Global fits of the SM 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: J. de Blas, A. Goncalves, V. Miralles, M. Pierini, L. Silvestrini, M. Valli, and members of the HEPfit collaboration.

Global fits of precision measurements

- The symmetry structure of the Standard Model defines specific relations among couplings and masses.

- The renormalizability of the theory assures that tree-level relations are modified by finite calculable corrections.

- **Precision measurements** of masses and couplings via multiple observables:
  - Test the consistency of the theory at the quantum level
  - Indirectly probe new physics via virtual effects

A comprehensive program of precision physics (EW, top, Higgs, flavor, …) can be a very powerful tool to explore physics beyond the Standard Model

EW Global fit: general framework

- Set of input parameters (α or M_W scheme):
  - Fixed: G_F, α
  - Floating: M_W, M_Z, M_H, m_t, $\alpha_s(M_Z)$, $\Delta\alpha_{had}^{(5)}$
- Compute EW Precision Observables (EWPO), including all known higher-order SM corrections:
  - 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)

See talk by Ayres Freitas

- Perform best fit to EW precision data through different fitting procedures and compare with experimental measurements.
- Parametrize new physics effects on EWPO (tree-level) and constrain deviations in terms of chosen parameters:
  - Oblique parameters : S,T, U
  - **Effective interactions: SMEFT**
  - ….

focus of this talk

Framework we used

Open-source tool

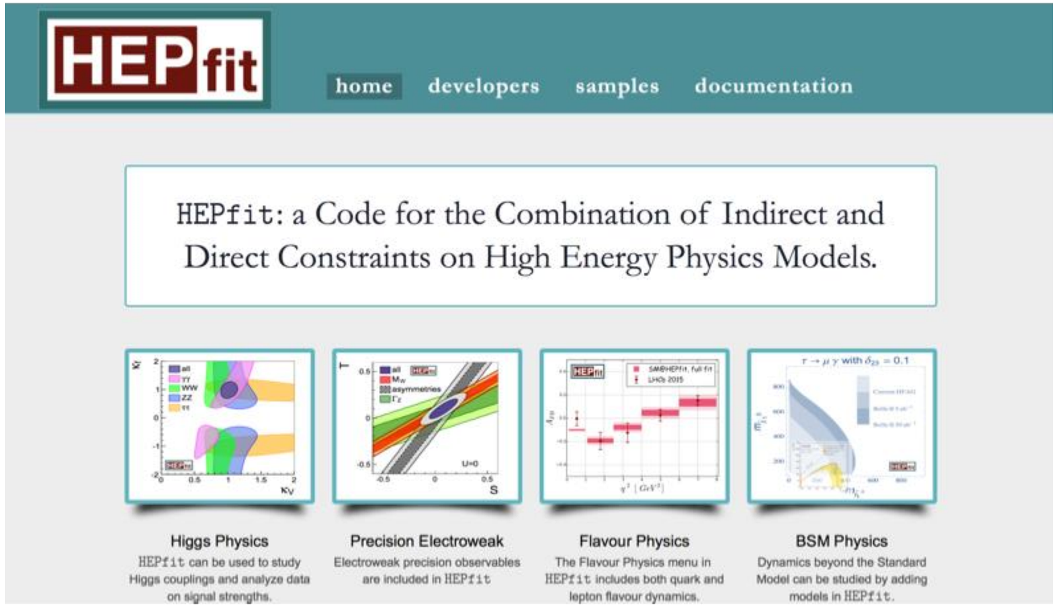
Statistical framework based on a Bayesian MCMC analysis as implemented in
BAT (Bayesian Analysis Toolkit)
Caldwell et al., arXiv:0808.2552

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 flavor observables in the SM and the SMEFT with

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



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

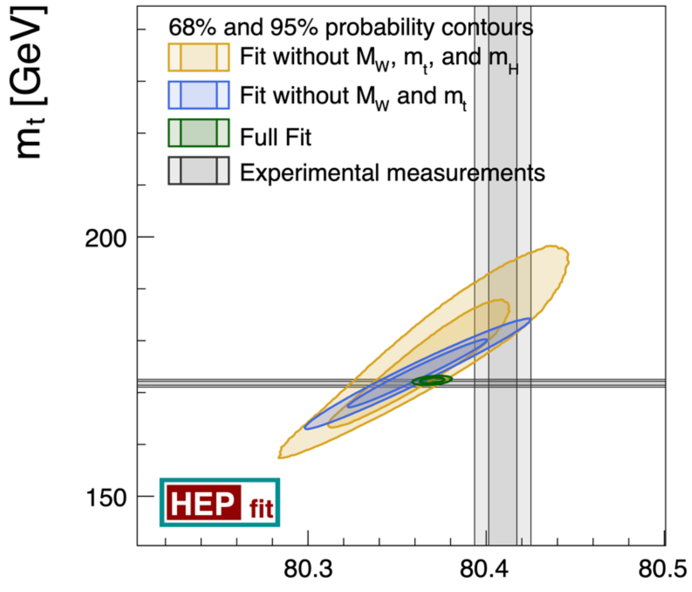
EW global fit of the SM - excerpt

J. de Blas et al. 2112.07274, 2204. 04204, plus updates

For M_W we combine:
- ❑ All LEP 2 measurements;
- ❑ Previous Tevatron average
- ❑ ATLAS and LHCb measurements
- ❑ CDF measurement [M_W=(80.4335±0.0094) GeV]
- ❑ ATLAS measurement [M_W=(80.360±0.016) GeV]

