EFT global fits - Discussion

What do we learn about new physics – Can we learn more

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Based on work in collaboration with:
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EFT Global Fits - Overview

Using the case of the SMEFT for illustration

- Given the precision reached at the LHC and expected at the HL-LHC for a broad set of measurements, **precision tests have grown to much more global fits** (beyond EWPO).

- The **EFT formalism provides a systematic way to explore new physics that most likely lies above the TeV scale** since we have found so far neither direct nor indirect evidence.

Beyond EW precision fits: global precision fits

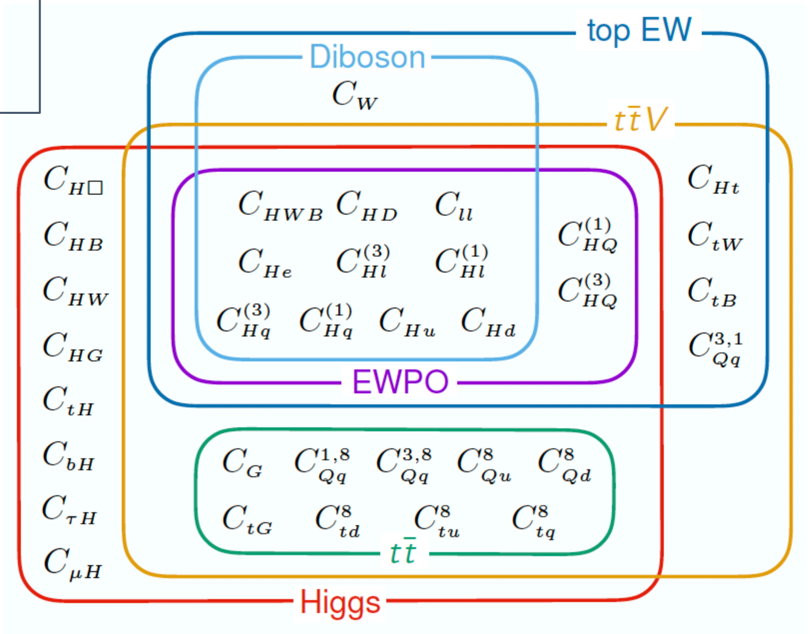
Constraining new physics through a broad spectrum of collider and flavour observables

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

Including most recent LHC measurements (M_W, m_t, …)

- **Higgs boson observables**
  - Production and decay rates
  - Simplified Template Cross Sections (STXS)
- **Top quark observables**
  - $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \ldots$
- **Drell-Yan, Di-boson measurements**
  - $pp \to W, Z \to f_i \bar{f}_j$
  - $pp \to WZ, WW, ZZ, Z\gamma$

