Four top final states with NLO accuracy in perturbative QCD: 4 and 3 lepton channels

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

Why four tops?

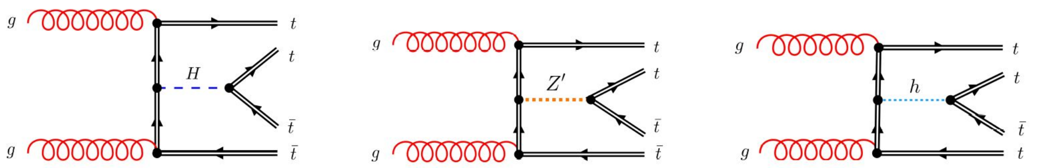
- Four top production is an extremely rare process with an estimated cross section

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

  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 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

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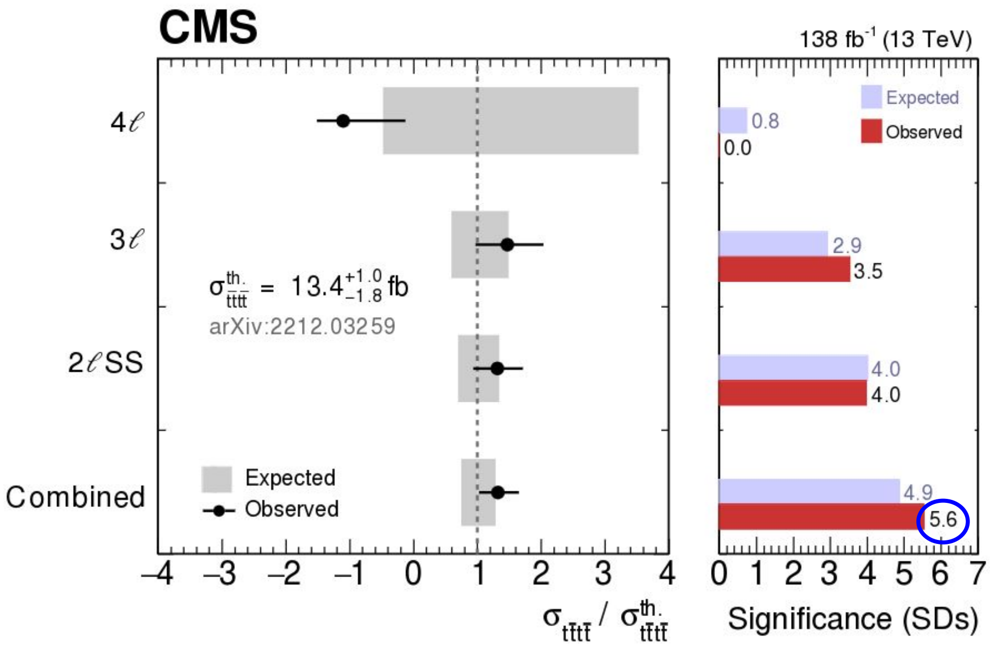
Observation of four top production

Discovery of four top production in 2023

CMS: *arXiv:2305.13439 [hep-ex]*
ATLAS: arXiv:2303.15061 [hep-ex]

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

Observed significance of 5.6σ for CMS



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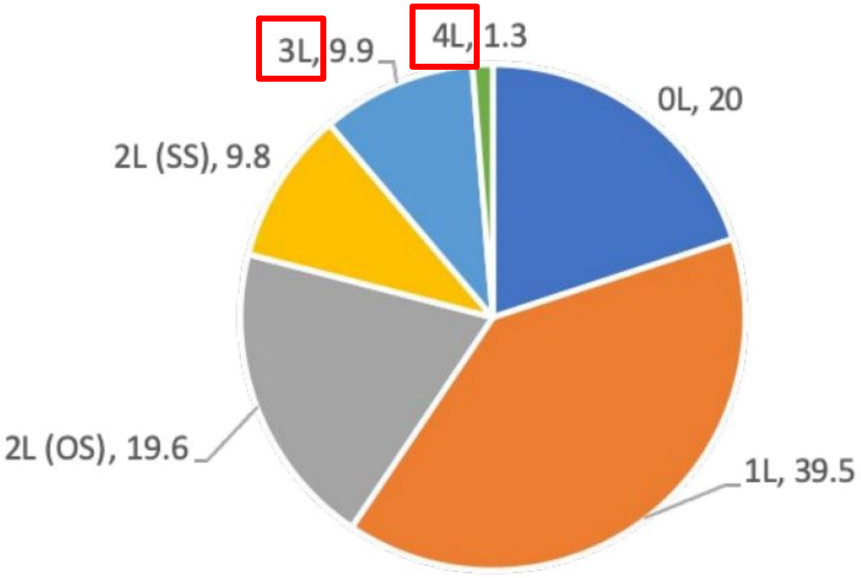
Branching ratios in four-top production



Manganelli, Quinnan '22

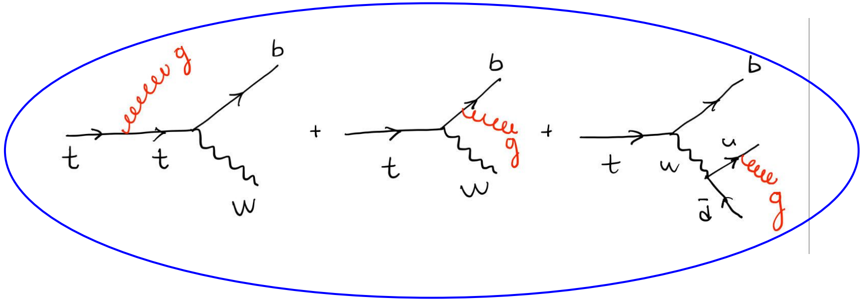
- $t \to Wb$: Top quark decays almost entirely through weak interaction to a W boson and a bottom quark with a branching ratio of ~ 100%
- W boson decays to either a pair of lepton with its corresponding neutrino or a pair of two quarks.

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

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

Process description in full NWA

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



QCD corrections in top-quark decays

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

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& + 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} \\
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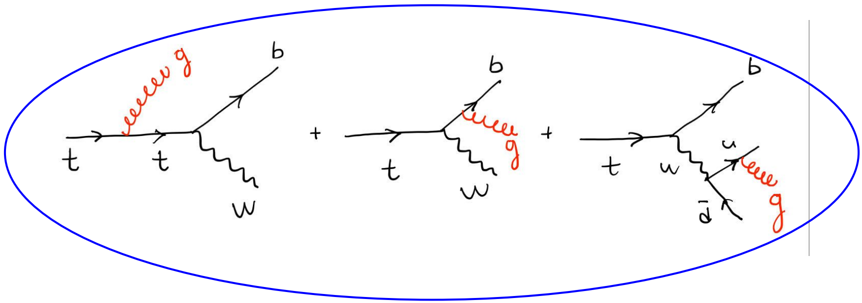

QCD corrections in top-quark decays

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

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

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

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

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

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

where $\Gamma_t^{\rm NLO} = \Gamma_t^{(0)} + \alpha_s \Gamma_t^{(1)}$

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

4 lepton decay channel

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Abstract: Triggered by the observation of four top-quark production at the LHC by the ATLAS and CMS collaboration we report on the calculation of the next-to-leading order QCD corrections to the Standard Model process $pp \to t\bar{t}t\bar{t}$ in the 4ℓ top-quark decay channel. We take into account higher-order QCD effects in both the production and decays of the four top quarks. The latter effects are treated in the narrow width approximation, which preserves top-quark spin correlations throughout the calculation. We present results for two selected renormalisation and factorisation scale settings and three different PDF sets. Furthermore, we study the main theoretical uncertainties that are associated with the neglected higher-order terms in the perturbative expansion and with the parameterisation of the PDF sets. The results at the integrated and differential fiducial cross-section level are shown for the LHC Run III center-of-mass energy of $\sqrt{s} = 13.6$ TeV. Our findings are particularly relevant for precise measurements of the four top-quark fiducial cross sections and for the modelling of top-quark decays at the LHC.

