SMEFT fit HL-LHC prospects: the role of top

Workshop on top quark mass measurements
Valencia, 12th November 2025

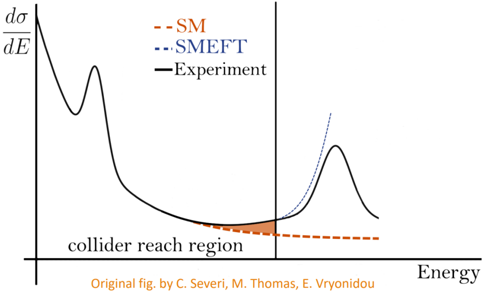
Víctor Miralles

Based on
[Cornet-Gómez, VM, Miralles-López, Moreno-Llácer, Vos, 2503.11518]
[de Blas, Goncalves, VM, Reina, Silvestrini, Valli 2507.06191]

Universitat d'Alacant

The SMEFT framework

- Model agnostic approaches are an excellent alternative to particular NP extensions
- The SMEFT offers an excellent framework for testing new physics
- To study the top-quark sector we assume a $U(2)^5$ flavour symmetry



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

$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} \sigma_i^{(6)} + \mathscr{O}\left(\Lambda^{-4}\right)$$

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

$O^{(8)(1)}_{tu}$ $O^{(8)(1)}_{td}$ $O^{(1,8)(1,1)}_{Qq}$ $O^{(8)(1)}_{Qu}$ $O^{(8)(1)}_{Qd}$ $O^{(3,8)(3,1)}_{Qq}$ $O^{(8)(1)}_{tq}$

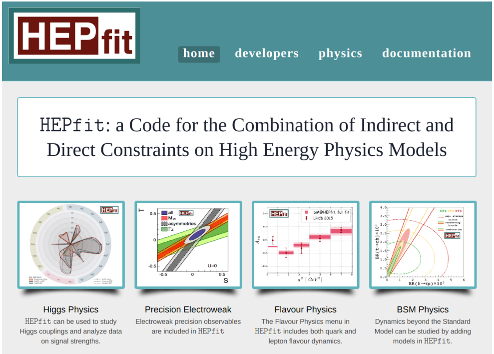
2-quark 2-lepton operators

Couplings of light leptons with t- and b-quarks

O_{eb} O_{lb} O_{et} O_{lt} O_{eQ} O^+_{lQ} O^-_{lQ}

The HEPfit code

- Open source written in C++
- Available under the GPL on GitHub: https://github.com/silvest/HEPfit
- The MCMC sampling based on BAT
- Sampling likelihoods with MCMC
- Parallelised with MPI



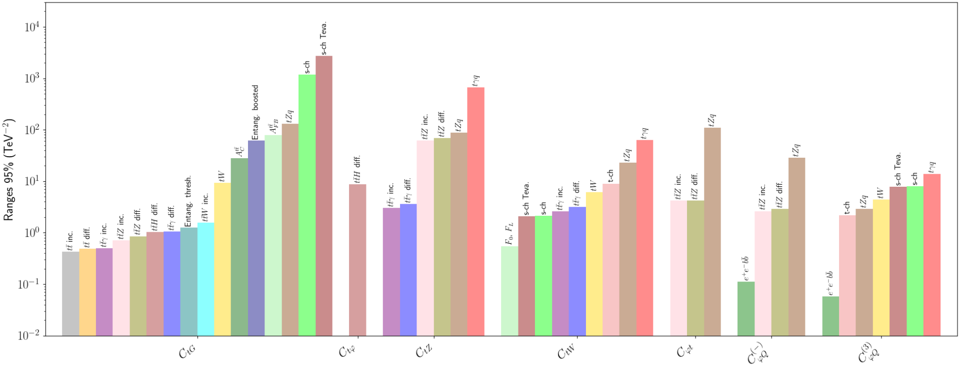
HEPfit webpage [J. de Blas et al., 1910.14012]

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

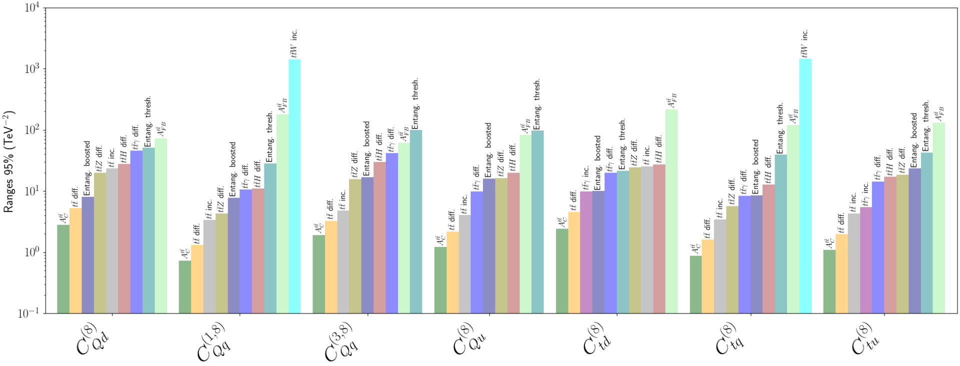
- Parametrisations obtained with `SMEFT@NLO` in `MadGraph`

