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

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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.
  - $t\bar{t} \sim 5\%$, $V_{tb} \sim 10\%$, 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.

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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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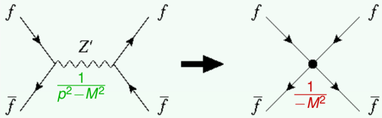
EFT

Effective Field Theory parametrizes unknown interactions in a model-independent way, by

- Integrating out heavy states.



- Expanding the resulting non-local interactions as a series of local interactions.

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

. . . 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 α_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-renomalizable” 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.

NLO

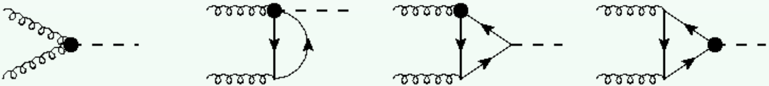
Going to NLO is not a trivial task:

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

$$dC_i(\mu)/\,d\mu = \gamma_{ij} C_j(\mu)$$

- A meaningful analysis can only be made by considering them all. $gg \to H$:

$O_{\varphi G} = (\varphi^\dagger \varphi)(G^a_{\mu\nu} G^{a\mu\nu})$ $O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu} T^A t_R)\tilde{\varphi} G^I_{\mu\nu}$ $O_{t\varphi} = (\varphi^\dagger \varphi)(\varphi \bar{Q})t$



C. Degrande et al
1205.1065

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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Outline

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

Top EFT@NLO in QCD

- Full analytical results for top-decay processes at NLO in QCD.
  C. Zhang
  1404.1264
  - Strategies for searching and constraining operators in top decay.
    (ongoing with G. Durieux and F. Maltoni)
  - $O(\alpha_s)$ mixing of relevant operators. **R. Alonso et al.** 1312.2014
- 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

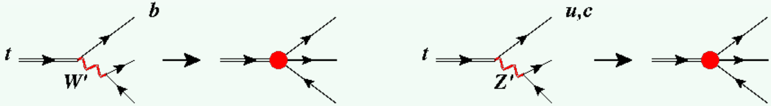
- Main decay channel $t \to bW$.
  W-helicity: $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$ in the SM

J. Drobnak et al.
1010.2402

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

J. Drobnak et al.
1007.2552
J.J. Zhang et al.
1004.0898
CZ and F. Maltoni
1305.7386

- 3-body decay $t \to bl\nu$, $t \to ull$, with contact interactions.

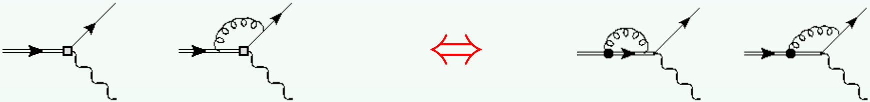


Top decay at NLO

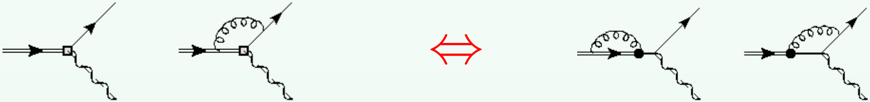
One has to keep in mind that

- New operators enter at NLO;
- They mix into the tree level operators.

$t \to bW$



$t \to qX$



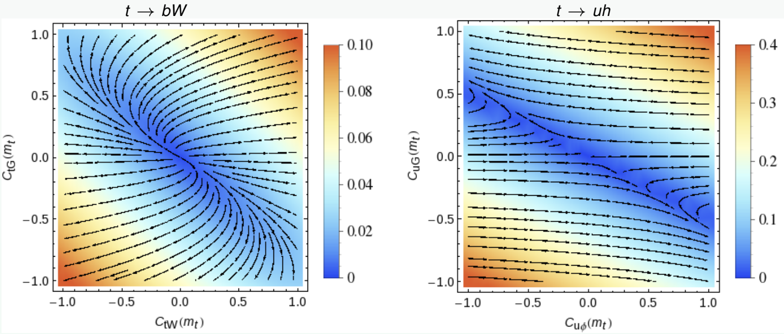
Top Decay at NLO

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.

Operator mixing



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

$$\gamma = \frac{2\alpha_s}{\pi}\begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -4 & 0 & 0 & -1 \end{pmatrix}$$

$$O^{(13)}_{uG} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$
$$O^{(13)}_{uW} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$
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Top-quark FCNC Production

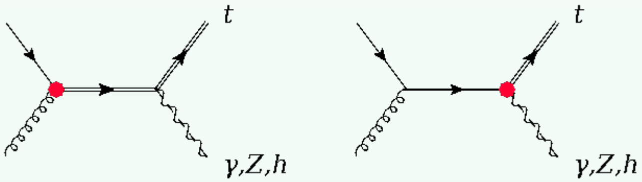
FCNC searches in $pp \to tX$

- Improve constraints on utX.
- Provide information to determine the interaction (ut/ct, L/R)

