Associated production of a top pair with a heavy boson at the LHC to NLO+NNLL accuracy

Alessandro Broggio

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Outline

▸ Introduction: Top quark pair + Higgs/W/Z production at the LHC

▸ Factorization of the partonic cross section in the partonic threshold limit and resummation of soft gluon emission corrections

▸ Results: total cross sections and differential distributions at NLO+NNLL accuracy for tTH, tTW, tTZ processes at the LHC

In collaboration with

▸ work on tTH at NNLL in collaboration with A. Ferroglia, B.D. Pecjak, A. Signer, L.L. Yang (JHEP 1603 (2016) 124 [arXiv:1510.01914], JHEP 1702 (2017) 126 [arXiv: 1611.00049])

▸ work on tTW and tTZ in collaboration with A. Ferroglia, G. Ossola, B.D. Pecjak, R.D. Sameshima (JHEP 1609 (2016) 089 [arXiv:1607.05303], JHEP 1704 (2017) 105 [arXiv:1702.00800])

Top quark and Higgs boson

the two heaviest Standard Model (SM) particles
$m_t \sim 173$ GeV, $m_H \sim 125$ GeV

# Top quark and Higgs boson

▶ Top quark & Higgs boson

  ‣ according to the SM, the top quark is the elementary particle which couples most strongly to the Higgs boson

  ‣ gluon fusion channel provides the largest Higgs production cross section at the LHC, but tTH process allows direct access to top-quark Yukawa coupling

  ‣ measurement of the top-quark Yukawa coupling is one of the goals of the Run II of LHC
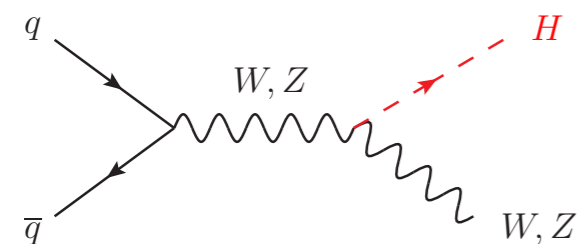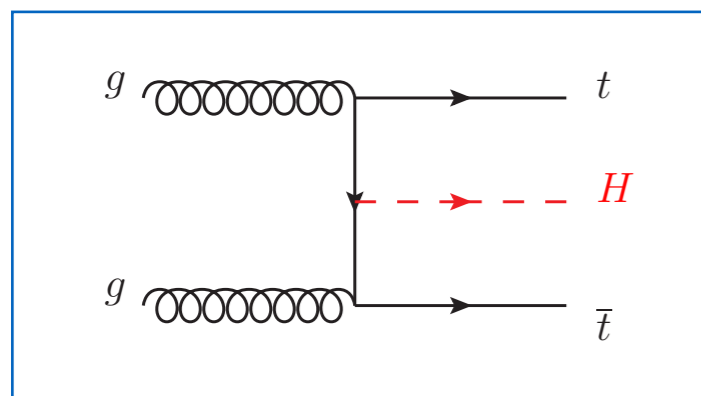
Higgs production channels

LHC @ 14 TeV
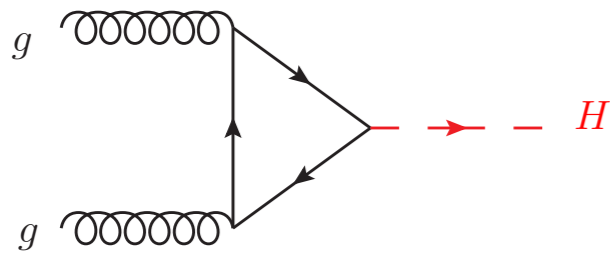
54.67 pb
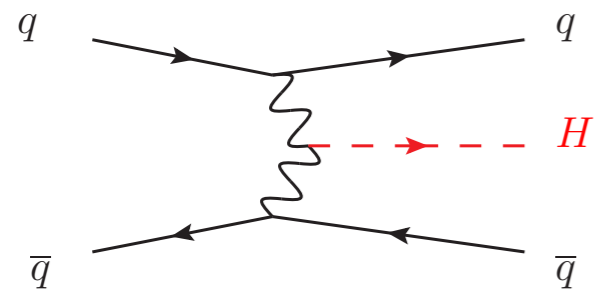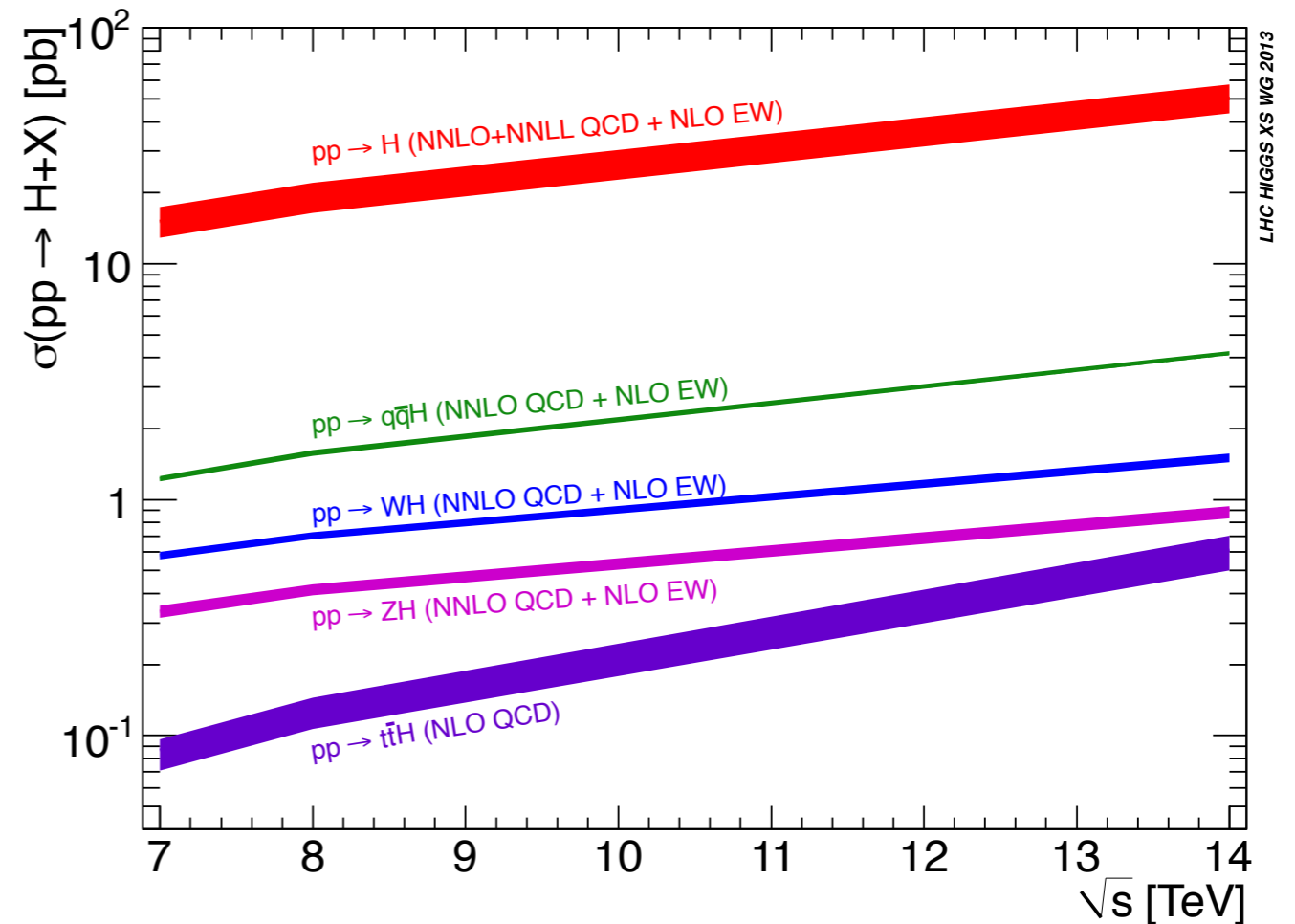
4.18 pb

1.50 pb (WH)
0.88 pb (ZH)

0.61 pb $\longrightarrow$ Expected to be seen at LHC 13 TeV, direct measurement of the top Yukawa coupling

$$\sigma \propto g_{ttH}^2$$

Plot labels:
- $\sigma(pp \to H+X)$ [pb]
- $\sqrt{s}$ [TeV]
- LHC HIGGS XS WG 2013
- $pp \to H$ (NNLO+NNLL QCD + NLO EW)
- $pp \to q\bar{q}H$ (NNLO QCD + NLO EW)
- $pp \to WH$ (NNLO QCD + NLO EW)
- $pp \to ZH$ (NNLO QCD + NLO EW)
- $pp \to t\bar{t}H$ (NLO QCD)

top pair + Higgs calculations

▸ Cross section and some distributions computed to NLO QCD (Beenakker, Dittmaier, Kraemer, Plumper, Spira, Zerwas '01-'02 and Dawson, Reina, Wackeroth, Orr, Jackson '01-'03)

▸ top pair + Higgs benchmark process to test automated NLO multileg codes (Frixione et al. '11; Hirschi et al '11; Garzelli et al '11; Bevilacqua et al. '11)

▸ EW corrections to the parton level cross section are known (Frixione, Hirshi, Pagani, Shao, Zaro '14; Zhang, Ma, Chen, Guo '14; Frixione, Hirshi, Pagani, Shao, Zaro '15)

▸ NLO QCD corrections were interfaced with SHERPA and POWHEG BOX (Gleisberg, Hoeche, Krauss, Schonherr, Schaumann '09; Hartanto, Jaeger, Reina, Wackeroth '15)

▸ NLO QCD corrections to $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}H$ (Denner, Feger '15)

▸ NLO+NLL resummation of soft gluon emissions for the total cross section (production threshold limit) (Kulesza, Motyka, Stebel, Theeuwes '15)

▸ nNLO in the "PIM" threshold limit from NNLL resummation formula (AB, A. Ferroglia, B. Pecjak, A. Signer, L. Yang '15)

and the list continues…

▸ NLO+NNLL resummation in "PIM" kinematics, RG-evolution in Mellin space
(AB, A. Ferroglia, B. Pecjak, A. Signer, L. Yang '16)

▸ NLO EW and QCD corrections with off-shell top-antitop pairs (A. Denner, J. Lang, M. Pellen, S. Uccirati '16)

▸ NLO+NNLL resummation in "PIM" kinematics with direct QCD approach (invariant mass distribution of the triplet) (Kulesza, Motyka, Stebel, Theeuwes '17)

▸ Pseudoscalar couplings at NLO+NLL accuracy (AB, A. Ferroglia, M. Fiolhais, A. Onofre '17)

Top pair + W or Z boson

▶ tTW and tTZ are the two heaviest set of particles measured at the LHC with c.o.m. energy of 7,8,13 TeV

▶ 8 TeV

$$\sigma_{t\bar{t}W} = 382^{+117}_{-102} \text{ fb (CMS)} \qquad \sigma_{t\bar{t}W} = 369^{+100}_{-91} \text{ fb (ATLAS)}$$

$$\sigma_{t\bar{t}Z} = 242^{+65}_{-55} \text{ fb (CMS)} \qquad \sigma_{t\bar{t}Z} = 176^{+58}_{-52} \text{ fb (ATLAS)}$$

▶ 13 TeV

$$\sigma_{t\bar{t}W} = 800^{+176.9}_{-162.8} \text{ (CMS)} \qquad \sigma_{t\bar{t}W} = 1400^{+800}_{-800} \text{ fb (ATLAS)}$$

$$\sigma_{t\bar{t}Z} = 1000^{+150}_{-128} \text{ (CMS)} \qquad \sigma_{t\bar{t}Z} = 900^{+300}_{-300} \text{ fb (ATLAS)}$$

▶ Important to detect anomalies in the top couplings of the Z boson, and can be considered background processes in new physics searches

▶ Both processes were calculated to NLO QCD accuracy by several groups (A. Lazopoulos, T. McElmurry, K. Melnikov, F. Petriello '07 - '08, M.V. Garzelli, A. Kardos, C.G. Papadopoulos, Z. Trocsanyi '12, J.M. Campbell, R.K. Ellis '12, F. Maltoni, M.L. Mangano, I. Tsinikos, M. Zaro '14)

▶ EW corrections are also known (Frixione, Hirshi, Pagani, Shao, Zaro '15)

▶ NLO+NNLL for ttW in momentum space (Li, Li and Li '14)

"Triplet" Invariant Mass kinematics

$$q(p_1) + \bar{q}(p_2) \to t(p_3) + \bar{t}(p_4) + H(p_5)$$

Tree Level subprocesses

$$g(p_1) + g(p_2) \to t(p_3) + \bar{t}(p_4) + H(p_5)$$

$$\hat{s} = (p_1 + p_2)^2 = 2p_1 \cdot p_2 \qquad\qquad M^2 = (p_3 + p_4 + p_5)^2$$

Partonic center of
mass energy squared

Invariant mass of the ttH final
state

When real radiation is
present in the final state $\longrightarrow$ $\hat{s} \neq M^2$ $\qquad z = \dfrac{M^2}{\hat{s}} \to 1$ $\qquad$ "PIM" soft limit

In the soft emission limit a scale hierarchy emerges

$$\boxed{\hat{s},\, M^2,\, m_t^2,\, m_H^2} \gg \boxed{\hat{s}(1-z)^2} \gg \Lambda_{\mathrm{QCD}}^2$$

Hard scales $\qquad\qquad$ Soft scale

Large logarithmic corrections

▸ The partonic cross section for top pair + H (or W or Z) production receives potentially large corrections from soft gluon emission diagrams

▸ The partonic cross section depends on logarithms of the ratio of two different scales

$$L \equiv \ln \left(\frac{\text{``hard'' scale}}{\text{``soft'' scale}} \right)$$

▸ It can be that $\alpha_s L \sim 1$

▸ One needs to reorganise the perturbative series: Resummation

▸ This can be carried out using effective field theory methods (soft-collinear effective theory)

