SMEFT-Tools 2022

Zürich, September 16, 2022

HEPfit

A Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models

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UNIÓN EUROPEA
Fondo Europeo de Desarrollo Regional

Funded by: FEDER/Junta de Andalucía-Consejería de Transformación Económica, Industria, Conocimiento y Universidades/Project P18-FRJ-3735

Introduction

- SMEFT interpretation toolbox:

Top-Down

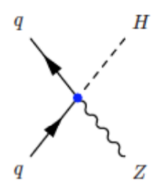
Bottom-Up

UV theory/BSM

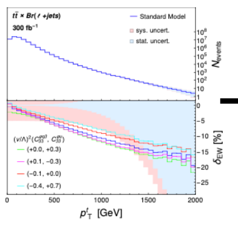
Λ

RGE

IR→EFT



EFT Pheno



EFT vs. Data

Tools for UV/IR matching

CoDEx

MatchingTools

MatchMakereft

MATCHETE

SUPER TRACER

EFT bases/operators

BasisGen

Sym2Int

EFT tools: RGE, SMEFT/LEFT matching,...

DsixTools

LHC event generation

Madgraph5_aMC@NLO

+

SMEFT UFOs

LO: SMEFTsim HEL SMEFTfr

NLO: SMEFT@NLO dim6top

High-p_T

HighPT

Flavor

EOS

Likelihood

Smelli

Likelihood + Fitting framework

EFTfitter

Fitmaker

HEPfit

SFitter

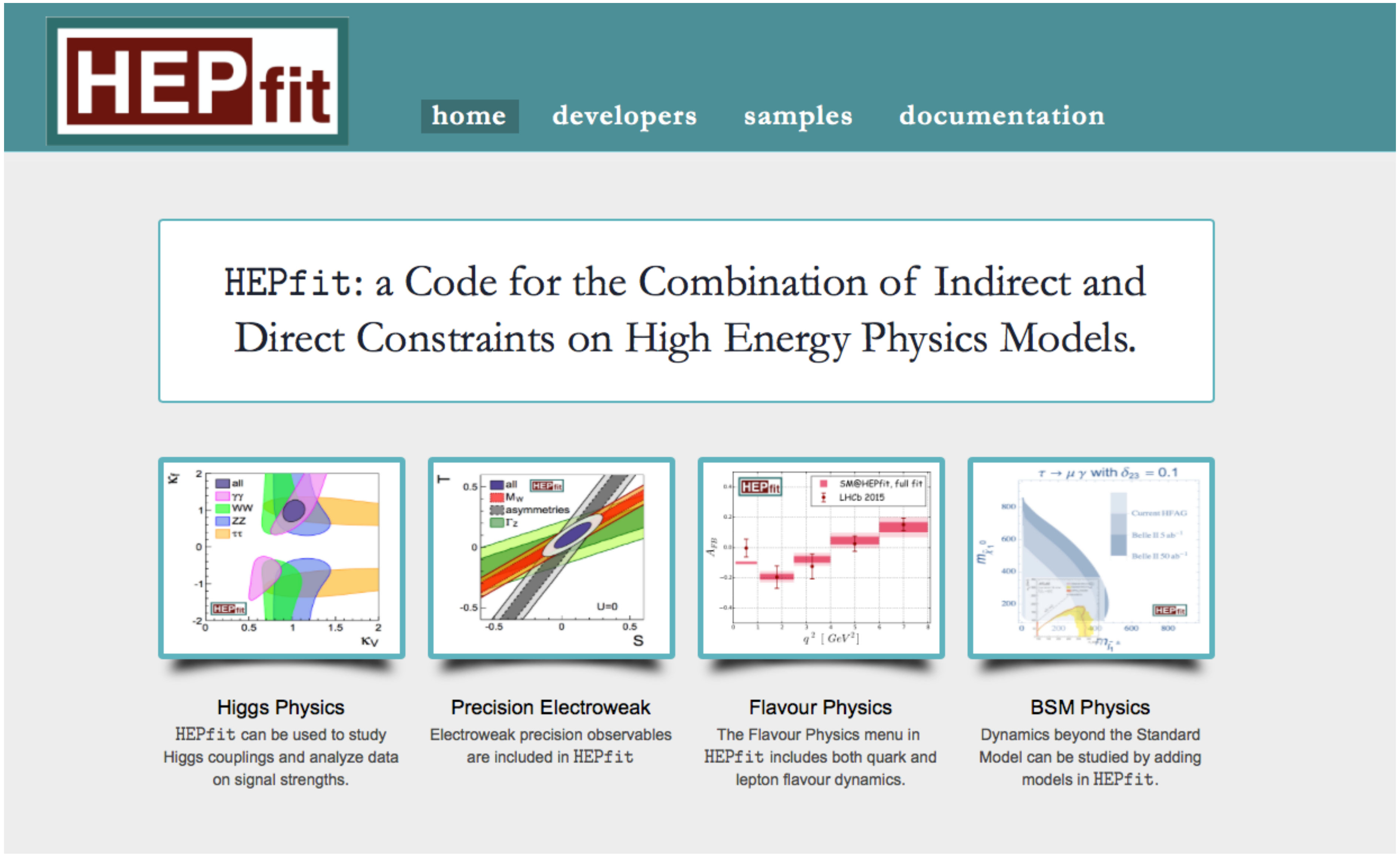
SMEFiT

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)

https://github.com/silvest/HEPfit

- Webpage: http://hepfit.roma1.infn.it



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- Reference: **JB et al., Eur. Phys. J. C (2020) 80:456, arXiv: 1910.14012 [hep-ph]**

Eur. Phys. J. C (2020) 80:456
https://doi.org/10.1140/epjc/s10052-020-7904-z

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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

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The HEPfit code: Publications

Publications using HEPfit
(In reverse chronological order)

1. A. J. Buras et al. , Global Analysis of Leptophilic Z' bosons, arXiv: 2105.03399 [hep-ph]
2. G. Arcadi et al. , Systematic approach to B-physics anomalies and t-channel dark matter , arXiv: 2103.15635 [hep-ph]
3. A. Crivellin et al., The Fermi constant from muon decay versus electroweak fits and CKM unitarity , arXiv: 2102.02825 hep-ph]
4. A. Crivellin et al., Searching for Lepton Flavour (Universality) Violation and Collider Signals from a Singly-Charged Scalar Singlet, Phys.Rev.D 103 (2021) 7, 073002
5. O. Eberhardt et al. , Global fits in the Aligned Two-Higgs-Doublet model, JHEP 05 (2021) 005
6. M. Ciuchini et al. , Lessons from the $B^{0,+} \to K^{*0,+}\mu^+\mu^-$ angular analyses, Phys.Rev.D 103 (2021) 1, 015030
7. A. Crivellin et al., Combined Explanation of the $Z \to bb$ Forward-Backward Asymmetry, the Cabibbo Angle Anomaly, $\tau \to \mu\nu\nu$ and $b \to sll$ Data, arXiv: 2010.14504 [hep-ph]
8. T. Husek et al., Lepton-flavour violation in hadronic tau decays and μ–τ conversion in nuclei, JHEP 01 (2021) 059
9. A. Crivellin et al., Global Electroweak Fit and Vector-Like Leptons in Light of the Cabibbo Angle Anomaly , JHEP 12 (2020) 166
10. L. Alasfar et al., B anomalies under the lens of electroweak precision, JHEP 12 (2020) 016
11. B. Capdevila et al., Explaining $b \to sl^+l^-$ and the Cabibbo Angle Anomaly with a Vector Triplet, Phys.Rev.D 103 (2021) 1, 015032
12. M. Endo et al. Muon $g-2$ and CKM Unitarity in Extra Lepton Models, JHEP 08 (2020) 08, 004
13. A. Crivellin et al. , Hadronic vacuum polarization: $(g-2)_\mu$ versus global electroweak fits, Phys.Rev.Lett. 125 (2020) 9, 091801
14. A. M. Coutinho et al., Global Fit to Modified Neutrino Couplings and the Cabibbo-Angle Anomaly , Phys.Rev.Lett. 125 (2020) 7, 071802
15. G. Durieux et al., *The electro-weak couplings of the top and bottom quarks global fit and future prospects*, arXiv:1907.10619 [hep-ph]
16. J. de Blas et al., *On the future of Higgs, electroweak and diboson measurements at lepton colliders*, JHEP **12** (2019) 117
17. D. Bečirević,et al., *Lepton Flavor Universality tests through angular observables of B decay modes*, arXiv:1907.02257 [hep-ph]
18. J. de Blas *et. al.*, *Higgs Boson Studies at Future Particle Colliders*, JHEP **01** (2020) 139

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(In reverse chronological order)

19. P. Arnan et al., *Generic loop effects of new scalars and fermions in $b\to s\ell\ell$ and a vector-like 4th generation*, JHEP **1906** (2019) 118
20. M. Ciuchiniet al., *New Physics in $b\to s\ell\ell$ confronts new data on Lepton Universality,* Eur. Phys. J. C **79** (2019) no.8, 719
21. F. Buccella et al., *$SU(3)_F$ breaking through final state interactions and CP asymmetries in $D\to PP$ decays,* Phys. Rev. D **99**>, no. 11, 113001 (2019)
22. P. Azzi *et al.* [HL-LHC Collaboration and HE-LHC Working Group], *Standard Model Physics at the HL-LHC and HE-LHC,* arXiv:1902.04070 [hep-ph]
23. M. Cepeda *et al.* [HL/HE WG2 group], *Higgs Physics at the HL-LHC and HE-LHC,* arXiv:1902.00134 [hep-ph]
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26. M. Ciuchini et al., *Hadronic uncertainties in semileptonic $B\to K\mu\mu$ decays,* PoS BEAUTY **2018** (2018) 044
27. E. Kou *et al.* [Belle-II Collaboration], *The Belle II Physics Book,* arXiv:1808.10567 [hep-ph]
28. L. Cheng, O. Eberhardt and C. W. Murphy, *Novel theoretical constraints for color-octet scalar models*, Chin. Phys. C **43** (2019) no.9, 093101
29. C. W. Chiang, G. Cottin and O. Eberhardt, *Global fits in the Georgi-Machacek model,* Phys. Rev. D **99** (2019) no.1, 015001
30. J. de Blas, O. Eberhardt and C. Krause, *Current and Future Constraints on Higgs Couplings in the Nonlinear Effective Theory*, JHEP **1807** (2018) 048
31. D. Chowdhury and O. Eberhardt, *Update of Global Two-Higgs-Doublet Model Fits*, JHEP **1805** (2018) 161
32. J. de Blas et al., *The Global Electroweak and Higgs Fits in the LHC era,* PoS EPS **HEP2017** (2017) 467
33. S. Gori, C. Grojean, A. Juste and A. Paul, *Heavy Higgs Searches: Flavour Matters,* JHEP **1801** (2018) 108
34. O. Eberhardt, *Two-Higgs-doublet model fits with HEPfit,* arXiv:1709.09414 [hep-ph]
35. *M. Ciuchini et al., On Flavourful Easter eggs for New Physics hunger and Lepton Flavour Universality violation,* *Eur. Phys. J. C* ***77*** *(2017) no.10, 688*
36. M. Ciuchini et al., *Updates on fits to electroweak parameters,* PoS LeptonPhoton **2015** (2016) 013

The HEPfit code: Publications

Publications using HEPfit
(In reverse chronological order)

37. J. de Blas et al., *Electroweak precision constraints at present and future colliders,* PoS ICHEP **2016** (2017) 690
38. M. Ciuchini et al.,, *$B\to K\ell\ell$ in the Standard Model: Elaborations and Interpretations,* PoS ICHEP **2016** (2016) 584
39. M. Ciuchini et al., *The $B\to K\mu\mu$ decay: A study in the Standard Model* Nuovo Cim. C **39** (2016) no.1, 234
40. V. Cacchio et al.,, *Next-to-leading order unitarity fits in Two-Higgs-Doublet models with soft $\mathbb{Z}2$ breaking*, JHEP **1611** (2016) 026
41. A. Paul and D. M. Straub, *Constraints on new physics from radiative B decays*, JHEP **1704** (2017) 027
42. J. de Blas et al., *EW precision observables and Higgs-boson signal strengths in the Standard Model and beyond: present and future*, JHEP **1612** (2016) 135
43. L. Reina et al., *Precision constraints on non-standard Higgs-boson couplings with HEPfit,* PoS EPS **HEP2015** (2015) 187
44. M. Ciuchini, et al., *$B\to K\ell\ell$ decays at large recoil in the Standard Model: a theoretical reappraisal,* JHEP **1606** (2016) 116
45. D. Ghosh et al., *Extending the Analysis of Electroweak Precision Constraints in Composite Higgs Models*, Nucl. Phys. B **914** (2017) 346
46. M. Ciuchini et al., *Electroweak Precision Observables, New Physics and the Nature of a 126 GeV Higgs Boson,* JHEP **1308** (2013) 106

Last updated: May 2021

As of today: Cited in ~90 papers

Outline

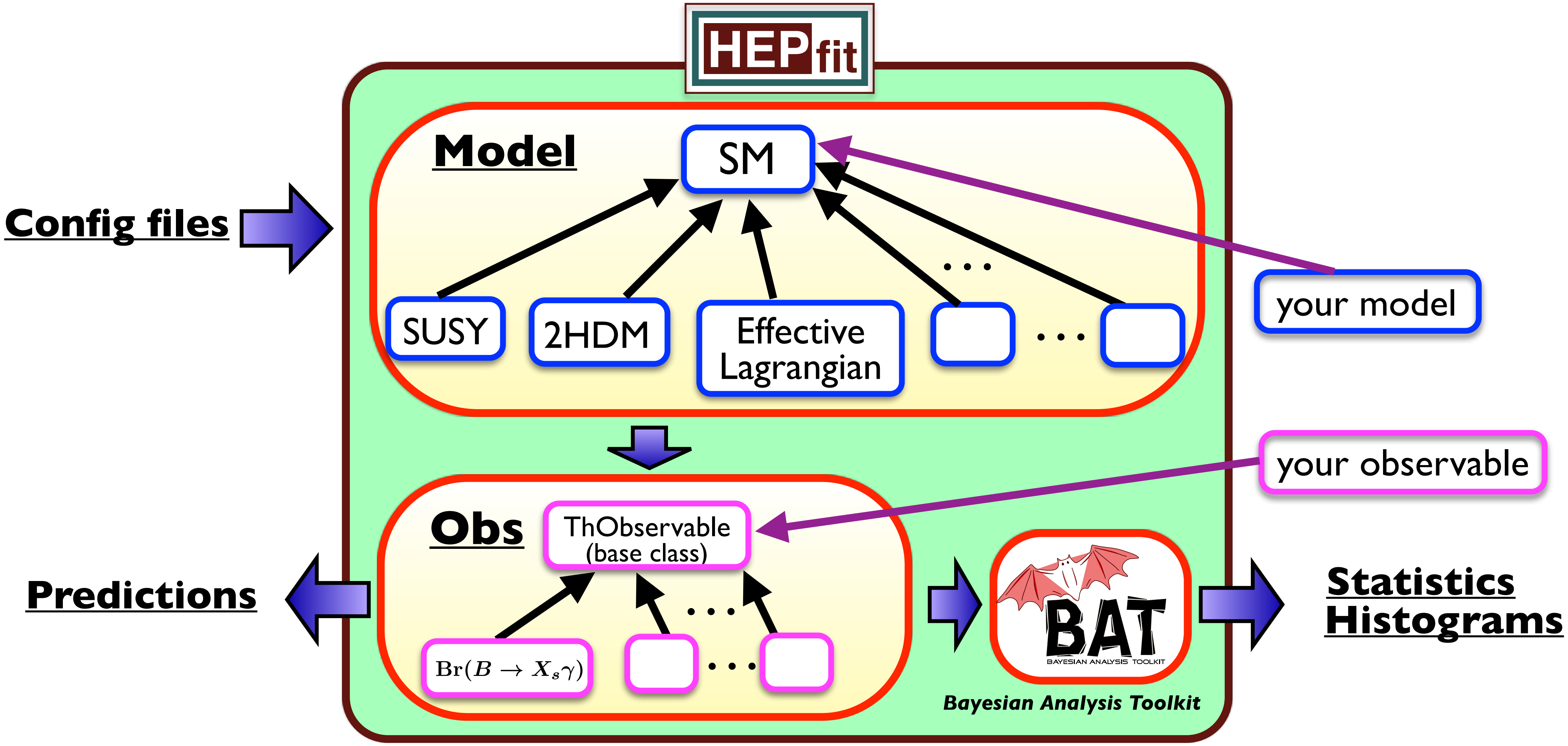
- **Brief description of the code**
- **Models and observables**
- **The dimension-6 SMEFT in HEPfit**
- **Making it work…**
    - **Installation**
    - **Running example**
    - **Adding models and observables**
- **Summary**

Brief description of the code

I/O and capabilities

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)



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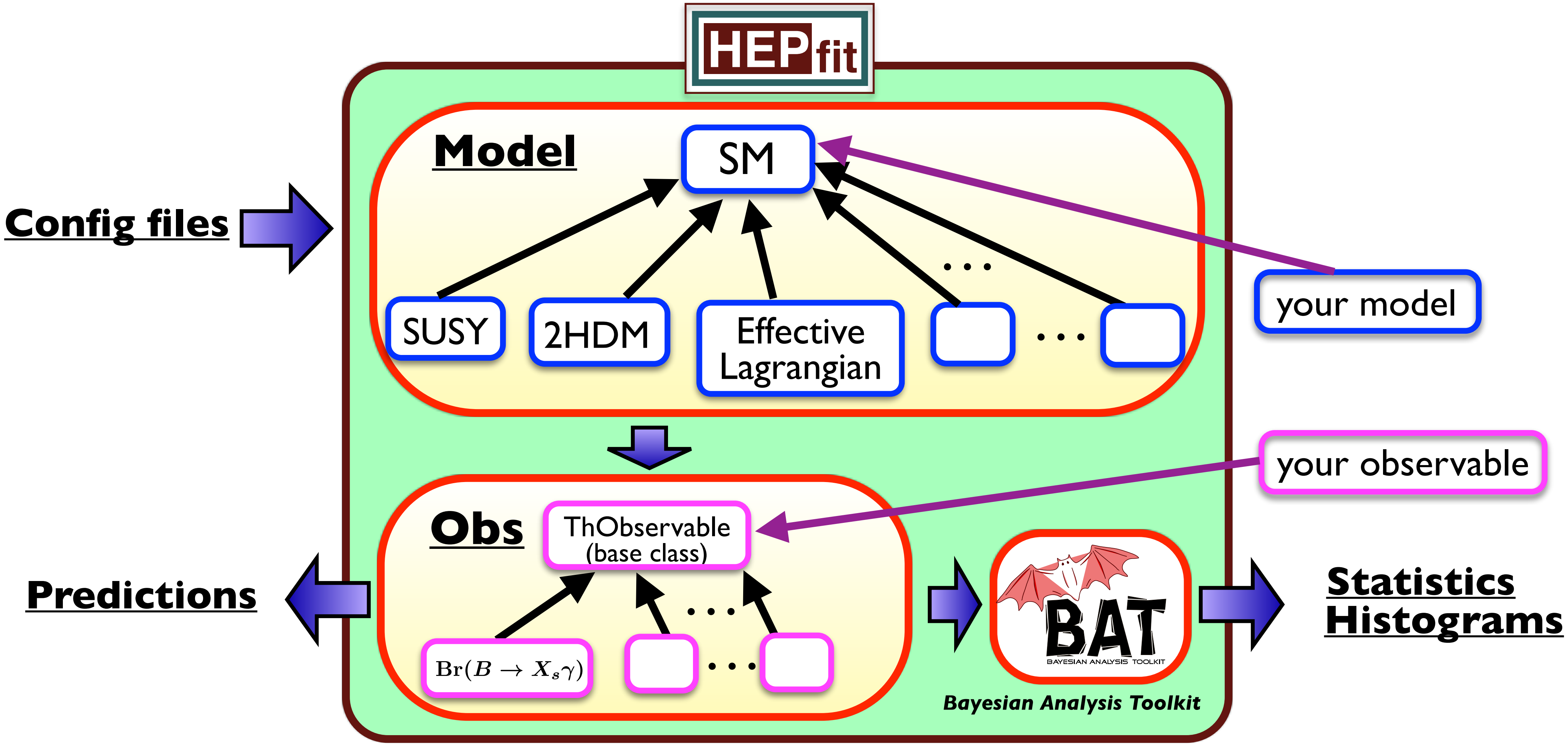

- Flexible open-source code written in C++

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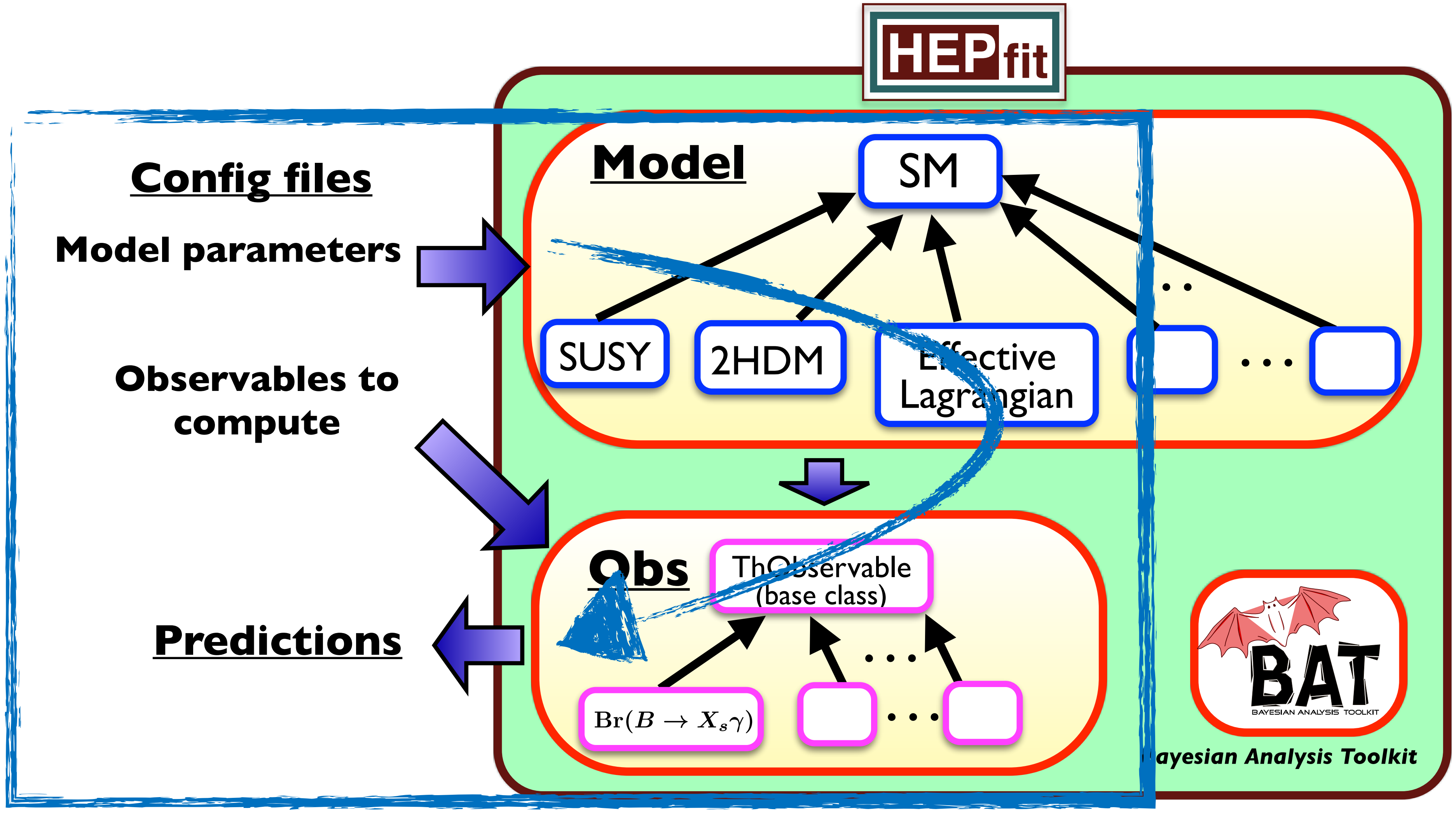

