top coupling measurements at future e+e- colliders

Marcel Vos, IFIC, CSIC/UV, Valencia, Spain

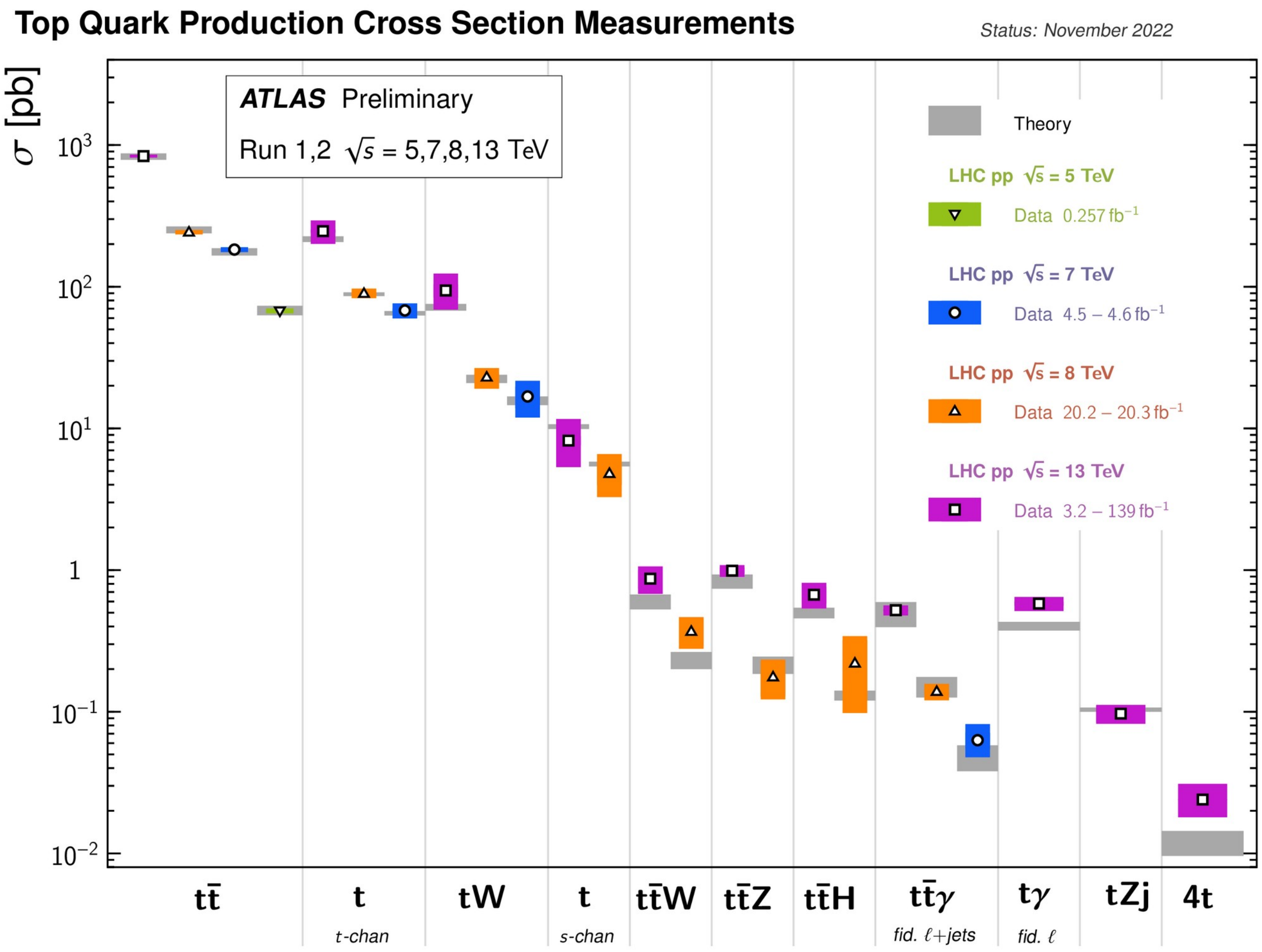
ECFA Higgs/top/EW factory studies, Paris, October 2024

IFIT/C: F. Cornet (Case Western), G. Durieux (Louvain), M. Miralles (Glasgow), V. Miralles (Manchester), M. Moreno (IFIC), M.V.,

Master students Abel Camacho, Pablo Copete, Belén Durán

Acknowledging contributions from many colleagues

The LHC top couplings programme



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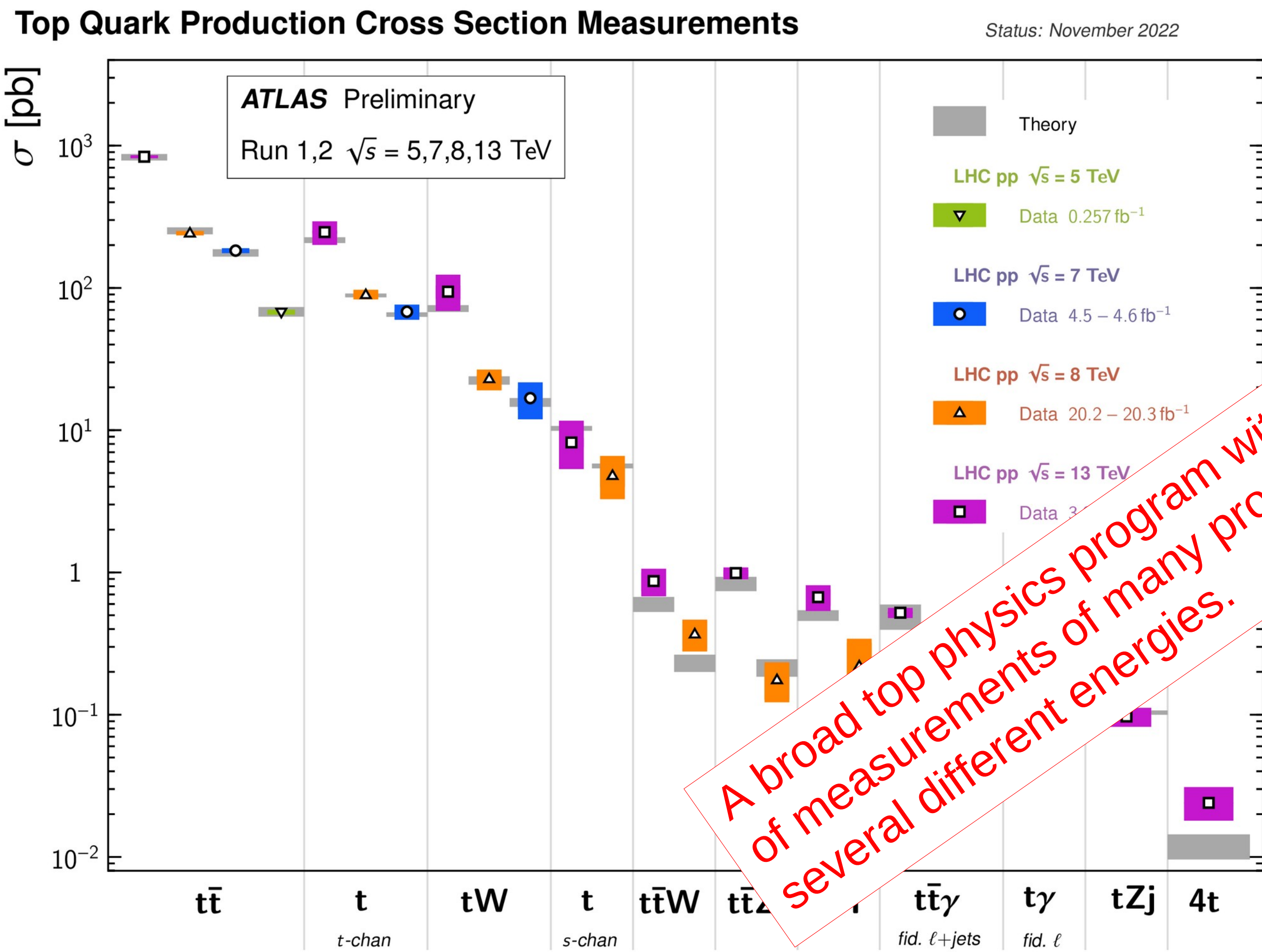

A broad top physics program with hundreds of measurements of many processes and at several different energies.

