The electroweak and top-quark sectors in the SMEFT at the HL-LHC

Workshop on High Luminosity LHC and Hadron Colliders

Rome, 4th October 2024

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Based on [1902.04070], [2209.11267], [2209.08078]

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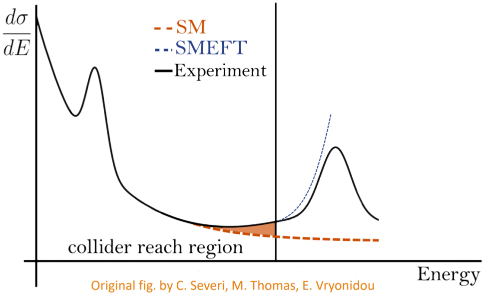
The SMEFT framework

- The astonishing statistics of the HL-LHC opens a great oportunity to probe NP
- Model agnostic approaches are an excellent alternative
- The SMEFT offers an excellent framework for precision physics
- Precision measurements are essential for a correct interpretation in the SMEFT



Original fig. by C. Severi, M. Thomas, E. Vryonidou

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} O_i + \frac{1}{\Lambda^4}\sum_i C_i^{(8)} O_i + \mathscr{O}\left(\Lambda^{-6}\right)$$

$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)}\sigma_i^{(6)} + \frac{1}{\Lambda^4}\sum_{i\geq j} C_i^{(6)} C_j^{(6)}\sigma_{ij}^{(6)} + \frac{1}{\Lambda^4}\sum_i C_i^{(8)}\sigma_i^{(8)} + \mathscr{O}\left(\Lambda^{-6}\right)$$

SMEFT operators in the Warsow basis

Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{quqd}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{quqd}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$

CP-even dim 6 ops. interfering with SM

EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\tilde{\phi} B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\tilde{\phi} W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\tilde{\phi} G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\overline{l_L}\,\phi\, e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)(\overline{q_L}\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\, W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\, \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\, W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\, \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\, G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\, \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_W$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$	$\mathcal{O}_{\widetilde{G}}$

Slide from J. de Blas at Seattle Snowmass Summer Study

Electroweak sector

Anomalous Triple Gauge Couplings

[Falkowski et al., 1609.06312]

$$\mathcal{L}_{tgc} = ie\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)A_\nu + ie\frac{c_\theta}{s_\theta}(1+\delta g_{1,z})\left(W^+_{\mu\nu}W^-_\mu - W^-_{\mu\nu}W^+_\mu\right)Z_\nu$$

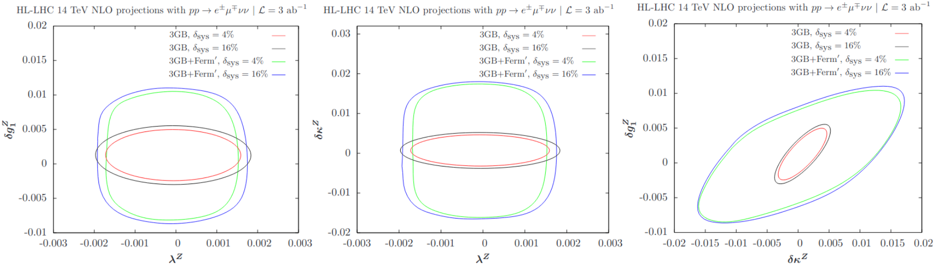
$$+ie(1+\delta\kappa_\gamma)A_{\mu\nu}W^+_\mu W^-_\nu + ie\frac{c_\theta}{s_\theta}(1+\delta\kappa_z)Z_{\mu\nu}W^+_\mu W^-_\nu$$

$$+i\frac{\lambda_z e}{m_W^2}\left[W^+_{\mu\nu}W^-_{\nu\rho}A_{\rho\mu} + \frac{c_\theta}{s_\theta}W^+_{\mu\nu}W^-_{\nu\rho}Z_{\rho\mu}\right],$$

$$\delta g_{1,z} = -\frac{v^2}{\Lambda^2}\frac{g_L^2+g_Y^2}{4(g_L^2-g_Y^2)}\left(\frac{4g_Y}{g_L}C_{HWB} + C_{HD} - [C_{\ell\ell}]_{1221} + 2[C^{(3)}_{H\ell}]_{11} + 2[C^{(3)}_{H\ell}]_{22}\right)$$

$$\delta\kappa_\gamma = \frac{v^2}{\Lambda^2}\frac{g_L}{g_Y}C_{HWB}, \qquad \lambda_z = -\frac{v^2}{\Lambda^2}\frac{3}{2}g_L C_W, \qquad \delta\kappa_Z = \delta g_{1,z} - \frac{s_\theta^2}{c_\theta^2}\delta\kappa_\gamma$$