Process	Observable	$\sqrt{s}$	L_{int}	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15 bins)	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (5 bins)	13 TeV	139 fb^{-1}	ATLAS
$pp \to t\bar{t}$	$D(m_{t\bar{t}} \sim 2m_t)$	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}$	$D_n(m_{t\bar{t}} > 0.8\ \mathrm{TeV})$	13 TeV	137 fb^{-1}	CMS
$pp \to t\bar{t}H$	$d\sigma/dp_T^H$ (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	8/13 TeV	20/140 fb^{-1}	LHC/ATLAS
$t \to Wb$	F_0, F_L	8/13 TeV	20/139 fb^{-1}	LHC/ATLAS
$p\bar{p} \to t\bar{t}$	$dA_{FB}/dm_{t\bar{t}}$ (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_{FBLR}^{bb}	~ 91 GeV	202.1 pb^{-1}	LEP/SLD

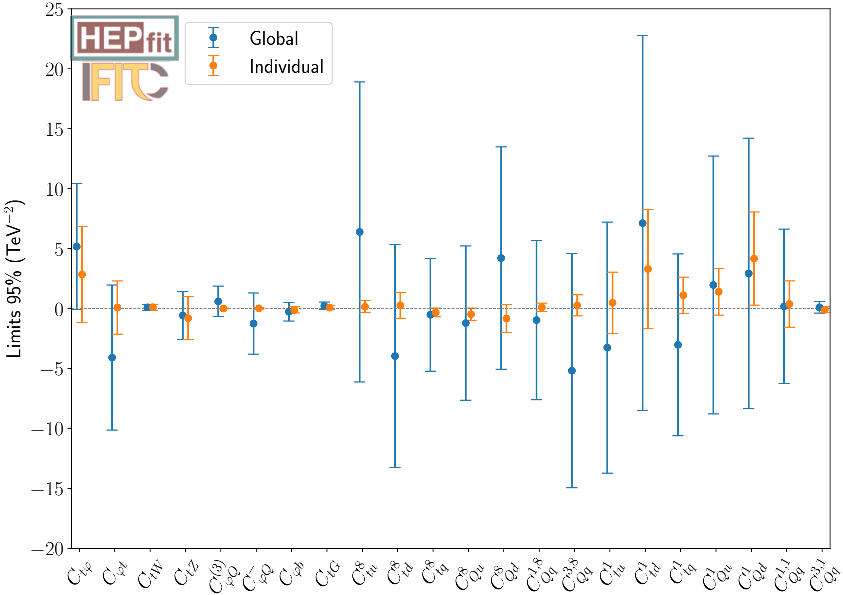
Individual constraints on 2-quark operators



Individual constraints on octets 4-quark operators



Current data constraints



High Luminosity LHC

Prospects for Measurements at HL-LHC

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

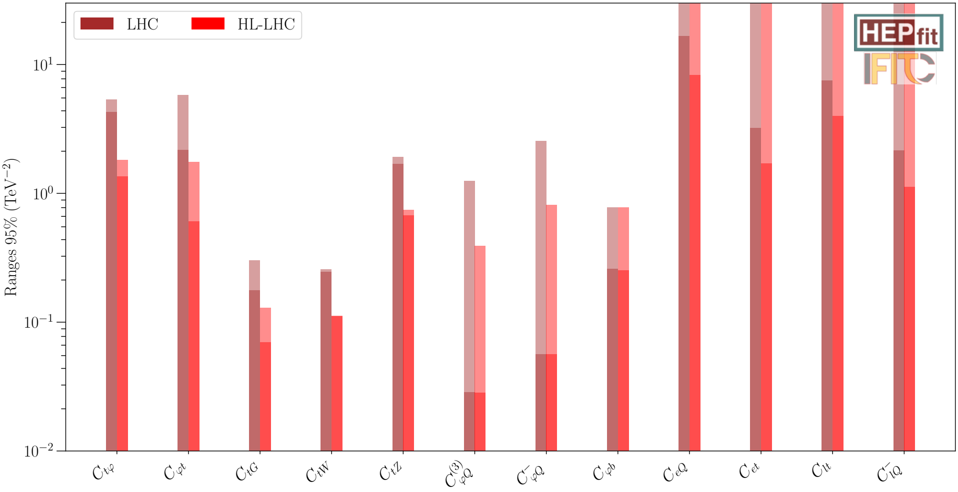
Experimental Uncertainties $\begin{cases} \text{Modelling} & \longrightarrow \quad \text{scale with } 1/2 \\ \text{Systematic} & \longrightarrow \quad \text{scale with } 1/\sqrt{\mathscr{L}} \\ \text{Statistical} & \longrightarrow \quad \text{scale with } 1/\sqrt{\mathscr{L}} \end{cases}$

