

Higher-order corrections in $tq\gamma$ production

Nikolaos Kidonakis

in collaboration with Nodoka Yamanaka

- NLO $tq\gamma$ cross sections
- Top-quark and photon differential distributions
- Soft-gluon resummation and aNNLO cross sections



DIS2022



$tq\gamma$ production

evidence for $pp \rightarrow tq\gamma$ 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

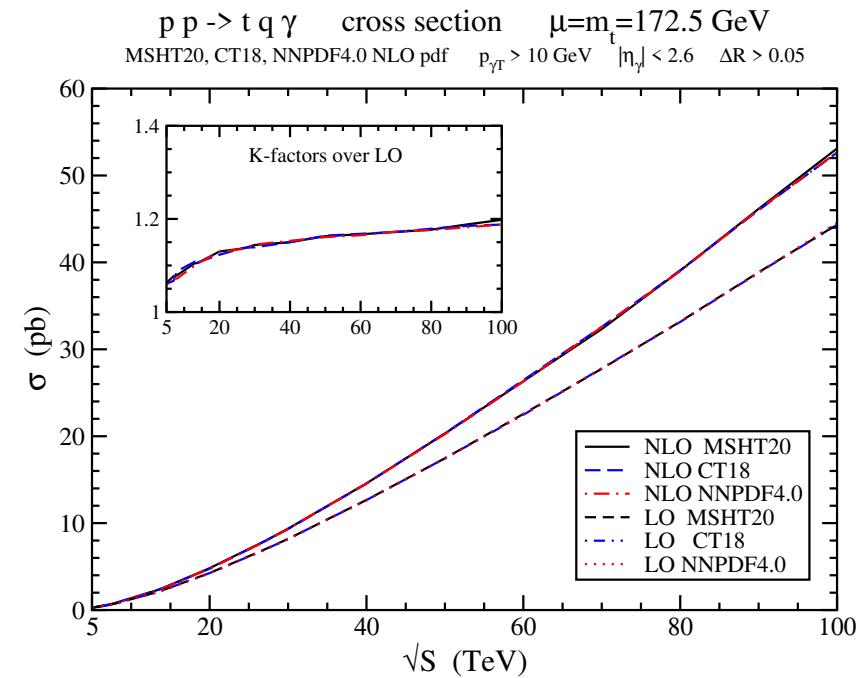
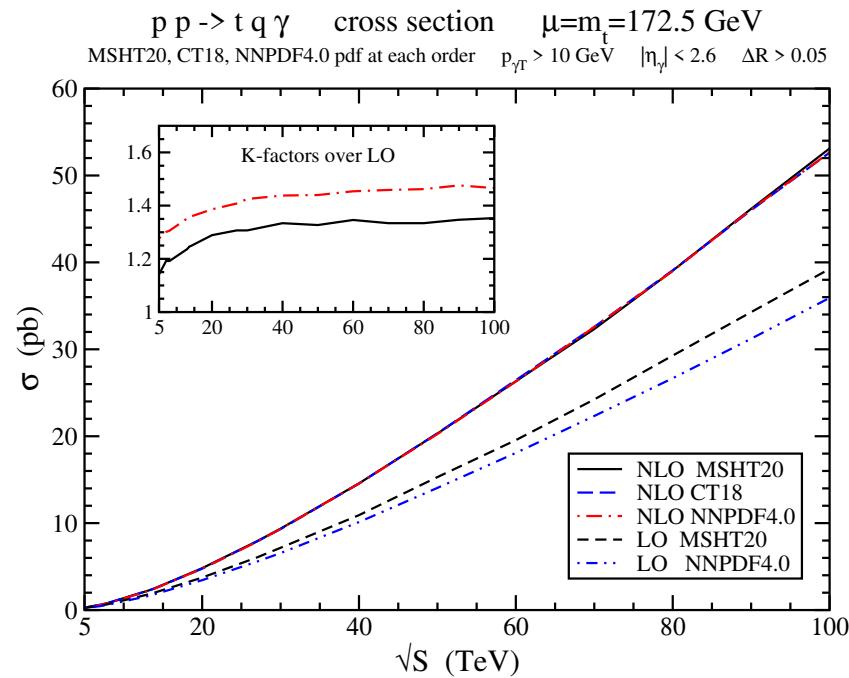
also sensitive to any anomalous t - q - γ couplings with FCNC

