NLO and off-shell effects in top-quark mass determinations

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[5]Department of Physics and Astronomy, Michigan State University

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Max-Planck-Institut für Physik

Introduction

Top-quark mass determinations

Experimentally:

- (MC) top quark mass determined from fitting distributions sensitive to m_t
- Final-state reconstruction: challenging in both $\ell +$ jets and dilepton channels

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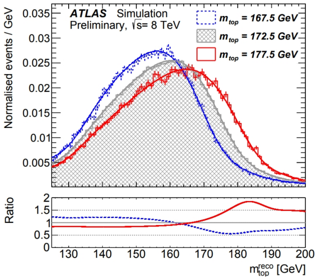

(a) $m_{\mathrm{top}}^{\mathrm{reco}}$ as a function of m_{top}

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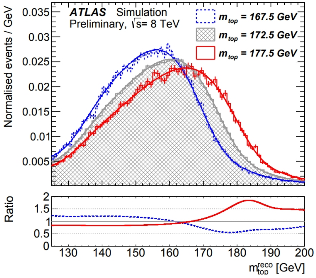

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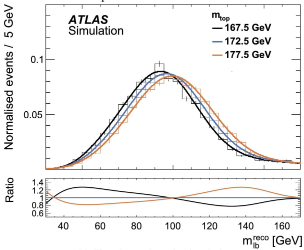

(a) Signal templates in simulation

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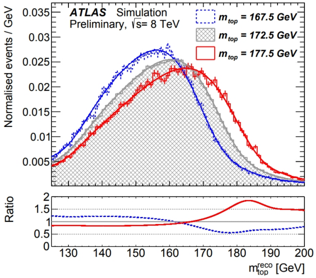
ATLAS combination (preliminary):

$$m_t = 172.51 \pm 0.27(\mathrm{stat}) \pm 0.42(\mathrm{syst})\ \mathrm{GeV}$$



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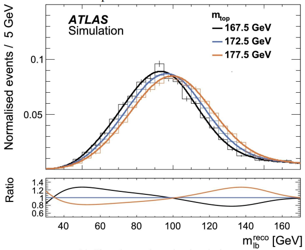

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Top-quark mass determinations

Theoretically: Narrow-width approximation

- On-shell $t\bar{t}$ NNLO QCD corrections to differential distributions, NLO EW corrections

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- Top decay: NNLO+NNLL QCD corrections

  [Beneke, Falgari, Klein, Schwinn '11], [Cacciari, Czakon, Mangano, Mitov, Nason '11], [Pecjak, Scott, Wang, Yang '16], [Ferroglia, Marzani, Pecjak, Yang '13], [Broggio, Papanastasiou, Signer '14], [Kidonakis '15], [Gao, Papanastasiou '17]

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$\rightsquigarrow$ Parton-shower matching

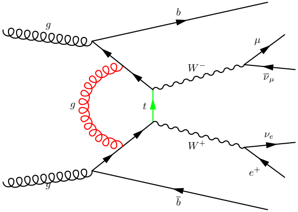
- Powheg ttb_NLO_dec [Campbell, Ellis, Nason, Re '14]
- Sherpa $t\bar{t}$+3j [Höche, Krauss, Maierhöfer, Pozzorini, Schönherr, Siegert '14]
- Herwig NLO $t\bar{t}$ multi-jet merging

  [Bellm, Cormier, Gieseke, Plätzer, Reuschle, Richardson et al. '17]

Top-quark mass determinations

Beyond the NWA: $W^+W^-b\bar{b}$ final-state

- Non-resonant contributions to $W^+W^-b\bar{b}$



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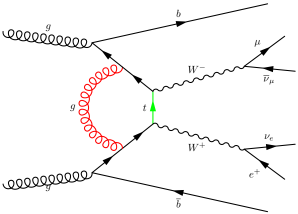

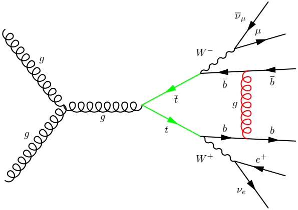

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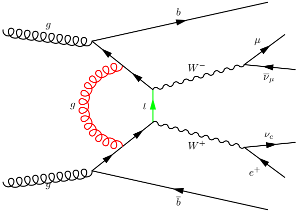

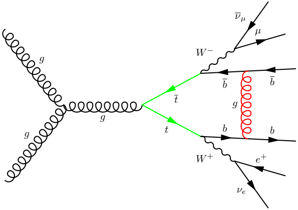

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- $W^+W^-b\bar{b}$ NLO QCD **[Garzelli, Kardos, Trocsanyi '14]**
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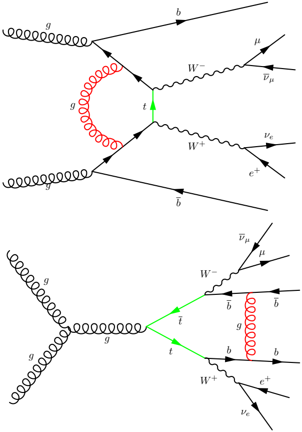

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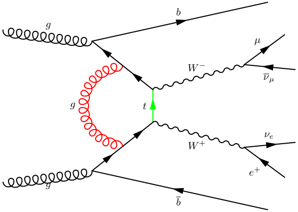

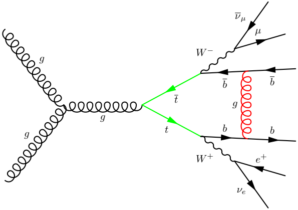

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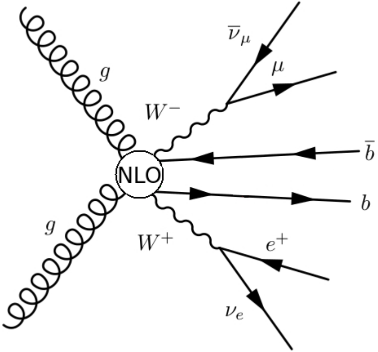
⟶ study importance of off-shell contributions to the dileptonic $W^+W^-b\bar{b}$ final-state in a realistic m_t extraction

Phenomenology

Levels of theoretical content

- Stages of the theoretical description:
  - **NLO$_{\text{full}}$**: full (QCD) NLO corrections to $pp \to W^+W^-b\bar{b}$



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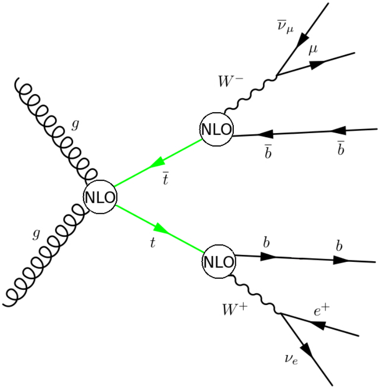

