

Theory overview of top-pair and single-top production at hadron colliders

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- Top-antitop pair production
- Single-top production
- $tq\gamma$, tqZ , tqH production



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Summer Meeting



Higher-order QCD corrections in top processes

Advanced calculations at fixed order and with soft-gluon resummation

NNLO for $t\bar{t}$ production as well as for t - and s -channel single-top production

NLO for tW production as well as for $tq\gamma$, tqZ , tqH production

Cross sections dominated by soft-gluon corrections at LHC energies (and beyond)

Soft-gluon resummation at NNLL (or higher)

Generate higher-order predictions (prescription-independent, matched to fixed-order) through approximate N³LO (aN³LO)

Soft-gluon corrections

$2 \rightarrow n$ processes $f_a(p_a) + f_b(p_b) \rightarrow t(p_1) + \dots$

with momenta $p_a + p_b \rightarrow p_1 + p_2 + \dots + p_n$

We define $s = (p_a + p_b)^2$, $t = (p_a - p_1)^2$, $u = (p_b - p_1)^2$ and $p_{2\dots n} = p_2 + \dots + p_n$

Then, if additional soft gluon with momentum p_g is emitted,

threshold variable $s_4 = (p_{2\dots n} + p_g)^2 - p_{2\dots n}^2 = s + t + u - p_1^2 - p_{2\dots n}^2$

At partonic threshold $s_4 \rightarrow 0$

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

Finite-order expansions \rightarrow no prescription needed

Approximate N³LO (aN³LO) predictions for total cross sections
and for (single and double) differential distributions

Soft-gluon resummation

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

take Laplace transforms $\tilde{\sigma}_{ab \rightarrow tX}(N) = \int_0^s (ds_4/s) e^{-Ns_4/s} \hat{\sigma}_{ab \rightarrow tX}(s_4)$ with N the transform variable
 and $\tilde{\phi}(N) = \int_0^1 e^{-N(1-x)} \phi(x) dx$

Then

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

Refactorization in terms of hard and soft functions

$$d\tilde{\sigma}_{ab \rightarrow tX}(N) = \tilde{\psi}_{a/a}(N_a, \mu_F) \tilde{\psi}_{b/b}(N_b, \mu_F) \left(\prod_{\text{f.s. } q,g} \tilde{J}(N, \mu_F) \right) \text{tr} \left\{ H_{ab \rightarrow tX} \left(\alpha_s(\mu_R) \right) \tilde{S}_{ab \rightarrow tX} \left(\frac{\sqrt{s}}{N\mu_F} \right) \right\}$$

Thus

$$d\tilde{\sigma}_{ab \rightarrow tX}(N) = \frac{\tilde{\psi}_{a/a}(N_a, \mu_F) \tilde{\psi}_{b/b}(N_b, \mu_F) \left(\prod_{\text{f.s. } q,g} \tilde{J}(N, \mu_F) \right)}{\tilde{\phi}_{a/a}(N_a, \mu_F) \tilde{\phi}_{b/b}(N_b, \mu_F)} \text{tr} \left\{ H_{ab \rightarrow tX} \left(\alpha_s(\mu_R) \right) \tilde{S}_{ab \rightarrow tX} \left(\frac{\sqrt{s}}{N\mu_F} \right) \right\}$$

Resummed cross section

Renormalization group evolution → resummation

$$d\tilde{\sigma}_{ab \rightarrow tX}^{\text{resum}}(N) = \exp \left[\sum_{i=a,b} E_i(N_i) \right] \exp \left[\sum_{i=a,b} 2 \int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu} \gamma_{i/i}(N_i) \right] \exp \left[\sum_{\text{f.s. } q,g} E'(N) \right]$$

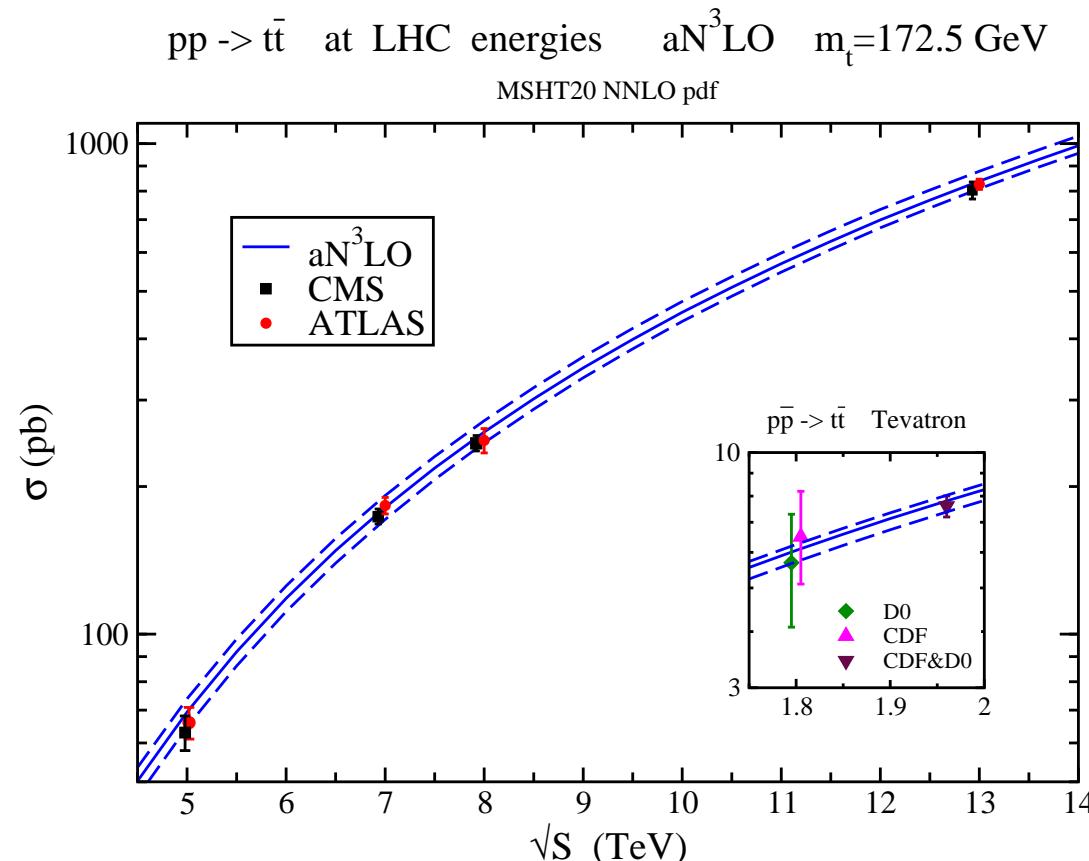
$$\times \text{tr} \left\{ H_{ab \rightarrow tX} \left(\alpha_s(\sqrt{s}) \right) \exp \left[\int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma_{S ab \rightarrow tX}^\dagger(\alpha_s(\mu)) \right] \tilde{S}_{ab \rightarrow tX} \left(\alpha_s \left(\frac{\sqrt{s}}{N} \right) \right) \exp \left[\int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma_{S ab \rightarrow tX}(\alpha_s(\mu)) \right] \right\}$$