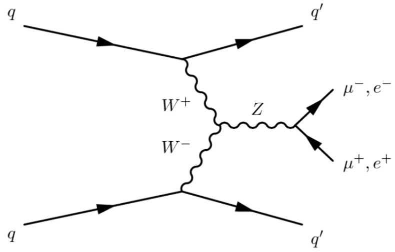
Diboson production

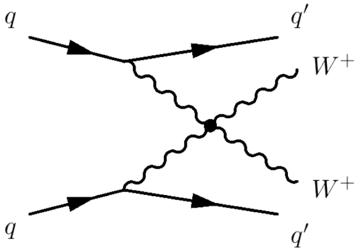


- Precision at permille level on aTGC could be reached from diboson processes

- In the wider regions the fermion couplings are allowed to vary up to the current allowed 2σ region

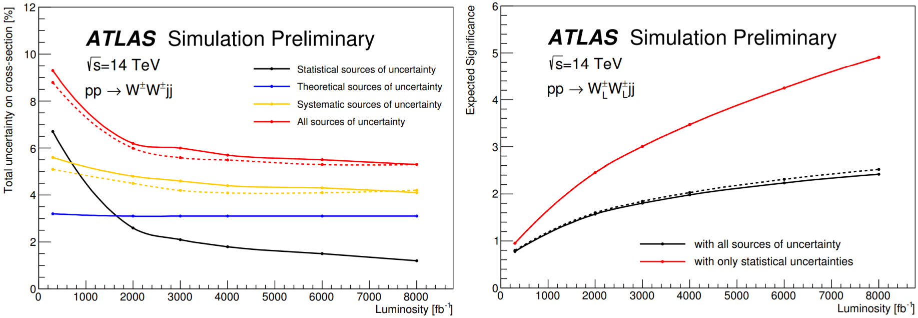
Vector Boson Scattering





- NP could spoil the precise cancellation that moderate the energy growth of VBS
- Measured but with moderate precision
- Precise measurements at the HL-LHC are key to constrain the bosonic SMEFT operators
- In the SMEFT at d6 the operators modifying aTGC also contribute to aQGC

Vector Boson Scattering



- Uncertainty expected around 5-8% for $VVjj$
- $V_L V_L jj$ does not seem to be available
- aTGC better probed in $q\bar{q} \to VV$, Vjj or Higgs decays
- The $VVjj$ can probe anomalous aQGC that test d8

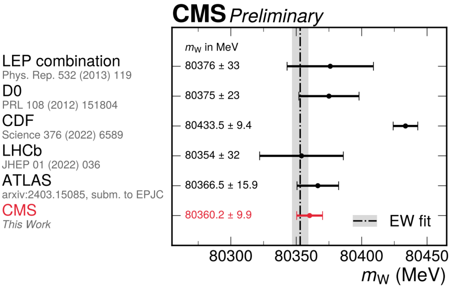
Triboson

	$W^{\pm}W^{\pm}W^{\mp} \to 3\ell 3\nu$	$W^{\pm}W^{\mp}Z \to 4\ell 2\nu$	$W^{\pm}ZZ \to 5\ell 1\nu$
Signal	312	168	19
Diboson	208	357	4.0
Triboson	37	11	3.0
Higgs+X	25	10	0.3
Top	60	390	15
fake-lepton	97	16	3.0
Total:	427	784	25
Significance Z_σ	6.7	3.0	3.0
Significance Z_σ (4000 fb^{-1})	7.0	3.1	3.4
Precision $\frac{\Delta\mu}{\mu}$	11%	27%	36%
Precision $\frac{\Delta\mu}{\mu}$ (4000 fb^{-1})	10%	25%	31%

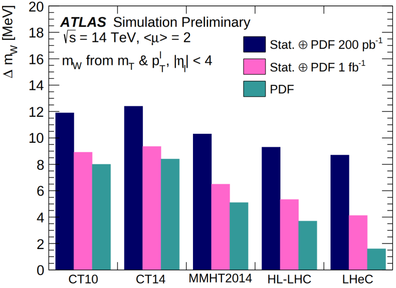
- Currently measured VVV, WWW, $WW\gamma$, $WZ\gamma$, $W\gamma\gamma$, $Z\gamma\gamma$
- Limited impact for aTGC [Celada, Durieux, Mimasu, Vryonidou, 2407.09600]
- Interesting to test aQGC and d8 operators

W-boson mass prospects at ATLAS detector

(CMS Sept. 2024 9.9 MeV)



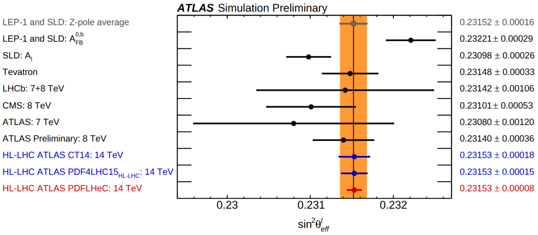
[ATLAS Collab., ATL-PHYS-PUB-2018-026]

