Global EFT fits: overview and discussion

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Global fit to SMEFT operator coefficients

- If new physics is confined to $\gtrsim$1 TeV, interactions can be described by an EFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \cdots$$

Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

Impact of new physics on a process can be expressed using a basis of higher dimension operators

A given process is typically affected by a few operators
 Need to combine processes to constrain a given set of operators
 In general processes will span Higgs, electroweak, and QCD (top, jet) processes

A global fit to a basis of operator coefficients broadly probes for new physics at high scales
 Specific high-scale models can be mapped into the basis coefficients

Individual new resonances can affect many operators
 Running from resonance to measurement can affect more operators

- A global fit to SMEFT operator coefficients provides a comprehensive picture of possible new physics in the range of 1-10 TeV

Fields	Operators
$\mathcal{B}$	$\mathcal{O}_{ll}, \mathcal{O}^{(1)}_{qq}, \mathcal{O}^{(1)}_{lq}, \mathcal{O}_{ee}, \mathcal{O}_{dd}, \mathcal{O}_{uu}, \mathcal{O}_{ed}, \mathcal{O}_{eu}, \mathcal{O}^{(1)}_{ud}, \mathcal{O}_{le}, \mathcal{O}_{ld}, \mathcal{O}_{lu}, \mathcal{O}_{qe}, \mathcal{O}^{(1)}_{qu}, \mathcal{O}^{(1)}_{qd}, \mathcal{O}_{\phi D}, \mathcal{O}_{\phi\Box}, \mathcal{O}_{e\phi}, \mathcal{O}_{d\phi}, \mathcal{O}_{u\phi}, \mathcal{O}^{(1)}_{\phi l}, \mathcal{O}^{(1)}_{\phi q}, \mathcal{O}_{\phi e}, \mathcal{O}_{\phi d}, \mathcal{O}_{\phi u}$
$\mathcal{B}_1$	$\mathcal{O}_{\phi 4}, \mathcal{O}^{(1)}_{ud}, \mathcal{O}^{(8)}_{ud}, \mathcal{O}_{\phi}, \mathcal{O}_{\phi D}, \mathcal{O}_{\phi\Box}, \mathcal{O}_{e\phi}, \mathcal{O}_{d\phi}, \mathcal{O}_{u\phi}, \mathcal{O}_{\phi ud}$
$\mathcal{W}$	$\mathcal{O}_{\phi 4}, \mathcal{O}_{ll}, \mathcal{O}^{(3)}_{qq}, \mathcal{O}^{(3)}_{lq}, \mathcal{O}_{\phi}, \mathcal{O}_{\phi D}, \mathcal{O}_{\phi\Box}, \mathcal{O}_{e\phi}, \mathcal{O}_{d\phi}, \mathcal{O}_{u\phi}, \mathcal{O}^{(3)}_{\phi l}, \mathcal{O}^{(3)}_{\phi q}$
$\mathcal{W}_1$	$\mathcal{O}_{\phi 4}, \mathcal{O}_{\phi}, \mathcal{O}_{\phi D}, \mathcal{O}_{\phi\Box}, \mathcal{O}_{e\phi}, \mathcal{O}_{d\phi}, \mathcal{O}_{u\phi}$
$\mathcal{G}$	$\mathcal{O}^{(1)}_{qq}, \mathcal{O}^{(3)}_{qq}, \mathcal{O}_{dd}, \mathcal{O}_{uu}, \mathcal{O}^{(8)}_{ud}, \mathcal{O}^{(8)}_{qu}, \mathcal{O}^{(8)}_{qd}$
$\mathcal{G}_1$	$\mathcal{O}^{(1)}_{ud}, \mathcal{O}^{(8)}_{ud}$
$\mathcal{H}$	$\mathcal{O}^{(1)}_{qq}, \mathcal{O}^{(3)}_{qq}$
$\mathcal{L}_1$	$\mathcal{O}_{\phi 4}, \mathcal{O}_{y^e}, \mathcal{O}_{y^d}, \mathcal{O}_{y^u}, \mathcal{O}_{le}, \mathcal{O}^{(1)}_{qu}, \mathcal{O}^{(8)}_{qu}, \mathcal{O}^{(1)}_{qd}, \mathcal{O}^{(8)}_{qd}, \mathcal{O}_{ledq}, \mathcal{O}^{(1)}_{quqd}, \mathcal{O}^{(1)}_{lequ}, \mathcal{O}_{\phi}, \mathcal{O}_{\phi D}, \mathcal{O}_{\phi\Box}, \mathcal{O}_{\phi B}, \mathcal{O}_{\phi \tilde{B}}, \mathcal{O}_{\phi W}, \mathcal{O}_{\phi \tilde{W}}, \mathcal{O}_{\phi WB}, \mathcal{O}_{\phi \tilde{W}B}, \mathcal{O}_{e\phi}, \mathcal{O}_{d\phi}, \mathcal{O}_{u\phi}, \mathcal{O}_{eB}, \mathcal{O}_{eW}, \mathcal{O}_{dB}, \mathcal{O}_{dW}, \mathcal{O}_{uB}, \mathcal{O}_{uW}, \mathcal{O}^{(1)}_{\phi l}, \mathcal{O}^{(3)}_{\phi l}, \mathcal{O}^{(1)}_{\phi q}, \mathcal{O}^{(3)}_{\phi q}, \mathcal{O}_{\phi e}, \mathcal{O}_{\phi d}, \mathcal{O}_{\phi u}$
$\mathcal{L}_3$	$\mathcal{O}_{le}$
$\mathcal{U}_2$	$\mathcal{O}^{(1)}_{lq}, \mathcal{O}^{(3)}_{lq}, \mathcal{O}_{ed}, \mathcal{O}_{ledq}$
$\mathcal{U}_5$	$\mathcal{O}_{eu}$
$\mathcal{Q}_1$	$\mathcal{O}_{lu}, \mathcal{O}^{(1)}_{qd}, \mathcal{O}^{(8)}_{qd}, \mathcal{O}_{duq}$
$\mathcal{Q}_5$	$\mathcal{O}_{qe}, \mathcal{O}^{(1)}_{qu}, \mathcal{O}^{(8)}_{qu}, \mathcal{O}_{ledq}, \mathcal{O}_{duq}, \mathcal{O}_{qqu}$
$\mathcal{X}$	$\mathcal{O}^{(1)}_{lq}, \mathcal{O}^{(3)}_{lq}$
$\mathcal{Y}_1$	$\mathcal{O}^{(1)}_{qd}, \mathcal{O}^{(8)}_{qd}$
$\mathcal{Y}_5$	$\mathcal{O}^{(1)}_{qu}, \mathcal{O}^{(8)}_{qu}$

