Photon associated top-quark pair production

A study at NLO QCD with off-shell effects

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LoopFest 2018
Michigan State University
17. July 2018

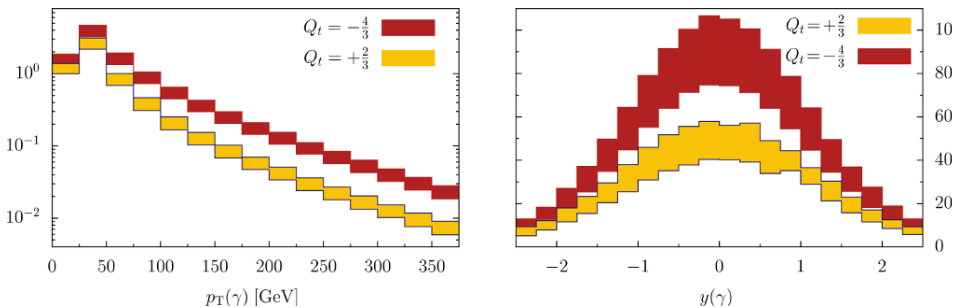
Outline

- Motivation
- Current status of $t\bar{t}\gamma$
- NWA vs. off-shell effects
- Results for $t\bar{t}\gamma$ in di-lepton channel
- Conclusions

Motivation for $t\bar{t}\gamma$

The study of (associated) $t\bar{t}$ production has a wide range of applications...

- SM benchmarks (e.g. $t\bar{t}$ cross section)
- precision measurements of SM parameters (e.g. m_t)
- probing Higgs-Yukawa sector (e.g. $t\bar{t}H$)
- constraining PDFs (especially gluon at large x)
- searches for BSM physics (e.g. heavy resonances decaying to tops)
- $t\bar{t}\gamma$ direct measurement of top charge $\sigma_{t\bar{t}\gamma} \sim Q_t^2$
- Indirect from $t\bar{t}$: $Q_t = Q_W - Q_{b-jet} = +\frac{2}{3}$



[Melnikov, Schulze, Scharf '11]

Motivation for $t\bar{t}\gamma$

- Probe the structure of the $t\bar{t}\gamma$ vertex

$$\mathcal{L}_{t\bar{t}\gamma} = -eQ_t\,\bar{t}\gamma^\mu t A_\mu - e\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(d_V^\gamma + id_A^\gamma\gamma_5)tA_\mu$$

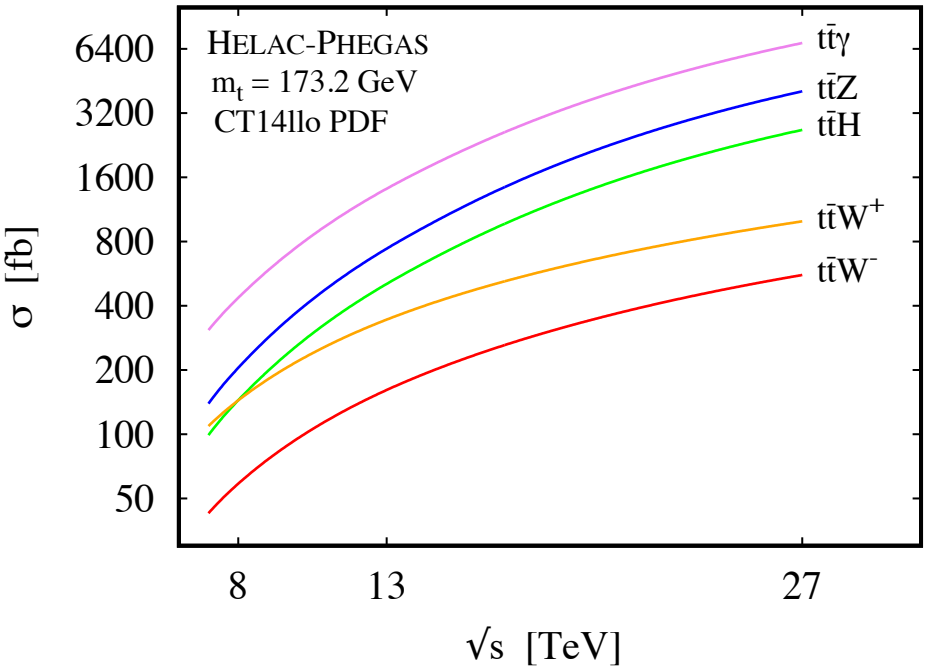
[Aguilar-Saavedra '09]

