top physics EFT fit
at a linear e^+e^- collider

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Indirect sensitivity

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

The Higgs fit at the LC

Linear collider fit of the Higgs sector

20 operator coefficients

EWPO + TGC + Higgs data

arXiv:1708.08912

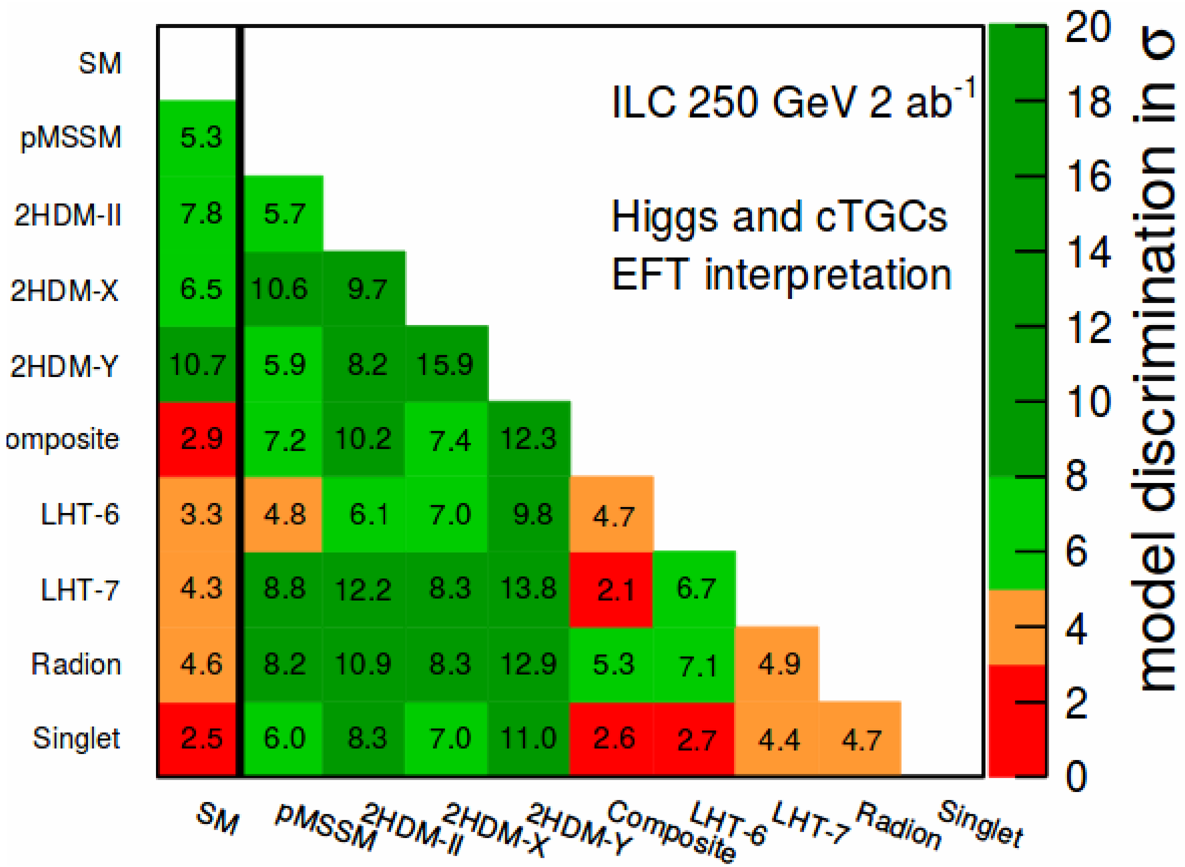
	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	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.

Higgs EFT fit

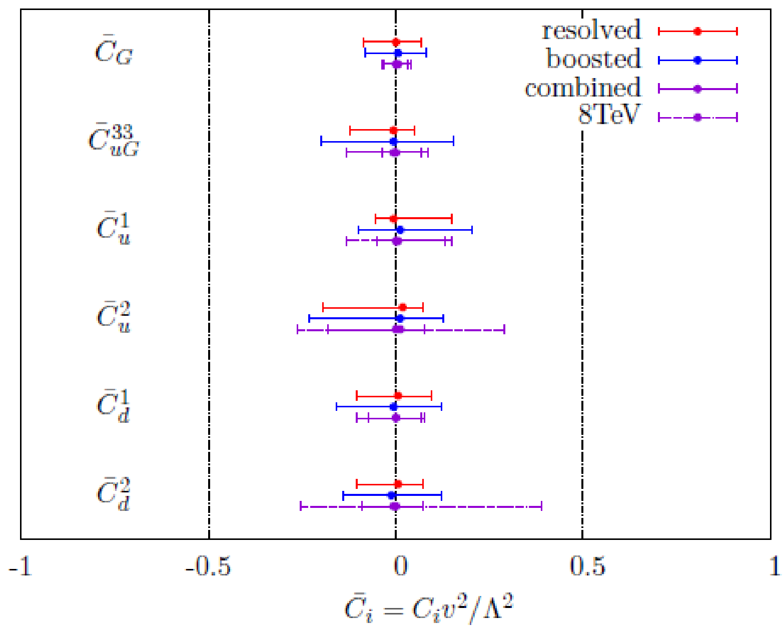
Results can easily be translated into limits on concrete new physics models

ILC fit Higgs sector arXiv:1708.08912



EFT constraints on top quark operators

The LHC has produced millions of top quarks. The "standard program" is nearly done, as inclusive measurements are mostly systematics-limited. Semi-global EFT fit to Tevatron+LHC8 data yields O(1) constraints on the Wilson coefficients of the relevant top operators.