- Dominant uncertainties at HL-LHC $\Rightarrow$ modelling and theoretical

Expected improvement at HL-LHC: 2-quark operators

Shadowed ⇒ Marginalised

Solid ⇒ Individual



Expected improvement at HL-LHC: 4-quark operators

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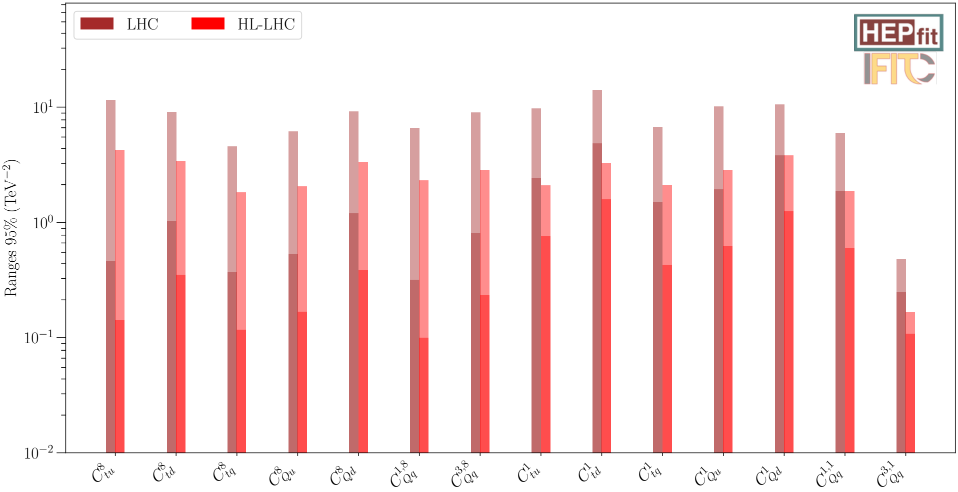


Future lepton colliders

Measurements at e^+e^- colliders: $b\bar{b}$ production

Machine	Polarisation	Energy	Luminosity	Observable
ILC	P(e^+, e^-):(−30%, +80%) P(e^+, e^-):(+30%, −80%)	250 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		500 GeV	4 ab^{-1}	
		1 TeV	8 ab^{-1}	
CLIC	P(e^+, e^-):(0%, +80%) P(e^+, e^-):(0%, −80%)	380 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
CEPC/FCC-*ee*	Unpolarised	Z-pole	57.5/150 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		240 GeV	20/5 ab^{-1}	
		360/365 GeV	1/1.5 ab^{-1}	

- Expected uncertainties from [A. Irles, et al., 2403.09144]
- These observables set constraints on the EW precision observables $C^+_{\varphi Q} = C^1_{\varphi Q} + C^3_{\varphi Q}$ and $C_{\varphi b}$
- Also relevant for 2-quark 2-lepton operators C^+_{lQ}, 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 ab^{-1}	Optimal Observables
	P(e^+, e^-):($+30\%$, -80%)	1 TeV	8 ab^{-1}	
CLIC	P(e^+, e^-):(0%, $+80\%$)	380 GeV	2 ab^{-1}	Optimal Observables
	P(e^+, e^-):(0%, -80%)	1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
CEPC/FCC-*ee*	Unpolarised	350 GeV	0.2 ab^{-1}	Optimal Observables
		365 GeV	1/1.5 ab^{-1}	

- Optimal observables maximally exploit the information in the fully differential $e^+e^- \to t\bar{t} \to bW^+\bar{b}W^-$ 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^-_{lQ}, C_{lt}, C_{et} and C_{eQ}
- With these we eliminate blind directions in the $C^{(1)}_{\varphi Q} - C^{(3)}_{\varphi Q}$ plane
- Two different energies above the $t\bar{t}$ threshold are need to constrain all the 2- and 4-fermion operators