- Constraints on anmalous couplings
- Measure cross section ratio

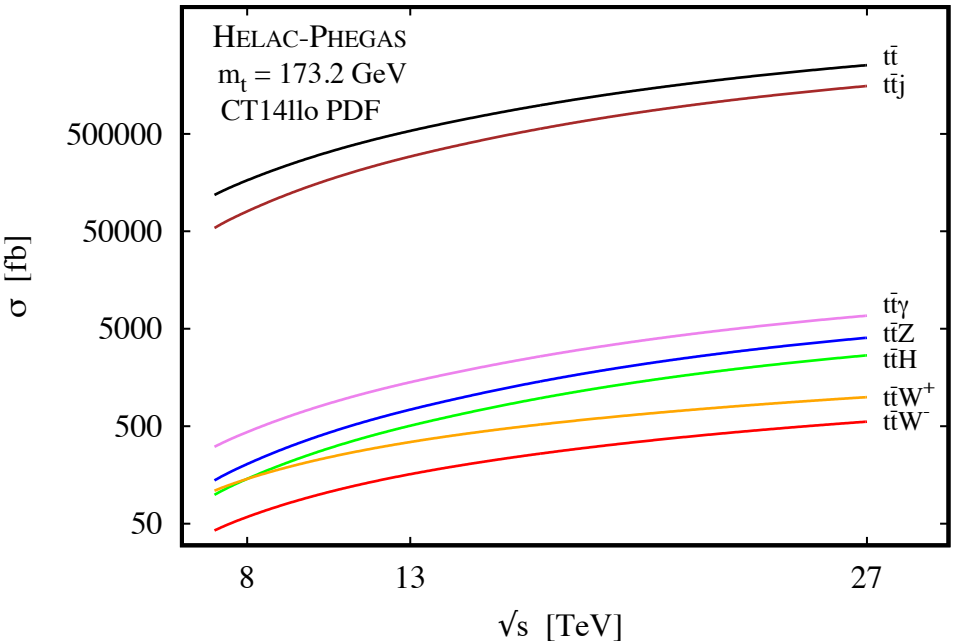
$$\mathcal{R} = \frac{\sigma_{pp\to t\bar{t}\gamma}}{\sigma_{pp\to t\bar{t}}}\,, \qquad \frac{d\mathcal{R}}{dX} = \frac{d\sigma_{pp\to t\bar{t}\gamma}/dX}{d\sigma_{pp\to t\bar{t}}/dX}$$

  - Various uncertainties cancel in ratio
  - More stable with respect to radiative corrections
  - Can probe new physics at the LHC

Motivation for $t\bar{t}\gamma$



Motivation for $t\bar{t}\gamma$



Status of $t\bar{t}\gamma$

Experimental:

- First evidence: CDF @ TeVatron [CDF Collaboration '11]
- Observation: ATLAS @ LHC 7 TeV [ATLAS Collaboration '15]
- Measurements: LHC 8 TeV [ATLAS, CMS Collaboration '16]

on-shell tops: Corrections only to the production mechanism

- NLO QCD fixed-order

  [Duan, Guo, Han, Ma, Wang, Zhang '09 '11]

  [Maltoni, Pagani, Tsinikos '15]
- NLO EW fixed-order

  [Duan, Guo, Han, Ma, Wang, Zhang '16]

Towards more realistic final states

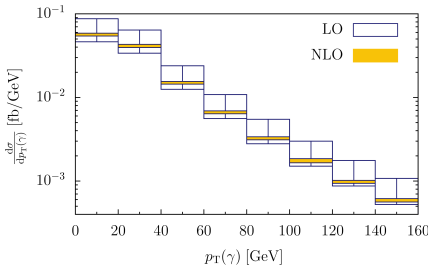
- Powheg + Pythia → no spin correlations, top decay in PS

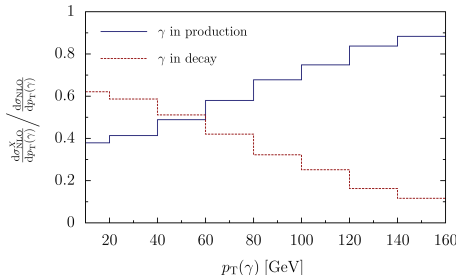
  [Kardos, Trocsanyi '14]
- NLO QCD in NWA → spin correlated, radiative decays

