

Top quark coupling measurements at the ILC

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More details in [2205.02140] and [2206.08326]
Also based on [1907.10619] and [2107.13917]



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Introduction

- Our goal is to constrain all the top-quark related Wilson coefficients of the SMEFT
- The fits have been performed using HEPfit [1910.14012]
- Estimations on the improvement of the measurements are presented for the HL-LHC
- Estimation for the relevant observables for this fit in future e^+e^- colliders are shown
- Prospects for our limits in the HL-LHC and a future e^+e^- colliders are obtained

SMEFT operators relevant for the top-quark

2-quark operators

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

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

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

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

EW dipole operators

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

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

Chromo-magnetic dipole op.

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

t-quark yukawa

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

4-quark operators

Couplings of light quarks with t- and b-quarks

$$O_{tu}^8$$

$$O_{td}^8$$

$$O_{Qq}^{1,8}$$

$$O_{Qu}^8$$

$$O_{Qd}^8$$

$$O_{Qq}^{3,8}$$

$$O_{tq}^8$$

2-quark 2-lepton operators

Couplings of light leptons with t- and b-quarks

$$O_{eb}$$

$$O_{lb}$$

$$O_{et}$$

$$O_{lt}$$

$$O_{eQ}$$

$$O_{IQ}^+$$

$$O_{IQ}^-$$

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

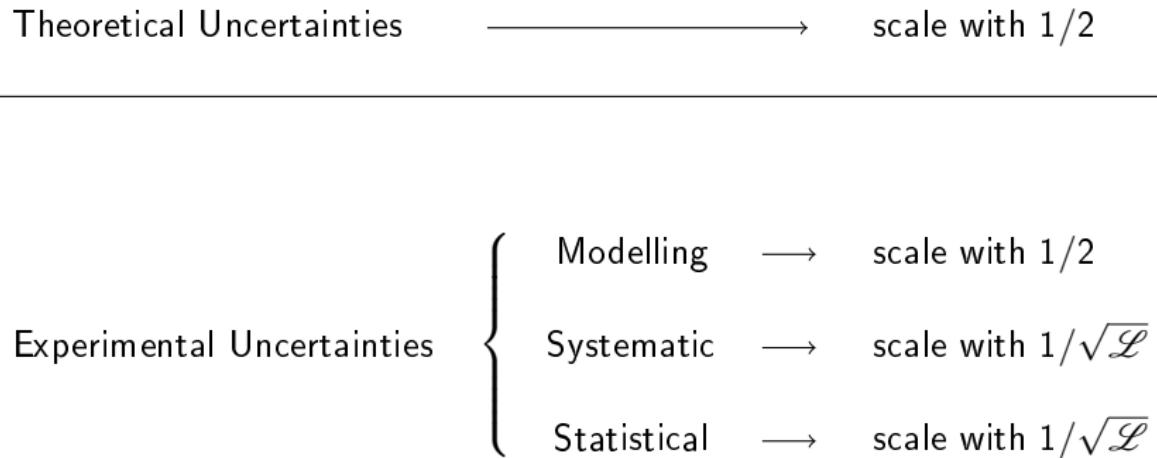
- Here we show the observables included that have been measured in the actual colliders

Process	Observable	\sqrt{s}	$\int \mathcal{L}$	Experiment
$pp \rightarrow t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS
$pp \rightarrow t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \rightarrow t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \rightarrow t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \rightarrow t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \rightarrow tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \rightarrow t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \rightarrow t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \rightarrow t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \rightarrow tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \rightarrow tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \rightarrow Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \rightarrow t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^- e^+ \rightarrow b\bar{b}$	R_b, A_{FBLR}^{bb}	~ 91 GeV	202.1 pb^{-1}	LEP/SLD

