

# SMEFT Fit for the top-quark sector

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More details in [2205.02140] and [2206.08326]

Also based on [1907.10619] and [2107.13917]



# 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)

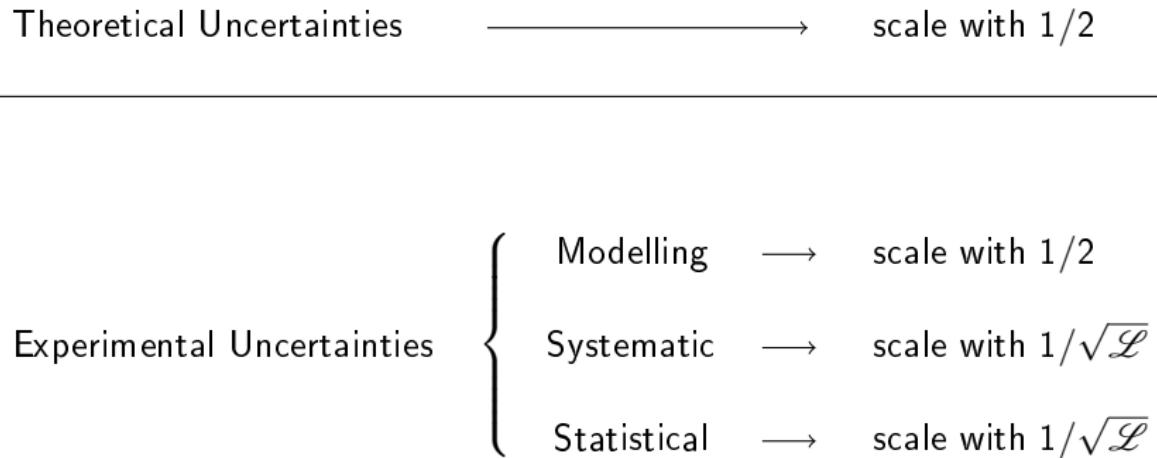
- Here we show the observables included that have been measured in the actual colliders