Factorization and Resummation

$$\sigma(s, m_t, m_H) = \frac{1}{2s} \int_{\tau_{\min}}^{1} \frac{d\tau}{\tau} \int_{\tau}^{1} \frac{dz}{\sqrt{z}} \sum_{ij} \mathff_{ij}\left(\frac{\tau}{z}, \mu\right) \qquad \text{parton luminosity}$$

$$\int d\mathrm{PS}_{t\bar{t}H} \mathrm{Tr}\left[\mathbf{H}_{ij}(\{p_i\}, \mu) \, \mathbf{S}_{ij}\left(\frac{M(1-z)}{\sqrt{z}}, \{p_i\}, \mu\right)\right] + \mathcal{O}(1-z)$$

Hard function (color matrix),
obtained using self-modified versions
of Openloops and Gosam

Soft function (color matrix)

$$\tau = \frac{M^2}{s}, \qquad \tau_{\min} = \frac{(2m_t + m_H)^2}{s} \qquad\qquad P_n(z) \equiv \left[\frac{\ln^n(1-z)}{1-z}\right]_+$$

The hard and soft functions satisfy RG equations that can be solved to obtain the
resummed hard-scattering kernels

$$C_{ij}(z, \mu_f) = \exp\left[4a_{\gamma_\phi}(\mu_s, \mu_f)\right] \mathrm{Tr}\left[\mathbf{U}_{ij}(\{p\}, \mu_h, \mu_s) \mathbf{H}_{ij}(\{p\}, \mu_h)\right.$$

$$\left. \times \mathbf{U}_{ij}^\dagger(\{p\}, \mu_h, \mu_s) \tilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\mu_s} + \partial_\eta, \{p\}, \mu_s\right)\right] \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)} \frac{z^{1/2 - \eta}}{(1-z)^{1-2\eta}}.$$

Factorization and Resummation

$$\sigma(s, m_t, m_H) = \frac{1}{2s} \int_{\tau_{\min}}^{1} \frac{d\tau}{\tau} \int_{\tau}^{1} \frac{dz}{\sqrt{z}} \sum_{ij} f\!f_{ij} \left(\frac{\tau}{z}, \mu\right)$$

parton luminosity

$$\cdots \mu \Big)\Big] + \mathcal{O}(1-z)$$

More details on factorization and resummation methods using effective field theory in this book

Lecture Notes in Physics 896

Thomas Becher
Alessandro Broggio
Andrea Ferroglia

Introduction to
Soft-Collinear
Effective
Theory

Springer

arXiv:1410.1892

$$\tau = \frac{M^2}{s}, \qquad \tau_{\mathrm{m}} \cdots$$
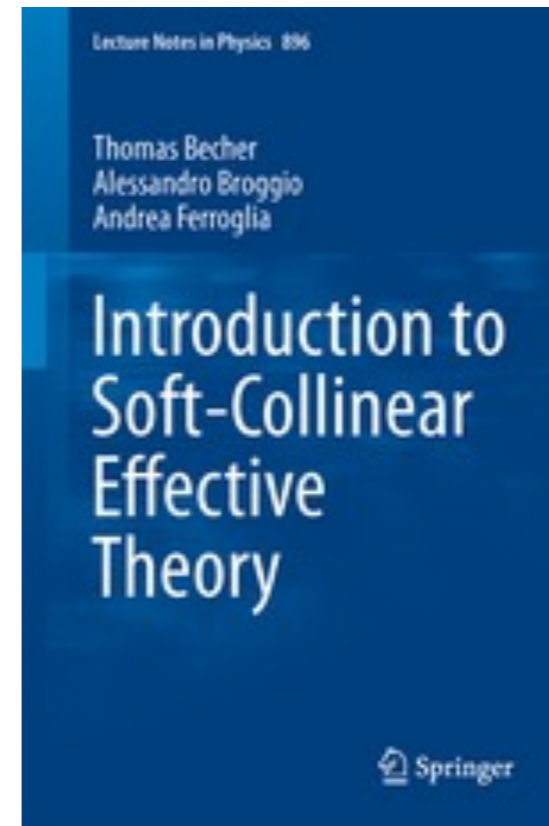
matrix)

$$\equiv \left[\frac{\ln^n(1-z)}{1-z}\right]_+$$

$$C_{ij}(z, \mu_f) = \exp\left[4a_{\gamma_\phi}(\mu_s, \mu_f)\right] \operatorname{Tr}\Big[\mathbf{U}_{ij}(\{p\}, \mu_h, \mu_s)\, \mathbf{H}_{ij}(\{p\}, \mu_h)$$

$$\times\, \mathbf{U}_{ij}^\dagger(\{p\}, \mu_h, \mu_s)\, \tilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\mu_s} + \partial_\eta, \{p\}, \mu_s\right)\Big] \frac{e^{-2\gamma_E \eta}}{\Gamma(2\eta)} \frac{z^{1/2-\eta}}{(1-z)^{1-2\eta}}.$$

Mellin space

▶ Resummation can also be carried out in Mellin space by taking the Mellin transform of the factorized cross section, more similar to "direct QCD" resummation

▶ The total cross section can be recovered with an inverse Mellin transform

$$\sigma(s, m_t, m_H) = \frac{1}{2s} \int_{\tau_{\min}}^{1} \frac{d\tau}{\tau} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} dN \tau^{-N} \sum_{ij} \widetilde{ff}_{ij}(N, \mu) \int d\mathrm{PS}_{t\bar{t}H} \, \widetilde{c}_{ij}(N, \mu)$$

▶ Hard and soft functions are evaluated at values of the scale where the large corrections are absent $\mu_h = M, \qquad \mu_s = M/\bar{N}$

▶ RG evolution to obtain the hard-scattering kernels at the factorization scale

$$\widetilde{c}_{ij}(N, \mu_f) = \mathrm{Tr}\left[\widetilde{\mathbf{U}}_{ij}(\bar{N}, \{p\}, \mu_f, \mu_h, \mu_s) \, \mathbf{H}_{ij}(\{p\}, \mu_h) \, \widetilde{\mathbf{U}}_{ij}^{\dagger}(\bar{N}, \{p\}, \mu_f, \mu_h, \mu_s) \right.$$

$$\left. \times \widetilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\bar{N}^2\mu_s^2}, \{p\}, \mu_s \right) \right]$$

$$\widetilde{\mathbf{U}}\left(\bar{N}, \{p\}, \mu_f, \mu_h, \mu_s \right) = \exp\left\{ \frac{4\pi}{\alpha_s(\mu_h)} g_1(\lambda, \lambda_f) + g_2(\lambda, \lambda_f) + \frac{\alpha_s(\mu_h)}{4\pi} g_3(\lambda, \lambda_f) + \cdots \right\}$$

$$\times \mathbf{u}(\{p\}, \mu_h, \mu_s), \qquad \lambda = \frac{\alpha_s(\mu_h)}{2\pi}\beta_0 \ln\frac{\mu_h}{\mu_s}, \qquad \lambda_f = \frac{\alpha_s(\mu_h)}{2\pi}\beta_0 \ln\frac{\mu_h}{\mu_f}$$
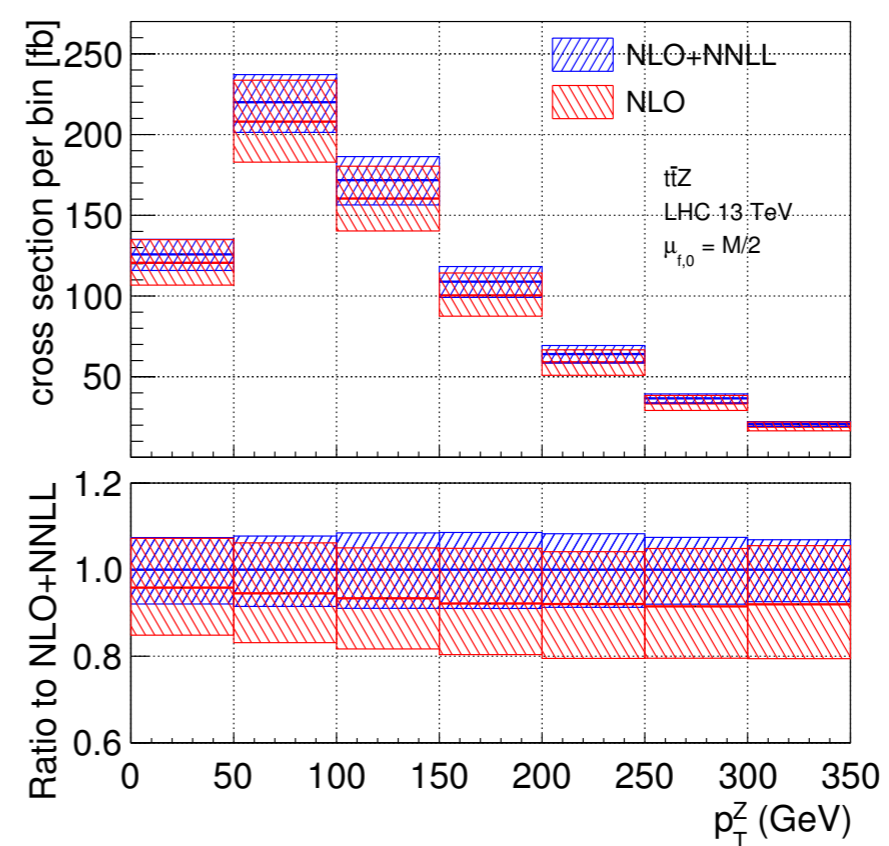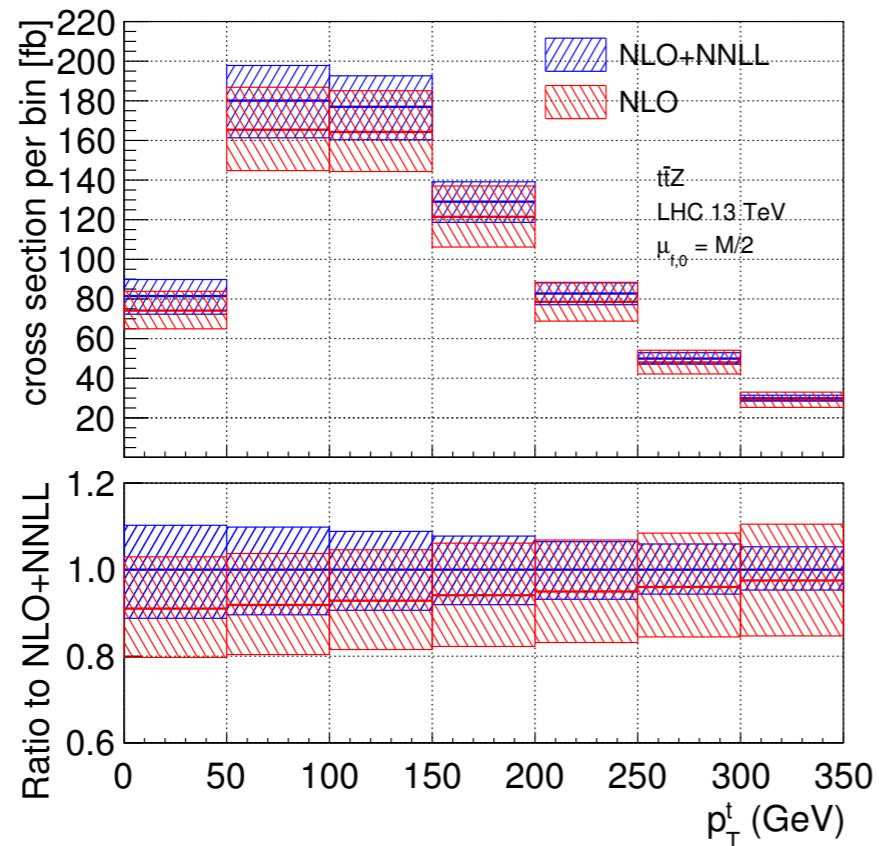
tTH: total cross section