Keywords: Higher-Order Perturbative Calculations, Specific QCD Phenomenology, Top Quark

ArXiv ePrint: 2401.10678

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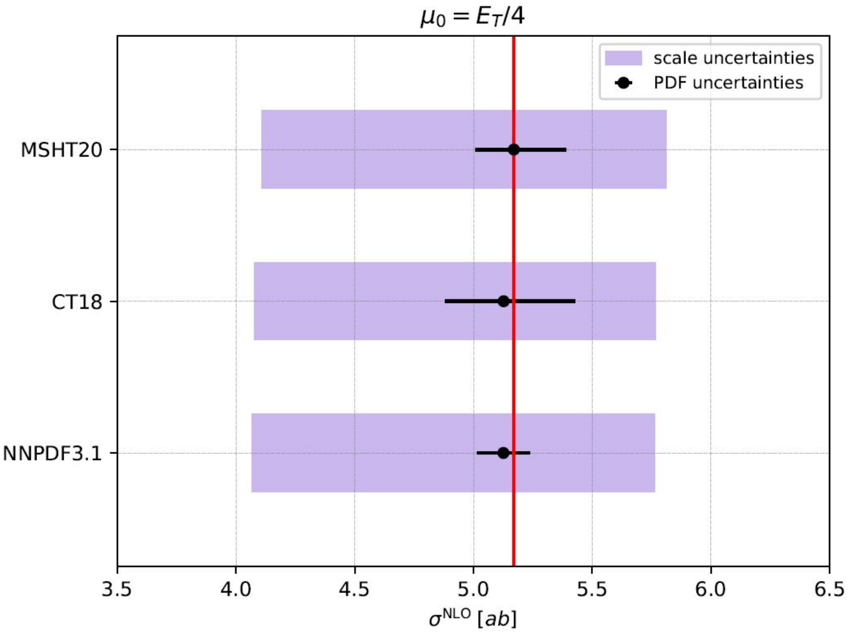
$$E_T = \sum_{i=1,2} \sqrt{m_t^2 + p_T^2(t_i)} + \sum_{i=1,2} \sqrt{m_t^2 + p_T^2(\bar{t}_i)}$$

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%)	–

- QCD corrections at the level of 10%-12%
- Impact of QCD corrections at the decays at the level of 8%-9%
- Reduction on the size of scale uncertainties when QCD corrections are applied in both production and decays

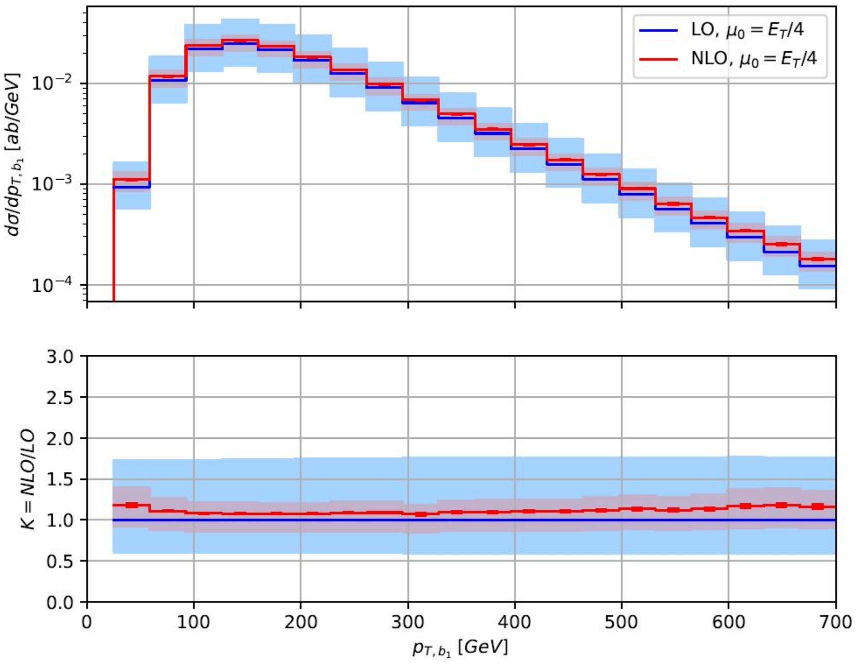
4 lepton decay channel

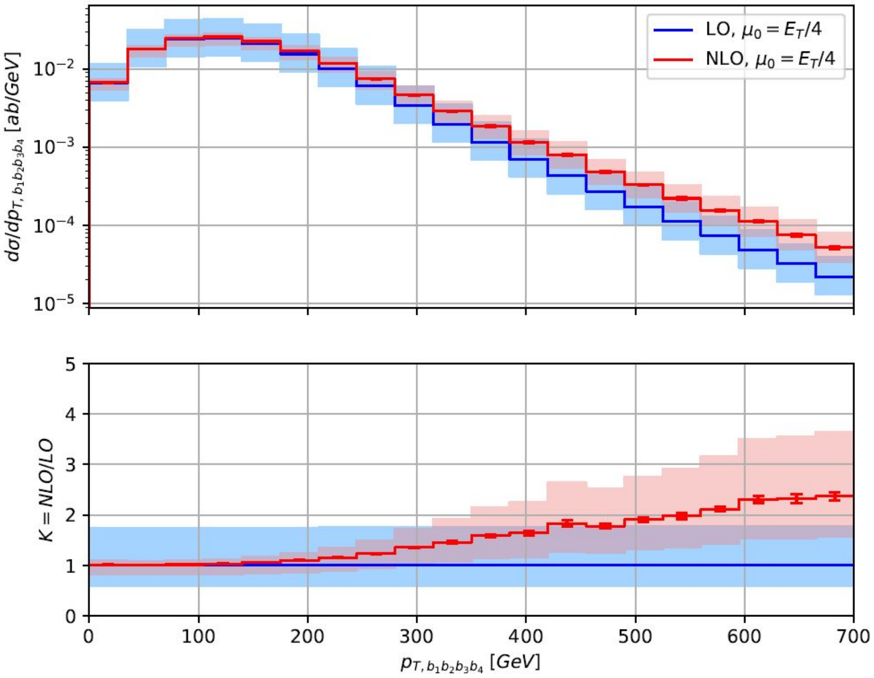


SCALE	ORDER	PDF	σ [ab]	$\mathcal{K} = \sigma^{NLO}/\sigma^{LO}$
$\mu_0 = 2m_t$	LO	NNPDF3.1_lo_as_0130	$3.7389(2)^{+72\%}_{-39\%}$	1.30
	LO	NNPDF3.1_lo_as_0118	$2.8835(2)^{+65\%}_{-37\%}$	1.68
	LO	NNPDF3.1_nlo_as_0118	$3.1068(2)^{+68\%}_{-38\%}$	1.56
	NLO	NNPDF3.1_nlo_as_0118	$4.846(2)^{+13\%}_{-21\%}$	-
$\mu_0 = E_T/4$	LO	NNPDF3.1_lo_as_0130	$4.0930(3)^{+73\%}_{-39\%}$	1.25
	LO	NNPDF3.1_lo_as_0118	$3.1356(3)^{+66\%}_{-37\%}$	1.64
	LO	NNPDF3.1_nlo_as_0118	$3.3633(2)^{+69\%}_{-38\%}$	1.52
	NLO	NNPDF3.1_nlo_as_0118	$5.126(3)^{+12\%}_{-21\%}$	-

- NLO fiducial cross sections are consistent among different PDF sets
- K factors are strongly dependent on the LO PDF under consideration

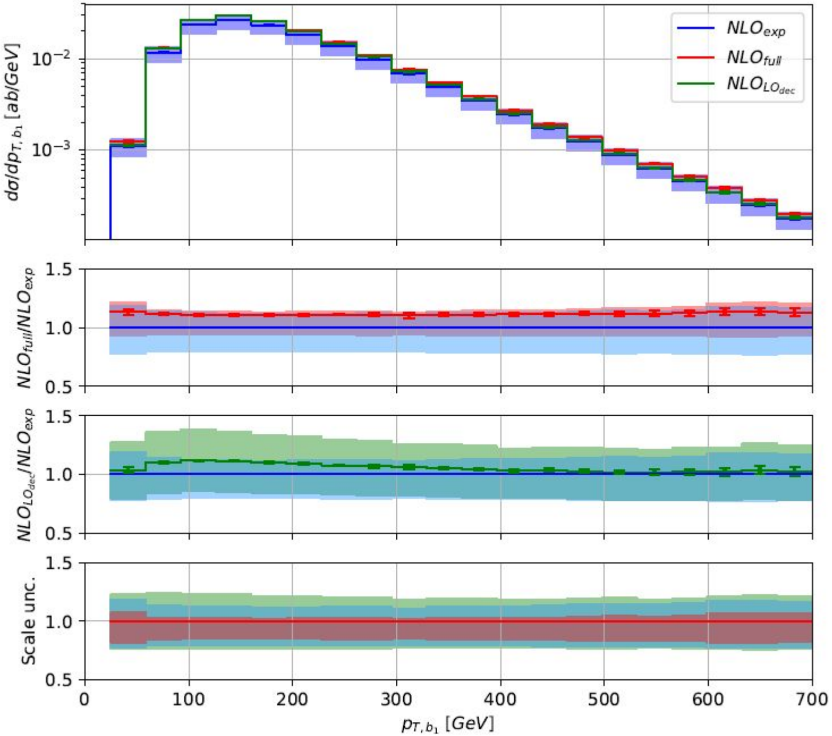
4 lepton decay channel - Differential distributions

