Northwestern University

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

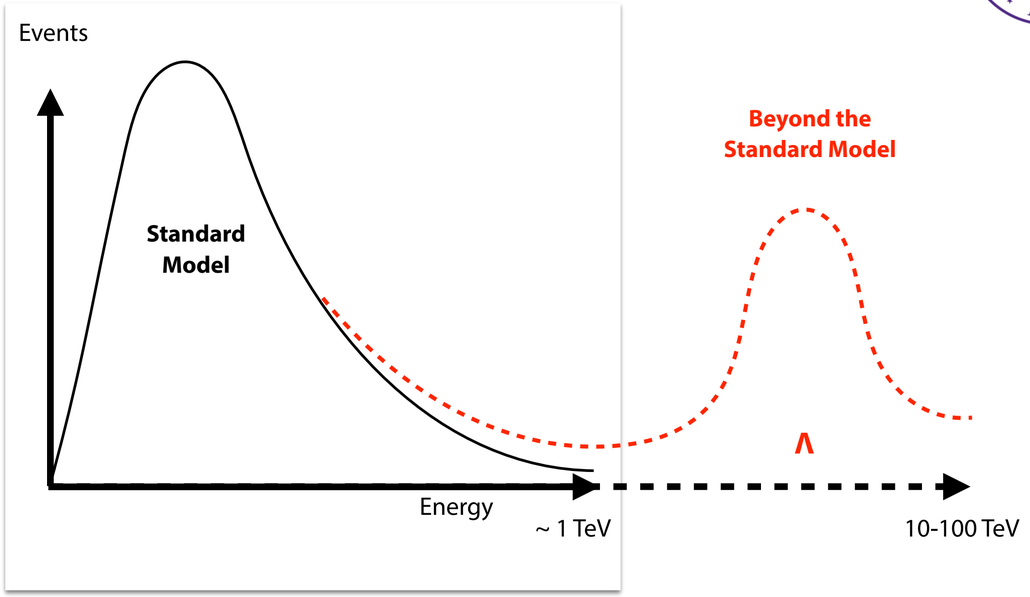
- Goal: Advise and develop recommendations for EFT measurements at the LHC
  - **General information:** [link], [Twiki], **Contact**: lhc-eftwg-admin@cern.ch

- 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 (**Λ**) 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/Λ):



$$L_{\text{EFT}} = L_{\text{SM}} + \sum_i \frac{C_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

Lepton-number violating

Violates B-L

$\mathcal{O}_i$: 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

arXiv:2111.12515

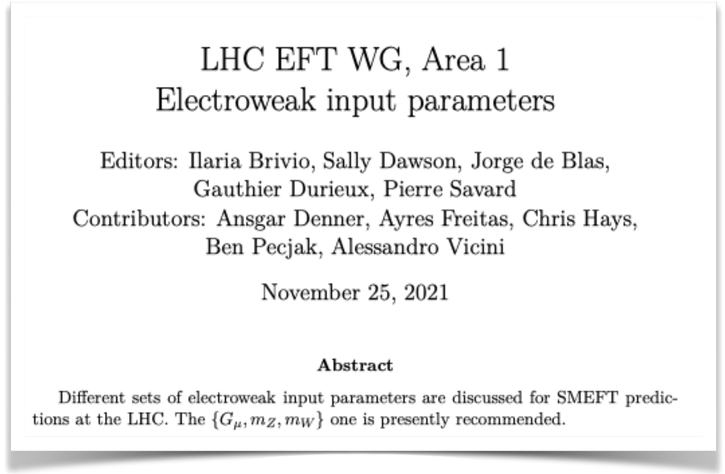
- Scheme dependence: {α, G_μ, m_Z}, {G_μ, m_Z, m_W} or {**α, m_Z, m_W**} ?

Used at LEP

Used in many tools

Avoid leptonic corrections to G_μ

Avoid large W/Z propagator corrections


LHC EFT WG, Area 1
Electroweak input parameters

Editors: Ilaria Brivio, Sally Dawson, Jorge de Blas, Gauthier Durieux, Pierre Savard
Contributors: Ansgar Denner, Ayres Freitas, Chris Hays, Ben Pecjak, 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 presently recommended.

