Status report from the LHC EFT WG

A. Gilbert on behalf of the LHC EFT WG conveners
19th Workshop of the LHC Higgs Working Group | 30 November 2022
The LHC EFT WG

- Goal: Advise and develop recommendations for EFT measurements at the LHC
  - General information: [link], [Twiki], Contact: lhc-eftwg-admin@cern.ch

- Organisation:
  - Area 1: EFT formalism
  - Area 2: Predictions and tools
  - Area 3: Experimental measurements and observables
  - Area 4: Fits and related systematics
  - Area 5: Benchmark scenarios from UV models
  - Area 6: Interplay/connection with flavour

- Conveners:
  - ATLAS: Nicolas Berger, Sandra Kortner, Jacob Kempster, Kristin Lohwasser
  - CMS: Matteo Presilla, Nadjieh Jafari, Robert Schoefbeck, Nicholas Wardle
  - LHCb: Patrick Owen
  - Theory: Ilaria Brivio, Anke Biekoetter, Shankha Banerjee, Gauthier Durieux, Admir Greljo, Ken Mimasu
The SM EFT approach

- Strong motivation for new physics at the TeV scale
  - Energy scale of new physics ($\Lambda$) may be beyond our direct reach

- Construct an effective field theory starting from the known SM fields and symmetries
  - No specific high-energy (UV complete) theory required
  - Provides a renormalisable quantum field theory
  - Universal - can connect to other experiments

- Expand in powers of $1/\Lambda$:

$$L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda^5} \mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^6} \mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^7} \mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^8} \mathcal{O}_i^{(8)} + \ldots$$

$\mathcal{O}_i$ : operators = interaction terms at a given expansion order
$C_i$ : operators = Wilson coefficients, free parameters

- First relevant order at dimension 6
- Dimension 8 also important for certain processes
Area 1: EFT formalism

- **Goal:** establish the key parameters of the EFT formalism: what *operators*, what *bases*, what *perturbation orders*, how to combine operators of different dimensions, which *flavour* and *symmetry* assumptions

- **Scheme dependence:** \{\alpha, G_{\mu}, m_Z\}, \{G_{\mu}, m_Z, m_W\} or \{\alpha, m_Z, m_W\}?

- **Public note released,** recommending the \{G_{\mu}, m_Z, m_W\} scheme:

- **EFT expansion:**

  \[
  L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \sigma_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} \sigma_i^{(8)} + \ldots
  \]

  \[
  \sigma \propto A_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} A_i^{(6)} + \sum_{i,j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} A_{ij}^{(6)} + \sum_k \frac{C_k^{(8)}}{\Lambda^4} A_k^{(8)} + \ldots
  \]

  - **Baseline assumption:** \textbf{dim6}, however:
    - SM-dim8 interference also at $1/\Lambda^4$
    - Dim8 calculated for subset of processes
    - $(\text{dim6})^2$ may be large compared with SM-dim6 interference

  \textit{arXiv:2111.12515}

**LHC EFT WG, Area 1**
Electroweak input parameters

Editors: Ilaria Brivio, Sally Dawson, Jorge de Blas, Gauthier Durieux, Pierre Savard
Contributors: Anggar Denner, Ayres Freitas, Chris Hays, Ben Pociak, Alessandro Vicini
November 25, 2021

Abstract
Different sets of electroweak input parameters are discussed for SMEFT predictions at the LHC. The \{G_{\mu}, m_Z, m_W\} one is currently recommended.
Area 1: EFT validity

- Want to know if our EFT prediction for \( \sigma(c_i^{(6)}c_k^{(8)}...) \) is valid - i.e. does it describe the true model underlying the data?
  - Depends on the concrete NP model, but hope generically valid for \( E < \Lambda \)

- Which terms to keep in the EFT expansion?
  - Ideally: \( 1/\Lambda^4 \) terms small compared to \( 1/\Lambda^2 \), and \( \text{dim}8 \) small compared to \( \text{dim}6 \)
  - Known not to be the case (e.g. WV cross sections has large \( \text{dim}6^2 \), VBS w/ large \( \text{dim}8 \))
  - Consensus: by default include \( \text{dim}6 \) \text{linear+quadratic}, linear-only for comparison

- Up to which energy scale is the EFT valid? Considerations:
  - How to define it - which quantity? \( \Rightarrow \) Process (and EFT operator) dependent
  - Violation of unitarity (depends on \( c_i \) and \( \Lambda \))
  - What to do if experimental measurement includes regions where the EFT is known to be invalid?