- Flexible open-source code written in C++
- **Stand-alone mode** to compute observables in the SM & BSM

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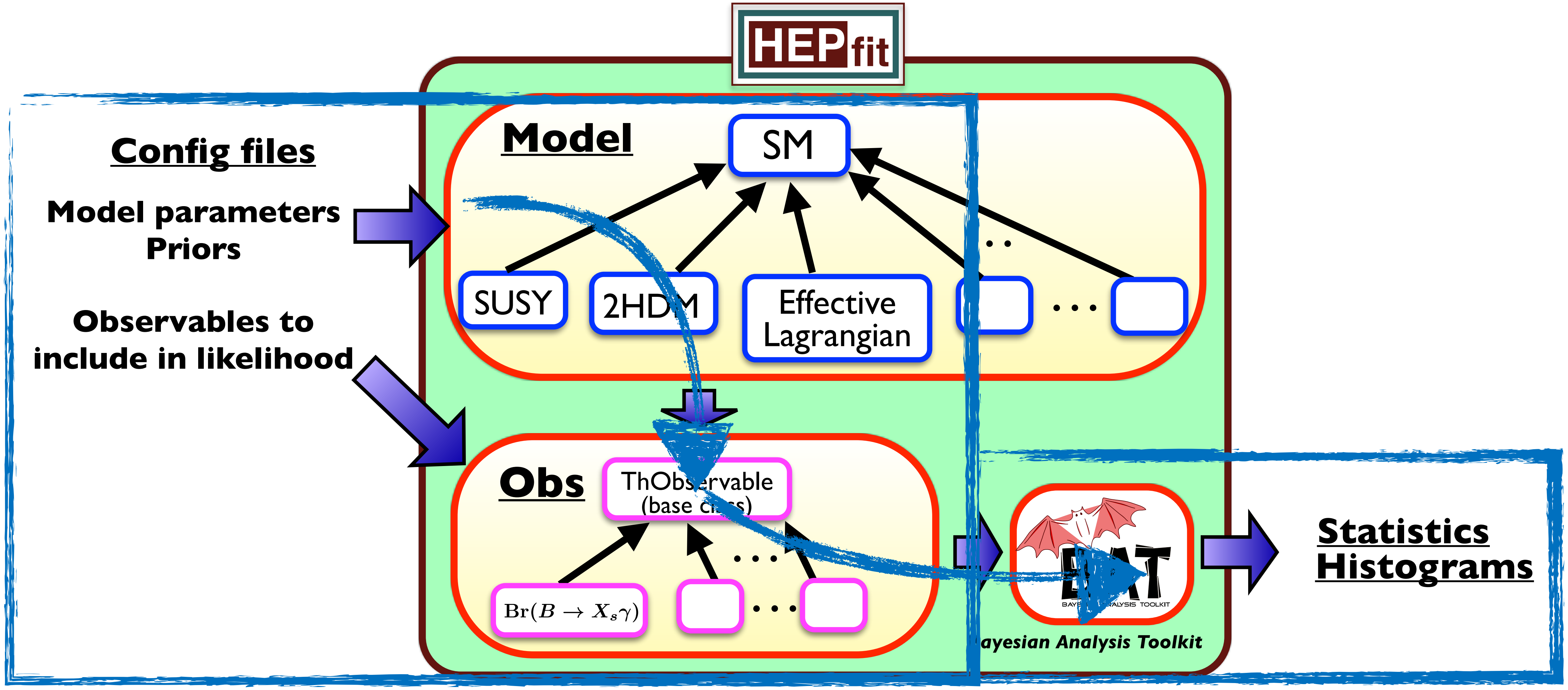

- Flexible open-source code written in C++
- **Stand-alone mode** to compute observables in the SM & BSM
- Optional **Bayesian Stat. Analysis framework** (supports MPI parall.)

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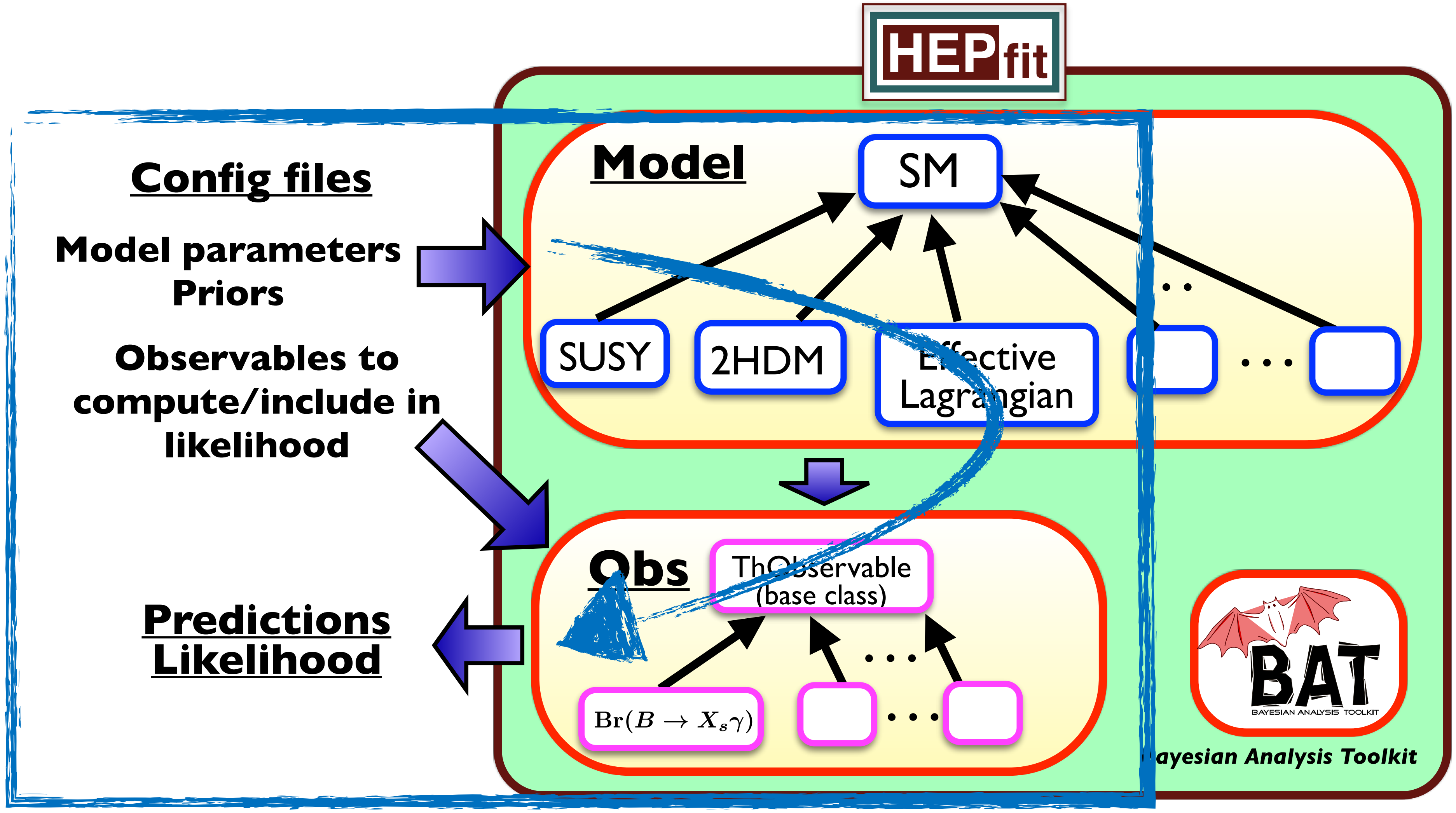

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- Optional **Bayesian Stat. Analysis framework** (supports MPI parall.)
- **Library mode** to compute observables in the SM & BSM

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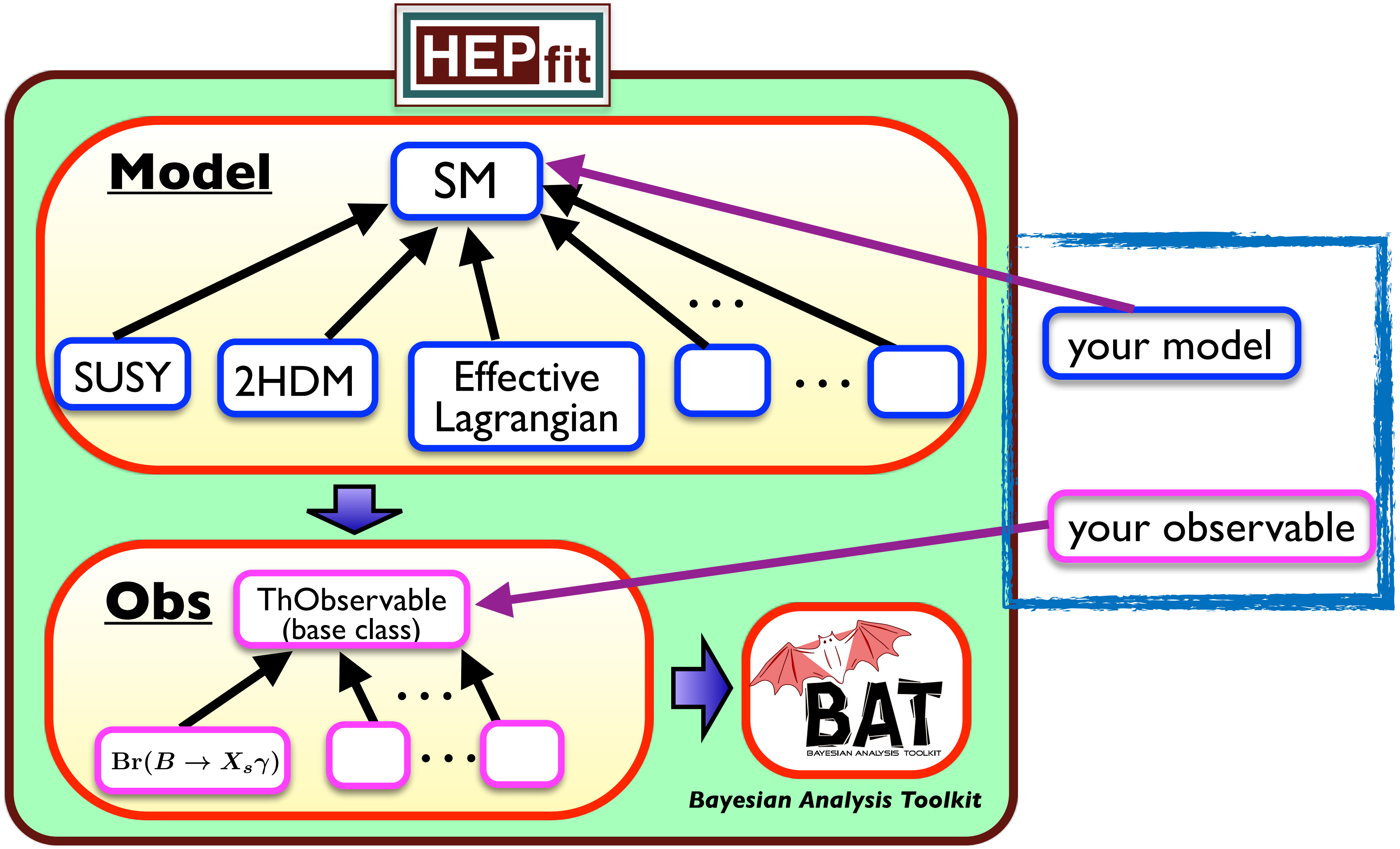
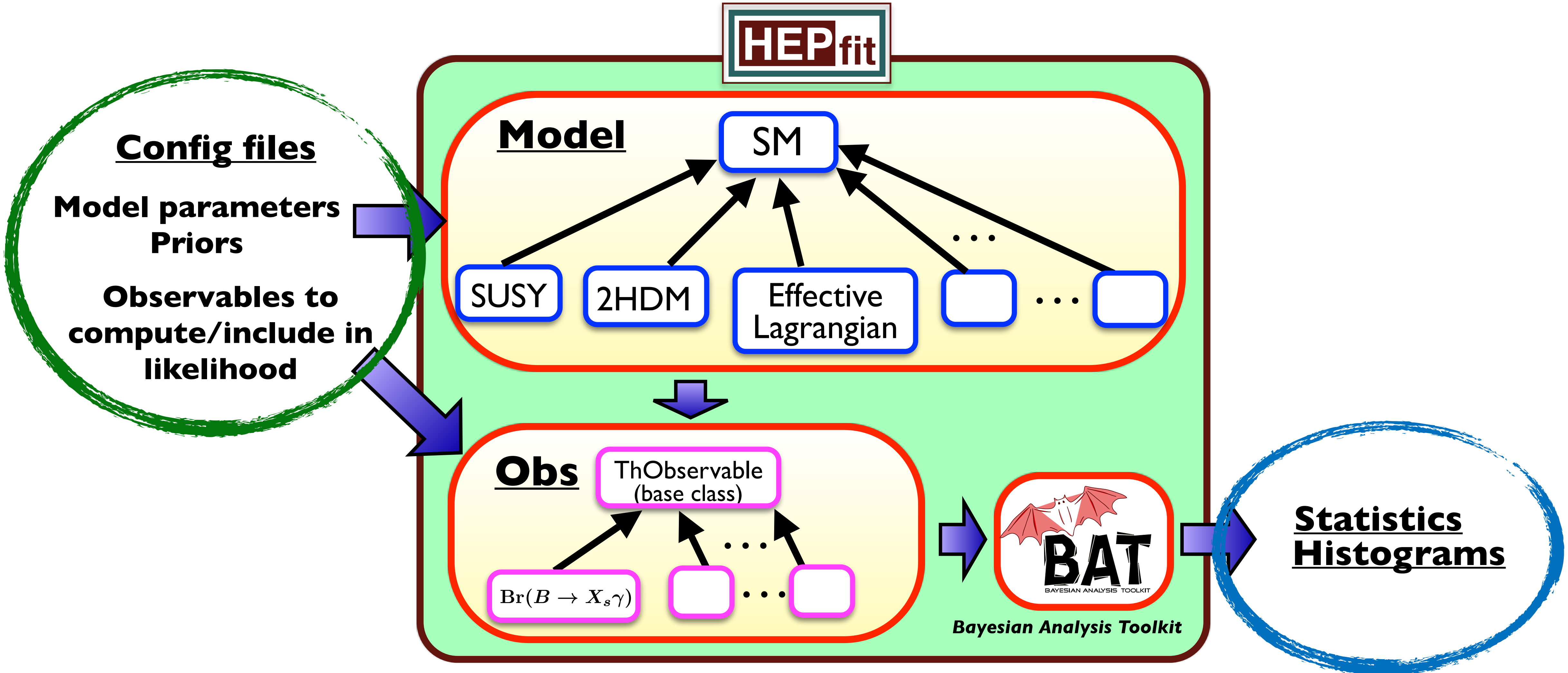


- Flexible open-source code written in C++
- **Stand-alone mode** to compute observables in the SM & BSM
- Optional **Bayesian Stat. Analysis framework** (supports MPI parall.)
- **Library mode** to compute observables in the SM & BSM
- Users can **add new models and/or observables as external modules**

The HEPfit code

- General **H**igh **E**nergy **P**hysics **fit**ting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)



- **Input:** Model priors ($p(\theta)$) and observable info to build the likelihood ($\mathcal{L}(\theta)$)
- **Output:** Posterior of the fit. Predictions

$$p(\theta|D) = \frac{p(D|\theta)p(\theta)}{p(D)} = \frac{\mathcal{L}(\theta)p(\theta)}{p(D)}$$

The HEPfit code Inputs: Likelihoods

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

- **Work in Progress:** Implementing "full" experimental likelihoods from Machine Learning proxies ⇒ DNNLikelihoods
  - ✓ Experiments could provide full likelihood information via a DNN trained on the real likelihood ⇒ This DNN could be used in HEPfit
  - ✓ Efficient distribution (lightweight, standard and framework-independent format) across software platforms through ONNX Open Neural Network Exchange The open standard for machine learning interoperability

- Any other numeric likelihood scheme can be implemented

The HEPfit code Inputs: SYS/TH uncertainties

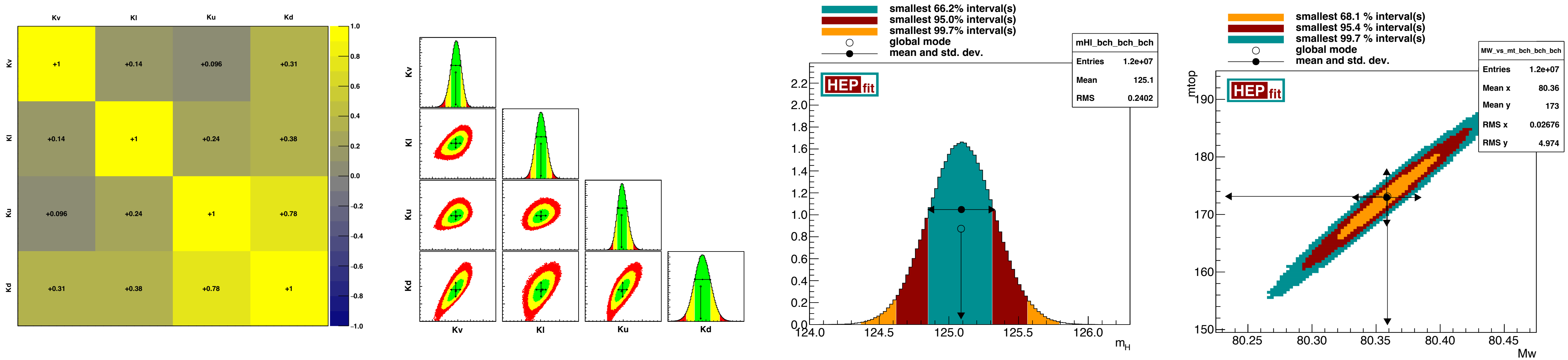
- Treatment of **systematic uncertainties:**
  - ✓ Experimental systematic uncertainties implemented as any other uncertainty, including the possibility of correlations
  - ✓ The same applies to "intrinsic" theory uncertainties, e.g. unknown higher-order corrections in the predictions of observables
  - ✓ Modeling via "nuisance" parameters:
    - Different types of distributions: Flat, Gaussian,…
    - Correlations

- Other internal theory uncertainties can also be taken into account
  - ✓ In-run, by varying e.g. α_S, matching scale, etc.
  - ✓ Post-run, e.g. comparing EFT results with and without including $O(\Lambda^{-4})$ terms

The HEPfit code Output

- The output of the default MCMC run is a numerical approximation to the joint P.D.F. for the model parameters and observables.

- Information provided:
  - ✓ Averages, errors and correlations for inferred parameters
  - ✓ Averages, errors (and correlations) for all (correlated) observables in the fit
  - ✓ 1D and 2D histograms of marginal distributions, correlations plots, …



  - ✓ Optional: full MCMC chains → Useful for combination with more data

- Work in Progress: providing also a DNNLikelihood as output of the HEPfit run

The HEPfit code

Performance and Limitations

- No limitation in the number of parameters and/or observables that can be defined in the fits
- Largest fit we have performed contains more than 90 parameters and 200 observables. Other fits have been done with several hundreds observables but smaller number of parameters.
- Performance examples:

Physics Problem	Hardware	Run Configuration	Time
Unitarity Triangle Fit	3 nodes, 120 CPUs	120 chains, 1.4M iterations	00:02:10
	1 nodes, 40 CPUs	40 chains, 600K iterations	00:00:21
$b \to s$ decays in SMEFT†	6 nodes, 240 CPUs	240 chains, 12.5K iterations	02:05:00
	6 nodes, 240 CPUs	240 chains, 39K iterations	05:20:00
combination of Higgs signal strengths and EWPO	1 node, 16 CPUs	16 chains, 5M iterations	00:14:15
	1 node, 16 CPUs	16 chains, 24M iterations	02:08:00
$D \to PP$ decays and CP asymmetry	3 nodes, 240 CPUs	240 chains, 4M iterations	00:18:30
	1 node, 8 CPUs	8 chains, 200K iterations	00:00:10

←(DD: HH:MM)

Tested at the BIRD or Maxwell clusters at DESY, Hamburg

Models and Observables

Some Physics Results

The HEPfit code: Models and Observables

Some models/observables already available in the code

Models

Standard Model

Oblique pars: S,T,U
ε_i parameters
Modified *Zbb* couplings
κ-framework
SMEFT: dim 6
HEFT

General 2HDM
Georgi-Machacek

SUSY-MSSM
LR models
(WIP)

Observables*

EWPO
LEP 2 obs: $e^+e^-\to ff$, W^+W^-
LHC Higgs observables
LHC diboson
LHC Top
Flavor: ΔF=2, UT, B decays
LFV

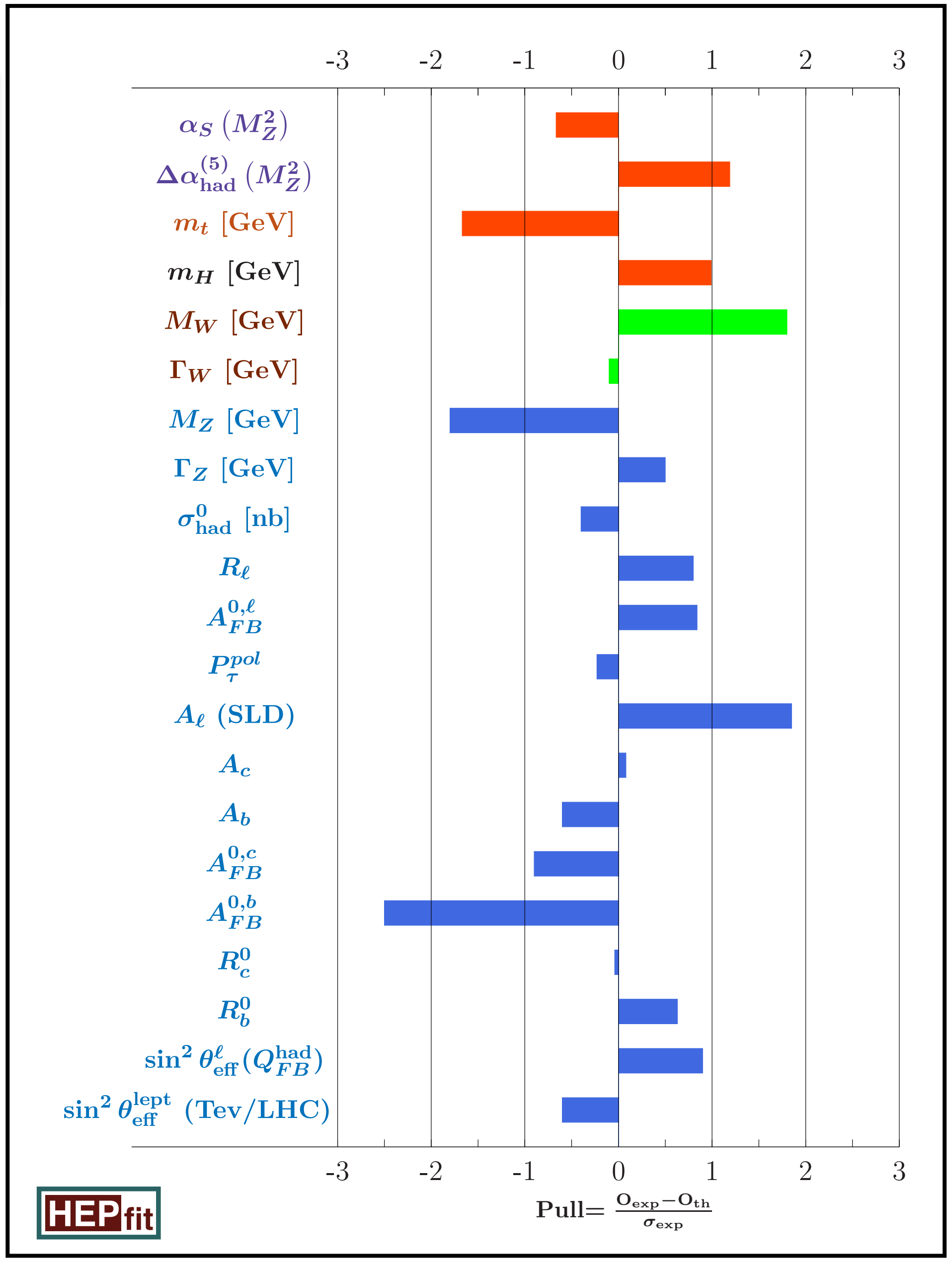
Theory constr.: Unitarity, Perturbativity, …

