Top quark physics and the EFT

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The top is special
The top is special

1. It is rich

   It is the elementary particle with the largest mass so far.
The top is special

1. It is rich

It is the elementary particle with the largest mass so far.

2. It is strong

\[ m_{\text{top}} = y_t \sqrt{v^2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1 \]

Since last Monday we know that it "strongly" interacts with the Higgs sector.

Exciting results!
A new chapter in Higgs and top physics is now open.
The top is special

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It is the elementary particle with the largest mass so far.

2. **It is strong**

\[ m_{\text{top}} = y_t v / \sqrt{2} \approx 174 \text{ GeV} \Rightarrow y_t \approx 1 \]

Since last Monday we know that it “strongly" interacts with the Higgs sector.

3. **It is naked**

\[ \tau_{\text{had}} \approx \frac{h}{\Lambda_{\text{QCD}}} \approx 2 \times 10^{-24} \text{ s} \]
\[ \tau_{\text{top}} \approx \frac{h}{\Gamma_{\text{top}}} = \frac{1}{(\text{GF} m_t^3 |V_{tb}|^2 / 8\pi \sqrt{2})} \approx 5 \times 10^{-25} \text{ s} \]

(with \( h = 6.6 \times 10^{-25} \text{ GeV s} \))

(Compare with \( \tau_b \approx (\text{GF}^2 \text{ mb}^5 |V_{bc}|^2)^{-1} \approx 10^{-12} \text{ s} \))
The top is special

4. It is popular

**Strong**

\[
\begin{aligned}
q & \rightarrow \bar{q} + t + \bar{t} \\
\bar{q} & \rightarrow q + \bar{t} + t \\
g & \rightarrow \bar{t} + t
\end{aligned}
\]

**Weak**

\[
\begin{aligned}
q & \rightarrow W + t + \bar{t} \\
\bar{q} & \rightarrow b + \bar{t} + t \\
g & \rightarrow W + t
\end{aligned}
\]

**Associated**

\[
\begin{aligned}
ttH & \\
ttZ & \\
tttt & \leq (2 - 3) \cdot 10^3
\end{aligned}
\]

\[10^6\] \[250 \cdot 10^3\] \[\leq (2 - 3) \cdot 10^3\]

number of events @13TeV \(1\) fb\(^{-1}\)
The top is special

5. It goes beyond (the SM)

\[ \Delta(m_{h_0}^2) = \frac{8}{3\pi^2} m_T^2 \log \Lambda \]

\[ \mathcal{L} = y_t \left[ i q h \bar{t}^c + f \left( 1 - \frac{h^\dagger h}{2f^2} \right) T T^c + \ldots \right] + h.c. \]
The top is special

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2. It is strong
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4. It is popular
5. It goes beyond
The top is special

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2. It is strong
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4. It is popular
5. It goes beyond

The top quark is the Ronaldo of elementary particles
Search for New Physics at the LHC

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

\[ \mathcal{L}_\text{SM}^{(6)} = \mathcal{L}_\text{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6
• Based on all the symmetries of the SM
• Extends the reach of searches for NP beyond the collider energy.
• Valid only up to the scale $\Lambda$
• 59 operators (when flavour universal)
SMEFT

\[ \mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \ldots \]

Three important observations:

1. The SMEFT is **not** stress-testing the SM, it is measuring the parameters of the SM Lagrangian…at dim=6. In other words it is a consistent QFT, i.e. it is renormalisable in QCD and EW (order by order in 1/\(\Lambda\)) interactions. Loops can be consistently included.

2. Without UV model/bias, all operators enter on the same footing. In particular the \(c_i\) cannot be ordered a priori. The SM (and anomalous coupling) naive classification in terms of strong and EW top couplings does not hold.

3. A global fitting strategy at the EW scale needs to be set in place to extract information from the LHC data. In particular, one has to assume all couplings might not be zero at the EW scale.
Top operators and processes

Several operators typically enter each process at LO (or at LO$^2$) and

<table>
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<tr>
<th>NLO</th>
<th>Process</th>
<th>$O_{tG}$</th>
<th>$O_{tB}$</th>
<th>$O_{tW}$</th>
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<th>$O_{\varphi Q}^{(1)}$</th>
<th>$O_{\varphi t}$</th>
<th>$O_{t\varphi}$</th>
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LO fit at the LHC

- EFT based, fit on Tevatron and LHC data: total as well as differential information from ttbar and t-channel single-top.

