The top quark EW couplings in the SMEFT

LCWS 2024

July 9, 2024

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Together with: Victor Miralles, Marcos Miralles, Maria Moreno and Marcel Vos

Based on:

- Cotinuation of Snowmass: [2205.02140] and [2206.08326]
  - By members of the EF04 team: Jorge de Blas, Yong Du, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael E. Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou and also additional members of the EF03 team: Gauthier Durieux, Abel Gutiérrez Camacho, Luca Mantani, Marcos Miralles López , María Moreno Llácer, René Poncelet

- and near future paper (stay tuned)

- Newer results will be presented at ICHEP by Victor Miralles

Introduction

- Goal: constrain the top-quark Wilson coefficients of the SMEFT
- Numerical fits performed using `HEPfit` [1910.14012]
- The following topics will be discussed:
  - Relevant observables constraining each Wilson Coefficient
  - Estimations on the improvement of the measurements for the HL-LHC
  - Estimation of the relevant observables for this fit in future lepton colliders
  - Prospects for our limits in the HL-LHC, the ILC and the rest of lepton colliders

Relevant operators

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

Rotation of Warsaw basis fo llowing [1802.07237] (LHC Top WG)

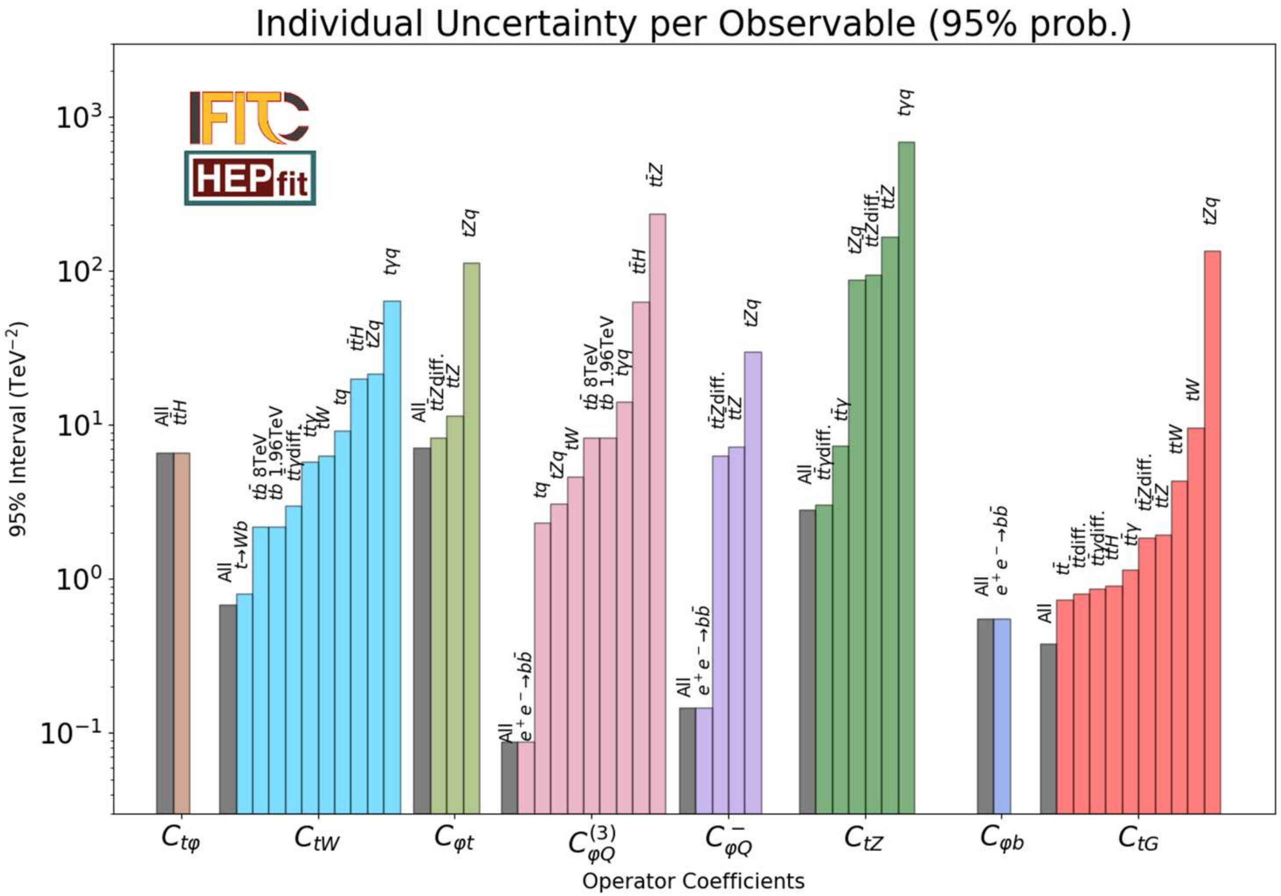
$$O^1_{\varphi Q} \rightarrow O^-_{\varphi Q} = O^1_{\varphi Q} - O^3_{\varphi Q}$$

