HEPfit as a SMEFT fitting framework

Luca Silvestrini
INFN, Rome

- Introduction
- The HEPfit framework:
  - Statistical approach
  - Likelihood input and output: correlations, non-Gaussianities, parametrization
  - Status of the SMEFT implementation
- Outlook

HEPfit: INTRODUCTION

Basic ideas behind HEPfit:

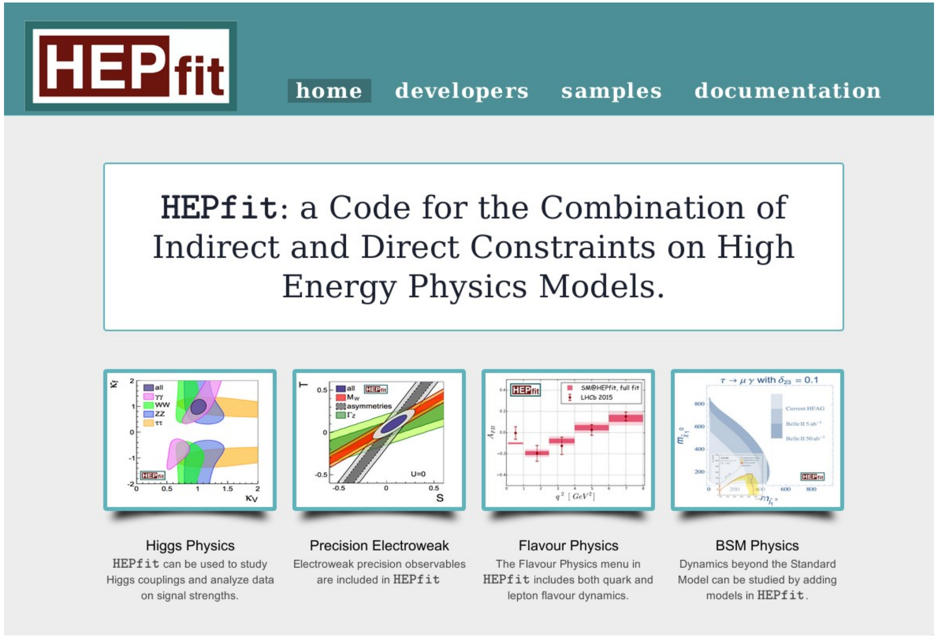
- combine state-of-the-art theoretical calculations and current experimental data to
  - perform a Bayesian fit of model parameters, i.e. obtain a numerical representation of the (joint) p.d.f of model parameters (and observables) given priors for parameters and exp. data
  - predict observables
  - compare models using e.g. information criteria

for any model $\supseteq$ Standard Model

HEPfit: INTRODUCTION II

- Provide a flexible, open source tool written in C++, with different levels of usage possible:
  - Full Bayesian fits with MCMC engine
  - Likelihood calculation
  - Observable calculation
- Users can:
  - add models
  - add observables

THE HEPfit FRAMEWORK



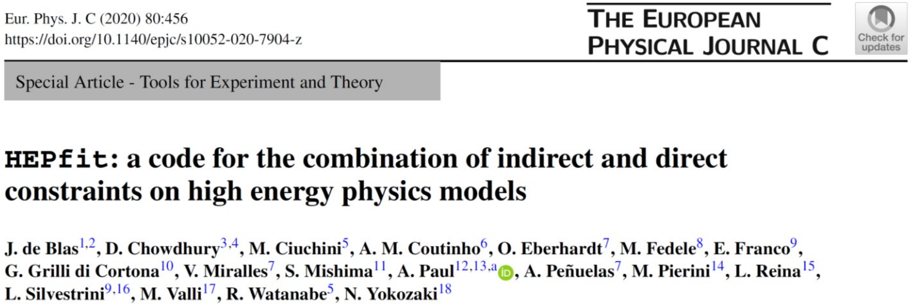
HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.

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.