- SM at NLO (or NNLO) and EFT at LO in QCD (Feynrules+MadGraph).

**TABLE 1:** All dimension-six operators relevant to top quark production, in the notation of Ref. [12]. Details of each are included in the text. We do not include explicit flavor indices here. 13 operators are shown, but $O_{tW}$ and $O_{tG}$ have both real and imaginary parts which should be considered as independent operators; the latter produce $\mathcal{CP}$-violating effects.
Need for NLO

1. Operators run and mix under RGE

2. EFT scale dependence

3. Genuine NLO corrections (finite terms) are important

4. New operators arise
Need for NLO

4. New operators arise

New operators can arise at one-loop or via real corrections.

• At variance with the SM, loop-induced processes might not be finite.

• Including the full set of operators at a given order implies that no extra UV divergences appear (closure check).

• Use tree-level, loop-level, hierarchy but not gauge couplings.

[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15a]
[Hartmann and Trott, 15]
[Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, 15b]
[Dawson, Giardino, 2018]
[Dedes et al, 2018]
[Vryonidou and Zhang, 2018]
SMEFT for top physics

Implementations and results in FeynRules + MG5aMC

Top SMEFT : Implementation
arXiv:1802:07237 : Interpreting top-quark LHC measurements in the SMEFT (Benchmarks for exp analyses and minimal strategy. Two independent FeynRules implementation)

Top FCNC @NLO
arXiv:1305.7386 : Top-quark decay into Higgs boson and a light quark at next-to-leading order in QCD
arXiv:1412.5594 : Automatic computations at NLO in QCD for top-quark flavour-changing neutral processes
arXiv:1412.7166 : Global approach to top-quark flavour-changing interactions

Top SMEFT @NLO
arXiv:1404.1264 : Top decays at NLO in QCD in the SMEFT
arXiv:1503.08841 : Probing the top-quark chromo-magnetic dipole moment at next-to-leading order in QCD
arXiv:1601.06163 : Single Top Production at NLO in the Standard Model Effective Field Theory
arXiv:1601.08193 : Probing top quark neutral couplings in the SMEFT at NLO in QCD
arXiv:1607.05330 : Higgs production in association with a top-anti-top pair in the SMEFT at NLO in QCD
arXiv:1708.00460 : Gluon-fusion Higgs production in the SMEFT
arXiv:1804.07773 : Single-top associated production with a Z or H at the LHC: the SMEFT interpretation
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Top SMEFT : Implementation

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Case study: tZj/tHj

• Single top rate about 1/4 of QCD tt
• Purely EW processes => no QCD contribution
• Sensitive to 2 four-fermion and 3 top/EW operators that modify tbW vertex
• Requiring the presence of an additional Z or Higgs
  • Unique possibility of probing full set of top/Higgs/EW operators at once
• Higher thresholds may enhance EFT effects
• Recent LHC measurement of tZj cross section at 4.2σ

SMEFT in tHj/tZj

tHj (tZj = h → Z) : classes of operators

- **Accessing the** $bW \to tH$ & $bW \to tZ$ sub-amplitudes
  - Rich interplay between EFT operators from different sectors
  - Different energy growth and interference with the SM
  - Four fermion interactions also present
SMEFT in $tHj/tZj$

\[ O_{\phi W} \]

\[ tHj \]

\[ tZj \]

\[ O_{t\phi} \]

\[ O^{(3,1)}_{Q_q} \quad O^{(3,8)}_{Q_q} \quad (O_{tG}) \]

\[ O_{\phi Q} \quad O_{tW} \quad O_{\phi tb} \]

\[ V_{H,VBF} \]

\[ O_{tB} \quad O_{\phi Q} \]

\[ O_{tW} \quad O_{\phi Q} \]

\[ O_{D_{WB}} \quad O_{W} \]

\[ O_{D_{WB}} \quad O_{W} \]
Existing limits

Combination of LHC single-top
$c_{Qq}^{(3,8)} \subset [-1.40, 1.20]$

Combination of ttH @ 13 TeV
$c_{t\varphi} \subset [-6.5, 1.3]$

<table>
<thead>
<tr>
<th>Op.</th>
<th>TF (I)</th>
<th>TF (M)</th>
<th>RHCC (I) tree/loop</th>
<th>SFitter (I)</th>
<th>PEWM$^2$</th>
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</table>

