SM predictions for 4-top production

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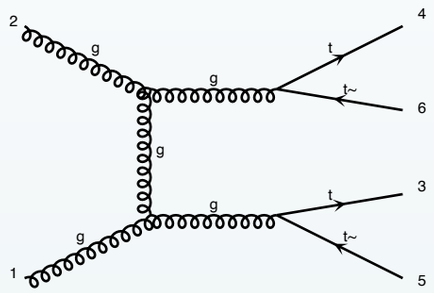
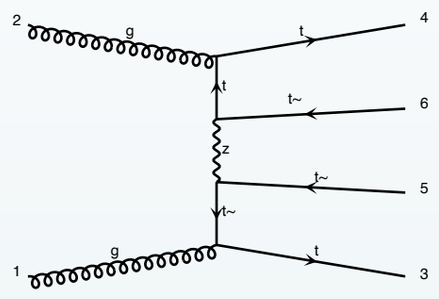
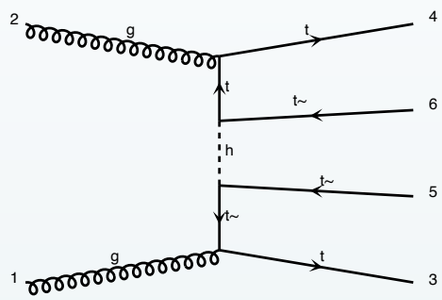
Discussion on the physics of Four Tops, 19 Feb. 2021

Anatomy of four-tops



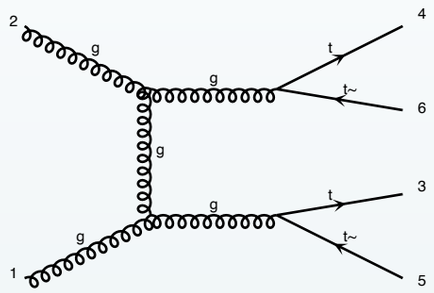


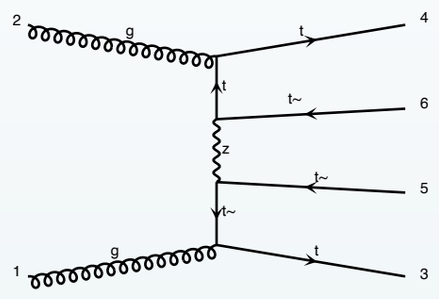


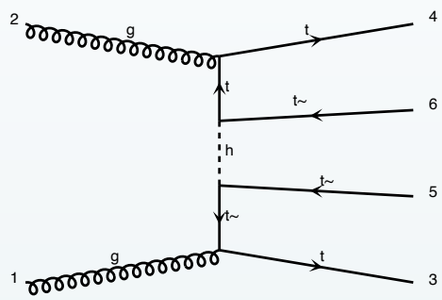
- Small cross section at the LHC, ~5-15 fb @ 13 TeV
- Dominated by gluon fusion
- "Subleading orders" can be significant: sensitive to top Yukawa

Leading order	X-section LHC-13	scale dependence
QCD^2	6.8 fb	+73% -40%
EW^2	2.6 fb	+45% -30%
QCD*EW	-1.8 fb	+62% -36%

"Subleading orders"







- Large "subleading" contributions due to scattering of tt -> tt through the exchange of (heavy) bosons
- Rather different kinematics as compared to QCD 4-top production:
  - Scale uncertainties are different — LO scale dependence is not a good estimate of the actual uncertainties
  - No reason to expect (theoretical) correlations among contribution (and similar behaviour when computing NLO corrections

Leading order	X-section LHC-13	scale dependence
QCD^2	6.8 fb	+73% -40%
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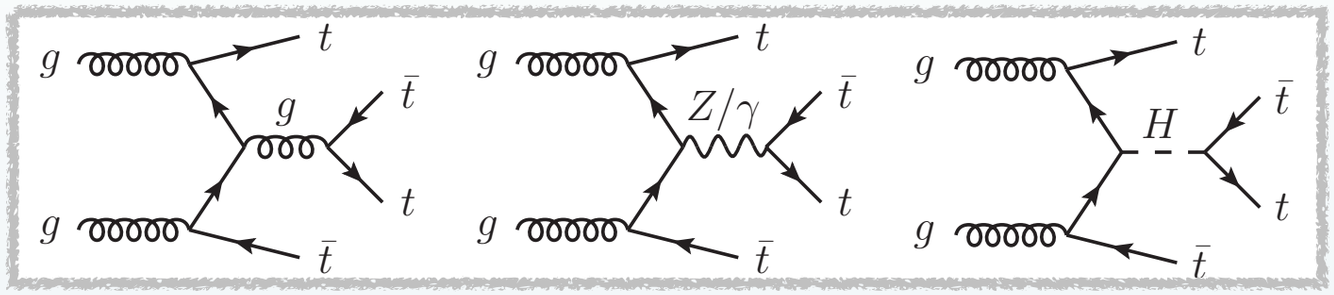
Four-top production and Top Yukawa coupling

