Constraining the SMEFT in the top sector at the LHC

Gauthier Durieux
(DESY)

for the current authors:
J.A. Aguilar Saavedra, C. Degrande, F. Maltoni, E. Vryonidou, C. Zhang

with input and feedback from:

and EFT enthusiasts from ATLAS and CMS

TOP LHC WG Meeting
CERN, 2-3 Nov 2017
Timeline

Spring: TH brainstorming

June: first ideas on paper, presentation, first feedback, new contributions

Summer: re-thinking and implementation,
         UFO as mediator between TH and EXP teams

Mid-October: v0 put together

November−ε: 10^+ pages of feedback received, overall agreement on principles,
             interesting suggestions, questions raised, clarifications requested

Today: open discussion

November+ε: implementation in v1 and release
Content

For v1
▶ guiding principles
▶ an example of EFT analysis strategy
  – flavour assumptions
  – corresponding degrees of freedom
  – indicative direct constraints
  – UFO implementation and benchmarks

Foreseen
  – FCNCs
  – NLO QCD
  – indirect constraints, from EDMs, flavour, etc.
    ...  
  – theory uncertainties
  – unstable tops
    ...
Guiding principles
Guiding principles

Still Warsaw as reference basis, still only operators involving tops, but:

Previous approach

- attempt to determine the d.o.f. relevant for given processes
- hierarchize their contributions
  (QCD vs. EW, $m_b/m_t$ or PDF suppressions...)

!! model dependent
!! observable/phase-space dependent
!! not fitting the global EFT scheme

Now more general and phenomenological

1. all tree-level contributions on the same footing
2. hierarchies derive from existing constraints for each observable $O^k$
3. compute higher orders in SM couplings where necessary
Guiding principles

Implications

- Give up, for now, on the stating which d.o.f. is relevant in which process.
- Recommend to determine the EFT dependence observable-by-observable.
  - Naive hierarchies are upset in too many instances.
  - Use MC for instance. Some benchmarks given, notably for total rates.
  - The picture will become clearer/more specific with time.

- The d.o.f. relevance in a measurement may change as constraints are collected!
Guiding principles

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⇒ Measurement should be re-interpretable!
  - in an evolving global EFT picture
  - with more sophisticated predictions
  - with less restrictive assumptions
    (e.g. about flavour, non-top operators, etc.)
An example of EFT analysis strategy
An example of EFT analysis strategy

Warning: dangerous territory for a theorist!
· to show how EFT challenges could be addressed
· to fix ideas on what are useful outputs from a TH perspective

Choose a (particle-level) fiducial volume close enough to the detector level for unfolding to be very model independent.

Check it!
→ allows re-interpretation without full simulation
→ greatly facilitates multi-dimensional EFT analyses
An example of EFT analysis strategy

For $O^k$ observables

total rate, binned $p_T$, $\eta$, $m_{xy}$, etc. distributions,
binned MVA output, ratios, asymmetries, *optimal* observables,…

Unfold

detector level

particle level

Provide

- observable definitions (code if non-standard)
- stat. uncertainties
- systematics breakdown

(→ re-interpretable in any model)
Global EFT interpretation

- Compute EFT predictions to the particle level

\[ O^k = B_i^k + \frac{C_i}{\Lambda^2} S_i^k + \frac{C_i C_j}{\Lambda^4} S_{ij}^k + \ldots \]

- Obtain and release likelihoods in the full \( \{ C_i \} \) space

\( \equiv \text{global} \) constraints to combine with other measurements
- also quote **individual** constraints

  → information about sensitivity and the magnitude of approximate degeneracies

- quote both the **linear** and **quadratic** dim-6 approx.

  → information about the importance of higher powers of dim-6 coeff.

- quote limits as functions of $E_{\text{cut}}$

  → valid interpretation for models with lower scales

  → perturbativity possibly ensured by minimal $E_{\text{cut}}$

\[
\sum_{n=1}^{\infty} \cdots \cdots \cdots \cdots \sim \sum_{n} \left( \text{cst} \frac{C_{i} E_{\text{cut}}^{2}}{(4\pi \Lambda)^{2}} \right)^{n}
\]
Degrees of freedom
Flavour assumptions

(not applicable for top FCNCs, treated separately)

Lepton sector (not critical)
- rather loose $U(1)_{l_1+e_1} \times U(1)_{l_2+e_2} \times U(1)_{l_3+e_3}$ aka flavour diagonality
- could easily be restricted to $U(3)_{l+e}$, or even $U(3)_l \times U(3)_e$

Quark sector (baseline and variants)
to effectively reduce the huge number of four-quark operators