(I) : Individual
(M) : Marginalised

[Butler et al.; JHEP 1607 (2016) 152]
[Alioli et al.; JHEP 1705 (2017) 086]
[Buckley et al.; JHEP 1604 (2016) 015]
[Zhang et al.; PRD 86 (2012) 014024]
LHC sensitivity

Effects of operators with coefficients set at the boundaries of current exclusions
LHC sensitivity

Usual EFT story: looking at high energy tails increases sensitivity
Important to put into context w.r.t single top which has a much larger rate

\[
\begin{array}{cccccc}
 & l_j & l_j & lZ_j & lZ_j & lW_j \\
\tau = \sigma_i / \sigma_{SM} & \left( p_T^l > 350 \text{ GeV} \right) & \left( p_T^l > 250 \text{ GeV} \right) & & & \\
\sigma_{SM} & 221 \text{ pb} & 880 \text{ fb} & 839 \text{ fb} & 69 \text{ fb} & 75.9 \text{ fb} \\
\tau_{WW} & 0.0275 & 0.024 & 0.016 & 0.010 & 0.292 \\
\tau_{W^+W^-W} & 0.0162 & 0.35 & 0.095 & 0.67 & 0.940 \\
\tau_{QQ^{(3)}} & 0.121 & 0.121 & 0.192 & 0.172 & -0.132 \\
\tau_{Q^3Q^{(3)}} & 0.0037 & 0.0037 & 0.029 & 0.114 & 0.21 \\
\tau_{ttb,tQb} & 0.00090 & 0.0008 & 0.0050 & 0.027 & 0.050 \\
\tau_{LG} & 0.0003 & -0.01 & 0.00053 & -0.0048 & -0.0055 \\
\tau_{LG,AC} & 0.00062 & 0.045 & 0.0027 & 0.022 & 0.025 \\
\tau_{Q^3Q^{(3)}} & -0.353 & -4.1 & -0.59 & -2.22 & -0.39 \\
\tau_{Q^3Q^{(3)},Q^3Q^{(3)}} & 0.126 & 11.5 & 0.65 & 5.1 & 1.21 \\
\tau_{Q^3Q^{(3)},Q^3Q^{(3)}} & 0.0308 & 2.73 & 0.133 & 1.01 & 1.08 \\
\end{array}
\]

- Increased sensitivity for dipoles, RHCC
- Consistent with 2→2 subamplitude analysis
- Single top should eventually outperform tHj/tZj for four fermion operators
Current/Future sensitivity in tZj
Conclusions and Outlook

• The top quark is special (i.e. is the only normal) quark in the SM. It plays an important role and its electroweak behaviour could be a gateway to new physics.

• The most beaten path for searching new physics at the LHC so far it has involved top-down (or simplified models) approach to detecting new resonances.

A far reaching approach to new physics is that of searching for new interactions employing an EFT.

• The EFT approach provides a consistent QFT to work with. Predictions can be obtained and systematically improved. To be fully meaningful and useful, predictions have to be available at NLO accuracy in QCD (and EW) and constraints need to be obtained in a global way.

• TH results and MC tools to put in action this strategy have become available.

• New joint theoretical/experimental effort
Back-up slides
Need for NLO

1. Operators run and mix under RGE

**Running** means that the Wilson coefficients depend on the scale where they are measured (as the couplings in the SM). Note that this introduces also an additional uncertainty in the perturbative computations.

**Mixing** means that in general the Wilson coefficients at low scale (=where the measurements happen) are related. One immediate consequence is that assumptions about some coefficients being zero at low scales are in general not valid (and in any case have to be consistent with the RGEs). Note also that operator mixing is not symmetric: Op1 can mix into Op2, but not viceversa.
Need for NLO

2. EFT scale dependence

By including the mixing, the overall scale dependence at LO, is very much reduced with respect to the single ones. A global point of view is required: contribution from each coupling may not make sense; only their sum is meaningful.

\[\sigma(\text{total}) = c_1 \sigma_1 + c_2 \sigma_2 + c_3 \sigma_3\]

