Associated production of a top quark pair with a W or Z boson at the LHC at NNLL+NLO

Daniel Schwartländer

Institut für Theoretische Physik, WWU Münster

in collaboration with
Anna Kulesza, Leszek Motyka, Tomasz Stebel, Vincent Theeuwes

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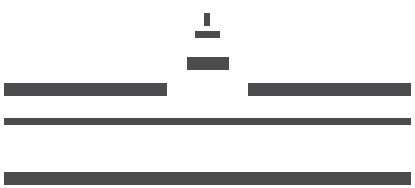

Westfälische Wilhelms-Universität Münster

DFG Deutsche Forschungsgemeinschaft

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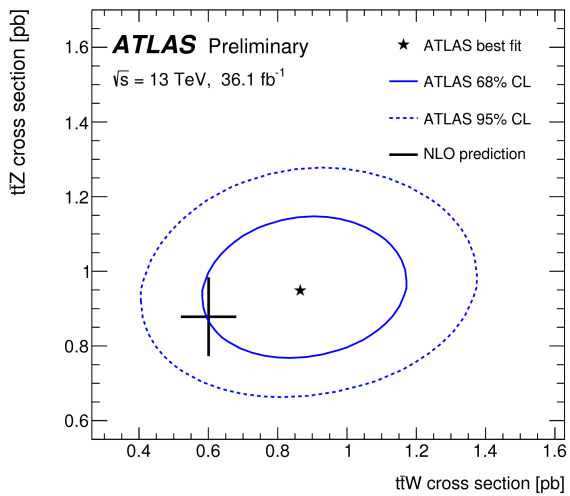

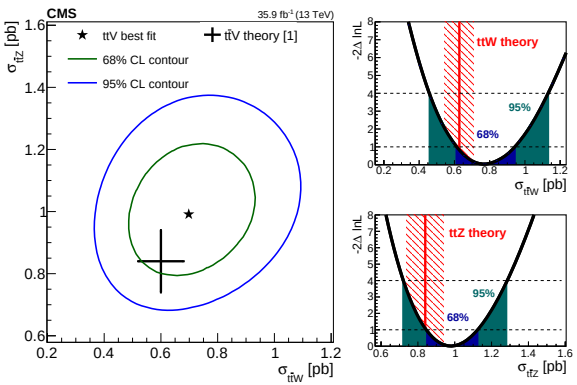

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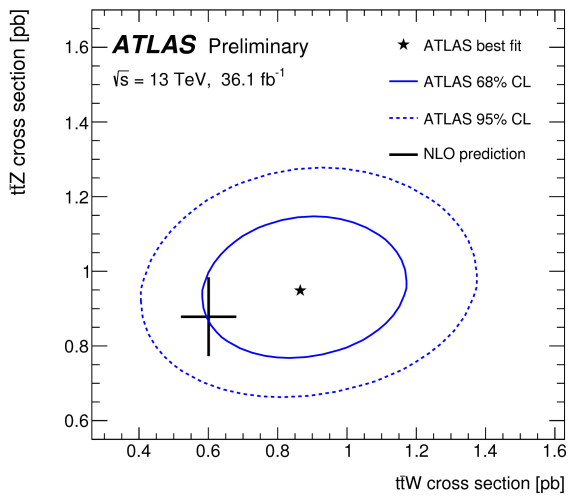

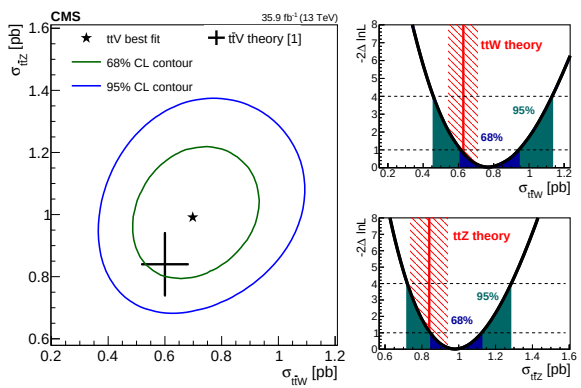

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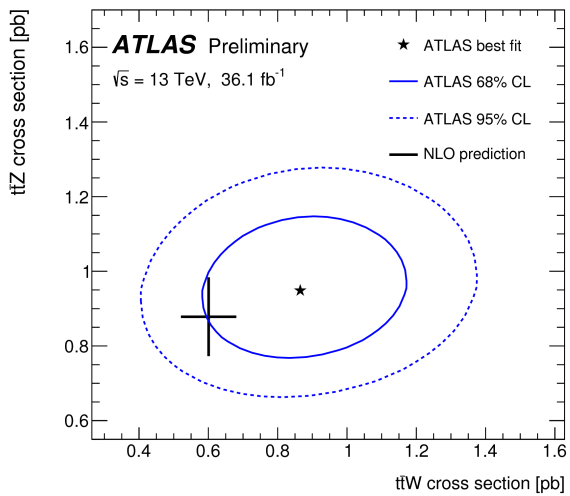
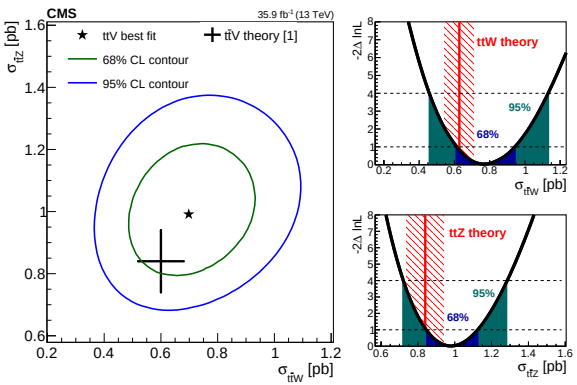
- Resummation: class of corrections beyond NLO





Status of $t\bar{t}V$

$t\bar{t}W/t\bar{t}Z$:

- NLO QCD

  [Lazopoulos, Melnikov, Petriello, '08] [Lazopoulos, McElmurry, Melnikov, Petriello, '08] [Kardos, Trocsanyi, Papadopoulos '12] [Campbell, Ellis, '12]

- NLO QCD matched to PS

  [Garzelli, Kardos, Papadopoulos, Trocsanyi, '12] [Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro '14] [Maltoni, Mangano, Tsinikos, Zaro, '14]

- EW and QCD NLO corrections

  [Frixione, Hirschi, Pagani, Shao, Zaro, '15] [Frederix, Pagani, Zaro, '18] [Frederix, Frixione, Hirschi, Pagani, Shao, Zaro, '18]

Status of $t\bar{t}V$

Resummation:

- $t\bar{t}H$:
  - Direct QCD approach (Mellin space approach) [Kulesza, Motyka, Stebel, Theeuwes, '15 '16 '17]
  - SCET-based methods [Broggio, Ferroglia, Pecjak, Signer, Yang, '16] [Broggio, Ferroglia, Pecjak, Yang, '17]
- $t\bar{t}W/t\bar{t}Z$:
  - SCET-based methods [H. T. Li, C. S. Li, S. A. Li, '14] [Broggio, Ferroglia, Ossola, Pecjak, '16] [Broggio, Ferroglia, Ossola, Pecjak, Sameshima '17]

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- Resummed logarithms

$$\alpha_S^m \left(\frac{\log^n (1 - \hat{\tau})}{1 - \hat{\tau}} \right)_+ \qquad m \leq 2n - 1$$

$$\int_0^1 \mathrm{d}x (f(x))_+ = \int_0^1 \mathrm{d}x (f(x) - f(x_0))$$

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Resummed cross section in Mellin space:

$$\frac{\mathrm{d}\tilde{\sigma}^{res}_{ij\to t\bar{t}V}}{\mathrm{d}Q^2} = \mathrm{Tr}[\mathbf{H}_{ij\to t\bar{t}V}\mathbf{S}_{ij\to t\bar{t}V}]\Delta_i\Delta_j$$

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Colour matrices $\mathbf{H}_{ij\to t\bar{t}V}$, $\mathbf{S}_{ij\to t\bar{t}V}$

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- Universal function, depends only on emitting parton (quark or gluon)
- Here needed at NLL/NNLL, known [Catani, Mangano, Nason, Trentadue '96], [Bonciani, Catani, Mangano, Nason '98]/[Catani, de Florian, Grazzini, Nason '03]

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$$\mathbf{H}_{ij\to t\bar{t}V} = \mathbf{H}^{(0)}_{ij\to t\bar{t}V} + \frac{\alpha_S}{\pi}\mathbf{H}^{(1)}_{ij\to t\bar{t}V} + \ldots : \text{ hard contributions}$$

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- $\mathbf{H}^{(1)}_{ij\to t\bar{t}V}$ includes virtual loop corrections, numerically extracted from PowHel [Garzelli, Kardos, Papadopoulos, Trocsanyi '11][Garzelli, Kardos, Papadopoulos, Trócsányi '12]

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$$\Gamma^{(i)}_R = \mathbf{R}^{-1}\Gamma^{(i)}_{ij\to t\bar{t}V}\mathbf{R}$$
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- At NLL:

$$\mathbf{S}_{R,IL} = \bar{\mathbf{U}}_{R,IJ}\tilde{\mathbf{S}}_{R,JK}\mathbf{U}_{R,KL} = \tilde{\mathbf{S}}_{R,IL}\exp\left[\frac{\log(1-2\lambda)}{2\pi b_0}\left(\left(\lambda^{(1)}_I\right)^* + \lambda^{(1)}_L\right)\right]$$

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$$\mathbf{U}_R = \left(\mathbf{1} + \frac{\alpha_s(\mu_R^2)}{\pi(1-2\lambda)}\mathbf{K}\right)\left[e^{g_s(N)\vec{\lambda}^{(1)}}\right]_D\left(\mathbf{1} - \frac{\alpha_s(\mu_R^2)}{\pi}\mathbf{K}\right)$$

