Global fits of the Standard Model and beyond

Constraining new physics via improved global fits of the Standard Model Effective Field Theory

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Based on work in collaboration with:
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Stress-testing the Standard Model and beyond

Searching for indirect evidence of new physics through precision

- **EW precision fits**: testing the **quantum consistency** of the SM to the highest precision.
- **More observables** are and will be measured with high precision: towards **global fits.**
- Testing models **beyond the SM** in the framework of EFT: **the SMEFT as a proof of concept.**

State of the art of SM theory calculations of EW precision observables

- Γ_W: only EW one loop
  - D.Y. Bardin, P.K. Khristova, O. Fedorenko, Nucl. Phys B197 (1982) 1
  - D.Y. Bardin, S. Riemann, T. Riemann, Z. Phys C32 (1986) 121
- M_W: Full EW 2-loop corr. + leading 3-loop & some 4-loop
  - M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev. D69 (2004) 053006
- $sin^2\theta^f_{eff}$: (light fermions): Full EW 2-loop corr. + leading higher order
  - M. Awramik, M. Czakon, A. Freitas, JHEP 11 (2006) 048
  - M. Awramik, M. Czakon, A. Freitas, B.A. Kniehl, Nucl. Phys. B 813 (2009) 174
- Γ^f_Z: Full EW 2-loop corr. + leading higher order
  - I. Dubovyk, A. Freitas, J. Gluza. T. Riemann, J. Usovitsch, Phys. Lett. B 783 (2018) 86
- $sin^2\theta^b_{eff}$: Full EW 2-loop corr. + leading higher order
  - I. Dubovyk, A. Freitas, J. Gluza. T. Riemann, J. Usovitsch, Phys. Lett. B 762 (2016) 184
- Leading 3-loop EW-QCD fermionic corr. $(M_W, sin^2\theta^f_{eff}, \Gamma^f_Z)$
  - L. Cheng, A. Freitas, JHEP 07 (2020) 210, JHEP 03 (2021) 215

In fit: used **2-loop parametrizations** from:
Dubovyk, Freitas, Gluza, Riemann, Usovitsch
JHEP 08 (2019) 113

From same reference:
estimate of residual
theoretical uncertainties

The HEPfit framework

Open-source tool

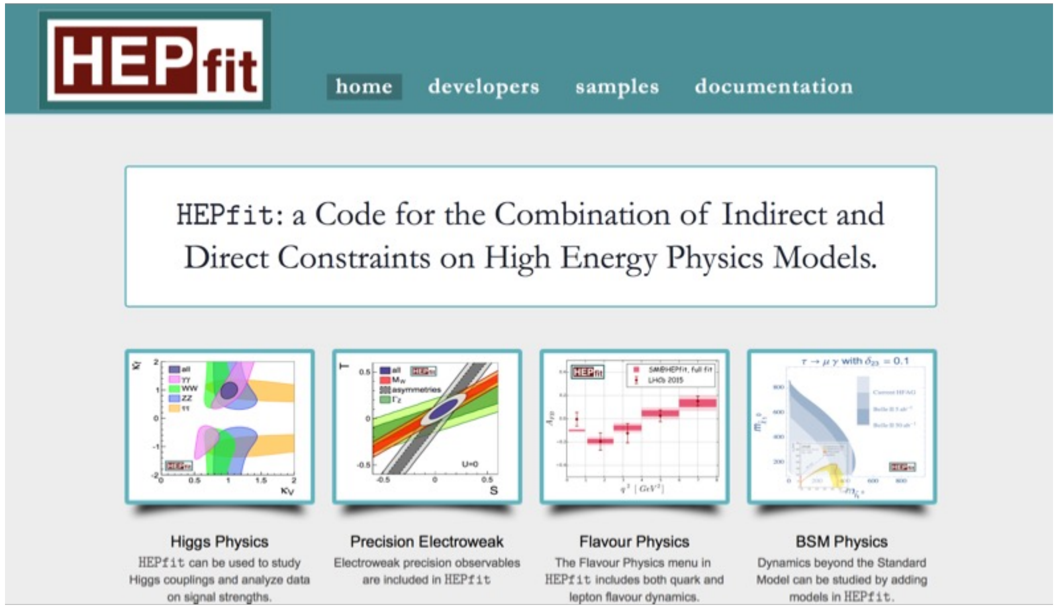
Statistical framework based on a Bayesian MCMC analysis as implemented in
BAT (Bayesian Analysis Toolkit)
Caldwell et al., arXiv:0808.2552

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 flavor 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.



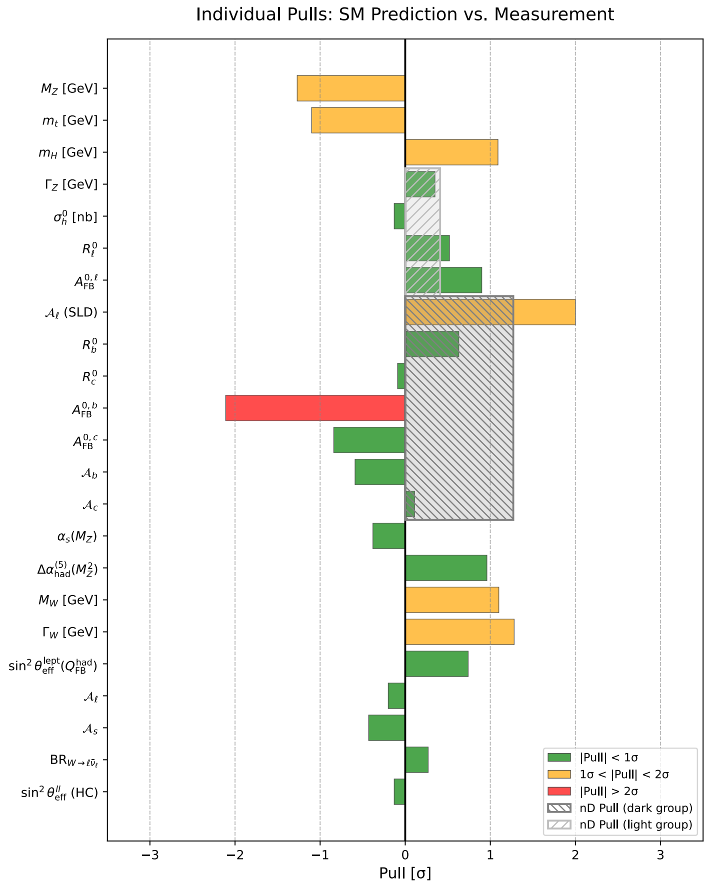
http://hepfit.roma1.infn.it

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
Aebischer et al., 1810.07698
Allwicher et al, 2311.00020
Cirigliano et al. 2311.00021
Bartocci et al. 2311.04963
} Include flavor

EW precision observables: status of SM precision fit



α input scheme:
$\{\alpha, G_F, M_Z, m_H, m_t, \alpha_s\}$

All parameters and observables floating except α and G_F

Posterior:
the full fit result

Individual prediction:
remove one observable (set of), fit predict the removed observable.

