# Photon associated top-quark pair production

## Precise cross section ratios for $t\bar{t}\gamma/t\bar{t}$

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# Motivations for $t\bar{t}\gamma$

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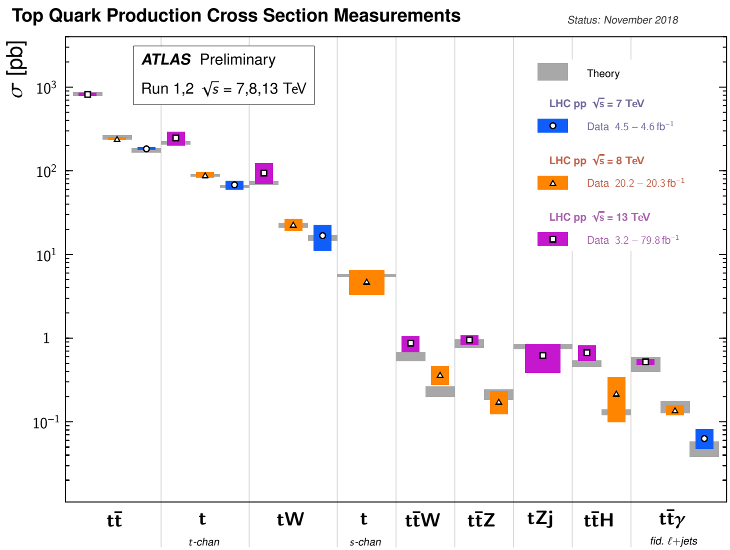



- At the LHC @ 13 TeV rare top-quark processes become accessible
- A new window for precision measurements of top-quark properties

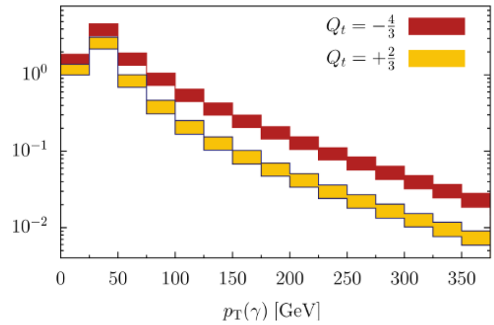
# Motivations for $t\bar{t}\gamma$

Direct probe of top quark charge

$$\sigma_{t\bar{t}\gamma} \sim Q_t^2$$

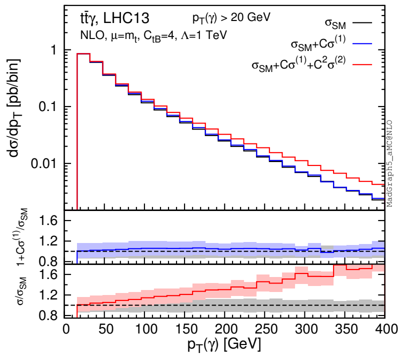
Indirect from $t\bar{t}$

$$Q_t = Q_W - Q_b$$




[Melnikov, Scharf, Schulze '11]

[Bessidskaia Bylund, Maltoni et al. '16]




Probe top-quark couplings to EW bosons

- SMEFT: $\mathscr{L}_6$ operators
- anomalous couplings

[Baur et al. '05, Aguilar Saavedra '09]

[Schulze et al.'16, Maltoni et al.'16]

# NLO predictions 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]
- Measurements: LHC 13 TeV [ATLAS Collaboration '18]

**on-shell tops:** Corrections only to the production mechanism

- NLO QCD/EW fixed-order

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

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

  [Maltoni, Pagani, Tsinikos '15]

**Towards more realistic final states**

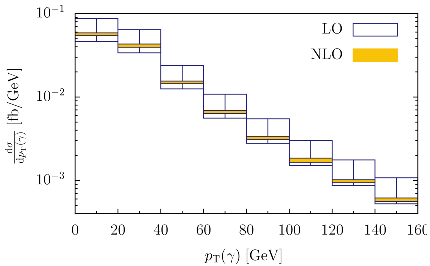
- Powheg + Pythia $\longrightarrow$ no spin correlations, top decay in PS

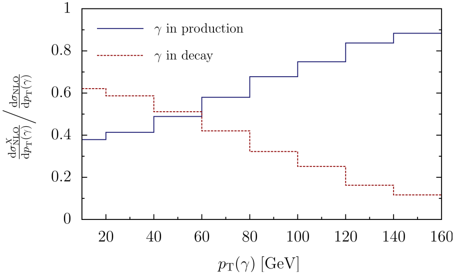
  [Kardos, Trocsanyi '14]
- NLO QCD in NWA $\longrightarrow$ spin correlated, radiative decays