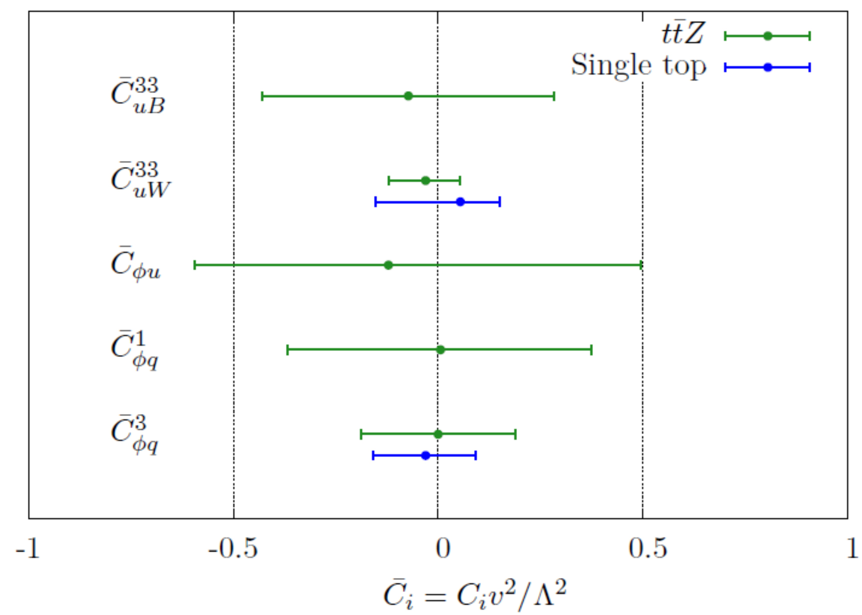


Boosted measurements are surpassing precise inclusive measurements

Englert et al., arXiv:1607.04304

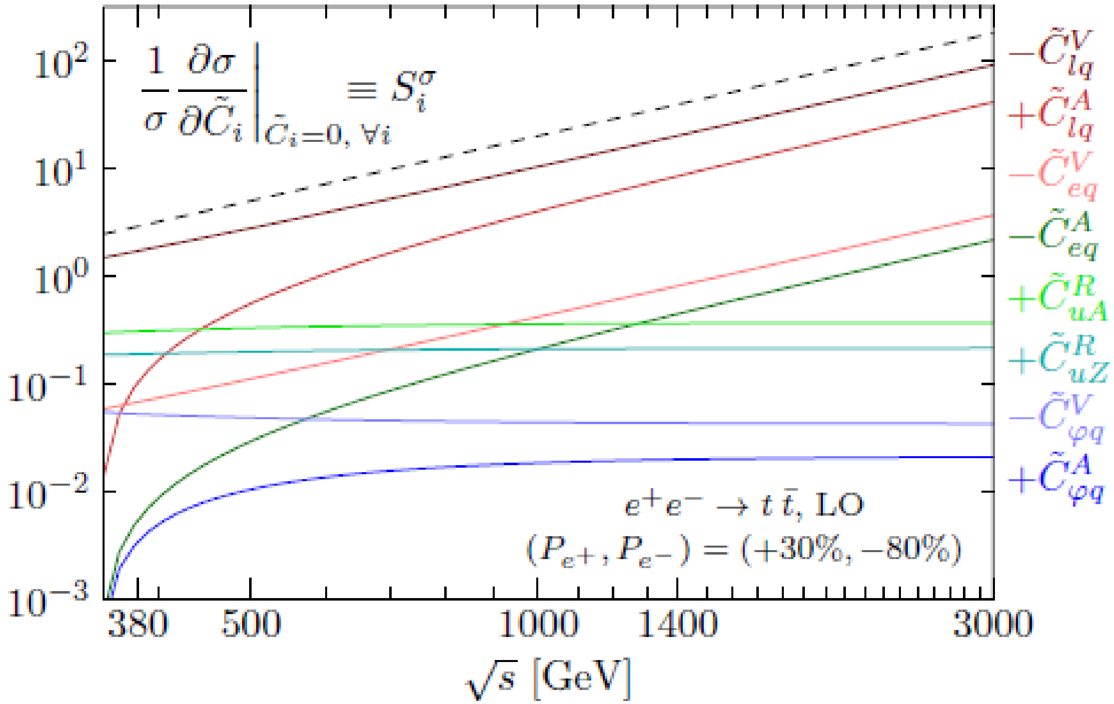
Rare associated production processes yield limits on top quark EW couplings

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,...)

EFT: characterize sensitivity vs. energy



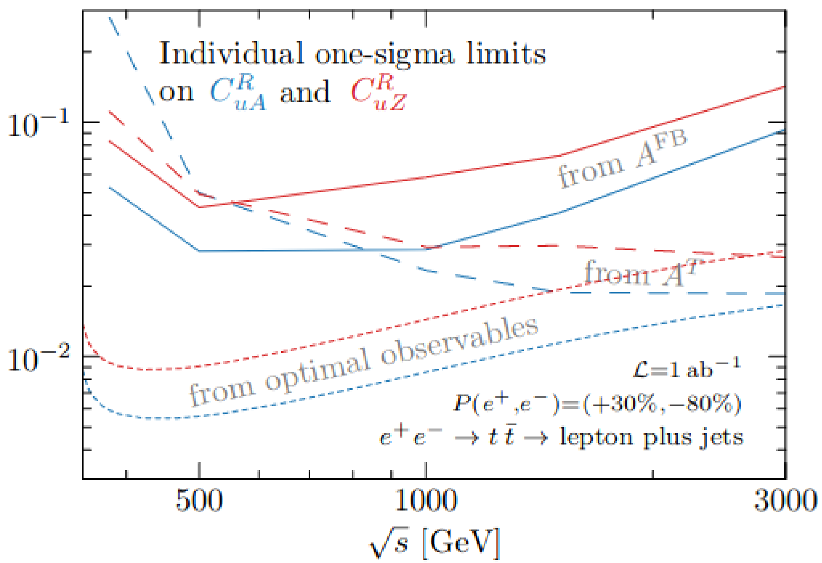
Effect of four-fermion operators felt most strongly at high energy

Effect of two-fermion operators best probed at ~400-500 GeV

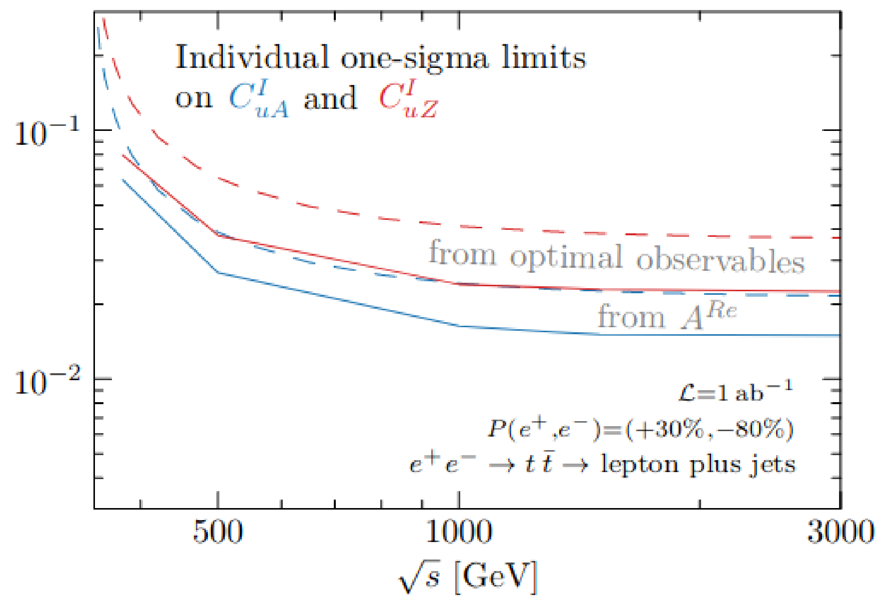
(See also Fiolhiais et al., arXiv:1206.1033)

