Probing top-quark couplings at NLO accuracy

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Pheno 15

Based on
arXiv:1412.5594, C. Degrande, F. Maltoni, J. Wang and CZ
arXiv:1503.08841, D. B. Franzosi and CZ
and ongoing works.

Main result

We provide a framework based on MadGraph5_aMC@NLO, that

- provides automatic predictions at NLO in QCD + PS;
- is based on effective field theory of the top quark. (i.e. with dim-6 operators.)

Outline

1. EFT@NLO motivation
2. Applications
   - Top flavor-conserving couplings
   - Top FCNC couplings
   - Top-DM couplings
3. Summary

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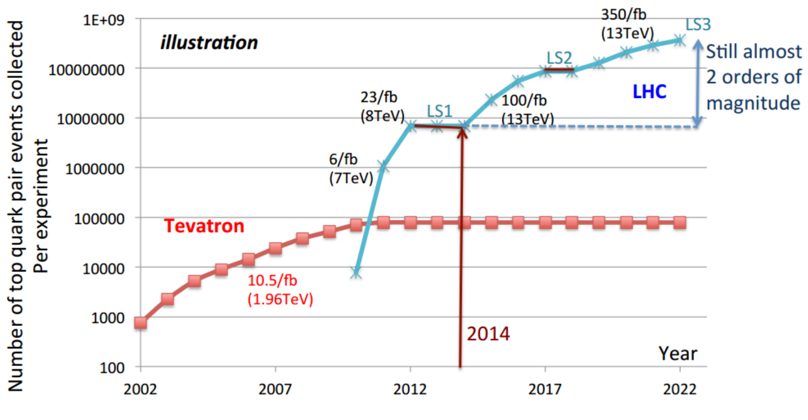
Production at Tevatron and LHC

20 years for almost 6 orders of magnitude → the Top Quark era



(caveat: assumed 13 TeV collisions with a cross section of 800 pb)

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"Status of Top Quark Physics" **Jorgen D'Hondt (Vrije Universiteit Brussel)** 6

Top precision era

With millions of top quarks,

- some top-related parameters have already been accurately measured
  - Top mass ($\sim 0.4\%$)
  - $t\bar{t}$ and single t cross section ($\sim 5 - 10\%$)
  - W helicity in top decay ($\sim 10\%$)
  - FCNC at a level of Br $\sim 10^{-5}$
  - ...
- and more will be determined by run 2.
  - To this end we need predictions from theory side.

NLO for BSM effects

For theorists: ready to provide accurate predictions?

- Within SM, of course.
- However, disentangling BSM effects requires accurate predictions not only for SM but also for NP signal.
- Top-quark effective field theory ($\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{SM} + C_i O_i/\Lambda^2 + \cdots$) provides suitable framework
  - Allows for renormalization order by order in $1/\Lambda$ ($\Lambda =$ NP scale)
  - Predictions can be systematically improved, by going to higher order in α_s, $1/\Lambda^2$,...

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

SM NLO EFT EFT @ NLO

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  - Predictions can be systematically improved, by going to higher order in α_s, $1/\Lambda^2$,...
- Some "EFT@NLO" results are available:
  decay [J. Drobnak 10] [CZ and Maltoni 13] [CZ 14]
  FCNC [J. J. Liu et al. 05] [J.Gao et al. 09] [Y. Zhang et al. 11] [B. H. Li et al. 11] [Y. Wang et al. 11] [Degrande, Maltoni, Wang and CZ 14]
  FB asymmetry [D. Y. Shao et al. 11]
  $t\bar{t}Z$ [Rontsch and Schulze 14]

Towards automatic EFT@NLO

Our goal is to provide complete EFT@NLO results, by providing a framework based on MadGraph5_aMC@NLO [J. Alwall et al., 1405.0301], that allows for automatic simulations in the presence of higher-dimensional operators of the top quark.

- Automatic for many processes, all in one EFT model.
- Accurate and Realistic: NLO in QCD with parton shower (EW planned)
- User friendly.