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



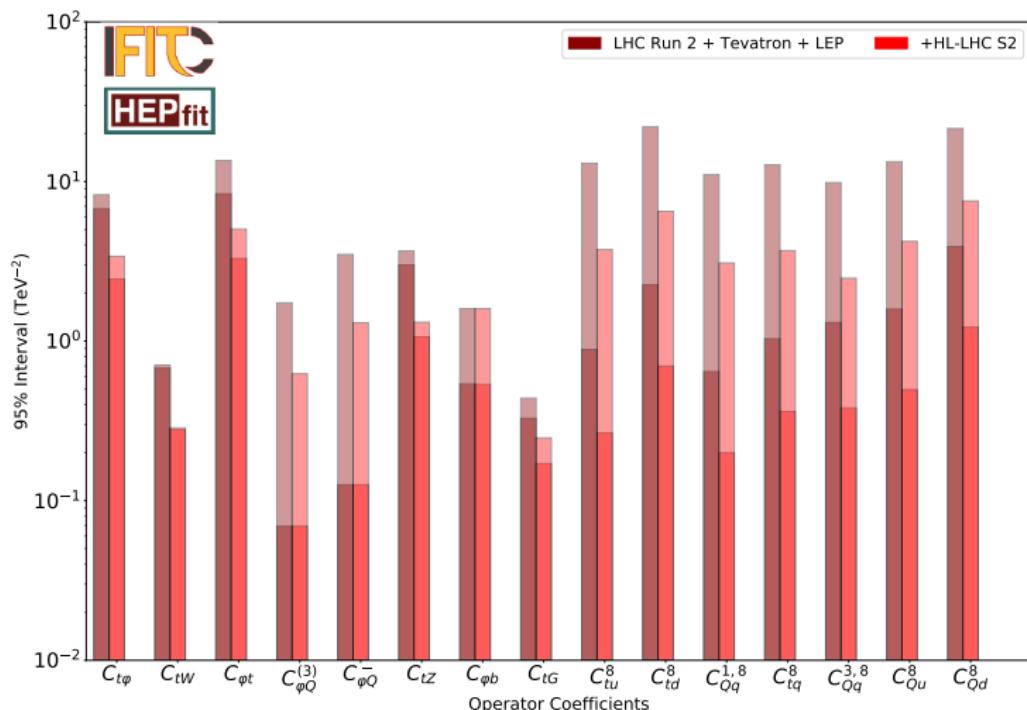
# Prospects for Measurements at HL-LHC

## 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
$pp \rightarrow t\bar{t}W + EW$	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	$2 \text{ ab}^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
	$P(e^+, e^-):(+30\%, -80\%)$	500 GeV	$4 \text{ ab}^{-1}$	
		1 TeV	$8 \text{ ab}^{-1}$	
CLIC	$P(e^+, e^-):(0\%, +80\%)$	380 GeV	$2 \text{ ab}^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
	$P(e^+, e^-):(0\%, -80\%)$	1.5 TeV	$2.5 \text{ ab}^{-1}$	
		3 TeV	$5 \text{ ab}^{-1}$	
CEPC/FCC-ee	Unpolarised	Z-pole	$57.5/150 \text{ ab}^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		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	$4 \text{ ab}^{-1}$	Optimal Observables
	$P(e^+, e^-):(+30\%, -80\%)$	1 TeV	$8 \text{ ab}^{-1}$	
CLIC	$P(e^+, e^-):(0\%, +80\%)$	380 GeV	$2 \text{ ab}^{-1}$	Optimal Observables
	$P(e^+, e^-):(0\%, -80\%)$	1.5 TeV	$2.5 \text{ ab}^{-1}$	
		3 TeV	$5 \text{ ab}^{-1}$	
CEPC/FCC-ee	Unpolarised	350 GeV	$0.2 \text{ ab}^{-1}$	Optimal Observables
		365 GeV	$1/1.5 \text{ ab}^{-1}$	

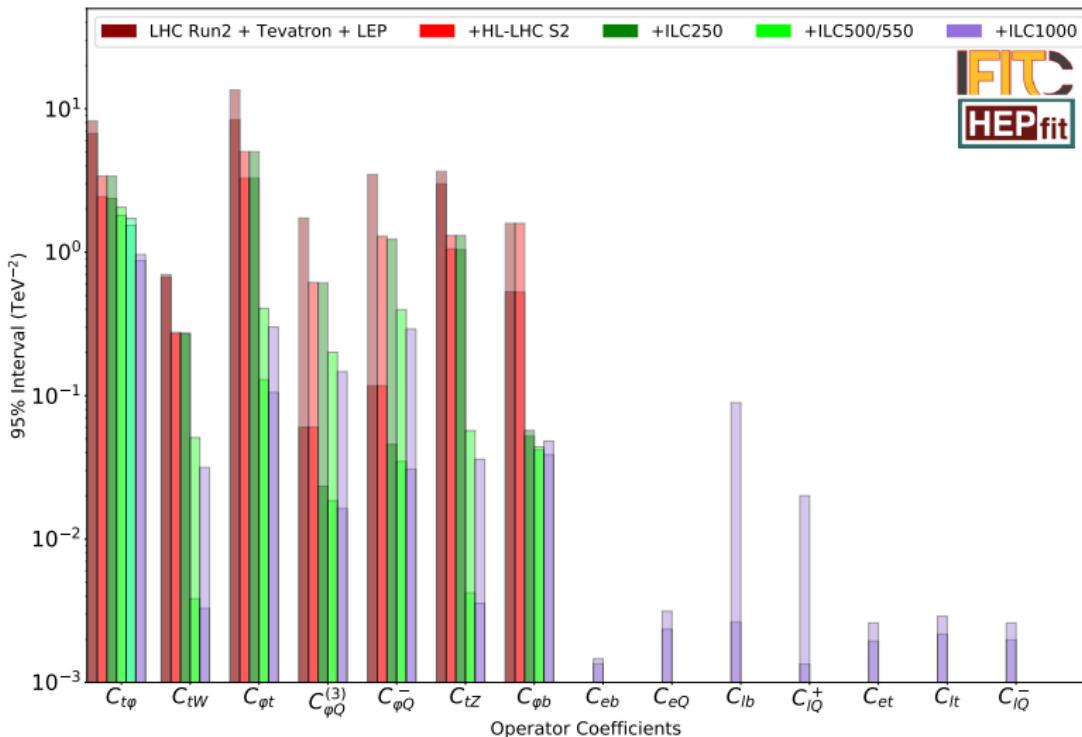
- Optimal observables maximally exploit the information in the fully differential  $e^+e^- \rightarrow t\bar{t} \rightarrow bW^+\bar{b}W^-$  distribution [1807.02121]
- These constrain the 2-fermion operators  $C_{\varphi Q}^-$ ,  $C_{\varphi t}$ ,  $C_{tW}$  and  $C_{tZ}$
- Also the 2-quark 2-lepton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

