Four top final states with NLO accuracy in perturbative QCD: 4 lepton decay channel

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Based on:
arXiv:2401.10678

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LHCtopWG

Research Training Group Physics of the Heaviest Particles at the LHC | RWTH AACHEN UNIVERSITY

Why top quark physics?

- Top quark is the heaviest SM particle $m_t \approx 172.5\ GeV$
- Substantial Yukawa coupling ⇨ $y_t = \sqrt{2}\, m_t / v \approx 1$
- Top quarks are produced copiously at the LHC
  - ➔ Their properties can be studied in high precision
- Top quark is extremely *short-lived*
  - ➔ Decays before bound states can form
  - ➔ Unique opportunity to study a “bare” quark
  - ➔ Study of top-quark properties through its decay products

Why four tops?

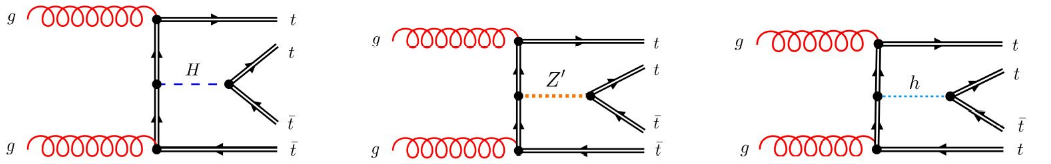
- Four top production is an extremely rare process with an estimated cross section

$$\sigma^{NLO(QCD+EW)+NLL'}_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}\ fb \quad \text{at} \quad \sqrt{s} = 13\ TeV$$

van Beekveld, Kulesza, Valero '22

- Direct way to measure the top Yukawa coupling complementary to ttH production
  Cao, Chen, Liu '17

- Very sensitive to many New Physics (NP) models
  - ➔ Study modifications in the Higgs sector e.g. two-Higgs-doublet models
  - ➔ Top philic models → new BSM heavy resonances decaying to top quark pairs



Diagrams were created via FeynGame: *Harlander, Klein, Lipp '20*

Highly accurate SM calculations are essential alongside BSM modeling

$t\bar{t}t\bar{t}$ theory status

- First NLO QCD predictions for 4 stable tops: General idea about the size of the NLO QCD calculations. Top decays are not considered.
  Bevilacqua, Worek '12 / Maltoni, Pagani, Tsinikos '16

- Complete-NLO predictions for 4 stable tops with sub-leading effects: All the non-vanishing contributions of $\mathcal{O}(\alpha_s^i \alpha^j)$ with $i + j = 4, 5$ are taken into account without any approximation. Top quark decays are omitted.
  Frederix, Pagani, Zaro '18

- NLO QCD matched to parton shower (NLO+PS): Besides NLO QCD corrections, the inclusion of subleading EW production channels at LO accuracy was also considered. LO spin correlated effects in top quark decays were also studied for the first time.
  Ježo, Kraus '22

- Threshold resummation for the production of four top quarks: Results for the total cross section for 4-top production at next-to-leading logarithmic (NLO + NLL') accuracy. Top quark decays are not included either.
  van Beekveld, Kulesza, Valero '22

- NLO QCD predictions in perturbative QCD in the 4 lepton channel: Higher-order QCD effects in both the production and decays of the top quarks are taken into account.
  Dimitrakopoulos, Worek '24

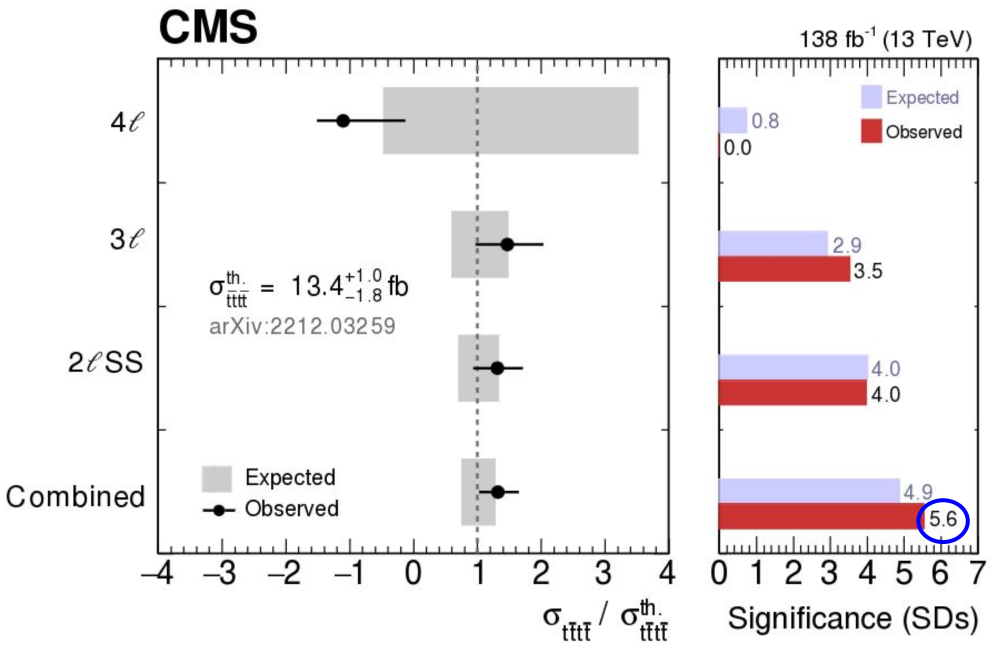
Observation of four top production

Discovery of four top production in 2023

CMS: *arXiv:[2305.13439]*
ATLAS: arXiv:[2303.15061]

