IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA — CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

EXCELENCIA SEVERO OCHOA

Bounds on top operators in the SMEFT from recent LHC measurements

IFIC Severo Ochoa Scientific days - L1 Higgs Force

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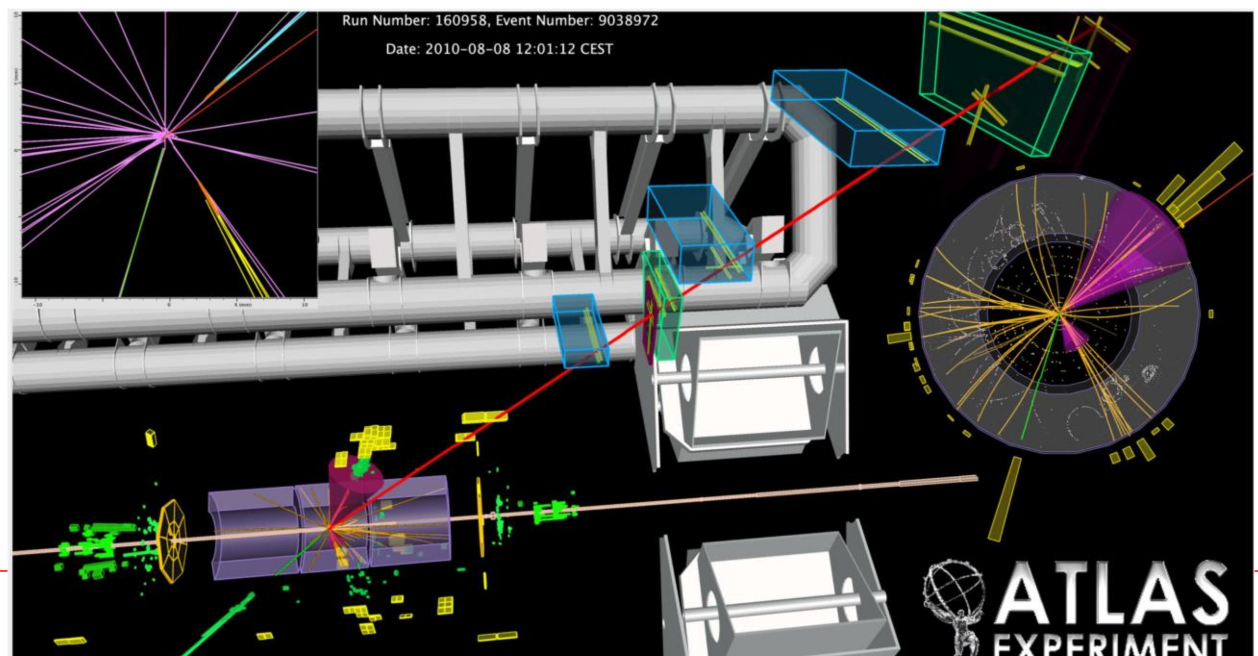


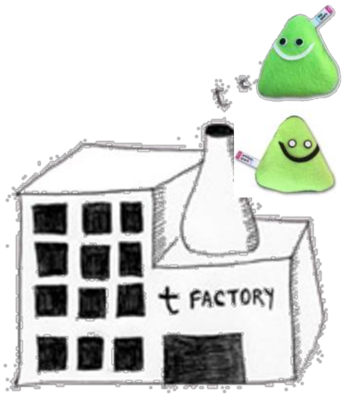
based on results in JHEP02(2022)032, arXiv: 2205.02140 & arXiv: 2206.08326

Introduction / Goal

- Our goal is to constrain the top-quark related Wilson coeficients of the SMEFT
- The fits have been performed using HEPfit [Eur. Phys. J. C (2020) 80:456]
- Limits using the latest LHC measurements have been extracted
- Estimations for the HL-LHC derived
- Prospects for our limits in the HL-LHC and possible future e^+e^- colliders also obtained

Possible future e^+e^- colliders

Machine	P(e^+, e^-)	Energy	Luminosity
ILC	(±30%, ∓80%)	250 GeV	2 ab^{-1}
		500 GeV	4 ab^{-1}
	(±20%, ∓80%)	1 TeV	8 ab^{-1}
CLIC	(0%, ±80%)	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.41 ab^{-1}
		365 GeV	2.65 ab^{-1}
CEPC	Unpolarised	Z-pole	57.5 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}

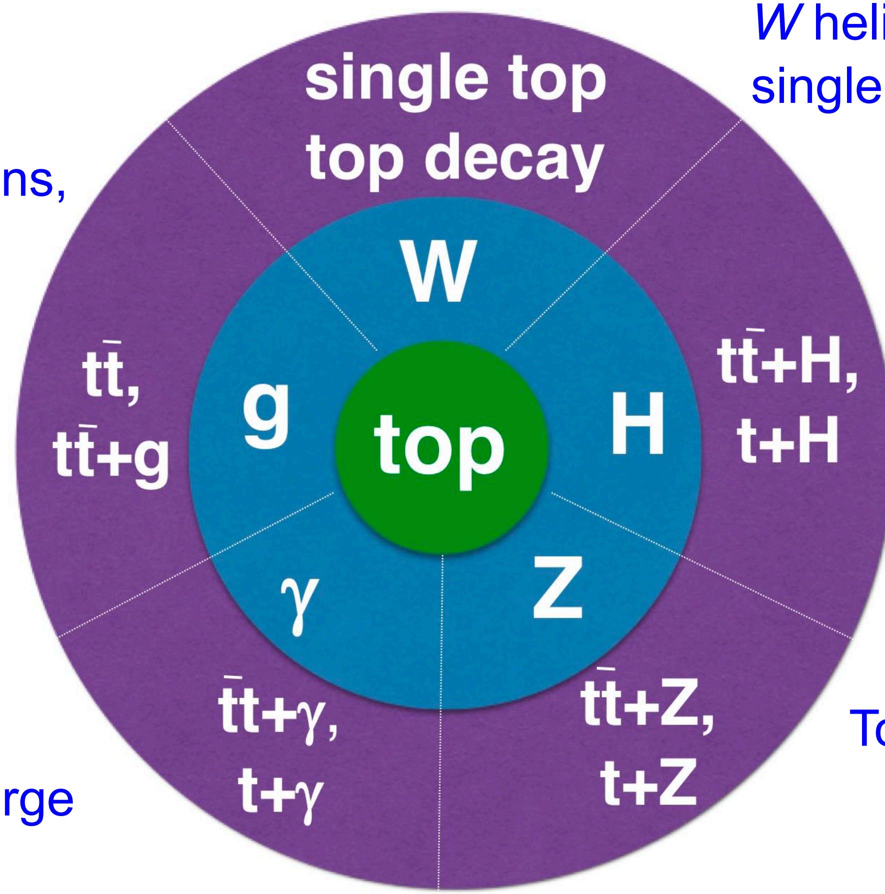


Top quark couplings

Top quark couples to other SM fields through its **gauge and Yukawa interactions**
t→*Wb* coupling and *tt* strong production studied already at the Tevatron
High statistics at the LHC: *tt*+bosons (γ, *Z*, *W* and *H*) became available

W helicity and several single top quark measurements

Differential cross-sections, spin correlations, charge asymmetry, etc.



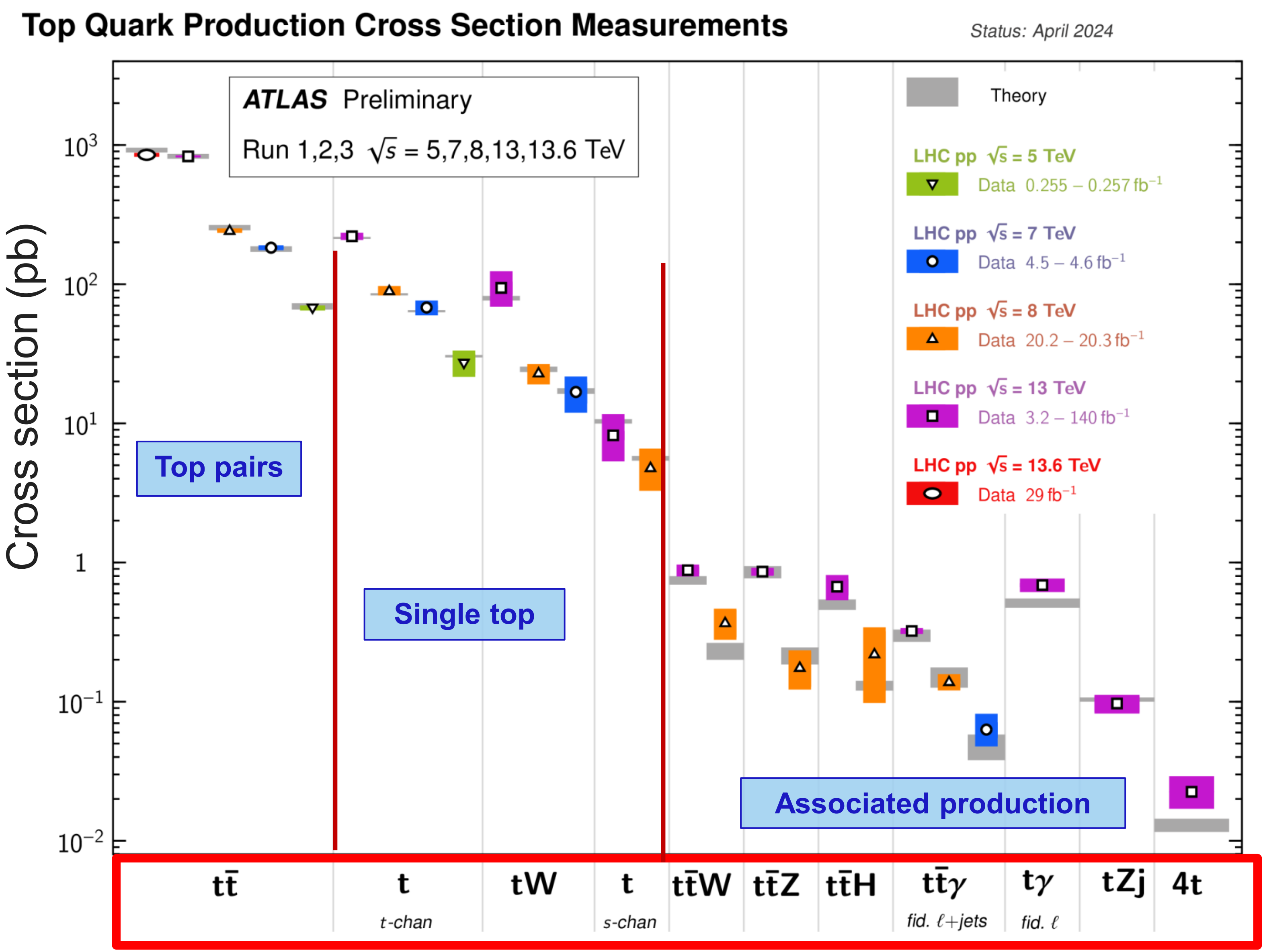
Top Yukawa coupling

Top weak isospin

Top electric charge

top + X coupling: how to measure it?

Reaching very rare processes as data increase



1 event every second

1 event every 100 s

So far, experimental results confirm the Standard Model

Increasing number of differential measurements and reaching very high precision.

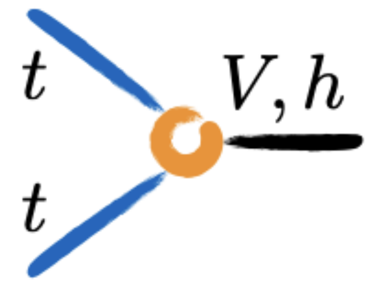
Measurements used in our fit to top quark EW couplings

JHEP02(2022)032

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}H + tHq$	σ	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
$pp \to tZq$	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

SMEFT operators relevant for the top quark

Basis: complete, non-redundant set of operators
Dimension 6: several operators affecting top quark interactions



Two-fermion op. (2F): QQ + V,G,φ

Four-fermion op. (4F): QQQQ, QQqq, QQll

- The exact number depends on CP/flavour assumptions
- In our studies, we consider only real parameters
- In this first study, we considered eight 2F operators

Left and right-handed couplings of the t- and b-quark to the Z (vector)

$O^3_{\varphi Q} \equiv \frac{1}{2}(\bar{q}\tau^I\gamma^\mu q)\left(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi\right)$

$O^1_{\varphi Q} \equiv \frac{1}{2}(\bar{q}\gamma^\mu q)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$

$O_{\varphi u} \equiv \frac{1}{2}(\bar{u}\gamma^\mu u)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$

~~$O_{\varphi d} \equiv \frac{1}{2}(\bar{d}\gamma^\mu d)\left(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi\right)$~~

EW dipole operators (tensor)

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

$O_{dW} \equiv (\bar{q}\tau^I\sigma^{\mu\nu}d)\left(\varphi W^I_{\mu\nu}\right)$

$O_{uB} \equiv (\bar{q}\sigma^{\mu\nu}u)(\varepsilon\varphi^* B_{\mu\nu})$

~~$O_{dB} \equiv (\bar{q}\sigma^{\mu\nu}d)(\varphi B_{\mu\nu})$~~

Chromo magnetic dipole operators (tensor)

$O_{uG} \equiv (\bar{q}\sigma^{\mu\nu}T^A u)\left(\varepsilon\varphi^* G^A_{\mu\nu}\right)$

$O_{dG} \equiv (\bar{q}\sigma^{\mu\nu}T^A d)\left(\varphi G^A_{\mu\nu}\right)$

Top/Bottom yukawa (scalar)

$O_{u\varphi} \equiv (\bar{q}u)(\varepsilon\varphi^*\,\varphi^\dagger\varphi)$

$O_{d\varphi} \equiv (\bar{q}d)(\varphi\,\varphi^\dagger\varphi)$

Charged current interaction (vector)

$O_{\varphi ud} \equiv \frac{1}{2}(\bar{u}\gamma^\mu d)(\varphi^T\varepsilon i D_\mu\varphi)$

2F operators relevant for top quark physics

$\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{\phi Q^1}$ - $t\bar{t}Z$ vertex

$\mathcal{O}_{tW}, \mathcal{O}_{tB}$ - $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices