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$$K_{IJ} = \delta_{IJ}\lambda_I^{(1)}\frac{b_1}{2b_0^2} - \frac{\left(\Gamma_R^{(2)}\right)_{IJ}}{2\pi b_0 + \lambda_I^{(1)} - \lambda_J^{(1)}}$$

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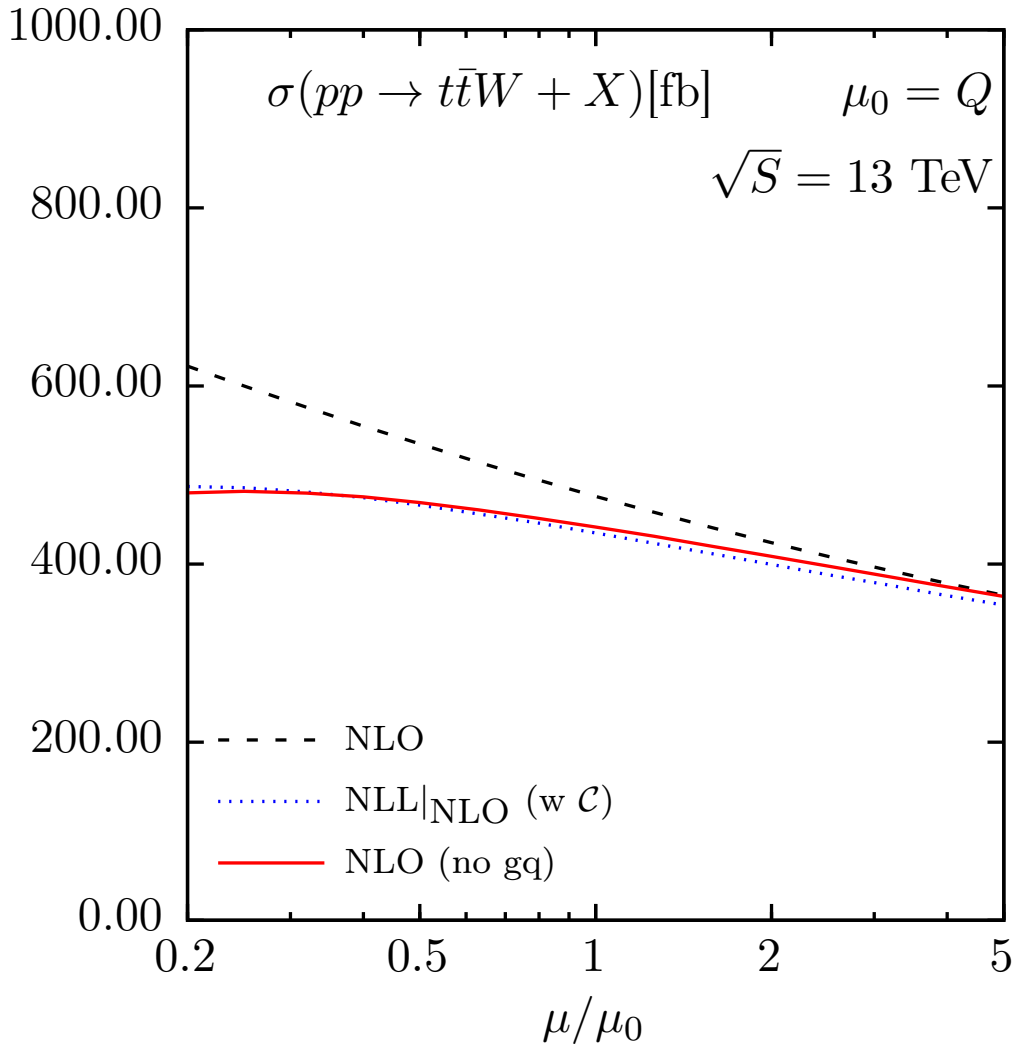
- scale choices: $\mu = Q$, $\mu = \frac{2m_t+m_V}{2} = \frac{M}{2}$ and $\mu = \frac{Q}{2}$

Comparison NLO and expanded $t\bar{t}W$



Preliminary

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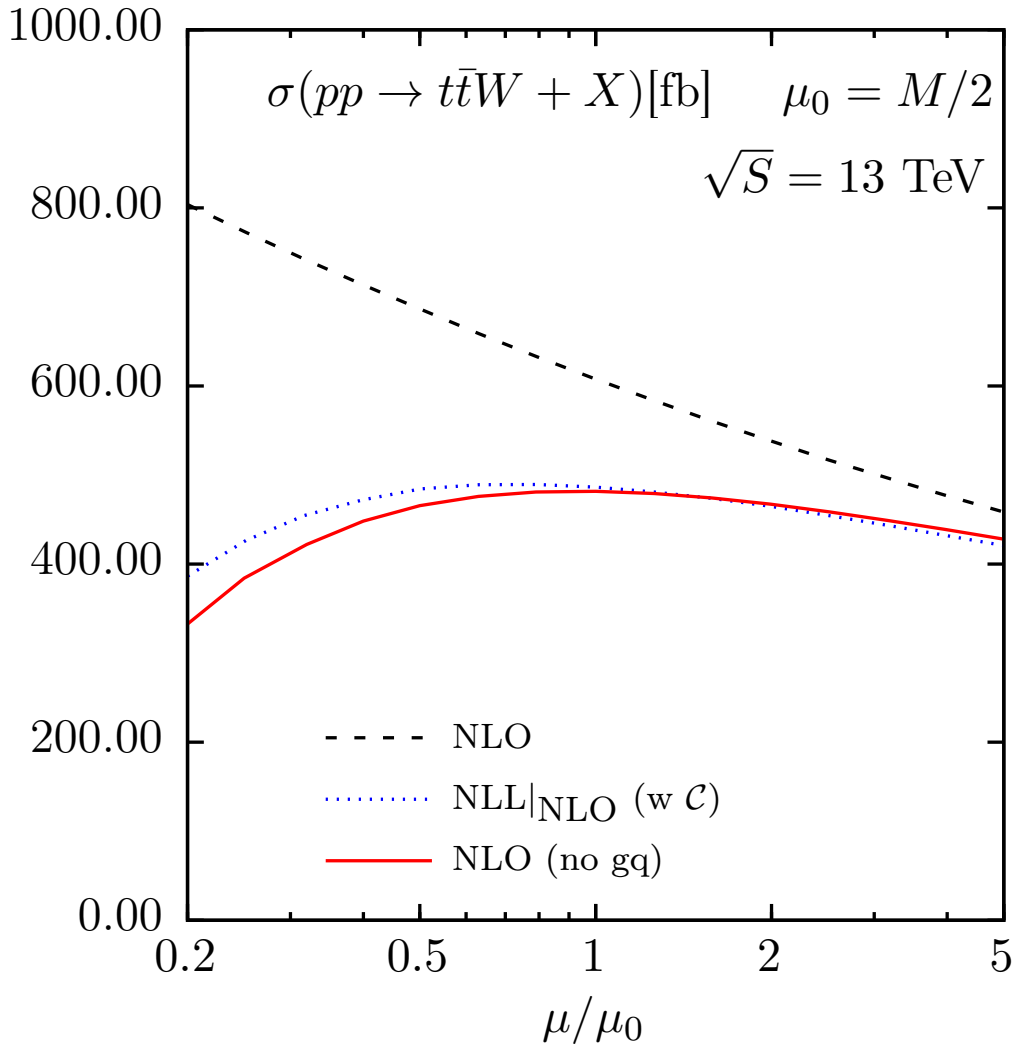
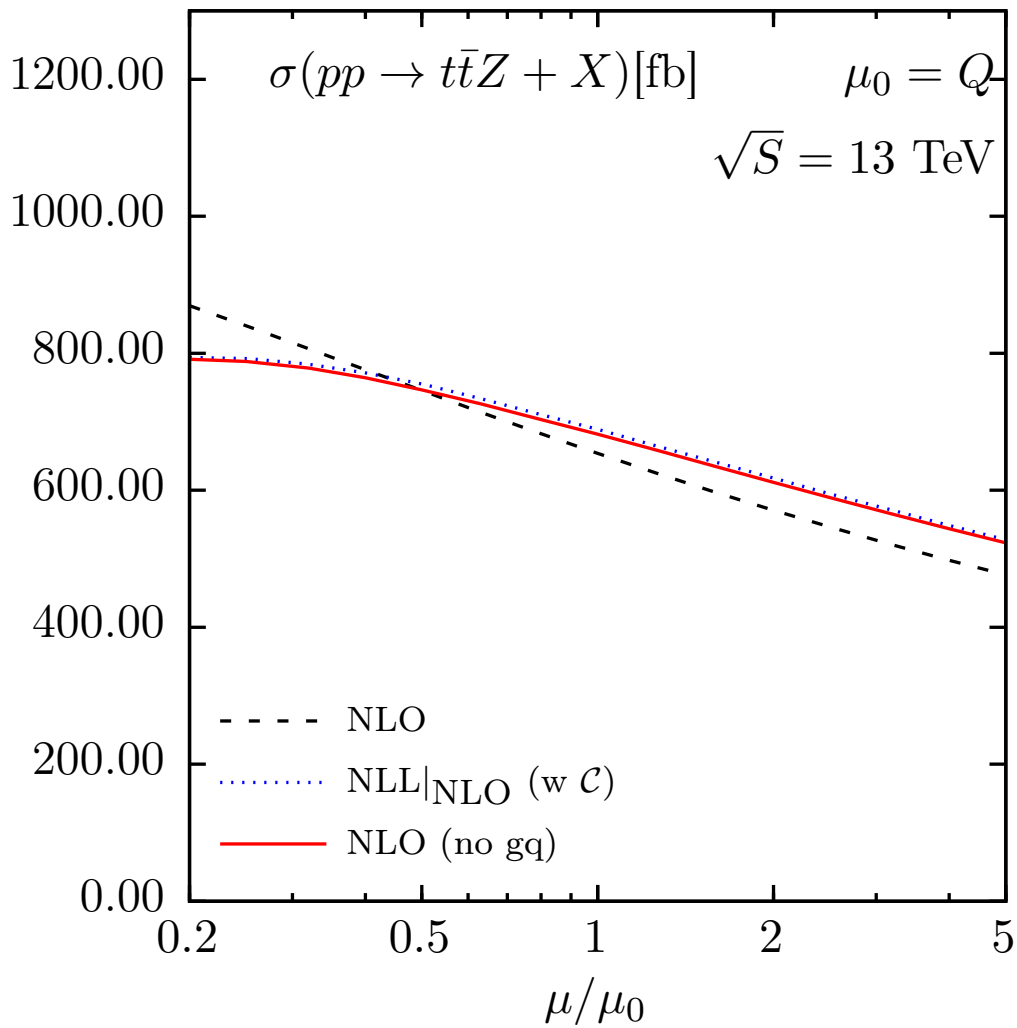


