Probing the SMEFT using HEPfit

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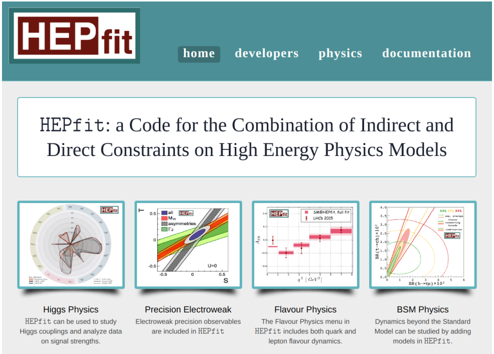
Introduction

- 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 $\Rightarrow$ `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 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],. . .

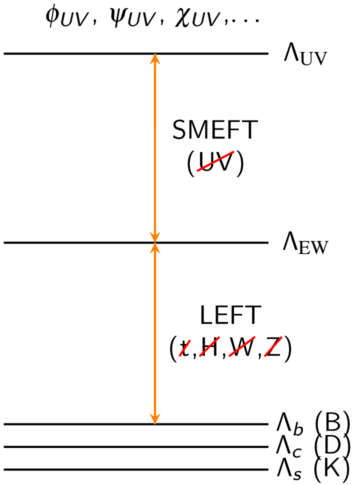
Theoretical Framework

- 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



Slide from L. Reina at LoopFest XXII

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

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

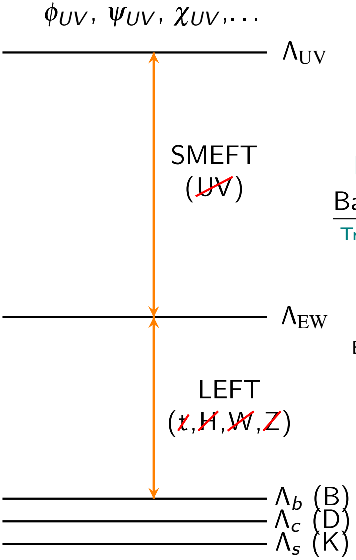
↓ **SMEFT RGE**

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

↓ **LEFT RGE**

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

Global picture



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]

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

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

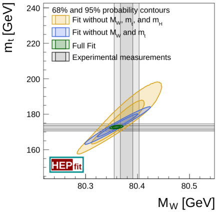
Observables included

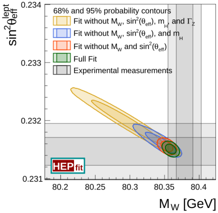
- **Electroweak precision observables** at LEP, SLD, Tevatron, and LHC
- **Di-boson** production cross sections at LEP
- **Higgs boson** measurements at LHC
- **Top-quark** measurements at LHC and Tevatron
- **Drell-Yan** measurements at LHC
- **LEP-II** production of leptons and quarks
- **Flavour observables**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



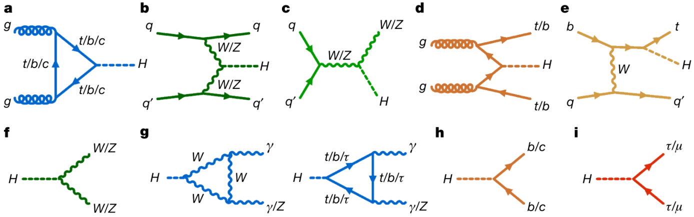


  Same framework for the SMEFT including LO contributions on it

- **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)

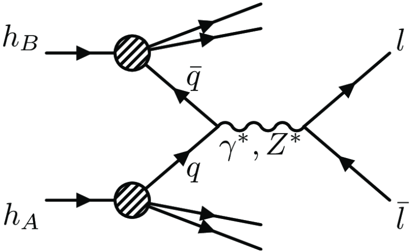


- **Top-quark** measurements
  - Asymmetries plus inclusive and differential cross sections $pp \to t\bar{t}, t\bar{t}Z, t\bar{t}W, t\bar{t}\gamma, tZq, t\gamma q, tW, \ldots$

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

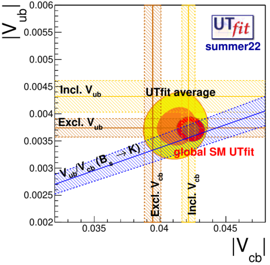
- **Drell-Yan:**
  - Cross sections for Drell-Yan dilepton ($pp \to \bar{\ell}\ell$) and mono-lepton ($pp \to \bar{\ell}\nu$) searches by ATLAS and CMS
  - Added using the package `HighPT` [L. Allwicher, D. A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch, 2207.10756, 2207.10714]

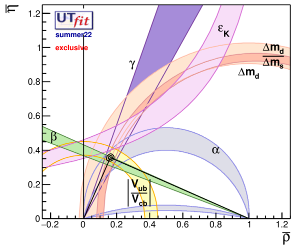


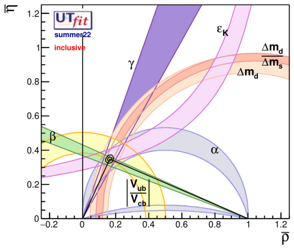
- **LEP-II** production cross sections computed analytically by J. de Blas
  - $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$, hadrons