M_W = 80.409 ± 0.008 GeV (**standard**, with CDF)
M_W = 80.360± 0.012 GeV (**standard**, without CDF)

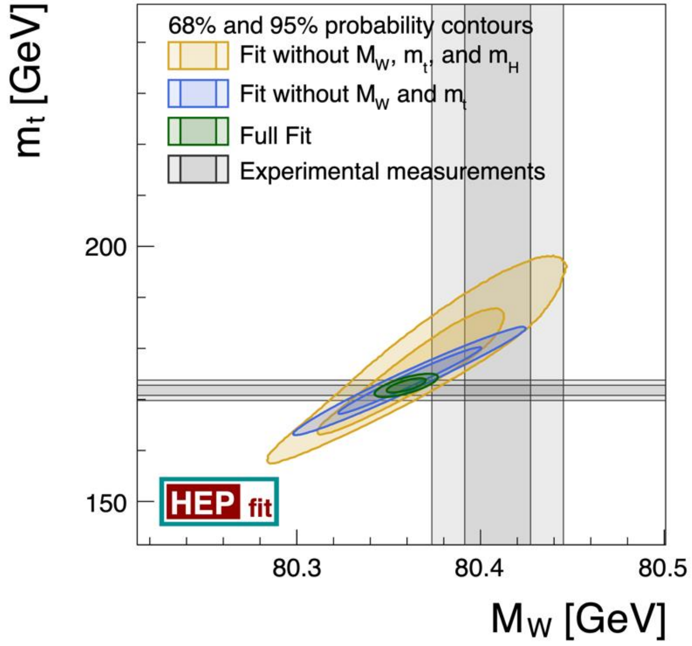
“standard”
(6.1 σ pull)



For m_t we combine:
- ❑ 2016 Tevatron combination
- ❑ ATLAS Run 1 and Run2 results
- ❑ CMS Run 1 and Run 2 results
- ❑ Recent CMS l+j measurement [m_t=(171.77±0.38) GeV]

m_t = 172.61 ±0.58 GeV (**standard**)

“conservative
(3.0 σ pull)



Due to tension between LEP, Tevatron, and LHC measurements consider also a **conservative** error of δM_W=18 MeV and δm_t=1 GeV (à la PDG)

Beyond EW fits: adding Higgs, top, DY, di-boson, flavor

Constraining new physics through the spectrum of LHC measurements and beyond

See talk by Matthew Klein

- Higgs boson observables
  - Signal strengths.
  - Simplified Template Cross Sections (STXS)

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

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

Preliminary results in this talk

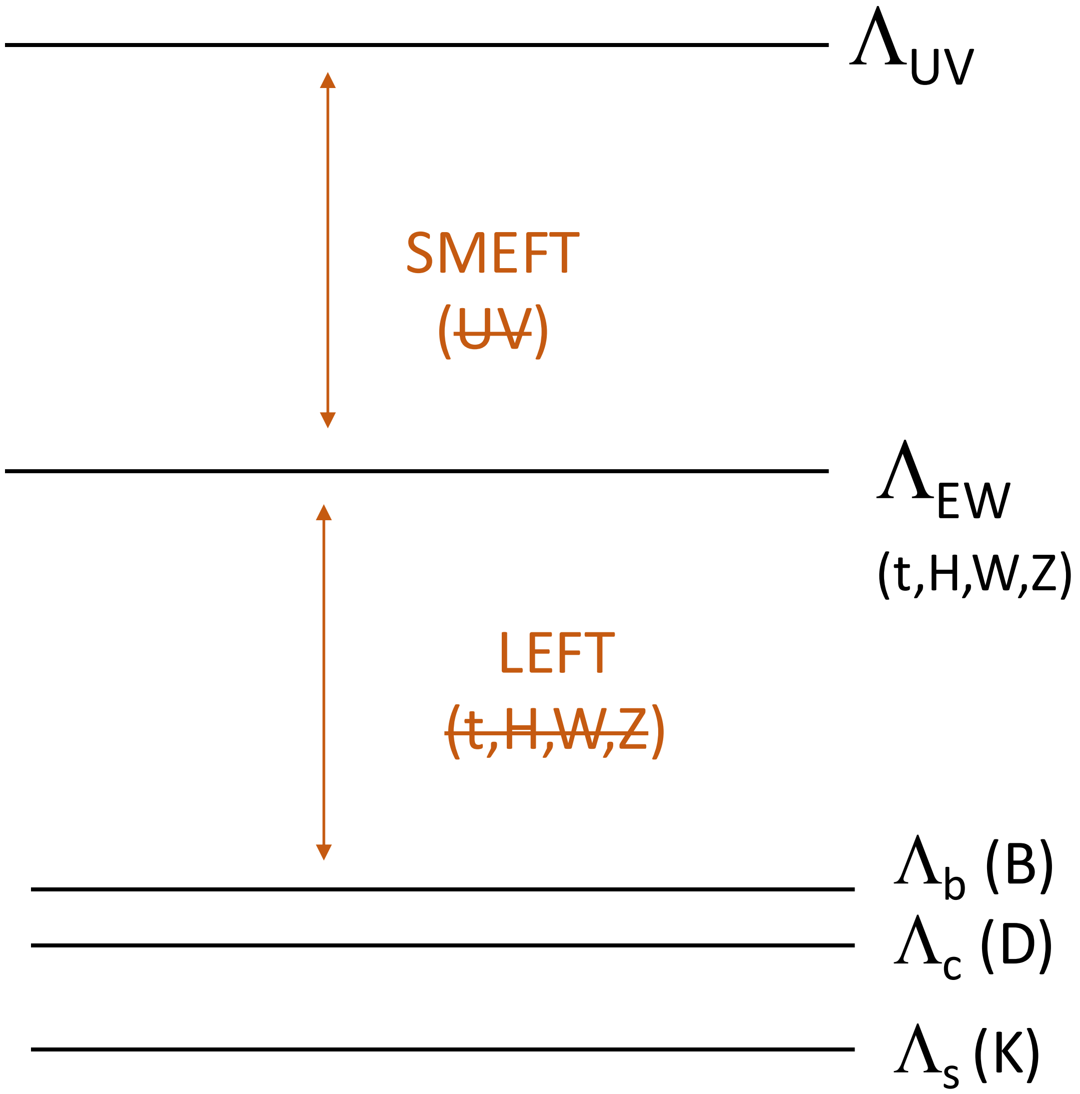
- Drell-Yan, Di-boson measurements
  - $pp \to W, Z \to f_i \bar{f}_j$
  - $pp \to WZ, WW, ZZ, Z\gamma$

