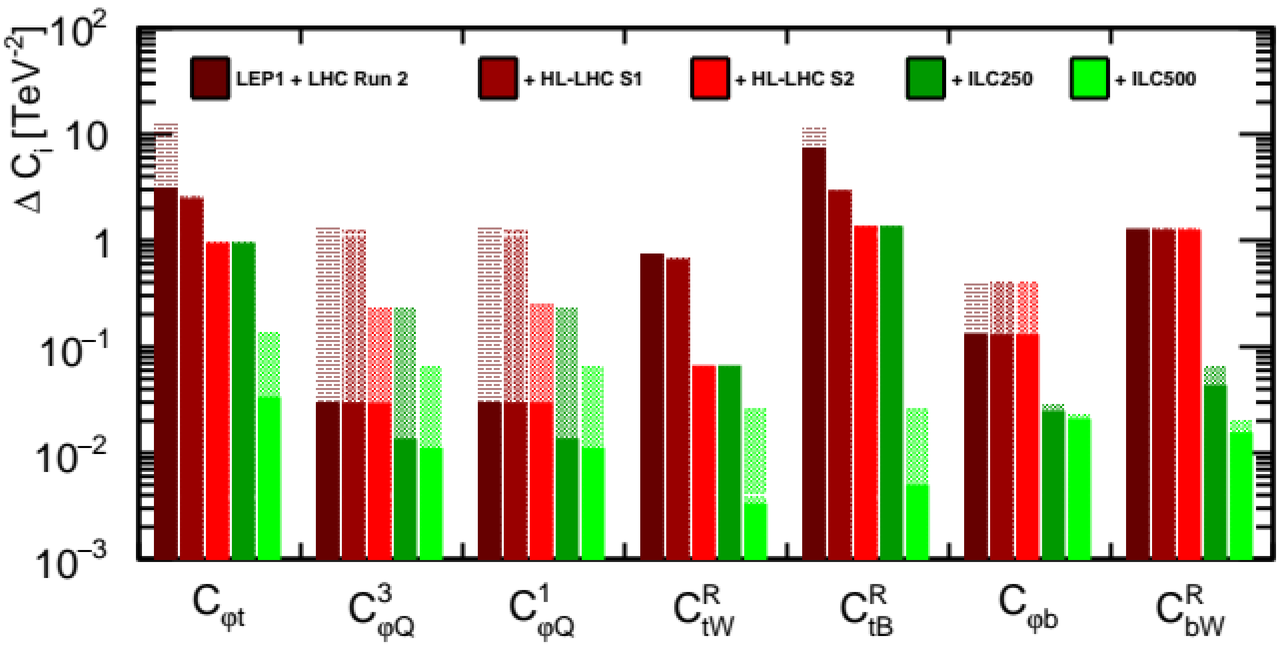


Bottom production provides an exactly complementary constraint

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

Dedicated fit to top EW operators: prospects

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



Current LEP+LHC limits improve in future scenarios

- HL-LHC S1: reduce stat. uncertainty, today's systematics → little or no progress
- HL-LHC S2: exp. systematics/sqrt(L), theory/2 → factor 2-5 for top operators
- ILC250: nominal Higgs run, 2 ab^{-1} → strong impact bottom operators
- ILC500: as per H20 scenario, 4 ab^{-1} → top operators improve dramatically

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The Higgs fit and the top Yukawa coupling

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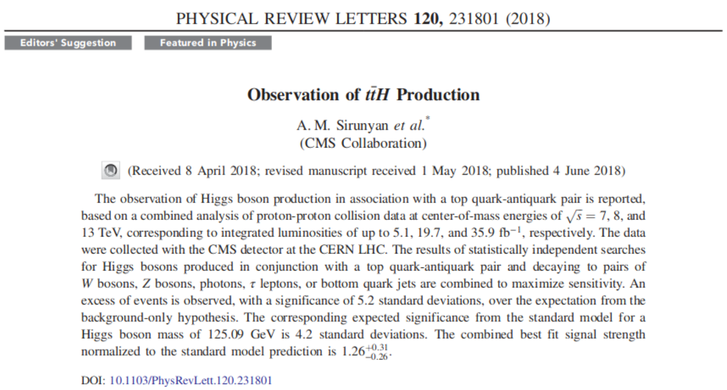
LHC establishes $t\bar{t}H$ production!