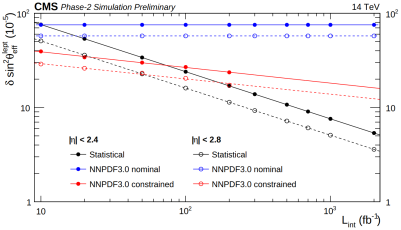


- Dedicated dataset collected at low instantaneous luminosity
- Benefit from the inner tracking detector upgrade
- Needed 1 (5) week(s) to collect 0.2 (1) fb^{-1}
- Uncertainties up to 5 MeV

Effective weak mixing angle $\sin\theta^{\ell}_{\rm eff}$

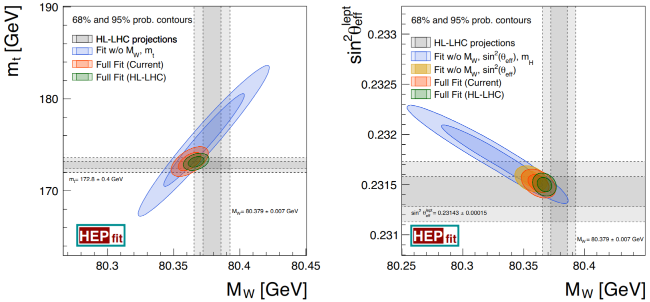
[ATL-PHYS-PUB-2022-018 & CMS-PAS-FTR-22-001]





- Precise measurements of $A_{\rm FB}$ on Drell-Yan dilepton events ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$) can be used to extract $\sin^2\theta^{\ell}_{\rm eff}$
- In HL-LHC increased forward coverage of ATLAS and CMS
- Uncertainty limited by PDF uncertainties

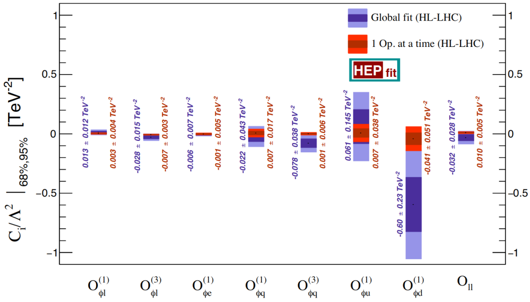
Global EW fit in the SM



Further EW inputs improving:

- δm_t set to 0.4 GeV [CMS, 2302.01967] (more later)
- δm_H set at 0.05 GeV (Next talk!!!)
- $\delta \Gamma_W$ expected to be (at least) as good as in LEP2
- $\delta \Delta\alpha_{had}^{(5)}(M_Z)$ expected 5×10^{-5} from dedicated experiments on $e^+e^- \to \mathrm{had.}$
- $\delta\alpha_s(M_Z)$ expected at 0.0002 from future lattice QCD

Global EW fit the SMEFT



Operator Coefficient	Current uncertainty [TeV^{-2}] 1 op. at a time	Current uncertainty [TeV^{-2}] Global fit	Precision at HL-LHC [TeV^{-2}] 1 op. at a time	Precision at HL-LHC [TeV^{-2}] Global fit
$\overline{C}_{\phi l}^{(1)}$	0.004	0.012	0.004	0.012
$\overline{C}_{\phi q}^{(1)}$	0.018	0.044	0.017	0.043
$\overline{C}_{\phi e}$	0.005	0.009	0.005	0.007
$\overline{C}_{\phi u}$	0.040	0.146	0.038	0.145
$\overline{C}_{\phi d}$	0.054	0.237	0.051	0.230
$\overline{C}_{\phi l}^{(3)}$	0.004	0.017	0.003	0.015
$\overline{C}_{\phi q}^{(3)}$	0.007	0.040	0.006	0.038
$\overline{C}_{ll}$	0.007	0.028	0.005	0.028
$\overline{C}_{\phi WB}$	0.003	–	0.002	–
$\overline{C}_{\phi D}$	0.007	–	0.005	–

- 10 operators affect the EWPO but only 8 can be constrained

$$\mathcal{O}_{HD} = |H^\dagger D^\mu H|^2, \quad \mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{HF}^{(1)} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{F}\gamma^\mu F), \quad \mathcal{O}_{HF}^{(3)} = (H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{F}\gamma^\mu \tau^I F), \quad \mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l),$$

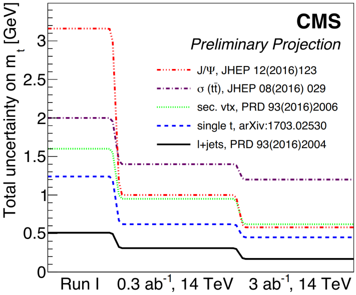
- $\mathcal{O}_{HD}$ and $\mathcal{O}_{HWB}$ can be rotated to lift the two flat directions