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Towards automatic EFT@NLO

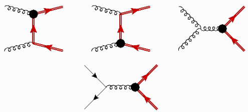
Let's say you want to investigate top-CMDM in $t\bar{t}$ production

- $\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + C_{tG}O_{tG}/\Lambda^2$

```
your_shell> ./bin/mg5
MG5_aMC> import model Top_EFT_model
MG5_aMC> generate p p > t t~ EFT=1 [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch

>order=NLO
>shower=ON
>set CtG=2.0
>...
```

LO diagrams at $\mathcal{O}(C/\Lambda^2)$



and you will get:

- Total cross section: $K = 1.43$ at LHC 8 TeV

Limits on C_{tG}

	LO [TeV^{-2}]	NLO [TeV^{-2}]
LHC 8	[-0.56,0.41]	[-0.42,0.30]

- Distributions $\Rightarrow$ FB asymmetry, spin correlation, ... (More details in arXiv:1503.08841, D. B. Franzosi and CZ)

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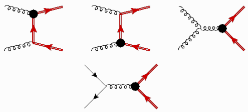

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The top EFT

- $tt\gamma/ttg$, EM/color dipole

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

- tbW
  - V/A

$$O^{(3)}_{\varphi Q} = i(\varphi^\dagger D_\mu \tau^I \varphi)(\bar{Q}\tau^I \gamma^\mu Q) \qquad O_{\varphi\varphi} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

  - Weak dipole

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

- ttZ
  - V/A

$$O^{(1)}_{\varphi Q} = i(\varphi^\dagger D_\mu \varphi)(\bar{Q}\gamma^\mu Q) \qquad O_{\varphi u} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu t)$$

  - Weak dipole O_{tW}
- ttH

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

Global fit at NLO

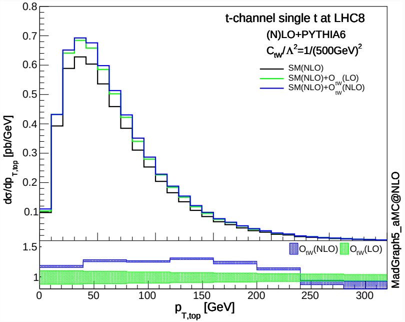
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L

($O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ and $O_{\varphi G} = g_s^2 \left(\varphi^\dagger \varphi\right) G^A_{\mu\nu} G^{A\mu\nu}$ are included because they mix with other top-quark operators and play a role in NLO calculations.)

What we can provide:

- NLO simulation for all "$pp \to \cdots$" processes.
- All two-quark operators included.
- Four-fermion operators planned.

i.e. global fit for top couplings at NLO accuracy already possible.



A toy fit

- Use 8 TeV data, total cross section only.
- Following processes are included
  - W helicity from top decay.
  - $t\bar{t}$ production.
  - Single top production, all 3 channels.
  - $t\bar{t}Z$ and $t\bar{t}\gamma$.
  - Assuming $Z \to b\bar{b}$ takes the SM value.
- Simple χ^2 fit.
- Limits ($\Lambda = 1$ TeV, 95%) (preliminary)

	C_{tG}	$C_{\phi Q}^{(-)}$	$C_{\phi t}$	C_{tB}	C_{tW}
NLO	[-.4 .3]	[-3.2,1.7]	[-9.0,5.9]	[-163,373]	[-2.4,1.4]
LO	[-.6 .5]	[-3.6,1.9]	[-10.6,6.9]	[-222,506]	[-2.4,1.6]

- Key message: this is not a serious fit, but it demonstrates that the theoretical ingredients for performing a global fit are already available.

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Top FCNC@NLO

In collaboration with

- C. Degrande, F. Maltoni and J. Wang, arXiv:1412.5594
  Automatic NLO for FCNC processes.
- G.Duriex, and F. Maltoni, arXiv:1412.7166
  A global approach to FCNC couplings.

FCNC operators

1. $(\bar{u}\gamma^\mu t)Z_\mu$

$$O_{\varphi Q}^{(3,1+3)} = i\left(\varphi^\dagger \tau^I D_\mu \varphi\right)\left(\bar{q}\gamma^\mu \tau^I Q\right)$$
$$O_{\varphi Q}^{(1,1+3)} = i\left(\varphi^\dagger D_\mu \varphi\right)\left(\bar{q}\gamma^\mu Q\right)$$
$$O_{\varphi u}^{(1+3)} = i\left(\varphi^\dagger D_\mu \varphi\right)\left(\bar{u}\gamma^\mu t\right)$$

2. $(\bar{u}\sigma^{\mu\nu} q_\nu t)V_\mu$, “weak dipole”

$$O_{uW}^{(13)} = (\bar{q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I$$
$$O_{uB}^{(13)} = (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