[Deutschmann, Duhr, FM, Vryonidou, 17]

\[O_{i\Phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q} t) \tilde{\phi},\]

\[O_{\Phi G} = y_t^2 \left( \phi^\dagger \phi \right) G_{\mu\nu}^A G_{A\mu\nu}^A,\]

\[O_{iG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \phi G_{\mu\nu}^A.\]

\[\frac{dC_i(\mu)}{d \log \mu} = \frac{\alpha_s}{\pi} \gamma_{ij} C_j(\mu),\]

\[\gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}\]
Need for NLO

3. Genuine NLO corrections (finite terms) are important

- pp → ttH
  
  \[ O_{t\phi} = y_t^3 \left( \phi \dagger \phi \right) (\bar{Q} t) \tilde{\phi}, \]
  
  \[ O_{\phi G} = y_t^2 \left( \phi \dagger \phi \right) G^A_{\mu\nu} G^{A\mu\nu}, \]
  
  \[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A_t) \tilde{\phi} G^A_{\mu\nu}. \]

- EFT scale uncertainties are very much reduced at NLO.

- RG are sometimes thought to be an approximation for full NLO, but it is often not the case.
Bounding OtG at NLO from $t\bar{t}$bar

Recent analysis at NLO in QCD

\[ \sigma = \sigma_{\text{SM}} + \frac{C_{tG}}{\Lambda^2} \beta_1 + \left( \frac{C_{tG}}{\Lambda^2} \right)^2 \beta_2 \]

Limits on $c tG$ from LHC8

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<th>NLO [TeV$^{-2}$]</th>
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<tbody>
<tr>
<td>Tevatron</td>
<td>[-0.33, 0.75]</td>
<td>[-0.32, 0.73]</td>
</tr>
<tr>
<td>LHC8</td>
<td>[-0.56, 0.41]</td>
<td>[-0.42, 0.30]</td>
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<tr>
<td>LHC14</td>
<td>[-0.56, 0.61]</td>
<td>[-0.39, 0.43]</td>
</tr>
</tbody>
</table>
SMEFT in $tHj/tZj$

\begin{align*}
\mathcal{O}_W & \quad \varepsilon_{IJK} W^I_{\mu
u} W^{J,\mu\rho} W^K_{\rho}^\mu \\
\mathcal{O}_{\varphi W} & \quad \left( \phi^\dagger \phi - \frac{v^2}{2} \right) W^{\mu\nu} W^I_{\mu\nu} \\
\mathcal{O}_{\varphi W_B} & \quad (\phi^\dagger \tau_I \phi) B^{\mu\nu} W^I_{\mu\nu} \\
\mathcal{O}_{\phi_D} & \quad (\phi^\dagger D^\mu \phi) (\phi^\dagger D^\mu \phi) \\
\mathcal{O}_{\phi L} & \quad (\phi^\dagger \phi) (\phi^\dagger \phi) \\
\mathcal{O}_{\varphi t} & \quad \left( \phi^\dagger \phi - \frac{v^2}{2} \right) \bar{Q} t \phi + \text{h.c.} \\
\mathcal{O}_{\varphi W} & \quad i(\bar{Q} \gamma^{\mu \nu} \tau_I t) \phi W^I_{\mu\nu} + \text{h.c.} \\
\mathcal{O}_{\varphi B} & \quad i(\bar{Q} \gamma^{\mu \nu} t) \phi B_{\mu\nu} + \text{h.c.} \\
\mathcal{O}_{\varphi G} & \quad i(\bar{Q} \gamma^{\mu \nu} T^A t) \phi G^A_{\mu\nu} + \text{h.c.} \\
\mathcal{O}_{\varphi Q} & \quad i(\phi^\dagger \bar{D}_\mu \tau_I \phi) (\bar{Q} \gamma^\mu \tau^I Q) + \text{h.c.} \\
\mathcal{O}_{\varphi Q}^{(3)} & \quad i(\phi^\dagger \bar{D}_\mu \tau_I \phi) (\bar{Q} \gamma^\mu \tau^I Q) + \text{h.c.} \\
\mathcal{O}_{\varphi Q}^{(1)} & \quad i(\phi^\dagger \bar{D}_\mu \phi) (\bar{Q} \gamma^\mu Q) + \text{h.c.} \\
\mathcal{O}_{\varphi l} & \quad i(\phi^\dagger D^\mu \phi) (\bar{t} \gamma^\mu t) + \text{h.c.} \\
\mathcal{O}_{\varphi q} & \quad i(\phi^\dagger D^\mu \phi) (\bar{q} \gamma^\mu q) + \text{h.c.} \\
\mathcal{O}_{\varphi q}^{(3)} & \quad i(\phi^\dagger \bar{D}_\mu \tau_I \phi) (\bar{q} \gamma^\mu \tau^I q) + \text{h.c.} \\
\mathcal{O}_{\varphi u} & \quad i(\phi^\dagger \bar{D}_\mu \phi) (\bar{u} \gamma^\mu u) + \text{h.c.} \\
\mathcal{O}_{\varphi q}^{(3,1)} & \quad (\bar{q} \gamma^\mu \tau_I q) (\bar{Q} \gamma^\mu \tau^I Q) \\
\mathcal{O}_{\varphi q}^{(3,8)} & \quad (\bar{q} \gamma^\mu \tau_I T^A q) (\bar{Q} \gamma^\mu \tau^I T^A Q)
\end{align*}
Single-top in the EFT at NLO