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

- The measurements of $pp \rightarrow t\bar{t}$ are extremely relevant for constraining C_{tG} and the 4-quark operators
- The measurements of $pp \rightarrow t\bar{t}H + tHq$ are needed to constrain $C_{t\phi}$
- The helicities and $pp \rightarrow t\bar{t}\gamma$ generate important constraints on C_{tW}
- $pp \rightarrow t\bar{t}\gamma$ also relevant for $C_{tZ} = \cos \theta_W C_{tW} - \sin \theta_W C_{tB}$
- $pp \rightarrow t\bar{t}Z$ generates restrictions on $C_{\phi t}$ and C_{tZ}
- LEP observables are extremely important for $C_{\phi b}$,
 $C_{\phi Q}^- = C_{\phi Q}^{(1)} - C_{\phi Q}^{(3)}$ and $C_{\phi Q}^{(3)}$
- $pp \rightarrow tZq$ becomes relevant to fully constrain the $C_{\phi Q}^- - C_{\phi Q}^{(3)}$ plane

Prospects for Measurements at HL-LHC



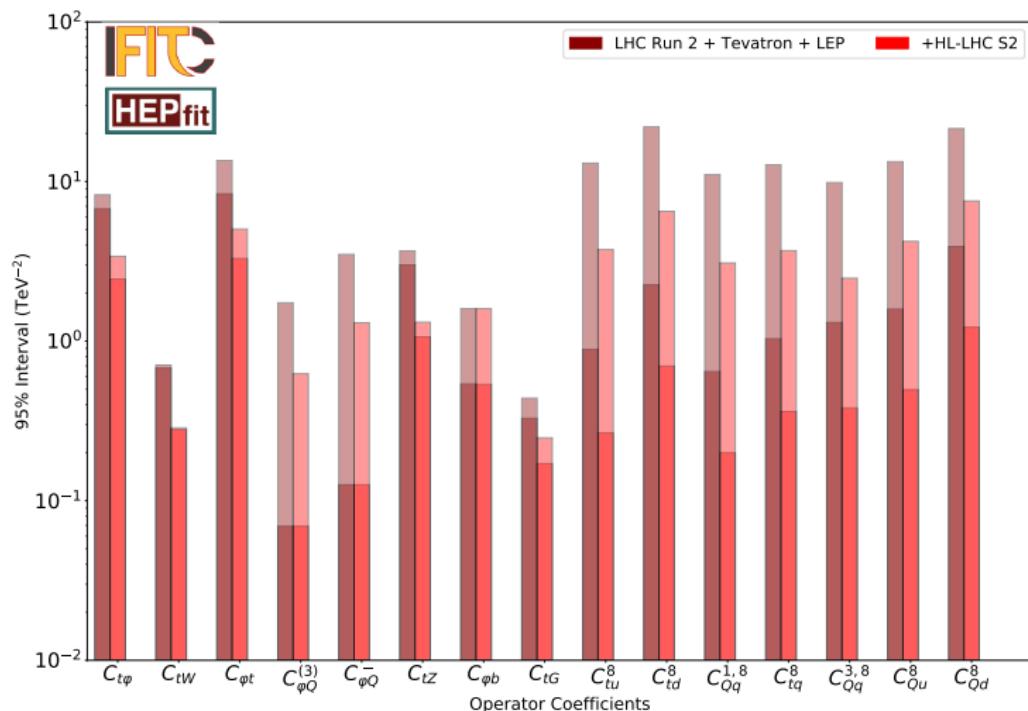
Prospects for Measurements at HL-LHC

Inclusive cross sections and helicities

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

Current constraints vs expected HL-LHC constraints

Shadowed (solid) bars → marginalised from global (individual) fit



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

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

- These observables set constraints on the EW precision observables $C_{\varphi Q}^+ = C_{\varphi Q}^1 + C_{\varphi Q}^3$ and $C_{\varphi b}$
- Also relevant for 2-quark 2-lepton operators C_{IQ}^+ , 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 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	$1/1.5 \text{ ab}^{-1}$	