Factorization scale choice
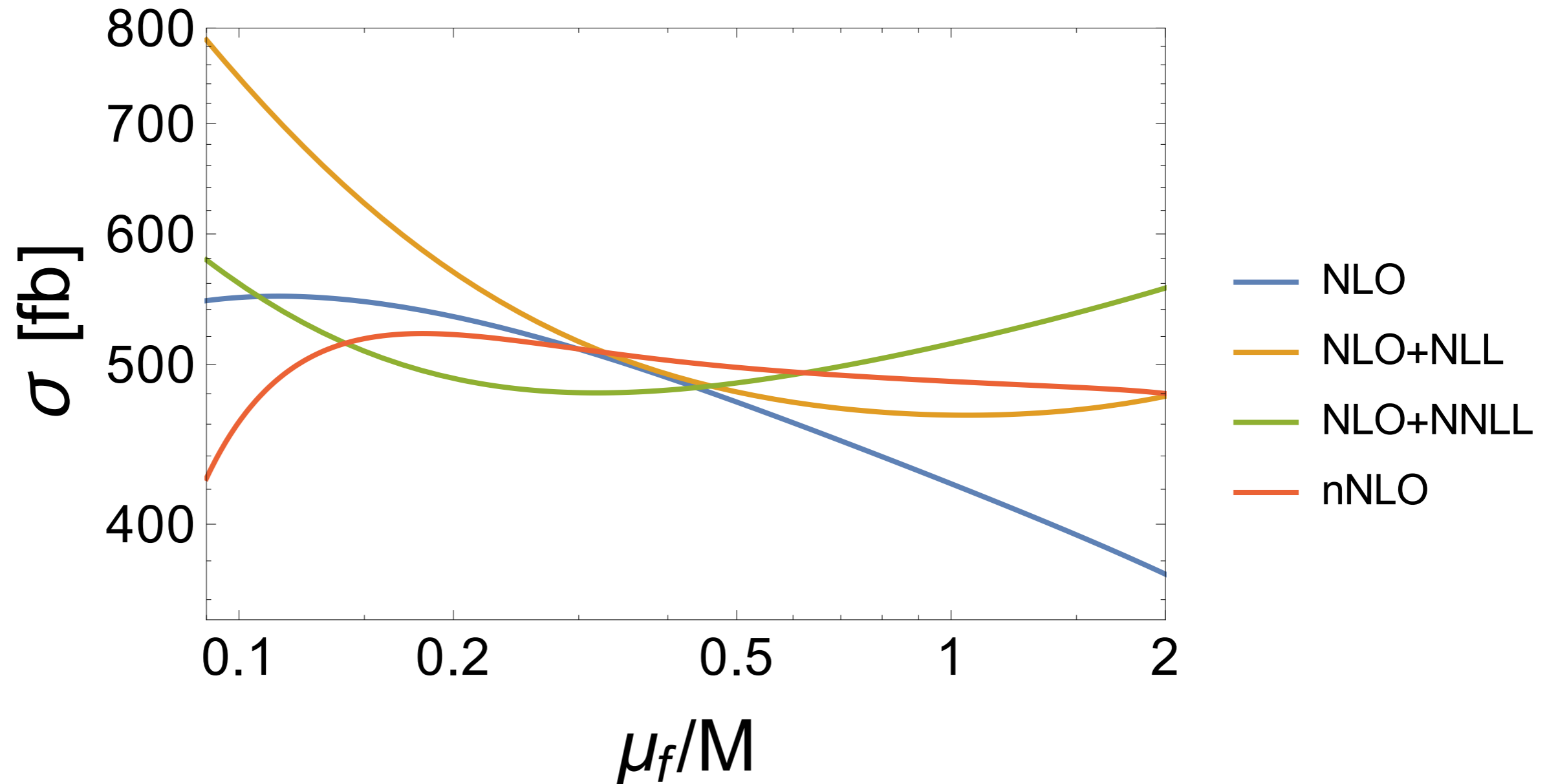
Total cross section tTH

NLO obtained from MadGraph5_aMC@NLO

$$\sqrt{s} = 13 \, \text{TeV} \qquad \mu_{f,0} = M/2$$

order	PDF order	code	σ [fb]
LO	LO	MG5_aMC	$378.7^{+120.5}_{-85.2}$
app. NLO	NLO	in-house MC	$473.3^{+0.0}_{-28.6}$
NLO no qg	NLO	MG5_aMC	$482.1^{+10.9}_{-35.1}$
NLO	NLO	MG5_aMC	$474.8^{+47.2}_{-51.9}$
NLO+NLL	NLO	in-house MC +MG5_aMC	$480.1^{+57.7}_{-15.7}$
NLO+NNLL	NNLO	in-house MC +MG5_aMC	$486.4^{+29.9}_{-24.5}$
nNLO (Mellin)	NNLO	in-house MC +MG5_aMC	$497.9^{+18.5}_{-9.4}$
(NLO+NNLL)$_{\text{NNLO exp.}}$	NNLO	in-house MC +MG5_aMC	$482.7^{+10.7}_{-21.1}$

Uncertainties

$$\Delta O_i^+ = \max\{O(\kappa_i = 1/2), O(\kappa_i = 1), O(\kappa_i = 2)\} - \bar{O},$$
$$\Delta O_i^- = \min\{O(\kappa_i = 1/2), O(\kappa_i = 1), O(\kappa_i = 2)\} - \bar{O},$$

