EPS-HEP 2025 Conference

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Electroweak, Top and Higgs physics in SMEFT fits

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Based on arXiv: 2507.06191 [hep-ph], in collaboration with

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Introduction

- Effective Field Theories have become the one of the standards in the field to combine the information from multiple data sets so that it can be interpreted in terms of possible effects beyond the Standard Model
  - ✓ Theoretically robust framework
  - ✓ General description of many classes of models (but still needs assumptions, hence not fully model-independent)
- With some minimal assumptions about the UV, the IR effects of new physics can be parameterized via *the SMEFT Lagrangian*:

$$\mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}}\mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots \longleftarrow \mathcal{L}_{\rm UV}(?)$$

$$E \ll \Lambda$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

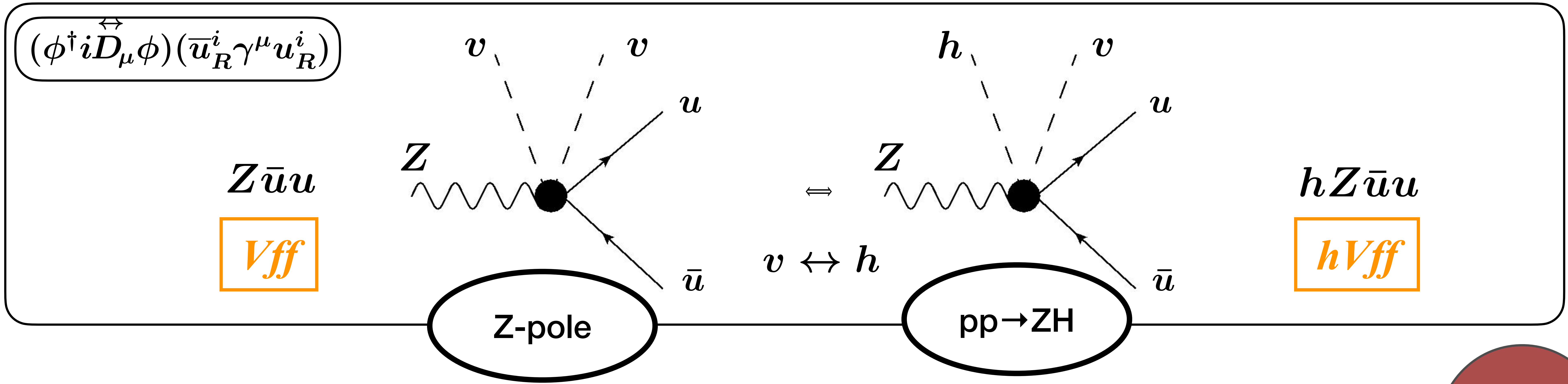
$$q = v, E < \Lambda$$

IR: SM Symmetries & Fields (H in 2~$SU(2)_L$) + Decoupling for $\Lambda \to \infty$

Approximates the effect of any model under these assumptions

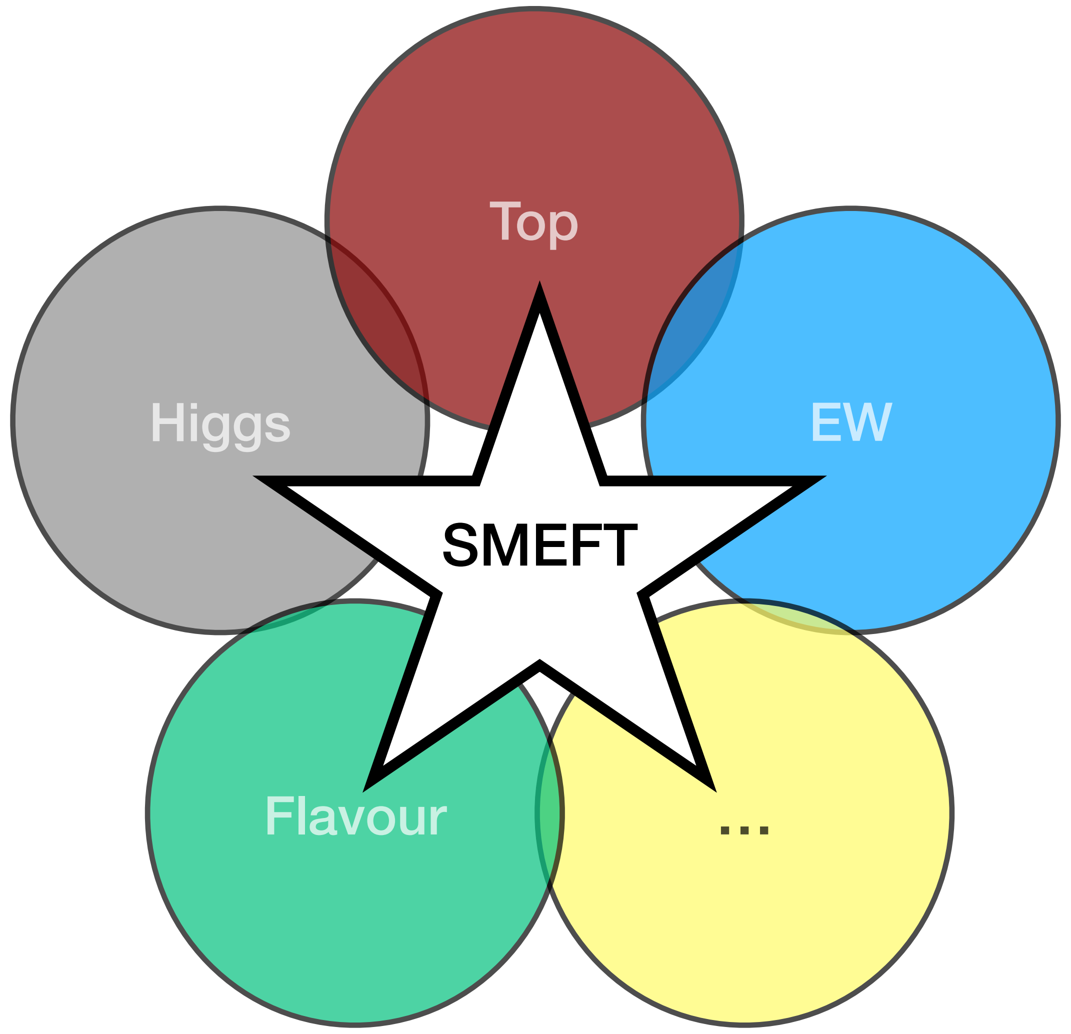
Introduction

- Even at dimension-6 there are many interactions:
  - Assuming B and L conservation → 2499 (Most of these are flavor!)
  - SMEFT theory correlations typically help in constraining these many BSM directions



⇒ ***Global fits to many observables needed to constrain all directions***

Different fitting tools available for this purpose



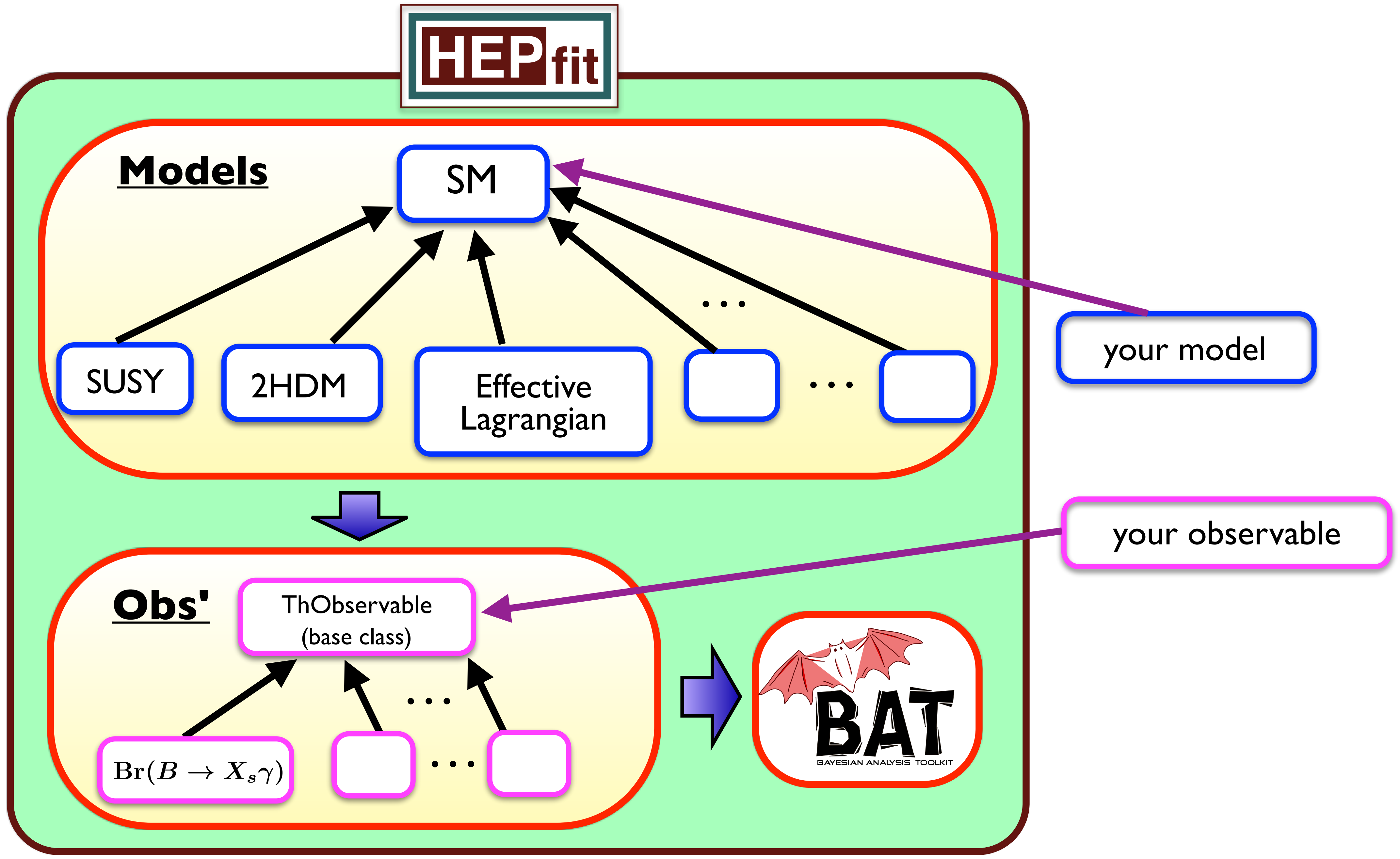
The Fitting Framework

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)

https://github.com/silvest/HEPfit

- Main Reference: **JB et al., Eur. Phys. J. C (2020) 80:456, arXiv: 1910.14012 [hep-ph]**



Designed as flexible open-source tool (e.g. easy to add external models/observables)

Stand-alone mode to compute observable predictions (In the SM & BSM)

MCMC implementation for Bayesian Statistical Analyses (Via modified version of BAT)

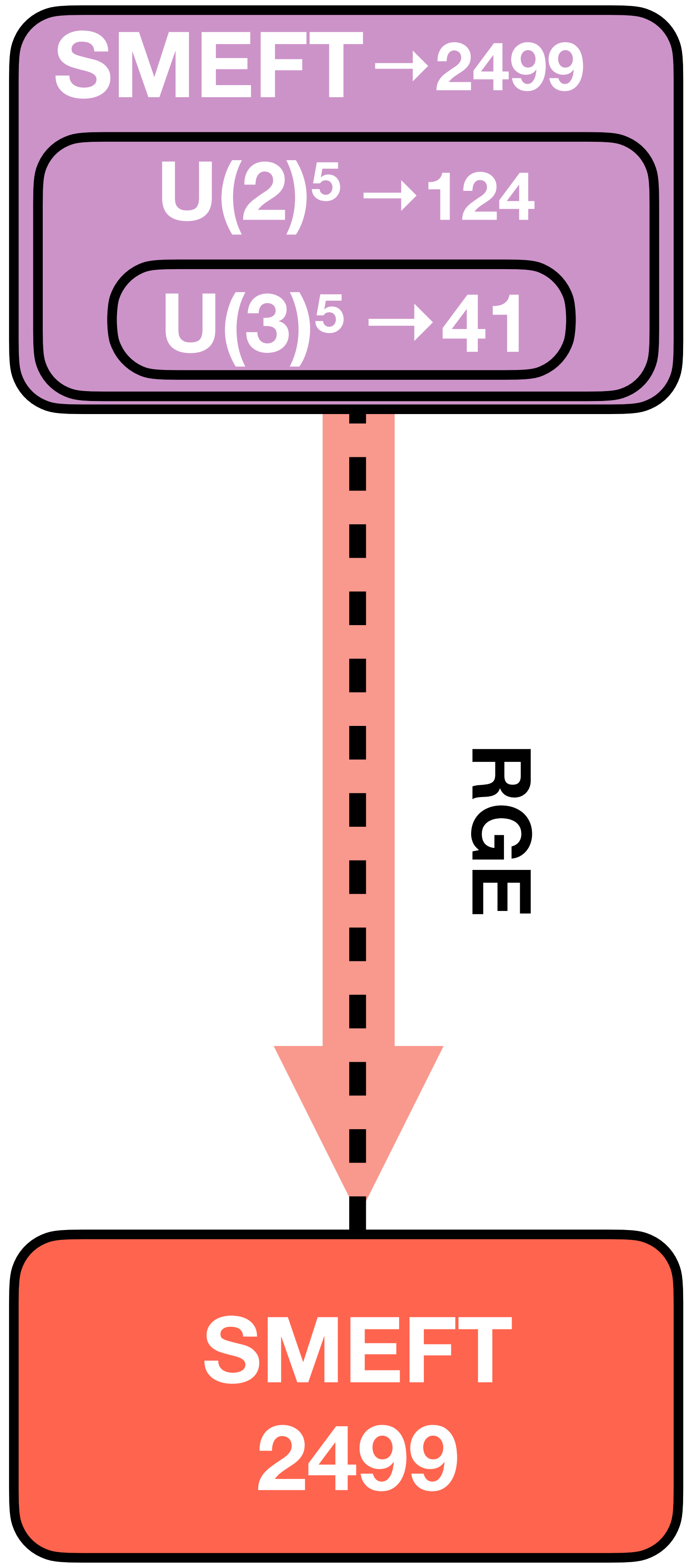
A. Caldwell et al., Comput. Phys. Commun. 180 (2009) 2197-2209

- Original code already containing a base SMEFT class with a setup for EW/Higgs LO studies

