aNNLO results for $t\bar{t}\gamma$ cross sections

Nikolaos Kidonakis

in collaboration with Alberto Tonero

- $t\bar{t}\gamma$ **production**
- **Soft-gluon resummation**
- **aNNLO cross sections**
- **Top-quark p_T and rapidity distributions**

KENNESAW STATE UNIVERSITY
COLLEGE OF SCIENCE AND MATHEMATICS
Department of Physics

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$t\bar{t}\gamma$ production

observation of $t\bar{t}\gamma$ events at 7, 8, 13 TeV collisions at the LHC

the cross section for $t\bar{t}\gamma$ is sensitive to the top-quark charge and any modifications of the t-γ interaction vertex

QCD corrections at NLO are large and similar to $t\bar{t}$ production $\sim 50\%$

electroweak corrections are smaller than 1%

the QCD corrections are dominated by soft-gluon emission

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

$\rightarrow$ approximate NNLO (aNNLO) predictions

Soft-gluon corrections

processes: $pp \to t\bar{t}\gamma$

partonic processes at LO $a(p_a) + b(p_b) \to t(p_t) + \bar{t}(p_{\bar{t}}) + \gamma(p_\gamma)$

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

then we define the variable $s_4 = (p_{\bar{t}} + p_\gamma + p_g)^2 - (p_{\bar{t}} + p_\gamma)^2$

At partonic threshold $s_4 \to 0$

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

Factorization and Resummation of these soft-gluon corrections

Soft anomalous dimension $\Gamma_{S\, ab \to t\bar{t}\gamma}$ controls the evolution of the soft function

two-loop results for $\Gamma_{S\, ab \to t\bar{t}\gamma}$

Finite-order expansions $\to$ no prescription needed

Approximate NNLO (aNNLO) theoretical predictions

aNNLO = NLO + soft-gluon NNLO corrections

Soft-gluon resummation

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

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

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

Then

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

Refactorization in terms of hard and soft functions

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

Thus

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

Resummed cross section

Renormalization group evolution $\rightarrow$ resummation

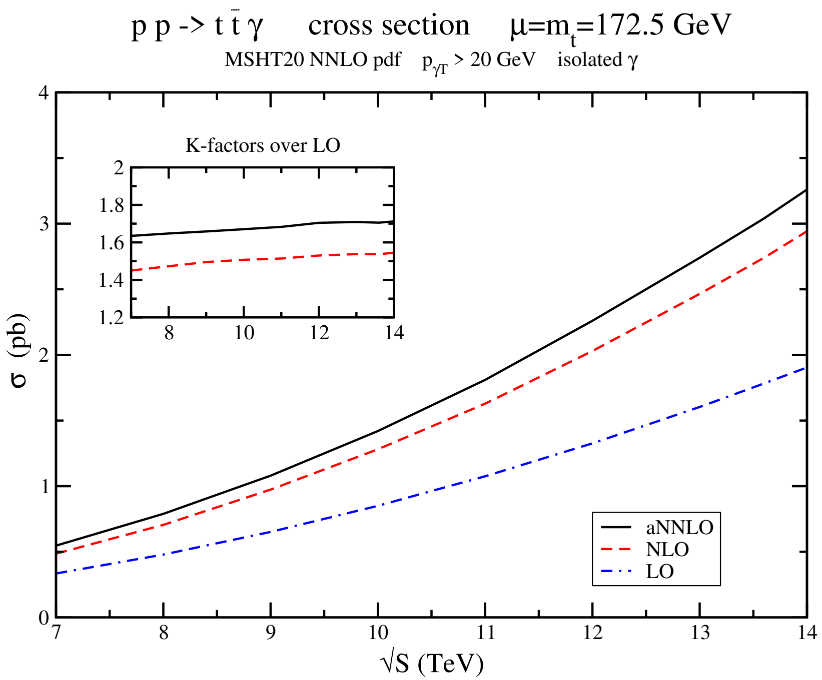
$$d\tilde{\hat{\sigma}}^{\rm resum}_{ab\to t\bar{t}\gamma}(N) = \exp\left[\sum_{i=a,b} E_i(N_i)\right] \exp\left[\sum_{i=a,b} 2\int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu}\gamma_{i/i}(N_i)\right]$$
$$\times {\rm tr}\left\{H_{ab\to t\bar{t}\gamma}\left(\alpha_s(\sqrt{s})\right) \bar{P}\exp\left[\int_{\sqrt{s}}^{\sqrt{s}/N}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