Basis rotated following the prescription of the LHC Top WG:

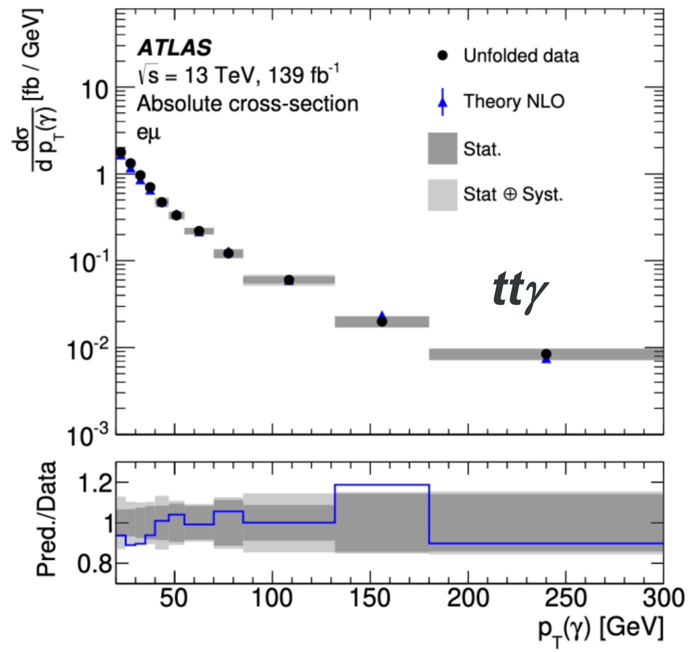
$O_{tB} \rightarrow O_{tZ} = \cos\theta_W O_{tW} - \sin\theta_W O_{tB}$

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

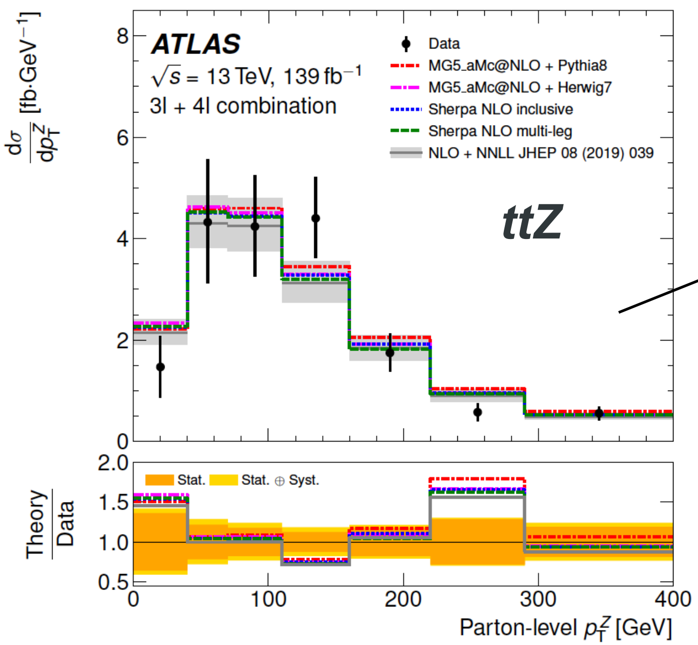
arXiv: 1802.07237

The power of differential cross sections

JHEP 09 (2020) 049



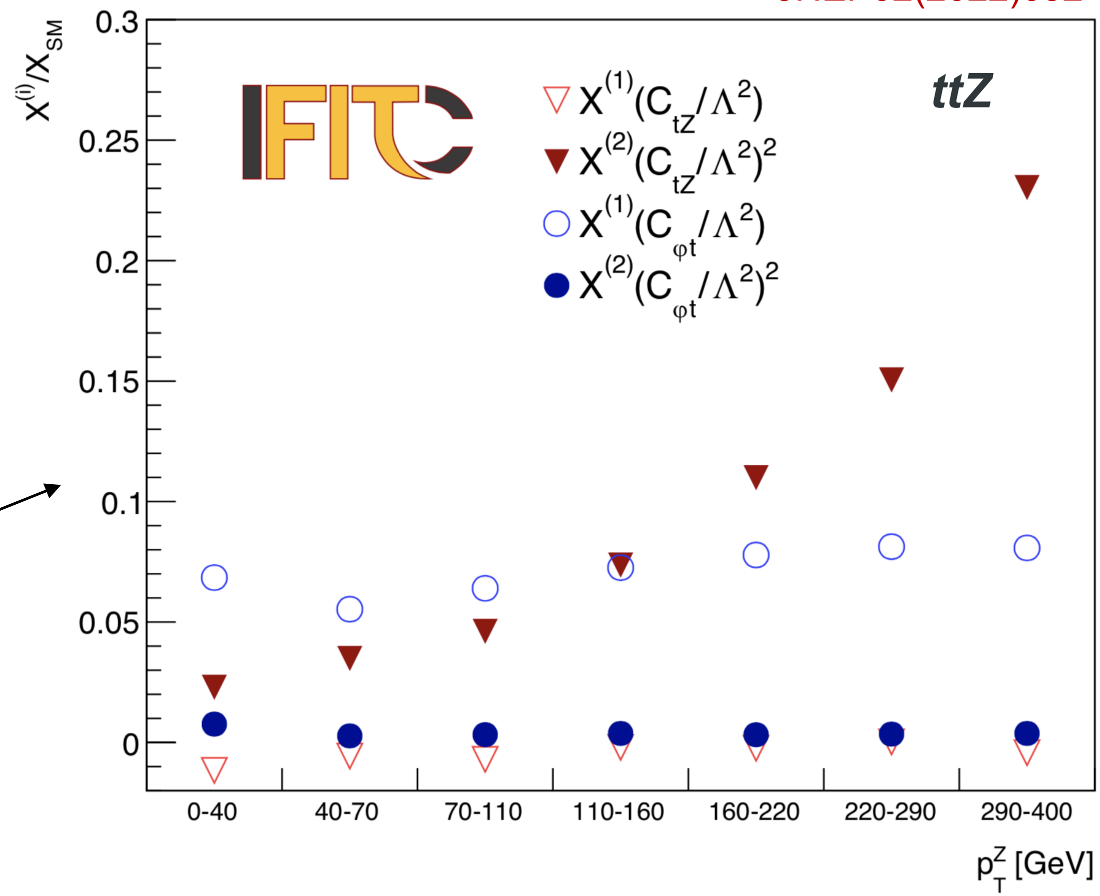
Eur. Phys. J. C 81 (2021) 737



Dependence derived with **MadGraph5_aMC@NLO**, plus **SMEFT@NLO** and **TEFT_EW**

$$X = X_{SM} + \underbrace{\frac{1}{\Lambda^2}\sum_i C_i X_i^{(1)}}_{\text{Linear Terms}} + \underbrace{\frac{1}{\Lambda^4}\sum_{ij} C_i C_j X_{ij}^{(2)}}_{\text{Quadratic Terms}} + \mathcal{O}(\Lambda^{-4})$$

JHEP02(2022)032

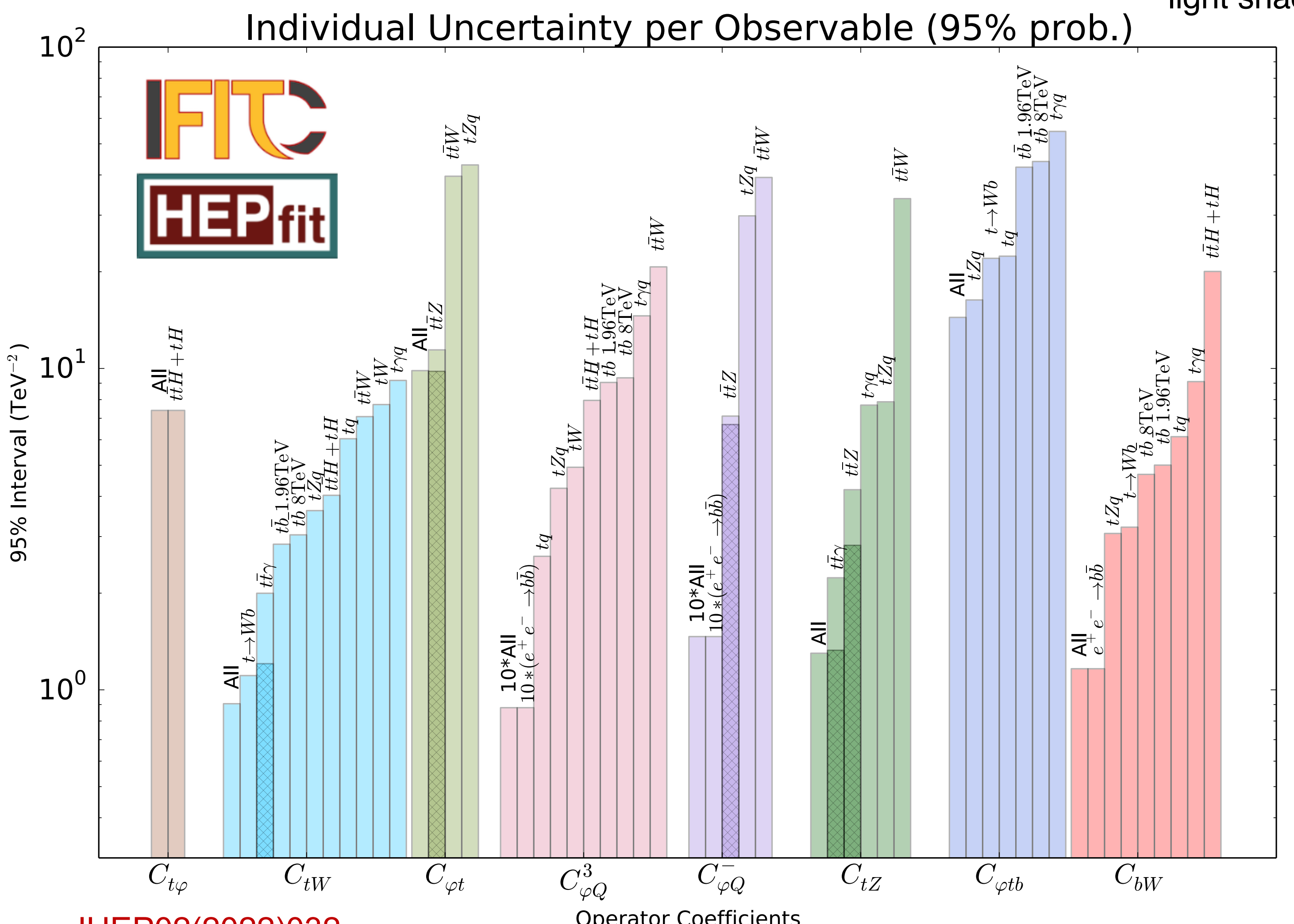


Sensitivity of each observable

* LH/RH couplings of t/b quarks to Z: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

$$X = X_{\rm SM} + \underbrace{\frac{1}{\Lambda^2}\sum_i C_i X_i^{(1)}}_{\text{Linear Terms}} + \underbrace{\frac{1}{\Lambda^4}\sum_{ij} C_i C_j X_{ij}^{(2)}}_{\text{Quadratic Terms}} + \mathcal{O}(\Lambda^{-4})$$

dark shades: differential $t\bar{t}Z$ and $t\bar{t}\gamma$ meas.
light shades (full length): inclusive ”



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Sensitivity coming from:

C_{tW} → W helicity and $t\bar{t}\gamma$

$C_{\varphi t}$ → $t\bar{t}Z$

$C^{-}_{\varphi Q}$ & $C^{(3)}_{\varphi Q}$ → LEP/SLD

C_{tZ} → $t\bar{t}\gamma$ and $t\bar{t}Z$

$C_{\varphi tb}$ → tZ and W helicity

Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

Complementarity between observables

* LH/RH couplings of t/b quarks to Z: $O_{\varphi t}, O_{\varphi Q}^{-}, O_{\varphi Q}^{(3)}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

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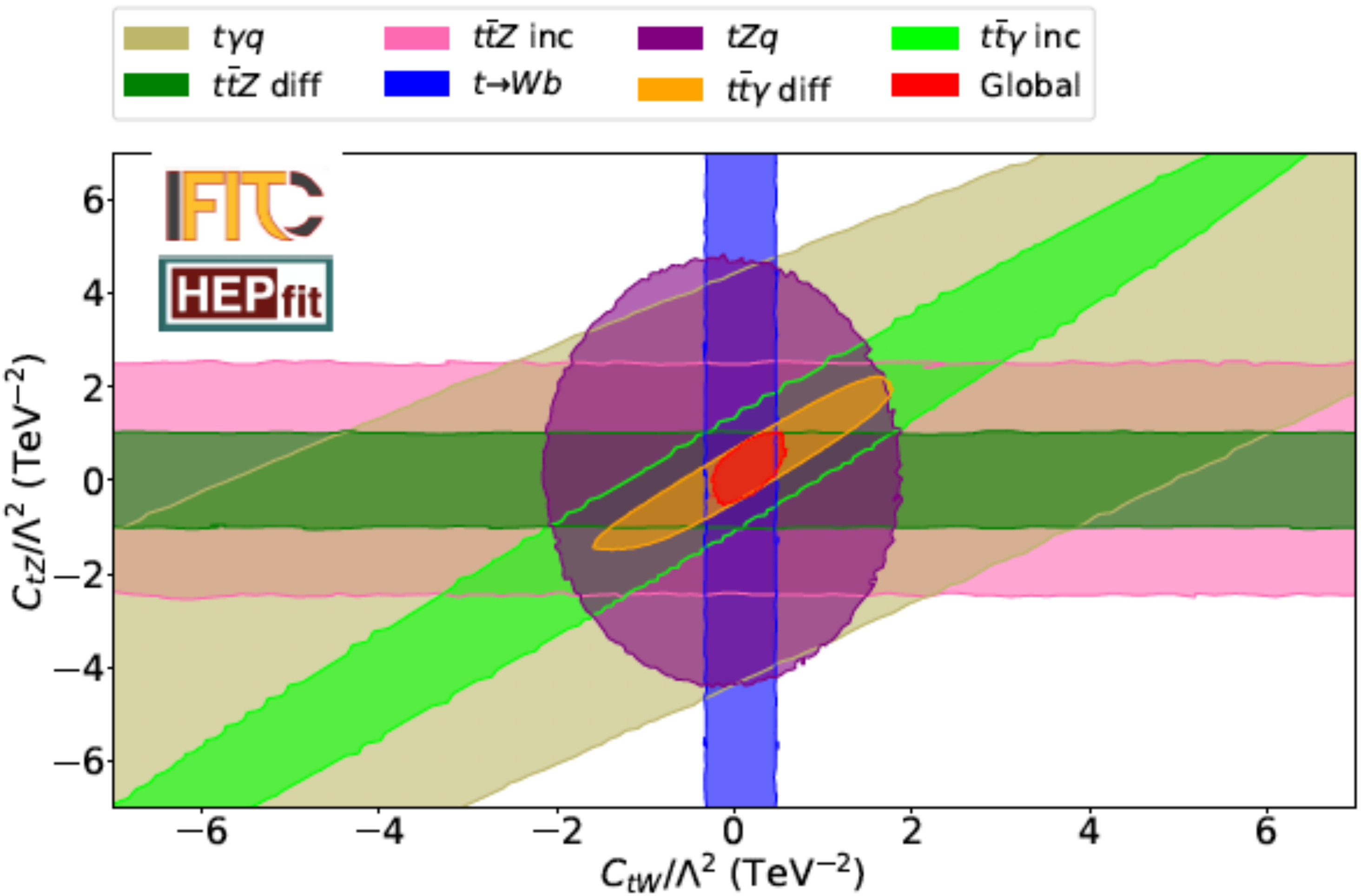