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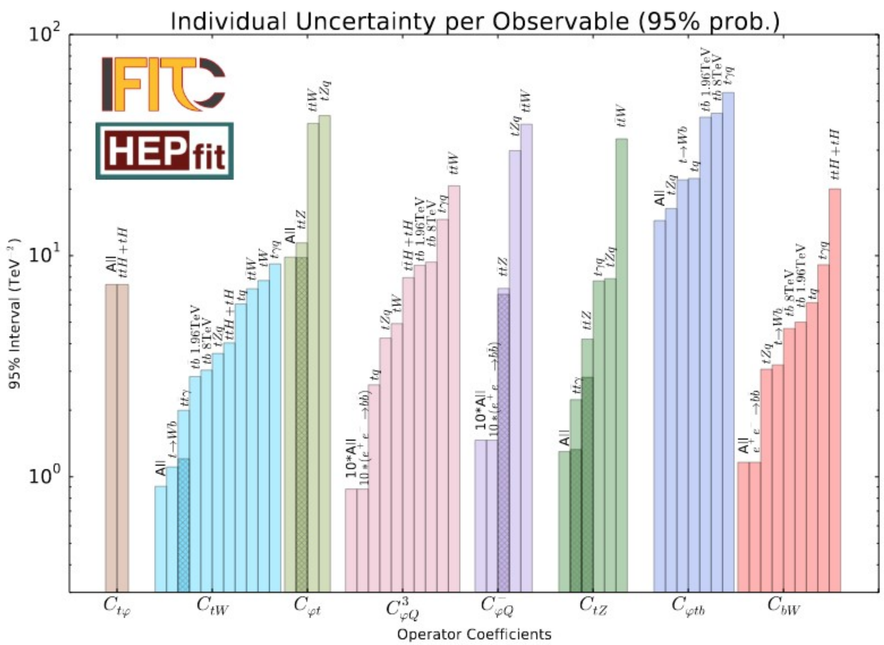
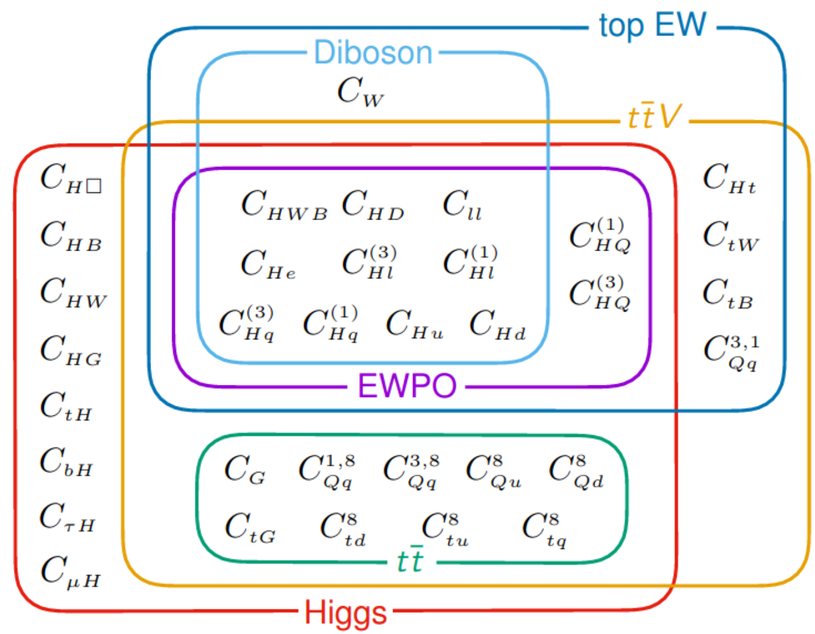
Top couplings at the LHC

Tevatron and LHC have characterized top quark QCD couplings precisely

Charged-current tWb interaction constrained by single top and W-helicity

Couplings with γ/Z/H probed directly in top+X production for the first time
- ttZ, tZq, ttγ, tγq, ttH, ttW observed in run 2





Constraining electro-weak couplings that were not probed directly before (as the top quark escaped scrutiny at LEP) and the top Yukawa coupling

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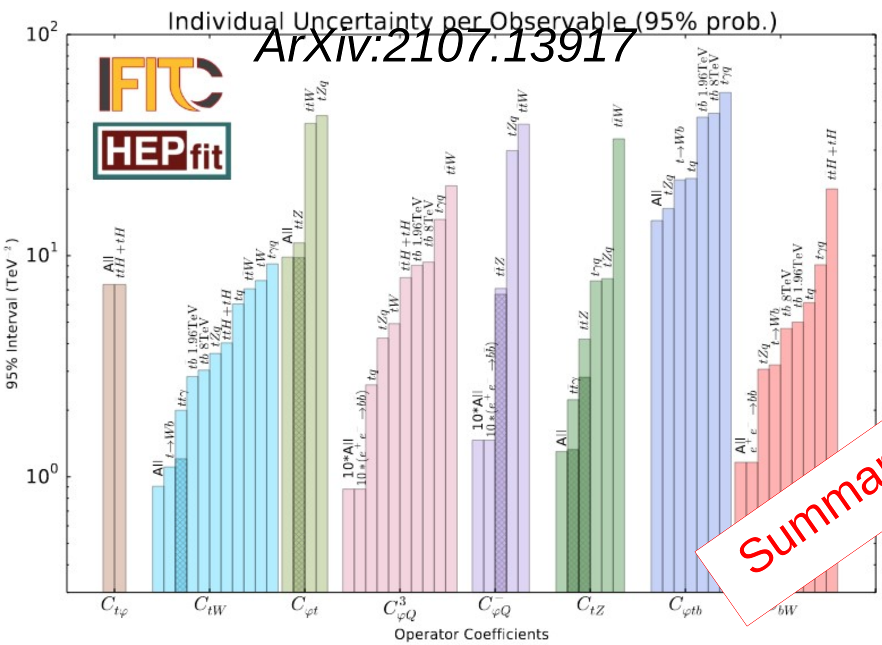
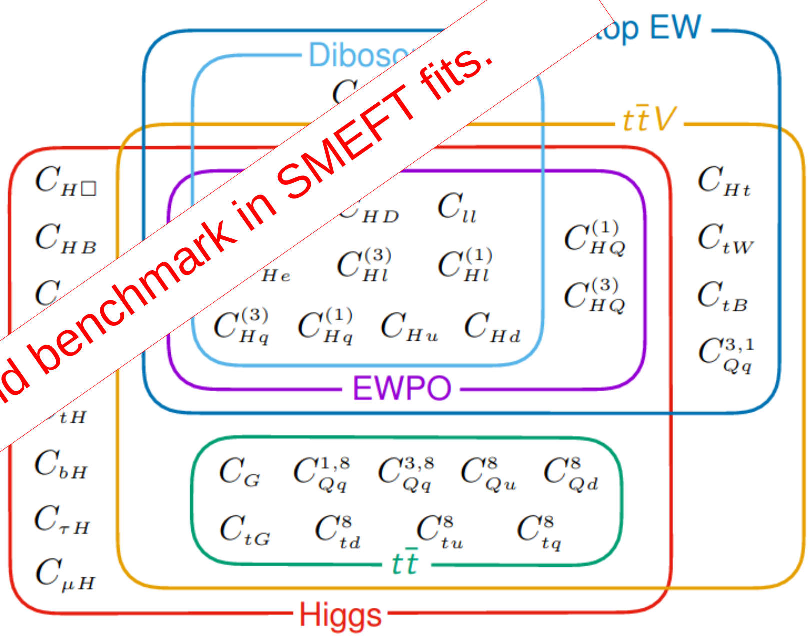
ArXiv:2107.13917





Summarize and benchmark in SMEFT fits.

Constraining electro-weak couplings that were not probed directly before (as the top quark escaped scrutiny at LEP) and the top Yukawa coupling

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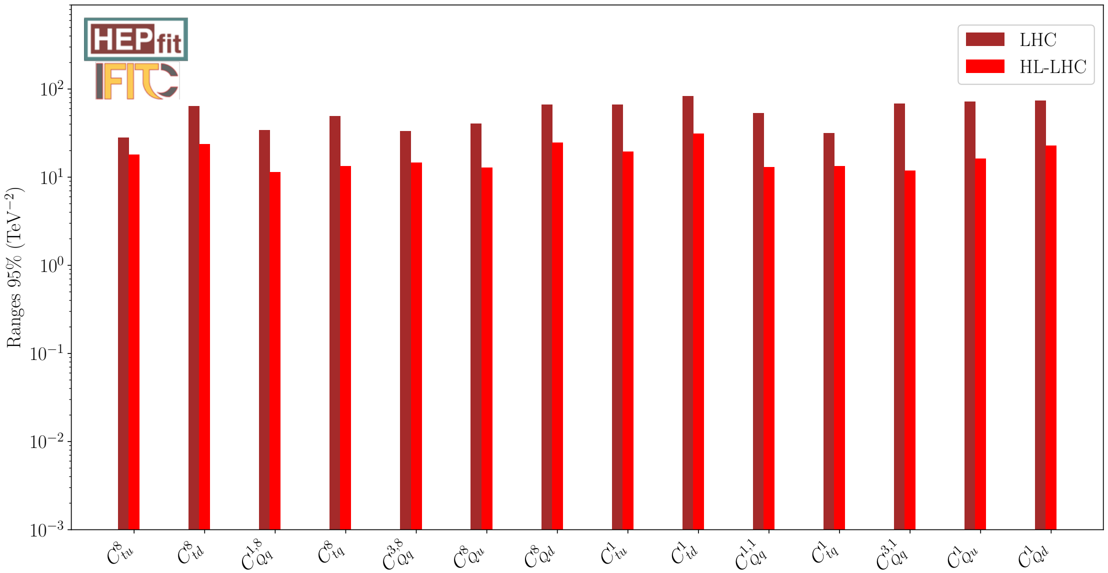
Global fit to the top sector of the SMEFT

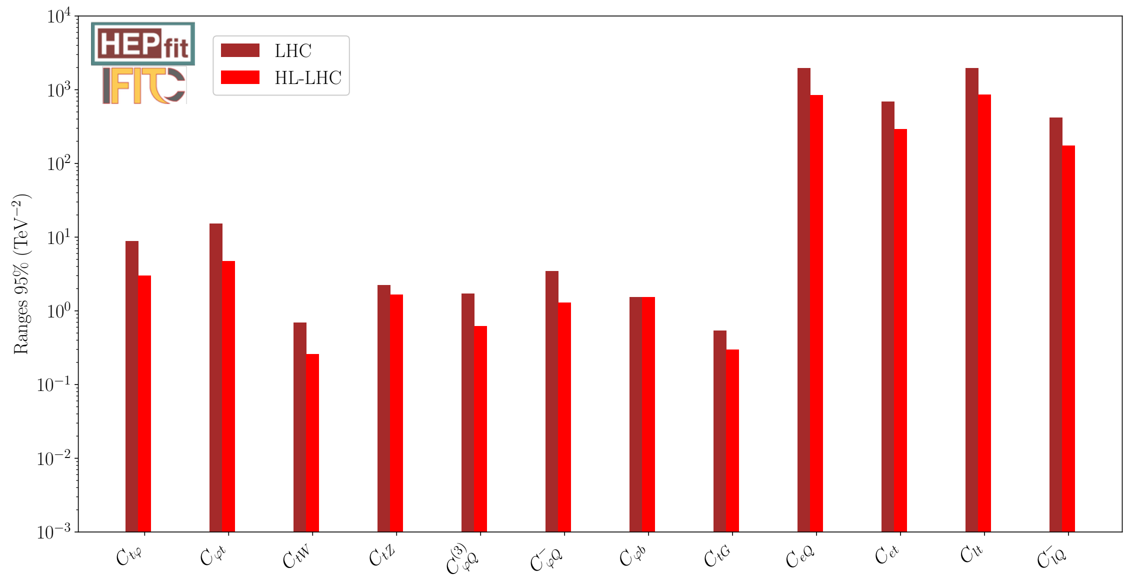


LHC offers sufficient handles to constrain the top sector

Global bounds on four-quark operators from ttbar production reach O(10 TeV^{-2}) after complete HL-LHC program