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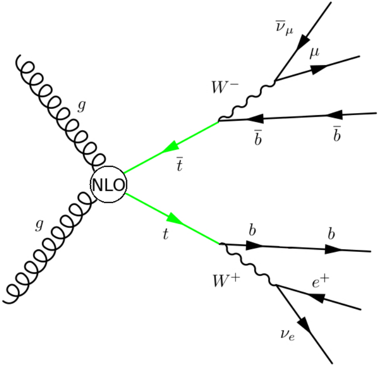
  - $\textbf{NLO}_{\textbf{NWA}}^{\textbf{LOdec}}$: NLO $t\bar{t}$ production $\otimes$ LO decay



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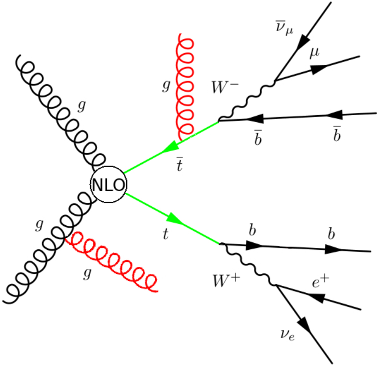
  - **NLO_{PS}**: NLO $t\bar{t}$ production + shower $\otimes$ decay via parton showering



Setup

- $\sqrt{s} = 13$ TeV
- PDF4LHC15_nlo_30_pdfas
- Fastjet anti-k_T algorithm with $R = 0.4$
- EW parameters:

$$\begin{aligned} \Gamma_t^{\rm LO} &= 1.4806\ \text{GeV} & \Gamma_t^{\rm NLO} &= 1.3535\ \text{GeV}, \\ \Gamma_W^{\rm LO} &= 2.0454\ \text{GeV} & \Gamma_W^{\rm NLO} &= 2.1155\ \text{GeV}, \\ \Gamma_Z &= 2.4952\ \text{GeV} \end{aligned}$$

$$G_\mu = 1.16637 \cdot 10^{-5}\ \text{GeV}^{-2}$$

$$M_W = 80.3850\ \text{GeV} \qquad M_Z = 91.1876\ \text{GeV}$$

- 5FNS (massless b's)

For the NLO_{full}, $\text{NLO}_{\text{NWA}}^{\text{LOdec}}$, NLO_{PS} calculations:

- Sherpa 2.2.3 interfaced to GoSam OLP

Setup: scale variations

- Central scale: $\mu_R = \mu_F = m_t$
- Scale variations: $\mu_R = \mu_F = 0.5 m_t$, $\mu_R = \mu_F = 2.0 m_t$
- Shower scale variations:

Scheme	Central scale μ_i	Variations $\xi_i\ \mu_i$
$\mu_F \mu_R \alpha_s^{\mathrm{PS}}$	$\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = m_t,\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$ $\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = \mu_{t\bar{t}},\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$	$\xi_R = \xi_F = \xi_R^{\mathrm{PS}} = \{0.5, 1.0, 2.0\}$
$\mu_F \mu_R \mu_Q$	$\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = m_t,\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$	$\xi_R = \xi_F = \{0.5, 1.0, 2.0\}$ and $\xi_Q = \{\sqrt{2}, 1.0, 1/\sqrt{2}\}$
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Definition of the observables

Top-quark mass $m_t^{(\mathrm{MC})}$ extracted from fitting $\frac{d\sigma}{d\Omega}(m_t^{\mathrm{MC}})$

- Differential distributions particularly sensitive to m_t:
  - $m_{\ell b}^2 = (p_\ell + p_b)^2$
  - $m_{T2}^2 = \min_{\mathbf{p}_T^{\nu_1} + \mathbf{p}_T^{\nu_2} = \mathbf{p}_T^{miss}} \left[\max \left\{ m_T^2 \left(\mathbf{p}_T^{(\ell b)_1}, \mathbf{p}_T^{\nu_1} \right), m_T^2 \left(\mathbf{p}_T^{(\ell b)_2}, \mathbf{p}_T^{\nu_2} \right) \right\} \right]$
  - $E_T^{\Delta R} = \frac{1}{2} \left(E_T^{\ell_1} \Delta R(\ell_1, b_1) + E_T^{\ell_2} \Delta R(\ell_2, b_2) \right)$
  - $m_{\ell\ell}^2 = (p_{\ell_1} + p_{\ell_2})^2$

where we choose the lepton-b-jet pairing (ℓ^+, b), (ℓ^-, b') minimizing $m_{\ell^+ b} + m_{\ell^- b'}$.

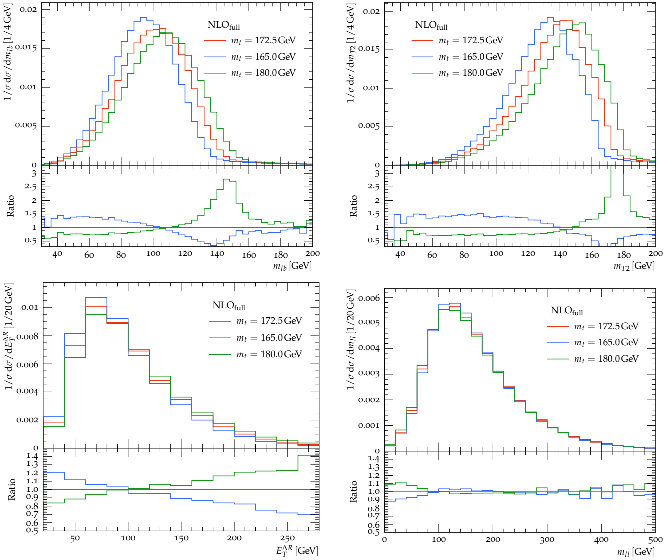
Experimental cuts

The following criteria are required to be fulfilled for our selection:

- Exactly two *b*-tagged jets with
  - $p_T^{\mathrm{jet}} > 25$ GeV and $|\eta^{\mathrm{jet}}| < 2.5$
- Exactly two oppositely charged leptons with
  - $p_T^{\mu} > 28$ GeV, $|\eta^{\mu}| < 2.5$
  - $p_T^{e} > 28$ GeV,$|\eta^{e}| < 2.47$ with the exclusion of $1.37 < |\eta^{e}| < 1.52$
  - $\Delta_R(\ell, \mathrm{jets}) > 0.4$
- $p_T^{\ell b} > 120$ GeV