ATLAS and CMS Run 1+2 results

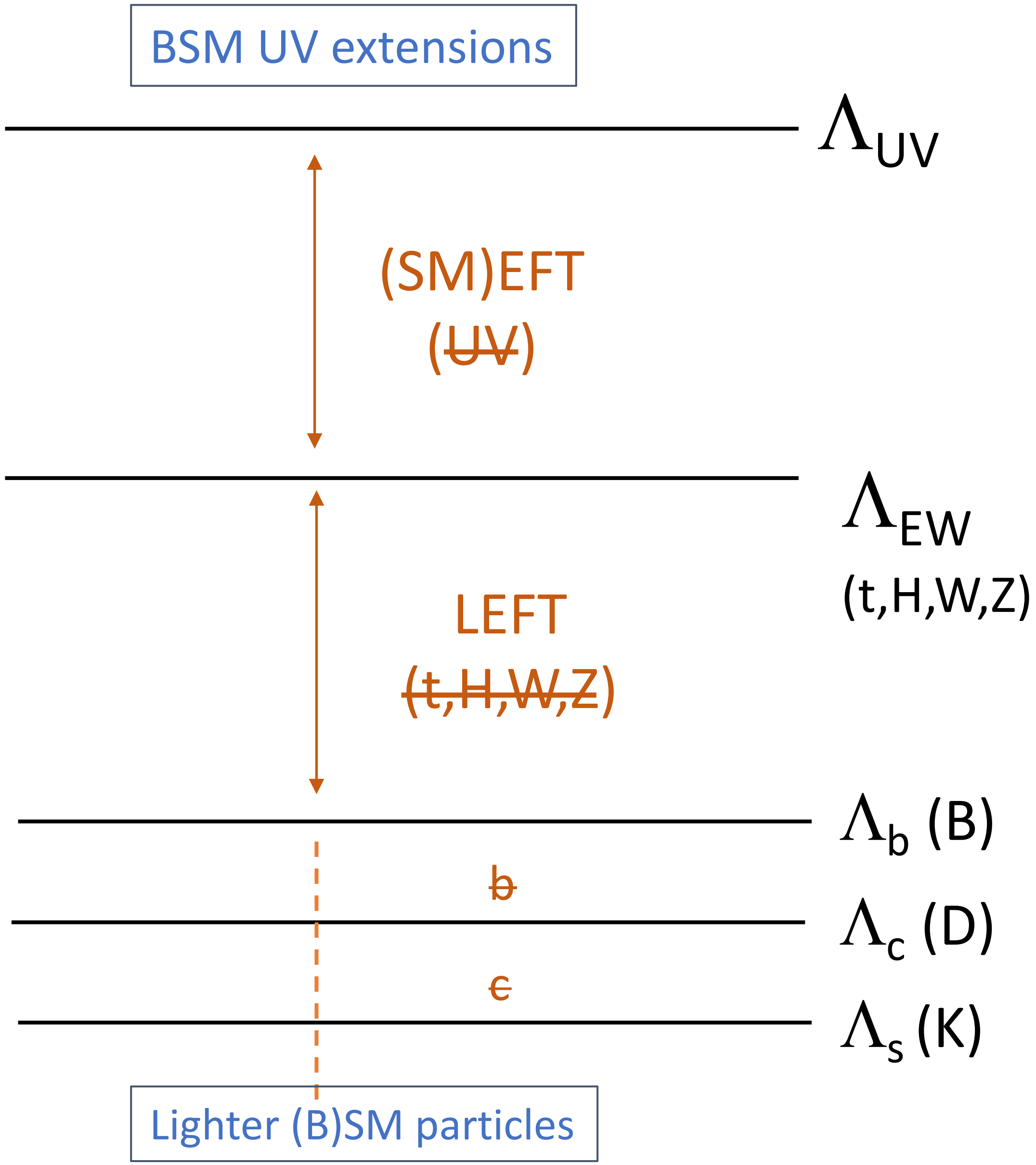


Flavour strongly constrains some of them either directly or through RGE

- **Flavour observables**
  - $\Delta F=2$: $\Delta m_{B_{d,s}}$, $A_{sl}^{s,d}$, $D^0 - \bar{D}^0(\phi_{12}^M)$, ε_K
  - Leptonic decays: $B_s \to \mu^+\mu^-$, $B \to \tau\nu$, $K \to \ell\nu$, $\pi \to \ell\nu$
  - Semi-leptonic decays: $B \to D^{(*)}l\nu$, $B \to \pi\ell\nu$, $K \to \pi\ell\nu$
  - Radiative B decays: $B \to X_{s,d}\gamma$

<u>Exp</u>: PDG, HFLAV
<u>Th</u>: best available predictions

Connecting far apart scales: the EFT picture



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

RGE

EFT operators in terms of SM fields

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{i,d} \frac{C_{i,d}^{SMEFT}}{\Lambda^{d-4}} O_{i,d}^{SMEFT}$$

RGE

WC depend on m_t, M_W, M_Z, M_H, …M_X

$$\mathcal{L}_{LEFT} = \mathcal{L}_{QED+QCD} + \sum_{i,d} \frac{C_{i,d}^{LEFT}}{\Lambda_{EW}^{d-4}} O_{i,d}^{LEFT}$$

Calculate physical processes at each scale and derive constraints on the UV theory

