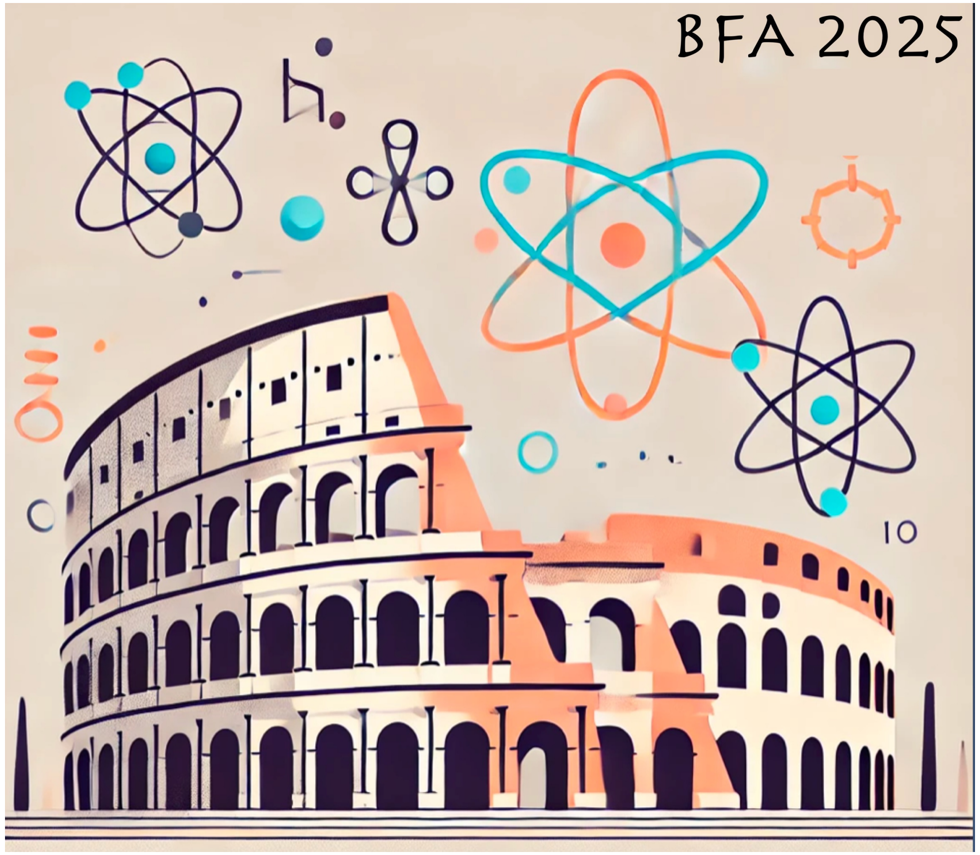
Global fits of the SM Effective Field Theory

The impact of flavour observables on constraining SMEFT interactions



Beyond the Flavour Anomalies

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Based on work in collaboration with:
J. de Blas, A. Goncalves, V. Miralles, L. Silvestrini, and M. Valli

Setting the stage

- **Global fits** are a **powerful means** to test the consistency of a theory and point to new physics effects.
- They are **typical of a mature precision program** such as the one we can build today thanks to the level of accuracy reached both in theory and experiments over a very broad range of observables.
- **Adding flavour physics observables is a big change** given the strong constraints imposed by flavour on new physics.
- In this section we will present **two complementary examples**:
  - A global fit of the SMEFT **This talk**
  - A global analysis of a class of strong-dynamics models through their EFT projection at and below the EW scale

Alfredo Glioti's talk

Emphasizing in particular the **role of flavour observables**.

General framework

Extend the SM Lagrangian by effective interactions (SM EFT)

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

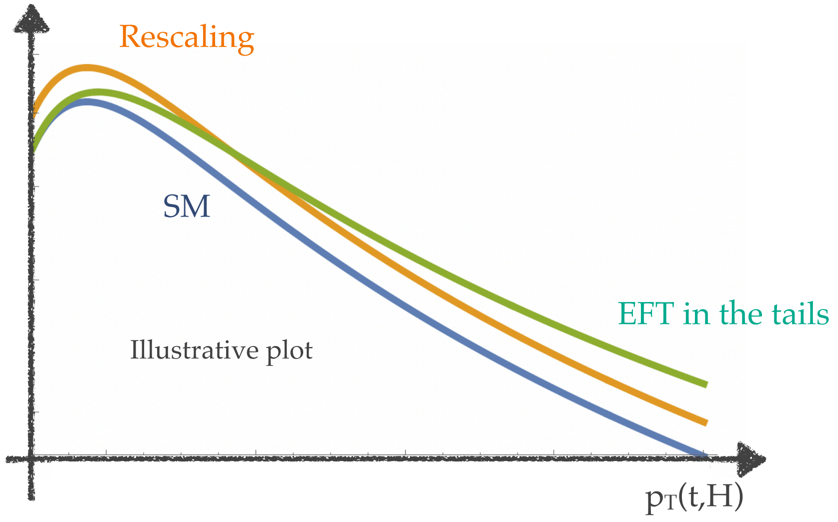
Under the assumption that new physics leaves at scales $\Lambda > \sqrt{s}$

$$\mathcal{L}_d = \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}, \quad \left[\mathcal{O}_i^{(d)}\right] = d$$

