Higher-order corrections for tqZ production

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in collaboration with Nodoka Yamanaka

- tqZ **production**
- **Resummation of soft gluon corrections**
- **aNNLO cross sections**
- **Top-quark rapidity distributions**

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tqZ production

observation of $pp \to tqZ$ at 13 TeV collisions at the LHC

recent data is well above NLO theoretical prediction

the cross section for tqZ allows study of t-Z and W-W-Z couplings

and is sensitive to any anomalous top-quark couplings and moments

QCD corrections are significant at NLO and they are needed for good theoretical predictions

further improvement in theoretical accuracy by inclusion of soft-gluon corrections

$\to$ approximate NNLO (aNNLO) predictions

Soft-gluon corrections

processes: $pp \to tqZ$

partonic processes at LO $a(p_a) + b(p_b) \to t(p_t) + q(p_q) + Z(p_Z)$

if an additional gluon is emitted with momentum p_g in the final state

then we define the variable $s_4 = (p_q + p_Z + p_g)^2 - (p_q + p_Z)^2$

At partonic threshold $s_4 \to 0$

Soft corrections $\left[\frac{\ln^k(s_4/m_t^2)}{s_4}\right]_+$ **with** $k \leq 2n-1$ **for the order** α_s^n **corrections**

Factorization and Resummation of these soft-gluon corrections

Soft anomalous dimension $\Gamma_{S\,ab\to tqZ}$ **controls the evolution of the soft function**

two-loop results and partial three-loop results are known for $\Gamma_{S\,ab\to tqZ}$

Finite-order expansions $\to$ **no prescription needed**

Approximate NNLO (aNNLO) theoretical predictions

aNNLO = NLO + soft-gluon NNLO corrections

Soft-gluon resummation

$$d\sigma_{pp\to tqZ} = \sum_{a,b} \int dx_a\, dx_b\, \phi_{a/p}(x_a,\mu_F)\, \phi_{b/p}(x_b,\mu_F)\, d\hat{\sigma}_{ab\to tqZ}(s_4,\mu_F)$$

take Laplace transforms $d\tilde{\hat{\sigma}}_{ab\to tqZ}(N) = \int_0^s (ds_4/s)\, e^{-Ns_4/s}\, d\hat{\sigma}_{ab\to tqZ}(s_4)$ **with** N **the transform variable**

and $\tilde{\phi}(N) = \int_0^1 e^{-N(1-x)}\phi(x)\, dx$

Then

$$d\tilde{\sigma}_{ab\to tqZ}(N) = \tilde{\phi}_{a/a}(N_a,\mu_F)\, \tilde{\phi}_{b/b}(N_b,\mu_F)\, d\tilde{\hat{\sigma}}_{ab\to tqZ}(N,\mu_F)$$

Refactorization in terms of hard and soft functions

$$d\tilde{\sigma}_{ab\to tqZ}(N) = \tilde{\psi}_{a/a}(N_a,\mu_F)\, \tilde{\psi}_{b/b}(N_b,\mu_F)\, \tilde{J}_q(N,\mu_F)\, \mathrm{tr}\left\{ H_{ab\to tqZ}\left(\alpha_s(\mu_R)\right)\, \tilde{S}_{ab\to tqZ}\left(\frac{\sqrt{s}}{N\mu_F}\right)\right\}$$

Thus

$$d\tilde{\hat{\sigma}}_{ab\to tqZ}(N) = \frac{\tilde{\psi}_{a/a}(N_a,\mu_F)\, \tilde{\psi}_{b/b}(N_b,\mu_F)\, \tilde{J}_q(N,\mu_F)}{\tilde{\phi}_{a/a}(N_a,\mu_F)\, \tilde{\phi}_{b/b}(N_b,\mu_F)}\ \mathrm{tr}\left\{ H_{ab\to tqZ}\left(\alpha_s(\mu_R)\right)\, \tilde{S}_{ab\to tqZ}\left(\frac{\sqrt{s}}{N\mu_F}\right)\right\}$$