Top-quark mass sensitivity

$m_{\ell b}$ m_{T2} $E_T^{\Delta R}$ $m_{\ell\ell}$



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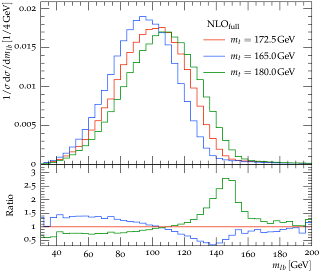
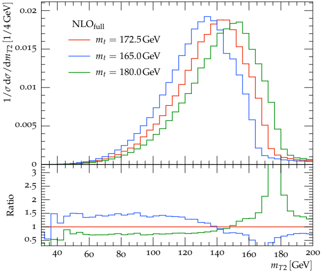
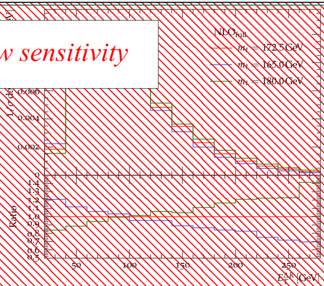


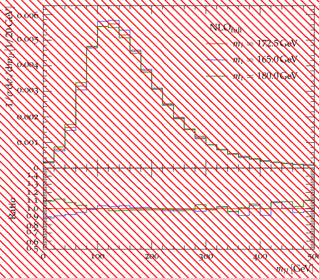


m_{T2}

Low sensitivity

$E_T^{\Delta R}$





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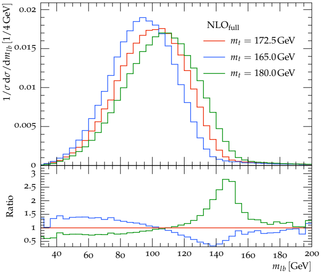
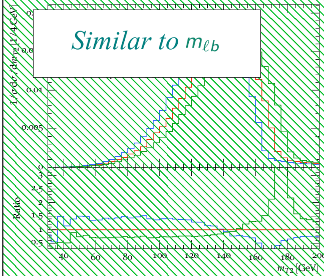


Similar to $m_{\ell b}$



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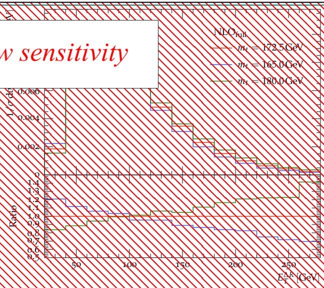
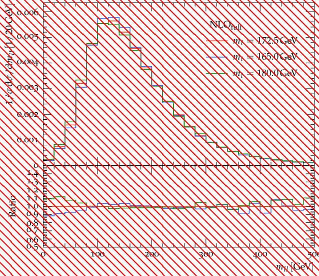
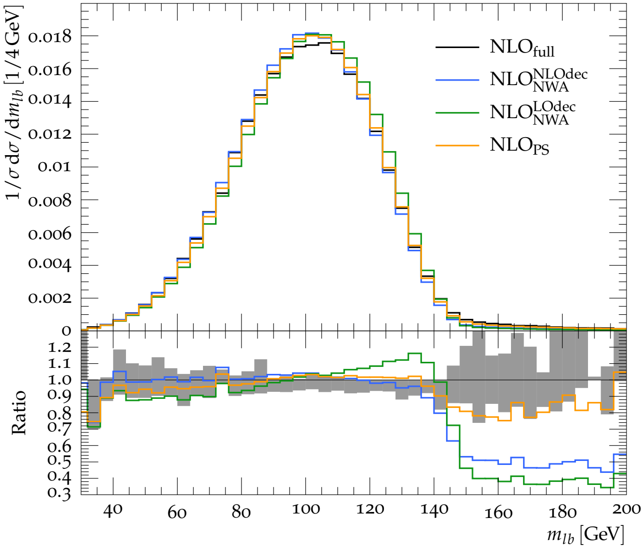




$m_{\ell\ell}$

$m_{\ell b}$: NWA ↔ full description **(normalized)**



$m_{\ell b}$: NWA $\leftrightarrow$ full description **(normalized)**

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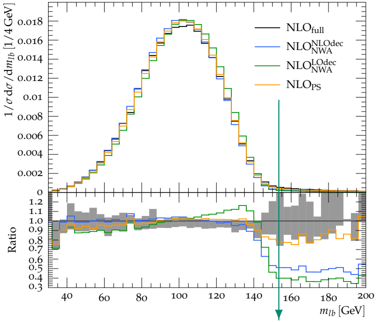

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$$(m_t = 172.5 \text{ GeV})$$

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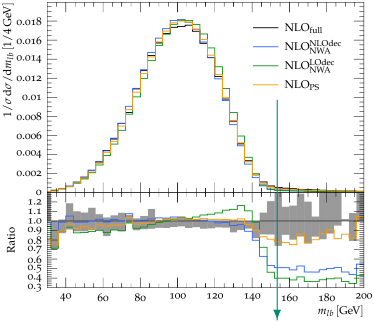

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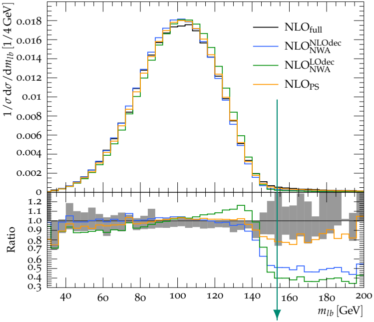

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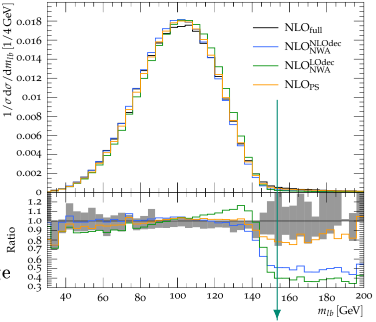

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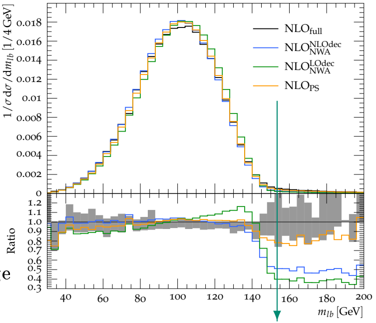

- $\mathrm{NLO}_{\mathrm{PS}}$ starts populating the high $m_{\ell b}$ region and reduces the difference

$m_{\ell b}$: NWA $\leftrightarrow$ full description **(normalized)**

- Kinematic edge ⇝ sizeable dependence on theoretical description
- $\mathrm{NLO}^{\mathrm{NLOdec}}_{\mathrm{NWA}}$ in good agreement with $\mathrm{NLO}_{\mathrm{full}}$ in the bulk of the cross-section
- $\mathrm{NLO}^{\mathrm{LOdec}}_{\mathrm{NWA}}$ introduces shape differences of $\mathcal{O}(20\%)$ up to the kinematic edge
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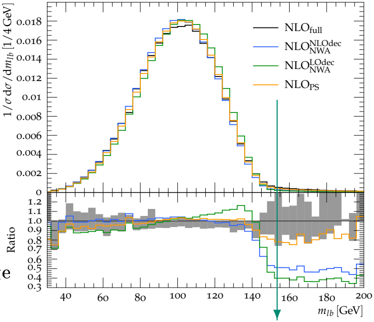

