Effective Field Theory for Top Quark Physics at NLO Accuracy

Cen Zhang

Université Catholique de Louvain

Centre for Cosmology, Particle Physics and Phenomenology

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

20 May 2014
Rencontres de Blois

Outline

Outline

Top Quark Physics

- TH motivations for studying the top quark as a portal to NP remains there.
- Connections between Top/Higgs measurements.
  - 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 $\sim 0.5\%, \ldots$
- 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?

Top Quark Physics

- TH motivations for studying the top quark as a portal to NP remains there.
- Connections between Top/Higgs measurements.
  - 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 $\sim 0.5\%, \ldots$
- 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?

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.
  - NP in top loops.

⇒EFT @ NLO

- Analytical results for top decay processes.
- Tool for NLO in production in progress.

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.
  - NP in top loops.

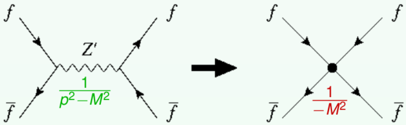
$\Rightarrow$EFT @ NLO

- Analytical results for top decay processes.
- Tool for NLO in production in progress.

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.



$$\frac{1}{p^2 - M^2} = \frac{1}{-M^2}\left[1 + \left(\frac{p^2}{M^2}\right) + \left(\frac{p^2}{M^2}\right)^2 + \cdots\right]$$

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{Dim6}} + \cdots, \text{ where } \mathcal{L}_{\mathrm{Dim6}} = \frac{C}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

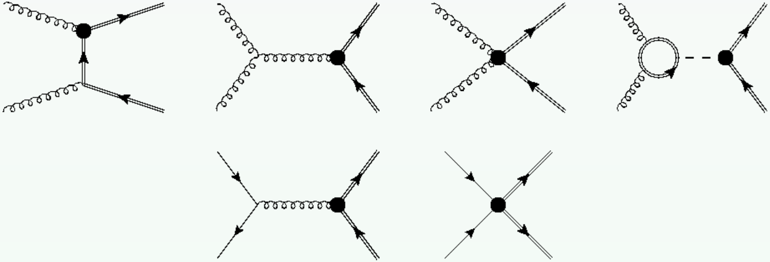
EFT

$$\begin{array}{rcccc} \mathcal{L}_{\text{EFT}} = & \mathcal{L}_{\text{SM}} + & \sum_i \frac{C_i}{\Lambda^2} O_i & + \cdots \\ & \uparrow & \uparrow & \\ \dim = & \leq 4+ & 6 & \end{array}$$

- LO effects: 59 operators at dim-6.
- At tree level, not so many operators for a given process.

$t\bar{t}$ production

- Diagrams



- Operators

$$O_{tG} = \left(\bar{Q}\sigma^{\mu\nu}T^A t\right)\tilde{\varphi}G^A_{\mu\nu}$$

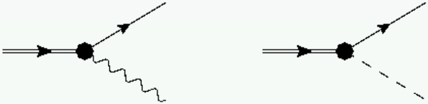
$$O_{t\varphi} = \left(\varphi^\dagger\varphi\right)\left(\bar{Q}t\tilde{\varphi}\right)$$

$$O^{(1,3)}_{qQ} = \left(\bar{q}\gamma_\mu\tau^I q\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right)$$

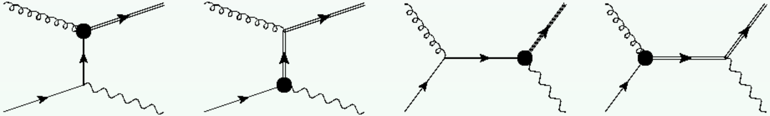
and more 4-fermion operators

Top FCNC

- FCNC decay



- FCNC production



- Operators

$$O_{\varphi Q}^{(1,1+3)} = i y_t^2 \left(\varphi^\dagger D_\mu \varphi\right) (\bar{q}\gamma^\mu Q) \qquad O_{uW}^{(13)} = y_t g_W (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W_{\mu\nu}^I$$

$$O_{uB}^{(13)} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu} \qquad O_{u\varphi}^{(13)} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}$$

NLO

- In EFT, radiative corrections can be consistently included. Predictions can be systematically improved. (Can go to higher order in α_s, $1/\Lambda^2$,...)