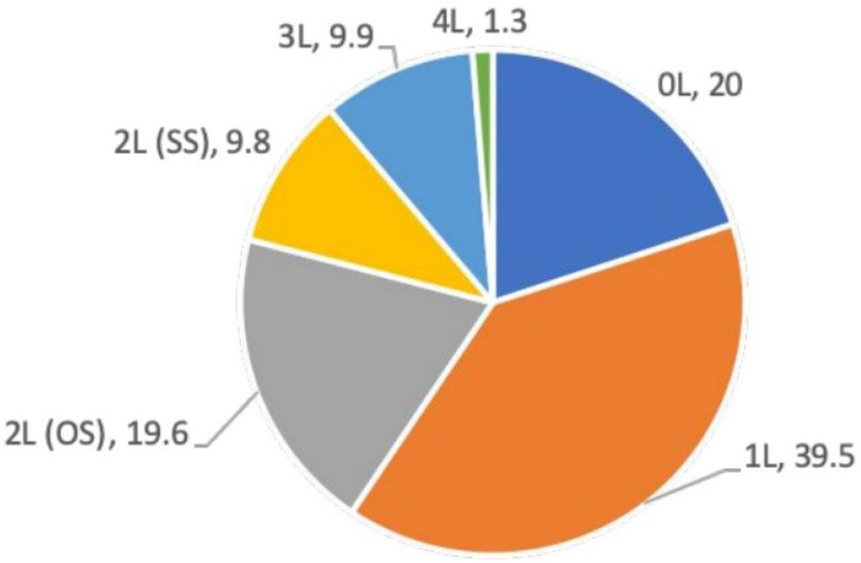
Three different Signal Regions (SR) were taken into account:
4-lepton channel, 3-lepton channel and 2lSS channel

Observed significance of 5.6σ for CMS



CMS: arXiv:[2305.13439]

Branching ratios in four-top production



Manganelli, Quinnan '22

- $t \to Wb$: Top quark decays almost entirely through weak interaction to a W boson and a bottom quark with a branching ratio of ~ 100%

- W boson decays to either a pair of lepton with its corresponding neutrino or a pair of two quarks.

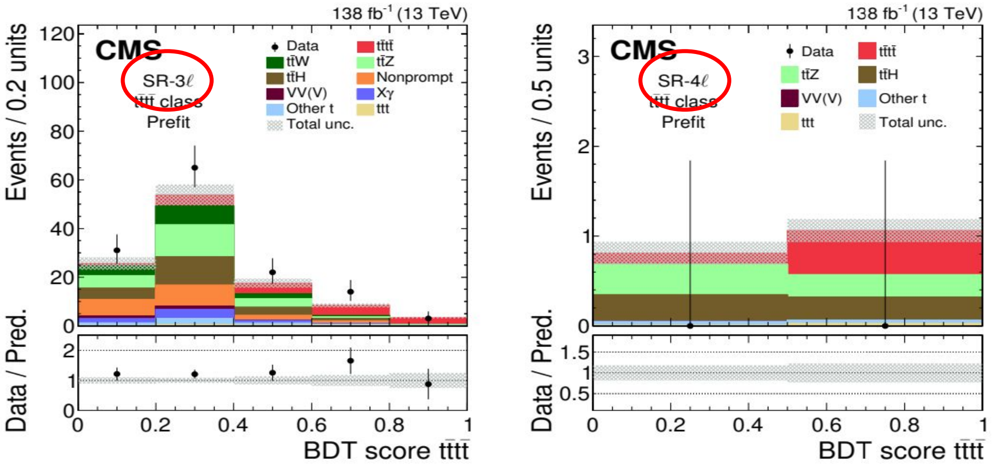
$$Br(W \to l\nu_l) \approx 10.8\%$$

$$\sum_{qq'} Br(W \to q\bar{q}') \approx 67.6\%$$

Project description / Motivation

➔ The 3-lepton and 2-lepton channels are currently more promising due to bigger cross sections!

➔ However, the **4-lepton** channel is a stepping stone to studying the 3-lepton and 2-lepton channels!

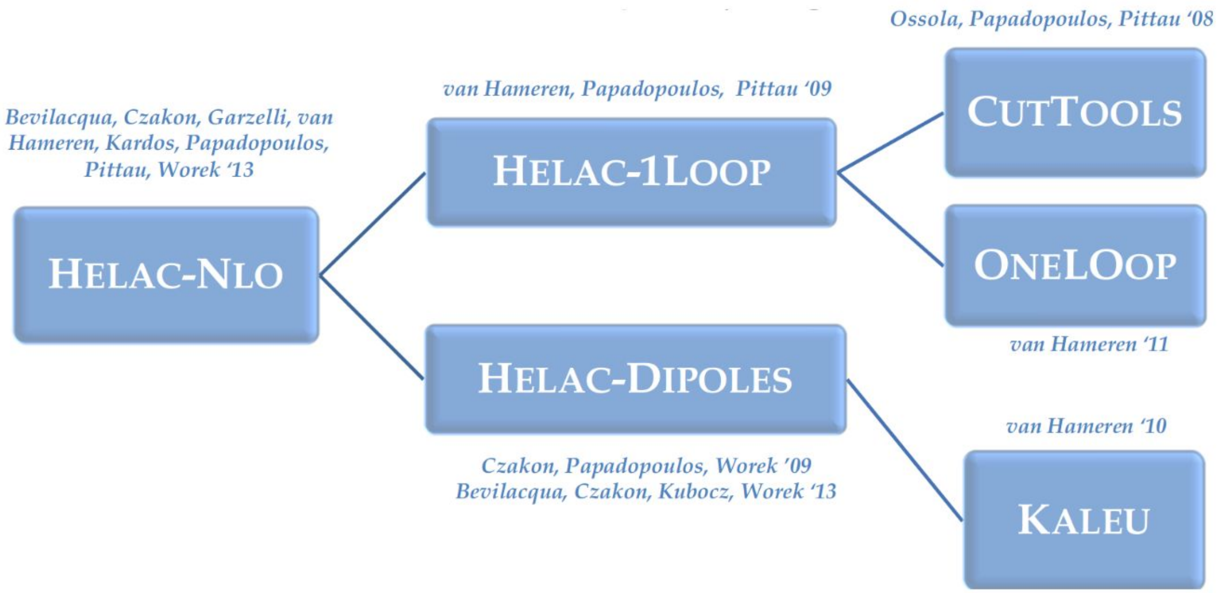


CMS: arXiv:[2305.13439]

Main aspects of the paper

- *Theoretical predictions for NLO QCD calculations for the fully leptonic channel using the NWA*
- *Study the impact of QCD corrections in top-quark decays already at the matrix element level*
- *Investigate the effects of expanding/not expanding the total top-quark width in the calculation*

HELAC-NLO



- The output is saved in Les Houches & ROOT Ntuple files https://arxiv.org/abs/hep-ph/0609017, https://arxiv.org/abs/1310.7439
- It can be further analysed by adding new cuts, changing the renormalization and factorization scales, using different PDF set

Process description

LO

$$pp \to t\bar{t}t\bar{t} \to W^+W^-W^+W^-b\bar{b}\,b\bar{b} \to \ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,\ell^+\nu_\ell\,\ell^-\bar{\nu}_\ell\,b\bar{b}\,b\bar{b}$$

