Top quark EW couplings and EFT fits

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Introduction

- Being the heaviest particle of the SM the top-quark is a good candidate for searching for new physics
- Its EW couplings are specially relevant in many extensions of the SM
- 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 top-quark EW couplings
- We used the most recent available data from the LHC (ATLAS and CMS), and also from LEP and Tevatron
- We include the QCD corrections at NLO on most of the observables used
- The fits have been performed using `HEPfit` [1910.14012]

Theoretical Framework

- We adopt an EFT description to parametrize the deviations from the SM.

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathscr{O}\left(\Lambda^{-4}\right).$$

- The Wilson coefficients can be later interpreted in terms of NP mediators.
- We include Λ^{-2} terms from the interference between the SM and D6 operators.
- We also include Λ^{-4} operators arising from two insertions of D6 operators.
- The effects of D8 operators, contributing to the same Λ^{-4} order, are omitted.

$$\sigma = \sigma_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}\sum C_i O_i}_{\text{SM }\times\text{D6}} + \underbrace{\left(\frac{1}{\Lambda^2}\sum C_i O_i\right)\left(\frac{1}{\Lambda^2}\sum C_i O_i\right)}_{\text{D6}\times\text{D6}} + \underbrace{O(1/\Lambda^4)}_{\text{SM }\times\text{D8}}$$

- We only consider the EW two-fermion operators and ignore the imaginary parts.
- The four-fermion operators are ignored.

EW top-quark EFT Basis

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

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

EW dipole operators

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

Chromo magnetic dipole operators

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

Top/Bottom yukawa

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

Charged current interaction

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

- Rotation of Warsaw basis following [1802.07237] (LHC Top WG)

$$O^1_{\varphi Q} \to O^-_{\varphi Q} = O^1_{\varphi Q} - O^3_{\varphi Q}; \qquad O_{xB} \to O_{xZ} = -\sin\theta_W O_{xB} + \cos\theta_W O_{xW}$$

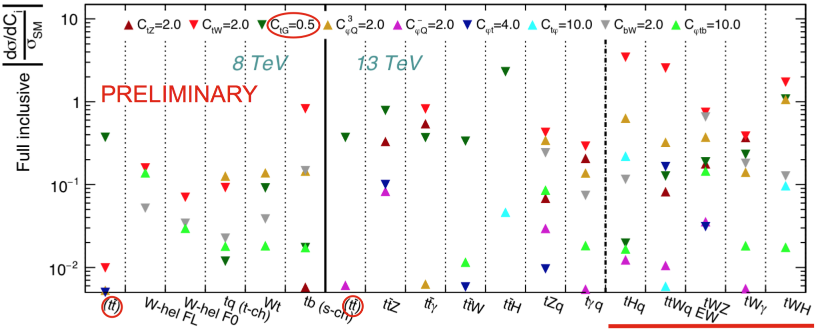
Methods & Data

- Dependence of the observables calculated at NLO in QCD with the Monte Carlo generator `MG5_aMC@NLO` [JHEP 07 (2014) 079]
- `SMEFT@NLO` [arXiv:2008.11743] UFO model was used except for C_{bW}, $C_{\varphi tb}$, C_{bZ} and $C_{\varphi b}$ where the `TEFT_EW` [JHEP 05 (2016) 052] UFO model was used
- The fit is performed as a Bayesian statistical analysis of the model using the open source `HEPfit` [1910.14012]

Process	Observable	$\sqrt{s}$	$\int \mathscr{L}$	Experiment
$pp \to t\bar{t}H$ NLO	cross section	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}W$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}Z$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$ NLO	(differential) x-sec.	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$ NLO	cross section	13 TeV	140 fb^{-1}	CMS
$pp \to t\gamma q$ NLO	cross section	13 TeV	36 fb^{-1}	CMS
$pp \to tb$ (s-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tW$ LO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$pp \to tq$ (t-ch) NLO	cross section	8 TeV	20 fb^{-1}	ATLAS+CMS
$t \to W^+ b$ LO	F_0, F_L	8 TeV	20 fb^{-1}	ATLAS+CMS
$p\bar{p} \to t\bar{b}$ (s-ch) LO	cross section	1.96 TeV	9.7 fb^{-1}	Tevatron
$e^- e^+ \to b\bar{b}$ LO	R_b , A^{bb}_{FBLR}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP

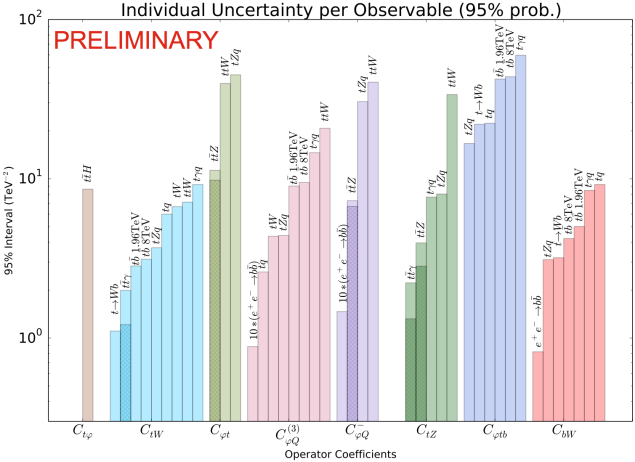
Sensitivity

- The observables and coefficients in red are not included
- The $pp \to t\bar{t}$ process is omitted in the fit in order to be consistent as it is used to reduce the dependence of $pp \to t\bar{t}X$ on Wilson coefficients that have not been included.