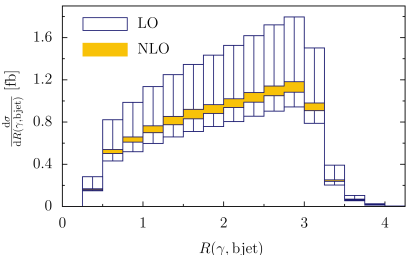
  [Melnikov, Schulze, Scharf '11]
- Full off-shell calculation in dilepton channel

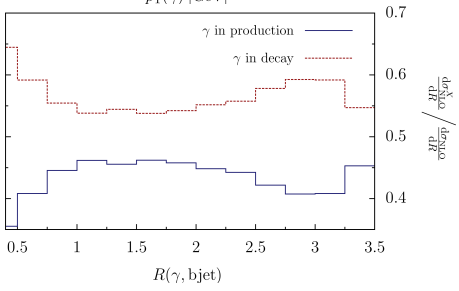
  [Bevilacqua, Hartanto, MK, Weber, Worek '18]

$t\bar{t}\gamma$ in NWA @ LHC







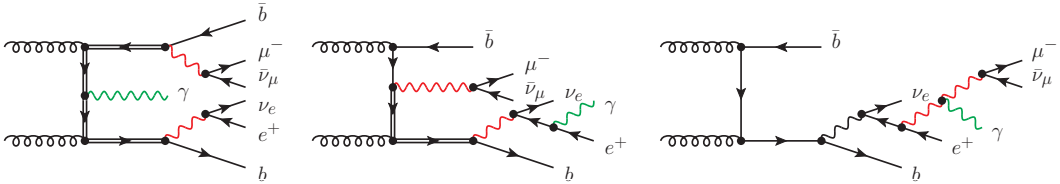


Large contribution from radiative top decays

$$\sigma^{\text{NLO}} = 138.1\text{fb} \qquad \sigma^{\text{NLO}}_{\gamma-Prod.} = 60.9\text{fb}\,, \qquad \sigma^{\text{NLO}}_{\gamma-Dec.} = 77.2\text{fb}$$

[Melnikov, Schulze, Scharf '11]

Quality of the NWA?



[Double-resonant] [Single-resonant] [Non-resonant]

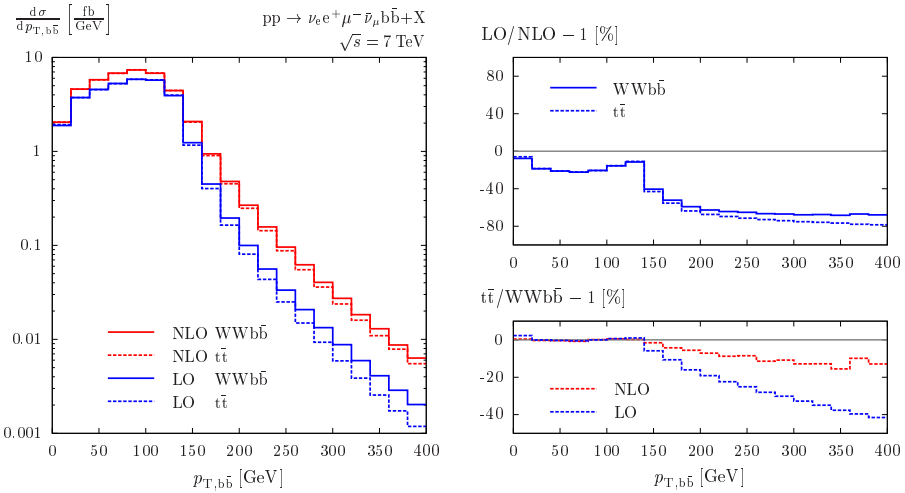
- NWA:

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \to \frac{\pi}{m_t\Gamma_t}\delta(p^2 - m_t^2) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

- Keep diagrams with only two resonant top-quarks
- Sufficiently accurate for inclusive observables: $\Gamma_t/m_t \sim 0.8\%$
- Confirmed case-by-case:
  - $t\bar{t}$ (di-lepton) [Denner, Dittmaier, Kallweit, Pozzorini '11'12] [Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11]
  - $t\bar{t}$ (semi-lepton) [Denner, Pellen '18]
  - $t\bar{t}H$ (di-lepton) [Denner, Feger '18]
  - $t\bar{t}j$ (di-lepton) [Bevilacqua, Hartanto, MK, Worek '16'18]
  - $t\bar{t}\gamma$ (di-lepton) [Bevilacqua, Hartanto, MK, Weber, Worek '18]