Preliminary

Comparison $t\bar{t}Z$ NLO vs expanded



Preliminary

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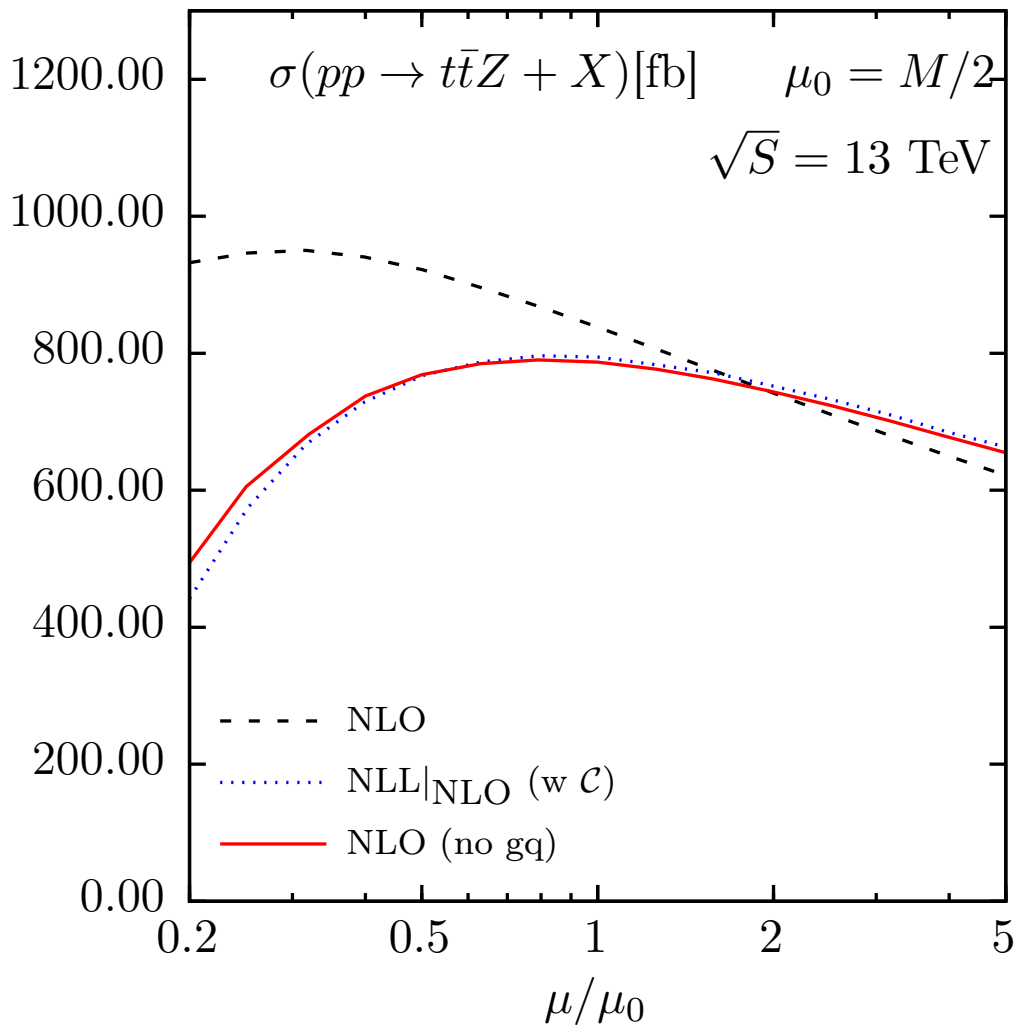

Preliminary

Cross sections for $t\bar{t}W/Z$

Total inclusive cross sections, $\mu_F = \mu_R = Q$:

- $\sigma_{t\bar{t}W^+} = 320^{+12.2\%}_{-10.9\%}\,\text{fb}$
- $\sigma_{t\bar{t}W^-} = 162^{+12.4\%}_{-11.0\%}\,\text{fb}$
- $\sigma_{t\bar{t}Z} = 652^{+14.1\%}_{-12.7\%}\,\text{fb}$

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NNLL matched to NLO:

- $\sigma_{t\bar{t}W^+} = 339^{+8.9\%}_{-8.6\%}\,\text{fb}$ $\quad K_{\text{NNLL}} = 1.06$
- $\sigma_{t\bar{t}W^-} = 174^{+8.8\%}_{-8.6\%}\,\text{fb}$ $\quad K_{\text{NNLL}} = 1.08$ $\quad$ Preliminary
- $\sigma_{t\bar{t}Z} = 841^{+8.2\%}_{-8.4\%}\,\text{fb}$ $\quad K_{\text{NNLL}} = 1.29$

Cross sections for $t\bar{t}W/Z$

Total inclusive cross sections, $\mu_R = \mu_F = \frac{M}{2}$
NLO:

- $\sigma_{t\bar{t}W^+} = 409^{+12.7\%}_{-11.4\%}$ fb
- $\sigma_{t\bar{t}W^-} = 206^{+13.3\%}_{-11.6\%}$ fb
- $\sigma_{t\bar{t}Z} = 834^{+9.6\%}_{-11.3\%}$ fb

Cross sections for $t\bar{t}W/Z$

Total inclusive cross sections, $\mu_R = \mu_F = \frac{M}{2}$

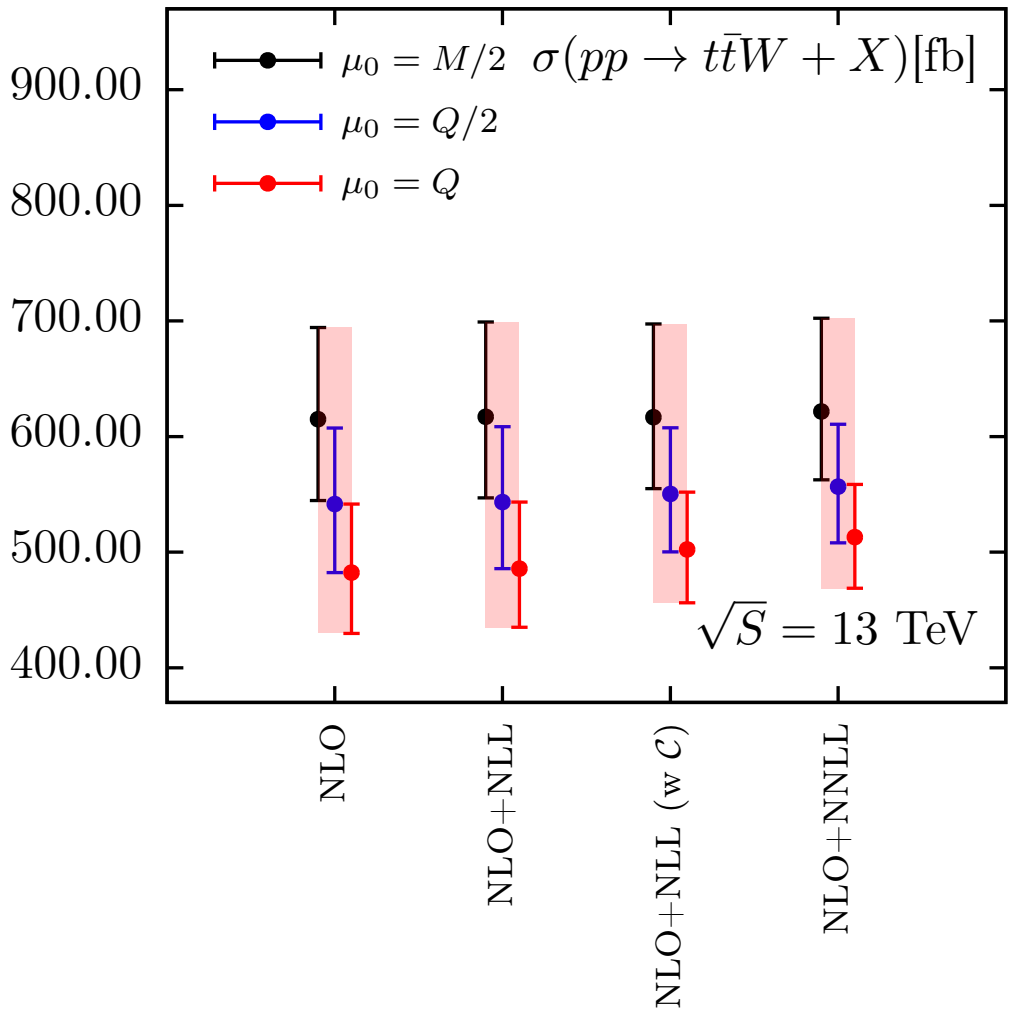
NLO:

- $\sigma_{t\bar{t}W^+} = 409^{+12.7\%}_{-11.4\%}$ fb
- $\sigma_{t\bar{t}W^-} = 206^{+13.3\%}_{-11.6\%}$ fb
- $\sigma_{t\bar{t}Z} = 834^{+9.6\%}_{-11.3\%}$ fb

NNLL matched to NLO:

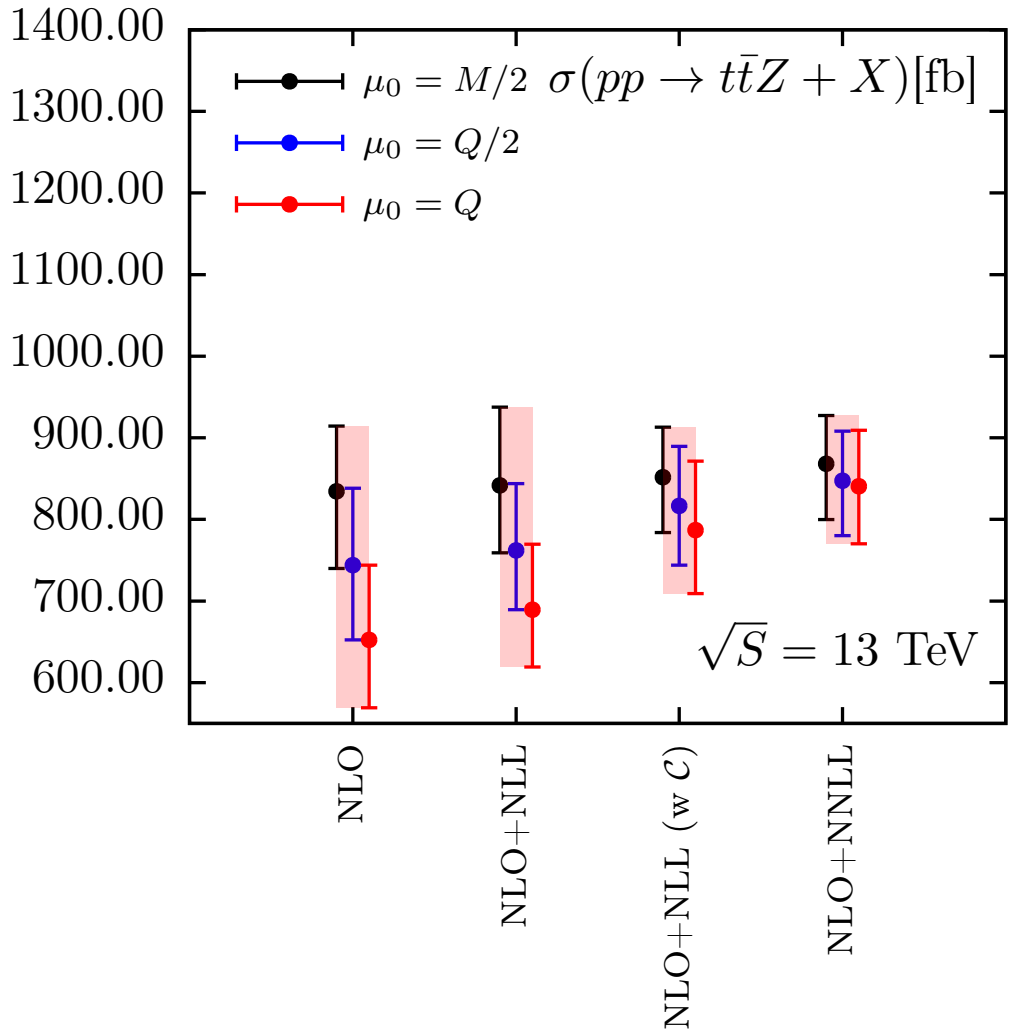
- $\sigma_{t\bar{t}W^+} = 412^{+12.9\%}_{-9.6\%}$ fb $\quad K_{\text{NNLL}} = 1.01$
- $\sigma_{t\bar{t}W^-} = 210^{+13.1\%}_{-9.5\%}$ fb $\quad K_{\text{NNLL}} = 1.02$ $\quad$ Preliminary
- $\sigma_{t\bar{t}Z} = 868^{+6.8\%}_{-7.9\%}$ fb $\quad K_{\text{NNLL}} = 1.04$