➡ Massive upgrades in the work presented here

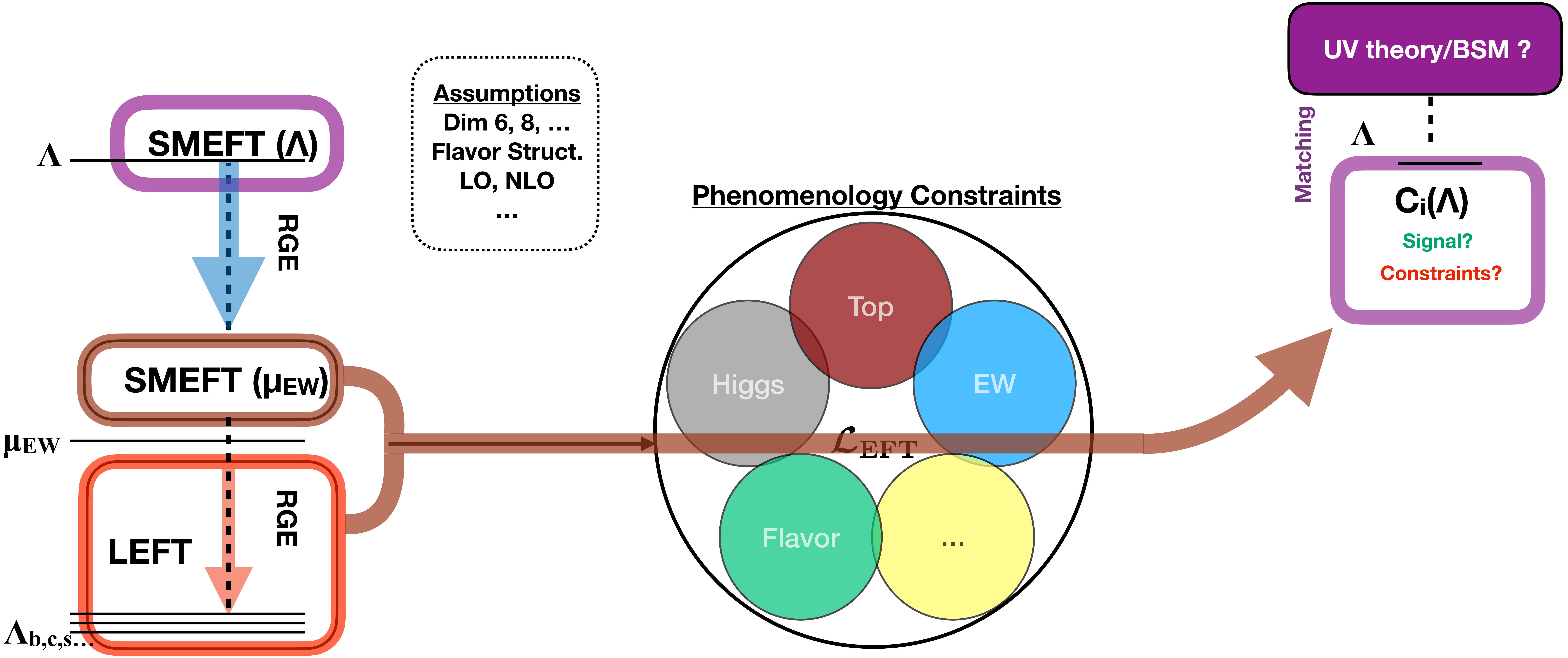
The HEPfit code

- The **SMEFT class** in HEPfit :
- Implementation of full dimension-6 SMEFT basis:
  - Warsaw basis: All 2499 operators
  - Restrictions assuming different flavor assumptions available
    - $U(3)^5$ flavour symmetry
    - $U(2)^5$ flavour symmetry: both in the "UP" and "DOWN" bases
- Calculations in both "α" and "M_W" scheme for most observables
- RGE evolution included via **RGESolver** S. Di Noi, L. Silvestrini, Eur. Phys.J.C 83 (2023) 3, 200
  - Multiple possibilities: Exact integration / Matrix Evolution (much faster)
  - Possibility of RGE to multiple scales
    - **Careful:** RGE available only at LO (1-loop). Running between similar scales < TH unc.
- NLO SMEFT finite terms available for several of the most precise observables
  - **Careful:** Consistent NLO study requires 2-loop RGE. Not available in literature (yet)