*Not all observables available for all models

The Global SM EW fit

- State-of-the-art SM calculation of EWPO (2-loop + leading HO)

	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1177±0.0010	0.1179±0.0009	0.1197±0.0028	-0.7
$\Delta\alpha_{\text{had}}^{(5)}(M_Z)$	0.027611±0.000111	0.027572±0.000106	0.027168±0.000355	1.2
M_Z [GeV]	91.1875±0.0021	91.1880±0.0020	91.2038±0.0087	-1.8
m_t [GeV]	172.59±0.45	172.76±0.44	175.97±1.98	-1.7
m_H [GeV]	125.30±0.13	125.30±0.13	112.68±12.89	0.98
M_W [GeV]	80.379±0.012	80.360±0.005	80.355±0.006	1.8
Γ_W [GeV]	2.085±0.042	2.0883±0.0006	2.0883±0.0006	-0.08
$\text{BR}_{W\to\text{had}}$	0.6741±0.0027	0.67486±0.00007	0.67486±0.00007	-0.28
$\text{BR}_{W\to\ell\nu}$	0.1086±0.0009	0.10838±0.00002	0.10838±0.00002	0.24
$P_\tau^{\text{pol}} = \mathcal{A}_\ell$	0.1465±0.0033	0.1473±0.0004	0.1473±0.0005	-0.23
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.2324±0.0012	0.23149±0.00006	0.23149±0.00006	0.91
Γ_Z [GeV]	2.4955±0.0023	2.4945±0.0006	2.4943±0.0007	0.50
σ_h^0 [nb]	41.4802±0.0325	41.4910±0.0076	41.4930±0.0080	-0.38
R_ℓ^0	20.7666±0.0247	20.750±0.0080	20.7460±0.0087	0.79
$A_{\text{FB}}^{0,\ell}$	0.0171±0.0010	0.01627±0.00010	0.01626±0.00010	0.84
$\mathcal{A}_\ell$ (SLD)	0.1513±0.0021	0.14727±0.00045	0.14731±0.00047	1.9
R_b^0	0.21629±0.00066	0.21588±0.00010	0.21587±0.00010	0.63
R_c^0	0.1721±0.0030	0.17221±0.00005	0.17221±0.00005	-0.04
$A_{\text{FB}}^{0,b}$	0.0992±0.0016	0.1032±0.0003	0.10327±0.00033105	-2.5
$A_{\text{FB}}^{0,c}$	0.0707±0.0035	0.0738±0.0002	0.0738±0.0002	-0.88
$\mathcal{A}_b$	0.923±0.020	0.93475±0.00004	0.93475±0.00004	-0.59
$\mathcal{A}_c$	0.670±0.027	0.6679±0.0002	0.6679±0.0002	0.08
$\sin^2\theta_{\text{eff}}^{\text{lept}}(\text{Tev/LHC})$	0.23137±0.00022	0.23149±0.00006	0.23150±0.00006	-0.57



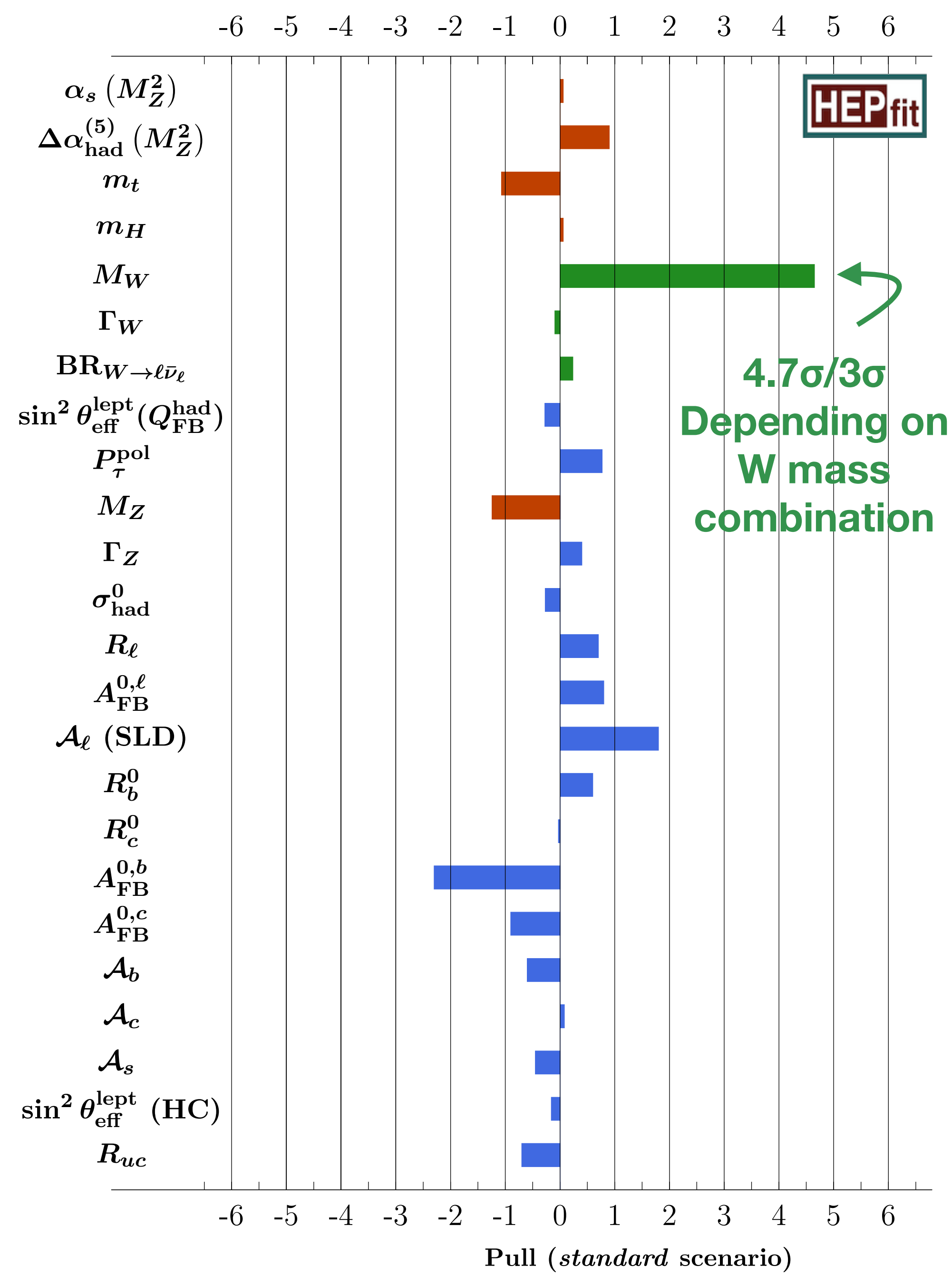
Status of the EW fit before the new CDF measurement of the W mass

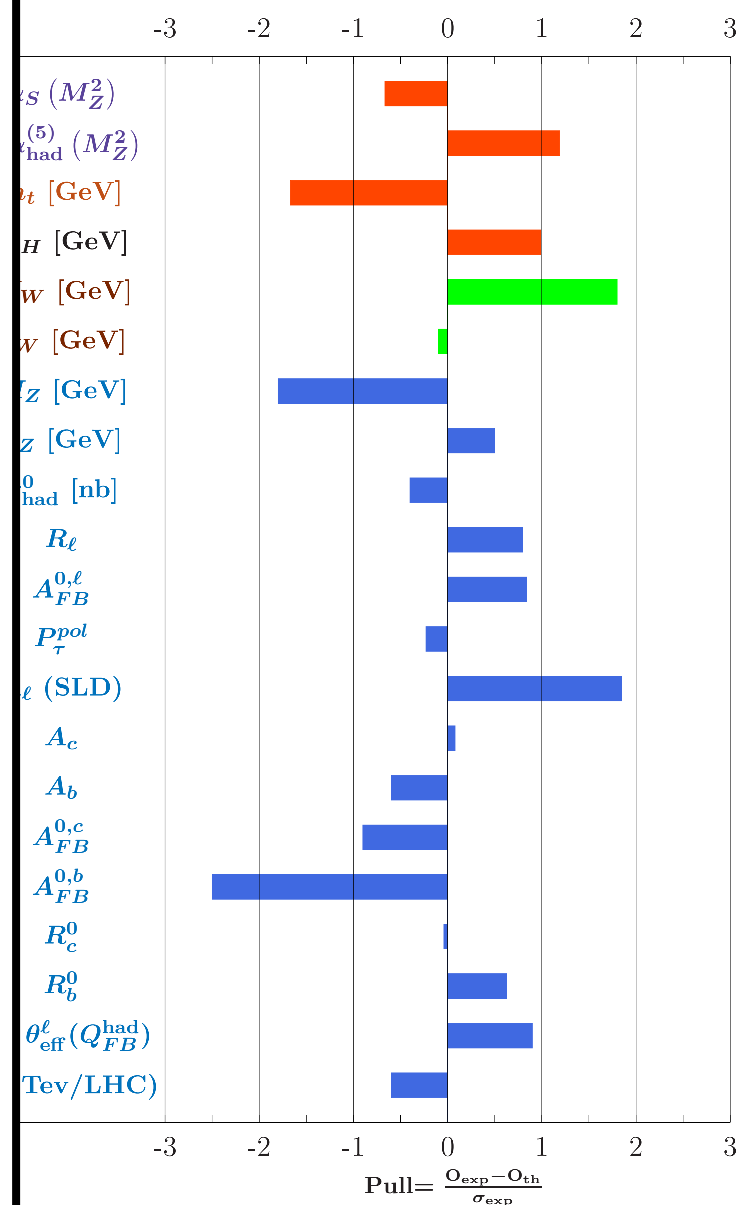
The Global SM EW fit

- State-of-the-art SM calculation of EWPO (2-loop + leading HO)

	Measurement
$\alpha_s(M_Z)$	0.1177 ± 0.0010
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.027611 ± 0.000111
M_Z [GeV]	91.1875 ± 0.0021
m_t [GeV]	172.59 ± 0.45
m_H [GeV]	125.30 ± 0.13
M_W [GeV]	80.379 ± 0.012
Γ_W [GeV]	2.085 ± 0.042
$\mathrm{BR}_{W\to \rm had}$	0.6741 ± 0.0027
$\mathrm{BR}_{W\to \ell\nu}$	0.1086 ± 0.0009
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012
Γ_Z [GeV]	2.4955 ± 0.0023
σ_h^0 [nb]	41.4802 ± 0.0325
R_ℓ^0	20.7666 ± 0.0247
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
R_b^0	0.21629 ± 0.00066
R_c^0	0.1721 ± 0.0030
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035
$\mathcal{A}_b$	0.923 ± 0.020
$\mathcal{A}_c$	0.670 ± 0.027
$\sin^2\theta_{\rm eff}^{\rm lept}(\mathrm{Tev/LHC})$	0.23137 ± 0.00022

“Posterior”

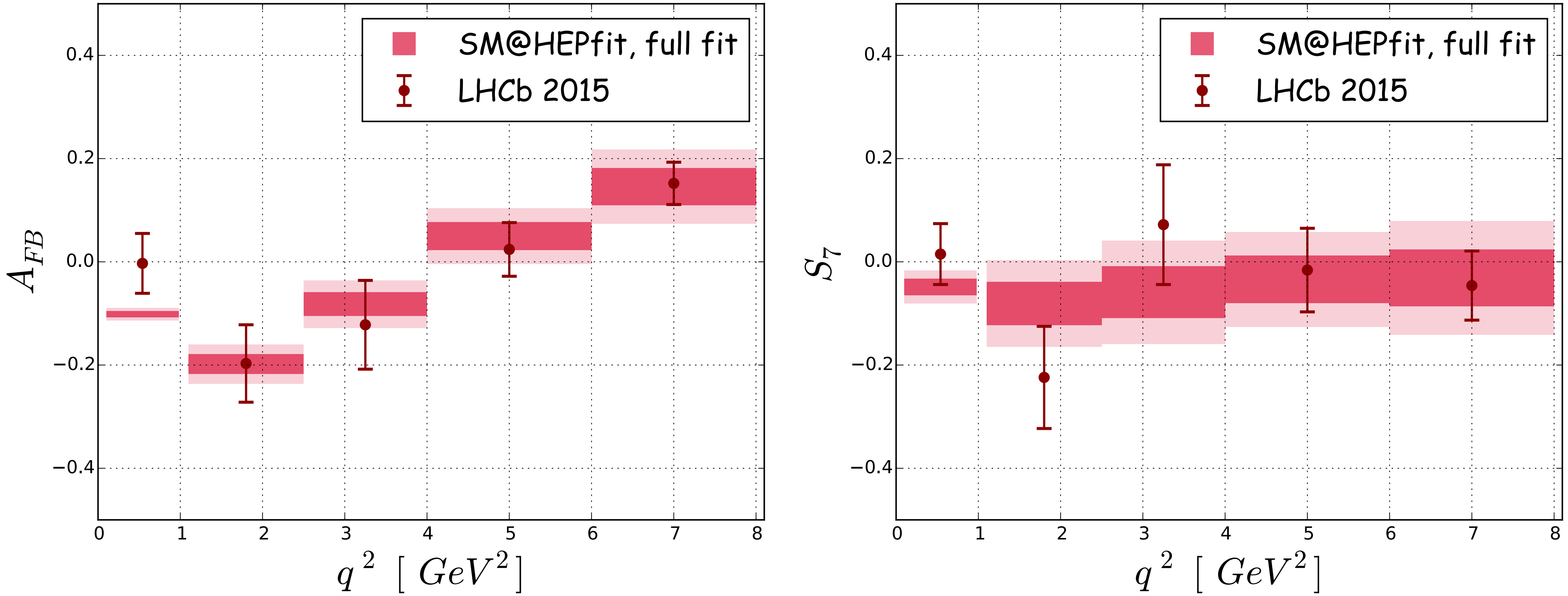




Including the new CDF measurement of W mass

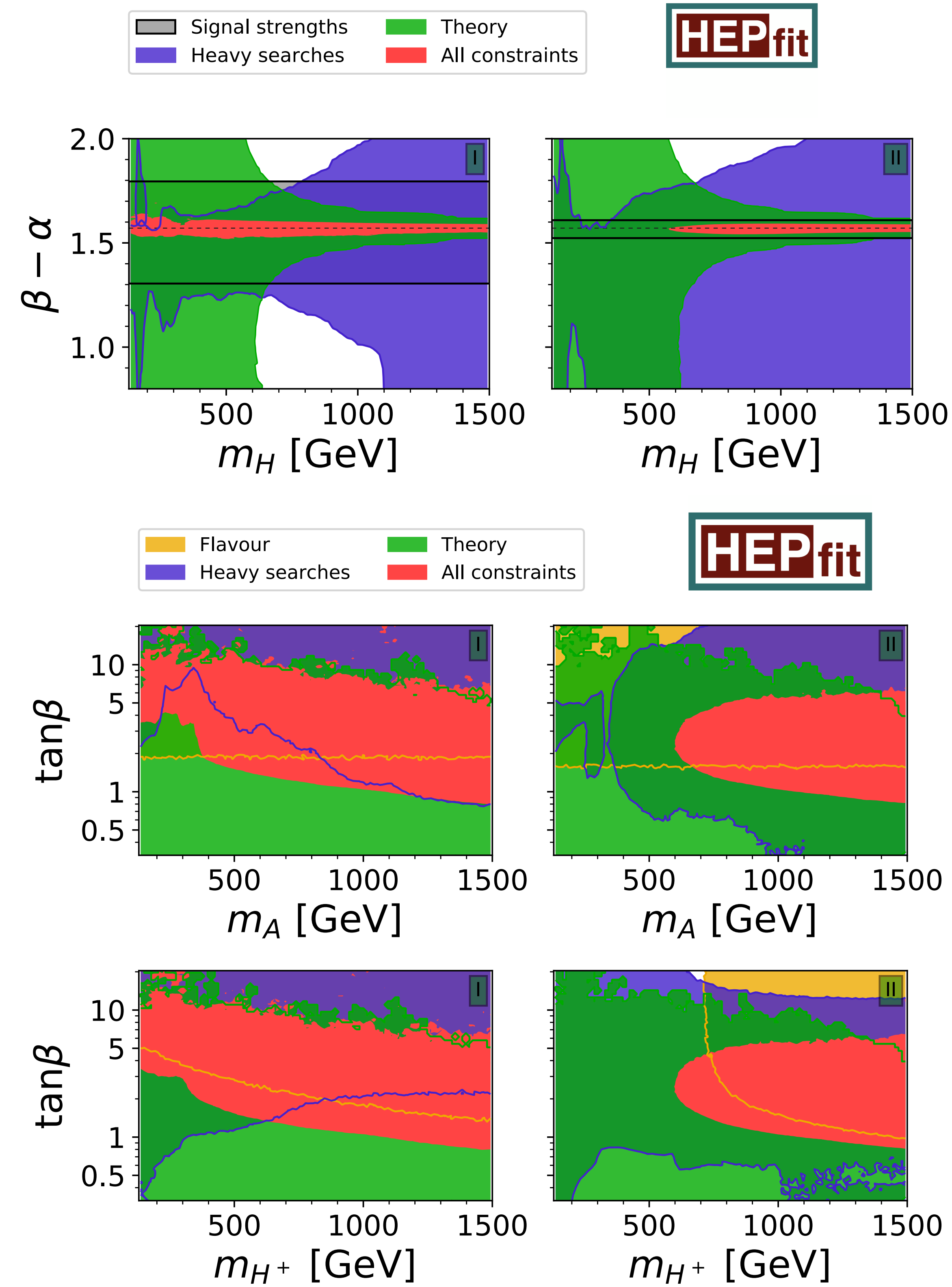
SM Flavour observables

- State-of-the-art SM calculation of Flavor observables:
  - Flavor observables: Rare decays, non-leptonic decays, … Most of them at the highest available precision
  - Example: $B \to K^{*}\ell\ell$ M. Ciuchini et al. , arXiv: 1512.07157 [hep-ph]



The Global SM EW fit

- **BSM:** 2HDM with softly broken Z_2 symmetry
- Fits in Type I and Type II 2HDM with:
  - ✓ EWPO
  - ✓ Higgs signal strengths
  - ✓ Flavor ($b \to s\gamma$, B_s mixing)
  - ✓ LHC searches direct searches of neutral and singly charged scalars
  - ✓ Theory constraints: V bounded by below, Perturbativity



O. Eberhardt, PoS ICHEP2018 (2019) 457

The Global SM EW fit

- **BSM:** Direct+Indirect constraints on color-octet scalars: S~(8,2)$_{1/2}$

Scalar Potential

$$
\begin{aligned}
V_{\rm MW} = {} & m_\Phi^2 \Phi^\dagger \Phi + \tfrac{1}{2}\lambda \left(\Phi^\dagger\Phi\right)^2 + 2 m_S^2 \mathrm{Tr}\left(S^{\dagger i} S_i\right) + \mu_1 \mathrm{Tr}\left(S^{\dagger i} S_i S^{\dagger j} S_j\right) + \mu_2 \mathrm{Tr}\left(S^{\dagger i} S_j S^{\dagger j} S_i\right) \\
& + \mu_3 \mathrm{Tr}\left(S^{\dagger i} S_i\right) \mathrm{Tr}\left(S^{\dagger j} S_j\right) + \mu_4 \mathrm{Tr}\left(S^{\dagger i} S_j\right) \mathrm{Tr}\left(S^{\dagger j} S_i\right) + \mu_5 \mathrm{Tr}\left(S_i S_j\right) \mathrm{Tr}\left(S^{\dagger i} S^{\dagger j}\right) \\
& + \mu_6 \mathrm{Tr}\left(S_i S_j S^{\dagger j} S^{\dagger i}\right) + \nu_1 \Phi^{\dagger i}\Phi_i \mathrm{Tr}\left(S^{\dagger j} S_j\right) + \nu_2 \Phi^{\dagger i}\Phi_j \mathrm{Tr}\left(S^{\dagger j} S_i\right) \\
& + \left[\nu_3 \Phi^{\dagger i}\Phi^{\dagger j} \mathrm{Tr}\left(S_i S_j\right) + \nu_4 \Phi^{\dagger i} \mathrm{Tr}\left(S^{\dagger j} S_j S_i\right) + \nu_5 \Phi^{\dagger i} \mathrm{Tr}\left(S^{\dagger j} S_i S_j\right) + \mathrm{h.c.}\right], \quad (2.1)
\end{aligned}
$$