$t\bar{t}H$ production observed in both ATLAS and CMS [see T. Masubuchi]

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)

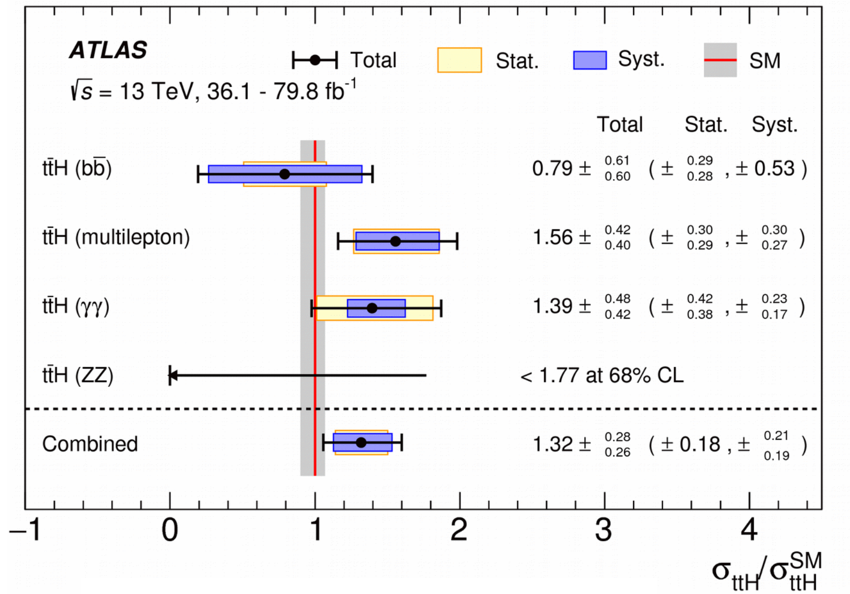
(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

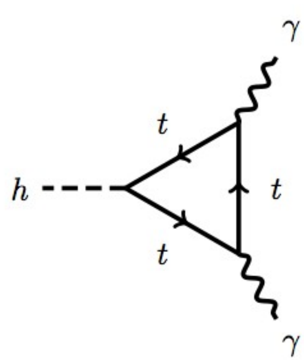
The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, and 35.9 fb^{-1}, 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: $\mu_{ttH} = 1.32 \pm 0.3$