Total cross section tTH
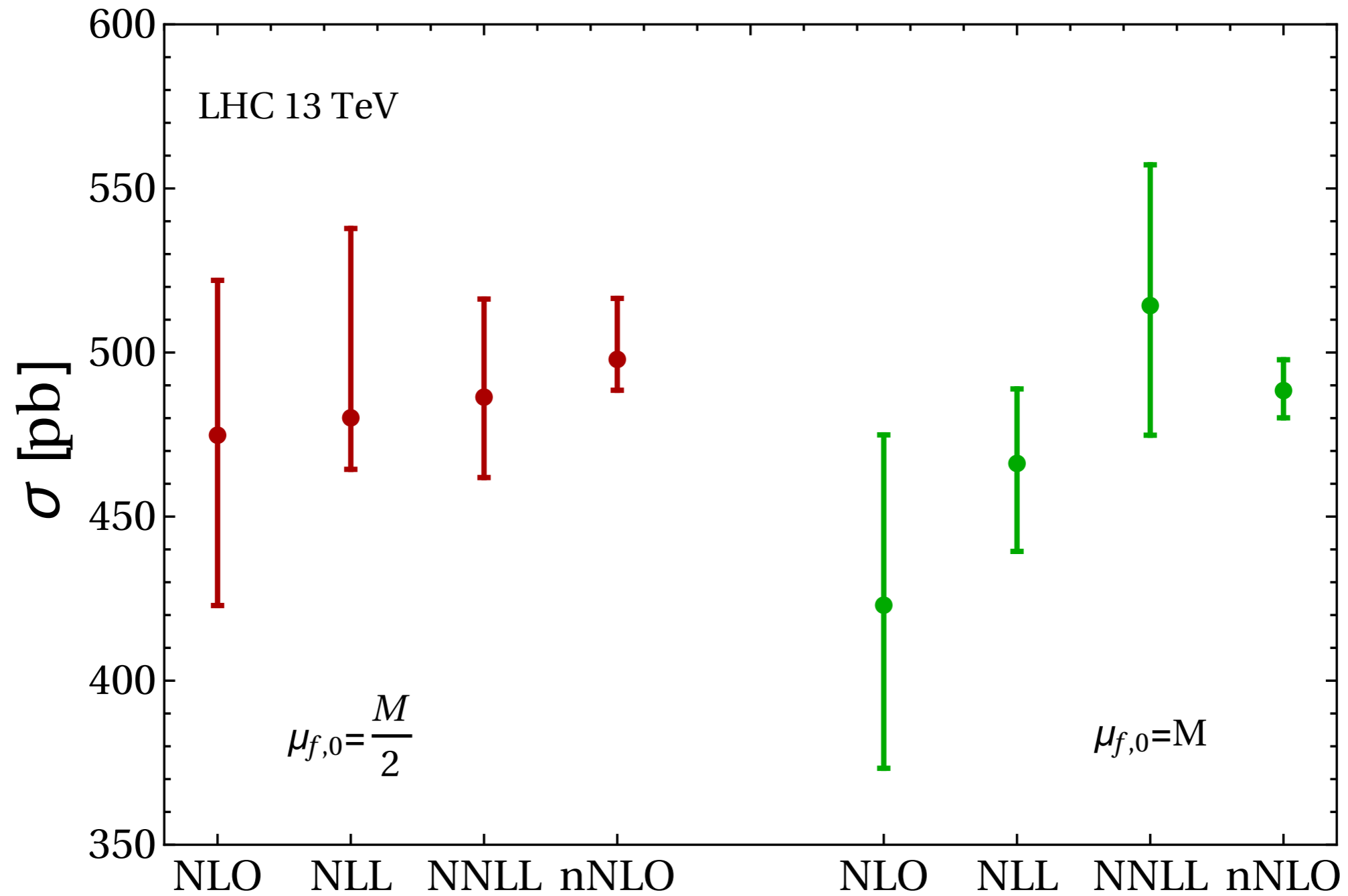
Distributions tTH: NLO vs NLO+NNLL
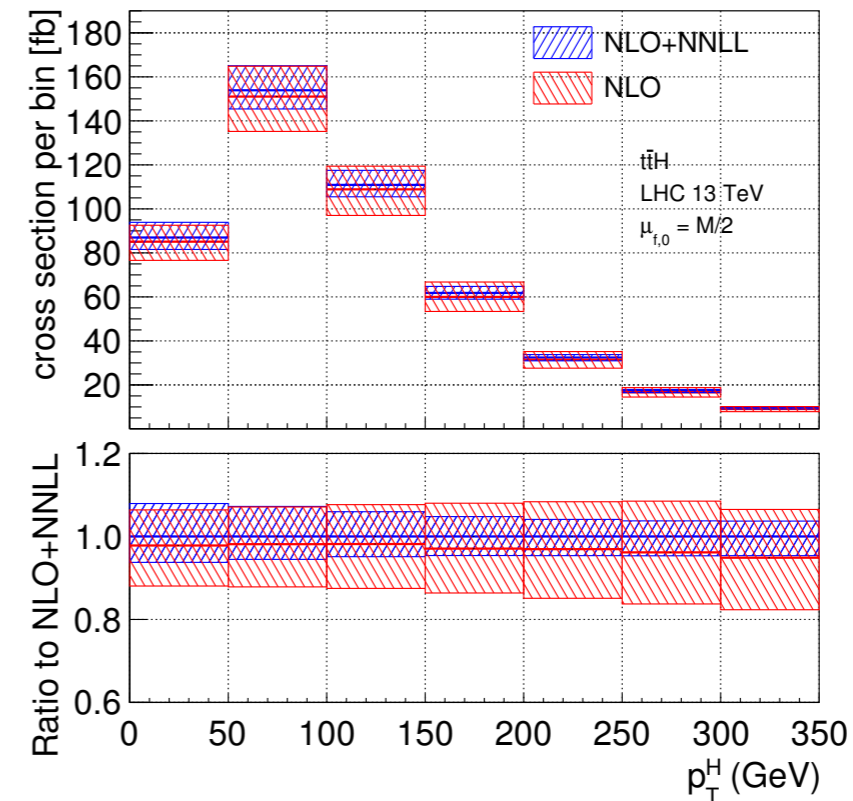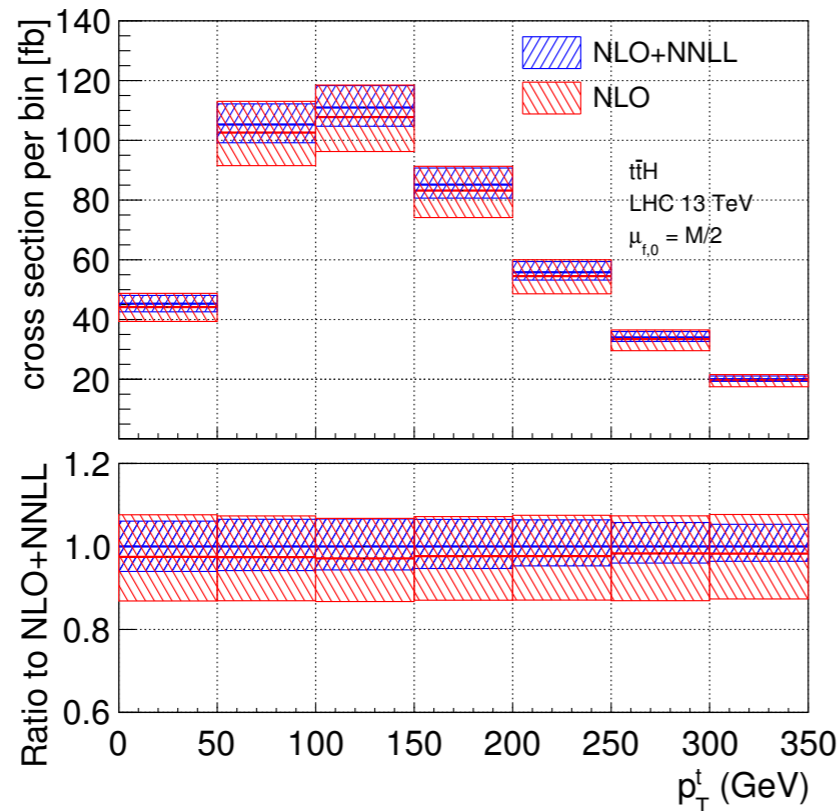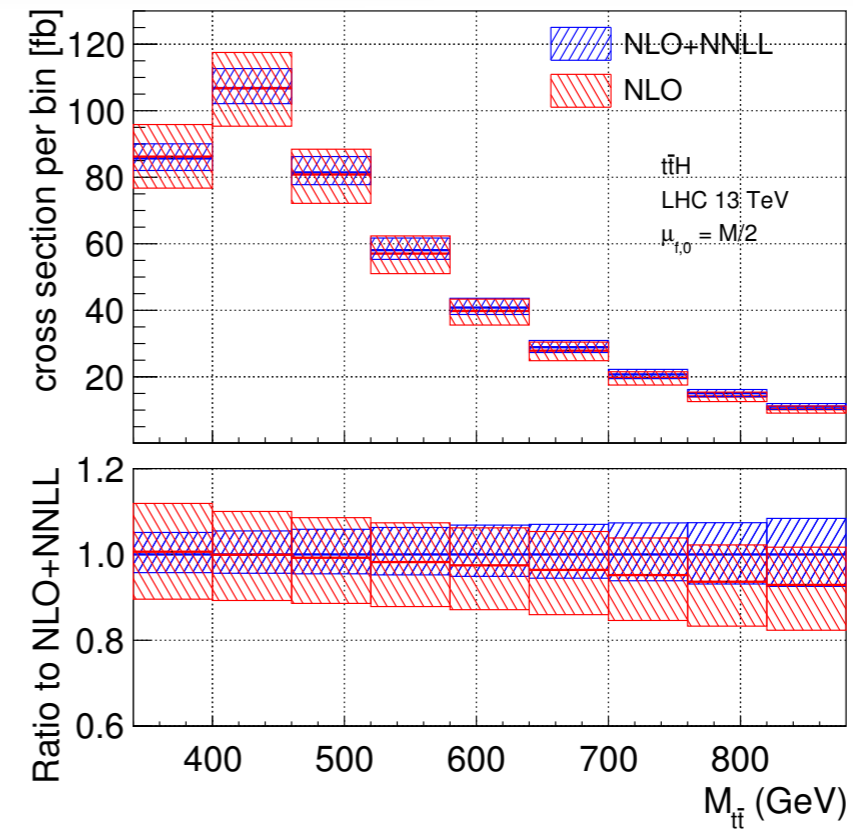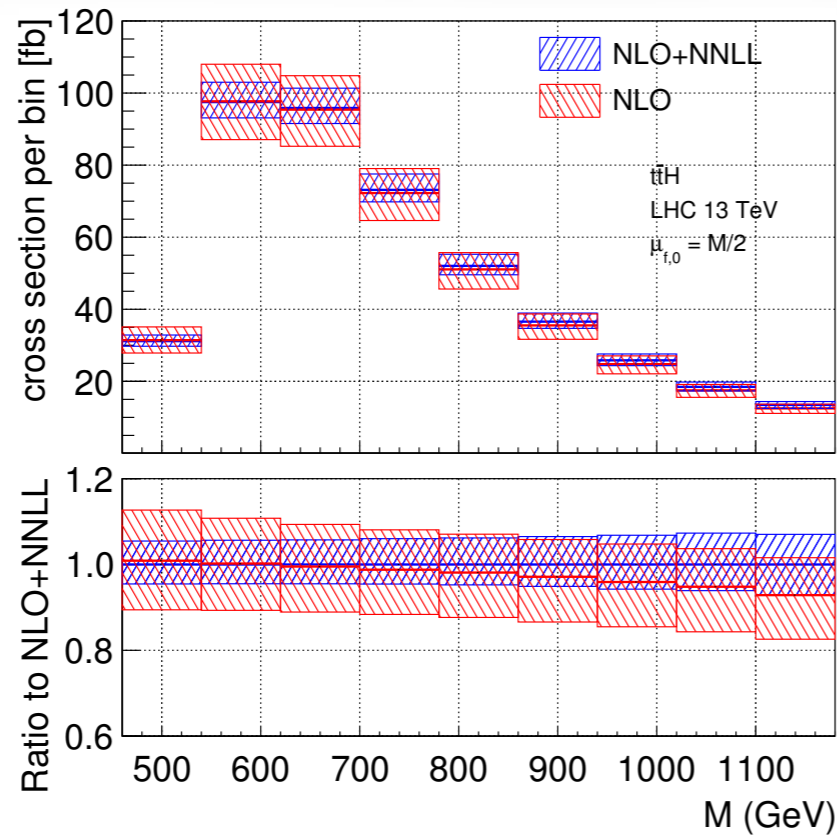
Distributions tTH: NLL vs NNLL
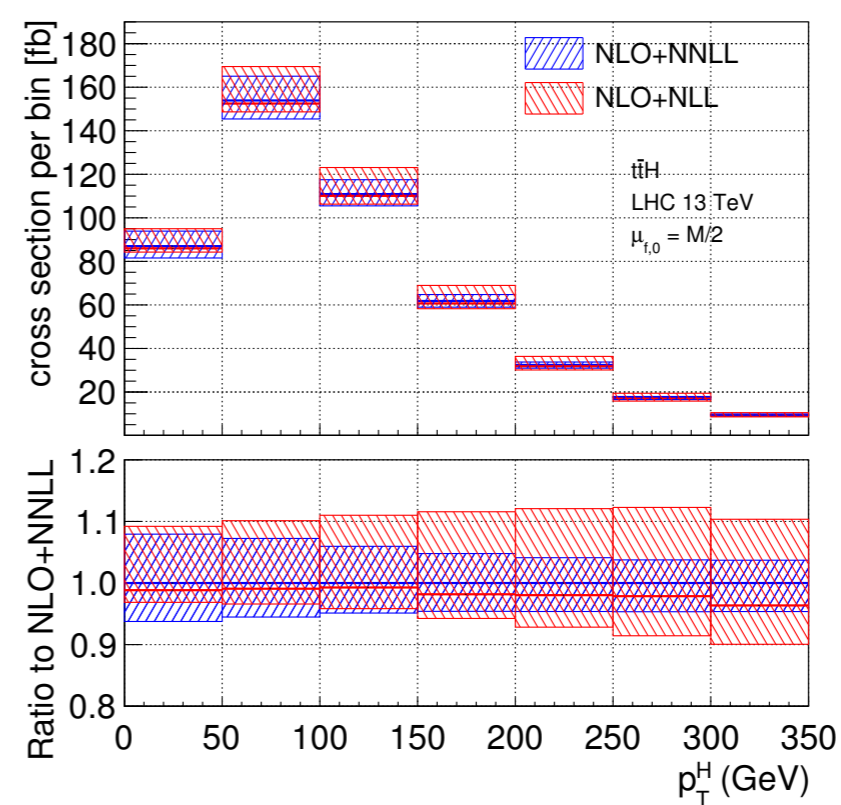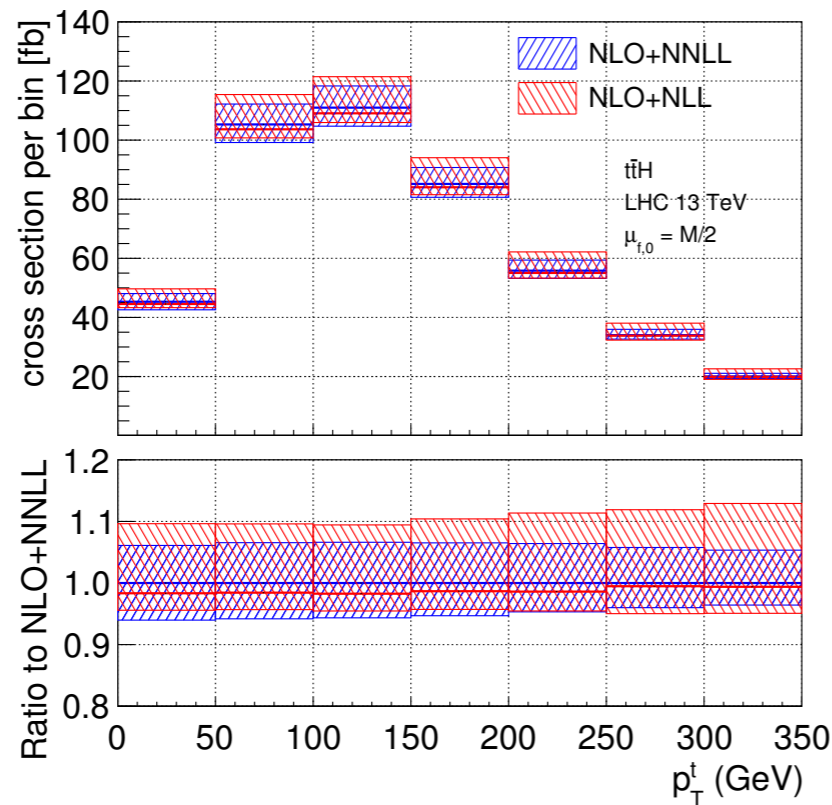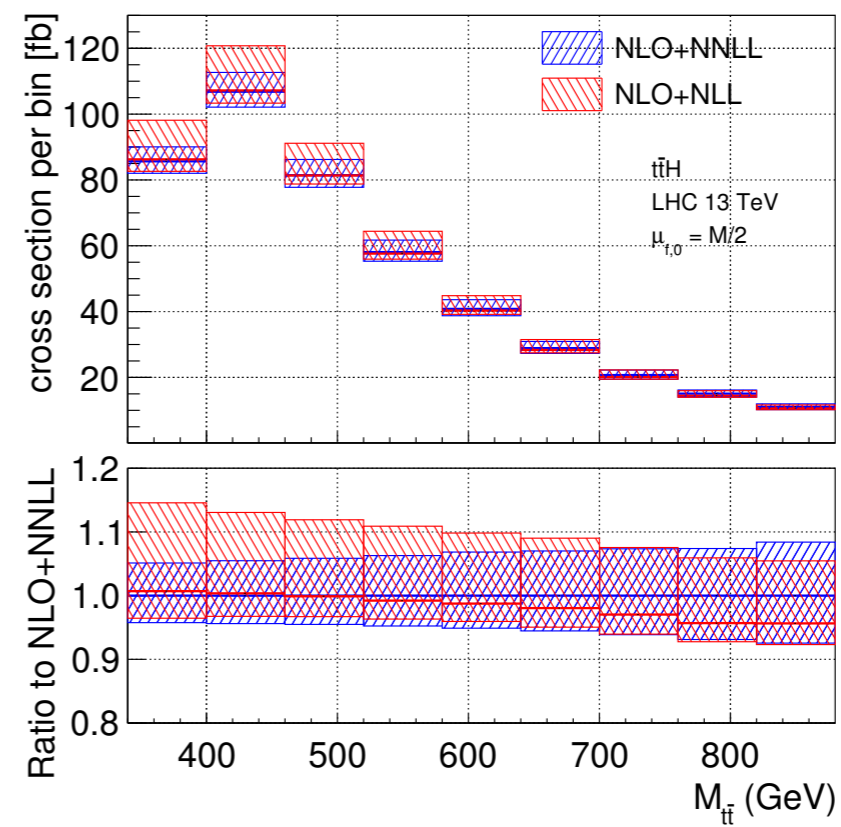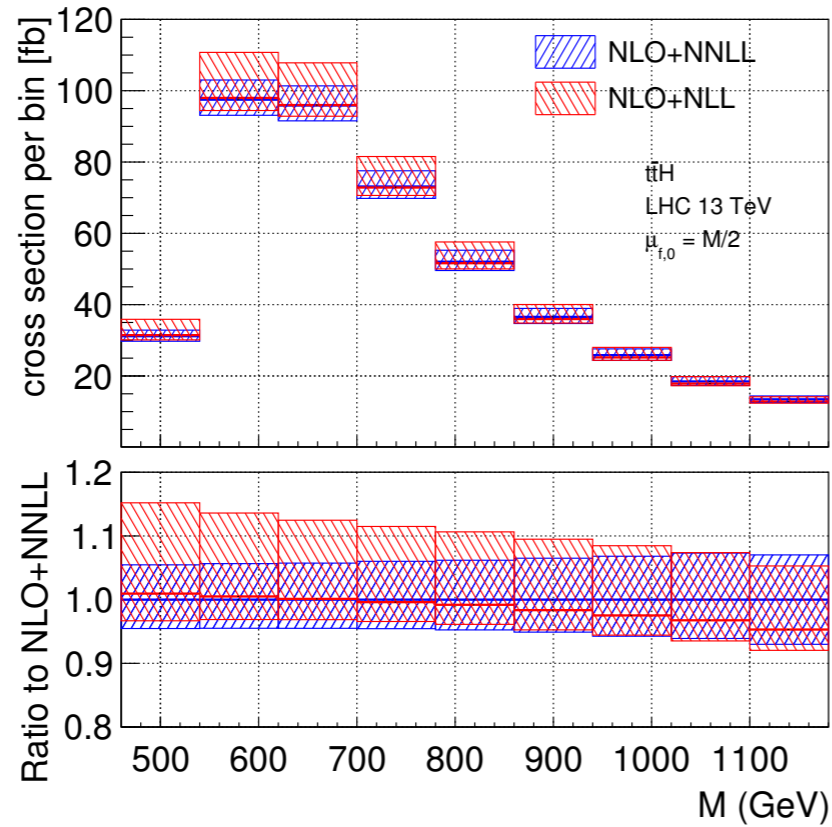