- Flavor observables
  - ΔF=2: $\Delta M B_{d,s}$, $D^0 - \bar{D}^0$, ε_K
  - Leptonic decays: $B_{d,s} \to \mu^+\mu^-$, $B \to \tau\nu$, $D \to \tau\nu$, $K \to \mu\nu$, $\pi \to \mu\nu$
  - Semi-leptonic decays: $B \to D^{(*)} l\nu$, $K \to \pi\nu\bar{\nu}$, $B \to K\nu\bar{\nu}$, $B, K \to \pi l\nu$
  - Radiative B decays ($B \to X_{s,d}\gamma$)

Still being tested

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework



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

RGE

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

RGE

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

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

Beyond EW fits – Higgs, top, flavor observables

Connecting far apart scales naturally lends itself to the EFT framework

Matchmakereft, 2112.10787
MATCH2FIT, 2309.04523

Λ_{UV}

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

Will be constrained by the fit

SMEFT
(~~UV~~)

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)

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

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

Match to LEFT operators to calculate flavor observables

Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270

Λ_{b} (B)

Λ_{c} (D)

Λ_{s} (K)

Notice that the NLO evolution requires tree level initial conditions at Λ_{UV} and matrix elements at Λ_{EW}

The SMEFT framework for this study

Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884

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

"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 $\varphi^4 D^2$		$\psi^2\varphi^3$	
$\mathcal{O}_G$	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	$\mathcal{O}_\varphi$	$(\varphi^\dagger\varphi)^3$	$\mathcal{O}_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p \varphi e_r)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$	$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \tilde{\varphi} u_r)$
		$\mathcal{O}_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$\mathcal{O}_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p \varphi d_r)$
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$\mathcal{O}_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$\mathcal{O}_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\tilde{\varphi}\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$\mathcal{O}_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \tilde{\varphi}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$\mathcal{O}_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tilde{\varphi}\, B_{\mu\nu}$	$\mathcal{O}^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$\mathcal{O}_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$\mathcal{O}_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
		$\mathcal{O}_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$\mathcal{O}_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
		$\mathcal{O}_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$\mathcal{O}_{\varphi ud}$	$(\tilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

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

4-fermion interactions: tt, ttH, DY

- Dim-6 operators only, including linear and quadratic effects
- Obeying SM symmetries, CP even
- Assuming $U(2)^5$ flavor symmetry (3^{rd} generation singled out)
- One Higgs doublet of $SU(2)_L$, SSB linearly realized.