We treat top and W in the NWA $\to$ valid for inclusive observables since Γ_t and Γ_W are much smaller compared to m_t and m_W respectively

$$\Gamma_t/m_t \approx 0.008$$
$$\Gamma_W/m_W \approx 0.026$$

$$\lim_{\Gamma/m\to 0} \frac{1}{(p^2-m^2)^2+m^2\Gamma^2} = \frac{\pi}{m\Gamma}\delta(p^2-m^2)$$

NLO

Emission of an extra parton either at the production stage or during a top quark decay

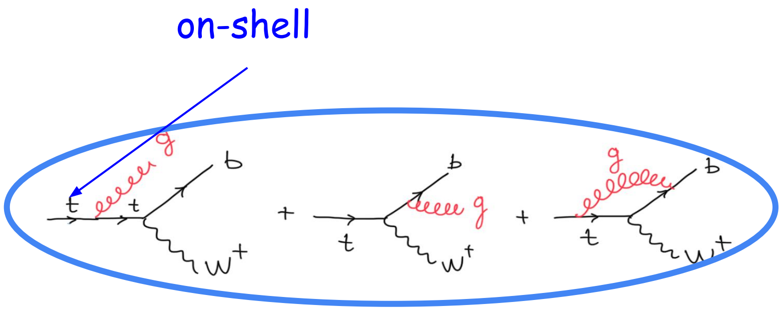
+

Virtual corrections both at the production and the decays

★ Only the combination of real emission and virtual corrections is IR safe!

Process description in full NWA

$$
\begin{aligned}
d\sigma^{\rm NLO}_{\rm full} = \; & \boxed{d\sigma^{\rm NLO}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t}} \\
& + d\sigma^{\rm LO}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^1_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \\
& + d\sigma^{\rm LO}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \\
& + d\sigma^{\rm LO}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \\
& + d\sigma^{\rm LO}_{t\bar{t}t\bar{t}} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_{\bar{t}}}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^0_t}{\Gamma^{\rm NLO}_t} \times \frac{d\Gamma^1_{\bar{t}}}{\Gamma^{\rm NLO}_t} \, .
\end{aligned}
$$



QCD corrections in top-quark decays

NLO$_{\text{LOdecays}}$: No QCD corrections at the decays stage → Only the first term contributes with the replacement $\Gamma_t^{NLO} \to \Gamma_t^{LO}$

Process description in expanded NWA

- NLO$_{\text{exp}}$: Expansion of the decay rate of the top quark is taken place. To all orders of perturbation theory it holds that:

$$d\sigma = d\sigma_{tt\bar{t}\bar{t}} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_t}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t} \times \frac{d\Gamma_{\bar{t}}}{\Gamma_t}$$

$$d\sigma_{tt\bar{t}\bar{t}} = d\sigma^{(0)}_{tt\bar{t}\bar{t}} + \alpha_s d\sigma^{(1)}_{tt\bar{t}\bar{t}} + \mathcal{O}(\alpha_s^2)$$

$$d\Gamma_t = d\Gamma^{(0)}_t + \alpha_s d\Gamma^{(1)}_t + \mathcal{O}(\alpha_s^2)$$

- By expanding the above formula and keeping terms up to $\mathcal{O}(\alpha_s)$ we end up with

$$d\sigma^{\text{NLO}}_{\text{exp}} = d\sigma^{\text{NLO}} = d\sigma^{\text{NLO}}_{\text{full}} \times \left(\frac{\Gamma^{\text{NLO}}_t}{\Gamma^{\text{LO}}_t}\right)^4 - d\sigma^{\text{LO}} \times \frac{4(\Gamma^{\text{NLO}}_t - \Gamma^{\text{LO}}_t)}{\Gamma^{\text{LO}}_t}$$

where $\Gamma^{\text{NLO}}_t = \Gamma^{(0)}_t + \alpha_s \Gamma^{(1)}_t$

- Advantage of not including higher order effects when top quarks decay with LO accuracy

Integrated fiducial cross sections at LO, NLO

PDF	σ^{LO} [ab]	δ_{scale}	σ^{NLO} [ab]	δ_{scale}	δ_{PDF}	$\mathcal{K} = \sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}}$
			$\mu_R = \mu_F = \mu_0 = 2m_t$			
MSHT20	4.3868(3)	+3.2237 (73%) −1.7332 (40%)	4.895(2)	+0.624 (13%) −1.002 (20%)	+0.211 (4%) −0.156 (3%)	1.12
NNPDF3.1	3.7389(2)	+2.6811 (72%) −1.4545 (39%)	4.846(2)	+0.632 (13%) −1.002 (21%)	+0.105 (2%) −0.105 (2%)	1.30
CT18	4.6757(3)	+3.3754 (72%) −1.8311 (39%)	4.857(2)	+0.620 (13%) −0.992 (20%)	+0.289 (6%) −0.236 (5%)	1.04
			$\mu_R = \mu_F = \mu_0 = E_T/4$			
MSHT20	4.7479(3)	+3.5156 (74%) −1.8855 (40%)	5.170(3)	+0.638 (12%) −1.056 (20%)	+0.219 (4%) −0.162 (3%)	1.09
NNPDF3.1	4.0930(3)	+2.9792 (73%) −1.6063 (39%)	5.126(3)	+0.634 (12%) −1.055 (21%)	+0.110 (2%) −0.110 (2%)	1.25
CT18	5.0003(3)	+3.6151 (72%) −1.9623 (39%)	5.127(3)	+0.636 (12%) −1.045 (20%)	+0.299 (6%) −0.245 (5%)	1.03