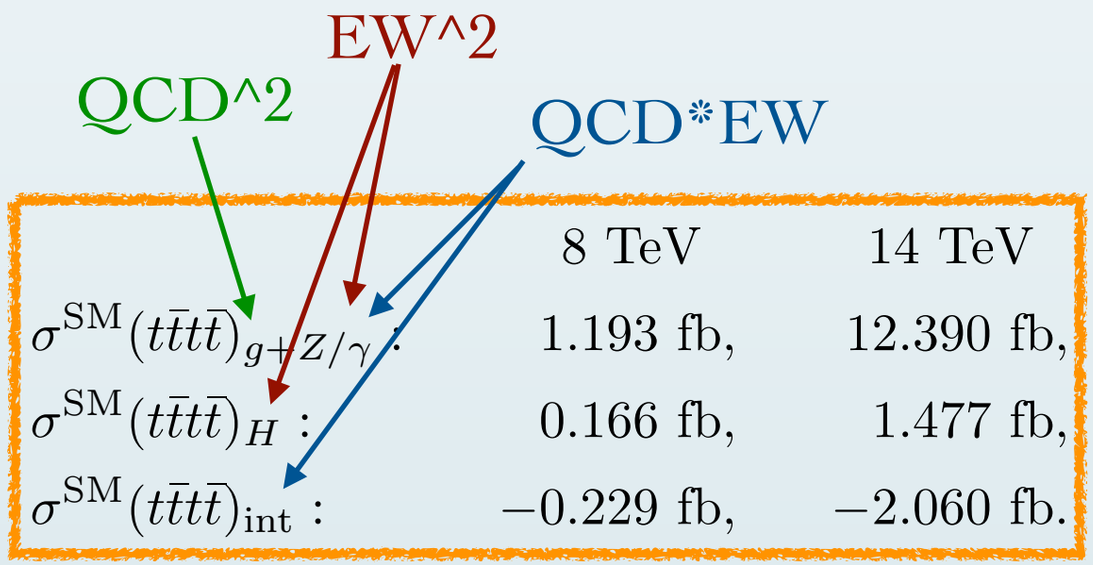
[Cao, Chen & Liu, 2016]



$$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

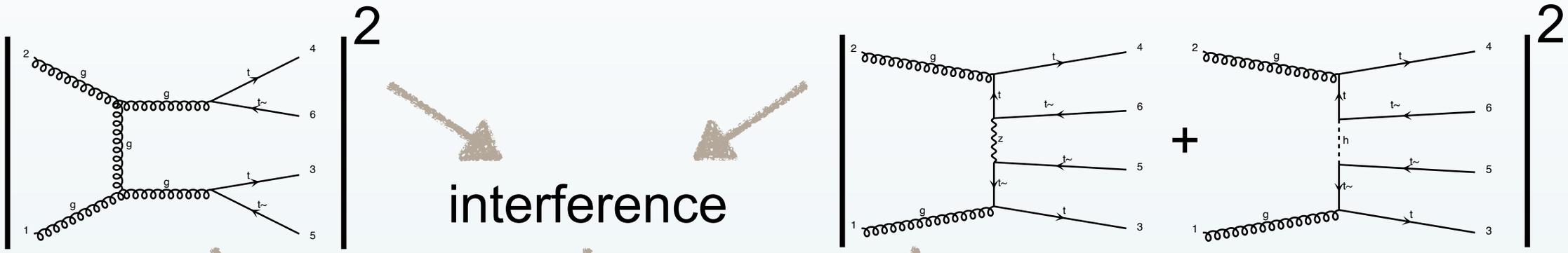
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \kappa_t^2\sigma^{\mathrm{SM}}_{\mathrm{int}} + \kappa_t^4\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_H$$