Direct and indirect SMEFT effects

Example: Higgs sector

$$\mathcal{L}_\varphi = (D_\mu\varphi)^\dagger(D^\mu\varphi) + m^2(\varphi^\dagger\varphi) - \frac{\lambda}{2}(\varphi^\dagger\varphi)^2 + \hat{C}_\varphi(\varphi^\dagger\varphi)^3 + \hat{C}_{\varphi\Box}(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi) + \hat{C}_{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$$

VEV identified from the minimization of V(φ):

$$\bar{v} = \sqrt{\frac{2m^2}{\lambda}}\left(1 + \frac{3m^2\hat{C}_\varphi}{2\lambda^2} + \frac{63m^4\hat{C}_\varphi^2}{8\lambda^4} + \dots\right)$$

$$\varphi = \begin{pmatrix} 0 \\ \frac{\bar{v}+h}{\sqrt{2}} \end{pmatrix}$$

Expansion of SU(2) scalar doublet around the VEV and Higgs field (unitary gauge)

Shift on the Higgs field identified from the normalization of its kinetic-term:

$$\bar{h} \equiv Z_h h = \left(1 + \frac{\bar{v}^2}{4}\left(\hat{C}_{\varphi D} - 4\hat{C}_{\varphi\Box}\right) - \frac{\bar{v}^4}{32}\left(\hat{C}_{\varphi D} - 4\hat{C}_{\varphi\Box}\right)^2 + \dots\right) h$$

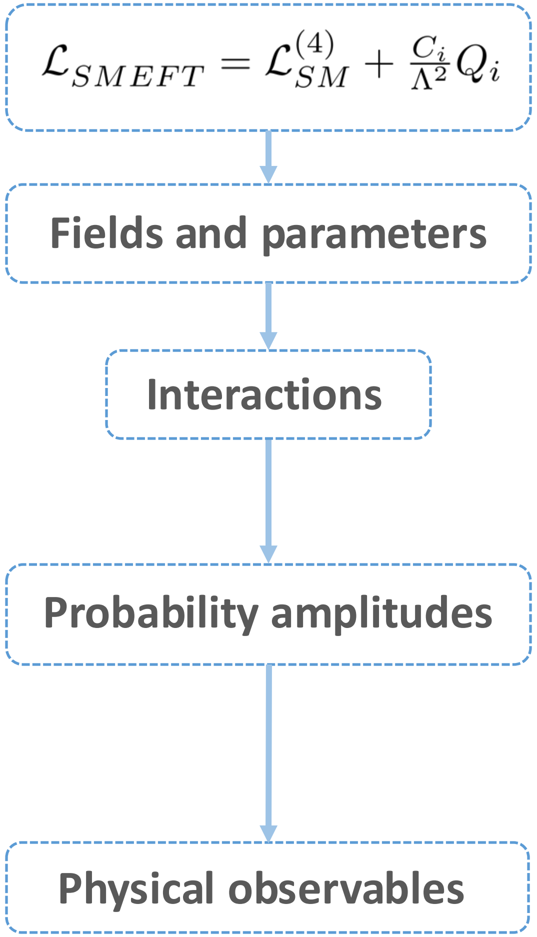
Shift on the physical mass of the Higgs field identified from the normalization of its mass-term:

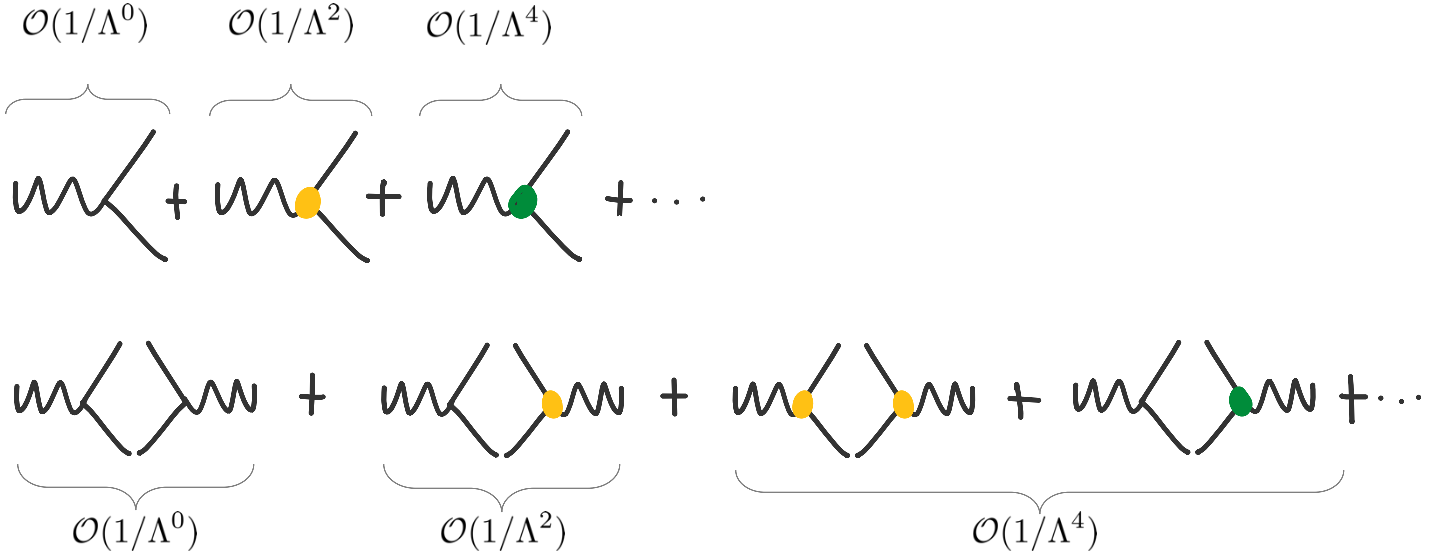
$$M_h^2 = \lambda\bar{v}^2 - \bar{v}^4\left(3\hat{C}_\varphi - 2\hat{C}_{\varphi\Box}\lambda + \frac{1}{2}\hat{C}_{\varphi D}\lambda\right) - \frac{\bar{v}^6}{2}(4\hat{C}_{\varphi\Box} - \hat{C}_{\varphi D})\left(3\hat{C}_\varphi - 2\hat{C}_{\varphi\Box}\lambda + \frac{1}{2}\hat{C}_{\varphi D}\lambda\right) + \dots$$