Distributions tTH: NNLL vs expansions
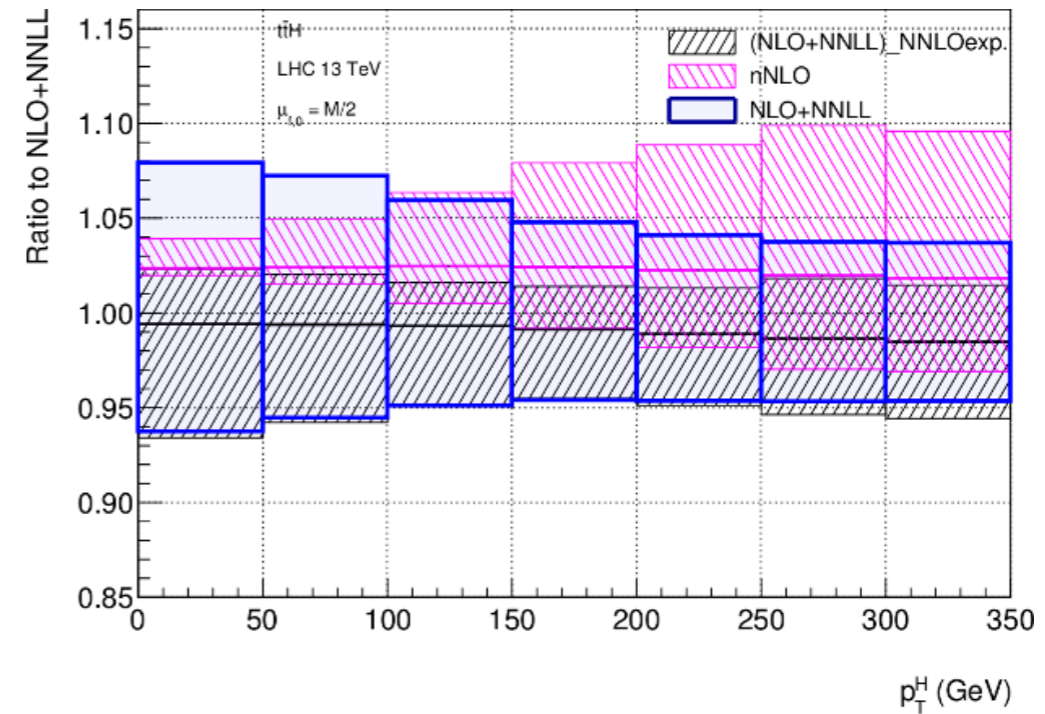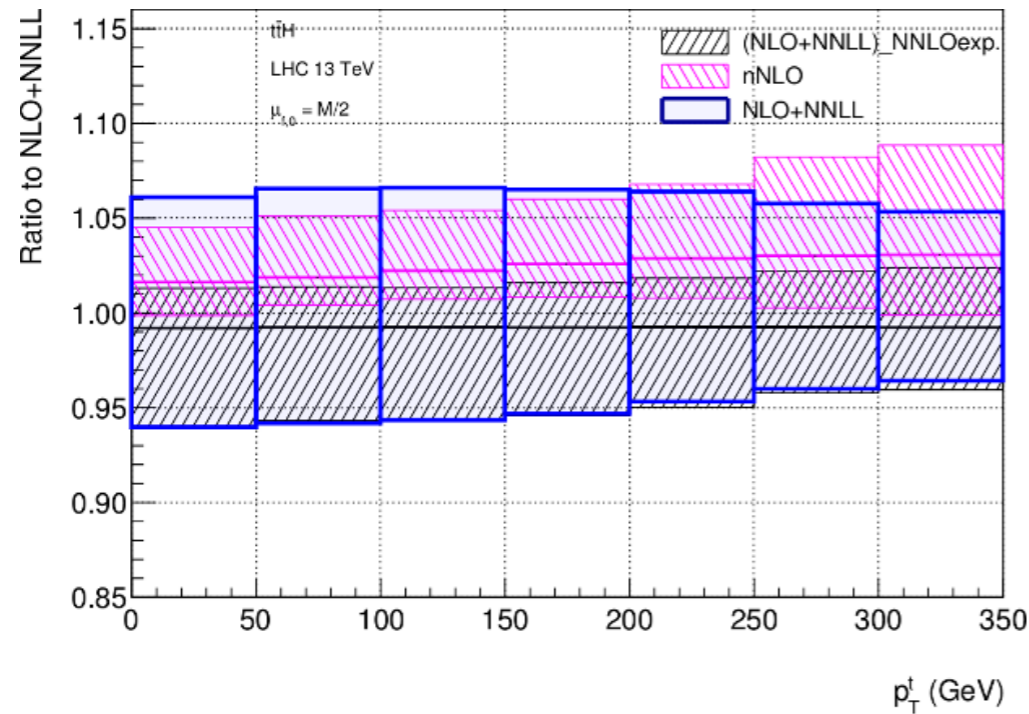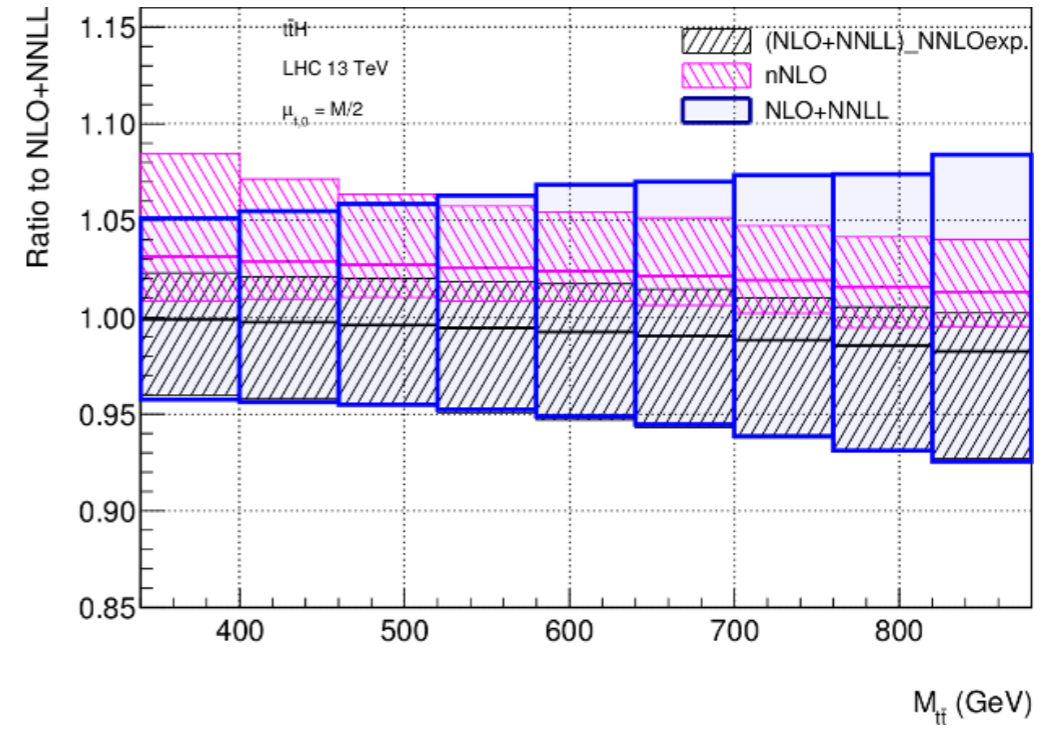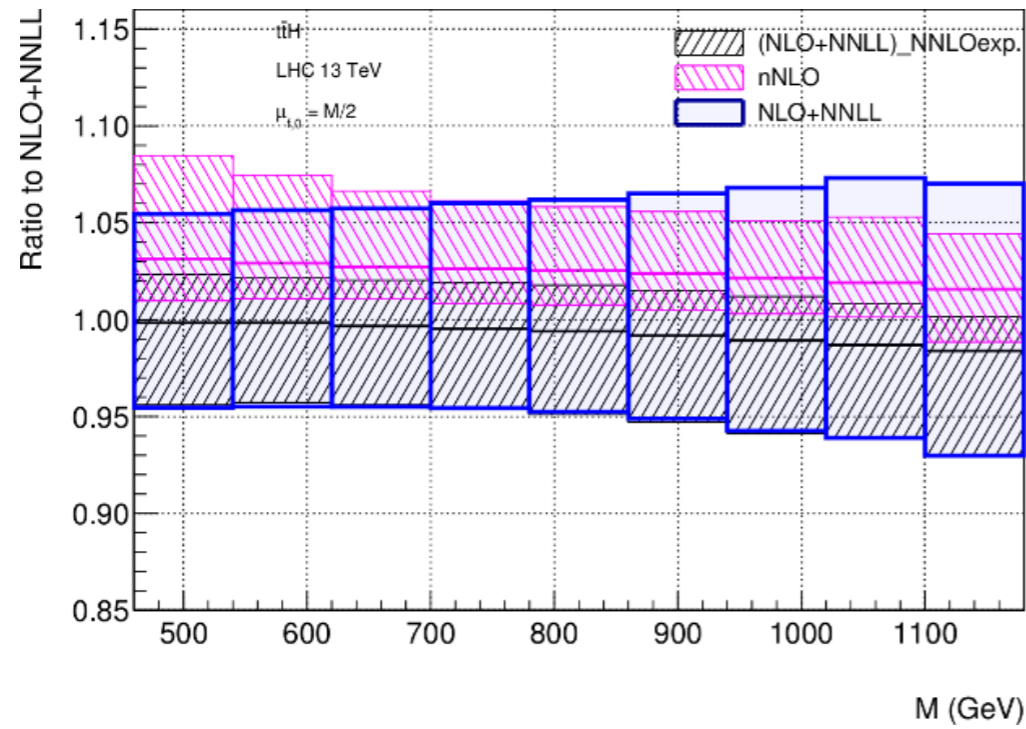
$$\mathcal{L}_0^t = -\frac{m_t}{v} \overline{\psi} \left(\cos\alpha + i\sin\alpha\gamma_5 \right) \psi X_0$$
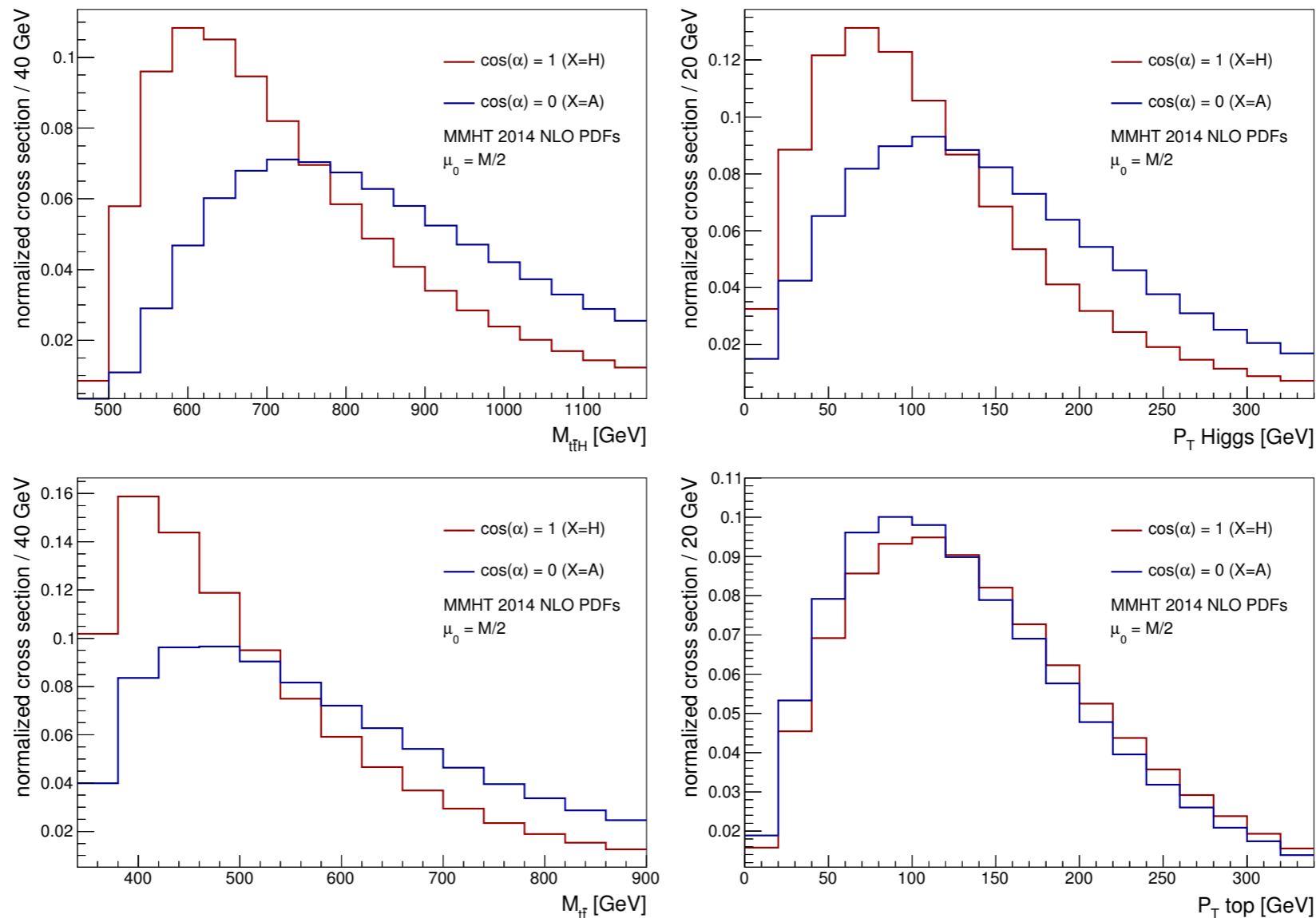
5 sigmas observation of this channel (on the SM hypothesis) would set the limit