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Special Article - Tools for Experiment and Theory

HEPfit: a code for the combination of indirect and direct constraints on high energy physics models

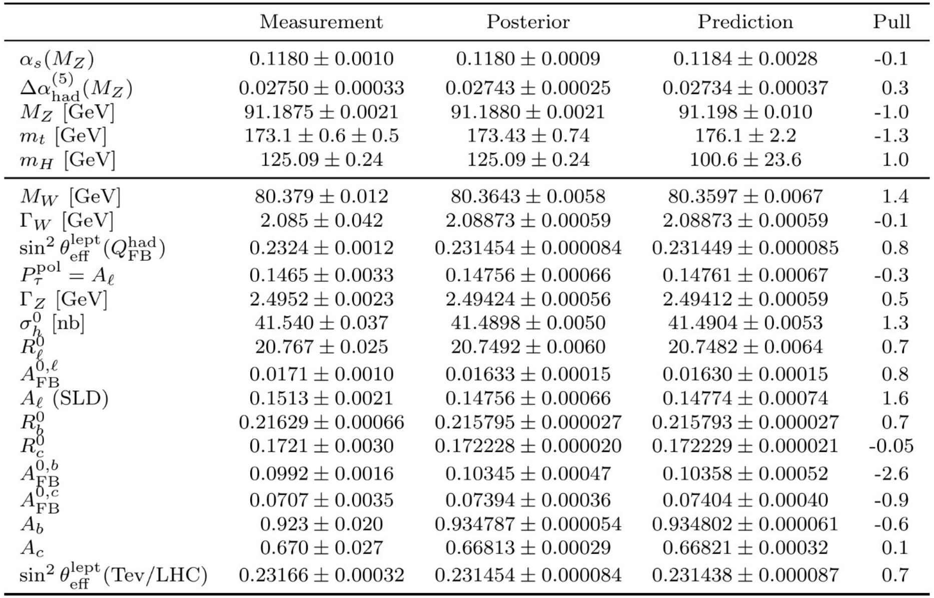
J. de Blas[1,2], D. Chowdhury[3,4], M. Ciuchini[5], A. M. Coutinho[6], O. Eberhardt[7], M. Fedele[8], E. Franco[9], G. Grilli di Cortona[10], V. Miralles[7], S. Mishima[11], A. Paul[12,13,a], A. Peñuelas[7], M. Pierini[14], L. Reina[15], L. Silvestrini[9,16], M. Valli[17], R. Watanabe[5], N. Yokozaki[18]

- HEPfit web page
- HEPfit documentation
- GitHub repository

GENERAL STRUCTURE

- Basic building blocks:
  - Models, defined by a set of parameters (possibly correlated) and complemented by model-specific contributions to observables;
  - Observables, defined by a theoretical prediction and possibly by an experimental likelihood which can be binned, multi-dimensional w. correlation, numerical…
  - A parallel MCMC engine based on BAT and ROOT
  - Everything coded from scratch and validated against other public codes