Direct effect on hVV interaction

$$\hat{C}_{\varphi D}(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi) \longrightarrow V^\mu V_\mu h$$

SMEFT predictions





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

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

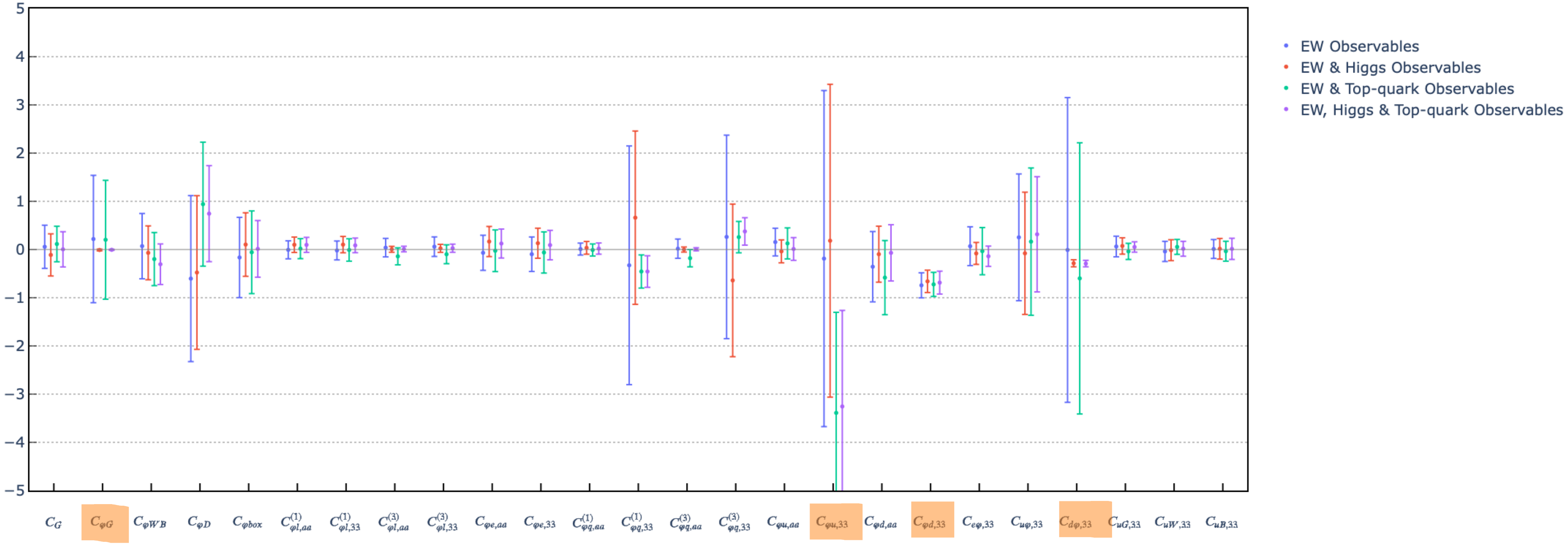
SMEFT: tree level

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, …)

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

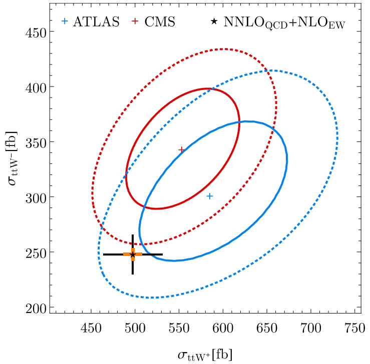
Including direct and indirect SMEFT effects from dim-6 operators up to O(1/Λ^4), **by A. Goncalves**

Preliminary results



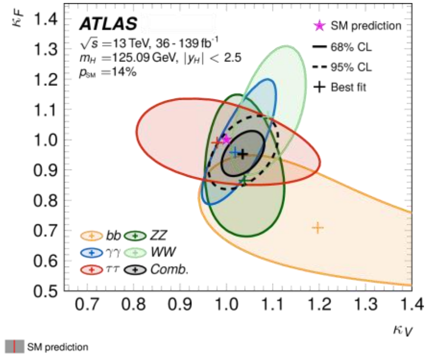
Highly constrained from ggH
RGE effects visible