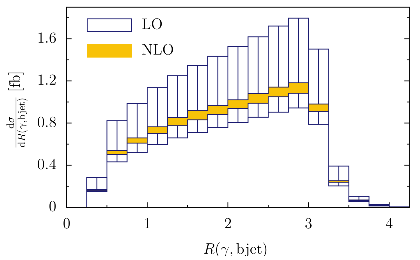
  [Melnikov, Schulze, Scharf '11]
- Full off-shell calculation in dilepton channel

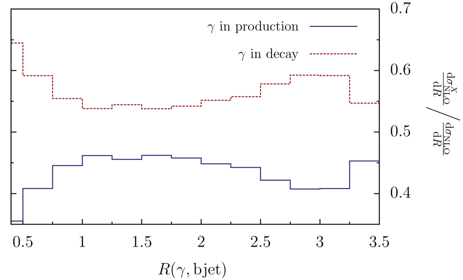
  [Bevilacqua, Hartanto, MK, Weber, Worek '18]

# $t\bar{t}\gamma$ in NWA @ LHC 14 TeV



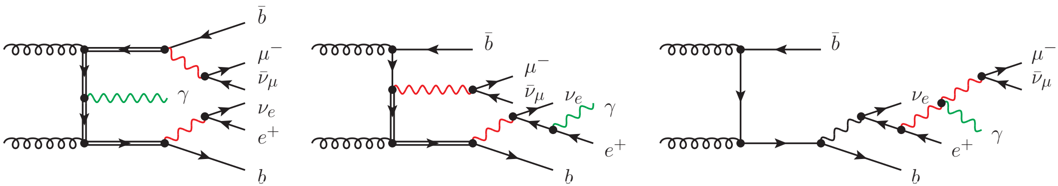




**Large contribution from radiative top decays**

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

[Melnikov, Schulze, Scharf ’11]

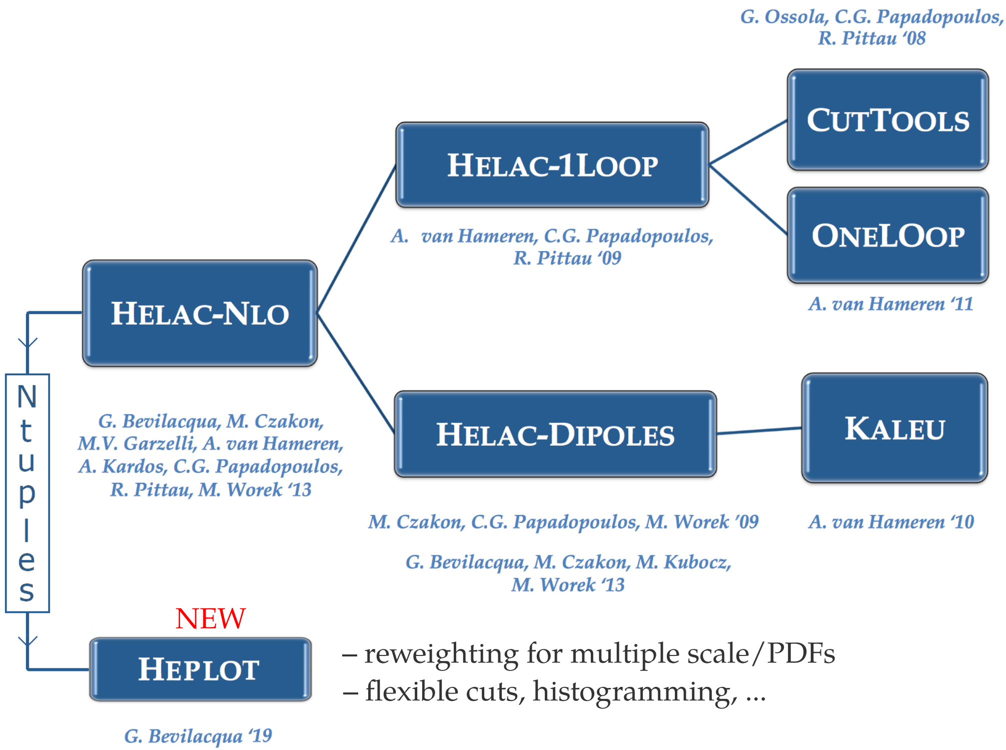
# Full off-shell $t\bar{t}\gamma$ @ NLO




- 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 |

# The HELAC-NLO framework



# Setup for LHC 13 TeV

## Final state and parameters

- Fully leptonic decays: $pp \longrightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$
- Light quarks (also bottom) and leptons are massless $\longrightarrow$ 5 FS