Resummed cross section

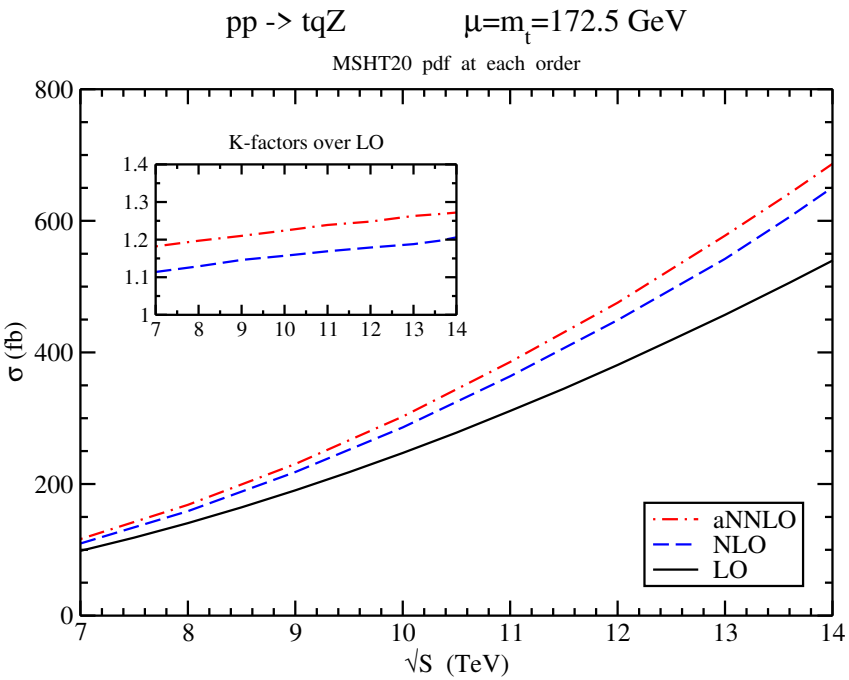
Renormalization group evolution → resummation

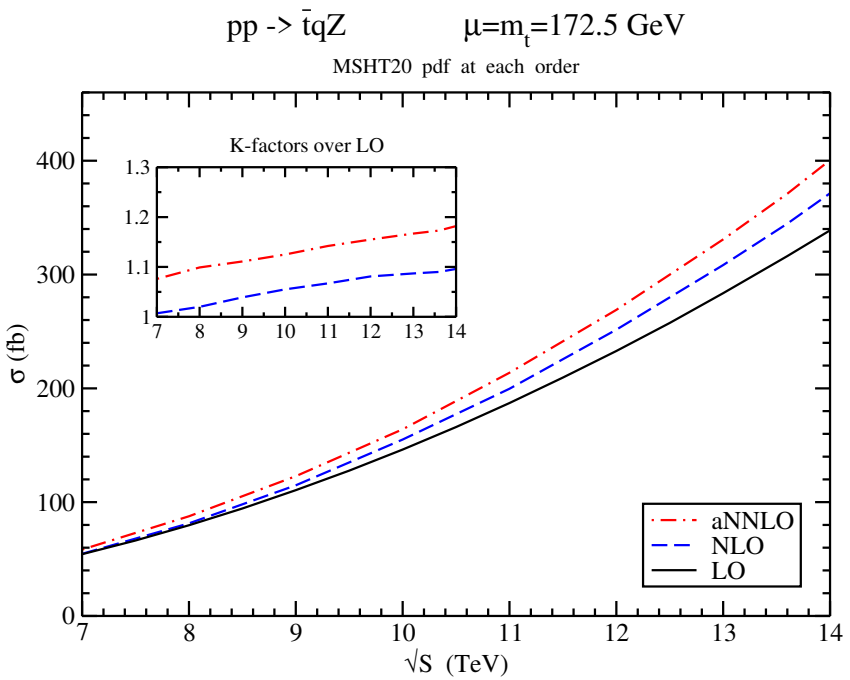
$$d\tilde{\hat{\sigma}}^{\rm resum}_{ab\to tqZ}(N) = \exp\left[\sum_{i=a,b} E_i(N_i)\right] \exp\left[\sum_{i=a,b} 2\int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu}\gamma_{i/i}(N_i)\right] \exp\left[E'_q(N)\right]$$
$$\times {\rm tr}\left\{H_{ab\to tqZ}\left(\alpha_s(\sqrt{s})\right) \bar{P} \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma^\dagger_{S\, ab\to tqZ}\left(\alpha_s(\mu)\right)\right]\right.$$
$$\left.\times \tilde{S}_{ab\to tqZ}\left(\alpha_s\left(\frac{\sqrt{s}}{N}\right)\right) P \exp\left[\int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma_{S\, ab\to tqZ}\left(\alpha_s(\mu)\right)\right]\right\}$$

The soft anomalous dimensions $\Gamma_{S\, ab\to tqZ}$ for this process are 2×2 matrices and are known at one and two loops, and partly at three loops