NWA vs. Off-shell effects in $t\bar{t}$

- Comparison: NWA @ NLO QCD vs. Full off-shell @ NLO QCD
- Large off-shell effects, where $t\bar{t}$ is suppressed as a signal
- Important as background to Higgs and BSM searches

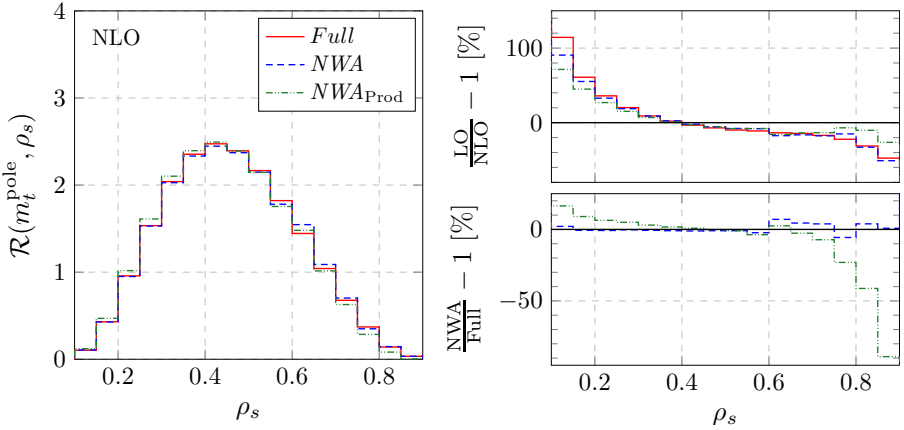


[Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12]

NWA vs. Off-shell effects in $t\bar{t}j$

Can impact top-quark mass determination in $pp \to t\bar{t}j$

$$\mathcal{R}(m_t, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t, \rho_s) \qquad \rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$$



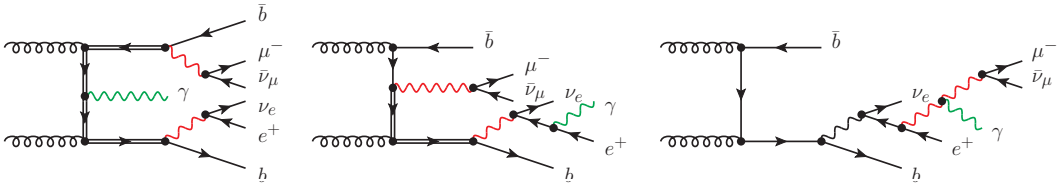
[Bevilacqua, Hartanto, MK, Worek, Schulze '18]

NWA vs. Off-shell effects in $t\bar{t}j$

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
		31 bins		
Full, $\mu_0 = H_T/2$	173.38 ± 1.34	1.04	0.40 (0.8σ)	-0.18
Full, $\mu_0 = E_T/2$	172.84 ± 1.33	1.05	0.39 (0.9σ)	$+0.36$
Full, $\mu_0 = m_t$	174.11 ± 1.39	1.07	0.37 (0.9σ)	-0.91
NWA, $\mu_0 = m_t$	175.70 ± 0.96	1.17	0.24 (1.2σ)	-2.50
$NWA_{Prod.}$, $\mu_0 = m_t$	169.93 ± 0.98	1.20	0.20 (1.3σ)	$+3.27$
		5 bins		
Full, $\mu_0 = H_T/2$	173.15 ± 1.32	0.93	0.44 (0.8σ)	$+0.05$
Full, $\mu_0 = E_T/2$	172.55 ± 1.18	1.07	0.37 (0.9σ)	$+0.65$
Full, $\mu_0 = m_t$	173.92 ± 1.38	1.48	0.20 (1.3σ)	-0.72
NWA, $\mu_0 = m_t$	175.54 ± 0.97	1.38	0.24 (1.2σ)	-2.34
$NWA_{Prod.}$, $\mu_0 = m_t$	169.37 ± 1.43	1.16	0.33 (1.0σ)	$+3.83$

[Bevilacqua, Hartanto, MK, Worek, Schulze '18]