95% prob. bounds

Sensitivity coming from:
C_{tW} → W helicity and $t\bar{t}\gamma$
C_{tZ} → $t\bar{t}\gamma$ and $t\bar{t}Z$

Significant improvement from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential measurements ☺

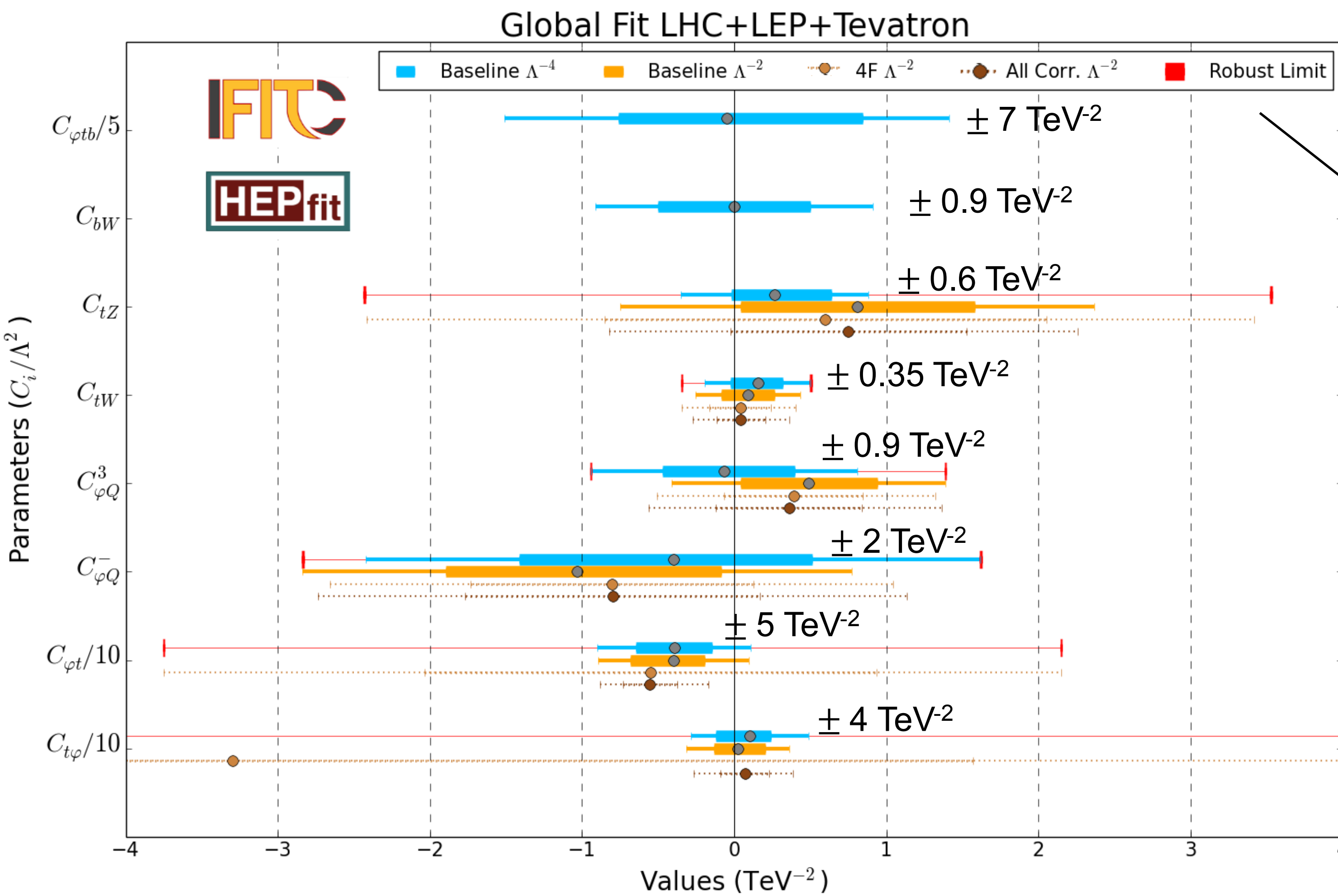
Results of the global fit

✓ Constraints of **linear** (only Λ^{-2} terms) global fit are similar to those of the **quadratic** (Λ^{-2}+Λ^{-4}) fit

- Overall comparable results
- Main difference between the two sets of results seen for C_{tZ}

✓ Bounds compatible with SM within 2σ

✓ 95% prob. bounds: $\pm$ 0.35-7 TeV^{-2}



JHEP02(2022)032

Check the robustness of the fit:

1) Extension of our basis: with 4F QQqq operators and C_{tG}

2) Correlations between different observables (ansatzs for non-published correlations have been estimated)

3) Missing higher-orders in α_S in EFT parametrisations

→ **Robust limits:** envelope obtained from results of new fits with these effects

Currently updating the fit – various updates

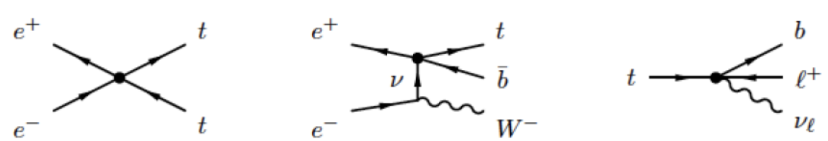
- New LHC results available
- Expanding basis, now also bounds on QQqq and QQll operators
- Extrapolations to HL-LHC (3000 fb^{-1})
  - Scaling of uncertainties (HL-LHC S2 scenario):
    - theoretical: 1/2
    - stat. & experimental syst.: $1/\sqrt{L}$
    - modelling syst.: 1/2
- Projections for HL-LHC and future lepton colliders
  - Inputs for Snowmass White Paper & European Strategy

Inputs used for lepton colliders

σ_{bb} & A^{FB}_{bb}

optimal observables for top (arXiv:1807.02121)

σ_{ttH}



- Now quoting expected bounds (centered in 0, SM)
- Quoting bounds as full-interval divided by 2
- Very preliminar results – work ongoing
- Shown today: only linear results

- Besides the 2F op, also including QQqq and QQll operators in the global fit

Coefficients fitted

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}

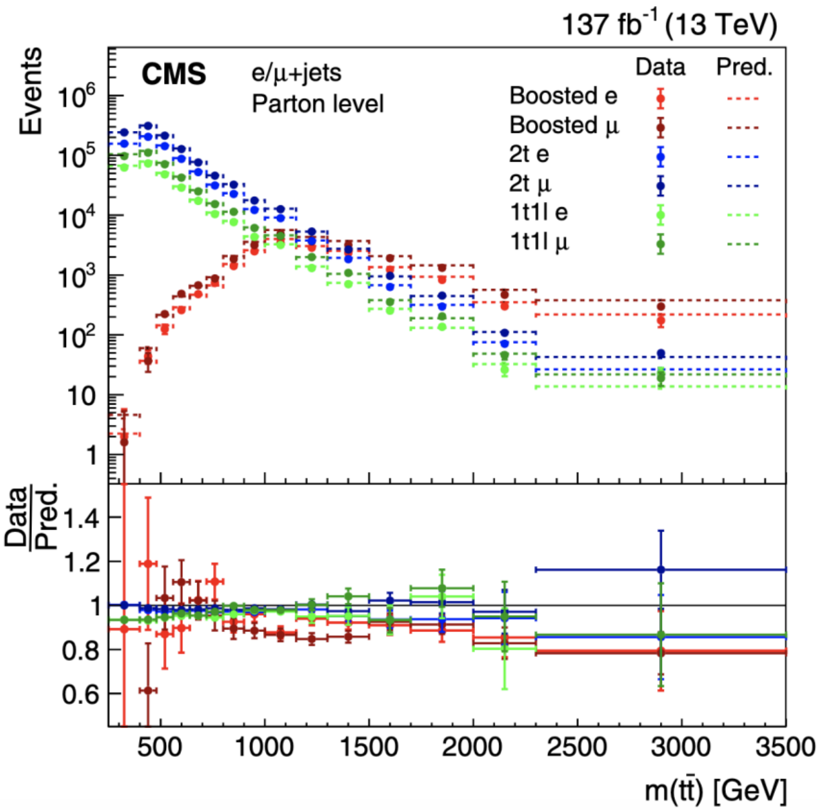
Measurements used in our NEW fit to top quark couplings

Process	Observable	$\sqrt{s}$	L_{int}	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (5+2 bins)	13 TeV	139 fb^{-1}	ATLAS
$pp \to t\bar{t}H$	$d\sigma/dp_T^H$ (6 bins)	13 TeV	139 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (8 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (10 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}W$	σ	13 TeV	138 fb^{-1}	CMS
$pp \to tZq$	σ	13 TeV	138 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{b}$ (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
$p\bar{p} \to t\bar{t}$	$\text{dA}_{FB}/dm_{t\bar{t}}$ (4 bins)	1.96 TeV	9.7 fb^{-1}	Tevatron
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^-e^+ \to b\bar{b}$	R_b, A^{bb}_{FBLR}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD

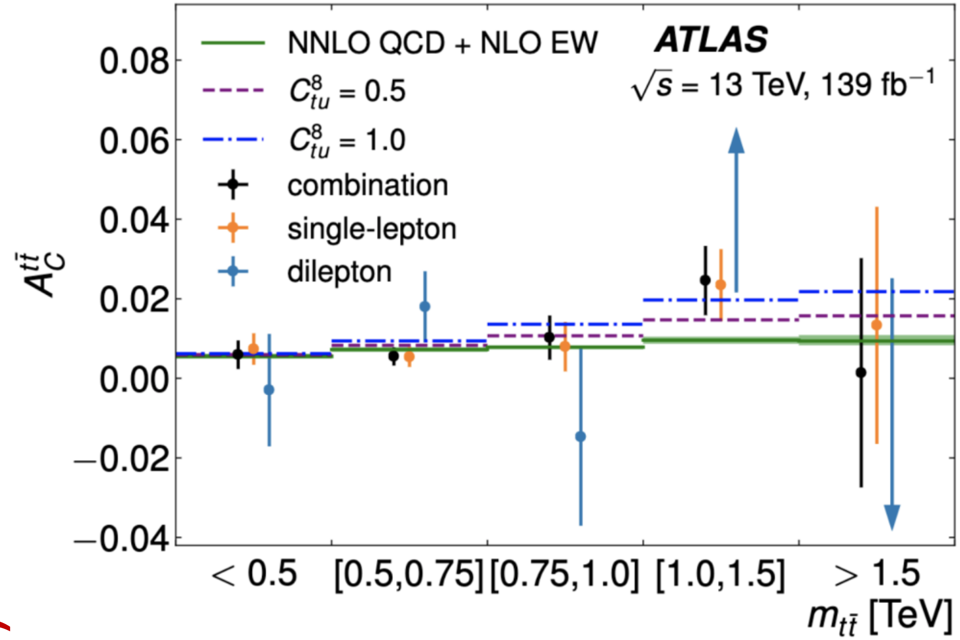
Also: ttll cross-section (for $m_{ll}>m_Z$) sensitive to QQll operators
and quantum observables sensitive to QQqq and ctG (work from MSc students)