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

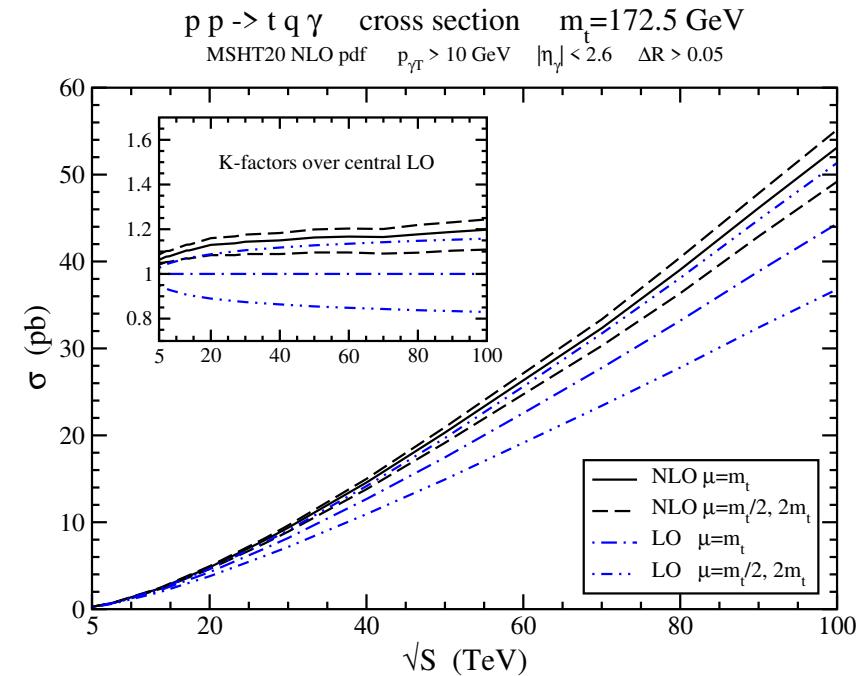
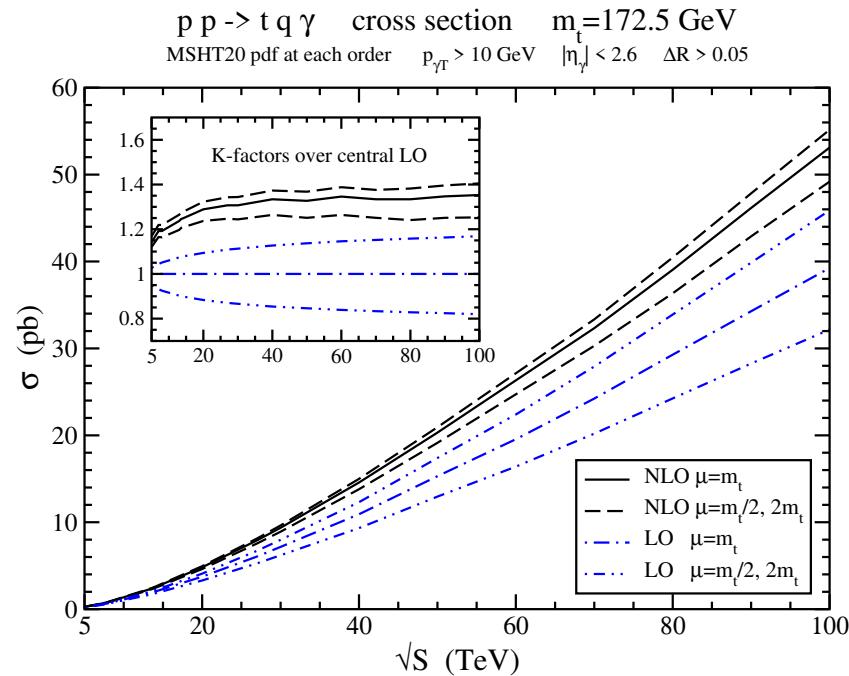
further improvement in theoretical accuracy by inclusion of soft-gluon corrections