1D/nD pull: single (set of) observable(s) pull

J. de Blas et al. 2204.04204
Update: LR+L.Silvestrini 2511.16534

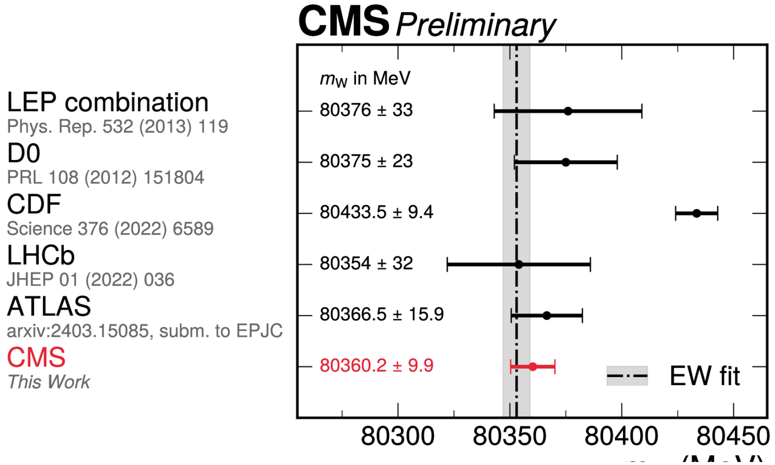
Global SM EW fit

	Measurement	Posterior	Individual Prediction	1D Pull	nD Pull
$\alpha_s(M_Z)$	0.11873 ± 0.00056	0.11878 ± 0.00055 $[0.11769, 0.11986]$	0.1199 ± 0.0028 $[0.1144, 0.1253]$	-0.38	
$\Delta\alpha_{had}^5(M_Z^2)$	0.02766 ± 0.00010	0.027631 ± 0.000096 $[0.027443, 0.027819]$	0.02734 ± 0.00032 $[0.02670, 0.02797]$	0.96	
M_Z [GeV]	91.1875 ± 0.0021	91.1885 ± 0.0019 $[91.1847, 91.1923]$	91.1964 ± 0.0068 $[91.1832, 91.2097]$	-1.27	
m_t [GeV]	172.31 ± 0.32	172.38 ± 0.31 $[171.77, 173.00]$	174.0 ± 1.5 $[171.1, 177.0]$	-1.10	
m_H [GeV]	125.100 ± 0.090	125.101 ± 0.090 $[124.925, 125.278]$	106.2 ± 16.3 $[76.2, 141.4]$	1.09	
M_W [GeV]	80.3635 ± 0.0080	80.3562 ± 0.0045 $[80.3475, 80.3650]$	80.3529 ± 0.0054 $[80.3423, 80.3635]$	1.10	
Γ_W [GeV]	2.151 ± 0.049	2.08844 ± 0.00041 $[2.08762, 2.08925]$	2.08843 ± 0.00042 $[2.08761, 2.08923]$	1.28	
$\sin^2\theta_{eff}^{lept}(Q_{FB}^{had})$	0.2324 ± 0.0012	0.231523 ± 0.000055 $[0.231415, 0.231631]$	0.231523 ± 0.000057 $[0.231412, 0.231634]$	0.74	
$-P_\tau^{pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14701 ± 0.00043 $[0.14616, 0.14785]$	0.14702 ± 0.00043 $[0.14616, 0.14788]$	-0.20	
Γ_Z [GeV]	2.4955 ± 0.0023	2.49474 ± 0.00052 $[2.49372, 2.49577]$	2.49466 ± 0.00054 $[2.49361, 2.49573]$	0.35	
σ_h^0 [nb]	41.480 ± 0.033	41.4862 ± 0.0067 $[41.4731, 41.4995]$	41.4871 ± 0.0068 $[41.4735, 41.5005]$	-0.13	0.41
R_ℓ^0	20.767 ± 0.025	20.7545 ± 0.0067 $[20.7413, 20.7676]$	20.7529 ± 0.0069 $[20.7394, 20.7668]$	0.52	
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.016208 ± 0.000095 $[0.016023, 0.016397]$	0.016197 ± 0.000096 $[0.016011, 0.016386]$	0.90	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14701 ± 0.00043 $[0.14616, 0.14785]$	0.14700 ± 0.00045 $[0.14613, 0.14789]$	2.00	
R_b^0	0.21629 ± 0.00066	0.215881 ± 0.0000100 $[0.215684, 0.216074]$	0.21588 ± 0.00010 $[0.21567, 0.21607]$	0.63	
R_c^0	0.1721 ± 0.0030	0.172218 ± 0.000052 $[0.172117, 0.172320]$	0.172218 ± 0.000051 $[0.172116, 0.172319]$	-0.09	
$A_{FB}^{0,b}$	0.0996 ± 0.0016	0.10306 ± 0.00031 $[0.10247, 0.10366]$	0.10305 ± 0.00031 $[0.10244, 0.10368]$	-2.11	1.27
$A_{FB}^{0,c}$	0.0707 ± 0.0035	0.07363 ± 0.00022 $[0.07318, 0.07407]$	0.07362 ± 0.00023 $[0.07316, 0.07409]$	-0.84	
$\mathcal{A}_b$	0.923 ± 0.020	0.934735 ± 0.000039 $[0.934658, 0.934812]$	0.934735 ± 0.000039 $[0.934658, 0.934813]$	-0.59	
$\mathcal{A}_c$	0.670 ± 0.027	0.66777 ± 0.00021 $[0.66735, 0.66819]$	0.66777 ± 0.00022 $[0.66735, 0.66820]$	0.11	
$\mathcal{A}_s$	0.895 ± 0.091	0.935642 ± 0.000040 $[0.935564, 0.935719]$	0.935642 ± 0.000039 $[0.935565, 0.935719]$	-0.43	
$BR_{W\ell\bar{\nu}_\ell}$	0.10860 ± 0.00090	0.108361 ± 0.000013 $[0.108336, 0.108386]$	0.108361 ± 0.000013 $[0.108336, 0.108386]$	0.27	
$\sin^2\theta_{eff}^{ll}$ (HC)	0.23150 ± 0.00023	0.231523 ± 0.000055 $[0.231415, 0.231631]$	0.231523 ± 0.000057 $[0.231412, 0.231634]$	-0.13	

EW precision observables: status of SM precision fit

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]

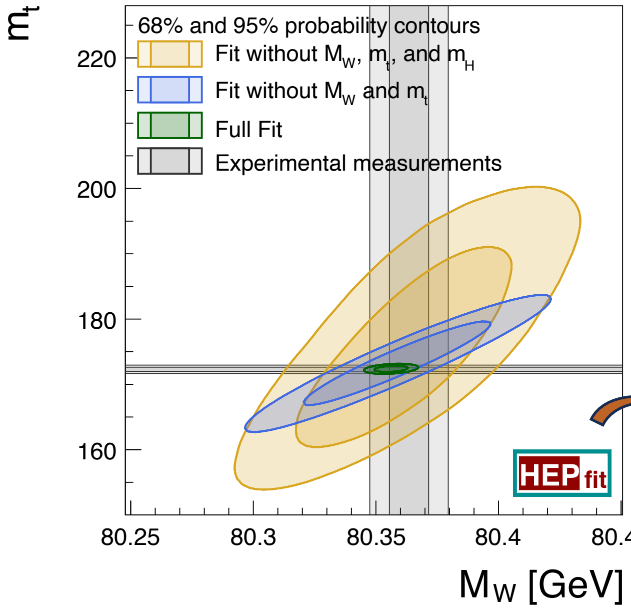


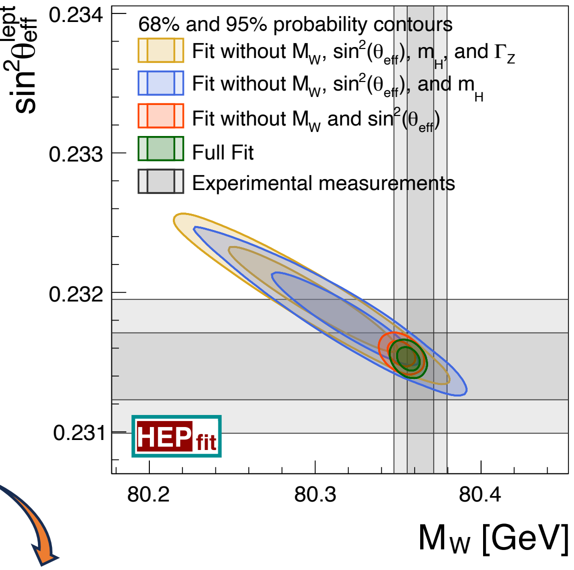
M_W = 80.366 ± 0.0080 GeV (without CDF)
80.356 ± 0.0045 GeV (from fit)

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)