$$O_{xB}$$
$$\searrow$$
$$O_{xZ} = -\sin\theta_W O_{xB} + \cos\theta_W O_{xW}$$

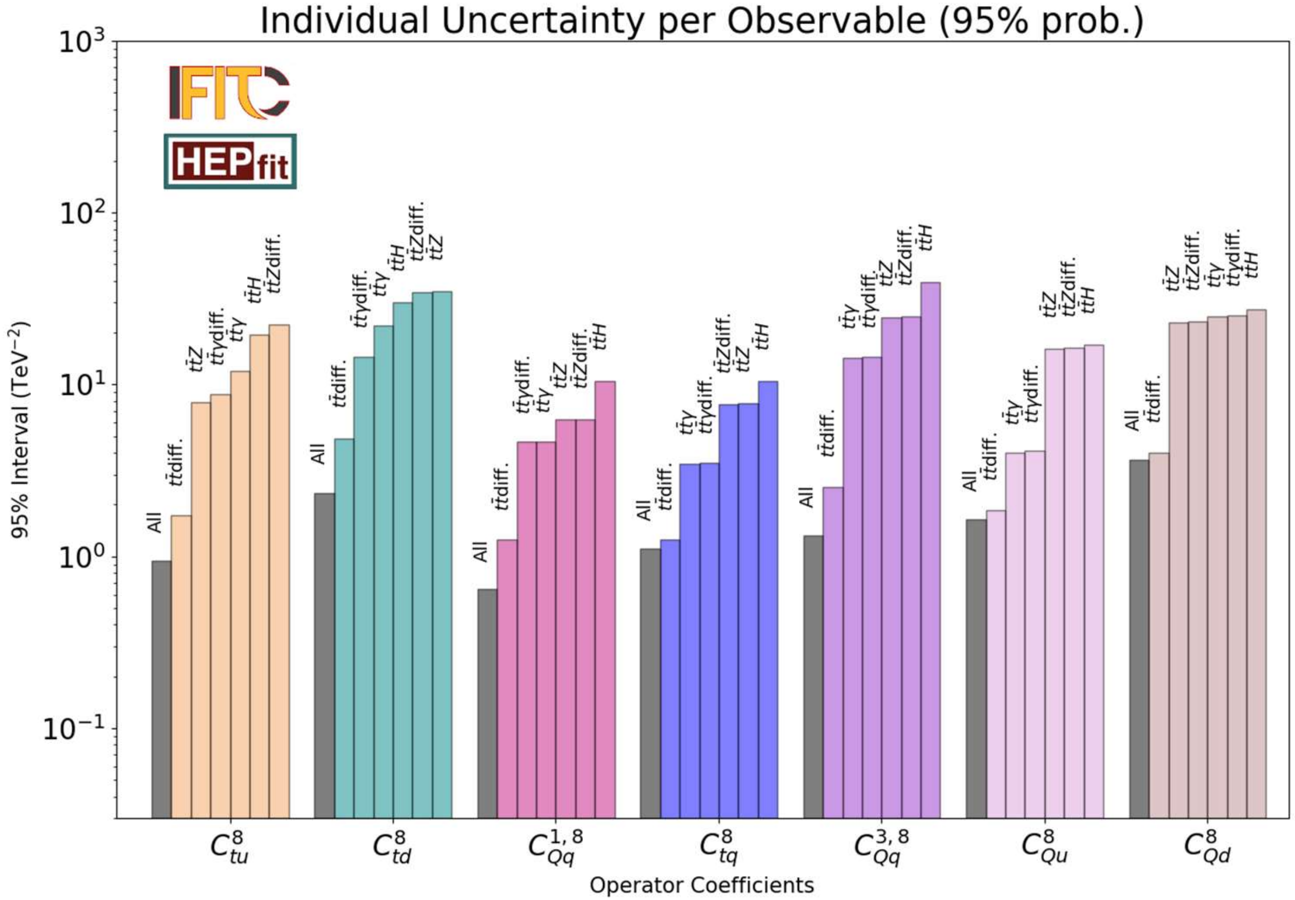
Relevant observables (current colliders)