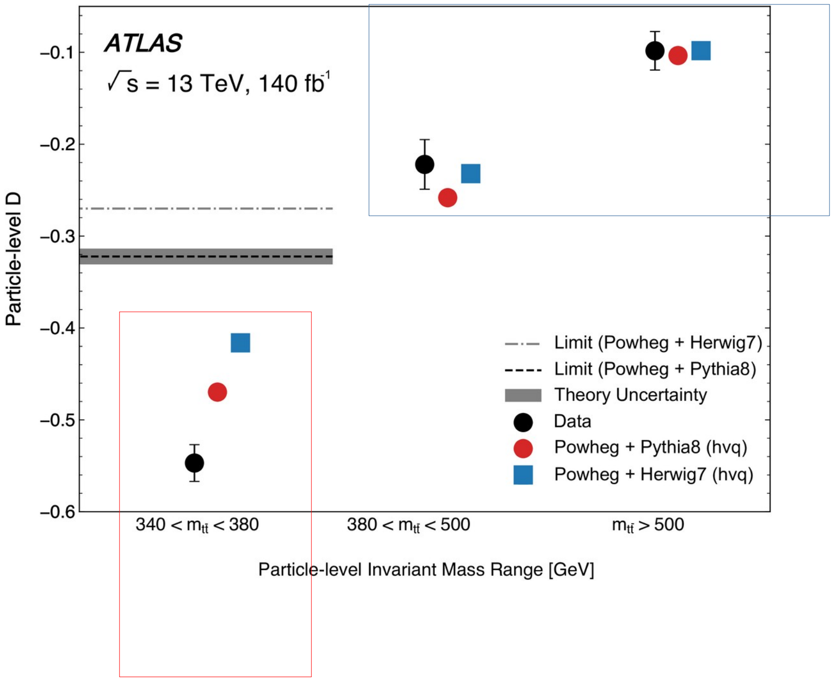
Global bounds on two-quark operators from top+X processes reach O(1 TeV^{-2})

Bounds on two lepton-two-top (eett) operators are poor

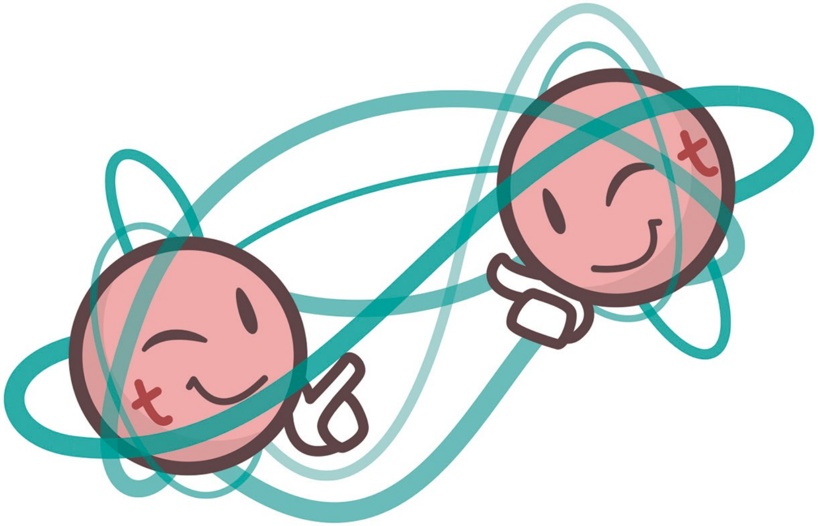


Observation of entanglement

ATLAS, TOP23, September '23



D != 0 top spins are correlated
(nice, but known since 2013)



D < -1/3 top spin correlations are "quantum"
(new! Opens the door to QI@LHC)

ATLAS, Nature 633 (2024)
CMS, arXiv:2406.03976
CMS, arXiv:2409.11067
CMS, HIG-22-013

Quantum entanglement observed in top quark pair production

Observation of entanglement

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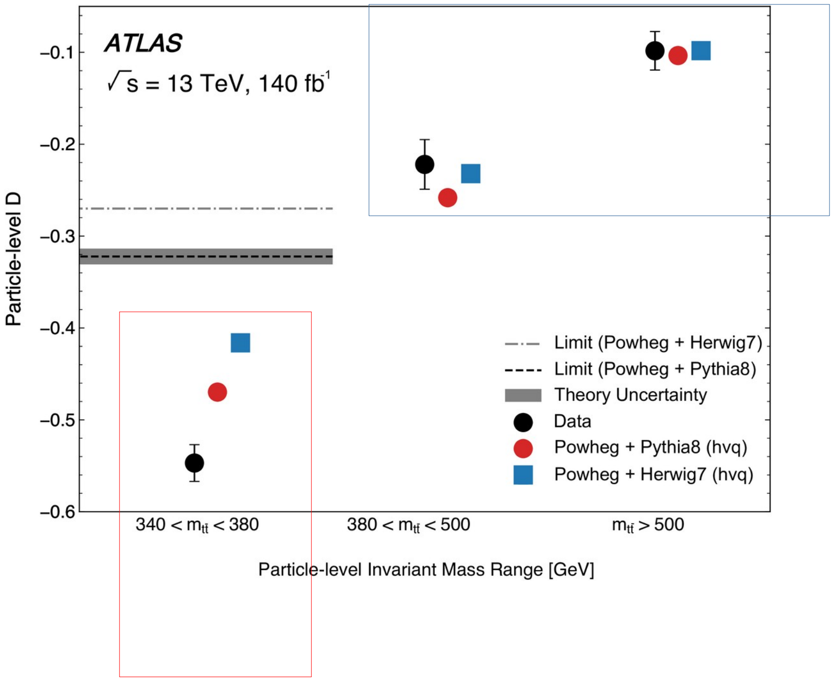

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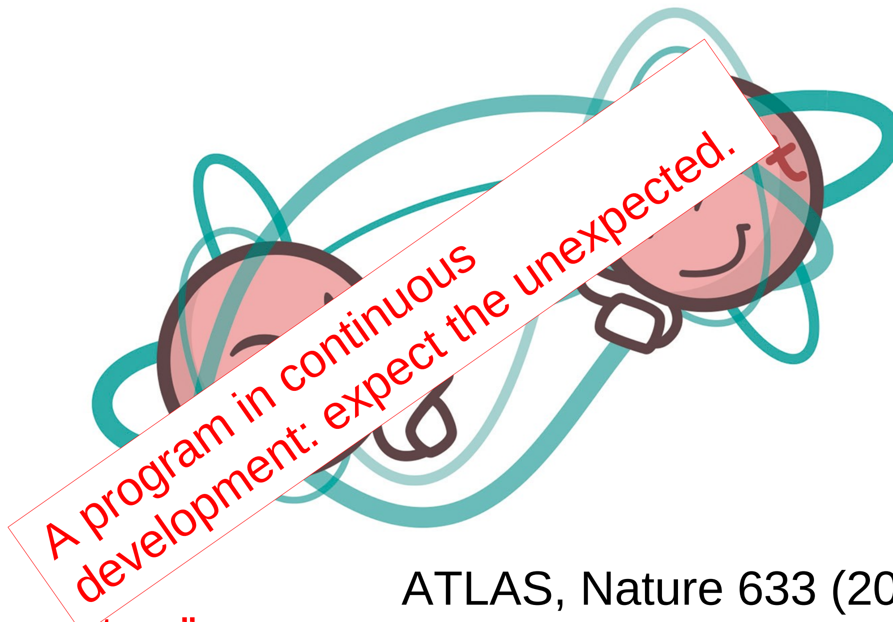

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Entanglement observables

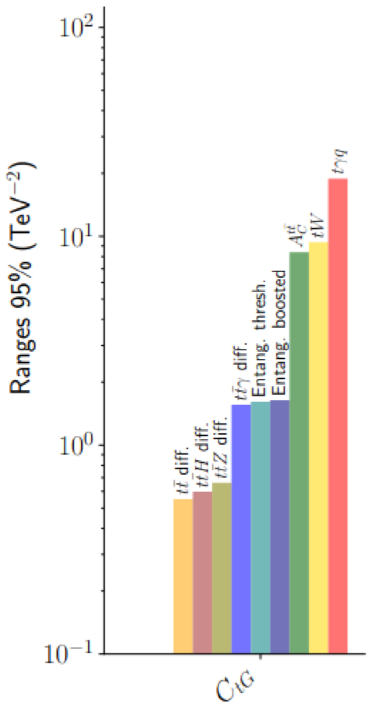
Following Severi et al.,
EPJC82 (2022), JHEP01 (2023), JHEP09 (2023), JHEP03 (2024), JHEP09 (2024)

Added CMS results at threshold and in boosted region to SMEFT fit of top sector

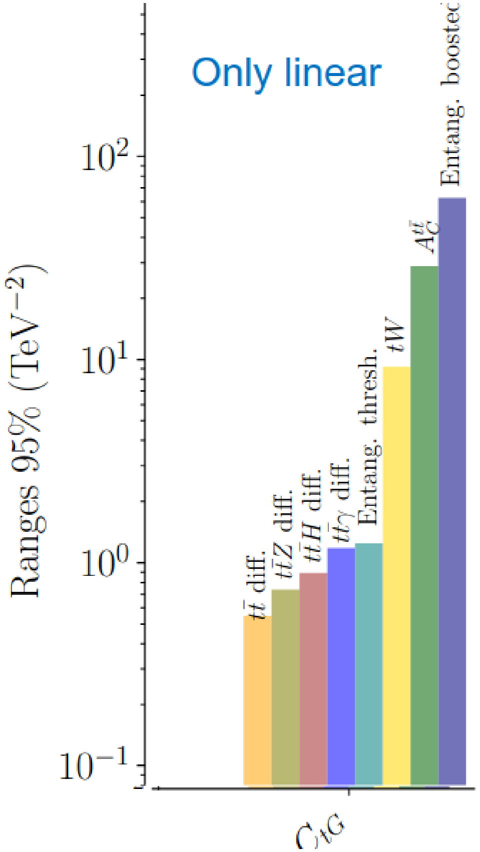
Interesting sensivitity, but no game-changer just yet.

