The top-quark couplings at the LHC and beyond

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Based on [1907.10619], [2006.14631], [2107.13917] and [2205.02140]

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Beyond the Standard Model

The SM has been extremely successful but many phenomena require for a better understanding:

- Matter-antimatter asymmetry
- Neutrino masses
- Dark matter
- Strong CP-problem
- Flavour puzzle
- Origin of charged quantisation
- ...

Many extensions of the SM have been proposed $\rightarrow$ Why not using a **model independent** framework?

- The SM is not complete, it is just an EFT
- The complete theory is unknown $\rightarrow$ Follow a **bottom-up** approach
- Assuming invariance under the same gauge symmetries as in the SM $\rightarrow$ SMEFT

The SM Effective Field Theory

- The SMEFT Lagrangian is build with the particle content of the SM and with the operators invariant under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{j} \frac{C_j^{(d)}}{\Lambda^{d-4}} \mathscr{O}_j^{(d)}$$

- Any heavy NP field, invariant under the same gauge group, can be integrated out, translating its effects on physical observables in terms of the Wilson coefficients ($C_j^{(d)}$)

- The operators of odd dimension generate baryon and lepton number violation and will not be considered

- The leading even-dimensional contribution will be the one of $d = 6$

- At $d = 6$ the total number of 2499 operators is overwhelming

- In this work we will only consider the subset of operators related to top-quark physics

Why the top-quark?

- Being the heaviest particle of the SM the top-quark is a good candidate for searching for new physics

- As the top-quark was not produced in LEP its EW sector could not be precisely measured until now

- The LHC data allows, finally, for precise measurements of this sector

- Here we present results of a global fit to the new physics couplings of the top-quark

- We used the most recent available data from the LHC (ATLAS and CMS), and also from LEP and Tevatron

- We study the effects of the HL-LHC and e^+e^- future colliders like ILC, CLIC, CEPC, FCC-*ee*

- The fits have been performed using `HEPfit` [1910.14012]

Data treatment

- The general goal is to know if the new physics extensions are compatible with data
- Need to find constraints on their parameter space
- Huge amounts of data $\rightarrow$ efficient tool for dealing with data $\rightarrow$ HEPfit [1910.14012]

HEPfit:
- Flexible open-source C++ code
- Based on BAT (bayesian statistical framework)
- Markov Chain Monte Carlo procedure
- Useful for SM, new physics models or EFTs
- Flavour, electroweak and Higgs observables

SMEFT operators relevant for the top-quark

2-quark operators

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

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

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

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

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}

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

- Here we show the observables included that have been measured in the actual colliders

| Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	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
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 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
$pp \to t\bar{t}H + tHq$	σ	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

Global Fit LHC+LEP+Tevatron

Prospects for Measurements at HL-LHC

Theoretical Uncertainties $\longrightarrow$ scale with 1/2

Experimental Uncertainties $\begin{cases} \text{Modelling} & \longrightarrow \quad \text{scale with 1/2} \\ \text{Systematic} & \longrightarrow \quad \text{scale with } 1/\sqrt{\mathscr{L}} \\ \text{Statistical} & \longrightarrow \quad \text{scale with } 1/\sqrt{\mathscr{L}} \end{cases}$

HL-LHC results
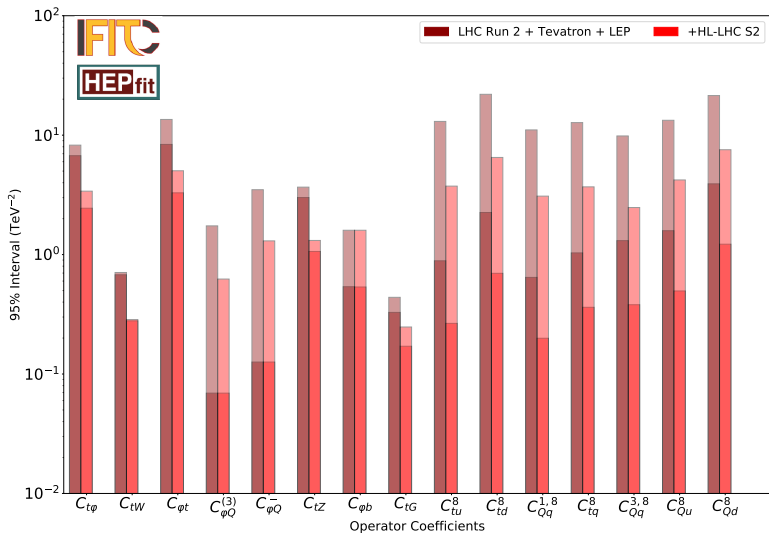
Future e^+e^- colliders

- International Linear Collider (ILC)
  - Linear collider with three stages (250 GeV, 500 GeV and 1 TeV)
  - Length between 20 and 50 km
  - Would be built in Japan