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⇝ **higher-order corrections to production *and* decay are crucial**

Scale dependence: NWA $\leftrightarrow$ full description

$\mathrm{LO_{full}} \leftrightarrow \mathrm{NLO_{full}}$

- NLO corrections to $W^+W^-b\bar{b}$: shape differences of $\mathcal{O}(50\%)$ also at low $m_{\ell b}$
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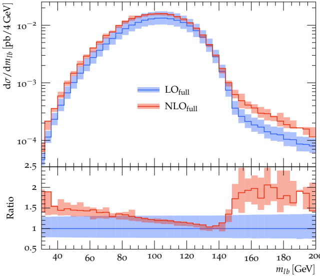

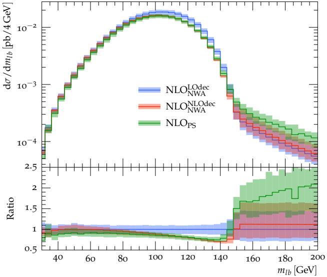

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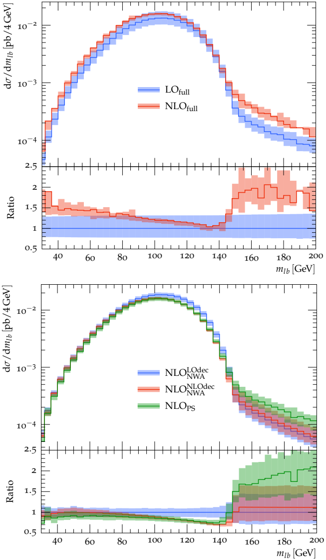

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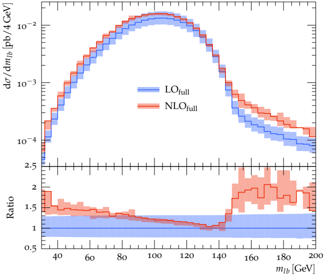

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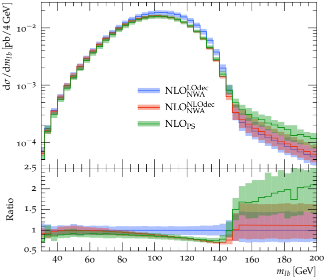
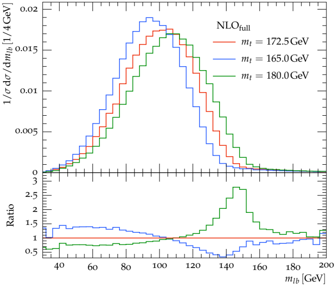


⇝ **quantify the theoretical uncertainty in emulating a realistic analysis**

Template method

Calibration of the template fit function

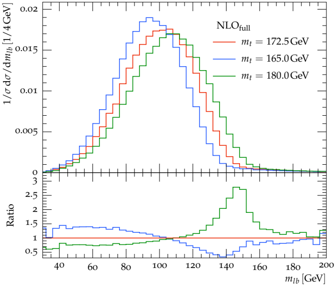
- 1. Choose distributions sensitive to the top-quark mass



Calibration of the template fit function

- 1. Choose distributions sensitive to the top-quark mass
- 2. Generate distributions for different input m_t^{in}:

$$m_t^{in} \in [165.0, 172.5, 180.0] \ \mathrm{GeV}$$



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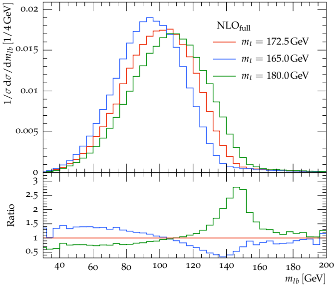

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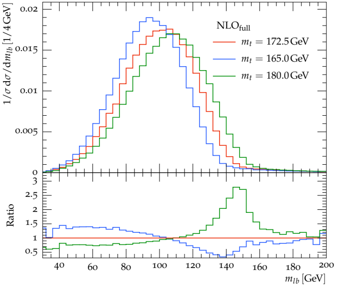

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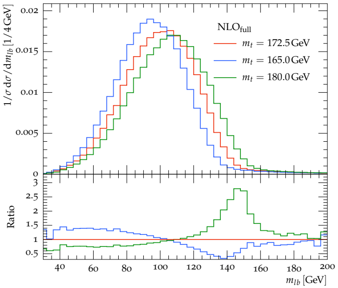

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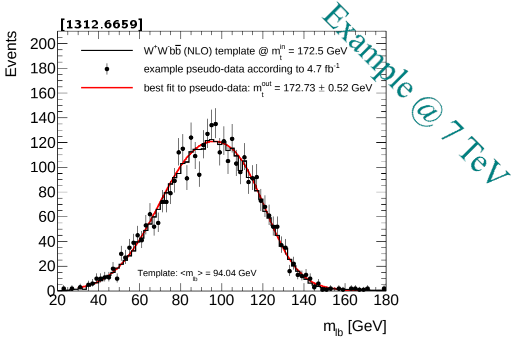
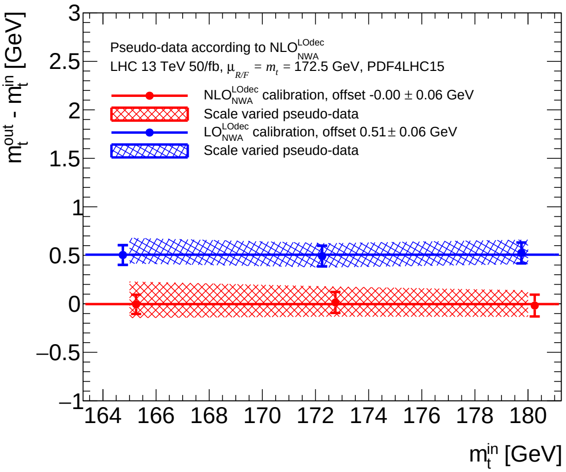