- Public note released, recommending the **{G_μ, m_Z, m_W}** scheme:

- EFT expansion:

$$L_{\rm EFT} = L_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

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

Leading dim-6 interference term with the SM

Quadratic "pure BSM" dim-6

SM - dim-8 interference

Baseline assumption: 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

Area 1: EFT validity

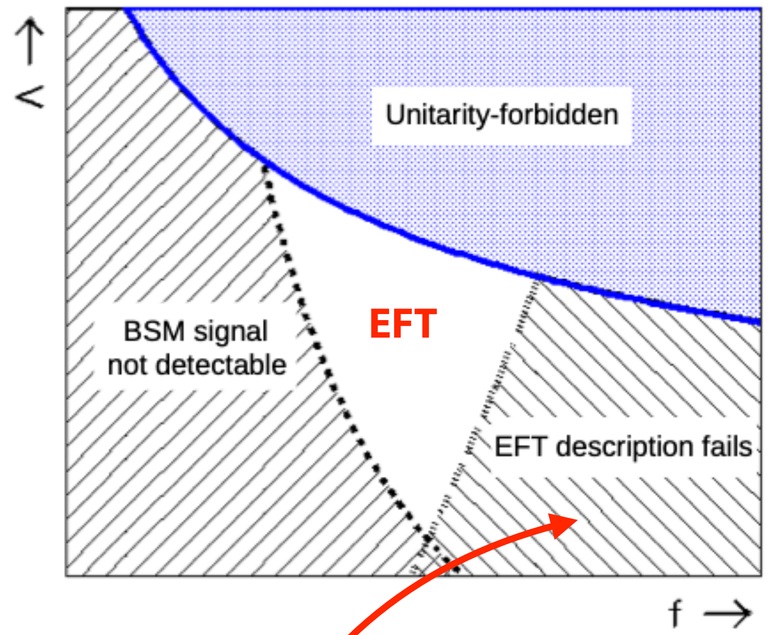
- Want to know if our EFT prediction for $\sigma(c_i^{(6)}, c_k^{(8)}, \ldots)$ is valid - i.e. does it describe the true model underlying the data?
  - Depends on the concrete NP model, but hope generically valid for $E < \Lambda$

- Which terms to keep in the EFT expansion?
  - Ideally: $1/\Lambda^4$ terms small compared to $1/\Lambda^2$, and dim8 small compared to dim6
  - Known not to be the case (e.g. WV cross sections has large dim6^2, VBS w/ large dim8)
  - **Consensus**: by default include **dim6 linear+quadratic**, linear-only for comparison

- Up to which energy scale is the EFT valid? Considerations:
  - How to define it - which quantity? ⇒ Process (and EFT operator) dependent
  - Violation of unitarity (depends on c_i and Λ)
  - 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

arXiv:1802.02366



$$f_i^{(6)} = \frac{C_i^{(6)}}{\Lambda^2}, \quad f_i^{(8)} = \frac{C_i^{(8)}}{\Lambda^4}, \ldots.$$

Λ too low: dim6-only assumption not valid

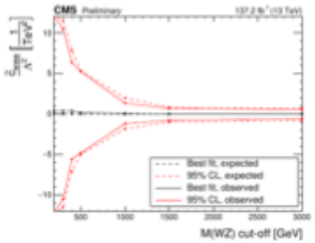
Area 1: Proposals

- 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**

N. Berger

"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 ?)