- Compact Linear Collider (CLIC)
  - Linear collider with three stages (380 GeV, 1.5 GeV and 3 TeV)
  - Length between 11 and 50 km
  - Would be built in CERN

- Future Circular Collider with e^+e^- stage (FCC-ee)
  - Circular collider three stages (Z-pole, 240 GeV and 365 GeV)
  - Length of circumference between 80 and 100 km
  - Would be built in CERN

- Circular electron positron collider (CEPC)
  - Circular collider three stages (Z-pole, 240 GeV and 360 GeV)
  - Length of circumference around 100 km
  - Would be built in China

Measurements at e^+e^- colliders

Machine	Polarisation	Energy	Luminosity
ILC	P(e^+, e^-):(-30%, $+80\%$) P(e^+, e^-):($+30\%$, -80%)	250 GeV	2 ab^{-1}
		500(550) 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}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
CEPC/FCC-ee	Unpolarised	Z-pole	57.5/150 ab^{-1}
		240 GeV	20/5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360/365 GeV	1/1.5 ab^{-1}

- In all the configurations it would be measure $e^+e^- \to b\bar{b}$ ($\sigma_{b\bar{b}}$, $A_{\text{FB}}^{b\bar{b}}$)
- For energies above $t\bar{t}$-threshold ($\sim$350 GeV) $e^+e^- \to t\bar{t}$ (optimal observables)
- For energies above $t\bar{t}H$-threshold ($\sim$500 GeV) $e^+e^- \to t\bar{t}H$ ($\sigma_{t\bar{t}H}$)

Comparison of future colliders
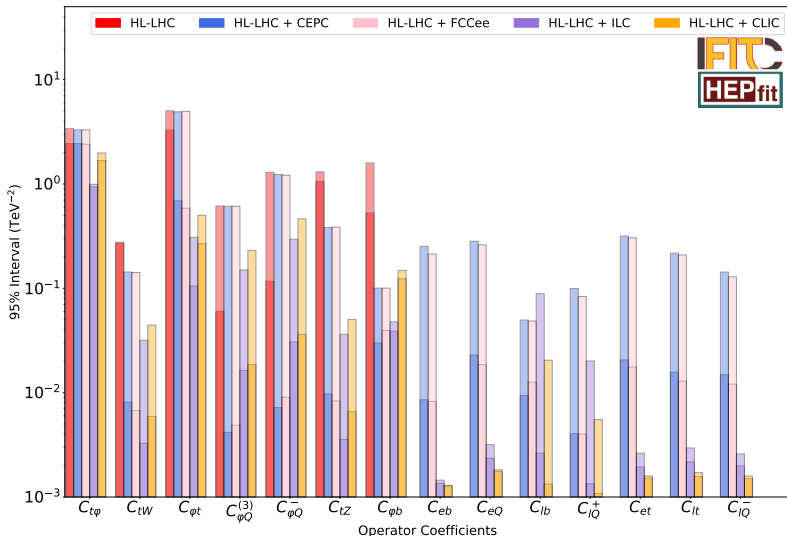
Summary

- Current data is compatible with the SM within a 95% probability

- HL-LHC expected to improve the bounds by roughly a factor 3 w.r.t. current state-of-the-art LHC run 2 + Tevatron + LEP/SLC

- An e^+e^- collider can significantly improve bounds on bottom-quark operators, and on top-quark operators if operated above the $t\bar{t}$ threshold

- Circular colliders (FCC-*ee* and CECP) operated at and slightly above the $t\bar{t}$ threshold can improve bottom- and top- operators by factor 5 and 2 for 2-fermion operators.