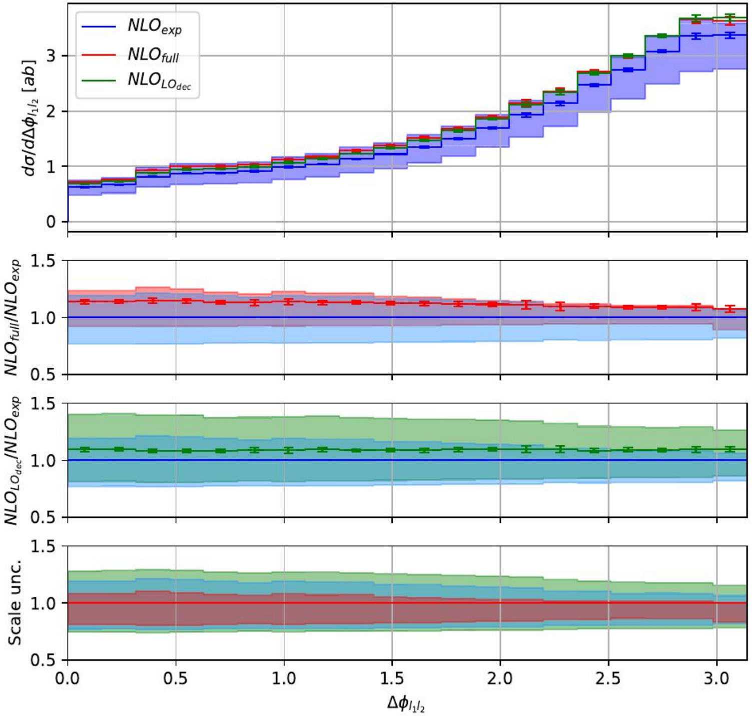




NLO QCD corrections up to 18% for p_{T,b_1} and up to 140% for $p_{T,b_1b_2b_3b_4}$

4 lepton decay channel - Differential distributions





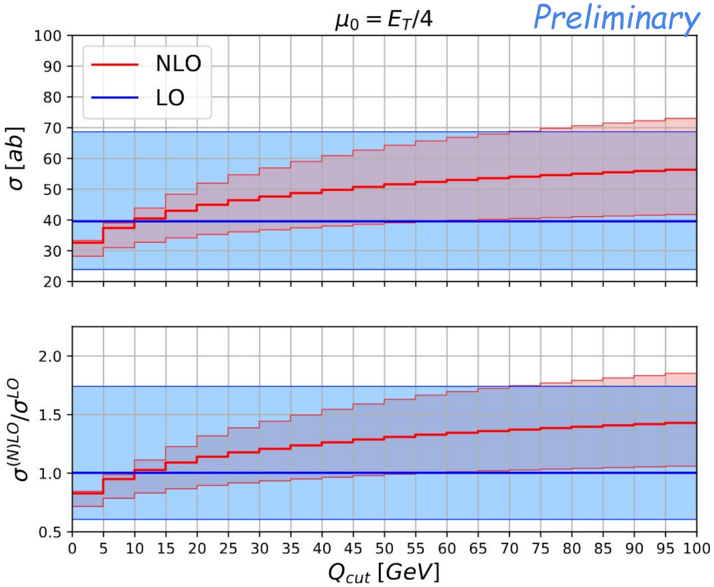
The effects of QCD corrections in top-quark decays are up to 10-12%

3 lepton channel - Qcut dependence

- We require at least one light-jet pair to have an invariant mass close to m_W

$$|M_{jj} - m_W| < Q_{cut}$$

- Large K factors are avoided → perturbative regime is applicable



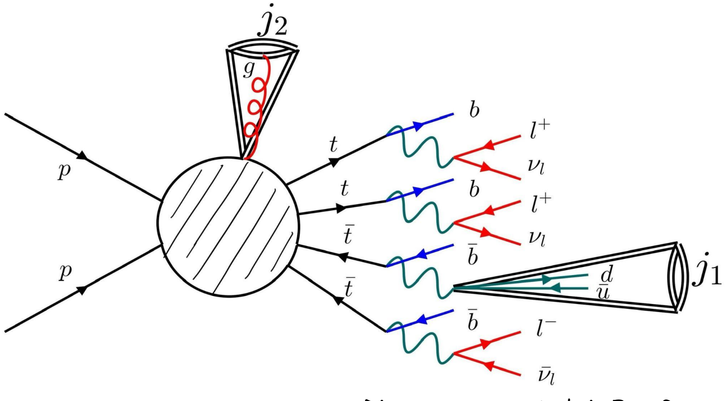


Diagram was created via FeynGame:
Harlander, Klein, Lipp '20

- NLO fiducial cross section increases with increasing values of Qcut

- K factor is 1.5 when Qcut = 100 GeV and 1.8 if no restriction is applied (no Qcut)

3 lepton channel - NLO_{full} vs NLO_{LOdec} vs NLO_{exp}

Preliminary

$\sqrt{s}$ = 13.6 TeV

Decay treatment	$\sigma_i^{\rm NLO}$ [ab]	$+\delta_{scale}$ [ab]	$-\delta_{scale}$ [ab]	$\sigma_i^{\rm NLO}/\sigma_{\rm exp}^{\rm NLO} - 1$
$Q_{cut} = 25$ GeV				
$\mu_R = \mu_F = \mu_0 = 2m_t$				
full	47.92(2)	+4.56 (10%)	−9.22 (19%)	+13.4%
$\rm LO_{dec}$	46.76(2)	+12.33 (26%)	−11.51 (25%)	+10.7%
exp	42.25(2)	+8.27 (20%)	−9.72 (23%)	–
$\mu_R = \mu_F = \mu_0 = E_T/4$				
full	50.45(3)	+3.47 (7%)	−9.32 (19%)	+12.3%
$\rm LO_{dec}$	50.17(3)	+12.95 (26%)	−12.34 (25%)	+11.7%
exp	44.91(2)	+7.91 (18%)	−10.16 (23%)	–

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$Q_{cut} \to \infty$				
$\mu_R = \mu_F = \mu_0 = 2m_t$				
full	82.45(7)	+33.16 (40%)	−24.17 (29%)	+24.2%
$\rm LO_{dec}$	67.80(3)	+30.49 (45%)	−20.64 (30%)	+2.2%
exp	66.36(5)	+29.01 (44%)	−20.17 (30%)	–
$\mu_R = \mu_F = \mu_0 = E_T/4$				
full	86.7(1)	+33.1 (38%)	−25.0 (29%)	+23.5%
$\rm LO_{dec}$	72.05(3)	+31.83 (44%)	−21.83 (30%)	+2.6%
exp	70.19(7)	+29.69 (42%)	−21.12 (30%)	–

- In the Qcut → ∞ scenario we obtain K = (1.8-1.9) for the expanded case and K = (2.2-2.3) for the full NWA
- Substantial increase in the size of scale uncertainties if no Qcut is applied, from 23% to 42%
- The differences between various NWA treatments are also very sensitive to the choice of Qcut

3 lepton channel - NLO_{full} vs NLO_{LOdec} vs NLO_{exp}

Preliminary

$\sqrt{s}$ = 13.6 TeV

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3 lepton channel - NLO_{full} vs NLO_{LOdec} vs NLO_{exp}