Top-quark sector

Top-quark mass

- **Direct measurement:** From fitting parameter of the MC generator
  - More precise but renormalisation scheme not completely well defined
- **Indirect measurement:** From cross sections sensitive to m_t
  - Less precise but renormalisation scheme well defined
  - For precise measurements needs presicion theory predictions
- m_t^{MC} and m_t^{pole} differ by 500-200 MeV
- The renormalon ambiguity (110-250 MeV) does ot affect the physics

		Tev.	Run 1	Run 2	HL-LHC
δm_t^{MC} [MeV]	Stat.	350	130	40	20
	Syst.	540	470	380	170
	Tot.	650	480	380	170
$\delta m_t^{\mathrm{pole}}$ [GeV]	Exp.	2.2	1.0	0.8	0.5
	Theo.	1.4	0.7	1.0	0.25
	Tot.	2.5	1.2	1.3	0.56



SMEFT operators relevant for the top-quark

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}

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

- We expect higher sensitivity for the tails of the distributions in the HL-LHC

Process	Observable	$\sqrt{s}$	$\int \mathscr{L}$	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (8 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}H$	$d\sigma/dp_T^H$ (6 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 prediction

- Prediction for the cross section are usually generated with `MadGraph5_aMC@NLO`

- Many efforts to develop UFO models

  - `SMEFTsim 3.0` [Brivio, 2212.11343]: Tree-level but full at d6

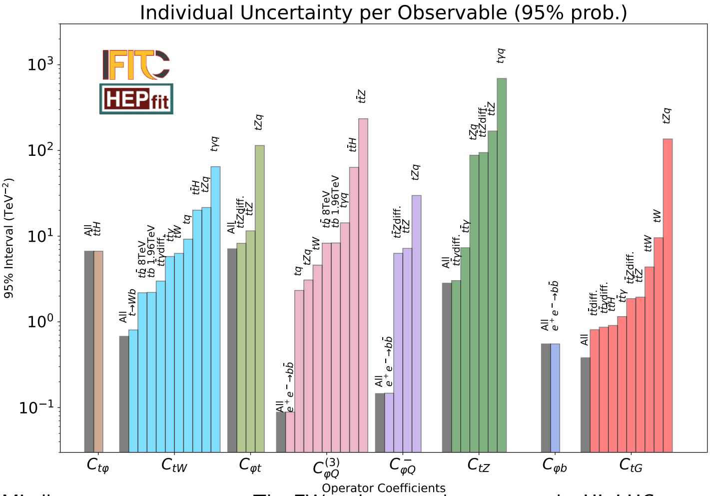
  - `SmeftFR v3` [Dedes, Rosiek, Ryczkowski, Suxho, Trifyllis, 2302.01353]: Tree-level but full quadratic d6 and bosonic d8

  - `SMEFT@NLO` [Degrande, Durieux, Maltoni, Mimasu, Vryonidou, Zhang, 2008.11743]: NLO in QCD for top-quark sector

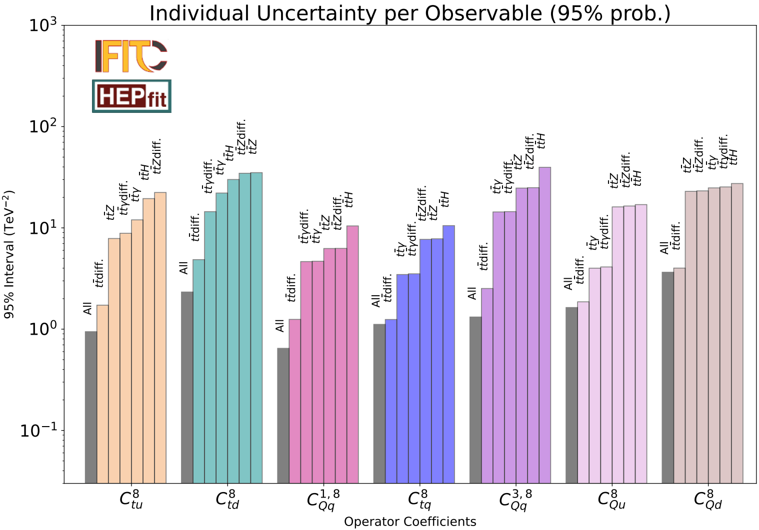
  - Some EW corrections available in `MadGraph5_aMC@NLO` [Pagani, Zaro, 2110.03714] and efforts to include Sudakov EW corrections in the SMEFT [El Faham, Mimasu, Pagani, Severi, Vryonidou, Zaro, in progress]