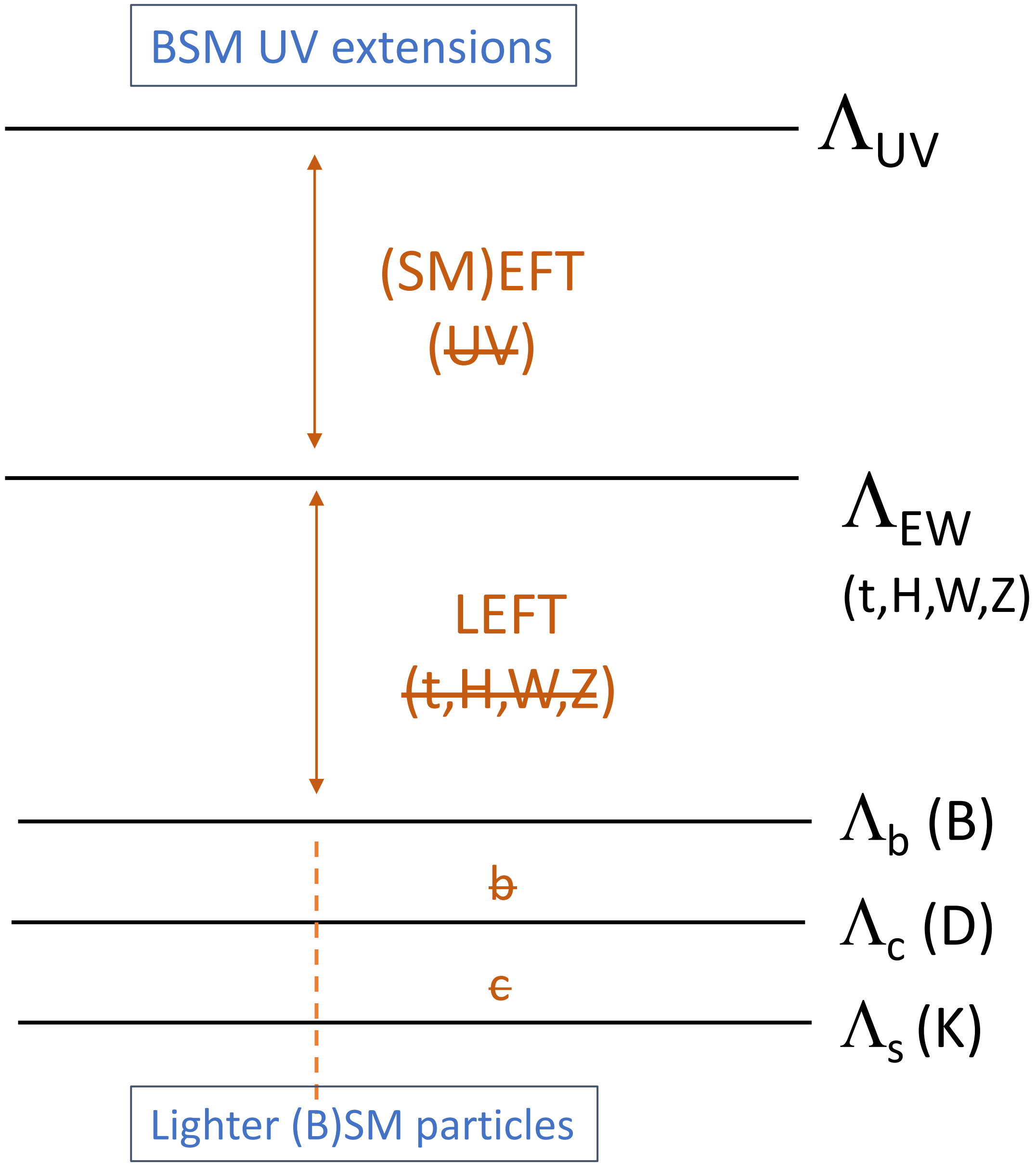
Built of SM fields and respecting the SM gauge symmetry.

Expansion in $(v, E)/\Lambda$: **affects all SM observables** at both low and high energy

- **SM masses and couplings** → **rescaling**
- **Rates and branching ratios** → **new tree-level contributions**
- **Differential rates** → **shape distortions** in kinematic distributions



Connecting far apart scales: the EFT picture



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

RGE ↓

SMEFT 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 ↓

LEFT operators in terms of *light* fields

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

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

The SMEFT framework for this study

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{C_i}{\Lambda^2} Q_i + \dots$$