MCMC example: EW FIT in SM & oblique



	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.1180 ± 0.0009	0.1184 ± 0.0028	-0.1
$\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z)$	0.02750 ± 0.00033	0.02743 ± 0.00025	0.02734 ± 0.00037	0.3
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0021	91.198 ± 0.010	-1.0
m_t [GeV]	$173.1 \pm 0.6 \pm 0.5$	173.43 ± 0.74	176.1 ± 2.2	-1.3
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	100.6 ± 23.6	1.0
M_W [GeV]	80.379 ± 0.012	80.3643 ± 0.0058	80.3597 ± 0.0067	1.4
Γ_W [GeV]	2.085 ± 0.042	2.08873 ± 0.00059	2.08873 ± 0.00059	-0.1
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}(Q^{\mathrm{had}}_{\mathrm{FB}})$	0.2324 ± 0.0012	0.231454 ± 0.000084	0.231449 ± 0.000085	0.8
$P^{\mathrm{pol}}_\tau = A_\ell$	0.1465 ± 0.0033	0.14756 ± 0.00066	0.14761 ± 0.00067	-0.3
Γ_Z [GeV]	2.4952 ± 0.0023	2.49424 ± 0.00056	2.49412 ± 0.00059	0.5
σ^0_h [nb]	41.540 ± 0.037	41.4898 ± 0.0050	41.4904 ± 0.0053	1.3
R^0_ℓ	20.767 ± 0.025	20.7492 ± 0.0060	20.7482 ± 0.0064	0.7
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	0.01633 ± 0.00015	0.01630 ± 0.00015	0.8
A_ℓ (SLD)	0.1513 ± 0.0021	0.14756 ± 0.00066	0.14774 ± 0.00074	1.6
R^0_b	0.21629 ± 0.00066	0.215795 ± 0.000027	0.215793 ± 0.000027	0.7
R^0_c	0.1721 ± 0.0030	0.172228 ± 0.000020	0.172229 ± 0.000021	-0.05
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.10345 ± 0.00047	0.10358 ± 0.00052	-2.6
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	0.07394 ± 0.00036	0.07404 ± 0.00040	-0.9
A_b	0.923 ± 0.020	0.934787 ± 0.000054	0.934802 ± 0.000061	-0.6
A_c	0.670 ± 0.027	0.66813 ± 0.00029	0.66821 ± 0.00032	0.1
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ (Tev/LHC)	0.23166 ± 0.00032	0.231454 ± 0.000084	0.231438 ± 0.000087	0.7

Table 1: Experimental measurement, posterior, prediction, and pull for the 5 input parameters ($\alpha_s(M_Z)$, $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z)$, M_Z, m_t, m_H), and for the main EWPO considered in the SM fit. The values in the column *Prediction* are determined without using the experimental information for the corresponding observable.

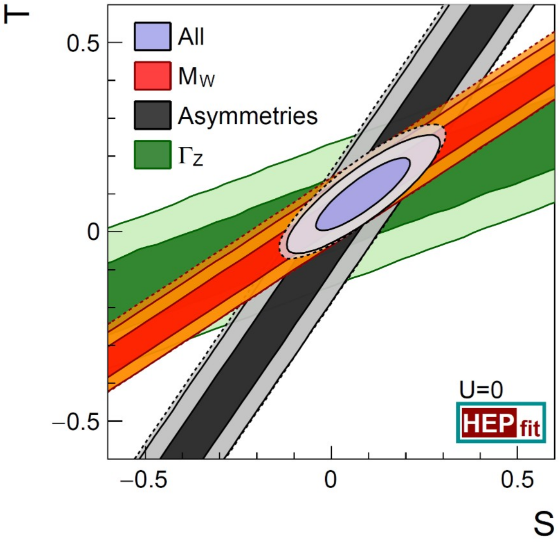
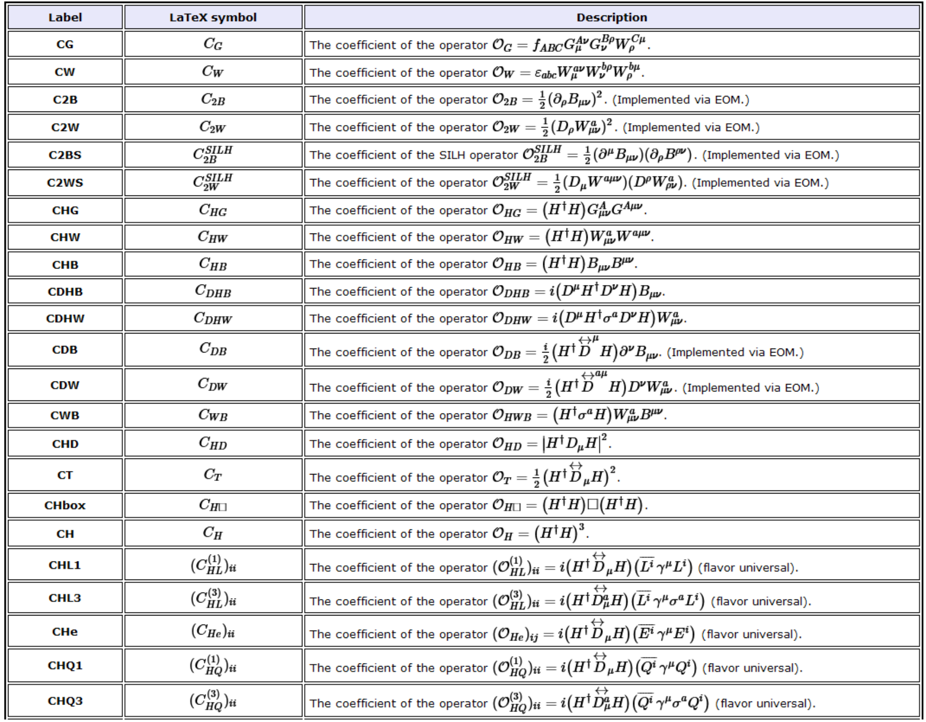