New heavy vector bosons

1711.10391

Global fit to SMEFT operator coefficients

- Experiments have infrastructure for a global EFT fit
  - Most effort comes in correlating systematics when combining datasets
  - Existing Higgs combinations could be reparameterized for EFT
    - Tools available for this purpose

- Two main issues for global experimental fit
  - extending experimental combination to top & EW data
    - needs coordination across experiment
  - defining procedures for EFT parameterization

- A strategy is to build up the fit in stages
  - E.g. start with 20-30 complementary measurements and operators
  - Then add measurements and expand applicability

EFT parameterization issues

- Parameter ranges and constraints
- Order of EFT expansion
- SM coupling order & EFT running
- Scales

Parameter ranges and constraints

- EFT parameterization is greatly simplified if a high-scale perturbative theory is required
  - Allows the truncation of coefficients whose maximum contribution is much less than the uncertainty in a given measurement
    - Require e.g. new physics scale Λ > vev and operator coefficients <1?
  - Also allows a marginalization over unconstrained parameters
    - flat over the full multidimensional parameter space

- LHC top WG recommends presenting two constraints on individual parameters: all parameters varied or only individual parameters varied
  - Gives an indication of correlations in constraints
  - WG also recommends giving individual constraints from each process

From LHC top WG EFT report: (1802.07237)

- Main recommendations:
  1. Provide individual (also by process) and global (marginalised) constraints
  2. Provide constraints using i) linear and ii) linear+squared terms
  3. Provide information on the energy scales probed by the process

Order of SMEFT expansion

- General form of expansion is in orders of $1/\Lambda^n$
  - First order preserving lepton number is $1/\Lambda^2$
    - Deviations from SM expressed in terms of operators at dimension 6 (& 5)

$$|\mathcal{M}_{SMEFT}|^2 = |\mathcal{M}_{SM}|^2 + \mathcal{M}_{SM}^{*}\mathcal{M}_{d6} + \mathcal{M}_{SM}\mathcal{M}_{d6}^{*} + |\mathcal{M}_{d6}|^2 + \mathcal{M}_{SM}^{*}\mathcal{M}_{d8} + \mathcal{M}_{SM}\mathcal{M}_{d8}^{*} + \ldots$$

$$\sim c_6 Q^2/\Lambda^2 \qquad \sim c_6^2 Q^4/\Lambda^4 \qquad \sim c_8 Q^4/\Lambda^4$$

Non-zero dimension-6 operator coefficients give specific contributions at $O(1/\Lambda^4)$

Including these contributions in a calculation only captures a portion of the terms at $O(1/\Lambda^4)$

Other contributions come from dimension-8 operators and from field redefinitions expanded to $1/\Lambda^4$

Some new physics effects may first appear at $O(1/\Lambda^4)$

Generally due to suppressed interference with the SM

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- Main recommendations:
  1. Provide individual (also by process) and global (marginalised) constraints
  2. Provide constraints using i) linear and ii) linear+squared terms
  3. Provide information on the energy scales probed by the process