$$|\cos\alpha| > 0.83^{+0.01}_{-0.02}$$

Total cross section tTZ

NLO obtained from MadGraph5_aMC@NLO

$$\sqrt{s} = 13\,\text{TeV} \qquad \mu_{f,0} = M/2$$

order	PDF order	code	σ [fb]
LO	LO	MG5_aMC	$521.4^{+165.4}_{-116.9}$
app. NLO	NLO	in-house MC	$737.7^{+38.5}_{-64.5}$
NLO no qg	NLO	MG5_aMC	$730.4^{+41.8}_{-64.9}$
NLO	NLO	MG5_aMC	$728.3^{+93.8}_{-90.3}$
NLO+NLL	NLO	in-house MC +MG5_aMC	$742.0^{+90.1}_{-30.3}$
NLO+NNLL	NNLO	in-house MC +MG5_aMC	$777.8^{+61.3}_{-65.2}$
nNLO	NNLO	in-house MC +MG5_aMC	$798.7^{+36.2}_{-23.6}$
(NLO+NNLL)$_{\text{NNLO exp.}}$	NNLO	in-house MC +MG5_aMC	$766.2^{+17.2}_{-50.1}$

Distributions tTZ
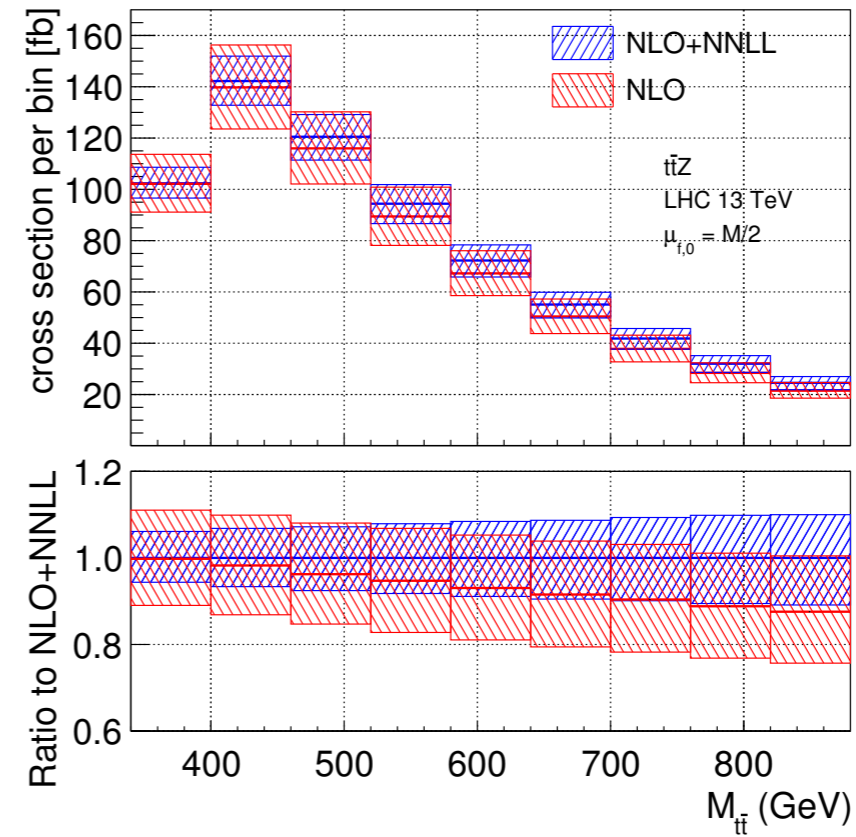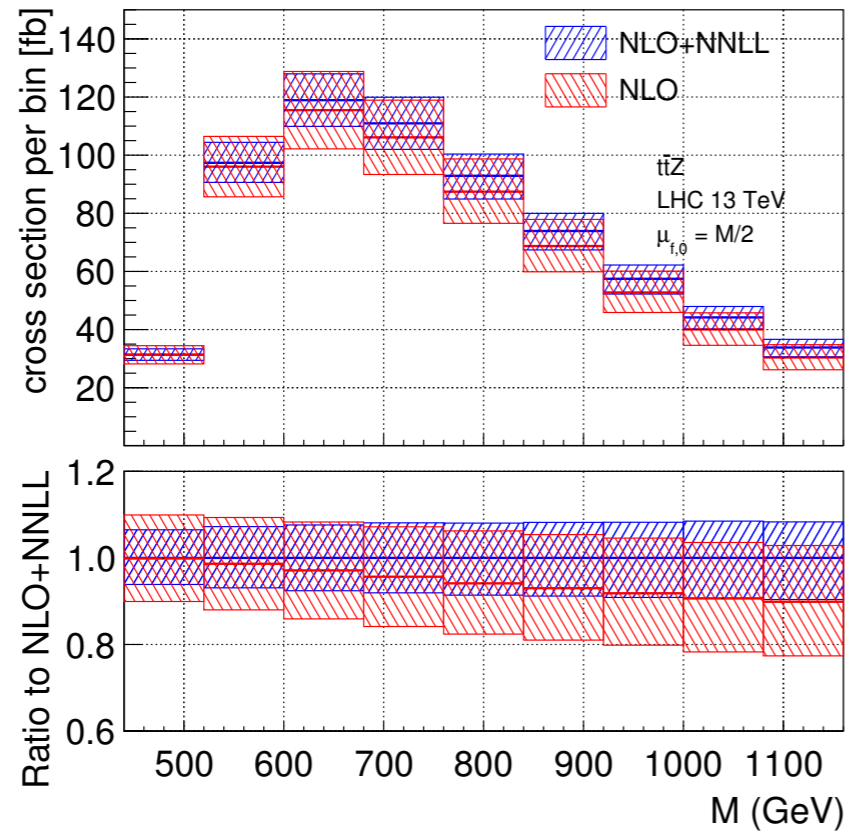
# Top pair + W or Z production
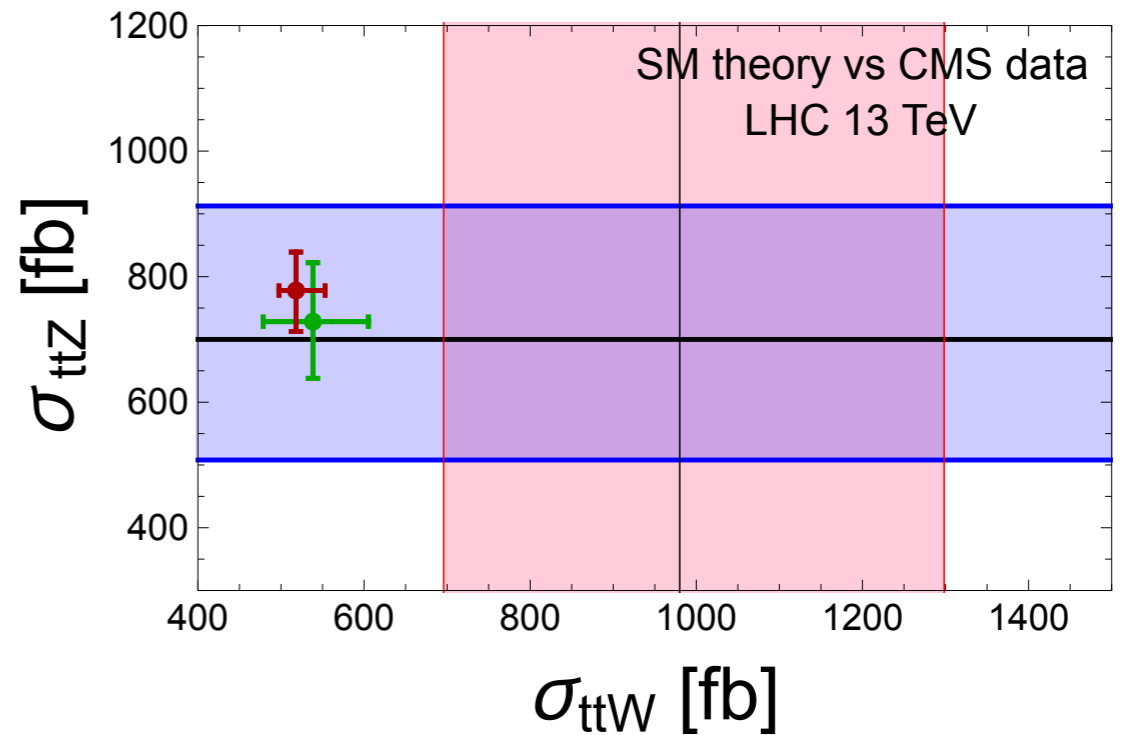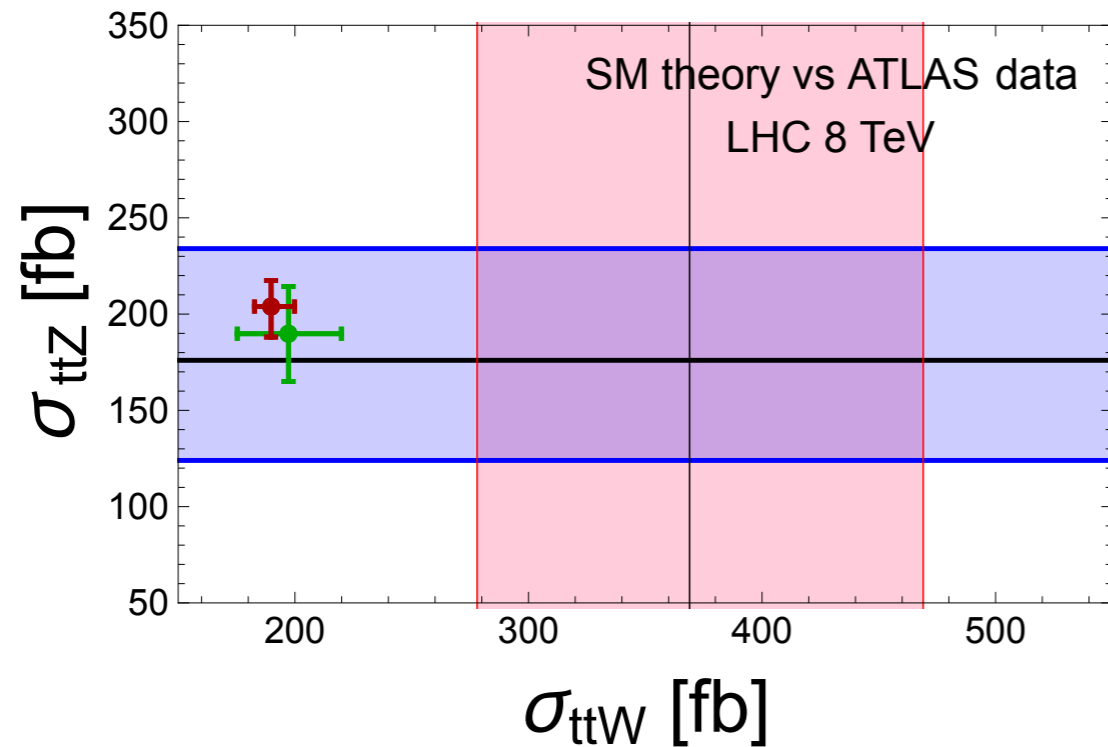
New CMS data at 13 TeV (May '17)
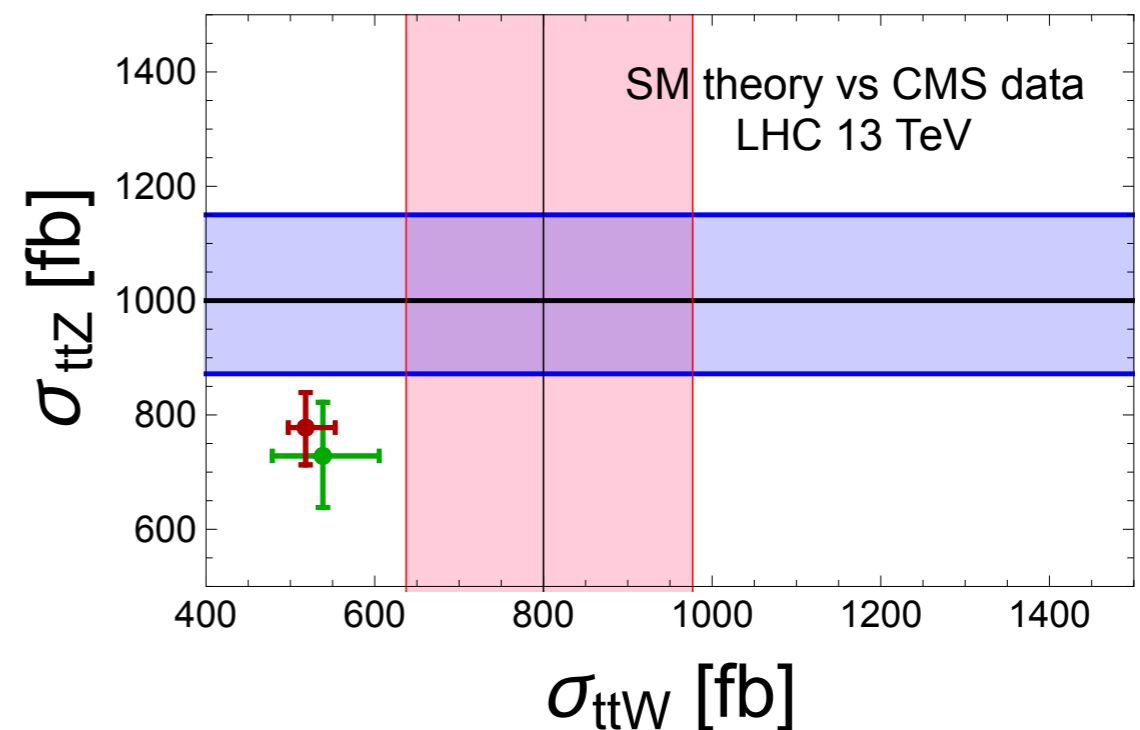
Summary & Outlook

▸ Predictions for the total cross sections together with several differential distributions were obtained at NLO+NNLL for tTH, tTW, tTZ production at LHC

▸ Reduction of the theoretical uncertainty

▸ In principle cuts on the momenta of the final-state particles can be easily applied