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

"Warsaw" basis

$$\mathcal{L}_{SM}^{(4)} = -\frac{1}{4} G^A_{\mu\nu} G^{A,\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{I,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$
$$+ (D_\mu\varphi)^\dagger (D^\mu\varphi) + m^2 \varphi^\dagger\varphi - \frac{1}{2}\lambda(\varphi^\dagger\varphi)^2$$
$$+ i\left(\bar{l}'_L \not{D} l'_L + \bar{e}'_R \not{D} e'_R + \bar{q}'_L \not{D} q'_L + \bar{d}'_R \not{D} d'_R\right)$$
$$- \left(\bar{l}'_L \Gamma_e e'_R \varphi + \bar{q}'_L \Gamma_u u'_R \tilde{\varphi} + \bar{q}'_L \Gamma_d d'_R \varphi\right) + h.c.$$

with covariant derivative:

$$D_\mu = \partial_\mu + i g_s G^A_\mu T^A + i g_W W^I_\mu T^I + i g_1 B_\mu Y$$

gauge fields and masses, HVV, VVV

Higgs field and Mh

Yukawa couplings

Vff, Hff

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
$\mathcal{O}_G$	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$\mathcal{O}_\varphi$	$(\varphi^\dagger\varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p \varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \tilde{\varphi} u_r)$
		$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \varphi d_r)$

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{\varphi} G^A_{\mu\nu}$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\varphi} W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\varphi} B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi G^A_{\mu\nu}$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi W^I_{\mu\nu}$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$\mathcal{O}^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$\mathcal{O}^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$\mathcal{O}^{(1)}_{qd}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$\mathcal{O}^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{L}R)$	$(\bar{L}R)(\bar{R}L)$
$\mathcal{O}^{(1)[prst]}_{quqd} = (\bar{q}^i_p u_r)\epsilon_{ij}(\bar{q}^j_s d_t)$	$\mathcal{O}^{[prst]}_{ledq} = (\bar{l}^i_p e_r)(\bar{d}_s q_{ti})$
$\mathcal{O}^{(8)[prst]}_{quqd} = (\bar{q}^i_p T^A u_r)\epsilon_{ij}(\bar{q}^j_s T^A d_t)$	
$\mathcal{O}^{(1)[prst]}_{lequ} = (\bar{l}^i_p e_r)\epsilon_{ij}(\bar{q}^j_s u_t)$	
$\mathcal{O}^{(3)[prst]}_{lequ} = (\bar{l}^i_p \sigma_{\mu\nu} e_r)\epsilon_{ij}(\bar{q}^j_s \sigma^{\mu\nu} u_t)$	

4-fermion interactions: tt, ttH, DY, flavour

- Dim-6 operators only, including linear (and quadratic effects)
- Obeying SM gauge symmetry
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.
- Assuming different flavour symmetries: $U(3)^5$, $U(2)^5$ …; no CPV

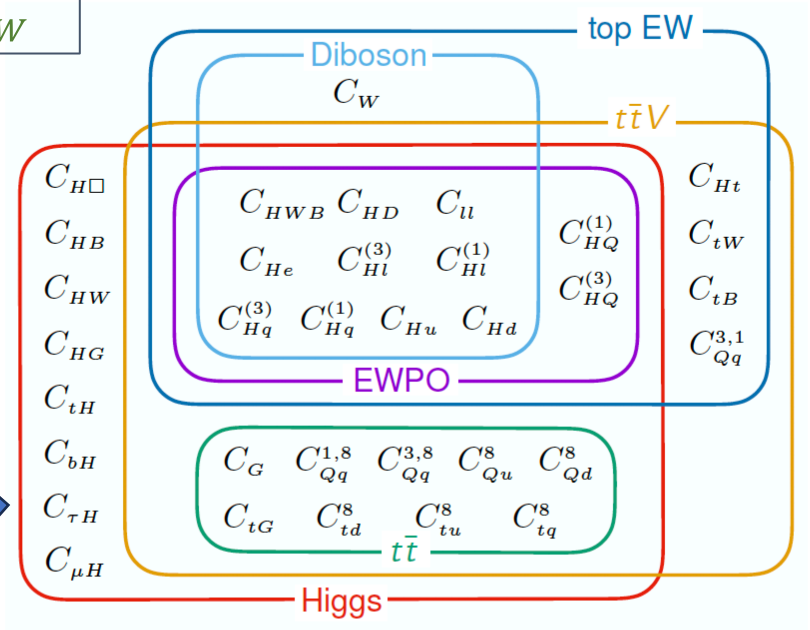
Global fits: EW, DY, di-boson, Higgs, top, flavour

Constraining new physics through 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)
- 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
  - $pp \to W, Z \to f_i \bar{f}_j$
  - $pp \to WZ, WW, ZZ, Z\gamma$