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$Q_{cut} \to \infty$

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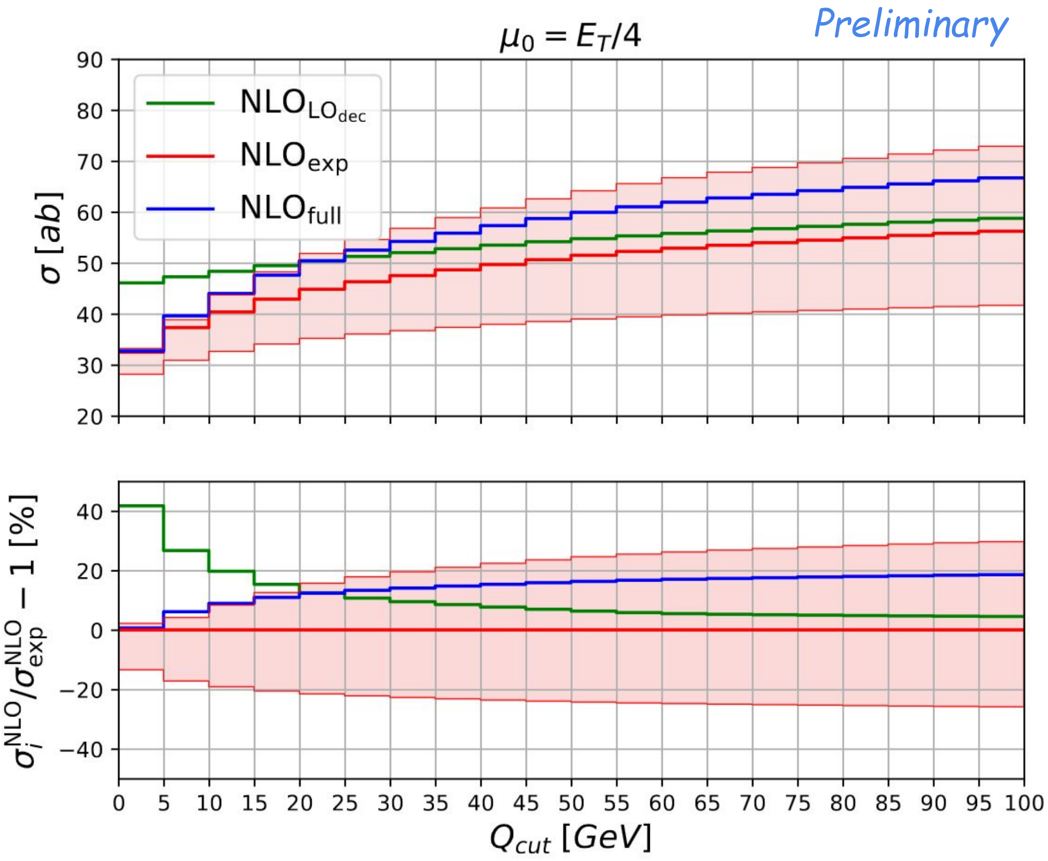
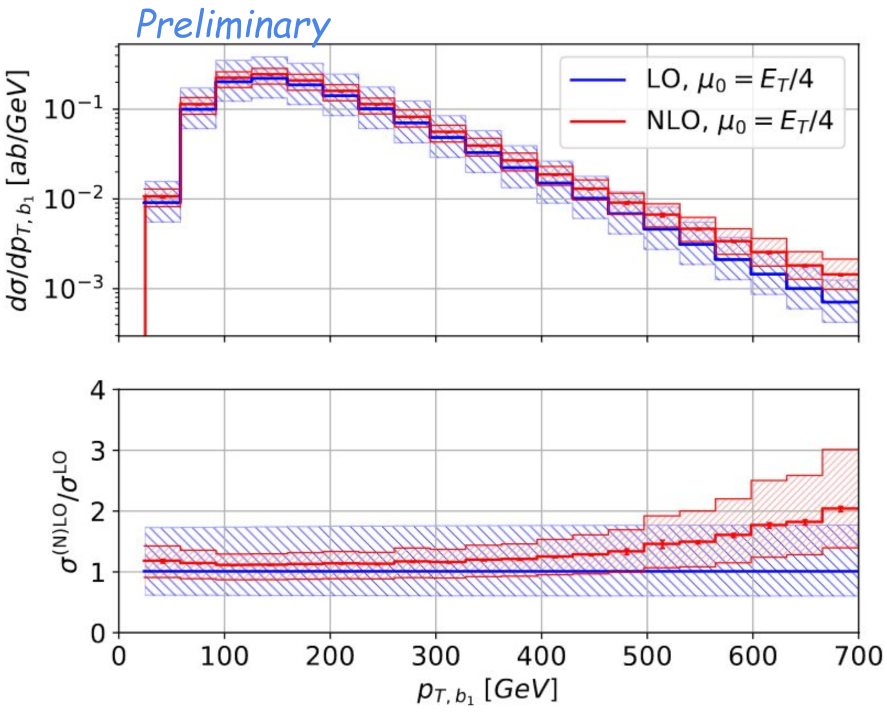
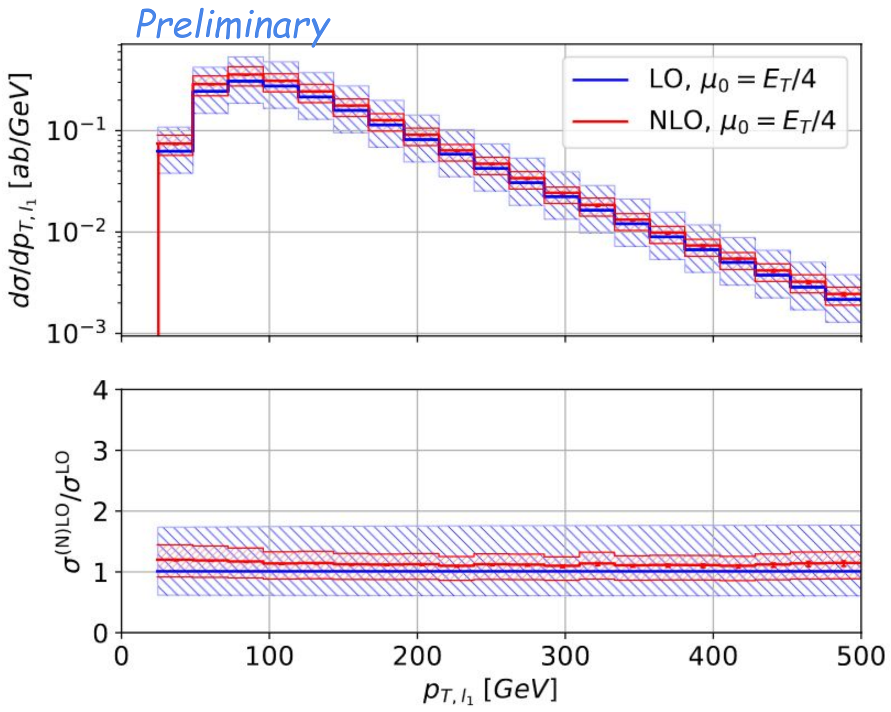
3 lepton channel - NLO_{full} vs NLO_{LOdec} vs NLO_{exp}



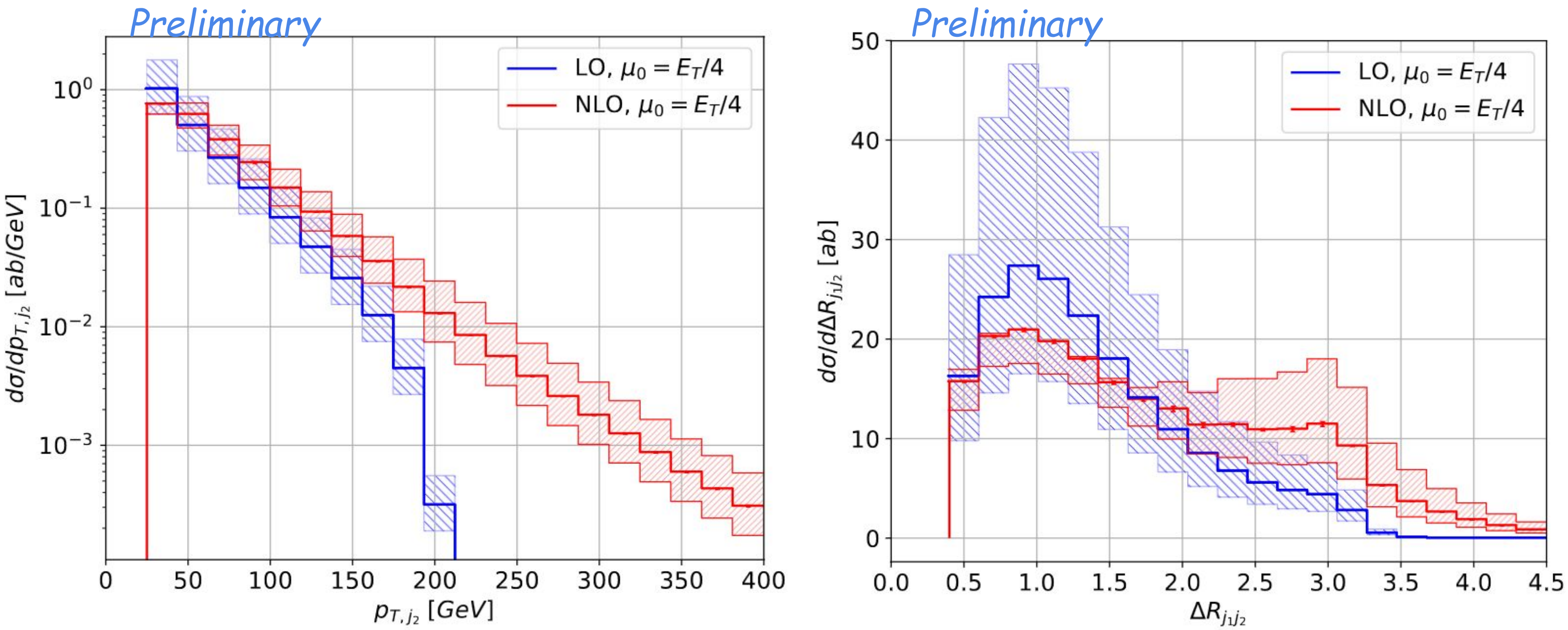
3 lepton channel - Differential distributions with Qcut = 25 GeV