Expansion of the resummed cross section and inversion to momentum space → aNNLO corrections

aNNLO cross sections for tqZ production





soft-gluon emission dominates the corrections

K-factors not sensitive to cuts on p_T of the Z-boson

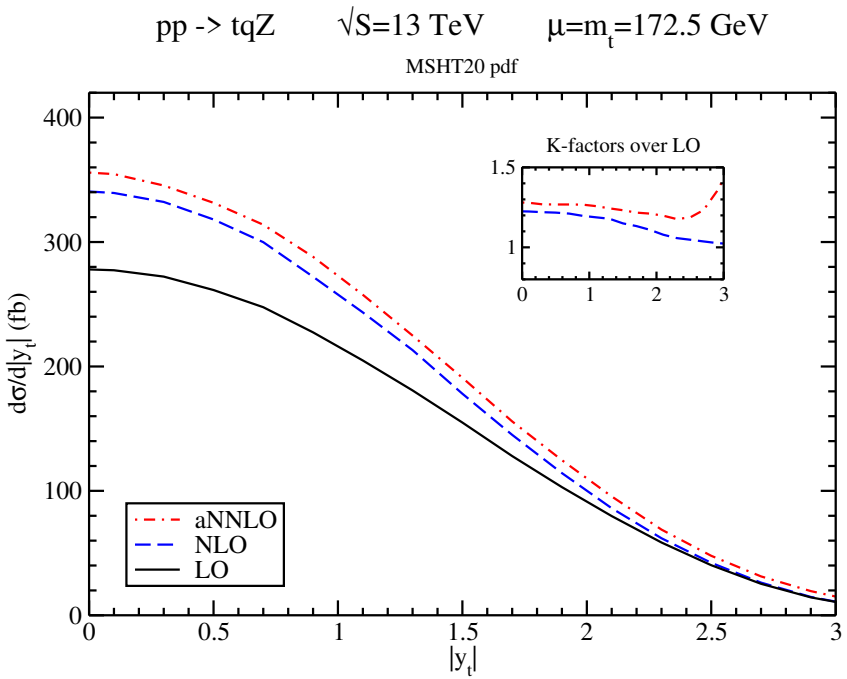
aNNLO cross sections for tqZ production

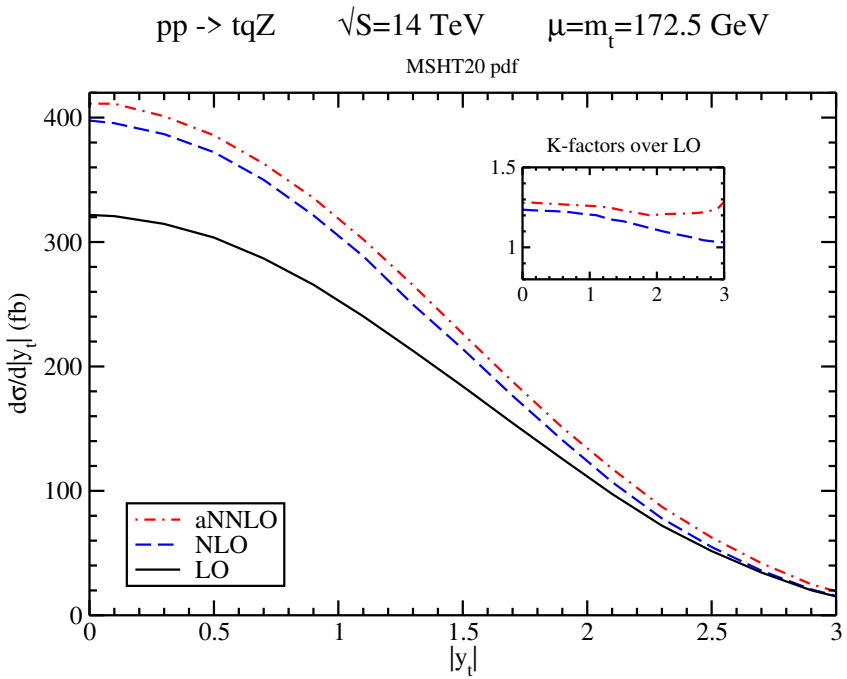
tqZ cross sections in pp collisions at the LHC					
σ in fb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO	$98.4^{+1.6+1.6}_{-3.9-0.9}$	$141^{+3}_{-7} \pm 2$	457^{+21+6}_{-32-3}	506^{+24+6}_{-36-4}	540^{+26+6}_{-40-4}
NLO	$110 \pm 2^{+1}_{-2}$	$159^{+3}_{-2} \pm 2$	$542 \pm 11^{+6}_{-5}$	$606^{+11}_{-12} \pm 6$	$651^{+14}_{-16} \pm 6$
aNNLO	$116^{+1}_{-2} \pm 2$	$168 \pm 2^{+3}_{-2}$	577^{+4+6}_{-9-5}	$641^{+4\ +6}_{-10-5}$	$686^{+5\ +7}_{-13-5}$