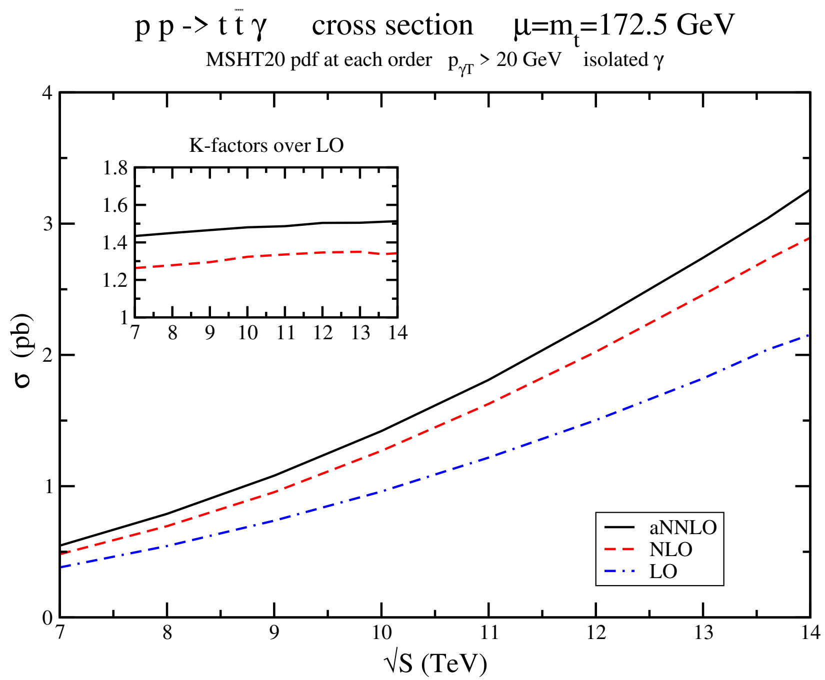
The soft anomalous dimensions $\Gamma_{S\,q\bar{q}\to t\bar{t}\gamma}$ are 2×2 matrices while $\Gamma_{S\,gg\to t\bar{t}\gamma}$ are 3×3 matrices

$\Gamma_{S\,q\bar{q}\to t\bar{t}\gamma}$ and $\Gamma_{S\,gg\to t\bar{t}\gamma}$ are known at one and two loops

Expansion of the resummed cross section and inversion to momentum space $\rightarrow$ aNNLO corrections

aNNLO cross sections for $t\bar{t}\gamma$ production





The NLO K-factors are large for all LHC energies and the further aNNLO corrections are significant

$t\bar{t}\gamma$ cross sections in pp collisions at the LHC, $p_{\gamma\,T} > 20$ GeV, isolated γ, MSHT20 NNLO pdf					
σ in pb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO QCD	$0.333^{+0.116}_{-0.080}$	$0.478^{+0.163}_{-0.113}$	$1.59^{+0.50}_{-0.35}$	$1.77^{+0.54}_{-0.39}$	$1.89^{+0.57}_{-0.41}$
LO QCD+EW	$0.335^{+0.116}_{-0.080}$	$0.479^{+0.162}_{-0.112}$	$1.60^{+0.49}_{-0.34}$	$1.78^{+0.54}_{-0.38}$	$1.90^{+0.58}_{-0.40}$
NLO QCD	$0.490^{+0.063}_{-0.065}$	$0.708^{+0.090}_{-0.094}$	$2.49^{+0.34}_{-0.33}$	$2.76^{+0.38}_{-0.36}$	$2.96^{+0.41}_{-0.38}$
NLO QCD+EW	$0.485^{+0.062}_{-0.063}$	$0.705^{+0.089}_{-0.092}$	$2.47^{+0.32}_{-0.32}$	$2.74^{+0.37}_{-0.35}$	$2.94^{+0.39}_{-0.37}$
aNNLO	$0.547^{+0.032}_{-0.027}$	$0.789^{+0.044}_{-0.040}$	$2.74^{+0.18}_{-0.16}$	$3.04^{+0.20}_{-0.16}$	$3.26^{+0.21}_{-0.17}$