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







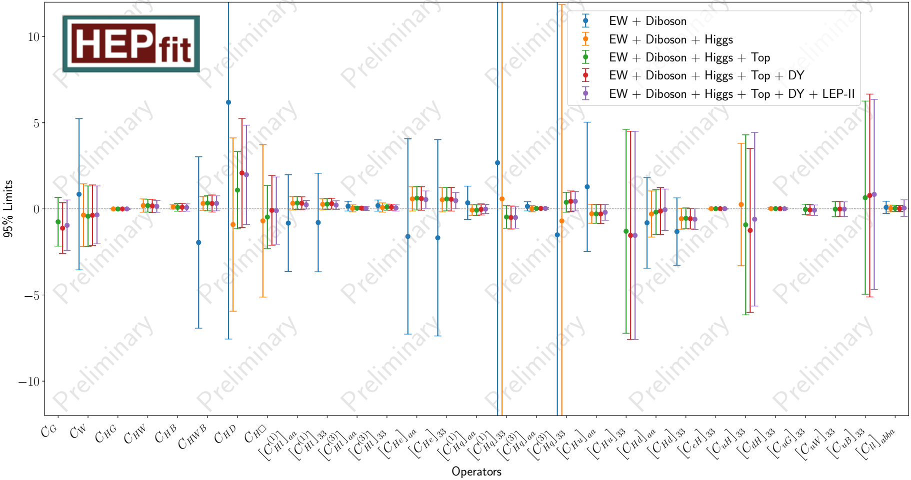
Fits with $U(2)^5$ flavour symmetry: WC considered

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

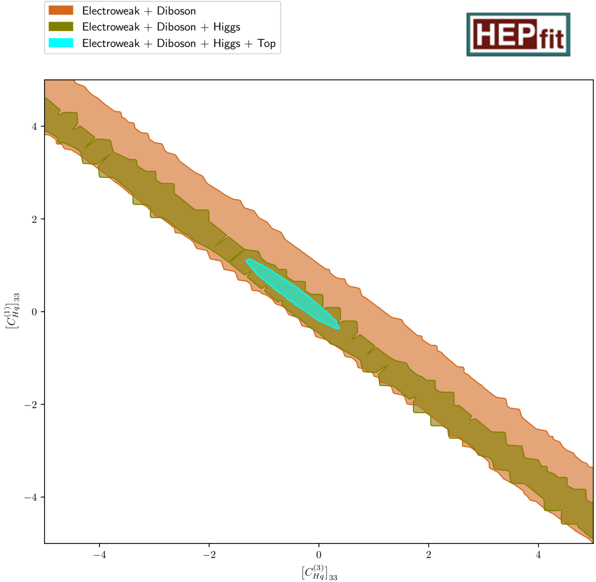
- **EWPO + Diboson** (17 WC):
  $\{C_W,\ C_{HWB},\ C_{HD},\ [C_{Hl}^{(1)}]_{aa},\ [C_{Hl}^{(1)}]_{\mathbf{33}},\ [C_{Hl}^{(3)}]_{aa},\ [C_{Hl}^{(3)}]_{\mathbf{33}},\ [C_{He}]_{aa},\ [C_{He}]_{\mathbf{33}},\ [C_{Hq}^{(1)}]_{aa},\ [C_{Hq}^{(1)}]_{\mathbf{33}},\ [C_{Hq}^{(3)}]_{aa},\ [C_{Hq}^{(3)}]_{\mathbf{33}},\ [C_{Hu}]_{aa},\ [C_{Hd}]_{aa},\ [C_{Hd}]_{\mathbf{33}},\ [C_{ll}]_{abba}\}$
- **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