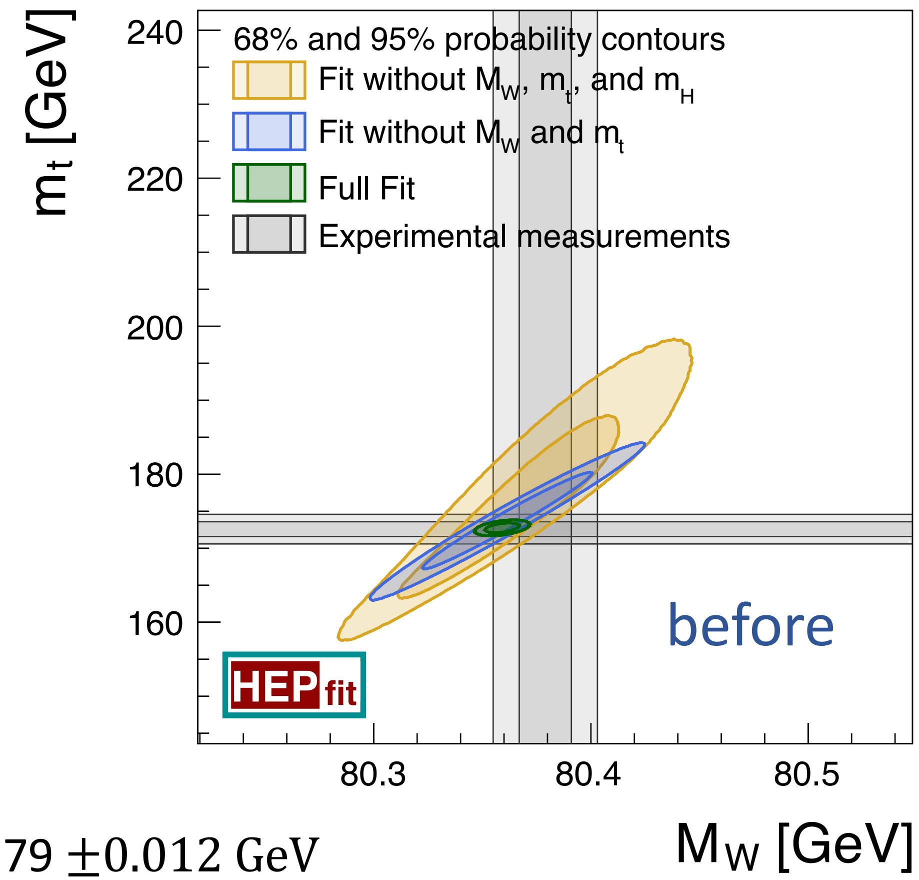




J. de Blas et al. 2204.04204
Update: LR+L.Silvestrini 2511.16534

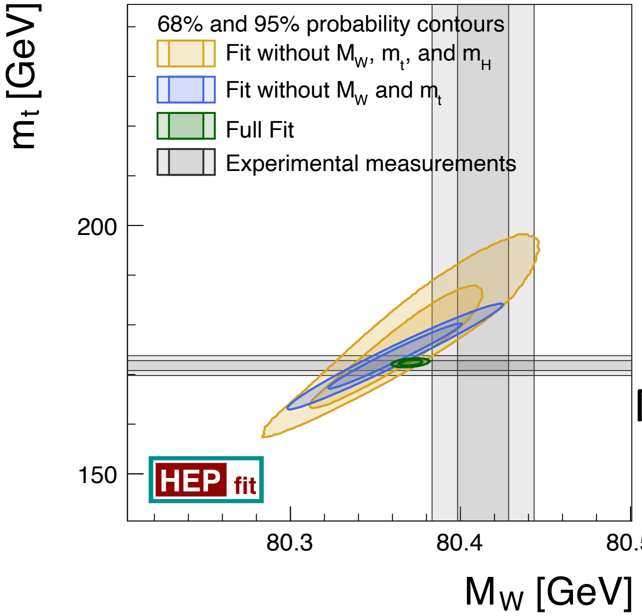
Highlighting sensitivity to anomalies

Challenge: CDF M_W measurement



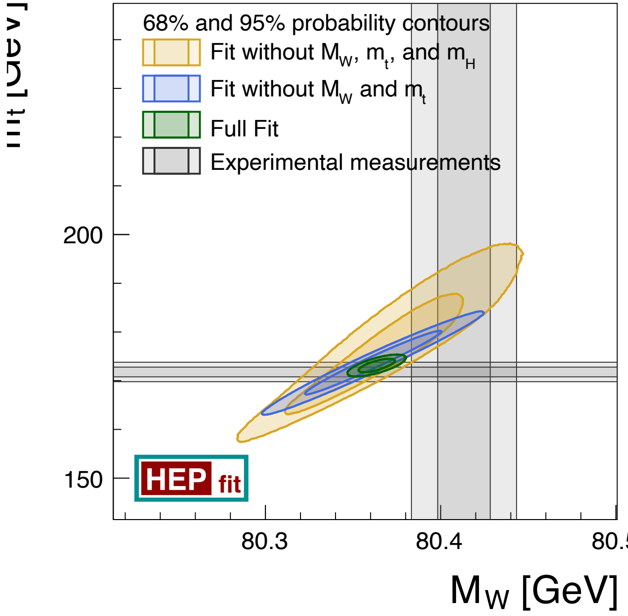
De Blas et al. [2204.04204]

M_W=80.379 ±0.012 GeV



after "standard"