4F operator can also be included (on-going).

NLO corrections distort LO distributions, they impact the limits in accuracy and precision.
ttZ and t\textgamma\textgamma in the EFT at NLO

\[ \sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2} \sigma_i^{(1)} + \sum_{i<j} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4} \sigma_{ij}^{(2)} \]

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]

Small contribution from OtW and OtB at \(O(1/\Lambda^2)\) but large at \(O(1/\Lambda^4)\)

How should we treat \(O(1/\Lambda^4)\) terms?

\[
C_i^2 \frac{E^4}{\Lambda^4} > C_i \frac{E^2}{\Lambda^2} > 1 > \frac{E^2}{\Lambda^2}
\]

EFT condition satisfied. To be checked on a case-by-case basis

\[
O_{\varphi Q}^{(3)} = \frac{1}{2} y_t^2 \left( \varphi^\dagger D_\mu \varphi \right) (\bar{Q} \gamma^\mu \tau^I Q)
\]
\[
O_{\varphi Q}^{(1)} = \frac{1}{2} y_t^2 \left( \varphi^\dagger \bar{D}_\mu \varphi \right) (\bar{Q} \gamma^\mu Q)
\]
\[
O_{\varphi t} = \frac{1}{2} y_t^2 \left( \varphi^\dagger \bar{D}_\mu \varphi \right) (t \gamma^\mu t)
\]
\[
O_{tW} = y_t g_w (Q \sigma^{\mu \nu} \tau^I t) \bar{\varphi} W^I_{\mu \nu}
\]
\[
O_{tB} = y_t g_Y (\bar{Q} \sigma^{\mu \nu} t) \bar{\varphi} B_{\mu \nu}
\]
\[
O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu \nu} T^A t) \bar{\varphi} G^A_{\mu \nu}
\]

Anom. dim. matrix:

\[
\begin{pmatrix}
\frac{2\alpha_s}{\pi} & 0 & 0 \\
\frac{1}{6} & 0 & 0 \\
\frac{1}{6} & \frac{1}{3} & 0 \\
\frac{5}{9} & \frac{5}{9} & \frac{1}{3}
\end{pmatrix}
\]

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Fabio Maltoni
Using SM k-factors is not enough

Large contribution at $O(1/\Lambda^4)$ rising with energy

[Bylund, FM, Tsinikos, Vryonidou, Zhang, 2016]
ttZ and t\bar{t}\gamma in the EFT at NLO

Chromomagnetic operator affecting all processes in the same way.

LHC measurements of ttV processes can set constraints on the Wilson coefficients See also: [Rontsch and Schulze et al. 2014, 2015] and [Schulze 2016] in the anomalous coupling framework.
## Status of the SMEFT at NLO: Higgs production