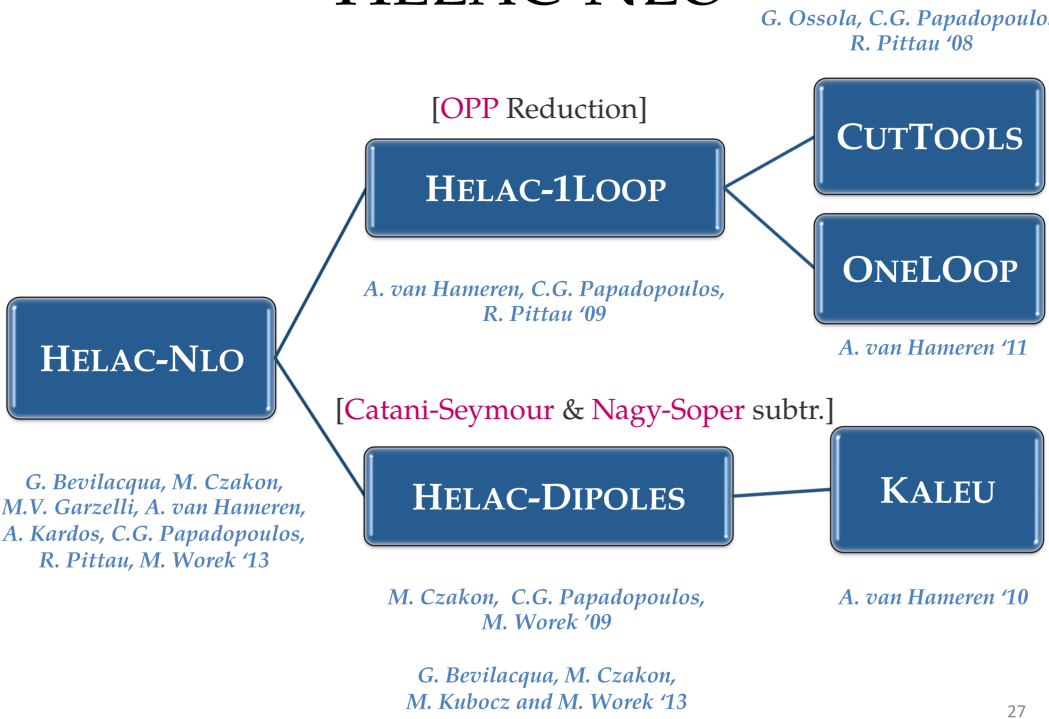
Full off-shell $t\bar{t}\gamma$ @ NLO



- 628 diagrams for gg channel for $t\bar{t}\gamma$ @ $\mathcal{O}(\alpha_s^2\alpha^5)$
- 36032 one-loop diagrams for gg channel for $t\bar{t}\gamma$ @ $\mathcal{O}(\alpha_s^3\alpha^5)$
  - includes up to 958 hexagons and 90 heptagons
  - scalar integrals with complex masses
  - NWA only up to pentagons!
- Number of sutraction terms for representative subprocesses

Subprocess	# Diags	# CS dipoles	# NS dipoles
$gg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma g$	4348	27	9
$qg \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma q$	2344	15	5
$\bar{q}g \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma \bar{q}$	2344	15	5
$q\bar{q} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma g$	2344	15	5

HELAC-NLO



- NEW: Ntuple generation + re-weighting for different $\mu_{R,F}$ and PDFs

Final state and parameters

- Fully leptonic decays: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$
- Light quarks (also bottom) and leptons are massless → 5 FS
- Top quark mass and width: [Jesabek,Kühn,'99, Denner et al. '12]
  $m_t = 173.2\,\text{GeV}$ $\Gamma_t^{\text{LO}} = 1.47834\,\text{GeV}$ $\Gamma_t^{\text{NLO}} = 1.35146\,\text{GeV}$
- Complex Mass Scheme: $m_t^2 \to m_t^2 - im_t\Gamma_t$ [Denner et al. '99, '05]

