New physics constraints via a global fit of electroweak, Higgs, top, and flavor observables

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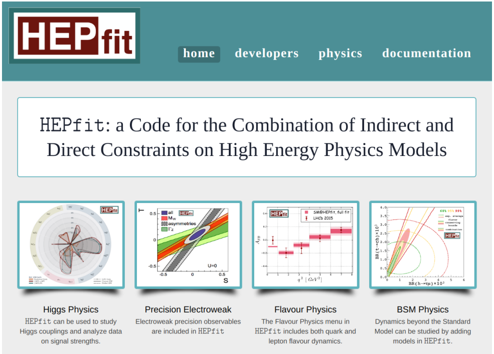
Introduction

- The significant effort on the experimental side has provided astonishing amounts of data
- Combining all these data in one framework may be crucial to discover new physics
- Powerful codes are essential for this regard ⇒ `HEPfit` with an integration of `RGESolver`
- Ability to combine EWPO, Diboson, Higgs, Top, DY, LEP-II cross sections and Flavour in the same framework
- Fitting both the SM parameters and the NP contributions from dim-6 operators simultaneously

Fitting tools

- Open source written in C++
- Based on the Bayesian Analysis Toolkit [A. Caldwell, D. Kollar, K. Kröninger, 0808.2552]
- Sampling likelihoods with MCMC
- Supports SM, implemented NP extensions, and the SMEFT



HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models

Higgs Physics
HEPfit can be used to study Higgs couplings and analyze data on signal strengths.

Precision Electroweak
Electroweak precision observables are included in HEPfit

Flavour Physics
The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.

BSM Physics
Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

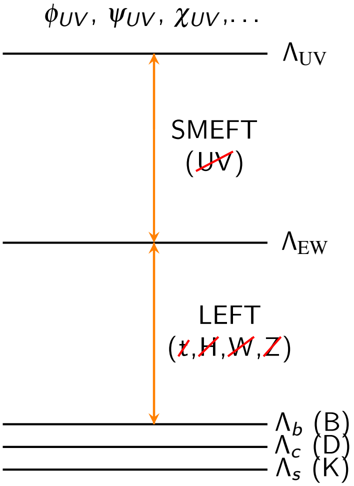
HEPfit webpage [J. de Blas et al., 1910.14012]

Other frameworks for SMEFT global fits: [SMEFiT, 2105.00006, 2302.06660, 2404.12809], [Fitmaker, 2012.02779], [Aebischer et al., 1810.07698], [Allwicher et al., 2311.00020], [Cirigliano et al., 2311.00021], [Bartocci et al., 2311.04963], [Garosi et al., 2310.00047],. . .

Theoretical Framework

- The SM is treated as an EFT
$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathscr{O}\left(\Lambda^{-4}\right)$$
- The Lagrangian is expanded up to D6
- For the SMEFT contributions to observables, we keep only LO terms, consistently neglecting $\mathscr{O}\left(\Lambda^{-4}\right)$ contributions.
- For the SM, NLO or higher, relevant to determine the SM parameters
- CP-conservation in the NP is assumed
- Both $U(3)^5$ and $U(2)^5$ flavour symmetries are studied at the NP scale [Faroughy, Isidori, Wilsch, Yamamoto, 2005.05366]
- WC are run from NP-scale to EW-scale

Global picture



$\phi_{UV}, \psi_{UV}, \chi_{UV}, \ldots$

Λ_{UV}

SMEFT
$(\cancel{\text{UV}})$

Λ_{EW}

LEFT
$(\cancel{t}, \cancel{H}, \cancel{W}, \cancel{Z})$

Λ_b (B)
Λ_c (D)
Λ_s (K)