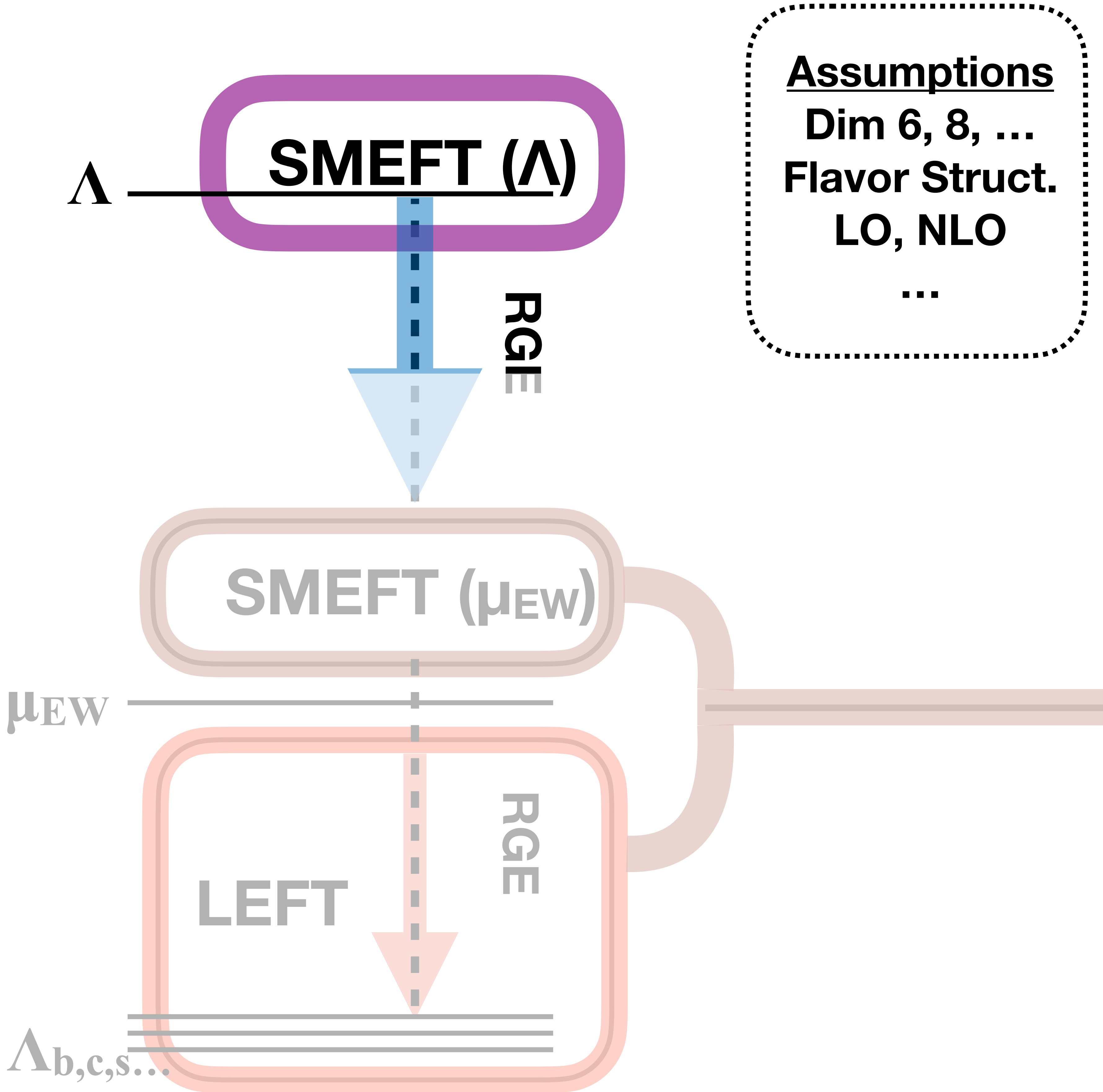


The Global Fit
Combining EW/Higgs/Top/Flavor

The Global SMEFT fit



The Global SMEFT fit



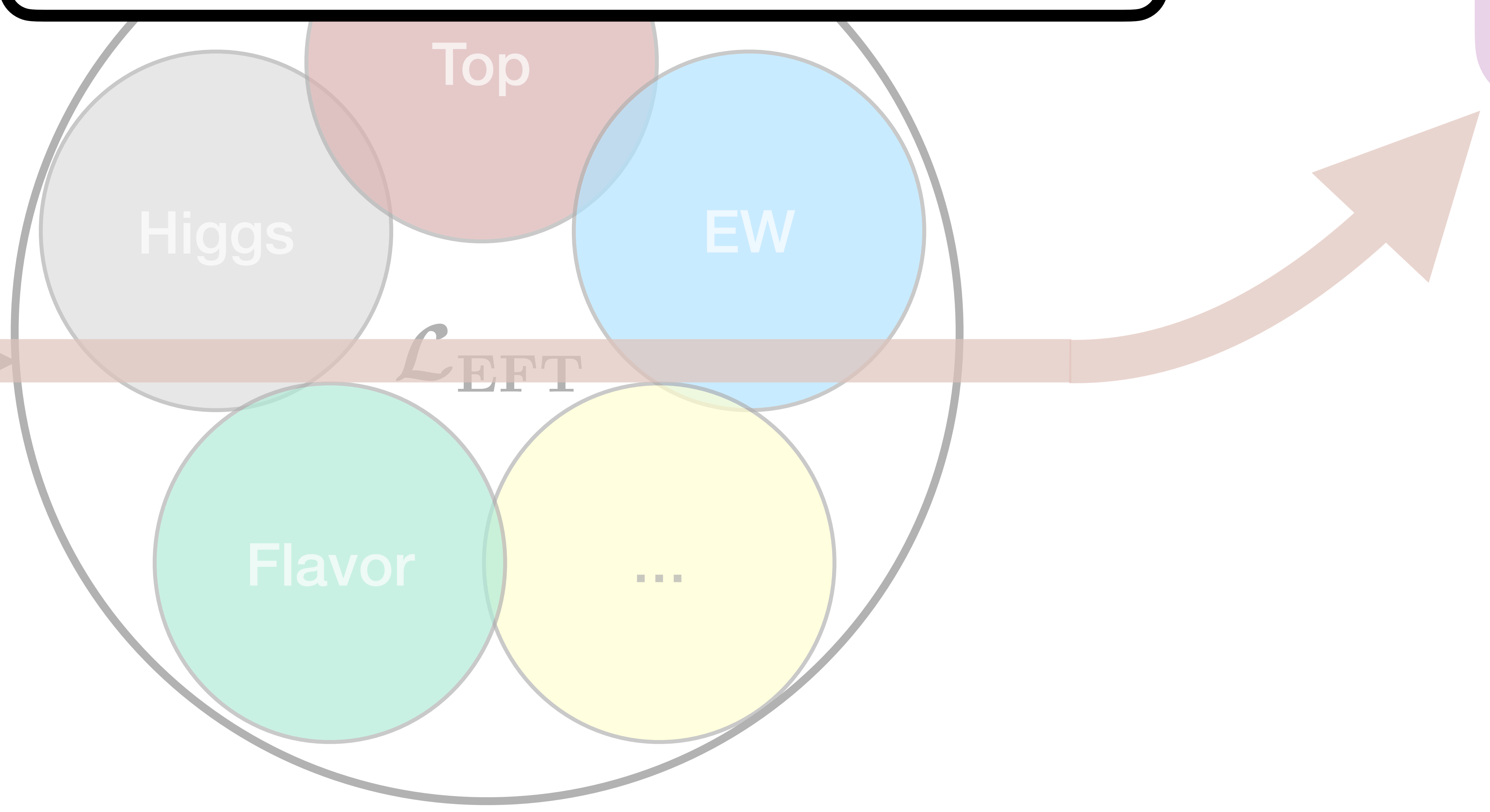
2 choices of flavor assumptions

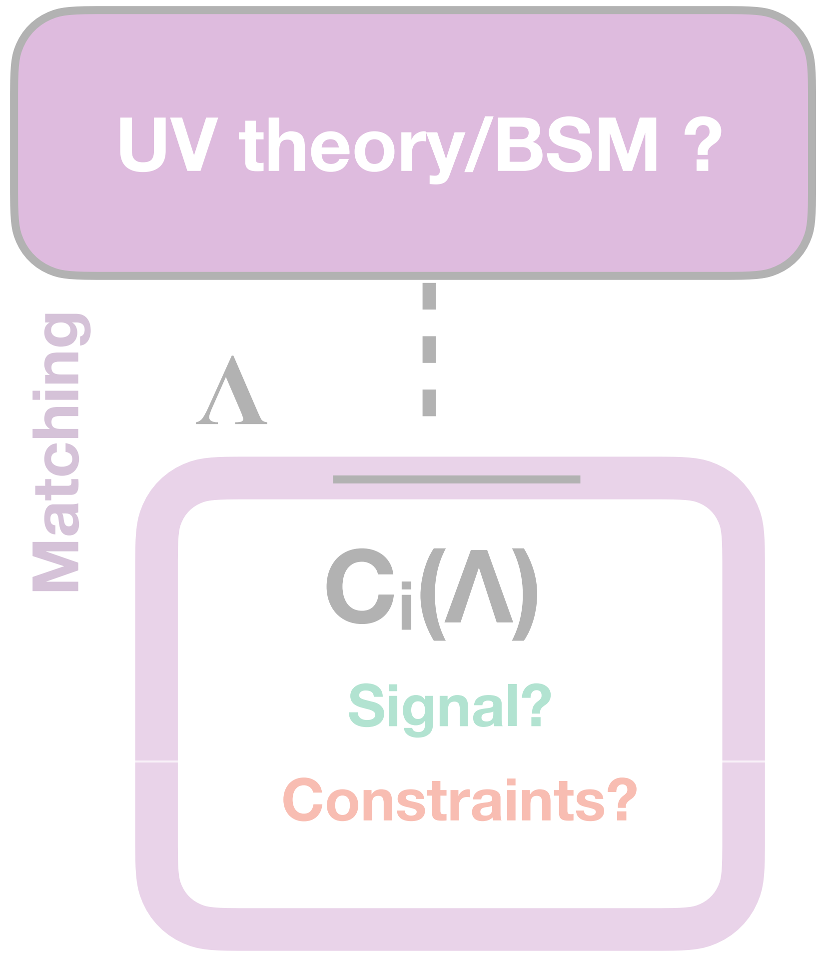
CP + U(3)^5: 41 BSM operators

CP + U(2)^5: 124 BSM operators

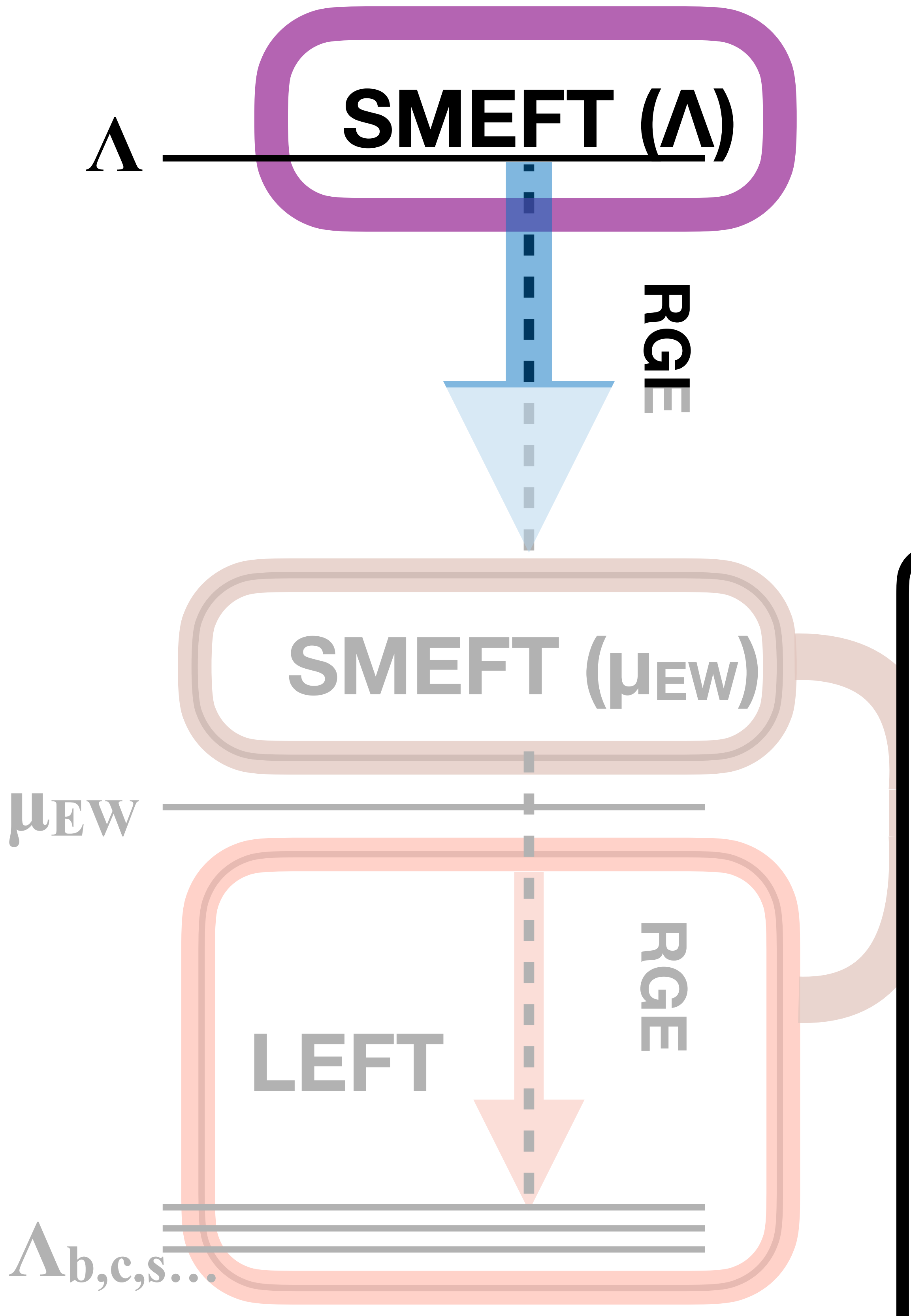
2 choices for Λ = 3, 10 TeV

(Plus scenario w/o RGE)





The Global SMEFT fit



Assumptions
Dim 6, 8, …
Flavor Struct.
LO, NLO
…

2 choices of flavor assumptions

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2 choices for Λ = 3, 10 TeV

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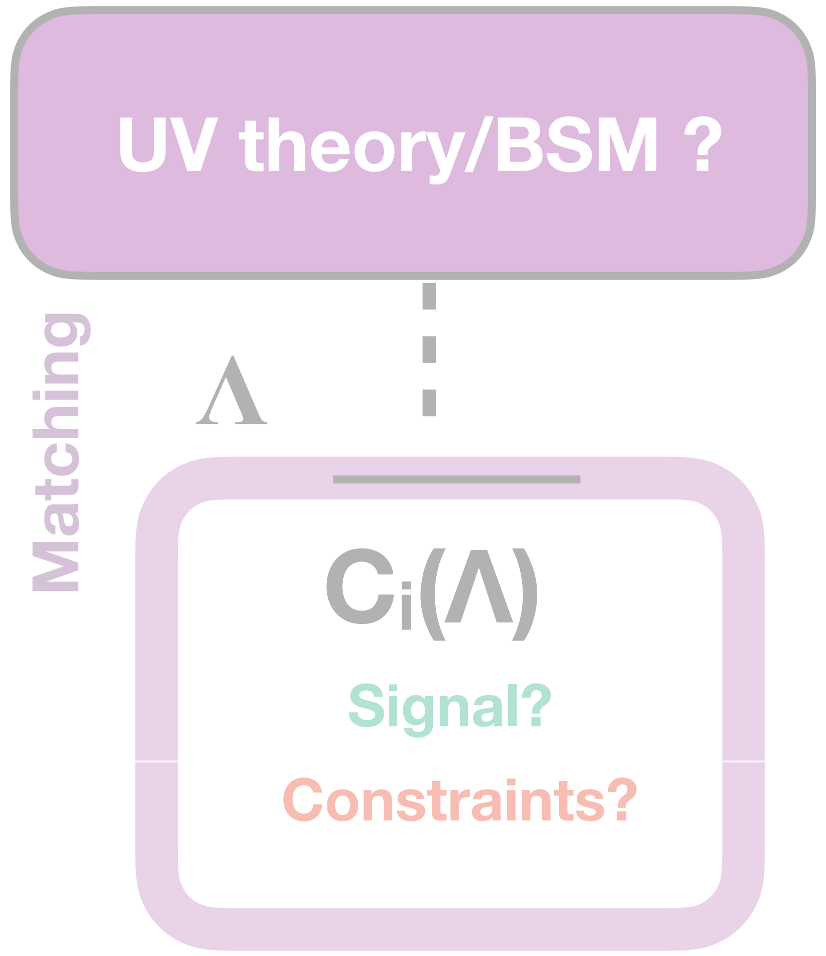
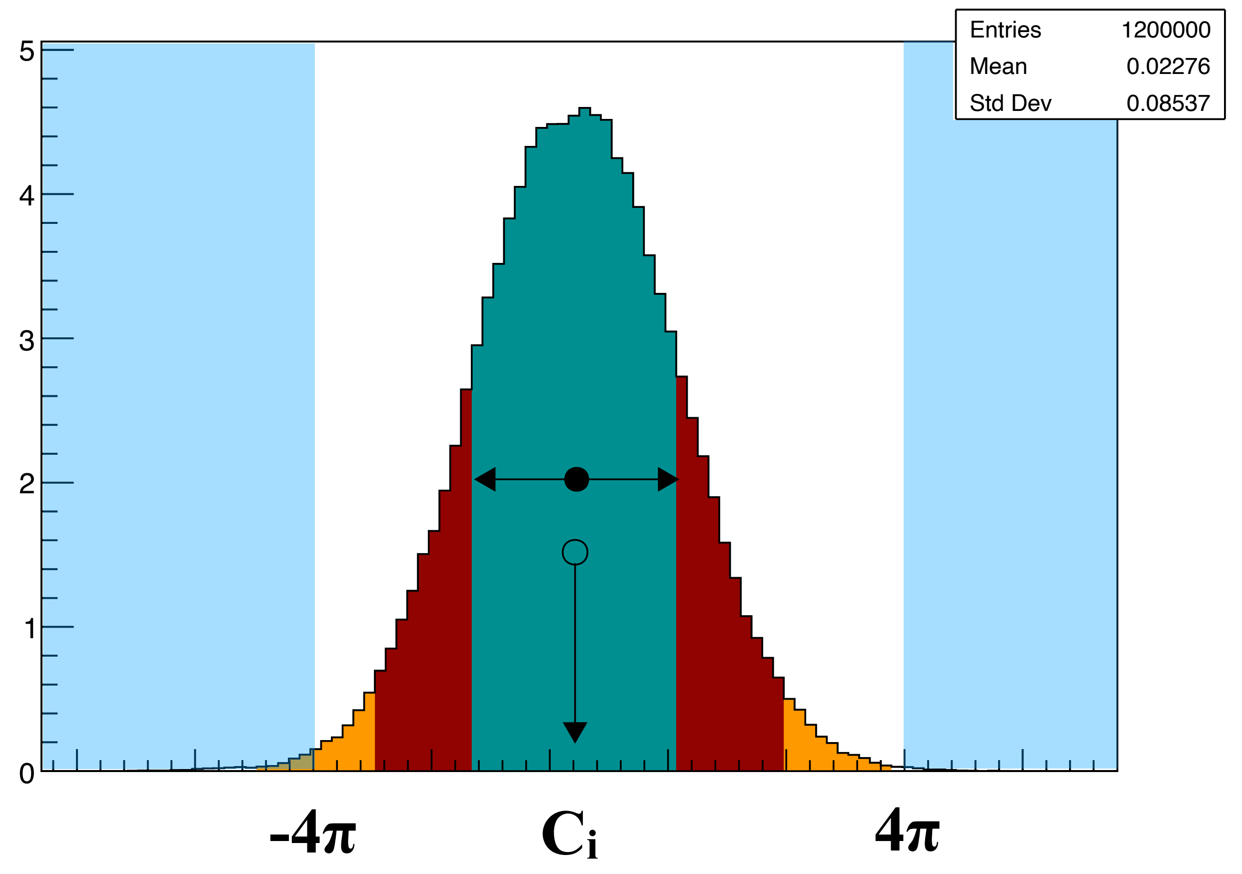


New Physics priors

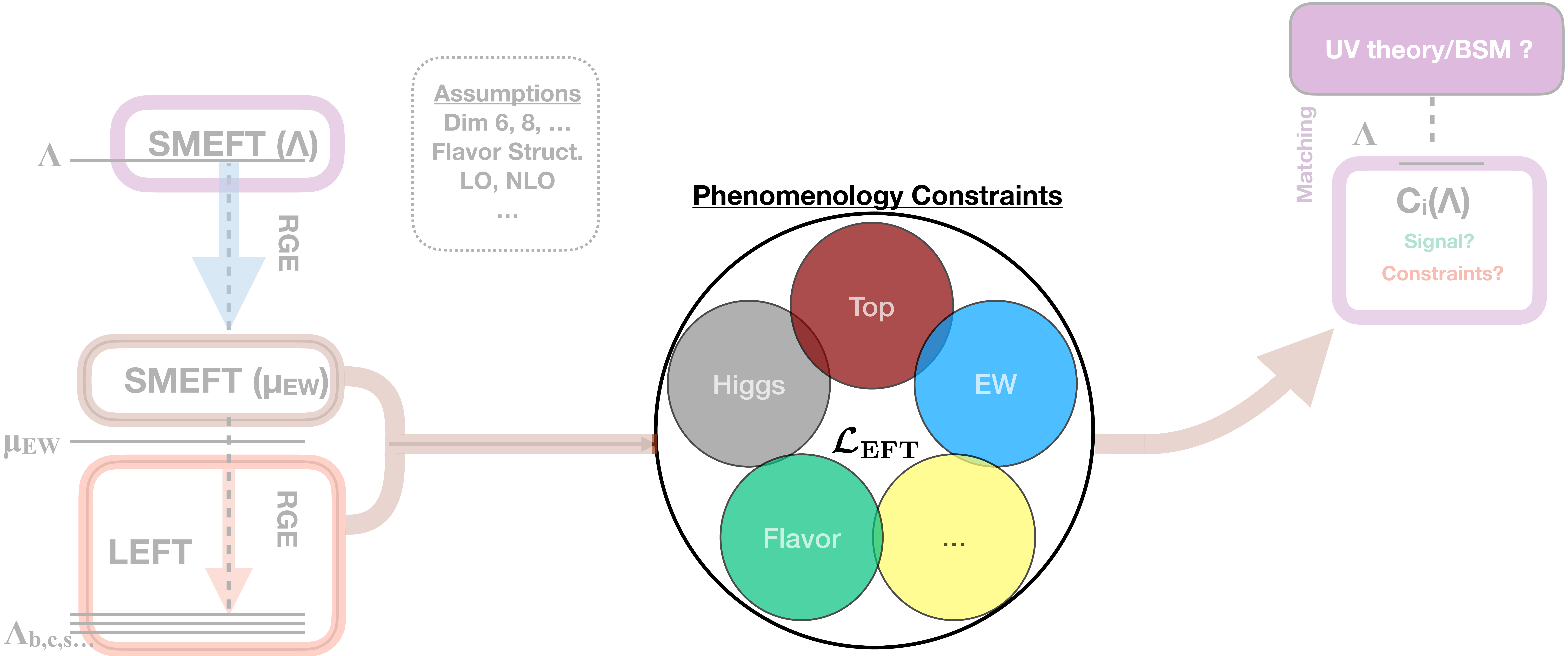


To ensure perturbative EFT expansion we impose flat prior for all WC:

$C_i(\Lambda) \in [-4\pi, 4\pi]$

(Other choices possible within HEPfit)