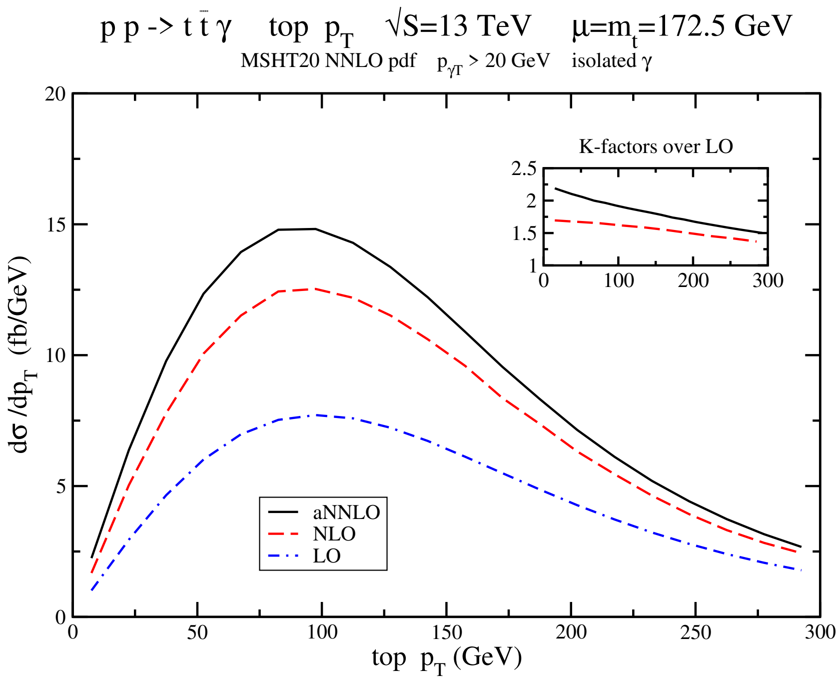
Comparison with 13 TeV CMS data

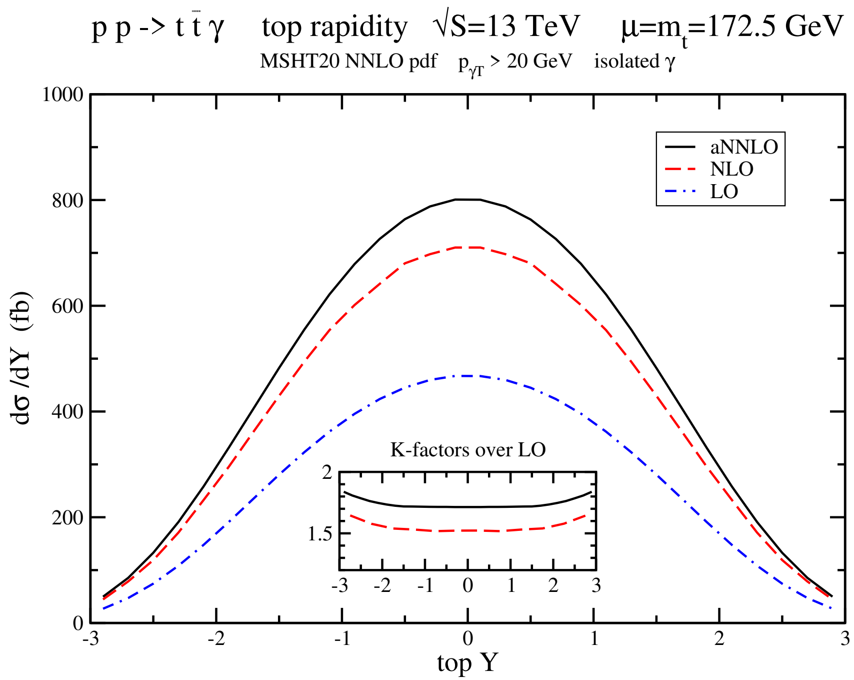
CMS measure a cross section in dilepton decay channel of 175.2 ± 2.5(stat) ± 6.3(syst) fb

which is compared to an NLO prediction (with scale + pdf uncertainty) of 155 ± 27 fb

Our aNNLO result is $173^{+11}_{-10}{}^{+3}_{-2}$ fb which is much closer to the data