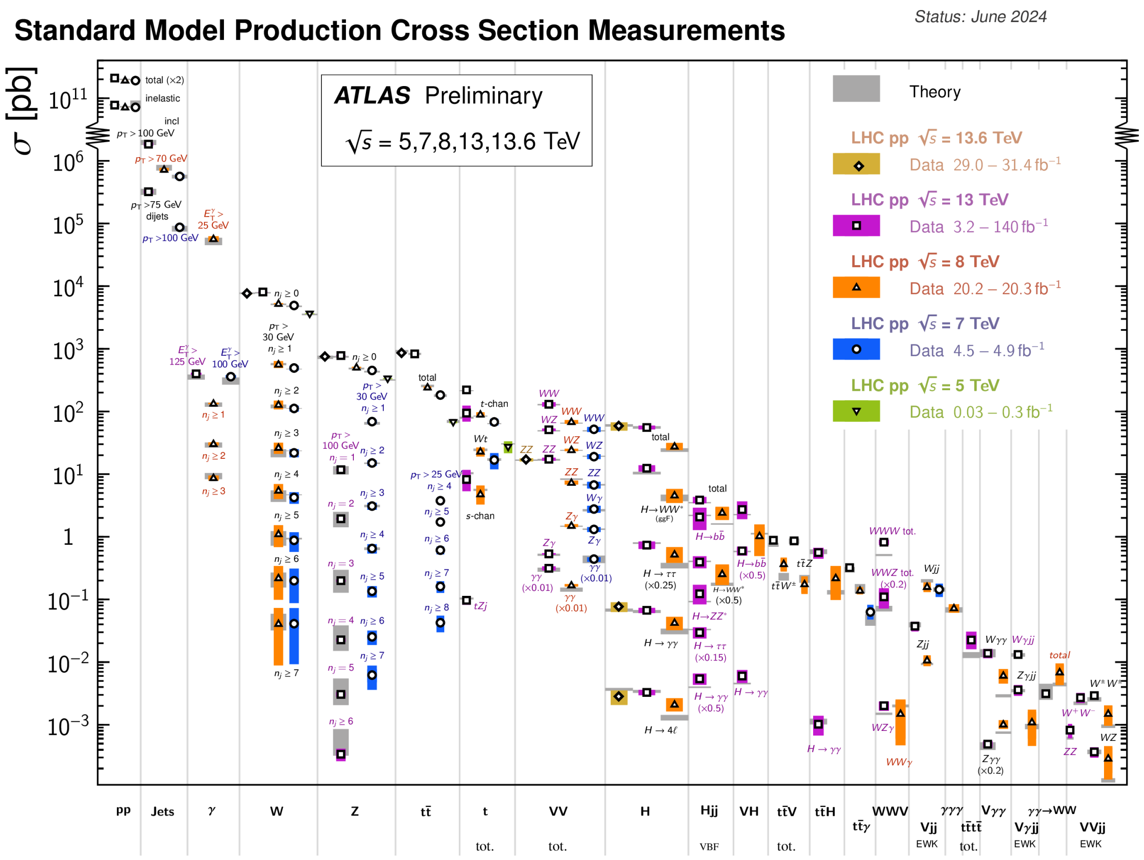
M_W=80.4133 ±0.0088 GeV

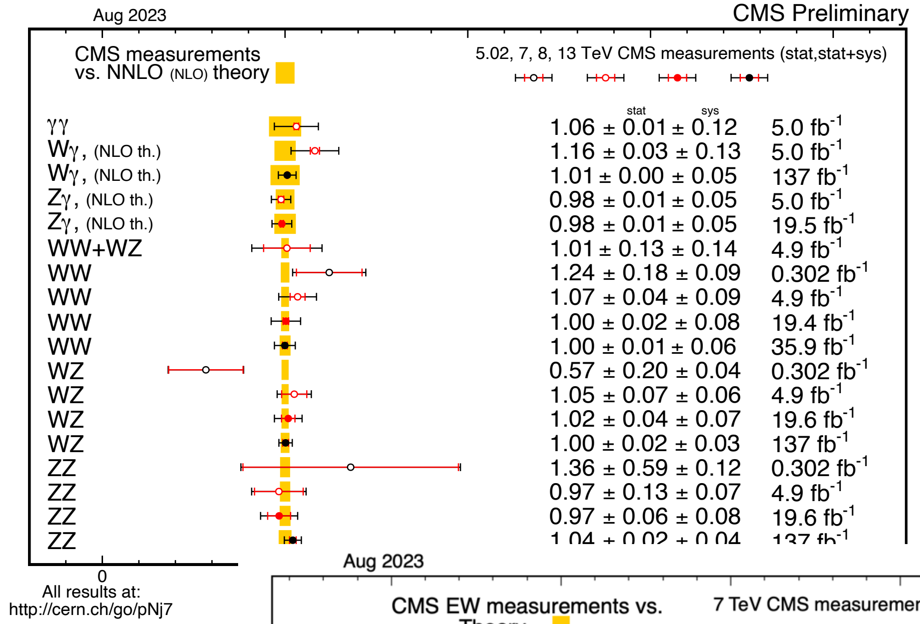


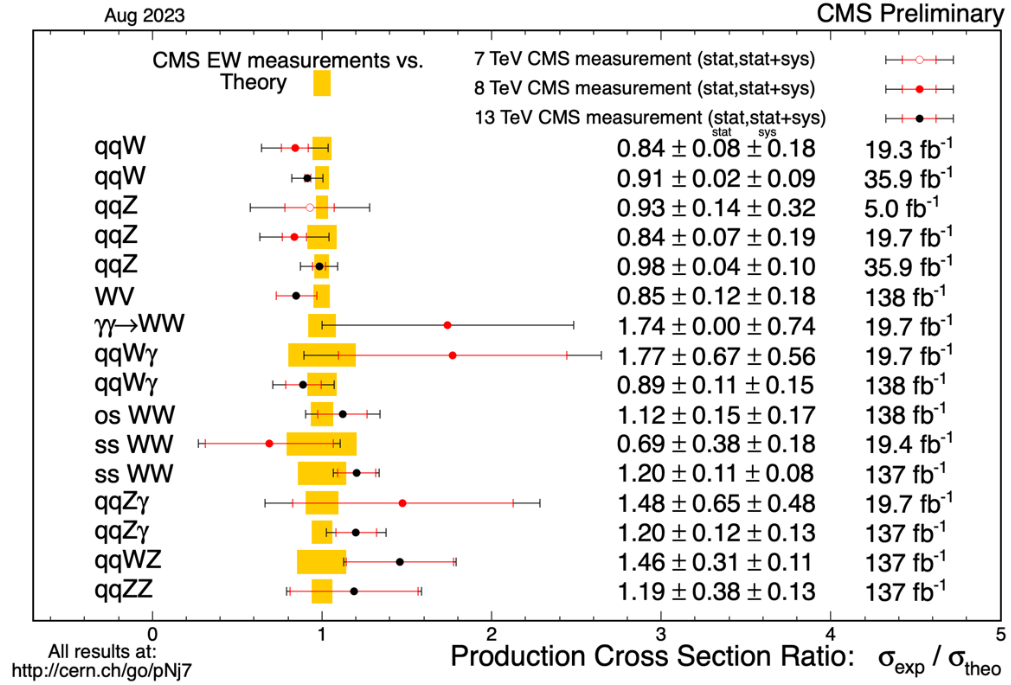
after "conservative"

M_W=80.4133 ±0.015 GeV

Beyond EW precision fits: SM broadly consistency with all LHC measurements







Across multiple energy scales, signatures, and kinematic regions

Exploring new physics effects via EFT

- The SM Effective Field Theory (SMEFT) approach.
- SMEFT effects on SM parameters and SM interactions.
- Calculating observables in the SMEFT.

Reaching beyond the SM within very general assumptions

The SM Effective Field Theory (SMEFT) as testing ground

Consider the **SM as an effective low-energy realization of some UV completion**.

Extend the Lagrangian of the SM by effective interactions of dim>4

Since the UV completion is unknown, it is necessarily a **bottom-up approach**

$$\mathcal{L}_{SMEFT}(\psi,\phi,A) = \mathcal{L}_{SM}(\psi,\phi,A) + \sum_{d=5}^{\infty}\sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{(d-4)}} Q_i^{(d)}(\psi,\phi,A)$$

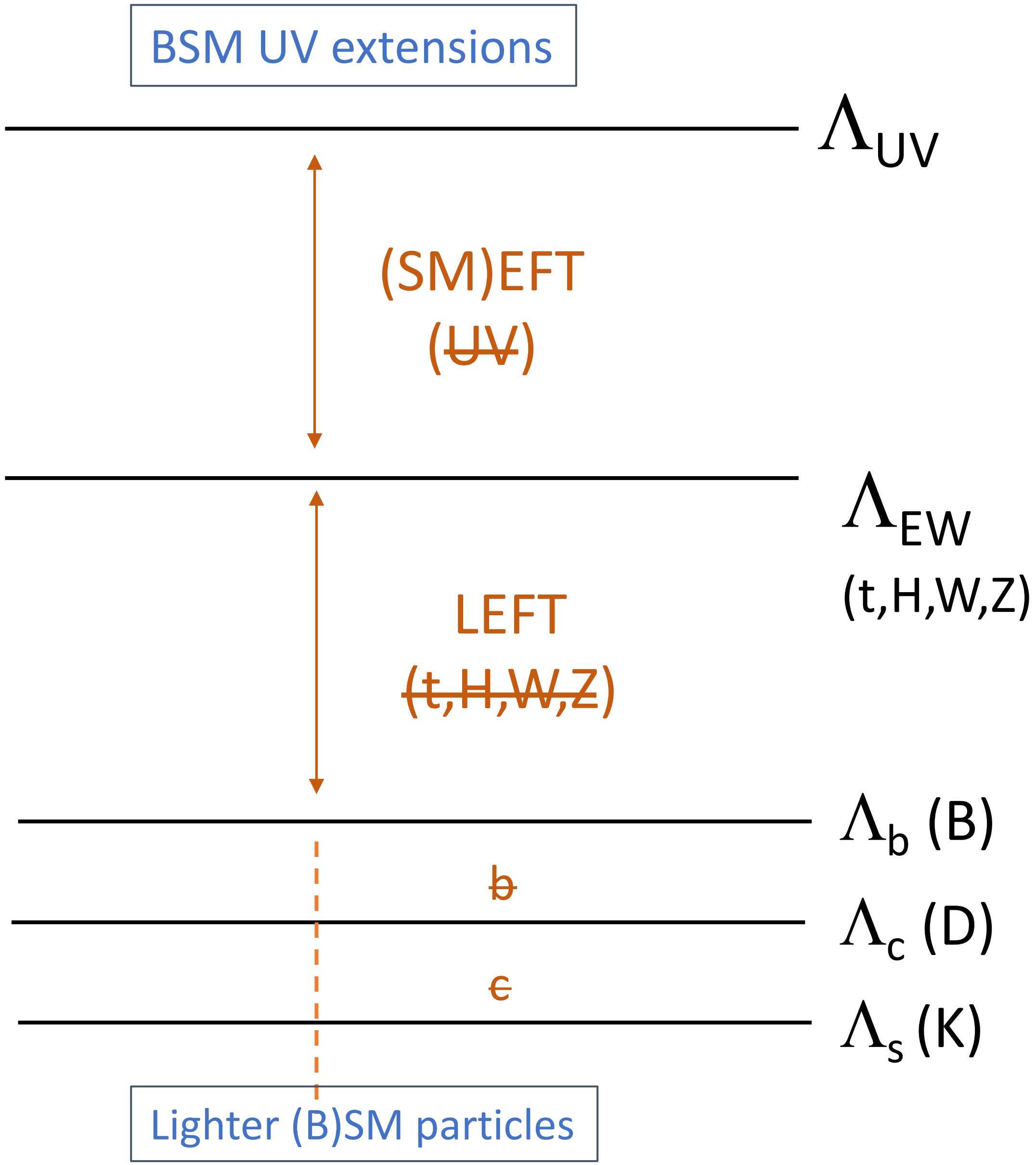
ψ → fermions
ϕ → scalars
A → gauge bosons

where the $Q_i^{(d)}$ are functions of the fields of the SM (ψ,ϕ,A) and respect

- Lorentz invariance
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ SM gauge symmetry
- Global symmetry such as lepton (L) and baryon (B) number conservation

We will analyze in detail the case of dim=6 operators and discuss how to further connect the SMEFT to the low-energy EFT (LEFT) describing flavor dynamics of B, D, and K mesons.

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 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

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

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 flavor symmetries: $U(3)^5$, $U(2)^5$ …; no CPV

SMEFT predictions

A given observable will be written as

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

SM: including SM higher-order corrections

SMEFT: tree level + SM K-factors

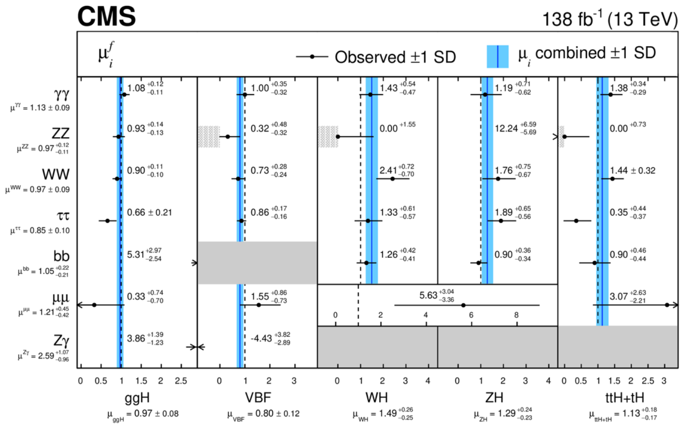
Observables have been calculated either analytically and via parametrizations reported in the literature (e.g. EW observables) or obtained using various tools (analytic results, MG5_aMC@NLO or in-house codes with **SMEFTci2**, a new UFO file developed for this study, Feynart+Feyncalc, …)