Current individual constraints on 2-quark operators

The basis is rotated following the prescription of the LHC top-quark working group: $C_{tZ} = \cos\theta_W C_{tW} - \sin\theta_W C_{tB}$, $\quad C^{-}_{\varphi Q} = C^{(1)}_{\varphi Q} - C^{(3)}_{\varphi Q}$



Current individual constraints on 4-quark operators



Prospects for Measurements at HL-LHC

Theoretical Uncertainties $\longrightarrow$ scale with $1/2$

Experimental Uncertainties

- Modelling $\longrightarrow$ scale with $1/2$
- Systematic $\longrightarrow$ scale with $1/\sqrt{\mathscr{L}}$
- Statistical $\longrightarrow$ scale with $1/\sqrt{\mathscr{L}}$

Prospects for Measurements at HL-LHC

- Modelling and theory uncertainties expected to dominate

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

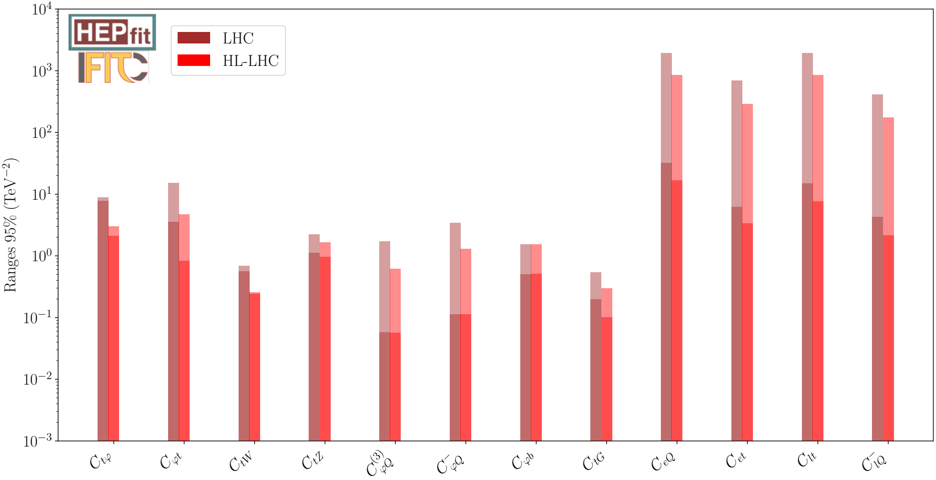
Prospects for Measurements at HL-LHC

- ATLAS is making efforts to measure $pp \to t\bar{t}\ell\ell$ ($m_{\ell\ell} \neq m_Z$)
- Sensitive to 2-quark 2-lepton operators

Process	Inclusive (10^{-6} pb)	Differential: $m_{\ell\bar{\ell}}$ (GeV)			
		100-120	120-140	140-180	> 180
$pp \to t\bar{t}\ell\ell$	1830	1000	340	230	260
Unc. LHC	915	490	235	200	260
Unc. HL-LHC	400	190	85	70	99

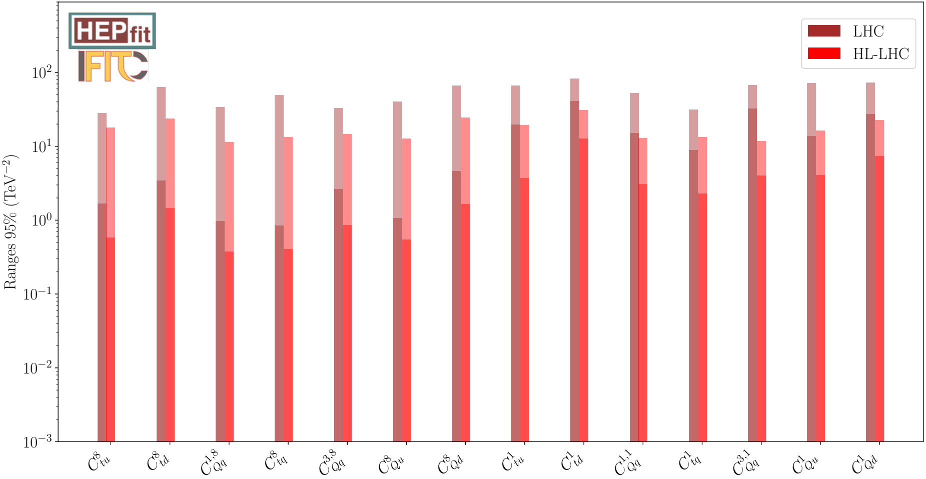
Current constraints vs expected HL-LHC constraints