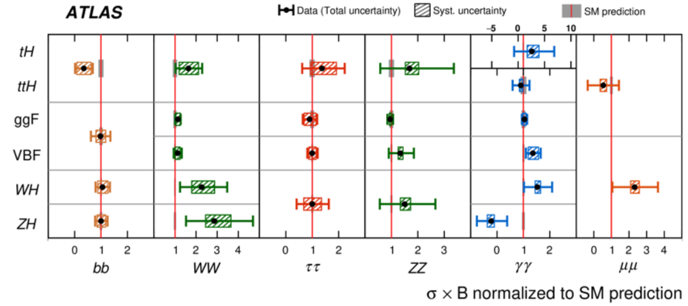
Effect of Vtt (V=Z,W,γ)



Driven by EW

Effect on H to bb

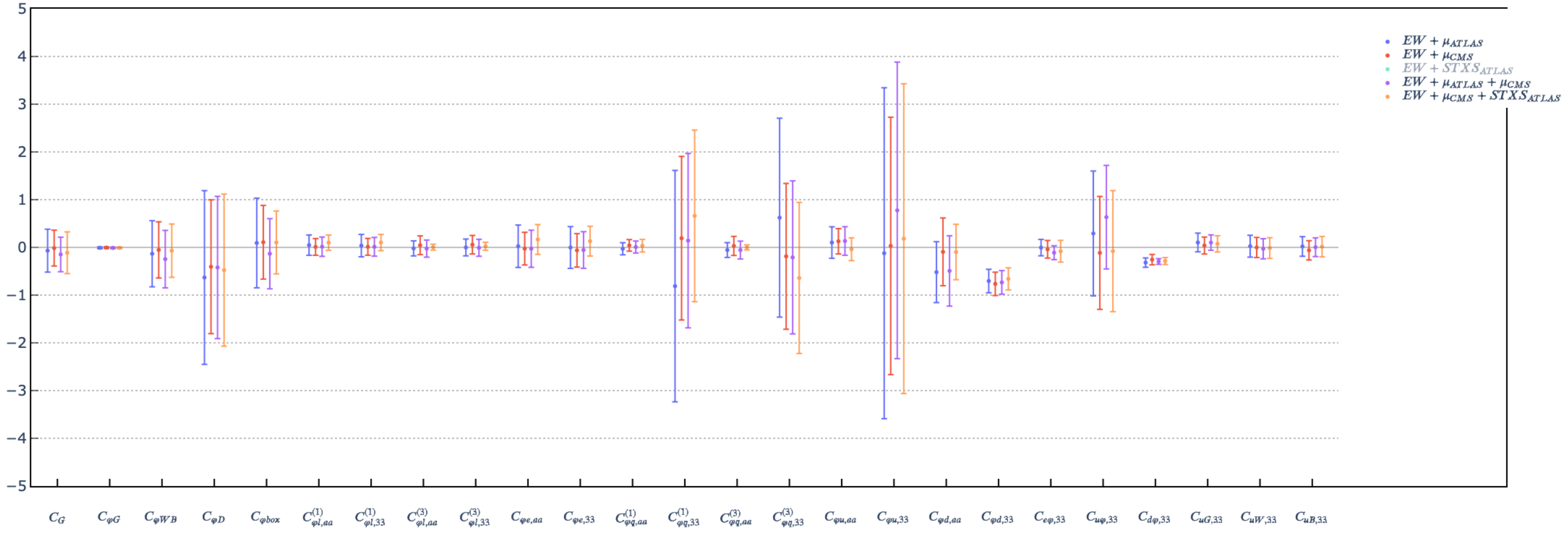




Preliminary results

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

Breakdown of Higgs-boson observables – **consistent picture from signal strength measurements**



Conclusions

- **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.**
- With **increasing precision** in both theory and experiments, constraints **could start to show intriguing patterns and guide future explorations.**

Back-up slides

EW Observables:

- **Analytic parametrization of *Z* and *W* observables:**

$$\Gamma_{Z,f} = N_f \frac{G_F M_Z^3}{24\sqrt{2}\pi} 4\left[(g_{V,f})^2 + (g_{A,f})^2\right]$$

$$R_e^0 = \frac{\Gamma_{had}}{\Gamma_e} \qquad R_{q,\nu}^0 = \frac{\Gamma_{q,\nu}}{\Gamma_{had}}$$

$$\sigma_{had}^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e \Gamma_{had}}{\Gamma_Z^2}$$

$$A_f = \frac{2\left(\frac{g_{V,f}}{g_{A,f}}\right)}{1+\left(\frac{g_{V,f}}{g_{A,f}}\right)^2} \qquad A_{FB,f} = \frac{3}{4}A_e A_f$$

Z

$$sin^2\theta_{eff,l} = \frac{1}{4}\left(1 - \frac{g_{V,l}}{g_{A,l}}\right)$$

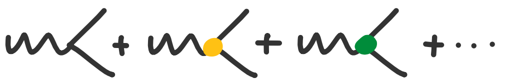
$W^{\pm}$ $\quad M_W \quad \Gamma_{(W\to f_i f_j)} \quad BrW_{f_i f_j}$