Slide from L. Reina at LoopFest XXII

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

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

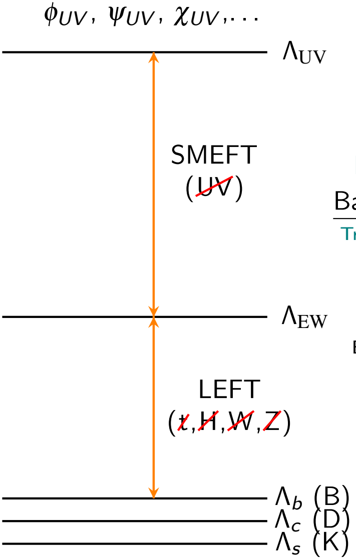
↓ **SMEFT RGE**

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

↓ **LEFT RGE**

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

Global picture



$\phi_{UV}, \psi_{UV}, \chi_{UV}, \ldots$

$\Lambda_{\rm UV}$

SMEFT
(~~UV~~)

$\Lambda_{\rm EW}$

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

Λ_b (B)
Λ_c (D)
Λ_s (K)

Matching at Λ_{UV}
`Matchete` [Fuentes-Martín et al. , 2212.04510]
`Matchmakereft` [Carmona et al. , 2112.10787]

$C_{i,d}^{\rm SMEFT}(\Lambda_{UV})$ satisfy the flav. symmetry of UV

`RGESolver` (C++ library)
[Stefano di Noi and Luca Silvestrini, 2210.06838]

<u>Based on 1-loop:</u> [Jenkins, Manohar, Trott, 1308.2627, 1310.4838,1312.2014]

Others:
`DsixTools`
(`Mathematica`)
`wilson`
(`python`)

SMEFT RGE

$C_{i,d}^{\rm SMEFT}(\Lambda_{EW})$ to calculate collider observables

Matching SMEFT with LEFT added in `HEPfit`

Based on: [Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270]

Obtain $C_{i,d}^{\rm LEFT}(\Lambda_{EW})$

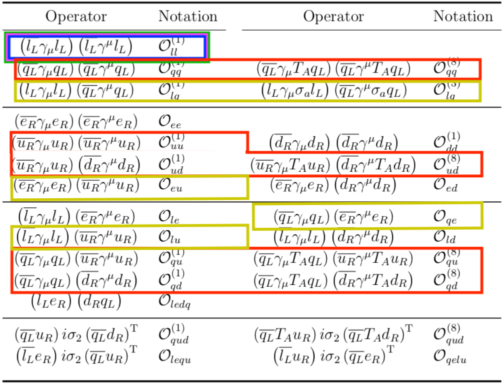
Running of LEFT included in `HEPfit`

LEFT RGE

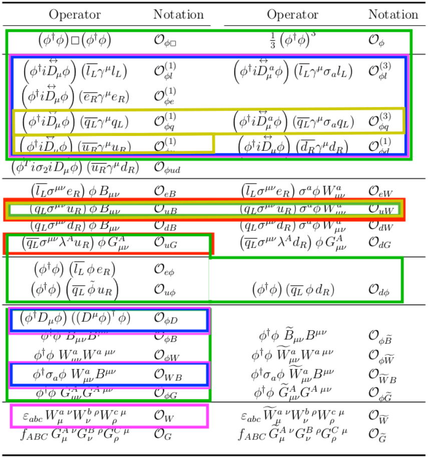
$C_{i,d}^{\rm LEFT}(\Lambda_{\rm had.})$ to calculate flavour observables