Results for $t\bar{t}W$



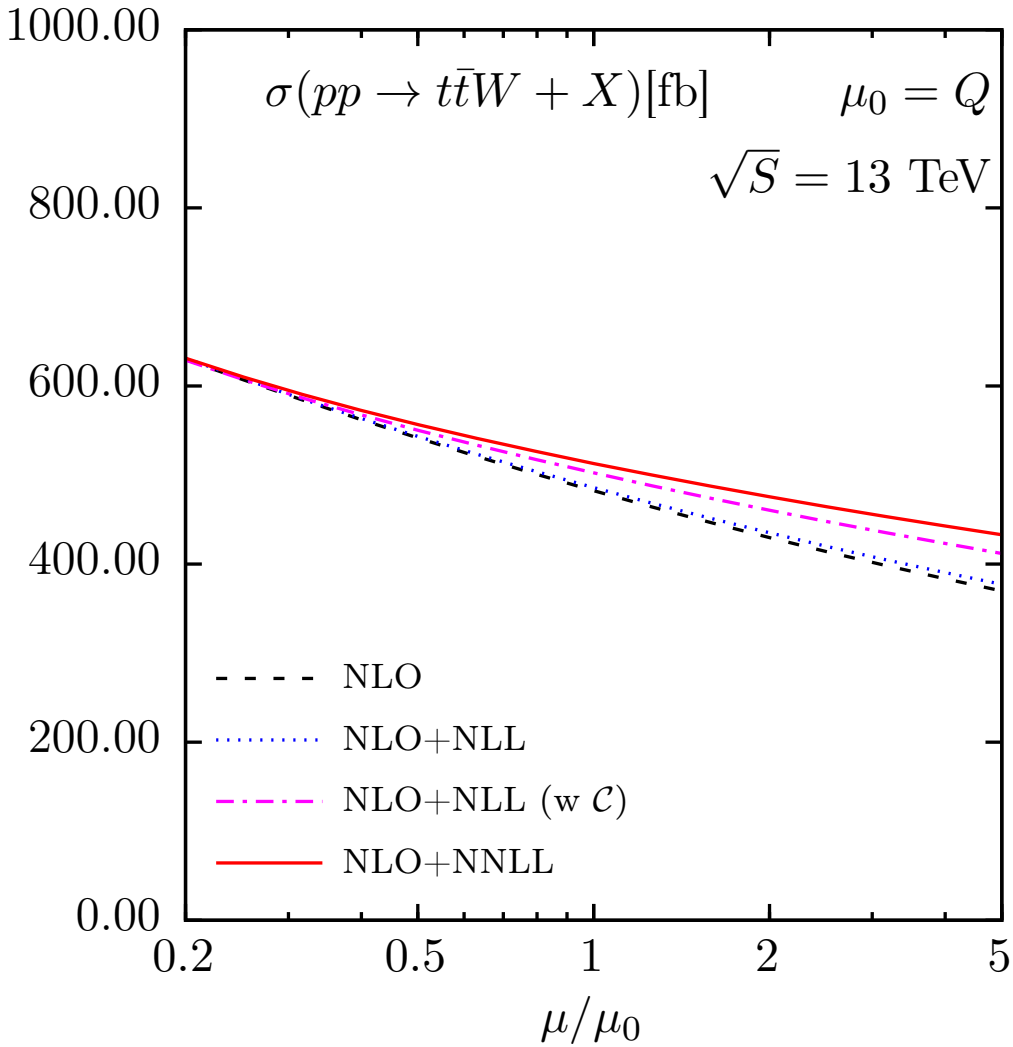
Preliminary

Results for $t\bar{t}Z$



Preliminary

Scale dependence $t\bar{t}W$ $\mu_F = \mu_R$



Preliminary

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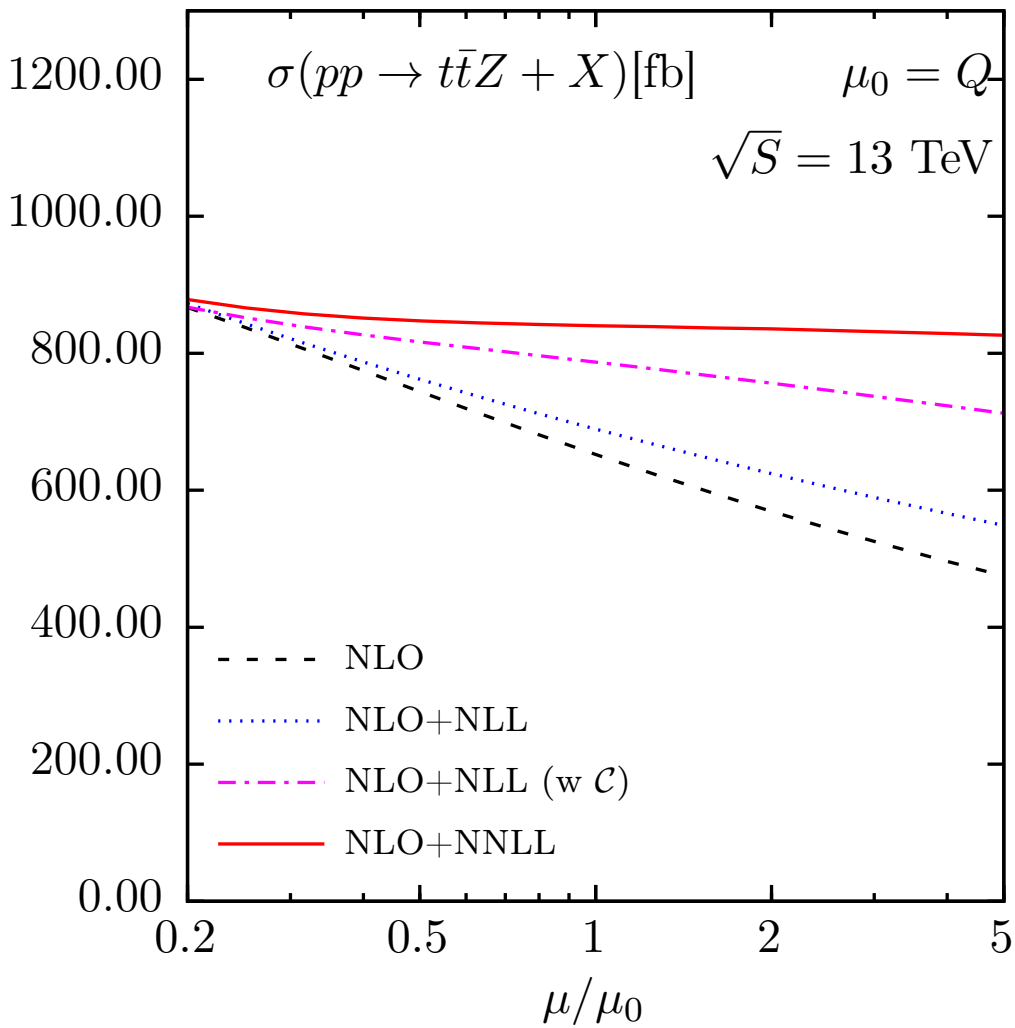
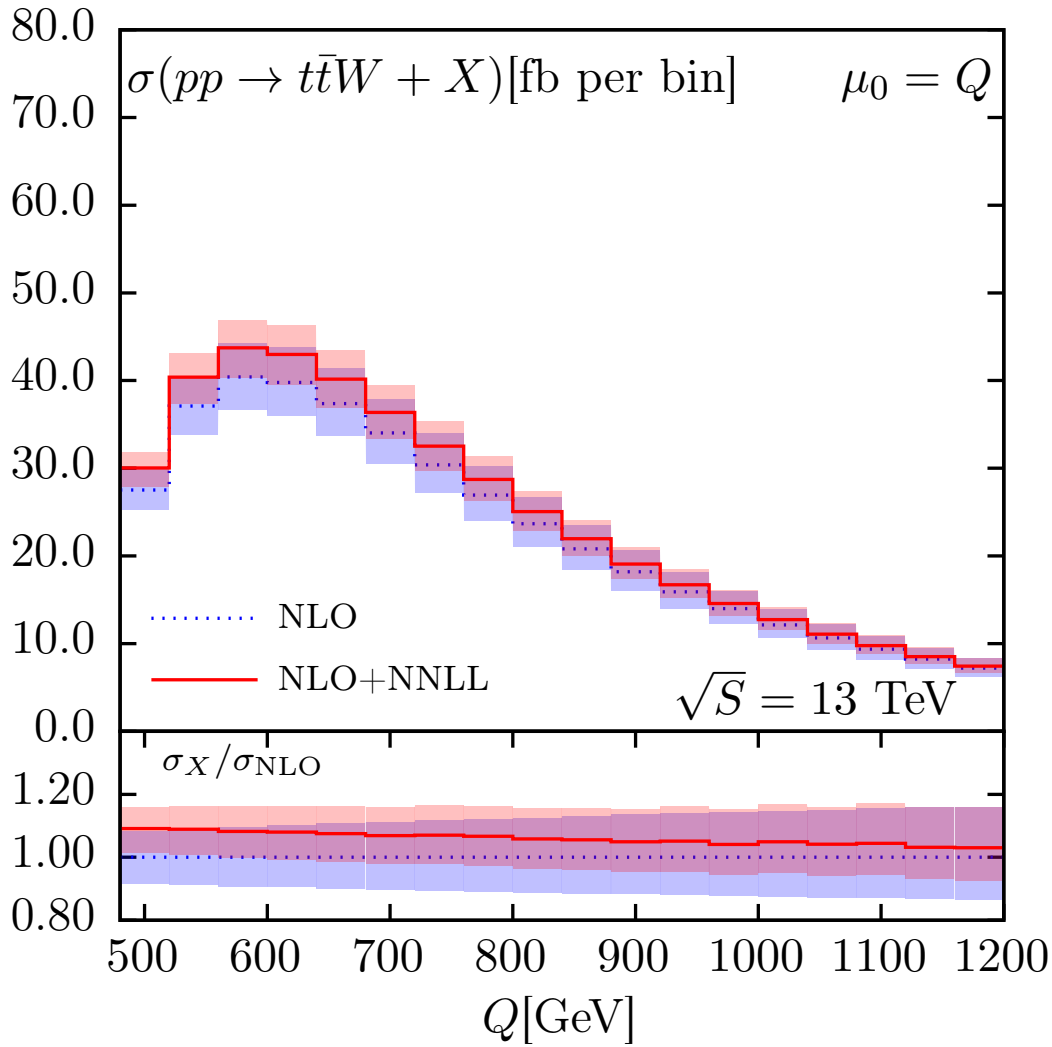