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

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

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

$$g_{V,f} = g_{V,f}^{SM} + \Delta g_{V,f}^{(1)} + \Delta g_{V,f}^{(2)} + \ldots$$
$$g_{A,f} = g_{A,f}^{SM} + \Delta g_{A,f}^{(1)} + \Delta g_{A,f}^{(2)} + \ldots$$



$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{l}'_p\gamma^\mu l'_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{l}'_p\tau^I\gamma^\mu l'_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{e}'_p\gamma^\mu e'_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{q}'_p\gamma^\mu q'_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar{q}'_p\tau^I\gamma^\mu q'_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{u}'_p\gamma^\mu u'_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar{d}'_p\gamma^\mu d'_r)$
$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}'_p\gamma^\mu d'_r)$

EW Observables:

- **Preliminary Global Fit of EW observables at quadratic order in the d=6 SMEFT:**

Observable	$C_{\varphi D}$	$C_{\varphi WB}$	$C_{\varphi L}^{(3)}$	C_{LL}	$C_{\varphi L}^{(1)}$	$C_{\varphi e}$	$C_{\varphi Q}^{(1)}$	$C_{\varphi Q}^{(3)}$	$C_{\varphi u}$	$C_{\varphi d}$	$C_{\varphi B}$	$C_{\varphi W}$	$C_{\varphi ud}$
A_l, A_{FB}^l, P_τ^{pol}, $\sin\theta_{eff,l}^2$	✓	✓	✓	✓	✓	✓					✓	✓	
A_c, R_c^0	✓	✓	✓	✓			✓	✓	✓		✓	✓	
A_b, A_s, R_b^0	✓	✓	✓	✓			✓	✓		✓	✓	✓	
A_{FB}^c	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
A_{FB}^b	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	
R_l^0, Γ_Z, σ_{had}^0	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
M_W	✓	✓	✓	✓									
Γ_W, BrW	✓	✓	✓	✓	✓		✓			✓	✓	✓	✓

O(1/Λ⁴) : degeneracy is (analytically) lifted

O(1/Λ²) : Constrain 8 independent relations

$$\mathbf{\hat{C}_{\varphi L}^{(3)}} = \hat{C}_{\varphi L}^{(3)} + \frac{1}{4}\frac{\widetilde{c_W}^2}{\widetilde{s_W}^2}\hat{C}_{\varphi D} + \frac{\widetilde{c_W}}{\widetilde{s_W}}\hat{C}_{\varphi WB}$$

$$\mathbf{\hat{C}_{\varphi Q}^{(3)}} = \hat{C}_{\varphi Q}^{(3)} + \frac{1}{4}\frac{\widetilde{c_W}^2}{\widetilde{s_W}^2}\hat{C}_{\varphi D} + \frac{\widetilde{c_W}}{\widetilde{s_W}}\hat{C}_{\varphi WB}$$

$$\mathbf{\hat{C}_{\varphi L}^{(1)}} = \hat{C}_{\varphi L}^{(1)} + \frac{1}{4}\hat{C}_{\varphi D}$$

$$\mathbf{\hat{C}_{\varphi Q}^{(1)}} = \hat{C}_{\varphi Q}^{(1)} - \frac{1}{12}\hat{C}_{\varphi D}$$

$$\mathbf{\hat{C}_{\varphi e}} = \hat{C}_{\varphi e} + \frac{1}{2}\hat{C}_{\varphi D}$$

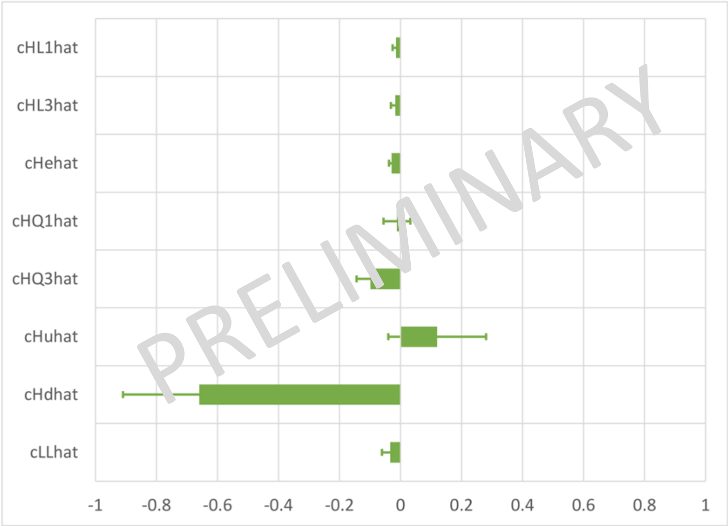
$$\mathbf{\hat{C}_{\varphi u}} = \hat{C}_{\varphi e} - \frac{1}{3}\hat{C}_{\varphi D}$$

$$\mathbf{\hat{C}_{LL}} = \hat{C}_{LL}$$

EW Observables:

- **Preliminary Global Fit of EW observables at quadratic order in the d=6 SMEFT:**