Baseline $U(2)_q \times U(2)_u \times U(2)_d$
  $\equiv$ SM flavour symmetry in the limit $y_{u,d,s,c} \rightarrow 0$, $V_{CKM} \rightarrow I$
  forces the first two generations to appear as $\sum_{i=1,2} \bar{q}_i q_i, \; \bar{u}_i u_i, \; \bar{d}_i d_i$

Extended to $U(2)_{q+u+d}$ [sugg. by J.A.Aguilar Saavedra]
- allows light right-handed charged currents $\sum_{i=1,2} \bar{u}_i d_i$
- allows light chirality flipping currents $\sum_{i=1,2} \bar{q}_i u_i, \; \bar{q}_i d_i$

Restricted to top-philic scenario [sugg. by A.Wulzer]
- assumes NP generates all operators with tops and bosons
- then project that over-complete set on the Warsaw basis with EOM, etc.
d.o.f. and constraints

<table>
<thead>
<tr>
<th></th>
<th>benchmark</th>
<th>extended</th>
<th>restricted</th>
</tr>
</thead>
<tbody>
<tr>
<td>four heavy quarks</td>
<td>9</td>
<td>9 + 10 CPV</td>
<td>5</td>
</tr>
<tr>
<td>two light and two heavy quarks</td>
<td>14</td>
<td>10 + 10 CPV</td>
<td>5</td>
</tr>
<tr>
<td>two heavy quarks and two leptons</td>
<td>(8 + 3 CPV)×3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>two heavy quarks and bosons</td>
<td>9 + 6 CPV</td>
<td>9 + 6 CPV</td>
<td></td>
</tr>
</tbody>
</table>

Indicative direct constraints: [many from TopFitter]

### Four-heavy (9 d.o.f.)

<table>
<thead>
<tr>
<th></th>
<th>Indicative direct limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{QQ}^1$</td>
<td>$2C_{qq}^{1(3333)} - \frac{2}{3} C_{qq}^{3(3333)}$ [-2.92, 2.80] ($E_{cut} = 3$ TeV) [4]</td>
</tr>
<tr>
<td>$c_{QQ}^8$</td>
<td>$8C_{qq}^{3(3333)}$</td>
</tr>
<tr>
<td>$c_{QQ}^+$</td>
<td>$C_{qq}^{1(3333)} + C_{qq}^{3(3333)}$ [-4.97, 4.90] ($E_{cut} = 3$ TeV) [4]</td>
</tr>
<tr>
<td>$c_{Qt}^1$</td>
<td>$C_{qu}^{1(3333)}$</td>
</tr>
<tr>
<td>$c_{Qt}^8$</td>
<td>$C_{qu}^{3(3333)}$</td>
</tr>
<tr>
<td>$c_{Qb}^1$</td>
<td>$C_{qd}^{1(3333)}$</td>
</tr>
<tr>
<td>$c_{Qb}^8$</td>
<td>$C_{qd}^{3(3333)}$</td>
</tr>
<tr>
<td>$c_{tt}^1$</td>
<td>$C_{uu}^{3(3333)}$</td>
</tr>
<tr>
<td>$c_{tt}^8$</td>
<td>$C_{ud}^{3(3333)}$</td>
</tr>
<tr>
<td>$c_{tb}^1$</td>
<td>$C_{ud}^{1(3333)}$</td>
</tr>
<tr>
<td>$c_{tb}^8$</td>
<td>$C_{ud}^{3(3333)}$</td>
</tr>
</tbody>
</table>

### Two-light-two-heavy (14 d.o.f.)

<table>
<thead>
<tr>
<th></th>
<th>Indicative direct limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{Qq}^{3,1}$</td>
<td>$C_{qq}^{3(1333)} + \frac{1}{6} (C_{qq}^{1(1331)} - C_{qq}^{3(1331)})$ [-0.66, 1.24] [5], [-3.11, 3.10] [4]</td>
</tr>
<tr>
<td>$c_{Qq}^{3,8}$</td>
<td>$C_{qq}^{1(1331)} - C_{qq}^{3(1331)}$ [-6.06, 6.73] [4]</td>
</tr>
<tr>
<td>$c_{Qq}^{1,1}$</td>
<td>$C_{qq}^{1(1331)} + \frac{1}{6} C_{qq}^{1(1331)} + \frac{1}{2} C_{qq}^{3(1331)}$ [-3.13, 3.15] [4]</td>
</tr>
<tr>
<td>$c_{Qq}^{1,8}$</td>
<td>$C_{qq}^{1(1331)} + 3C_{qq}^{3(1331)}$ [-6.92, 4.93] [4]</td>
</tr>
</tbody>
</table>
UFO implementation

- $90^+$ d.o.f. of the extended flavour scenario
- LO for now

Benchmark dependences

\[ \text{e.g. linear contributions } (S^k_i) \text{ to total rates:} \]