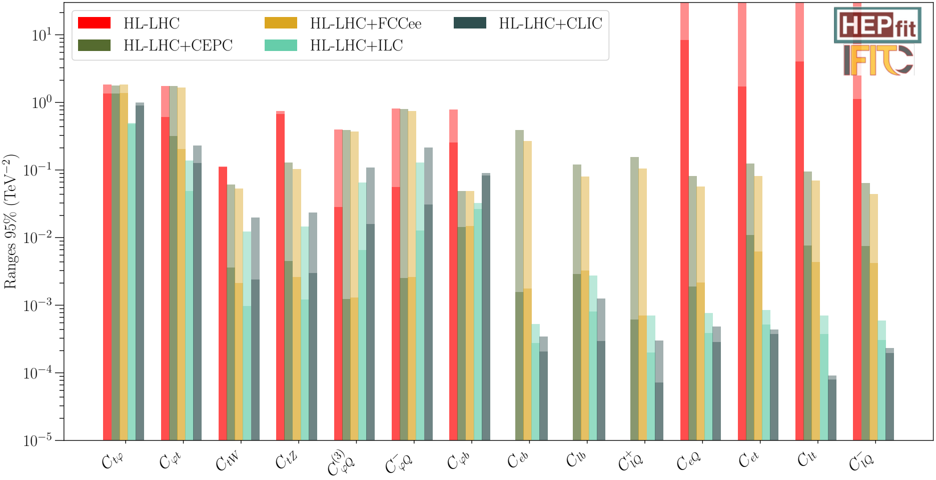
Measurements at e^+e^- colliders: $t\bar{t}H$ production

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

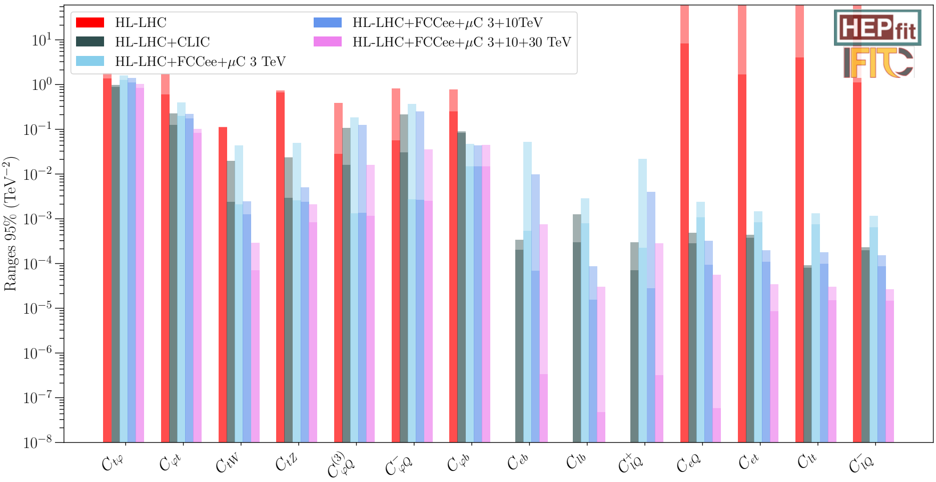
Comparison of future e^+e^- colliders



Measurements at a muon colliders

Machine	Polarisation	Energy	Luminosity	Observable
Muon Collider	Unpolarised	3 TeV	1 ab^{-1}	$\sigma_{b\bar{b}}$, $A_{\text{FB}}^{b\bar{b}}$ Optimal Observables ($t\bar{t}$ s-channel) $t\bar{t}$ VBF $t\bar{t}H$
		10 TeV	10 ab^{-1}	
		30 TeV	90 ab^{-1}	

Effects of future $\mu^+\mu^-$ colliders

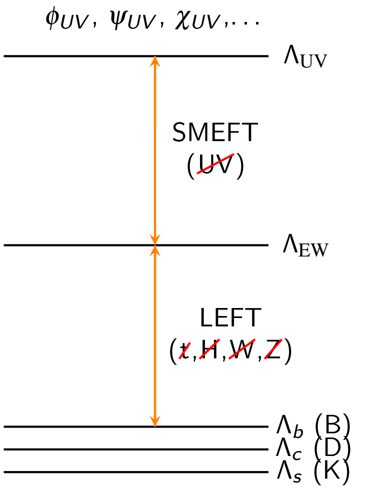


Impact of top-quark data in global SMEFT fits with current data

Observables included

- **Electroweak precision observables** at LEP, SLD, Tevatron, and LHC
- **Di-boson** production cross sections at LEP
- **Higgs boson** measurements at LHC
- **Top-quark** measurements at LHC and Tevatron
- **Drell-Yan** measurements at LHC
- **LEP-II** production of leptons and quarks
- **Flavour observables** measurements at Flavour Factories and LHC