M. Moreno-Llacer,
Quantum tests in collider physics
Oxford, October 2024

Linear+Quad.



Only linear



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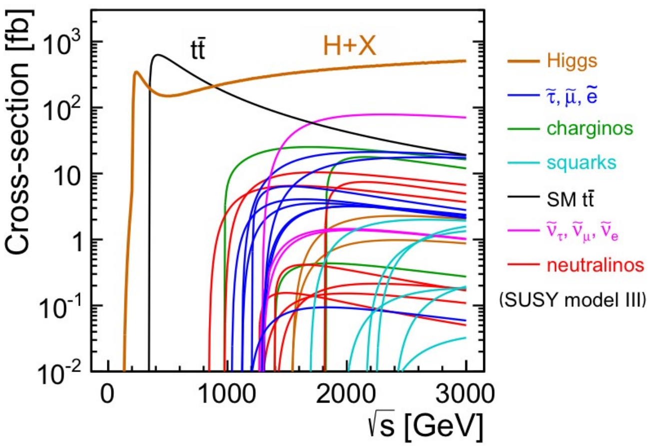
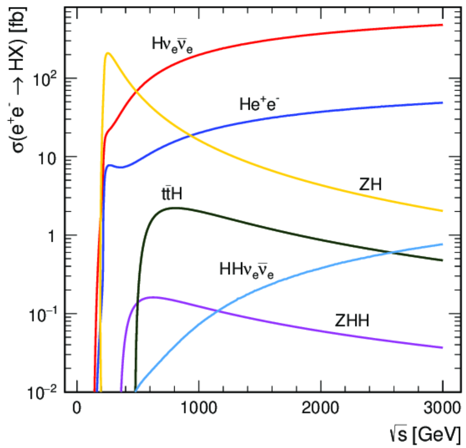
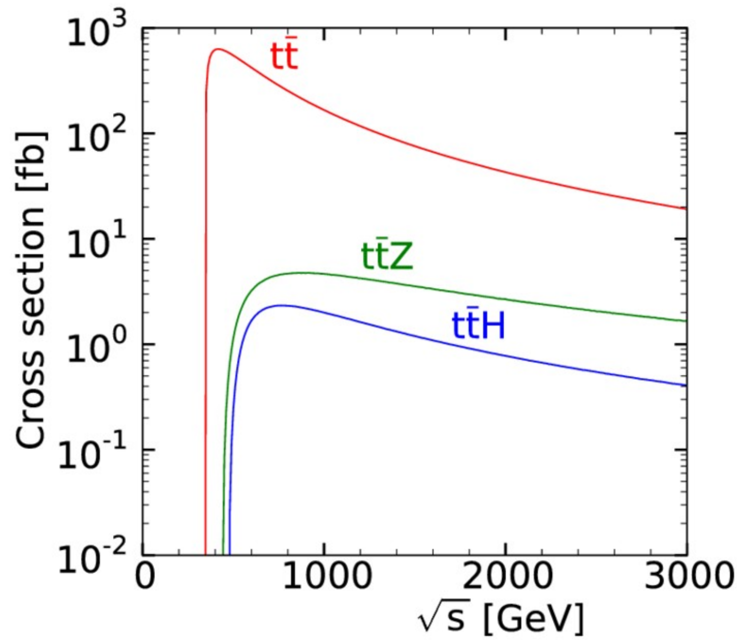
So, what about lepton colliders?

Top production in e+e- colliders

The ideal facility covers a broad energy range.







Top physics thresholds:

~ 90 GeV indirect, through EW precision
~ 250 GeV indirect, through H→gg, H→ γγ
searches for FCNC e+e- → tc
~ 350 GeV direct, pair production
~ 550 GeV direct, ttH
~ few TeV for VBF tt production, single top

Precision

Remember that ATLAS $t\bar{t}$ cross section with <2% uncertainty?

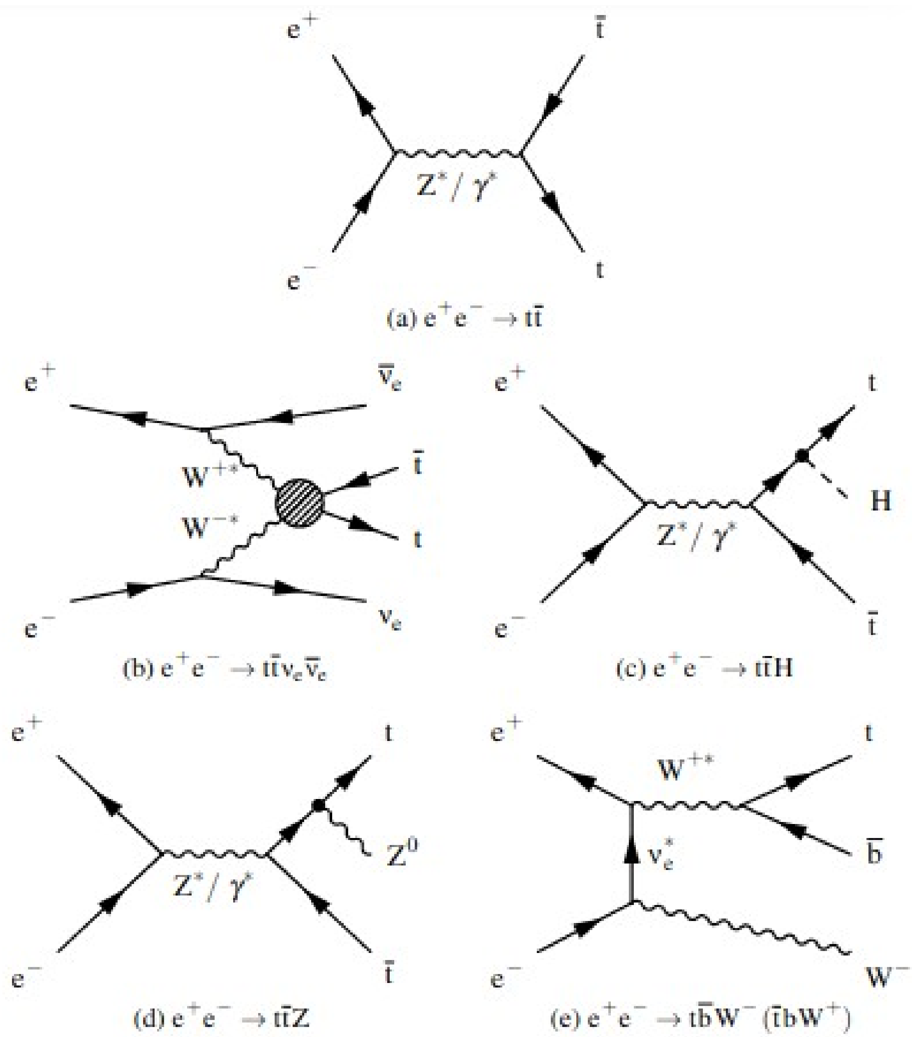
Main bottle neck at the LHC today remains NNLO+NNLL theory

At an e+e- collider realistic statistical uncertainties are O(few ‰)
→ *See e.g. CLIC top paper, arXiv:1807.02441*

Experimental systematic uncertainties can be controlled to that level
→ *requires work on techniques, calibrations and MC*

Theoretical uncertainties can be made small enough
→ *partial NNNLO QCD is available today*
X. Chen et al., Heavy-quark pair production at lepton colliders at NNNLO in QCD, arXiv:2209.14259

The top physics program at e+e- colliders



CLIC top physics paper, 1807.02441

Initial studies used classical obs.
[σ, A_{FB}] x 2 P_e x 2 √s
(arXiv:1505.06020)

P. Janot uses final-state lepton distributions (arXiv:1503.01325)

Durieux et al. e+e- → WbWb
Pair production + single top
arXiv:1807.02121 → input to EFT

Added ttH for top Yukawa and VBF production for muon collider

Further information in ttγ, ttg, ttZ not exploited so far

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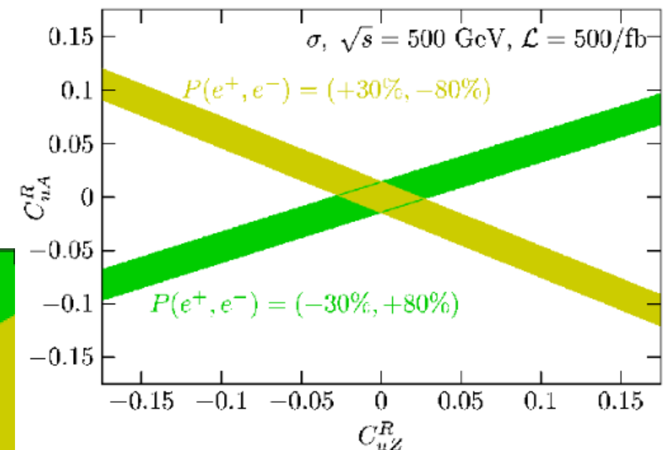
The e+e- top physics programme