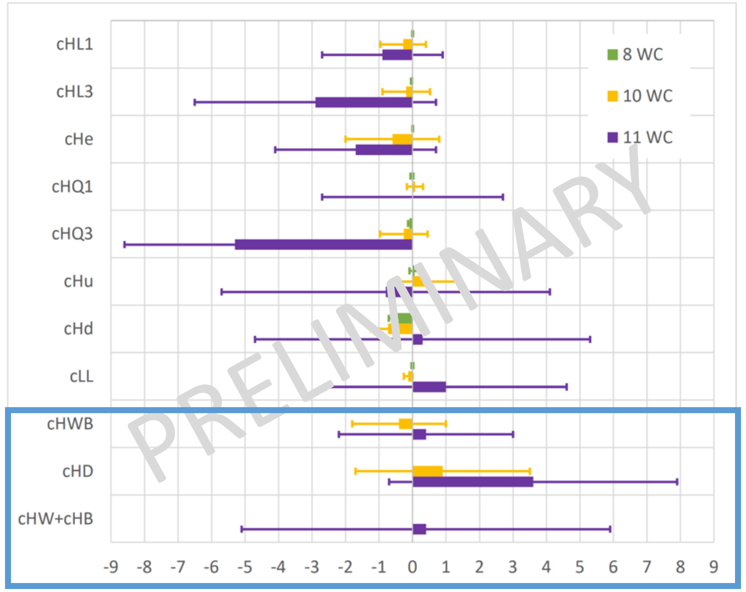
$O(1/\Lambda^2)$



Fit parameters	Analytically	Numerically
≤8	✓	✓
>8	✗	✗

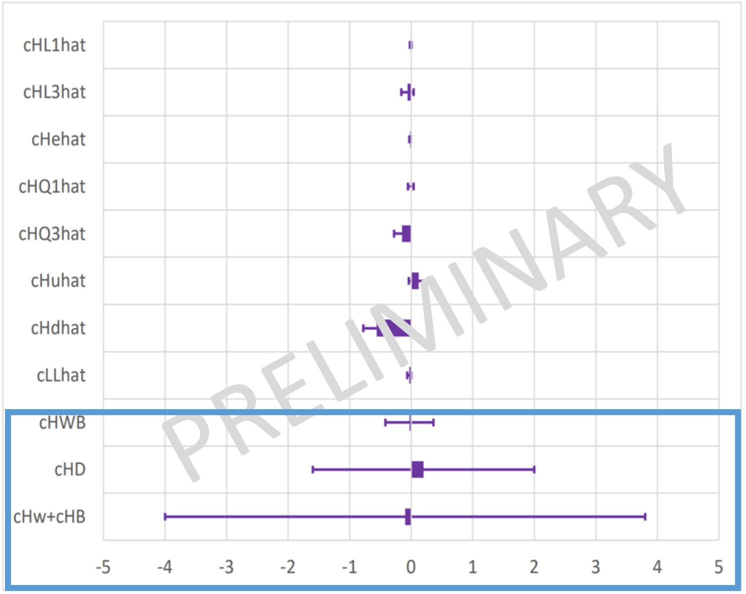
flat distributions
full correlations

$O(1/\Lambda^4)$ original-representation



Fit parameters	Analytically	Numerically
≤8	✓	✓
>8	✓	✗

$O(1/\Lambda^4)$ hat-representation



Fit parameters	Analytically	Numerically
≤8	✓	✓
>8	✓	✓

improve sensitivity
for $\{C_{HWB}, C_{HD}, C_{HW}+C_{HB}\}$

Change of input-scheme:

$$\{\bar{g}, \bar{g}', \bar{v}, \lambda\} \to \{\tilde{\alpha}, \widetilde{M}_Z, \tilde{G}_F, \widetilde{M}_h\}$$

1

Write "barred" initial parameters in terms of "barred" final parameters:

$$\bar{g} = \sqrt{8\pi\bar{\alpha}}\left[1 - \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{g}' = \sqrt{8\pi\bar{\alpha}}\left[1 + \sqrt{1 - \frac{2\sqrt{2}\pi\bar{\alpha}}{\bar{G}_F \bar{M}_Z^2}}\right]^{-1/2}$$

$$\bar{v} = \frac{1}{\sqrt{\sqrt{2}\bar{G}_F}}$$

$$\lambda = \frac{\bar{M_h}^2}{\bar{v}^2}$$

2

Write final input parameters ("tilded") in terms of their "barred" and shifts:

$$\tilde{\alpha} \equiv \bar{\alpha}\left(1 + \delta_\alpha\right)$$

$$\widetilde{M}_Z^2 \equiv \bar{M}_Z^2\left(1 + \delta_{M_Z^2}\right)$$

$$\tilde{G}_F \equiv \bar{G}_F\left(1 + \delta_{G_F}\right)$$

$$\widetilde{M}_h^2 \equiv \bar{M_h}^2\left(1 + \delta_{M_h^2}\right)$$

3

Obtain δ's from the derived physical parameters and express in terms of input-scheme

4

Compute appropriately up to quadratic order