→ approximate NNLO predictions

NLO cross sections for $tq\gamma$ production



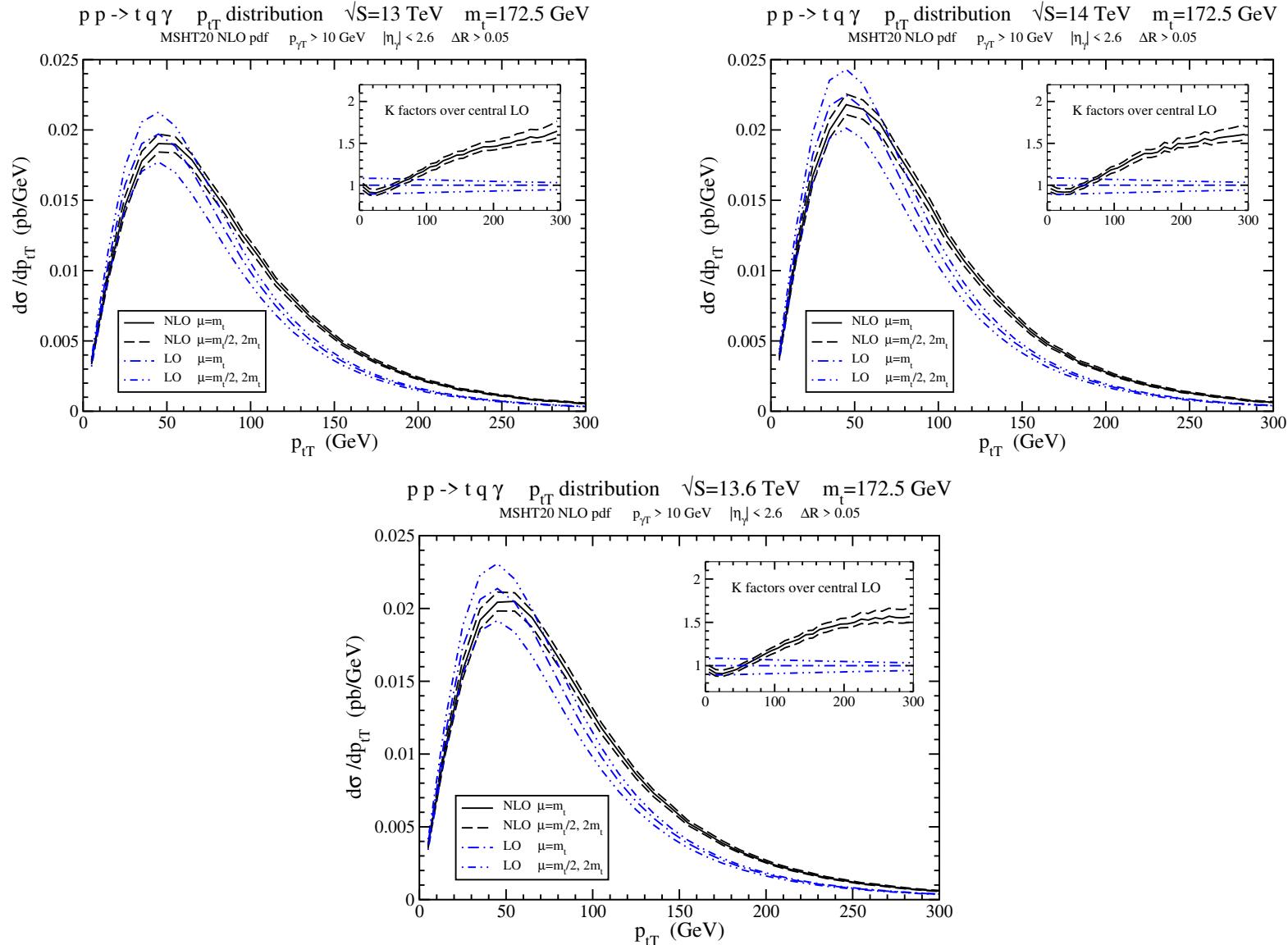
**The NLO K -factors are significant throughout the energy range
from 5 to 100 TeV**