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)NEW!	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
$pp \to t\bar{t}H + tHq$	σ + diff NEW!	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

Individual 2 quarks-WC constraints



Individual 4 quarks-WC constraints



Prospects for Measurements at HL-LHC

Uncertainty	Reduced by a factor of
Theoretical	1/2
Modelling	1/2
Systematic	$1/\sqrt{\mathcal{L}}$
Statistical	$1/\sqrt{\mathcal{L}}$

Inclusive Crossections & Helicities

Process	Measured (fb)	SM (fb)	LHC Unc.					HL-LHC Unc.				
			theo.	exp.				theo.	exp.			
				stat.	sys.	mod.	tot.		stat.	sys.	mod.	tot.
$pp \to t\bar{t}H + tHq$	640	664.3	41.7	90	40	70.7	121.2	20.9	19.4	8.6	35.4	41.3
$pp \to t\bar{t}Z$	990	810.9	85.8	51.5	48.9	67.3	97.8	42.9	11.1	10.6	33.6	37.0
$pp \to t\bar{t}\gamma$	39.6	38.5	1.76	0.8	1.25	2.16	2.62	0.88	0.17	0.27	1.08	1.13
$pp \to tZq$	111	102	3.5	13.0	6.1	6.2	15.7	1.75	2.09	0.98	3.1	3.87
$pp \to t\gamma q$	115.7	81	4	17.1	21.1	21.1	34.4	2	1.9	2.3	10.6	11.0
$pp \to t\bar{t}W + \text{EW}$	770	647.5	76.1	120	59.6	73.0	152.6	38.1	13.1	6.5	36.5	39.4
$pp \to t\bar{b}$ (s-ch)	4900	5610	220	784	936	790	1454	110	35	42	395	399
$pp \to tW$	23100	22370	1570	1086	2000	2773	3587	785	49	89	1386	1390
$pp \to tq$ (t-ch)	87700	84200	250	1140	3128	4766	5810	125	51	140	2383	2390
F_0	0.693	0.687	0.005	0.009	0.006	0.009	0.014	0.003	0.0004	0.0003	0.004	0.004
F_L	0.315	0.311	0.005	0.006	0.003	0.008	0.011	0.003	0.0003	0.0002	0.004	0.004