Figure 1: 68% and 95% probability contours for S and T ($U = 0$), together with the individual constraints from M_W, the asymmetry parameters $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, P^{pol}_τ, A_f, and $A^{0,f}_{\mathrm{FB}}$ ($f = \ell, c, b$), and Γ_Z. Dashed lines indicate the results from the fit without the updates from HC EWPO.

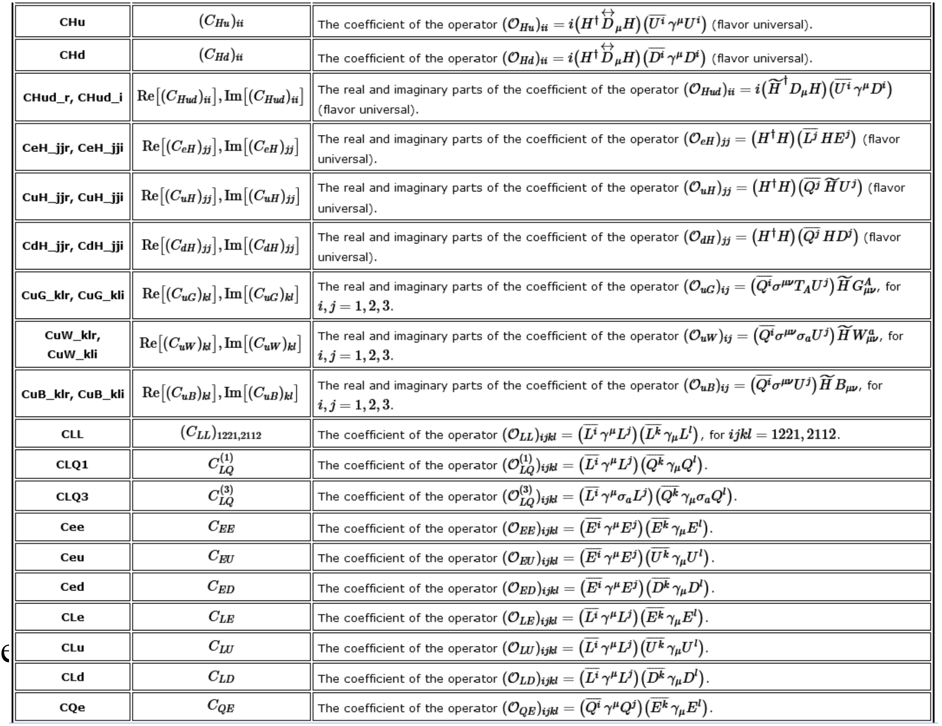
de Blas et al. 1710.05402

The SMEFT in HEPfit: the Model

- SMEFT in Warsaw basis with flavour universality almost fully implemented as a model:



Label	LaTeX symbol	Description
CG	C_G	The coefficient of the operator $\mathcal{O}_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\rho} W_\rho^{C\mu}$.
CW	C_W	The coefficient of the operator $\mathcal{O}_W = \varepsilon_{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{b\mu}$.
C2B	C_{2B}	The coefficient of the operator $\mathcal{O}_{2B} = \frac{1}{2}(\partial_\rho B_{\mu\nu})^2$. (Implemented via EOM.)
C2W	C_{2W}	The coefficient of the operator $\mathcal{O}_{2W} = \frac{1}{2}(D_\rho W_{\mu\nu}^a)^2$. (Implemented via EOM.)
C2BS	C_{2B}^{SILH}	The coefficient of the SILH operator $\mathcal{O}_{2B}^{SILH} = \frac{1}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu})$. (Implemented via EOM.)
C2WS	C_{2W}^{SILH}	The coefficient of the operator $\mathcal{O}_{2W}^{SILH} = \frac{1}{2}(D_\mu W^{a\mu\nu})(D^\rho W_{\rho\nu}^a)$. (Implemented via EOM.)
CHG	C_{HG}	The coefficient of the operator $\mathcal{O}_{HG} = (H^\dagger H) G_{\mu\nu}^A G^{A\mu\nu}$.
CHW	C_{HW}	The coefficient of the operator $\mathcal{O}_{HW} = (H^\dagger H) W_{\mu\nu}^a W^{a\mu\nu}$.
CHB	C_{HB}	The coefficient of the operator $\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$.
CDHB	C_{DHB}	The coefficient of the operator $\mathcal{O}_{DHB} = i(D^\mu H^\dagger D^\nu H) B_{\mu\nu}$.
CDHW	C_{DHW}	The coefficient of the operator $\mathcal{O}_{DHW} = i(D^\mu H^\dagger \sigma^a D^\nu H) W_{\mu\nu}^a$.
CDB	C_{DB}	The coefficient of the operator $\mathcal{O}_{DB} = \frac{i}{2}(H^\dagger \overset{\leftrightarrow}{D}{}^\mu H)\partial^\nu B_{\mu\nu}$. (Implemented via EOM.)
CDW	C_{DW}	The coefficient of the operator $\mathcal{O}_{DW} = \frac{i}{2}(H^\dagger \overset{\leftrightarrow}{D}{}^{a\mu} H) D^\nu W_{\mu\nu}^a$. (Implemented via EOM.)
CWB	C_{WB}	The coefficient of the operator $\mathcal{O}_{HWB} = (H^\dagger \sigma^a H) W_{\mu\nu}^a B^{\mu\nu}$.
CHD	C_{HD}	The coefficient of the operator $\mathcal{O}_{HD} = \lvert H^\dagger D_\mu H \rvert^2$.
CT	C_T	The coefficient of the operator $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overset{\leftrightarrow}{D}_\mu H)^2$.
CHbox	$C_{H\Box}$	The coefficient of the operator $\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$.
CH	C_H	The coefficient of the operator $\mathcal{O}_H = (H^\dagger H)^3$.
CHL1	$(C_{HL}^{(1)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HL}^{(1)})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{L^i} \gamma^\mu L^i)$ (flavor universal).
CHL3	$(C_{HL}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HL}^{(3)})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}{}_\mu^a H)(\overline{L^i} \gamma^\mu \sigma^a L^i)$ (flavor universal).
CHe	$(C_{He})_{ii}$	The coefficient of the operator $(\mathcal{O}_{He})_{ij} = i(H^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{E^i} \gamma^\mu E^i)$ (flavor universal).
CHQ1	$(C_{HQ}^{(1)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(1)})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{Q^i} \gamma^\mu Q^i)$ (flavor universal).
CHQ3	$(C_{HQ}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(3)})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}{}_\mu^a H)(\overline{Q^i} \gamma^\mu \sigma^a Q^i)$ (flavor universal).