Yukawa interactions

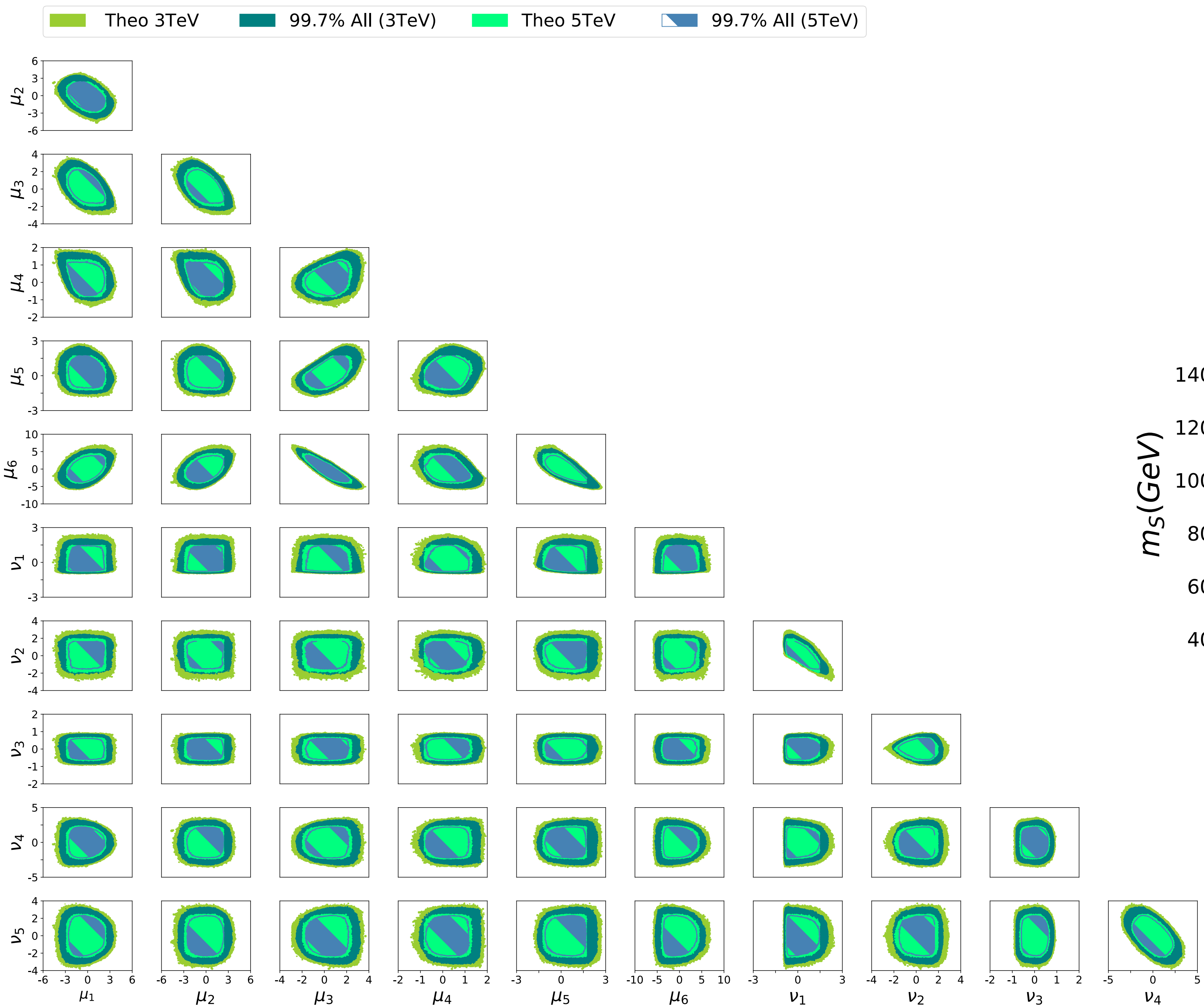
$$
\mathcal{L}_Y \supset - \sum_{i,j=1}^{3} \left[\eta_D Y^d_{ij} \bar{Q}_{L_i} S d_{R_j} + \eta_U Y^u_{ij} \bar{Q}_{L_i} \tilde{S} u_{R_j} + \mathrm{h.c.}\right]
$$

- Fits in a CP conserving and MFV scenario (14 parameters) including:
  - ✓ EWPO
  - ✓ Higgs signal strengths
  - ✓ Flavor (impact on the CKM fit)
  - ✓ ATLAS and CMS direct searches of heavy particles decaying into gluons and quarks
  - ✓ Theory constraints: Unitarity, Perturbativity

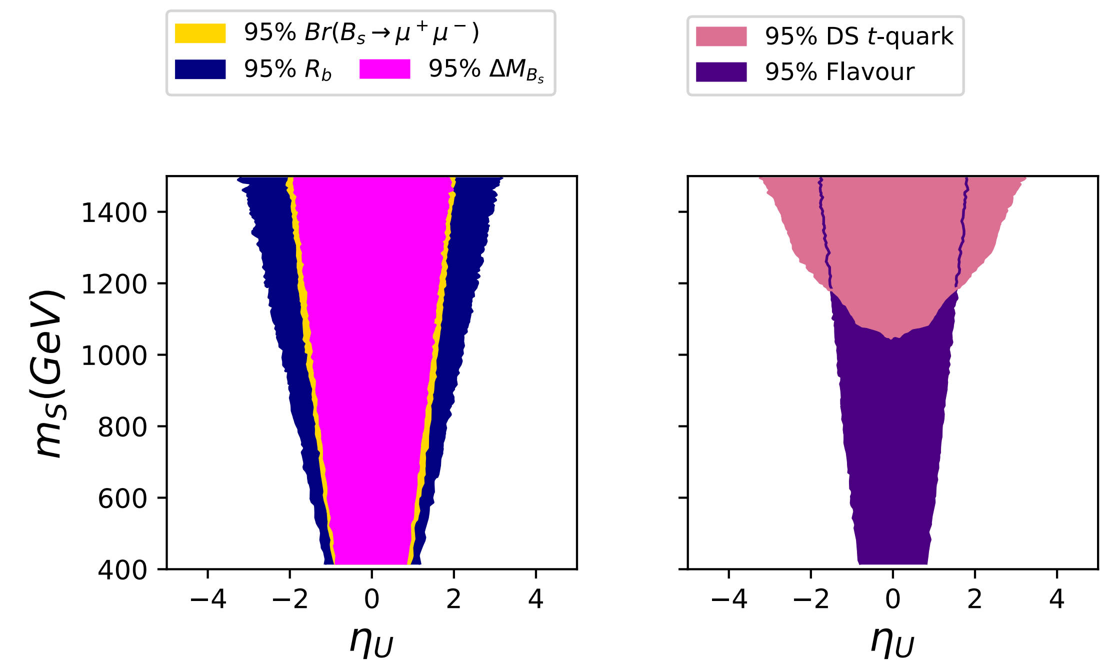
O. Eberhardt, V. Miralles, A. Pich, *JHEP* 10 (2021) 123

The Global SM EW fit

- **BSM:** Direct+Indirect constraints on color-octet scalars: $S \sim (8,2)_{1/2}$



Quartic couplings of the scalar potential



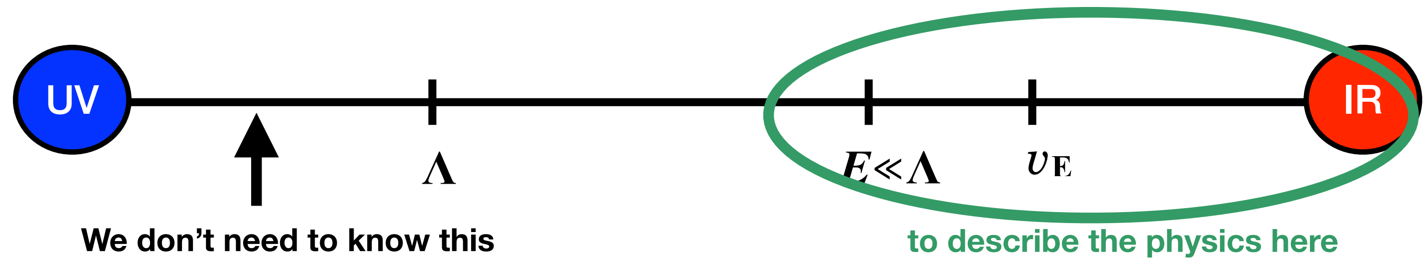
Yukawa interactions

O. Eberhardt, V. Miralles, A. Pich, *JHEP* 10 (2021) 123

The dimension-6 SMEFT
in HEPfit

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT



$$\mathcal{L}_{\mathrm{UV}}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\mathrm{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Implementation in HEPfit via model class NPSMEFTd6 (separate results for LHC Top physics in NPSMEFT6dtopquark)

Inheritance diagram

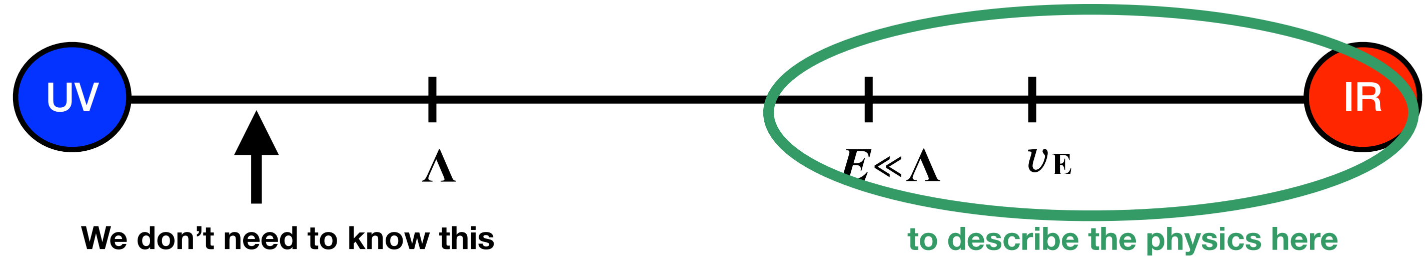
Model ← **QCD** ← **StandardModel** ← **NPBase** ← **NPSMEFTd6**

Template class for all models

Auxiliary base class for all new physics models

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT



$$\mathcal{L}_{\rm UV}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

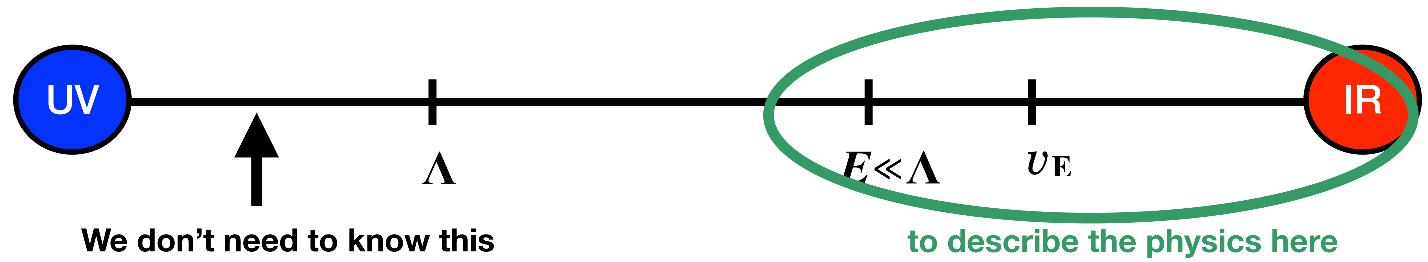
- Implementation of model for *the Warsaw basis* with flavor universality almost completed

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

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

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT



$$\mathcal{L}_{\rm UV}(?) \xrightarrow[E \ll \Lambda]{} \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

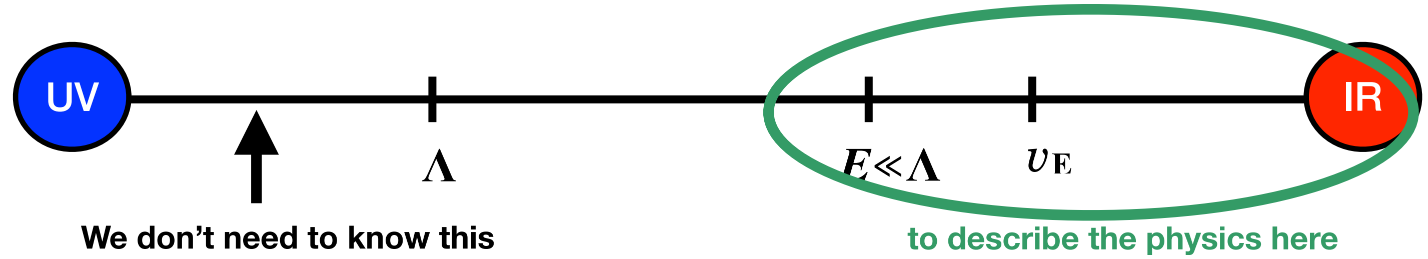
$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Implementation of model for *the Warsaw basis* with flavor universality almost completed

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 $\mathcal{O}_{DB} = \frac{i}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$. (Implemented via EOM.)
CDW	C_{DW}	The coefficient of the operator $\mathcal{O}_{DW} = \frac{i}{2}(H^\dagger \overleftrightarrow{D}^{a\mu} H) D^\nu W_{\mu\nu}^a$. (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 $\mathcal{O}_{HD} = \left\vert H^\dagger D_\mu H \right\vert^2$.
CT	C_T	The coefficient of the operator $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$.
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 $(\mathcal{O}_{HL}^{(1)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{L^i}\gamma^\mu L^i)$ (flavor universal).
CHL3	$(C_{HL}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HL}^{(3)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu^a H)(\overline{L^i}\gamma^\mu \sigma^a L^i)$ (flavor universal).
CHe	$(C_{He})_{ii}$	The coefficient of the operator $(\mathcal{O}_{He})_{ij} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{E^i}\gamma^\mu E^i)$ (flavor universal).
CHQ1	$(C_{HQ}^{(1)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(1)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{Q^i}\gamma^\mu Q^i)$ (flavor universal).
CHQ3	$(C_{HQ}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(3)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu^a H)(\overline{Q^i}\gamma^\mu \sigma^a Q^i)$ (flavor universal).
CHu	$(C_{Hu})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hu})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{U^i}\gamma^\mu U^i)$ (flavor universal).
CHd	$(C_{Hd})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hd})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{D^i}\gamma^\mu D^i)$ (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 dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT



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$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Implementation of model for *the Warsaw basis* with flavor universality almost completed (+ other redundant, in case you prefer other operator basis)

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 $\mathcal{O}_{DB} = \frac{i}{2}(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$. (Implemented via EOM.)
CDW	C_{DW}	The coefficient of the operator $\mathcal{O}_{DW} = \frac{i}{2}(H^\dagger \overleftrightarrow{D}^{a\mu} H) D^\nu W_{\mu\nu}^a$. (Implemented via EOM.)
CWB	C_{HWB}	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 $\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$.
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 $(\mathcal{O}_{HL}^{(1)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{L^i}\gamma^\mu L^i)$ (flavor universal).
CHL3	$(C_{HL}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HL}^{(3)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu^a H)(\overline{L^i}\gamma^\mu \sigma^a L^i)$ (flavor universal).
CHe	$(C_{He})_{ii}$	The coefficient of the operator $(\mathcal{O}_{He})_{ij} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{E^i}\gamma^\mu E^i)$ (flavor universal).
CHQ1	$(C_{HQ}^{(1)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(1)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{Q^i}\gamma^\mu Q^i)$ (flavor universal).
CHQ3	$(C_{HQ}^{(3)})_{ii}$	The coefficient of the operator $(\mathcal{O}_{HQ}^{(3)})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu^a H)(\overline{Q^i}\gamma^\mu \sigma^a Q^i)$ (flavor universal).

CHu	$(C_{Hu})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hu})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{U^i}\gamma^\mu U^i)$ (flavor universal).
CHd	$(C_{Hd})_{ii}$	The coefficient of the operator $(\mathcal{O}_{Hd})_{ii} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{D^i}\gamma^\mu D^i)$ (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 $(\mathcal{O}_{QE})_{ijkl} = (\overline{Q^i}\gamma^\mu Q^j)(\overline{E^k}\gamma_\mu E^l)$.

Observables implemented in the dim-6 SMEFT

- Electroweak precision observables (LEP/SLD and LHC):

Z-pole obs. (SLD/LEP)

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

W obs. (LEP2, Tevatron, LHC)

$$M_W,\ \Gamma_W$$

Hadron colliders

$$m_t \qquad M_H$$

✓ Computed to the highest accuracy in the SM. Compared against ZFITTER and updated with latest developments.

✓ Computed analytically at LO in the dimension-6 SMEFT

✓ NLO: S. Dawson, P.P. Giardino, PRD 101 (2020) 1, 013001, PRD 105 (2022) 7, 073006
PRD 97 (2018) 9, 093003 & PRD 98 (2018) 9, 09005

- Diboson production at LEP2 $e^+e^-\to W^-W^+$:

✓ Implemented following L. Berthier, M. Bjorn, M. Trott ., JHEP 09 (2016) 157

Observables implemented in the dim-6 SMEFT

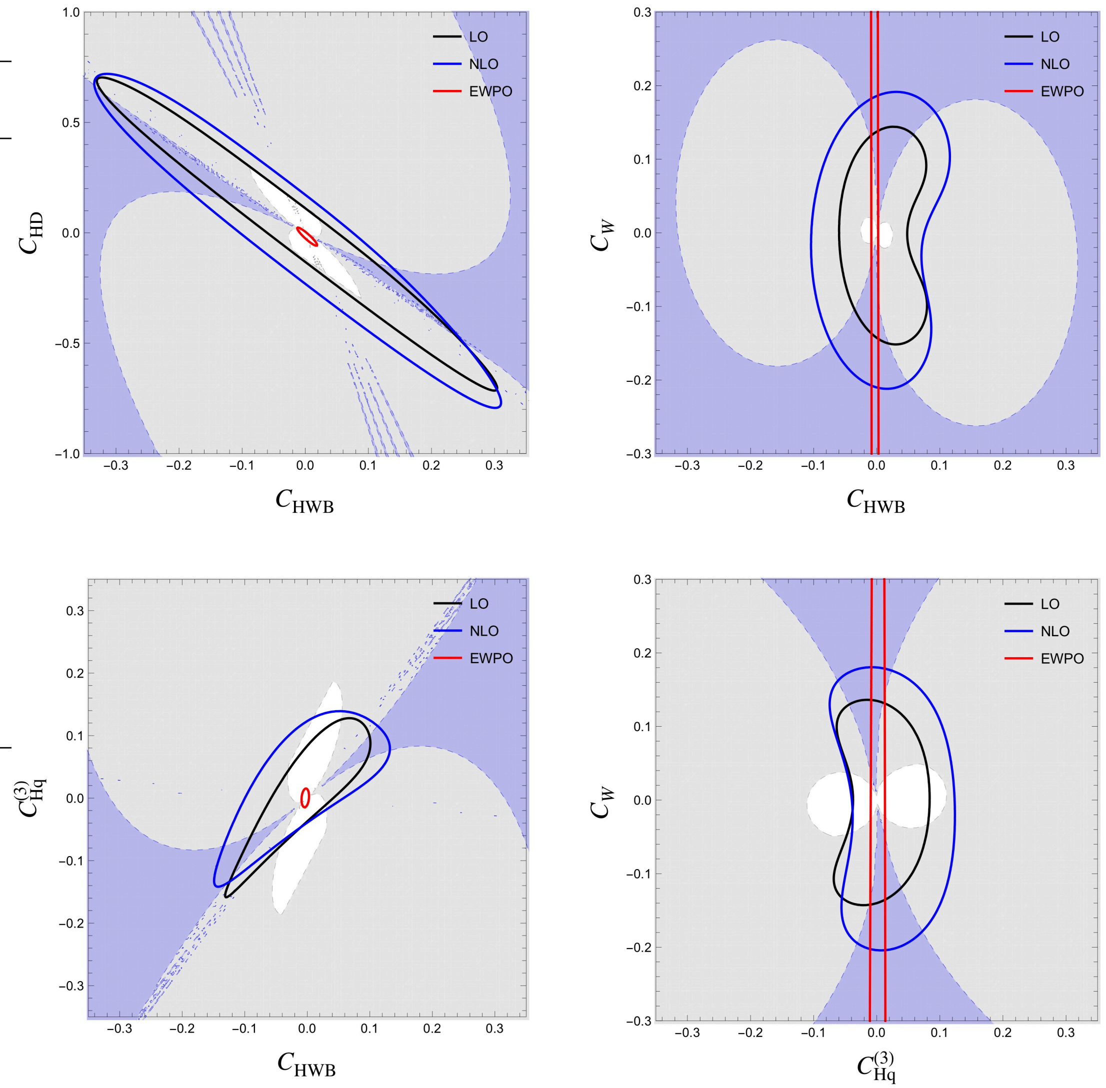
- **LHC observables**
  - Included from available studies in the literature
    - Diboson production at the LHC: ***pp→WW, WZ*** (and ***WH, ZH***)

J. Baglio, S. Dawson, I. Lewis, PRD 99 (2019) 3, 035029

J. Baglio, S. Dawson, S. Homiller, PRD 100 (2019) 11, 113010

J. Baglio et al. , PRD 101 (2020) 11, 115004

Channel	Distribution	# bins	Data set	Int. Lum.
$W^{\pm}H \to b\bar{b}\ell^{\pm} + \not{E}_T$	p_T^W, Fig. 3	2	ATLAS 8 TeV	79.8 fb^{-1}
$ZH \to b\bar{b}\ell^+\ell^-$ or $b\bar{b} + \not{E}_T$	p_T^Z, Fig. 3	3	ATLAS 8 TeV	79.8 fb^{-1}
$W^+W^- \to \ell^+\ell'^- + \not{E}_T$ $(0j)$	$p_T^{\text{leading,lepton}}$, Fig. 11	1	ATLAS 8 TeV	20.3 fb^{-1}
$W^+W^- \to e^{\pm}\mu^{\mp} + \not{E}_T$ $(0j)$	$p_T^{\text{leading,lepton}}$, Fig. 7	5	ATLAS 13 TeV	36.1 fb^{-1}
$W^{\pm}Z \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}, Fig. 5	2	ATLAS 8 TeV	20.3 fb^{-1}
$W^{\pm}Z \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$, Fig. 5	9	CMS 8 TeV	19.6 fb^{-1}
$W^{\pm}Z \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ} Fig. 4c	6	ATLAS 13 TeV	36.1 fb^{-1}
$W^{\pm}Z \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	m^{WZ}, Fig. 15a	3	CMS 13 TeV,	35.9 fb^{-1}



Observables implemented in the dim-6 SMEFT

- **LHC observables**
  - Included from available studies in the literature
  - or computed in-house via `Madgraph5_aMC@NLO` simulations using our own (partial) implementation of the dimension-6 SMEFT
    - Validated against `SMEFTsim` (← To be adopted in Future calculations) **I. Brivio, Y. Jiang, M. Trott, JHEP 12 (2017) 070**
      I. Brivio, JHEP 04 (2021) 073
    - `SMEFT@NLO` used for some observables
      C. Degrande et al., PRD 103 (2021) 9, 096024
    - SMEFT dependence parametrized fitting the coefficients of a semi-analytical approximation:

$$\sigma = \sigma_{\rm SM} + \sum_i a_i \frac{C_i}{\Lambda^2} + \sum_{i\leq j} b_{ij} \frac{C_i C_j}{\Lambda^4} + \ldots$$

Generate events (→ σ)

Fit to obtain these (→ a_i, b_{ij})