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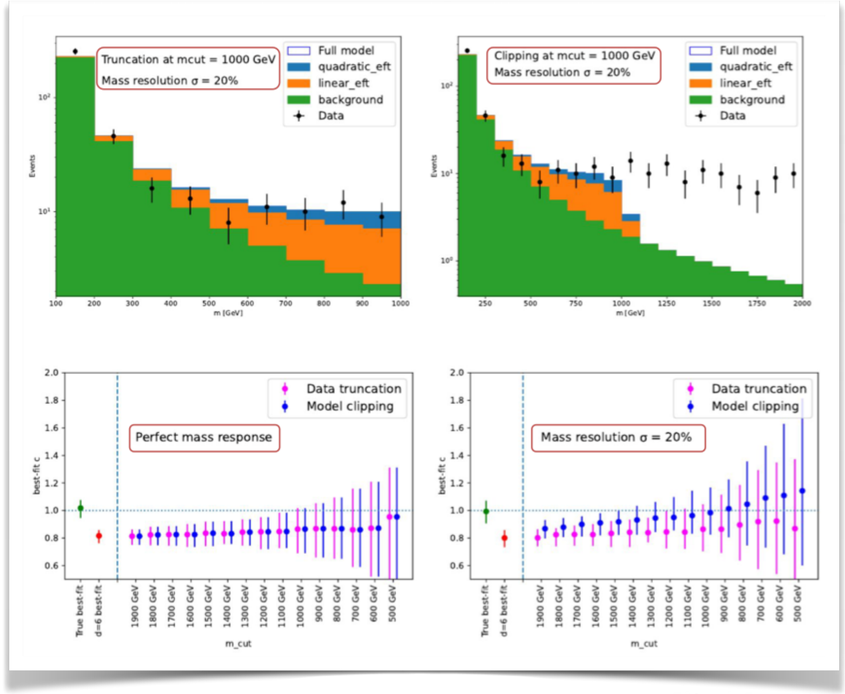
Toy studies of different approaches:

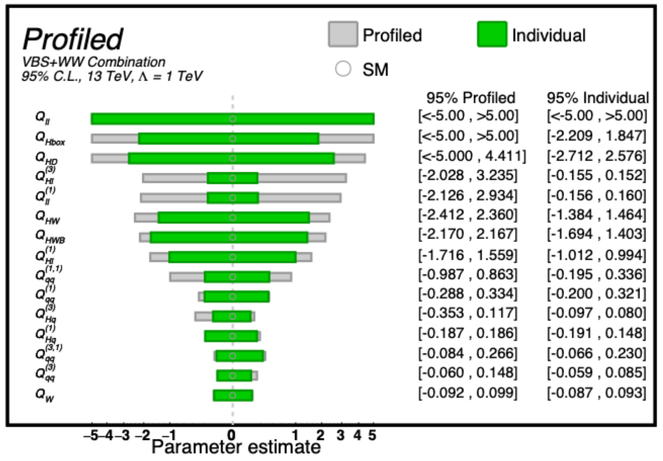


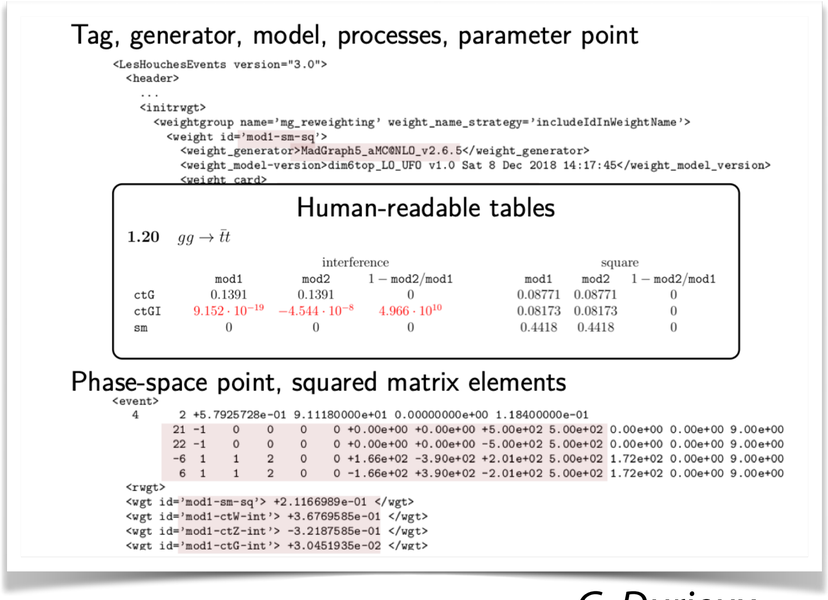
[link]