<table>
<thead>
<tr>
<th>Channel</th>
<th>SM: QCD, EW</th>
<th>dim=6 : QCD</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>N3LO,NLO</td>
<td>NLO: $C_{t\phi}, C_{\phi G}, C_{tG}$</td>
<td>——</td>
</tr>
<tr>
<td>$gg \rightarrow Hj$</td>
<td>NNLO, LO</td>
<td>NLO: $C_{\phi G}$, LO: $C_{t\phi}, C_{tG}$</td>
<td>NLO hard to complete</td>
</tr>
<tr>
<td>$ttH$</td>
<td>NNLO, NLO</td>
<td>NLO</td>
<td>——</td>
</tr>
<tr>
<td>$bbH$</td>
<td>NNLO, LO</td>
<td>LO</td>
<td>NLO to do</td>
</tr>
<tr>
<td>$gg \rightarrow HH$ (LI)</td>
<td>NLO, LO</td>
<td>LO (apart $C_{\phi G}$)</td>
<td>NLO very hard</td>
</tr>
<tr>
<td>$gg \rightarrow HZ$ (LI)</td>
<td>LO, LO</td>
<td>LO</td>
<td>NLO very hard</td>
</tr>
<tr>
<td>$tHj$</td>
<td>NLO, LO</td>
<td>NLO</td>
<td>——</td>
</tr>
<tr>
<td>VBF</td>
<td>N3LO, NLO</td>
<td>(N)NLO</td>
<td>NLO EW welcome</td>
</tr>
<tr>
<td>VH</td>
<td>NNLO,NLO</td>
<td>(N)NLO</td>
<td>NLO EW welcome</td>
</tr>
</tbody>
</table>
ttH in the EFT

4 - fermion operators

\[ O_{t\phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q} t) \tilde{\phi} \]
\[ O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G^A_{\mu\nu} G^{A\mu\nu} \]
\[ O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu} \]

[In progress]

[Multijet constraints: Krauss et al arXiv:1611.00767]
ttH in the SMEFT

NLO: smaller uncertainties, non-flat K-factors

Different shapes for different operators for the squared terms

[FM, Vryonidou, Zhang, 16]
A global approach on top/Higgs on a subset of ops

\[ O_{t\phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q}t) \tilde{\phi} \]
\[ O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G^A_{\mu\nu} G^{A\mu\nu} \]
\[ O_{tG} = y_t g_s (\bar{Q}_\phi^{\mu\nu} T^A t) \tilde{\phi} G^{A}_{\mu\nu} \]
ggH in the SMEFT

Earlier studies of ggH in the SMEFT  [Degrande et al. 12]  [Grojean et al. 13]

More recently,  [Grazzini, Ilnicka, Spira, Wiesemann,16]
ggH in the SMEFT

Now known at NLO (two-loop virtuals+1-loop real)

\[
\mathcal{R}_3 = i \pi m_t \beta_0 \left( 1 + 2 \log \tau \right) \left( \frac{\alpha^2}{\tau} \right) \left( 18 \log \tau - 35 \right) \\
+ \frac{m_t}{\tau} \left[ \theta \left( - 48 \text{Cl}_{-2}(\theta) - \frac{8}{3} \text{Cl}_{2,1}(\theta) + \frac{1}{3} \text{Cl}_2(\theta) \right) \log \tau - \frac{64}{3} \text{Cl}_{-2}(\theta) - 74 \text{Cl}_2(\theta) \right] \\
- 96 \text{Cl}_{-1}(\theta) - 9 \text{Cl}_{2,2}(\theta) - \frac{8}{3} \text{Cl}_{3,1}(\theta) - \frac{4}{3} \text{Cl}_3(\theta) \log \tau + \frac{5}{3} \text{Cl}_3(\theta)^2 \\
+ \frac{64}{48} \theta^2 - 2 \theta^3 + \theta^2 \left( \frac{1}{4} \log \tau^2 + \frac{92}{3} \log \tau + \frac{16}{3} \log(1 - \tau) + 5 \zeta_2 - \frac{100}{3} \right) \\
- \frac{64}{3} \text{Cl}_{-3}(\theta) - 64 \text{Cl}_3(\theta) - 18 \log \tau - \frac{104}{3} \zeta_1 \log \tau + 8 \zeta_3 - \frac{151}{3} \zeta_4 + \frac{71}{3} \right] \\
+ \frac{m_t}{\tau} \left[ \frac{32}{3} \left( 2 \text{Cl}_{-2}(\theta) - \frac{82}{3} \text{Cl}_{2,1}(\theta) - \frac{64}{3} \text{Cl}_2(\theta) \right) \right] \\
- \frac{32}{3} \text{Cl}_{-1}(\theta) - 16 \text{Cl}_3(\theta) + 8 \zeta_3 + \frac{5}{3} \log^2 \tau + \frac{62}{3} \log \tau \\
- \theta^2 \left( \frac{8}{3} \log(4 - \tau) + \frac{4}{3} \log \tau + \frac{1}{4} \right) + \frac{238}{3} \\
+ \frac{\alpha^2 m_t}{\sqrt(4 - \tau)} \phi_0 + \frac{64 \alpha^2 m_t}{\sqrt(4 - \tau)} - \frac{2 m_t}{\sqrt(4 - \tau)} \left( \frac{1 - 2 \tau}{\tau} \right) \mathcal{R}(\theta) \\
+ \frac{\theta m_t}{6 \sqrt(4 - \tau)} \left[ 13 \theta^2 + 62 - \frac{4}{\tau} (63 \theta^2 + 62) \right] - \frac{(4 - \tau) m_t}{\sqrt(4 - \tau)} \left[ - \frac{32}{3} \text{Cl}_2(\theta) + 3 \text{Cl}_3(\theta) \right. \\
+ \theta \left( \frac{16}{3} \log(4 - \tau) - \frac{1}{6} \log \tau - \frac{71}{2} \right) \right].
\]
ggH in the SMEFT