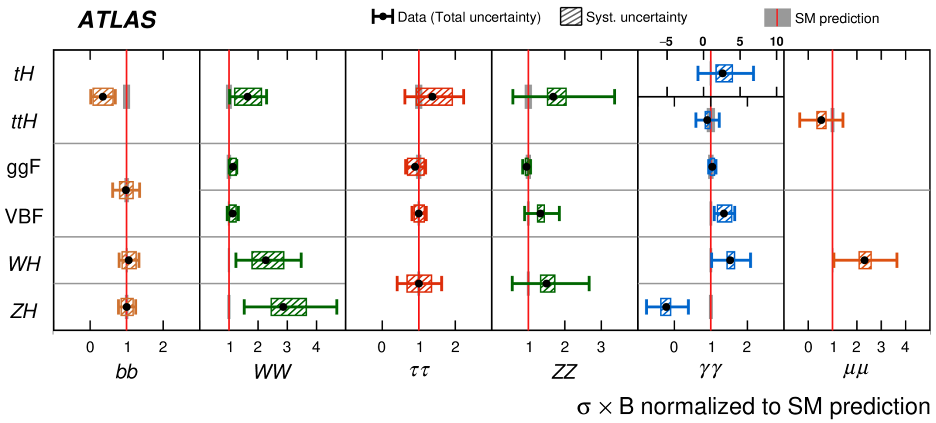
See also, SmeftFR-v3, Dedes et al. 2302.01353

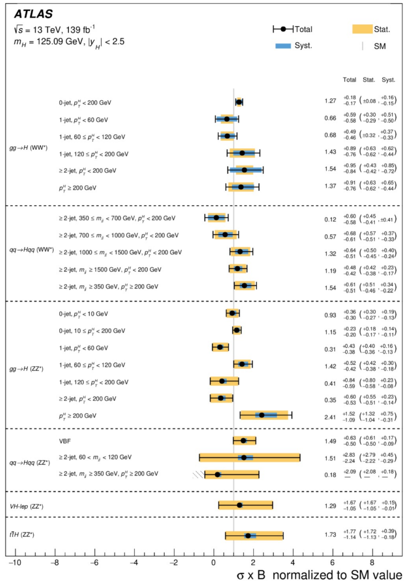
Including direct and indirect SMEFT effects from dim-6 operators up to O(1/Λ^4), **by A. Goncalves**

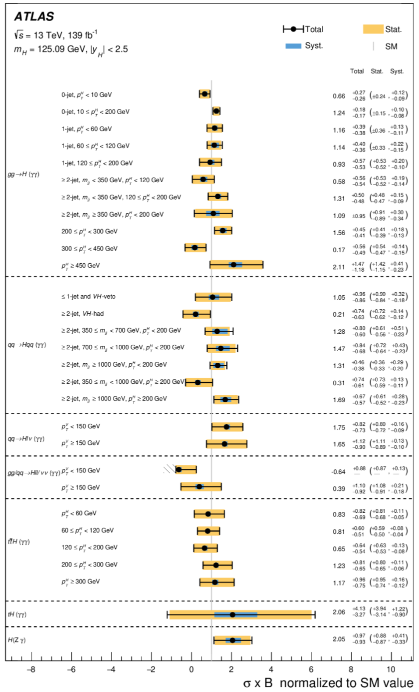
Higgs-boson Observables: exp. measurements

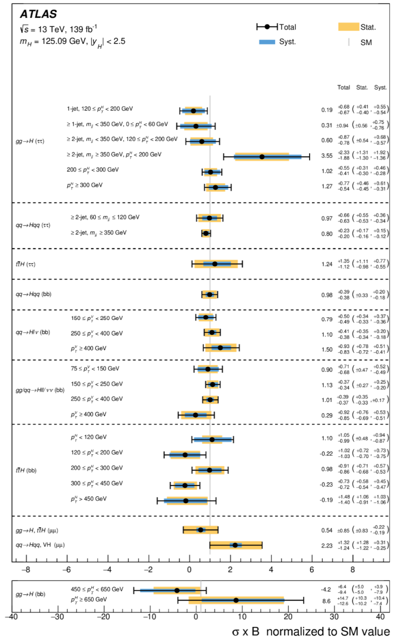
- **Higgs-boson inclusive and fiducial $\mu's$ measured by ATLAS and CMS:**





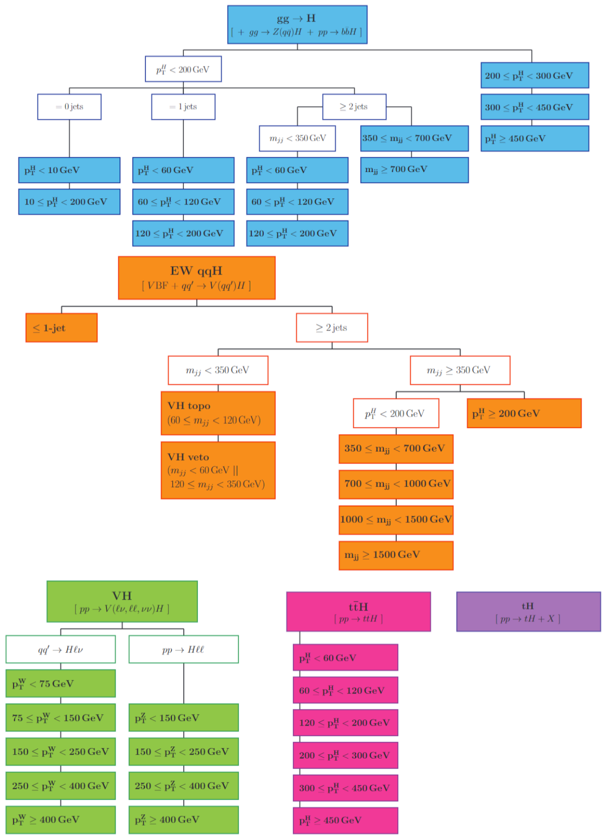






SMEFT Predictions: Higgs-boson Observables

- Higgs-boson production cross-sections and branching ratios
- **Signal strength modifiers:**
  - **Production cross-sections as inclusive or fiducial observables through *Simplified Template Cross-Sections* (STXS)**
  - **SMEFT predictions obtained differently depending on their complexity: Analytic vs. Numeric computations with *Madgraph*** [J. Alwall, et al, arXiv:1405.0301]



$$\mu_{ij} = \frac{\sigma_i \times Br_j}{\sigma_i^{SM} \times Br_j^{SM}}$$

With SMEFT expansion:

$$\mu_{ij} = 1 + \left(\frac{\Delta\sigma_i^{(1)}}{\sigma_i^{SM}} + \frac{\Delta Br_j^{(1)}}{Br_j^{SM}}\right) + \left(\frac{\Delta\sigma_i^{(2)}}{\sigma^{SM}} + \frac{\Delta Br_j^{(2)}}{Br^{SM}} + \frac{\Delta\sigma_i^{(1)}\Delta Br_j^{(1)}}{\sigma_i^{SM} Br_j^{SM}}\right) + \ldots$$

$$Br_j^{SM} = \frac{\Gamma_j^{SM}}{\Gamma_H^{SM}} \qquad \Delta Br_j^{(1)} = \frac{\Delta\Gamma_j^{(1)}}{\Gamma_j^{SM}} - \frac{\Delta\Gamma_H^{(1)}}{\Gamma_H^{SM}} \qquad \Delta Br_j^{(2)} = \frac{\Delta\Gamma_j^{(2)}}{\Gamma_j^{SM}} - \frac{\Delta\Gamma_H^{(2)}}{\Gamma_H^{SM}} - \frac{\Delta\Gamma_j^{(1)}}{\Gamma_j^{SM}}\frac{\Delta\Gamma_H^{(1)}}{\Gamma_H^{SM}} + \left(\frac{\Delta\Gamma_H^{(1)}}{\Gamma_H^{SM}}\right)^2$$

"Building blocks"

$$\frac{\Delta\sigma_i^{(1,2)}}{\sigma_i^{SM}} \qquad \frac{\Delta\Gamma_j^{(1,2)}}{\Gamma_j^{SM}}$$

Extending the reach of precision fits
beyond EW observables: Higgs, top, and flavor

- **Global fits of the SMEFT can constrain NP** in a fairly model-independent way
- **Improved theoretical and experimental precision** will enable their constraining power.