## Kinematics

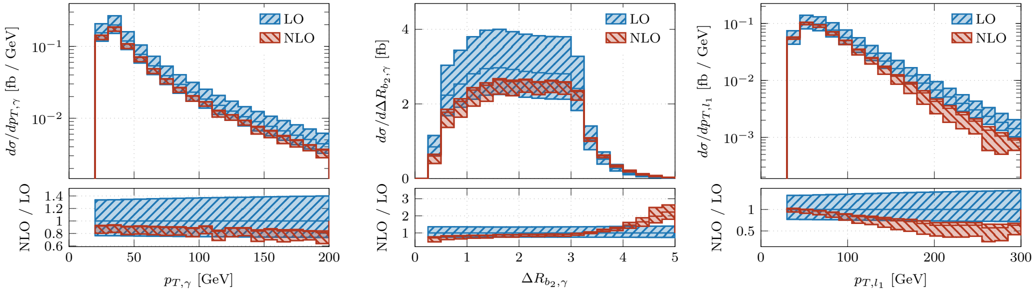
- exactly 2 b-jets, 1 photon, 2 charged leptons, missing $p_T$
- partons with $|\eta| < 5$, anti-$k_T$, $\Delta R = 0.4$
- cuts:

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

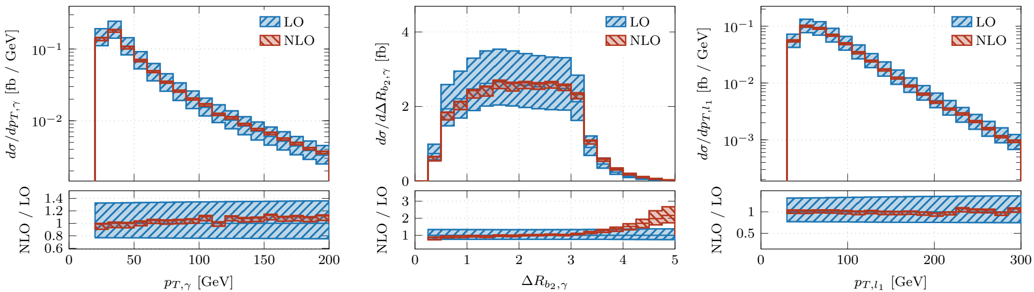
- Frixione isolation: $R_{\gamma i} = 0.4$ [Frixione '98]
- For hard photon: $\alpha = \alpha(0) = 1/137$

# Differential cross sections

## $\mu_0 = m_t/2$




## $\mu_0 = H_T/4$




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

# Cross section ratios for $t\bar{t}\gamma/t\bar{t}$

# The cross section ratio

Can we decrease theoretical uncertainties further for $t\bar{t}\gamma$ by using ratios?

$$R = \frac{\sigma(pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma)}{\sigma(pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b})}$$

## Advantages

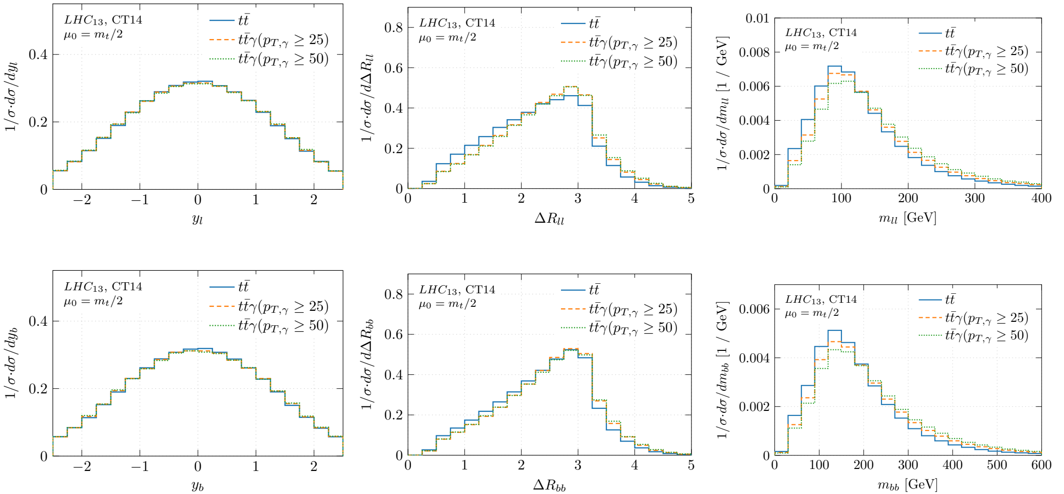
- Experiment: more accurate measurement
  - Cancellation of common systematics, e.g.. luminosity, jet energy, ...
- Theory: more precise predictions
  - Cancellation of theoretical uncertainties, e.g. scale/PDF variation if the processes are correlated

    [Melnikov, Scharf, Schulze ’11; Mangano, Rojo ’12; Bevilacqua, Worek ’14; Schulze, Soreq ’16 ...]