The HEPfit framework

Open-source tool

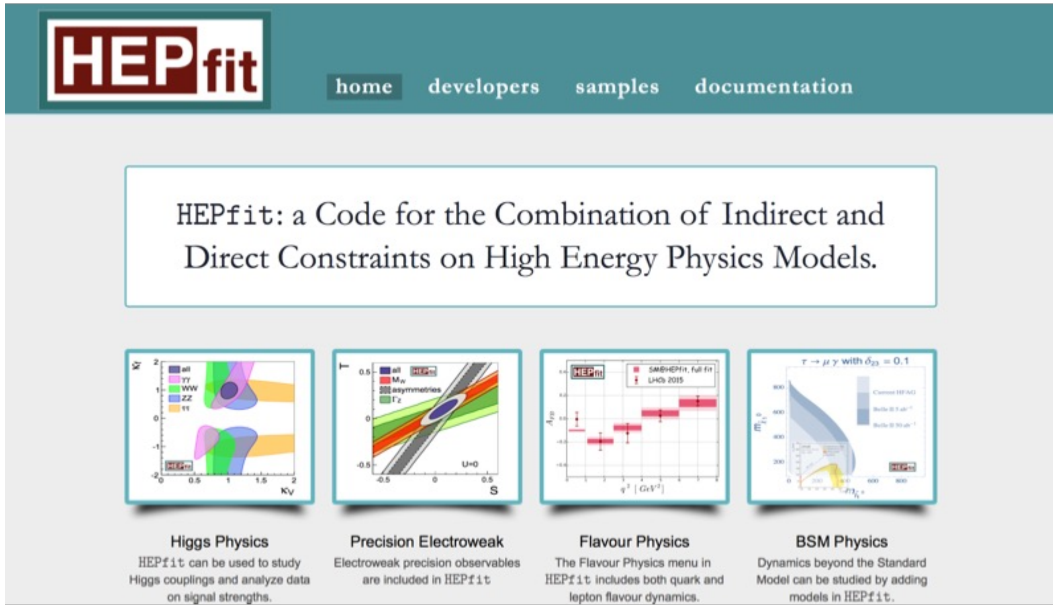
Statistical framework based on a Bayesian MCMC analysis as implemented in
BAT (Bayesian Analysis Toolkit)
Caldwell et al., arXiv:0808.2552

Supports SM (fully implemented) and BSM models, in particular the dim-6 SMEFT

Used for several global fits and future collider projections.

New release includes EW, Higgs, top, and flavour observables in the SM and the SMEFT with

- ❑ SM predictions at NLO or higher.
- ❑ SMEFT at tree level (dim-6 operators only).
- ❑ Linear (and quadratic) effects from dim-6 operators.
- ❑ RGE running of the SMEFT Wilson Coefficients.
- ❑ Fitting both SMEFT and SM parameters.



http://hepfit.roma1.infn.it

J. De Blas et al., 1910.14012

Other existing frameworks for SMEFT global fits:

SMEFiT, Celada et al. 2105.00006, 2302.06660, 2404.12809, 2604.596
Fitmaker, Ellis et al. 2012.02779
Smelli+Wilson+Flavio, Aebischer et al., 1810.07698
Allwicher et al, 2311.00020
Cirigliano et al. 2311.00021
Bartocci et al. 2311.04963, 2412.09674
ATLAS (2604.21670) and CMS (2504.02958)

Include flavour

Beyond EW fits – Higgs, top, DY, flavour observables

Connecting far apart scales naturally lends itself to the EFT framework

Imposing flavour symmetry

Λ_{UV}

SMEFT (~~UV~~)

Constrained by the fit together with SM parameters

$C_{i,d}^{SMEFT}(\Lambda_{UV})$ (from **matching to UV theory**)

Evolved to $C_{i,d}^{SMEFT}(\Lambda_{EW})$ using **RGEsolver++**

Di Noi and Silvestrini, 2210.06838

Based on 1-loop SMEFT anomalous dimension

Jenkins, Manohar, and Trott, 1308.2627, 1310.4838,1312.2014

Λ_{EW} (t,H,W,Z)

At Λ_{EW} observables are calculated in terms of $C_{i,d}^{SMEFT}(\Lambda_{EW})$

LEFT (~~t,H,W,Z~~)

Evolved to $C_{i}^{LEFT}(\Lambda_{b,c,..})$

Match to LEFT operators to calculate flavour observables In terms of $C_{i}^{LEFT}(\Lambda_{b,c,..})$

Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270

Λ_b (B)

Λ_c (D)

Λ_s (K)

Notice that LO RGE uses one-loop evolution matched with tree-level matrix elements and matching (at Λ_{EW} and $\Lambda_{b,c,s}$)

SMEFT predictions

A given observable will be written as

$$O_{\mathrm{SMEFT}} = \underbrace{O_{\mathrm{SM}}}_{\text{SM: including SM higher-order corrections}} + \underbrace{\Delta O^{(1)}}_{\text{SMEFT: tree level + SM K-factors}} + \Delta O^{(2)} + \cdots$$