- Incorporate theoretical uncertainties in the SMEFT?
  - Different options, e.g. geoSMEFT
  - May also need to account for higher orders in QCD & EW

\[ f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^4}, \quad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \ldots \]

\( \Lambda \) too low: \text{dim}6-only assumption not valid
Area 1: Proposals

- Several options for dealing with the case that EFT model is not valid in some parts of the phase space
- Based on topical meetings in January and June 2021 - public note first released in January and recently updated with additional proposal

"A & B"
- Include $d=6$ linear $(1/\Lambda^2) +$ quadratic $(1/\Lambda^4)$ terms, linear-only model for comparison only.
- Apply clipping on data: most natural for theory, but more difficult for analyses (need to repeat the analysis for several cutoffs)
- Provide exp. results as a function of $E_{cut}$, use best $E_{cut}$ for each UV model.

"D"
- Same as above, but apply clipping on the EFT prediction.
  → Experimentally easier, equivalent to clipping data for well-measured $E$ observables but questionable in other cases (is the clipped model a consistent description of the data?)

"C"
- Add uncertainties: closest to usual treatment of theory unknowns in LHC measurements, but need proper determinations of magnitudes (use size of $(d=6)^2$ terms as proxy ?) and correlation scheme (decorrelate across observables and $c_i$ ?)

N. Berger

Toy studies of different approaches:
Area 2: Predictions & tools

• Goals: (twiki)
  - Track the various tools that are used to provide EFT predictions
  - Organise cross-validation
  - E.g. this year compared predictions of JHUGen vs SMEFTsim, SMEFT@NLO vs SMEFTsim
  - Provide recipes and recommendations on usage

• Topical meeting in January this year, topics including:
  - Effect of additional jets in tt+X EFT modelling - can lead to sizeable corrections
  - Framework for MC/MC comparisons
  - LHE level study of dim6 sensitivity in VBS (and global fit with WW)

Proposal for comparison between different tools
(comparison of dim6top/SMEFTsim/SMEFT@NLO already studied)
Area 3: Experimental measurements & observables

- **Goals (twiki):**
  - Study **experimental approaches** for EFT inference, **choice of observables** and **optimisation for sensitivity**

- **Strategies:**
  - **Two-step approach** (reinterpretation of diff./fid. measurements)
    - Easier to recast / incorporate in external global fits
    - Less sensitive, typically only 1-2 observables
  - **Direct approach**
    - Use of optimal / multi-variate observables for best sensitivity
    - Reinterpretation more difficult

- **Observables:**
  - Differential / fiducial XS
  - Higgs simplified template cross sections
  - Optimal observables: ME ratios, ML discriminators, etc.

- **Associated uncertainties:**
  - Detector / acceptance effects, unfolding, EFT in backgrounds

- **Note released today!**

---

**Fiducial/differential measurements with EFT interpretation**

Two sets of fits:

\[
\mathcal{L}(\text{data}|\sigma_i) \quad \mathcal{L}(\text{data}|\sigma(c_j))
\]

Possible to recast from \(\sigma_i\) to give \(c_j\), or other parametrization of \(\sigma_i\).

**Direct EFT constraints (w/ optimised analysis) aka “full-sim”**

One direct fit:

\[
\mathcal{L}(\text{data}|c_j)
\]

Can recast from \(c_j\) to other congruent EFT basis

---

**Event generator**

\[
\mathcal{P}(\vec{x}_{\text{truth}} | \vec{\theta}_i)
\]

**Pythia, GEANT, reco**

\[
p(\vec{x}_{\text{full, reco}} | \vec{x}_{\text{truth}})
\]

**Matrix Element**

\[
\vec{x}_{\text{reco}} = f(\vec{x}_{\text{reco}})
\]

---

**L(data|c_j)**

\[
\mathcal{L}(\text{data}|c_j)
\]

Can recast from \(c_j\) to other congruent EFT basis
Area 4: Fits and related systematics

- **Long term goal**: combined likelihood fit of Higgs, top & EW measurements to give strongest constraints on the widest possible set of EFT operators

- Goal is to provide guidance for:
  - Experimental combinations
  - Benchmarks for "theory" fits (typically use public information only)
  - Input/output formats, the level of information the experiments should provide
  - Implementation of common experimental + theoretical uncertainties in combination
  - Inclusion of non-LHC constraints (EWPO, flavour, g-2, ...)