Prospects for the measurement of $pp \to t\bar{t}\ell\bar{\ell}$

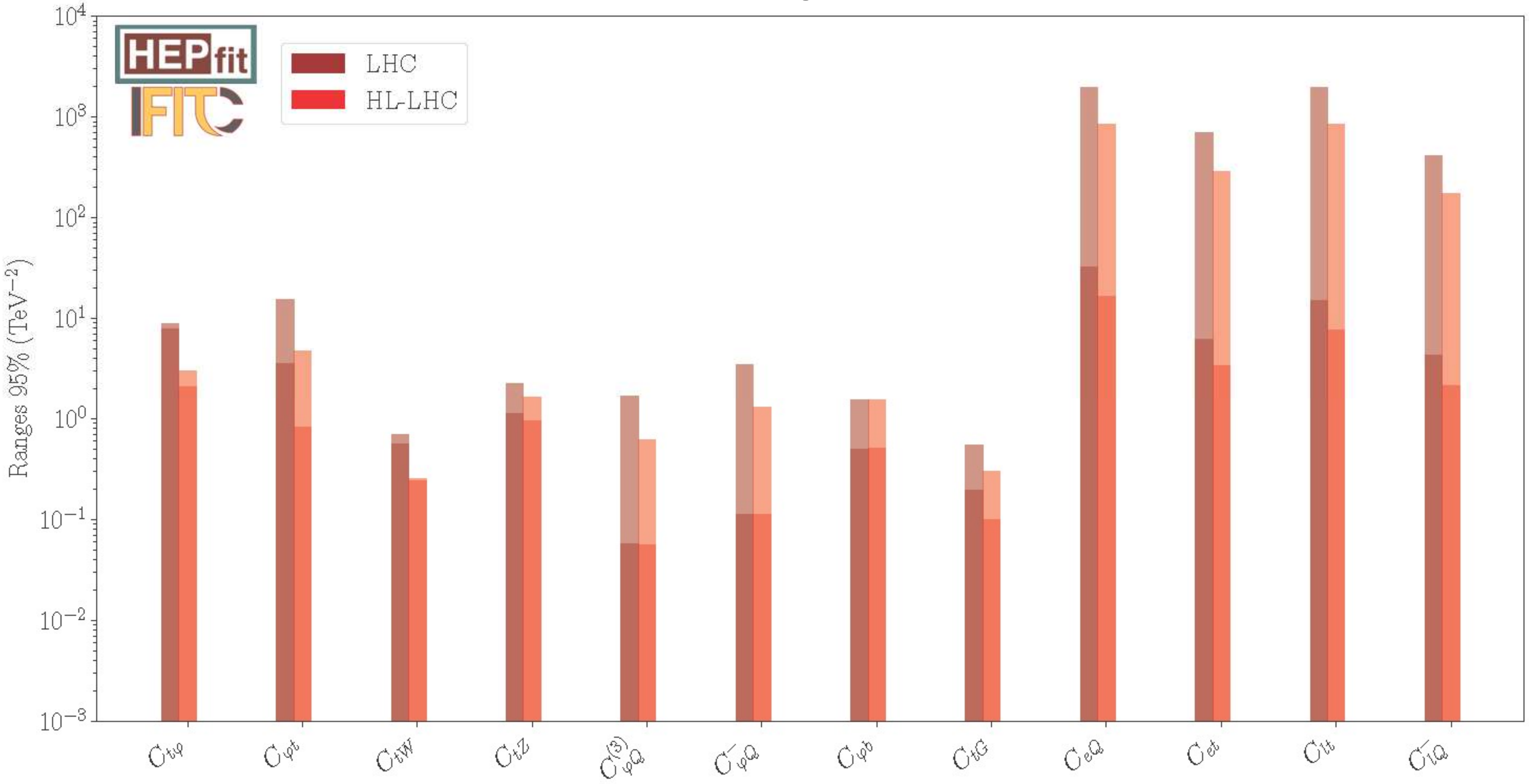
- ATLAS is making an effort to measure $pp \to t\bar{t}\ell\bar{\ell}$
  - We expect to restrict them at HL-LHC to compare with lepton colliders

		Differential: $m_{\ell\bar{\ell}}$ (GeV)			
Process	Inclusive	100-120	120-140	140-180	> 180
$\sigma(10^{-6}pb)$ parton-level $pp \to t\bar{t}\ell\bar{\ell}$	2700	1500	500	340	400
$\sigma(10^{-6}pb)$ reco-level $pp \to t\bar{t}\ell\bar{\ell}$	500	230	110	80	90
$\sigma(10^{-6}pb)$ parton-level $pp \to t\bar{t}e\bar{e}$	900	500	170	110	130
$\sigma(10^{-6}pb)$ reco-level $pp \to t\bar{t}e\bar{e}$	230	130	50	40	40
$\sigma(10^{-6}pb)$ parton-level $pp \to t\bar{t}\mu\bar{\mu}$	900	500	170	120	130
$\sigma(10^{-6}pb)$ reco-level $pp \to t\bar{t}\mu\bar{\mu}$	270	130	60	40	40

MsC Thesis of Abel Gutiérrez Camacho

Expected HL-LHC constraints improvement:

2-fermion operators

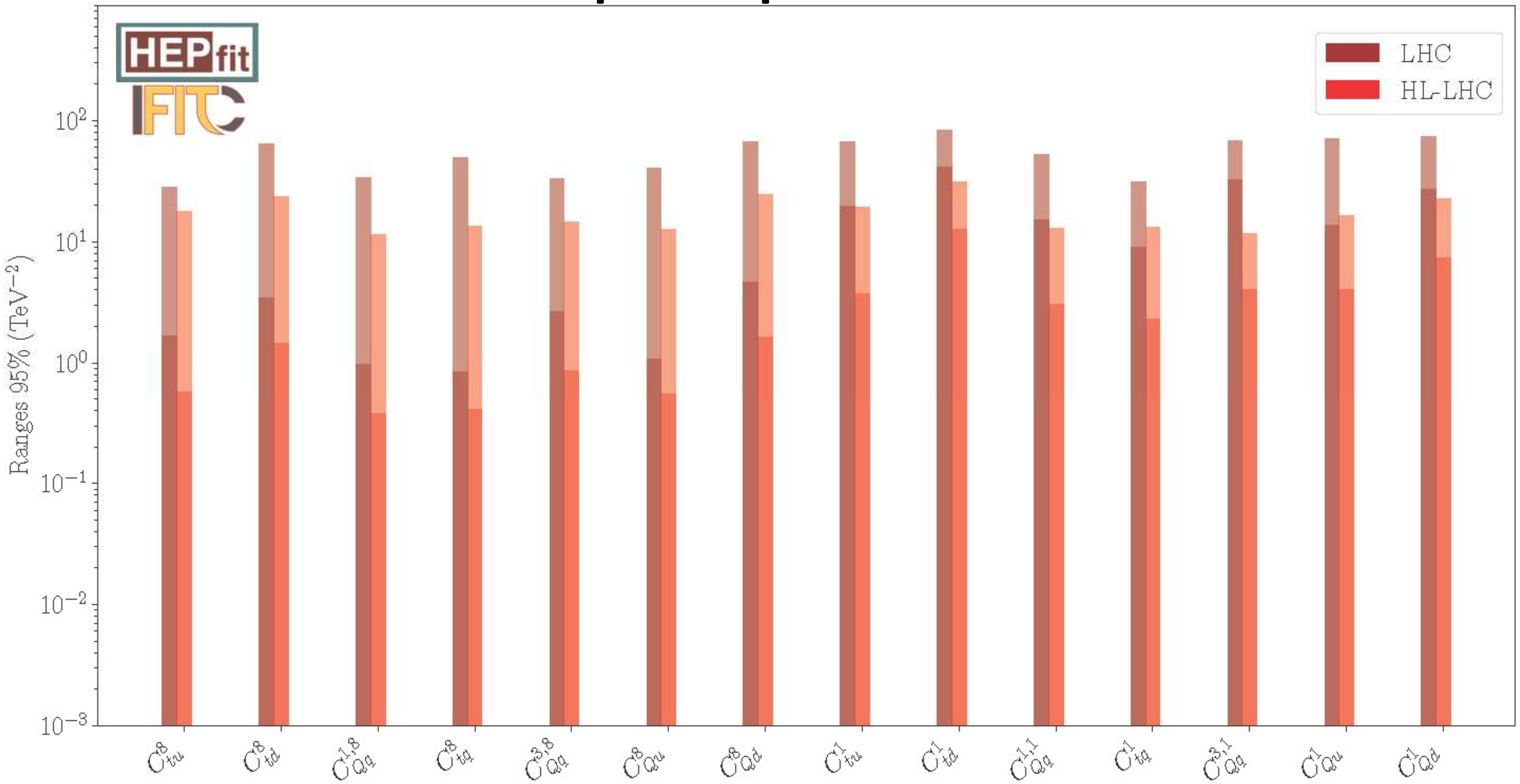


Shadowed ➡ Marginalized from global fit

Solid ➡ Individual fit

Expected HL-LHC constraints improvement

4-quark operators



Shadowed → Marginalized from global fit

Solid → Individual fit

Bottom-pair production at e+e- colliders

Machine	Polarisation	Energy	Luminosity	Observable
ILC	P(e^+, e^-):(−30%, +80%) P(e^+, e^-):(+30%, −80%)	250 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\text{FB}}^{b\bar{b}}$
		500 GeV	4 ab^{-1}	
		1 TeV	8 ab^{-1}	
CLIC	P(e^+, e^-):(0%, +80%) P(e^+, e^-):(0%, −80%)	380 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\text{FB}}^{b\bar{b}}$
		1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
CEPC/FCC-*ee*	Unpolarised	Z-pole	57.5/150 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\text{FB}}^{b\bar{b}}$
		240 GeV	20/5 ab^{-1}	
		360/365 GeV	1/1.5 ab^{-1}	