\[ C_1(\mu^2) = C_1(Q^2) - \frac{\alpha_s(Q^2)}{\pi} \log \frac{\mu^2}{Q^2} \left( C_1(Q^2) + 8 C_3(Q^2) \frac{m_t^2(Q^2)}{v^2} \right) + \mathcal{O}(\alpha_s(Q^2)^2), \]

\[ C_2(\mu^2) = C_2(Q^2) + \sqrt{2} \frac{C_3(Q^2)}{16 \pi^2} \log \frac{\mu^2}{Q^2} \frac{m_t(Q^2)}{\langle v \rangle} \]

\[ - \sqrt{2} \frac{\alpha_s(Q^2)}{192 \pi^3} C_3(Q^2) \log \frac{\mu^2}{Q^2} \frac{m_t(Q^2)}{\langle v \rangle} \left( 5 \log \frac{\mu^2}{Q^2} - 69 \right) + \mathcal{O}(\alpha_s(Q^2)^2), \]

\[ C_3(\mu^2) = C_3(Q^2) + C_3(Q^2) \frac{\alpha_s(Q^2)}{6\pi} \log \frac{\mu^2}{Q^2} + \mathcal{O}(\alpha_s(Q^2)^2). \]
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

\[
\sigma = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}
\]
ggH in the SMEFT

[Deutschmann, Duhr, FM, Vryonidou, 17]

Only linear terms:

\[-0.28 < -0.128C_1 + 114C_2 + 2.28C_3 < 0.48.\]

One operator at the time:

\[-3.8 < C_1 < 2.2, -0.0025 < C_2 < 0.0043, -0.12 < C_3 < 0.21.\]

At one operator at the time, inclusion of the quadratic terms change the limits by only 10%.

\[-0.28 < -0.128C_1 + 114C_2 + 2.28C_3 + 0.0038C_1^2 + 3000C_2^2 + 1.13C_3^2 - 6.78C_1C_2 - 0.138C_1C_3 + 122C_2C_3 < 0.48.\]

\[
\sigma = \sigma_{SM} + \sum_i \frac{1\text{TeV}^2}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1\text{TeV}^4}{\Lambda^4} C_i C_j \sigma_{ij}
\]
ggH in the SMEFT

Interference w/ SM

Squared (diagonal)

Squared (crossed)

The effects of the chromo are “degenerate” with those of the $O_{\phi G}$ operator in the interference and diagonal squared terms.

Note also the behaviour at small pT due to the bottom loop which has been only included in the SM part.
HH in the EFT

Contribution of the chromomagnetic operator to HH computed for the first time

To be investigated: the impact of the chromomagnetic operator in EFT analyses that focus on the extraction of the triple Higgs coupling $\lambda$ (e.g. arXiv:1502.00539 and arXiv:1410.3471)
Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]

Current limits using LHC measurements

\[
O_{t\phi} = y_t^3 \left( \phi^\dagger \phi \right) (\bar{Q}t) \tilde{\phi} \\
O_{\phi G} = y_t^2 \left( \phi^\dagger \phi \right) G_{\mu\nu}^A G^{A\mu\nu} \\
O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}^A
\]

14 TeV projection
3000 fb-1
Current/Future sensitivity in tHj
Approaches

EFT@NLO+PS

Data Analysis

Exp fit on $C_i$
Approaches

EFT@NLO Fit on $C_i$

Observable

SM Data Analysis