Slide adapted from L. Reina at LoopFest XXII

SMEFT operators in the Warsow basis



Operator	Notation	Operator	Notation
$(\overline{l_L}\gamma_\mu l_L)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{ll}^{(1)}$		
$(\overline{q_L}\gamma_\mu q_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{qq}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{q_L}\gamma^\mu T_A q_L)$	$\mathcal{O}_{qq}^{(8)}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{lq}^{(1)}$	$(\overline{l_L}\gamma_\mu \sigma_a l_L)(\overline{q_L}\gamma^\mu \sigma_a q_L)$	$\mathcal{O}_{lq}^{(3)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{ee}$		
$(\overline{u_R}\gamma_\mu u_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{uu}^{(1)}$	$(\overline{d_R}\gamma_\mu d_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{dd}^{(1)}$
$(\overline{u_R}\gamma_\mu u_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ud}^{(1)}$	$(\overline{u_R}\gamma_\mu T_A u_R)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{ud}^{(8)}$
$(\overline{e_R}\gamma_\mu e_R)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{eu}$	$(\overline{e_R}\gamma_\mu e_R)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ed}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{le}$	$(\overline{q_L}\gamma_\mu q_L)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{qe}$
$(\overline{l_L}\gamma_\mu l_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{lu}$	$(\overline{l_L}\gamma_\mu l_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{ld}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{qu}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{u_R}\gamma^\mu T_A u_R)$	$\mathcal{O}_{qu}^{(8)}$
$(\overline{q_L}\gamma_\mu q_L)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{qd}^{(1)}$	$(\overline{q_L}\gamma_\mu T_A q_L)(\overline{d_R}\gamma^\mu T_A d_R)$	$\mathcal{O}_{qd}^{(8)}$
$(\overline{l_L}e_R)(\overline{d_R}q_L)$	$\mathcal{O}_{ledq}$		
$(\overline{q_L}u_R)\, i\sigma_2\, (\overline{q_L}d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(1)}$	$(\overline{q_L}T_A u_R)\, i\sigma_2\, (\overline{q_L}T_A d_R)^{\mathrm{T}}$	$\mathcal{O}_{qud}^{(8)}$
$(\overline{l_L}e_R)\, i\sigma_2\, (\overline{q_L}u_R)^{\mathrm{T}}$	$\mathcal{O}_{lequ}$	$(\overline{l_L}u_R)\, i\sigma_2\, (\overline{q_L}e_R)^{\mathrm{T}}$	$\mathcal{O}_{qelu}$



Operator	Notation	Operator	Notation
$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi\Box}$	$\frac{1}{3}(\phi^\dagger\phi)^3$	$\mathcal{O}_{\phi}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{l_L}\gamma^\mu l_L)$	$\mathcal{O}_{\phi l}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)(\overline{l_L}\gamma^\mu\sigma_a l_L)$	$\mathcal{O}_{\phi l}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{e_R}\gamma^\mu e_R)$	$\mathcal{O}_{\phi e}^{(1)}$		
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{q_L}\gamma^\mu q_L)$	$\mathcal{O}_{\phi q}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\right)(\overline{q_L}\gamma^\mu\sigma_a q_L)$	$\mathcal{O}_{\phi q}^{(3)}$
$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{u_R}\gamma^\mu u_R)$	$\mathcal{O}_{\phi u}^{(1)}$	$\left(\phi^\dagger i\overleftrightarrow{D}_\mu\phi\right)(\overline{d_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi d}^{(1)}$
$(\phi^T i\sigma_2 iD_\mu\phi)(\overline{u_R}\gamma^\mu d_R)$	$\mathcal{O}_{\phi ud}$		
$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{eB}$	$(\overline{l_L}\sigma^{\mu\nu}e_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{eW}$
$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{uB}$	$(\overline{q_L}\sigma^{\mu\nu}u_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{uW}$
$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\phi\, B_{\mu\nu}$	$\mathcal{O}_{dB}$	$(\overline{q_L}\sigma^{\mu\nu}d_R)\,\sigma^a\phi\, W^a_{\mu\nu}$	$\mathcal{O}_{dW}$
$(\overline{q_L}\sigma^{\mu\nu}\lambda^A u_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{uG}$	$(\overline{q_L}\sigma^{\mu\nu}\lambda^A d_R)\,\phi\, G^A_{\mu\nu}$	$\mathcal{O}_{dG}$
$(\phi^\dagger\phi)(\overline{l_L}\,\phi\, e_R)$	$\mathcal{O}_{e\phi}$		
$(\phi^\dagger\phi)(\overline{q_L}\,\tilde{\phi}\, u_R)$	$\mathcal{O}_{u\phi}$	$(\phi^\dagger\phi)(\overline{q_L}\,\phi\, d_R)$	$\mathcal{O}_{d\phi}$
$(\phi^\dagger D_\mu\phi)((D^\mu\phi)^\dagger\phi)$	$\mathcal{O}_{\phi D}$		
$\phi^\dagger\phi\; B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi B}$	$\phi^\dagger\phi\; \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\widetilde{B}}$
$\phi^\dagger\phi\; W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi W}$	$\phi^\dagger\phi\; \widetilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{W}}$
$\phi^\dagger\sigma_a\phi\; W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{WB}$	$\phi^\dagger\sigma_a\phi\; \widetilde{W}^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\widetilde{W}B}$
$\phi^\dagger\phi\; G^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$\phi^\dagger\phi\; \widetilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$	$\mathcal{O}_{\phi\widetilde{G}}$
$\varepsilon_{abc}\, W^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{W}$	$\varepsilon_{abc}\, \widetilde{W}^{a\,\nu}_{\mu}W^{b\,\rho}_{\nu}W^{c\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{W}}$
$f_{ABC}\, G^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{G}$	$f_{ABC}\, \widetilde{G}^{A\,\nu}_{\mu}G^{B\,\rho}_{\nu}G^{C\,\mu}_{\rho}$	$\mathcal{O}_{\widetilde{G}}$