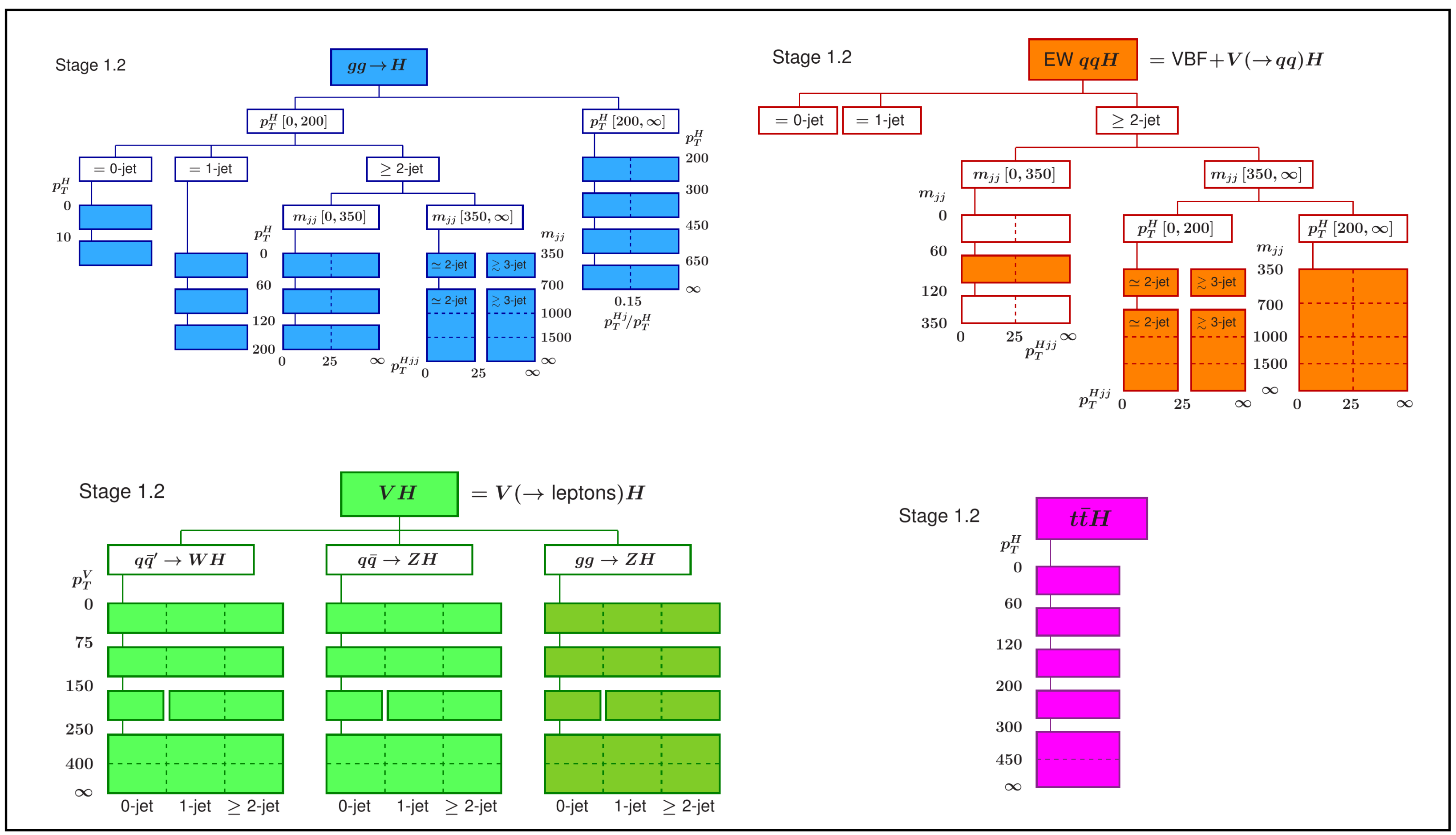
Jorge de Blas
University of Granada

Observables implemented in the dim-6 SMEFT

- Higgs observables at the LHC:
  - ✓ Full SMEFT dependence in Higgs decays:
    - $H \to ff;\ H \to gg,\ \gamma\gamma,\ Z\gamma;\ \ H \to VV^* \to 4f$

Validated against
I. Brivio, T. Corbett, M. Trott ., *JHEP* 10 (2019) 056

  - ✓ Inclusive signal strengths at Tevatron and LHC (7, 8 13, 14 TeV)
  - ✓ Simplified Template Cross Section (STXS) Bins:



STXS vs. Signal strengths

Less model-dependence

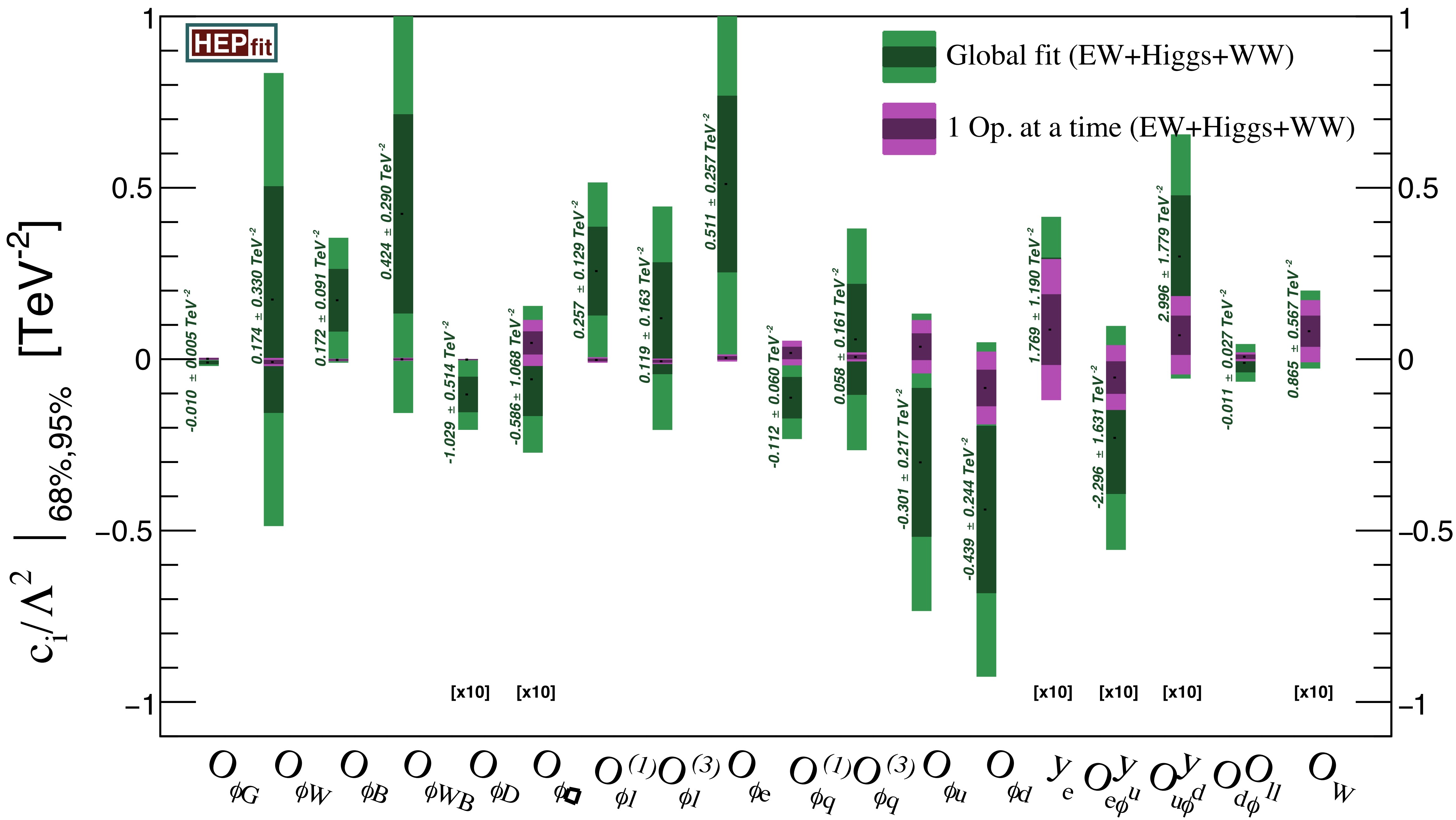
But still relies on SM for extrapolations

Not fully differential but more kinematical info

Measurements in exclusive regions of phase space (STXS bins)

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT: EW/Higgs Run 1+Run2 fit



New Physics assumptions: CP-even, U(3)[5]. Fit in the Warsaw basis.

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT: EW/Higgs Run 1+Run2 fit

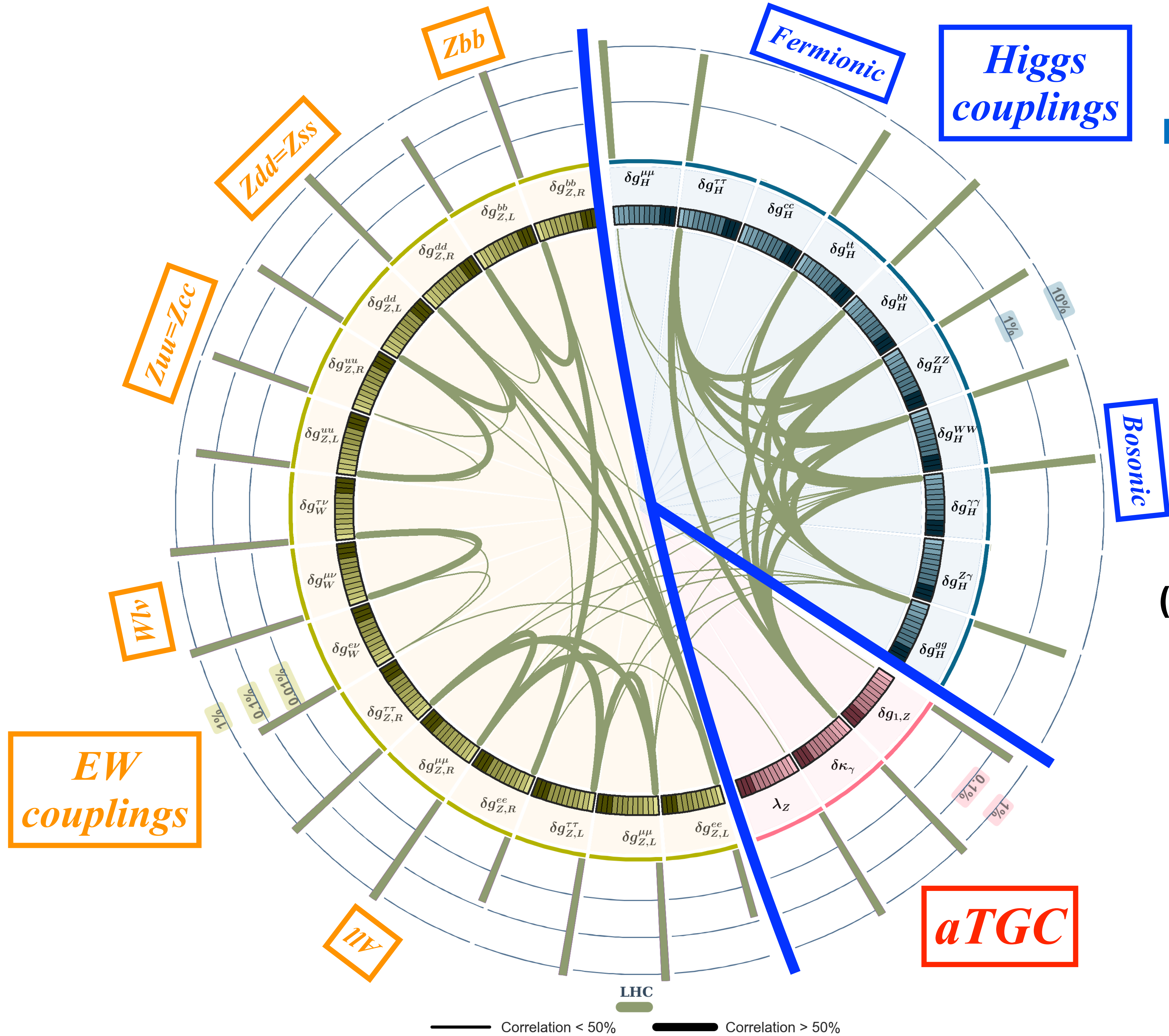
SMEFT EW/Higgs fit $U(3)^5$

	O_W	$O_{\phi G}$	$O_{\phi W}$	$O_{\phi B}$	$O_{\phi WB}$	$O_{\phi D}$	$O_{\phi \Box}$	$O_{\phi l}^{(1)}$	$O_{\phi l}^{(3)}$	$O_{\phi e}$	$O_{\phi q}^{(1)}$	$O_{\phi q}^{(3)}$	$O_{\phi u}$	$O_{\phi d}$	$y_e O_{e\phi}$	$y_u O_{u\phi}$	$y_d O_{d\phi}$	O_{ll}
O_W	100	6	53	34	52	−41	−18	41	−57	41	−31	−56	−35	17	7	−9	−13	0
$O_{\phi G}$	6	100	−2	1	−1	6	18	−6	−15	−6	4	−15	4	−2	−16	71	−46	0
$O_{\phi W}$	53	−2	100	41	83	−72	−56	72	−75	72	−51	−76	−56	25	12	−28	6	0
$O_{\phi B}$	34	1	41	100	84	−89	−23	89	−28	89	−63	−29	−70	31	12	−9	7	0
$O_{\phi WB}$	52	−1	83	84	100	−96	−47	96	−61	96	−68	−62	−75	33	14	−23	7	0
$O_{\phi D}$	−41	6	−72	−89	−96	100	51	−99.6	38	−99.9	69	40	76	−32	−14	25	−20	1
$O_{\phi \Box}$	−18	18	−56	−23	−47	51	100	−51	13	−51	37	13	40	−19	6	54	−47	0
$O_{\phi l}^{(1)}$	41	−6	72	89	96	−99.6	−51	100	−38	99.7	−69	−39	−75	31	14	−25	20	−8
$O_{\phi l}^{(3)}$	−57	−15	−75	−28	−61	38	13	−38	100	−38	31	97	35	−20	−7	6	36	8
$O_{\phi e}$	41	−6	72	89	96	−99.9	−51	99.7	−38	100	−70	−40	−76	31	14	−25	20	−1
$O_{\phi q}^{(1)}$	−31	4	−51	−63	−68	69	37	−69	31	−70	100	26	81	9	−9	18	−14	−4
$O_{\phi q}^{(3)}$	−56	−15	−76	−29	−62	40	13	−39	97	−40	26	100	26	−9	−8	5	35	0
$O_{\phi u}$	−35	4	−56	−70	−75	76	40	−75	35	−76	81	26	100	−20	−10	19	−15	−5
$O_{\phi d}$	17	−2	25	31	33	−32	−19	31	−20	31	9	−9	−20	100	4	−9	6	1
$y_e O_{e\phi}$	7	−16	12	12	14	−14	6	14	−7	14	−9	−8	−10	4	100	9	29	−1
$y_u O_{u\phi}$	−9	71	−28	−9	−23	25	54	−25	6	−25	18	5	19	−9	9	100	−13	0
$y_d O_{d\phi}$	−13	−46	6	7	7	−20	−47	20	36	20	−14	35	−15	6	29	−13	100	−1
O_{ll}	0	0	0	0	0	1	0	−8	8	−1	−4	0	−5	1	−1	0	−1	100

New Physics assumptions: CP-even, $U(3)^5$. Fit in the Warsaw basis.

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT: EW/Higgs Run 1+Run2 fit



You can present correlations between parameters, observables, observables and parameters

New Physics assumptions: CP-even, NO U(3)[5]

Fit in the Warsaw basis
⇩
Projected into deformations of effective SM-like couplings (defined from pseudo-observables)

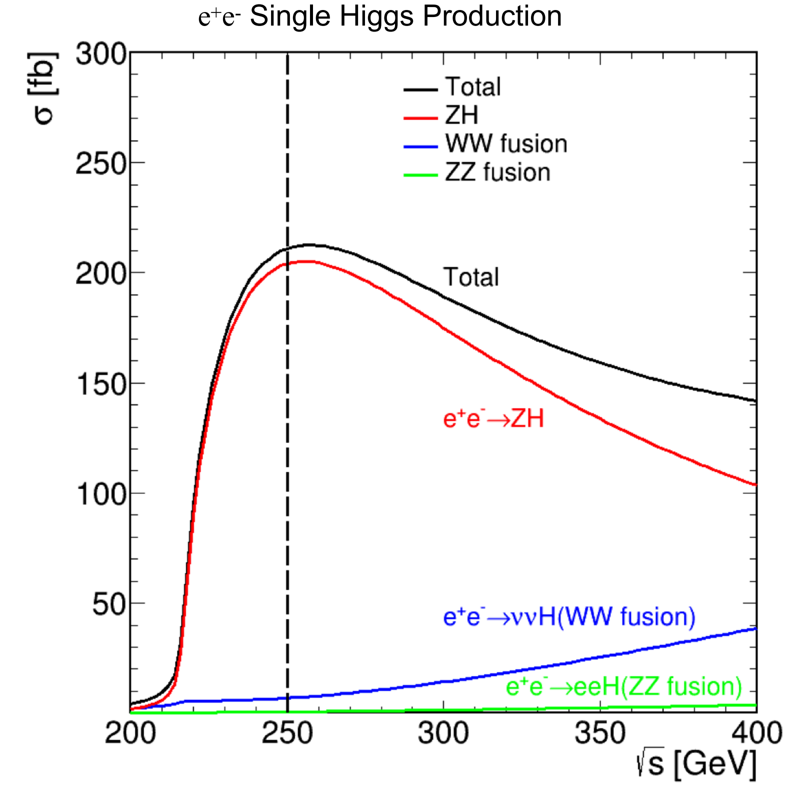
E.g. $g_{HX}^{\mathrm{eff}\;2} \equiv \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{\mathrm{SM}}}.$

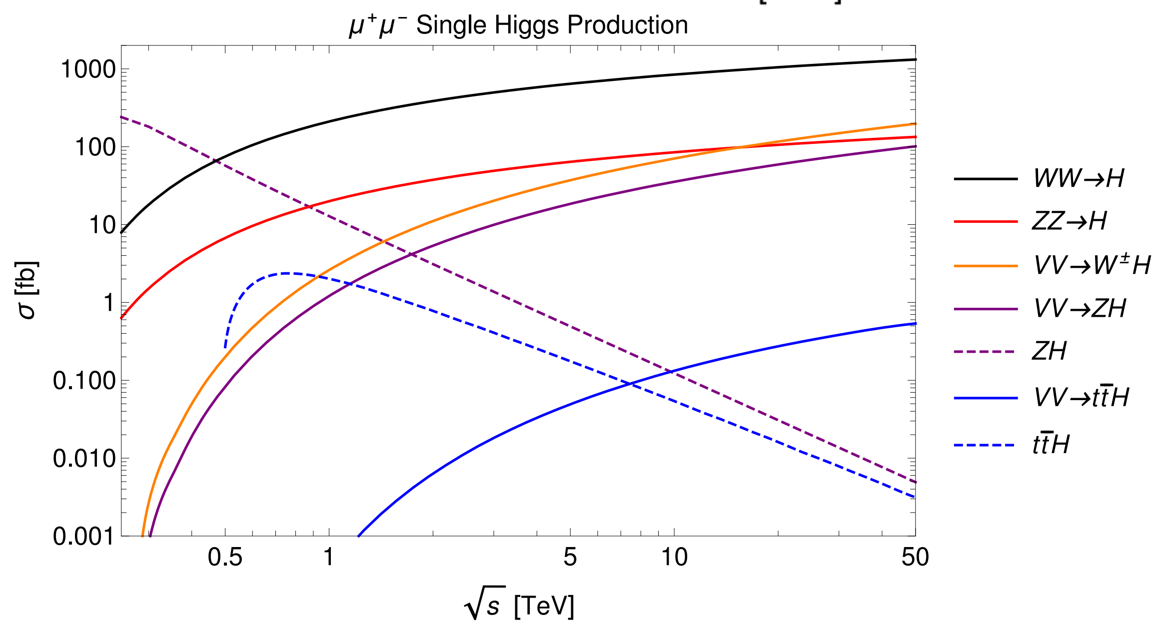
HEPfit output contains all the relevant information
You decide how to present it

Observables implemented in the dim-6 SMEFT

- Higgs observables at future e^+e^- and $\mu^+\mu^-$ colliders:

Machine	Pol. (e^-, e^+)	Energy	Luminosity
HL-LHC	Unpolarised	14 TeV	3 ab^{-1}
ILC	(∓80%, ±30%)	250 GeV	2 ab^{-1}
		350 GeV	0.2 ab^{-1}
		500 GeV	4 ab^{-1}
	(∓80%, ±20%)	1 TeV	8 ab^{-1}
CLIC	(±80%, 0%)	380 GeV	1 ab^{-1}
		1.5 TeV	2.5 ab^{-1}
		3 TeV	5 ab^{-1}
FCC-*ee*	Unpolarised	Z-pole	150 ab^{-1}
		$2m_W$	10 ab^{-1}
		240 GeV	5 ab^{-1}
		350 GeV	0.2 ab^{-1}
		365 GeV	1.5 ab^{-1}
CEPC	Unpolarised	Z-pole	100 ab^{-1}
		$2m_W$	6 ab^{-1}
		240 GeV	20 ab^{-1}
		350 GeV	0.2 ab^{-1}
		360 GeV	1 ab^{-1}
MuC	Unpolarised	125 GeV	0.02 ab^{-1}
		3 TeV	3 ab^{-1}
		10 TeV	10 ab^{-1}