Running



Slide from L. Reina at LoopFest XXII

Heavy physics decouples and leaves effective contact interactions of dim > 4

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{i,d} \frac{C_{i,d}^{\mathrm{SMEFT}}}{\Lambda^2} \mathscr{O}_{i,d}^{\mathrm{SMEFT}}$$

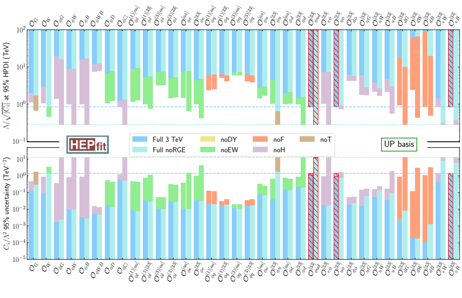
$\downarrow$ **SMEFT RGE**

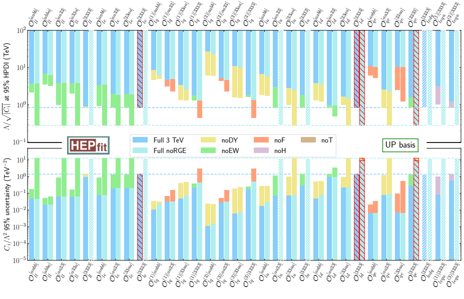
$$\mathscr{L}_{\mathrm{LEFT}} = \mathscr{L}_{\mathrm{QCD+QED}} + \sum_{i,d} \frac{C_{i,d}^{\mathrm{LEFT}}}{v^2} \mathscr{O}_{i,d}^{\mathrm{LEFT}}$$

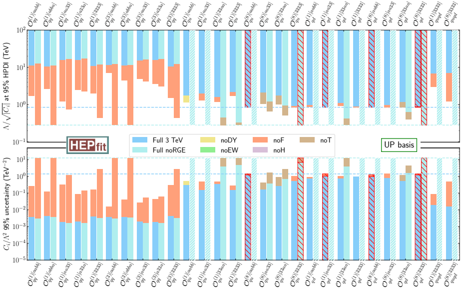
$\downarrow$ **LEFT RGE**

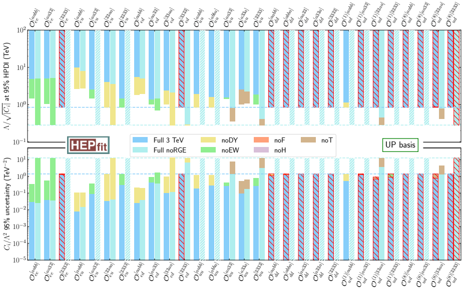
Operators mix through RGE and what we really want to know is the SMEFT structure at the high scale