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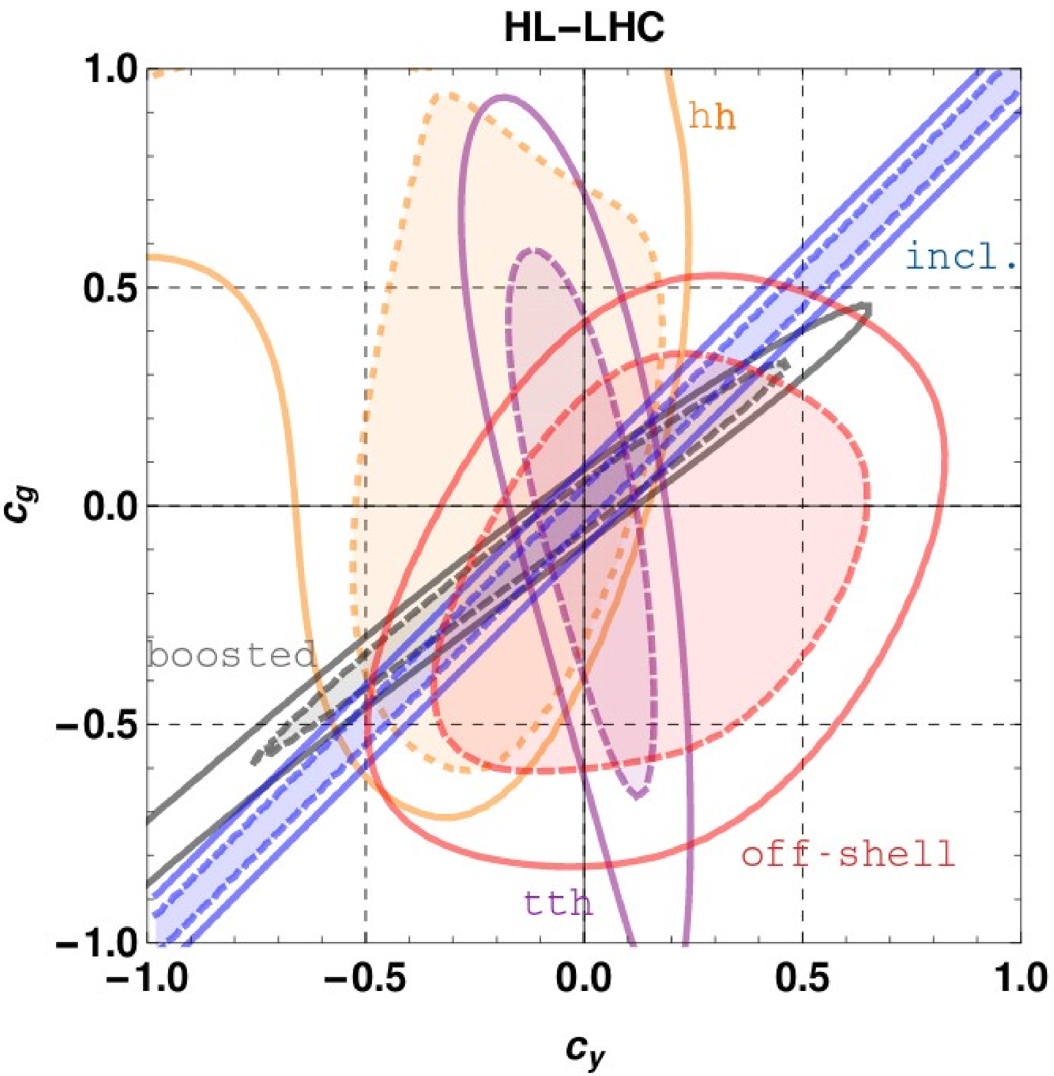
Example: Indirect Yukawa coupling at the LHC