Beyond EW precision fits: global precision fits

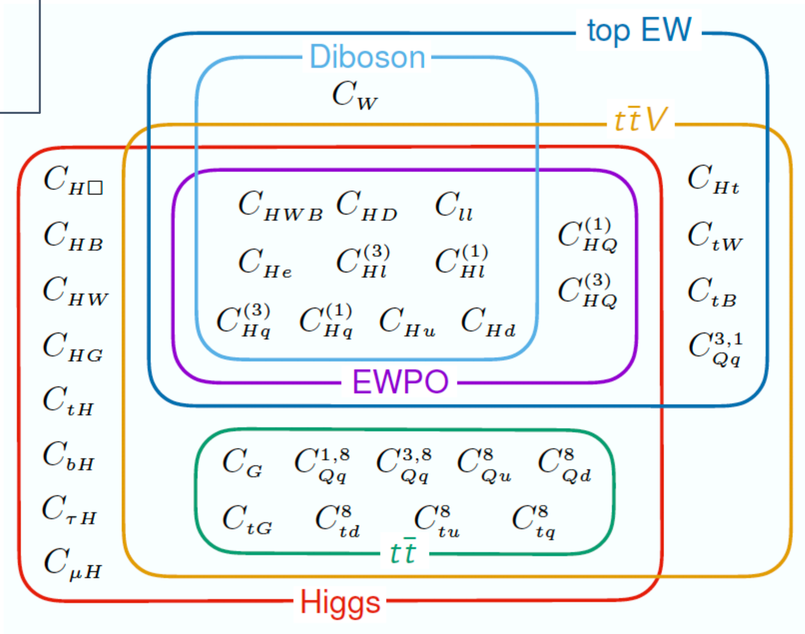
Constraining new physics through a broad spectrum of collider and flavor observables

- **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 recent LHC measurements of m_t and M_W

- **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



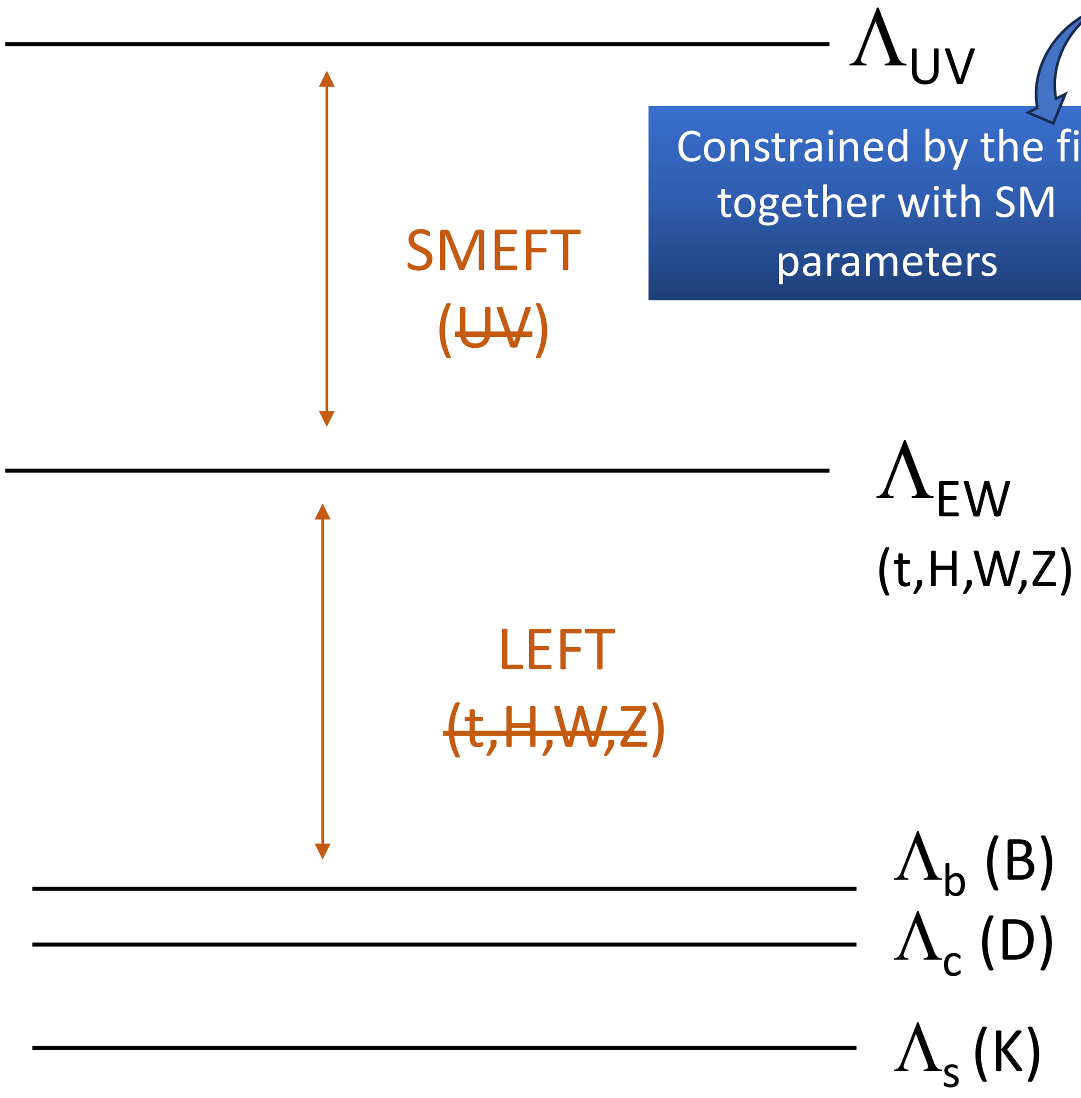
Flavor involves almost all of them either directly or through RGE

- **Flavor 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: $B\to X_{s,d}\gamma$

Exp: PDG, HFLAV
Th: best available predictions

Beyond EW fits – Higgs, top, EW, and flavor observables

Connecting far apart scales naturally lends itself to the EFT framework



Constrained by the fit together with SM parameters

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

Impose NP flavor 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 $C_i^{LEFT}(\Lambda_{b,c,..})$

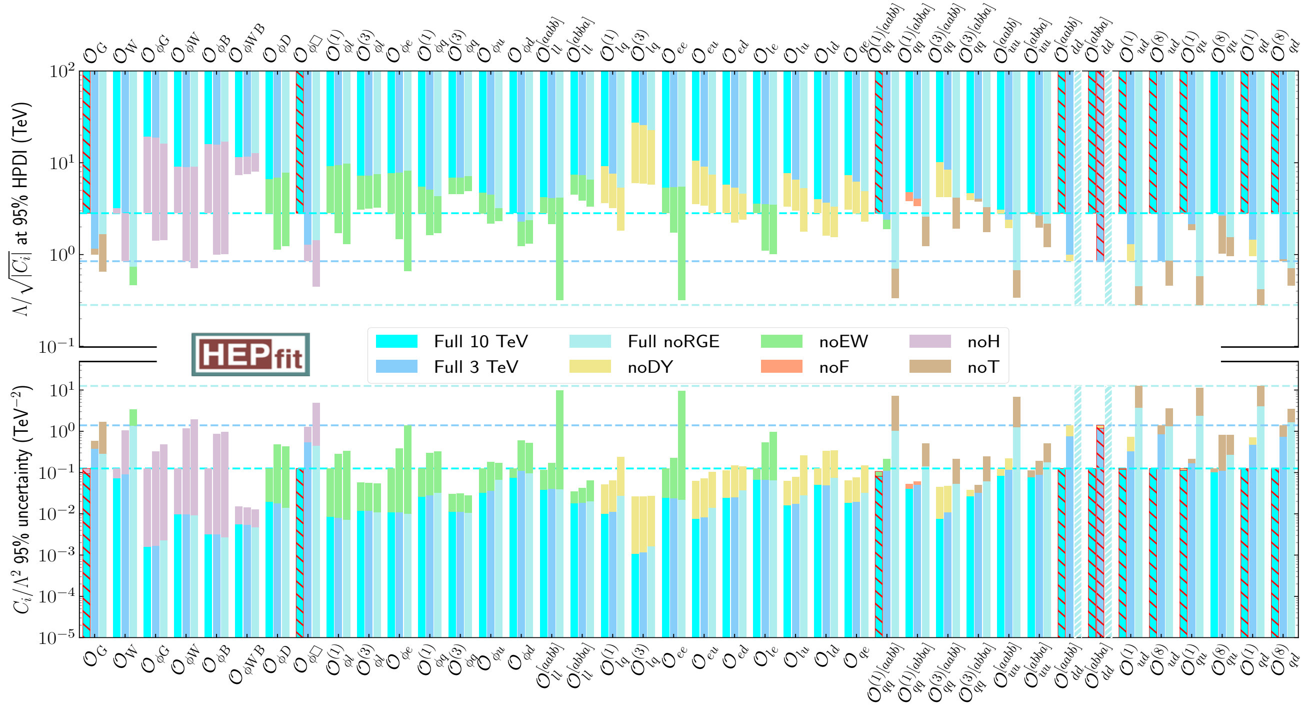
Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270

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

UV theory flavor 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^2 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

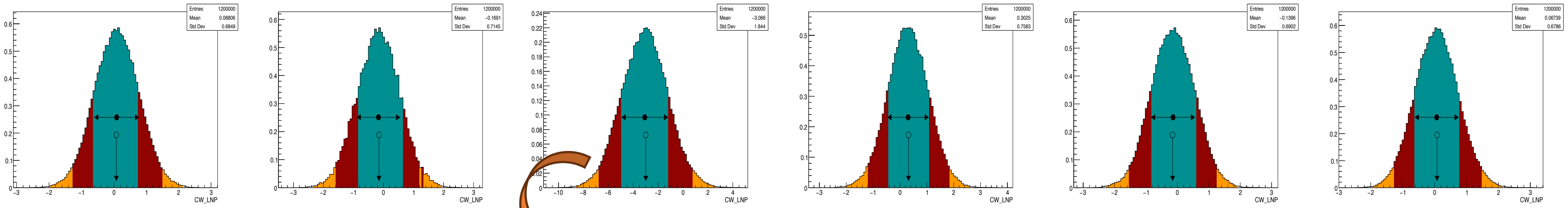
White shades: posterior completely flat → need more observables