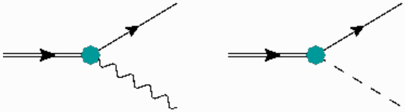
3. $(\bar{u}\sigma^{\mu\nu} q_\nu t)G_\mu$, “color dipole”

$$O_{uG}^{(13)} = (\bar{q}\sigma^{\mu\nu} T^A t)\tilde{\varphi}G_{\mu\nu}^A$$

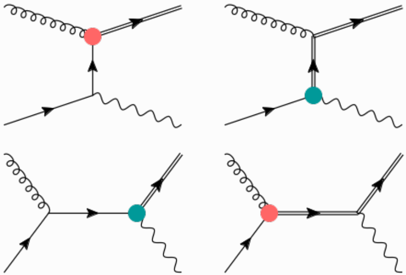
4. $\bar{u}th$, ”Yukawa”

$$O_{u\varphi}^{(13)} = (\varphi^\dagger\varphi)(\bar{q}t)\tilde{\varphi}$$

FCNC *t* decay



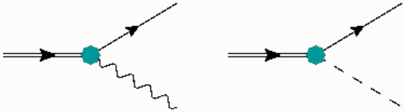
FCNC *t* production



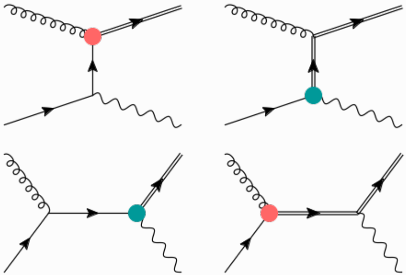
FCNC processes

- FCNC decays: available (analytically) at NLO.
- We focus on single top production
  $pp \to t\gamma$, $pp \to tZ$, $pp \to th$.
  - Competitive limits
  - More kinematic variables accessible.
  - Probe higher scale.

FCNC t decay



FCNC t production



FCNC production at NLO

$pp \to t\gamma$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{uB}^{(13)} = 1.0$	546	$+14.4\% - 11.8\%$	764	$+6.9\% - 6.4\%$
$C_{uG}^{(13)} = 0.04$	1.00	$+12.0\% - 10.2\%$	2.34	$+15.2\% - 11.5\%$
$C_{uG}^{(13)}$, veto	0.739	$+11.50\% - 9.8\%$	1.19	$+7.7\% - 6.5\%$
$C_{uB}^{(23)} = 1.9$	152	$+10.6\% - 9.6\%$	258	$+6.8\% - 6.0\%$
$C_{uG}^{(23)} = 0.09$	0.590	$+12.1\% - 11.1\%$	1.95	$+16.4\% - 12.3\%$
$C_{uG}^{(23)}$, veto	0.457	$+12.2\% - 11.2\%$	1.04	$+10.3\% - 8.9\%$

$pp \to tZ$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{\varphi u}^{(1+3)} = 1.0$	905	$+12.9\% - 10.9\%$	1163	$+6.2\% - 5.6\%$
$C_{uW}^{(13)} = 0.9$	1737	$+11.5\% - 9.8\%$	2270	$+6.6\% - 6.2\%$
$C_{uG}^{(13)} = 0.04$	30.1	$+17.5\% - 13.8\%$	36.0	$+3.8\% - 5.2\%$
$C_{uG}^{(31)} = 0.04$	29.4	$+17.7\% - 13.9\%$	34.9	$+3.4\% - 5.1\%$
$C_{\varphi u}^{(2+3)} = 1.0$	73.2	$+10.4\% - 9.3\%$	107	$+6.5\% - 5.9\%$
$C_{uW}^{(23)} = 1.1$	172	$+7.5\% - 7.2\%$	255	$+6.1\% - 5.2\%$
$C_{uG}^{(23)} = 0.09$	6.92	$+11.3\% - 9.9\%$	10.6	$+5.8\% - 5.4\%$
$C_{uG}^{(32)} = 0.09$	6.58	$+11.5\% - 10.1\%$	10.0	$+5.7\% - 5.3\%$

$pp \to th$

	LO		NLO	
Coefficient	σ[fb]	Scale uncertainty	σ[fb]	Scale uncertainty
$C_{u\varphi}^{(13)} = 3.5$	2603	$+13.0\% - 11.0\%$	3858	$+7.4\% - 6.7\%$
$C_{uG}^{(13)} = 0.04$	40.1	$+16.5\% - 13.2\%$	50.7	$+4.0\% - 5.2\%$
$C_{u\varphi}^{(23)} = 3.5$	171	$+9.7\% - 8.7\%$	310	$+7.3\% - 6.3\%$
$C_{uG}^{(23)} = 0.09$	9.53	$+11.0\% - 9.7\%$	16.6	$+5.5\% - 5.1\%$