$\bar{t}qZ$ cross sections in pp collisions at the LHC					
σ in fb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO	$54.3^{+0.8+0.9}_{-2.1-1.2}$	$79.7^{+1.8+1.2}_{-3.6-1.5}$	284^{+13+3}_{-20-5}	316^{+15+3}_{-23-5}	339^{+17+3}_{-25-5}
NLO	$54.6^{+1.3+1.3}_{-0.8-1.0}$	$81.3^{+1.9+1.7}_{-1.3-1.4}$	308^{+8+5}_{-7-4}	$345^{+8}_{-9} \pm 5$	$371^{+10+6}_{-9\ -4}$
aNNLO	$58.4^{+0.4+1.2}_{-0.7-1.0}$	$87.6^{+0.4+1.7}_{-1.2-1.4}$	$331^{+2}_{-6} \pm 4$	$371^{+2}_{-8} \pm 4$	401^{+2+5}_{-8-4}

Sum of tqZ and $\bar{t}qZ$ cross sections in pp collisions at the LHC					
σ in fb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO	153^{+2+3}_{-6-2}	$221^{+5\ +3}_{-11-4}$	741^{+34+9}_{-52-8}	$822^{+39}_{-59} \pm 9$	$879^{+43}_{-65} \pm 9$
NLO	$165 \pm 3^{+2}_{-3}$	240^{+5+4}_{-3-3}	850^{+19+11}_{-18-9}	$951^{+19}_{-21} \pm 11$	1022^{+24+12}_{-25-10}
aNNLO	$174^{+1}_{-3} \pm 3$	256^{+2+5}_{-3-3}	$908^{+6\ +10}_{-15-9}$	$1012^{+6\ +10}_{-18-9}$	$1087^{+7\ +12}_{-21-9}$

Top-quark rapidity distributions in tqZ production

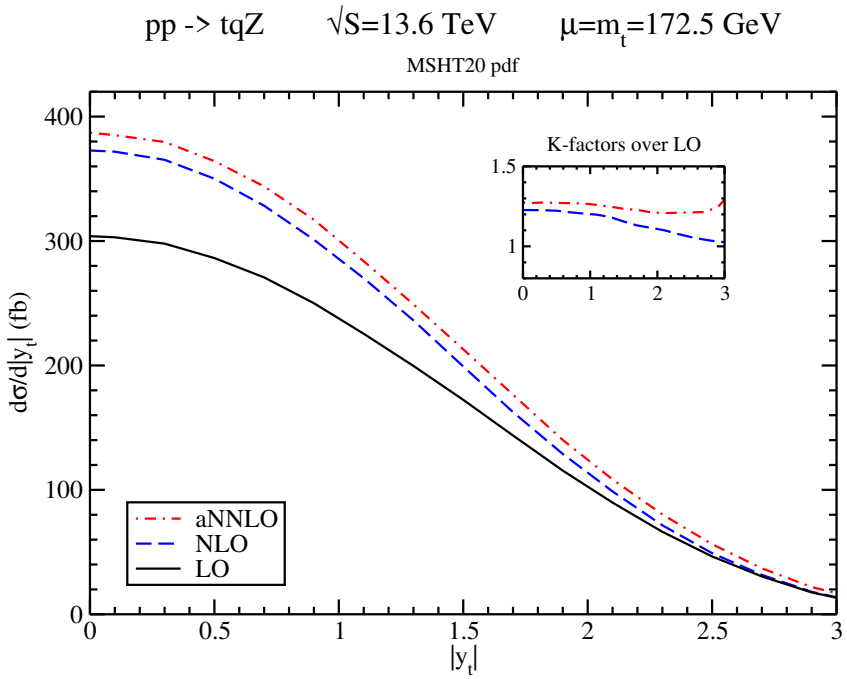




significant enhancements from aNNLO corrections

particularly at large rapidities

Top-quark rapidity distributions in tqZ production



scale and pdf uncertainties get bigger at larger rapidities, $|y_t| > 2$

Summary

- **tqZ production in high-energy pp collisions**
- **NLO corrections are significant**
- **soft-gluon resummation improves the theoretical predictions**
- **aNNLO corrections for total cross section and top-quark rapidity distributions**