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

NLO EFT EFT @ NLO

  - Effective Field Theory contains "non-renomalizable" terms, but it is renormalizable order by order in $1/\Lambda^2$.

NLO

Going to NLO is not a trivial task:

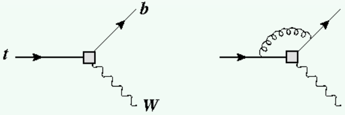
- New contributions from new operators at NLO.
- Mixing effects. (i.e. one operator renormalizes the others)

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

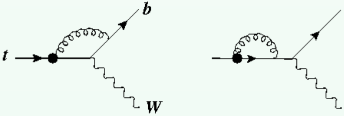
- A meaningful analysis can only be made by considering them all.

$t \to bW$:

$O_{tW} = y_t g_W (\bar{Q}\sigma^{\mu\nu}\tau^I t_R)\tilde{\varphi} W^I_{\mu\nu}$



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



NLO

Going to NLO is not a trivial task:

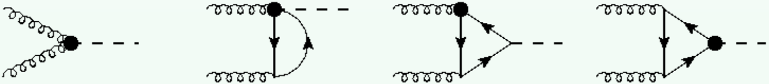
- New contributions from new operators at NLO.
- Mixing effects. (i.e. one operator renormalizes the others)

$$\mathrm{d}C_i(\mu)/\mathrm{d}\mu = \gamma_{ij}C_j(\mu)$$

- 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 operator 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.

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 operator 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.

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 operator 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.

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 operator 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.

Outline

Top EFT@NLO in QCD

1. 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
2. Automatic calculation of FCNC top-production in the framework of MG5_aMC@NLO (1405.0301)
   (ongoing with C. Degrande, F. Maltoni, J. Wang)
3. Eventually the full EFT@NLO framework for top, automatic in aMC@NLO.

Top decay at NLO

1. Main decay channel $t \to bW$.

   W-helicity: $F_+ : F_0 : F_- \sim 0 : 0.7 : 0.3$ in the SM

   But can be modified by dim-6 operators

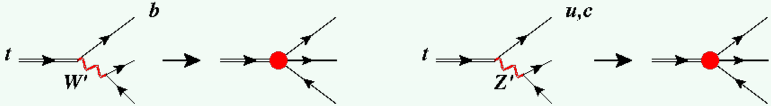
   J. Drobnak et al.
   1010.2402

2. 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, much larger in NP scenarios

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

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



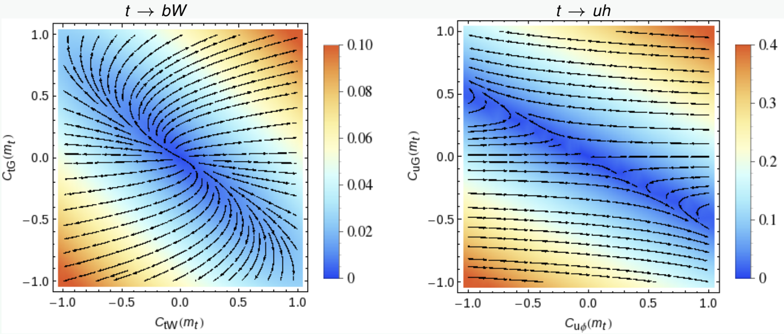
Top Decay at NLO

- We provide the complete set of NLO calculations for top decay:

  1. 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.
  2. Provide $t \to uh$. Confirm old results on $t \to ug, u\gamma$.
  3. Mixing effects.

- Complete information needed for model-independent study for top decay at NLO in QCD.