Including recent LHC measurements of m_t and M_W

ATLAS and CMS Run 1+2 results



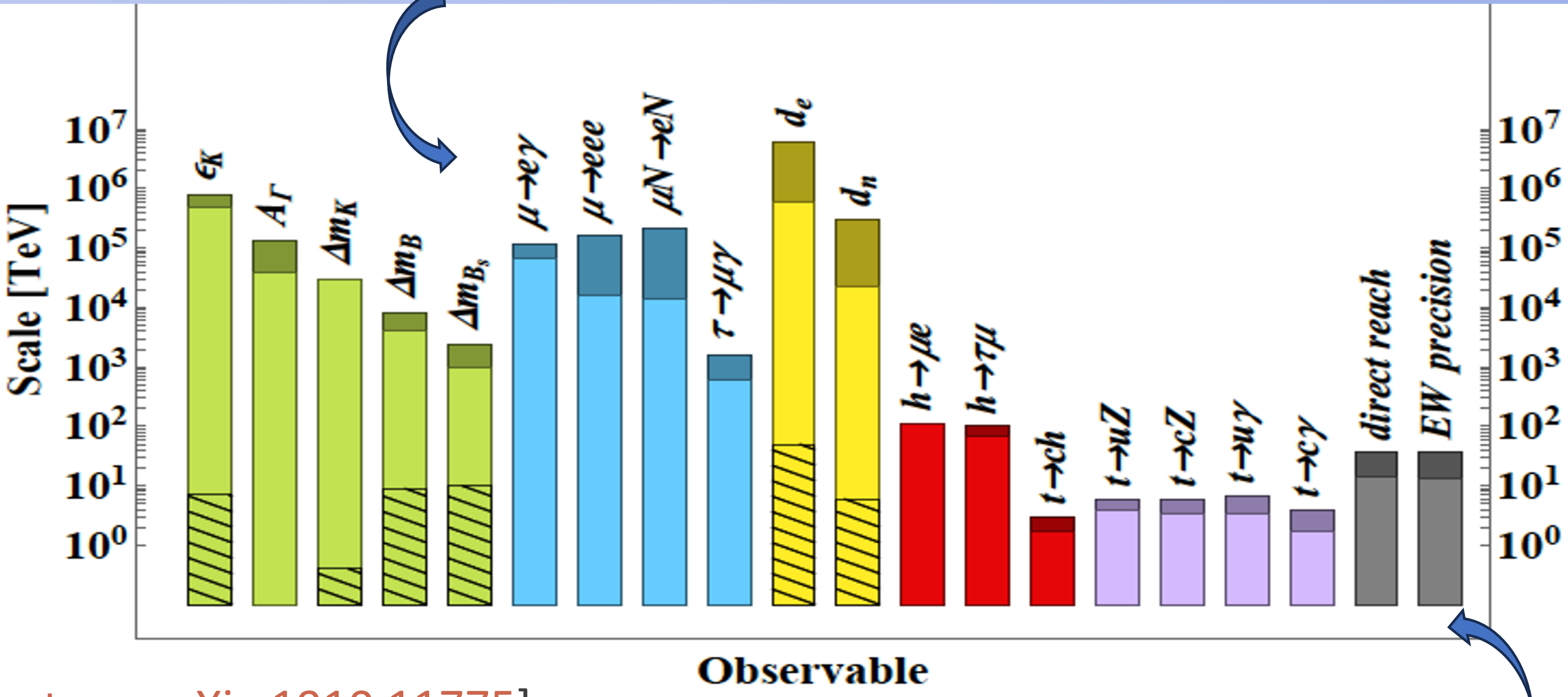
Either directly or through RGE flavour overlap with most SMEFT coefficients

- **Flavour observables**
  - $\Delta F=2$: $\Delta M B_{d,s}$, $D^0 - \bar{D}^0$, 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: $B \to X_{s,d}\gamma$

Exp: PDG
Th: best available predictions

Complementarity in bounding new physics

Flavour- and low-energy observables can be more sensitive to the scale of new physics, but they may not be able to unambiguously test it.



[European Strategy, arXiv:1910.11775]

High-energy collider have less sensitivity but can test the compatibility of new physics over a uniquely broad spectrum of measurements.

SMEFT predictions

A given observable is written as

$$O_{\text{SMEFT}} = O_{\text{SM}} + \Delta O^{(1)} + \Delta O^{(2)} + \cdots$$

SM: including available SM higher-order corrections and state-of-the-art parametrizations

SMEFT: tree level

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

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

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework

Λ_{UV}

SMEFT
(~~UV~~)

Λ_{EW}
(t,H,W,Z)

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

Λ_b (B)
Λ_c (D)
Λ_s (K)

Will be constrained by the fit together with SM parameters

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

Imposing flavour symmetry

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

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

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

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

Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270

Notice that LO evolution is only consistent with tree-level initial conditions at Λ_{UV} and tree-level matrix elements at Λ_{EW}.