Fits for $U(2)^5$ flavour symmetry: Individual

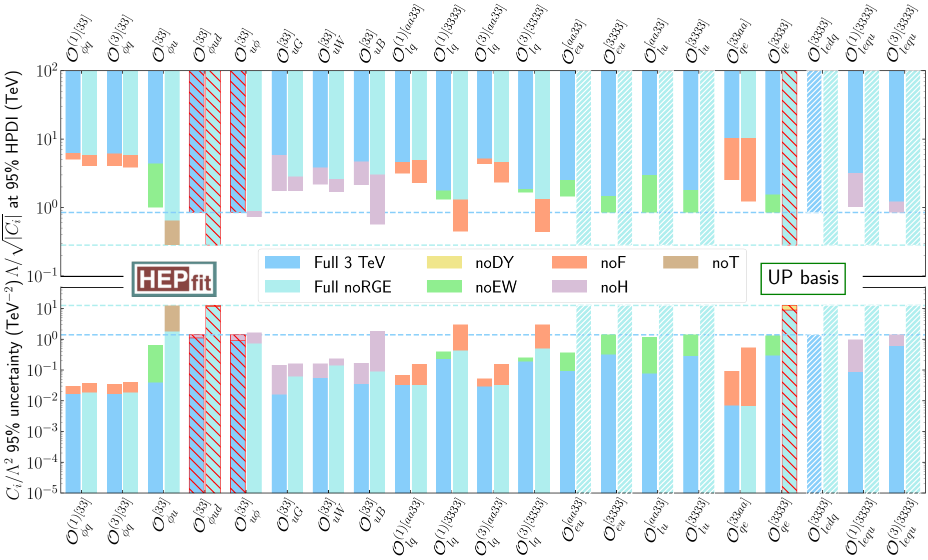




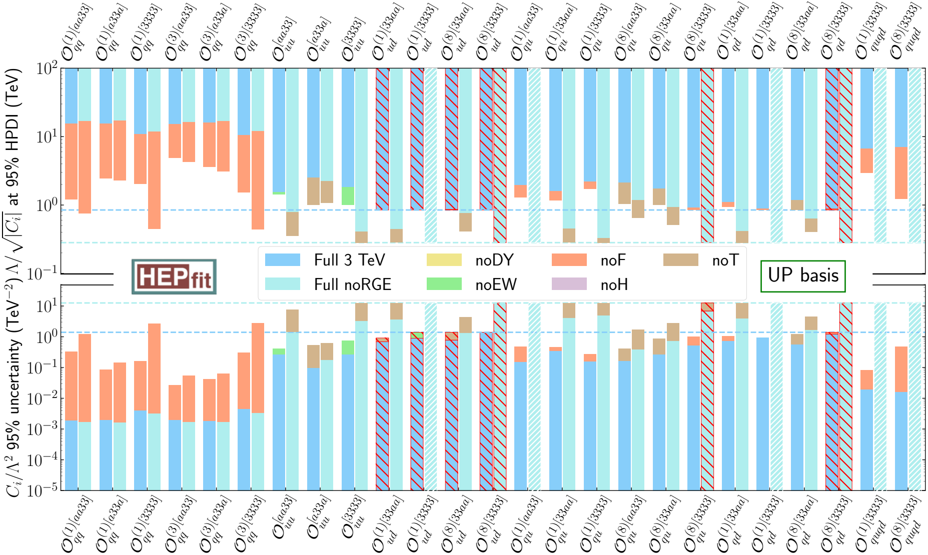




Fits for $U(2)^5$ flavour symmetry: Individual 2-quark top op.

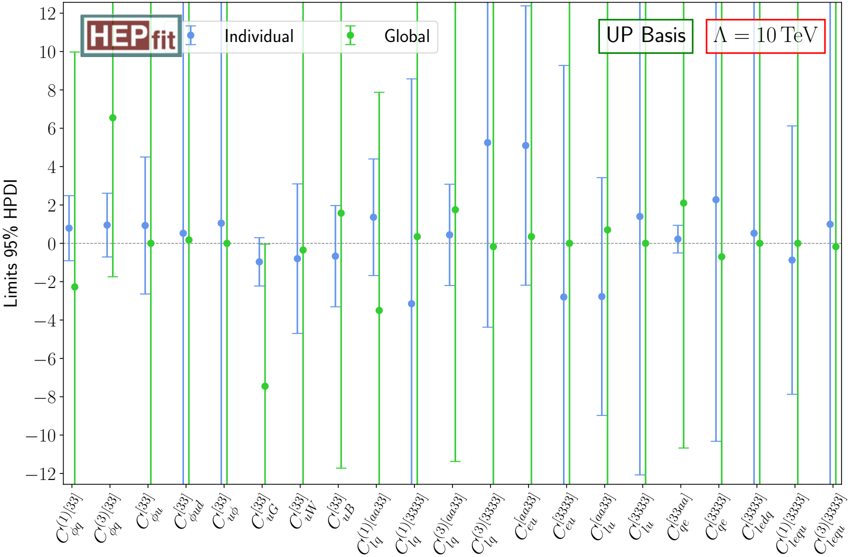


Fits for $U(2)^5$ flavour symmetry: Individual 4-quark top op.



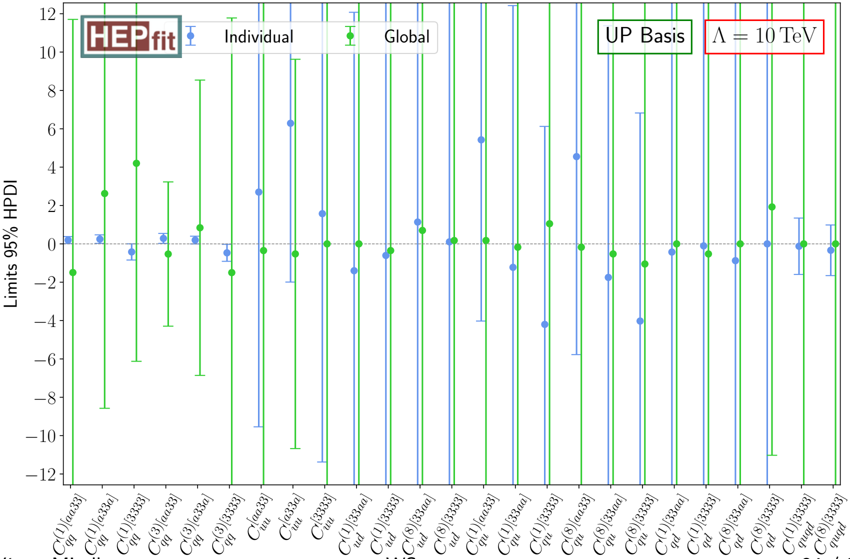
Fits for $U(2)^5$ flavour symmetry: Global