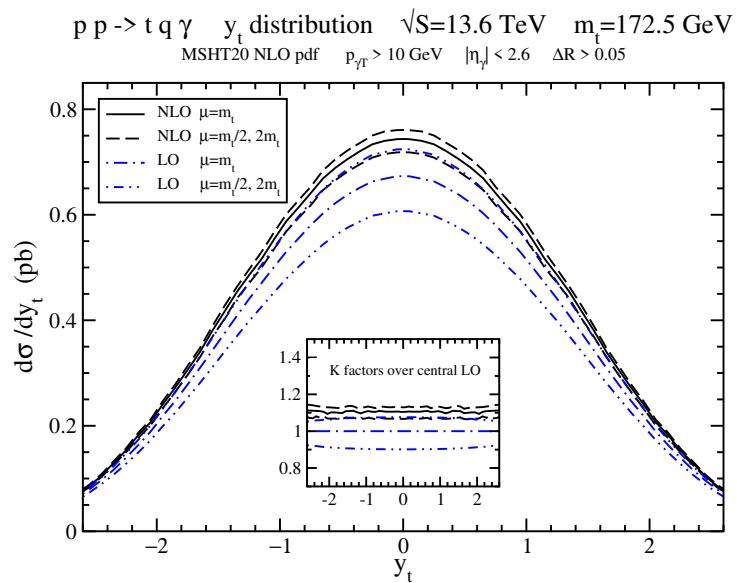
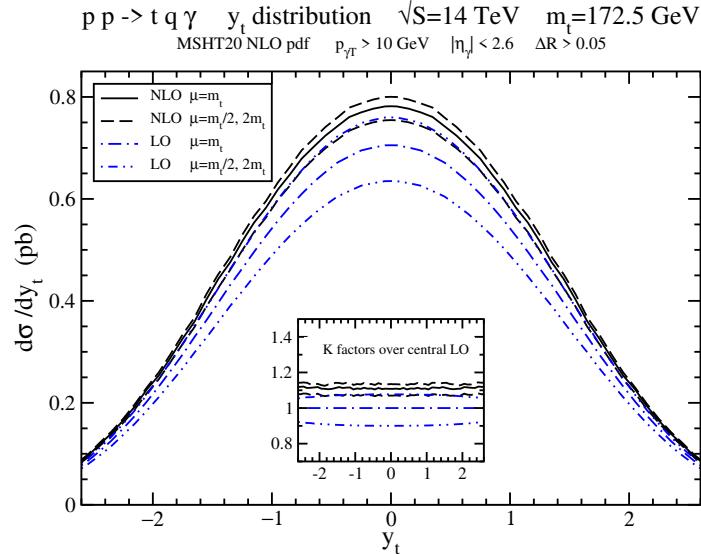
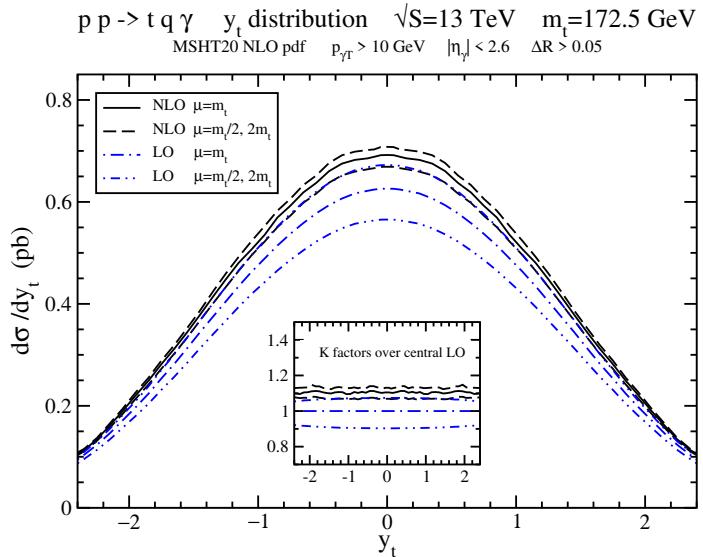
decreased scale dependence at NLO