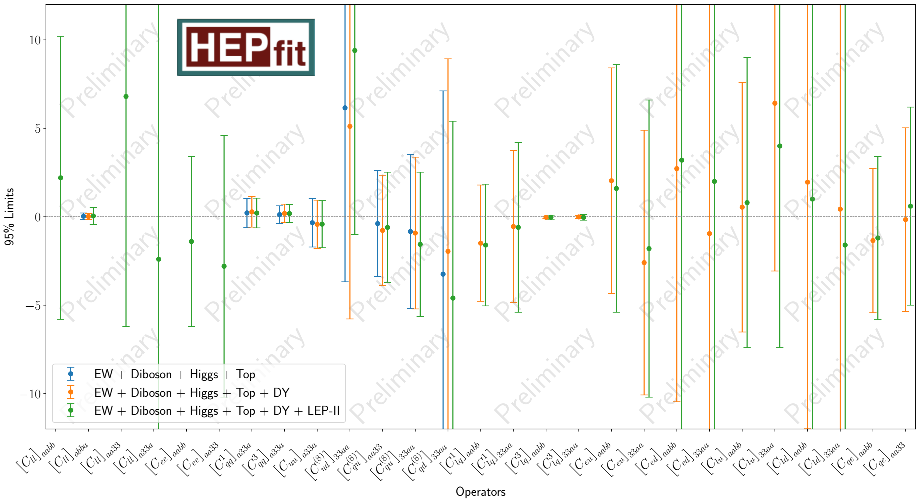


Fits with $U(2)^5$ flavour symmetry: 2-Fermion

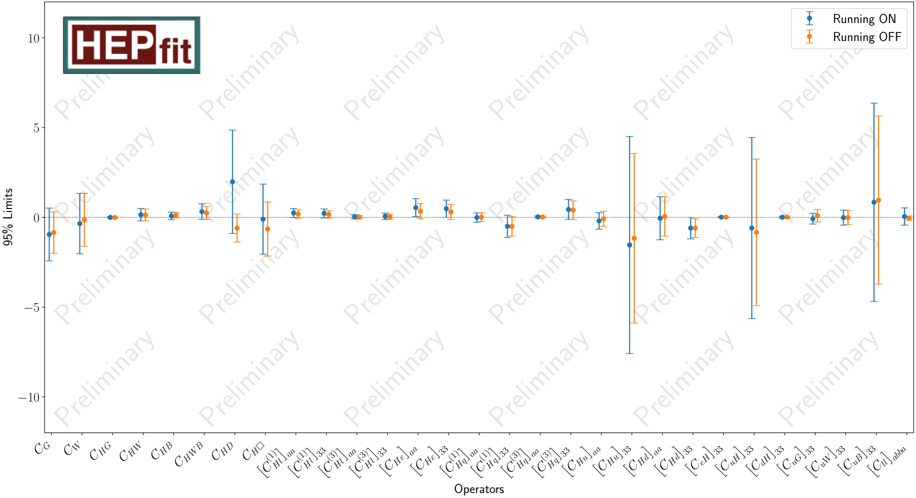


With enough data the flat directions in the 2-fermion operators are lifted

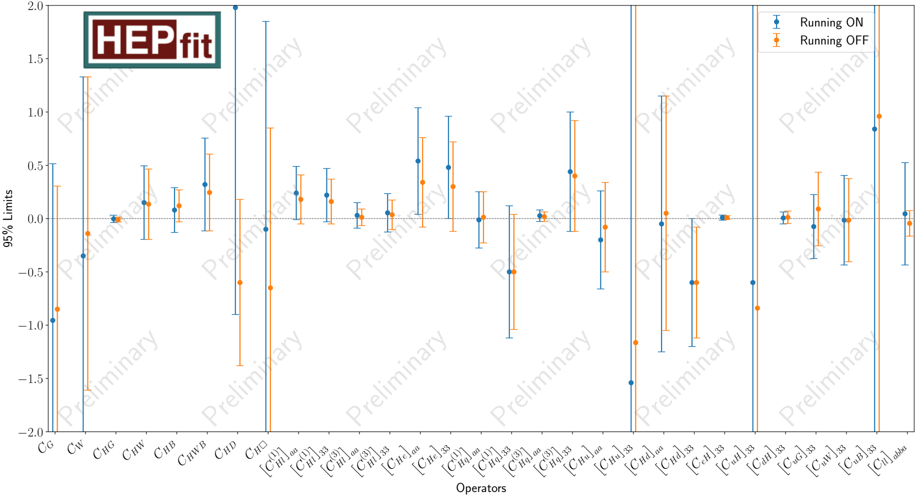
Fits with $U(2)^5$ flavour symmetry: 4-Fermion



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

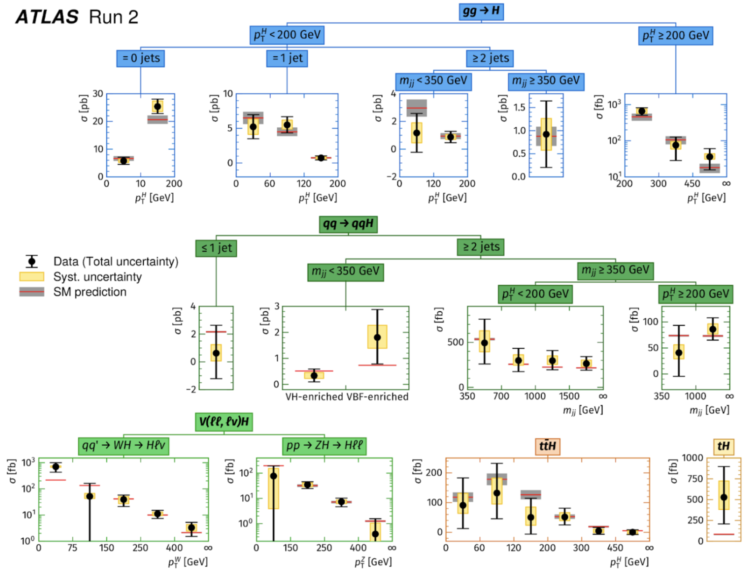
- At the moment finishing the validation of the flavour sector
- All the boson and the 2-fermion WC are bounded in its perturbative regime
- The sensitivity for the 4-fermion is not enough (without flavour)
- The running has a huge effect in some WC
- The very precise limits on $\left[C_{ll}\right]_{abba}$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