The Global SMEFT fit

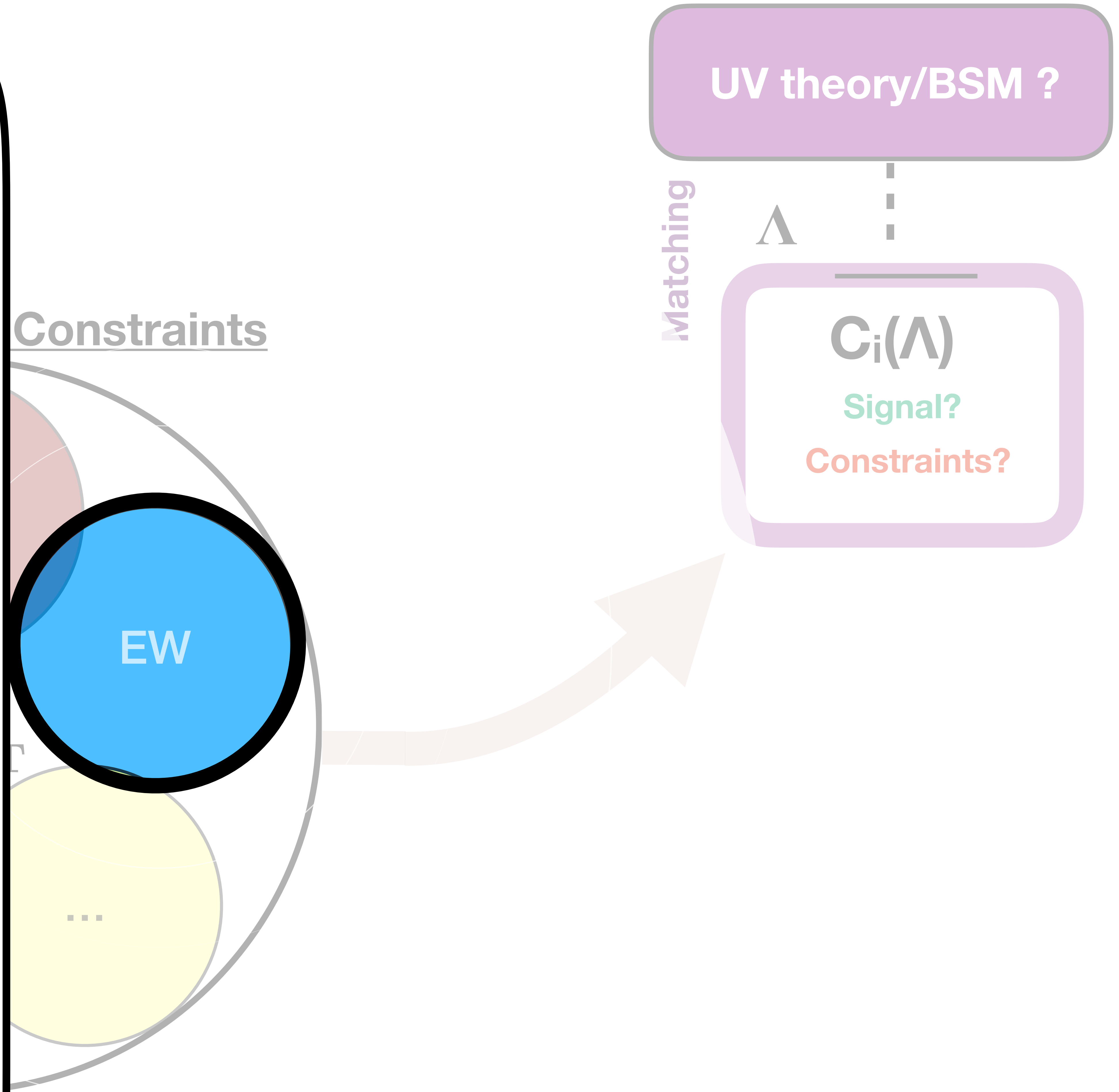


The Global SMEFT fit

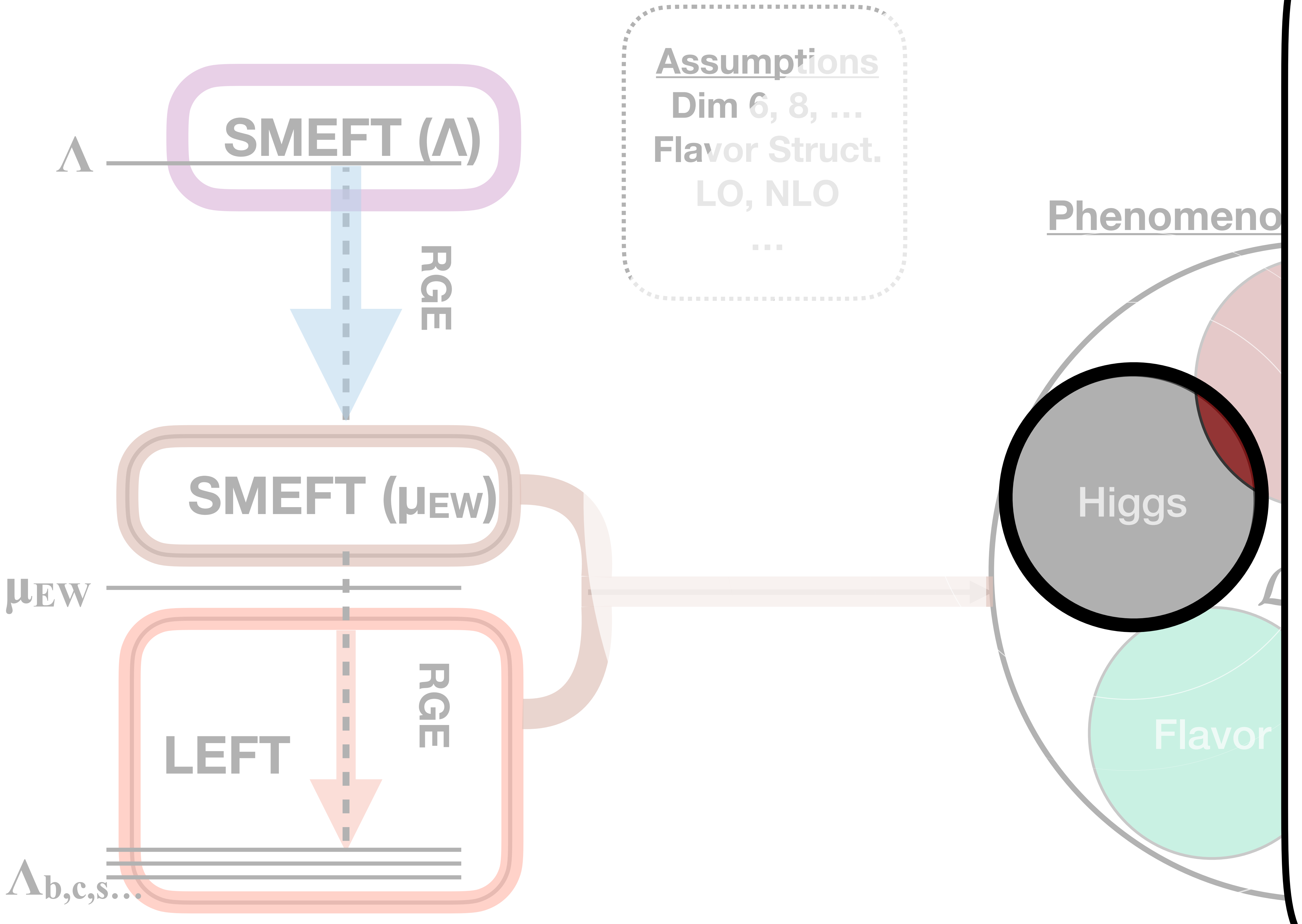
Electroweak Observables

- Electroweak Precision Observables:
  - Z-pole (LEP/SLD): $\Gamma_Z,\ A_f,\ A^f_{FB},\ R_f,\ \ldots$
  - W properties (LEP2/Tevatron/LHC): $M_W,\ \Gamma_W,\ \mathrm{BR}_{\ell^i\nu}$
  - Higgs and Top properties (Tevatron/LHC): $M_H,\ m_t$
  - Tests of lepton universality from Tevatron & LHC
- LEP2 observables
  - Di-Boson: $e^+e^- \to W^+W^-$ Berthier et al., 1606.06693 [hep-ph]
  - $e^+e^- \to f\bar{f}$: leptonic cross sections and asymmetries, hadronic cross section
- Drell-Yan at LHC: $pp \to \ell^+\ell^-,\ \ell\nu$
  - Differential distributions
  - Implemented from HighPT code

L. Allwicher et al., 2207.10756, 2207.10714 [hep-ph]



The Global SMEFT fit

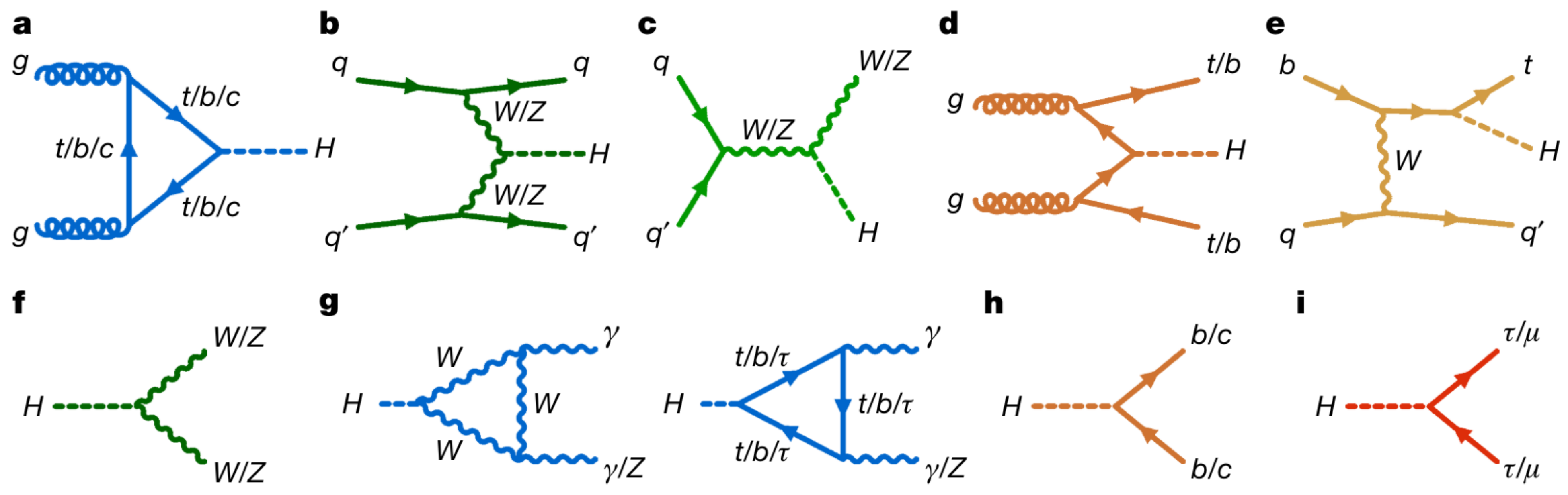


Higgs Boson Observables

- ATLAS+CMS 8 TeV combination for single strengths:

$$\mu_{ij} = \frac{\sigma_i \times BR_j}{(\sigma_i \times BR_j)_{\rm SM}}$$

- ATLAS and CMS 13 TeV results (139 fb^{-1})
  - STXS Stage 1.2 binning
- Including full information on all available channels (production and decay)

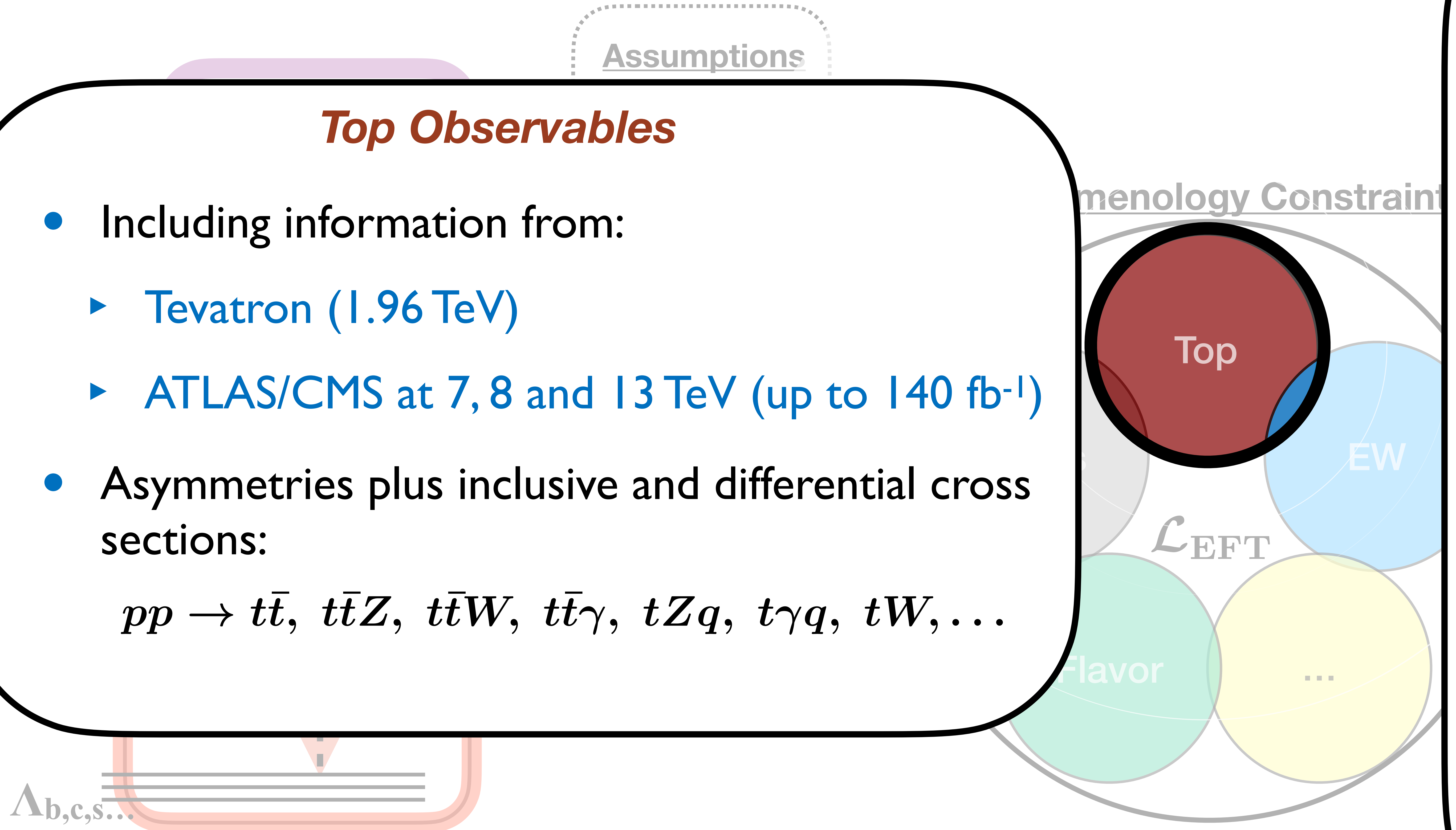


The Global SMEFT fit

Top Observables

- Including information from:
  - Tevatron (1.96 TeV)
  - ATLAS/CMS at 7, 8 and 13 TeV (up to 140 fb^{-1})
- Asymmetries plus inclusive and differential cross sections:

$$pp \to t\bar{t},\ t\bar{t}Z,\ t\bar{t}W,\ t\bar{t}\gamma,\ tZq,\ t\gamma q,\ tW, \ldots$$