<table>
<thead>
<tr>
<th>SM</th>
<th>$pp \to t\bar{t}$</th>
<th>$pp \to t\bar{t}b\bar{b}$</th>
<th>$pp \to t\bar{t}t\bar{t}$</th>
<th>$pp \to t\bar{t} e^+\nu$</th>
<th>$pp \to t\bar{t} e^+ e^-$</th>
<th>$pp \to t\bar{t} \gamma$</th>
<th>$pp \to t\bar{t} h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{Qq}$</td>
<td>cQQ1</td>
<td>-0.25</td>
<td>-1.5</td>
<td>$-1 \times 10^2$</td>
<td>-1.6</td>
<td>-0.66</td>
<td>-0.71</td>
</tr>
<tr>
<td>$c_{Qt}$</td>
<td>cQt1</td>
<td>-0.15</td>
<td>-4.3</td>
<td>$1 \times 10^2$</td>
<td>-0.77</td>
<td>-0.19</td>
<td>-0.56</td>
</tr>
<tr>
<td>$c_{Qb}$</td>
<td>cQb1</td>
<td>-0.0055</td>
<td>0.53</td>
<td>-0.051</td>
<td>-0.014</td>
<td>-0.0069</td>
<td>-0.029</td>
</tr>
<tr>
<td>$c_{tb}$</td>
<td>ctb8</td>
<td>0.14</td>
<td>3.2</td>
<td>0.12</td>
<td>0.35</td>
<td>0.16</td>
<td>0.57</td>
</tr>
<tr>
<td>$c_{tt}$</td>
<td>ctt1</td>
<td>0</td>
<td>-1.6 $\times 10^2$</td>
<td>0.056</td>
<td>-0.02</td>
<td>-0.023</td>
<td>-0.04</td>
</tr>
<tr>
<td>$c_{td}$</td>
<td>ctd8</td>
<td>4.8</td>
<td>7.2</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>28</td>
</tr>
<tr>
<td>$c_{q1}$</td>
<td>cQq13</td>
<td>3.3</td>
<td>5.3</td>
<td>5.1</td>
<td>1.1 $\times 10^2$</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>$c_{tq}$</td>
<td>ctq1</td>
<td>0.67</td>
<td>2.7</td>
<td>-8.3</td>
<td>8.7</td>
<td>0.66</td>
<td>3.5</td>
</tr>
<tr>
<td>$c_{tq}$</td>
<td>cQq11</td>
<td>0.82</td>
<td>0.19</td>
<td>-7.9</td>
<td>-6.1</td>
<td>-4.8</td>
<td>2.8</td>
</tr>
<tr>
<td>$c_{tu}$</td>
<td>ctu1</td>
<td>1.1</td>
<td>0.86</td>
<td>-4</td>
<td>2.3</td>
<td>3.5</td>
<td>6.9</td>
</tr>
<tr>
<td>$c_{tq}$</td>
<td>ctd1</td>
<td>-0.38</td>
<td>-1.2</td>
<td>-4.9</td>
<td>-0.94</td>
<td>-1.2</td>
<td>-2.1</td>
</tr>
<tr>
<td>$c_{tq}$</td>
<td>ctp</td>
<td>$-2.1 \times 10^{-5}$</td>
<td>-23</td>
<td>-8.7</td>
<td>-0.034</td>
<td>-0.0093</td>
<td>$-2.9 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

[permil of the SM rate, $\Lambda = 1$ TeV]
UFO implementation

- 90⁺ d.o.f. of the extended flavour scenario
- LO for now

Benchmark dependences

e.g. quadratic contributions ($S_{ij}^k$) to total rates:

<table>
<thead>
<tr>
<th>$c_{ij}$</th>
<th>$S_{ij}^k$</th>
<th>$S_{ij}^l$</th>
<th>$S_{ij}^m$</th>
<th>$S_{ij}^n$</th>
<th>$S_{ij}^o$</th>
<th>$S_{ij}^p$</th>
<th>$S_{ij}^q$</th>
<th>$S_{ij}^r$</th>
<th>$S_{ij}^s$</th>
<th>$S_{ij}^t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0041</td>
<td>$2 \times 10^{-13}$</td>
<td>0.0035</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
<td>0.0041</td>
</tr>
<tr>
<td>0.0042</td>
<td>$2 \times 10^{-13}$</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
<td>0.0042</td>
</tr>
</tbody>
</table>

Table 5: Quadratic dependence on the various degrees of freedom of the total rate. Absolute values for $[\text{pb, pp} \rightarrow t\bar{t}, \Lambda = 1 \text{ TeV}]$
That’s it for the overview!

Thanks for all the contributions and feedback!

The floor is open for discussion!

Watch for v1!