The soft anomalous dimensions $\Gamma_{S ab \rightarrow tX}$ control the evolution of the soft function and are matrices in color space

At NLL accuracy we need one-loop results for $\Gamma_{S ab \rightarrow tX}$; at NNLL, two-loop; at N^3LL , three-loop

two-loop $\Gamma_{S ab \rightarrow tX}$ known for all the processes discussed here; three loops known fully for tW production and partially for the other processes

Top-antitop pair production



soft-gluon corrections are dominant in total & differential cross sections

excellent agreement with collider data

$t\bar{t}$ production cross sections

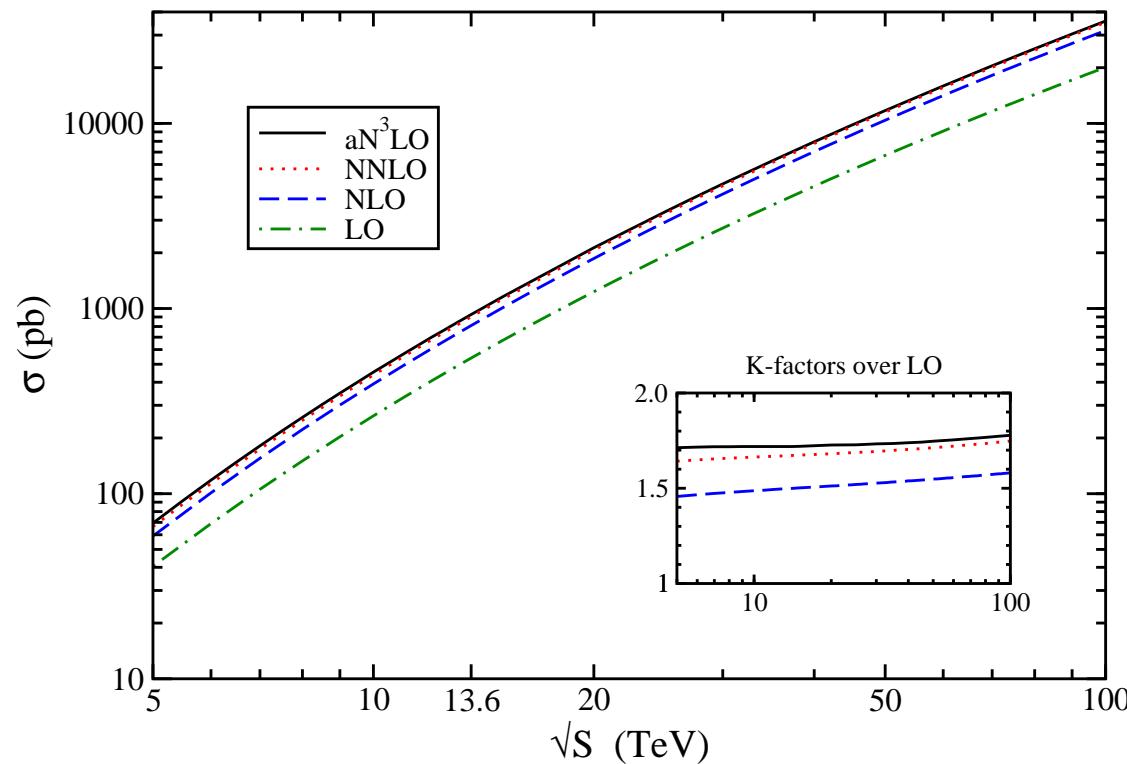
$t\bar{t}$ cross sections at LHC energies					
σ in pb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO	106	150	488	540	576
NLO	155	222	730	809	864
NNLO	174	249	814	902	963
aN ³ LO	181	258	839	928	990

$$\text{aN}^3\text{LO} = \text{NNLO} + \text{soft-gluon N}^3\text{LO corrections}$$

$t\bar{t}$ cross sections in high-energy pp collisions			
σ in pb	27 TeV	50 TeV	100 TeV
LO	2.23×10^3	6.72×10^3	20.1×10^3
NLO	3.39×10^3	10.4×10^3	31.8×10^3
NNLO	3.77×10^3	11.5×10^3	35.1×10^3
aN ³ LO	3.86×10^3	11.7×10^3	35.8×10^3

aN³LO $t\bar{t}$ cross sections

pp $\rightarrow t\bar{t}$ cross sections $\mu=m_t=172.5$ GeV
 MSHT20 NNLO pdf



aN³LO cross section at 13 TeV $\rightarrow 839^{+23+17}_{-18-11}$ pb

at 13.6 TeV $\rightarrow 928^{+25+18}_{-20-12}$ pb

at 14 TeV $\rightarrow 990^{+27+19}_{-22-13}$ pb

K-factors at LHC and higher energies

K-factors for $t\bar{t}$ production at LHC energies					
K-factor	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
NLO/LO	1.47	1.48	1.50	1.50	1.50
NNLO/LO	1.65	1.66	1.67	1.67	1.67
aN ³ LO/LO	1.72	1.72	1.72	1.72	1.72
aNLO/NLO	1.01	1.00	0.99	0.99	0.99
aNNLO/NNLO	1.01	1.01	1.00	1.00	1.00