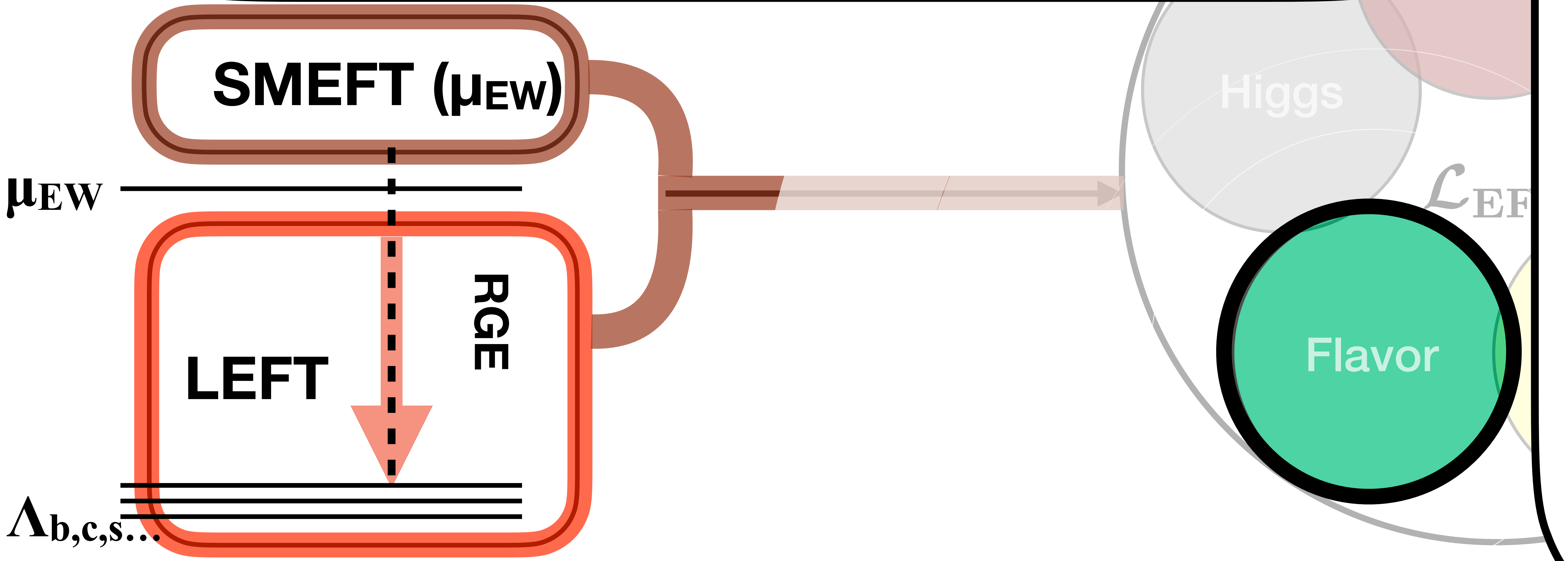
Top Observables

Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$
$p\bar{p} \to t\bar{t}$	$dA_{FB}^{t\bar{t}}/dm_{t\bar{t}}$	1.96 TeV	9.7 fb^{-1}
$pp \to t\bar{t}$	$\sigma_{t\bar{t}}^{13TeV}/\sigma_{t\bar{t}}^{8TeV}$ $\sigma_{t\bar{t}}^{8TeV}/\sigma_{t\bar{t}}^{7TeV}$ $\sigma_{t\bar{t}}$ $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$ $(d\sigma_{t\bar{t}}/dm_{t\bar{t}})/\sigma_{t\bar{t}}$ $dA_C/dm_{t\bar{t}}$	13 & 8 TeV 8 & 7 TeV 13 TeV 13 TeV 13 TeV 13 TeV	20 & 36 fb^{-1} 20 & 5 fb^{-1} 36/139 fb^{-1} 36 fb^{-1} 36/137 fb^{-1} 140 fb^{-1}
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$	13 TeV	77.5/140 fb^{-1}
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$	13 TeV	140 fb^{-1}
$pp \to t\bar{t}W$	$\sigma_{ttW^\pm}$ $\sigma_{ttW^+}/\sigma_{ttW^-}$	13 TeV	140 fb^{-1}
$t \to Wb$	$F_0,\ F_L$	8 TeV 13 TeV	20 fb^{-1} 140 fb^{-1}
$pp \to tW$	σ	7 TeV 8 TeV 13 TeV	4.6 & 1.5 fb^{-1} 20 fb^{-1} 3.2/140 fb^{-1}
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV 13 TeV	20 fb^{-1} 140 fb^{-1}
$pp \to tq$ (t-ch)	σ	7 TeV 8 TeV 13 TeV	4.6 & 1.5 fb^{-1} 20 fb^{-1} 36/140 fb^{-1}
$pp \to t\gamma q$	σ	13 TeV	140/36 fb^{-1}
$pp \to tZq$	σ	13 TeV	140 fb^{-1}
$pp \to t\bar{t}b\bar{b}$	σ	13 TeV	36 fb^{-1}
$pp \to t\bar{t}t\bar{t}$	σ	13 TeV	140 fb^{-1}

The Global SMEFT fit

Flavour Observables

- Several ΔF=1, 2 observables included
- Relevant for determination of CKM elements and set bounds on FCNC
- Computed in the LEFT (integrate W/Z/H/Top)
  - RGE to each relevant scale implemented directly for the different observables
- SM pars. (CKM and hadronic) also free in the fit



Flavour Observables

Observable	Value
$\Delta m_{B_s}\ (ps^{-1})$	17.765 ± 0.006
ϕ_s	-0.049 ± 0.019
A^s_{sl}	-0.0006 ± 0.00028
$\Delta m_{B_d}\ (ps^{-1})$	0.5069 ± 0.0019
$S_{J/\psi K_S}$	0.692 ± 0.016
A^d_{sl}	-0.0021 ± 0.0017
$\Delta M_K\ (ns^{-1})$	5.293 ± 0.009
ϵ_K	$(2.228 \pm 0.011) \times 10^{-3}$
$\phi^M_{12} (^\circ)$	1.9 ± 1.6
$\mathrm{BR}(B \to \tau\nu) \times 10^4$	1.09 ± 0.24
$\mathrm{BR}(D \to \tau\nu) \times 10^4$	9.9 ± 1.2
$\mathrm{BR}(D \to \mu\nu) \times 10^4$	3.981 ± 0.089
$\mathrm{BR}(D_s \to \tau\nu) \times 10^3$	5.31 ± 0.11
$\mathrm{BR}(D_s \to \mu\nu) \times 10^2$	5.37 ± 0.10
$\Gamma(K \to \mu\nu)/\Gamma(\pi \to \mu\nu)$	1.3367 ± 0.0029
$\mathrm{BR}(\pi \to \mu\nu) \times 10^5$	3.8408 ± 0.0007
$d\Gamma(B \to D\ell\nu)/dw$	$[\Delta\Gamma_i/\Delta w]_{10\times 10}$
$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) \times 10^{10}$	1.175 ± 0.365
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.49 ± 0.19
$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \times 10^9$	3.41 ± 0.29

The Global SMEFT fit

All Observables computed consistently to dimension 6

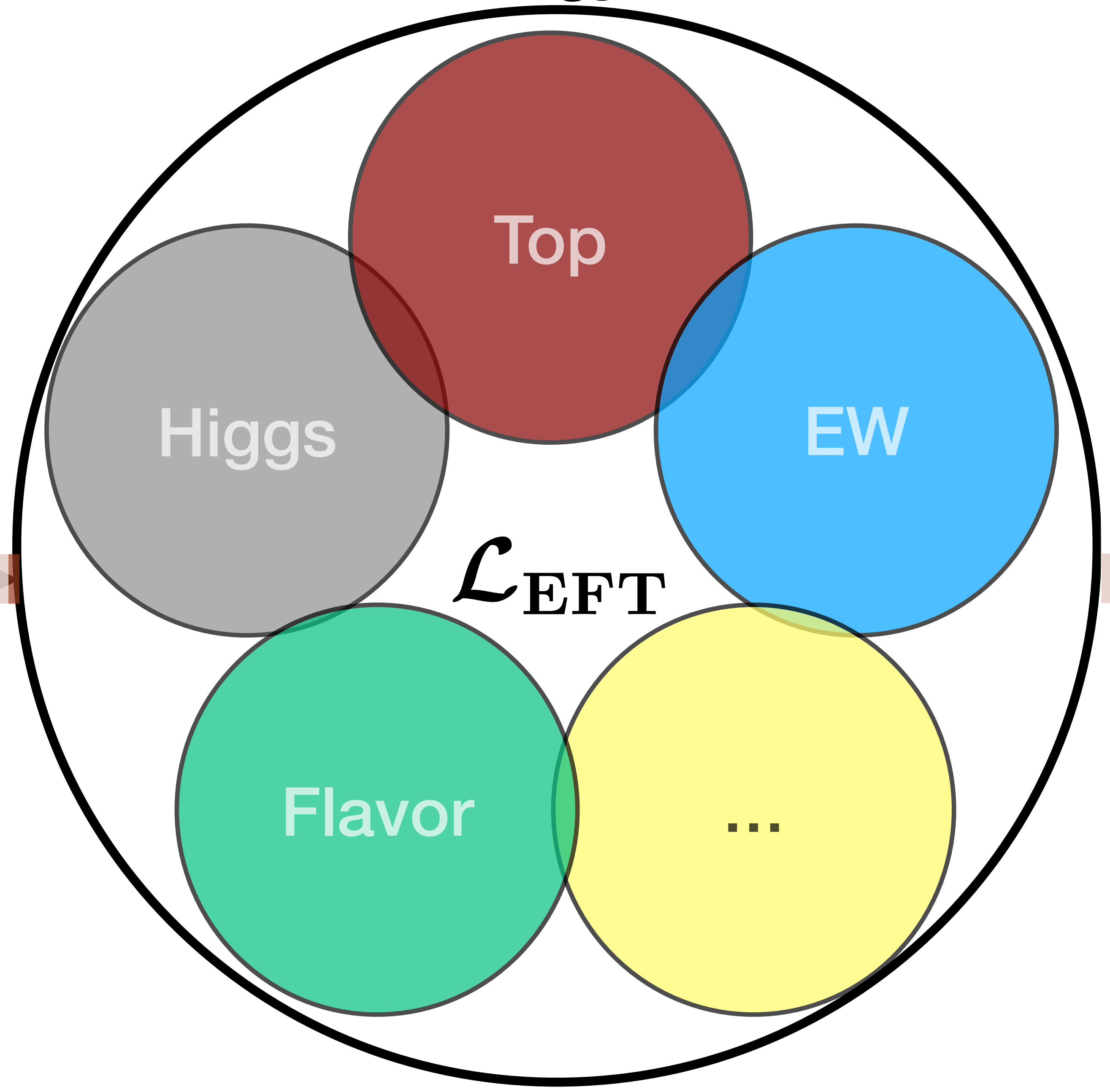
$$O = O_{\rm SM} + \delta O_{\rm NP} \frac{1}{\Lambda^2}$$

$$O_{\rm SM}$$

State-of-the-art for SM predictions in most precise observables (EWPO, Flavour)

SM parameters (EW and flavor) floated in the fit, together with all the Wilson Coefficients

Phenomenology Constraints



$$\delta O_{\rm NP} \frac{1}{\Lambda^2}$$

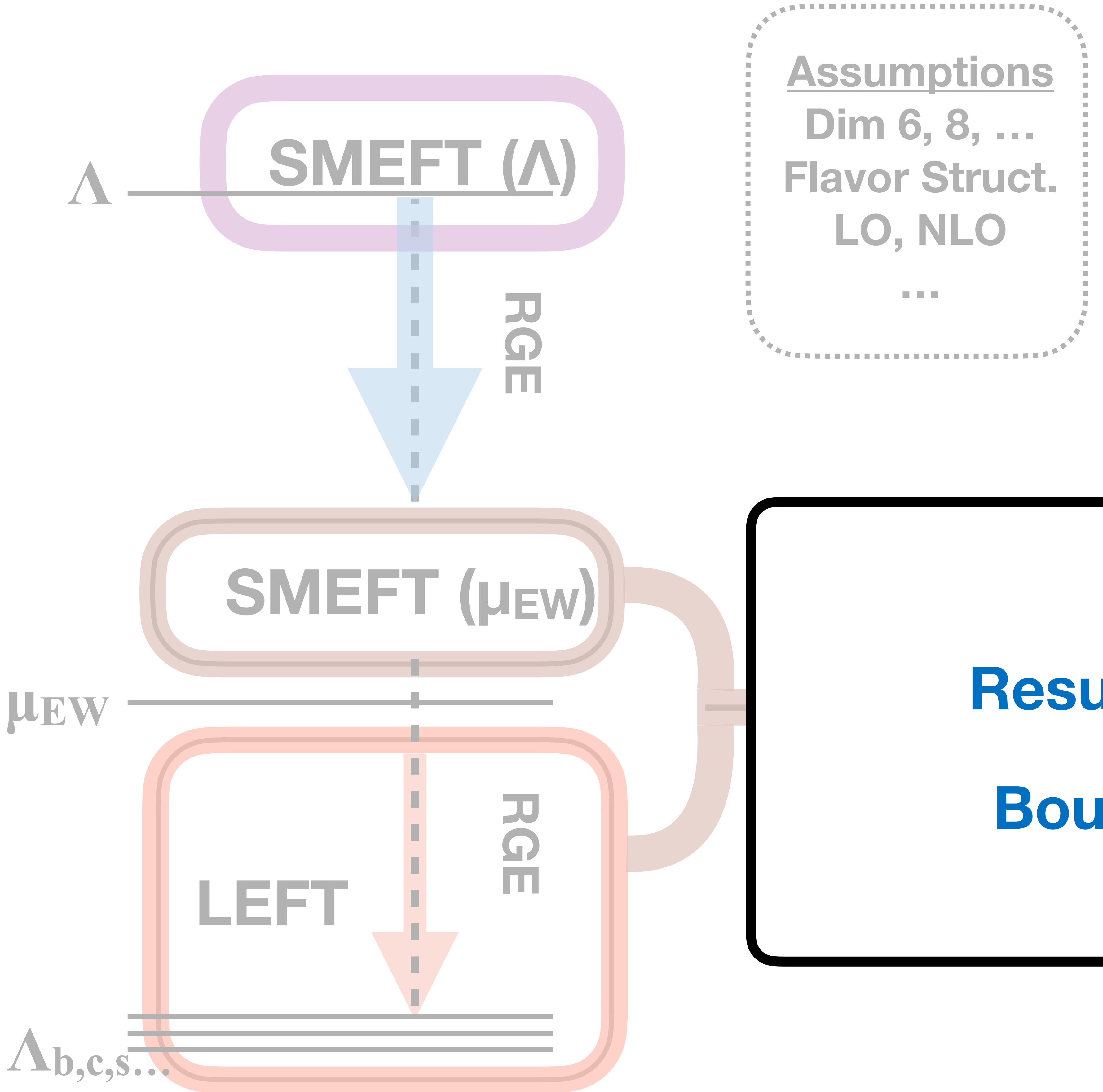
Current knowledge of SMEFT RGE (1-loop) limits a consistent calculation to an RG improved LO analysis:

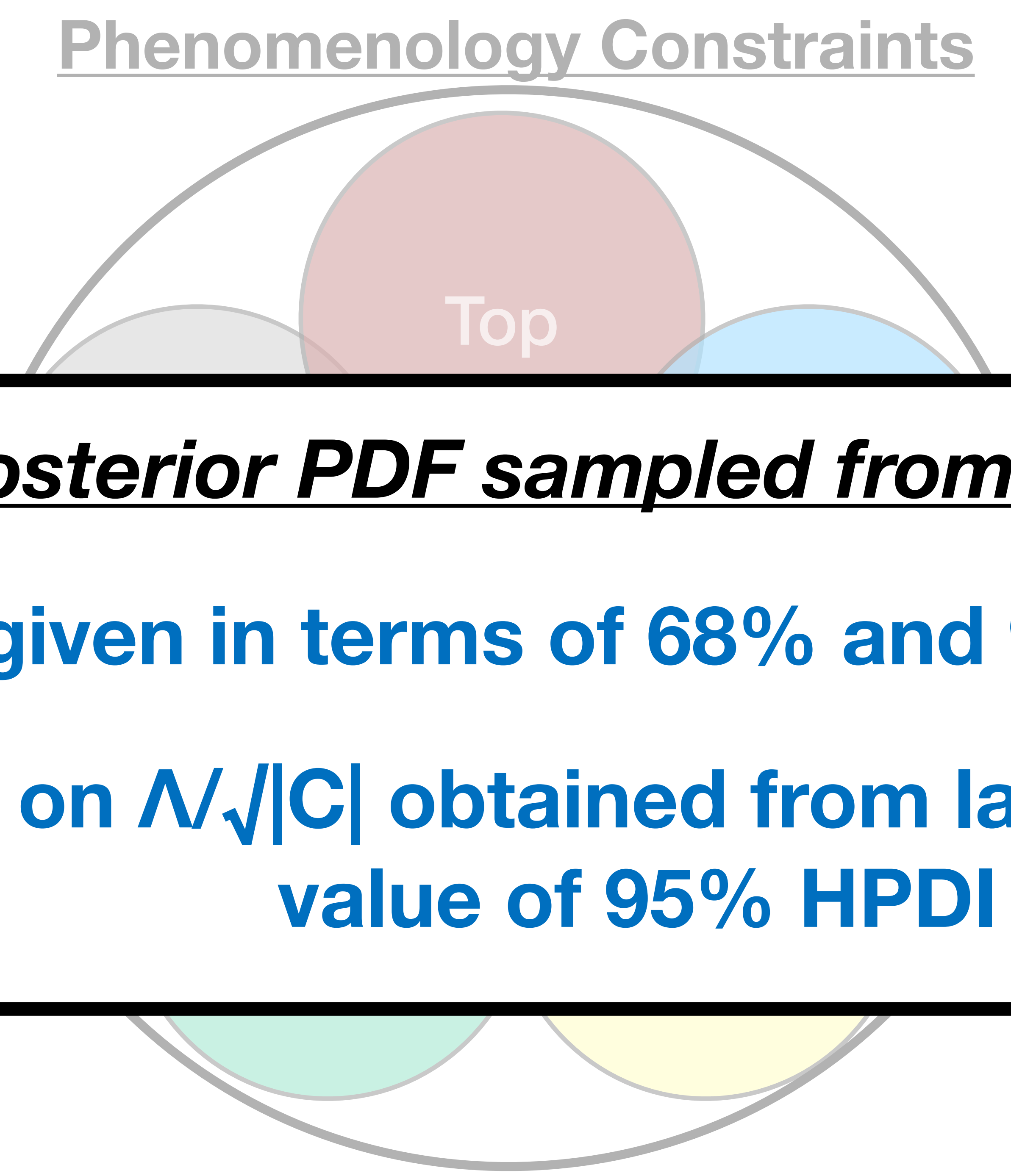
$\Lambda \to \mu_{EW} \to \Lambda_{b,c,s}$

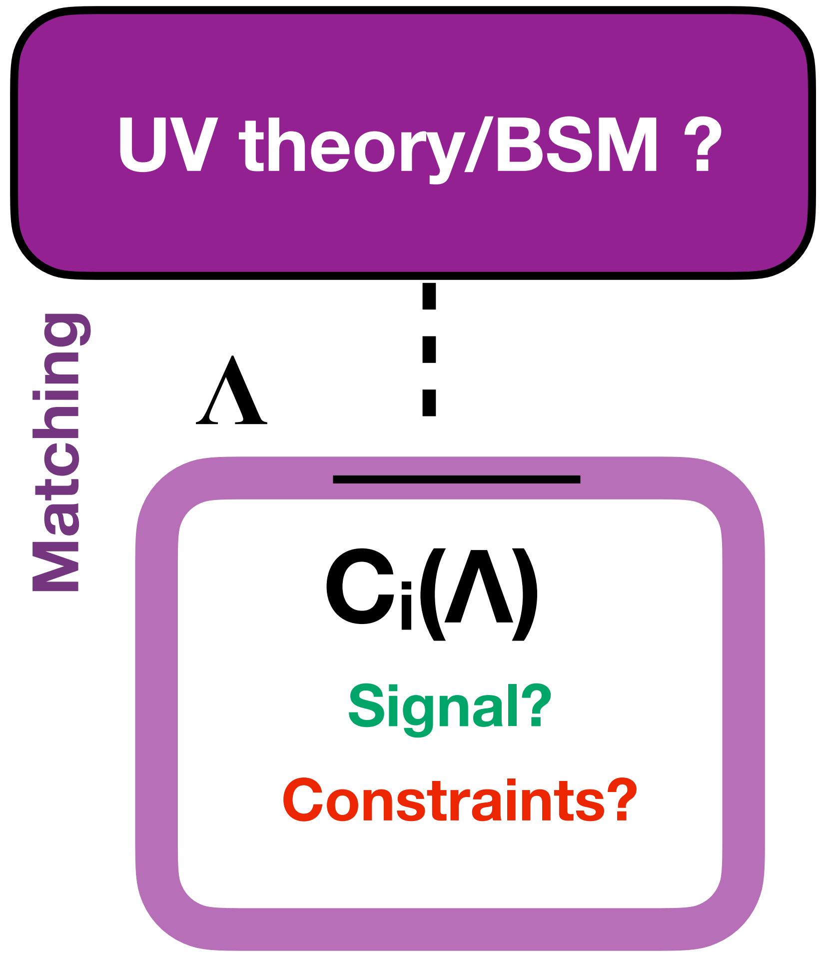
LO computed in M_W scheme:

- *Analytically for most EW/ Flavour observables*
- *Via MG5@NLO or* **HighPT** *for LHC observables*

The Global SMEFT fit







<u>Posterior PDF sampled from MCMC</u>

Results given in terms of 68% and 95% HPDI on $C_i(\Lambda)$

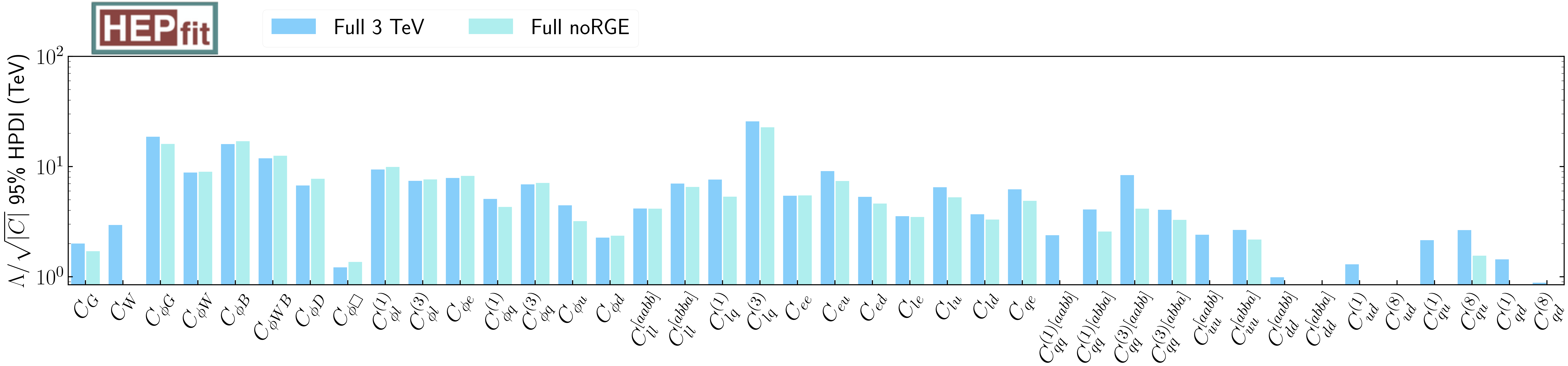
Bounds on $\Lambda/\sqrt{|C|}$ obtained from largest absolute value of 95% HPDI

Some fit results
Combining EW/Higgs/Top/Flavor

*More details tomorrow in Flavor parallel session

SMEFT fit results: U(3)^5

Comparison of individual fit results: Impact of RGE effects



With few (notable) exceptions, moderate impact of RGE effects in individual bounds:

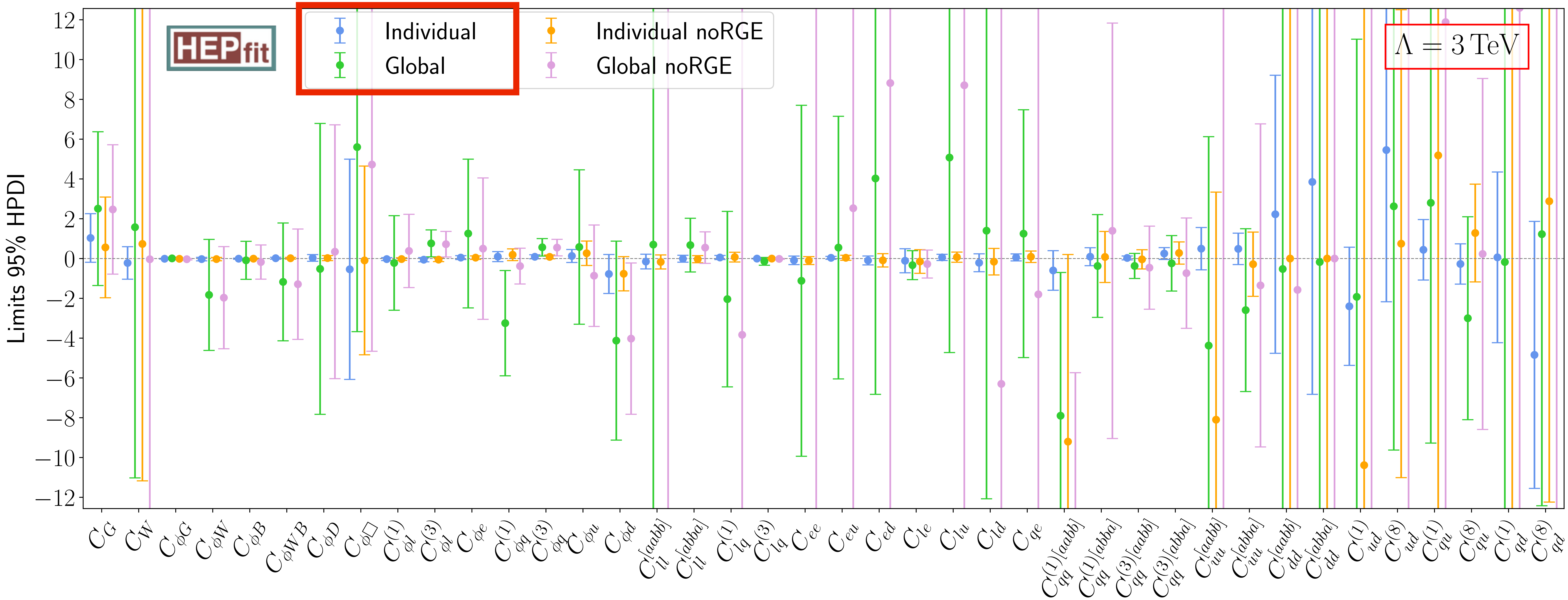
LH 4Q: Constrained by Top observables at LO → DY/EW/Flav via Logs

CW: Weak bound from diBoson/Higgs at LO → RG mixing with C_{HW}, C_{HB} strengthens Higgs bounds

⇒ At the level of individual fits, due to RG effects, for Λ=3 TeV most limits controlled by EW/Higgs