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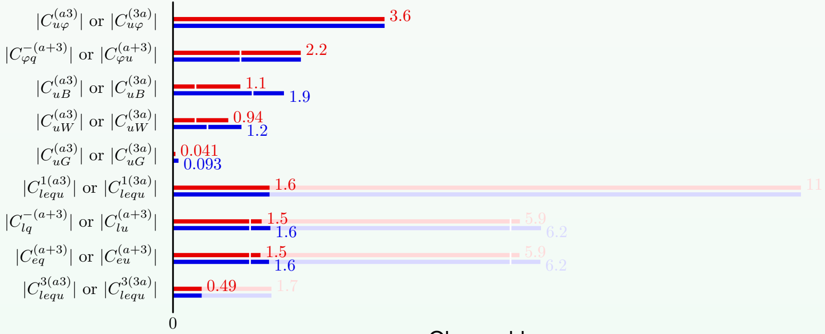
A toy fit

Similar to flavor-conserving sector, a global fit for the FCNC sector at NLO can already be performed.



$\Lambda = 1$ TeV
red: a=1 (tuX)
blue: a=2 (tcX)

Observables:
$t \to qh$
$t \to qZ$
$pp \to t, \bar{t}$
$pp \to t\gamma, \bar{t}\gamma$
$e^+e^- \to tj, \bar{t}j$

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Top-DM couplings

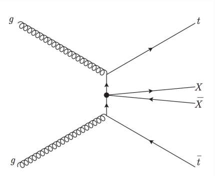
- Scalar mediated quark-DM interactions:

$$O = \frac{m_q}{\Lambda^3}\bar{q}q\bar{\chi}\chi$$

  where m_q is fixed by minimal flavor violation.

- DM production in association with t can enhance the reach of the LHC.

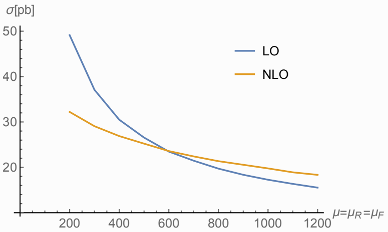
Lin, Kolb, Wang
1303.6638



DM production at NLO

- DM processes in MadGraph5_aMC@NLO are being investigated.
  M. Neubert, J. Wang, CZ
  F. Maltoni, K. Mawatari, A. Martini, M. Backovic
  O. Mattelaer, E. Vryonidou
  M. Kraemer, M. Pellen
- General framework, both in EFT and simplified models
- Some preliminary results for mono-$t\bar{t}$ at LHC13

Scale dependence



$m_\chi = 100$ GeV

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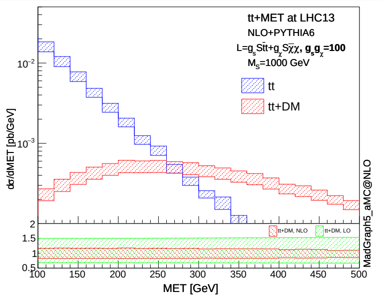
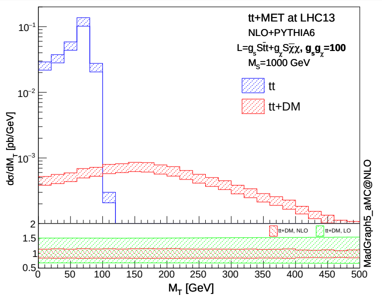


Transverse mass



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. . . and DM-mediated top-quark FCNC couplings are being studied.

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Summary

- A framework based on MADGRAPH5_AMC@NLO, that allows for automatic simulations in top-quark EFT at NLO+PS.
- Theoretical ingredients for performing global analysis at NLO accuracy for top couplings are available.

