Effective Field Theory for Top Quark Physics at NLO in QCD

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Based on 1404.1264 and on going works with C. Degrande, G. Durieux, F. Maltoni and J. Wang

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Outline

1. Top EFT @ NLO Motivation
2. Top EFT for Top Decay and FCNC Production
3. Top EFT Summary
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Top facts:

- TH motivations for studying the top quark as a portal to NP remains there.
- More issues/possibilities with the Higgs discovery.
  - What does Higgs measurement tell us about the top?
- Top properties have been measured at high precision level.
  - $t\bar{t} \sim 5\%, V_{tb} \sim 10\%, \text{mass} \sim 0.5\%$,
- Accurate SM predictions from the TH side.
  - Key observables at NNLO in QCD, NLO in EW.
  - Various processes available at NLO in the form of MC generators.

What are TH needs for NP in top physics?
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  - What does Higgs measurement tell us about the top?
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What are TH needs for NP in top physics?
Needs for NP study

Apart from high precision predictions for SM observables:

- **EFT** for BSM: A consistent and complete model-independent framework
  - Quantify and constrain deviations from the SM.
  - Connections between top EFT and Higgs EFT.

- **NLO** for BSM top processes
  - Potentially large QCD corrections to top processes.

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⇒ **EFT @ NLO**
Effective Field Theory parametrizes unknown interactions in a model-independent way, by

- Integrating out heavy states.

\[ \mathcal{L}_{\text{Eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} O_i^{(8)} + \cdots \]

...an expansion of NP effects in $1/\Lambda^2$. 
EFT

- Well-defined field theory, has full SM gauge symmetry.
- Provides guidance to NP. Leading effects are parametrized by 59 dimension-six operators.
- Consistent global analyses can be performed to constrain NP.
- Radiative corrections can be consistently included. Predictions can be systematically improved. (Can go to higher order in $\alpha_s$, $1/\Lambda^2$, . . .)

$$\mathcal{O}(\alpha_s) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \cdots$$
Renormalizability

Effective Field Theory contains “non-renormalizable” terms, but it is renormalizable in the modern sense, i.e. order by order in $1/\Lambda^2$.

- In principle need to include all 59 at order $1/\Lambda^2$ to make the calculation renormalizable, — but we have to include them anyway for a global analysis.
Going to NLO is not a trivial task:

- More operators will enter.
- In general there can be mixing effects among them. (i.e. one will renormalize the others)

\[
\frac{dC_i(\mu)}{d\mu} = \gamma_{ij} C_j(\mu)
\]

- A meaningful analysis can only be made by considering them all.

\[
\begin{align*}
O_{\varphi G} &= (\varphi^\dagger \varphi)(G^a_{\mu\nu} G^a_{\mu\nu}) \\
O_{tG} &= y_t g s (\bar{Q}_{\sigma\mu\nu} T^A t_R) \varphi G^I_{\mu\nu} \\
O_{t\varphi} &= (\varphi^\dagger \varphi)(\varphi \bar{Q}) t
\end{align*}
\]
Mixing and global fit

- If a specific (arbitrary) choice of operator coefficients is made at high scales (where one can imagine a full theory to live), many operators become active when evolved to lower scales.
- Constraining one or few “anomalous coupling” at the time is not consistent with the fact that the operators mix and run under RGE equations: they need to be determined via a global fit at a given scale.
- To combine measurements from different processes at different scales (precision/decay/production), the running and mixing effects should be taken into account.
- Consistent global EFT analyses for top physics to be performed at NLO, i.e. considering both operator mixing and genuine short distance QCD effects.
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Full analytical results for top-decay processes at NLO in QCD.

- Strategies for searching and constraining operators in top decay.
  (ongoing with G. Durieux and F. Maltoni)
- $O(\alpha_s)$ mixing of relevant operators.

Fully automatic calculation of FCNC top-production in the framework of MG5_aMC@NLO (1405.0301)

(ongoing with C. Degrande, F. Maltoni, J. Wang)

Eventually the full EFT@NLO framework for top, automatic in aMC@NLO, global analysis, etc...
Top decay at NLO

- Main decay channel $t \rightarrow bW$.
  
  $W$-helicity: $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$ in the SM

- FCNC decay $t \rightarrow uZ$, $t \rightarrow u\gamma$, $t \rightarrow ug$, $t \rightarrow uh$.
  
  $BR \approx 10^{-13} \sim 10^{-16}$ in the SM

- 3-body decay $t \rightarrow bl\nu$, $t \rightarrow ull$, with contact interactions.
One has to keep in mind that
- New operators enter at NLO;
- They mix into the tree level operators.

$t \rightarrow bW$

$t \rightarrow qX$
We provide the complete set of NLO calculations for top decay:

- Analytical results for differential decay rate, $\frac{d\Gamma}{ds\,d\cos\theta}$, for $t \to bW \to bl\nu$ and $t \to uZ \to ull$.
  - Four-fermion operators included.
  - New contributions at NLO included.