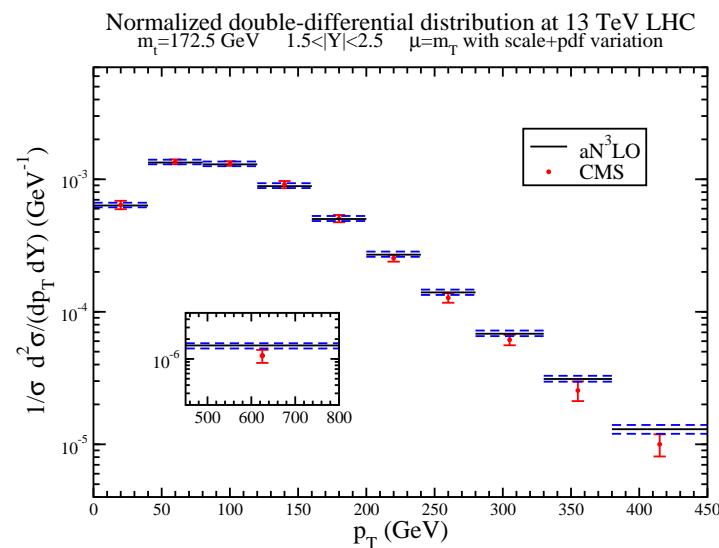
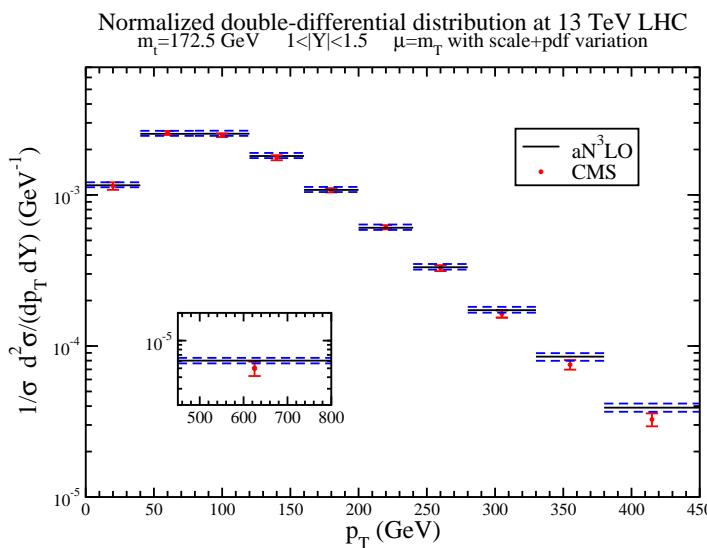
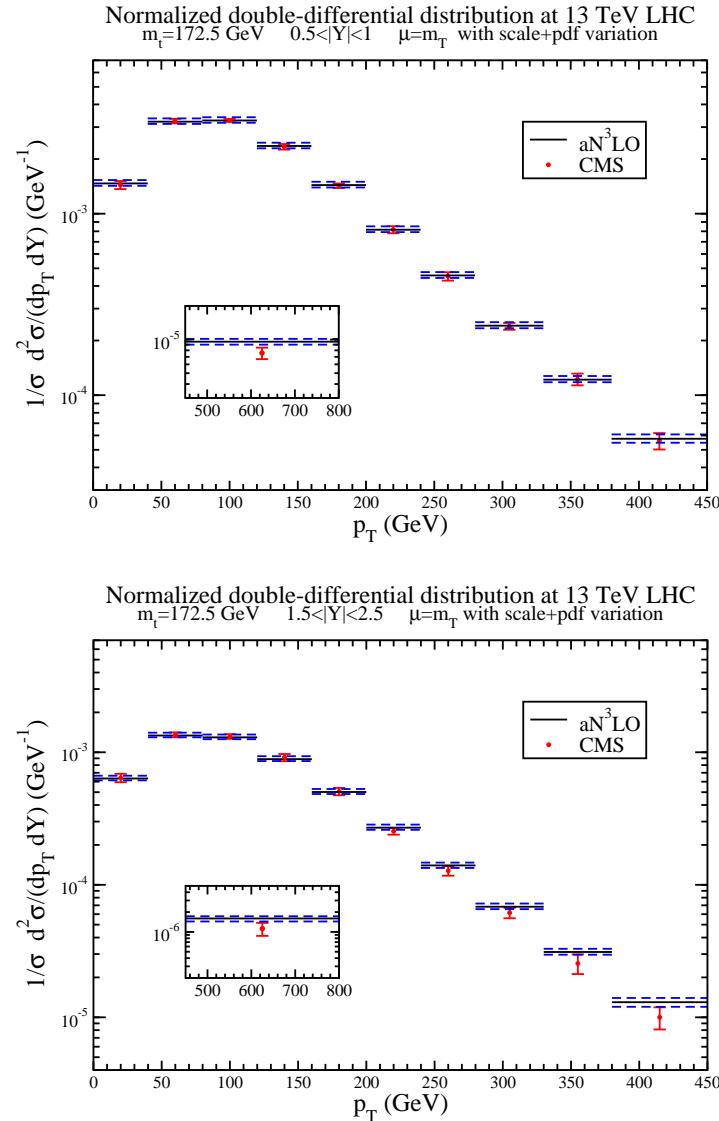
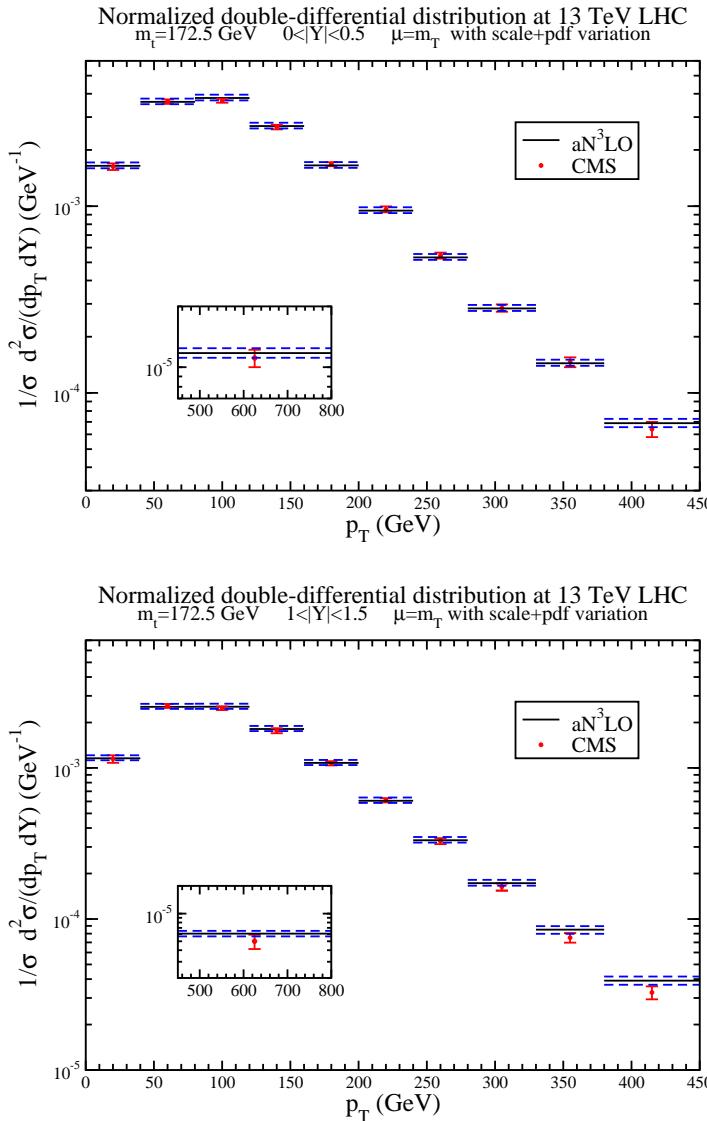
$\text{aNLO} = \text{LO} + \text{soft-gluon NLO corrections}$