The HEPfit framework

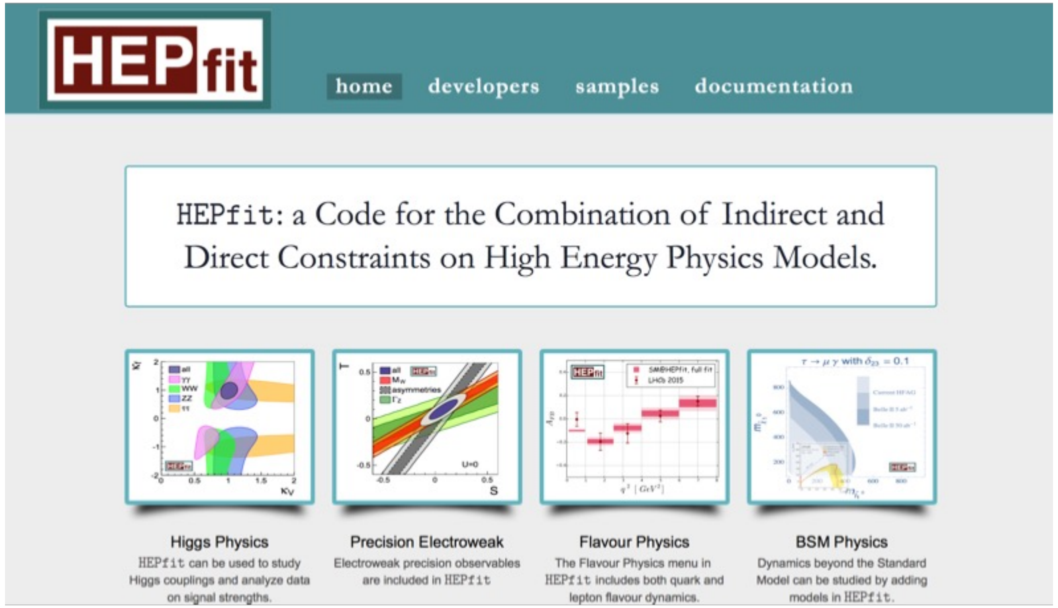
Open-source tool

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 fit and future collider projections

New release will include 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



http://hepfit.roma1.infn.it

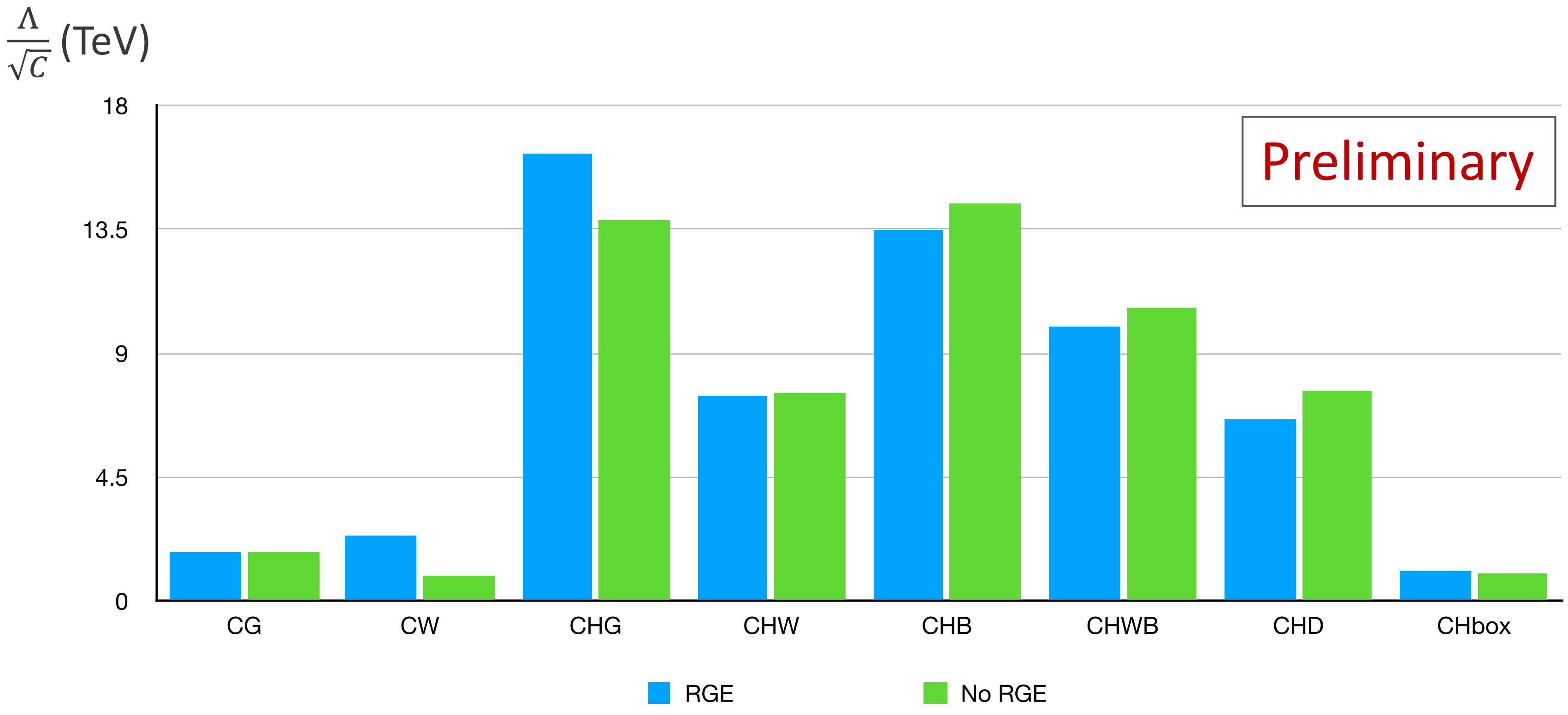
J. De Blas et al., 1910.14012

Other existing frameworks for SMEFT global fits:
SMEFiT, Celada et al. 2105.00006, 2302.06660, 2404.12809
Fitmaker, Ellis et al. 2012.02779
Allwicher et al, 2311.00020
Cirigliano et al. 2311.00021
Bartocci et al. 2311.04963