Top-quark p_T and rapidity distributions in $t\bar{t}\gamma$ production





K-factors decrease at larger top p_T

K-factors are relatively flat at central and small top rapidities but increase at larger rapidities

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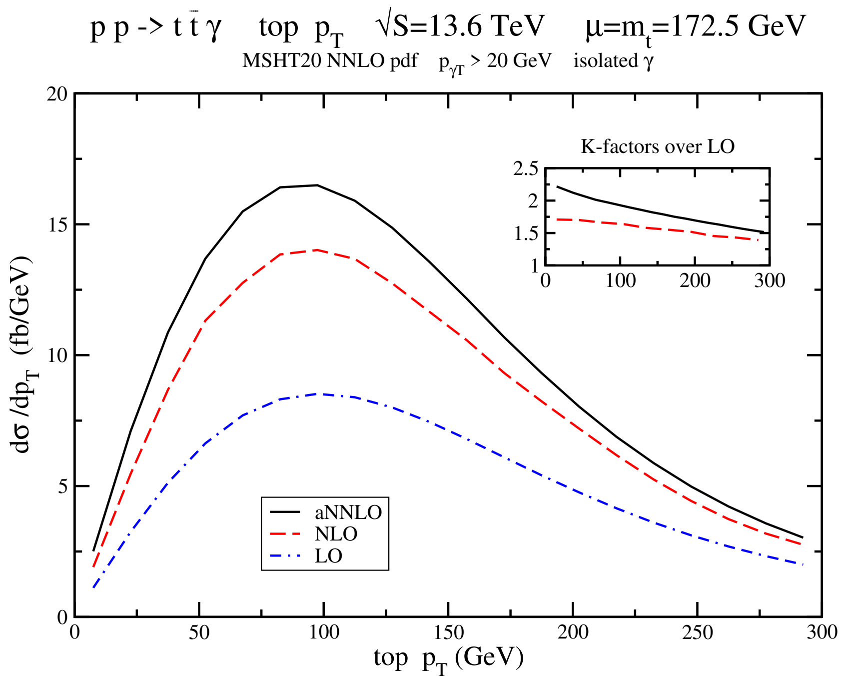

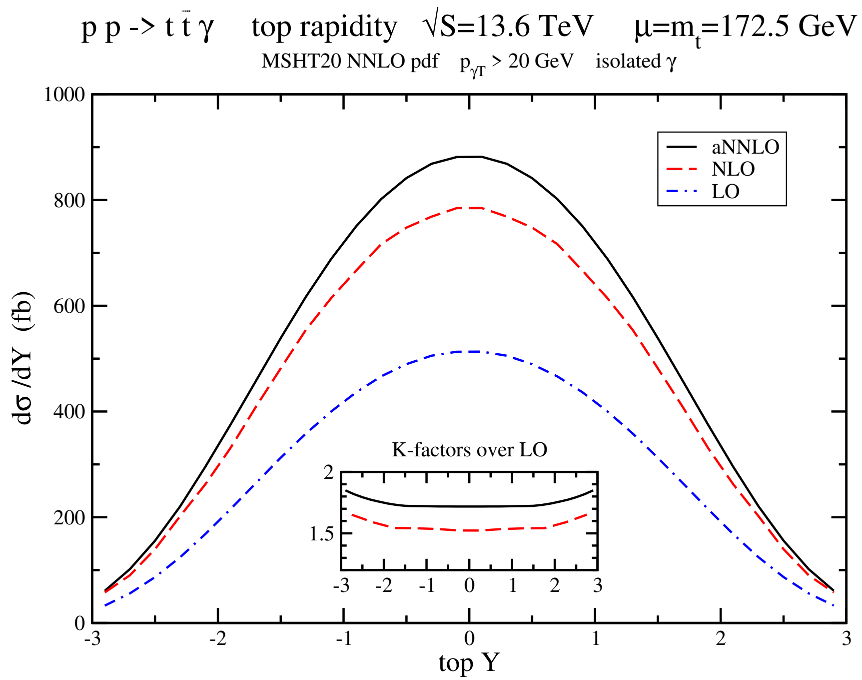

scale uncertainties in most of p_T and rapidity range are similar to those of the total cross section