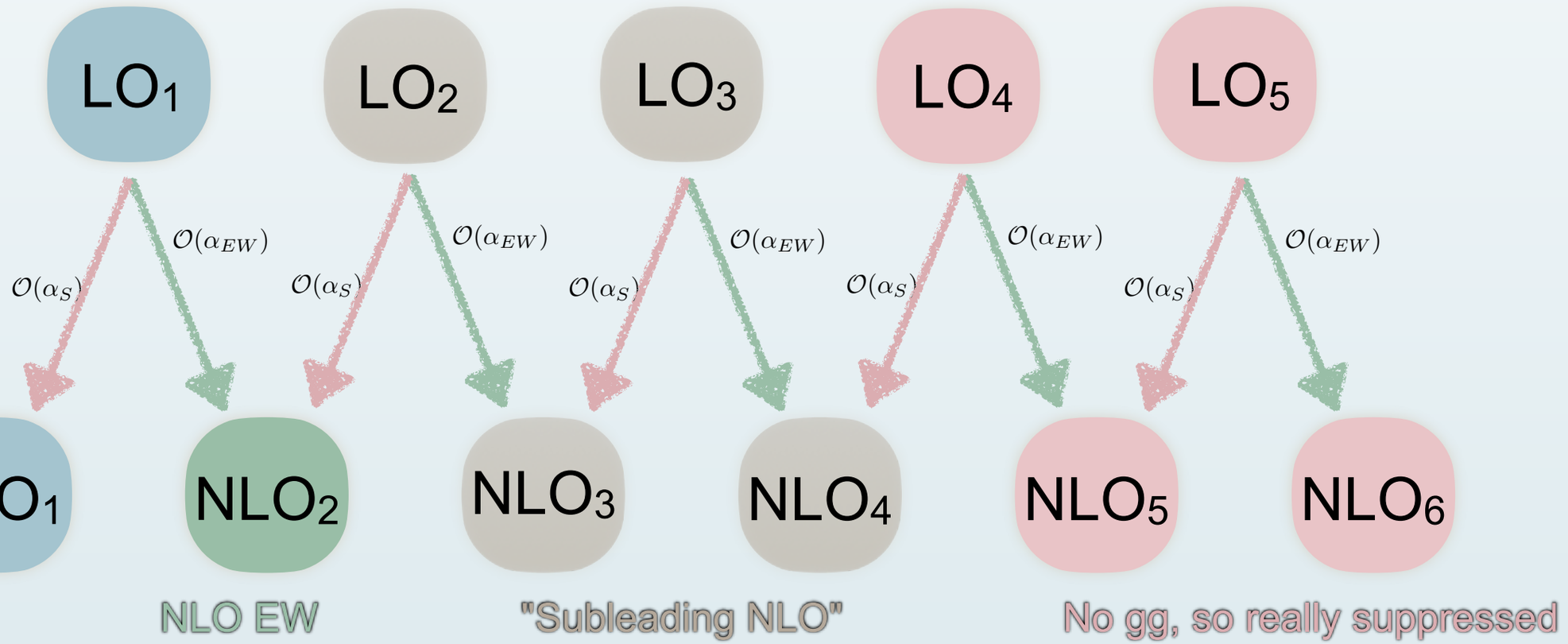
- Four-top production can be used to constrain/measure a **anomalous top Yukawa coupling** independently from the Higgs width
  - kappa-framework
- Large contributions from subleading **LO$_i$**, with large cancelations
  - How do NLO corrections affect these?



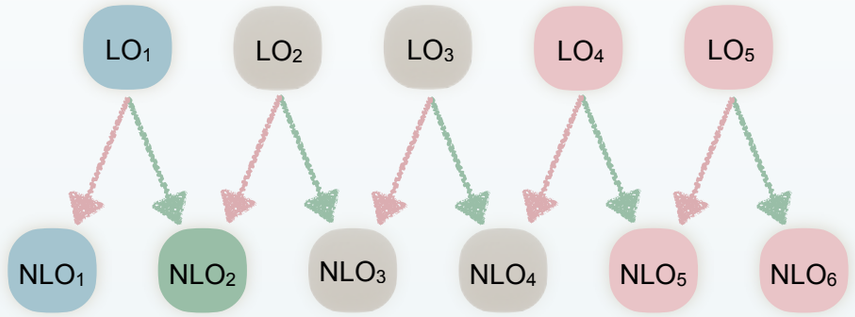
	8 TeV	14 TeV
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	1.193 fb,	12.390 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{H}$:	0.166 fb,	1.477 fb,
$\sigma^{\mathrm{SM}}(t\bar{t}t\bar{t})_{\mathrm{int}}$:	−0.229 fb,	−2.060 fb.