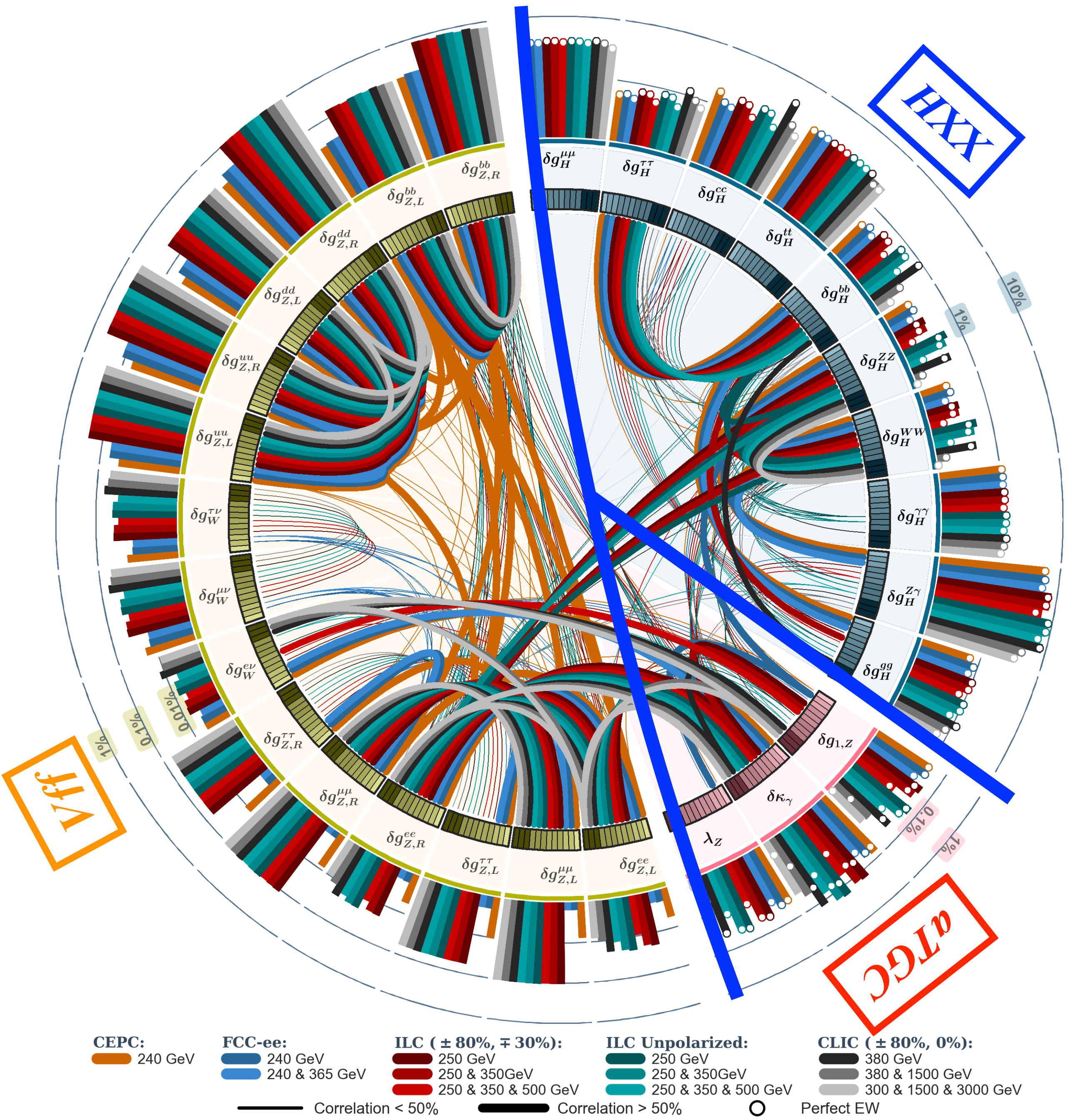


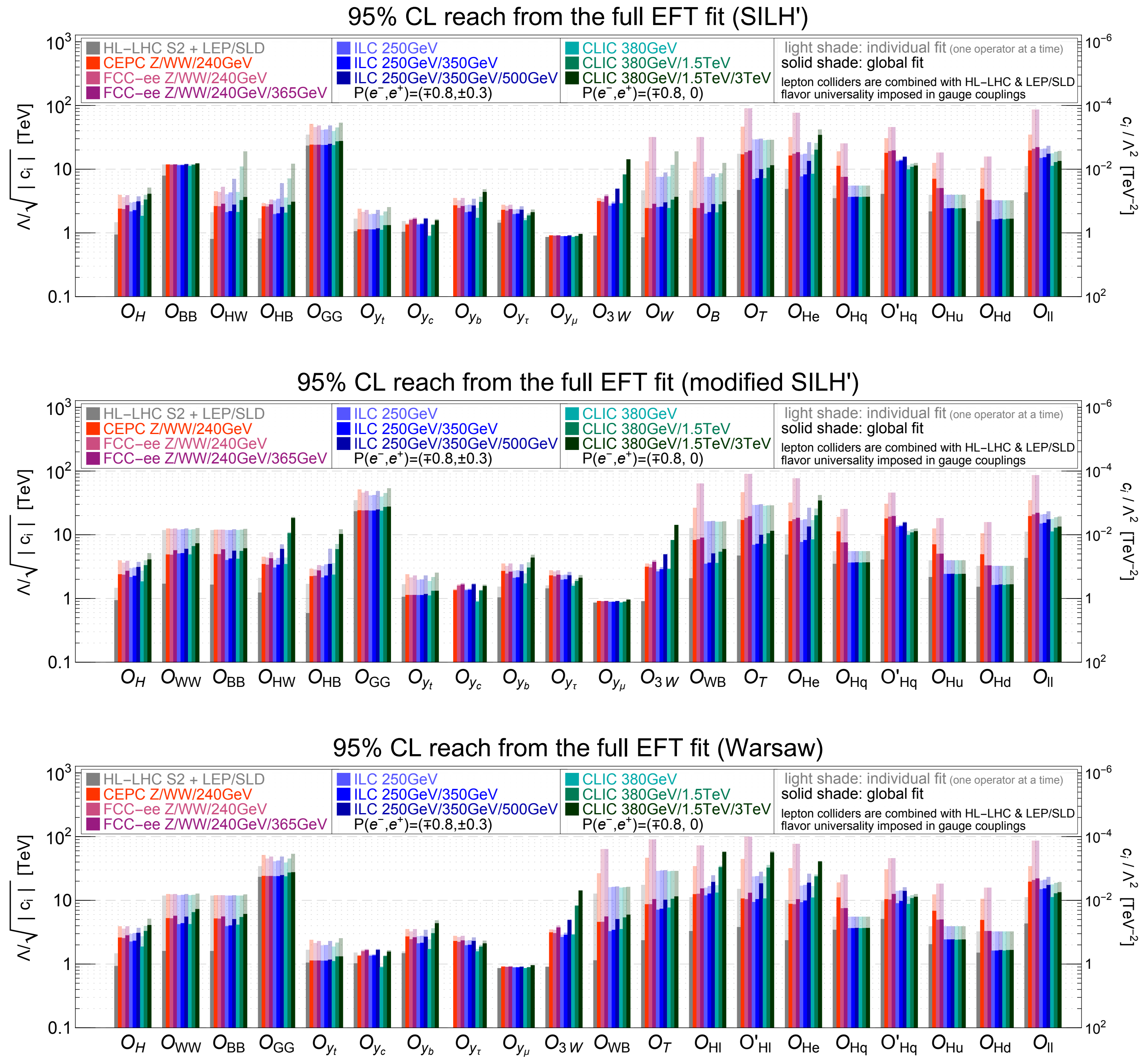


SMEFT calculations available for *ZH, WBF, ZBF, ttH* with and without polarized beams

Observables implemented in the dim-6 SMEFT

- Higgs observables at future e^+e^- and $\mu^+\mu^-$ colliders:





[SMEFT projections at future colliders]

JB, G. Durieux, C. Grojean, J. Gu, A. Paul, JHEP 12 (2019) 117

Observables implemented in the dim-6 SMEFT

- Top observables at the LHC and future colliders

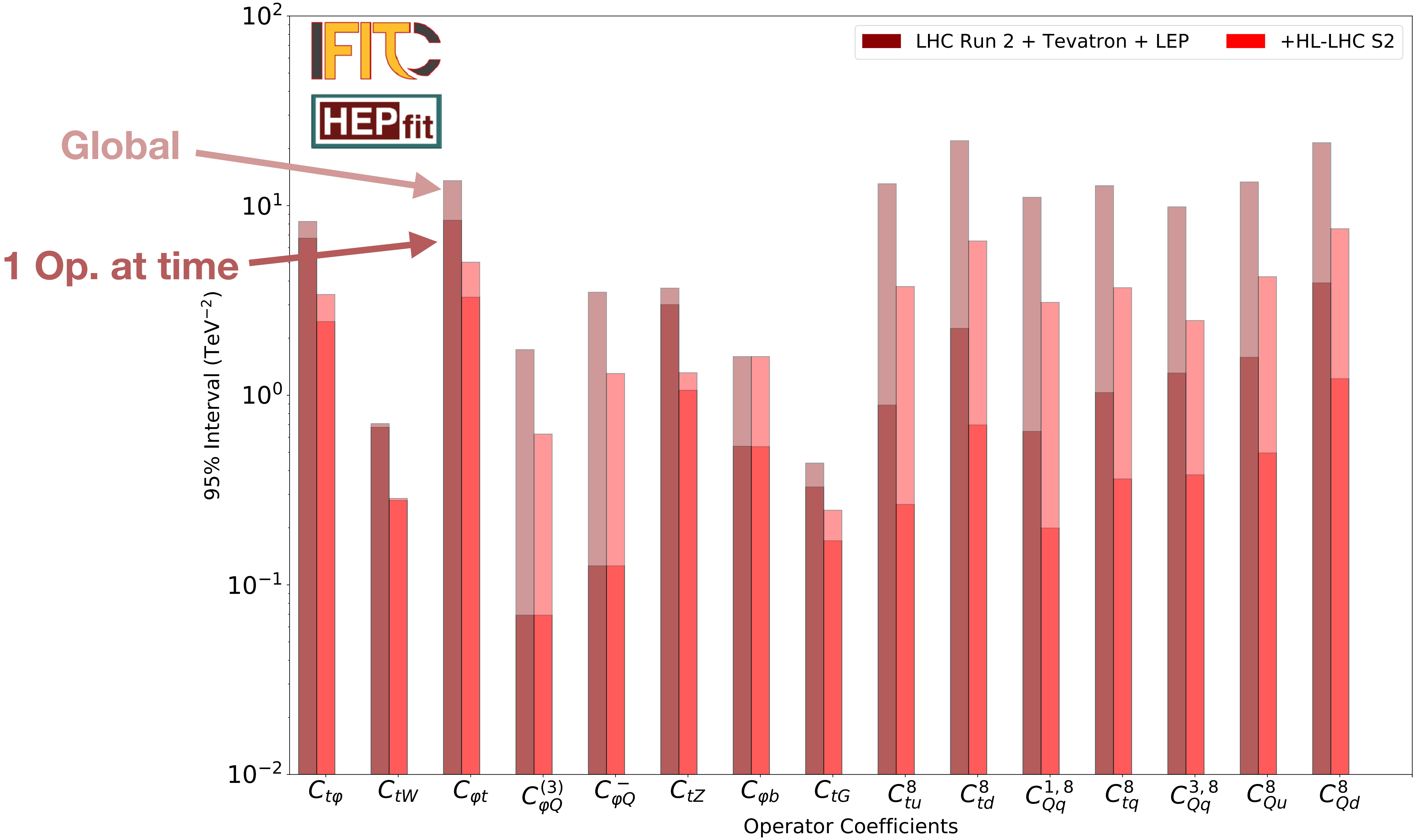
Process	Observable	$\sqrt{s}$	$\int \mathcal{L}$	Experiment
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC
$t \to Wb$	$F_0,\ F_L$	8 TeV	20 fb^{-1}	LHC
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron

SMEFT Top calculations at NLO via **SMEFT@NLO**

Implementated by V. Miralles in **NPSMEFT6dtopquark class**

Observables implemented in the dim-6 SMEFT

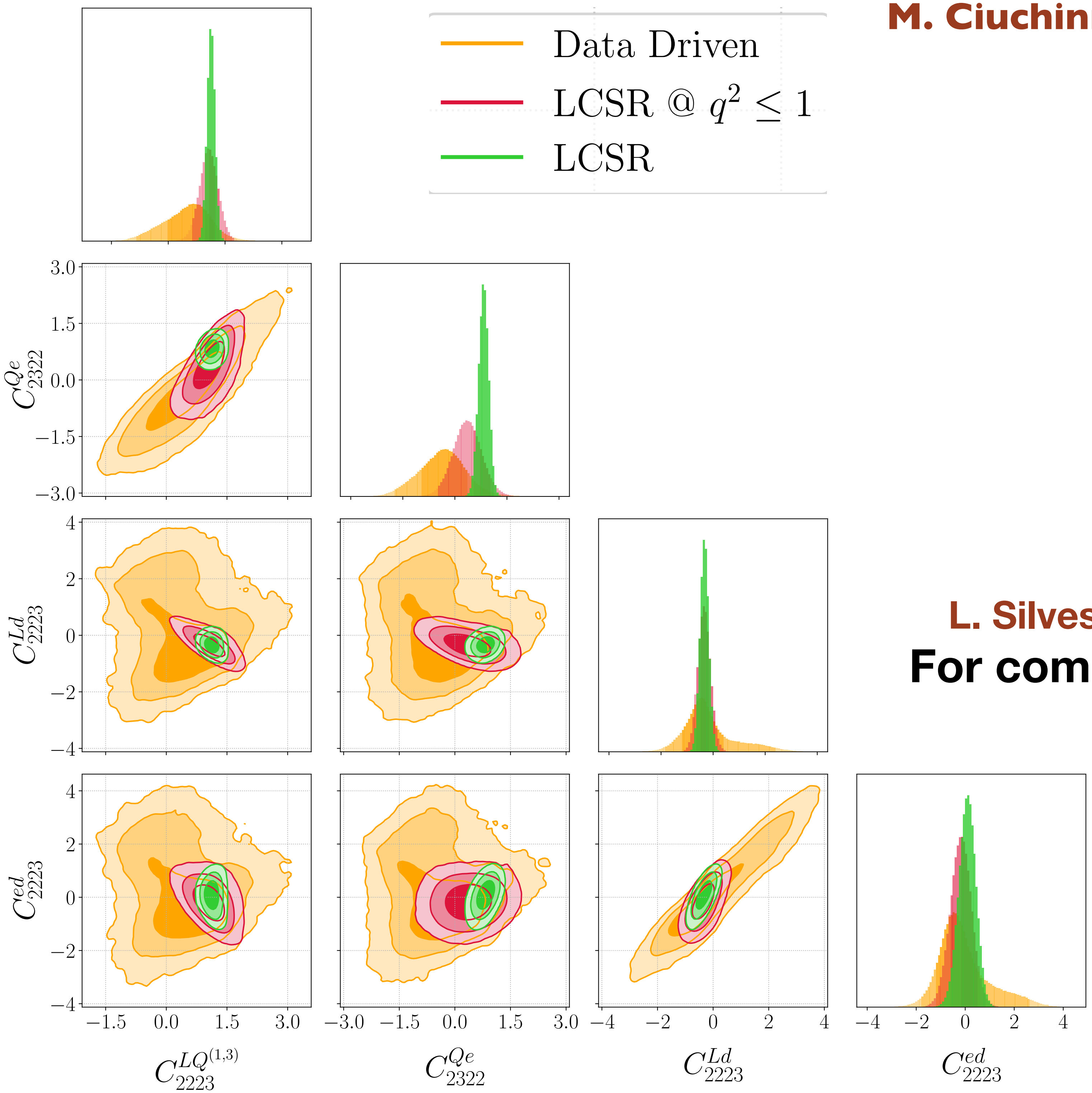
- Top observables at the LHC and future colliders



G. Durieux et al., arXiv: 2205.02140 [hep-ph]
JB et al., arXiv: 2206.08326 [hep-ph]

Observables implemented in the dim-6 SMEFT

- Flavor observables: B-anomaly fit



M. Ciuchini et al. , arXiv: 2110.10126 [hep-ph]

$$O^{LQ(1)}_{2223} = (\bar{L}_2\gamma_\mu L_2)(\bar{Q}_2\gamma^\mu Q_3)\,,$$
$$O^{LQ(3)}_{2223} = (\bar{L}_2\gamma_\mu\tau^A L_2)(\bar{Q}_2\gamma^\mu\tau^A Q_3)\,,$$
$$O^{Qe}_{2322} = (\bar{Q}_2\gamma_\mu Q_3)(\bar{e}_2\gamma^\mu e_2)\,,$$
$$O^{Ld}_{2223} = (\bar{L}_2\gamma_\mu L_2)(\bar{d}_2\gamma^\mu d_3)\,,$$
$$O^{ed}_{2223} = (\bar{e}_2\gamma_\mu e_2)(\bar{d}_2\gamma^\mu d_3)\,,$$

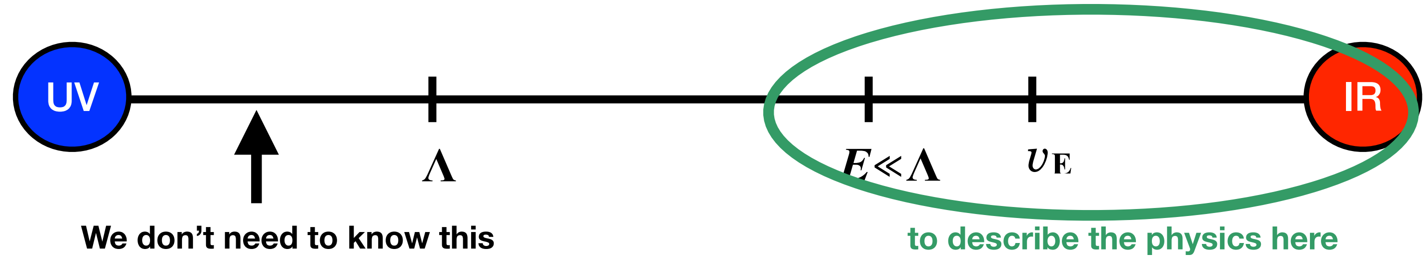
See also

L. Silvestrini, M. Valli, PLB 799 (2019) 135062

For combined analyses of Flavor+EWPO

The dimension-6 SMEFT in HEPfit

- The dimension-6 SMEFT



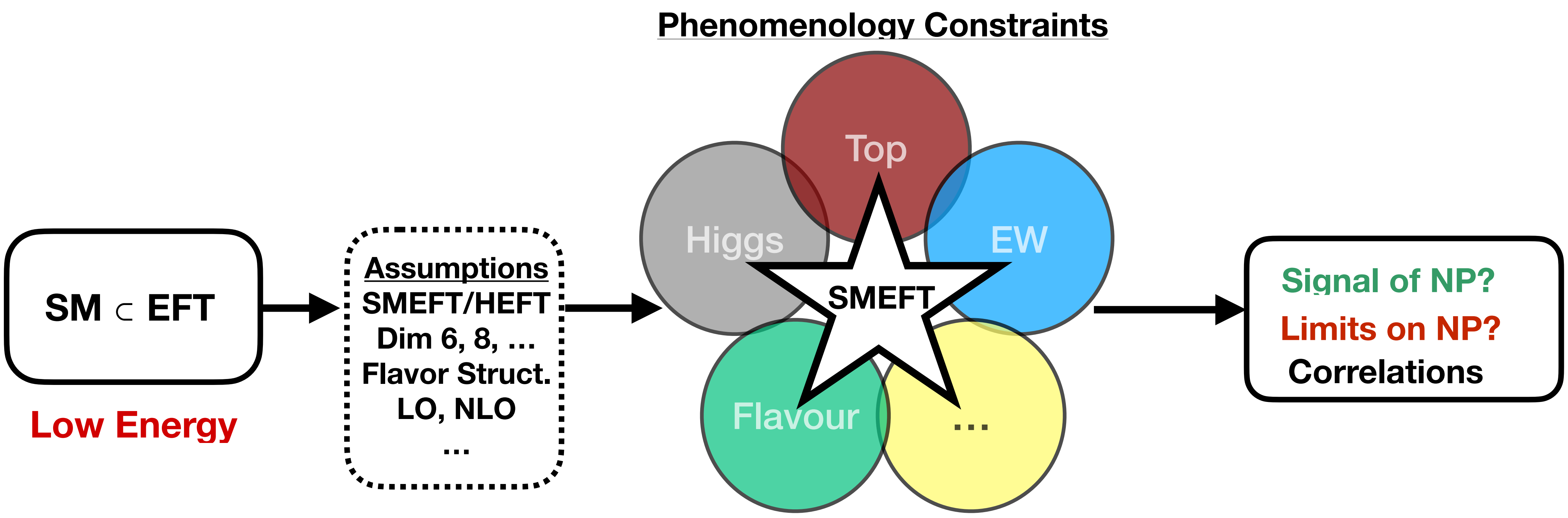
$$\mathcal{L}_{\rm UV}(?) \underset{E \ll \Lambda}{\longrightarrow} \quad \mathcal{L}_{\rm Eff} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_d = \sum_i C_i^d \mathcal{O}_i \qquad [\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$$

- Work in progress:
  - Implementation of (most) general flavor structure
    - ✓ So far: some non-universality for EW, Higgs & B anomalies
  - Implementation of full SMEFT RG running (Weak Effective Theory (WET) 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
  - Matching with UV?

Effective Field Theories: Matching in the SMEFT

- The question now is: What can we learn from new physics from these EFT fits?



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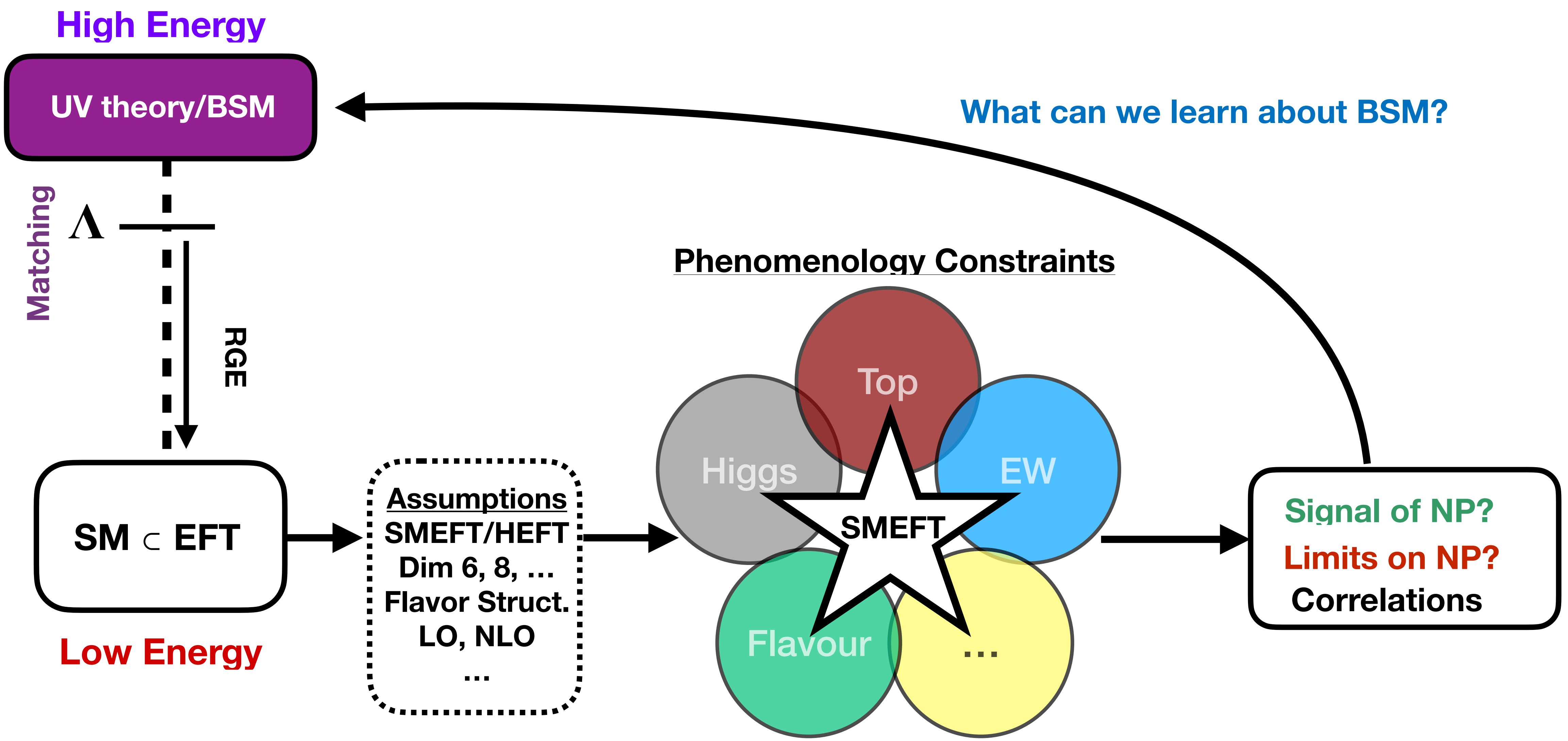