→ See talk by Lukas Allwicher

Lower bounds on NP scale - Bosonic operators

SU(2)^5 - Global fit
one operator at a time



Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

$$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$\mathcal{O}_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

$$\mathcal{O}_{\phi G} = \phi^\dagger \phi\, G_{\mu\nu}^A G^{A\mu\nu}$$

$$\mathcal{O}_{\phi W} = \phi^\dagger \phi\, W_{\mu\nu}^I W^{I\mu\nu}$$

$$\mathcal{O}_{\phi B} = \phi^\dagger \phi\, B_{\mu\nu} B^{\mu\nu}$$

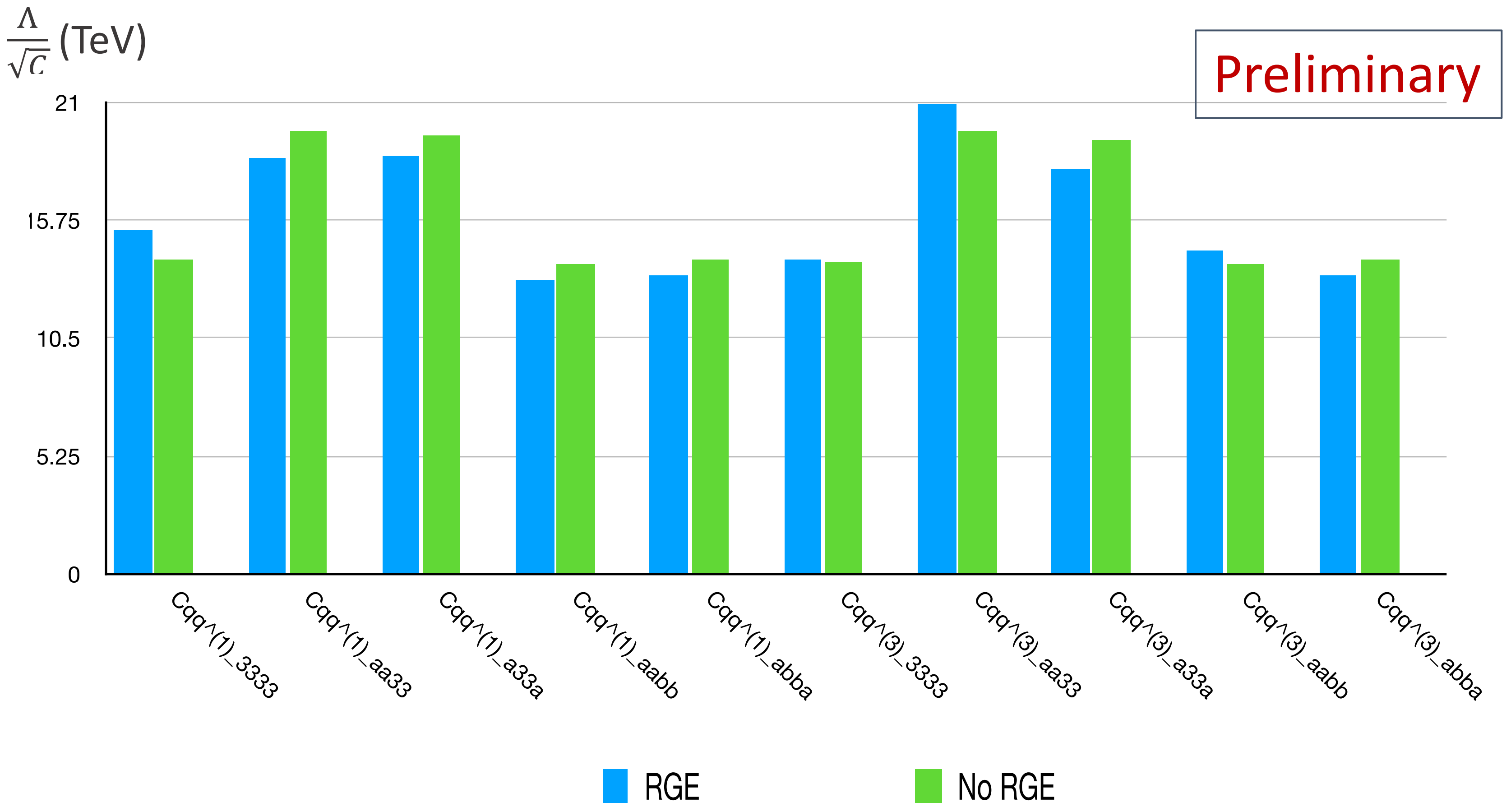
$$\mathcal{O}_{\phi WB} = \phi^\dagger \tau^I \phi\, W_{\mu\nu}^I B^{\mu\nu}$$

$$\mathcal{O}_{\phi\Box} = (\phi^\dagger\phi)\Box(\phi^\dagger\phi)$$

$$\mathcal{O}_{\phi D} = \left(\phi^\dagger D^\mu \phi\right)^\star \left(\phi^\dagger D_\mu \phi\right)$$

- **Most important effects from EW and Higgs observables**
  - Very strong bound from main Higgs production mode ($gg \to H$)
- RGE can enhance/suppress sensitivity to NP

Lower bounds on NP scale – Effect of B^0-$\bar{B}^0$ mixing



- Much **higher lower bound** on NP scales
- **Bound entirely from flav**our
- RGE can enhance/suppress sensitivity to NP