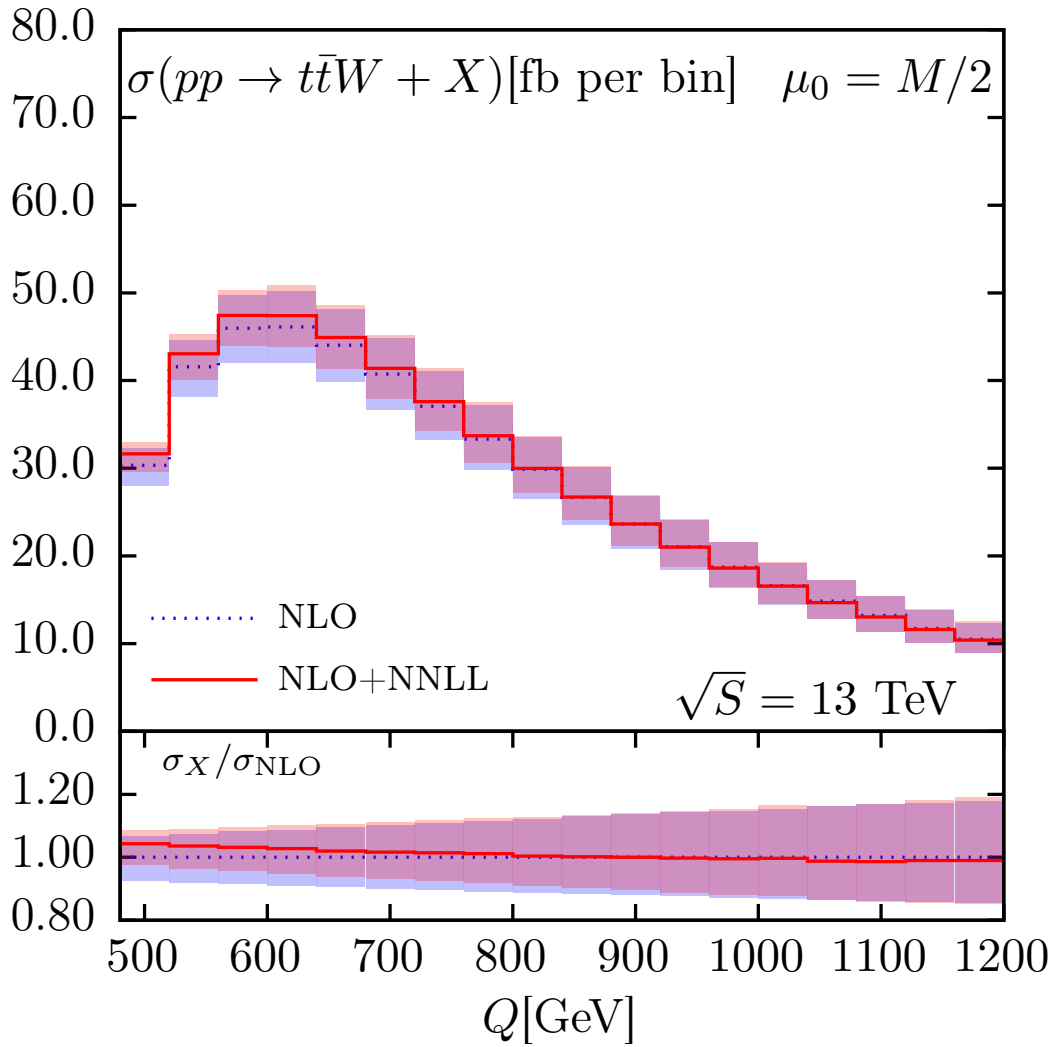
Preliminary

Differential in Q $t\bar{t}W$ $\mu_F = \mu_R = Q$



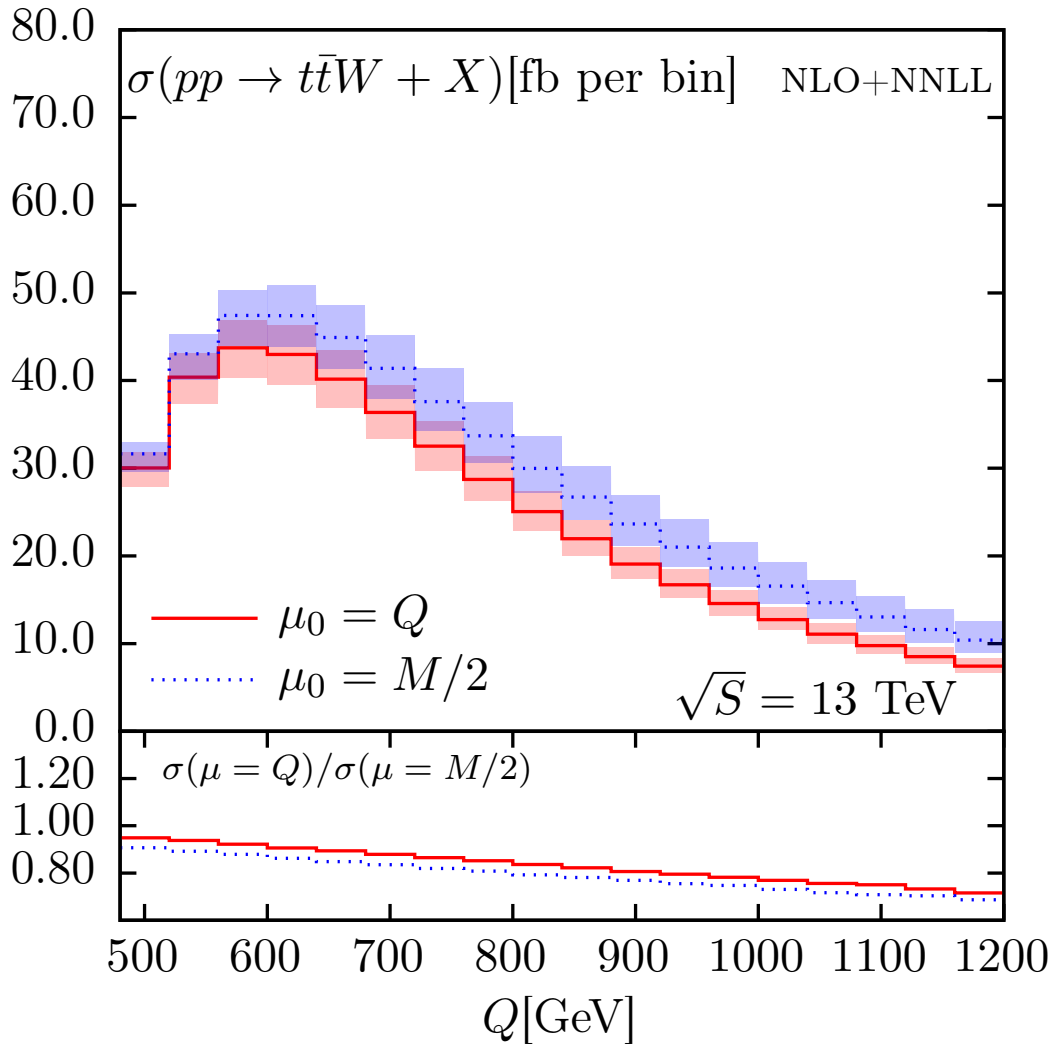
Preliminary

Differential in Q $t\bar{t}W$ $\mu_F = \mu_R = \frac{M}{2}$



Preliminary

Differential in Q $t\bar{t}W$



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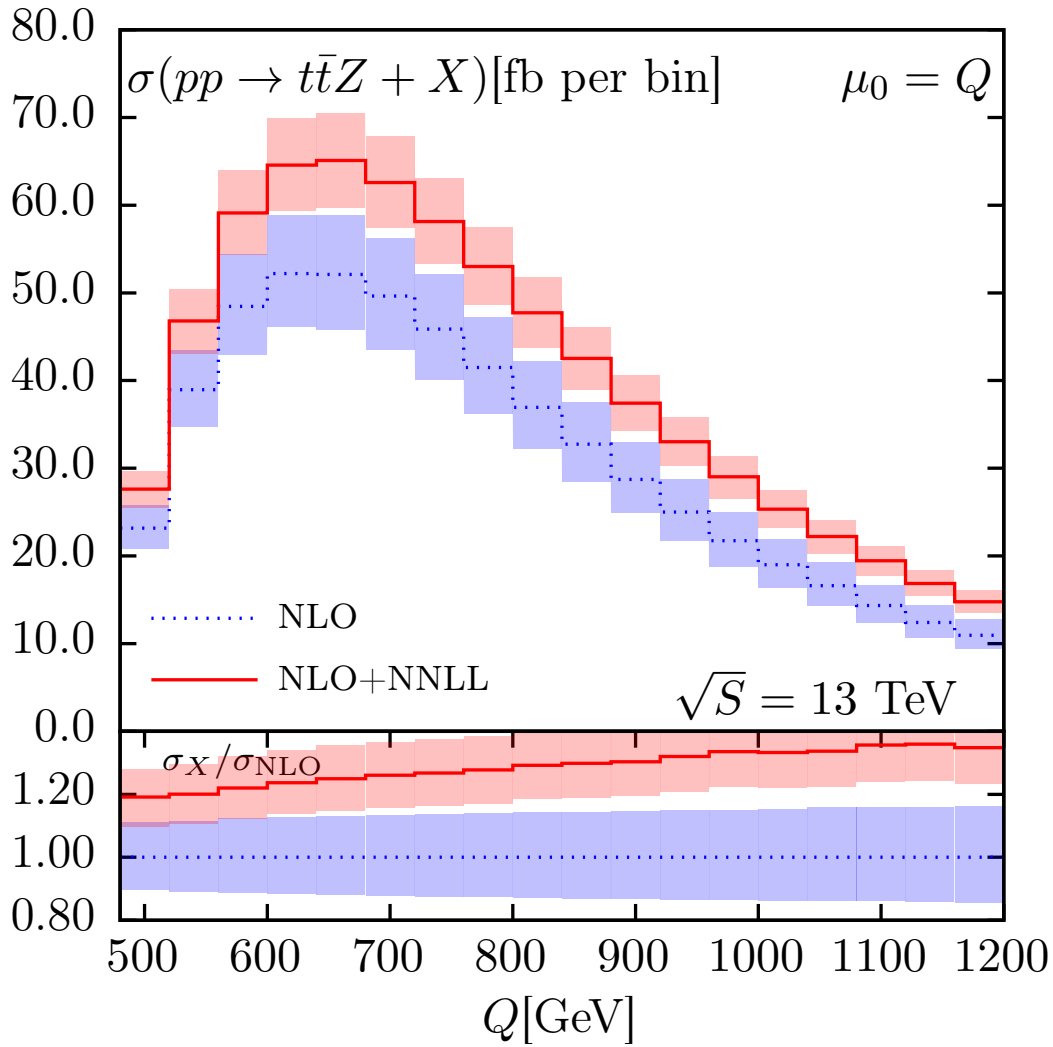

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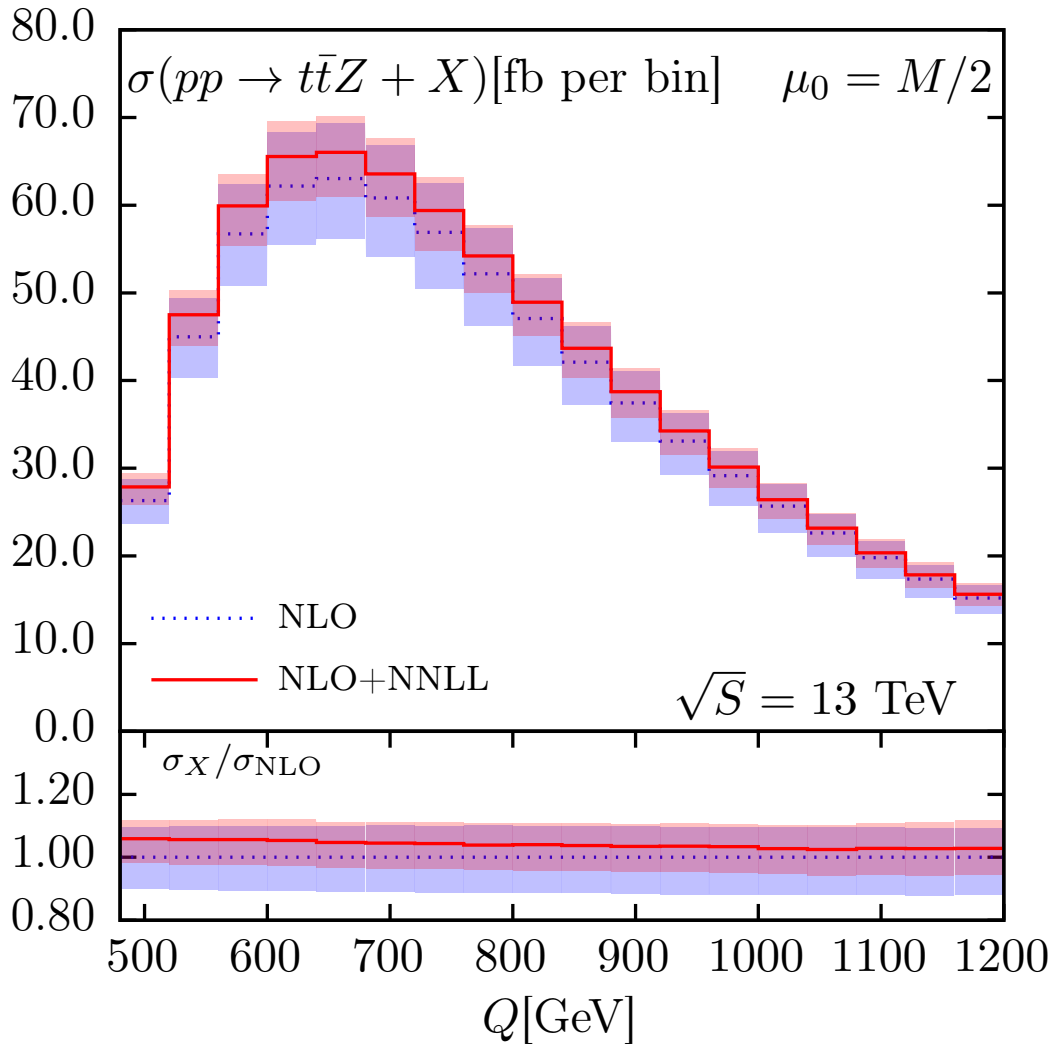

