Theory input for $t\bar{t}j$ experimental analyses at the LHC

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The precise measurement of the top quark mass constitutes one of the main goals of the LHC top physics program. One approach to measure this quantity uses the ρ distribution, an observable depending on the invariant mass of the $t\bar{t}j$ system. To fully exploit the experimental accuracy achievable in measuring top quark production cross sections at the LHC, the theory uncertainties associated to these measurements need to be well under control. To this end we present a study of the effect of varying the theoretical input parameters in the calculation of differential cross sections of the $t\bar{t}j$ process. Thereby we studied the influence of the jet reconstruction procedure, as well as the effect of various renormalization and factorization scale definitions and different PDF sets. A similar behaviour to the one presented here in case of the ρ-distribution was found for other differential distributions.

Top quark mass studies with the $t\bar{t}j$ process

Top quark mass measurement with the normalized ρ distr. $\mathcal{R}$ [1]

$$\mathcal{R}(m_t,\rho) = \frac{1}{\sigma_{t\bar{t}+1\,\text{jet}}}\frac{d\sigma_{t\bar{t}+1\,\text{jet}}}{d\rho}(m_t,\rho)$$

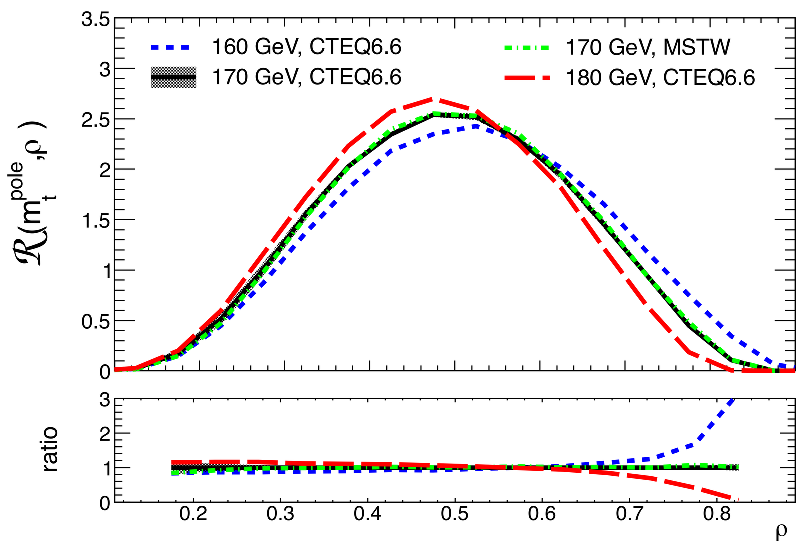
$$\rho = \frac{2m_0}{m_{t\bar{t}j}},\quad m_0 = 170\,\text{GeV}$$

($\rho' = 2m_0/m_{t\bar{t}}$ shown to be less senstive to m_t in [1])

ATLAS measurement ($\sqrt{s} = 8\,\text{TeV}$, 2019)[2]

$$m_t^{\text{pole}} = 171.1 \pm 0.4(\text{stat}) \pm 0.9(\text{sys}) \,^{+0.7}_{-0.3}(\text{th})\,\text{GeV}$$

theory uncertainty dominated by scale uncertainty $^{+0.6}_{-0.2}$ GeV (PDF and α_s uncertainty lead to ± 0.2 GeV)



→ shape of the normalized ρ distribution depends on m_t[1]

Simulation settings & scales

- POWHEG-BOX $t\bar{t}j$ reimplementation V2 (previous version V1[3])
- $N_j \geq 1$, $p_T^j > 30\,\text{GeV}$, $|\eta_j| < 2.4$, anti-k_T with $R = 0.4$
- PDF set: CT18NLO

Study of fixed ($\mu_0 = m_t$) and dynamical scale ($\mu_0 \in \{H_T^B/2, H_T^B/4\}$

$$H_T^B = \left(\sqrt{{p_{T,t}^B}^2 + m_t^2} + \sqrt{{p_{T,\bar{t}}^B}^2 + m_t^2} + p_{T,j}^B\right)$$

superscript B: variables evaluated with underlying Born kinematics (configuration before real emission)

Motivation: scale uncertainty in high energy tails of distributions calculated with dynamical scales shown to be smaller w.r.t. scale uncertainty in fixed scale $\mu_0 = m_t$ predicitions [4].

