Top-quark EW coupling after LHC Run 2

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Introduction

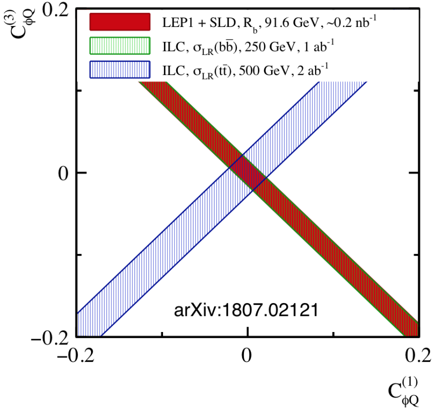
What do we want to do in this work?

- Present results of a global fit to top EW couplings
- Use current available data (ATLAS, CMS, LEP)
- Consider dimension-six operators
- Include QCD corrections at NLO
- Study the impact of differential $t\bar{t}Z$ and $t\bar{t}\gamma$ measurements

$\rightarrow$ fits performed with `HEPfit` [1910.14012]

Theoretical framework

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



Complementarity between $b\bar{b}$ (LEP) and $t\bar{t}$ (future e^+e^- collider)

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

Theoretical framework

Left and right couplings of the top/bottom to the Z

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

EW dipole operators

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

Top/Bottom yukawa

$$
\begin{aligned}
O_{u\varphi} &\equiv \left(\bar{q}u\right)\left(\epsilon\varphi^*\ \varphi^\dagger\varphi\right)\\
O_{d\varphi} &\equiv \left(\bar{q}d\right)\left(\varphi\ \varphi^\dagger\varphi\right)
\end{aligned}
$$

Charged current interaction

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

Theoretical framework

- Λ^{-4} from D6 $\times$ D6 included but D8 omitted (be carefull!)
- Imaginary parts omitted
- Four-fermions operators ignored
- Following LHC Working group [arXiv:1802.07237]:

Theoretical framework

- Λ^{-4} from D6 $\times$ D6 included but D8 omitted (be carefull!)

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

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

Theoretical framework

- Λ^{-4} from D6 $\times$ D6 included but D8 omitted (be carefull!)
- Imaginary parts omitted
- Four-fermions operators ignored
- Following LHC Working group [arXiv:1802.07237]:

$$O^{1}_{\varphi Q} \to O^{-}_{\varphi Q} = O^{1}_{\varphi Q} - O^{3}_{\varphi Q};$$
$$O_{xB} \to O_{xZ} = -\sin\theta_W O_{xB} + \cos\theta_W O_{xW}, \quad x = u, d$$

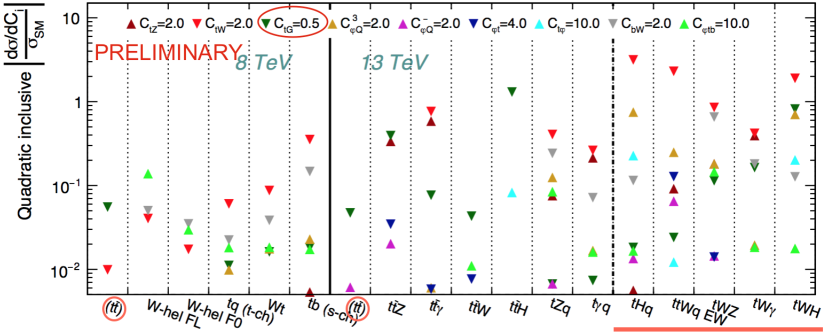
Observables of the fit

Process	Observable	$\sqrt{s}$	Experiment
$pp \to t\bar{t}H$ NLO	cross section	13 TeV	ATLAS
$pp \to t\bar{t}W$ NLO	cross section	13 TeV	CMS
$pp \to t\bar{t}Z$ NLO	(differential) x-sec.	13 TeV	ATLAS
$pp \to t\bar{t}\gamma$ NLO	(differential) x-sec.	13 TeV	ATLAS
$pp \to tZq$ NLO	cross section	13 TeV	CMS
$pp \to t\gamma q$ NLO	cross section	13 TeV	CMS
$pp \to tb$ (s-ch) NLO	cross section	8 TeV	ATLAS+CMS
$pp \to tW$ LO	cross section	8 TeV	ATLAS+CMS
$pp \to tq$ (t-ch) NLO	cross section	8 TeV	ATLAS+CMS
$t \to W^+ b$ LO	$F_0,\ F_L$	8 TeV	ATLAS+CMS
$e^- e^+ \to b\bar{b}$ LO	$R_b\ ,\ A_{FBLR}^{bb}$	$\sim$ 91 GeV	LEP