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

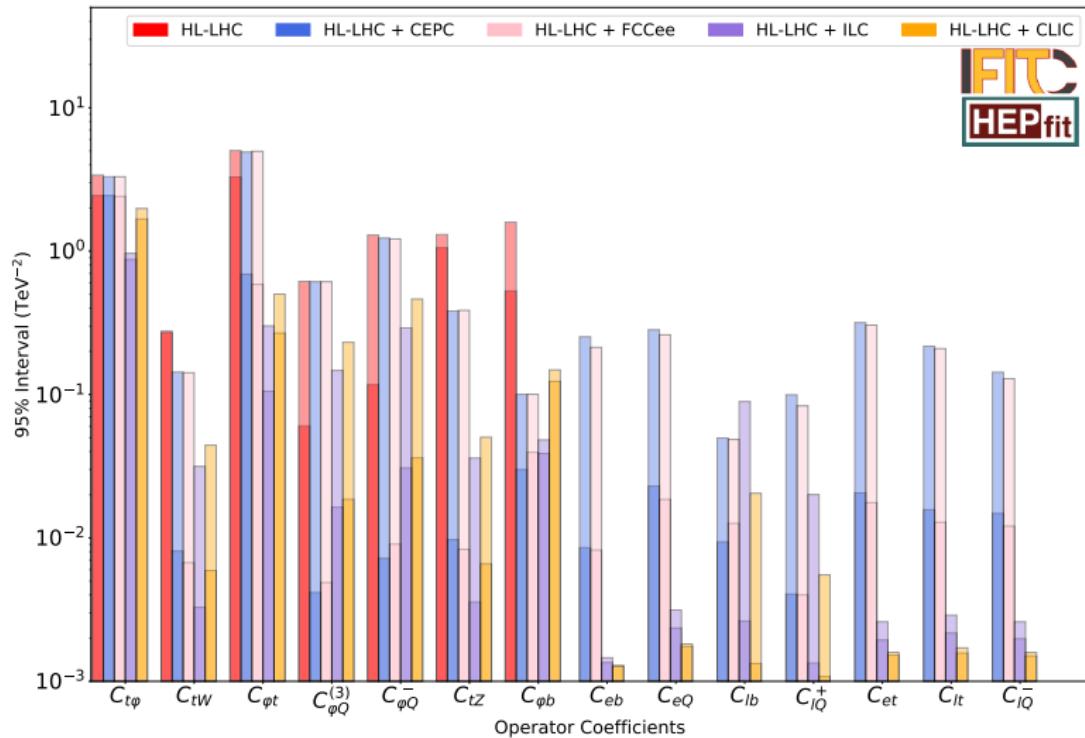
Machine	Polarisation	Energy	Luminosity	Observable
ILC	$P(e^+, e^-):(-30%, +80%)$	500/550 GeV	$4 \text{ ab}^{-1}$	Inclusive cross section
	$P(e^+, e^-):(+30%, -80%)$	1 TeV	$8 \text{ ab}^{-1}$	
CLIC	$P(e^+, e^-):(0%, +80%)$ $P(e^+, e^-):(0%, -80%)$	1.5 TeV	$2.5 \text{ ab}^{-1}$	Inclusive cross section