$\text{aNNLO} = \text{NLO} + \text{soft-gluon NNLO corrections}$

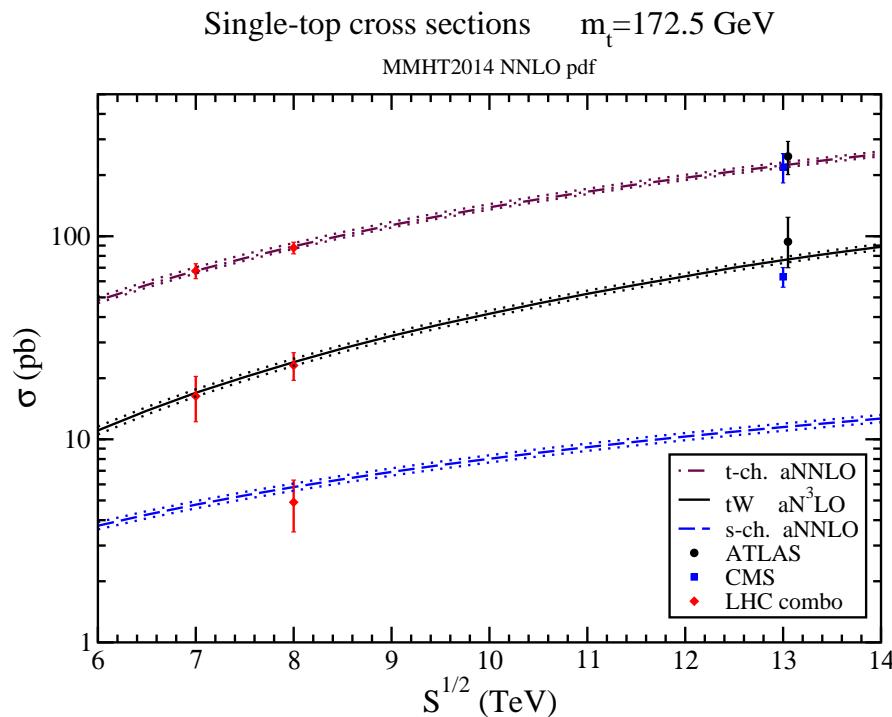
K-factors for $t\bar{t}$ production in pp collisions			
K-factor	27 TeV	50 TeV	100 TeV
NLO/LO	1.52	1.55	1.58
NNLO/LO	1.69	1.71	1.75
aN ³ LO/LO	1.73	1.75	1.78
aNLO/NLO	0.97	0.95	0.92
aNNLO/NNLO	1.00	0.99	0.98