Perturbative expansion at NLO



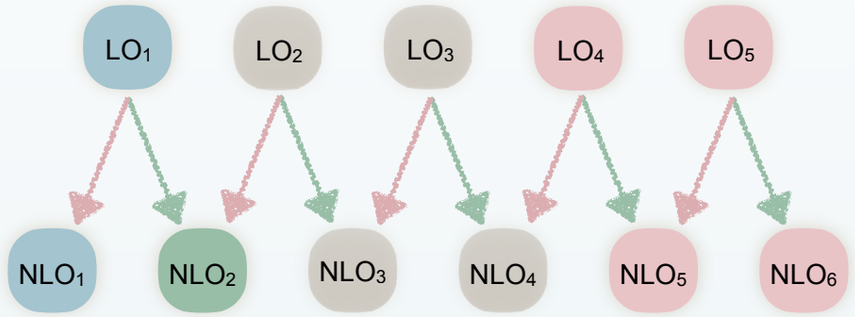


EW & Subleading NLO corrections



- **Additive** vs Multiplicative EW corrections
  - Differ at NNLO; multiplicative is preferred if QCD and EW corrections factorise. Not the case here.
- Not possible to single out the Higgs Yukawa coupling and compute QCD corrections to those separately
  - When computing EW corrections, the Yukawa is linked to the top mass and other EW couplings through renormalisation: they are not independent
  - Need complete SMEFT to be able to compute NLO corrections and study in the impact of NLO corrections: currently beyond our capabilities
  - At NLO, also contributions that have single, triple, quintuple powers of the Yukawa coupling (and not only double or quadruple)
- Compute NLO corrections in the Standard Model
- Central scale values in our studies follow the recipe by Maltoni et al. [arXiv:1507.05640]

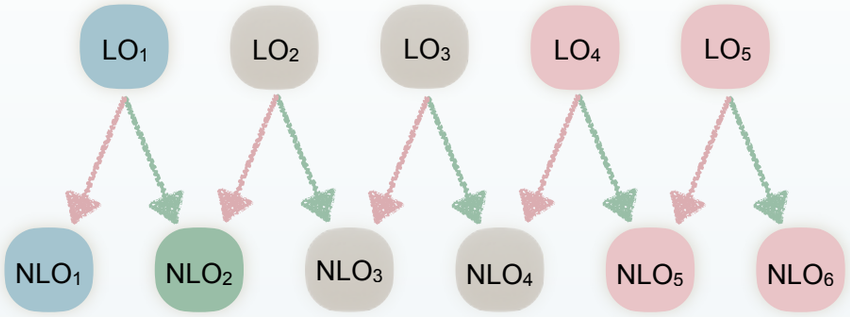
4-top: total cross section



σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}} + \mathrm{NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO}(+\mathrm{NLO})}{\mathrm{LO_{QCD}}(+\mathrm{NLO_{QCD}})}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{+19\%}_{-23\%}$	$7.59^{+64\%}_{-36\%}$	$11.97^{+18\%}_{-21\%}$	$1.11\,(1.08)$