- Know from experience that these large-scale combinations take a long time
  - Pragmatic approach: started a fitting exercise, with a simplified \( \chi^2 \) fit, based on public information
  - Previous meetings: [June 22] [Feb 22]
  - Twiki to document conventions
Area 4: Fitting exercise

- **Current inputs:**
  - Higgs (CMS $H \to \gamma\gamma$, ATLAS $H \to \gamma\gamma$, 4l, bb); EW (ATLAS WW, WZ $Zjj$, CMS $W\gamma$, LEP EWPO); top (CMS single top)
  - Use public covariance matrices, neglect inter-analysis uncertainty correlations
  - **Future plans:** add more channels, use as benchmark for flavour choice, truncation/validity studies

![Diagram of model](image)
Area 5: benchmark scenarios from UV models

- **Goals (twiki):**
  - Study matching to specific models
  - Identify BSM-driven subsets of operators
  - Benchmarks beyond SMEFT, incl. non-linear EFT

- **Two topical meetings:** [Feb 21] [March 22]
  - Comparison of EFT constraints vs. direct BSM searches beyond EFT

- **Note in development:**
  - Review of (automated) codes: STrEAM, SuperTracer, Matchmakereft, CoDEx, Matchete, MatchingTools, …
  - Provide comparison framework
  - Define relevant benchmark models, e.g. SMEFT ↔ MSSM

### Two Higgs Doublet Models

S. Homiller

Generates $C_{H}$, $C_{bH}$, $C_{tH}$, $C_{\tau H}$ at the matching scale

Note that these are SMEFT Fits — not 2HDM fits!

---

Heavy vector triplet model

E. Geoffray

We get constraints for $m_V = \sqrt{\sum m_i^2} = 8\text{TeV}$, where direct resonance searches don’t exist. And we fit in the full 5 parameter model space.
Area 6: flavour assumptions

- Goals (\textit{twiki}):  
  - Define relevant flavour scenarios for EFT interpretations (not possible to constrain all 2499 SMEFT dim6 operators simultaneously)  
  - Depends on the scope of the combination, e.g. EW+Higgs+top ⇒ requires some separation of 3rd gen. fermions  
  - Understand interplay with other experiments (flavour, EDM, g-2, …) - some coefficients stronger constrained elsewhere

- \textbf{Note} on flavour assumptions in preparation

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{SMEFT $O(1)$ terms (dim-6, $\Delta B = 0$)} & \textbf{Lepton sector} & \textbf{MFV} & \textbf{$U(3)_{V}$} & \textbf{$U(2)^2 \times U(1)$} & \textbf{$U(2)$} & \textbf{$U(1)$} & \textbf{$U(1)^6$} & \textbf{$U(1)^3$} & \textbf{No symm.} \\
\hline
\textbf{Quark sector} & MFV & 47 & 54 & 65 & 71 & 80 & 87 & 111 & 339 \\
\hline
$U(2)^2 \times U(3)_{d}$ & 82 & 93 & 105 & 115 & 128 & 132 & 168 & 450 & \\
\hline
$U(2)^3 \times U(1)_{b_{R}}$ & 96 & 107 & 121 & 128 & 144 & 150 & 186 & 480 & \\
\hline
$U(2)^4$ & 110 & 123 & 135 & 147 & 162 & 164 & 206 & 512 & \\
\hline
No symm. & 1273 & 1334 & 1347 & 1407 & 1470 & 1425 & 1611 & 2499 & \\
\hline
\end{tabular}
\caption{SMEFT $O(1)$ terms (dim-6, $\Delta B = 0$) with various assumptions.}
\end{table}

- MFV with all breakings neglected apart from $y_{t}$. Radiatively stable (approximate symmetry of $\text{dim}[\mathcal{O}] = 4$)
- Third-family specific. Discriminates $t$ and $b$ from light jets, and $t$ from $\mu/e$ (experimentally possible). Motivated by the charged-current $B$ anomalies.
- Allows for LFUV between $e$ and $\mu$ which is experimentally accessible. Neutral-current $B$ anomalies.
- Work out which linear combinations actually contribute to the Top/Higgs/EW.
Summary

• LHC EFT working group aims to cover all the main aspects of EFT interpretation
  - Develop recommendations that will ultimately facilitate full-scale global EFT fits

• Public notes already released:
  - Electroweak input parameters
  - Truncation, validity & uncertainties
  - Experimental Measurements and Observables

• In preparation:
  - Matching to UV models beyond tree level
  - Flavour schemes

• Work on the prototype fitting exercise ongoing ⇒ start to focus on studying proposals from other areas

• Excellent time to get involved!