- Challenging to obtain constraints within perturbative limit



Fits for $U(2)^5$ flavour symmetry: Global

- Additional observables and improvement of experimental precision



Summary

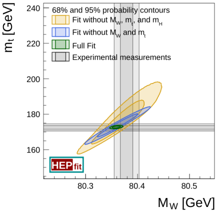
- HEPfit has proven to be a robust and efficient code extremely useful to fit the SMEFT
- When considering the running/mixing the strongest individual constraints do not usually come from the top sector
- To lift blind directions in the global fit is best to include as many observables as possible
- For the demanding $U(2)^5$ case HEPfit is able to perform a fit with EW, di-boson, Higgs, top, Drell-Yan, LEP-II, and flavour data, including around 200 parameters
- Given the current data included few coefficients can be constrained for the $U(2)^5$ case beyond the perturbative limit for realistic values of $\Lambda = 10$ TeV
- Constraints from future collider will provide complementary information helping to constrain more operators beyond the perturbative limit

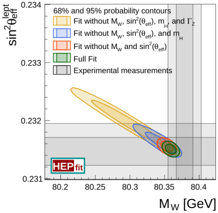
Thanks for your attention!

Observables included: EWPO and Di-boson

- **Electroweak precision observables**
  - Z-pole observables (LEP/SLD): Γ_Z,$\sin^2\theta_{\text{eff}}$, A_l, A_{FB},. . .
  - W observables (LEP-II, Tevatron, LHC):M_W, Γ_W
  - m_t, M_H, $\sin\theta_{\text{eff}}$ (Tevatron/LHC)

  `HEPfit` contains all the predictions to EWPO in the SM at highest available precision [J. de Blas, M. Ciuchini, E. Franco, A. Goncalves, S. Mishima, M. Pierini, L. Reina, and L. Silvestrini, 2112.07274]



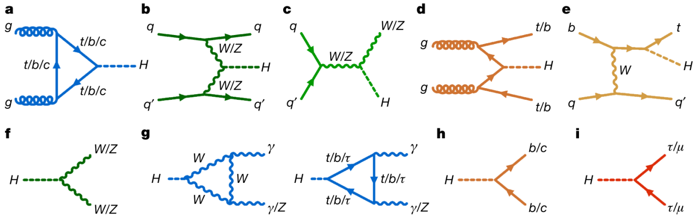


  Same framework for the SMEFT including LO contributions on it

- **Di-boson** production
  - $e^+e^- \to W^+W^-$ [Berthier, Bjørn, Trott, 1606.06693]

Observables included: Higgs and Top quark

- **Higgs boson** observables
  - Simplified Template Cross Sections (ATLAS and CMS)

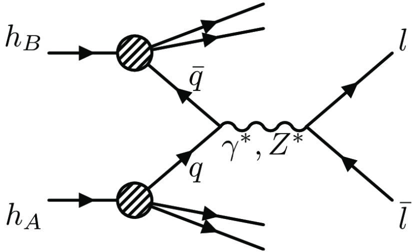


- **Top-quark** measurements
  - Asymmetries plus inclusive and differential cross sections $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \ldots$

The SMEFT parametrisations are obtained using `MG5_aMC@NLO` with the UFOs `SMEFTsim3.0` [I. Brivio, 2012.11343] and `SMEFT@NLO` [Degrande et al., 2008.11743] cross checked with in-house UFO models from J. de Blas and `SMEFTci2` developed by Angelica Goncalves

Observables included: Drell-Yan and LEP-II

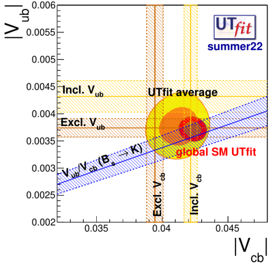
- **Drell-Yan:**
  - Cross sections for Drell-Yan dilepton ($pp \to \bar{\ell}\ell$) and mono-lepton ($pp \to \bar{\ell}\nu$) searches by ATLAS and CMS
  - Added using the package `HighPT` [L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756, 2207.10714]

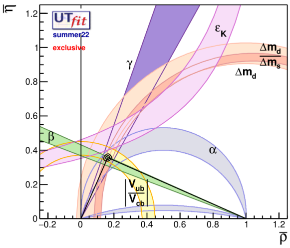


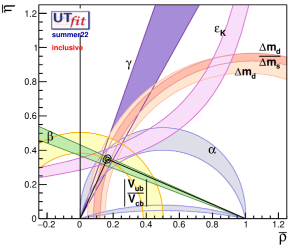
- **LEP-II** production cross sections computed analytically by J. de Blas
  - $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$, hadrons