Fit results

NWA: NLO corrections



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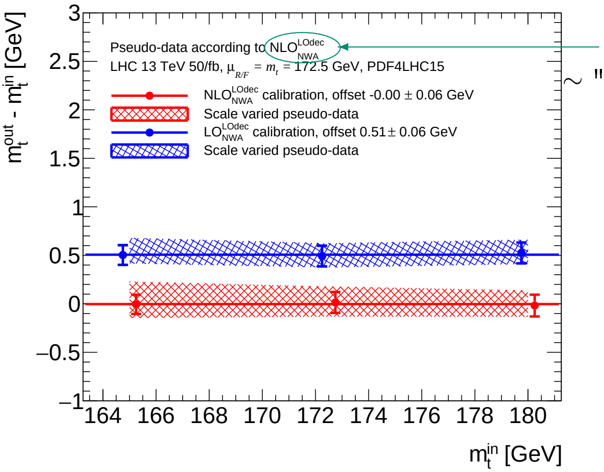
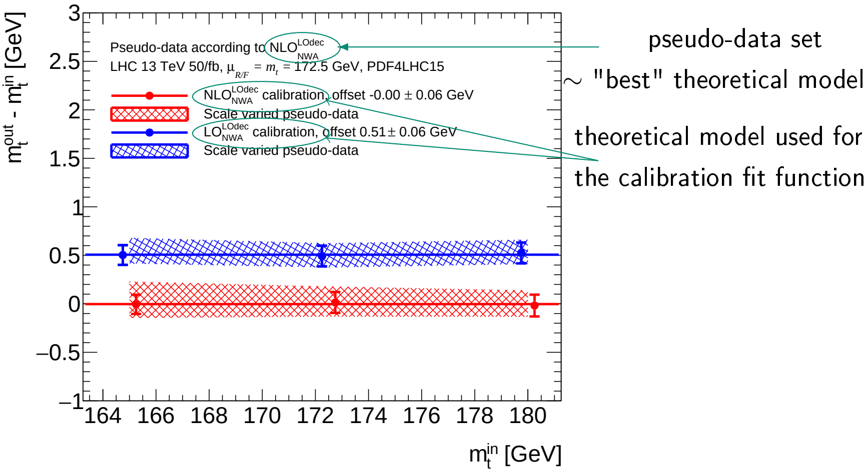


pseudo-data set

∼ "best" theoretical model

NWA: NLO corrections

Fit range: $40 \text{ GeV} \leq m_{lb} \leq 160 \text{ GeV}$



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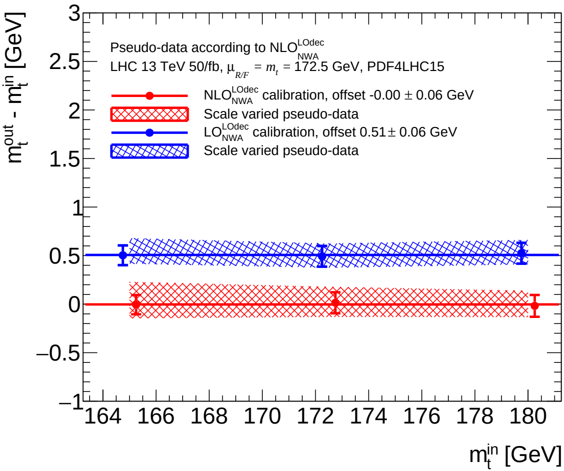

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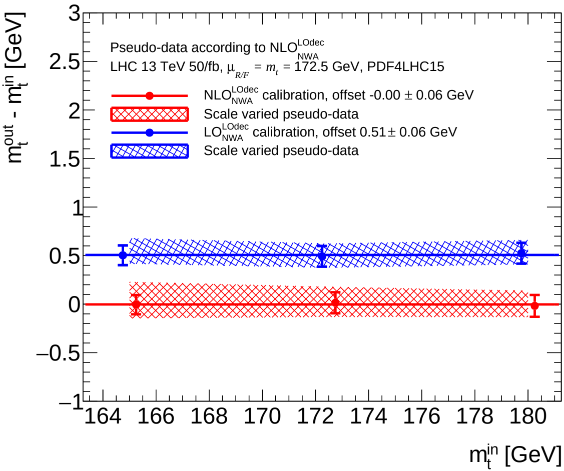

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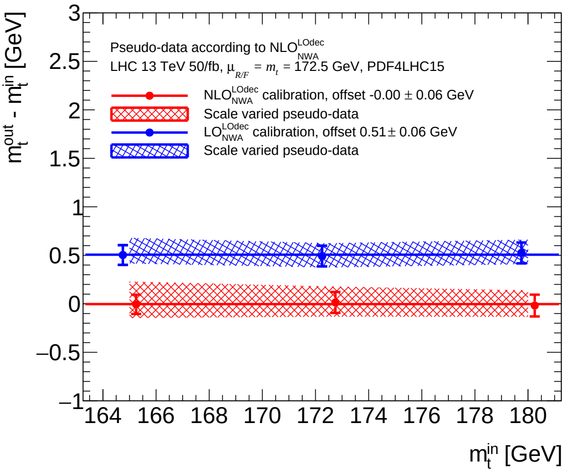

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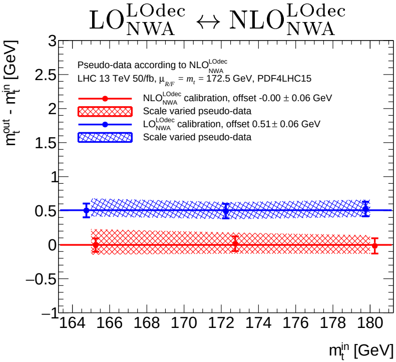
NWA: NLO corrections

NLO corrections in $t\bar{t}$ production and decay



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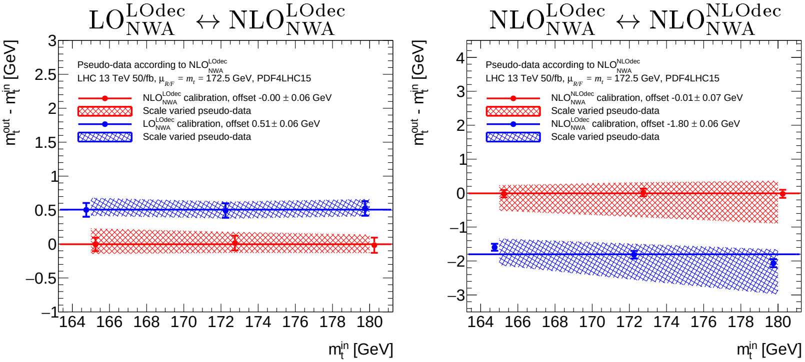