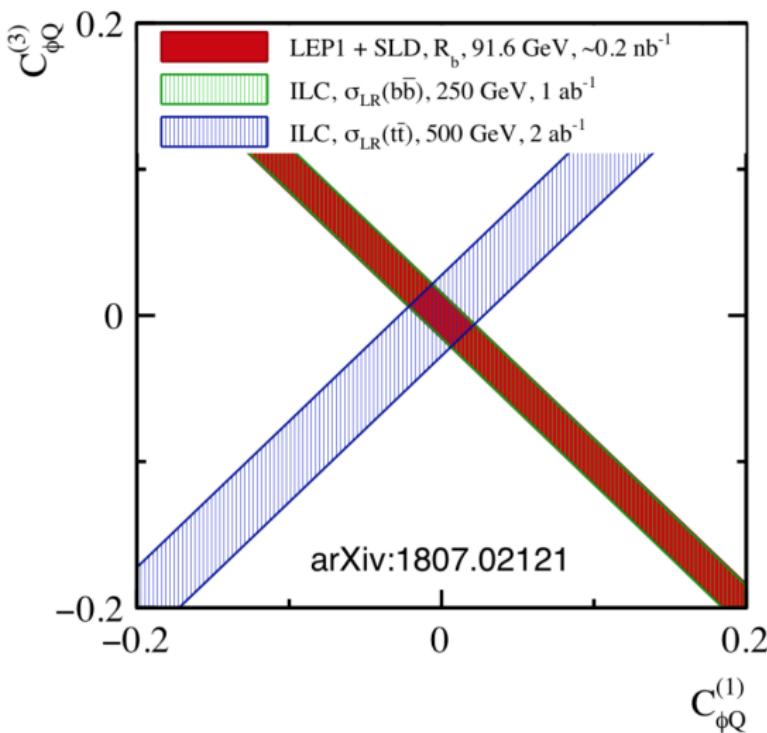
- Optimal observables maximally exploit the information in the fully differential $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$ distribution [1807.02121]
- These constrain the 2-fermion operators $C_{\varphi Q}^-$, $C_{\varphi t}$, C_{tW} and C_{tZ}
- Also the 2-quark 2-lepton operators C_{IQ}^- , 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 needed to constrain all the 2- and 4-fermion operators