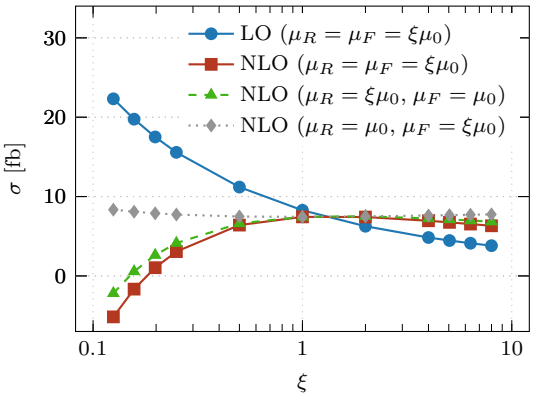
Kinematics

- exactly 2 b-jets, 1 photon, 2 charged leptons, missing p_T
- partons with $|\eta| < 5$, anti-k_T, $\Delta R = 0.4$
- cuts:

$$p_{T\,\ell} > 30\,\text{GeV}\,, \quad p_{T\,b} > 40\,\text{GeV}\,, \quad \not{p}_T > 20\,\text{GeV}\,, \quad p_{T,\gamma} > 25\,\text{GeV}\,,$$
$$\Delta R_{bb} > 0.4\,, \quad \Delta R_{\ell\ell} > 0.4\,, \quad \Delta R_{\ell b} > 0.4\,,$$
$$|y_\ell| < 2.5\,, \quad |y_b| < 2.5\,, \quad |y_\gamma| < 2.5$$

- Frixione isolation: $R_{\gamma i} = 0.4$ [Frixione '98]
- For hard photon: $\alpha = \alpha(0) = 1/137$

Inclusive cross section



$$\sigma^{\text{LO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma+X} = 8.27^{+2.92\ (+35\%)}_{-2.01\ (-24\%)}\ \text{fb}$$

$$\sigma^{\text{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma+X} = 7.44^{+0.07\ (+\ 1\%)}_{-1.03\ (-14\%)}\ \text{fb}$$

$$\frac{1}{2} < \mu_R/\mu_F < 2$$

- fixed scale: $\mu_0 = m_t/2$
- at LO: $gg \sim 79\%$, and $q\bar{q} \sim 21\%$
- Photon radiation dominated by final state radiation
- NLO corrections: -10%

[Bevilacqua, Hartanto, MK, Weber, Worek '18]

Cross section ratio

- Assuming same setup for LO and NLO

$$\mathcal{R} = \frac{\sigma^{\text{LO}}_{t\bar{t}\gamma}}{\sigma^{\text{LO}}_{t\bar{t}}} = (4.94 \pm 0.08) \cdot 10^{-3}$$

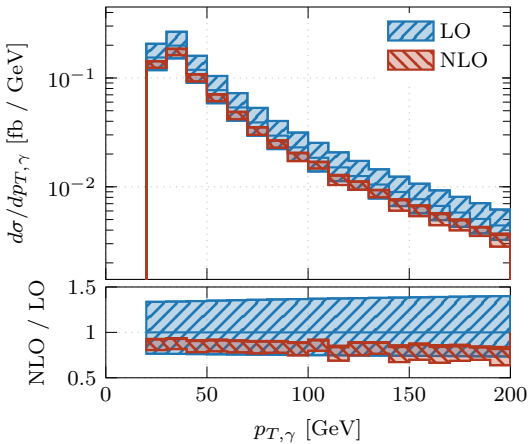
$$\mathcal{R} = \frac{\sigma^{\text{NLO}}_{t\bar{t}\gamma}}{\sigma^{\text{NLO}}_{t\bar{t}}} = (4.56 \pm 0.28) \cdot 10^{-3}$$

- uncertainties from scale dependence assuming correlation of the processes
- -8% NLO corrections
- $\pm 6\%$ scale uncertainties at NLO $\rightarrow$ underestimated at LO
- Ratio more stable against radiative corrections
- Allows to probe new physics at the LHC

[Bevilacqua, Hartanto, MK, Weber, Worek '18]

Distributions

- Impact of corrections on differential distributions?
- Focus on BSM relevant observables [Baur, Buice, Orr '01]
  $p_{T,\gamma}$ and $\Delta R(b_2, \gamma)$ [Baur, Juste, Orr, Rainwaiter '04]



- $p_{T,\gamma}$
- Uncertainties: (μ_R, μ_F) envelopes
- K-factor: -8% to -18%
- Stable wrt radiative corrections
- Good candidate for BSM searches

[Bevilacqua, Hartanto, MK, Weber, Worek '18]