Different values of α_s have been used for the PDFs at LO and NLO

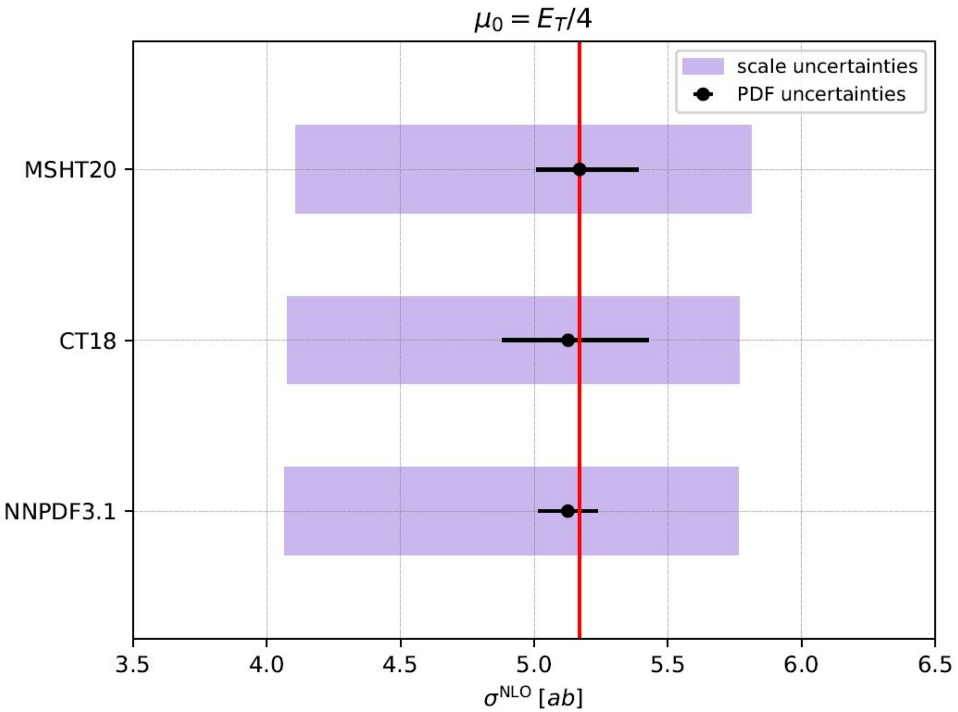
K factors are very sensitive to that choice due to the large powers of α_s appearing in the cross section:

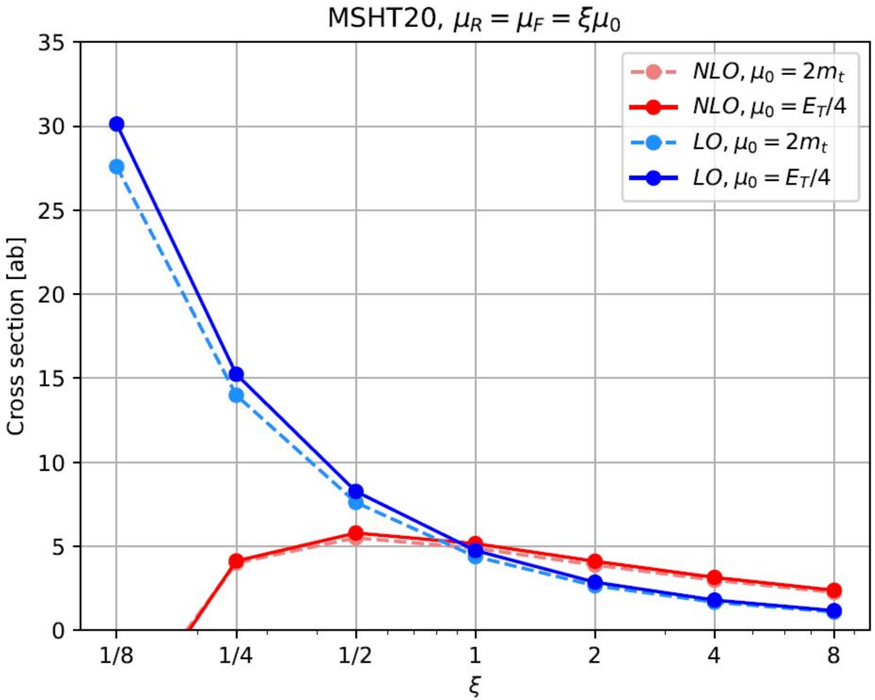
$$\sigma_{LO} \sim \alpha_s^4 \quad , \quad \sigma_{NLO} \sim \alpha_s^5$$

LO results are only sufficient for an order-of-magnitude estimation: No reliable conclusions can be drawn