EFT: finding constraining observables

Is there information beyond the classical x-section and forward-backward asymmetry?



Yes! The dipole moments (C_{tW} and C_{tB}) are better constrained by transverse polarization at high energy



Yes! The imaginary parts of the dipole moments (C_{tW} and C_{tB}) are best constrained by dedicated CP-odd observables (see arXiv:1710.06737)

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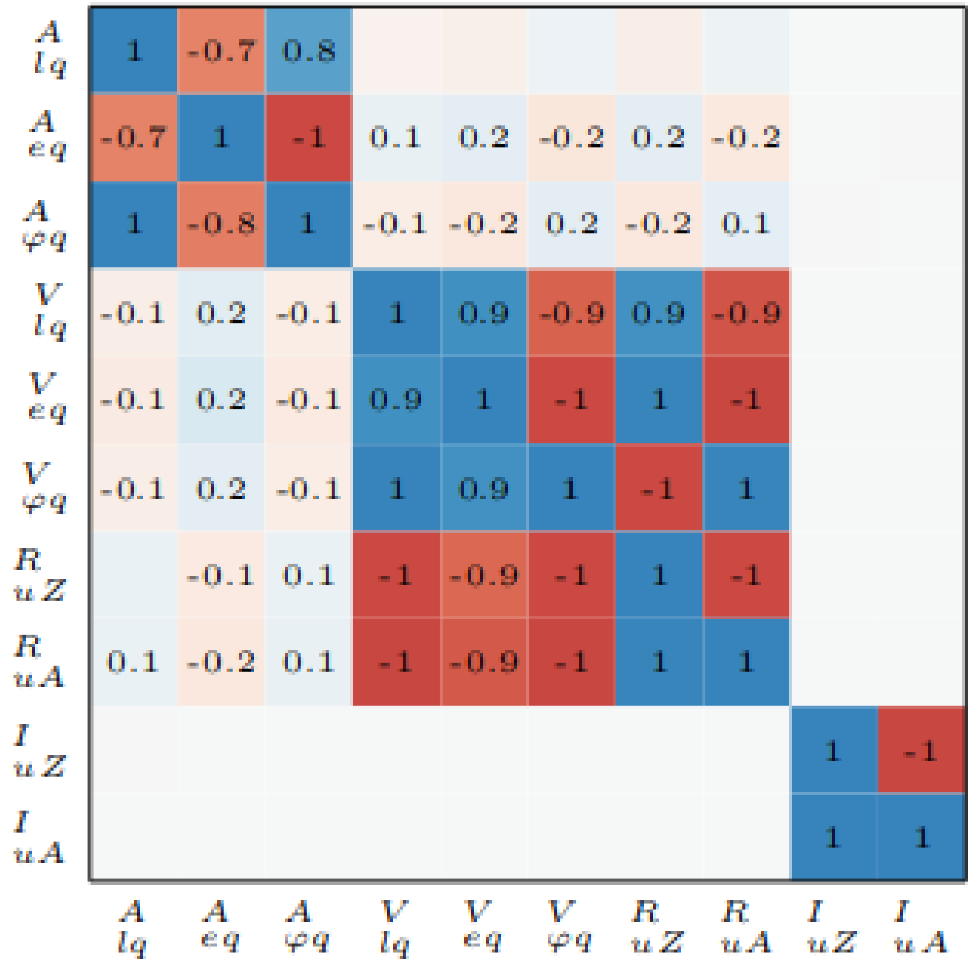
EFT: finding constraining observables

Is there information beyond the classical x-section and forward-backward asymmetry?

Construct set of optimal observables that minimize the (hyper-) volume of the allowed parameter space

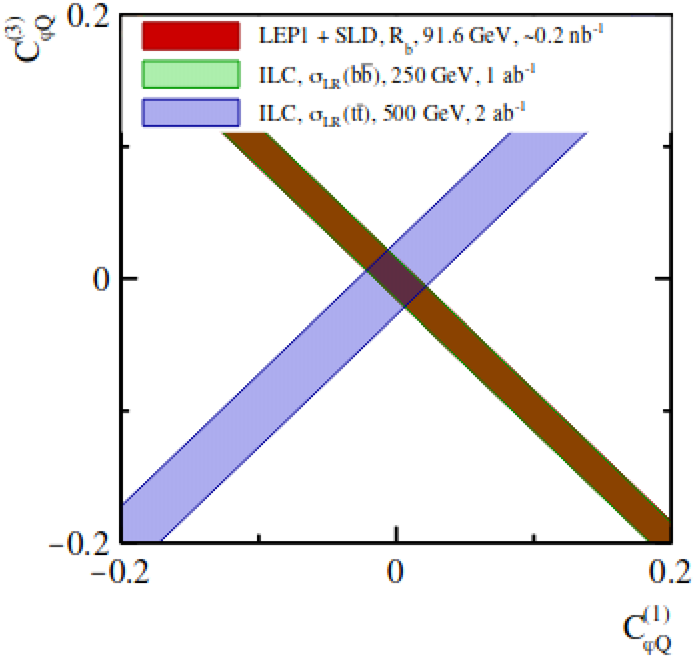
Some observables are strongly correlated: there is not enough information in a single run