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

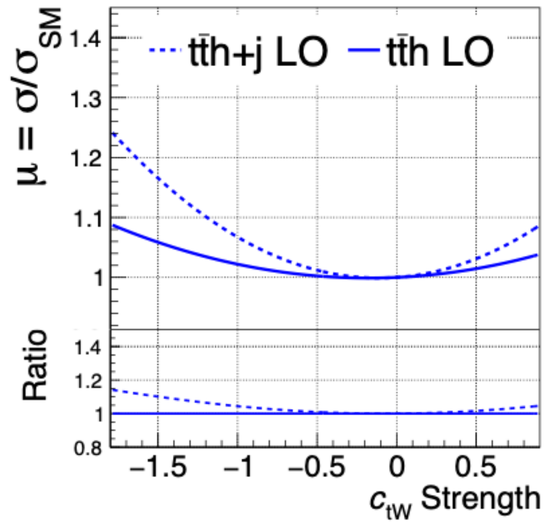
- Topical meeting in January this year, topics including:
  - Effect of additional jets in tt+X EFT modelling - can lead to sizeable corrections
  - Framework for MC/MC comparisons
  - LHE level study of dim6 sensitivity in VBS (and global fit with WW)





G. Durieux

K. Mohrman



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** (reinterpretion 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 **(1)**

Two sets of fits:

$L(\text{data}|\sigma_i)$

$L(\text{data}|\sigma_i(c_j))$

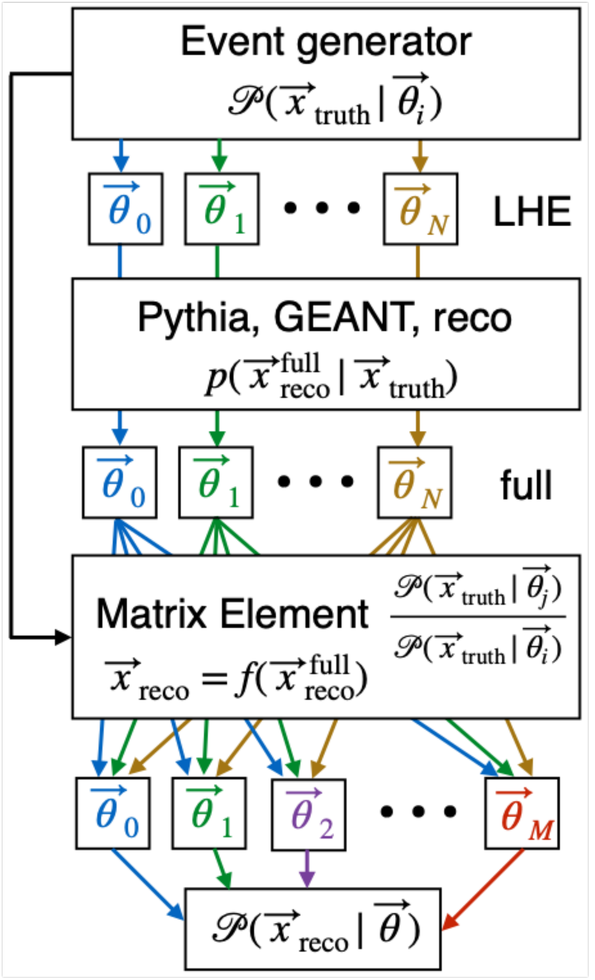
Possible to recast from σ_i to give c_j, or other parametrization of σ_i

Direct EFT constraints (w/ optimised analysis) aka "full-sim" **(2)**

One direct fit:

$L(\text{data}|c_j)$

Can recast from c_j to other congruent EFT basis



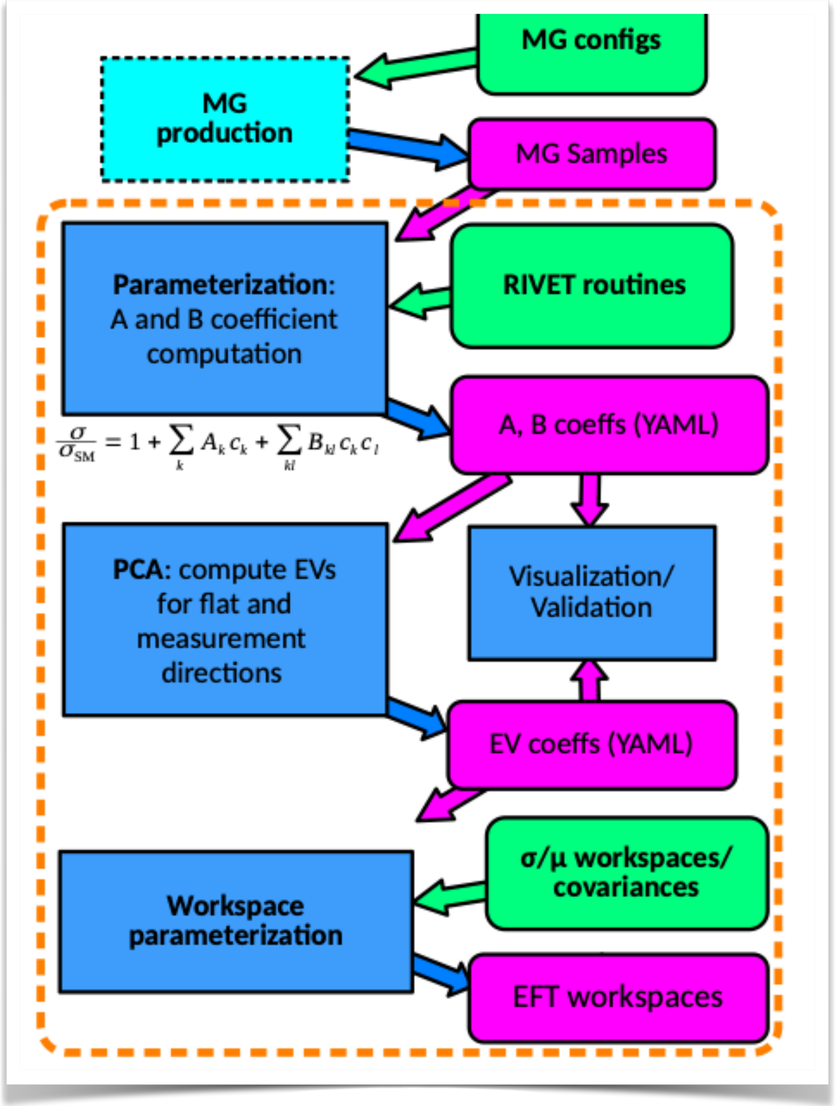
Area 4: Fits and related systematics

N. Berger

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

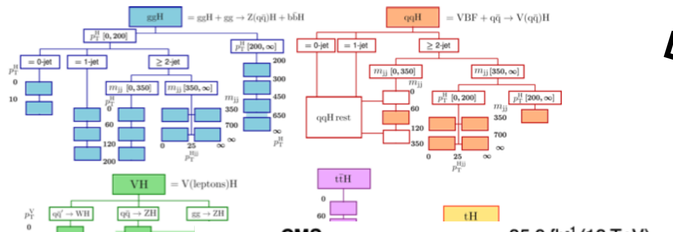
- Goal is to provide guidance for:
  - Experimental combinations
  - Benchmarks for "theory" fits (typically use public information only)
  - Input/output formats, the level of information the experiments should provide
  - Implementation of common experimental + theoretical uncertainties in combination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

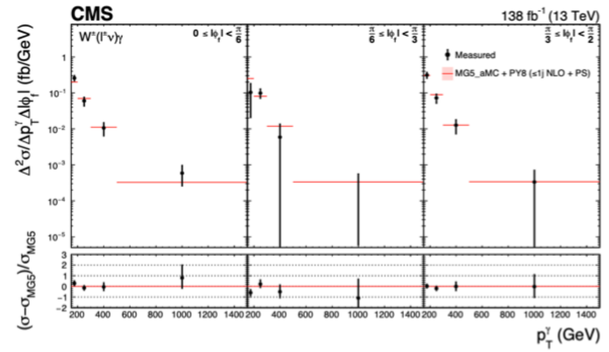
- Know from experience that these large-scale combinations take a long time
  - Pragmatic approach: started a fitting exercise, with a simplified χ2 fit, based on public information
  - Previous meetings: [June 22] [Feb 22]
  - Twiki to document conventions