aNNLO is excellent approximation to NNLO throughout

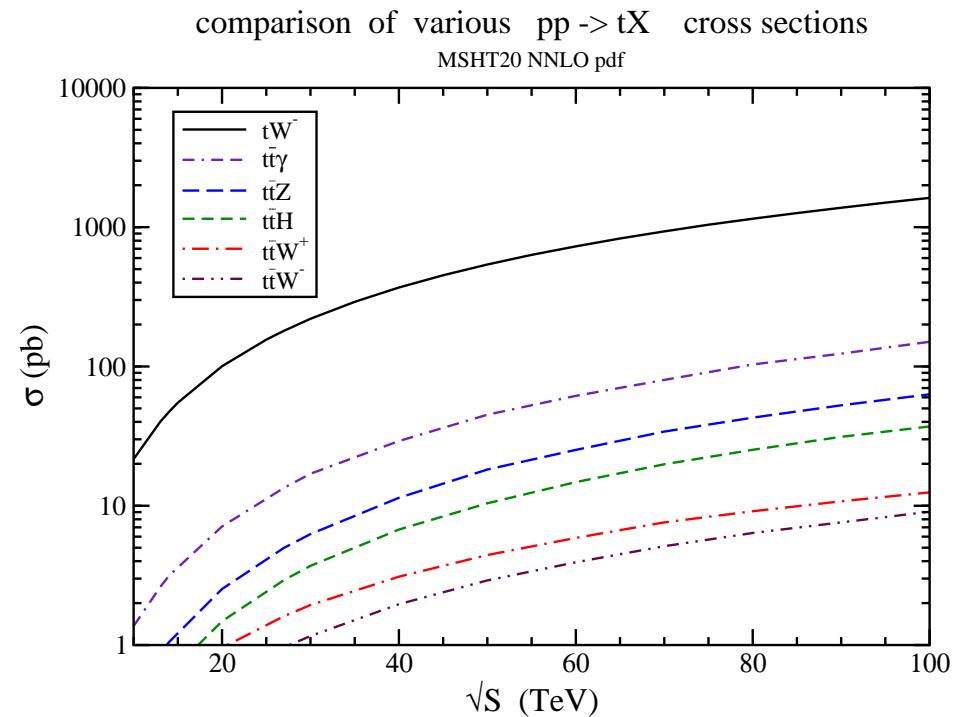
Top double-differential distributions in $t\bar{t}$ production



Single-top production



t-channel is numerically largest
tW second largest at LHC
s-channel is smallest
(older plot)



tW production cross sections
are larger than for other top-quark
processes with final-state
electroweak and Higgs bosons

tW production

At one loop

$$\Gamma_S^{(1)bg \rightarrow tW} = C_F \left[\ln \left(\frac{m_t^2 - t}{m_t \sqrt{s}} \right) - \frac{1}{2} \right] + \frac{C_A}{2} \ln \left(\frac{u - m_t^2}{t - m_t^2} \right)$$

At two loops

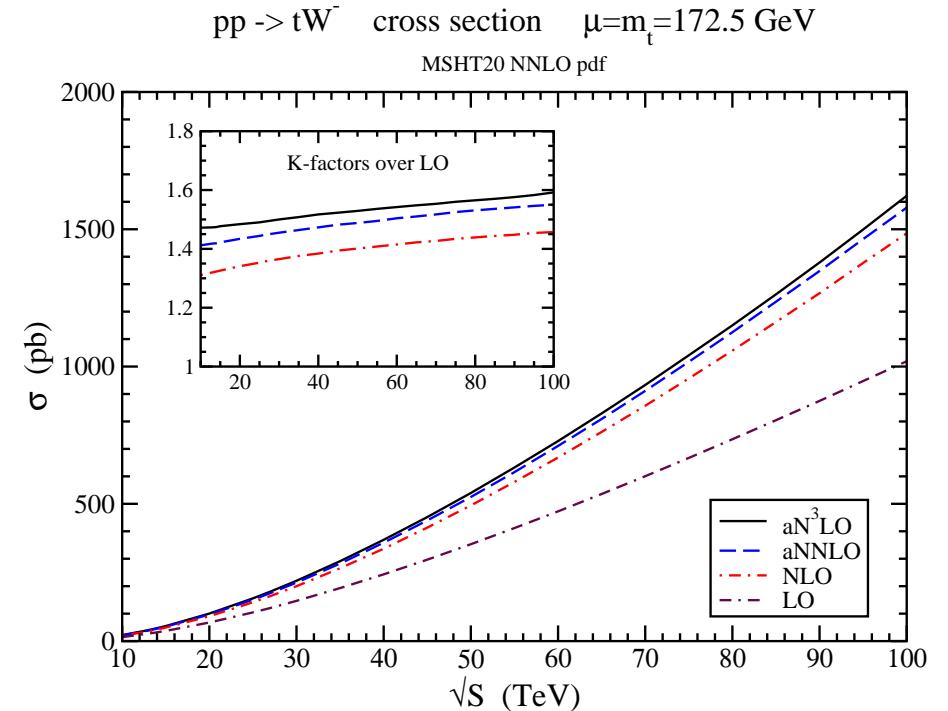
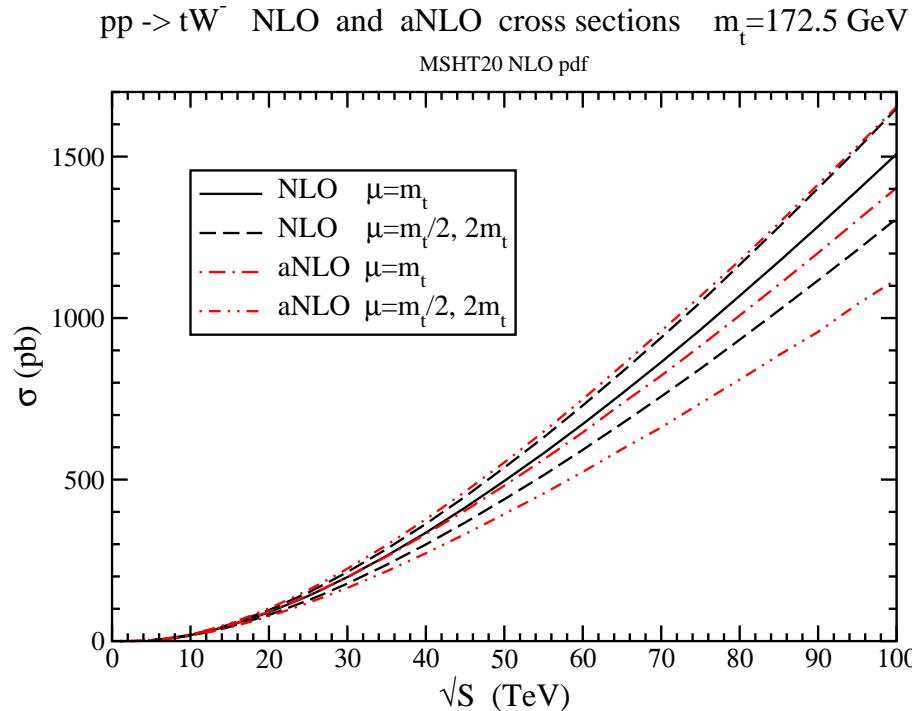
$$\Gamma_S^{(2)bg \rightarrow tW} = K_2 \Gamma_S^{(1)bg \rightarrow tW} + \frac{1}{4} C_F C_A (1 - \zeta_3)$$