CP-even dim 6 ops. interfering with SM

EWPO **EW diboson** **Higgs** **Top (Had. Coll., Lept. Coll.)**

Slide from J. de Blas at Seattle Snowmass Summer Study

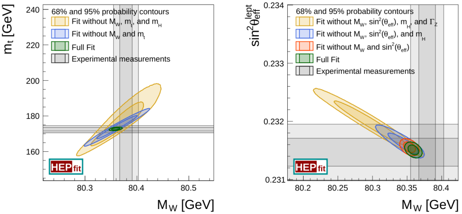
Observables included

- **Electroweak precision observables** at LEP, SLD, Tevatron, and LHC
- **Di-boson** production cross sections at LEP
- **Higgs boson** measurements at LHC
- **Top-quark** measurements at LHC and Tevatron
- **Drell-Yan** measurements at LHC
- **LEP-II** production of leptons and quarks
- **Flavour observables** measurements at Flavour Factories and LHC

Observables included: EWPO and Di-boson

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

`HEPfit` contains all the predictions to EWPO in the SM at highest available precision [J. de Blas, M. Ciuchini, E. Franco, A. Goncalves, S. Mishima, M. Pierini, L. Reina, and L. Silvestrini, 2112.07274]

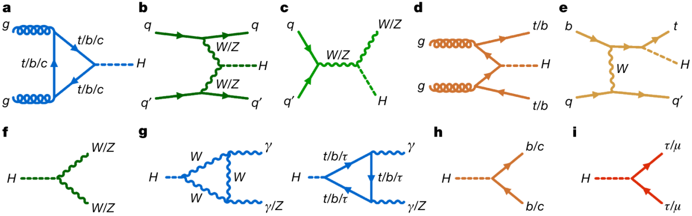


Same framework for the SMEFT including LO contributions on it

- **Di-boson** production
  - $e^+e^- \to W^+W^-$ [Berthier, Bjørn, Trott, 1606.06693]

Observables included: Higgs and Top quark

- **Higgs boson** observables
  - Higgs Signal sterngths (CMS): $\mu_{ij} = \frac{\sigma_i \times \mathrm{Br_j}}{(\sigma_i \times \mathrm{Br_j})_{\mathbf{SM}}}$
  - Simplified Template Cross Sections (ATLAS)

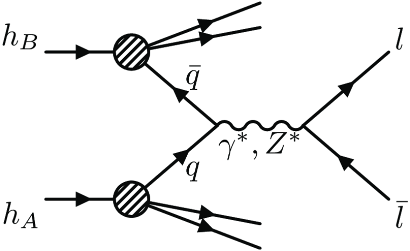


- **Top-quark** measurements
  - Asymmetries plus inclusive and differential cross sections $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \ldots$