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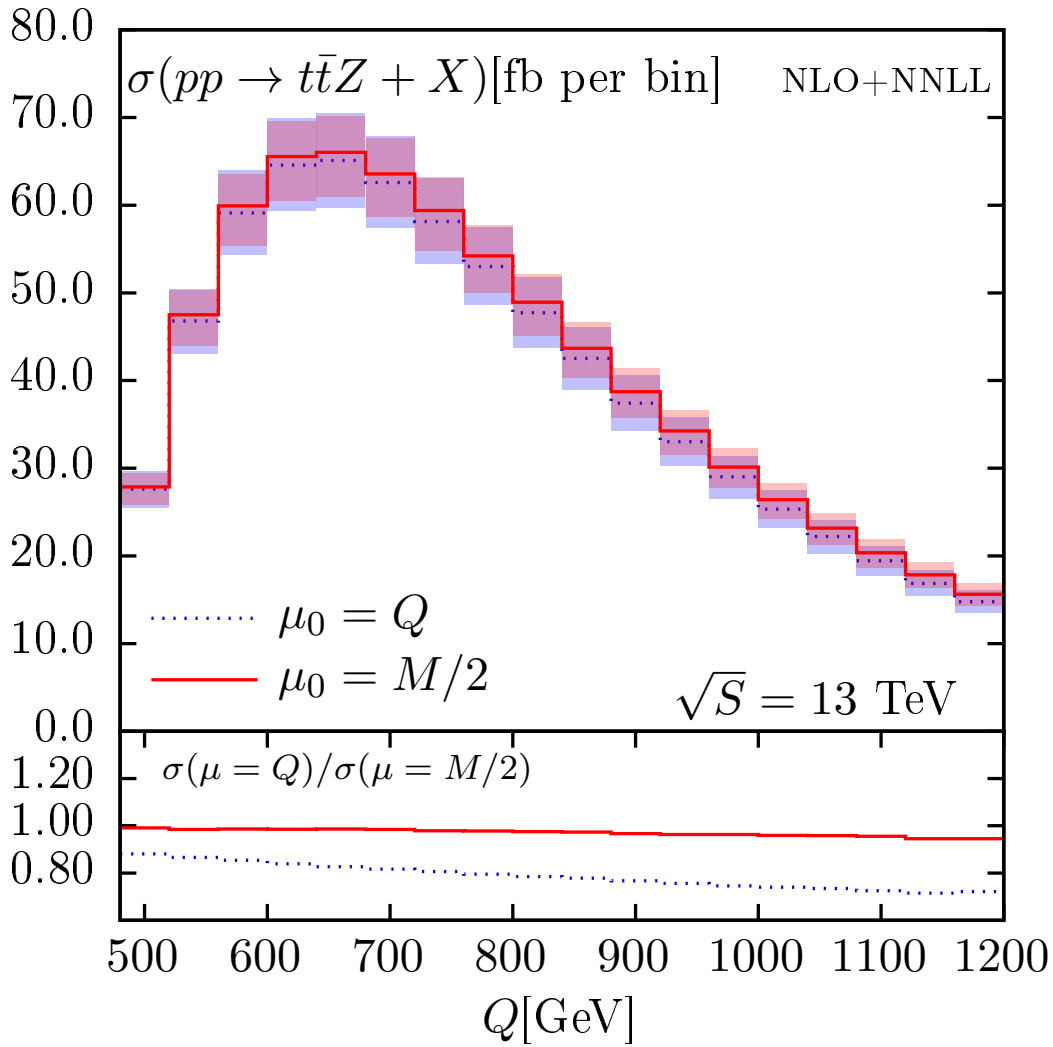
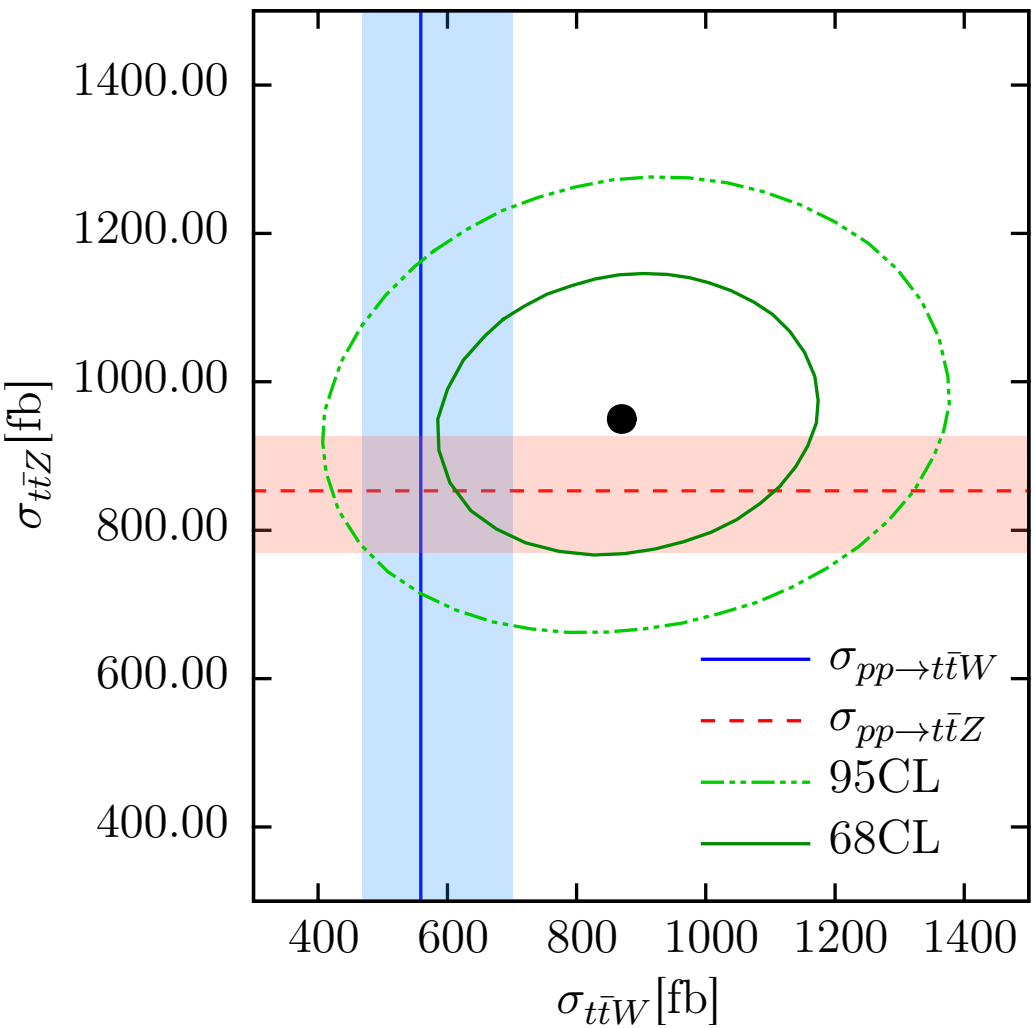