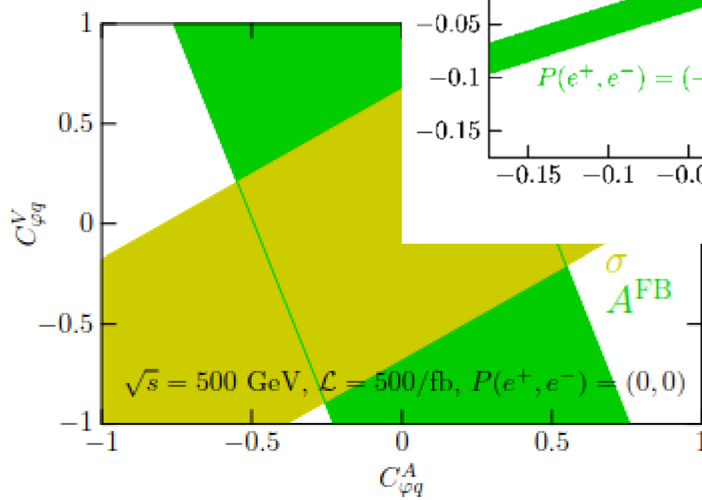
Experimental study: CLIC, arXiv:1807.02441, Amjad et al., arXiv:
SMEFT fit and projections: Durieux, Perello, Vos, Zhang, arXiv:1808.02121

The main work-horse:

- e+e- → WbWb (+ttH, +VBF)
- many measurements with complementary constraints
  optimal observables to constrain top sector
- realistic projections from CLIC full-sim study
  acceptance from interpolation 380GeV-3 TeV
  systematic uncertainties verified to be small

$\sqrt{s}$	380 GeV [a]		1.4 TeV [b]		3 TeV [b]	
P(e$^-$)	-80%	+80%	-80%	+80%	-80%	+80%
$\sigma_{t\bar{t}}$ [c] [fb]	161.00	75.97	18.44	9.84	3.52	1.91
stat. unc. [fb]	0.77	0.52	0.21	0.29	0.07	0.09
A_{FB}	0.1761	0.2065	0.567	0.620	0.596	0.645
stat. unc.	0.0067	0.0059	0.008	0.020	0.014	0.034

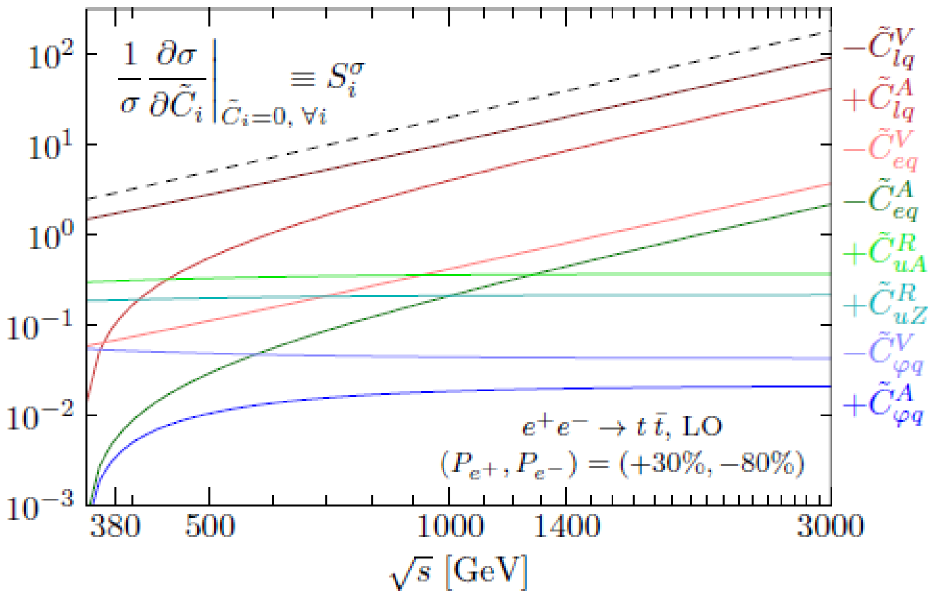




The optimal e$^+$e$^-$ program

An optimal top physics program must cover two energies above the tt threshold

Total cross section (left pol.):



Energy & precision

Getting close to the New Physics pays off; impact grows with energy

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

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

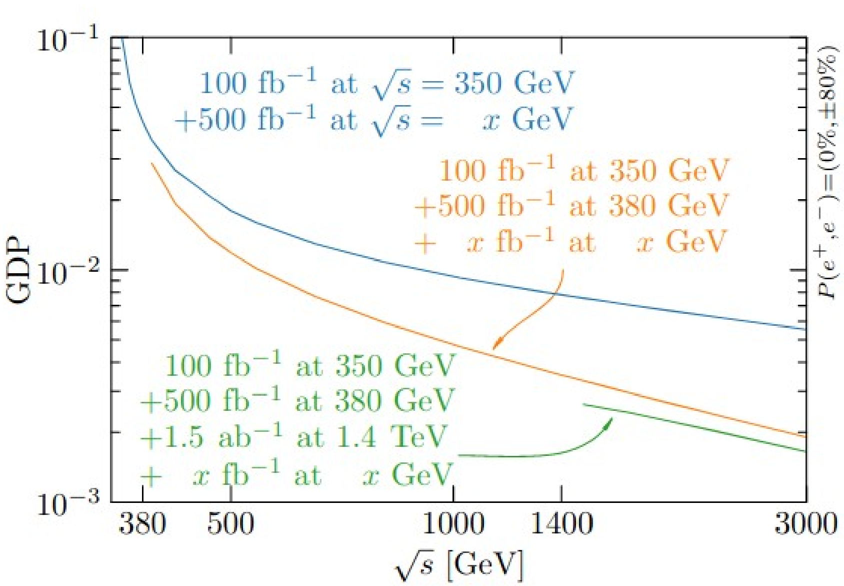
Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

CLIC New Physics paper, arXiv:1812.02093

The optimal e^+e^- program (bonus slide added a posteriori)

An optimal top physics program must cover two energies above the tt threshold



Energy & precision

Running at two energies above the tt threshold, we disentangle contributions by 2- and 4-fermion operators

The bounds (quantified with GDP – the hypervolume of allowed parameter space) decrease rapidly as the lever arm of the second energy point increases

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

CLIC New Physics paper, arXiv:1812.02093

top EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

Circular
Collider
350+365

Sensitivity to four-fermion operators increases strongly with energy

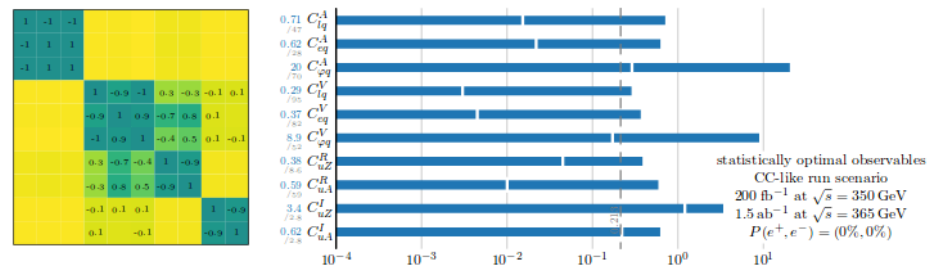


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

ILC500+
ILC1000

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

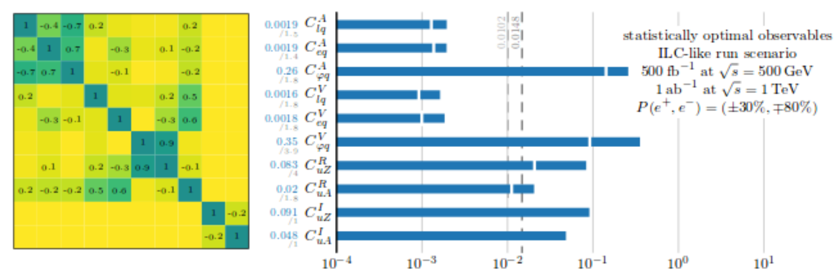


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

CLIC380+
CLIC1500+
CLIC3000

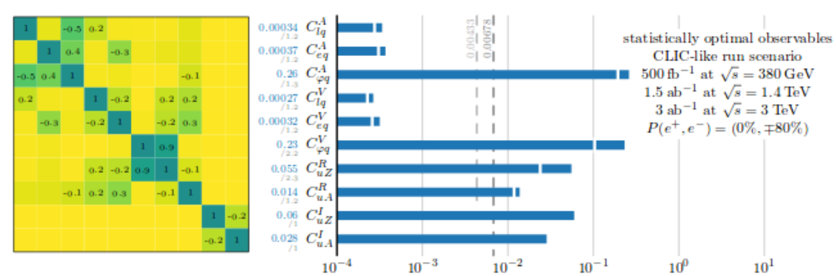
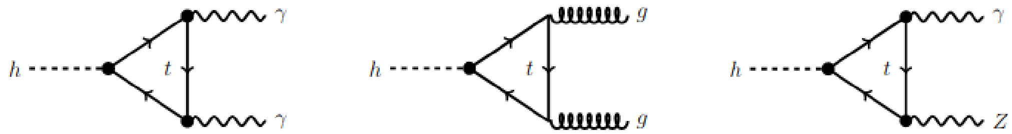


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

Warning: versions with old luminosity

The top Yukawa coupling at a lepton collider



250 GeV run offers "indirect" sensitivity to the top Yukawa

$\Delta y/y < 1\%$ from $H \rightarrow gg$ — *Mitov et al., arXiv:1805.12027*

$\Delta y/y < 1\%$ from $H \rightarrow \gamma\gamma$ — *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings: not (yet) included in our analysis