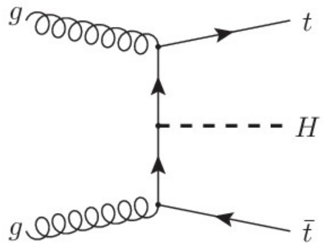
- Cross-section and Assymmetry FB constrain:
  - The WC related with EW precision observables: $C_{\varphi Q}^{+} = C_{\varphi Q}^{1} + C_{\varphi Q}^{3}$, $C_{\varphi b}$
  - Relevant for 2-quark 2-lepton WC: C_{lQ}^{+} , C_{lb} , C_{eb}
  - The higher-energy measurement are more relevant for the 2-quark 2-lepton operators

Top-pair production at e+e- colliders

Machine	Polarisation	Energy	Luminosity	Observable
ILC	P(e^+, e^-):(−30%, +80%)	500 GeV	4 ab^{-1}	Optimal Observables
	P(e^+, e^-):(+30%, −80%)	1 TeV	8 ab^{-1}	
CLIC	P(e^+, e^-):(0%, +80%)	380 GeV	2 ab^{-1}	Optimal Observables
	P(e^+, e^-):(0%, −80%)	1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
CEPC/FCC-*ee*	Unpolarised	350 GeV	0.2 ab^{-1}	Optimal Observables
		365 GeV	1/1.5 ab^{-1}	

- Optimal observables maximally exploit the information in the fully diferential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ dist. [1807.02121], constraining:
  - The 2-fermion coefficients: $C^-_{\varphi Q}$, $C_{\varphi t}$, C_{tW} , C_{tZ}
  - The 2-quark 2-lepton: C^-_{lQ} , C_{lt} , C_{et} , C_{eQ}
  - Two different energies above the top-pair threshold are needed to constrain all the 2- and 4-fermion operators (constant/linear vs quadratically with energy)

$t\bar{t}H$ production at e+e- colliders



Machine	Polarisation	Energy	Luminosity	Observable
ILC	$P(e^+, e^-):(-30\%, +80\%)$	500/550 GeV	4 ab^{-1}	Inclusive cross section
	$P(e^+, e^-):(+30\%, -80\%)$	1 TeV	8 ab^{-1}	
CLIC	$P(e^+, e^-):(0\%, +80\%)$ $P(e^+, e^-):(0\%, -80\%)$	1.5 TeV	2.5 ab^{-1}	Inclusive cross section