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 $\sqrt{s} > 2m_t$

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

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

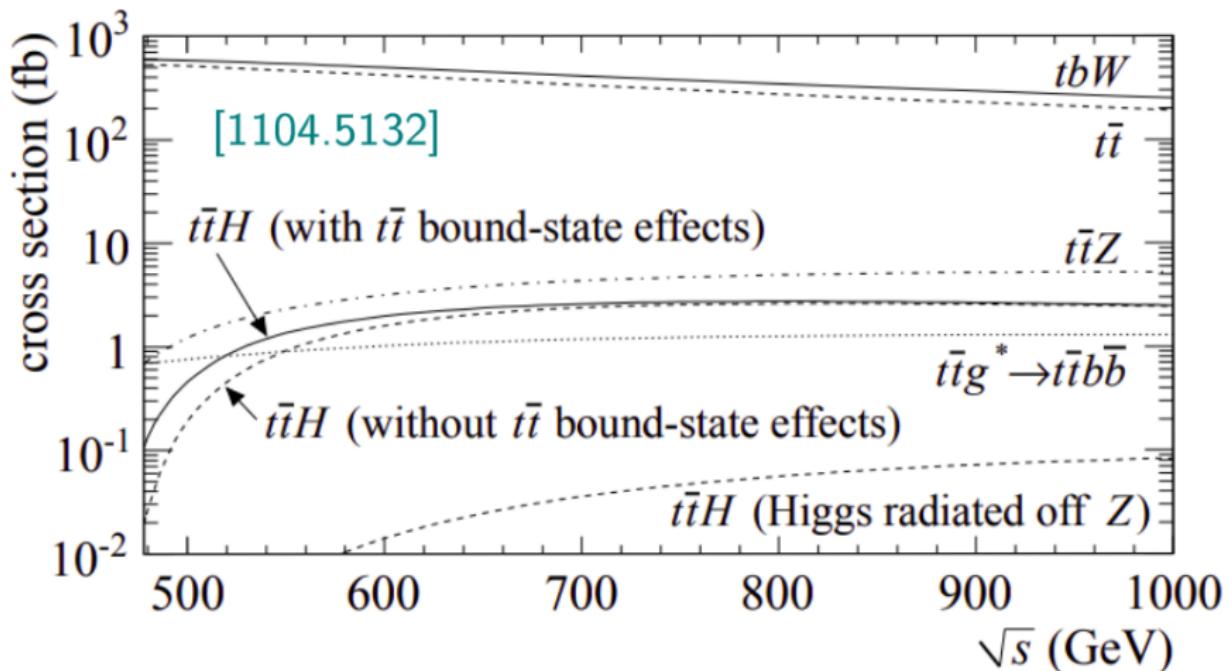


Measurements at e^+e^- colliders: $t\bar{t}H$ production

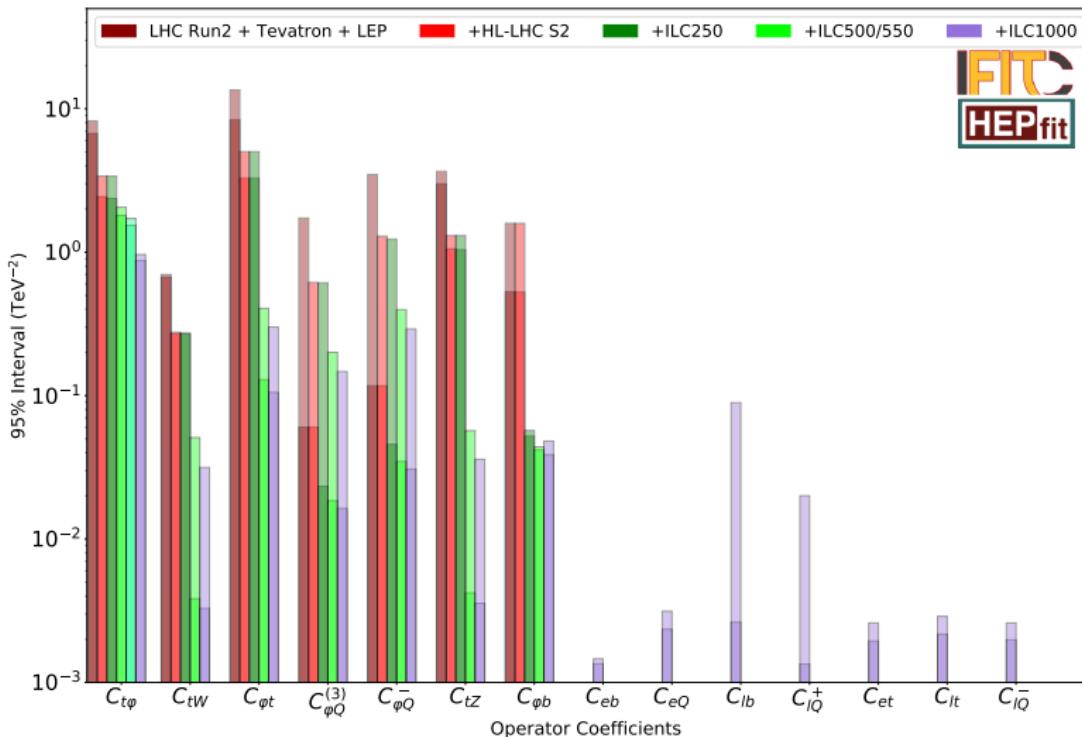
Machine	Polarisation	Energy	Luminosity	Observable
ILC	$P(e^+, e^-):(-30\%, +80\%)$	500/550 GeV	4 ab^{-1}	Inclusive cross section
	$P(e^+, e^-):(+30\%, -80\%)$	1 TeV	8 ab^{-1}	
CLIC	$P(e^+, e^-):(0\%, +80\%)$ $P(e^+, e^-):(0\%, -80\%)$	1.5 TeV	2.5 ab^{-1}	Inclusive cross section