Observables have been calculated either analytically and via parametrizations reported in the literature (e.g. EW observables) or obtained using various tools (analytic results, MG5_aMC@NLO or in-house codes with **SMEFTci2**, a new UFO file developed for this study, Feynart+Feyncalc, …)

Including direct and indirect SMEFT effects from dim-6 operators up to O(1/Λ^4), **by A. Goncalves**

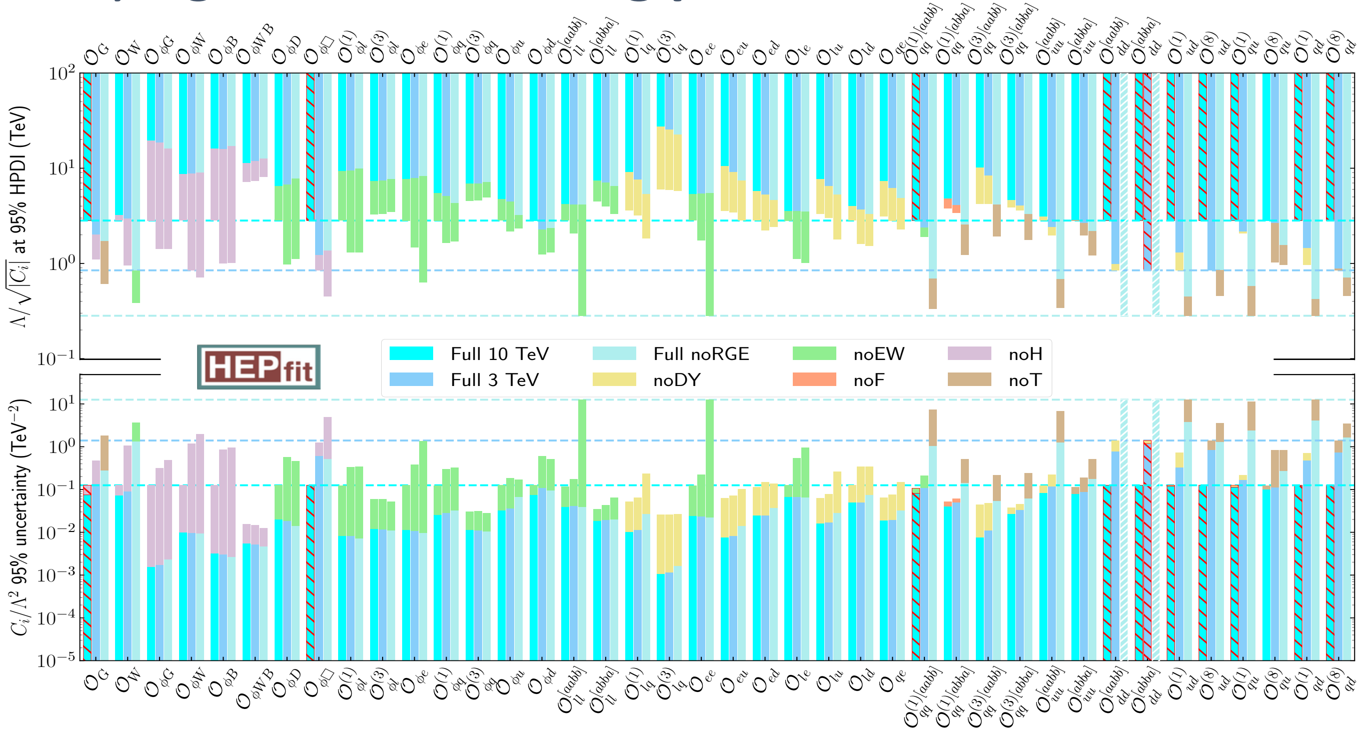
See also, SmeftFR-v3, Dedes et al. 2302.01353

Athanasios Dedes (Fri-w1), *From operators to observables: SmeftFR as an engine to SMEFT phenomenology*

UV theory flavour symmetry: $U(3)^5\ (Q_L, u_R, d_R, L_L, e_R)$

De Blas, Goncalves, Miralles, L.R., Silvestrini, Valli, 2507.06191, *JHEP* 03 (2026) 013

Studying the **constraining power of different sets of observables** and the **effect of RGE**