Operator mixing



$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

$$O_{tW} = y_t g_W (\bar{Q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O_{t\varphi} = -y_t^3 (\varphi^\dagger \varphi)(\bar{Q}t)\tilde{\varphi}$$

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

$$O^{(13)}_{uG} = y_t g_s (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}$$

$$O^{(13)}_{uW} = y_t g_W (\bar{q}\sigma^{\mu\nu} \tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

$$O^{(13)}_{uB} = y_t g_Y (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

$$O^{(13)}_{u\varphi} = -y_t^3 (\varphi^\dagger \varphi)(\bar{q}t)\tilde{\varphi}$$

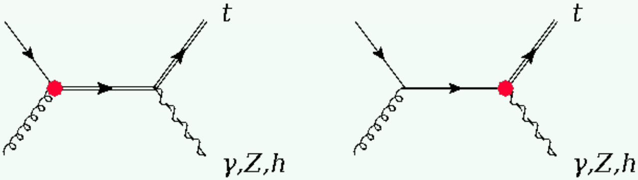
$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ \frac{5}{9} & 0 & \frac{1}{3} & 0 \\ -2 & 0 & 0 & -1 \end{pmatrix}$$

Top-quark FCNC Production

FCNC searches in $pp \to tX$ can bring information.

J. Gao et al.
1104.4945

- Typical k factor ~ 1.3
- 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.

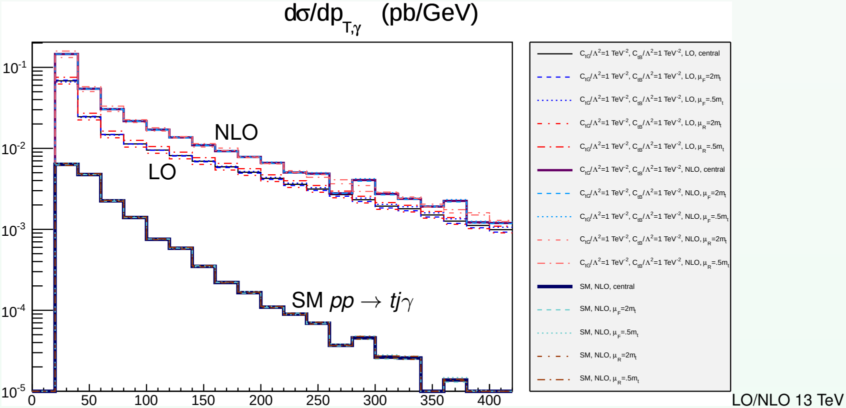


Huge amount of calculation (408 real + 276 virt diagrams for $t\gamma$), but can be automated.

Top-quark FCNC Production

Implementation of FCNC operators in aMC@NLO is on going.

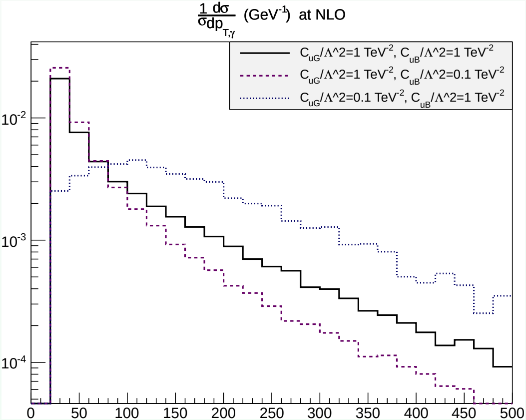
- Automatic calculation, any process, matched to PS at NLO
  - Preliminary results for $pp \to t\gamma$ at NLO: p_T distribution for γ (Background: $pp \to tj\gamma$)



Top-quark FCNC Production

Implementation of FCNC operators in aMC@NLO is on going.