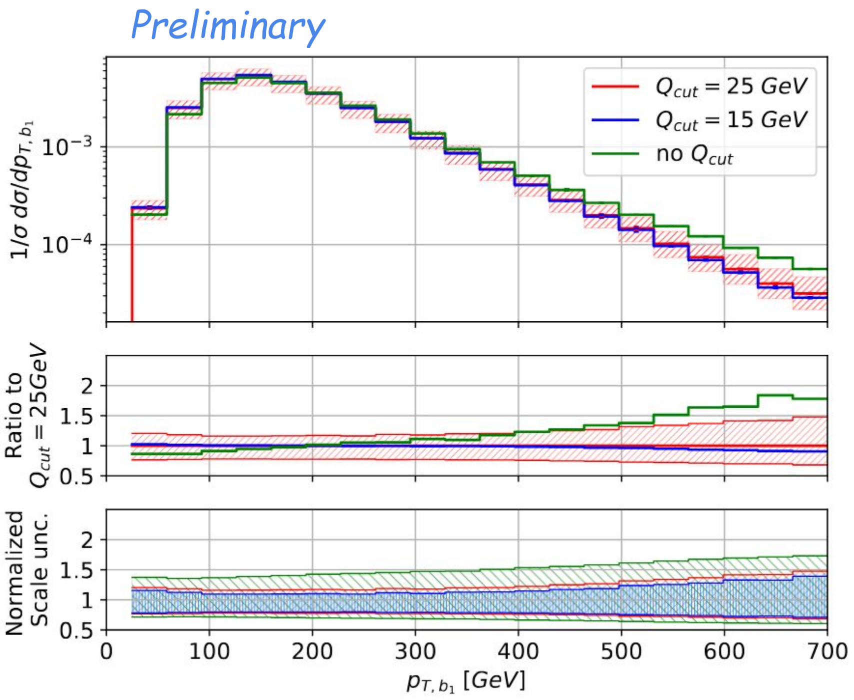
- QCD corrections are up to 100% in the tail of the distribution for p_{T,b_1}
- QCD corrections only up to 19% for p_{T,l_1}

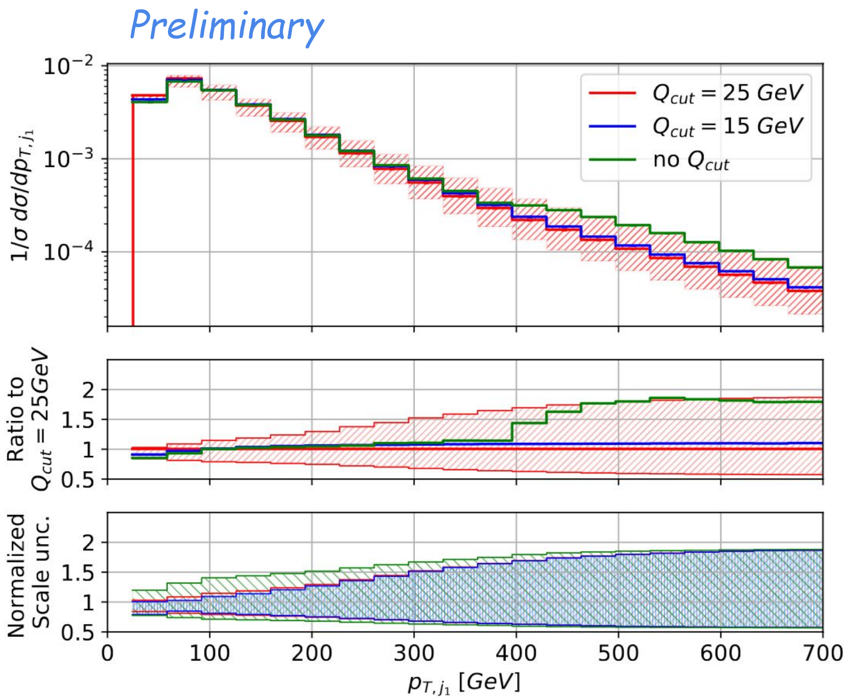
3 lepton channel - Differential distributions with Qcut = 25 GeV



- Very large shape distortions between LO and NLO predictions in observables related to light jet kinematics
- At LO pure kinematics imply that $(p_{T,j_2})_{max} \approx \frac{m_W}{(\Delta R_{j_1j_2})_{min}} \approx 201 \text{ GeV}$

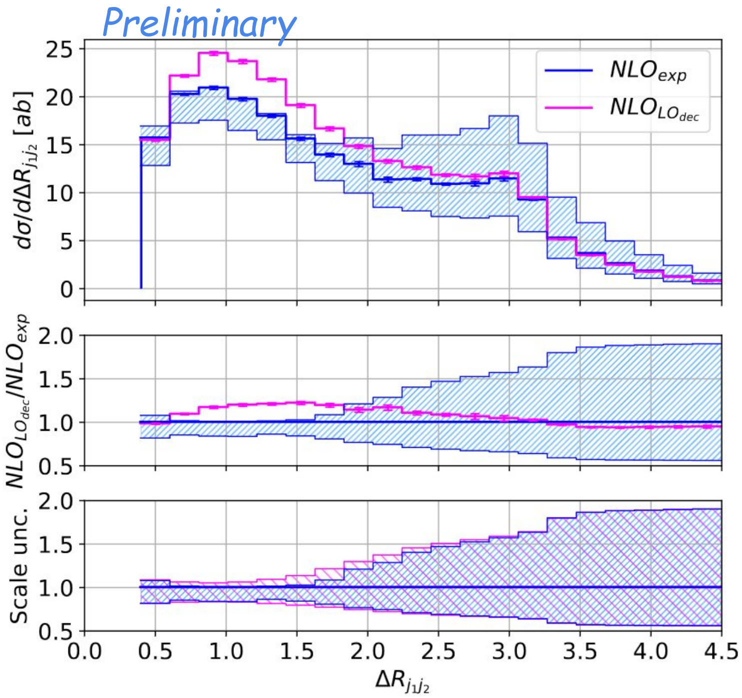
3 lepton channel - Normalized differential distributions with varying Qcut