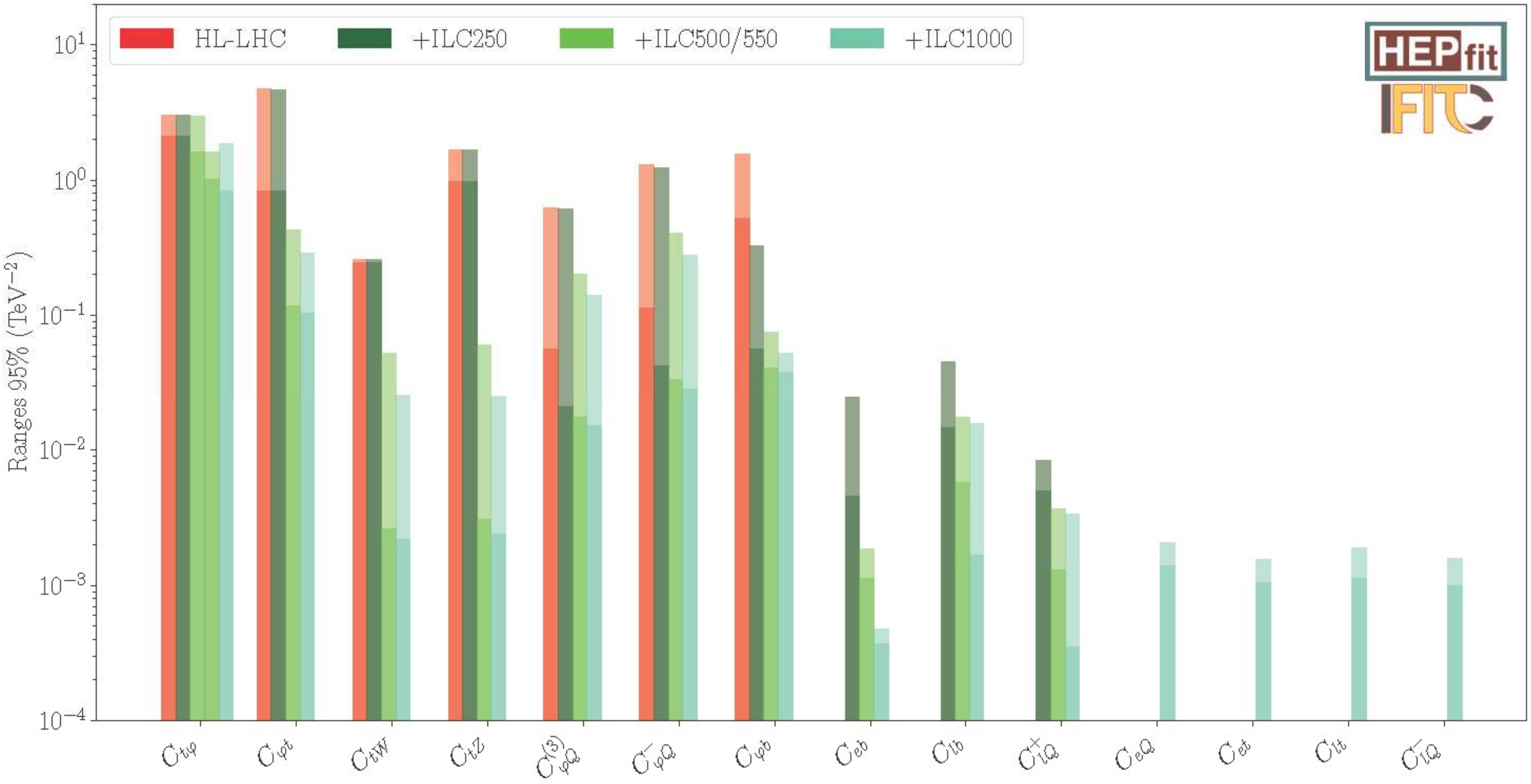
- Key observable for the top quark Yukawa coupling
- The production cross section is 3 times bigger at ILC 550 than at ILC500
  - Improved statistical sensitivity by more than a 50%
- ILC550, CLIC1500 and HL-LHC have similar sensitivities
- ILC1000 improves the expected HL-LHC sensitivity by a factor of two