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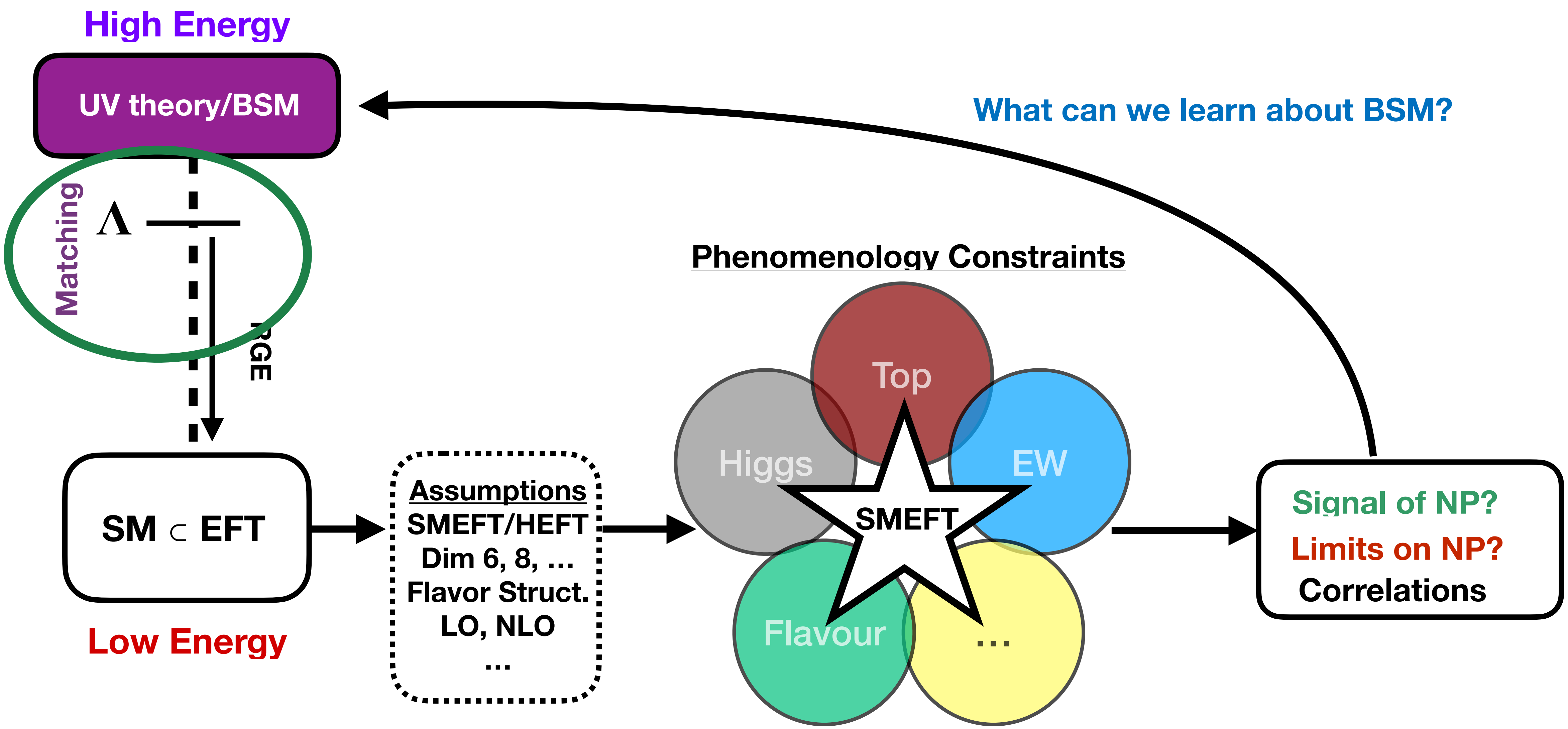

- Projecting (SM)EFT results to specific scenarios requires matching between the NP model and the EFT

Matching: Wilson coefficients as function of BSM model couplings and masses

Limits on EFT Wilson coefficients → Limits on BSM

Effective Field Theories: Matching in the SMEFT

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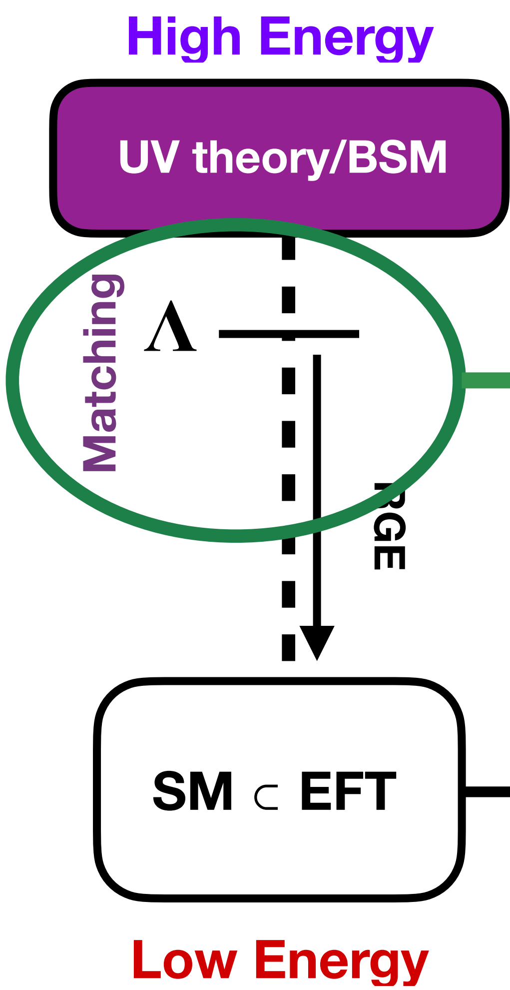


UV - IR (SMEFT) Matching

The full UV/IR tree-level dictionary:

48 multiplets contribute to dim 6

J. B., J.C. Criado, M. Pérez- Victoria, J. Santiago, JHEP 1803 (2018) 109

$\mathcal{L}^{d=6}_{Eff}$

~30 pages

Tree-level matching automated in

MatchingTools: **J.C. Criado, arXiv: 1710.06445 [hep-ph]**

Tools available or in development for 1-loop matching

Automated 1-loop matching

MatchMakereft — **A. Carmona et al. , arXiv: 2112.10787 [hep-ph]**

MATCHETE — **Fuentes-Martin et al. , WiP**

CoDEx — **S.D. Bakshi et al. , arXiv: 1808.04403 [hep-ph] + WiP**

Calculation of functional supertraces with CDE

STrEAM — **T. Cohen et al. , arXiv: 2012.07851 [hep-ph]**

SUPER TRACER — **Fuentes-Martin et al. , arXiv: 2012.08506 [hep-ph]**

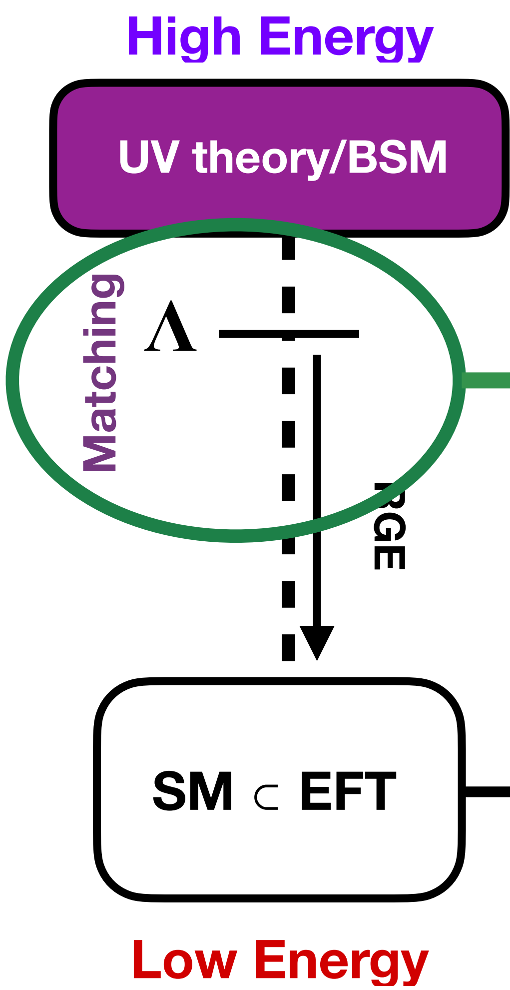
- Projecting (SM)E
NP model and th

Matchin

Limits on EFT Wilson coefficients → Limits on BSM

Effective Field Theories: Matching in the SMEFT

- The question now is: What can we learn from new physics from these EFT fits?



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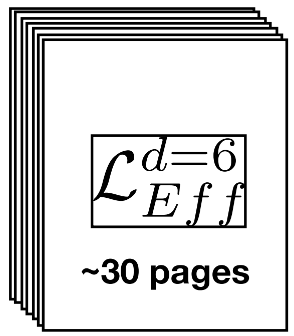

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Tools available or in development for 1-loop matching

Automated 1-loop matching

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MATCHETE Fuentes-Martin et al. , WiP

Building interface with **MatchMakereft** output via class inheriting from current SMEFT class

Model ← **QCD** ← **StandardModel** ← **NPBase** ← **NPSMEFTd6** ← **NPd6MatchEFT**

→ It will allow direct use of SMEFT likelihood for whichever (weakly coupled) heavy new physics model you can think of

Making it work…
Installation

Dependencies - Mandatory

- ROOT (https://root.cern.ch)
  - ✓ Plotting. Stores all histograms generated at run time (*.pdf & *.root)
  - ✓ Compatible with ROOT v5 and v6
- BOOST C++ Libraries (http://www.boost.org)
  - ✓ Used for efficient and safe memory handling
- GSL (https://www.gnu.org/software/gsl/):
  - ✓ GNU Scientific Libraries are used for efficient matrix operations and integrals
- NetBeans IDE (https://netbeans.org)
  - ✓ Only required to work with developer's version (available through GitHub)

The HEPfit code

Dependencies - Optional

- BAT (https://www.mppmu.mpg.de/bat/)
  - ✓ Bayesian Analysis Tool based Markov Chain Monte Carlo routines
  - ✓ Required if using our MCMC engine
- OpenMPI (https://www.open-mpi.org)
  - ✓ Required only for parallel runs (e.g. Cluster computing)
  - ✓ Tested for large scale @ $O(10^3)$ cores in batch submission systems

Quick Installation

- Download tarball from https://hepfit.roma1.infn.it

```
$ tar xvzf HEPfit-x.y.tar.gz
$ mkdir HEPfit-x.y/build
$ cd HEPfit-x.y/build
$ cmake .. -DLOCAL_INSTALL_ALL=ON -DMPIBAT=ON
$ make
$ make install
```

V1 to be updated soon with all the newest developments

Making it work...

Running example

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

Running HEPfit

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

# of CPU cores to use (5)

Running HEPfit

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

Model parameter priors & Observables in input/output

Model pars.

```
StandardModel
# Model parameters:
ModelParameter  mtop        173.2       0.9         0.
ModelParameter  mHl         125.6       0.3         0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter   a_0V     0.496    0.067    0.
ModelParameter   a_1V    -2.03     0.92     0.
1.00     0.86
0.86     1.00

<All the model parameters have to be listed here>

# Observables:
Observable  Mw        Mw        M_{W}      80.3290 80.4064 MCMC weight 80.385 0.015 0.
Observable  GammaW    GammaW    #Gamma_{W} 2.08569 2.09249 MCMC weight 2.085  0.042 0.
#
# Correlated observables:
CorrelatedGaussianObservables Zpole2 7
Observable  Alepton   Alepton   A_{l}       0.143568 0.151850 MCMC weight 0.1513  0.0021  0.
Observable  Rbottom   Rbottom   R_{b}       0.215602 0.215958 MCMC weight 0.21629 0.00066 0.
Observable  Rcharm    Rcharm    R_{c}       0.172143 0.172334 MCMC weight 0.1721  0.0030  0.
Observable  AFBbottom AFBbottom A_{FB}^{b} 0.100604 0.106484 MCMC weight 0.0992  0.0016  0.
Observable  AFBcharm  AFBcharm  A_{FB}^{c} 0.071750 0.076305 MCMC weight 0.0707  0.0035  0.
Observable  Abottom   Abottom   A_{b}       0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable  Acharm    Acharm    A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00    0.00    0.00    0.00    0.00    0.09    0.05
0.00    1.00   -0.18   -0.10    0.07   -0.08    0.04
0.00   -0.18    1.00    0.04   -0.06    0.04   -0.06
0.00   -0.10    0.04    1.00    0.15    0.06    0.01
0.00    0.07   -0.06    0.15    1.00   -0.02    0.04
0.09   -0.08    0.04    0.06   -0.02    1.00    0.11
0.05    0.04   -0.06    0.01    0.04    0.11    1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu     BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu  BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5     1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5     1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Observables

Running HEPfit

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

Model parameter priors & Observables in input/output

Model name

Uncorrelated parameters: Initial values, priors

Correlated parameters

Model pars.

Observables

```
StandardModel
# Model parameters
ModelParameter  mtop            173.2       0.9             0.
ModelParameter  mH1             125.6       0.3             0.
...
CorrelatedGaussianParameters   V1_lattice 2
ModelParameter  a_0V     0.496    0.067    0.
ModelParameter  a_1V    -2.03     0.92     0.
1.00      0.86
0.86      1.00

<All the model parameters have to be listed here>

# Observables:
Observable   Mw        Mw        M_{W}        80.3290 80.4064 MCMC weight 80.385 0.015 0.
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Observable   Abottom   Abottom   A_{b}        0.934320 0.935007 MCMC weight 0.923   0.020   0.
Observable   Acharm    Acharm    A_{c}        0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00   0.00   0.00   0.00   0.00   0.09   0.05
0.00   1.00  -0.18  -0.10   0.07  -0.08   0.04
0.00  -0.18   1.00   0.04  -0.06   0.04  -0.06
0.00  -0.10   0.04   1.00   0.15   0.06   0.01
0.00   0.07  -0.06   0.15   1.00  -0.02   0.04
0.09  -0.08   0.04   0.06  -0.02   1.00   0.11
0.05   0.04  -0.06   0.01   0.04   0.11   1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5      1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5      1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Running example: Input

```
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Model parameter priors & Observables in input/output

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Observable  Acharm     Acharm     A_{c}       0.666374 0.670015 MCMC weight 0.670   0.027   0.
1.00    0.00    0.00    0.00    0.00    0.09    0.05
0.00    1.00   -0.18   -0.10    0.07   -0.08    0.04
0.00   -0.18    1.00    0.04   -0.06    0.04   -0.06
0.00   -0.10    0.04    1.00    0.15    0.06    0.01
0.00    0.07   -0.06    0.15    1.00   -0.02    0.04
0.09   -0.08    0.04    0.06   -0.02    1.00    0.11
0.05    0.04   -0.06    0.01    0.04    0.11    1.00
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...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)     1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)     1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5     1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5     1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Model pars.

Uncorrelated observables

Correlated Observables

Observables

2D obs, Binned Obs, ...

Running HEPfit

Running example: Input

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Model parameter priors & Observables in input/output

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0.86     1.00

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......................................................................
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1.00    0.00    0.00    0.00    0.00    0.09    0.05
0.00    1.00   -0.18   -0.10    0.07   -0.08    0.04
0.00   -0.18    1.00    0.04   -0.06    0.04   -0.06
0.00   -0.10    0.04    1.00    0.15    0.06    0.01
0.00    0.07   -0.06    0.15    1.00   -0.02    0.04
0.09   -0.08    0.04    0.06   -0.02    1.00    0.11
0.05    0.04   -0.06    0.01    0.04    0.11    1.00
#
# Output correlations:
Observable2D  MwvsGammaW Mw M_{W} 80.3290 80.4064 noMCMC noweight GammaW #Gamma_{W} 2.08569 2.09249
...
Observable2D Bd_Bsbar_mumu noMCMC noweight
Observable    BR_Bdmumu      BR(B_{d}#rightarrow#mu#mu)    1. -1.  1.05e-10   0.   0.
Observable    BRbar_Bsmumu   BR(B_{s}#rightarrow#mu#mu)    1. -1.  3.65e-9    0.   0.
...
Observable2D S5_P5 noMCMC noweight
BinnedObservable   S_5      S_5     1. -1.  0.   0.   0.   4.   6.
BinnedObservable   P_5      P_5     1. -1.  0.   0.   0.   4.   6.
#
# Including other configuration files
IncludeFile Flavour.conf
```

Model pars.

Observables

Include additional config files

Running HEPfit

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

MCMC settings for Bayesian studies

```
NChains                     10    (Default: 5)
PrerunMaxIter               50000 (Default: 1000000)
Iterations                  10000 (Default: 100000)
#Seed                        1
PrintAllMarginalized        true  (Default: false)
PrintCorrelationMatrix      true  (Default: false)
PrintKnowledgeUpdatePlots   false (Default: false)
PrintParameterPlot          false (Default: false)
OrderParameters             true  (Default: true)
```

```
FindModeWithMinuit        (Default: false)
MinimumEfficiency         (Default: 0.15, set to 0. - 1.)
WriteChain                (Default: false)
CalculateNormalization    (Default: false)
WritePreRunData           (Mandatory: name of file)
ReadPreRunData            (Read existing prerun data file)
```

See code documentation for more options

Running HEPfit

Running example: Input

```
$ cd examples/MonteCarloMode/
$ make
$ mpiexec -n 5 ./analysis ../config/StandardModel.conf MonteCarlo.conf
```

MCMC settings for Bayesian studies

Basic MCMC settings

Output plots, …

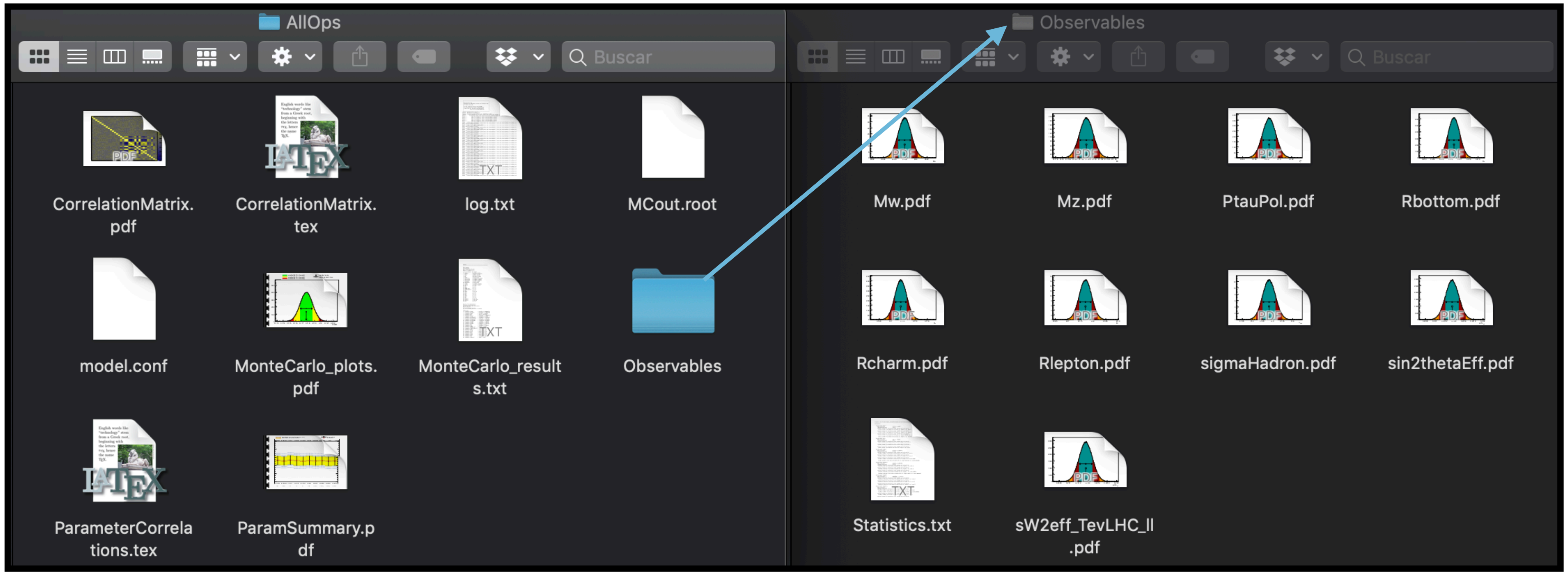
```
NChains                    10     (Default: 5)
PrerunMaxIter              50000  (Default: 1000000)
Iterations                 10000  (Default: 100000)
#Seed                      1
PrintAllMarginalized       true   (Default: false)
PrintCorrelationMatrix     true   (Default: false)
PrintKnowledgeUpdatePlots  false  (Default: false)
PrintParameterPlot         false  (Default: false)
OrderParameters            true   (Default: true)
```

Other options:

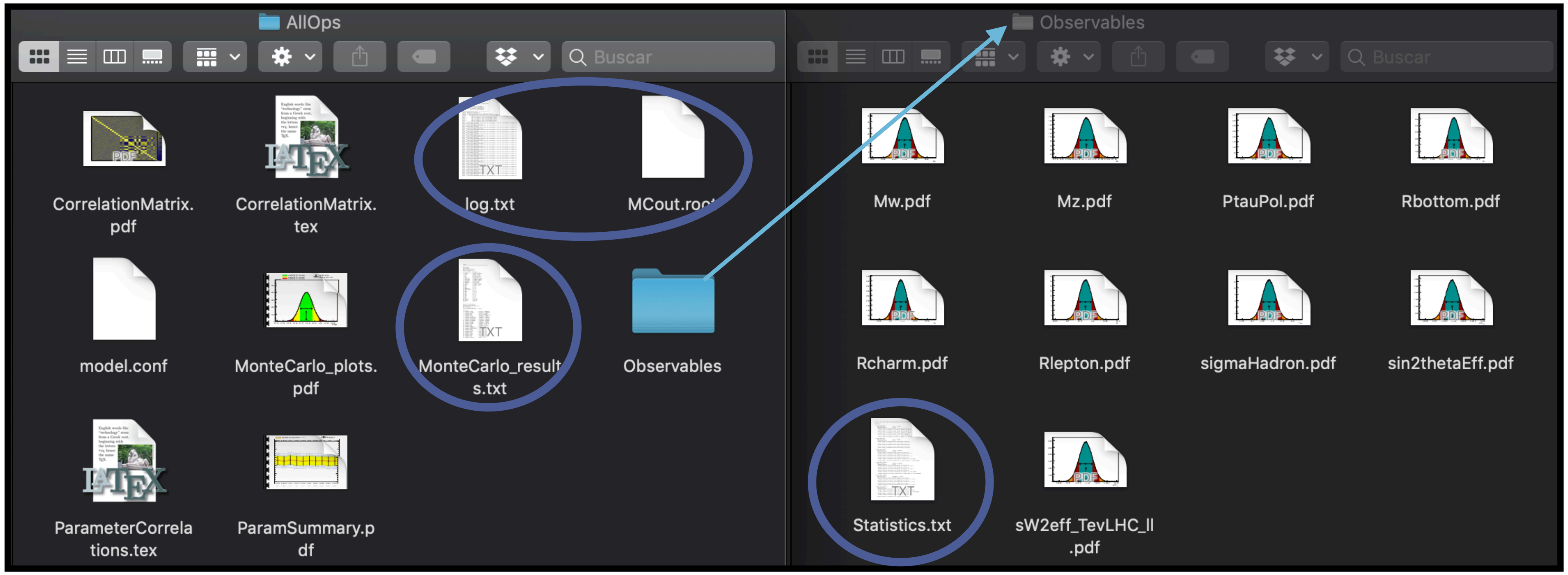
```
FindModeWithMinuit        (Default: false)
MinimumEfficiency         (Default: 0.15, set to 0. - 1.)
WriteChain                (Default: false)
CalculateNormalization    (Default: false)
WritePreRunData           (Mandatory: name of file)
ReadPreRunData            (Read existing prerun data file)
```

See code documentation for more options:
Convergence criteria, etc.