500+ GeV run offers a "direct" measurement in ttH production

1-2% precision — *Price et al., arXiv:1409.7157*

robust in global analysis — *Jung et al.,arXiv:2006.14631*

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, de Blas et al., arXiv:2206.08326

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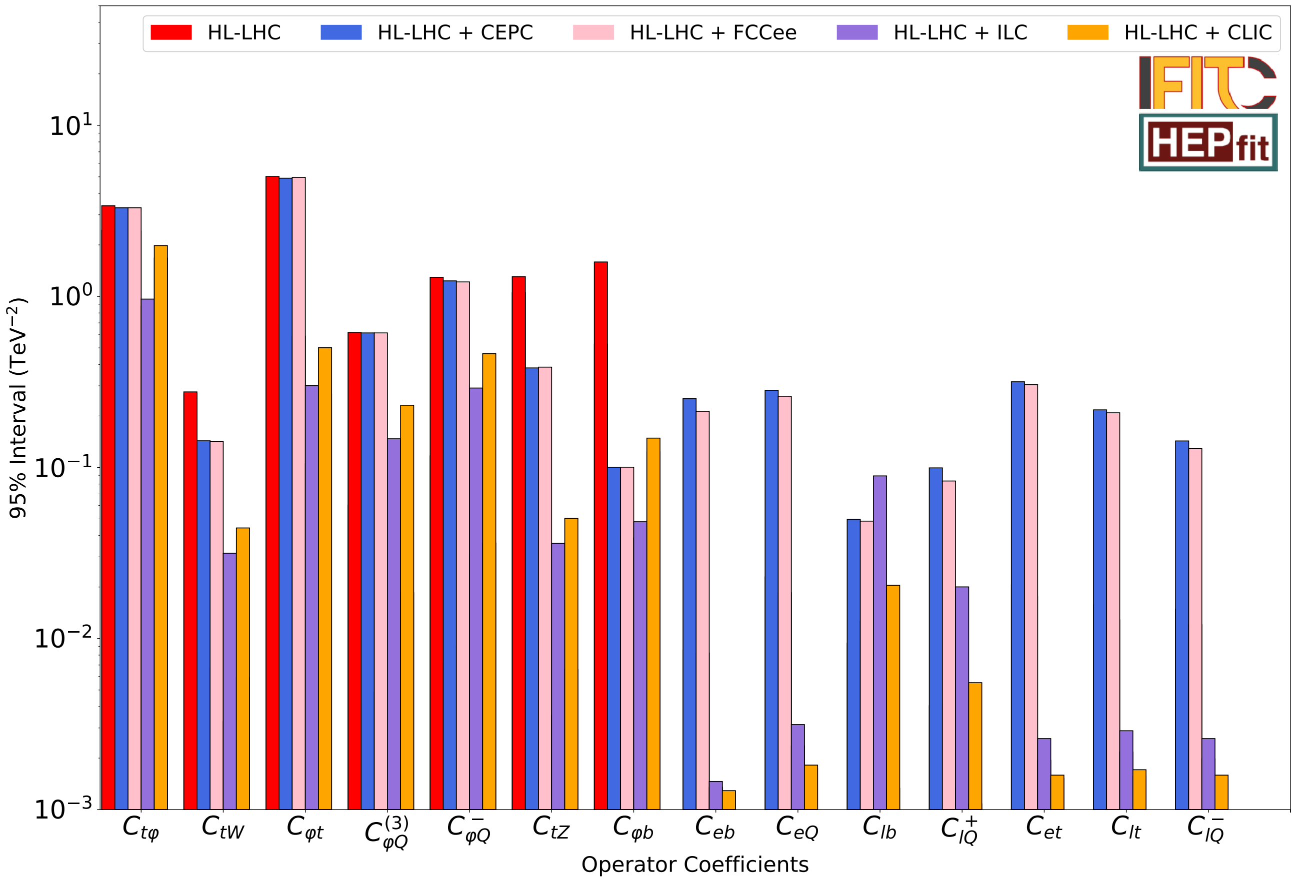
SMEFT fit of the top sector – anno 2022

Snowmass fit to the top sector: *de Blas et al., arXiv:2206.08326*



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New: HL-LHC prospects for ttll operators

ttll operators affect Higgs self-coupling from ZH
(see Junping Tian's talk on Friday)

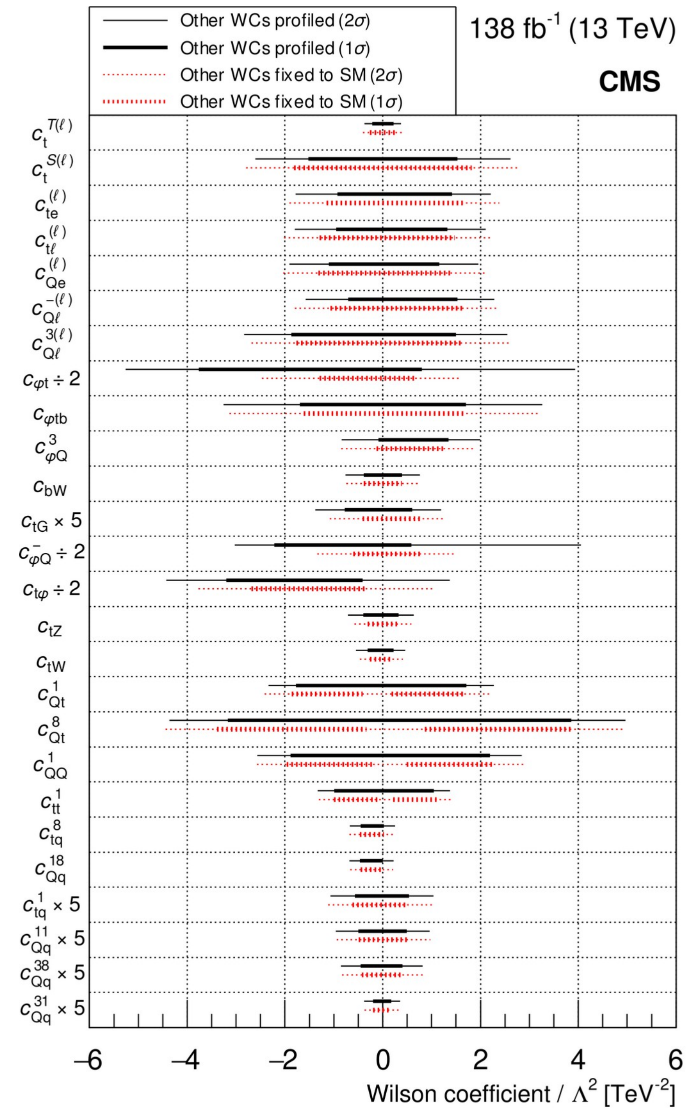
Impact on ZH known, Asteriades et al.,
(see, arXiv:2409.11466, P. Giardino tomorrow)

Everyone: LHC cannot constrain those
LHC: challenge accepted!

Global bounds @ 95 % CL:

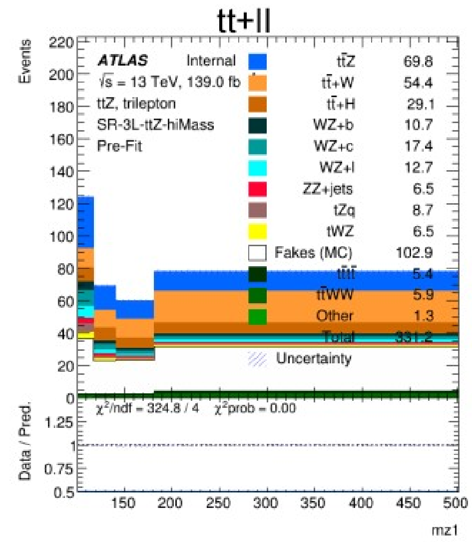
O(1 TeV^{-2})

Pretty good sensitivity!