SMEFT fit results: U(3)^5

Comparison of individual vs. global fit results



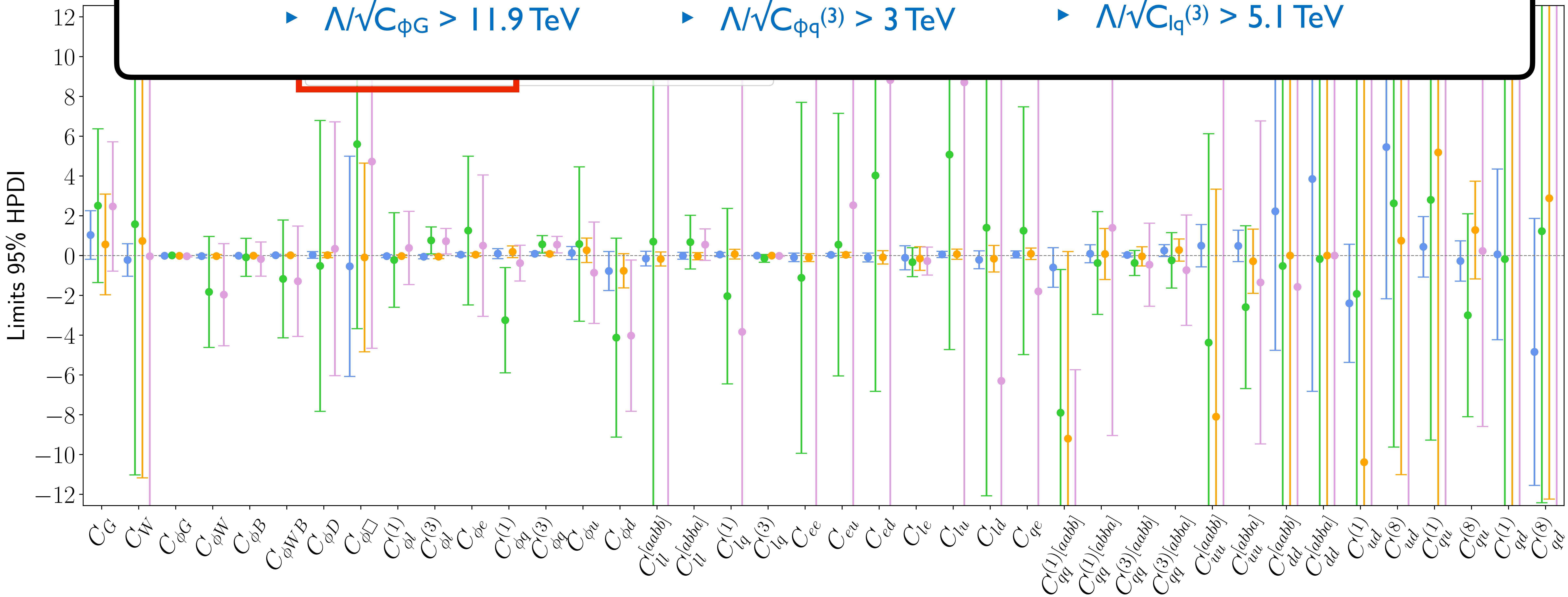
Strong correlations between coefficients significantly relax the bounds but many operators can still be constrained

Similar conclusions about the impact of RG effects observed at the level of the global fit (more prominent in some cases)

SMEFT fit results: U(3)⁵

Noteworthy limits that remain in the global fit

- $\Lambda/\sqrt{C_{\phi G}} > 11.9$ TeV
- $\Lambda/\sqrt{C_{\phi q}^{(3)}} > 3$ TeV
- $\Lambda/\sqrt{C_{lq}^{(3)}} > 5.1$ TeV

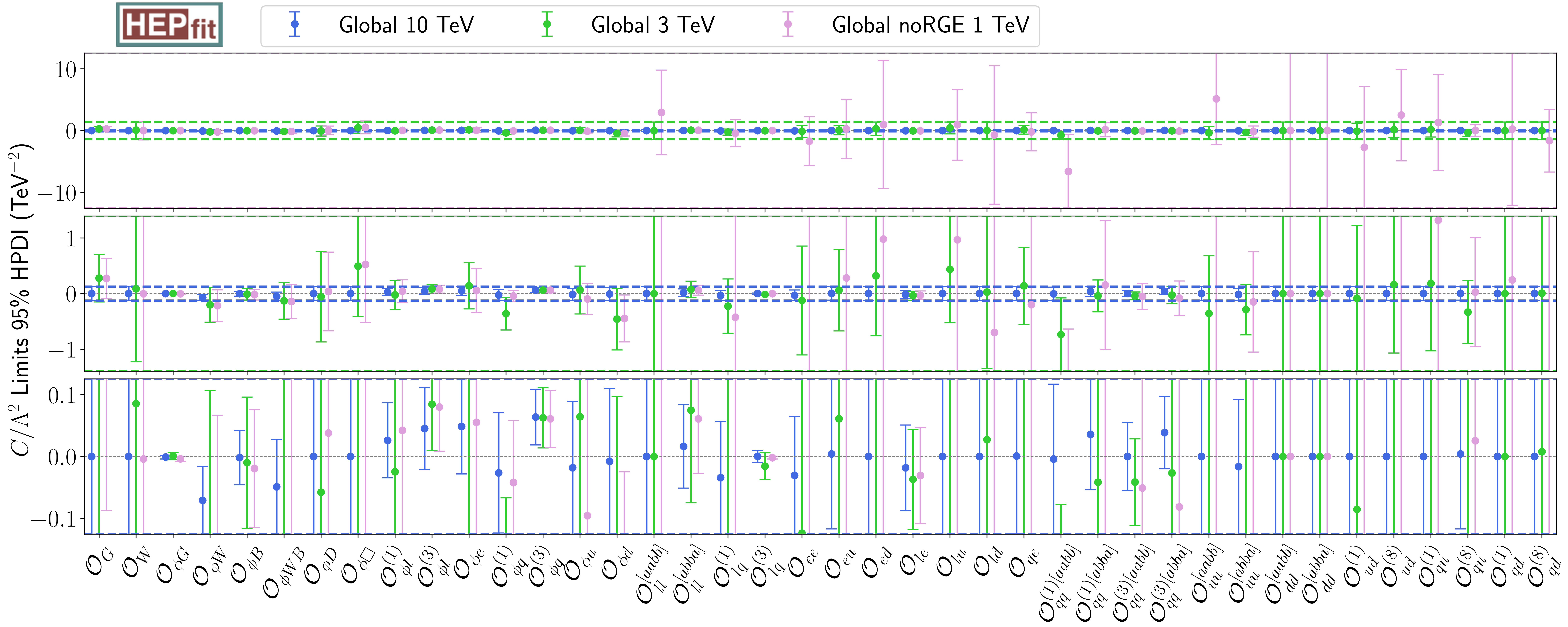


Strong correlations between coefficients significantly relax the bounds but many operators can still be constrained

Similar conclusions about the impact of RG effects observed at the level of the global fit (more prominent in some cases)

SMEFT fit results: U(3)^5

Global fit: comparison of different choices of Λ



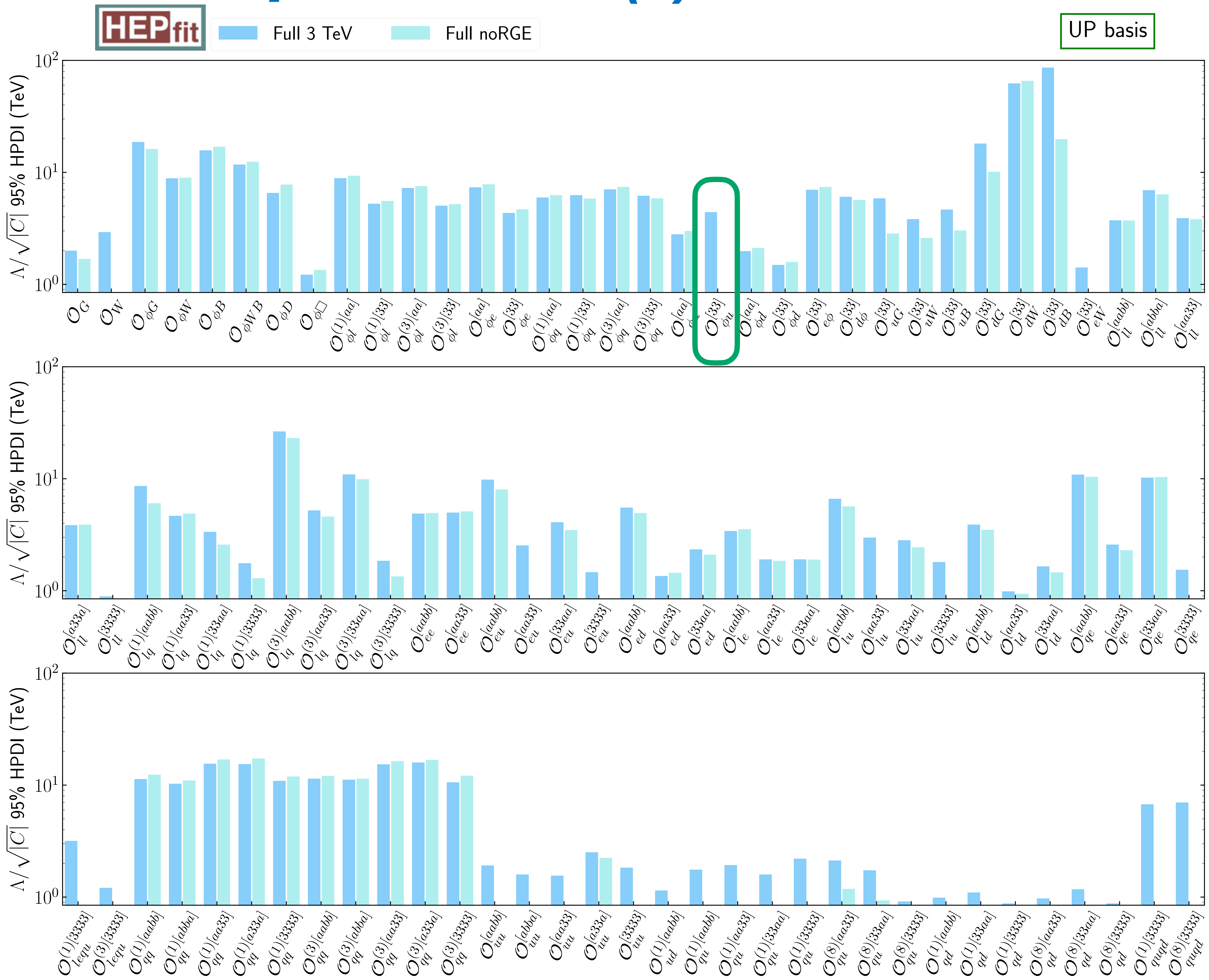
Despite the high-scale (10 TeV) still sensible bounds can be set in several WC (within the perturbative regime)

SMEFT fit results: U(2)⁵

Several interesting effects after separating 3rd and light families

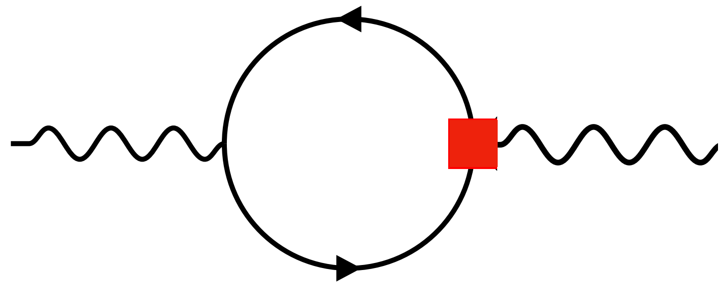
- Strong bounds on b-dipoles (Flavour)
  - $C_{dG,\,dW,\,dB}$ (Up to ~80 TeV!)

SMEFT fit results: U(2)^5



Several interesting effects after separating 3rd and light families

- Strong bounds on b-dipoles (Flavour)
  - $C_{dG,\,dW,\,dB}$ (Up to ~80 TeV!)
- RG-effects become more important in constraining Top-operators
  - $C_{\phi u}$
    - Constrained by Top data at LO
    - Much stronger bounds from EWPO via RG mixing with T parameters



SMEFT fit results: U(2)^5

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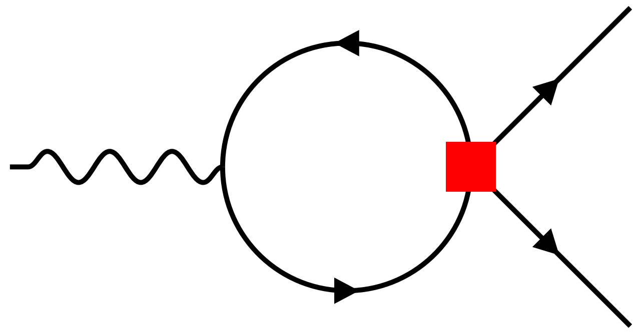
  - Similar effects for other operators mixing with interactions entering in EWPO (or Flavour)