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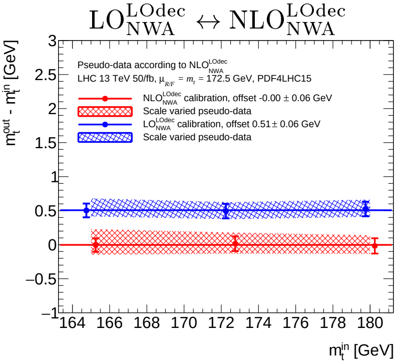
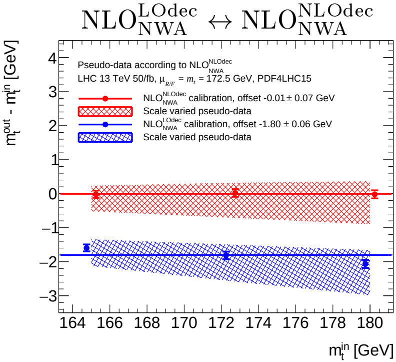
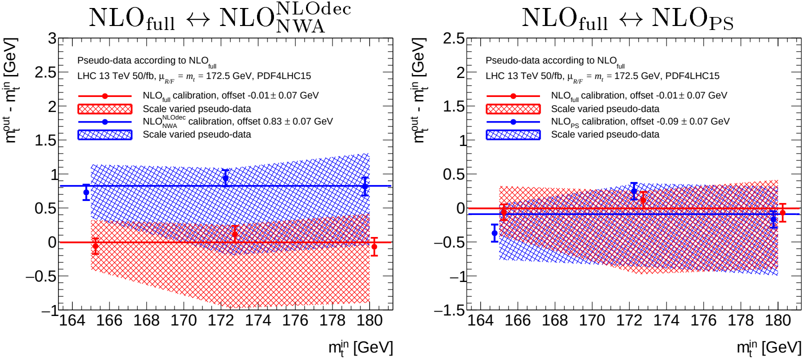




LO $\rightarrow$ NLO production offset:	0.51 ± 0.06 GeV
LO $\rightarrow$ NLO decay offset:	-1.80 ± 0.06 GeV

NWA: NLO top-quark decay ↔ PS decay



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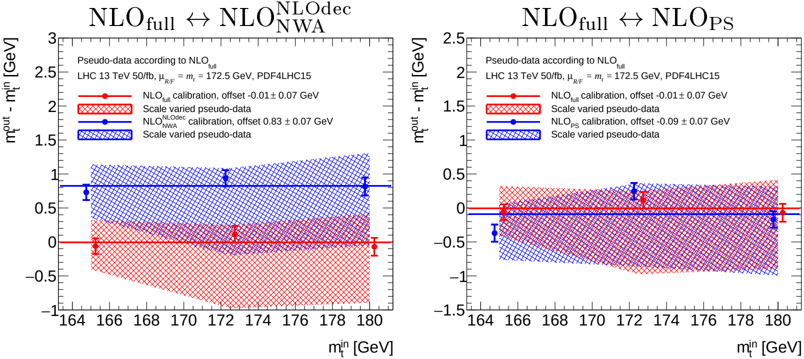

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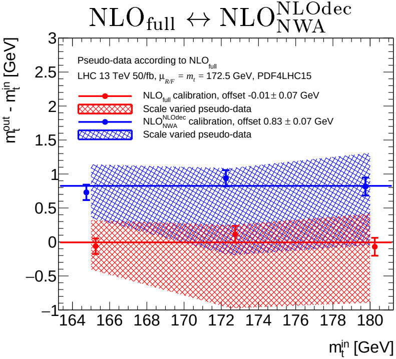

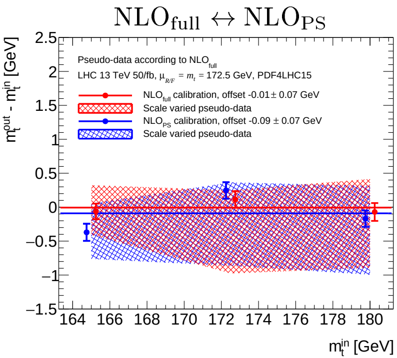

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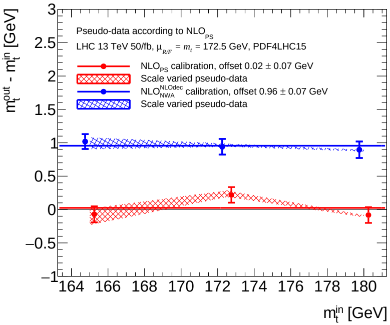
- $\rightsquigarrow$ scale uncertainty bands cover the observed offsets
- $\rightsquigarrow$ good agreement in the fit result between $\mathrm{NLO_{full}}$ and $\mathrm{NLO_{PS}}$

NWA: PS ↔ top-quark decay NLO corrections

- Origin of the offset between $\mathrm{NLO}_{\mathrm{PS}}$ and $\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$: NLO corrections to the top-quark decay, or resummation corrections?



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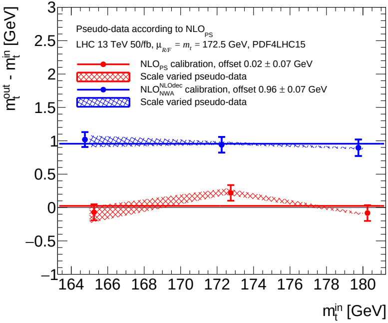

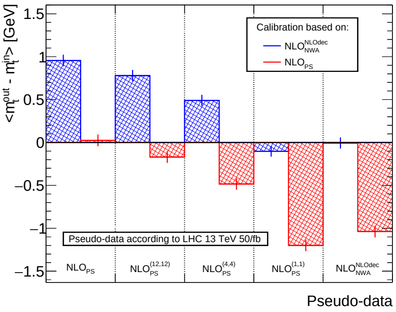

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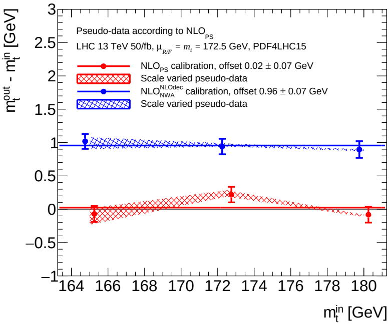

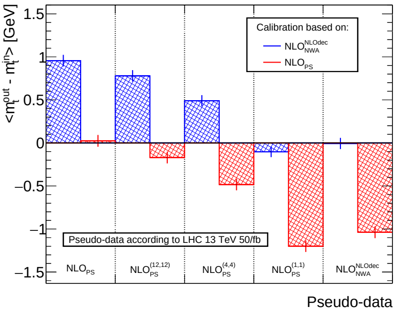

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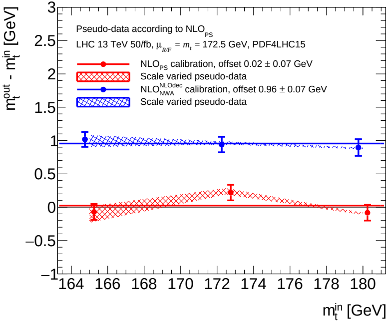

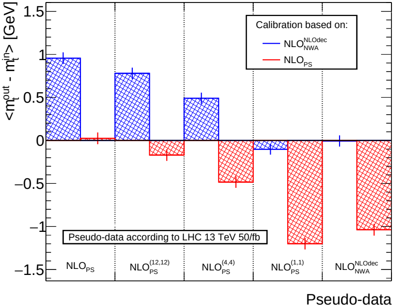

⇝ "emulation" of the NLO emission through the shower

$\mathrm{NLO_{PS}}^{(1,1)} \leftrightarrow \mathrm{NLO^{NLOdec}_{NWA}}$ offset: -0.12 ± 0.07 GeV

Conclusions

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- The numerical differences of various theory descriptions on the top-quark mass measurement have been quantified using a template method
  - 4 predictions: $\mathrm{NLO}_{\mathrm{full}}$, $\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$, $\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$, $\mathrm{NLO}_{\mathrm{PS}}$
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- Potential underestimation of theory uncertainties in the top-quark LO decay

Outlook

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- Compare the top-quark mass offset to the NNLO prediction in the NWA

Thank you!