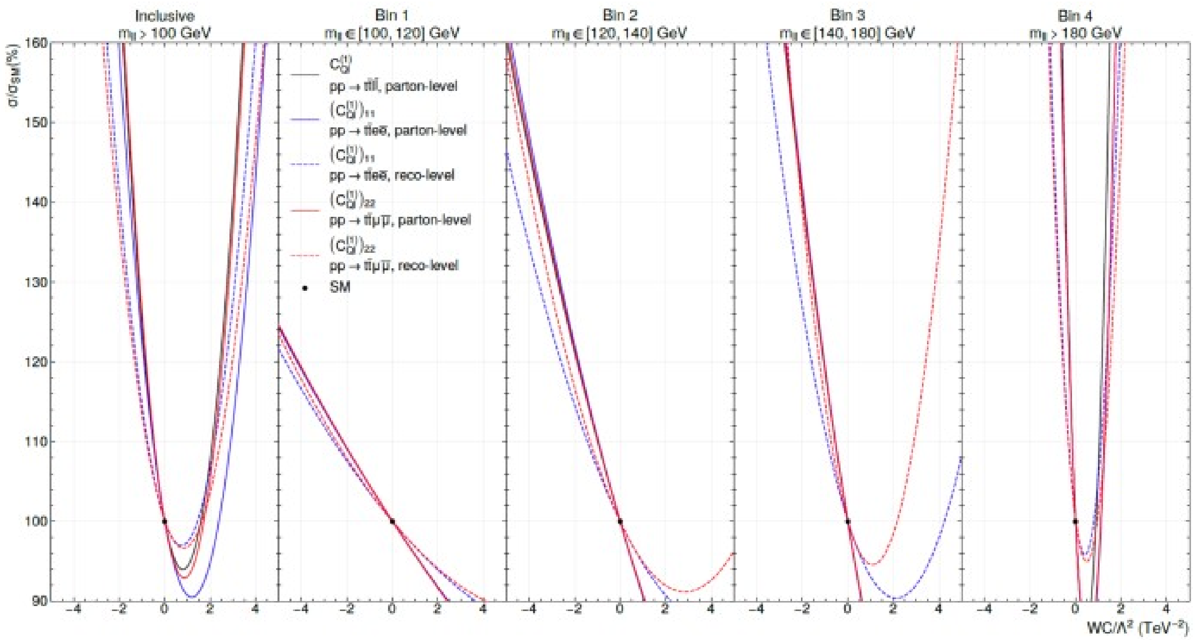


The ttll operators

LHC sensitivity – relies on quadratic terms



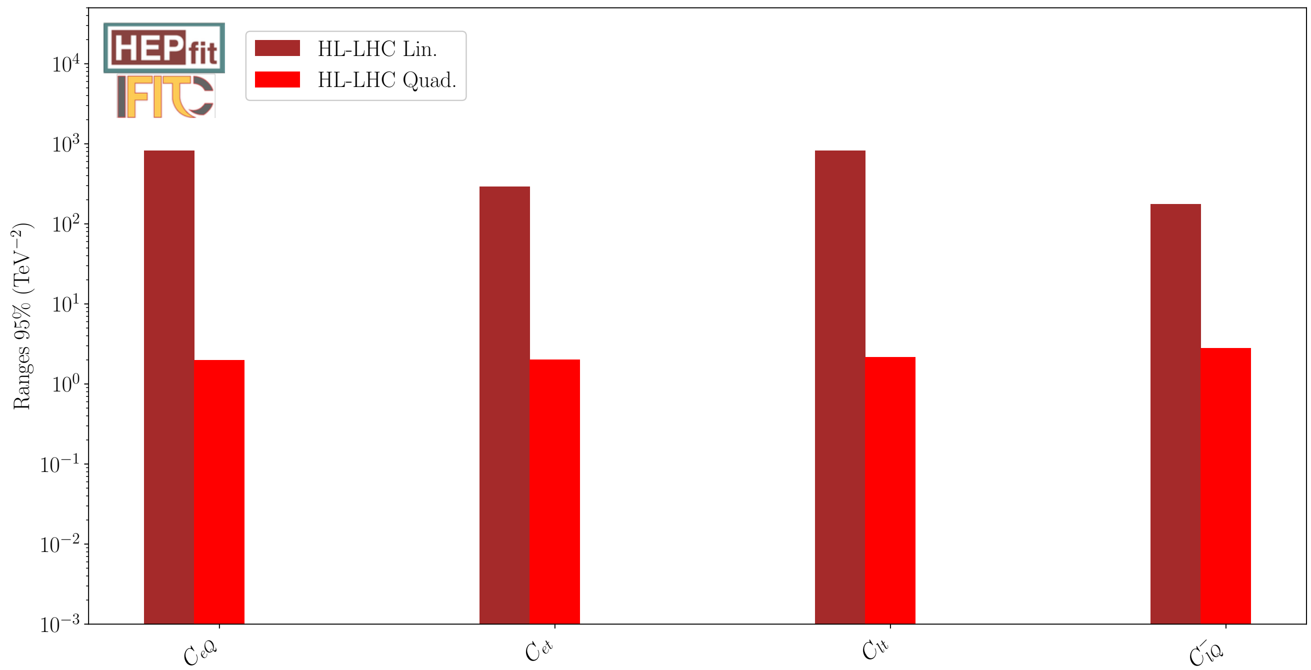
O(10) off-shell ttll events



EFT sensitivity of a hypothetical future ttll measurement – Abel Camacho, Maria Moreno, MV., master's thesis (extrapolating from published ATLAS ttZ results)

Prospects for ttll operators

PRELIMINARY
PRELIMINARY



LHC sensitivity – linear fits much degraded
Quadratic global: O(1)
Linear individual: O(1-10 TeV^{-2})
Linear global: O(100 TeV^{-2})

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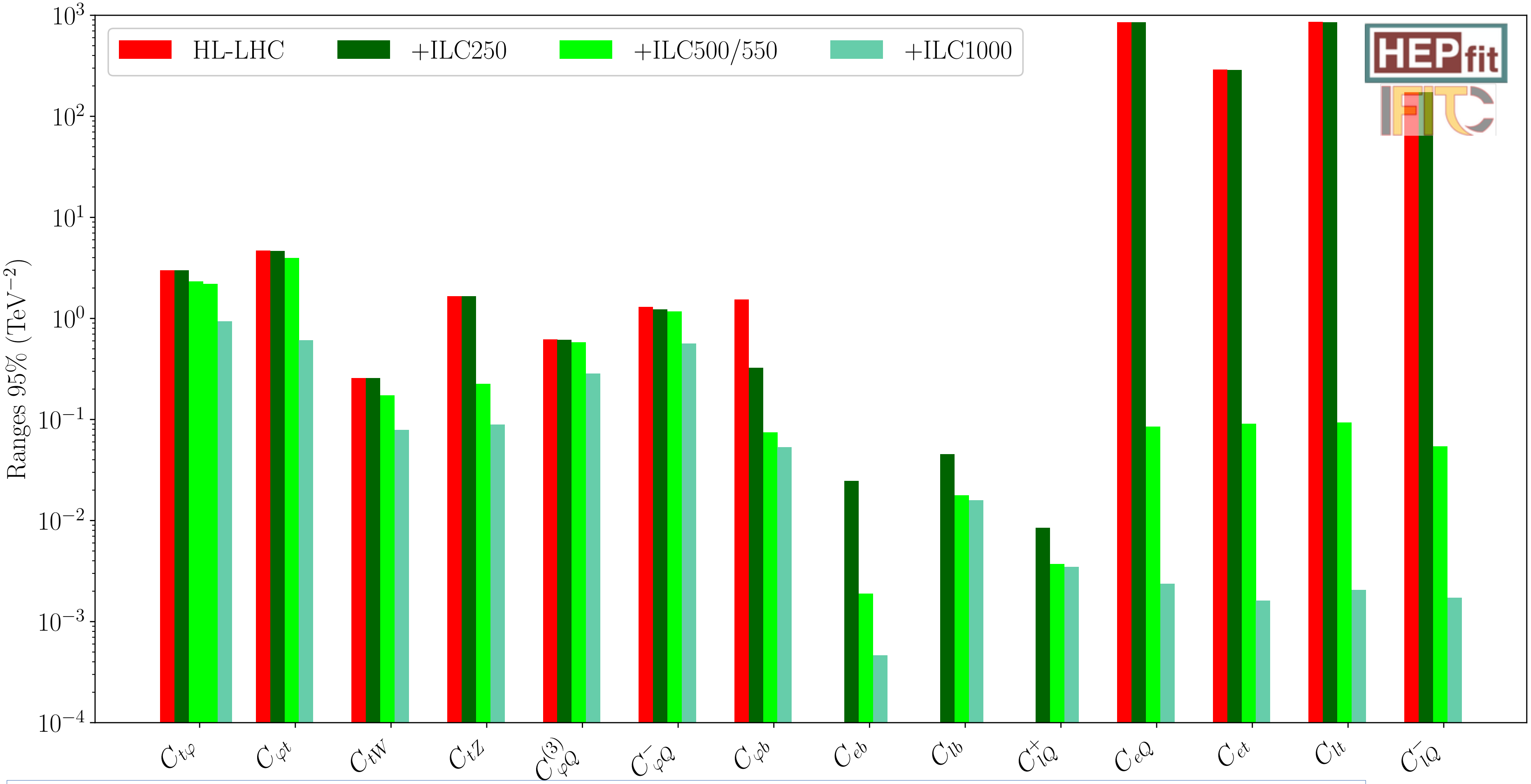
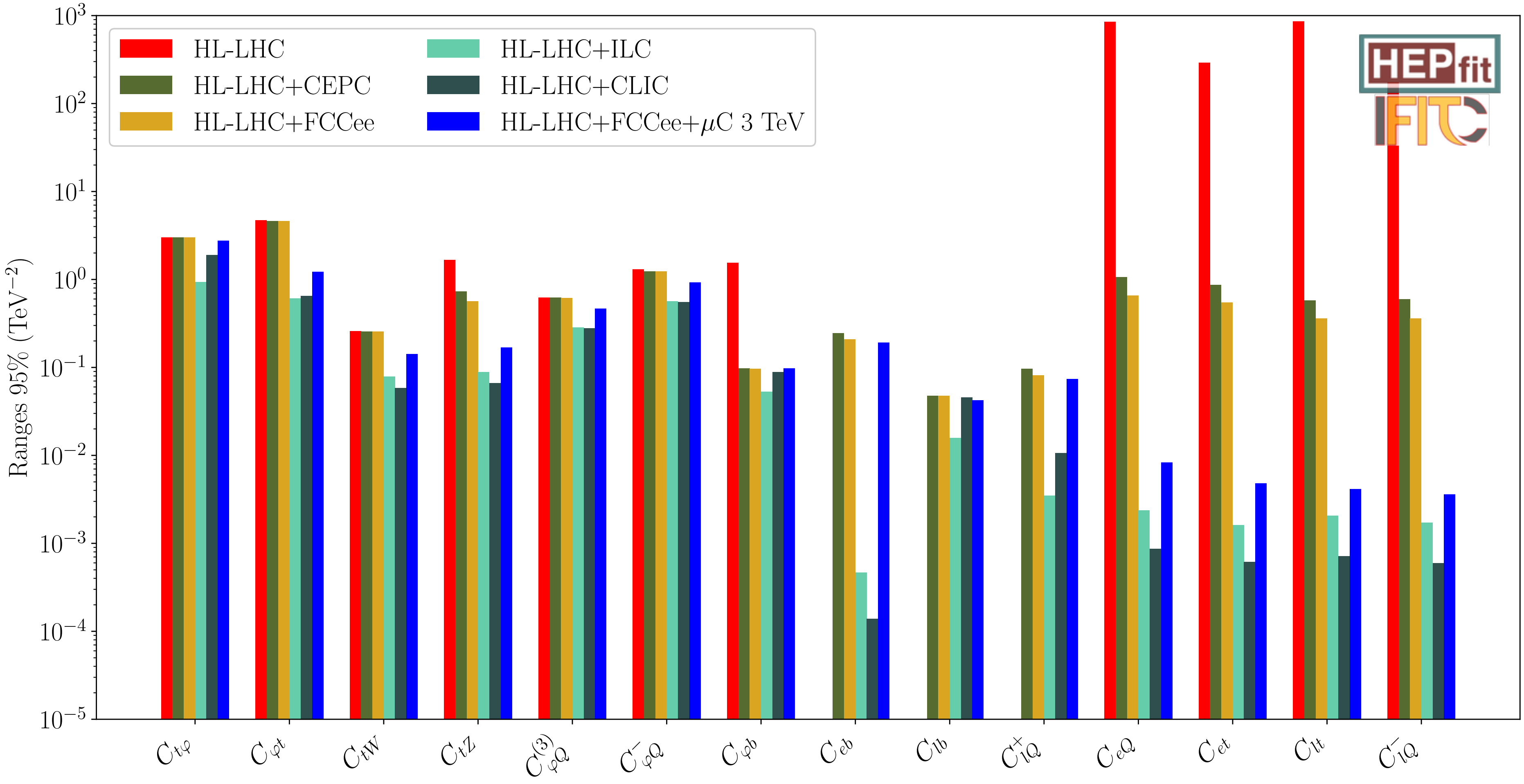
SMEFT fit of the top sector