<i>tqγ</i> cross sections at NLO for LHC energies with $p_{\gamma T} > 10$ GeV, $ \eta_\gamma < 2.6$, and $\Delta R > 0.05$				
σ in pb	8 TeV	13 TeV	13.6 TeV	14 TeV
MSHT20 (nlo pdf)	$0.812^{+0.018}_{-0.019} {}^{+0.009}_{-0.008}$	$2.20^{+0.05}_{-0.07} \pm 0.02$	$2.39^{+0.06}_{-0.08} \pm 0.02$	$2.52^{+0.06}_{-0.08} \pm 0.02$
CT18 (nlo pdf)	$0.817^{+0.019}_{-0.021} {}^{+0.022}_{-0.019}$	$2.20^{+0.05}_{-0.07} \pm 0.04$	$2.37^{+0.05}_{-0.07} \pm 0.04$	$2.52^{+0.06}_{-0.08} \pm 0.05$
NNPDF4.0 (nlo pdf)	$0.794^{+0.015}_{-0.017} \pm 0.005$	$2.16^{+0.05}_{-0.07} \pm 0.01$	$2.35^{+0.05}_{-0.08} \pm 0.01$	$2.49^{+0.06}_{-0.08} \pm 0.01$

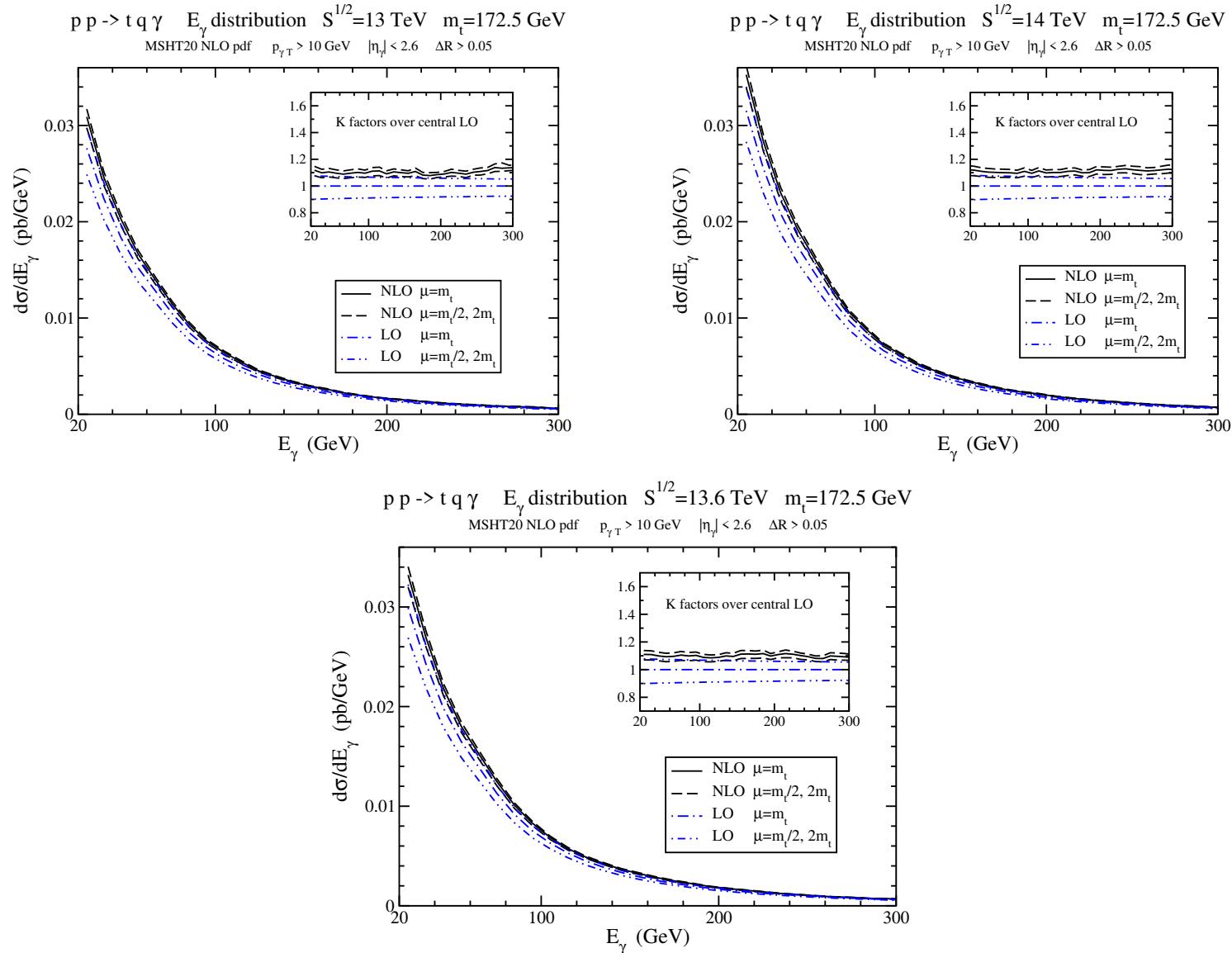
Top-quark p_T distributions in $tq\gamma$ production



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



Photon energy distributions in $tq\gamma$ production



Soft-gluon corrections

processes: $pp \rightarrow tq\gamma$

partonic processes at LO $a(p_a) + b(p_b) \rightarrow t(p_t) + q(p_q) + \gamma(p_\gamma)$

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

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

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