Backup

Results summary

		Offset [GeV]		
Pseudo-data	Calibration	m_{lb}	m_{T2}	χ^2
$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$	$\mathrm{LO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$	$+0.51 \pm 0.06$	$+0.48 \pm 0.04$	0.17
$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$	$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$	-1.80 ± 0.06	-1.67 ± 0.04	3.25
$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$	$\mathrm{LO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$	-1.38 ± 0.07	-1.24 ± 0.05	2.65
$\mathrm{NLO}_{\mathrm{full}}$	$\mathrm{LO}_{\mathrm{full}}$	-1.52 ± 0.07	-1.62 ± 0.05	1.35
$\mathrm{NLO}_{\mathrm{full}}$	$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$	$+0.83 \pm 0.07$	$+0.60 \pm 0.06$	6.22
$\mathrm{NLO}_{\mathrm{full}}$	$\mathrm{NLO}_{\mathrm{PS}}$	-0.09 ± 0.07	-0.07 ± 0.06	0.05
$\mathrm{NLO}_{\mathrm{PS}}$	$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{LOdec}}$	-0.92 ± 0.07	-1.17 ± 0.05	8.45
$\mathrm{NLO}_{\mathrm{PS}}$	$\mathrm{NLO}_{\mathrm{NWA}}^{\mathrm{NLOdec}}$	$+0.96 \pm 0.07$	$+0.68 \pm 0.05$	10.59
$\mathrm{NLO}_{\mathrm{PS}}$	$\mathrm{NLO}_{\mathrm{PS}}$ $(\mu_{t\bar{t}})$	-0.03 ± 0.07	$+0.02 \pm 0.05$	0.34

Table: Summary of the offsets observed when analysing pseudo-data listed in the first column with template fit functions calibrated based on various theoretical predictions as given in the second column.

$\text{NLO}^{\text{NLOdec}}_{\text{NWA}}$ calculation

- Factorize production $\mathscr{P}_{ij\to t\bar{t}}$ and decay $\mathscr{D}_{t\to bl\nu}$ in the amplitude

$$\mathscr{M}^{\text{NWA}}_{ij\to t\bar{t}\to b\bar{b}2l2\nu} = \mathscr{P}_{ij\to t\bar{t}} \otimes \mathscr{D}_{t\to bl^+\nu} \otimes \mathscr{D}_{\bar{t}\to \bar{b}l^-\bar{\nu}}$$

- Expansion to NLO:

$$\begin{aligned}\mathscr{M}^{\text{NWA, NLO}}_{ij\to t\bar{t}\to b\bar{b}2l2\nu} = \; & \mathscr{P}^{\text{LO}}_{ij\to t\bar{t}} \otimes \mathscr{D}^{\text{LO}}_{t\to bl^+\nu} \otimes \mathscr{D}^{\text{LO}}_{\bar{t}\to \bar{b}l^-\bar{\nu}} + \mathscr{P}^{\delta\text{NLO}}_{ij\to t\bar{t}} \otimes \mathscr{D}^{\text{LO}}_{t\to bl^+\nu} \otimes \mathscr{D}^{\text{LO}}_{\bar{t}\to \bar{b}l^-\bar{\nu}} \\ + \; & \mathscr{P}^{\text{LO}}_{ij\to t\bar{t}} \otimes \left(\mathscr{D}^{\delta\text{NLO}}_{t\to bl^+\nu} \otimes \mathscr{D}^{\text{LO}}_{\bar{t}\to \bar{b}l^-\bar{\nu}} + \mathscr{D}^{\text{LO}}_{t\to bl^+\nu} \otimes \mathscr{D}^{\delta\text{NLO}}_{\bar{t}\to \bar{b}l^-\bar{\nu}} \right)\end{aligned}$$

where the NLO corrections to the decay are

$$\mathscr{D}^{\text{virt(real)}}_{t\to bl\nu} = \frac{\mathscr{M}^{\text{virt(real)}}_{t\to bW(+g)}}{\sqrt{2m_t\Gamma_t^{\text{NLO}}}} \otimes \frac{\mathscr{M}_{W\to l\nu}}{\sqrt{2M_W\Gamma_W^{\text{NLO}}}}$$

Scale choice: parton-shower NWA

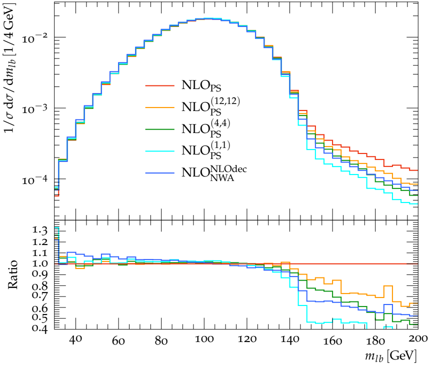
- Central scale: $\mu_R = \mu_F = \mu_{t\bar{t}}$

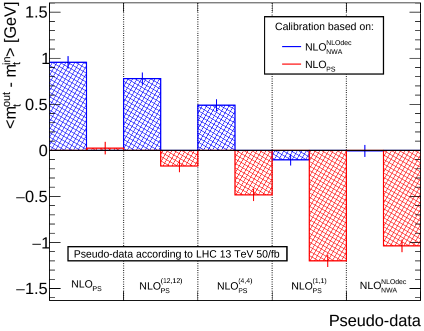
$$\mu^2_{t\bar{t}}(q\bar{q} \to t\bar{t}) \;=\; 2\,p_q p_t \;=\; m_t^2 - t\;,$$

$$\mu^2_{t\bar{t}}(\bar{q}q \to t\bar{t}) \;=\; 2\,p_q p_t \;=\; m_t^2 - u\;,$$

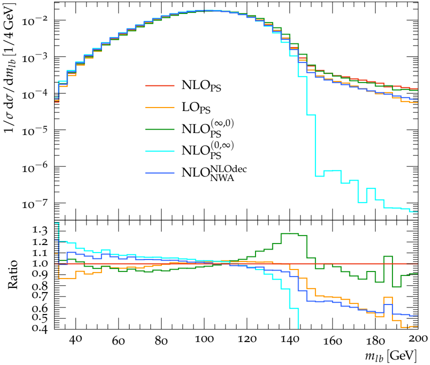
$$\mu^2_{t\bar{t}}(gg \to t\bar{t}) \;=\; \begin{cases} m_t^2 - t & \\ & \text{with weight} \\ m_t^2 - u & \end{cases} \qquad \begin{matrix} w_1 \propto \frac{u-m_t^2}{t-m_t^2} + \frac{m_t^2}{m_t^2-t}\left\{\frac{4\,t}{t-m_t^2} + \frac{m_t^2}{s}\right\} \\ \\ w_2 \propto \frac{t-m_t^2}{u-m_t^2} + \frac{m_t^2}{m_t^2-u}\left\{\frac{4\,u}{u-m_t^2} + \frac{m_t^2}{s}\right\} \end{matrix}$$