The 250 GeV run provides some information (interplay bottom-top)
Top production at an e+e- collider yields dramatic improvement
The fit benefits from a 2nd top run at high energy (2-vs-4 fermion operators)

SMEFT fit for different colliders



All e+e- colliders improve the bounds on the top sector dramatically
High-energy operation is important to provide the strongest global bounds

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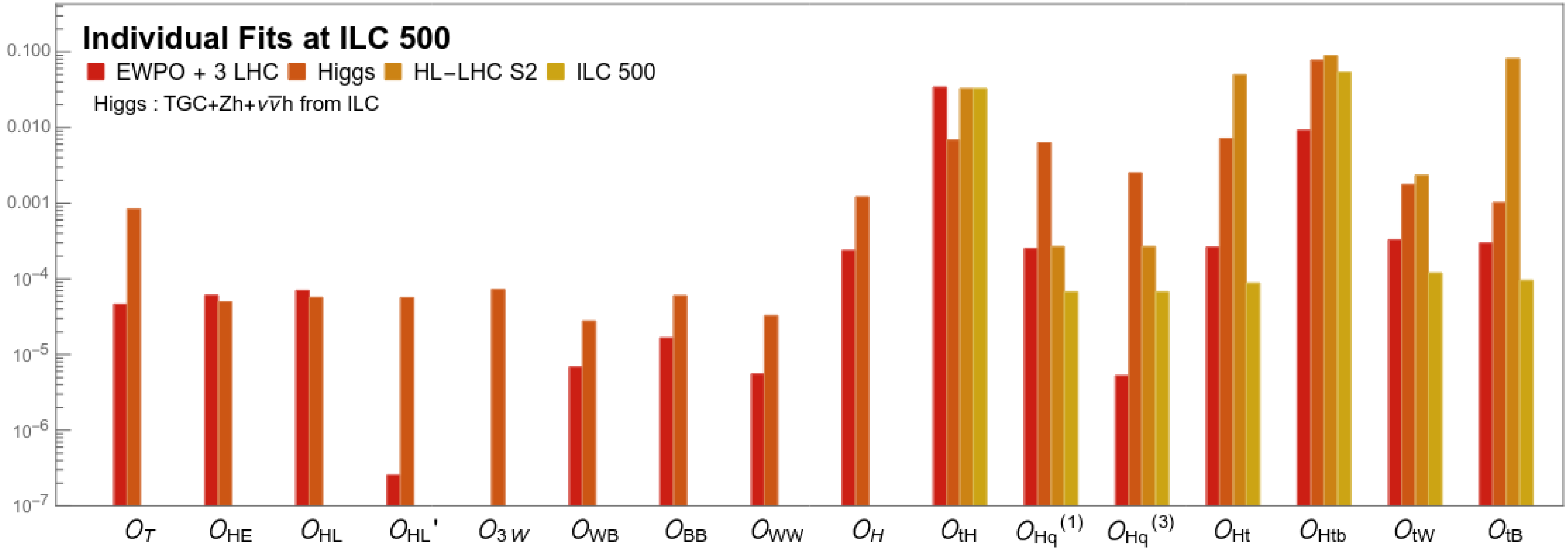
SMEFT fit – future work

EWPO and Higgs data have signficant constraining power on top operators
Need a complete data set – including precision top data - to constrain all angles



S. Jung et al., arXiv:2006. (see also work by Vryonidou et al.)

Possible next steps in ECFA Higgs/top/EW factory studies:
– merge Higgs/EW and top EFT fits on prospects (see J. Ter Hoeve)

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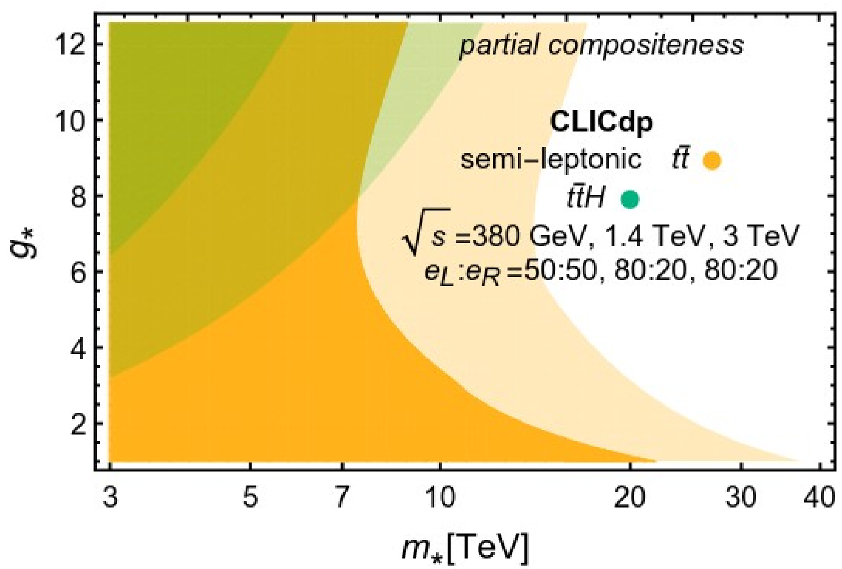
Reminder: BSM physics and top quark couplings

Top (and its couplings) are special in many BSM scenarios
Precision coupling measurements ARE a sensitive BSM search
Snowmass top physics report, https://arxiv.org/pdf/2209.11267.pdf

D. Top-quark compositeness

High-energy lepton colliders are sensitive probes of top-quark compositeness. For example, Fig. 30 shows the reach in the composite sector confinement scale m_* and the composite coupling strength parameter g_* of a partial top compositeness scenario at a multi-TeV e^+e^- collider [61] (see also [542]).



energy + precision
= BSM sensitivity

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Summary

The next large-scale e+e- facility in HEP can (should) do a lot of top physics!

A broad program of precision measurements unfolds above the top quark pair production threshold including many processes (tt, ttγ, ttg, single top, ttZ, ttH, VBF tt production) and many measurements (σ, A_{FB}, polarization, CP-odd observables…)

The SMEFT provides an ideal tool to compare and benchmark colliders. We provide a global analysis for LHC, as well as HL-LHC and future e+e- collider projections. The e+e- measurements offer complementary information and provide exquisite bounds on top EW couplings.

New publication in preparation, along with two-page summary. Results will be finalized in time for ECFA report.

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EFT basis for the top sector

2-quark operators

Couplings of the t- and b-quark to the Z

$$O^3_{\varphi Q} \equiv \left(\bar{Q}\tau^I \gamma^\mu Q\right)\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi\right)$$

$$O^1_{\varphi Q} \equiv \left(\bar{Q}\gamma^\mu Q\right)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$$

$$O_{\varphi t(b)} \equiv \left(\bar{t}(\bar{b})\gamma^\mu t(b)\right)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$$

EW dipole operators

$$O_{uW} \equiv \left(\bar{Q}\tau^I \sigma^{\mu\nu} t\right)\left(\varepsilon\varphi^* W^I_{\mu\nu}\right)$$

$$O_{tB} \equiv \left(\bar{Q}\sigma^{\mu\nu} t\right)\left(\varepsilon\varphi^* B_{\mu\nu}\right)$$

Chromo-magnetic dipole op.

$$O_{tG} \equiv \left(\bar{Q}\sigma^{\mu\nu} T^A t\right)\left(\varepsilon\varphi^* G^A_{\mu\nu}\right)$$

t-quark yukawa

$$O_{t\varphi} \equiv \left(\bar{Q}t\right)\left(\varepsilon\varphi^* \varphi^\dagger \varphi\right)$$

4-quark operators

Couplings of light quarks with t- and b-quarks

$O^{(8)(1)}_{tu}$ $O^{(8)(1)}_{td}$ $O^{(1,8)(1,1)}_{Qq}$ $O^{(8)(1)}_{Qu}$ $O^{(8)(1)}_{Qd}$ $O^{(3,8)(3,1)}_{Qq}$ $O^{(8)(1)}_{tq}$

2-quark 2-lepton operators

Couplings of light leptons with t- and b-quarks

O_{eb} O_{lb} O_{et} O_{lt} O_{eQ} O^{+}_{lQ} O^{-}_{lQ}

LHC dataset (+Tevatron, LEP/SLC)

Observables from current colliders (LEP/SLC, Tevatron, LHC run 1 & 2)

- Parametrisations obtained with `SMEFT@NLO` in `MadGraph`

Process	Observable	$\sqrt{s}$	$\int \mathscr{L}$	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (8 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}H$	$d\sigma/dp_T^H$ (6 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

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