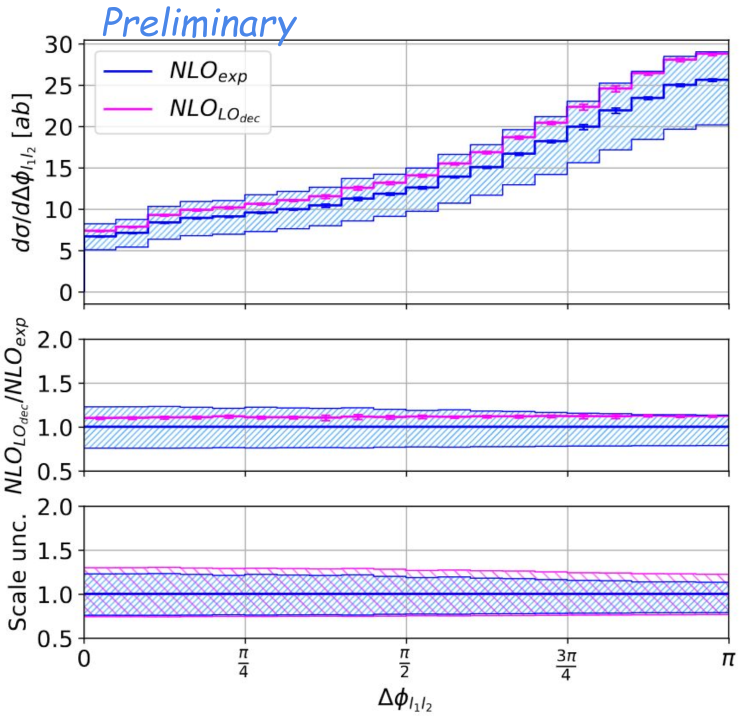




- No significant shape distortions between Qcut = 15 GeV and Qcut = 25 GeV
- Distortions up to 80% in the tails of the distributions for the no Qcut scenario
- Scale uncertainties are much higher in the no Qcut scenario even in regions where most events are anticipated

3 lepton channel - Differential distributions with Qcut = 25 GeV





- Differences up to 22% near $\Delta R_{j_1 j_2}$ = 1
- Differences at the level of 10%-12% for $\Delta\phi_{l_1l_2}$

Summary

4 lepton channel

- Reduction of the scale uncertainties when QCD corrections are applied both at the production and decay stages: $\mathrm{NLO}_{\mathrm{LOdecays}}$: 23% → $\mathrm{NLO}_{\mathrm{exp}}$: 20%, $\mathrm{NLO}_{\mathrm{full}}$: 16%
- Proper modeling of differential distributions → necessary for correct interpretation of possible new physics signals

3 lepton channel

- QCD corrections at the level of 14%-19% for Qcut = 25 GeV and up to 80%-90% for the no Qcut case
- Scale uncertainties up to 23% for Qcut = 25 GeV and 42% in the no Qcut scenario
- Large shape distortions at the differential level for observables related to light jet kinematics
- Differences up to 80% in the tails of the normalized distributions when no Qcut is applied
- Differences up to 22% for dimensionless observables between $\mathrm{NLO}_{\mathrm{exp}}$ and $\mathrm{NLO}_{\mathrm{LOdec}}$ for Qcut = 25 GeV

Outlook

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

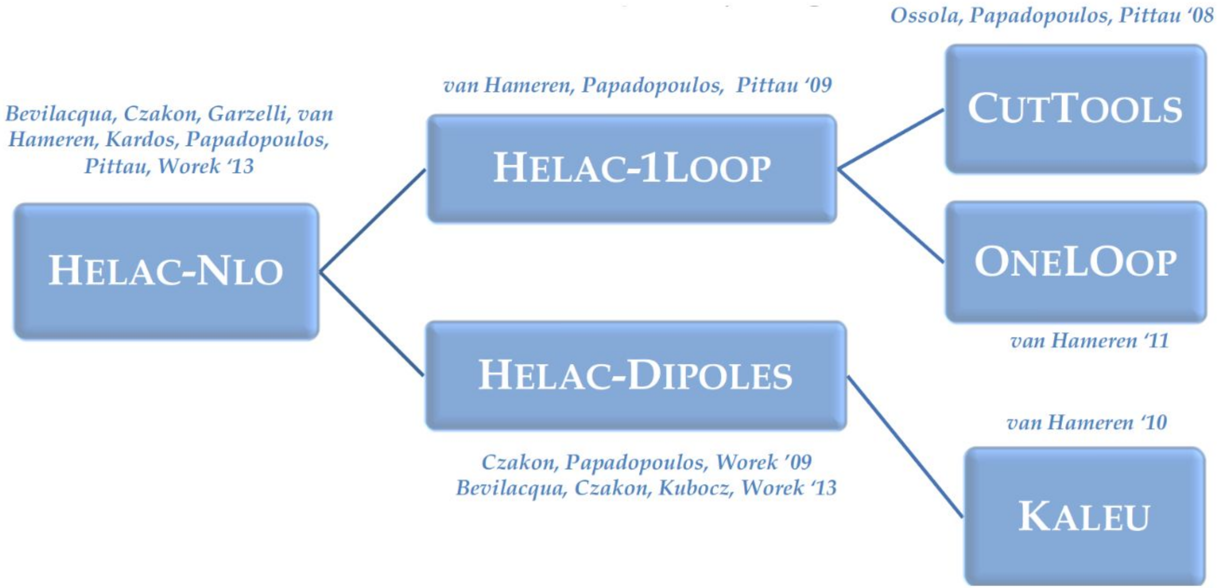
- Study the impact of including Matrix Element Corrections (MEC) in top quark decays during showering → already done for $t\bar{t}$ and $t\bar{t}W$
  Frixione, Amoroso, Mrenna '23 / Frederix, Gellersen, Nasufi '24

Thanks for your attention!

Backup

Backup slides

HELAC-NLO



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

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:

$$p_{T,\ell} > 25\text{ GeV}\,, \qquad |y_\ell| < 2.5\,, \qquad \Delta R_{\ell\ell} > 0.4\,,$$
$$p_{T,b} > 25\text{ GeV}\,, \qquad |y_b| < 2.5\,, \qquad \Delta R_{bb} > 0.4\,,$$
$$p_{T,j} > 25\text{ GeV}\,, \qquad |y_j| < 2.5\,, \qquad \Delta R_{bj} > 0.4\,.$$

- 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

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

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Input parameters

$$G_\mu = 1.1663787 \cdot 10^{-5}\ \text{GeV}^{-2}\,, \qquad m_t = 172.5\ \text{GeV}\,,$$

$$m_W = 80.379\ \text{GeV}\,, \qquad \Gamma_W^{\text{NLO}} = 2.0972\ \text{GeV}\,,$$

$$m_Z = 91.1876\ \text{GeV}\,, \qquad m_b = 0\ \text{GeV}\,.$$

$$\Gamma_t^{\text{LO}} = 1.4806842\ \text{GeV}\,, \qquad \Gamma_t^{\text{NLO}} = 1.3535983\ \text{GeV}\,.$$

↑ LO calculations

↑ NLO calculations

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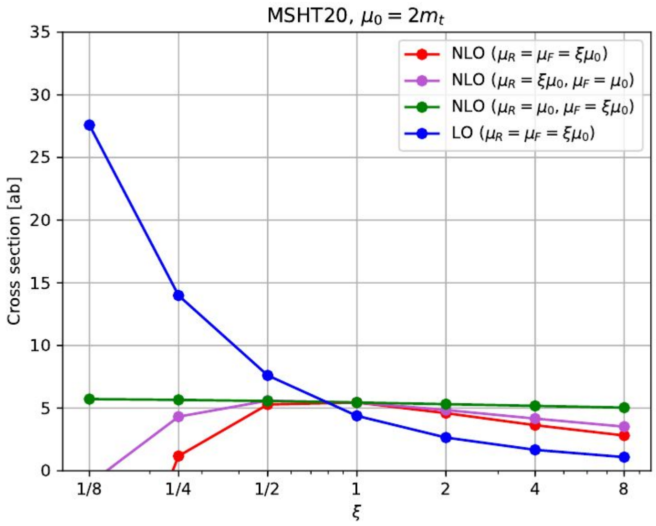
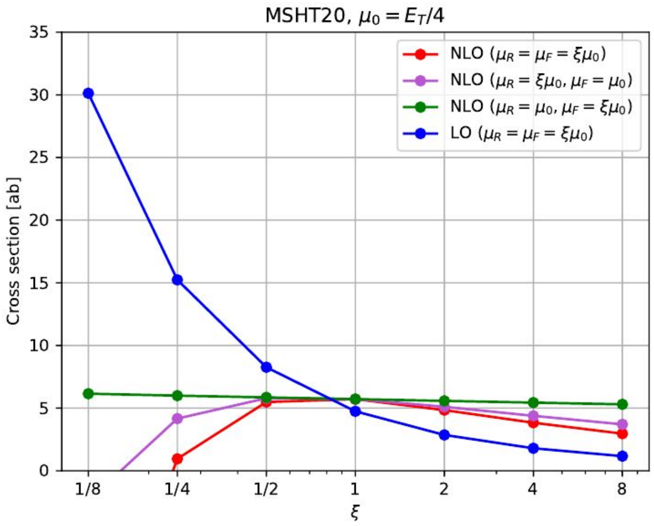
4 lepton channel - Scale variations