a little smaller at large p_T

bigger at large rapidities

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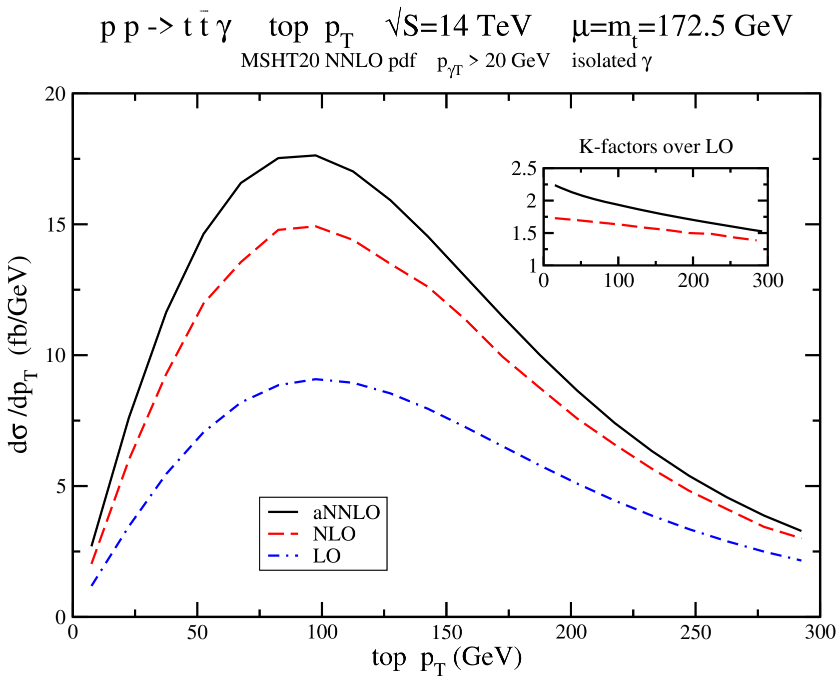

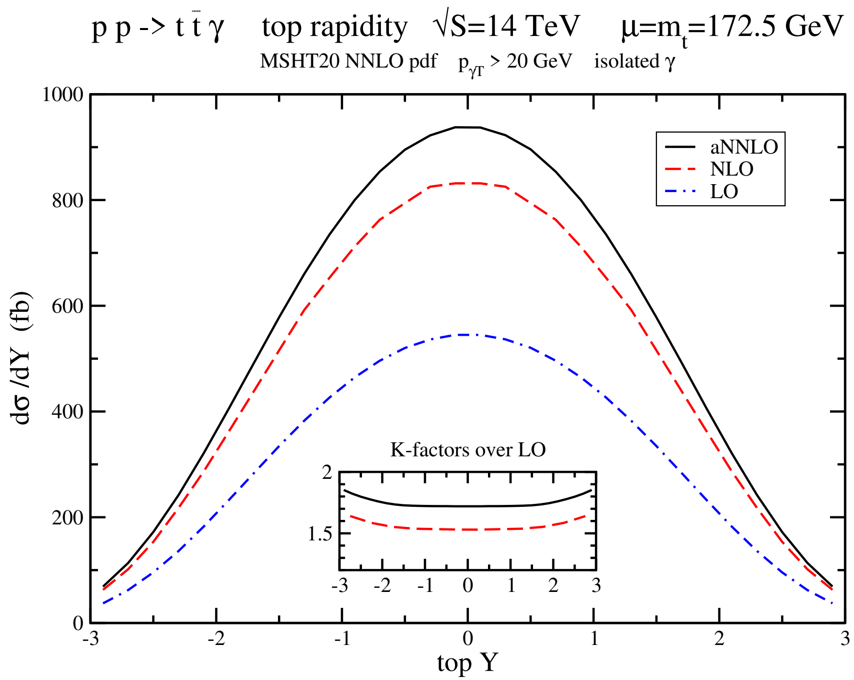

similar conclusions for all three energies

Summary

- $t\bar{t}\gamma$ **production in high-energy** pp **collisions**
- **NLO corrections for total cross section are large and similar to** $t\bar{t}$
- **EW corrections are small**
- **soft-gluon resummation and aNNLO corrections further enhance the theoretical predictions**
- **good agreement with 13 TeV data**
- **aNNLO top** p_T **and rapidity distributions**