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)

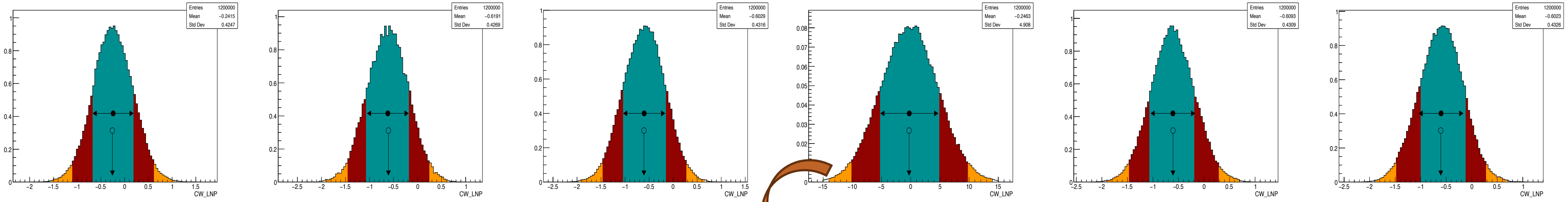
Full fit | No Flavor | No EW | No Higgs | No top | No DY



No RGE:
EW obs. are the strongest constraint

much broader range

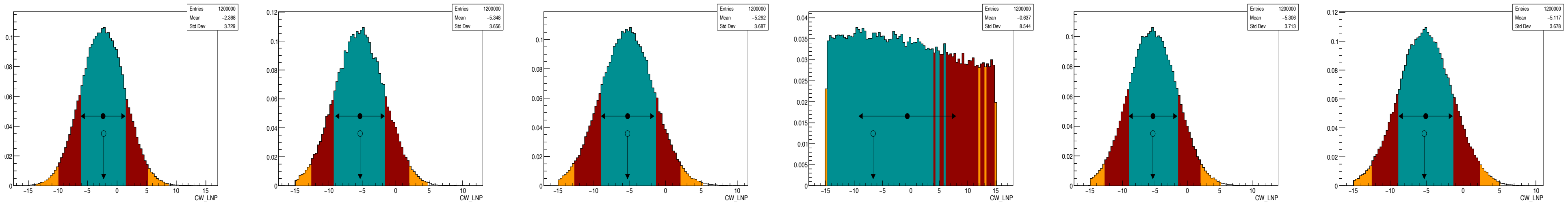
With RGE, $\Lambda = 3$ TeV



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

much broader range

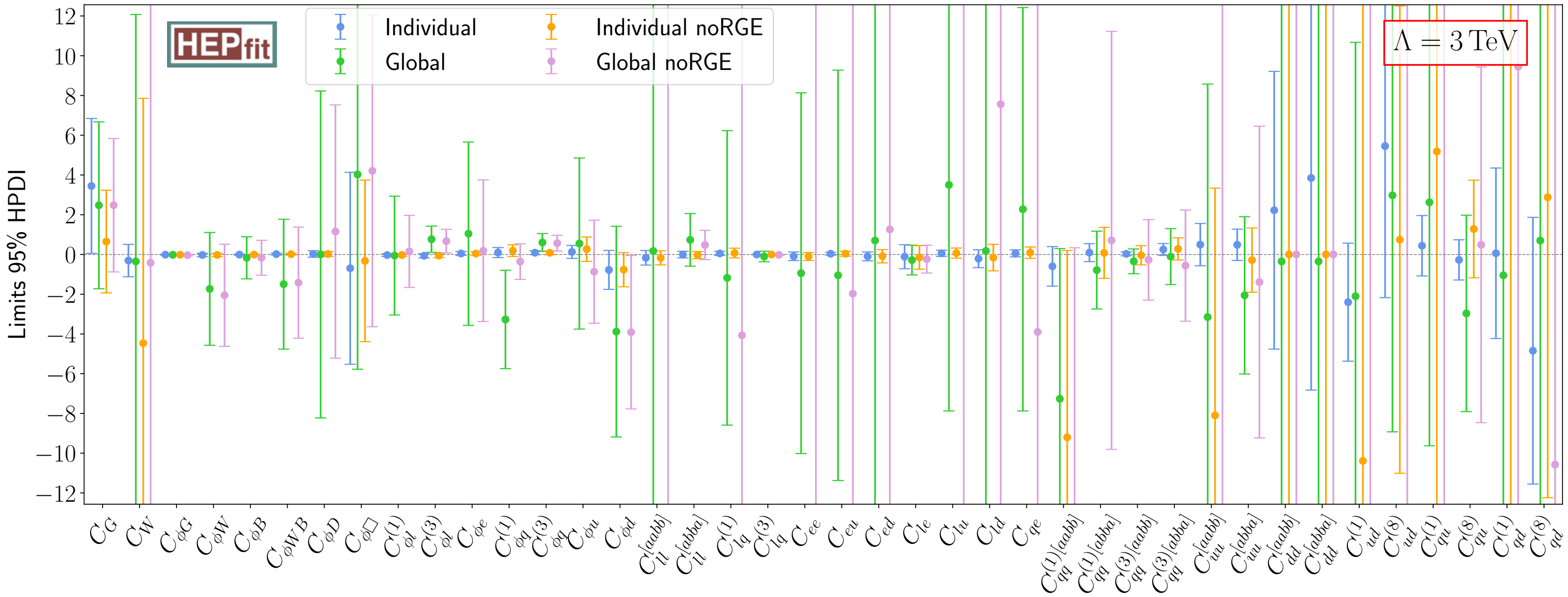
With RGE, $\Lambda = 10$ TeV



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

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

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

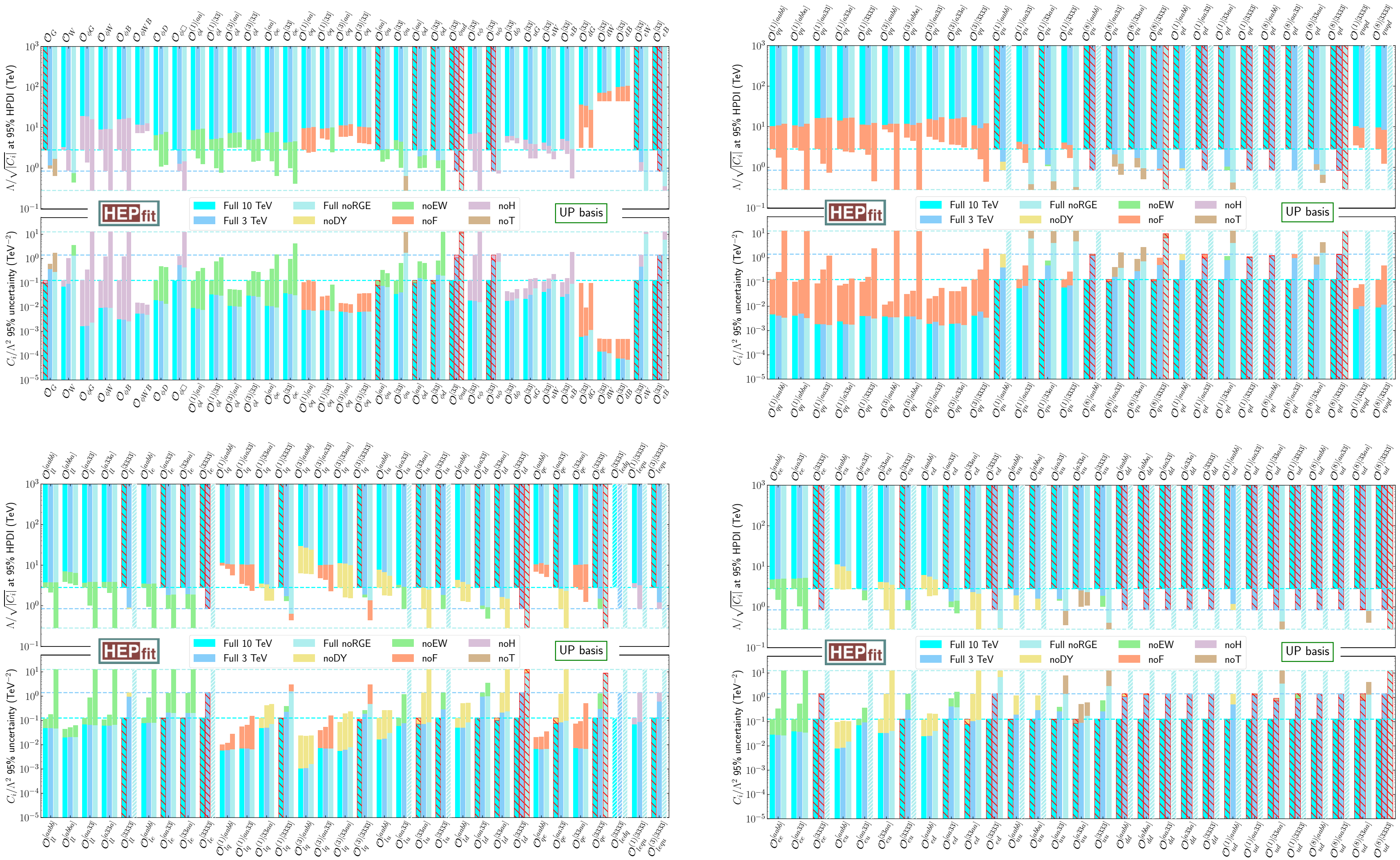


This is already relevant input to model building!