At three loops

$$\Gamma_S^{(3)bg \rightarrow tW} = K_3 \Gamma_S^{(1)bg \rightarrow tW} + \frac{1}{2} K_2 C_F C_A (1 - \zeta_3) + C_F C_A^2 \left(-\frac{1}{4} + \frac{3}{8} \zeta_2 - \frac{\zeta_3}{8} - \frac{3}{8} \zeta_2 \zeta_3 + \frac{9}{16} \zeta_5 \right)$$

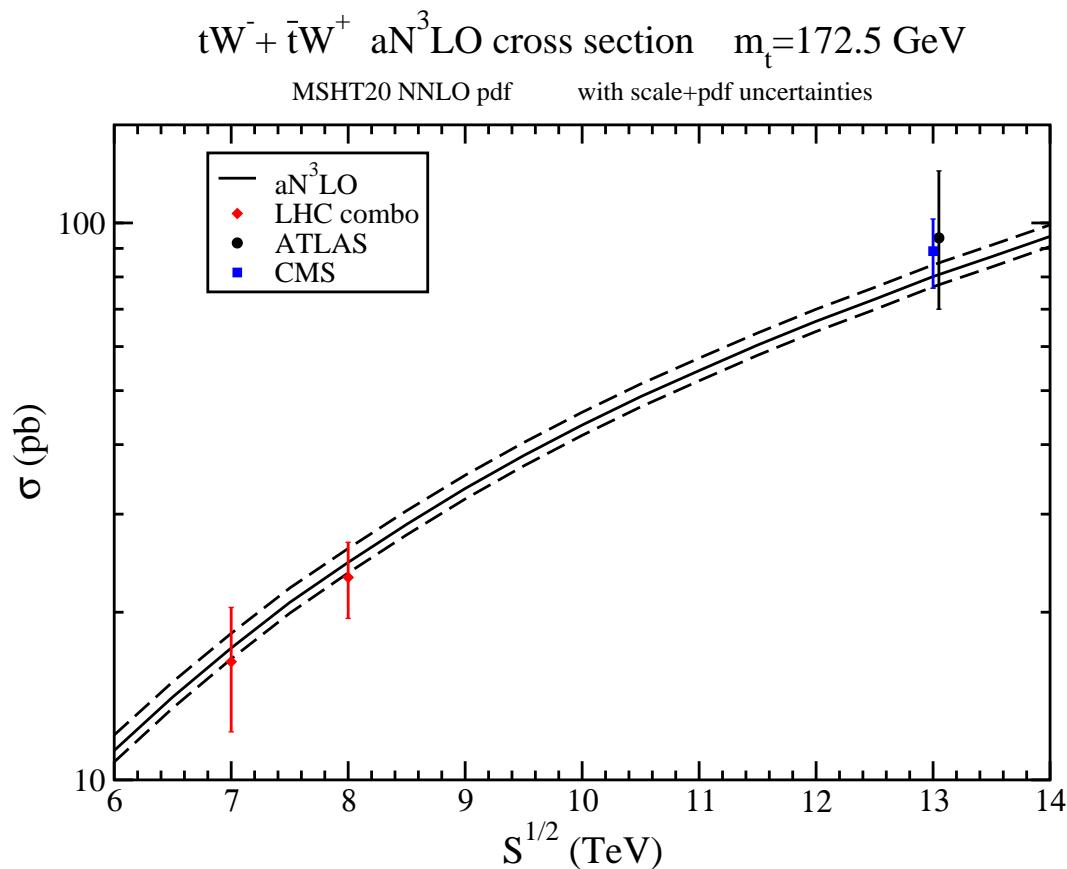
tW^- production at high-energy colliders

(with N. Yamanaka, arXiv:2102.11300, in JHEP)



The aNLO cross section is a very good approximation to the complete NLO result for all foreseeable collider energies
 → the soft-gluon corrections are dominant