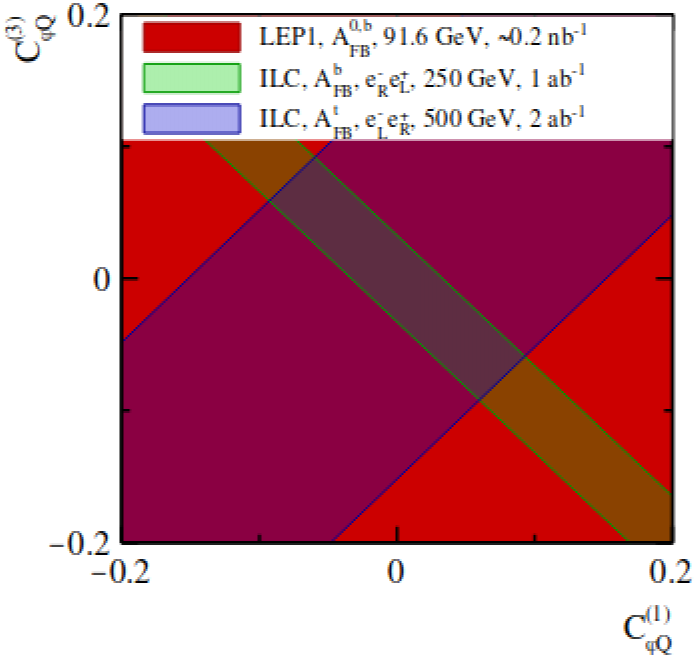
Runs with different polarization and energy are needed!



EFT: finding constraining observables

Is there useful information outside tt production?





Yes! Bottom production provides an exactly complementary constraint

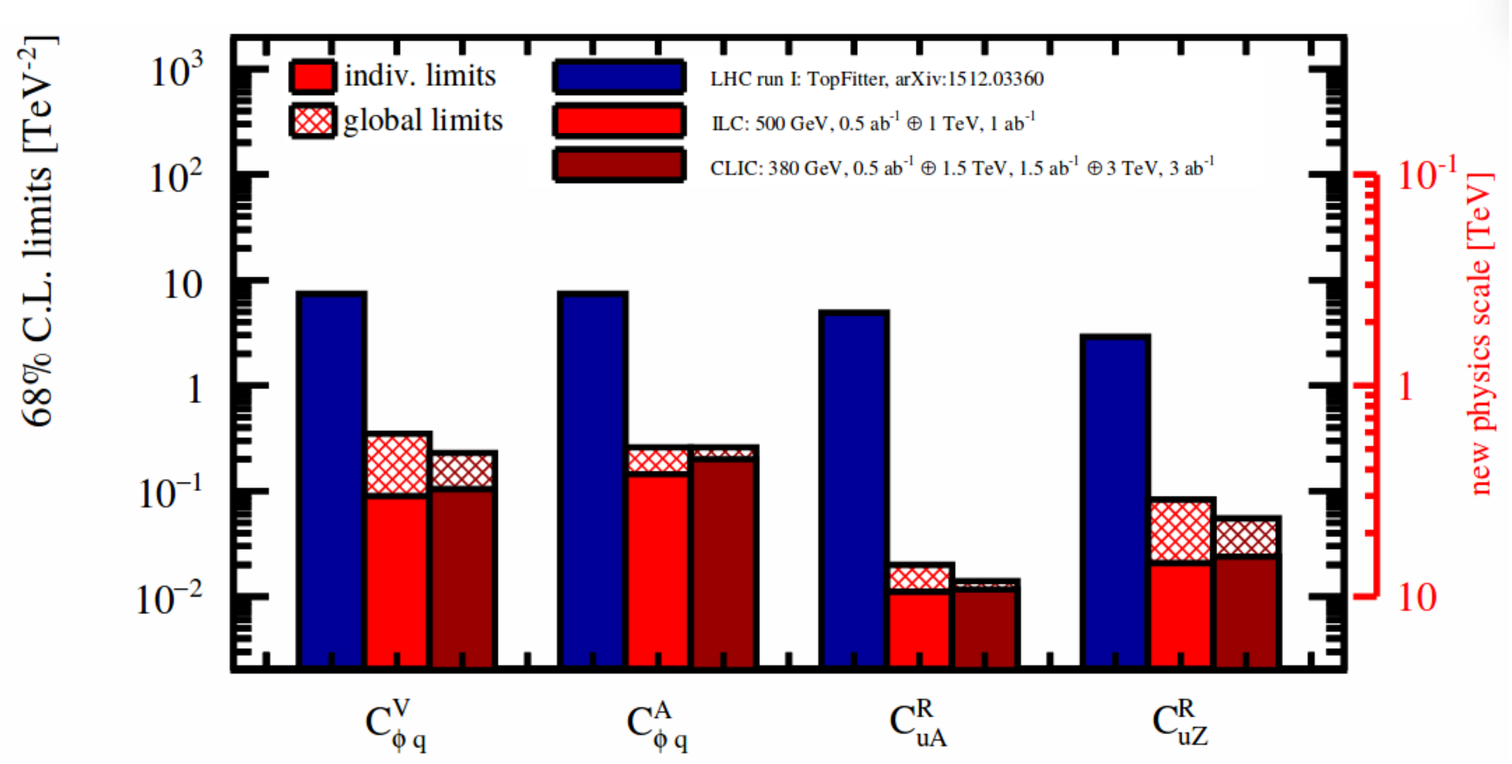
Other possibilities have been explored (top width, W polarization). These provide complementary information, but the sensitivity is low compared to sensitivity in $t\bar{t}$.

See also discussion on top-Higgs cross -talk later in this talk.

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 a large factor

Constraints on 4-fermion and dipole moment operators probe very high scale
- TeV LC competitive with qq → tt at the LHC and possibly FCChh