- Power to constrain 4-fermion operators limited by energy reach

- Linear colliders (ILC & CLIC) operated at 2 center-of-mass energies above the $t\bar{t}$-threshold provide tight bounds on all operators, with 4F bounds gaining from the energy-growing sensitivity

- The operation of the linear colliders above the *ttH*-thresholds allows for strong constraints on the top-quark Yukawa

Thank you!
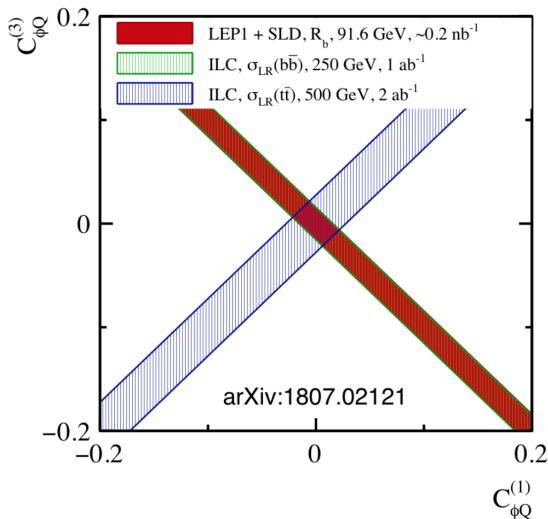
Back up

Sensitivity
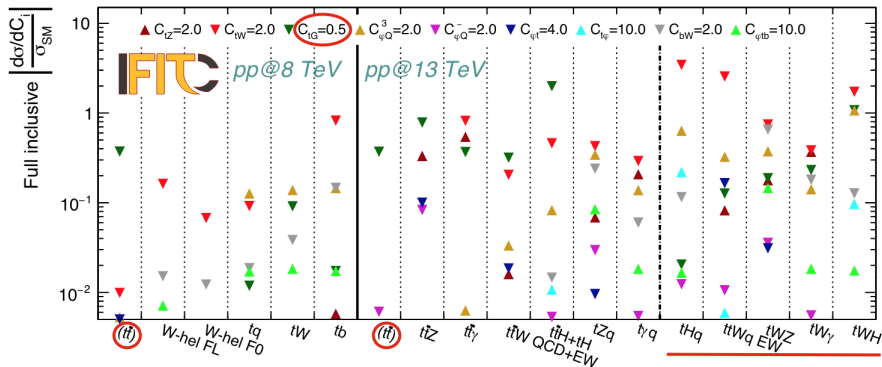
Future Colliders - Complementarity on e^+e^- Colliders

Good complementarity between $b\bar{b}$ (LEP) and $t\bar{t}$ (future e^+e^- collider) if we reach $\sqrt{s} > 2m_t$

$$\delta g_L^t = -(C_{\varphi Q}^1 - C_{\varphi Q}^3)m_t^2/\Lambda^2$$

$$\delta g_L^b = -(C_{\varphi Q}^1 + C_{\varphi Q}^3)m_t^2/\Lambda^2$$

Results - Differential Cross Section Effect
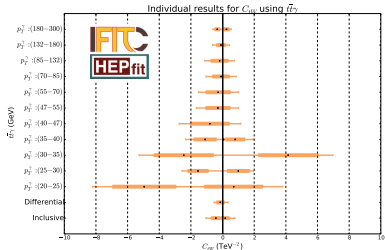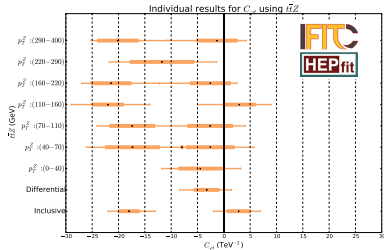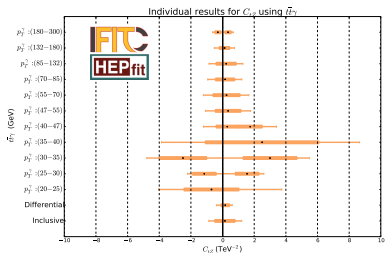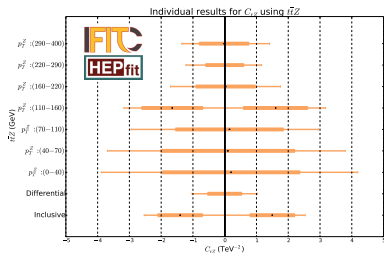
Results - Complementarity Between Observables

- Very good complementarity between the observables
- The data set is diverse enough to avoid the existence of blind directions