The aNNLO and aN^3LO corrections (at NNLL) are also significant



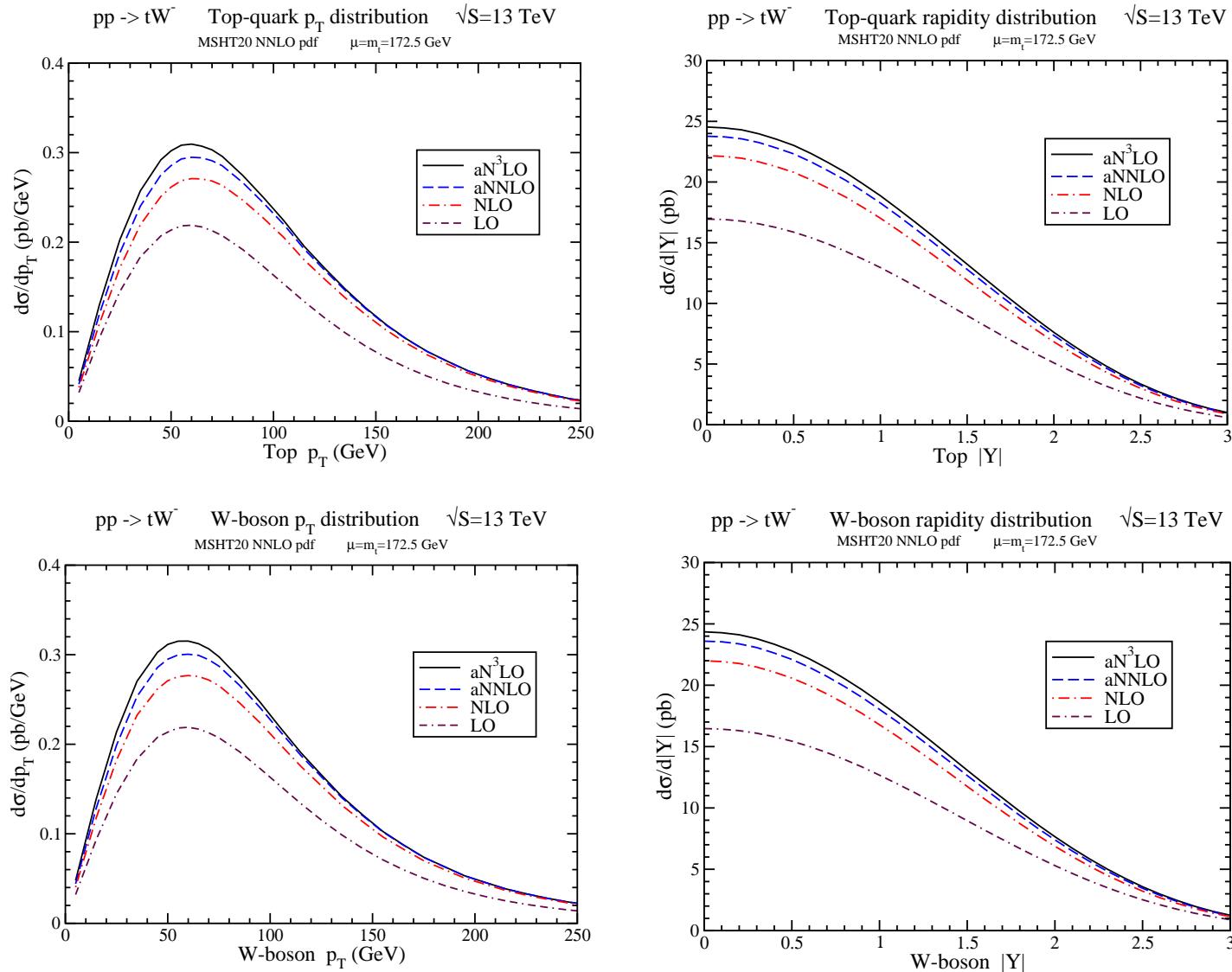
The aN³LO cross section with scale and pdf (MSHT20) uncertainty is

at 13 TeV $\rightarrow 79.5^{+1.9+2.0}_{-1.8-1.4}$ pb

at 13.6 TeV $\rightarrow 87.6^{+2.0+2.1}_{-1.9-1.5}$ pb

at 14 TeV $\rightarrow 94.0^{+2.2+2.2}_{-2.1-1.6}$ pb

Top-quark and W -boson distributions in tW^- production



$tq\gamma$ production

(with N. Yamanaka, arXiv:2201.12877)

observation of $pp \rightarrow tq\gamma$ at 13 TeV collisions at the LHC

the cross section for $tq\gamma$ is sensitive to the top-quark charge and any anomalous electric and magnetic dipole moments

also sensitive to any anomalous t - q - γ couplings with FCNC

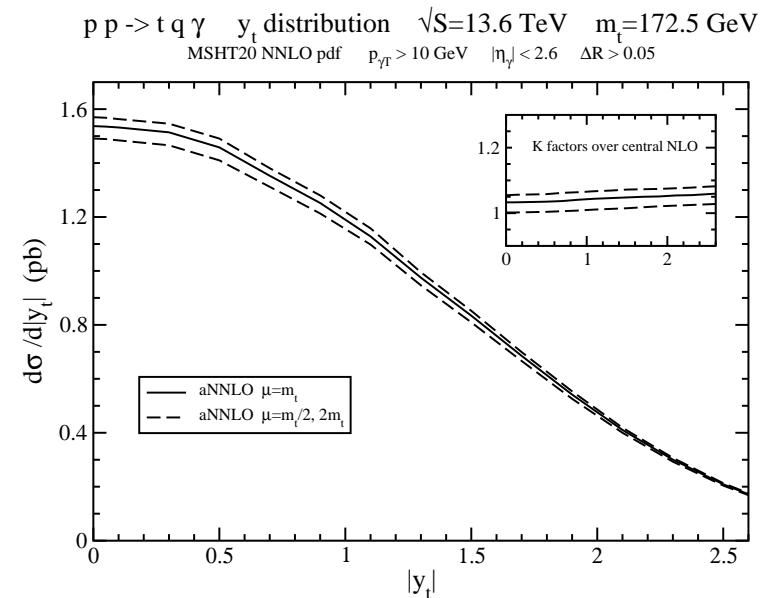
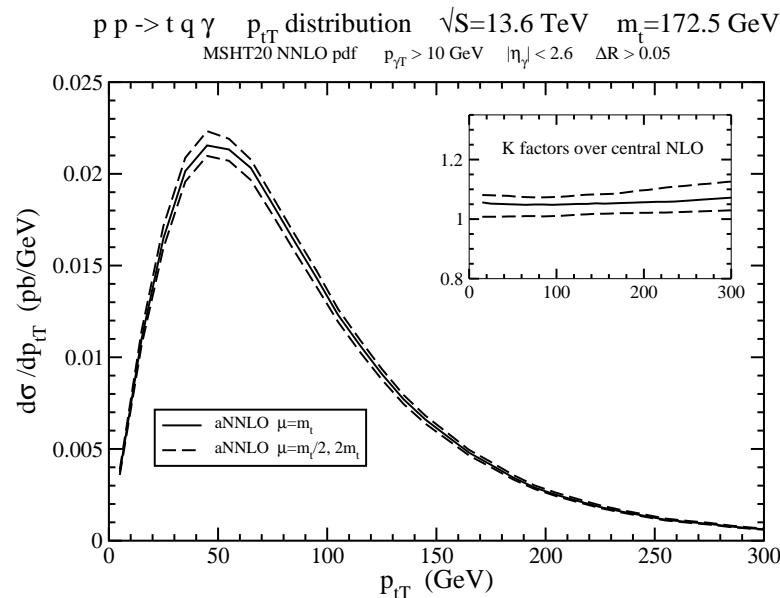
QCD corrections are significant at NLO and they are needed for good theoretical predictions