The SMEFT parametrisations are obtained using `MG5_aMC@NLO` with the UFOs `SMEFTsim3.0` [I. Brivio, 2012.11343] and `SMEFT@NLO` [Degrande et al., 2008.11743] cross checked with in-house UFO models from J. de Blas and `SMEFTci2` developed by Angelica Goncalves

Observables included: Drell-Yan and LEP-II

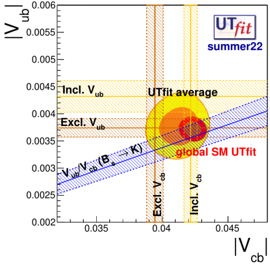
- **Drell-Yan:**
  - Cross sections for Drell-Yan dilepton ($pp \to \bar{\ell}\ell$) and mono-lepton ($pp \to \bar{\ell}\nu$) searches by ATLAS and CMS
  - Added using the package `HighPT` [L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756, 2207.10714]

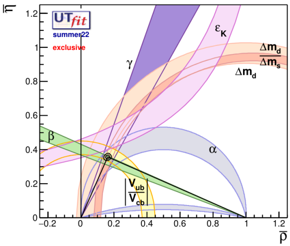


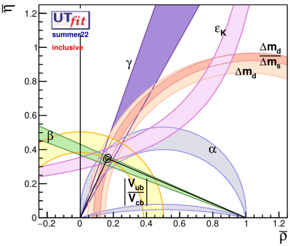
- **LEP-II** production cross sections computed analytically by J. de Blas
  - $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$, hadrons

Observables included: Flavour

- $|\Delta F| = 2$: Δm_{B_d}, Δm_{B_s}, ε_k, $D - \bar{D}$
- $|\Delta F| = 1$: $B \to X_{s,d}\gamma$ plus leptonic ($B_s \to \mu^+\mu^-$, $B \to \tau\nu$, $K \to \ell\nu$, $\pi \to \ell\nu$) and semileptonic ($B_s \to D^{(*)}\ell\nu$, $B \to \pi\ell\nu$, $K \to \pi\ell\nu$) mesonic decays
- These observables are used to determine the V_{CKM} in the SM fits
- The **UT***fit* collaboration (including L. Silvestrini and M. Valli) has been performing these fits in the SM [UTfit Collab., 2212.03894]
- `HEPfit` uses a similar framework (including the mentioned observables) to constrain the (SM +) SMEFT parameters







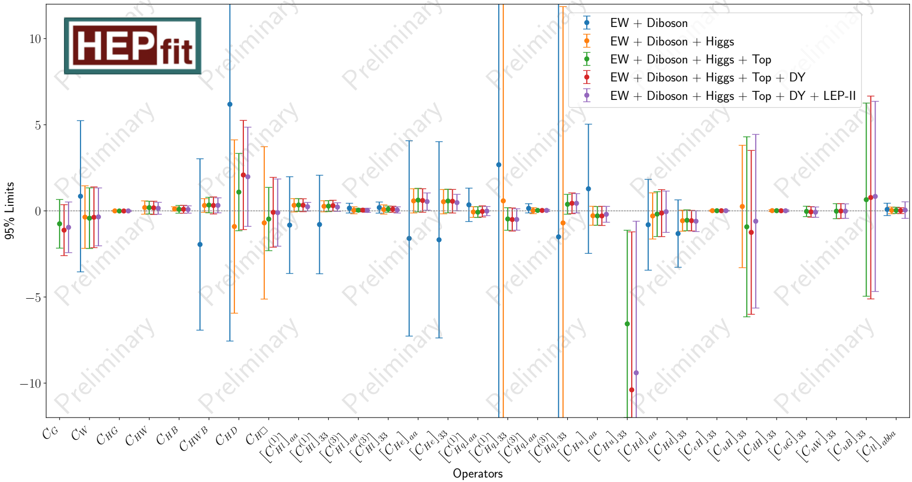
Fits with $U(2)^5$ flavour symmetry: WC considered