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

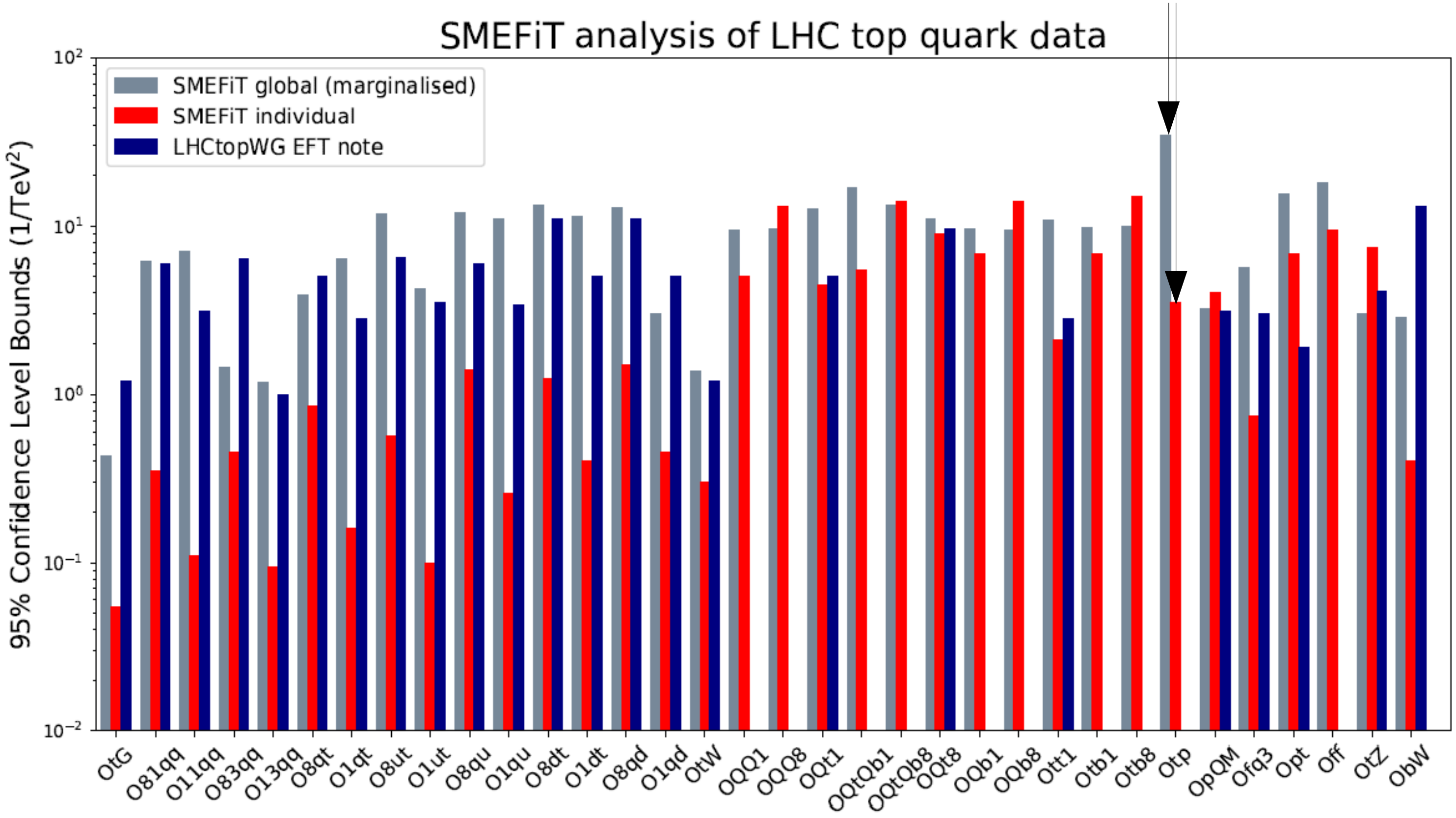
Azatov et al., arXiv:1608.00977



New: global fit to the top sector

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

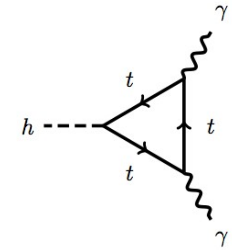
Marginalized limit >> individual for operator that shifts top Yukawa

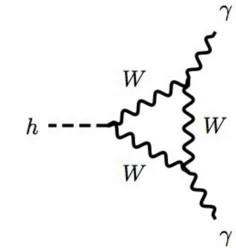


34 parameters, all LHC data (diff. x-sec for single and pair, associated prod., decay)

Top QCD : very good individual limits ~0.1, global limits O(1)

A combined Higgs-top-EW EFT fit?





The Higgs rates depend on top Yukawa coupling AND other top EW couplings

NLO relation between Higgs observables and top EFT operator coefficient known

Vryonidou & Zhang, arXiv:1804.09766

channel	$\mu_{\rm EFT}$ [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.