Input measurements: tt differential measurements

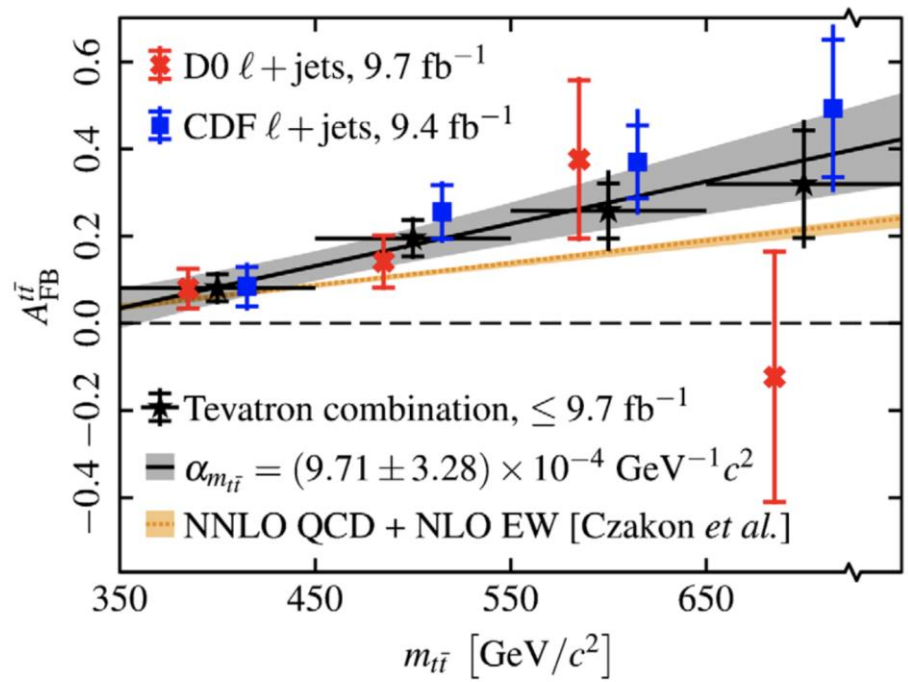
tt XS - PRD 104, 092013 (2021)



tt CA- JHEP08(2023)077

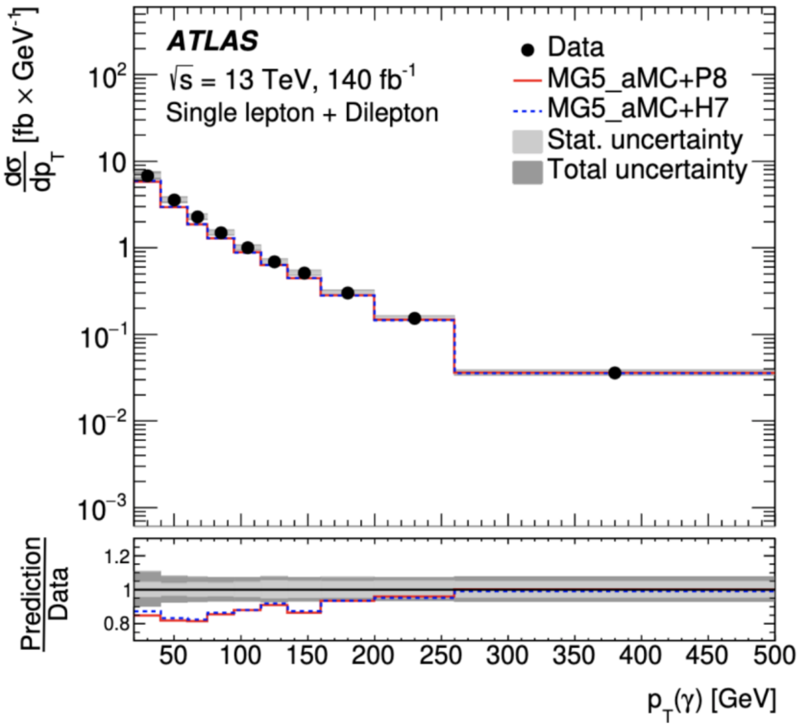


tt A_{FB} - PRL 120, 042001 (2018)

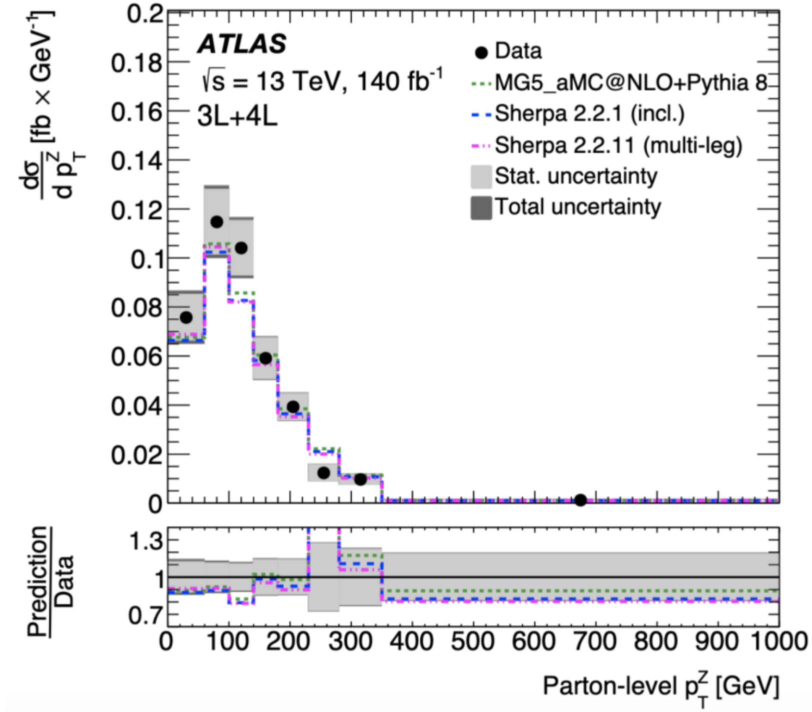


Input measurements: tt+X cross-sections

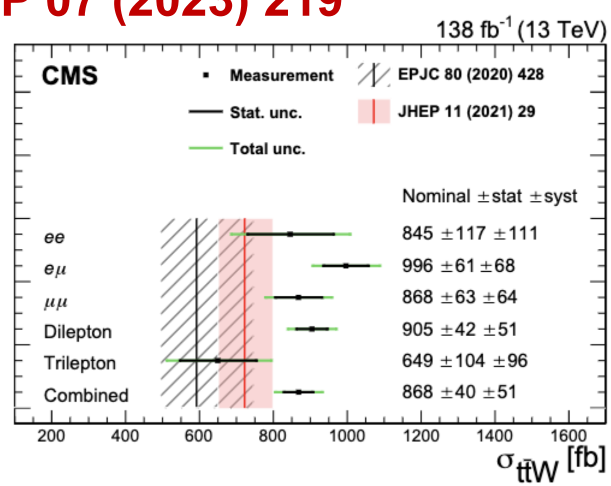
tty - JHEP 10 (2024) 191



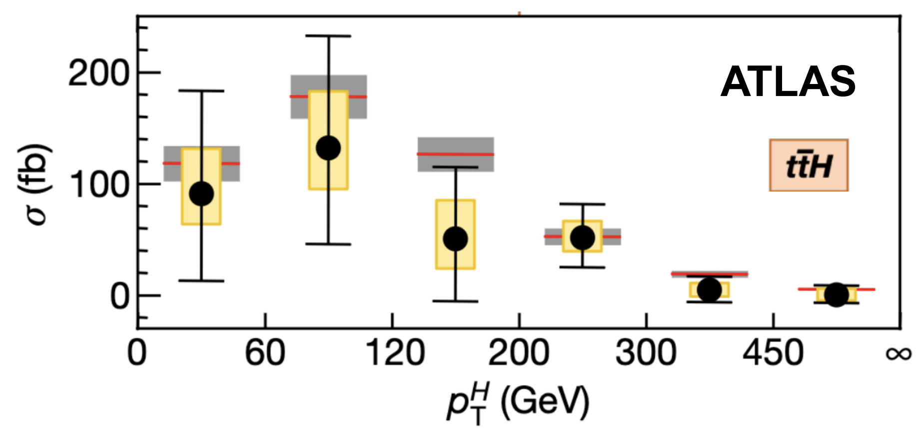
ttZ - JHEP 07 (2024) 163



ttW - JHEP 07 (2023) 219



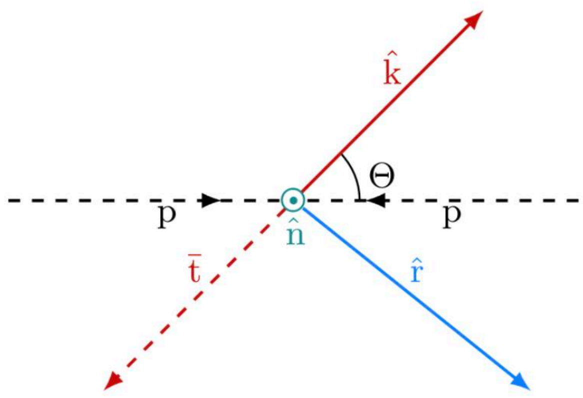
ttH - Nature 607, p.52-59 (2022)

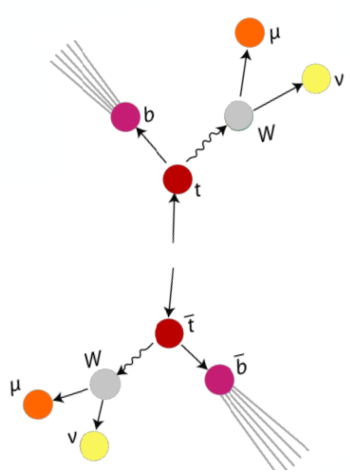


Sensitive observables to entanglement with top quarks

Sketch from PRD 100 (2019) 072002

Helicity basis $\{\hat{k}, \hat{r}, \hat{n}\}$





Threshold $$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{ab}} = \frac{1}{2}\left(1 + \alpha_a\alpha_b D\cos\theta_{ab}\right)$$

being $\cos\theta_{ab} \equiv \hat{p}_a \cdot \hat{p}_b$

angle between the directions of two decay products measured in their parent top quark and antiquark rest frames

Boosted $$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta'_{ab}} = \frac{1}{2}\left(1 + \alpha_a\alpha_b D_3\cos\theta'_{ab}\right)$$

being $\cos\theta'_{ab} \equiv \hat{p}_a \cdot \hat{p}'_b$

with inverted sign of n-component in one of the decay products

Conditions for entanglement

$$\boldsymbol{D = -\frac{(C_{kk} + C_{rr} + C_{nn})}{3} < -1/3}$$

$$\boldsymbol{D_n = -\frac{(C_{kk} + C_{rr} - C_{nn})}{3} > +1/3}$$

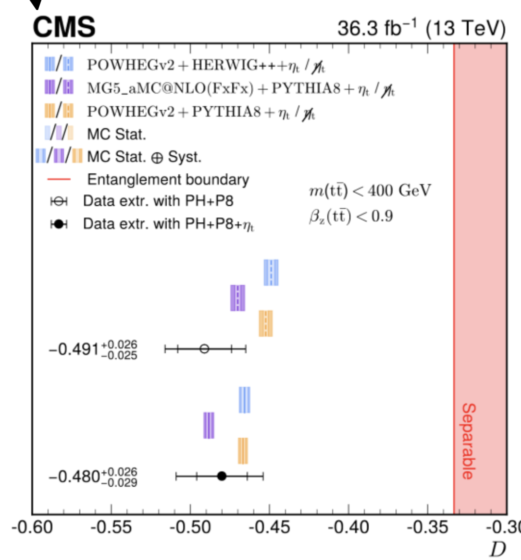
ATLAS & CMS results

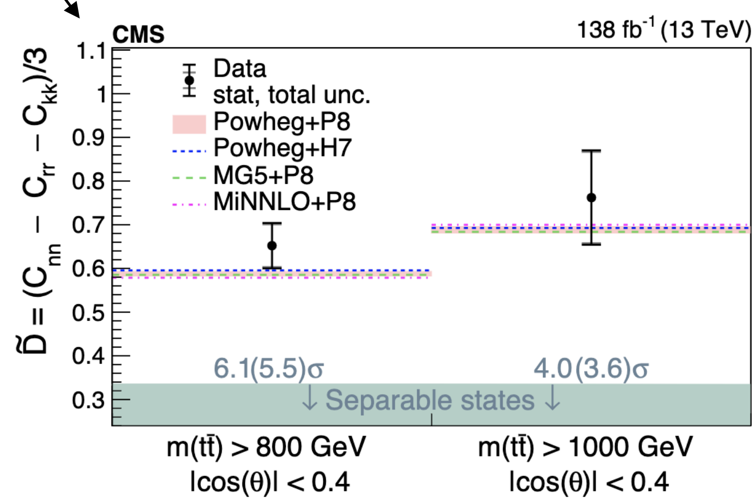
[1] Nature 633 (2024) 542
[2] arXiv:2406.03976
[3] arXiv:2409.11067

Channel	Threshold regime	Boosted regime
Dilepton	ATLAS (140/fb) >5σ [1] m_{tt}<380 GeV Particle-level **CMS (36/fb) >5σ [2]** **m_{tt}<400 GeV & β_z<0.9** **Parton-level**	
Lepton+jets	CMS (140/fb) 2.2σ [3] m_{tt}<400 GeV Parton-level	**CMS (140/fb) >5σ [3]** **m_{tt}>800 GeV & |cos(θ)|<0.4** **Parton-level**

CMS l+jets paper includes the full matrix measurements in various regions of the phase-space.