- NLO corrections are large but within the LO scale uncertainty band
- "Subleading" NLO corrections increase the X-section by an additional 8%
- Remaining scale uncertainty of the order of 20% at NLO

NLO 4-top production in the SM



- LO_2 and LO_3 have large cancelations
- NLO_2 and NLO_3 mainly given by QCD corrections on top of them
  - large and strongly dependent on the scale choice
- However, the sum of NLO_2+NLO_3 very stable and small
- Different scale choices have even more extreme cancelations between NLO_2 and NLO_3

[RF, Pagani, Zaro, 2017]

$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO_{QCD}}}(\mu)}$$

σ[fb]	$\mathrm{LO_{QCD}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$

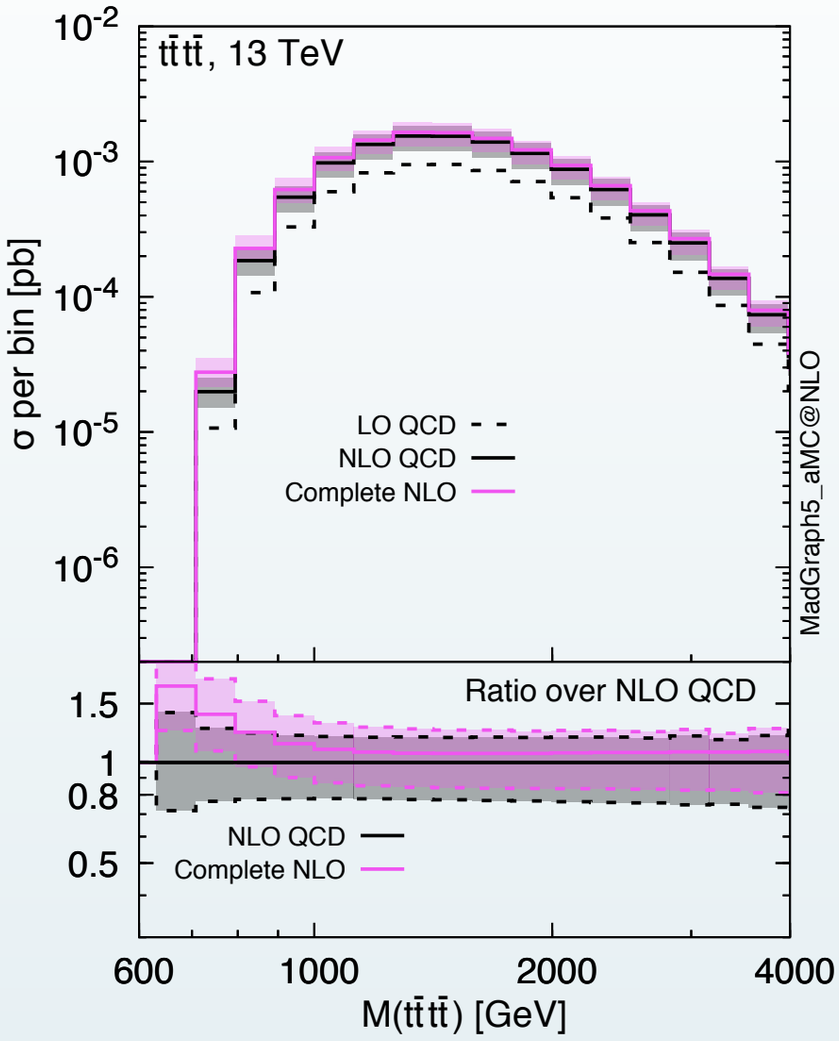
δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive expectation
LO_2	-26.0	-28.3	-30.5	10%
LO_3	32.6	39.0	45.9 ←	1%
LO_4	0.2	0.3	0.4	0.1%
LO_5	0.02	0.03	0.05	0.01%
NLO_1	14.0	62.7	103.5	10%
NLO_2	8.6	-3.3	-15.1 ←	1%
NLO_3	-10.3	1.8	16.1 ←	0.1%
NLO_4	2.3	2.8	3.6	0.01%
NLO_5	0.12	0.16	0.19	0.001%
NLO_6	< 0.01	< 0.01	< 0.01	0.0001%
$\mathrm{NLO}_2 + \mathrm{NLO}_3$	-1.7	-1.6	0.9	