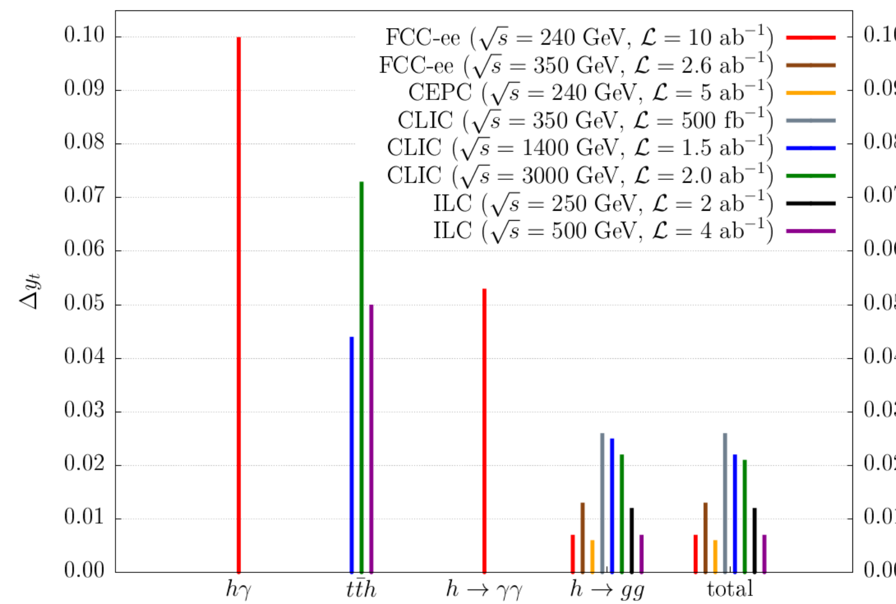
Coefficients are large and existing constraints are poor: cannot ignore the top EW operators in a global EFT analysis.
Crucial for on top Yukawa and Higgs self-coupling at a 250 GeV collider.
Durieux et al., arXiv:1809.03520

Indirect top Yukawa coupling at the ILC

Mitov et al., arXiv:1805.12027

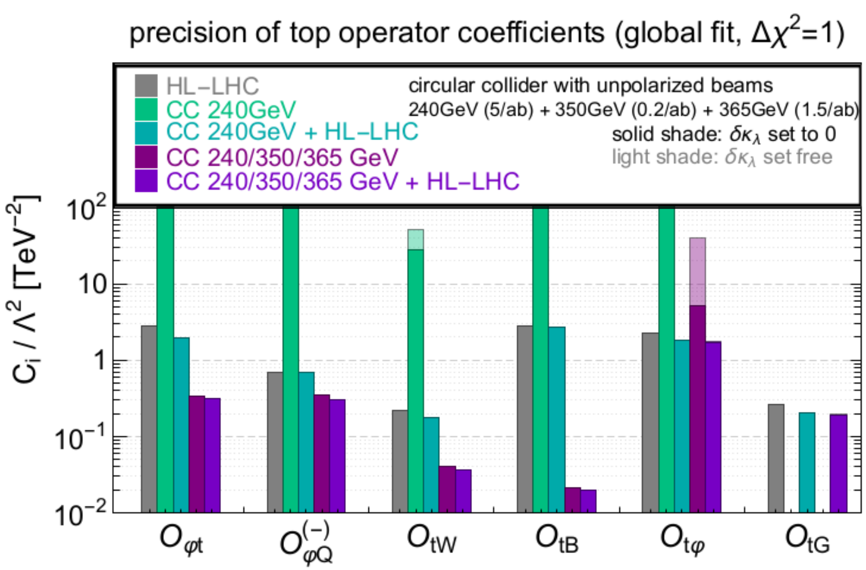
$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma^{\rm SM}_{h\to gg}} = 1 + 2\Delta y_t\,,$$

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



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

Design reports quote 2.8% uncertainty from $t\bar{t}$H analysis at 550 GeV

Towards a global analysis

Linear collider fit of
the Higgs sector
arXiv:1708.08912
[see J. Tian]

20 operator coefficients
EWPO + TGC + Higgs data

Adding top EW operators
(based on Vryonidou & Zhang,
additional work by S. Jung)

	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.