Observables of the fit

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

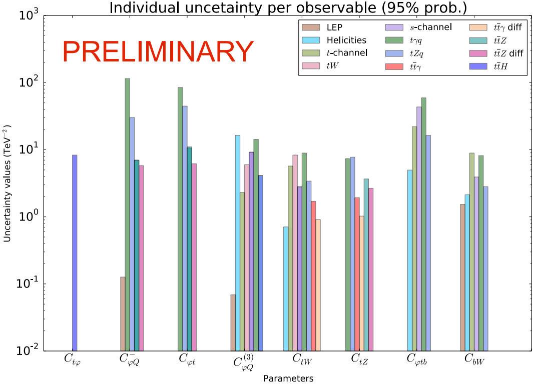
Observables of the fit - Sensitivity



not included in the fits

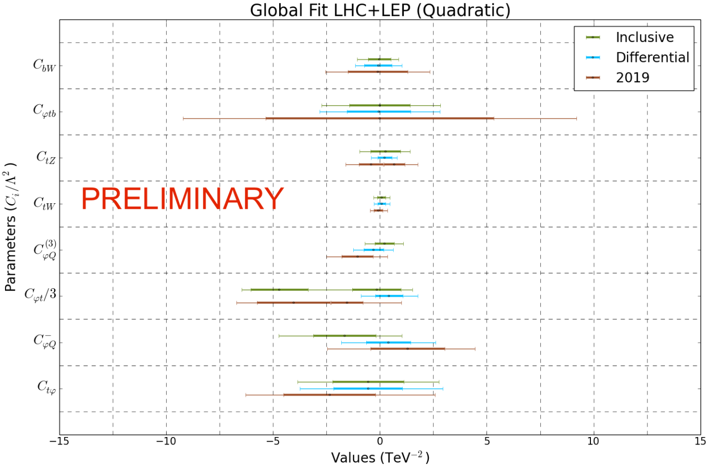
Results - LHC and LEP/SLC data

95% probability for each Wilson coefficient



- Good interplay between the parameters and chosen observables
- LHC: good observables for a LHC EW top fit

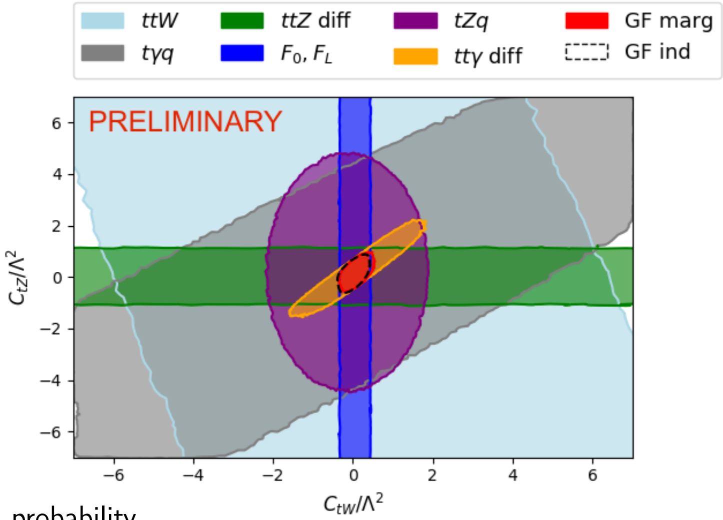
Results - LHC and LEP/SLC data



2019 fit: [JHEP12(2019)098] wide (narrow) bar: 68% (95%) probability

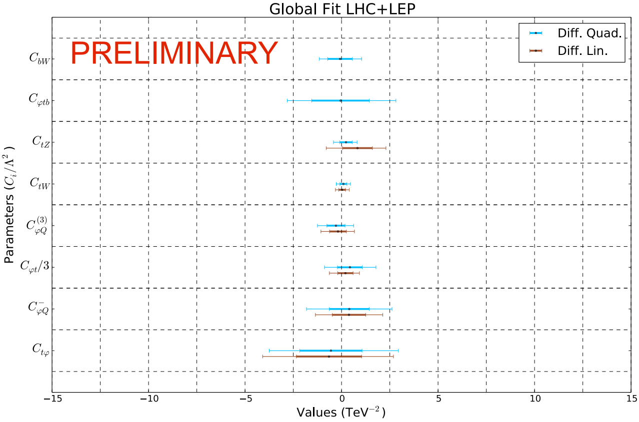
- Improvement of several Wilson coefficients (C_{bW}, C_{tZ}, $C_{\varphi t}$...)

Results - Complementarity between observables



95% probability

Results - Λ^{-4} impact [2020]



wide (narrow) bar: 68% (95%) probability

Conclusions

- All results compatible with $C_i = 0$ at 68% probability
- Important improvement for $C_{tZ}, C_{\varphi t}$ from $t\bar{t}Z$ and $t\bar{t}\gamma$ differential
- LEP measurements provide tight bounds on several operators $\rightarrow$ left-handed coupling $C^{-}_{\varphi Q}$ improved by a factor of two
- Most stringent bound on top EW couplings from an EFT including all relevant 2-fermions degrees of freedom JHEP 04 (2019) 100, JHEP 02 (2020) 131,CMS-PAS-TOP-19-001

Thank you!