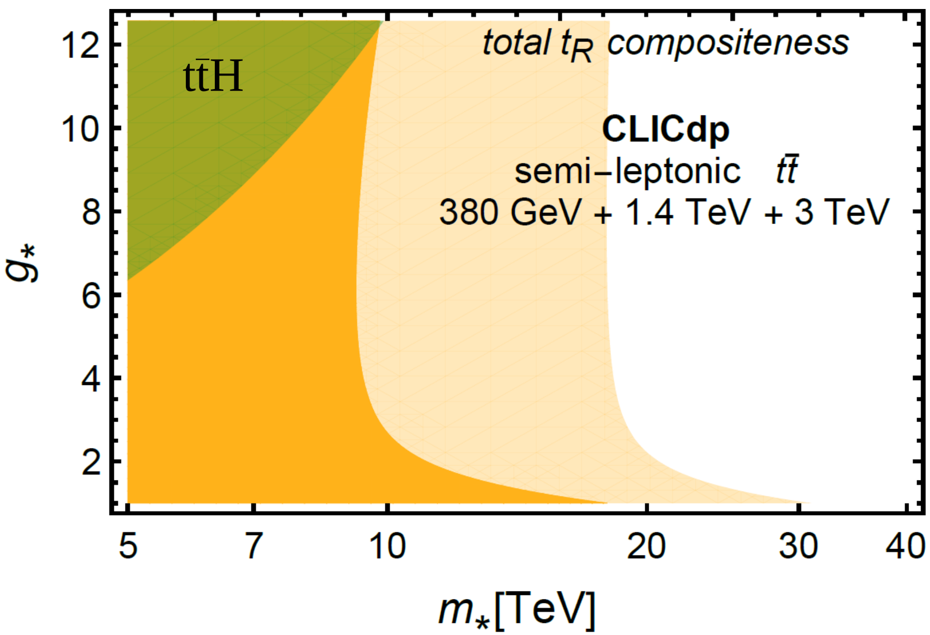
Durieux, Matsedonskiy, arXiv:1807.10273
CLIC top paper, arXiv:1807.02441

From EFT to concrete scenario

Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

The top quark is naturally composite in this framework (*Pomarol 2008*), the only viable option to generate the top Yukawa coupling (*Ratazzi 2008*)

Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)
Pessimistic 5σ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV



Sensitivity to new physics at 10-30 TeV!

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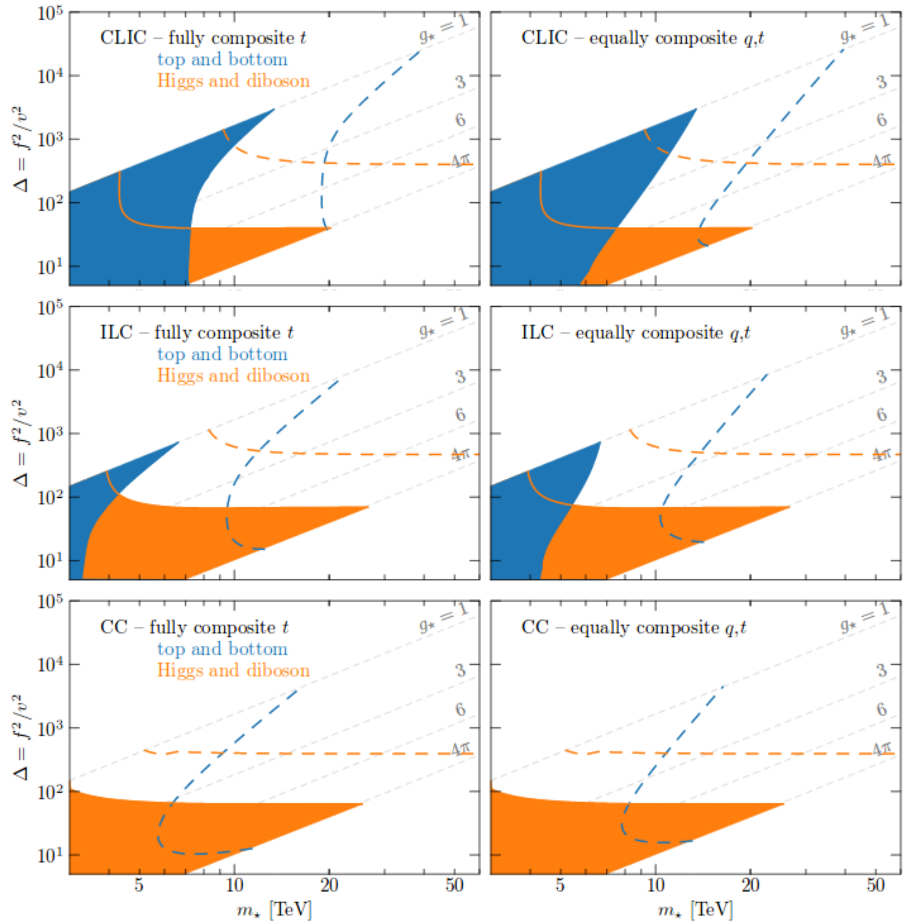
Durieux, Matsedonskiy, arXiv:1807.10273

Complementarity with Higgs physics

Measurements in top and Higgs/di-boson sector yield complementary constraints

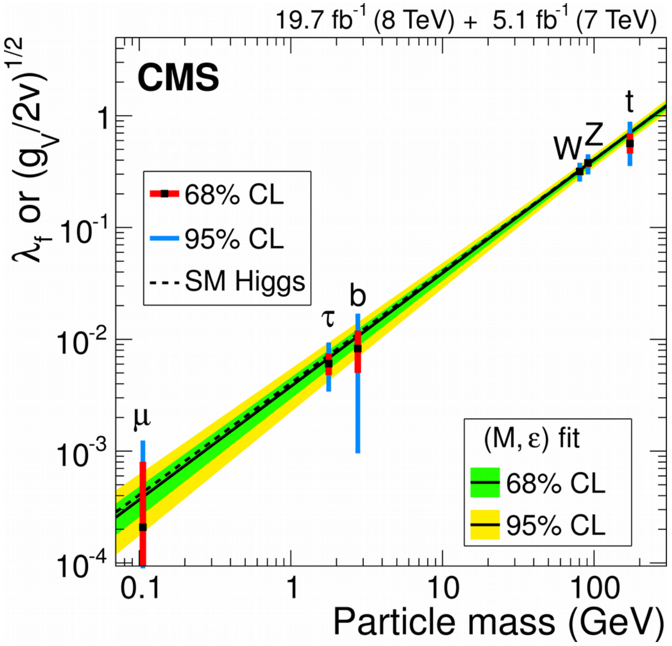
Coverage of model parameter space up to >10 TeV



"Our results show that one can probe a significant fraction of the natural CH parameter space through the top portal, especially at TeV centre-of-mass energies"

Top and Higgs

A combined fit of the top and Higgs sectors?