However, results for different PDF sets are stabilized at NLO

Scale and PDF uncertainties



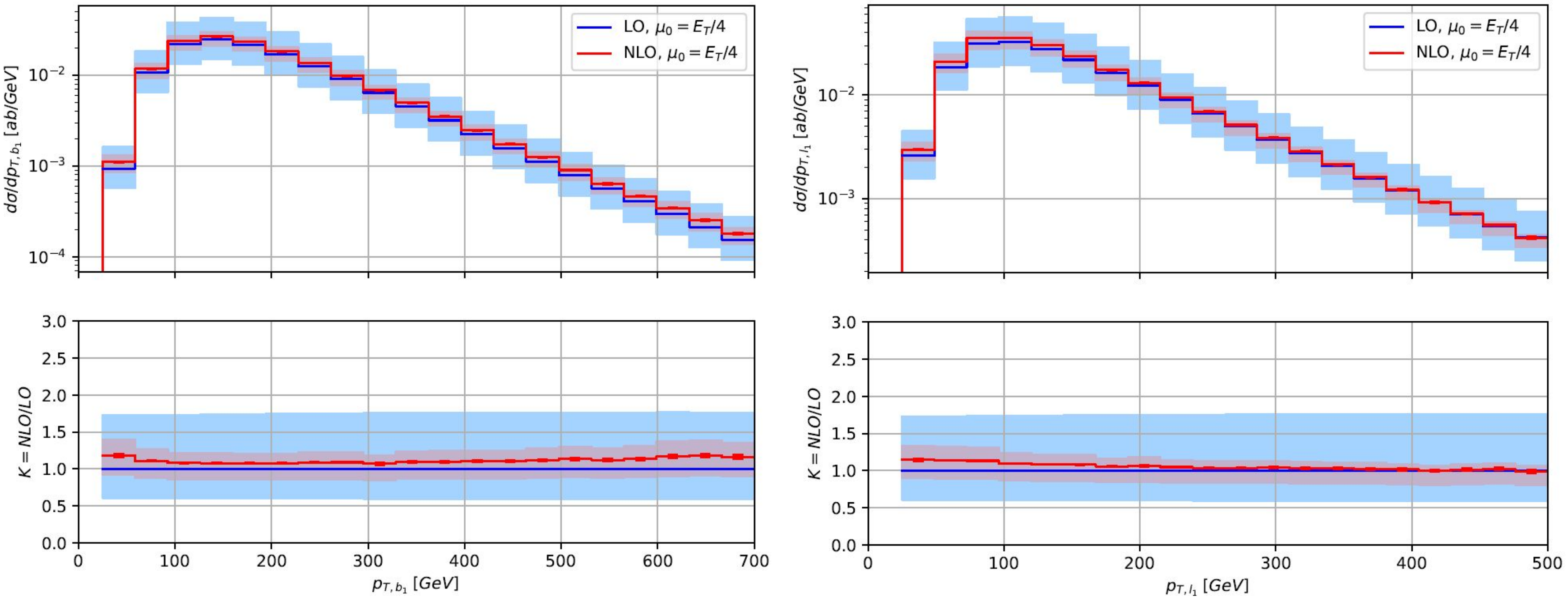


NLO_{full} vs NLO_{LOdec} vs NLO_{exp}

Decay treatment	$\sigma_i^{\rm NLO}$ [ab]	$+\delta_{scale}$ [ab]	$-\delta_{scale}$ [ab]	$\sigma_i^{\rm NLO}/\sigma_{\rm exp}^{\rm NLO} - 1$
$\mu_R = \mu_F = \mu_0 = 2m_t$				
full	5.462(3)	+0.156 (3%)	−0.853 (16%)	+11.6%
$\rm LO_{dec}$	5.295(3)	+1.123 (21%)	−1.224 (23%)	+8.2%
exp	4.895(2)	+0.624 (13%)	−1.002 (20%)	–
$\mu_R = \mu_F = \mu_0 = E_T/4$				
full	5.735(3)	+0.139 (2%)	−0.882 (15%)	+10.9%
$\rm LO_{dec}$	5.646(3)	+1.225 (22%)	−1.317 (23%)	+9.2%
exp	5.170(3)	+0.638 (12%)	−1.056 (20%)	–

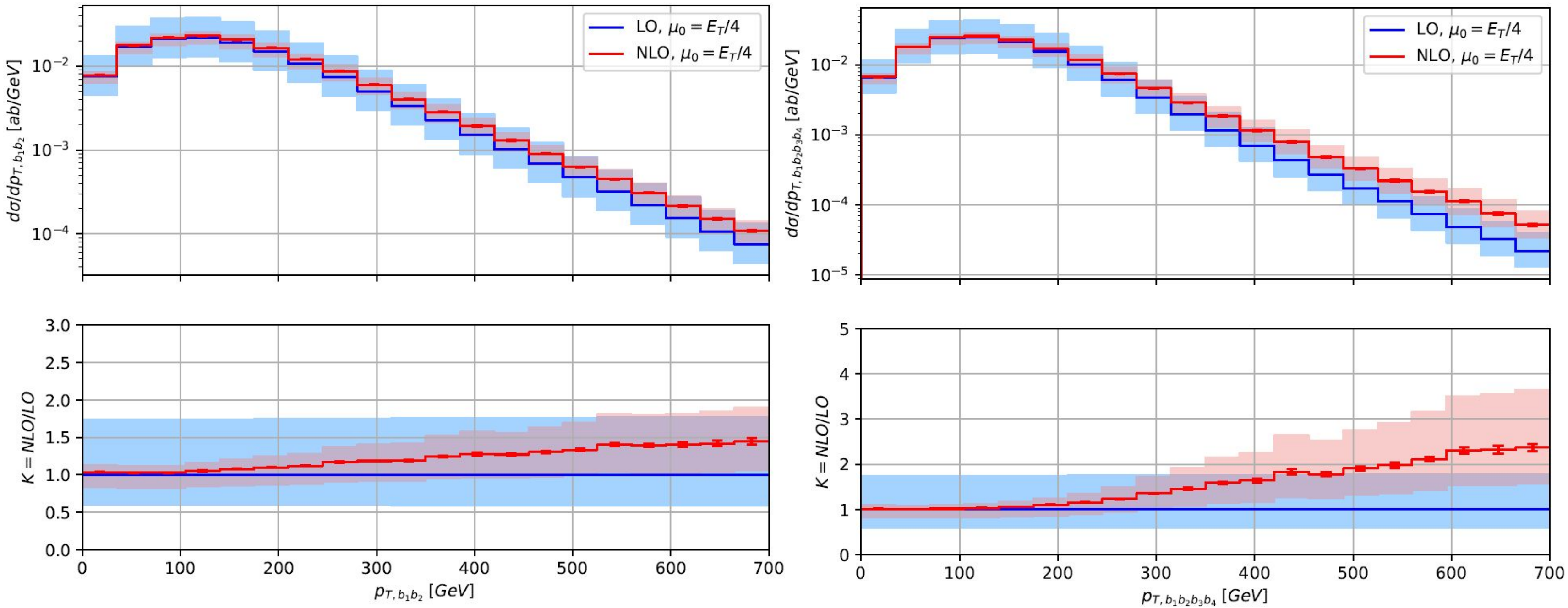
- Higher-order effects of the order of 11-12%
- QCD corrections at the decays ~ 8-9%
- Largest scale uncertainties for LO_{dec}, smallest for NLO_{full}