Running example: Output



Running example: Output

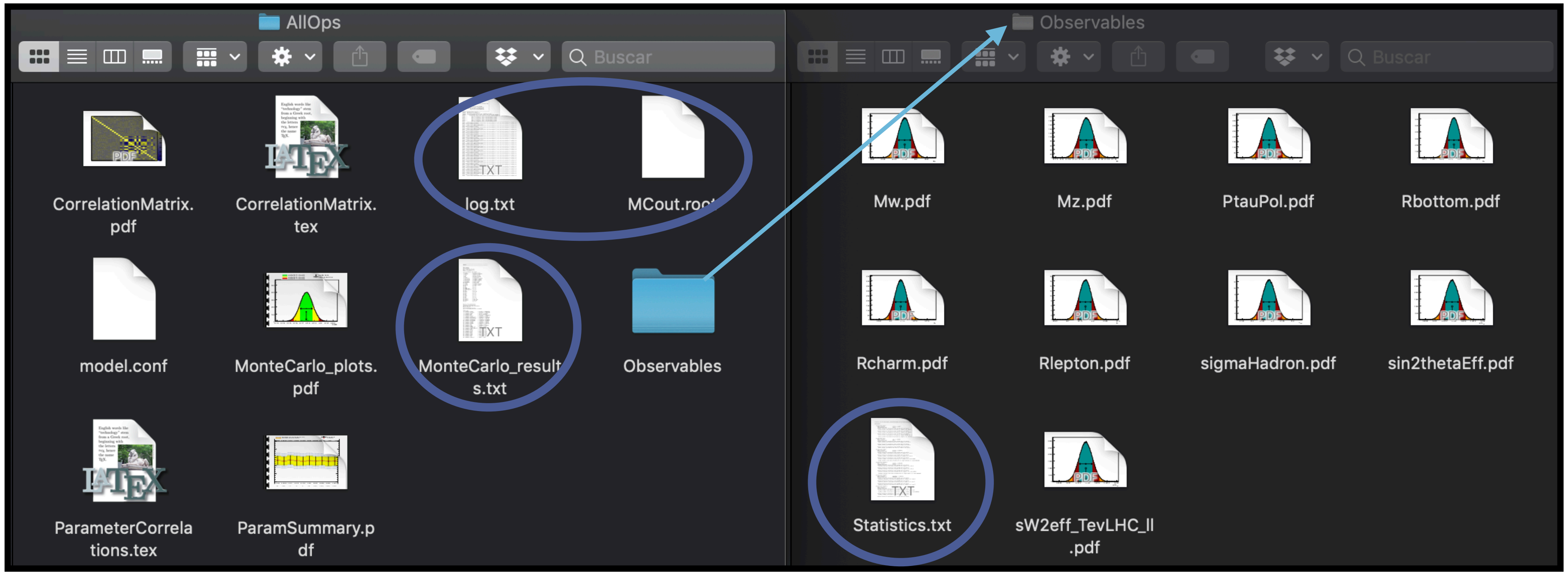


- **log.txt**: Info about convergence, check for problems, etc

```
Detail  :         eHccpar          :  1.004
Detail  :         eHbbpar          :  1.002
Summary :  --> Set of 8 Markov chains converged within 233000 iterations, and all scales are adjusted.
Summary :  --> 232 updates to multivariate proposal function's covariances were made.
Detail  :  --> Scale factors and efficiencies (measured in last 1000 iterations):
Detail  :        - Chain : Scale factor    Efficiency
Detail  :              0 :        0.0614        30.9 %
Detail  :              1 :        0.0614        36.7 %
Detail  :              2 :        0.0614        36.6 %
Detail  :              3 :        0.0614        37.3 %
Detail  :              4 :        0.0614        35.6 %
Detail  :              5 :        0.0921        30.2 %
Detail  :              6 :        0.0614        40.1 %
Detail  :              7 :        0.0614        39.3 %
Summary : Run Metropolis MCMC for model "NPSMEFTd6" ...
Summary :  --> Perform MCMC run with 8 chains, each with 1000000 iterations.
Detail  :  --> iteration number 100000 ( 10 %)
Detail  :  --> iteration number 200000 ( 20 %)
Detail  :  --> iteration number 300000 ( 30 %)
```

Running HEPfit

Running example: Output

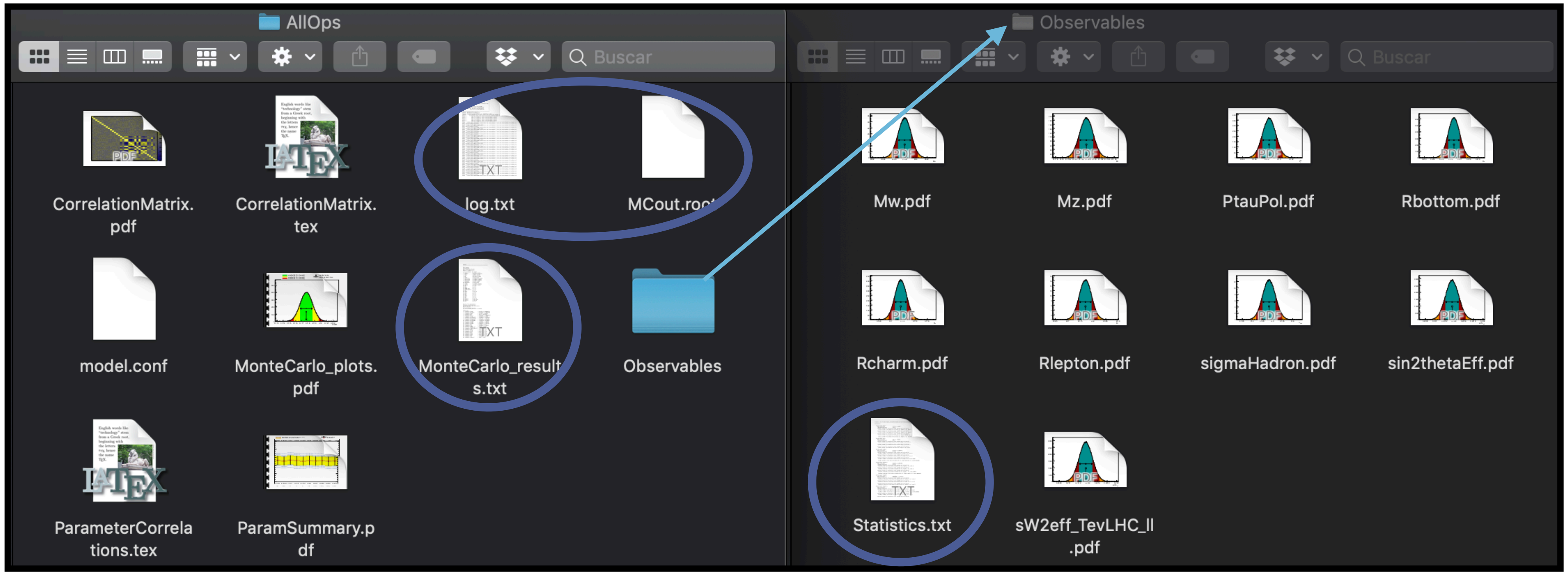


- **MonteCarlo_results.txt**: Info about the fitted parameters

```
(6) Parameter "CHG" :
     Mean +- sqrt(Variance):        +8.452e-06 +- 0.001056
     Median +- central 68% interval: +0.0001747 + 0.02708 - 0.02732
     (Marginalized) mode:            +0.02
      5% quantile:                   -0.03598
     10% quantile:                   -0.03196
     16% quantile:                   -0.02714
     84% quantile:                   +0.02726
     90% quantile:                   +0.03203
     95% quantile:                   +0.03602
     Smallest interval containing 100.0% and local mode:
     (-0.04, 0.04) (local mode at 0.02 with rel. height 1; rel. area 1)
```

Running HEPfit

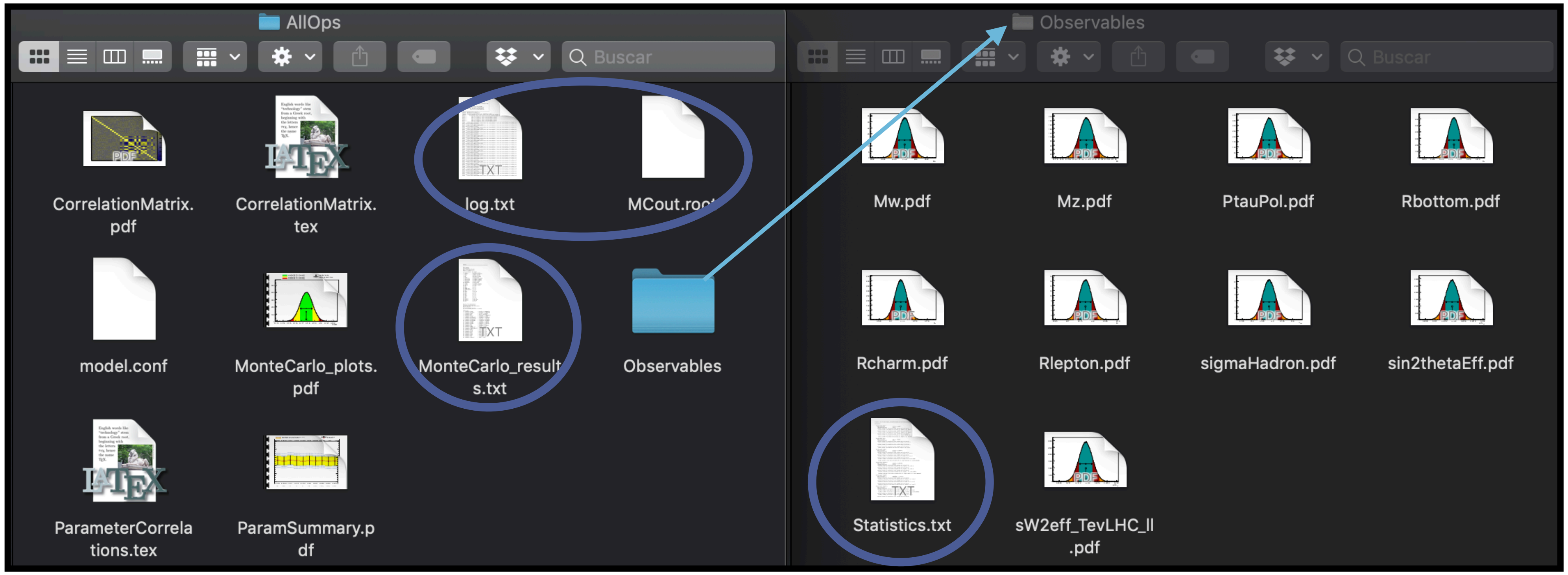
Running example: Output



- **log.txt**: Info about convergence, check for problems, etc
- **MonteCarlo_results.txt**: Info about the fitted parameters
- **MCout.root**: the whole output (histograms with info about posterior) in a .root file

Running HEPfit

Running example: Output



- **Observables/Statistics.txt:** compilation of the statistics about the model parameters and observables included in the fit, correlations, etc

```
(3) Observable "AFBbottom_C":
    Mean +- sqrt(V):                0.10328 +- 0.00012432
    (Marginalized) mode:            0.1033
    Smallest interval(s) containing at least 68.8642% and local mode(s):
     (0.10316, 0.10341) (local mode at 0.1033 with rel. height 1; rel. area 1)

    Smallest interval(s) containing at least 95.4808% and local mode(s):
     (0.10304, 0.10353) (local mode at 0.1033 with rel. height 1; rel. area 1)

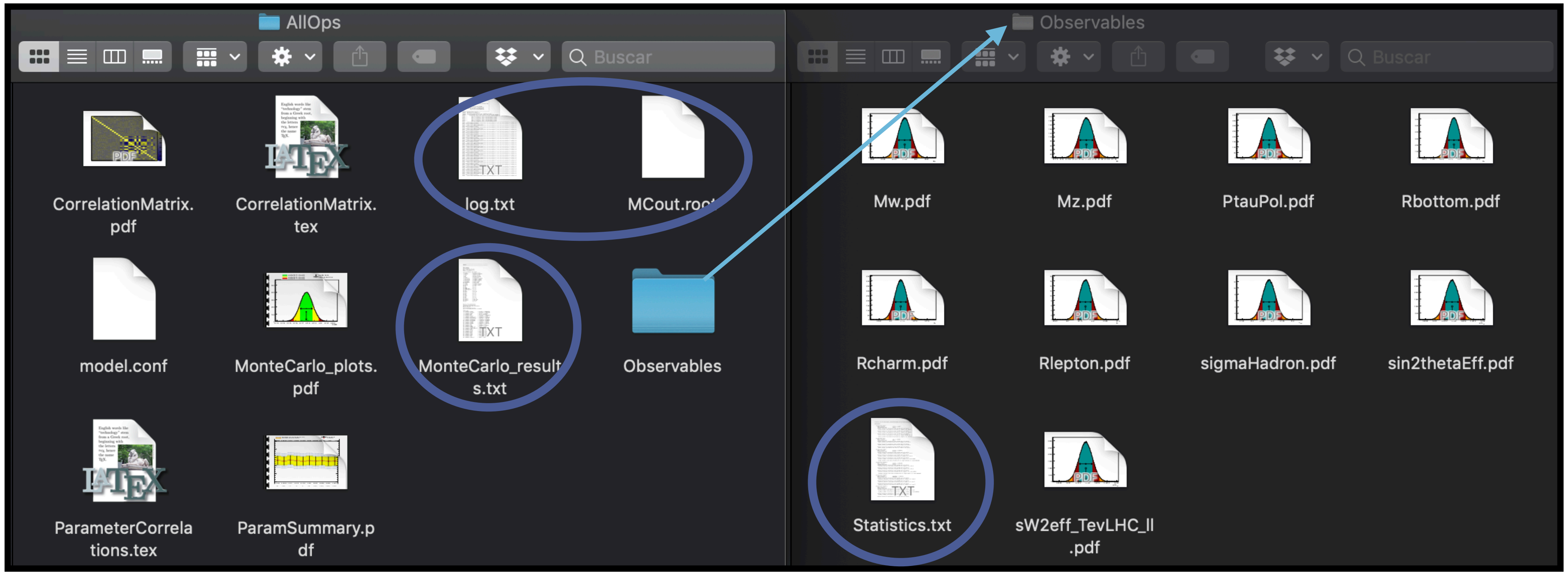
    Smallest interval(s) containing at least 99.7398% and local mode(s):
     (0.10289, 0.1029) (local mode at 0.1029 with rel. height 0.010387; rel. area 0.0001054)

     (0.10291, 0.10366) (local mode at 0.1033 with rel. height 1; rel. area 0.99979)

     (0.10366, 0.10366) (local mode at 0.10366 with rel. height 0.010214; rel. area 0.00010364)
```

Running HEPfit

Running example: Output



- **Observables/Statistics.txt:** compilation of the statistics about the model parameters and observables included in the fit, correlations, etc

```
 |CuH_33r                  |           0 |
 |CdH_33r                  |           0 |
 |CLL_1221                 | -5.4462e-10 |
 |---------------------------------------|

LogProbability at mode: -5.4477
LogLikelihood at mode: -2.8331e-10
LogAPrioriProbability at mode: -5.4477


LogLikelihood mean value: -16.083
LogLikelihood variance: 16.128
IC value: 96.68
DIC value: 64.423
```

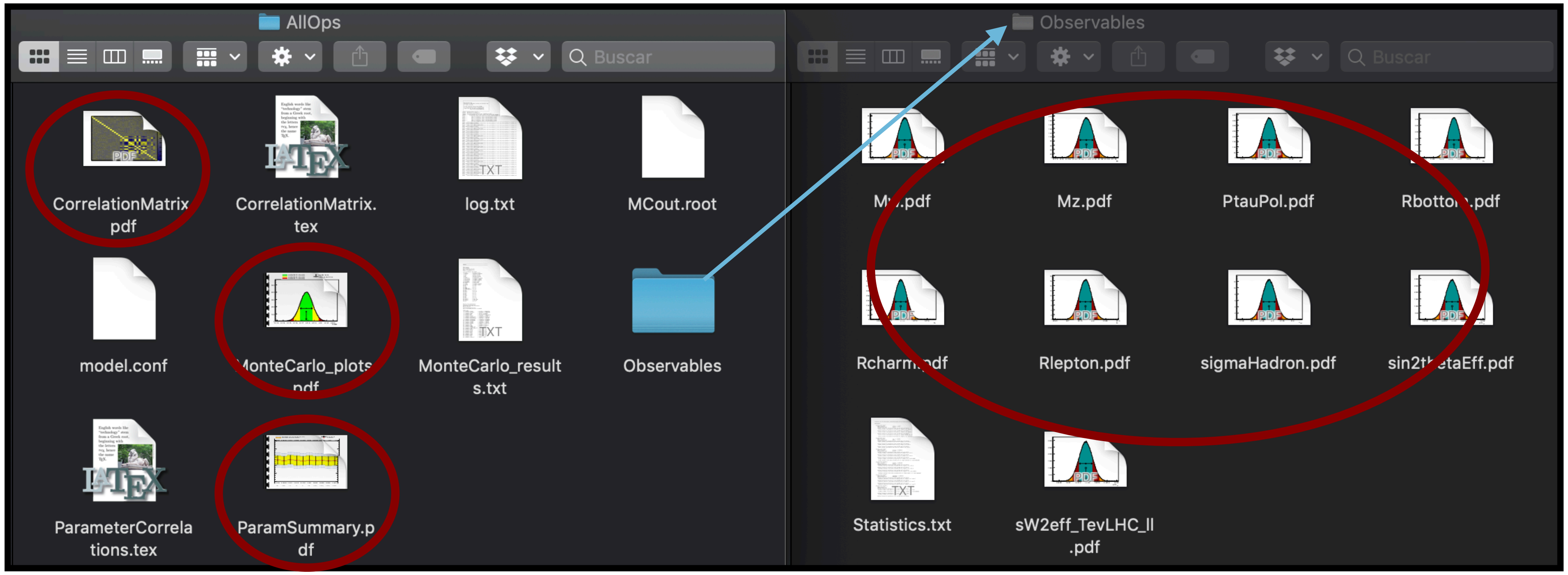
Information Criterion (IC): Useful for model comparison?

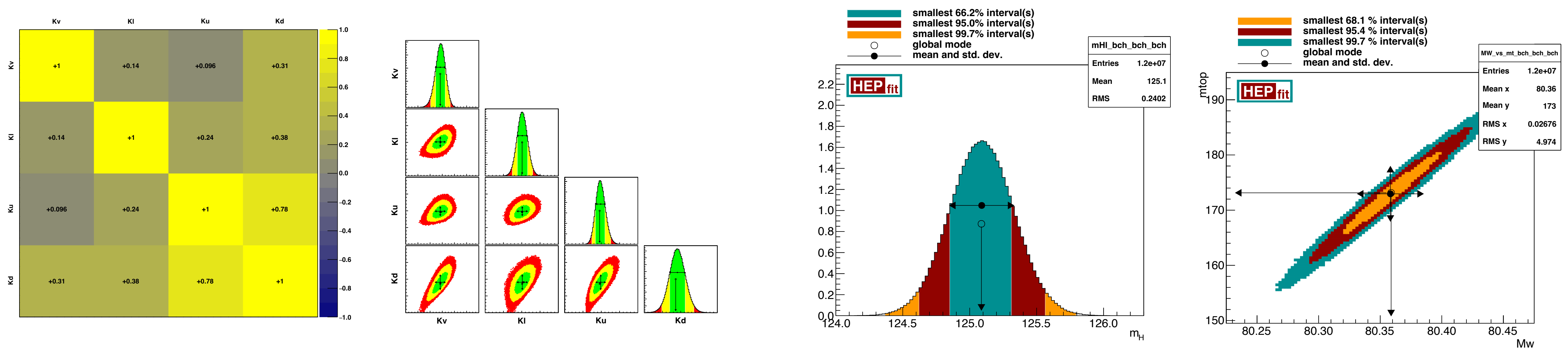
$$\mathrm{IC} \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}$$

Quality of fit **# d.o.f.**

Running HEPfit

Running example: Output





1D and 2D marginal distributions, correlations between parameters and/or observables, etc

Making it work…

Adding your own models/observables

Adding your model and Observables to HEPfit

- Check template in examples/myModel
- In myModel.h:

```
#include <HEPfit.h>

/**
 * @class myModel
 * @brief My own Model.
 */
class myModel: public StandardModel {
public:

    static const int NmyModelvars = 4; /* Define number of mandatory parameters in the model. */
    static const std::string myModelvars[NmyModelvars]; /* Vector of model variable names. */
```

Extend the SM (typically) or, if more convenient, the NPBase model, or the NPd6SMEFT model, …

```
double c1, c2, c3, c4; /* Model Parameters */

double getc1() const { return c1; }
double getc2() const { return c2; }
double getc3() const { return c3; }
double getc4() const { return c4; }
```

Define number and variables for model parameters and get methods

Adding your model and Observables to HEPfit

- In myModel.cpp:

```
#include "myModel.h"

/* Define mandatory model parameters here. */
const std::string myModel::myModelvars[NmyModelvars] = {"c1", "c2", "c3", "c4"};

myModel::myModel()
:   StandardModel()
{
    /* Define all the parameters here and port them as observables too */
    ModelParamMap.insert(std::make_pair("c1", std::cref(c1)));
    ModelParamMap.insert(std::make_pair("c2", std::cref(c2)));
    ModelParamMap.insert(std::make_pair("c3", std::cref(c3)));
    ModelParamMap.insert(std::make_pair("c4", std::cref(c4)));
}
```

Assign names to parameters and link to variables

```
/* Model parameters and their derived quantities can be set here. */
void myModel::setParameter(const std::string name, const double& value)
{
    if(name.compare("c1") == 0)
        c1 = value;
    else if(name.compare("c2") == 0)
        c2 = value;
    else if(name.compare("c3") == 0)
        c3 = value;
    else if(name.compare("c4") == 0)
        c4 = value;
    else
        StandardModel::setParameter(name,value);
}
```

Link to parameter names to variables and values in the setParameter method

Adding your model and Observables to HEPfit

- Finally register the model in the "Model Factory" in myModel_MCMC.cpp:

```
/* register user-defined model named ModelName defined in class ModelClass using the following syntax: */
ModelF.addModelToFactory("myModel", boost::factory<myModel*>() );
```

- **<u>Custom Observables</u>** do not depend on having a custom model or not. Defined as functions of parameters already defined in a HEPfit model, in a custom model or a combination of both

- Need to be added to the ThObsFactory, e.g. in myModel_MCMC.cpp

```
/* register user-defined ThObservable named ThObsName defined in class ThObsClass using the following syntax: */
ThObsF.addObsToFactory("BIN1", boost::bind(boost::factory<yield*>(), _1, 1) );
ThObsF.addObsToFactory("BIN2", boost::bind(boost::factory<yield*>(), _1, 2) );
ThObsF.addObsToFactory("BIN3", boost::bind(boost::factory<yield*>(), _1, 3) );
ThObsF.addObsToFactory("BIN4", boost::bind(boost::factory<yield*>(), _1, 4) );
ThObsF.addObsToFactory("BIN5", boost::bind(boost::factory<yield*>(), _1, 5) );
ThObsF.addObsToFactory("BIN6", boost::bind(boost::factory<yield*>(), _1, 6) );
ThObsF.addObsToFactory("C_3", boost::factory<C_3*>() );
ThObsF.addObsToFactory("C_4", boost::factory<C_4*>() );
```

Require argument

Do not require extra arguments

Summary

Summary

- HEPfit provides a flexible framework for the calculation of observables and studies of indirect constraints on new physics using the large amount of data collected at the LHC and lower energy experiments
  - ✓ Includes modules for the description of EFTs …
  - ✓ … as well as other more specific BSM extensions/models
  - ✓ User can extend default set of models/observables via external modules
  - ✓ Flexibility in input format for construction of likelihoods → WiP: DNN likelihoods
- Current implementation (Developer's version) includes (separate) SMEFT modules to describe EW/Higgs/diBoson, Top and Flavor physics:
  - ✓ **Ultimate goal:** Global consistent EW/Higgs/Top/Flavor
- A lot of work in progress (in particular in the SMEFT)
  - ✓ RGE evolution, extension of observables to NLO in SMEFT, …
  - ✓ GeoSMEFT
  - ✓ Complete the "interpretation" workflow chain by connecting the output of matching tools (MatchMakereft) directly to HEPfit