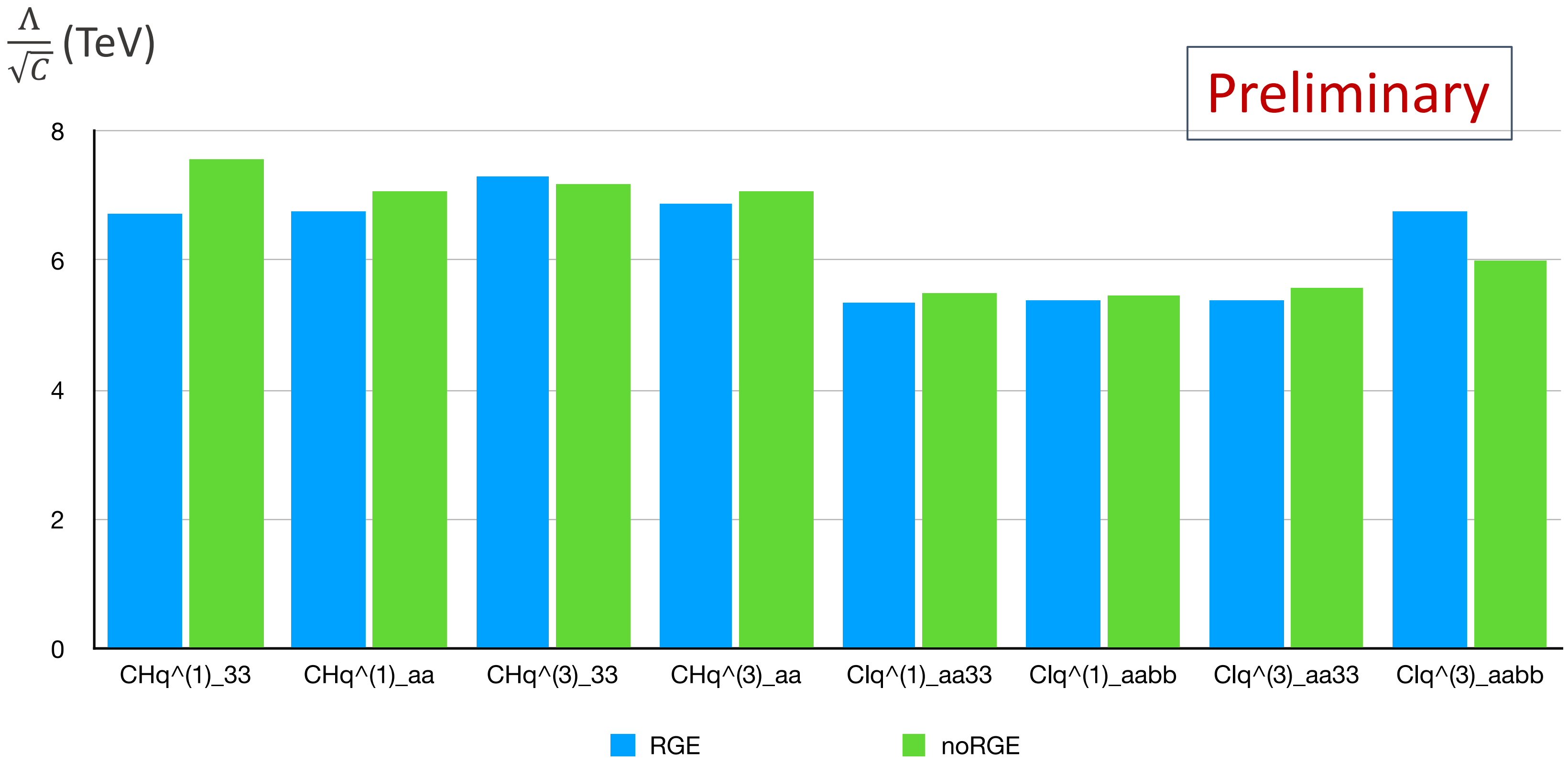
SU(2)^5 - Global fit
one operator at a time

Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

(LL- 4f operators)

$$\mathcal{O}_{qq}^{(1)[prst]} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$$
$$\mathcal{O}_{qq}^{(3)[prst]} = (\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$

Lower bounds on NP scale – Effect of $B_s \to \mu^+\mu^-$



SU(2)^5 - Global fit
one operator at a time

Bound on scale depends on assumptions on WC
Λ_{max} for $C \sim 4\pi \times O(1)$

$$\mathcal{O}_{lq}^{(1)[prst]} = (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$$
$$\mathcal{O}_{lq}^{(3)[prst]} = (\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$
$$\mathcal{O}_{\phi q}^{(1)[pr]} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}_p \gamma^\mu q_r)$$
$$\mathcal{O}_{\phi q}^{(3)[pr]} = (\phi^\dagger i \overleftrightarrow{D}_\mu^I \phi)(\bar{q}_p \tau^I \gamma^\mu q_r)$$

- **Higher lower bound** on NP scales
- **Bound mainly from flavour**
- RGE can slightly enhance/suppress sensitivity to NP
- Pattern may be complicated by full global fit

Transitioning to the next talk

- **Global fits** stress-test the SM and provide a **very strong indirect constraint on new physics.**
- Effects of new physics can then be constrained using the **broad spectrum of precision measurement available from EW, Higgs, top, flavor physics** and more.
- The **SMEFT (→LEFT) framework** can be used to connect unknown physics at the UV scale (> 1 TeV) to the EW scale and below within a **systematic framework that allows some model independence.**
- **Flavor assumptions at the UV scale** are **crucial** to **distinguish broad classes of models**, which can inform and add meaning to the SMEFT analysis.