Differential distributions



NLO QCD corrections up to 18% for p_{T,b_1} and up to 15% for p_{T,l_1}

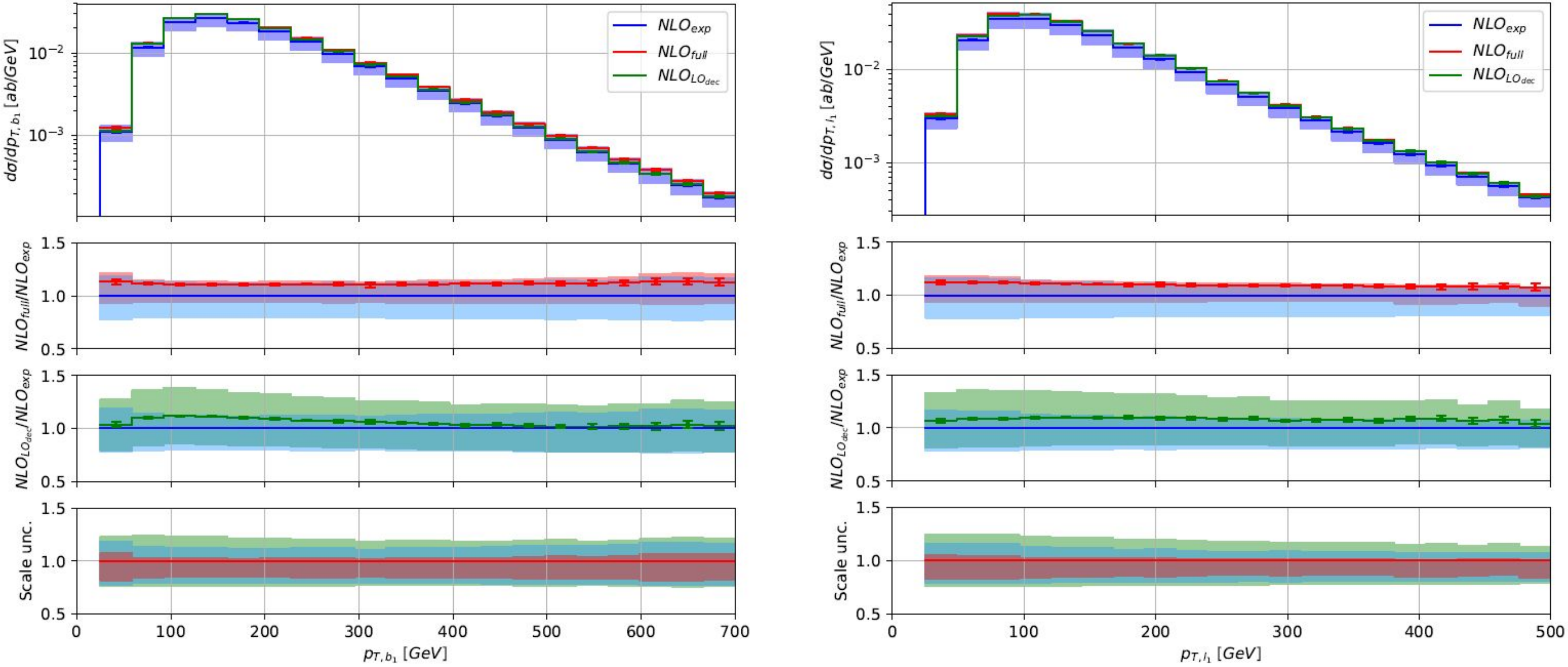
Differential distributions



NLO QCD corrections up to 45% for $p_{T,\,b_1b_2}$ and up to 240% for $p_{T,\,b_1b_2b_3b_4}$

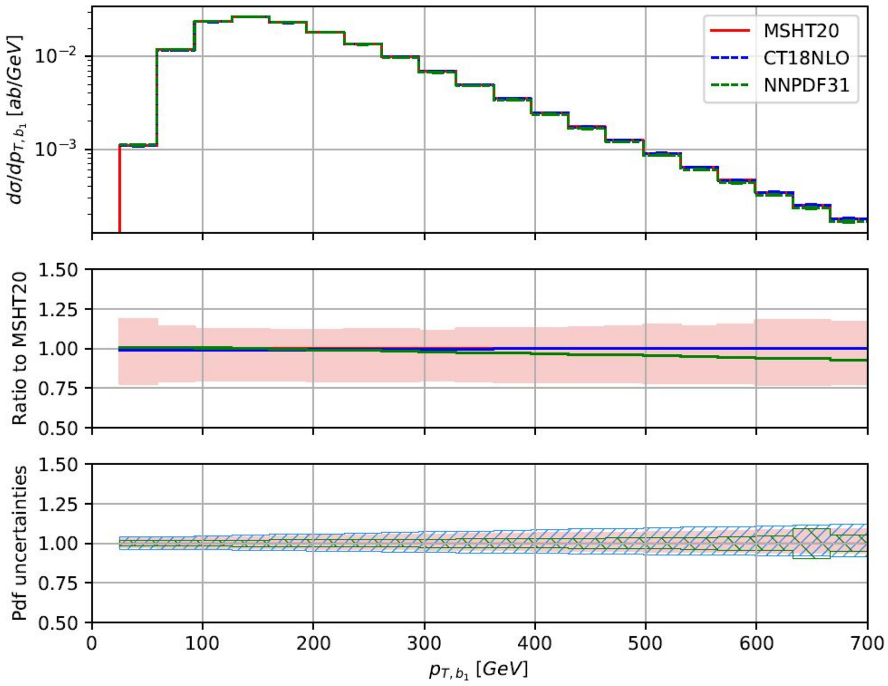
At NLO, the system of four-top quarks can acquire large transverse momentum by recoiling against the extra high-energetic light jet

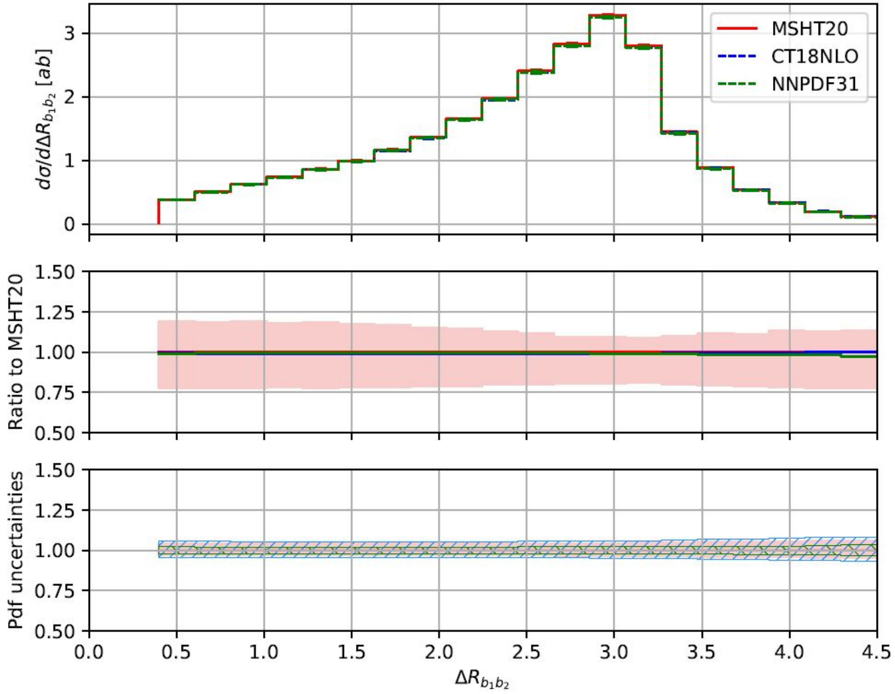
Differential distributions



The effects of QCD corrections in top-quark decays are up to 10-12%

Differential agreement among different PDF sets





Summary

- The recent observation of 4-top production makes high precision calculations more important than ever → need for inclusion of higher order effects also at top-quark decays

- Results are stable between different PDF sets at NLO in QCD where the scale uncertainties are of the order of ~ 20%