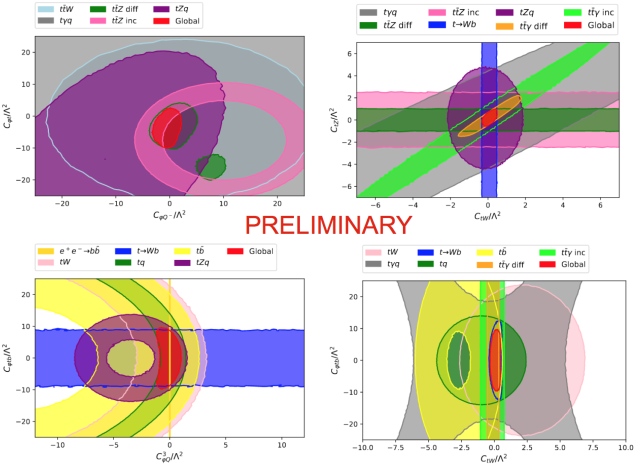
Results - Sensitivity Individual Constraints

- Good interplay between the parameters and chosen observables
- The differential cross sections (darker regions) provide the best constraints for some observables
- LEP still generates the best constraints in some cases



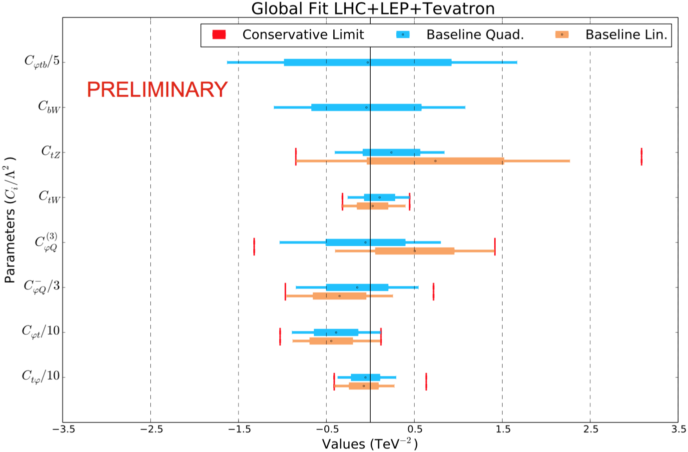
Results - Complementarity Between Observables

- Very good complementarity between the observables
- The global fit marginalised limit is quite close to the intersection of individual fits
  $\rightarrow$ The data set is diverse enough to avoid the existence of blind directions



Results - Global Fit

- We are able to find constraints even with the linear (only Λ^{-2} terms) global fit and they are similar to the ones from the quadratic ($\Lambda^{-2}+\Lambda^{-4}$ terms) global fit for most cases
- We have checked the impact of adding estimated correlations between the observables as well as the effect of extending our basis with three more operators, the four-fermion operators $C_x^+ = C_x^1 + C_x^2$ with $x = t, b$ using the notation of [1807.02121], and C_{tG}
- Conservative Limit: Envelope found from combining the results from all the global fits



Results - Conclusions

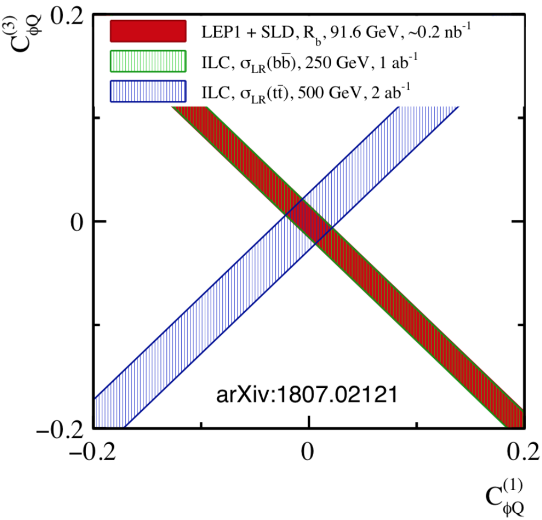
- All the results are compatible with the SM with a 95% probability
- We find a reduction of the uncertainty of all the parameters of around a factor two with respect to our previous work [JHEP12(2019)098]
- Adding important correlations between the observables or even some more operators does not dramatically change the results
- LEP measurements provide tight bounds on several operators as the left-handed coupling $C_{\varphi Q}^{-}$ and $C_{\varphi Q}^{(3)}$
- The limits are extremely robust even when we only consider linear terms, except for C_{bW}, $C_{\varphi tb}$ and C_{tZ}
- The addition of the differential cross sections of $pp \to t\bar{t}Z$ and $pp \to t\bar{t}\gamma$ have an important effect on C_{tZ} and $C_{\varphi t}$
- We find the most stringent bound on top EW couplings from an EFT including all relevant 2-fermions degrees of freedom (see [JHEP 04 (2019) 100], [JHEP 02 (2020) 131], [CMS-PAS-TOP-19-001])