CHu	$(C_{Hu})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hu})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{U^i} \gamma^\mu U^i)$ (flavor universal).
CHd	$(C_{Hd})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hd})_{ii} = i(H^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{D^i} \gamma^\mu D^i)$ (flavor universal).
CHud_r, CHud_i	$\mathrm{Re}[(C_{Hud})_{ii}], \mathrm{Im}[(C_{Hud})_{ii}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{Hud})_{ii} = i(\widetilde{H}^\dagger D_\mu H)(\overline{U^i} \gamma^\mu D^i)$ (flavor universal).
CeH_jjr, CeH_jji	$\mathrm{Re}[(C_{eH})_{jj}], \mathrm{Im}[(C_{eH})_{jj}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{eH})_{jj} = (H^\dagger H)(\overline{L^j} H E^j)$ (flavor universal).
CuH_jjr, CuH_jji	$\mathrm{Re}[(C_{uH})_{jj}], \mathrm{Im}[(C_{uH})_{jj}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{uH})_{jj} = (H^\dagger H)(\overline{Q^j} \widetilde{H} U^j)$ (flavor universal).
CdH_jjr, CdH_jji	$\mathrm{Re}[(C_{dH})_{jj}], \mathrm{Im}[(C_{dH})_{jj}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{dH})_{jj} = (H^\dagger H)(\overline{Q^j} H D^j)$ (flavor universal).
CuG_klr, CuG_kli	$\mathrm{Re}[(C_{uG})_{kl}], \mathrm{Im}[(C_{uG})_{kl}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{uG})_{ij} = (\overline{Q^i} \sigma^{\mu\nu} T_A U^j) \widetilde{H} G_{\mu\nu}^A$, for $i, j = 1, 2, 3$.
CuW_klr, CuW_kli	$\mathrm{Re}[(C_{uW})_{kl}], \mathrm{Im}[(C_{uW})_{kl}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{uW})_{ij} = (\overline{Q^i} \sigma^{\mu\nu} \sigma_a U^j) \widetilde{H} W_{\mu\nu}^a$, for $i, j = 1, 2, 3$.
CuB_klr, CuB_kli	$\mathrm{Re}[(C_{uB})_{kl}], \mathrm{Im}[(C_{uB})_{kl}]$	The real and imaginary parts of the coefficient of the operator $(\mathcal{O}_{uB})_{ij} = (\overline{Q^i} \sigma^{\mu\nu} U^j) \widetilde{H} B_{\mu\nu}$, for $i, j = 1, 2, 3$.
CLL	$(C_{LL})_{1221,2112}$	The coefficient of the operator $(\mathcal{O}_{LL})_{ijkl} = (\overline{L^i} \gamma^\mu L^j)(\overline{L^k} \gamma_\mu L^l)$, for $ijkl = 1221, 2112$.
CLQ1	$C_{LQ}^{(1)}$	The coefficient of the operator $(\mathcal{O}_{LQ}^{(1)})_{ijkl} = (\overline{L^i} \gamma^\mu L^j)(\overline{Q^k} \gamma_\mu Q^l)$.
CLQ3	$C_{LQ}^{(3)}$	The coefficient of the operator $(\mathcal{O}_{LQ}^{(3)})_{ijkl} = (\overline{L^i} \gamma^\mu \sigma_a L^j)(\overline{Q^k} \gamma_\mu \sigma_a Q^l)$.
Cee	C_{EE}	The coefficient of the operator $(\mathcal{O}_{EE})_{ijkl} = (\overline{E^i} \gamma^\mu E^j)(\overline{E^k} \gamma_\mu E^l)$.
Ceu	C_{EU}	The coefficient of the operator $(\mathcal{O}_{EU})_{ijkl} = (\overline{E^i} \gamma^\mu E^j)(\overline{U^k} \gamma_\mu U^l)$.
Ced	C_{ED}	The coefficient of the operator $(\mathcal{O}_{ED})_{ijkl} = (\overline{E^i} \gamma^\mu E^j)(\overline{D^k} \gamma_\mu D^l)$.
CLe	C_{LE}	The coefficient of the operator $(\mathcal{O}_{LE})_{ijkl} = (\overline{L^i} \gamma^\mu L^j)(\overline{E^k} \gamma_\mu E^l)$.
CLu	C_{LU}	The coefficient of the operator $(\mathcal{O}_{LU})_{ijkl} = (\overline{L^i} \gamma^\mu L^j)(\overline{U^k} \gamma_\mu U^l)$.
CLd	C_{LD}	The coefficient of the operator $(\mathcal{O}_{LD})_{ijkl} = (\overline{L^i} \gamma^\mu L^j)(\overline{D^k} \gamma_\mu D^l)$.
CQe	C_{QE}	The coefficient of the operator $(\mathcal{O}_{QE})_{ijkl} = (\overline{Q^i} \gamma^\mu Q^j)(\overline{E^k} \gamma_\mu E^l)$.