See next talk!

Back-up slides

SM strength: consistency at the quantum level

For M_W we combine:

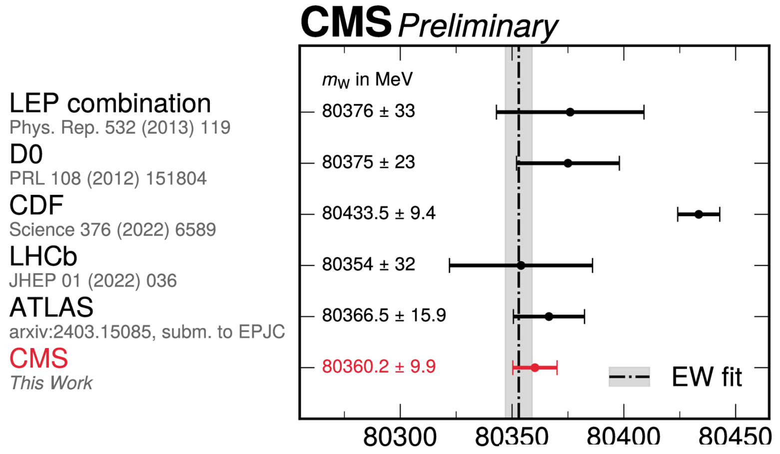
- ❑ All LEP 2 measurements
- ❑ Previous Tevatron average
- ❑ ATLAS and LHCb early measurements
- ❑ CDF [M_W=(80.4335±0.0094) GeV]
- ❑ ATLAS [M_W=(80.3665±0.016) GeV]
- ❑ CMS [M_W=(80.3602±0.010) GeV]

M_W = 80.366 ± 0.0080 GeV (without CDF)
80.356 ± 0.0045 GeV (from fit)

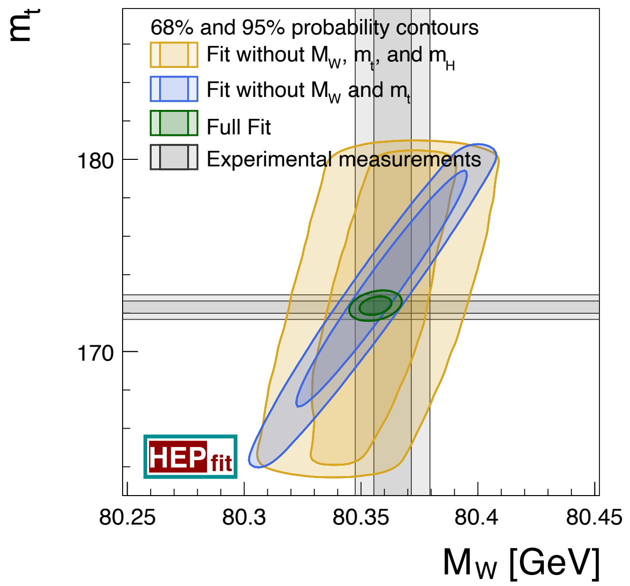
For m_t we combine:

- ❑ 2016 Tevatron combination
- ❑ ATLAS Run 1 and early Run2 results
- ❑ CMS Run 1 and early Run 2 results
- ❑ CMS l+j [m_t=(171.77±0.38) GeV]
- ❑ CMS l+j boosted [m_t=(173.06±0.83) GeV]
- ❑ ATLAS l+j boosted [mt=172.95±0.53) GeV

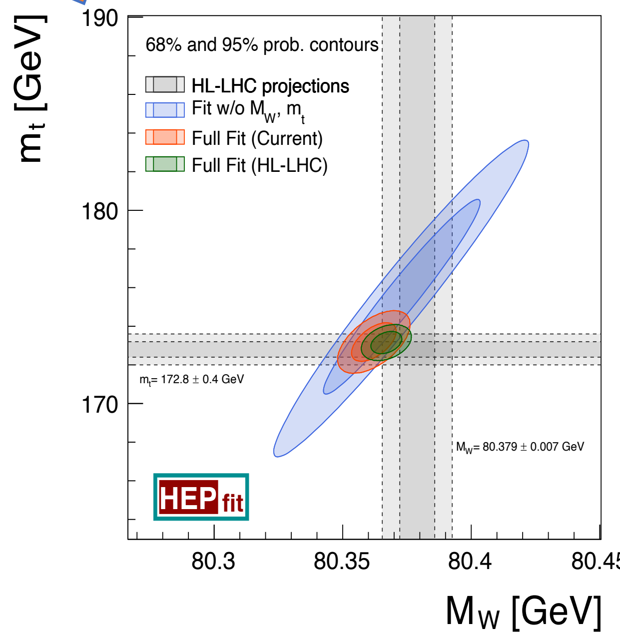
m_t = 172.31 ± 0.32 GeV
172.38 ± 0.31 GeV (from fit)



With HL precision



J. de Blas et al. 2204.04204, **updated**



J. de Blas et al. 1902.04070
HL/HE-LHC Report