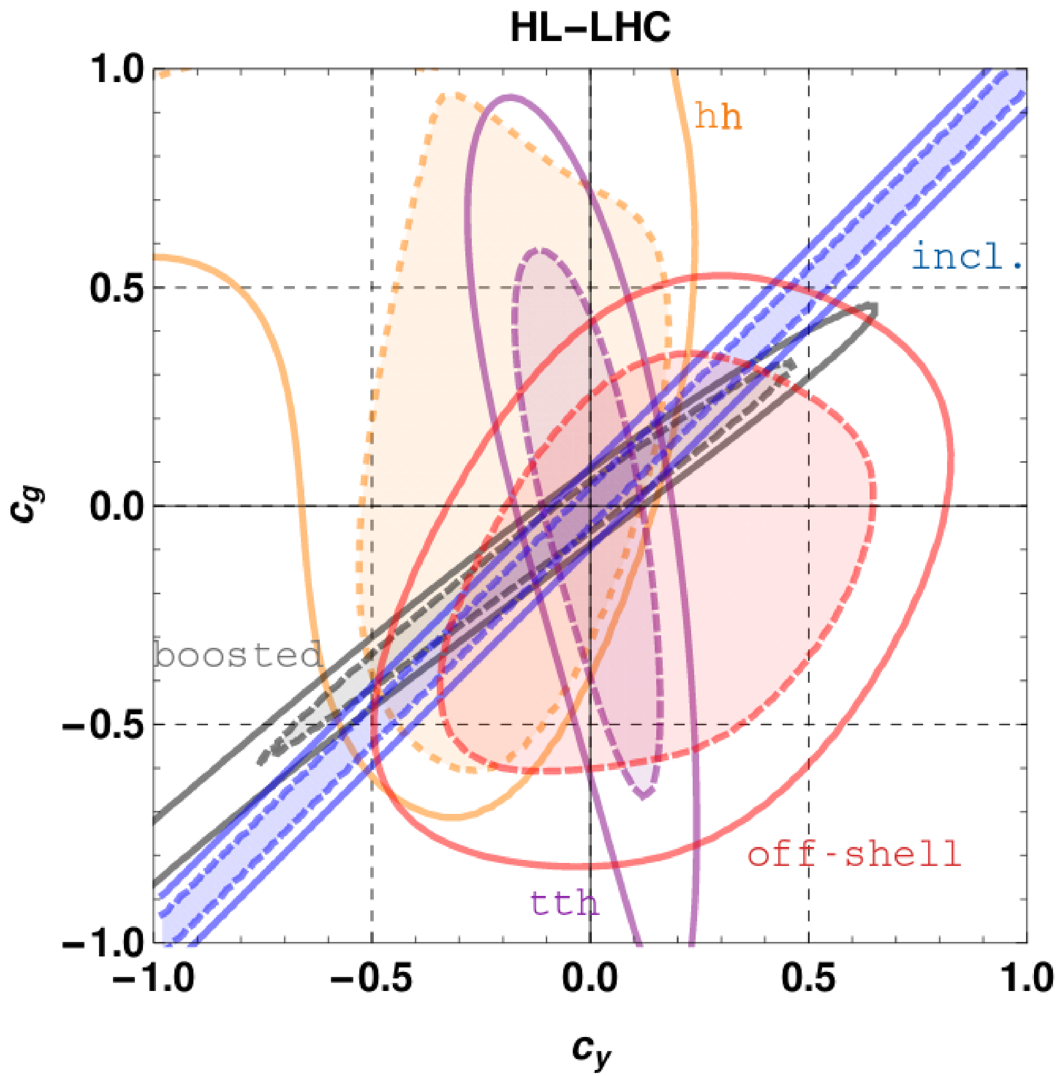
Global EFT analysis at the LHC

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)

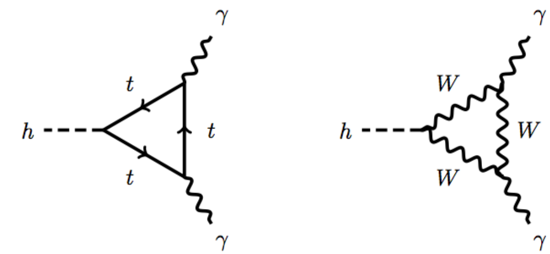
Direct measurement in $t\bar{t}$H is necessary in a global analysis

Azatov et al., arXiv:1608.00977



A combined 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

Coefficients can be large. Existing constraints are often poor. Cannot ignore the extra operators in a global EFT analysis.

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.

An opportunity: indirect top Yukawa coupling

Mitov et al., arXiv:1805.12027

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

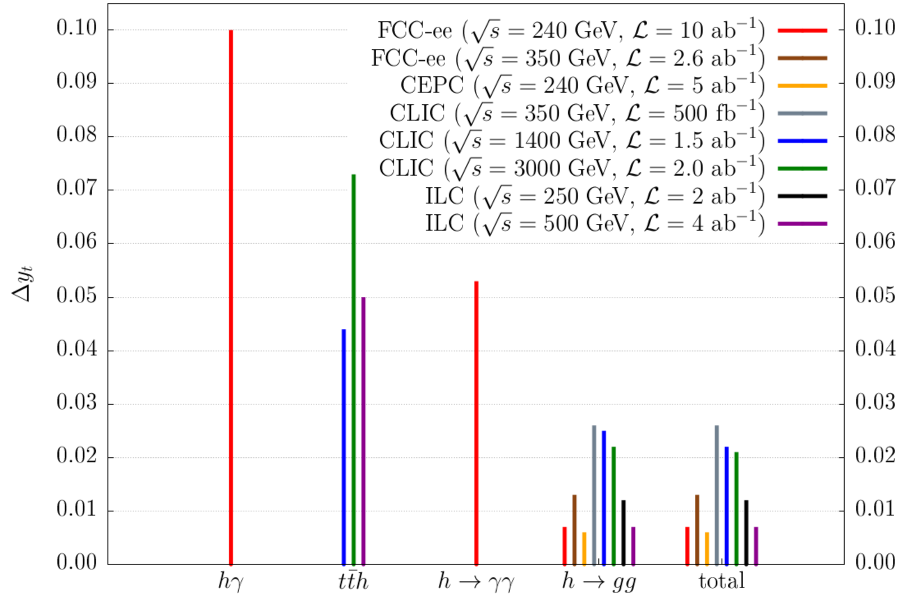
$$\mu_{h\to\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{\rm SM}_{h\to\gamma\gamma}} = 1 - 0.56\Delta y_t \,.$$

One-paramteter fit of H → gg rate <u>measured at 250 GeV</u> yields

1% precision on top Yukawa coupling

Confirmed in preliminary ILC fit by S. Jung, J. Tian, M. Perelló

They also show that H → $\gamma\gamma$ can be as powerful as H → gg



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A threat: global analysis of top and Higgs sector