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

→ approximate NNLO (aN^NLO) predictions

improved agreement with recent LHC data

Top-quark p_T and rapidity distributions in $tq\gamma$ production



significant enhancements from aNNLO corrections

tqZ production

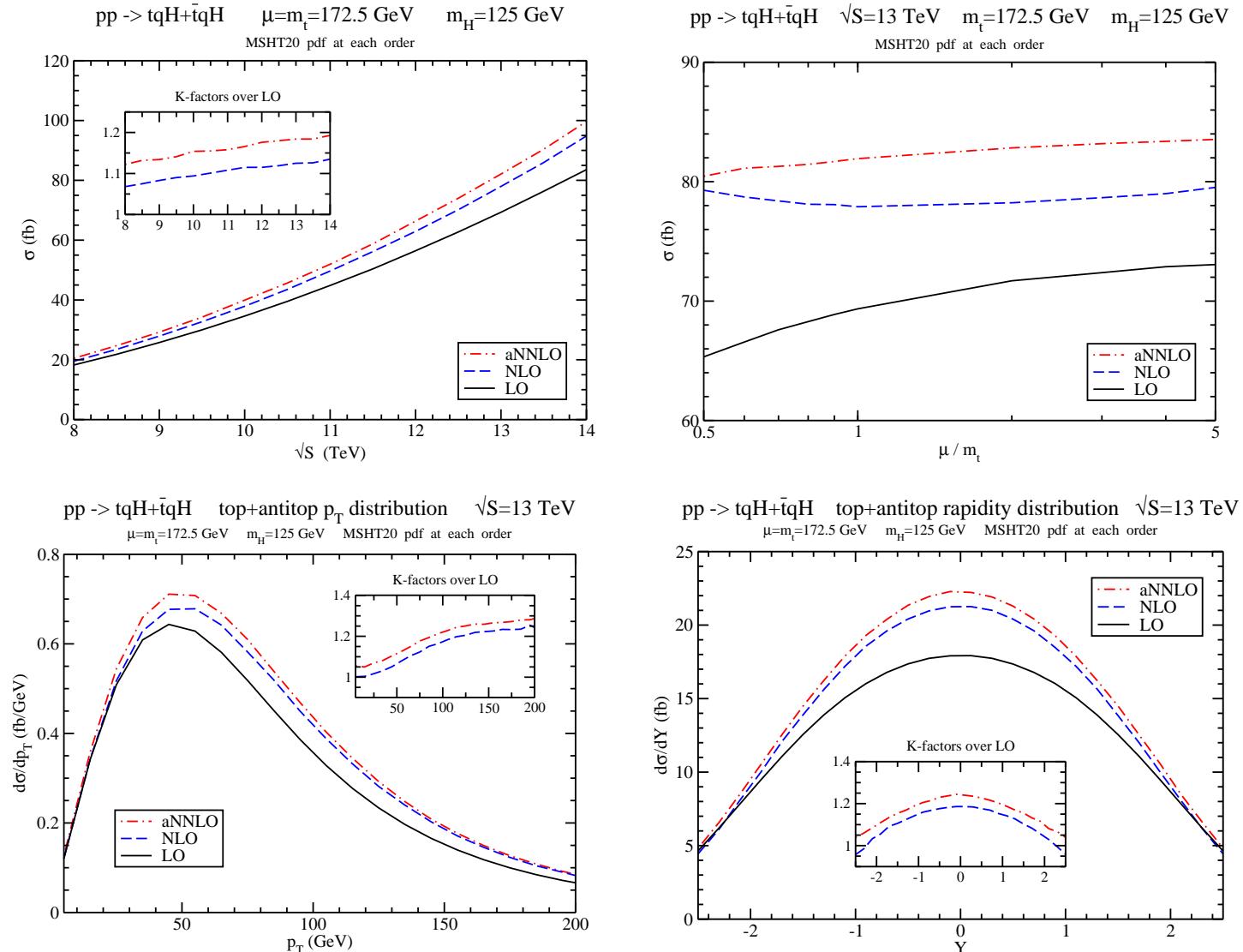
measurements of *tqZ* production at the LHC

soft-gluon contributions are important and enhance the cross section at aNNLO

detailed study in progress

related process: *tqW* production

tqH production (with M. Forslund, arXiv:2103.01228, in PRD)



Top BSM processes

Similar considerations apply to various BSM processes with top quarks

tH^- production in 2HDM

FCNC single-top processes: $t\gamma$, tZ , tZ' , tg production

FCNC tt production

large QCD corrections which are dominated by soft-gluon contributions

significant contributions at aNNLO and beyond

Summary

- top-antitop and single-top production in high-energy pp collisions
- higher-order QCD corrections are essential for good theoretical predictions
- quality of soft-gluon approximation at LHC energies is excellent and it remains very good even at much higher energies
- soft-gluon corrections are dominant and they are significant through aN^3LO