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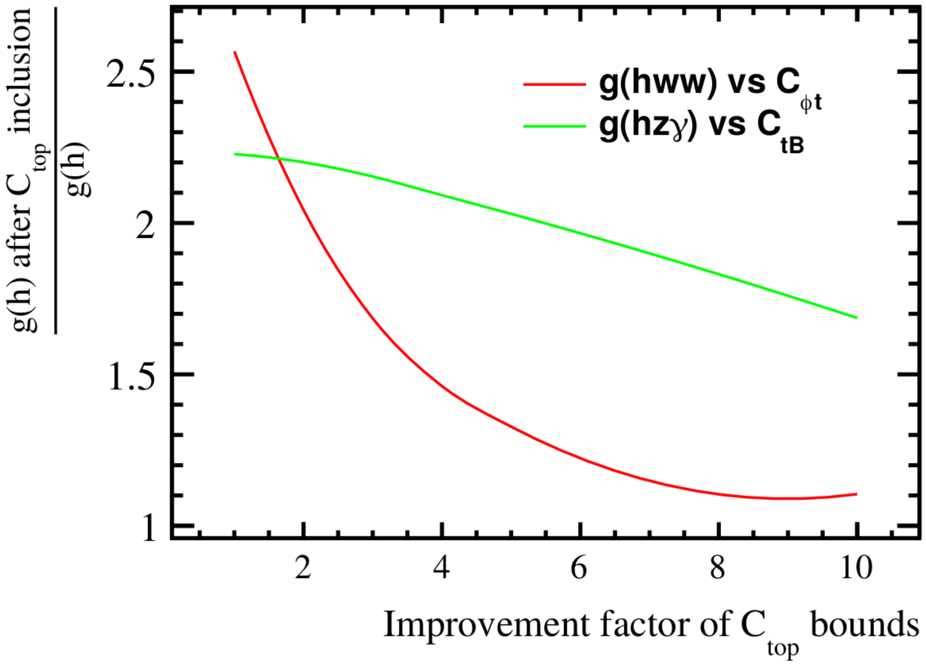
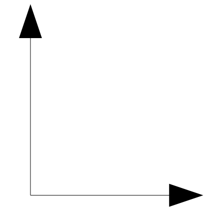
Towards a global analysis: ILC250 + LEP + HL-LHC

Higgs fit extended with relevant top operators, register change of bounds with respect to the nominal fit of arXiv:1710.07621



Degradation of Higgs parameters after inclusion of top operators



Improvement of top operator limits wrt current (TopFitter) results

The top operators (esp. C_{ft}, C_{tB}) prove to be a **real nuisance for the Higgs fit**:

- with current top operator bounds: 4 Higgs parameter degrade O(100%)
- with HL-LHC S2 bounds: g(hZγ), g(hWW), g(hZZ) affected >30%
- with HL-LHC S2 bounds: other Higgs parameters within 10 %
- with ILC500 data: fit returns to nominal results

Effect on indirect extraction of top Yukawa and Higgs self-coupling to be assessed

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Summary

Top quark properties/interactions are important for the Higgs program;

Three examples:

- Top quark mass:
  - → test internal consistency of SM; important for accurate predictions
  - → 500 MeV today, possibly 200 MeV at HL-LHC, 50 MeV in e+e- threshold scan
- Top quark EW couplings:
  - → sensitive probe of composite Higgs models; important in global fits
  - → 1-10 TeV^{-2} today, up to two orders improvement at LC with energy above 350 GeV
- Top quark Yukawa coupling:
  - → one of the key targets in HEP; complex interplay direct and indirect results
  - → large uncertainty today, (few) %-level sensitivity is possible at LC above 550 GeV

Global fit in Effective Field Theory is important to:

- → **avoid reliance on ad-hoc models**
- → **compare sensitivity across processes**
- → **understand complex relations of Higgs-top-EW sectors**