Sequentially increase of number of WC considered as we incorporate more observables

- **EWPO + Diboson** (17 WC):
  $\{C_W,\ C_{HWB},\ C_{HD},\ [C_{Hl}^{(\mathbf{1})}]_{aa},\ [C_{Hl}^{(\mathbf{1})}]_{\mathbf{33}},\ [C_{Hl}^{(\mathbf{3})}]_{aa},\ [C_{Hl}^{(\mathbf{3})}]_{\mathbf{33}},\ [C_{He}]_{aa},\ [C_{He}]_{\mathbf{33}},\ [C_{Hq}^{(\mathbf{1})}]_{aa},$
  $[C_{Hq}^{(\mathbf{1})}]_{\mathbf{33}},\ [C_{Hq}^{(\mathbf{3})}]_{aa},\ [C_{Hq}^{(\mathbf{3})}]_{\mathbf{33}},\ [C_{Hu}]_{aa},\ [C_{Hd}]_{aa},\ [C_{Hd}]_{\mathbf{33}},\ [C_{ll}]_{abba}\}$
- **EWPO + Diboson + Higgs** (24 WC):
  $+\ \{C_{HG},\ C_{HW},\ C_{HB},\ C_{H\Box},\ [C_{eH}]_{\mathbf{33}},\ [C_{uH}]_{\mathbf{33}},\ [C_{dH}]_{\mathbf{33}}\}$
- **EWPO + Diboson + Higgs + Top** (36 WC):
  $+\ \{C_G,\ [C_{Hu}]_{\mathbf{33}},\ [C_{uG}]_{\mathbf{33}},\ [C_{uW}]_{\mathbf{33}},\ [C_{uB}]_{\mathbf{33}},\ [C_{qq}^{\mathbf{1}}]_{a\mathbf{33}a},\ [C_{qq}^{\mathbf{3}}]_{a\mathbf{33}a},\ [C_{uu}]_{a\mathbf{33}a},\ [C_{ud}^{(\mathbf{8})}]_{\mathbf{33}aa},$
  $[C_{qu}^{(\mathbf{8})}]_{aa\mathbf{33}},\ [C_{qu}^{(\mathbf{8})}]_{\mathbf{33}aa},\ [C_{qd}^{(\mathbf{8})}]_{\mathbf{33}aa}\}$
- **EWPO + Diboson + Higgs + Top + DY** (50 WC):
  $+\ \{\ [C_{lq}^{\mathbf{1}}]_{aabb},\ [C_{lq}^{\mathbf{1}}]_{\mathbf{33}aa},\ [C_{lq}^{\mathbf{3}}]_{aabb},\ [C_{lq}^{\mathbf{3}}]_{\mathbf{33}aa},\ [C_{eu}]_{aabb},\ [C_{eu}]_{\mathbf{33}aa},\ [C_{ed}]_{aabb},\ [C_{ed}]_{\mathbf{33}aa},$
  $[C_{lu}]_{aabb},\ [C_{lu}]_{\mathbf{33}aa},\ [C_{ld}]_{aabb},\ [C_{ld}]_{\mathbf{33}aa},\ [C_{qe}]_{aabb},\ [C_{qe}]_{aa\mathbf{33}}\ \}$
- **EWPO + Diboson + Higgs + Top + DY + LEP-II** (55 WC):
  $+\ \{\ [C_{ll}]_{aabb},\ [C_{ll}]_{aa\mathbf{33}},\ [C_{ll}]_{a\mathbf{33}a},\ [C_{ee}]_{aabb},\ [C_{ee}]_{aa\mathbf{33}}\ \}$