- 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, some cases still very well constrained, giving strong lower bounds.
- Global fits, if really global, are numerically massive. Adding all existing measurements may prevent the fit from converging or take a lot of educated choices: fine balance between higher information and better convergence.

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

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



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

Main flavor constraints coming from:

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

Summary and Outlook

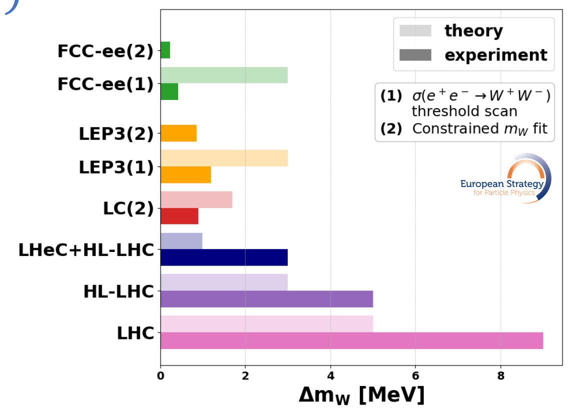
- After the Higgs discovery **collider physics** remains as a **unique and necessary test of BSM scenarios,** both via direct and indirect evidence.
- Extending **precision fits** beyond EW observables, allows to **connect Higgs, top, and flavour physics**, allowing to test the SM paradigm and its effective extensions at an unprecedented level.
- 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** and can provide hints of specific BSM physics.
- Improving the **precision of theoretical predictions** can add crucial **constraining power to global fits** of the SM and beyond and **provide indications towards future explorations**.

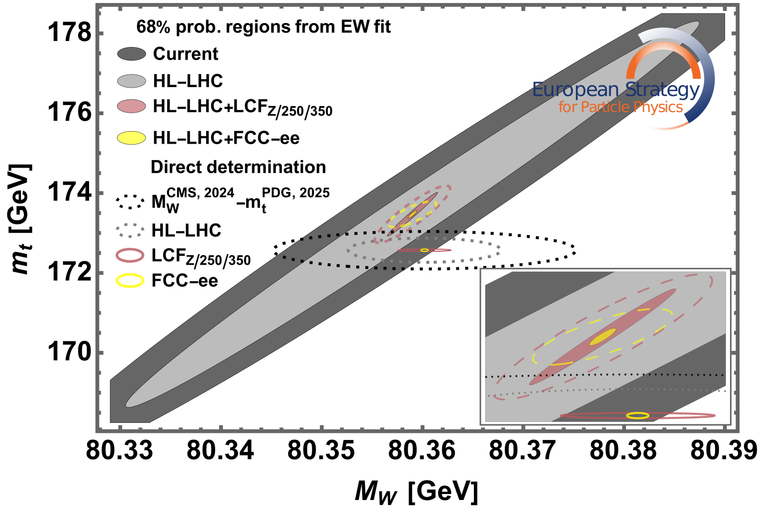
EW precision fits: reach of future colliders

Current and projected experimental precision (e^+e^-)

Observable	Current	FCC-ee	LCF	LEP3
Δm_Z (keV)	2000	4 (100)	200	7.5 (100)
$\Delta\Gamma_Z$ (keV)	2300	4 (12)	125	7.5 (23)
δR_μ $(\times 10^{-6})$ $R_\mu \equiv \frac{\Gamma_{had}}{\Gamma_\mu}$	1600	2.4 (2.3)	90 (90)	4.5 (2.3)
δR_b $(\times 10^{-6})$ $R_b \equiv \frac{\Gamma_b}{\Gamma_{had}}$	3300	1.2 (1.6)	70 (60)	2.2 (3.0)
$\Delta \sin^2\theta_W$ $(\times 10^6)$	130	0.4 (0.5)	2.7 (2.3)	0.75 (0.95)
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	14	0.8, 3.8	–	1.4, 7.3
Δm_W (keV)	9900	180 (160)	500 (1600)	430 (700)
$\Delta\Gamma_W$ (keV)	42000	270 (200)	2000	650 (500)

Parametric uncertainties





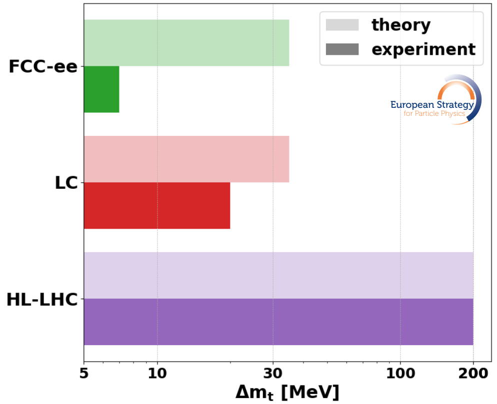
Current and projected theoretical precision (e^+e^-)

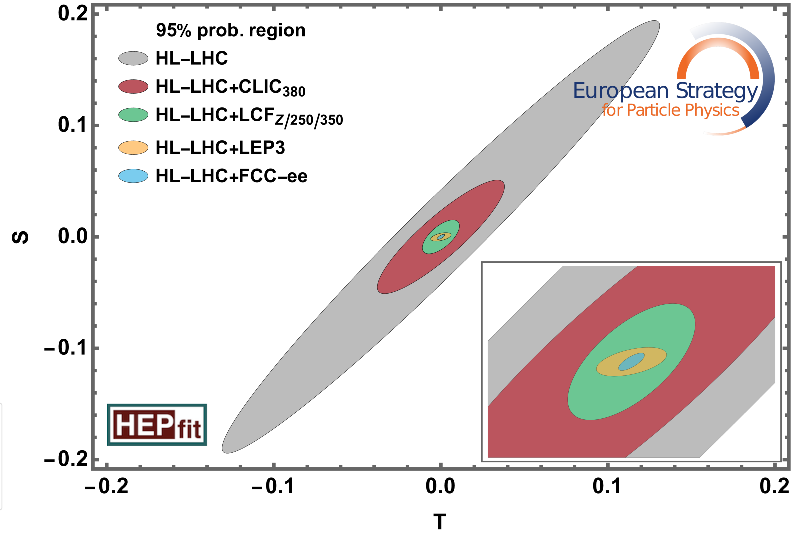
Observable	Current	Conservative	Aggressive
Γ_Z (MeV)	0.23	0.035	—
m_Z (MeV)	0.3	0.03	—
R_ℓ (10^{-3})	12	0.4	—
R_b (10^{-4})	4.4	0.44	0.09
R_c (10^{-4})	17	1.7	0.34
σ_{had} (pb)	25	1.7	—
A_{FB}^{ℓ} (10^{-4})	6	0.43	—
A_{FB}^{b} (10^{-4})	1.5	0.32	0.028
A_{FB}^{c} (10^{-4})	1.1	0.23	0.021

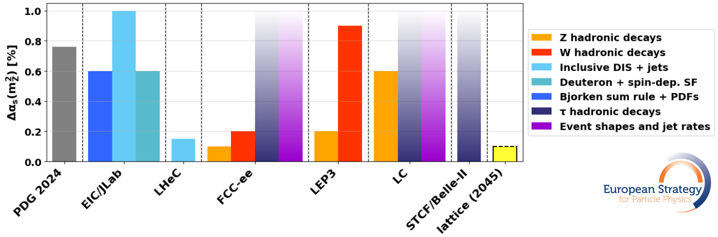
From extraction (background, ISR/FSR)

Observable	Current	Conservative	Aggressive
Γ_Z (MeV)	0.4	0.08	0.016
R_ℓ (10^{-3})	6.0	1.2	0.2
R_b (10^{-4})	1.0	0.2	0.035
R_c (10^{-4})	0.5	0.1	0.02
σ_{had} (pb)	6	1.6	0.3
$\sin^2\theta_{eff}$ (10^{-5})	4.5	0.7	0.06
m_W (MeV)	4.0	1.0	0.1

From SM prediction







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