Backups

NLO elements

- Virtual: MadLoop (+CutTools)
  - Loop integral reduction using OPP method.
  - Need UV and R2 counterterms.

$$A(\bar{q}) = \frac{N(q)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}, \qquad \begin{aligned} N(q) &= \sum_{i_0<i_1<i_2<i_3}^{m-1}\left[d(i_0i_1i_2i_3)+\tilde{d}(q;i_0i_1i_2i_3)\right]\prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\ &+ \sum_{i_0<i_1<i_2}^{m-1}\left[c(i_0i_1i_2)+\tilde{c}(q;i_0i_1i_2)\right]\prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\ &+ \sum_{i_0<i_1}^{m-1}\left[b(i_0i_1)+\tilde{b}(q;i_0i_1)\right]\prod_{i\neq i_0,i_1}^{m-1} D_i \\ &+ \sum_{i_0}^{m-1}\left[a(i_0)+\tilde{a}(q;i_0)\right]\prod_{i\neq i_0}^{m-1} D_i \\ &+ \tilde{P}(q)\prod_{i}^{m-1} D_i\,. \end{aligned}$$

- Real: MadFKS
  - Computes real ME and soft-collinear counterterms.
  - Organizes the integration of n and n+1 body cross section.
  - Generates events to be showered.

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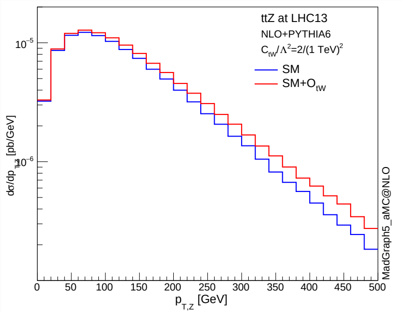
Top couplings: Differential cross sections

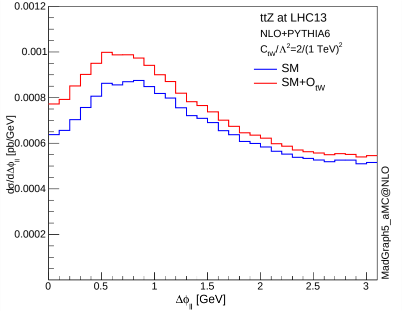
Apart from total cross section, could also provide fully differential event samples.

- Matched to HERWIG/PYTHIA via MC@NLO.
- Spin correlation taken into account by MADSPIN.

ttZ @ LHC13, pT of Z



$\Delta\Phi_{ll}$

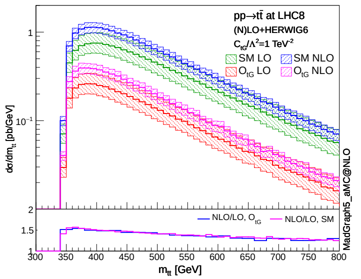


Top couplings: Differential cross sections

Apart from total cross section, could also provide fully differential event samples.

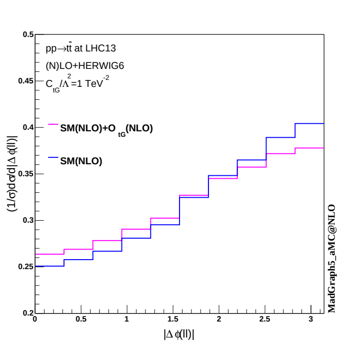
- Matched to HERWIG/PYTHIA via MC@NLO.
- Spin correlation taken into account by MADSPIN.

$t\bar{t}$ invariant mass



[Diogo B. Franzosi and CZ, 1503.08841]

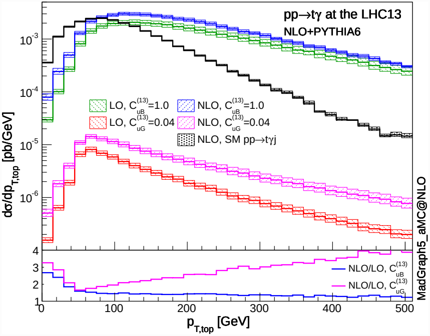
Decayed top: spin correlation



FCNC production at NLO

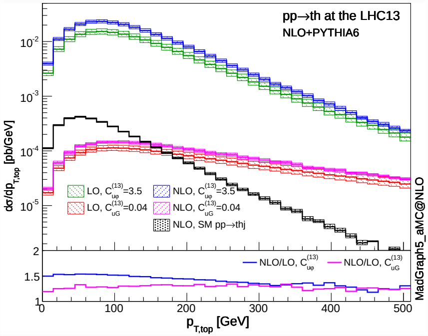
- Results for $pp \to t\gamma$ and $pp \to th$ at NLO+PS: p_T distribution for top (Λ=1 TeV)

$pp \to t\gamma$



$pp \to t\gamma$ 13 TeV

$pp \to th$



$pp \to th$ 13 TeV