Top at μ+μ- collider

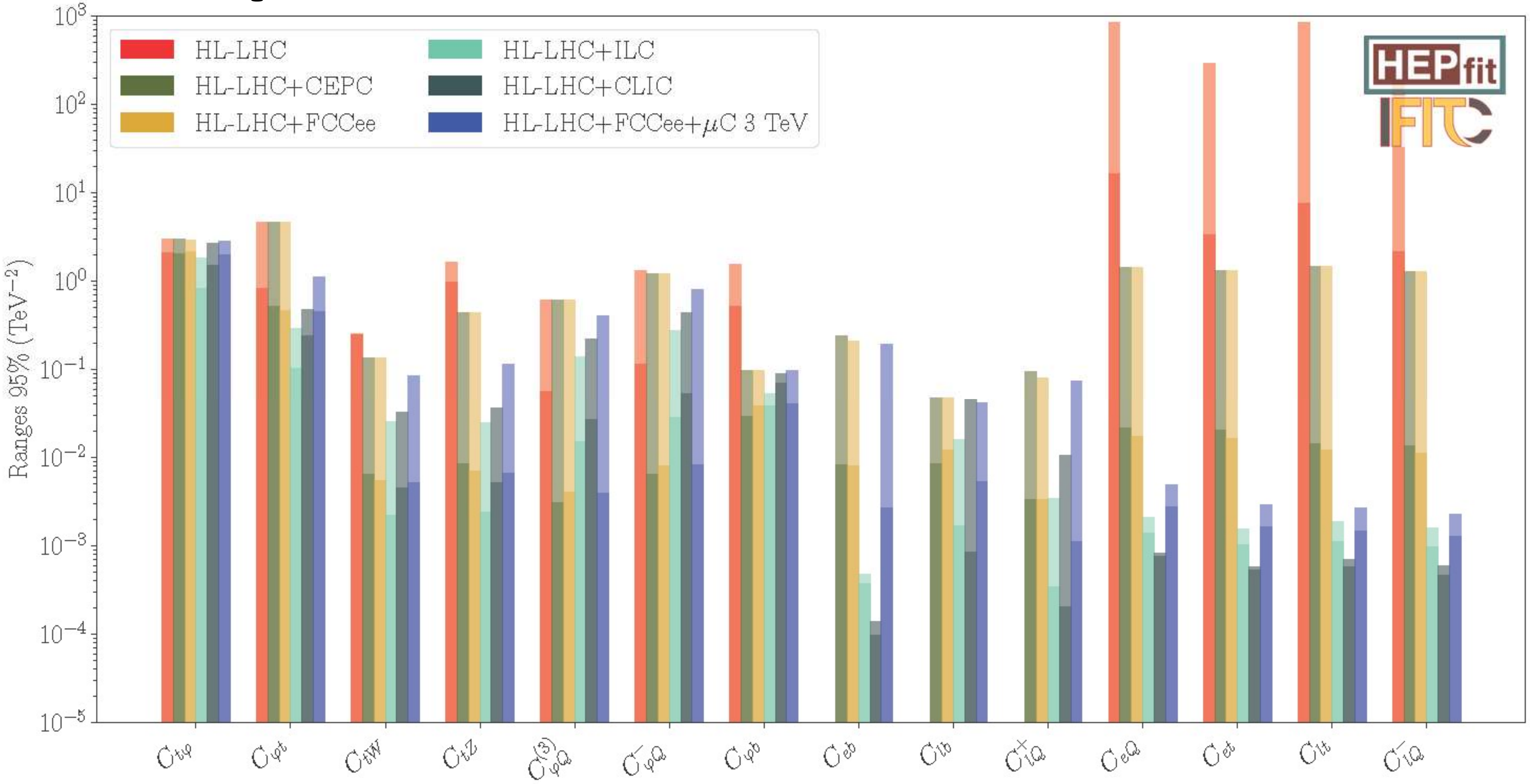
Machine	Polarisation	Energy	Luminosity	Observables
Muon Collider	Unpolarised	3TeV	$1\,ab^{-1}$	Optimal Observables (tt s-channel) tt (VBF) ttH (s-channel and VBF)
		10TeV	$10\,ab^{-1}$	
		30TeV	$90\,ab^{-1}$	

- Optimal observables extended for Muon Collider [1807.02121], constraining:
  - The 2-fermion coefficients: $C^{-}_{\varphi Q}\,,\,C_{\varphi t}\,,\,C_{tW}\,,\,C_{tZ}$
  - The 2-quark 2-lepton: $C^{-}_{lQ}\,,\,C_{lt}\,,\,C_{et}\,,\,C_{eQ}$
  - Energies highly above the top-pair threshold are the key o constrain all the 2- and 4-fermion operators (constant/linear vs quadratically with energy)

ILC


HL-LHC
+ILC250
+ILC500/550
+ILC1000
HEPfit
IFIC
Ranges 95% (TeV^{-2})
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$C_{t\varphi}$
$C_{\varphi t}$
C_{tW}
C_{tZ}
$C_{\varphi Q}^{(3)}$
$C_{\varphi Q}^{-}$
$C_{\varphi b}$
C_{eb}
C_{lb}
C_{lQ}^{+}
C_{eQ}
C_{et}
C_{lt}
C_{lQ}^{-}

Comparison of Future Colliders



Summary

- HL-LHC expected to improve the bounds by roughly a factor 3
- An e+e- collider can signicantly improve bounds on bottom-quark and on top-quark operators (operated above the tt threshold)
  - ILC and CLIC operated at two center-of-mass energies above the tt threshold can provide very tight bounds on all operators, with bounds on 4F taking advantage of energy-growing sensitivity
  - FCCee and CECP (at and slightly above the tt threshold) can improve bottom- and top-operators by factor 5 (2 for 2-fermion operators)
    - Power to constrain 4-fermion operators limited by energy reach
    - Muon Collider would play a key role puting bounds on 4F operators.

Thank you

LHC-HL + FCC-ee + μ-Collider