EFT fit of Higgs/EW sector must include 7 additional parameters

At 250 GeV the EWPO + TGC + Higgs data was sufficient to constrain 22 parameters

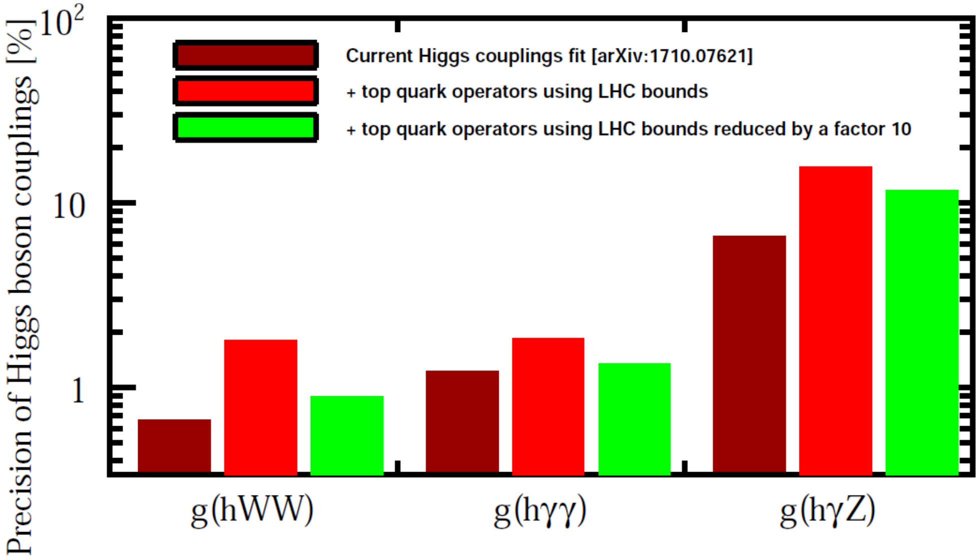
Cannot deal with 7 additional parameters. Need more data…

Scenario 1: use current LHC limits on top EW couplings

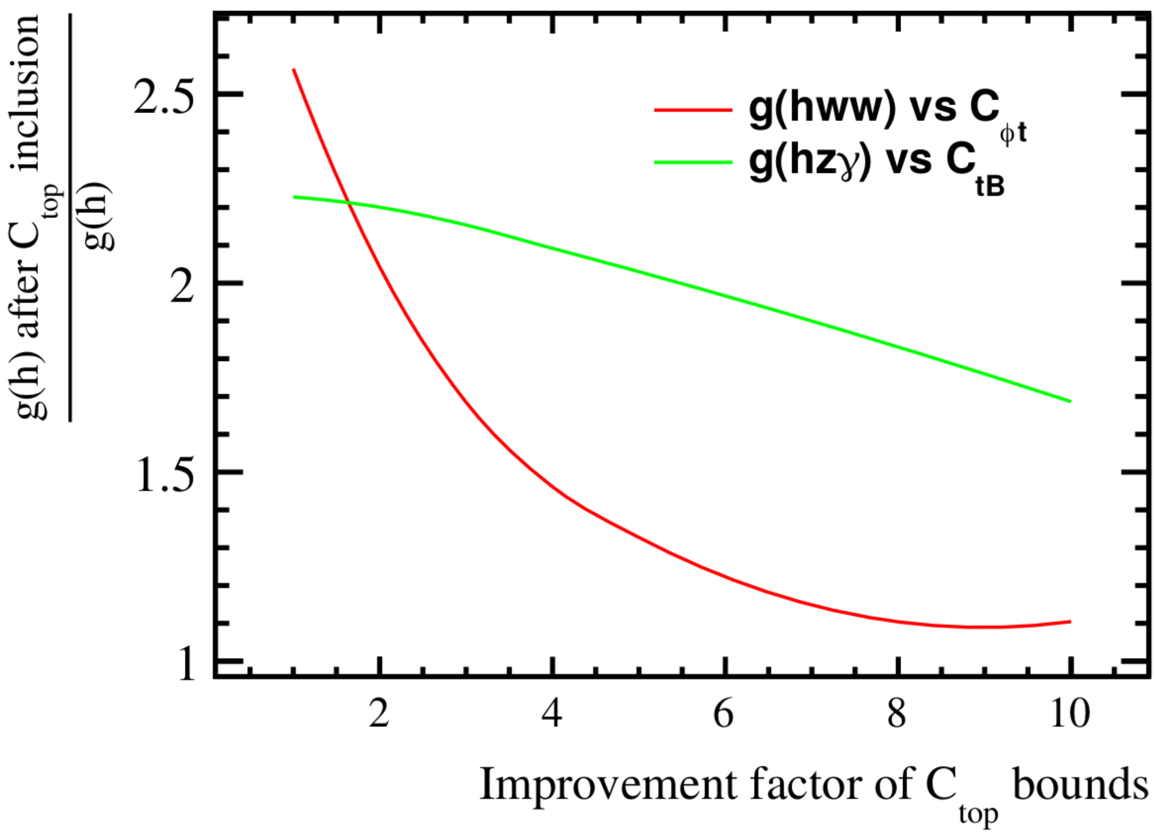
Scenario 2: count on very significant progress in remaining LHC programme

Higgs fit parameters that are most strongly affected by addition of top EW coupllings

Scenario 2 nearly restores Higgs operator coefficients to precision obtained before adding top EW couplings