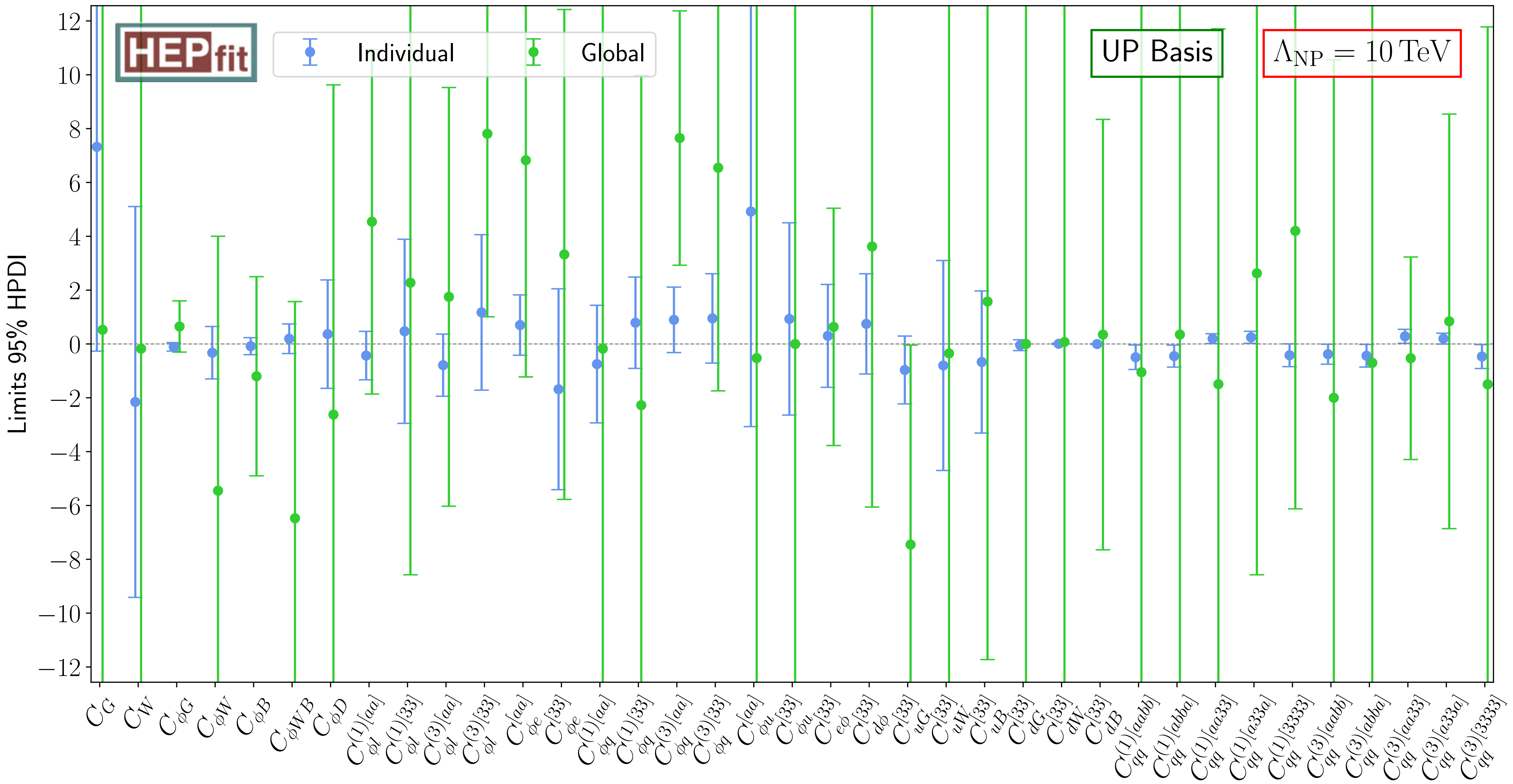
SMEFT fit results: $U(2)^5$

Several interesting effects after separating 3rd and light families

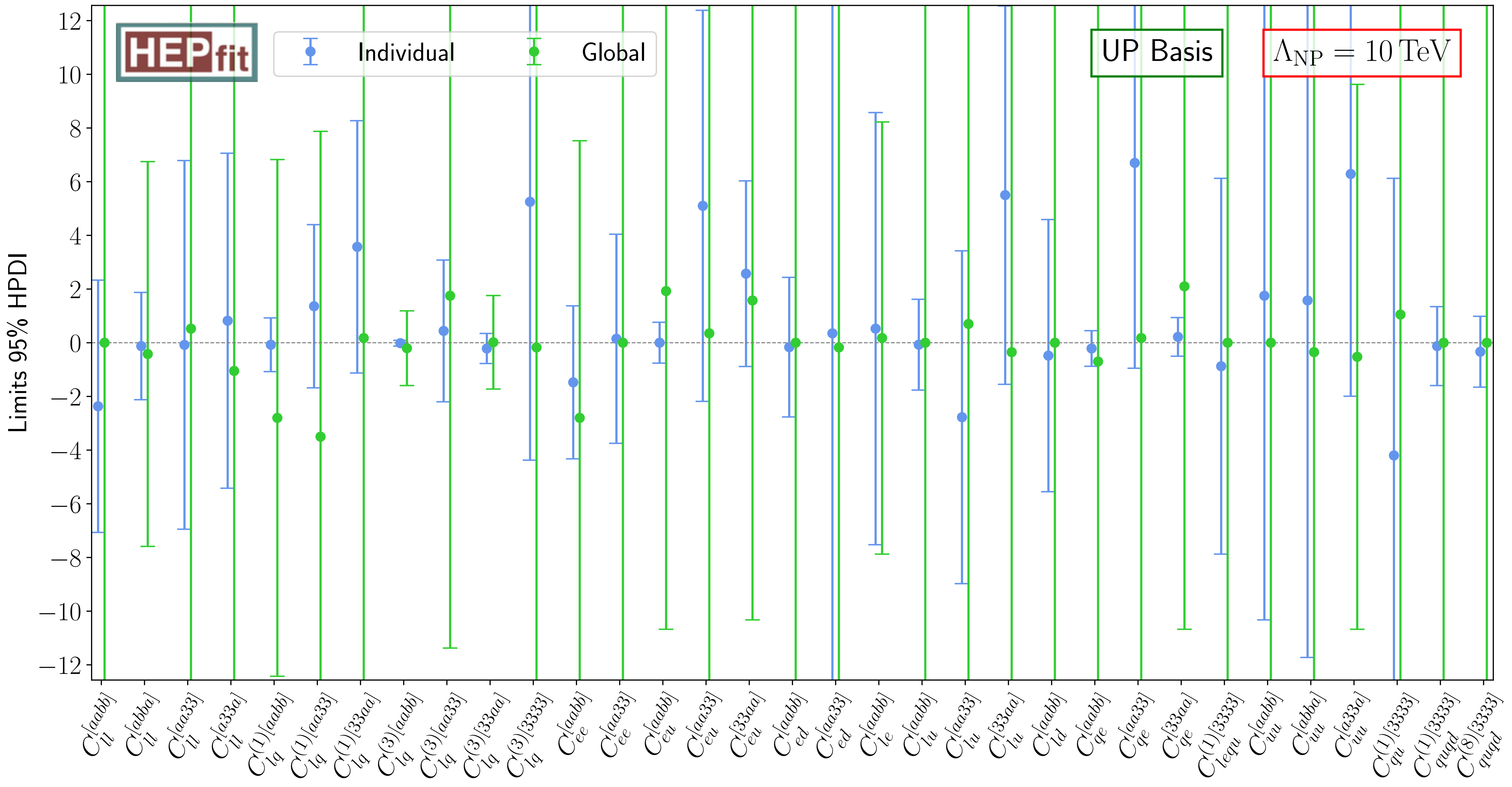
- Strong bounds on b-dipoles (Flavour)
  - $C_{dG, dW, dB}$ (Up to ~80 TeV!)
- RG-effects become more important in constraining Top-operators
  - $C_{\phi u}$
    - Constrained by Top data at LO
    - Much stronger bounds from EWPO via RG mixing with T parameter
  - Similar effects for other operators mixing with interactions entering in EWPO (or Flavour)
  - $C_{lequ}^{(1)3333}$: From mixing with $C_{e\phi}^{33}$ (modifies τ Yukawa)

SMEFT fit results: U(2)⁵

Comparison of individual vs. global fit results

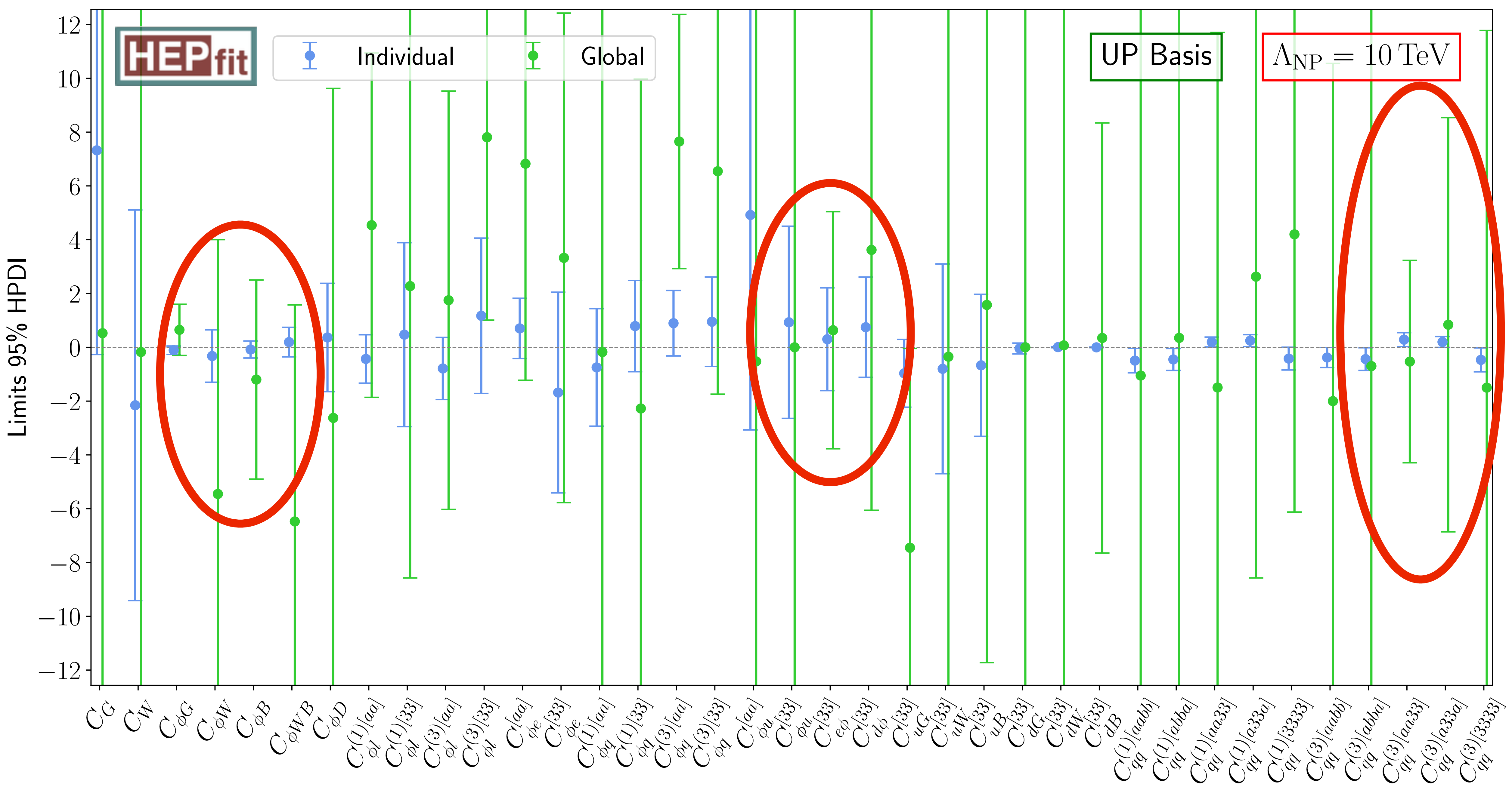


- Results shown (for illustration) only for those operators where a given WC can be constrained at least individually
- The larger number of degrees of freedom ***in the U(2)⁵ case weakens even more the global bounds*** compared to the individual limits



SMEFT fit results: U(2)⁵

Comparison of individual vs. global fit results



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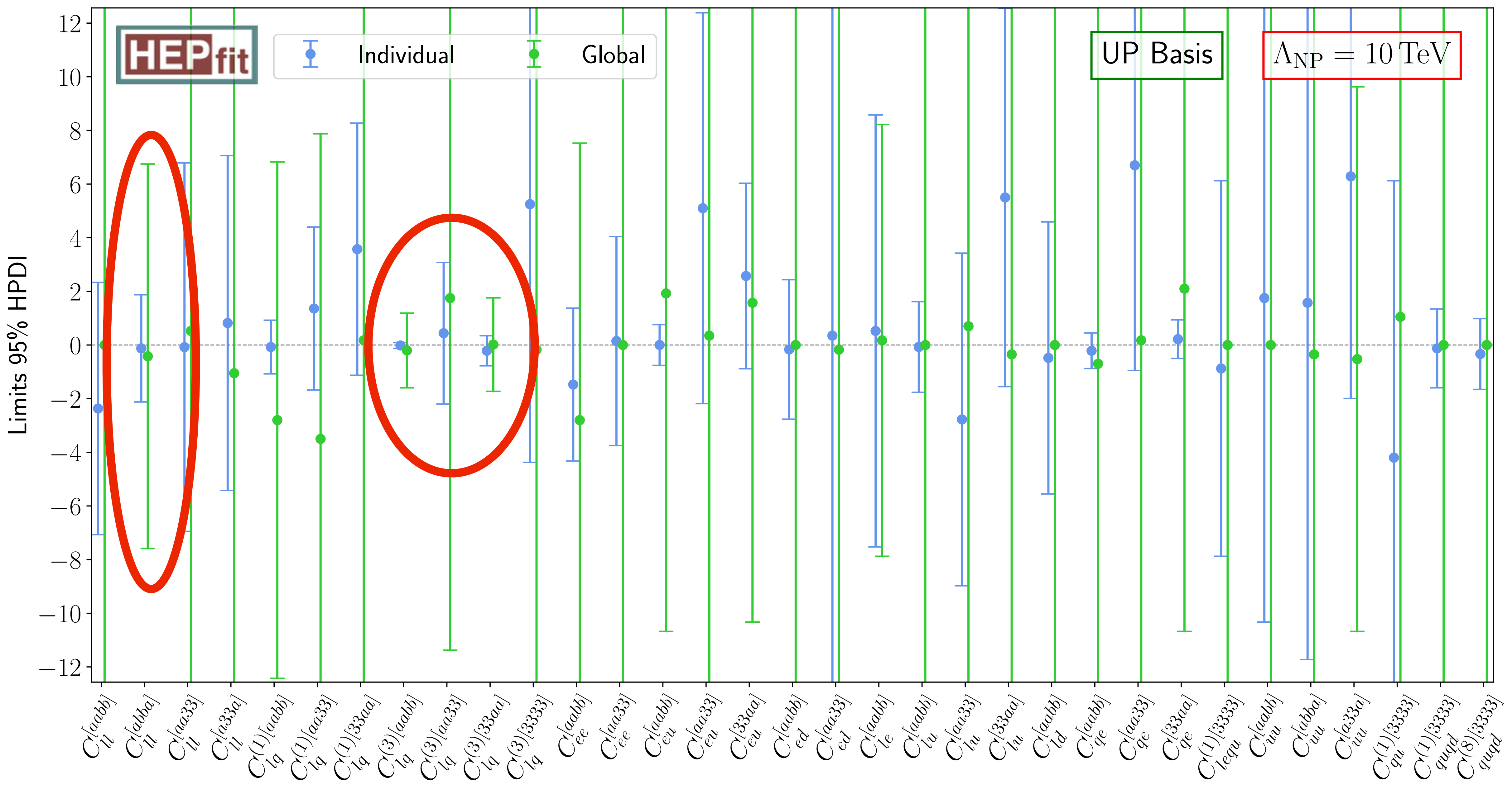

- With current precision, constraining the ***U(2)⁵*** SMEFT becomes challenging for Λ~10 TeV
- Meaningful constraints of several interactions can still be placed when restricting to the perturbative regime

Summary
Conclusions

Summary and Conclusions

- In this study, we have presented a consistent combination of EW/Higgs/Top/Flavour constraints in the dimension-6 SMEFT:
  - ✓ Including variations of the SMEFT Wilson coefficients and all the SM parameters (inputs + TH uncert.)
  - ✓ Including RGE evolution both in the SMEFT and LEFT starting from a full basis of SMEFT effects in the UV:
    - ▸ $U(3)^5$ flavour symmetry (41 operators)
    - ▸ $U(2)^5$ flavour symmetry (124 operators)

Around 200 parameters in the fit !

  - ✓ Including prior information to ensure the EFT is studied within its perturbative regime

- Some highlights from the finding of this study:
  - ✓ RG effects found to have crucial role in constraining several operators (and to connect with the UV)
  - ✓ Strong individual bounds get diluted due to strong correlations in global fit, hitting in many cases the perturbativity regime for high values of Λ.

$\Rightarrow$ Low scale NP must satisfy very specific correlations!

  - ✓ Sizable bounds (well above the TeV) can still be placed for certain operators
  - ✓ Crucial role of flavour assumptions → Discussed in more detail tomorrow in Flavour parallel session