Renormalization and factorization scale uncertainty

Studied seven point scale variation $\mu_{R/F} = K_{R/F}\mu_0$, $(K_R, K_F) \in \{(0.5,0.5),(0.5,1),(1,0.5),(1,1),(1,2),(2,1),(2,2)\}$: dynamical scale $\mu_0 = H_T^B/4$ seems preferable to fixed scale $\mu_0 = m_t$

strongly reduced scale uncertainty bands in the high energy tails using dynamical scale

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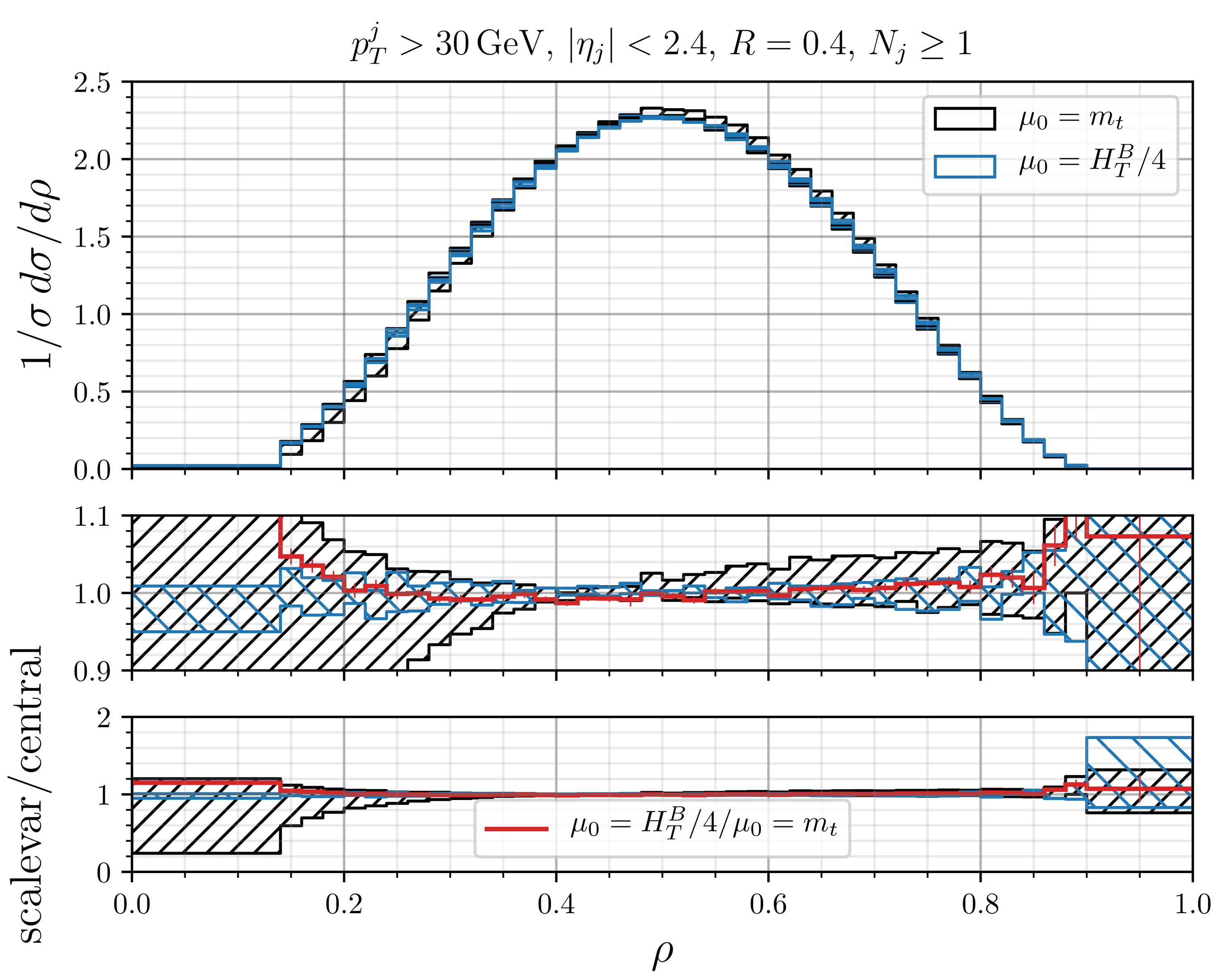
Comparison of NLO scale variation of the normalized ρ distribution



using $\mu_0 = H_T^B/4$ the scale variation does not induce large shape variations in ρ distr. w.r.t. using $\mu_0 = m_t$ → smaller scale variation uncertainty bands in normalized distr.