▸ State-of-the-art: combine QCD predictions (NLO+NNLL) with EW corrections

▸ top pair + photon

▸ Implement the decay of the final state particles in the NWA

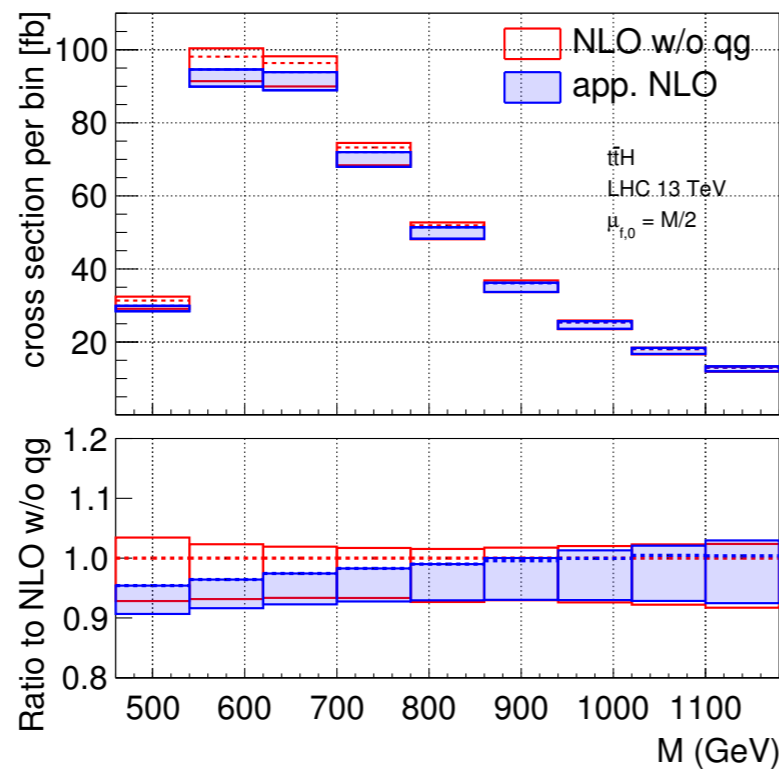# Backup slides
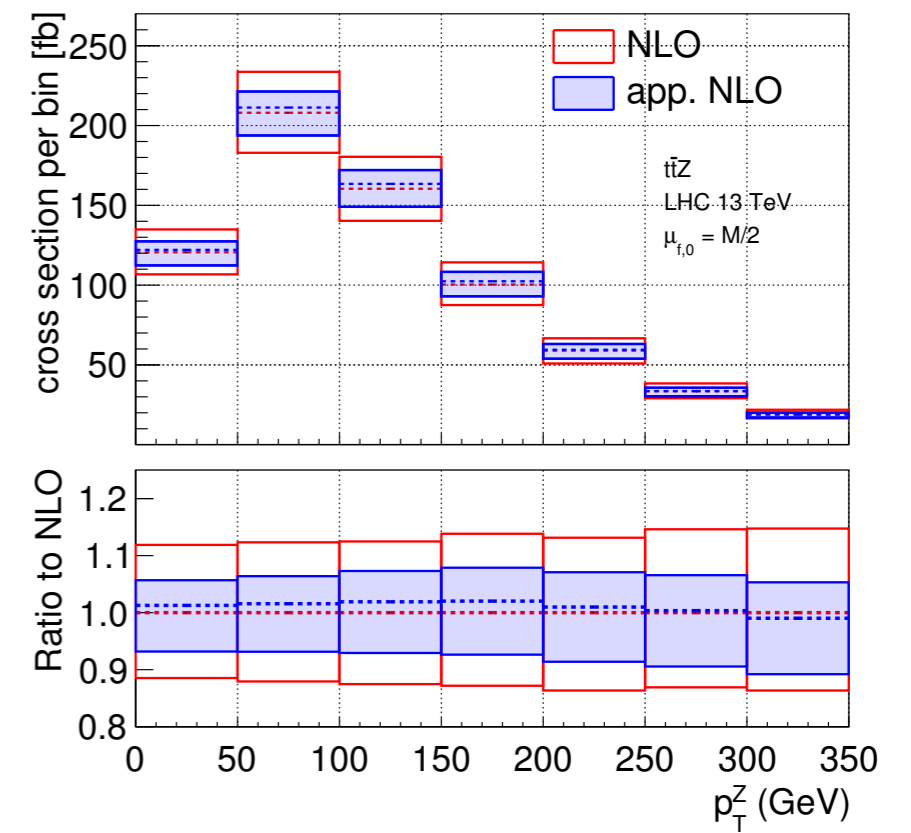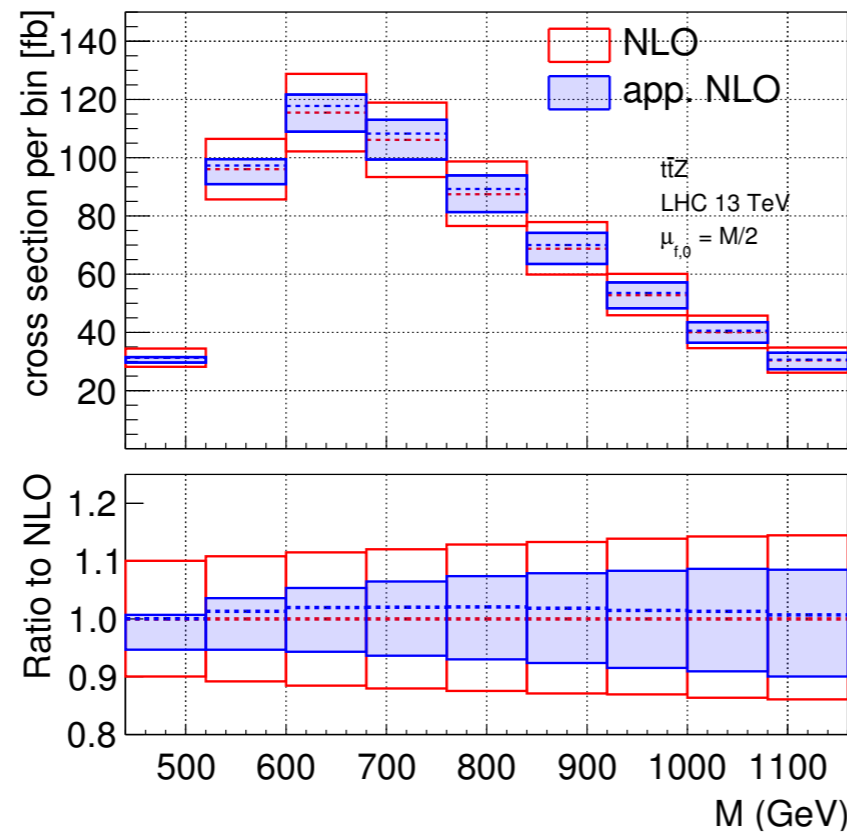
Distributions tTH: nLO vs NLO

nLO vs full NLO
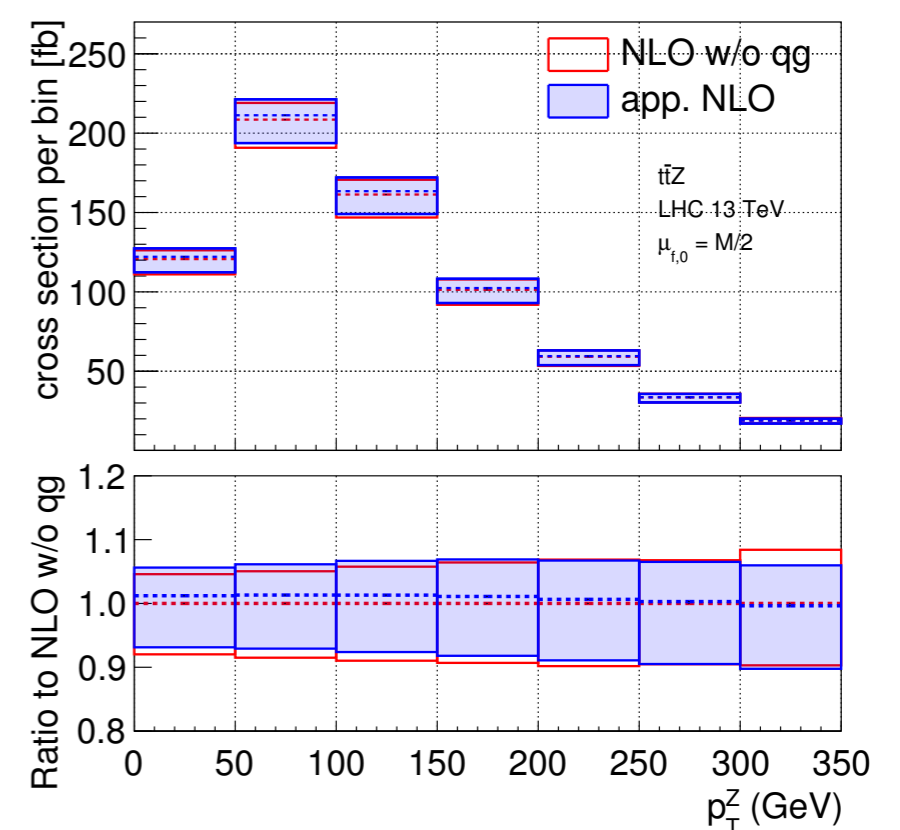

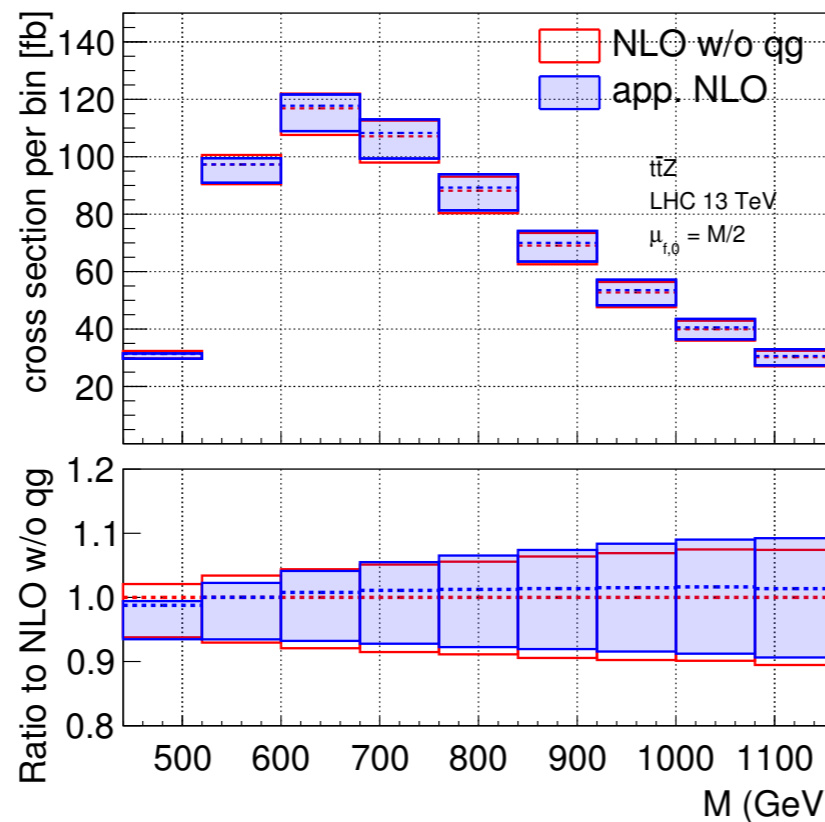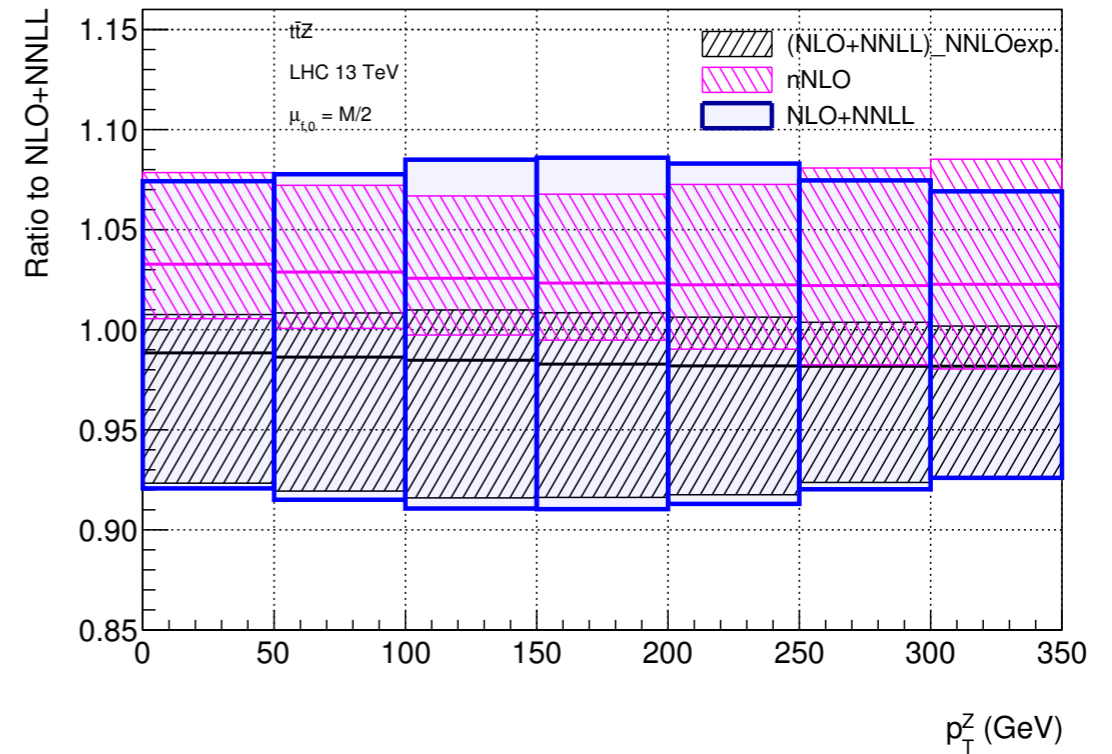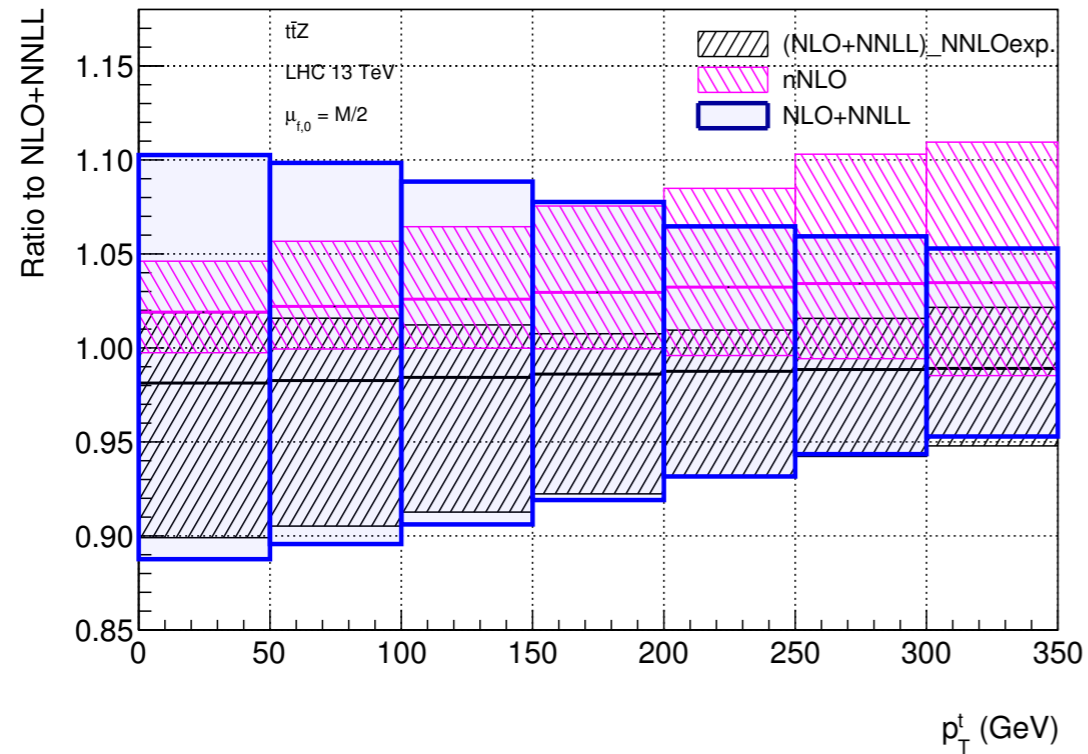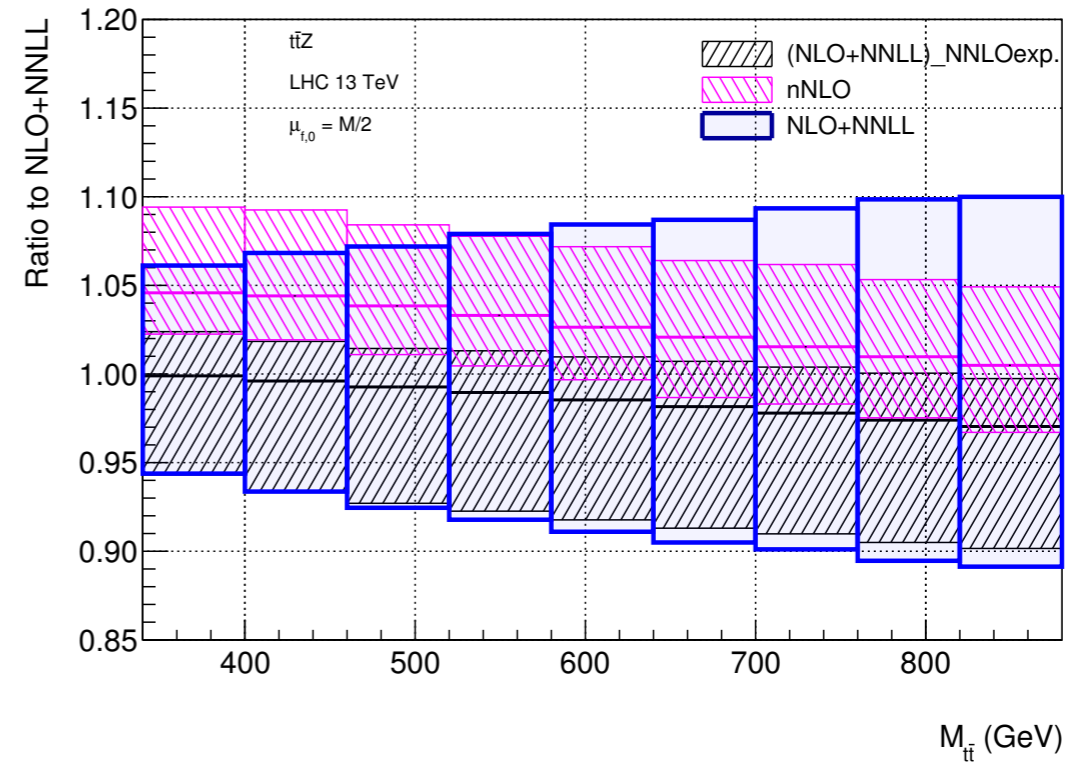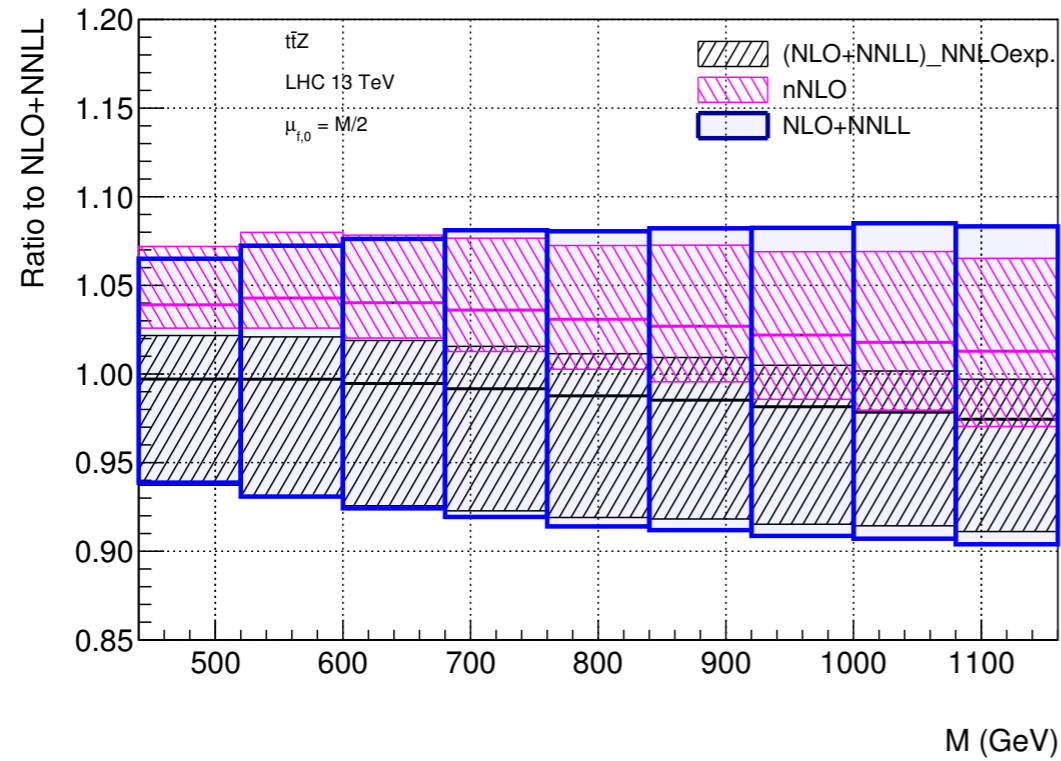**nLO vs NLO without qg channel**