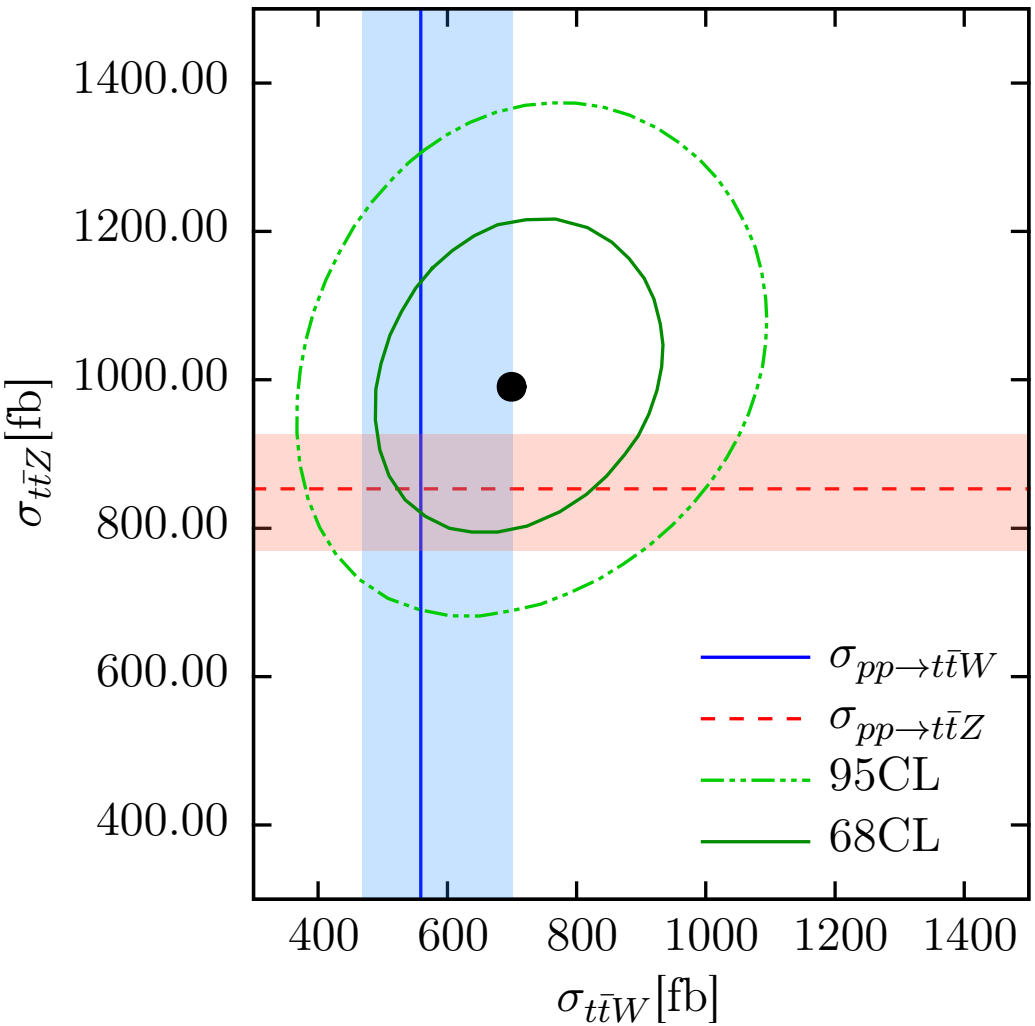
Preliminary

Comparison with ATLAS measurements



Preliminary

Comparison with CMS measurements



Preliminary

Summary and Outlook

- NLO+NNLL resummation in Mellin space for $t\bar{t}W/Z$

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Total inclusive cross sections, $\mu_F = \mu_R = Q$:

- $\sigma_{t\bar{t}W^+} = 320^{+12.2\%+3.2\%}_{-10.9\%-3.2\%}$ fb
- $\sigma_{t\bar{t}W^-} = 162^{+12.4\%+3.6\%}_{-11.0\%-3.6\%}$ fb
- $\sigma_{t\bar{t}Z} = 652^{+14.1\%+3.3\%}_{-12.7\%-3.3\%}$ fb

NNLL matched to NLO:

- $\sigma_{t\bar{t}W^+} = 339^{+8.9\%+3.2\%}_{-8.6\%-3.2\%}$ fb $\quad K_{\mathrm{NNLL}} = 1.06$
- $\sigma_{t\bar{t}W^-} = 174^{+8.8\%+3.7\%}_{-8.6\%-3.7\%}$ fb $\quad K_{\mathrm{NNLL}} = 1.08$
- $\sigma_{t\bar{t}Z} = 841^{+8.2\%+3.1\%}_{-8.4\%-3.1\%}$ fb $\quad K_{\mathrm{NNLL}} = 1.29$

Preliminary

Cross sections for $t\bar{t}W/Z$

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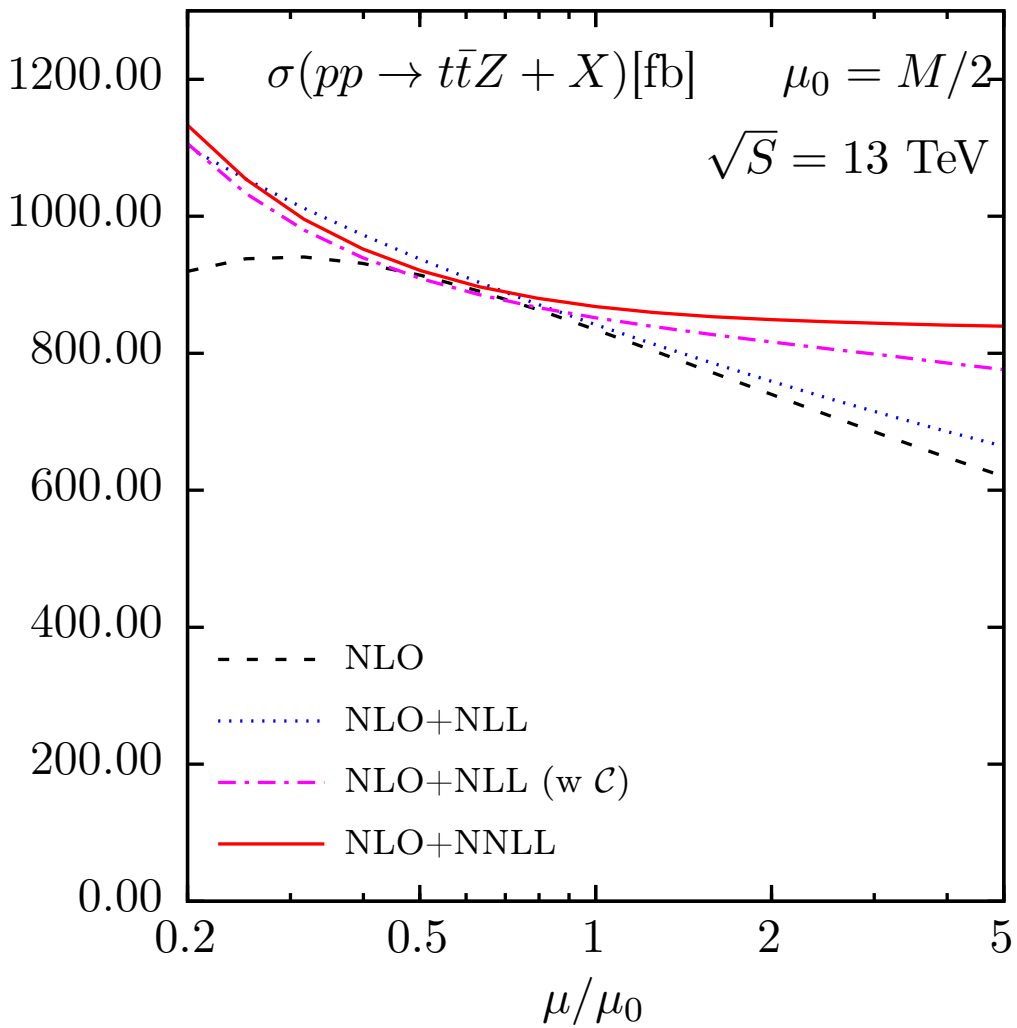
Preliminary

Scale dependence $t\bar{t}Z$ $\mu_F = \mu_R$



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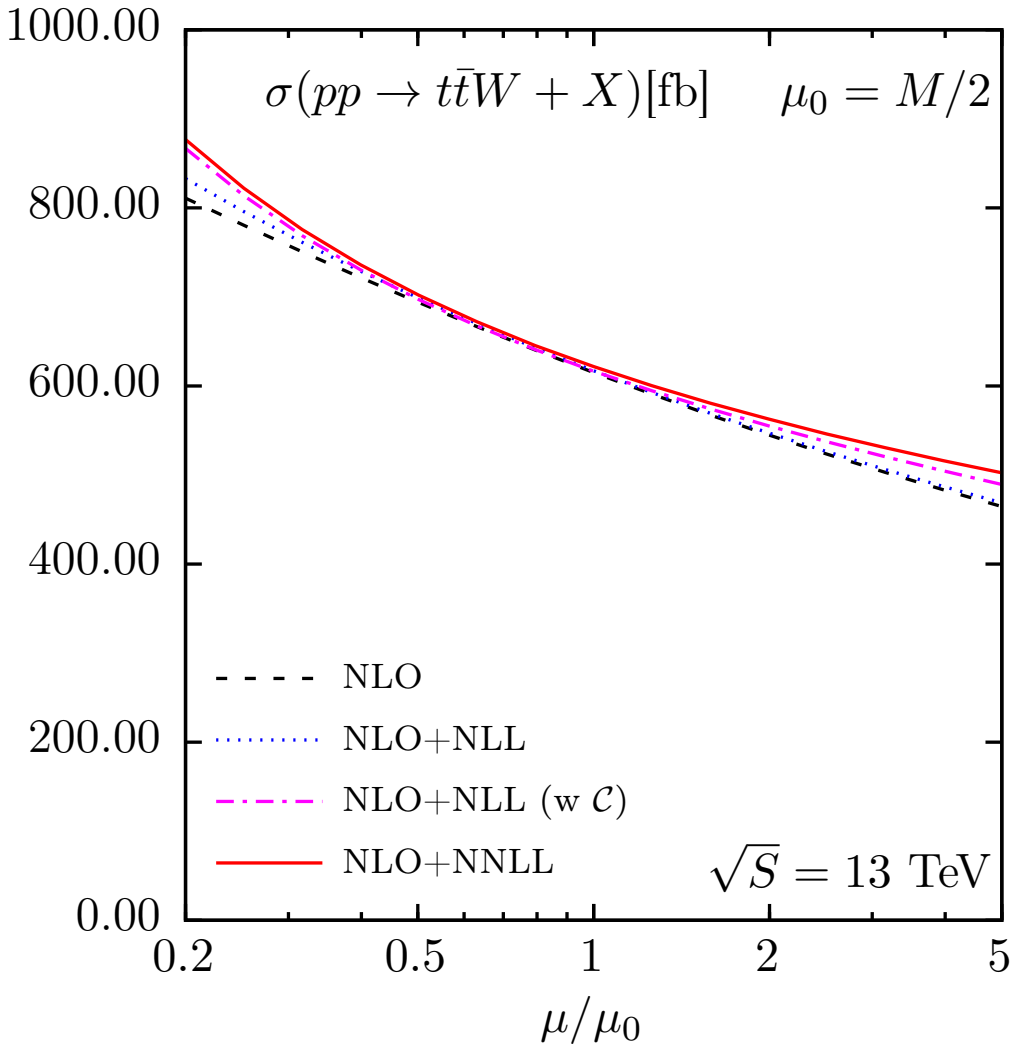
Scale dependence $t\bar{t}W$ $\mu_F = \mu_R$



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