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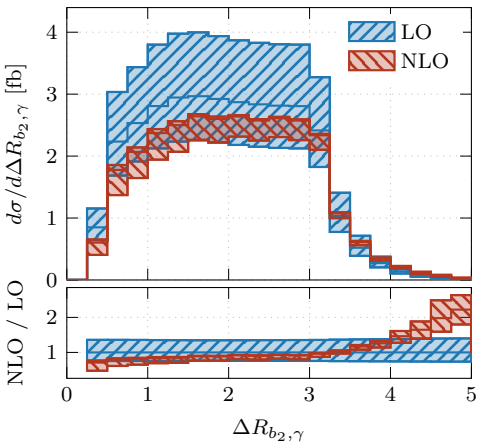
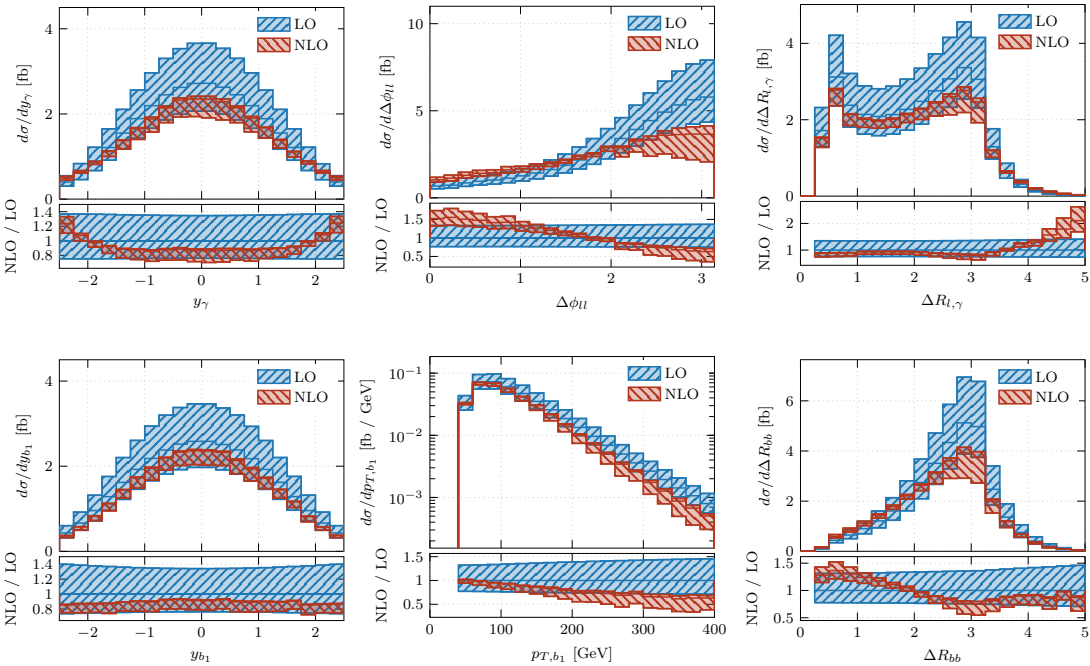


- $\Delta R(b_2, \gamma)$
- Uncertainties: (μ_R, μ_F) envelopes
- K-factor: −29% to +122%
- Shape distortion up to 150%
- Similar effect in other observables

[Bevilacqua, Hartanto, MK, Weber, Worek '18]

Distributions



[Bevilacqua, Hartanto, MK, Weber, Worek '18]

Conclusions

Full calculation of $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$ at NLO QCD

arXiv:1803.09916

- NLO QCD corrections for $t\bar{t}\gamma$ with all resonant and non-resonant contributions completed
- Includes:
  - QCD corrections to production and radiative decays of tops
  - Photon radiation from tops and top decay products
  - Spin correlated top decays
  - off-shell effects
  - QCD corrections to non-resonant background processes

Outlook:

- Dynamical scales, PDF uncertainties
- Comparison with NWA approximation
- Anomalous top-quark couplings

$$\mathcal{L}_{t\bar{t}\gamma} = -eQ_t\,\bar{t}\gamma^\mu t A_\mu - e\bar{t}\frac{i\sigma^{\mu\nu}q_\nu}{m_t}(d_V^\gamma + id_A^\gamma\gamma_5)tA_\mu$$

- Relevant for BSM searches

$$\mathcal{R} = \frac{\sigma_{t\bar{t}\gamma}}{\sigma_{t\bar{t}}}\,, \quad \frac{d\mathcal{R}}{dX} = \frac{\sigma_{t\bar{t}\gamma}/dX}{\sigma_{t\bar{t}}/dX}$$