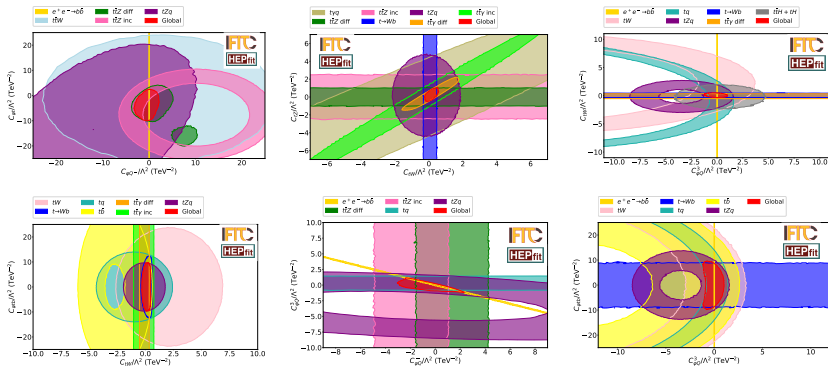| parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} [Λ^{-2}]	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{Qq}^{3,1}$	Λ^{-4} [Λ^{-2}]	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	–
C_{tq}^{1}	Λ^{-4} [Λ^{-2}]	–	–	–	–	Λ^{-4} [Λ^{-2}]	Λ^{-4} [Λ^{-2}]
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	[Λ^{-2}]	Λ^{-2}	–	[Λ^{-2}]	Λ^{-2}	Λ^{-2}

Table 1. Wilson coefficients in our analysis and their contributions to top-quark observables via SM-interference (Λ^{-2}) and via dimension-6 squared terms only (Λ^{-4}). A square bracket indicates that the Wilson coefficient contributes via SM-interference at NLO QCD. All quark masses except m_t are assumed to be zero. 'Single t' stands for $s-$ and $t-$channel electroweak top production.

Relevant Operators

- We use an EFT description to parametrise deviations from the SM

Relevant Operators			
Coefficient	Operator	Coefficient	Operator
$C_{\varphi Q}^1$	$(\bar{Q}\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C_{\varphi Q}^3$	$(\bar{Q}\tau^I\gamma^\mu Q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi\right)$
$C_{\varphi t}$	$(\bar{t}\gamma^\mu t)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)$
$C_{t\varphi}$	$(\bar{Q}t)\,(\varepsilon\varphi^*\,\varphi^\dagger\varphi)$	C_{tG}	$(\bar{t}\sigma^{\mu\nu}T^A t)\,(\varepsilon\varphi^* G_{\mu\nu}^A)$
C_{tW}	$(\bar{Q}\tau^I\sigma^{\mu\nu}t)\,(\varepsilon\varphi^* W_{\mu\nu}^I)$	C_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\,(\varepsilon\varphi^* B_{\mu\nu})$
$C_{qq}^{1(ijkl)}$	$(\bar{q}_i\gamma^\mu q_j)(\bar{q}_k\gamma_\mu q_l)$	$C_{qq}^{3(ijkl)}$	$(\bar{q}_i\tau^I\gamma^\mu q_j)(\bar{q}_k\tau^I\gamma_\mu q_l)$
$C_{uu}^{(ijkl)}$	$(\bar{u}_i\gamma^\mu u_j)(\bar{u}_k\gamma_\mu u_l)$	$C_{ud}^{8(ijkl)}$	$(\bar{u}_i\gamma^\mu T^A u_j)(\bar{d}_k\gamma_\mu T^A d_l)$
$C_{qu}^{8(ijkl)}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{u}_k\gamma_\mu T^A u_l)$	$C_{qd}^{8(ijkl)}$	$(\bar{q}_i\gamma^\mu T^A q_j)(\bar{d}_k\gamma_\mu T^A d_l)$
C_{lQ}^1	$(\bar{Q}\gamma_\mu Q)\,(\bar{l}\gamma^\mu l)$	C_{lQ}^3	$(\bar{Q}\tau^I\gamma_\mu Q)\,(\bar{l}\tau^I\gamma^\mu l)$
C_{lt}	$(\bar{t}\gamma_\mu t)\,(\bar{l}\gamma^\mu l)$	C_{lb}	$(\bar{b}\gamma_\mu b)\,(\bar{l}\gamma^\mu l)$
C_{eQ}	$(\bar{Q}\gamma_\mu Q)\,(\bar{e}\gamma^\mu e)$	C_{et}	$(\bar{t}\gamma_\mu t)\,(\bar{e}\gamma^\mu e)$
C_{eb}	$(\bar{b}\gamma_\mu b)\,(\bar{e}\gamma^\mu e)$	$-$	$-$

Theoretical Framework

- The Wilson coefficients are fitted are:

	Coefficients Fitted		
2-quark	C_{tG} $C_{\varphi t}$ $-$	$C_{\varphi Q}^3$ $C_{\varphi b}$ $C_{t\varphi}$	$C_{\varphi Q}^- = C_{\varphi Q}^1 - C_{\varphi Q}^3$ $C_{tZ} = c_W C_{tW} - s_W C_{tB}$ C_{tW}
4-quark	$C_{tu}^8 = \sum\limits_{i=1,2} 2C_{uu}^{(i33i)}$ $C_{Qu}^8 = \sum\limits_{i=1,2} C_{qu}^{8(33ii)}$ $-$	$C_{td}^8 = \sum\limits_{i=1,2,3} C_{ud}^{8(33ii)}$ $C_{Qd}^8 = \sum\limits_{i=1,2,3} C_{qd}^{8(33ii)}$ $-$	$C_{Qq}^{1,8} = \sum\limits_{i=1,2} C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$ $C_{Qq}^{3,8} = \sum\limits_{i=1,2} C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$ $C_{tq}^8 = \sum\limits_{i=1,2} C_{uq}^{8(ii33)}$
2-quark 2-lepton	C_{eb} C_{lb} $-$	C_{et} C_{lt} $-$	$C_{lQ}^+ = C_{lQ}^1 + C_{lQ}^3$ $C_{lQ}^- = C_{lQ}^1 - C_{lQ}^3$ C_{eQ}

Prospects for Measurements at HL-LHC

Inclusive cross sections and helicities

Process	Measured (fb)	SM (fb)	LHC Unc.					HL-LHC Unc.				
			theo.	stat.	sys.	mod.	tot.	theo.	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 + $ 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

HL-LHC and ILC results
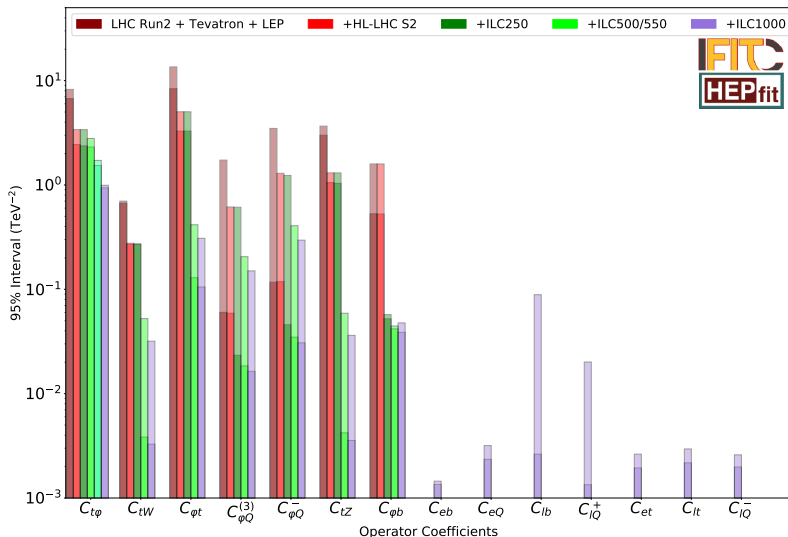
Measurements at e^+e^- colliders: $b\bar{b}$ production

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

- These observables set constraints on the EW precision observables $C^+_{\varphi Q} = C^1_{\varphi Q} + C^3_{\varphi Q}$ and $C_{\varphi b}$
- Also relevant for 2-quark 2-lepton operators C^+_{lQ}, C_{lb} and C_{eb}
- The higher-energy measurement are more relevant for the 2-quark 2-lepton operators

Measurements at e^+e^- colliders: $t\bar{t}$ production

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

- Optimal observables maximally exploit the information in the fully differential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ distribution [1807.02121]

- These constrain the 2-fermion operators $C_{\varphi Q}^-$, $C_{\varphi t}$, C_{tW} and C_{tZ}

- Also the 2-quark 2-lepton operators C_{lQ}^-, C_{lt}, C_{et} and C_{eQ}

- With these we eliminate blind directions in the $C_{\varphi Q}^{(1)} - C_{\varphi Q}^{(3)}$ plane

- Two different energies above the $t\bar{t}$ threshold are need to constrain all the 2- and 4-fermion operators

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

Machine	Polarisation	Energy	Luminosity	Observable
ILC	P(e^+, e^-):(-30%, $+80\%$)	500/550 GeV	4 ab^{-1}	Inclusive
	P(e^+, e^-):($+30\%$, -80%)	1 TeV	8 ab^{-1}	cross section
CLIC	P(e^+, e^-):(0%, $+80\%$)	380 GeV	2 ab^{-1}	Inclusive
	P(e^+, e^-):(0%, -80%)	1.5 TeV	2.5 ab^{-1}	cross section

- Essential measurement in order to improve the limits on the top-quark Yukawa

- The effect of a ILC run at 550 GeV is studied

- At 550 GeV the production cross section increases by a large factor and boosts the statistical sensitivity by a factor two