Global analysis



Degradation of Higgs parameters due to inclusion of top parameters

Improvement of top operator limits wrt current TopFitter results

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

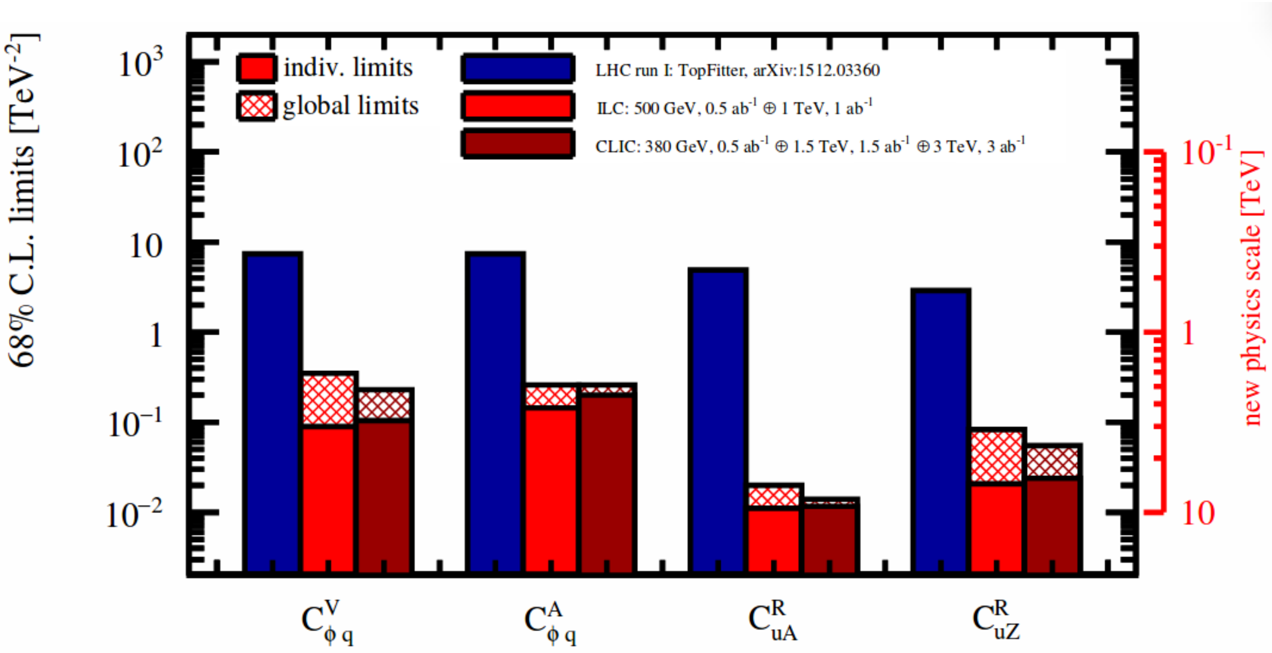
g(hWW) vs. $C_{\phi t}$ → factor 5 improvement restores fit to within 20% of previous result

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

LC top data

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441



Scenario 3: bring in top constraints from a higher-energy run at the linear collider

Two-fermion operator limits at CLIC380 or ILC500 exceed HL-LHC prospects by a very large factor (one energy is enough as we ignore 4-fermion operators)

This of course provides sufficiently strong constraints (but requires patience)

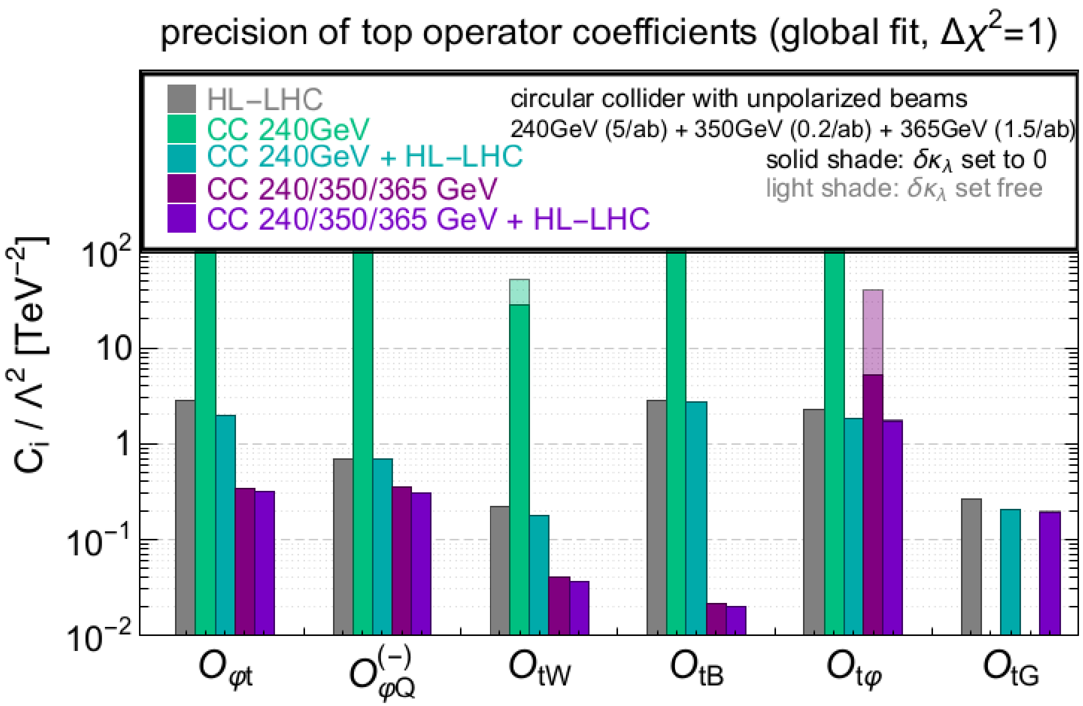
Top Yukawa coupling: global analyis at lepton colliders

Global limits on top operators from 250 GeV measurements
Durieux et al., arXiv:1809.03520

Indirect sensitivity is not robust in global analyis!
- global limits >> individual limits

Including $t\bar{t}$ data helps!
> 350 GeV

Ultimately, direct $t\bar{t}H$ production is crucial!
> 550 GeV



Repeat in ILC environment with realistic HL-LHC constraints

Summary

Top EFT fit at 380 GeV and 3 TeV evaluated in detail

CLIC top paper, arXiv:1807.02441

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

An understanding of the power of LC data for top EFT fit

→ comparison optimal vs. classical observables

→ specialized observables for CP-violating operators

→ role of polarization and center-of-mass energy

→ complementarity of top and bottom data

Outlook

Ongoing work with J. Tian, S. Jung, M. Perelló et al.

First attempts at a combined top+Higgs fit

→ *take into account loop-induced dependence on top EW couplings*

→ *simple setup exists, a full-fledged fit is being prepared*

Opportunity (for single-parameter fits):

→ *competitive results on top EW and Yukawa couplings already at 250 GeV*

Threat (if we insist on a proper global EFT treatment):

→ *inclusion of top EW couplings may deteriorate Higgs/EW fit*

→ *actual impact depends on HL-LHC prospects*

→ *higher-energy operation will eventually solve this problem*