- Automatic calculation, any process, matched to PS at NLO
  - Preliminary results for $pp \to t\gamma$ at NLO: normalized p_T distributions



NLO 13 TeV

Top-quark FCNC Production

Implementation of FCNC operators in aMC@NLO is on going.

- Comparison with previous works:

  - $pp \to t\gamma$:

Y. Zhang et al.
1101.5346

$\kappa_{tq}^{\gamma} = 0.3$, 14 TeV (pb)

	1101.5346	aMC@NLO
κ_{tu}^{γ}, LO	3.78	3.777±0.0066
κ_{tu}^{γ}, NLO	5.16	5.117±0.027
κ_{tc}^{γ}, LO	0.386	0.3874±0.0007
κ_{tc}^{γ}, NLO	0.537	0.5208±0.0029

$\kappa_{tq}^{\gamma} = 0.02$, $\kappa_{tq}^{g} = 0.01$, 14 TeV (fb)

	1101.5346	aMC@NLO
κ_{tu}^{V}, LO	27.8	28.02±0.11
κ_{tu}^{V}, NLO	42.7	42.1±0.29
κ_{tc}^{V}, LO	3.13	3.139±0.012
κ_{tc}^{V}, NLO	5.61	5.373±0.013

  - $pp \to tZ$:

B. Li et al.
1103.5122

$\kappa_{tq}^{Z} = 0.5$, 14 TeV (pb)

	1103.5122	aMC@NLO
κ_{tu}^{Z}, LO	15.9	15.79±0.061
κ_{tu}^{Z}, NLO	22.5	22.18±0.082
κ_{tc}^{Z}, LO	1.29	1.27±0.0049
κ_{tc}^{Z}, NLO	1.85	1.753±0.011

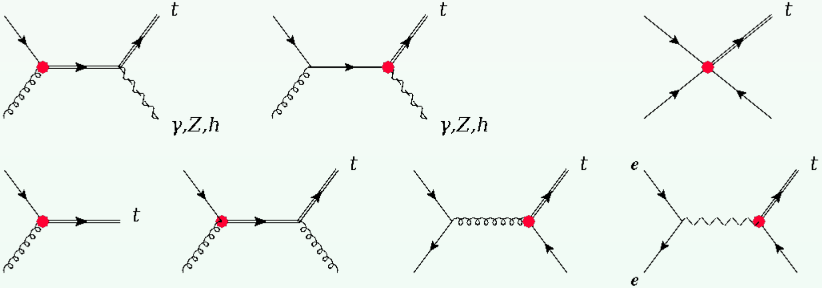
$\kappa_{tq}^{Z} = 0.5$, 1.96 TeV (fb)

	1103.5122	aMC@NLO
κ_{tu}^{Z}, LO	55.5	54.76±0.1
κ_{tu}^{Z}, NLO	88.6	87.45±0.44
κ_{tc}^{Z}, LO	1.62	1.607±0.0027
κ_{tc}^{Z}, NLO	2.45	2.461±0.0097

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...



Outline

Summary

- EFT is a consistent and complete theoretical approach to NP, where predictions can be systematically improved.
- 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
$t \to uZ(\gamma_\mu)$	3.6×10^{-5}	8.0×10^{-5}
$t \to uZ(\sigma_{\mu\nu})$	3.6×10^{-5}	2.3×10^{-5}
$t \to u\gamma$	1.2×10^{-5}	3.1×10^{-6}
$t \to ug$	–	2.5×10^{-6}
$t \to uH$	5.8×10^{-5}	5.1×10^{-4}

	Top decay	Single top
$t \to cZ(\gamma_\mu)$	3.6×10^{-5}	3.9×10^{-4}
$t \to cZ(\sigma_{\mu\nu})$	3.6×10^{-5}	1.4×10^{-4}
$t \to c\gamma$	1.2×10^{-5}	2.8×10^{-5}
$t \to cg$	–	1.6×10^{-5}
$t \to cH$	5.8×10^{-5}	2.6×10^{-3}

Table 4: 3σ 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.