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nearly uniform differential $\mathcal{K}$-factor with dynamical scale choice

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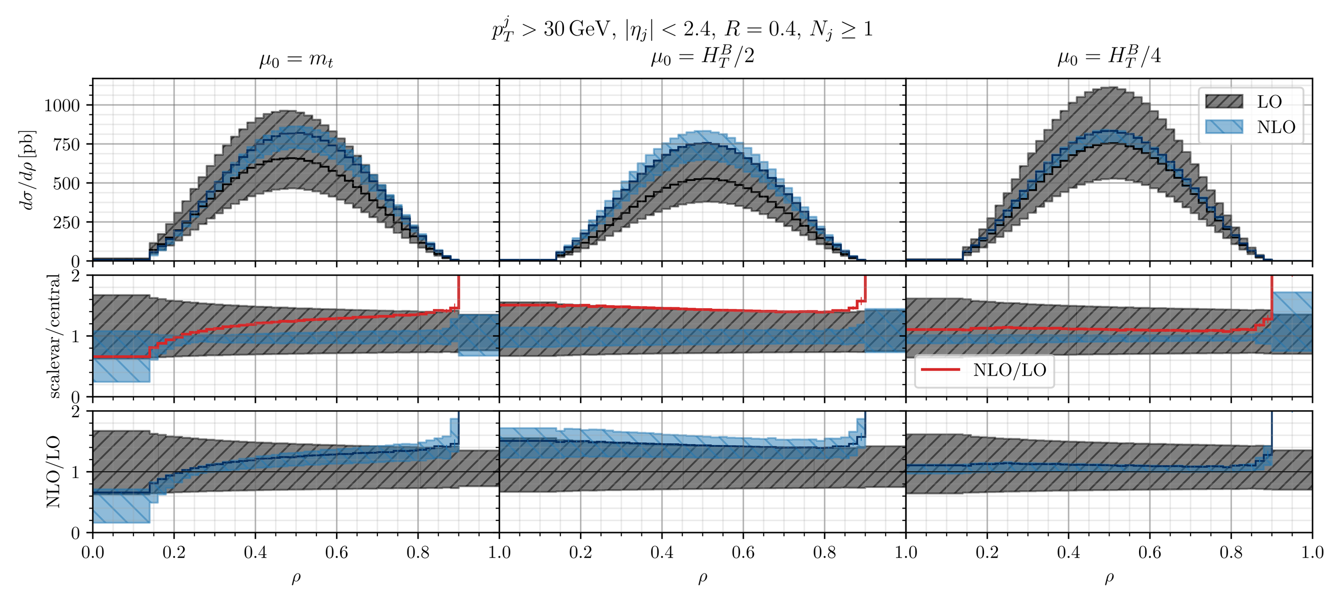
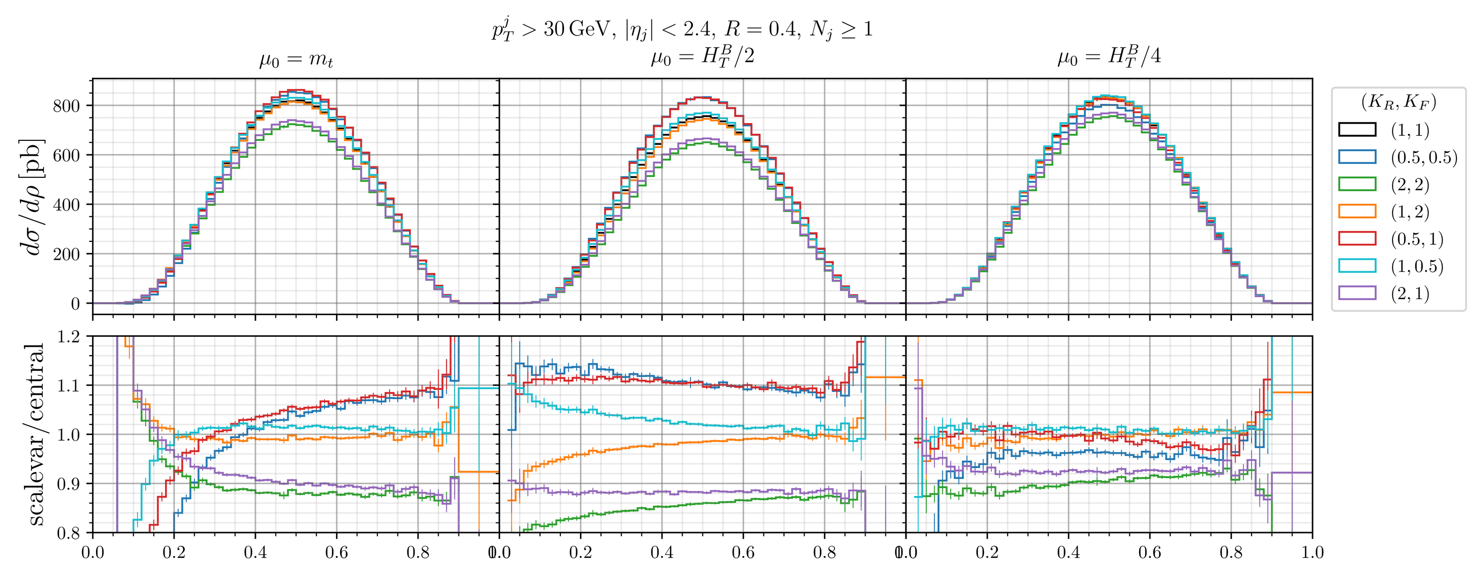
NLO and LO scale variation bands for ρ distribution