Soft anomalous dimension $\Gamma_{S ab \rightarrow tq\gamma}$ controls the evolution of the soft function

two-loop results and partial three-loop results are known for $\Gamma_{S ab \rightarrow tq\gamma}$

Finite-order expansions \rightarrow no prescription needed

Approximate NNLO (aNⁿNLO) theoretical predictions

aNNLO = NLO + soft-gluon NNLO corrections

Soft-gluon resummation

$$E_t \frac{d\sigma_{pp \rightarrow tq\gamma}}{d^3 p_t} = \sum_{a,b} \int dx_a dx_b \phi_{a/p}(x_a, \mu_F) \phi_{b/p}(x_b, \mu_F) E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}(s_4, \mu_F)}{d^3 p_t}$$

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

Then

$$E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}(N)}{d^3 p_t} = \tilde{\phi}_{a/a}(N_a, \mu_F) \tilde{\phi}_{b/b}(N_b, \mu_F) E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}(N, \mu_F)}{d^3 p_t}$$

Refactorization in terms of hard and soft functions

$$E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}(N)}{d^3 p_t} = \tilde{\psi}_{a/a}(N_a, \mu_F) \tilde{\psi}_{b/b}(N_b, \mu_F) \tilde{J}_q(N, \mu_F) \text{tr} \left\{ H_{ab \rightarrow tq\gamma} \left(\alpha_s(\mu_R) \right) \tilde{S}_{ab \rightarrow tq\gamma} \left(\frac{\sqrt{s}}{N \mu_F} \right) \right\}$$