- Reduction of the scale uncertainties when QCD corrections are applied both at the production and decay stages: $NLO_{LOdecays}$: 23% → NLO_{exp} : 20%

- NLO_{full}: the higher order effects are of the order of ~12% and therefore well within the scale uncertainties of the NLO_{exp}

- Projected uncertainties at the HL-LHC are estimated at 15-18% → sensitivity to higher-order effects in top-quark decays

- Proper modeling of differential distributions → necessary for correct interpretation of possible new physics signals

Outlook

- Comparisons to NLO QCD calculations matched to Parton Shower (PS) [POWHEG and MC@NLO] where the emission in top-quark decays is included in the soft/collinear approximation

- Study the impact of including Matrix Element Corrections (MEC) in top quark decays during showering → already done for $t\bar{t}$ and $t\bar{t}W$
  Frixione, Amoroso, Mrenna '23 / Frederix, Gellersen, Nasufi '24

- NLO calculations in perturbative QCD for the 3-lepton channel and comparison with results matched to Parton Shower

Thanks for your attention!

Backup

Backup slides

Setup for the calculation

- We perform our calculations with a center of mass energy $\sqrt{s} = 13.6\ TeV$
- We try to be as inclusive as possible in the fiducial phase-space:

$$p_{T,\ell} > 25\ \text{GeV}\,, \qquad |y_\ell| < 2.5\,, \qquad \Delta R_{\ell\ell} > 0.4\,,$$

$$p_{T,b} > 25\ \text{GeV}\,, \qquad |y_b| < 2.5\,, \qquad \Delta R_{bb} > 0.4$$

- In our fixed order calculation we use both a fixed and a dynamical scale $\mu_0 = 2m_t\ ,\ \mu_0 = E_T/4$

$$E_T = \sum_{i=1,2} \sqrt{m_t^2 + p_T^2(t_i)} + \sum_{i=1,2} \sqrt{m_t^2 + p_T^2(\bar{t}_i)}$$

- Scale variations are calculated by varying both μ_R and μ_F

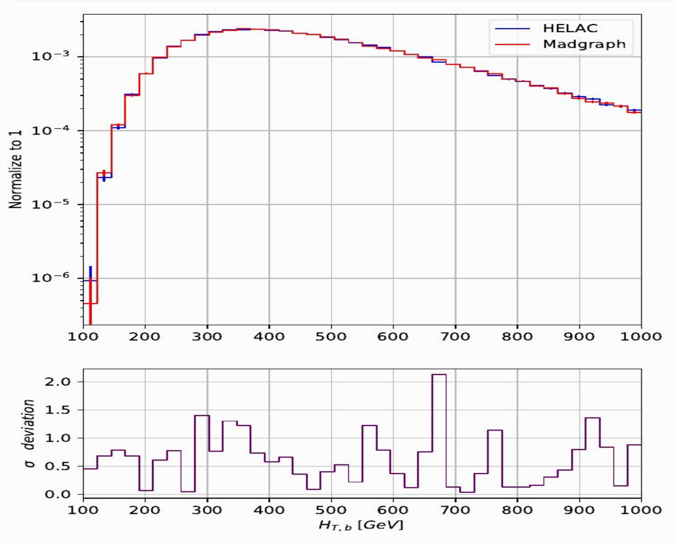
$$\left(\frac{\mu_R}{\mu_0}\,, \frac{\mu_F}{\mu_0}\right) = \Big\{ (2,1)\,, (0.5,1)\,, (1,2)\,, (1,1), (1,0.5), (2,2), (0.5,0.5) \Big\}\,.$$

Backup slides

Cross-checks

- LO calculations have been cross-checked both at the integrated and differential level with the help of MadSpin in MadGraph5_aMC@NLO *arxiv:[1405.0301]*

- For subtracting the IR divergences we employed two different subtraction schemes to cross-check our results, namely the Catani-Seymour and Nagy Soper subtraction schemes

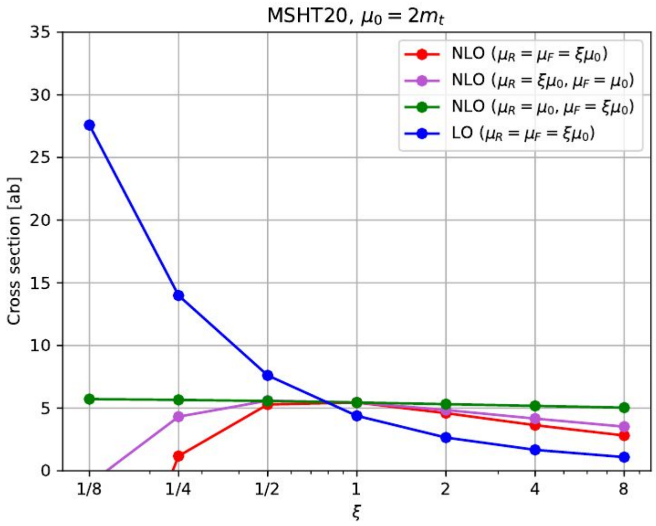


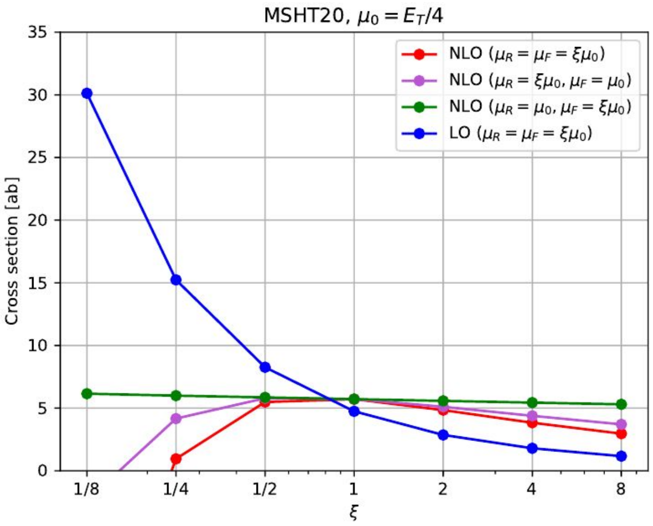
- Cancellation of the $1/\epsilon$ and $1/\epsilon^2$ poles between the virtual corrections and the real emission has also been confirmed for multiple phase space points

- The finite value for the virtual amplitude has also been cross-checked with RECOLA *arxiv:[1605.01090]*