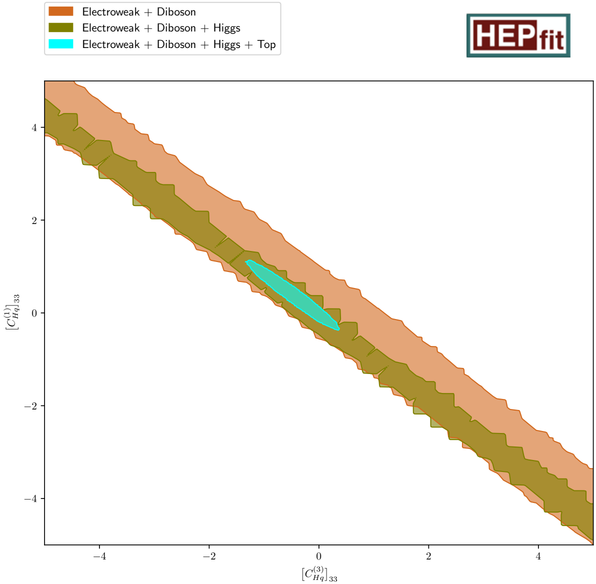
Fits with $U(2)^5$ flavour symmetry: 2-Fermion

Limits for WC at the scale $\Lambda_{UV} = 1$ TeV

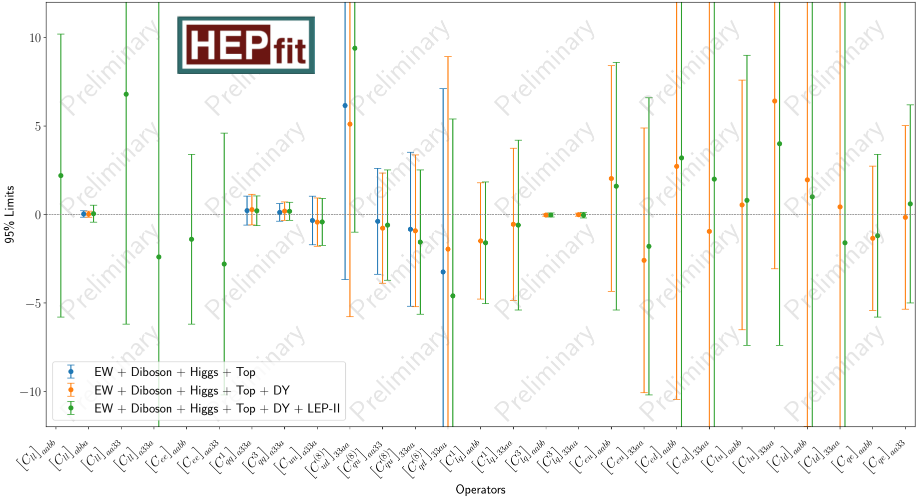


Fits with $U(2)^5$ flavour symmetry: 2-Fermion

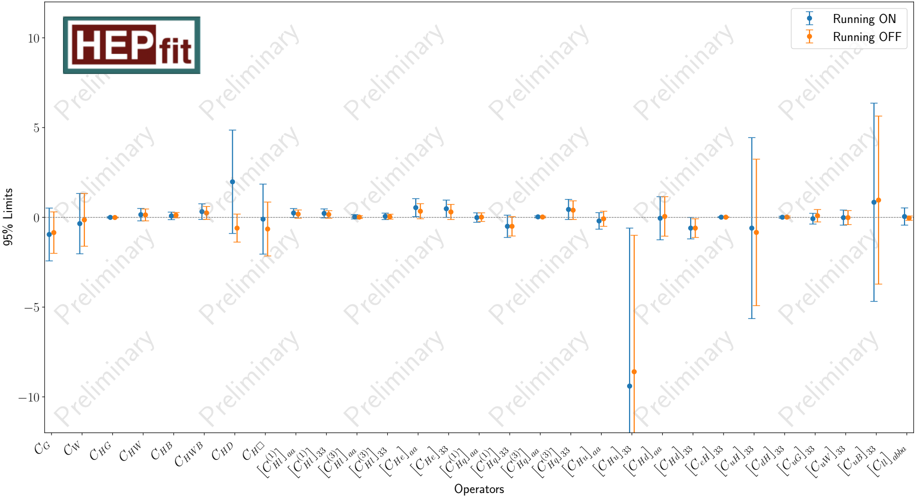
With enough data the flat directions in the 2-fermion operators are lifted