- 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

# 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
$\delta y_t$	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

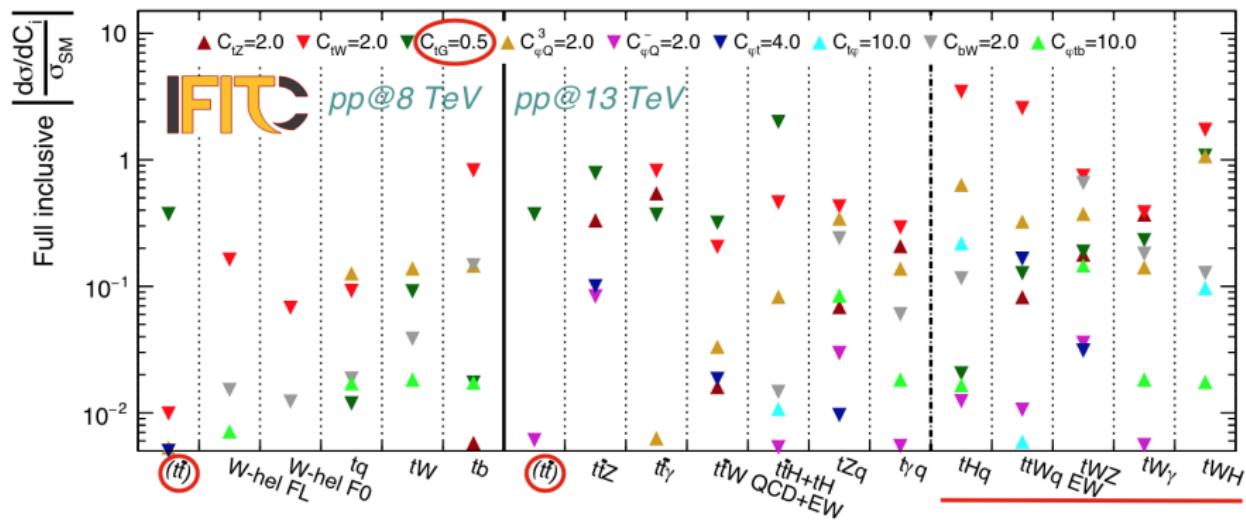
## Summary

- 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