Distr
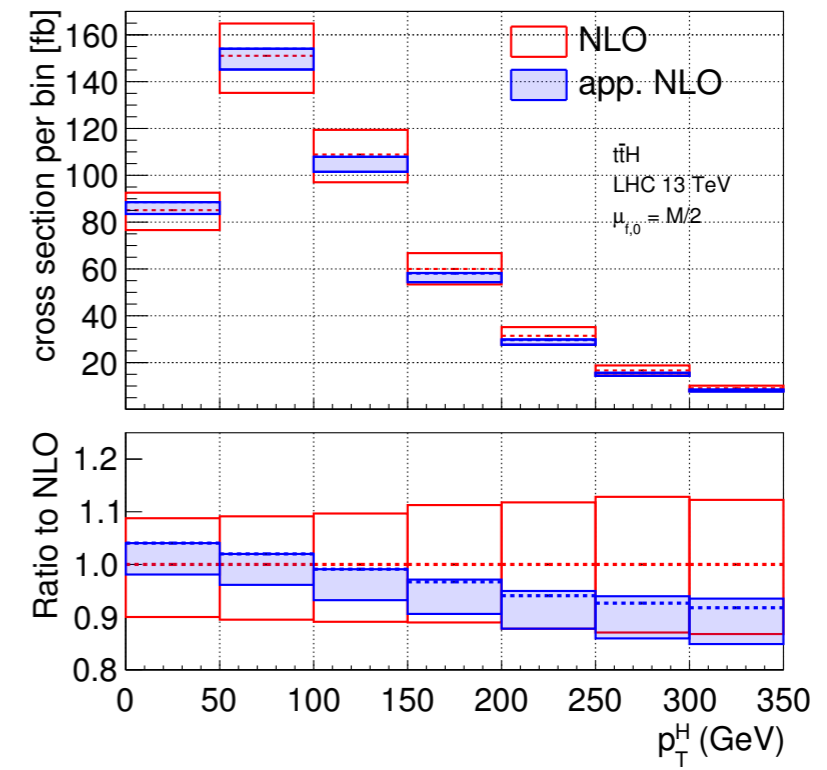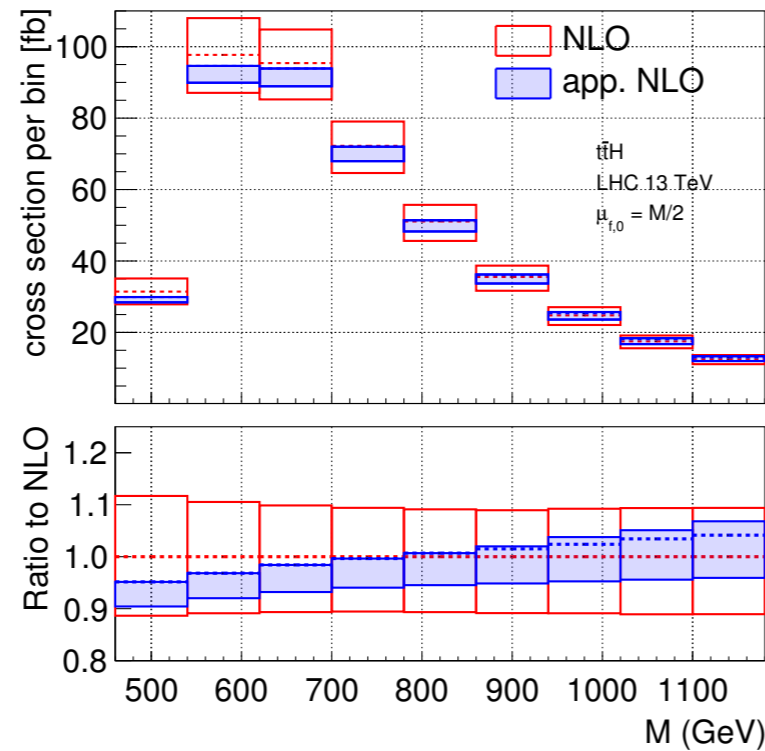
nLO vs full NLO

nLO vs NLO without qg channel
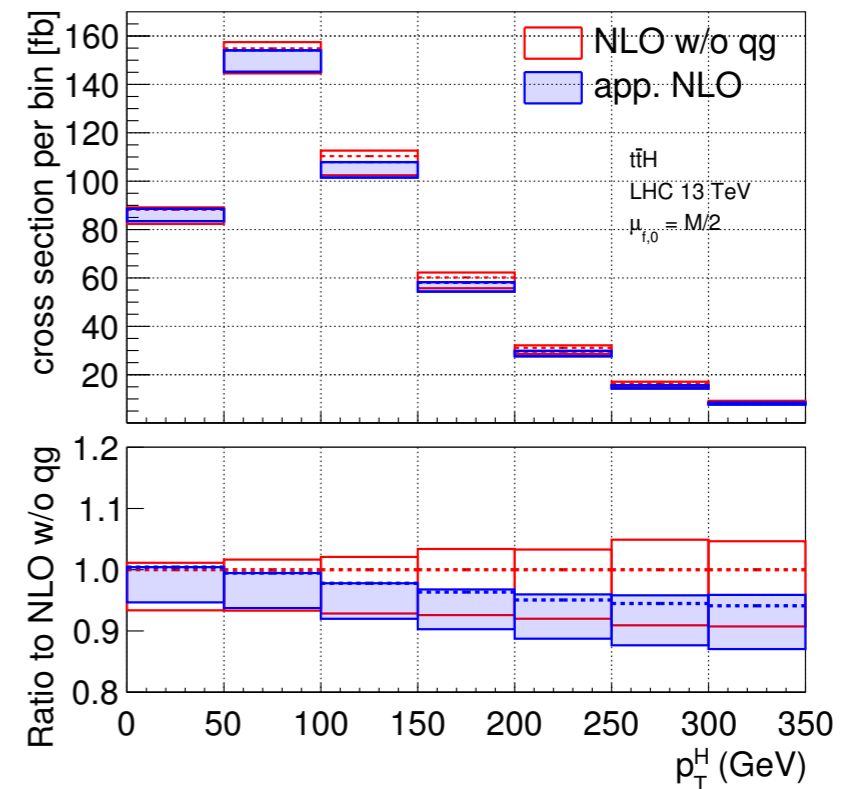
Distributions tTZ: nLO vs NLO

Total cross section tTH

NLO obtained from MadGraph5_aMC@NLO

$$\sqrt{s} = 13 \, \text{TeV} \qquad \mu_{f,0} = M$$

order	PDF order	code	σ [fb]
LO	LO	MG5_aMC	$293.5^{+85.2}_{-61.7}$
app. NLO	NLO	in-house MC	$444.7^{+28.6}_{-39.2}$
NLO no qg	NLO	MG5_aMC	$447.0^{+35.1}_{-40.4}$
NLO	NLO	MG5_aMC	$423.0^{+51.9}_{-49.7}$
NLO+NLL	NLO	in-house MC +MG5_aMC	$466.2^{+22.9}_{-26.8}$
NLO+NNLL	NNLO	in-house MC +MG5_aMC	$514.3^{+42.9}_{-39.5}$
nNLO (Mellin)	NNLO	in-house MC +MG5_aMC	$488.4^{+9.4}_{-8.3}$
(NLO+NNLL)$_{\text{NNLO exp.}}$	NNLO	in-house MC +MG5_aMC	$485.7^{+6.8}_{-15.0}$

Dynamical threshold enhancement

We rewrite the DY cross section introducing the luminosity function

$$\frac{d\sigma^{\text{thresh}}}{dM^2} = \frac{4\pi\alpha^2}{3N_c M^2 s} \int_\tau^1 \frac{dz}{z} C(z, M, \mu_f) f\!f(\tau/z, \mu_f) \qquad z \equiv \frac{M^2}{\hat{s}} \qquad \tau \equiv \frac{M^2}{s}$$

$$f\!f(y, \mu_f) = \sum_q e_q^2 \int_y^1 \frac{dx}{x} \left[f_{q/N_1}(x, \mu_f)\, f_{\bar{q}/N_2}(y/x, \mu_f) + (q \leftrightarrow \bar{q}) \right]$$

Does the soft limit z→1 provide a good approximation to the **exact** result?

Two situations in which the threshold region is enhanced:

- the threshold contributions are enhanced near the kinematic limit $\tau \sim 1$ and $z \geq \tau$ is near 1

- the relevance of the threshold region arises dynamically due to the steeply falling behaviour of the parton luminosity function