- **Fit individual operators** (one $C_i(\Lambda) \neq 0$ at a time, multiple $C_i(\mu)$ induced by RGE)
- Choose scales such that LO RGE effects can be relevant ($\log(\mu_1^2/\mu_2^2) \geq 2$)
- $\Lambda = 1, 3, 10$ TeV → reach of current/future colliders
- **Between different Λ: not a simple rescaling** because of RGE effects

Lower half: uncertainty on C_i/Λ reported as half of the 95% HPDI (high posterior density interval)

Upper half: lower bound on $\Lambda/\sqrt{|C_i|}$ from the maximum of the 95% HPDI of $|C_i|$

(since no interval is driven away from zero at 95% probability, we can only put a lower bound)

Dashed lines: perturbativity bounds ($|C_i| \sim 4\pi$)

Red shades: posteriors touches the edges of the prior (truncated) → need better measurements

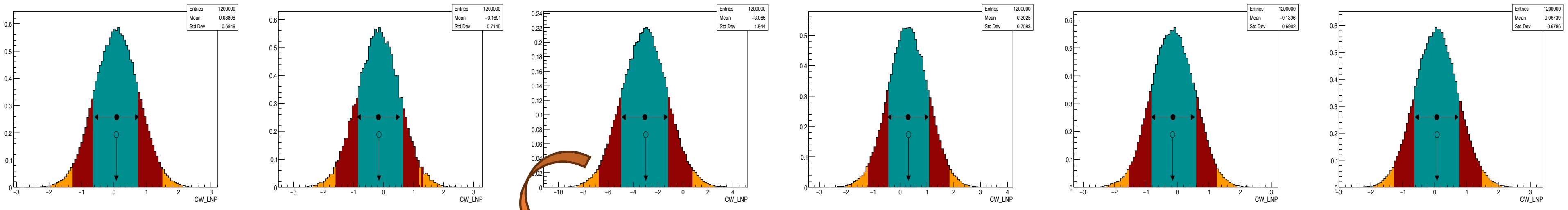
White shades: posterior completely flat → need more observables

For illustration (C_W)

All 95% intervals compatible with C_W=0: the bounds on C_W/Λ^2 can only establish a lower bound on Λ

No RGE ($\Lambda = 1$ TeV)

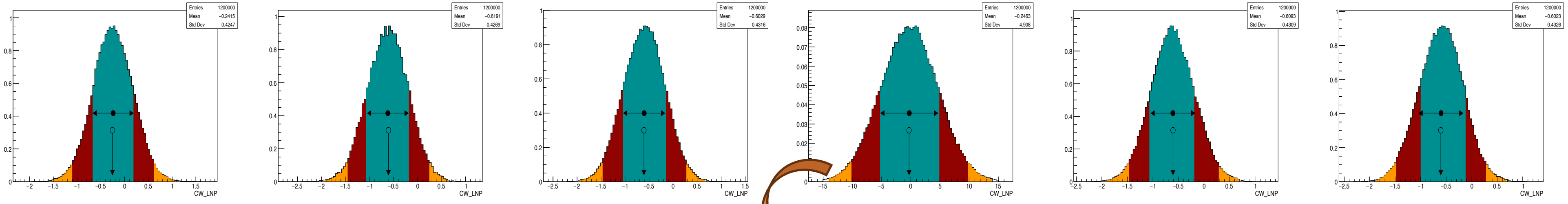
Full fit | No Flavor | No EW | No Higgs | No top | No DY