- Essential measurement in order to improve the limits on the top-quark Yukawa
- The effect of a ILC run at 550 GeV has been studied
- At ILC550 the production cross section increases a factor of 3 w.r.t. ILC500 improving the statistical sensitivity by more than a 50%
- ILC550 and CLIC1500 have a similar sensitivity as HL-LHC
- ILC1000 improves the expected HL-LHC sensitivity by a factor of two

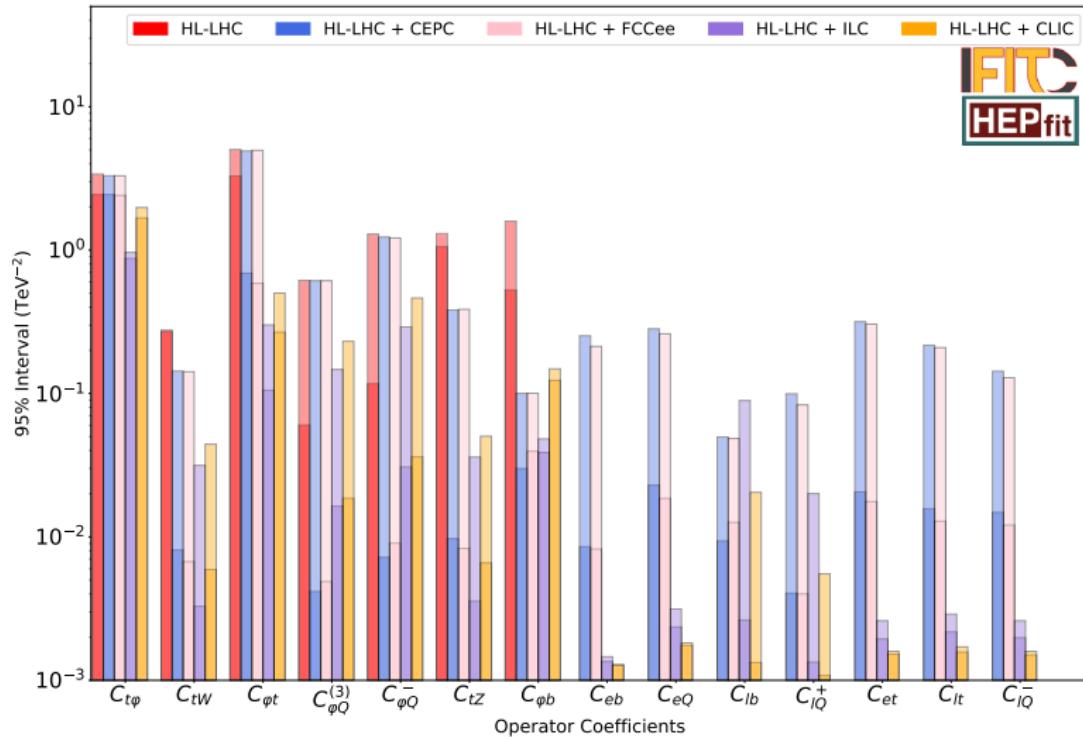
Measurements at e^+e^- colliders: $t\bar{t}H$ production



Expected constraints for different e^+e^- operation energies



Comparison of future colliders



Top-quark Yukawa coupling uncertainties

Values in % units	LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	6.12	2.53	1.57	1.30	0.739
	Indiv. fit	5.08	1.85	1.41	1.17	0.705