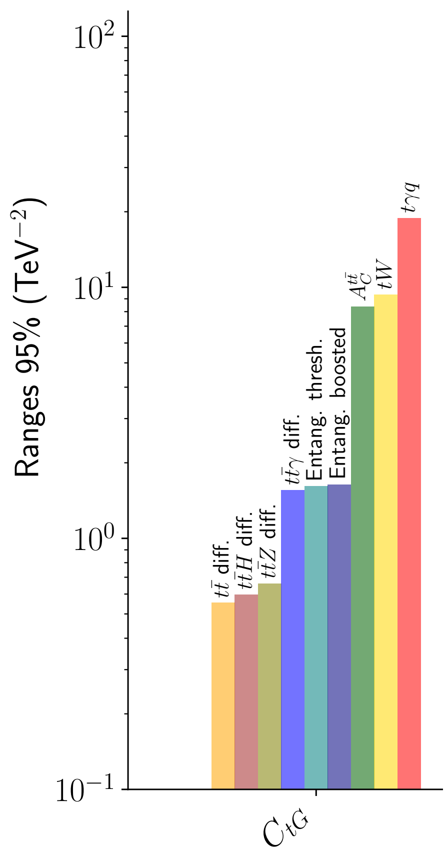
Here we have just explored the threshold and boosted regimes. More to explore in terms of EFT…



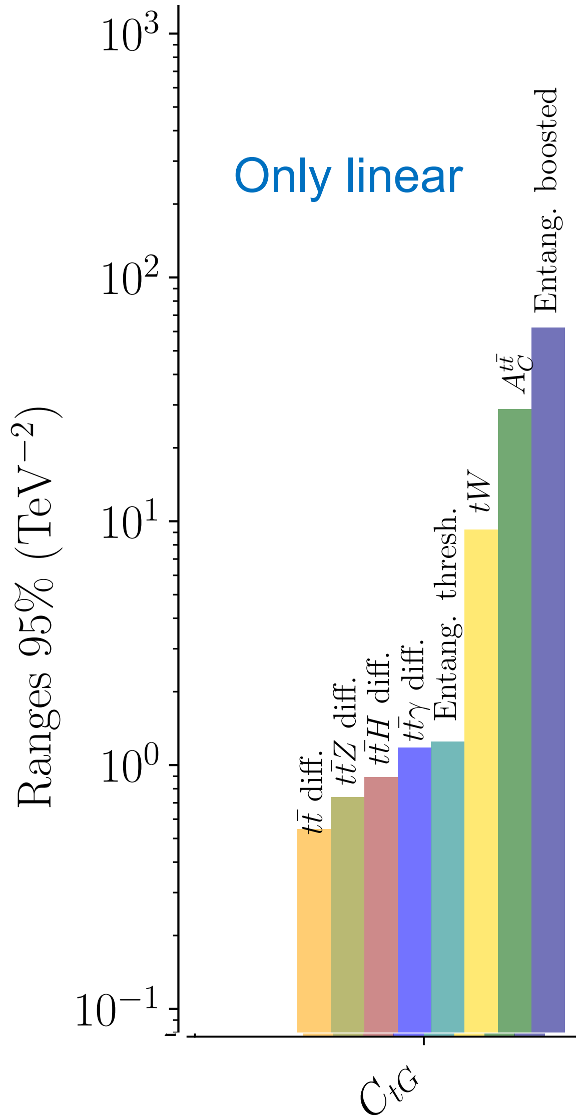


Individual limits

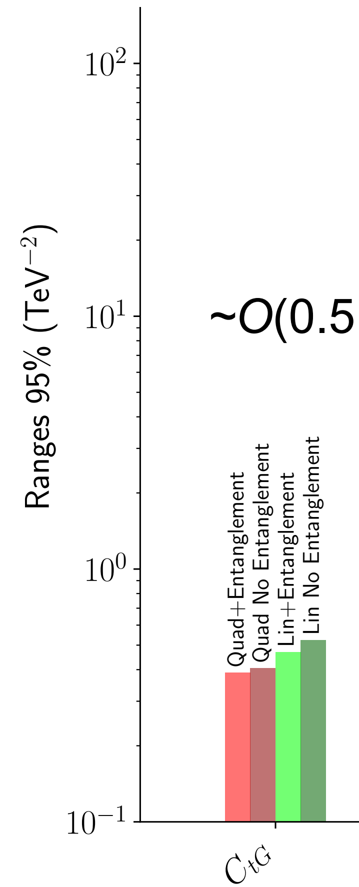
Linear+Quad.



Only linear



Global limits



~O(0.5 TeV^{-2})

MSc thesis of Belén Durán

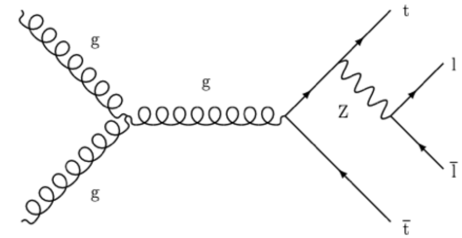
- Sensitivity from D @ threshold and D_n @ boosted compared to that from other observables: differential cross-sections in tt, diff. tt charge-asymmetry, diff. ttZ σ, diff. ttγ σ, ttH σ
- New entanglement observables may help to resolve blind directions
- When including only linear terms, bounds from D_n are degraded significantly

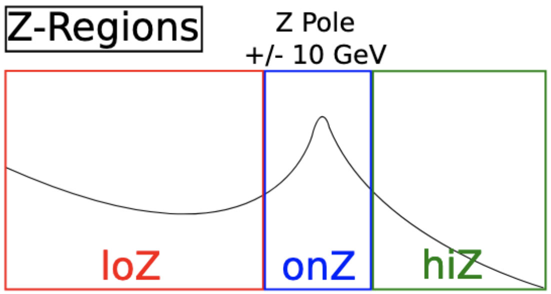
ttll process ($m_{ll} > m_Z$) to constrain QQll operators at LHC

Define high-m_{ll} region ($m_{ll}>m_Z$: $m_{ll}>100$ GeV) with 4 bins:
[100-120], [120-140], [140-180], >180 GeV

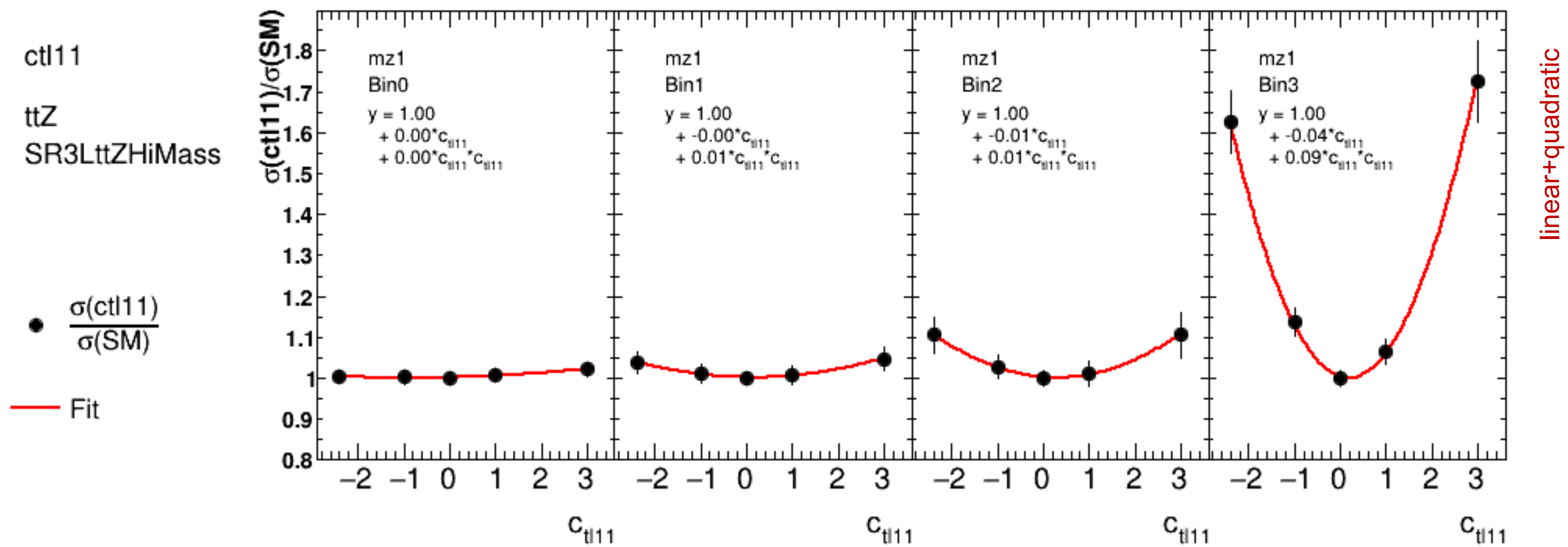
Expected cross-section: 2.7 fb

From ATLAS ttZ/W 36 fb^{-1} paper [Phys. Rev. D 99 (2019) 072009,
expect ~70 ttee+tt$\mu\mu$ events in that region for 140 fb^{-1} in 3l ch.





m_{ll}>100 GeV



MSc thesis of Abel Gutiérrez

Expected yields and uncertainty on σ (LHC Run-2)

Expected signal yields:

MSc thesis of
Abel Gutiérrez

Process	Inclusive	Bin 1	Bin 2	Bin3	Bin 4
Parton $pp \to t\bar{t}l\bar{l}$	400	210	70	50	60
Reco $pp \to t\bar{t}l\bar{l}$	70	32	15	11	12
Parton $pp \to t\bar{t}e\bar{e}$	130	70	24	15	18
Reco $pp \to t\bar{t}e\bar{e}$	32	14	7	5	6
Parton $pp \to t\bar{t}\mu\bar{\mu}$	130	70	24	15	18
Reco $pp \to t\bar{t}\mu\bar{\mu}$	38	18	8	6	6

pp → ttll at parton-level includes τ leptons, whereas reco-level does not.

Estimated relative uncertainties on the cross section:

Channel	1-POI-1-Bin	4-POIs-4-Bins				1-POI-4-Bins
	Inclusive	Bin 1	Bin 2	Bin 3	Bin 4	Bins 1-4
$pp \to t\bar{t}l\bar{l}$	±50 % (±26 %)	±49 % (±36 %)	±69 % (±56 %)	±88 % (±70 %)	±99 % (±74 %)	±46 % (±26 %)
$pp \to t\bar{t}e\bar{e}$	±62 % (±40 %)	±69 % (±57 %)	±94 % (±82 %)	±116 % (±103 %)	±125 % (±106 %)	±60 % (±40 %)
$pp \to t\bar{t}\mu\bar{\mu}$	±53 % (±35 %)	±54 % (±46 %)	±84 % (±76 %)	±109 % (±96 %)	±123 % (±103 %)	±49 % (±34 %)

In parenthesis: stat-only unc.

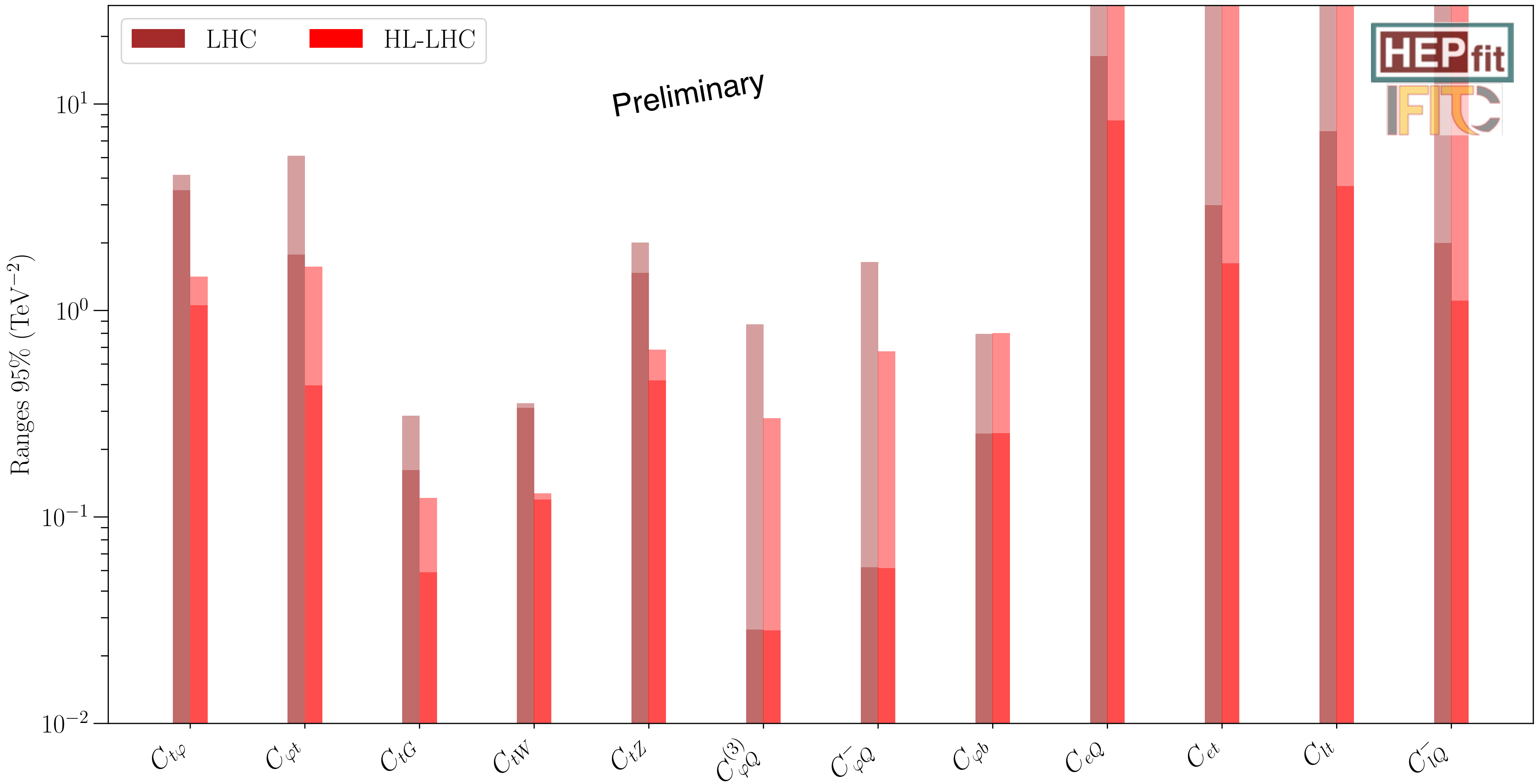
Cross-section could be estimated at HL-LHC with an unc. of ~20% (6% stat only)

Bounds from LHC results and prospects for HL-LHC

Solid bars: individual fit
Shadowed bars: global fit

Linear fit

2F & 4F-QQll



By the end of the HL-LHC:

2F global bounds expected to range from 0.1 (CtG & CtW) to 1 TeV^{-2} (Ctphi & Cphit)

4F-QQll global bounds are still poor *O*(100 TeV^{-2}) - individual limits could reach *O*(1 TeV^{-2})