The primary source of scale uncertainties originates from variations in μ_R

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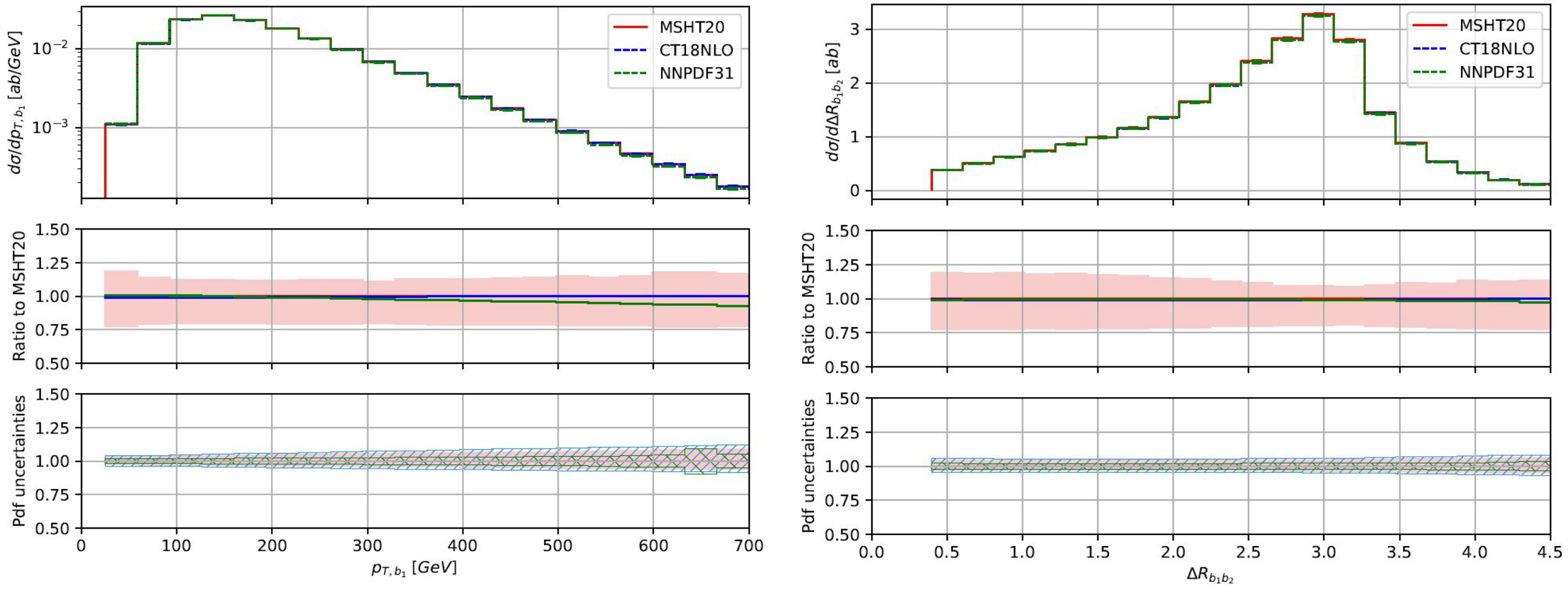
4 lepton channel - Differential agreement among different PDF sets



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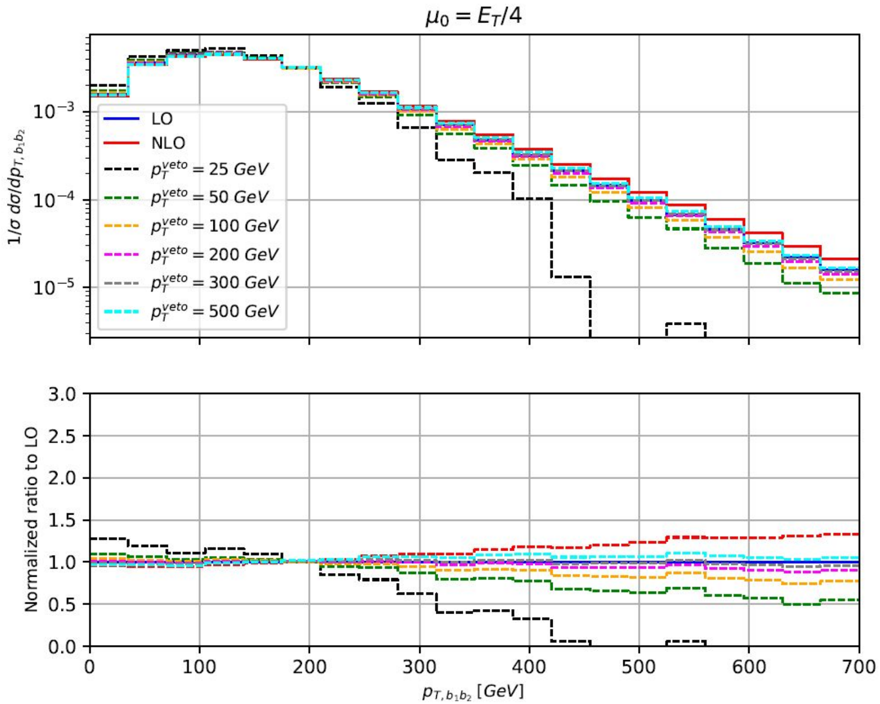
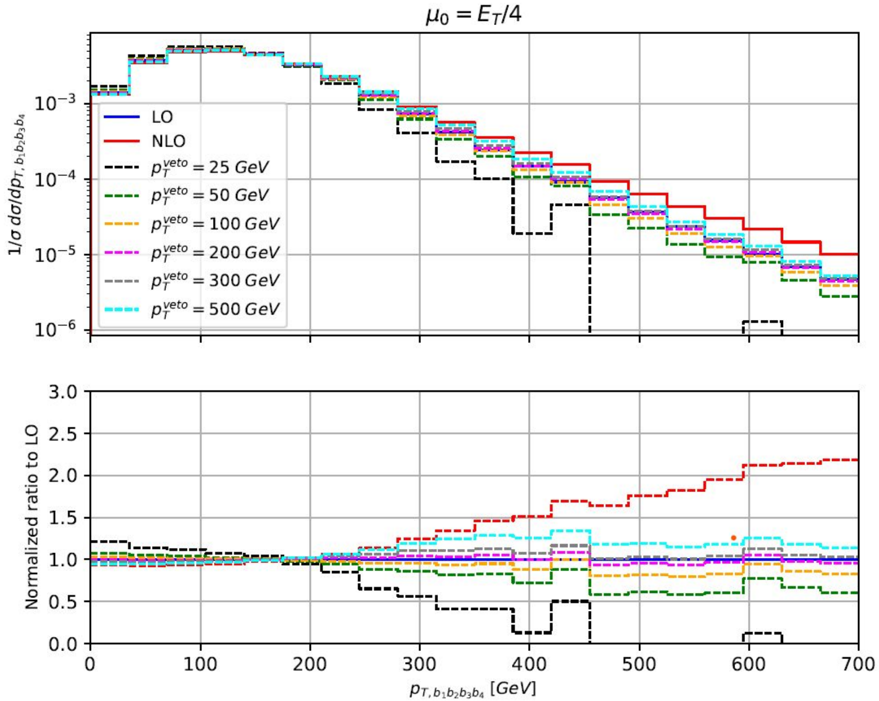
4 lepton channel - Applying p_T veto