- Since the sensitivity at ILC500 is worse than in HL-LHC there is no a huge improvement for the individual constraint
- For the global fit the improvement is relevant even for ILC500, thanks to constraining the Yukawa with more than one observable
- Increasing the energy by 50 GeV provides an important improvement in the constraints thanks to the growth in the cross section
- Similar results are found for CLIC
- An improvement higher than a factor of 2.5 would be obtain at the final stage of ILC w.r.t. the HL-LHC

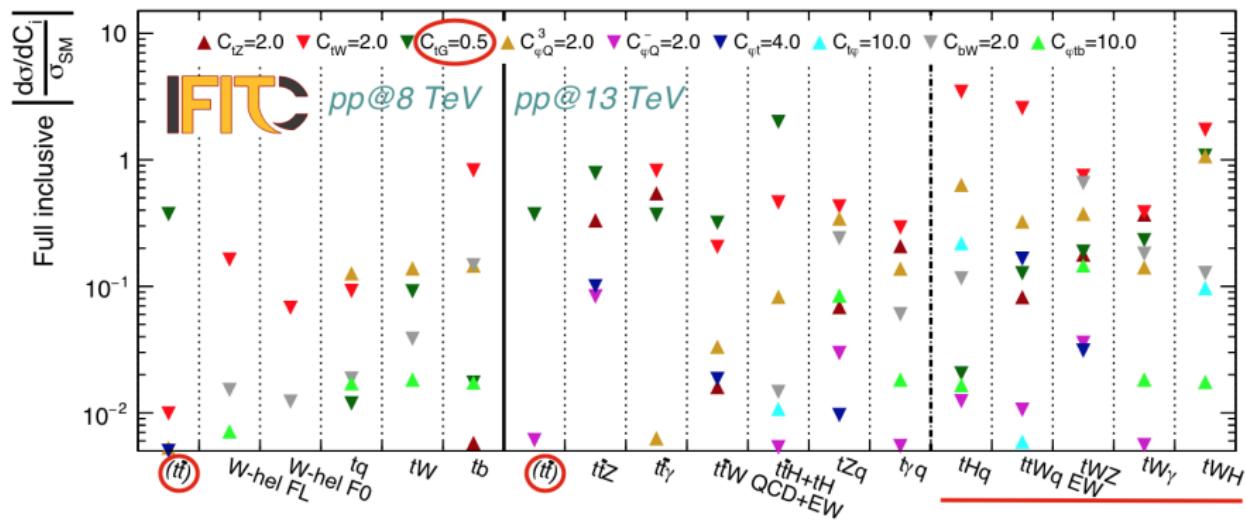
Summary

- 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 (FCCee 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 and CLIC) operated at two center-of-mass energies above the $t\bar{t}$ threshold can provide very tight bounds on all operators, with bounds on 4F taking advantage of energy-growing sensitivity
- Significant improvements for the limits on the top-quark yukawa are found when operating above 550 GeV

