Higher order corrections to $t\bar{t}\gamma$ cross section in the SM and Beyond

[Phys.Rev.D 107 (2023) 3, 034013 + work in progress with N. Kidonakis]

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August 8, 2023

SUSY 2023, Southampton

Motivation

- The top quark plays an important role in the search for new physics at the LHC
- $t\bar{t}\gamma$ is sensitive to the top-quark charge and to any modifications of the top-photon interaction vertex from new physics (e.g. SMEFT)
- It is very important to have precise determination of the rates
- QCD corrections at NLO are large and similar to $t\bar{t}$ ($\sim 50\%$), EW corrections are smaller that 1%
- QDC corrections dominated by soft-gluon emissions (for instance, excellent approximations at NLO and NNLO to the full $t\bar{t}$ calculation [N. Kidonakis, 1806.03336])
- We calculate total cross sections and differential distributions at approximate NNLO order (aNNLO): soft-gluon corrections at second order in QCD are added to the exact QCD+EW NLO results

Soft-gluon corrections and resummation

Soft-gluon corrections

- Partonic processes contributing to $pp \to t\bar{t}\gamma$

$$f_1(p_1) \, + \, f_2\,(p_2) \to t(p_t) \, + \, \bar{t}(p_{\bar{t}}) \, + \, \gamma(p_\gamma)$$

- At LO, the partonic channels are $q\bar{q} \to t\bar{t}\gamma$ and $gg \to t\bar{t}\gamma$
- Additional gluon emission in the final state with momentum p_g
- Define a partonic threshold variable $s_4 = (p_{\bar{t}} + p_\gamma + p_g)^2 - (p_{\bar{t}} + p_\gamma)^2$
- When $p_g \to 0$ we approach the partonic threshold and $s_4 \to 0$
- Soft-gluon corrections take the form of plus distributions of logarithms of s_4:

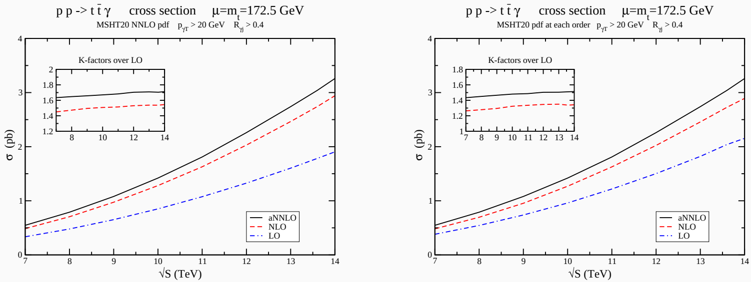
$$[(\ln^k(s_4/m_t^2))/s_4]_+$$

with $0 \leq k \leq 2n - 1$ at nth order in α_s

- Soft-gluon corrections factorize and can be resummed using RG
- The soft anomalous dimension $\Gamma_{S\,ab\to t\bar{t}\gamma}$ controls the evolution of the soft function $\tilde{S}_{ab\to t\bar{t}\gamma}$
- Finite order expansion of the resummed result (no prescription needed)
- aNNLO = NLO QCD+EW + soft-gluon NNLO corrections
- NLO QCD+EW rates obtained with `MadGraph5 aMC@NLO` [following D. Pagani et al. 2106.02059]

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

Results



Total cross section at LO, NLO, and aNNLO for $t\bar{t}\gamma$ production in pp collisions at LHC energies using MSHT20 NNLO pdf (left) and MSHT20 pdf at each order (right). The NLO K-factors are large for all LHC energies and aNNLO corrections are significant

Table of results with scale uncertainties for MSHT20 NNLO pdf

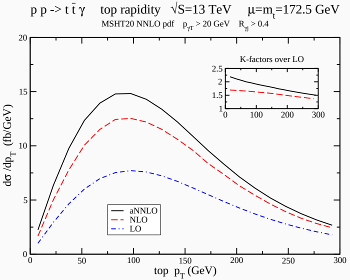
$t\bar{t}\gamma$ cross sections in pp collisions at the LHC, $p_{\gamma\,T} > 20$ GeV, isolated γ, NNLO pdf					
σ in pb	7 TeV	8 TeV	13 TeV	13.6 TeV	14 TeV
LO QCD	$0.333^{+0.116}_{-0.080}$	$0.478^{+0.163}_{-0.113}$	$1.59^{+0.50}_{-0.35}$	$1.77^{+0.54}_{-0.39}$	$1.89^{+0.57}_{-0.41}$
LO QCD+EW	$0.335^{+0.116}_{-0.080}$	$0.479^{+0.162}_{-0.112}$	$1.60^{+0.49}_{-0.34}$	$1.78^{+0.54}_{-0.38}$	$1.90^{+0.58}_{-0.40}$
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	$0.547^{+0.032}_{-0.027}$	$0.789^{+0.044}_{-0.040}$	$2.74^{+0.18}_{-0.16}$	$3.04^{+0.20}_{-0.16}$	$3.26^{+0.21}_{-0.17}$