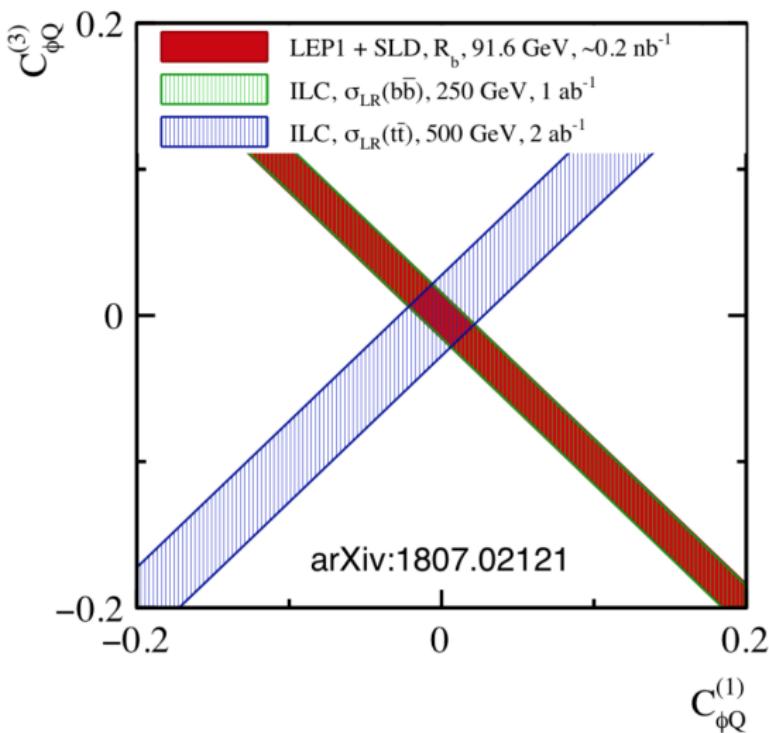


# Future Colliders - Complementarity on $e^+e^-$ Colliders

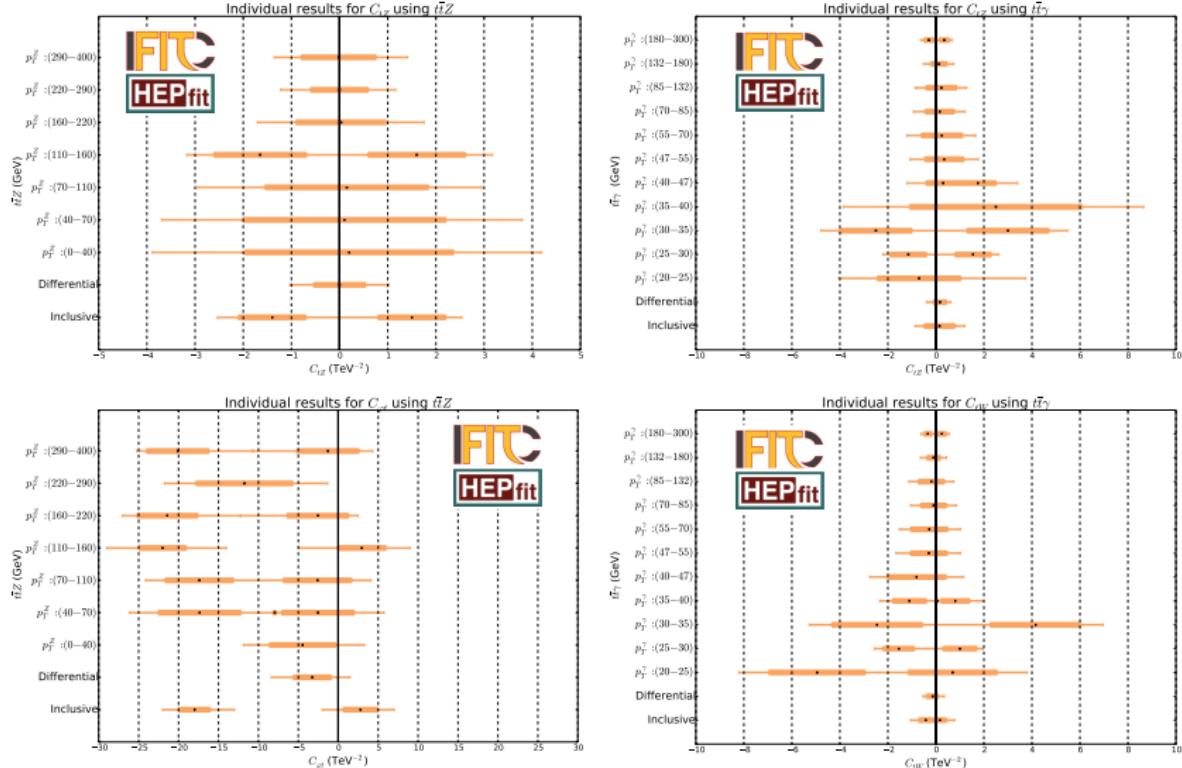
Good complementarity between  $b\bar{b}$  (LEP) and  $t\bar{t}$  (future  $e^+e^-$  collider) if we reach  $\sqrt{s} > 2m_t$