much broader range

No RGE: EW obs. are the strongest constraint

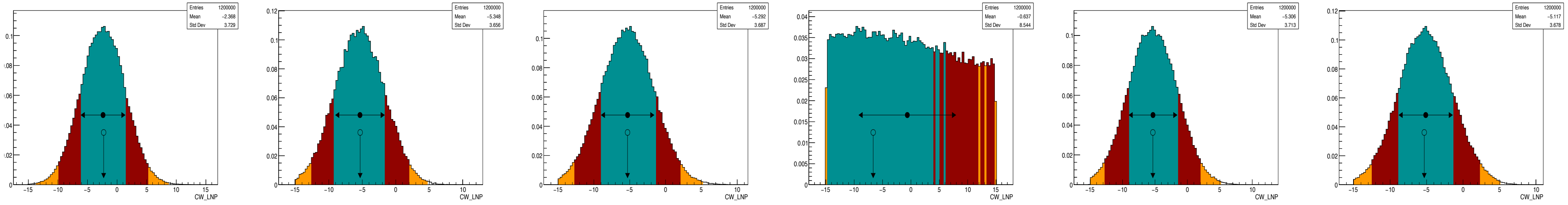
With RGE, $\Lambda = 3$ TeV



much broader range

With RGE, $\Lambda = 3$ TeV Higgs obs. are the strongest constraint

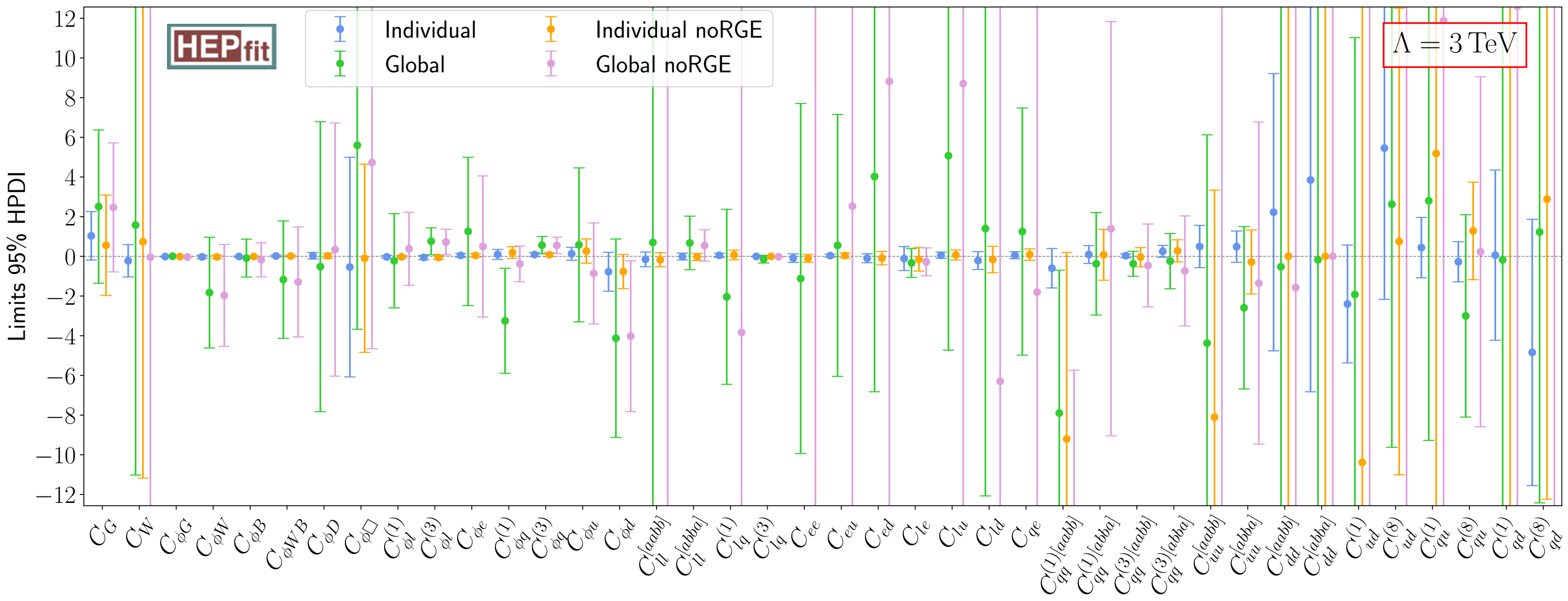
With RGE, $\Lambda = 10$ TeV



All ranges broader than for $\Lambda = 3$ TeV

With RGE, $\Lambda = 10$ TeV Higgs obs. are the strongest constraint, but overall less constrained.