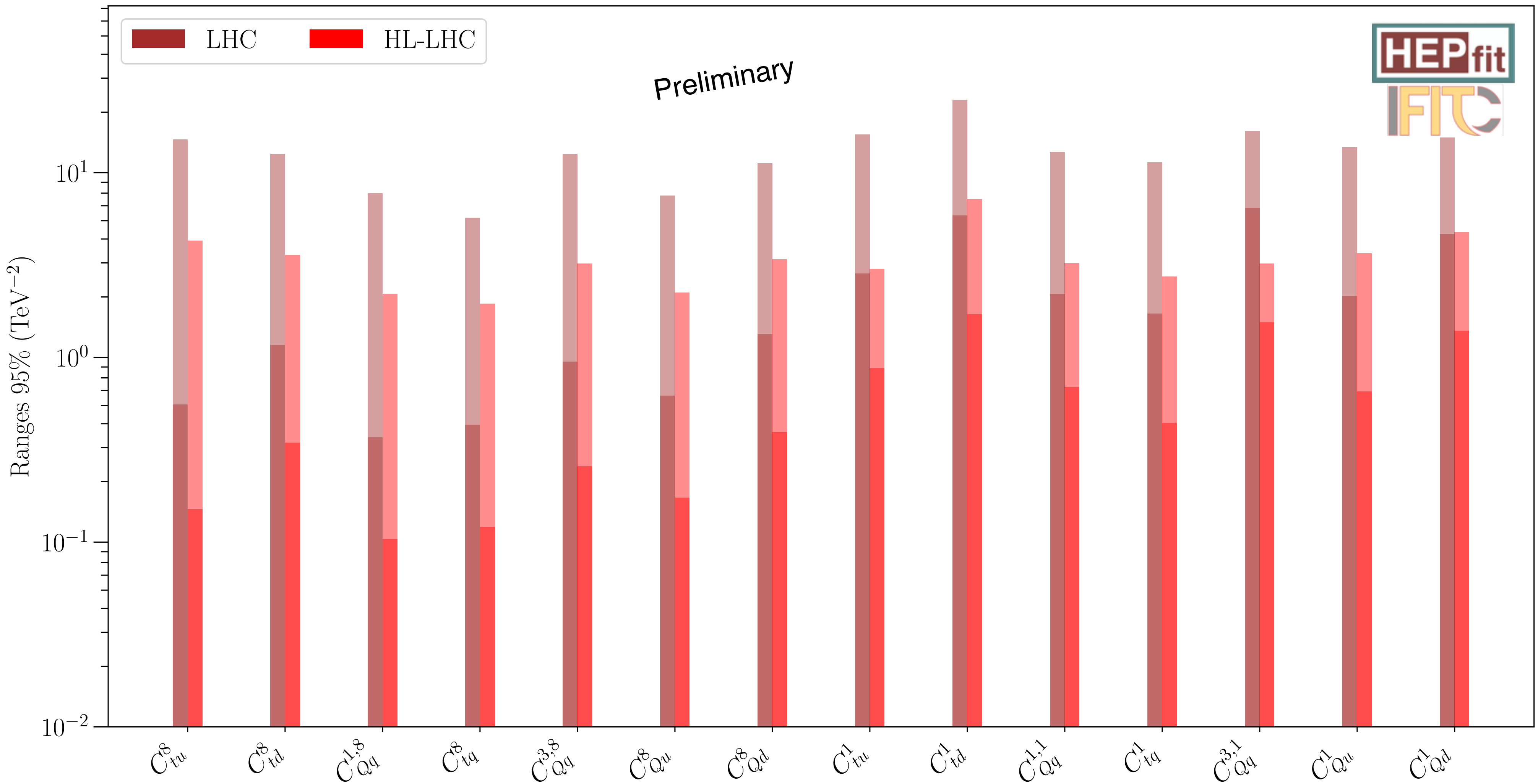
Including quadratic terms: 4F-QQll global bounds *O*(1 TeV^{-2})

Bounds from LHC results and prospects for HL-LHC

Solid bars: individual fit
Shadowed bars: global fit

Linear fit

4F-QQtt

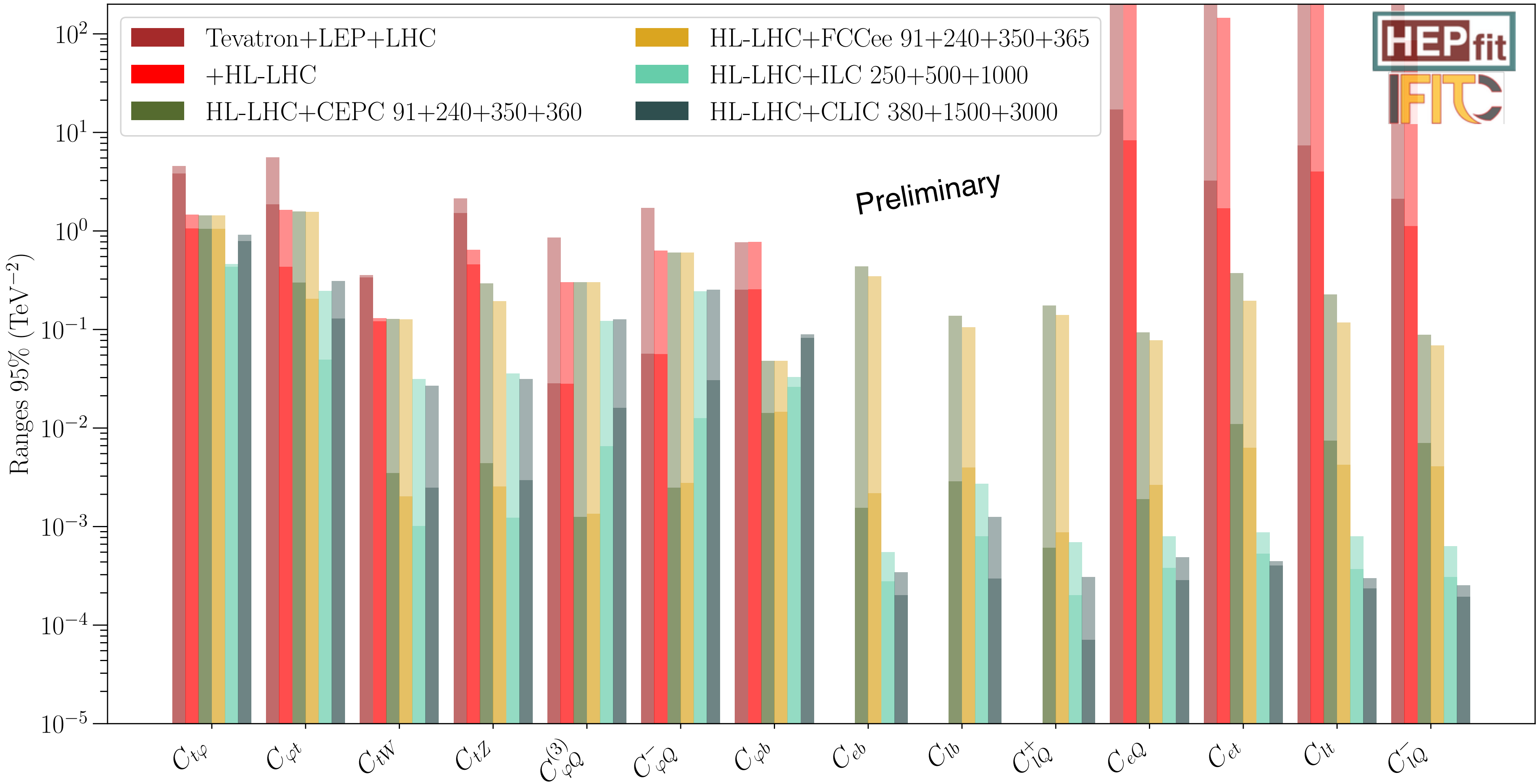


By the end of the HL-LHC: global bounds on 4F-QQtt operators from *tt* production could reach O(5 TeV^{-2})

Prospects for HL-LHC and future e⁺e⁻ colliders

Solid bars: individual fit
Shadowed bars: global fit

Linear fit



At future linear lepton colliders (running at various energies), QQll bounds improved various orders of magnitude. Limits are significantly better at linear e⁺e⁻ than circular e⁺e⁻ not only because of higher collision energies but also polarized beams which help lift degeneracies.

Global SMEFT analyses are expanding and new available experimental results allow to **constrain** a set of the **SMEFT operators**.

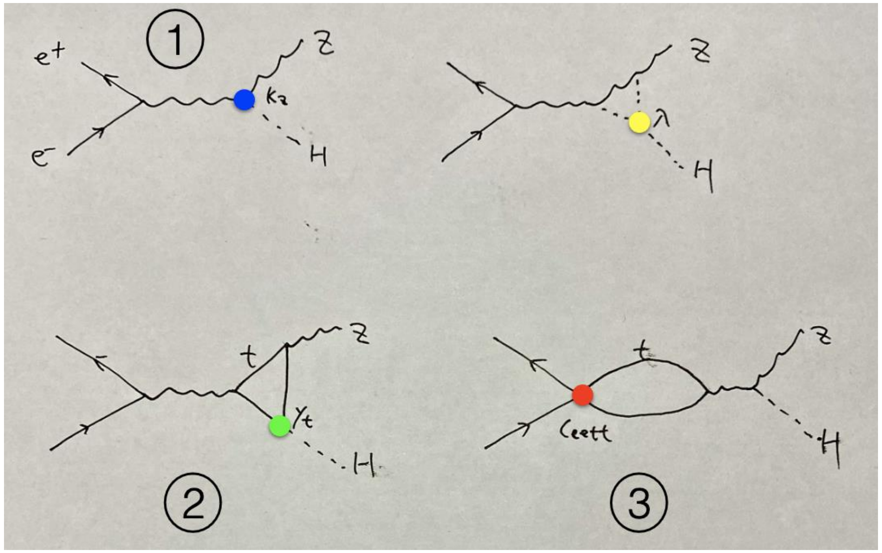
Here, we have presented some recent fits including legacy measurements from LEP and SLC, the current LHC and expected results for future colliders to probe the top quark couplings.

New publication in preparation, along with a contribution for ECFA report.

NLO SMEFT global fit $e^+e^- \rightarrow ZH$

Constraining QQee op. is important for Higgs self-coupling (using ZH process)

Corrections from QQee to ZH production at one loop



Acknowledgments

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◦ Grant RYC2019-028510-I funded by MCIN/AEI
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THANKS FOR YOUR ATTENTION

BACK-UP

EFT operators involving the top quark

QQqq

$q_i = (u_L^i, d_L^i)$	$u_i = u_R^i,\ d_i = d_R^i$	$i = 1, 2$
$Q = (t_L, b_L)$	$t = t_R,\ b = b_R$	

- 8 four-quark operators with LL and RR chiral structure

$$
\begin{aligned}
O_{Qq}^{1,8} &= (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) & O_{Qq}^{1,1} &= (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i) \\
O_{Qq}^{3,8} &= (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i\gamma^\mu T^A \tau^I q_i) & O_{Qq}^{3,1} &= (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i) \\
O_{tu}^{8} &= (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) & O_{tu}^{1} &= (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i) \\
O_{td}^{8} &= (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) & O_{td}^{1} &= (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;
\end{aligned}
$$

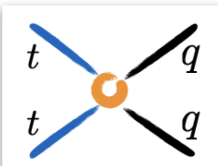
- 6 four-quark operators with LR and RL chiral structure

$$
\begin{aligned}
O_{Qu}^{8} &= (\bar{Q}\gamma^\mu T^A Q)(\bar{u}_i\gamma_\mu T^A u_i) & O_{Qu}^{1} &= (\bar{Q}\gamma^\mu Q)(\bar{u}_i\gamma_\mu u_i) \\
O_{Qd}^{8} &= (\bar{Q}\gamma^\mu T^A Q)(\bar{d}_i\gamma_\mu T^A d_i) & O_{Qd}^{1} &= (\bar{Q}\gamma^\mu Q)(\bar{d}_i\gamma_\mu d_i) \\
O_{tq}^{8} &= (\bar{q}_i\gamma^\mu T^A q_i)(\bar{t}\gamma_\mu T^A t) & O_{tq}^{1} &= (\bar{q}_i\gamma^\mu q_i)(\bar{t}\gamma_\mu t)\ ;
\end{aligned}
$$

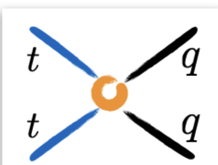
QQll

	Operator	Definition	Comment
top-lepton	O_{et}	$(\bar{e}_p\gamma_\mu e_r)(\bar{t}\gamma^\mu t)$	right-handed leptons and right-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex
	O_{Qe}	$(\bar{Q}\gamma_\mu Q)(\bar{e}_p\gamma^\mu e_r)$	right-handed leptons and left-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell\bar{\ell}$ vertices
	O_{lt}	$(\bar{l}_p\gamma_\mu l_r)(\bar{t}\gamma^\mu t)$	left-handed leptons and right-handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex
	$O_{lQ}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{Q}\gamma^\mu Q)$	left-handed leptons and left-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell\bar{\ell}$ vertices, weak-singlet
	$O_{lQ}^{(3)}$	$(\bar{l}_p\sigma^i\gamma_\mu l_r)(\bar{Q}\sigma^i\gamma^\mu Q)$	left-handed leptons and left-handed quarks in the $t\bar{t}\ell^+\ell^-$ and $b\bar{b}\ell\bar{\ell}$ vertices, weak-triplet
	O_{leQt}^{1}	$(\bar{l}_i e_j)\epsilon(\bar{Q}_k t_\ell)$	right and left handed leptons and right and left handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex, weak singlet
	O_{leQt}^{3}	$(\bar{l}_i\sigma^{\mu\nu} e_j)\epsilon(\bar{Q}_k\sigma_{\mu\nu} t_\ell)$	right and left handed leptons and right and left handed quarks in the $t\bar{t}\ell^+\ell^-$ vertex, weak triplet

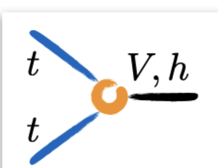
EFT operators involving the top quark



LL, RR



LR, RL



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}

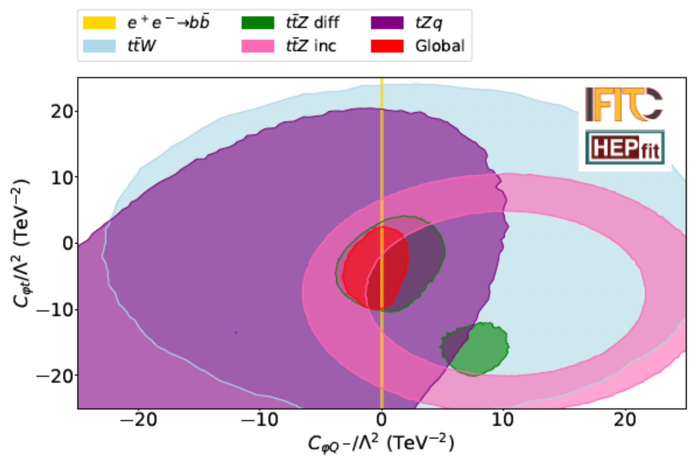
Hartland et al. 1901.05965; Brivio, SW et al. 1910.03606