Area 4: Fitting exercise

- Current inputs:
  - **Higgs** (CMS H→γγ, ATLAS H→γγ, 4l, bb); **EW** (ATLAS WW, WZ Zjj, CMS Wγ, 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





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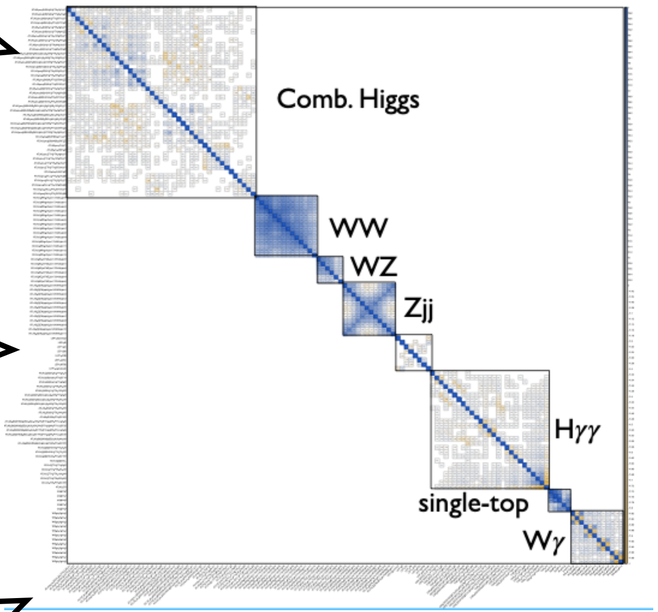
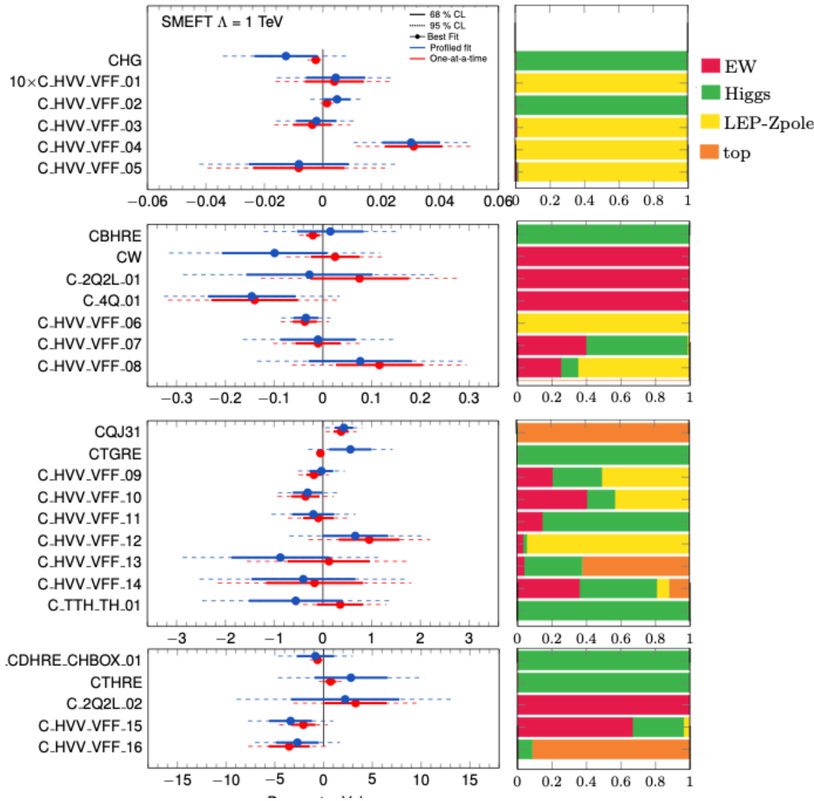