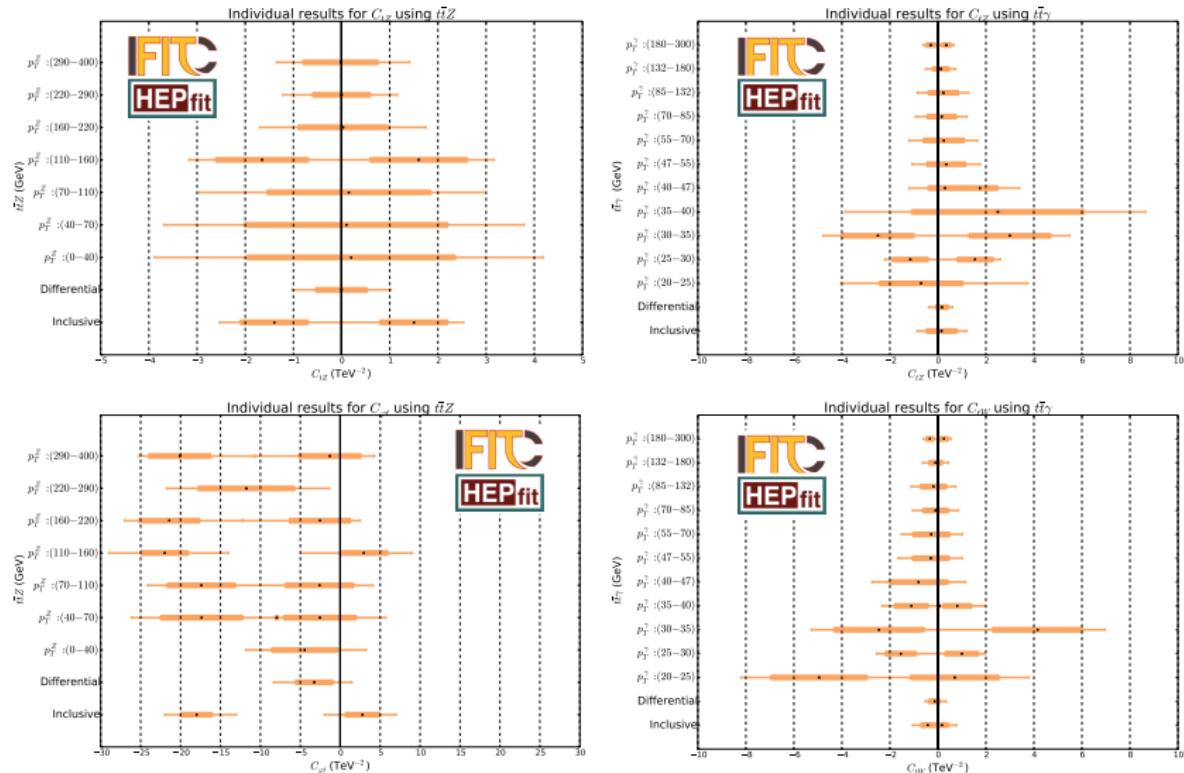
Thank you!

Back up

Sensitivity

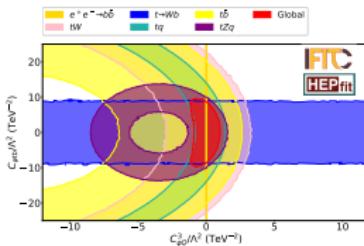
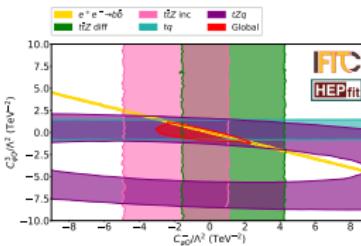
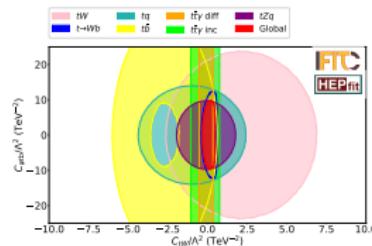
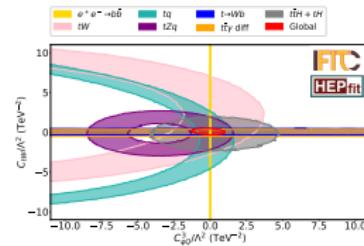
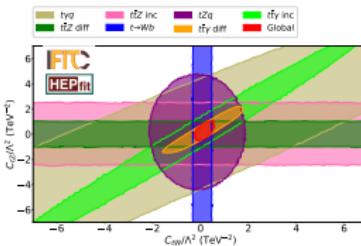
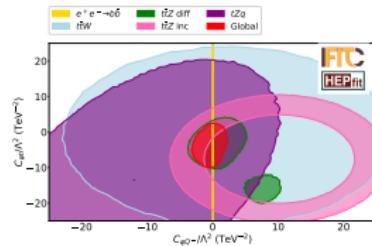