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

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

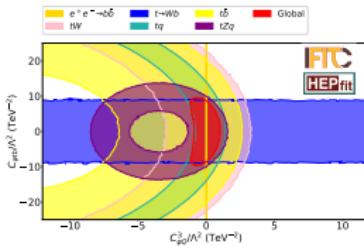
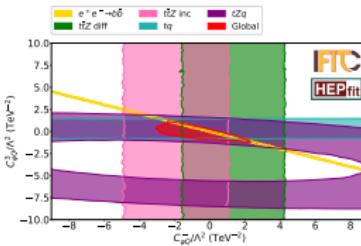
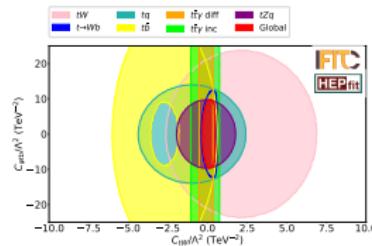
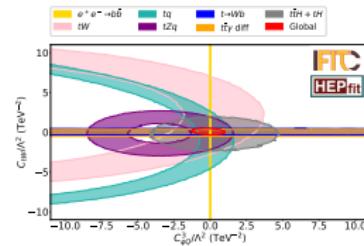
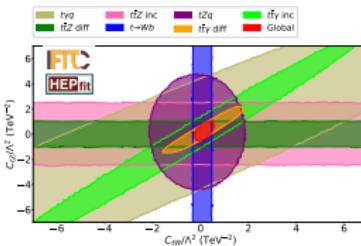
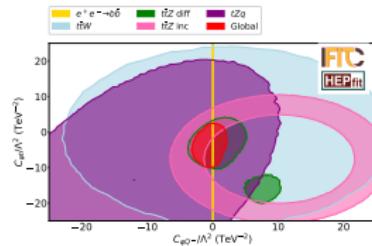


# Results - Differential Cross Section Effect



# 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	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	$\Lambda^{-2}$	—	—	—	—	$\Lambda^{-2}$	$\Lambda^{-2}$
$C_{Qq}^{3,8}$	$\Lambda^{-2}$	$\Lambda^{-4} [\Lambda^{-2}]$	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-2}$	$\Lambda^{-2}$
$C_{tu}^8, C_{td}^8$	$\Lambda^{-2}$	—	—	—	—	$\Lambda^{-2}$	—
$C_{Qq}^{1,1}$	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
$C_{Qq}^{3,1}$	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-2}$	—	$\Lambda^{-2}$	$\Lambda^{-2}$	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
$C_{tu}^1, C_{td}^1$	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	—
$C_{Qu}^8, C_{Qd}^8$	$\Lambda^{-2}$	—	—	—	—	$\Lambda^{-2}$	—
$C_{tq}^8$	$\Lambda^{-2}$	—	—	—	—	$\Lambda^{-2}$	$\Lambda^{-2}$
$C_{Qu}^1, C_{Qd}^1$	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	—
$C_{tq}^1$	$\Lambda^{-4} [\Lambda^{-2}]$	—	—	—	—	$\Lambda^{-4} [\Lambda^{-2}]$	$\Lambda^{-4} [\Lambda^{-2}]$
$C_{\phi Q}^-$	—	—	—	$\Lambda^{-2}$	—	$\Lambda^{-2}$	—
$C_{\phi Q}^3$	—	$\Lambda^{-2}$	$\Lambda^{-2}$	$\Lambda^{-2}$	$\Lambda^{-2}$	—	—
$C_{\phi t}$	—	—	—	$\Lambda^{-2}$	—	$\Lambda^{-2}$	—
$C_{\phi tb}$	—	$\Lambda^{-4}$	$\Lambda^{-4}$	$\Lambda^{-4}$	$\Lambda^{-4}$	—	—
$C_{tZ}$	—	—	—	$\Lambda^{-2}$	—	$\Lambda^{-2}$	—
$C_{tW}$	—	$\Lambda^{-2}$	$\Lambda^{-2}$	$\Lambda^{-2}$	$\Lambda^{-2}$	—	—
$C_{bW}$	—	$\Lambda^{-4}$	$\Lambda^{-4}$	$\Lambda^{-4}$	$\Lambda^{-4}$	—	—
$C_{tG}$	$\Lambda^{-2}$	$[\Lambda^{-2}]$	$\Lambda^{-2}$	—	$[\Lambda^{-2}]$	$\Lambda^{-2}$	$\Lambda^{-2}$