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



Current constraints vs expected HL-LHC constraints

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

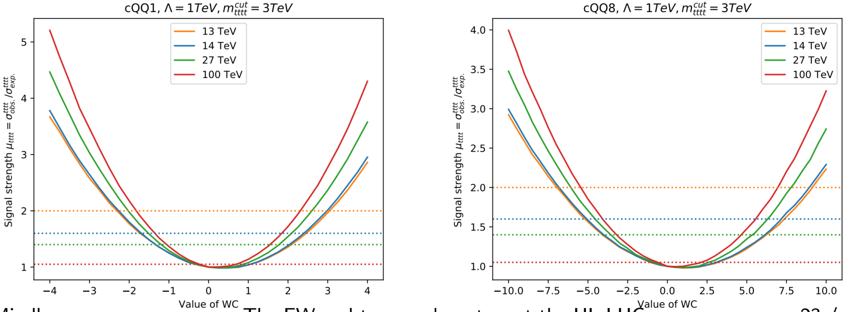


Four top-quark production

- Rare process sensitive to NP
- Sensitive to 4-heavy operators $O_{QQ}^{(1)(8)}$, $O_{Qt}^{(1)(8)}$, $O_{tt}^{(1)}$

Int. Luminosity	$\sqrt{s}$	*Stat. only* (%)	*Run-2* (%)	*YR18* (%)	*YR18+* (%)
300 fb^{-1}	14 TeV	$+30, -28$	$+43, -39$	$+36, -34$	$+36, -33$
3 ab^{-1}	14 TeV	± 9	$+28, -24$	$+20, -19$	± 18
3 ab^{-1}	27 TeV	± 2	$+15, -12$	$+9, -8$	$+8, -7$
15 ab^{-1}	27 TeV	± 1			

[Aoude, El Faham, Maltoni, Vryonidou, 2208.04962]

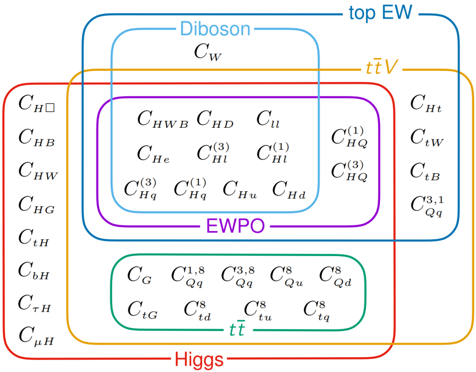


Global SMEFT analysis

Towards a global analysis

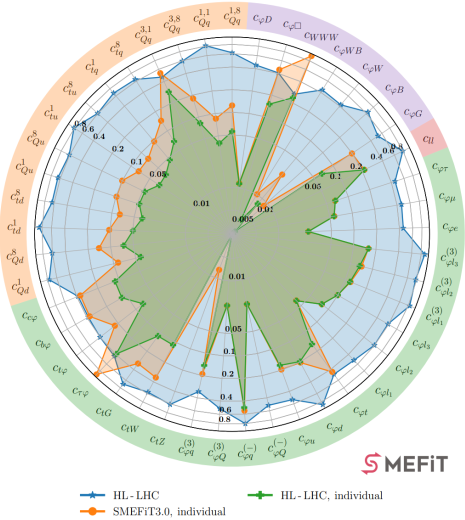
- There is a huge interplay among the different sectors
- The most reliable results are obtained when fitting all the sectors together
- Huge efforts have been done in this direction

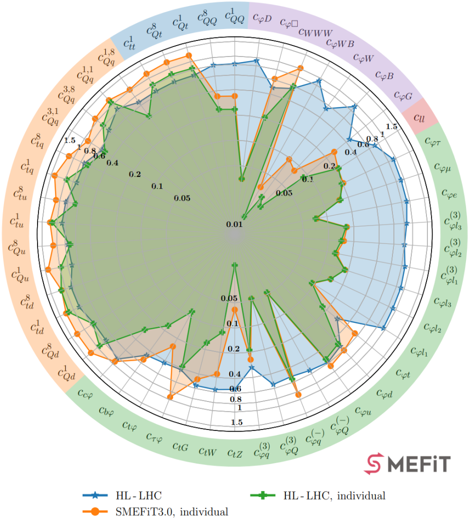
[Fitmaker, 2012.02779]



Global fit results at HL-LHC

[SMEFiT, 2404.12809]