A. Greljo et al.
1404.1278

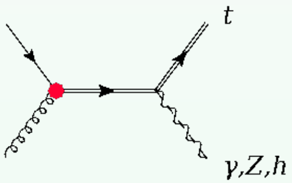
Typical k factor ~ 1.3

J. Gao et al.
1104.4945



Top-quark FCNC Production

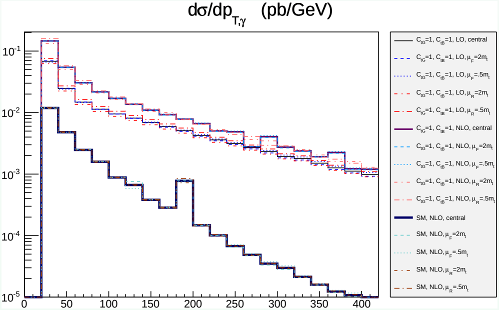
- Two (or more) contributions appear at LO. (O_{uB} and O_{uG})
- At NLO in QCD O_{uG} mixes with other operators. Always has to be included.
- Only a global approach on constraining such operators at the same time can be a useful strategy.



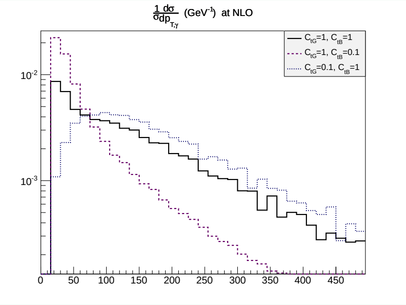
Top-quark FCNC Production

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 $pp \to t\gamma$ ($pp \to t\gamma j$ in SM):



LO/NLO 13 TeV



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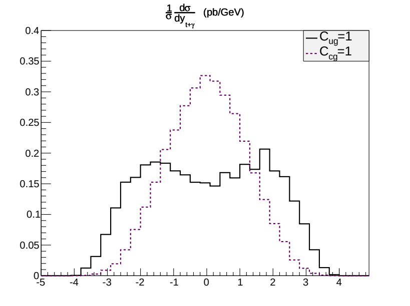

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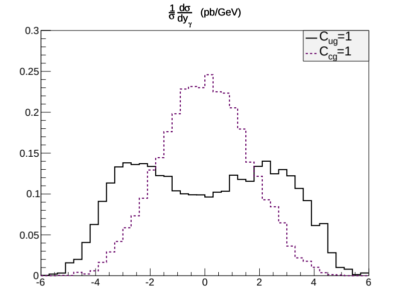
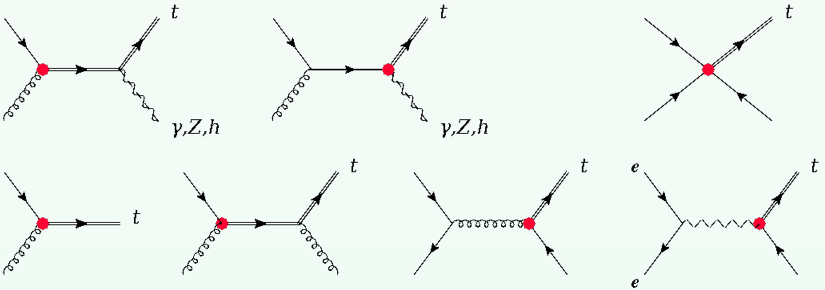


NLO 13 TeV

Top-quark FCNC Production

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

- $pp \to t, t\gamma, tZ, th, tj$, $e^+e^- \to tj$.
- $pp \to t\bar{t}$ with FCNC top decay. (or even $h \to t^* u$ 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

- $qg \to t$:
  Br$(t \to ug)$<3.1×10^{-5}, Br$(t \to cg)$<1.6×10^{-4} **ATLAS-CONF-2013-063**
- $qg \to tZ$:
  Br$(t \to ug)$<0.56%, Br$(t \to cg)$<7.12%
  Br$(t \to uZ)$<0.51%, Br$(t \to cZ)$<11.4% **CMS PAS TOP-12-021**
- $t \to qZ$:
  Br$(t \to qZ)$<0.05% **CMS-TOP-12-037**
- $t \to qh$:
  Br$(t \to ch)$<0.56% **CMS-PAS-HIG-13-034**

Projections

J.A. Aguilar-Saavedra
hep-ph/0409342

	Top decay	Single top		Top decay	Single top
$t \to uZ(\gamma_\mu)$	3.6×10^{-5}	8.0×10^{-5}	$t \to cZ(\gamma_\mu)$	3.6×10^{-5}	3.9×10^{-4}
$t \to uZ(\sigma_{\mu\nu})$	3.6×10^{-5}	2.3×10^{-5}	$t \to cZ(\sigma_{\mu\nu})$	3.6×10^{-5}	1.4×10^{-4}
$t \to u\gamma$	1.2×10^{-5}	3.1×10^{-6}	$t \to c\gamma$	1.2×10^{-5}	2.8×10^{-5}
$t \to ug$	–	2.5×10^{-6}	$t \to cg$	–	1.6×10^{-5}
$t \to uH$	5.8×10^{-5}	5.1×10^{-4}	$t \to cH$	5.8×10^{-5}	2.6×10^{-3}

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.