**Table 1.** Wilson coefficients in our analysis and their contributions to top-quark observables via SM-interference ( $\Lambda^{-2}$ ) and via dimension-6 squared terms only ( $\Lambda^{-4}$ ). 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
$C_{\varphi Q}^1$	$(\bar{Q}\gamma^\mu Q)(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)$	$C_{\varphi Q}^3$	$(\bar{Q}\tau' \gamma^\mu Q)(\varphi^\dagger i\overleftrightarrow{D}'_\mu \varphi)$
$C_{\varphi t}$	$(\bar{t}\gamma^\mu t)(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)$	$C_{\varphi b}$	$(\bar{b}\gamma^\mu b)(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)$
$C_{t\varphi}$	$(\bar{Q}t)(\varepsilon\varphi^* \varphi^\dagger \varphi)$	$C_{tG}$	$(\bar{t}\sigma^{\mu\nu} T^A t)(\varepsilon\varphi^* G_{\mu\nu}^A)$
$C_{tW}$	$(\bar{Q}\tau' \sigma^{\mu\nu} t)(\varepsilon\varphi^* W_{\mu\nu}^I)$	$C_{tB}$	$(\bar{Q}\sigma^{\mu\nu} t)(\varepsilon\varphi^* B_{\mu\nu})$
$C_{qq}^{1(ijkl)}$	$(\bar{q}_i \gamma^\mu q_j)(\bar{q}_k \gamma_\mu q_l)$	$C_{qq}^{3(ijkl)}$	$(\bar{q}_i \tau' \gamma^\mu q_j)(\bar{q}_k \tau' \gamma_\mu q_l)$
$C_{uu}^{(ijkl)}$	$(\bar{u}_i \gamma^\mu u_j)(\bar{u}_k \gamma_\mu u_l)$	$C_{ud}^{8(ijkl)}$	$(\bar{u}_i \gamma^\mu T^A u_j)(\bar{d}_k \gamma_\mu T^A d_l)$
$C_{qu}^{8(ijkl)}$	$(\bar{q}_i \gamma^\mu T^A q_j)(\bar{u}_k \gamma_\mu T^A u_l)$	$C_{qd}^{8(ijkl)}$	$(\bar{q}_i \gamma^\mu T^A q_j)(\bar{d}_k \gamma_\mu T^A d_l)$
$C_{lQ}^1$	$(\bar{Q} \gamma_\mu Q) (l \gamma^\mu l)$	$C_{lQ}^3$	$(\bar{Q} \tau' \gamma_\mu Q) (l \tau' \gamma^\mu l)$
$C_{lt}$	$(\bar{t} \gamma_\mu t) (\bar{l} \gamma^\mu l)$	$C_{lb}$	$(\bar{b} \gamma_\mu b) (\bar{l} \gamma^\mu l)$
$C_{eQ}$	$(\bar{Q} \gamma_\mu Q) (\bar{e} \gamma^\mu e)$	$C_{et}$	$(\bar{t} \gamma_\mu t) (\bar{e} \gamma^\mu e)$
$C_{eb}$	$(\bar{b} \gamma_\mu b) (\bar{e} \gamma^\mu e)$	-	-

# 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	$C_{tu}^8 = \sum_{i=1,2} 2C_{uu}^{(i33i)}$ $C_{Qu}^8 = \sum_{i=1,2} C_{qu}^{8(33ii)}$ —	$C_{td}^8 = \sum_{i=1,2,3} C_{ud}^{8(33ii)}$ $C_{Qd}^8 = \sum_{i=1,2,3} C_{qd}^{8(33ii)}$ —	$C_{Qq}^{1,8} = \sum_{i=1,2} C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$ $C_{Qq}^{3,8} = \sum_{i=1,2} C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$ $C_{tq}^8 = \sum_{i=1,2} C_{uq}^{8(ii33)}$
2-quark 2-lepton	$C_{eb}$ $C_{lb}$ —	$C_{et}$ $C_{lt}$ —	$C_{IQ}^+ = C_{IQ}^1 + C_{IQ}^3$ $C_{IQ}^- = C_{IQ}^1 - C_{IQ}^3$ $C_{eQ}$