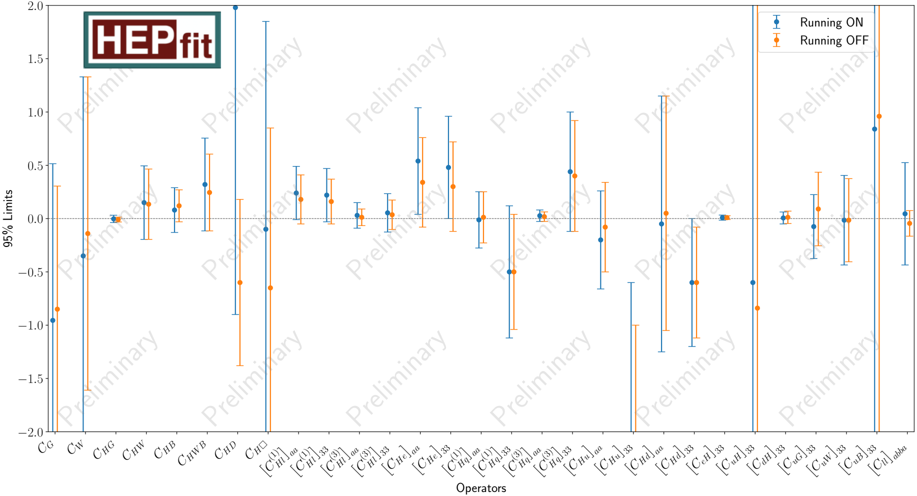
Fits with $U(2)^5$ flavour symmetry: 4-Fermion



Fits with $U(2)^5$ flavour symmetry: Running effects on 2-Fermion



Fits with $U(2)^5$ flavour symmetry: Running effects on 2-Fermion (ZOOM)



Summary and conclusion

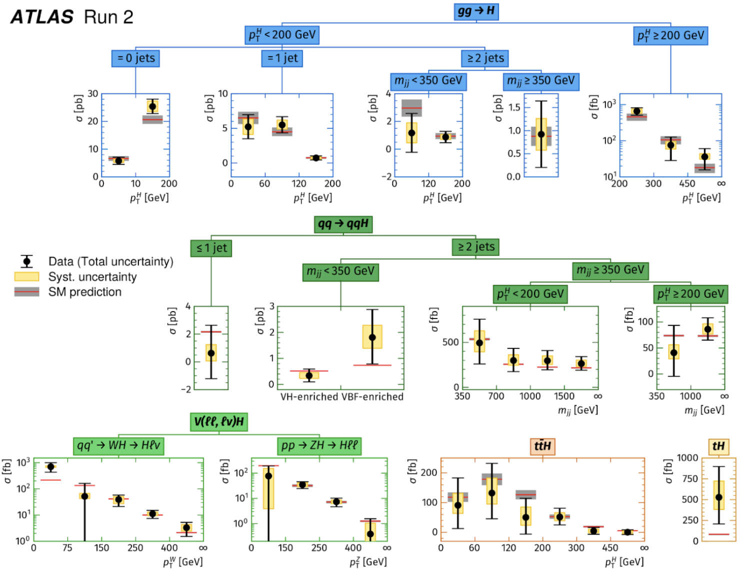
- At the moment finishing the validation of the flavour sector
- All the boson and the 2-fermion WC (except $\left[C_{Hu}\right]_{33}$) are bounded in its perturbative regime
- The sensitivity for the 4-fermion is not enough (without flavour)
- The running has a huge effect in some WC
- The very precise limits on $\left[C_{ll}\right]_{abba}$ suffer from the mixing with other 4-fermion

Stay tuned for the final results with full flavour implementation!

Thanks for your attention!

Back up

Simplified Template Cross Section



Fits with $U(2)^5$ flavour symmetry: Running effects on 4-Fermion