Order of SMEFT expansion

- Ideal (long-term?) solution: fit to $O(1/\Lambda^2)$ and $O(1/\Lambda^4)$
  - Specific models can be mapped to each order of results, providing an estimate of the truncation uncertainty on the model parameters

- Practical (short-term?) solution: prioritize fit to $O(1/\Lambda^2)$, partially fit to $O(1/\Lambda^4)$
  - Fit at $O(1/\Lambda^2)$ substantially simplifies the procedures
    - New physics at a low scale (~TeV) may have significant truncation uncertainty
  - Several options for partial fit to $O(1/\Lambda^4)$

    1. Maximize inclusion of $O(1/\Lambda^4)$ terms, e.g. all contributions from dim-6 operators (including field redefinitions) plus all known contributions from dim-8
       – Possible with current tools and marginalization over some dim-8 operators
    2. Maximize inclusion of dim-6 operators to $O(1/\Lambda^4)$
       – Effective Lagrangian approach

    - 3. Include only contributions from individual dim-6 operators at $O(1/\Lambda^4)$, i.e. $\sim c_i^2$
       – Simplified but only indicative: interpretation not well defined

SM coupling order & EFT running

- SMEFT prediction generally parameterized as LO correction to SM
  - e.g. $d\sigma = \sigma_{SM}^{best} (\sigma_{SMEFT}^{LO}/\sigma_{SM}^{LO} - 1)$
- At higher orders in the SM couplings additional coefficients appear
- These higher-order terms could be the leading source of new physics in a process if the EFT coefficients affecting the process at first order are small
  - In general aim to parameterize the EFT effects at highest available order
    - When the maximum effect of the EFT operators becomes small compared to the experimental uncertainty then the order is sufficient
    - Generally want to go to NLO to check this
      - Is partial NLO sufficient for these checks?
    - Alternatively: run EFT coefficients to capture dependence on new coefficients
      - Allows a clear definition of the scale of the evaluated coefficients (e.g. vev)
      - Also allows an estimate of the perturbative uncertainty

Scales

From LHC top WG EFT report:
(1802.07237)

- Main recommendations:
  1. Provide individual (also by process) and global (marginalised) constraints
  2. Provide constraints using i) linear and ii) linear+squared terms
  3. Provide information on the energy scales probed by the process

- YR4 discussed cutting out data at scales close to EFT scale
- However, determining the scale of the process is generally non-trivial
  - Even more so for EFT coefficients in high-multiplicity final states
- Approximate scale can be provided but prefer not to remove data
  - May not be appropriate for some models
  - For specific models one can consider the quoted scales and the applicability
  - Detailed checks and an alternative fit could be performed
- Prefer a more rigorous procedure to give limitations of EFT truncation
  - E.g. impact of dimension-8 operators on an observable

Backup

Operators

- A first global fit can focus on W, Z, Higgs, and top production on shell
  - This suppresses many four-fermion operators
- Operators primarily constrained by Higgs measurements are:
  - Hgg CP-even & odd (2 x 1)
  - HVV CP-even & odd (2 x 3)
  - Hff real and phase (2 x 3)
  - Higgs normalization (1)
  - Higgs self-coupling (1)
- 9 CP-even + 7 CP-odd
  - Many other operators appear in Higgs production: need top & EW constraints

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

arXiv:1610.07922

EFT tools

- Various options for studying operator dependence of a process
  - One straightforward method:
    - Import EFT model file into Madgraph
    - Run interference-only generation for various parameter values
    - Linearize parameter dependence for fit to $O(1/\Lambda^2)$
    - Additionally run BSM-only generation for parameters singly and in pairs
    - Truncate after quadratic terms ($c_i c_j$) for fit to $O(1/\Lambda^4)$
    - Fits using both cases give a handle on the uncertainty from truncating the EFT
- If NLO QCD is expected to modify the dependence of an observable on an operator then we can ask EFT authors for a preliminary implementation
- Can potentially also ask for dimension-8 operators affecting the process

Standard Model Effective Field Theory -- The SMEFTsim package

Authors

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Validation under way by comparing SMEFTsim to the NLO QCD implementation of Maltoni et al

Status report expected in general session of LHCXSWG on 12 December

Measurements

- Studying operator dependence of various distributions and backgrounds can help define sensitive measurements
  - Most widely useful is a straightforward fiducial differential measurement
  - Another strategy is to define a fiducial region, slice into several subregions
    - ‘Template’ cross sections (STXS)
    - Allows further optimization to reject background in measurement regions
    - Need to check the operator dependence in extrapolating from optimized phase space to fiducial phase space
      - Aim for negligible dependence

- Should check effect of background and splitting results by process
  - So far assume that operators in background are constrained elsewhere
  - Process splitting relies on SM kinematics

- Simplest procedure for interpretation is to measure a distribution and define selection to be orthogonal to other analyses
  - Not a requirement if bootstrapping can be used
  - Consider whether to use a uniform strategy or to choose case-by-case