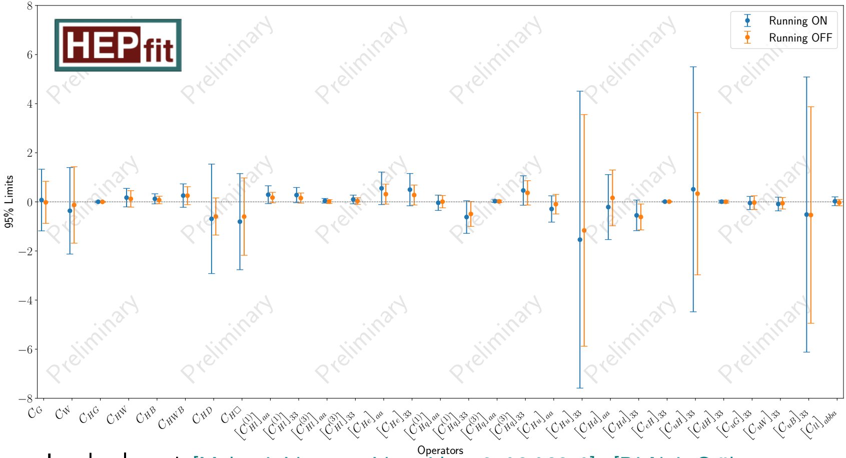




SMEFT running

- Most global fits have been ignoring running effects

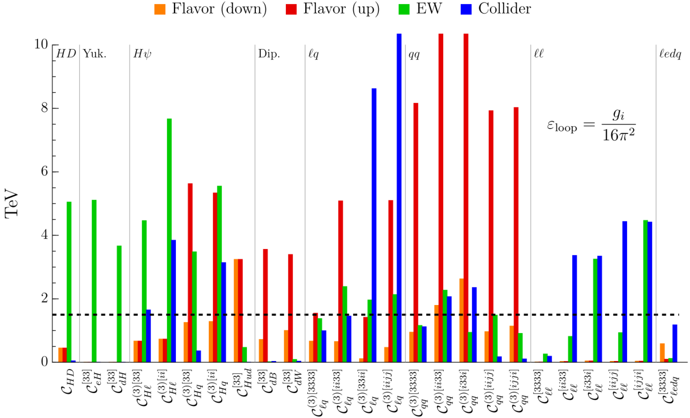
[J. de Blas, A. Goncalves, VM, L. Reina, L. Silvestrini and M. Valli, 24XX.XXXXX]



Look also at [Maltoni, Ventura, Vryonidou, 2406.06670], [Di Noi, Gröber, 2312.11327], [Aoude, Maltoni, Mattelaer, Severi, Vryonidou, 2212.05067]...

Flavour observables

[Allwicher, Cornella, Isidori, Stefanek, 2311.00020]



- Huge effert to consider also flavour observables some recent works include:[Allwicher et al., 2311.00020], [Cirigliano et al., 2311.00021], [Bartocci et al., 2311.04963], [Garosi et al., 2310.00047]

Full SMEFT global fit with $U^5(2)$ in `HEPfit` with **J. de Blas**, **A. Goncalves**, VM, **L. Reina**, **L. Silvestrini** and **M. Valli** → Stay tuned

Summary

- HL-LHC diboson data will provide tight constraints on aTGC and could test aQGC
- HL-LHC can provide leading precision measurements on EW observables like M_W, Γ_W and $\sin\theta^l_{\rm eff}$ (besides obviously m_t and m_H)
- The higher precision on m_t of around 200 MeV makes essential a more precise theoretical definition of the MC mass
- The uncertainties on the top-quark cross sections will be completely dominated by theory and modelling uncertainties
- HL-LHC expected to improve the bounds by roughly a factor 3 on the top-quark sector
- To provide reliable results it is essential to consider running effects
- Flavour observables provide the most stringent constraints in several operators and must be included on global fits

Thank you!