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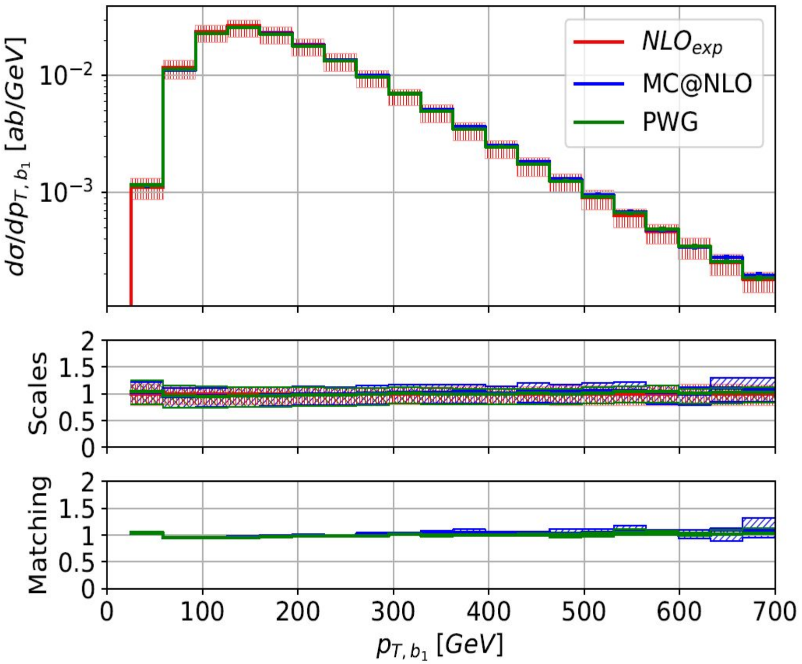
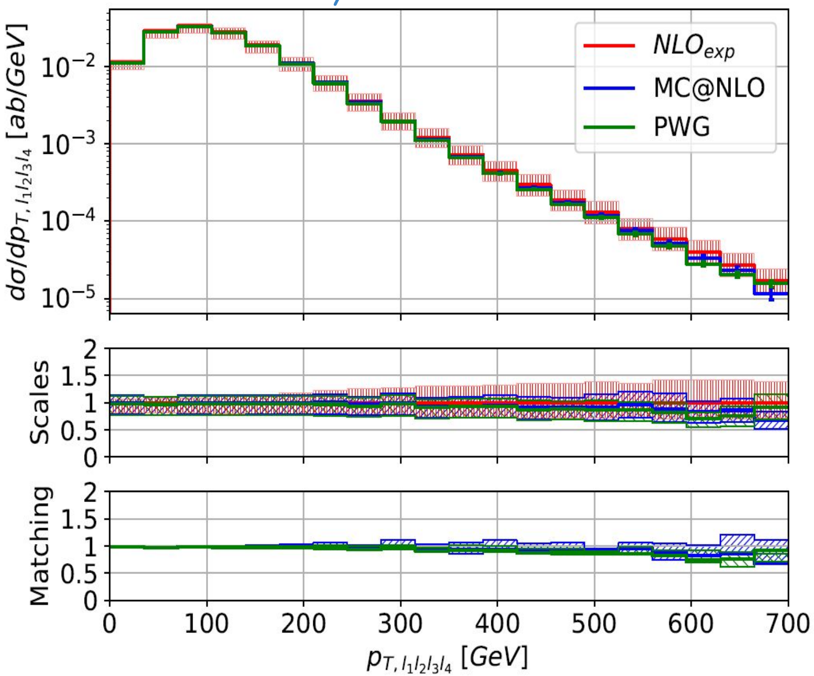
4 lepton channel

Preliminary results



Preliminary results



The size of the scale uncertainties is underestimated in POWHEG and MC@NLO for certain types of observables

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3 lepton channel - Integrated fiducial cross sections at LO, NLO

Qcut = 25 GeV, $\sqrt{s}$ = 13.6 TeV

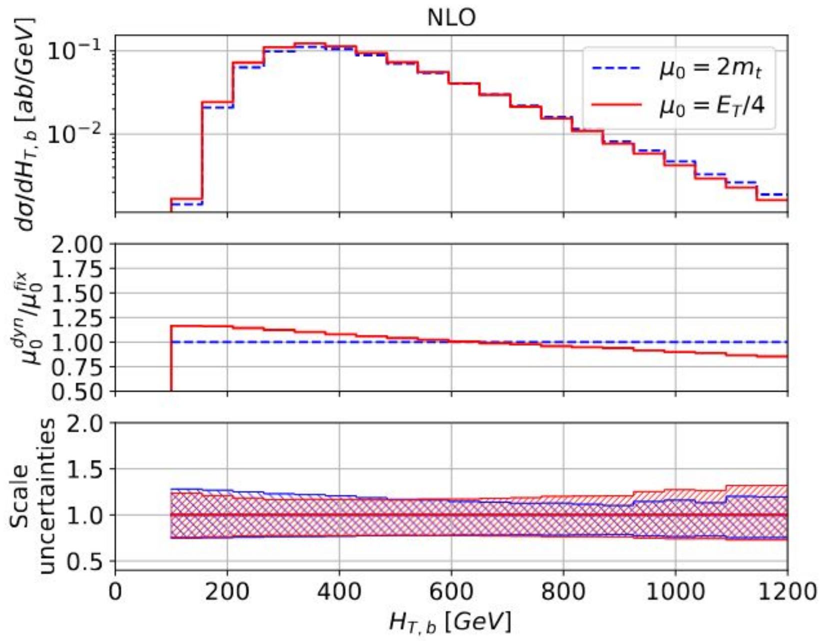
Preliminary

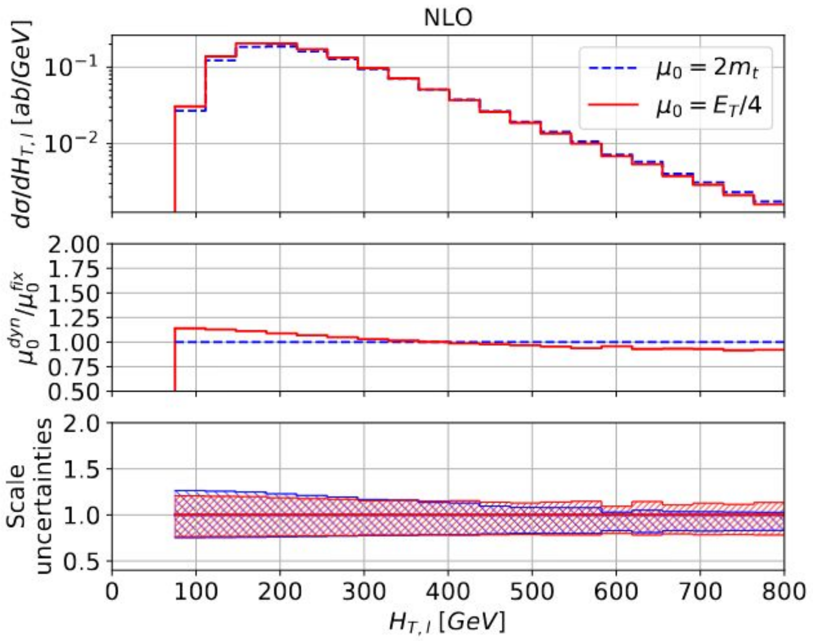
PDF	σ^{LO} [ab]	δ_{scale}	σ^{NLO} [ab]	δ_{scale}	δ_{PDF}	$\mathcal{K} = \sigma^{\mathrm{NLO}}/\sigma^{\mathrm{LO}}$
			$\mu_R = \mu_F = \mu_0 = 2m_t$			
MSHT20	35.575(2)	+25.883 (73%) −13.982 (39%)	42.25(2)	+8.27 (20%) −9.72 (23%)	+1.76 (4%) −1.32 (3%)	1.19
NNPDF3.1	30.581(2)	+21.781 (71%) −11.853 (39%)	41.89(2)	+8.28 (20%) −9.71 (23%)	+0.89 (2%) −0.89 (2%)	1.37
CT18	37.675(3)	+26.858 (71%) −14.655 (39%)	41.89(2)	+8.20 (20%) −9.62 (23%)	+2.42 (6%) −2.00 (5%)	1.11
			$\mu_R = \mu_F = \mu_0 = E_T/4$			
MSHT20	39.424(3)	+29.111 (74%) −15.632 (40%)	44.91(2)	+7.91 (18%) −10.16 (23%)	+1.84 (4%) −1.38 (3%)	1.14
NNPDF3.1	34.193(3)	+24.868 (73%) −13.413 (39%)	44.60(2)	+7.87 (18%) −10.16 (23%)	+0.94 (2%) −0.94 (2%)	1.30
CT18	41.306(3)	+29.728 (72%) −16.169 (39%)	44.50(2)	+7.86 (18%) −10.06 (23%)	+2.51 (6%) −2.08 (5%)	1.08

- LO results only provide a rough estimate with huge scale uncertainties ~74%
- Different PDF predictions are consistent at NLO within the uncertainties
- NLO scale uncertainties up to 23%
- K factors vary between different PDF sets from 1.08 to 1.37

Backup slides

3 lepton channel - Dynamical vs fixed scale





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Cross-checks

- 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 [hep-ph]*