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 $\sqrt{s} > 2m_t$

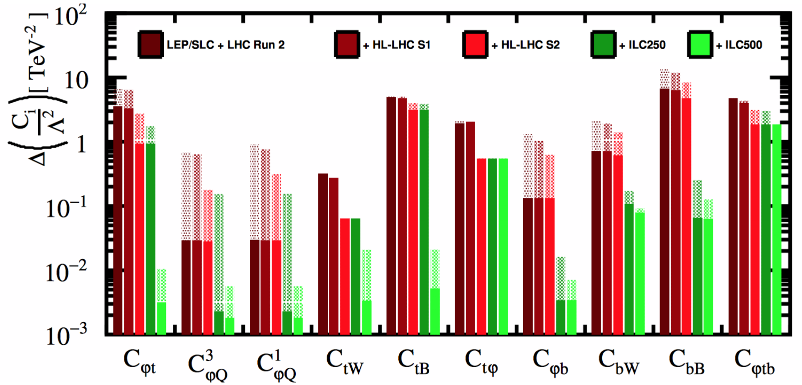
$$\delta g_L^t = -(C^1_{\varphi Q} - C^3_{\varphi Q}) m_t^2/\Lambda^2$$

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



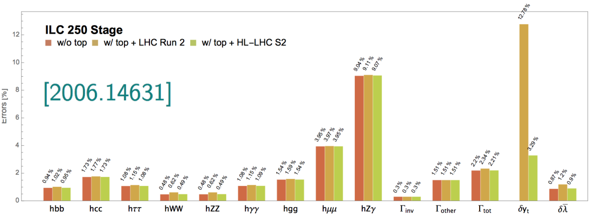
Future Colliders - Prospects for EW Top-Quark Couplings

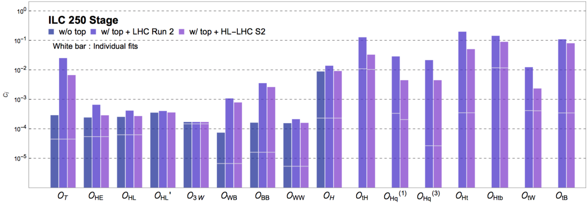
- Results from [JHEP12(2019)098] show the extraordinary impact of adding the data from a e^+e^- collider working at 500 GeV $\rightarrow$ It is crucial to go $\sqrt{s} > 2m_t$
- The LHC Run 2 data here refers to the data available in mid 2019, with the current data the errors are reduced around a factor two



For current limits on this sector look at [2012.02779] and [1910.03606]

- The determination of the Higgs boson couplings at ILC250 is degraded by the additional top-quark operators
- We can recover the original bounds by the inclusion of precise measurements of top-quark EW couplings at the LHC
- The physical Higgs couplings are relatively robust, as the top mass is larger than the energy scale of EW processes
- If the ILC reaches 500 GeV it will provide very precise constraints on the top operators





Summary

- With the current precision of the LHC we are able to constrain the top-quark EW sector even when we only consider the linear (Λ^{-2}) terms
- The quadratic terms (Λ^{-4}) are specially relevant for C_{bW} and $C_{\varphi tb}$ whose linear dependence with our observables is zero as we are in the limit $m_b \to 0$
- Although there is still no way for calculating the correlations between the observables it seems that they do not have a dramatic impact in the final result
- The addition of the dependence on more operators (like some four-fermion operators) does not appear to reduced the limits found significantly
- If we want to reduce the allowed ranges in some order of magnitudes it is crucial to build a e^+e^- collider working at $\sqrt{s} > 2m_t$
- For a precise fit on the combined sector of the top plus the Higgs it would be enough with the data of a e^+e^- collider working at $\sqrt{s} = 250$ GeV given the expected precision that the LHC could achieve for the top-quark EW couplings

Thank you!

PRELIMINARY Numerical values for the Wilson Coefficients

$C/\Lambda^2(\text{TeV}^{-2})$	Baseline Quad.	Baseline Lin.	Robust
$C_{t\varphi}$	[-3.7, 2.9]	[-4.1, 2.7]	[-4.1, 6.4]
$C^{-}_{\varphi Q}$	[-2.5, 1.6]	[-2.86, 0.76]	[-2.9, 2.2]
$C^{3}_{\varphi Q}$	[-1.0, 0.8]	[-0.40, 1.41]	[-1.3, 1.4]
$C_{\varphi t}$	[-8.9, 1.2]	[-8.8, 1.1]	[-10.3, 1.2]
C_{tW}	[-0.26, 0.45]	[-0.32, 0.40]	[-0.32, 0.45]
C_{tZ}	[-0.40, 0.84]	[-0.85, 2.27]	[-0.85, 3.08]
$C_{\varphi tb}$	[-8.1, 8.3]	–	–
C_{bW}	[-1.1, 1.1]	–	–