Basis rotation to remove flat directions



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

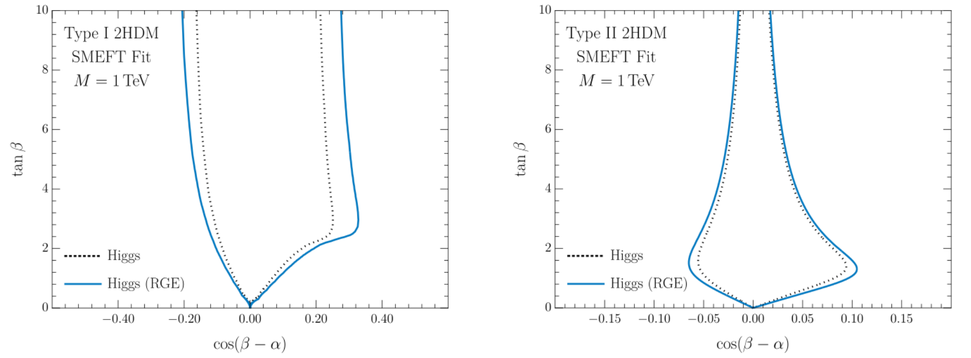
- Note in development:
  - Review of (automated) codes: STrEAM, SuperTracer, Matchmakereft, CoDEx, Matchete, MatchingTools, …
  - Provide comparison framework
  - Define relevant benchmark models, e.g. SMEFT ↔ MSSM

Two Higgs Doublet Models

S. Homiller

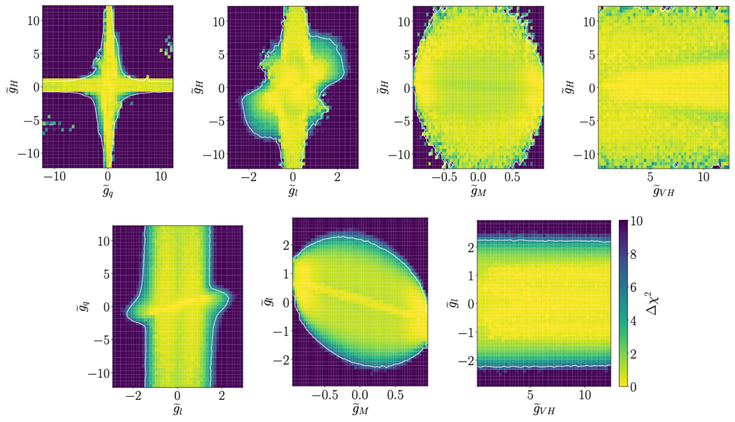
Generates C_H, C_{bH}, C_{tH}, $C_{\tau H}$ at the matching scale

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



Heavy vector triplet model

E. Geoffray



We get constraints for $m_V = \frac{\tilde{m}_V}{\sqrt{1-\tilde{g}_M^2}} = 8$TeV, where direct resonance searches don't exist. And we fit in the full 5 parameter model space.

Area 6: flavour assumptions

- Goals (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

- Note on flavour assumptions in preparation

From A. Greljo

SMEFT $\mathcal{O}(1)$ terms (dim-6, $\Delta B = 0$)		Lepton sector							
		MFV_L	$\mathrm{U}(3)_V$	$\mathrm{U}(2)^2 \times \mathrm{U}(1)$	$\mathrm{U}(2)^2$	$\mathrm{U}(2)_V$	$\mathrm{U}(1)^6$	$\mathrm{U}(1)^3$	No symm.
Quark sector	MFV_Q	47	54	65	71	80	87	111	339
	$\mathrm{U}(2)^2 \times \mathrm{U}(3)_d$	82	93	105	115	128	132	168	450
	$\mathrm{U}(2)^3 \times \mathrm{U}(1)_{b_\mathrm{R}}$	96	107	121	128	144	150	186	480
	$\mathrm{U}(2)^3$	110	123	135	147	162	164	206	512
	No symm.	1273	1334	1347	1407	1470	1425	1611	2499

MFV with all breakings neglected apart from y_t. Radiatively stable (approximate symmetry of $\dim[\mathcal{O}] = 4$)

Third-family specific. Discriminates t and b from light jets, and τ from μ/e (experimentally possible). Motivated by the charged-current B anomalies.

Allows for LFUV between e and μ 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!