Observables included: Flavour

- $|\Delta F| = 2$: Δm_{B_d}, Δm_{B_s}, ε_k, $D - \bar{D}$
- $|\Delta F| = 1$: $B \to X_{s,d}\gamma$ plus leptonic ($B_s \to \mu^+\mu^-$, $B \to \tau\nu$, $K \to \ell\nu$, $\pi \to \ell\nu$) and semileptonic ($B_s \to D^{(*)}\ell\nu$, $B \to \pi\ell\nu$, $K \to \pi\ell\nu$) mesonic decays
- These observables are used to determine the V_{CKM} in the SM fits
- The **UT***fit* collaboration (including L. Silvestrini and M. Valli) has been performing these fits in the SM [UTfit Collab., 2212.03894]
- `HEPfit` uses a similar framework (including the mentioned observables) to constrain the (SM +) SMEFT parameters

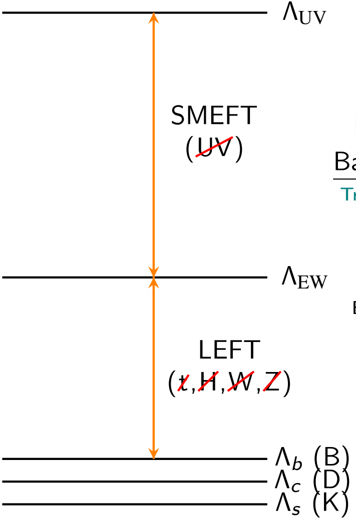






Global picture

$\phi_{UV}, \psi_{UV}, \chi_{UV}, \ldots$



Matching at Λ_{UV}

`Matchete` [Fuentes-Martín et al. , 2212.04510]

`Matchmakereft` [Carmona et al. , 2112.10787]

$C_{i,d}^{\rm SMEFT}(\Lambda_{UV})$ satisfy the flav. symmetry of UV

`RGESolver` (C++ library)
[Stefano di Noi and Luca Silvestrini, 2210.06838]

Based on 1-loop: [Jenkins, Manohar, Trott, 1308.2627, 1310.4838,1312.2014]

Others:
`DsixTools` (`Mathematica`)
`wilson` (`python`)

SMEFT RGE

$C_{i,d}^{\rm SMEFT}(\Lambda_{EW})$ to calculate collider observables

Matching SMEFT with LEFT added in `HEPfit`

Based on: [Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270]

Obtain $C_{i,d}^{\rm LEFT}(\Lambda_{EW})$

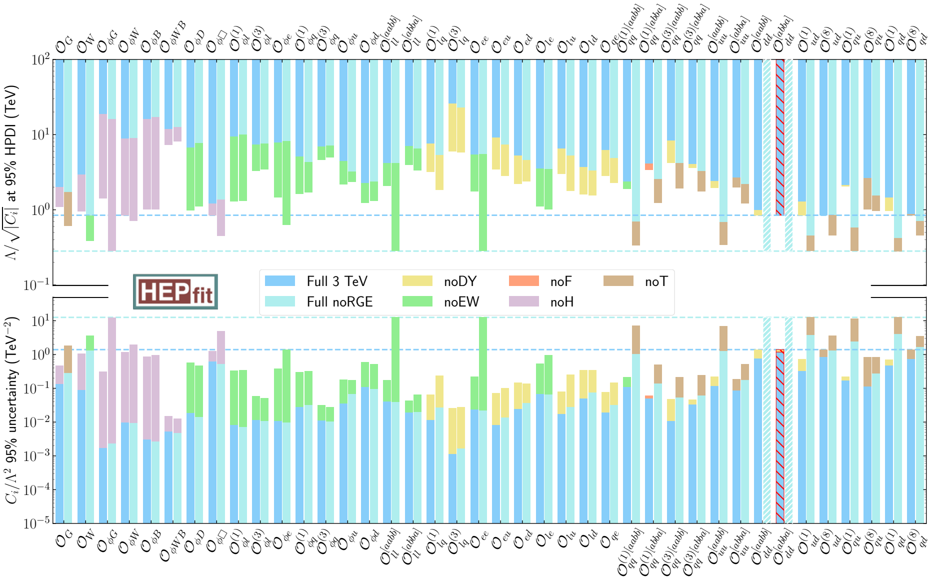
Running of LEFT included in `HEPfit`

LEFT RGE

$C_{i,d}^{\rm LEFT}(\Lambda_{\rm had.})$ to calculate flavour observables

Slide adapted from L. Reina at LoopFest XXII

Fits for $U(3)^5$ flavour symmetry: Individual



Fits for $U(3)^5$ flavour symmetry: Individual (quark op.)