Results - Differential Cross Section Effect



Results - Complementarity Between Observables

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



Dependencies

[1910.03606]

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}	$\Lambda^{-4} [\Lambda^{-2}]$	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^8, C_{td}^8	Λ^{-2}	—	—	—	—	Λ^{-2}	—
$C_{Qq}^{1,1}$	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
$C_{Qq}^{3,1}$	$\Lambda^{-4} [\Lambda^{-2}]$	Λ^{-2}	—	Λ^{-2}	Λ^{-2}	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
C_{tu}^1, C_{td}^1	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	—
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	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	—
C_{tq}^1	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
$C_{\phi Q}^-$	—	—	—	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}	$[\Lambda^{-2}]$	Λ^{-2}	—	$[\Lambda^{-2}]$	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.

Theoretical Framework

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

Relevant Operators			
Coefficient	Operator	Coefficient	Operator
$C_{\varphi Q}^1$	$(\bar{Q}\gamma^\mu Q) (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)$	$C_{\varphi Q}^3$	$(\bar{Q}\tau' \gamma^\mu Q) (\varphi^\dagger i \overleftrightarrow{D}'_\mu \varphi)$
$C_{\varphi t}$	$(\bar{t}\gamma^\mu t) (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b) (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)$
$C_{t\varphi}$	$(\bar{Q}t) (\varepsilon \varphi^* \varphi^\dagger \varphi)$	C_{tG}	$(\bar{t}\sigma^{\mu\nu} T^A t) (\varepsilon \varphi^* G_{\mu\nu}^A)$
C_{tW}	$(\bar{Q}\tau' \sigma^{\mu\nu} t) (\varepsilon \varphi^* W_{\mu\nu}')$	C_{tB}	$(\bar{Q}\sigma^{\mu\nu} t) (\varepsilon \varphi^* B_{\mu\nu})$
$C_{qq}^{1(ijkl)}$	$(\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$	$C_{qq}^{3(ijkl)}$	$(\bar{q}_i \tau' \gamma^\mu q_j)(\bar{q}_k \tau' \gamma_\mu q_l)$
$C_{uu}^{(ijkl)}$	$(\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l)$	$C_{ud}^{8(ijkl)}$	$(\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l)$
$C_{qu}^{8(ijkl)}$	$(\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l)$	$C_{qd}^{8(ijkl)}$	$(\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l)$
C_{lQ}^1	$(\bar{Q}\gamma_\mu Q) (I\gamma^\mu I)$	C_{lQ}^3	$(\bar{Q}\tau' \gamma_\mu Q) (I\tau' \gamma^\mu I)$
C_{lt}	$(\bar{t}\gamma_\mu t) (I\gamma^\mu I)$	C_{lb}	$(\bar{b}\gamma_\mu b) (I\gamma^\mu I)$
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	$C_{tu}^8 = \sum_{i=1,2} 2C_{uu}^{(i33i)}$ $C_{Qu}^8 = \sum_{i=1,2} C_{qu}^{8(33ii)}$ —	$C_{td}^8 = \sum_{i=1,2,3} C_{ud}^{8(33ii)}$ $C_{Qd}^8 = \sum_{i=1,2,3} C_{qd}^{8(33ii)}$ —	$C_{Qq}^{1,8} = \sum_{i=1,2} C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$ $C_{Qq}^{3,8} = \sum_{i=1,2} C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$ $C_{tq}^8 = \sum_{i=1,2} C_{uq}^{8(ii33)}$
2-quark 2-lepton	C_{eb} C_{lb} —	C_{et} C_{lt} —	$C_{IQ}^+ = C_{IQ}^1 + C_{IQ}^3$ $C_{IQ}^- = C_{IQ}^1 - C_{IQ}^3$ C_{eQ}