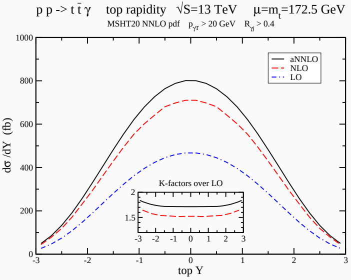
- aNNLO results with pdf uncertainties (are smaller than scale): $2.74^{+0.18+0.04}_{-0.16-0.03}$ pb at 13 TeV; $3.04^{+0.20+0.06}_{-0.16-0.03}$ pb at 13.6 TeV; and $3.26^{+0.21+0.06}_{-0.17-0.03}$ pb at 14 TeV
- K-factors over LO QCD at 13 TeV (central values):

$$K_{\rm NLO}^{\rm QCD} = 1.57 \qquad K_{\rm NLO}^{\rm QCD+EW} = 1.55 \qquad K_{\rm aNNLO}^{\rm QCD+EW} = 1.72$$

- CMS di-lepton channel measurement [2201.07301]: 175.2 ± 2.5(stat) ± 6.3(syst) fb (compared to an NLO prediction of 155 ± 27 fb)
- Our prediction: 173^{+14}_{-12} fb (better agreement!)

Differential distributions at 13 TeV





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

SMEFT contributions to $t\bar{t}\gamma$

SMEFT lagrangian

- Dimension-six effective lagrangian [Grzadkowski et al. 1008.4884]

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathrm{h.c.}$$

Λ is the scale of new physics and c_i are Wilson coefficients

- Consider the following EW dipole operator [CMS 2107.01508 and 2201.07301]

$$\frac{c_{tW} + i\, c^I_{tW}}{\Lambda^2}\, \bar{q}_{3L}\sigma_{\mu\nu}\sigma^I t_R \tilde{\varphi} W^{\mu\nu}_I + \mathrm{h.c.}$$

- Anomalous γtt couplings [Aguilar-Saavedra 2008]

$$V_{\gamma tt} = -e\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(d^\gamma_V + i d^\gamma_A \gamma_5) t A_\mu$$

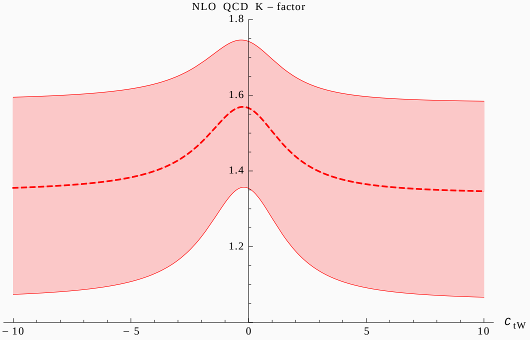
where $d^\gamma_V = \frac{\sqrt{2}}{e}\frac{c_{tW}}{\sin\theta_W}\frac{\upsilon\, m_t}{\Lambda^2}$ $\qquad d^\gamma_A = \frac{\sqrt{2}}{e}\frac{c^I_{tW}}{\sin\theta_W}\frac{\upsilon\, m_t}{\Lambda^2}$

- Cross section as function of c_{tW}:

$$\sigma(c_{tW}) = \sigma_{\rm SM} + \frac{c_{tW}}{(\Lambda/1\rm TeV)^2}\sigma_{\rm int} + \frac{c_{tW}^2}{(\Lambda/1\rm TeV)^4}\sigma_{\rm BSM}$$

- NLO QCD K-factor as function of c_{tW}:

$$K_{\rm NLO}^{\rm QCD}(c_{tW}) = \frac{\sigma_{\rm NLO}(c_{tW})}{\sigma_{\rm LO}(c_{tW})}$$



Summary

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- We have provided higher-order corrections for $t\bar{t}\gamma$ production at the LHC in the SM. We have included complete QCD and EW corrections at NLO as well as soft-gluon corrections at aNNLO.
- The total cross sections get large enhancements from the complete NLO QCD corrections (30 to 50%), EW effects negligible
- The additional aNNLO QCD corrections are significant (10 to 20% enhancement) and reduce the theoretical uncertainties
- $t\bar{t}\gamma$ is a process included in SMEFT global analysis
- SMEFT global analysis need precise theoretical predictions to improve sensitivity to new physics
- The next step is to produce aNNLO results for $t\bar{t}\gamma$ in the presence of SMEFT operators (in progress)

Thank you

BACK UP

Soft gluon resummation formalism

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

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

Taken from N. Kidonakis DIS 2023 talk

Resummed cross section

Renormalization group evolution → resummation

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

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 → aNNLO corrections

Taken from N. Kidonakis DIS 2023 talk