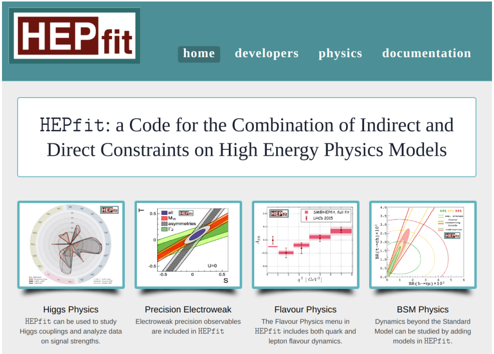
Back up

Inputs for EW fit

	Measurement	HL-LHC uncertainty	Posterior Current	Posterior HL-LHC	Pull Current/HL-LHC
$\alpha_s(M_Z)$	0.1180 ± 0.0010	± 0.0002	0.1180 ± 0.0009	0.1180 ± 0.0002	$0/0.5$
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.027611 ± 0.000111	± 0.00005	0.02758 ± 0.00011	0.02759 ± 0.00005	$1.1/2.1$
M_Z [GeV]	91.1875 ± 0.0021		91.1880 ± 0.0020	91.1890 ± 0.0020	$-1.3/-2.6$
m_t [GeV]	172.8 ± 0.7	± 0.4	173.2 ± 0.66	173.1 ± 0.38	$-1.7/-2.9$
M_H [GeV]	125.13 ± 0.17	± 0.05	125.13 ± 0.17	125.13 ± 0.05	$1.4/3$
M_W [GeV]	80.379 ± 0.012	± 0.007	80.362 ± 0.006	80.367 ± 0.004	$1.6/2.7$
Γ_W [GeV]	2.085 ± 0.042	± 0.042	2.0885 ± 0.0006	2.0889 ± 0.0003	-0.1
${\rm BR}_{W\to\ell\nu}$	0.1086 ± 0.0009		0.10838 ± 0.00002	0.10838 ± 0.000005	0.2
${\rm BR}_{W\to{\rm had}}$	0.6741 ± 0.0027		0.67486 ± 0.00007	0.67486 ± 0.00001	-0.3
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012		0.23151 ± 0.00006	0.23150 ± 0.00005	0.7
$P_\tau^{\rm pol} = A_\ell$	0.1465 ± 0.0033		0.14711 ± 0.0005	0.14713 ± 0.0004	-0.2
Γ_Z [GeV]	2.4952 ± 0.0023		2.4946 ± 0.0007	2.4947 ± 0.0005	0.3
σ_h^0 [nb]	41.540 ± 0.037		41.492 ± 0.008	41.491 ± 0.006	1.3
R_ℓ^0	20.767 ± 0.025		20.749 ± 0.008	20.749 ± 0.006	0.7
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010		0.01623 ± 0.0001	0.016247 ± 0.00008	0.9
A_ℓ (SLD)	0.1513 ± 0.0021		0.14711 ± 0.0005	0.14718 ± 0.0004	1.9
R_b^0	0.21629 ± 0.00066		0.21586 ± 0.0001	0.21586 ± 0.0001	$0.7/0.6$
R_c^0	0.1721 ± 0.0030		0.17221 ± 0.00005	0.17221 ± 0.00005	0
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016		0.10313 ± 0.00032	0.10319 ± 0.00026	$-2.4/-2.5$
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035		0.07369 ± 0.00024	0.07373 ± 0.0002	-0.9
A_b	0.923 ± 0.020		0.93475 ± 0.00004	0.93476 ± 0.00004	-0.6
A_c	0.670 ± 0.027		0.66792 ± 0.0002	0.66794 ± 0.0002	0.1
$\sin^2\theta_{\rm eff(Had.coll.)}^{\rm lept}$	0.23143 ± 0.00027	± 0.00015	0.23151 ± 0.00006	0.23150 ± 0.00005	$-0.5/-0.9$

Fitting tools

- Open source written in C++
- Based on the Bayesian Analysis Toolkit [A. Caldwell, D. Kollar, K. Kröninger, 0808.2552]
- Sampling likelihoods with MCMC
- Supports SM, implemented NP extensions, and the SMEFT



HEPfit webpage [J. de Blas et al., 1910.14012]

Other frameworks for SMEFT global fits: [SMEFiT, 2105.00006, 2302.06660, 2404.12809], [Fitmaker, 2012.02779], [Aebischer et al., 1810.07698], [Allwicher et al., 2311.00020], [Cirigliano et al., 2311.00021], [Bartocci et al., 2311.04963], [Garosi et al., 2310.00047],. . .

Dependencies of top-quark operators
[Brivio et. al., 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}	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}

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.

Top-quark yukawa

- HL-LHC great oportunity to measure top-Yuk. from $t\bar{t}h$ and thj

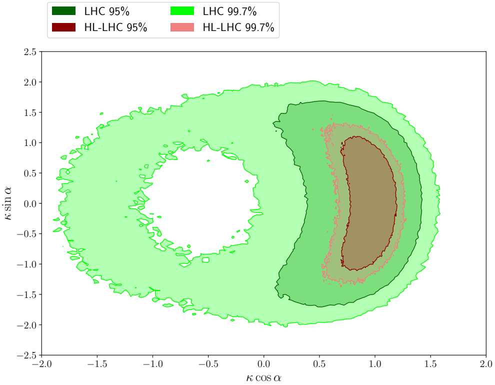
[VM, Y. Peters, E. Vryonidou, J.K. Winter, 24XX.XXXXX]

$\mathscr{L}_{h\bar{t}t} =$
$-\frac{m_t}{v}\bar{t}(\kappa\cos\alpha + i\gamma_5\kappa\sin\alpha)th$

$$\kappa\cos\alpha = 1 - \frac{3v^3}{2\sqrt{2}\,m_t}\frac{C_{t\varphi}}{\Lambda^2}$$

$$\kappa\sin\alpha = -\frac{3v^3}{2\sqrt{2}\,m_t}\frac{C^I_{t\varphi}}{\Lambda^2}$$

	LHC	HL-LHC
$\kappa\cos\alpha$	[0.29, 1.33]	[0.75, 1.15]
$\kappa\sin\alpha$	[-1.38, 1.34]	[-0.92, 0.91]



Global SMEFT fit observable break down

With J. de Blas, A. Goncalves, L. Reina, L. Silvestrini and M. Valli