The SMEFT in HEPfit: the Model

- Work in progress:
  - Implementation of (most) general flavour structure

    so far: some non-universality for EW, Higgs & B anomalies;
  - Implementation of full SMEFT RG running (WET running already state-of-the-art)

    so far: some effects relevant for B anomalies;
  - Implementation of full matching on WET

    so far: some matching relevant for B anomalies;

The SMEFT in HEPfit: model-specific contributions to observables

- EWPO in α scheme
- Systematic translation to M_W scheme (in progress)
- LEPII
- Higgs signal strengths
- Dibosons (in progress)
- STXS (in progress)

The SMEFT in HEPfit: likelihoods

- Experimental likelihoods can currently be implemented as:
  - Individual measurements with “exact” likelihood (Gaussian, …)
  - 1D or 2D measurements with “numeric” likelihood (1D or 2D Histograms)
  - Binned measurements with “exact” likelihood, including correlations
  - Multi-dimensional measurements with “exact” likelihood, including correlations

The SMEFT in HEPfit: likelihoods

- Work in progress to implement full experimental likelihoods using the DNNLikelihood. Basic idea: Coccaro et al., '19
  - Experiments publish full likelihood as a suitably trained DNN predictor
  - DNN predictor used for likelihood evaluation in HEPfit
- Allows for implementation of all correlations and non-Gaussianities
- Any other numeric likelihood scheme can be implemented

The SMEFT in HEPfit: theory (and systematic) uncertainties

- Experimental systematic uncertainties implemented as any other uncertainty, including correlations;
- Same for "External" theoretical uncertainties, e.g. from calculation of EWPO; when distribution unspecified, try different distributions (flat, Gaussian, …)
- "Internal" theoretical uncertainties taken into account
  - In-run, by varying e.g. α_s, matching scale, etc…
  - A posteriori, e.g. by comparing results with or without quadratic terms

The SMEFT in HEPfit: outputs

- The output of a successful MCMC run is a numerical approximation of the joint p.d.f. for model parameters and observables, represented as:
  - Averages and correlations for all parameters;
  - Averages (and correlations) for all (correlated) observables;
  - 1D and 2D histograms and highest probability regions corresponding to 1σ, 2σ, 3σ, ...;
  - Optionally, the full MCMC chains, useful for combination with more data;
  - In progress: the corresponding DNNLikelihood

CONCLUSION & OUTLOOK

- HEPfit is a public C++ code providing an ideal framework for Bayesian fits in the SMEFT
- It provides state-of-the-art calculations of EWPO and of several flavour and LHC observables; new observables are continuously added;
- The SMEFT implementation is being completed with a richer flavour structure and the inclusion of RG effects;

CONCLUSION & OUTLOOK

- Any multi-dimensional analytic likelihood can be used;
- The DNNLikelihood is being implemented both as input and as output, allowing for the full exploitation of experimental results and for efficient reuse of fit results;
- Any other numerical likelihood parameterization can be readily implemented.