$U(3)^5$ case: individual vs global fit



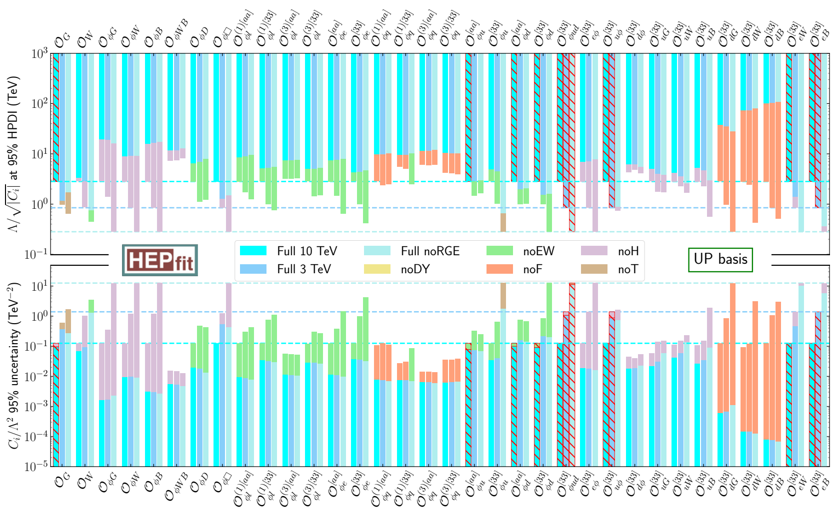
Already quite relevant input to model building!

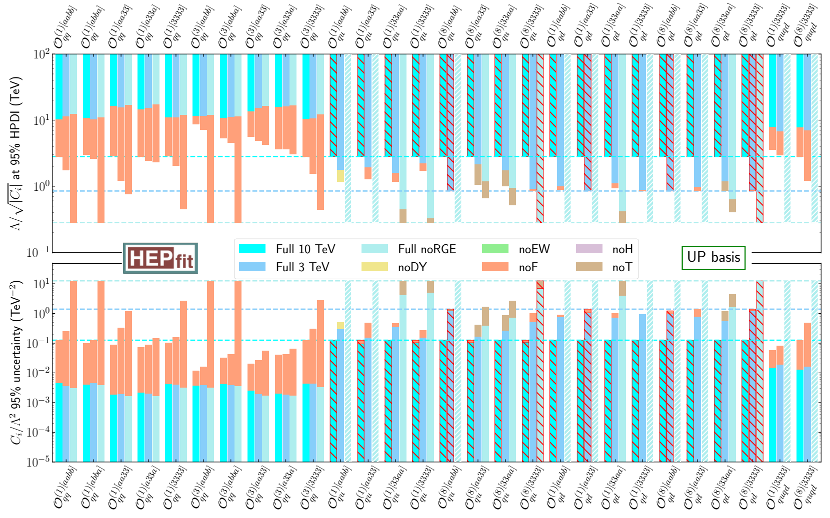
- In general (both individual and global): **adding more observables lift degeneracies but leaves strong correlations**
- Although bounds get diluted in the global fit, both with and without RGE, **the effect of RGE is still quite visible**.

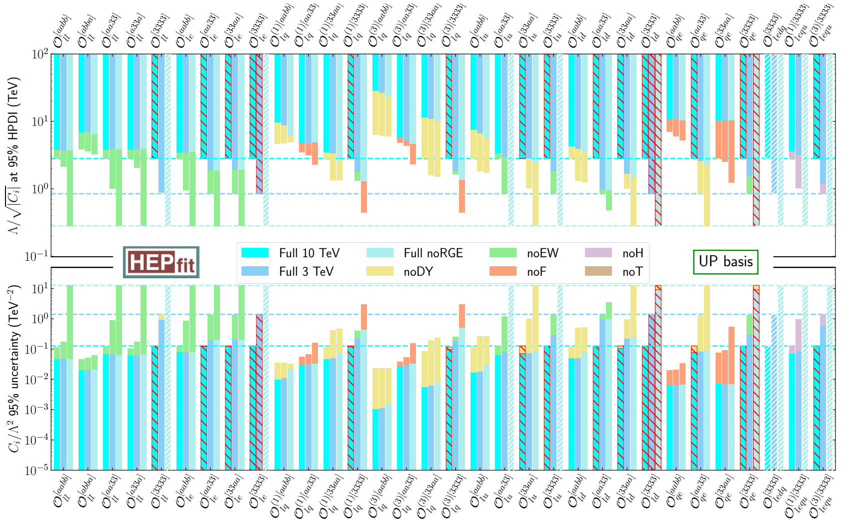
- Global fits, if really global, are **numerically heavy**. Adding all existing measurements may prevent the fit from converging or requires taking a lot of educated choices: fine balance between higher information and better convergence.