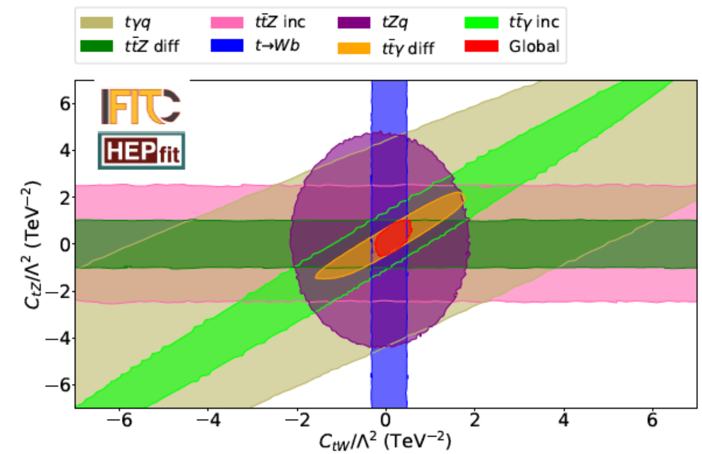
Complementarity between observables

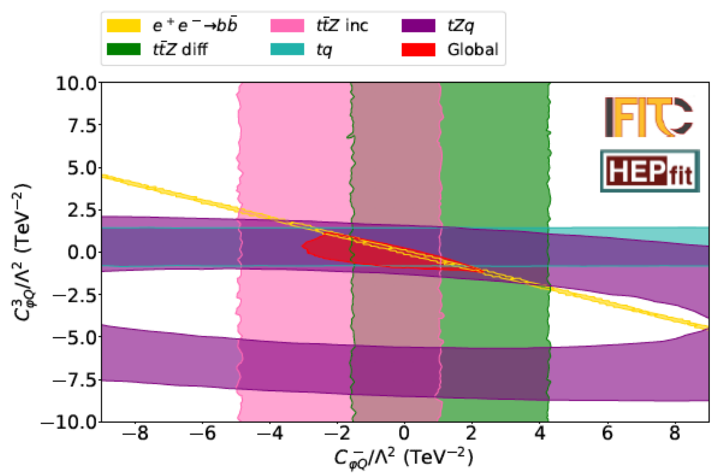
* Left/Right-handed couplings of top/bottom to Z: $O_{\varphi t}, O^{-}_{\varphi Q}, O^{(3)}_{\varphi Q}$
* EW dipole operators: O_{tZ}, O_{tW}, O_{bW}
* Top Yukawa: $O_{t\varphi}$
* Charged current interaction: $O_{\varphi tb}$

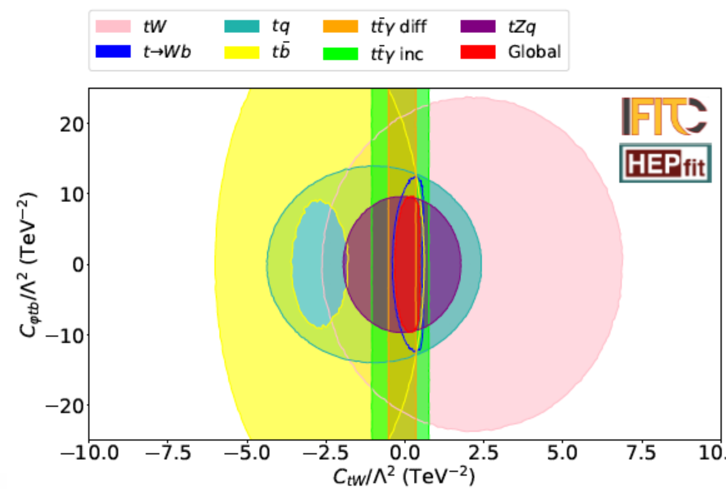
2D 95% prob. contours showing complementarity btw. measurements
Watch out for:

LEP in $C^{-}_{\varphi Q}, C^{(3)}_{\varphi Q}$; $t\bar{t}Z$ in C_{tZ}, $C_{\varphi t}$; $t\bar{t}\gamma$ and W hel. in C_{tW}; tZq in $C_{\varphi tb}$

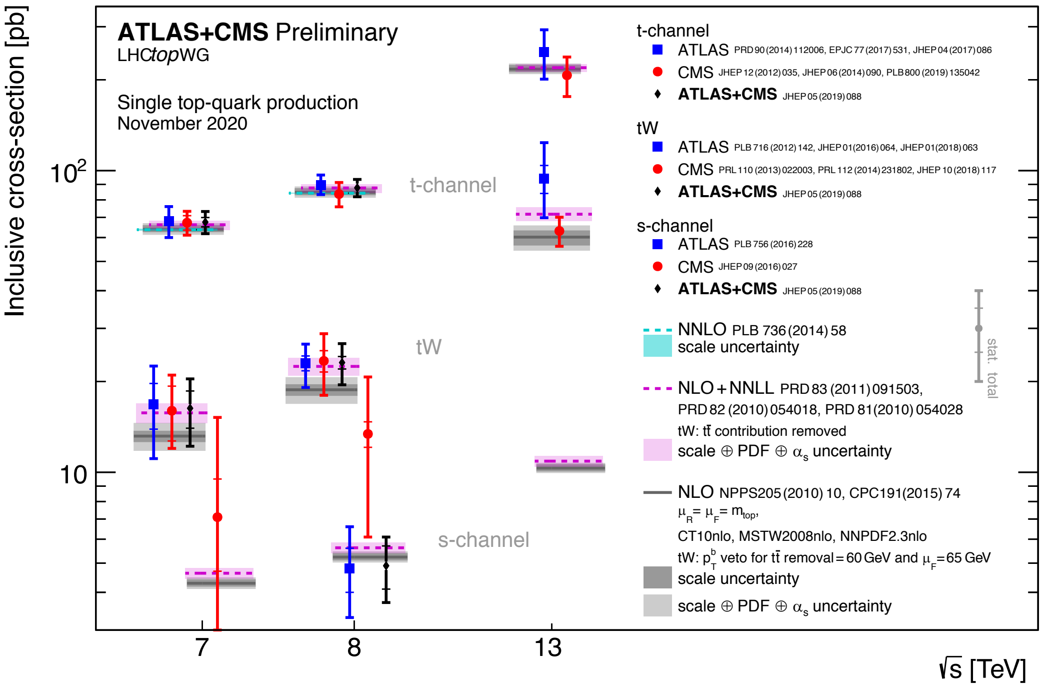


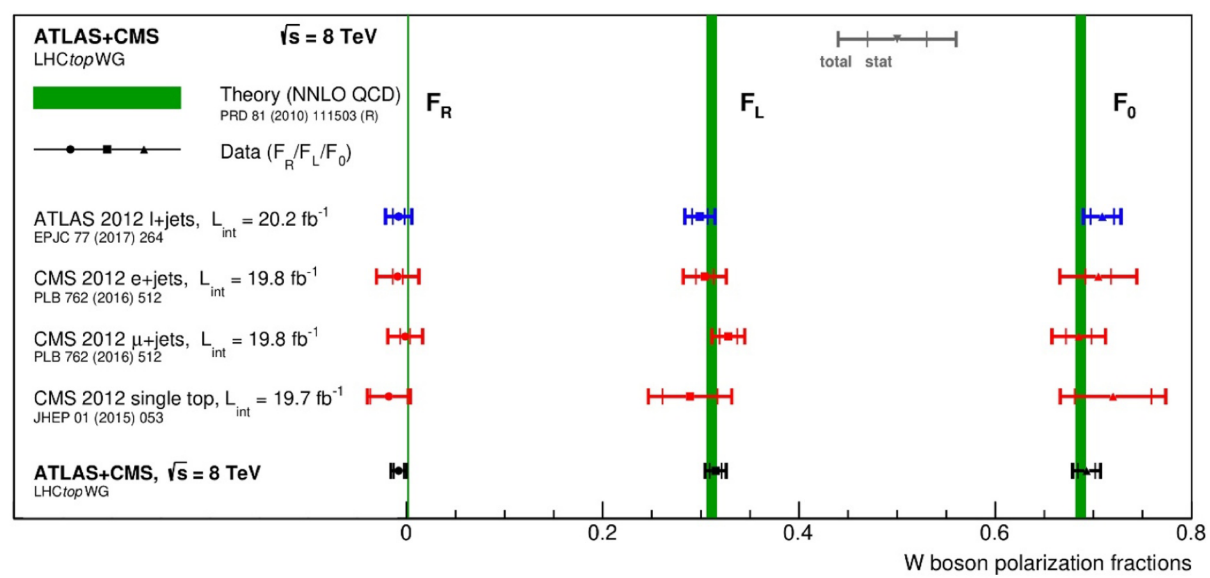






Other input measurements: single top XS and W helicity





Advantage of diff. CM energies and beam polarisations

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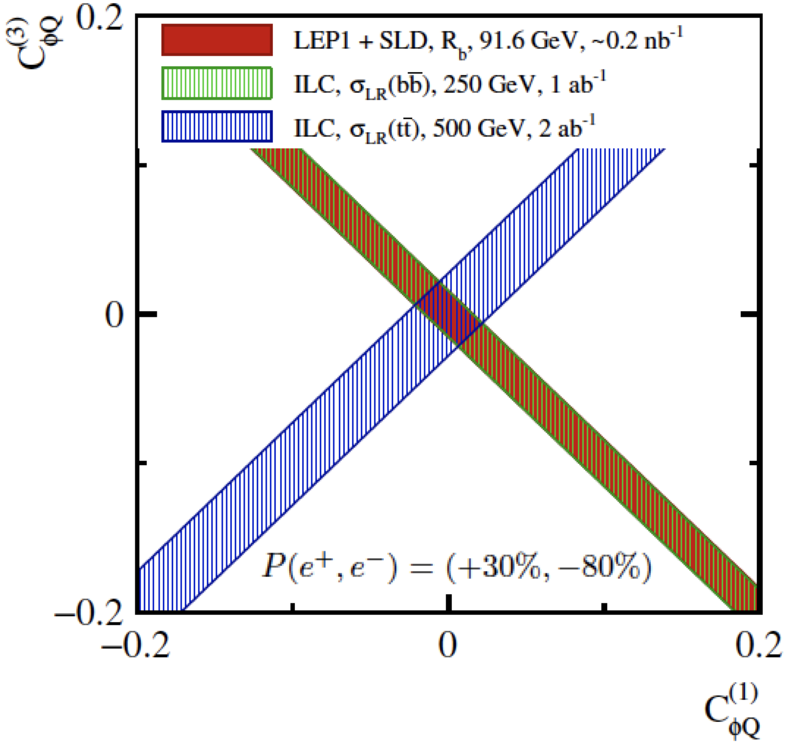
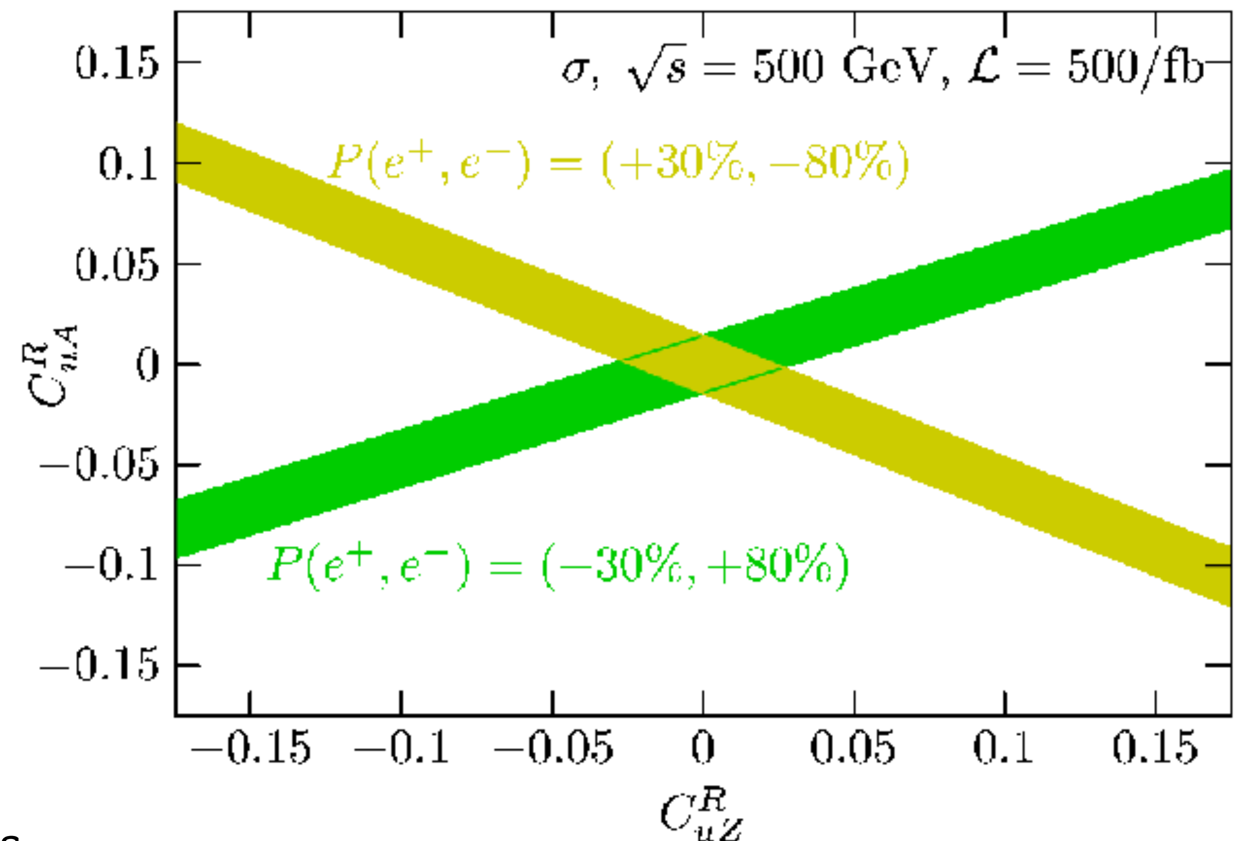
Full advantage of flexible running at ILC:
two CM energies, two beam polarisations