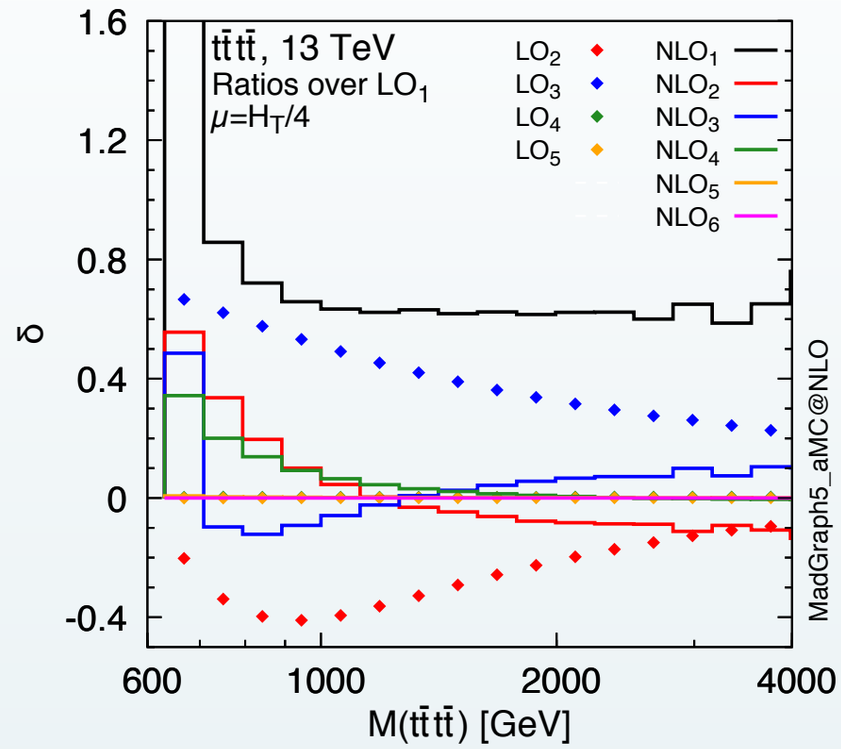
13 TeV

✦ LO_4, $(N)LO_5$ and NLO_6 only qqbar initial state. Hence, very small

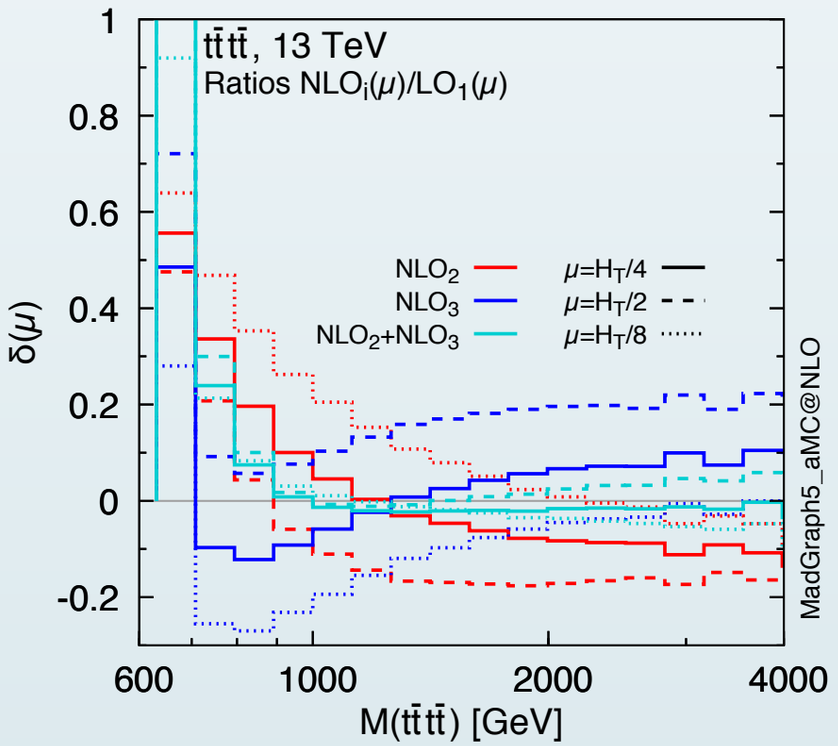
four-top invariant mass

[RF, Pagani, Zaro, 2017]