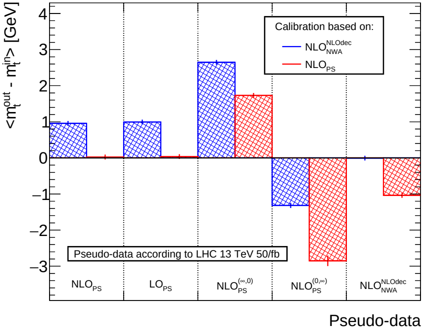
Restricted shower





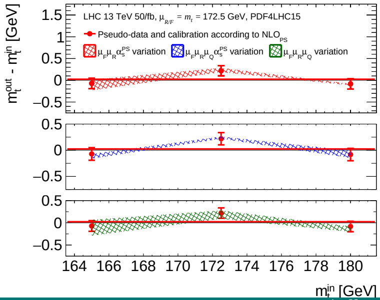
Production/decay showering

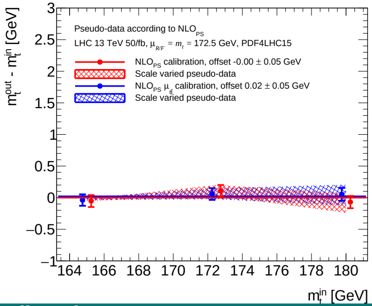




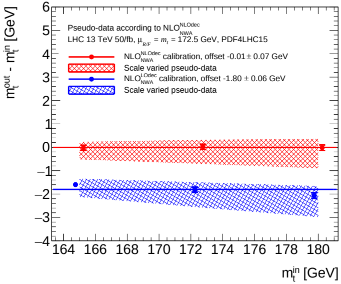
Scale uncertainties

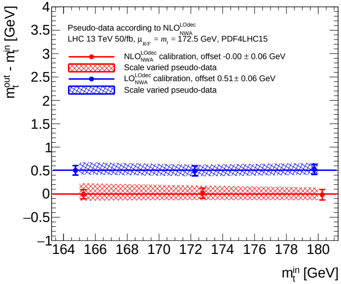
Scheme	Central scale μ_i	Variations $\xi_i\ \mu_i$
$\mu_F \mu_R \alpha_s \mathrm{PS}$	$\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = m_t,\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$ $\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = \mu_{t\bar{t}},\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$	$\xi_R = \xi_F = \xi_R^{\mathrm{PS}} = \{0.5, 1.0, 2.0\}$
$\mu_F \mu_R \mu_Q$	$\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = m_t,\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$	$\xi_R = \xi_F = \{0.5, 1.0, 2.0\}$ and $\xi_Q = \{\sqrt{2}, 1.0, 1/\sqrt{2}\}$
$\mu_F \mu_R \mu_Q \alpha_s \mathrm{PS}$	$\mu_F = \mu_R = \mu_Q^{\mathrm{prod}} = m_t,\ \mu_R^{\mathrm{PS}} = p_T^{\mathrm{emit}}$	$\xi_R = \xi_F = \xi_R^{\mathrm{PS}} = \{0.5, 1.0, 2.0\}$ and $\xi_Q = \{\sqrt{2}, 1.0, 1/\sqrt{2}\}$

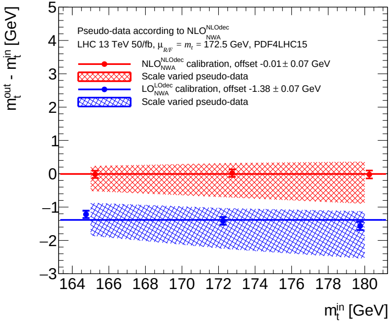




Factorized computation: offsets

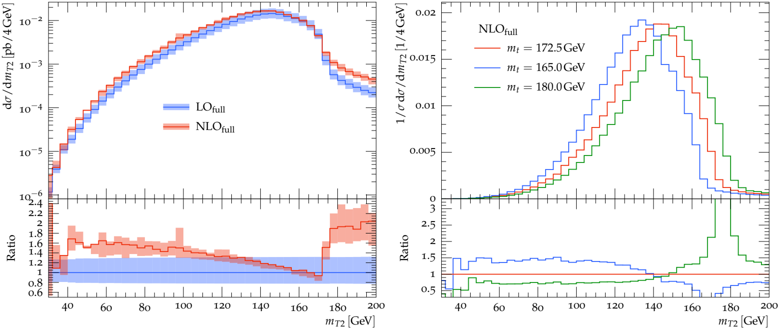






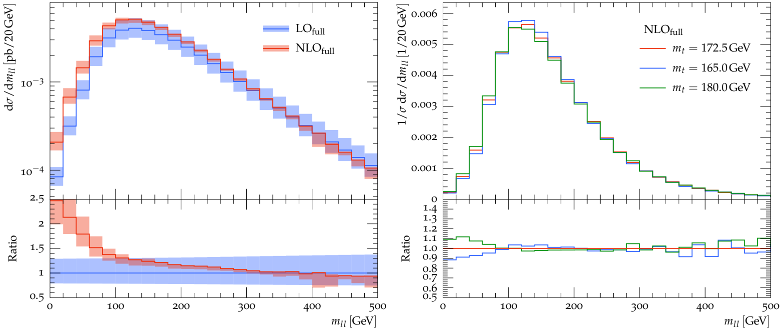
m_{T2} observable

$$m_{T2}^2 = \min_{\mathbf{p}_T^{\nu_1} + \mathbf{p}_T^{\nu_2} = \mathbf{p}_T^{miss}} \left[\max \left\{ m_T^2 \left(\mathbf{p}_T^{(\ell b)_1}, \mathbf{p}_T^{\nu_1} \right), m_T^2 \left(\mathbf{p}_T^{(\ell b)_2}, \mathbf{p}_T^{\nu_2} \right) \right\} \right]$$



m_{ll} observable

$$m_{\ell\ell}^2 = (p_{\ell_1} + p_{\ell_2})^2$$



$E_T^{\Delta R}$ observable

$$E_T^{\Delta R} = \frac{1}{2}\left(E_T^{\ell_1}\Delta R(\ell_1, b_1) + E_T^{\ell_2}\Delta R(\ell_2, b_2)\right)$$