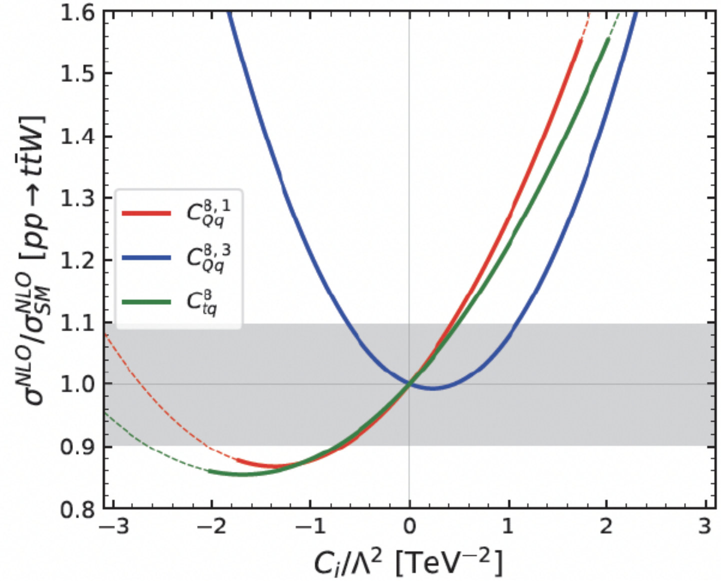
Good complementarity between
bb (LEP) and **tt** (future **e+e-** collider) data

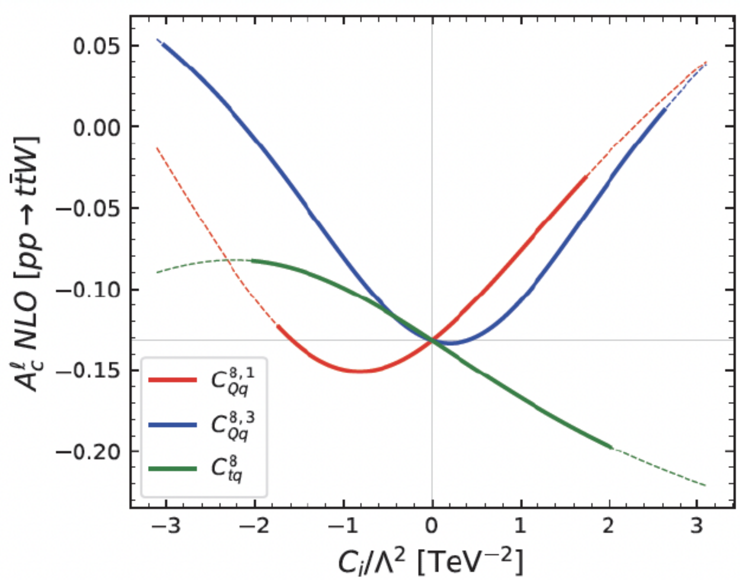
Sensitivity to 2-fermion op.: flat with CM energy

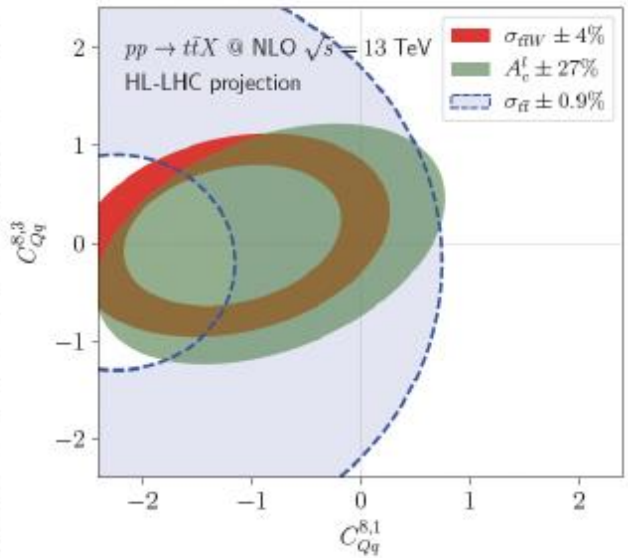
Note: transformations applied

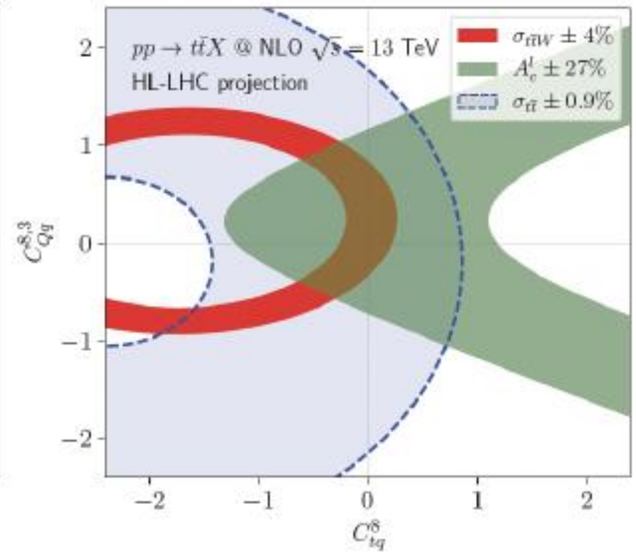
$$C_{uA}^{R,I} = \text{Re}, \text{Im}\{C_{uA}\} = \text{Re}, \text{Im}\{C_{uW} + C_{uB}\},$$
$$C_{uZ}^{R,I} = \text{Re}, \text{Im}\{C_{uZ}\} = \text{Re}, \text{Im}\{c_W^2 C_{uW} - s_W^2 C_{uB}\}/s_W c_W.$$

ttW XS and CA: potential constraints on 4F operators

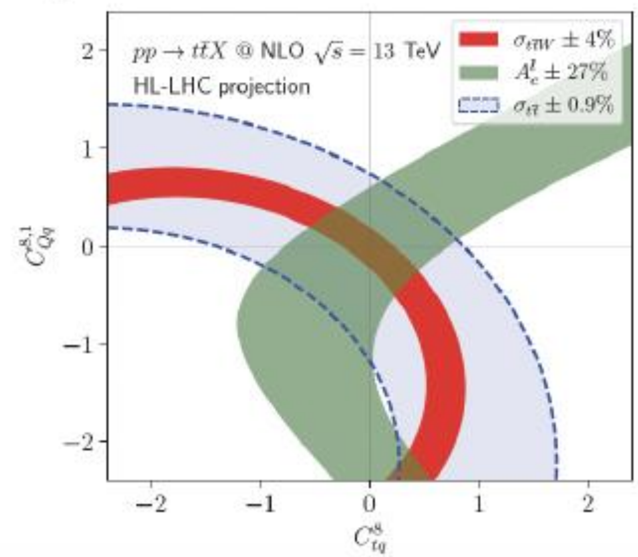








HL-LHC projection



EFT operators involving the top quark

Operator	Definition	Description
O_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\,\tau^I\tilde{\varphi}W^i_{\mu\nu}$	Modifies the tWb, $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices
O_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\,\tilde{\varphi}B_{\mu\nu}$	Modifies the tWb, $t\bar{t}\gamma$ and $t\bar{t}Z$ vertices
O_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^a t)\,\tilde{\varphi}G^a_{\mu\nu}$	Modifies the $t\bar{t}g$ vertex
$O^{(1)}_{\varphi Q}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(\bar{Q}\gamma^\mu Q)$	Modifies the $b\bar{b}Z$ and $t\bar{t}Z$ vertices
$O^{(3)}_{\varphi Q}$	$\left(\varphi^\dagger i\overleftrightarrow{D}^i_\mu\varphi\right)(\bar{Q}\tau^I\gamma^\mu Q)$	Modifies the tWb, $b\bar{b}Z$ and $t\bar{t}Z$ vertices
$O_{\varphi t}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(\bar{t}\gamma^\mu t)$	Modifies the $t\bar{t}Z$ vertex
$O_{t\varphi}$	$(\bar{Q}t)\,(\epsilon\varphi^*\varphi^\dagger\varphi)$	Modifies Yukawa coupling of the top quarks
$O_{\varphi b}$	$\left(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi\right)(\bar{b}\gamma^\mu b)$	Modifies the $b\bar{b}Z$ vertex
$\left(O^{(1)}_{qq}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu q_j)\,(\bar{q}_k\gamma_\mu q_l)$	Four left-handed quarks vertex, colour singlet, weak singlet
$\left(O^{(3)}_{qq}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu\tau^I q_j)\,(\bar{q}_k\gamma_\mu\tau^I q_l)$	Four left-handed quarks vertex, colour singlet, weak doublet
$\left(O^{(1)}_{qu}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu q_j)\,(\bar{u}_k\gamma_\mu u_l)$	Two left-handed and two up-right-handed quarks vertex, colour singlet
$\left(O^{(8)}_{qu}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu T^A q_j)\,(\bar{u}_k\gamma_\mu T^A u_l)$	Two left-handed and two up-right-handed quarks vertex, colour octet
$\left(O^{(1)}_{qd}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu q_j)\,(\bar{d}_k\gamma_\mu d_l)$	Two left-handed and two down-right-handed quarks vertex, colour singlet
$\left(O^{(8)}_{qd}\right)_{ijkl}$	$(\bar{q}_i\gamma^\mu T^A q_j)\,(\bar{d}_k\gamma_\mu T^A d_l)$	Two left-handed and two down-right-handed quarks vertex, colour octet
$(O_{uu})_{ijkl}$	$(\bar{u}_i\gamma^\mu u_j)\,(\bar{u}_k\gamma_\mu u_l)$	Four up-right-handed quarks vertex, linear combination of colour singlet and octet
$\left(O^{(1)}_{ud}\right)_{ijkl}$	$(\bar{u}_i\gamma^\mu u_j)\,(\bar{d}_k\gamma_\mu d_l)$	Two up-right-handed and two down-right-handed quarks vertex, colour singlet
$\left(O^{(8)}_{ud}\right)_{ijkl}$	$(\bar{u}_i\gamma^\mu T^A u_j)\,(\bar{d}_k\gamma_\mu T^A d_l)$	Two up-right-handed and two down-right-handed quarks vertex, colour octet
$\left(O^{(1)}_{lQ}\right)_{pp}$	$(\bar{l}_p\gamma_\mu l_p)\,(\bar{Q}\gamma^\mu Q)$	Left-handed leptons and left-handed quarks in the $QQll$ vertex, weak-singlet
$\left(O^{(3)}_{lQ}\right)_{pp}$	$(\bar{l}_p\gamma_\mu\tau^I l_p)\,(\bar{Q}\gamma^\mu\tau^I Q)$	Left-handed leptons and left-handed quarks in the $QQll$ vertex, weak-doublet
$(O_{et})_{pp}$	$(\bar{e}_p\gamma_\mu e_p)\,(\bar{t}\gamma^\mu t)$	Right-handed leptons and right-handed quarks in the $ttll$ vertex
$(O_{lt})_{pp}$	$(\bar{l}_p\gamma_\mu l_p)\,(\bar{t}\gamma^\mu t)$	Left-handed leptons and right-handed quarks in the $ttll$ vertex
$(O_{Qe})_{pp}$	$(\bar{Q}\gamma_\mu Q)\,(\bar{e}_p\gamma^\mu e_p)$	Right-handed leptons and left-handed quarks in the $QQll$ vertex

2-quark

4-quark

2-quark-2-lepton

Lagrangian (+ h.c.)	NP couplings	
$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu (V_L P_L + V_R P_R)\, tW_{\mu^-}$ $- \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(g_L P_L + g_R P_R)\, tW_{\mu^-}$	$\delta V_L = \frac{v^2}{\Lambda^2}C^3_{\varphi Q}$	$\delta V_R = \frac{v^2}{\Lambda^2}C_{\varphi tb}$
	$\delta g_L = \frac{\sqrt{2}v^2}{\Lambda^2}C_{bW}$	$\delta g_R = \frac{\sqrt{2}v^2}{\Lambda^2}C_{tW}$
$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\gamma^\mu \left(X^L_{tt}P_L + X^R_{tt}P_R - 2s^2_W Q_t\right) tZ_\mu$ $- \frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{M_Z}\left(d^Z_V + i d^Z_A \gamma_5\right) tZ_\mu$	$\delta X^L_{tt} = -\frac{v^2}{\Lambda^2}C^-_{\varphi Q}$	$\delta X^R_{tt} = -\frac{v^2}{\Lambda^2}C_{\varphi t}$
	$\delta d^Z_V = \frac{\sqrt{2}v^2}{\Lambda^2}\mathrm{Re}\left(C_{tZ}\right)$	$\delta d^Z_A = \frac{\sqrt{2}v^2}{\Lambda^2}\mathrm{Im}\left(C_{tZ}\right)$
$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\gamma^\mu tA_\mu - e\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}\left(d^\gamma_V + i d^\gamma_A \gamma_5\right) tA_\mu$	$\delta d^\gamma_V = \frac{\sqrt{2}vm_t}{e\Lambda^2}\mathrm{Re}\left(2c_W C_{tW} - C_{tZ}\right)$	$\delta d^\gamma_A = \frac{\sqrt{2}vm_t}{e\Lambda^2}\mathrm{Im}\left(2c_W C_{tW} - C_{tZ}\right)$
$\mathcal{L}_{Htt} = -\frac{1}{\sqrt{2}}\bar{t}\left(Y^V_t + iY^A_t\gamma_5\right) tH$	$\delta Y^V_t = -\frac{3v^2}{2\Lambda^2}\mathrm{Re}\left(C_{t\varphi}\right)$	$\delta Y^A_t = -\frac{3}{2}\mathrm{Im}C_{t\varphi}\frac{v^2}{\Lambda^2}$

Vertex corrections from dim 6 operators:
- Gauge interactions: only γ^μ (vector) and $\sigma^{\mu\nu}q_\nu$ (tensor) terms
- Higgs: only scalar and pseudo-scalar terms