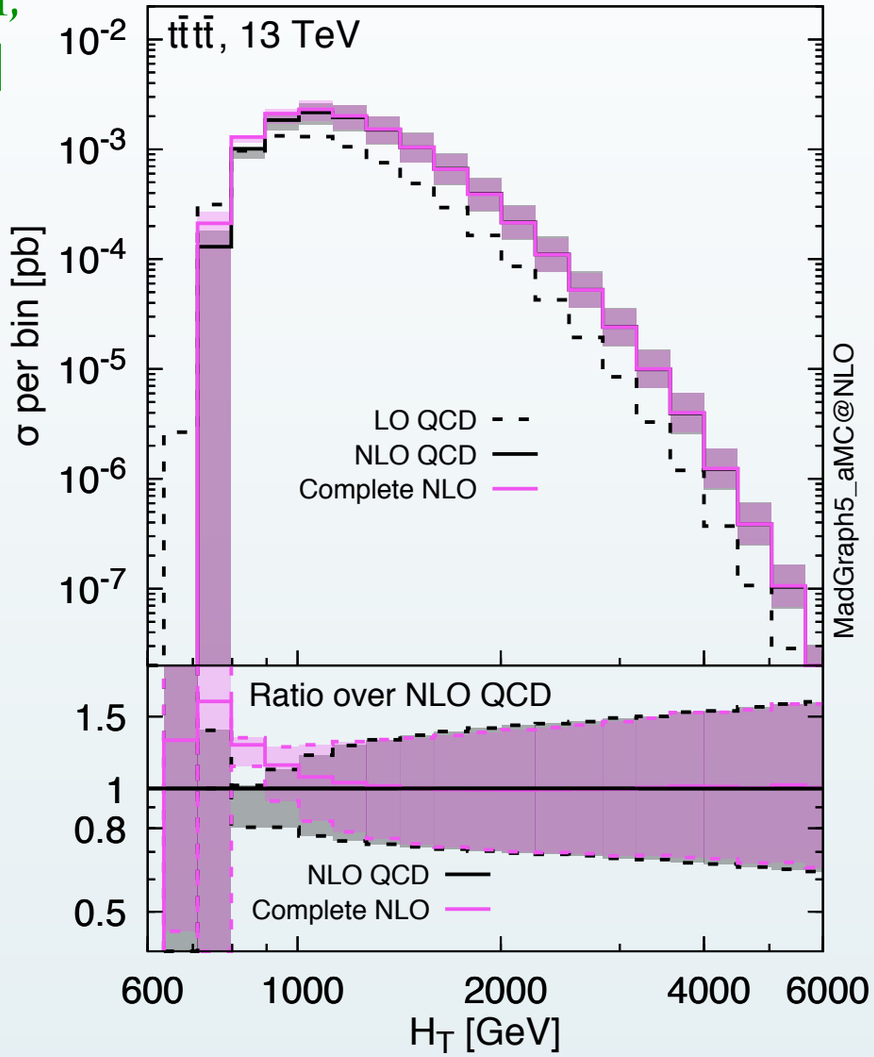


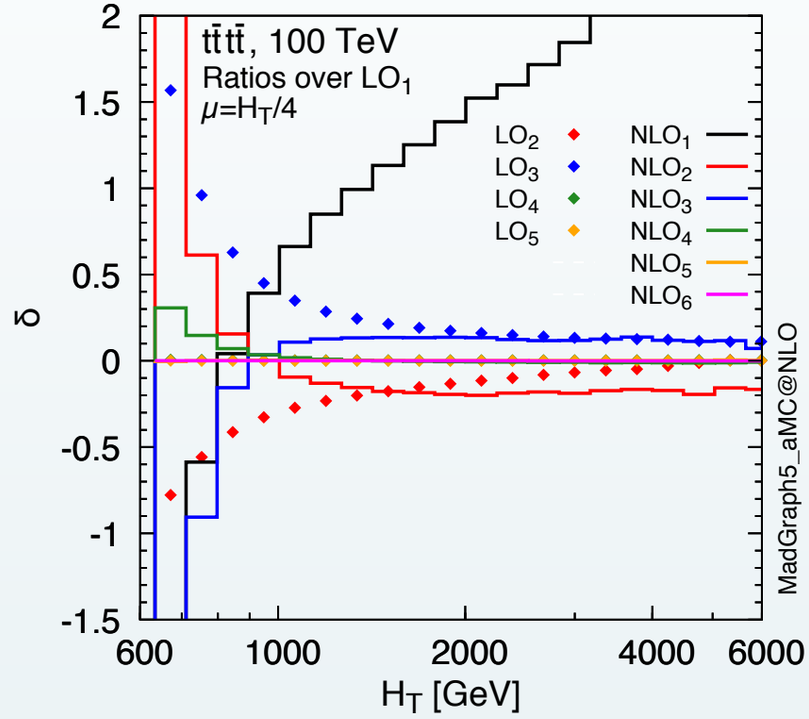
- Large cancelations between NLO_2 and NLO_3 also at the differential level
- NLO_4 large at threshold

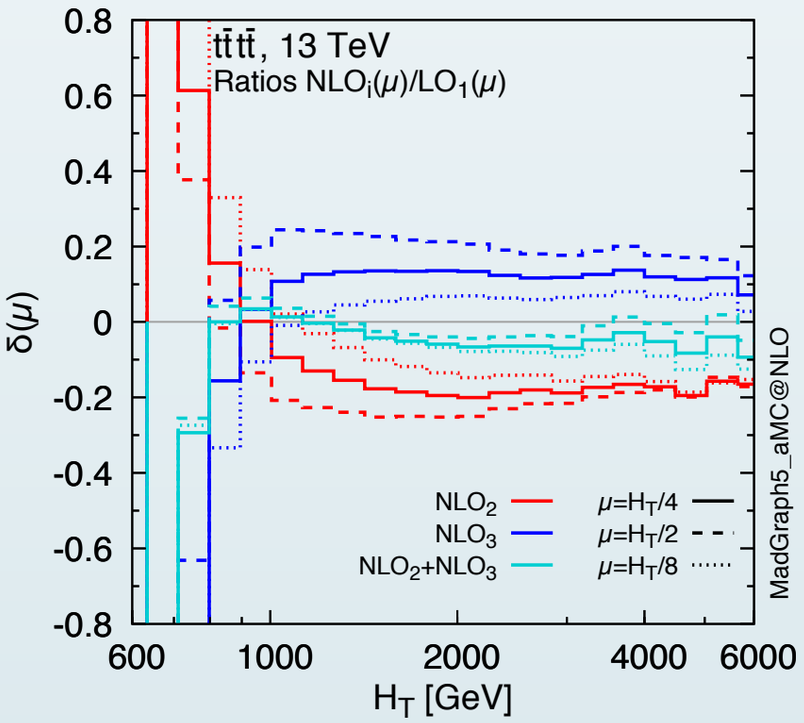


H_T distribution

[RF, Pagani, Zaro, 2017]