- Provide $t \to uh$. Confirm old results on $t \to ug, u\gamma$.

- Mixing effects.

Complete information needed for model-independent study for top decay at NLO in QCD.
Top EFT for Top Decay and FCNC Production

Operator mixing

\[ t \rightarrow bW \]

\[ t \rightarrow uh \]

\[
O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \phi G^A_{\mu\nu}
\]
\[
O_{tW} = y_t g_W (\bar{Q} \sigma^{\mu\nu} \tau^I t) \phi W^I_{\mu\nu}
\]
\[
O_{tB} = y_t g_Y (\bar{Q} \sigma^{\mu\nu} t) \phi B_{\mu\nu}
\]
\[
O_{t\varphi} = -y_t^3 (\varphi^\dagger \varphi) (\bar{Q} t) \phi
\]

\[
\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix}
\frac{1}{6} & 0 & 0 & 0 \\
\frac{1}{3} & 0 & 0 & 0 \\
9 & 0 & 1 & 0 \\
-4 & 0 & 0 & -1
\end{pmatrix}
\]

\[
O_{uG}^{(13)} = y_t g_s (\bar{q} \sigma^{\mu\nu} T^A t) \phi G^A_{\mu\nu}
\]
\[
O_{uW}^{(13)} = y_t g_W (\bar{q} \sigma^{\mu\nu} \tau^I t) \phi W^I_{\mu\nu}
\]
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O_{uB}^{(13)} = y_t g_Y (\bar{q} \sigma^{\mu\nu} t) \phi B_{\mu\nu}
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O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi) (\bar{q} t) \phi
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\]
Top-quark FCNC Production

FCNC searches in \( pp \rightarrow tX \)
- Improve constraints on \( utX \).
- Provide information to determine the interaction (ut/ct, L/R)

Typical k factor \( \sim 1.3 \)

\[ t \rightarrow \gamma, Z, h \]
Top-quark FCNC Production

- Two (or more) contributions appear at LO. ($O_{uB}$ and $O_{uG}$)
- At NLO in QCD $O_{uG}$ mixes with other operators. Always has to be included.
- Only a global approach on constraining such operators at the same time can be a useful strategy.
Implementation of FCNC operators at NLO in QCD in MG5_aMC@NLO is on going.

- Fully automatic, any process, matched to PS at NLO
- Some preliminary results at NLO for $pp \rightarrow t\gamma$ ($pp \rightarrow t\gamma j$ in SM):

![Graph 1](image1.png)

![Graph 2](image2.png)
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![Graph 2](image2)

NLO 13 TeV
Top-quark FCNC Production

A rich set of processes will be studied at NLO(+PS)

- $pp \rightarrow t, t\gamma, tZ, th, tj, e^+ e^- \rightarrow tj$
- $pp \rightarrow t\bar{t}$ with FCNC top decay. (or even $h \rightarrow t^* u$ etc.)
- More possibilities with four-fermion operators...
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Summary

- EFT is a consistent and complete theoretical approach to NP, where predictions can be systematically improved, several measurements of different processes can be interpreted, and useful information can be obtained by global fits.

- The complete set of analytical results for top-quark decay in EFT is available at NLO in QCD.

- Implementation of top quark FCNC processes in MG5_aMC@NLO is in progress. The full EFT framework at NLO will be available in future.
Thank you!
Backups
Current Limits

- $\bar{q}g \to t$:  
  \[ \text{Br}(t \to u\bar{g}) < 3.1 \times 10^{-5}, \text{Br}(t \to c\bar{g}) < 1.6 \times 10^{-4} \]  
  [ATLAS-CONF-2013-063]

- $\bar{q}g \to tZ$:  
  \[ \text{Br}(t \to u\bar{g}) < 0.56\%, \text{Br}(t \to c\bar{g}) < 7.12\% \]  
  \[ \text{Br}(t \to uZ) < 0.51\%, \text{Br}(t \to cZ) < 11.4\% \]  
  [CMS PAS TOP-12-021]

- $t \to qZ$:  
  \[ \text{Br}(t \to q\bar{Z}) < 0.05\% \]  
  [CMS-TOP-12-037]

- $t \to qh$:  
  \[ \text{Br}(t \to c\bar{h}) < 0.56\% \]  
  [CMS-PAS-HIG-13-034]
### Projections

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<td>$t \to u Z(\gamma_{\mu})$</td>
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<td>$t \to u Z(\sigma_{\mu\nu})$</td>
<td>$3.6 \times 10^{-5}$</td>
<td>$2.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$t \to u \gamma$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$3.1 \times 10^{-6}$</td>
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<tr>
<td>$t \to u g$</td>
<td>$-$</td>
<td>$2.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>$t \to u H$</td>
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Table 4: $3\sigma$ discovery limits for top FCN interactions at LHC, for an integrated luminosity of 100 fb$^{-1}$. The limits are expressed in terms of top decay branching ratios.