Bayesain framework

Bayes theorem (model parameters $\boldsymbol{x}$, data D):

$$P(\boldsymbol{x}|D) = \frac{P(D|\boldsymbol{x})P_0(\boldsymbol{x})}{\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x}}$$

$P_0(\boldsymbol{x}) \rightarrow$ prior distribution of the parameters. Prior knowledge of the parameters (can come from experiments or theory)
$\int P(D|\boldsymbol{x})P_0(\boldsymbol{x})d\boldsymbol{x} \rightarrow$ normalization or evidence
$P(D|\boldsymbol{x}) \rightarrow$ likelihood
Marginalized distributions (1D)

$$P(x_i|D) = \int P(\boldsymbol{x}|D)\prod_{j\neq i} dx_j$$

Markov Chain Monte Carlo

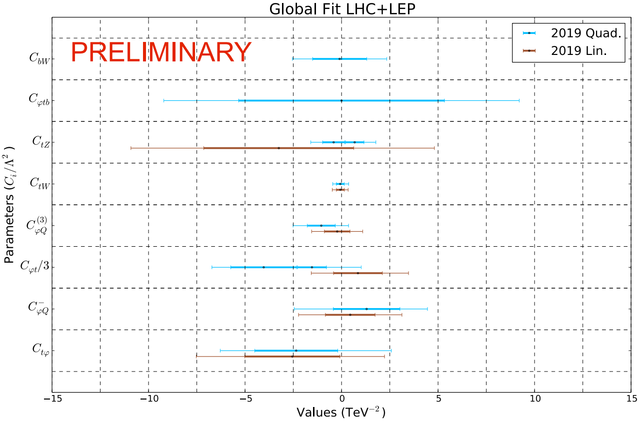
- Posterior distribution difficult to calculate when there is a prolifeation in model parameters
- Using naive Monte Carlo sampling algorithm can lead to unacceptable exectuion
- MCMC in BAT
  1. Start at a random point in the parameter space $\boldsymbol{x}$
  2. Generate a proposal point $\boldsymbol{y}$ according to a symmetric probability distribution $g(\boldsymbol{x}, \boldsymbol{y})$
  3. Compare the value of the function f at proposal point $\boldsymbol{y}$ with the value at the current point $\boldsymbol{x}$. The proposal point is accepted if:
     - $f(\boldsymbol{y}) \geq f(\boldsymbol{x})$
     - otherwise, generate a random number r from a uniform distribution in the range [0, 1] and accept the proposal if $f(\boldsymbol{y})/f(\boldsymbol{x}) > r$ If neither conditions are satisfied the proposal is rejected.
  4. Continue from step 1

MPI implementation

Physics Problem	Hardware	Run Configuration	Time
Unitarity Triangle Fit	3 nodes, 120 CPUs	120 chains, 1.4M iterations	00:02:10
	1 nodes, 40 CPUs	40 chains, 600K iterations	00:00:21
$b \to s$ decays in SMEFT† [?]	6 nodes, 240 CPUs	240 chains, 12.5K iterations	02:05:00
	6 nodes, 240 CPUs	240 chains, 39K iterations	05:20:00
combination of Higgs signal strengths and EWPO[?]	1 node, 16 CPUs	16 chains, 5M iterations	00:14:15
	1 node, 16 CPUs	16 chains, 24M iterations	02:08:00
$D \to PP$ decays and CP asymmetry[?]	3 nodes, 240 CPUs	240 chains, 4M iterations	00:18:30
	1 node, 8 CPUs	8 chains, 200K iterations	00:00:10

Table: Some representative runs with `HEPfit` to show the advantages of the MPI implementation. Times are given in DD:HH:MM. The number of iterations refer to the sum total of pre-run and main-run iterations. The number of chains are equal to the number of CPUs by choice. †The $b \to s$ analysis is done with factorized priors, hence the number of iterations should be multiplied by the number of parameters ($\sim$50) to get a comparative estimate with the other cases. All runs performed in the BIRD or Maxwell clusters at DESY, Hamburg.

Results - Λ^{-4} impact [2019]



wide (narrow) bar: 68% (95%) probability

Observables in the fit

2019 fit

- $pp \to t\bar{t}Z$ inclusive
- $pp \to t\bar{t}\gamma$ inclusive
- $pp \to t\bar{t}H$
- $pp \to t\bar{t}W$
- $pp \to tq$ (t-channel)
- $pp \to tW$
- $pp \to tZq$
- F_0, F_L
- R_b, A_{FBLR}^{bb}

2020 fit

- $pp \to t\bar{t}Z$ differential
- $pp \to t\bar{t}\gamma$ differential
- $pp \to t\bar{t}H$
- $pp \to t\bar{t}W$
- $pp \to tq$ (t-channel)
- $pp \to tW$
- $pp \to tZq$
- F_0, F_L
- R_b, A_{FBLR}^{bb}
- $pp \to t\gamma q$
- $pp \to tb$ (s-channel)

Suppression of linear terms

- $\sigma^{\mu\nu} q_\nu$ **structure:** resent in associated production $pp \to ttX$ with top-quark dipole operators involves the momentum of a photon or a Z boson that tends to be soft and therefore is suppressed [JHEP 05 (2016) 052]

- **Operators suppressed by the bottom mass:** The operators $O_{bW}, O_{\varphi tb}$ induce a tbW vertex involving a right-handed bottom quark. In the $m_b = 0$ approximation adopted here, the dependence on the Λ^{-2} terms vanishes. (O_{bB} chirality flipping)