Backup slides

Scale variations

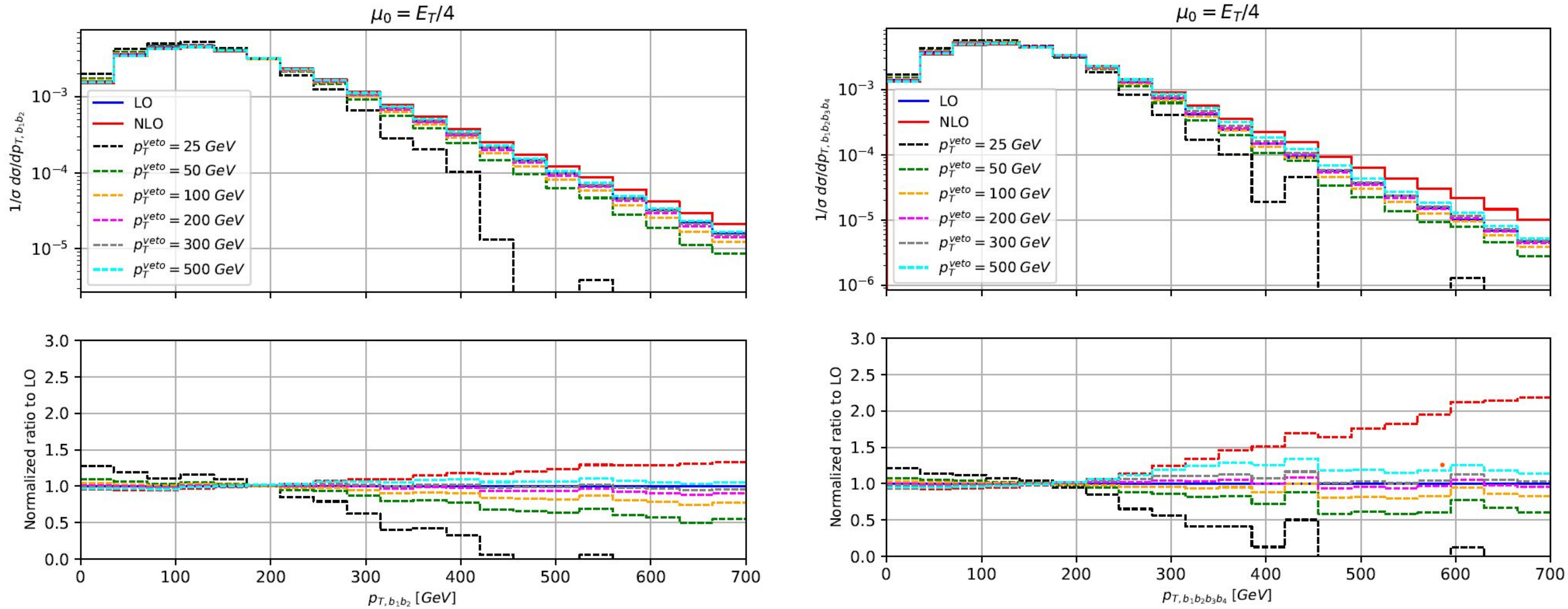




The primary source of scale uncertainties originates from variations in μ_R

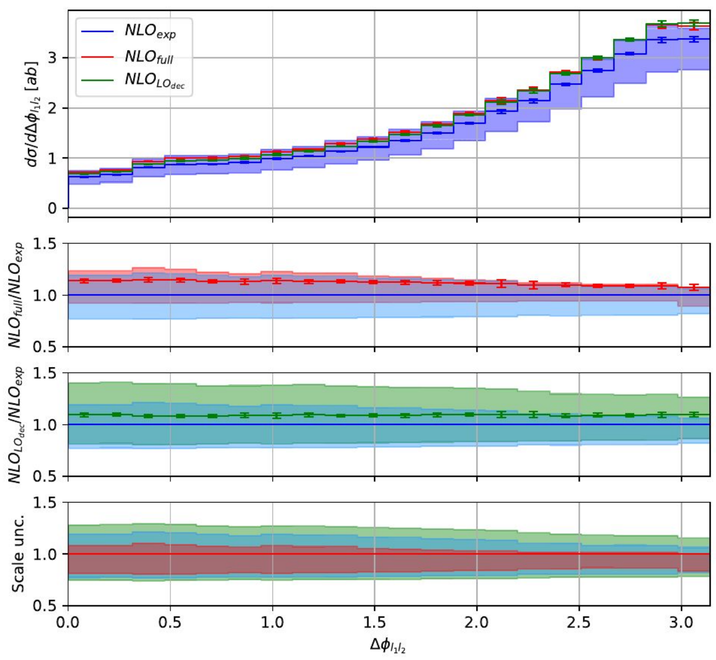
Backup slides

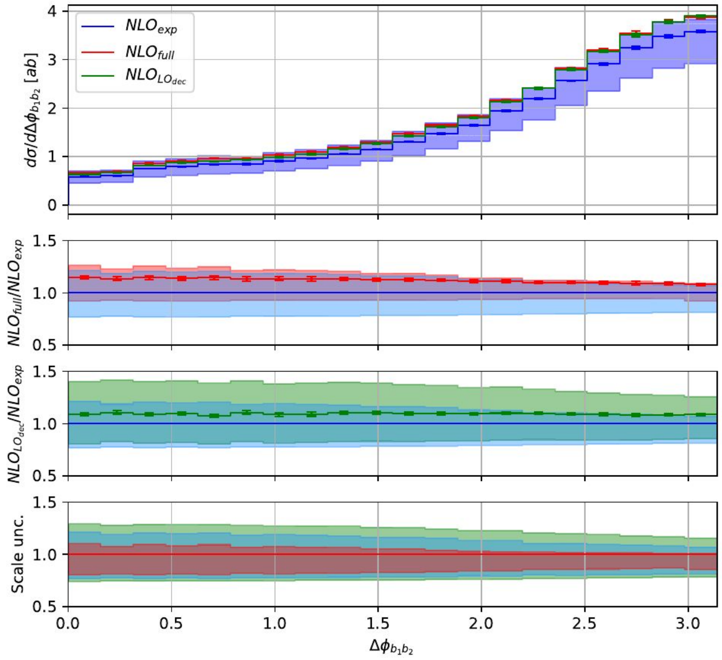
Applying p_T veto



Backup slides

Observables sensitive to spin correlations





Higher-order effects in top-quark decays are up to 10%