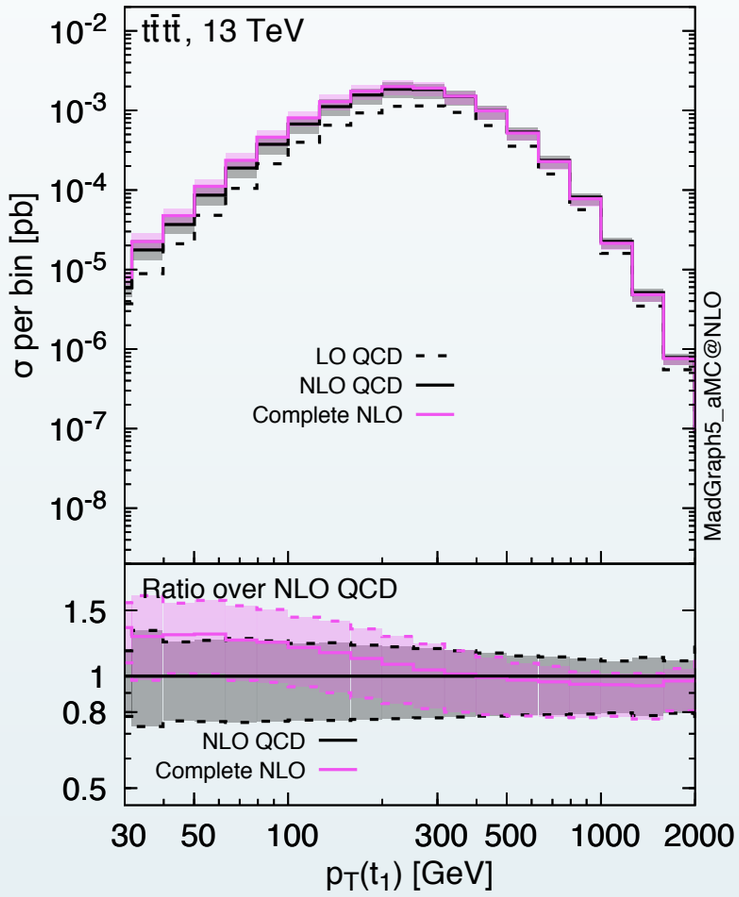


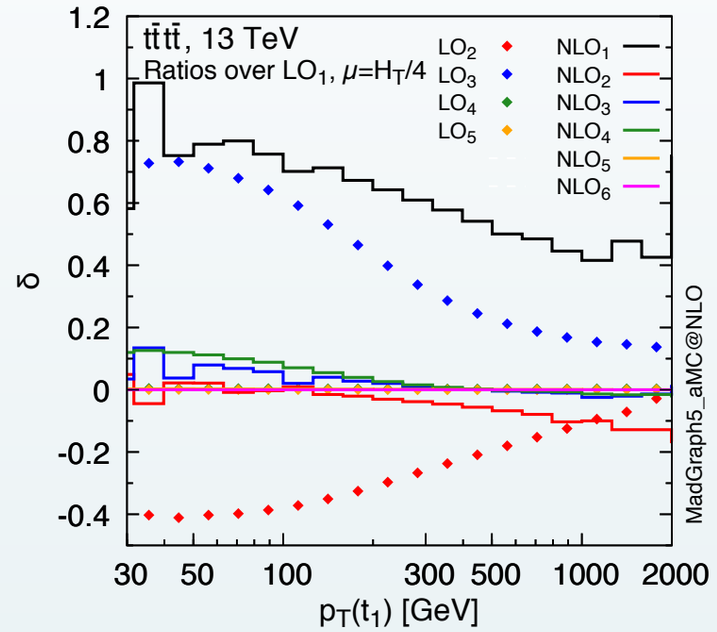


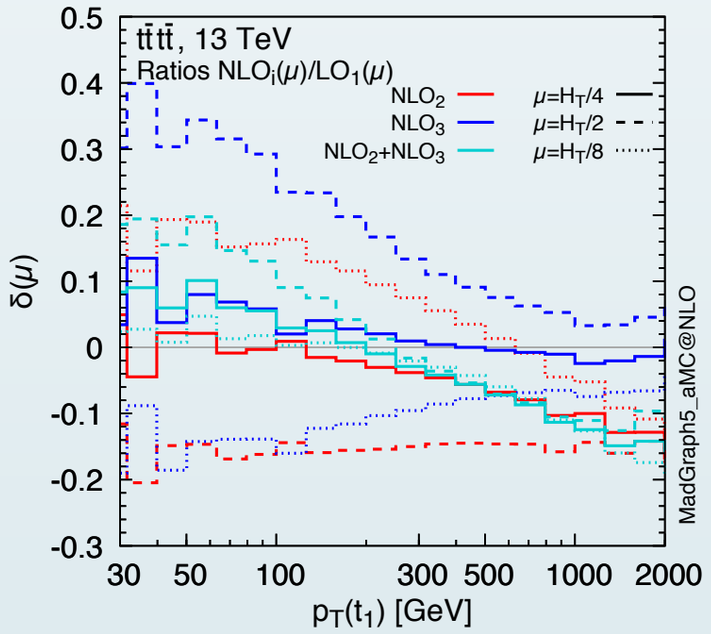
- Similar to 4-top invariant mass

[RF, Pagani, Zaro, 2017]

p_T of hardest top







- Large "subleading" corrections at small transverse momentum

Conclusions

- NLO corrections to 4-top production are special:
  - For no other process LO_2 is as large as here.
  - For no other process NLO_2 is dominated by QCD corrections (and not EW corrections)
- **Large cancelations among NLO_i corrections**
  - Surprising!
  - Not possible to estimate how this affects BSM physics (e.g. modified Yukawa coupling)
    - Is there still a cancelation?
    - Would require computing the complete-NLO corrections in the SMEFT, which is currently out-of-reach