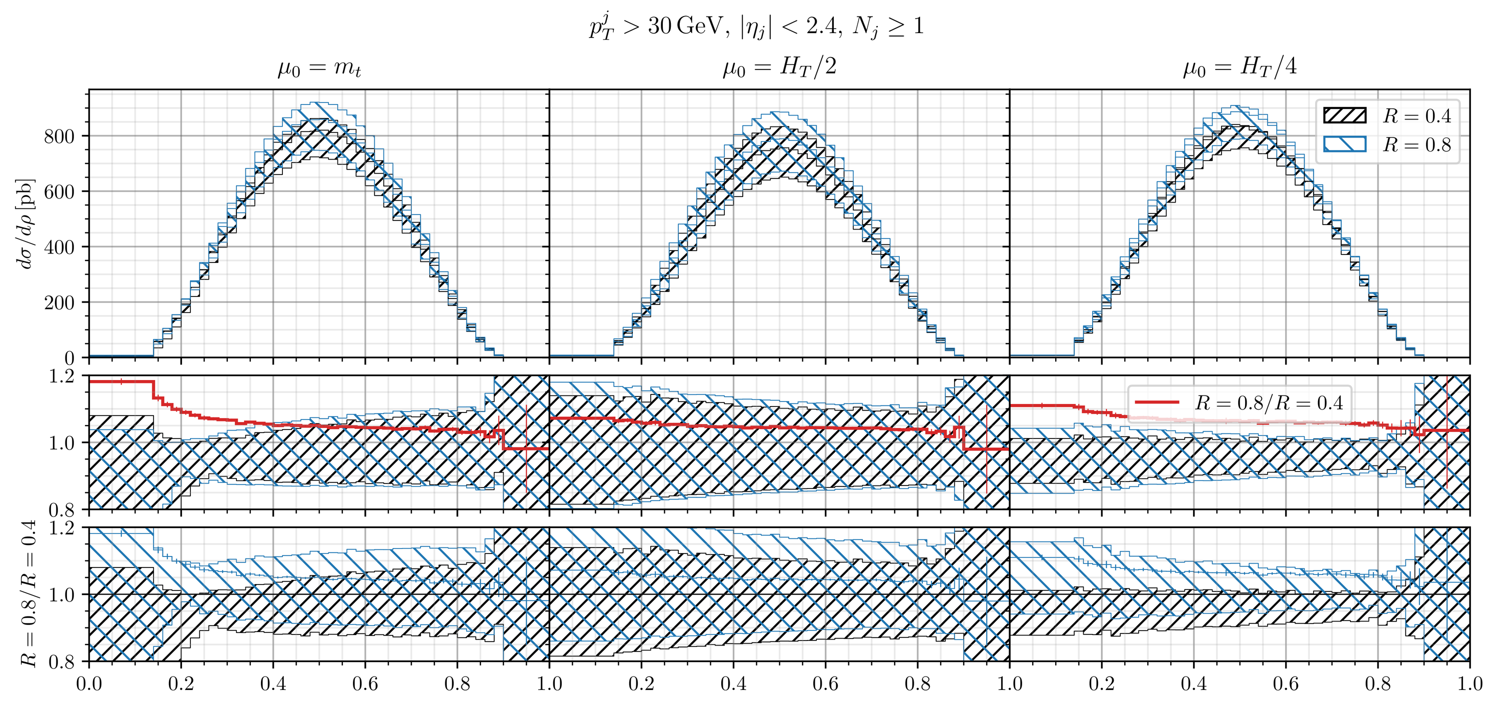




→ crossing of scale variation graphs and large increase in width of the scale variation uncertainty band in the high-energy tails (⇔ small ρ) in the ρ distr. using $\mu_0 = m_t$

R-dependence of scale uncertainty

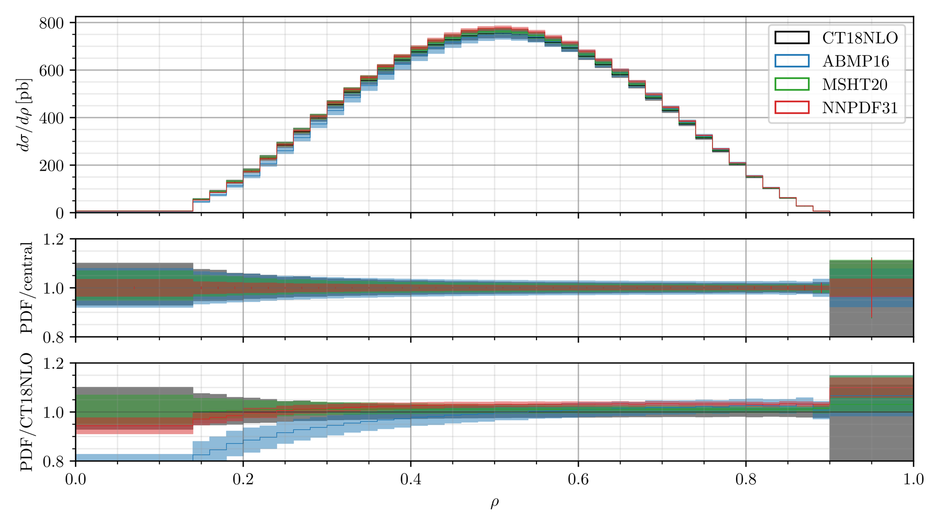
R parameter in anti-k_T algorithm ($R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$)



→ higher diff. cross section using larger R-value ⇒ larger statistics

→ dynamical scale: similar scale uncertainty using either $R = 0.4$ or $R = 0.8$

PDF variation uncertainty



PDF variation studied with LO partonic cross section and $\mu_0 = H_T^B/4$ (validated that PDF uncertainty is similar for NLO and LO matrix element with CT18NLO PDF set using $\mu_0 = H_T^B/2$)

→ good agreement between the PDF sets in the bulk of the distribution, differences more visible in high energy tails

→ PDF uncertainty becomes as relevant as scale uncertainty for the dyn. scale choice at low ρ

Conclusions: Using the dynamical scale $\mu_0 = H_T^B/4$ w.r.t. applying the fixed scale choice the scale variation uncertainty band is reduced, which is of similar size as the observed PDF uncertainty in the high-energy tails of the ρ distribution.

While the size of the scale uncertainty does not show dependence on the R-parameter in the anti-k_T jet clustering algorithm, the statistics can be increased by using a larger R-value.

[1] "A new observable to measure the top-quark mass at hadron colliders", Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos[hep-ph/1303.6415]

[2] "Measurement of the top-quark mass in $t\bar{t}$+1-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s} = 8\,\text{TeV}$"[hep-ex/1905.02302]

[3] "Hadronic top-quark pair-production with one jet and parton showering", Alioli, Moch, Uwer[hep-ph/1110.5251]

[4] "Off-shell Top Quarks with One Jet at the LHC: A comprehensive analysis at NLO QCD", Bevilacqua, Hartanto, Kraus, Worek[hep-ph/1609.01659]