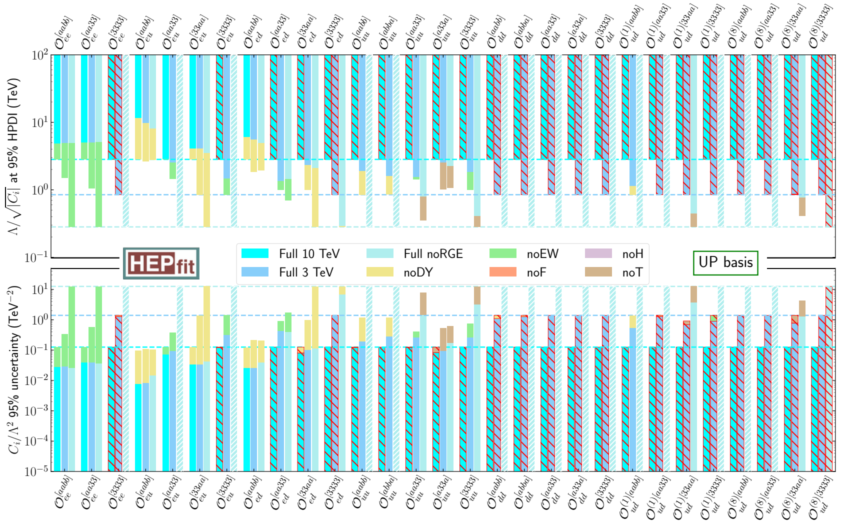
UV theory flavour symmetry: $U(2)^5$, testing third family

The **impact of a non flavour-blind choice**. More scenarios can be explored.









124 operators (123 if not considering $O_\phi = \left(\phi^\dagger\phi\right)^3$)

Main flavour constraints coming from:

- $B \to X_s\gamma$ (O_{dG}, O_{dW}, O_{dB})
- $B_s \to \mu^+\mu^-$ ($O_{qe}^{[ijlk]}$)
- meson mixing ($O_{qq}^{(1,3)}$)

In summary, some lessons

- Extending **precision fits** beyond EW observables, allows to **connect Higgs, top, and flavour physics**, and test EFT extensions of SM at an unprecedented level.
- **Global fits** are **computational very heavy**.
- Improving the **precision of experimental measurements and theoretical predictions** can add crucial **constraining power to EFT global fits.**
- The **scale evolution (RGE) of the EFT coefficients** can be very relevant.
- Physics-based **sets of observables** have **very specific impact**. Important to determine what matters most.

Where do we go from here?

To maximize the potential of EFTs in the HL-LHC era

- Let's kick off this discussion, and continue it while we add more perspectives during this workshop.

Two related discussion sessions →

Carmen Diez-Pardos (Thu-w1), *EFT at the LHC: progress, lessons learnt, questions, and directions to make the most out of data.*
Ken Mimasu (Fri-w1), *Mapping data to UV models via EFT fits.*

➢ Improve accuracy and interpretation of EFT global fits

- SMEFT (+LEFT) NLO RGE evolution: implement 2-loop anomalous dimension, 1-loop matching, and 1-loop matrix elements (QCD+EW)

> Ben Stefanek (Mon-w1), *Charting the path to new physics in the precision era.*
> Anders Eller Thomsen (Thu-w1), *Two-loop SMEFT RGEs.*
> Matthew Forslund (Wed-w2), *The SMEFT at NLO: when do higher orders matter?*

  - ❑ Check consistency, provide missing pieces (if any).
  - ❑ Explore new approaches: unitarity methods?

> Gauthier Durieux (Mon-w1), *Learning about EFTs from unitarity and analyticity*

- Extend frameworks to new EFT approaches (on-shell EFT, HEFT)

> Teng Ma (Tue-w1), *Scattering-amplitude methods in EFTs.*
> Hongkai Liu (Wed-w1), *On-shell amplitudes and EFT.*
> Stefano De Angelis (Fri-w2), *EFT matching with multiple UV scales: a new on-shell approach and magic zeros.*
> Anisha (Thu-w2), *Indirect probes of new physics with HEFT*

Useful for a better estimate of truncation errors?

> Spencer Change (Wed-w1), *Reopening the discussion of EFT truncation*

- Models generate only a handful of operators at the UV scale: useful to do “model inspired fits”?
  - ❑ Different UV flavour assumption already go in that direction, in very general terms.
- Improve fitting tools and procedures: refine statistical methods, explore new methods, AI/ML, …
- Remove SM biases in the interpretation of experimental measurements (PDF, backgrounds, etc.)