Thus

$$E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}(N)}{d^3 p_t} = \frac{\tilde{\psi}_{a/a}(N_a, \mu_F) \tilde{\psi}_{b/b}(N_b, \mu_F) \tilde{J}_q(N, \mu_F)}{\tilde{\phi}_{a/a}(N_a, \mu_F) \tilde{\phi}_{b/b}(N_b, \mu_F)} \text{tr} \left\{ H_{ab \rightarrow tq\gamma} \left(\alpha_s(\mu_R) \right) \tilde{S}_{ab \rightarrow tq\gamma} \left(\frac{\sqrt{s}}{N \mu_F} \right) \right\}$$

Resummed cross section

Renormalization group evolution → resummation

$$E_t \frac{d\tilde{\sigma}_{ab \rightarrow tq\gamma}^{\text{resum}}(N)}{d^3 p_t} = \exp \left[\sum_{i=a,b} E_i(N_i) \right] \exp \left[\sum_{i=a,b} 2 \int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu} \gamma_{i/i}(N_i) \right] \exp \left[E'_q(N) \right]$$

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

The soft anomalous dimensions $\Gamma_{S ab \rightarrow tq\gamma}$ 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 $tq\gamma$ production

$tq\gamma$ cross sections at aNNLO for LHC energies with $p_{\gamma T} > 10$ GeV, $ \eta_\gamma < 2.6$, and $\Delta R > 0.05$				
σ in pb	8 TeV	13 TeV	13.6 TeV	14 TeV
MSHT20 (nnlo pdf)	$0.857^{+0.019+0.011}_{-0.020-0.007}$	$2.26^{+0.05}_{-0.07} \pm 0.02$	$2.50^{+0.05}_{-0.08} \pm 0.02$	$2.65^{+0.06}_{-0.08} \pm 0.02$
CT18 (nnlo pdf)	$0.864^{+0.018+0.022}_{-0.019-0.020}$	$2.29^{+0.05+0.04}_{-0.07-0.05}$	$2.51^{+0.06+0.04}_{-0.08-0.05}$	$2.65^{+0.06+0.04}_{-0.08-0.05}$
NNPDF4.0 (nnlo pdf)	$0.829^{+0.017}_{-0.018} \pm 0.003$	$2.27^{+0.05}_{-0.07} \pm 0.01$	$2.45^{+0.06}_{-0.08} \pm 0.01$	$2.58^{+0.06}_{-0.08} \pm 0.01$

For $\bar{t}q\gamma$ production with the same cuts and MSHT NNLO pdf, the aNNLO cross section is $1.61^{+0.04+0.02}_{-0.05-0.01}$ pb at 13 TeV, $1.77^{+0.05+0.02}_{-0.06-0.01}$ pb at 13.6 TeV, and $1.89^{+0.05}_{-0.07} \pm 0.02$ pb at 14 TeV

Comparison with 13 TeV CMS data

For the CMS cuts of $p_{\gamma T} > 25$ GeV, $|\eta_\gamma| < 1.44$, $\Delta R > 0.5$ at 13 TeV, and MSHT20 NNLO pdf, the aNNLO $tq\gamma$ cross section is $0.584^{+0.011+0.007}_{-0.015-0.005}$ pb and the $\bar{t}q\gamma$ cross section is $0.406^{+0.010+0.005}_{-0.012-0.004}$ pb

Total $tq\gamma + \bar{t}q\gamma$ aNNLO cross section is $0.990^{+0.021+0.012}_{-0.027-0.008}$ pb

Multiplying by the branching fraction for $t \rightarrow \mu\nu b$ ($11.40 \pm 0.20\%$), we find $(113 \pm 2)^{+2}_{-3} \pm 1$ fb which agrees well with the measured value of 115 ± 17 (stat) ± 30 (syst) fb from CMS

Summary

- $tq\gamma$ production in high-energy pp collisions
- NLO corrections for total cross section and top-quark and photon distributions
- soft-gluon resummation and aNNLO corrections further enhance the theoretical predictions
- good agreement with 13 TeV data