How strong is the corellation between $t\bar{t}\gamma$ and $t\bar{t}$?

# Correlated kinematics

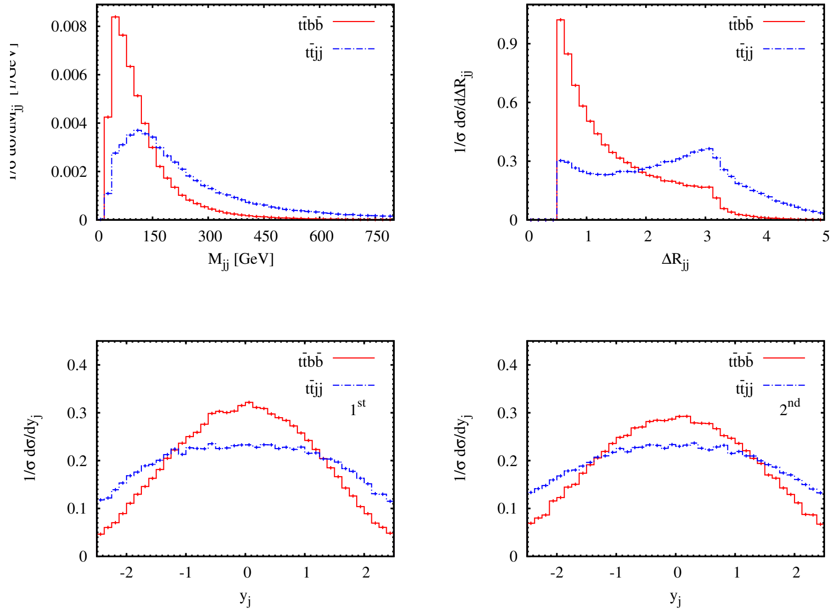
## Shape of distributions for $t\bar{t}\gamma$ vs. $t\bar{t}$




$t\bar{t}\gamma$ and $t\bar{t}$ are strongly correlated!

Shape of distributions for $t\bar{t}b\bar{b}$ vs. $t\bar{t}jj$

[Bevilacqua, Worek '14]




$t\bar{t}b\bar{b}$ and $t\bar{t}jj$ are uncorrelated!

[Bevilacqua,Hartanto,Kraus,Weber,Worek '19]

- Ratio for CT14 PDF set and $p_{T,\gamma} > 25$ GeV

$$R(\mu_0 = m_t/2) = (4.56 \pm 0.25) \cdot 10^{-3} \qquad (5\%)$$
$$R(\mu_0 = H_T/4) = (4.62 \pm 0.06) \cdot 10^{-3} \qquad (1\%)$$

- Ratio for CT14 PDF set and $p_{T,\gamma} > 50$ GeV

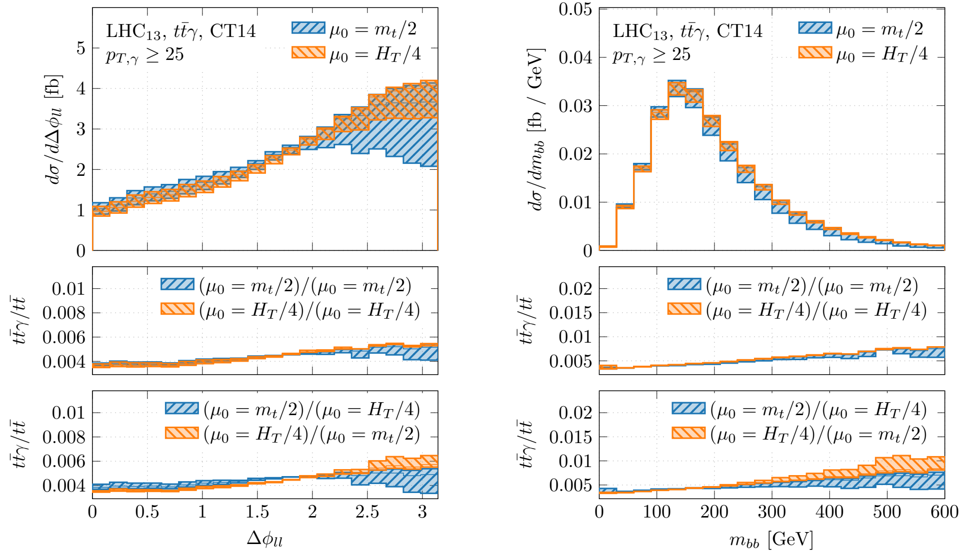
$$R(\mu_0 = m_t/2) = (1.89 \pm 0.16) \cdot 10^{-3} \qquad (8\%)$$
$$R(\mu_0 = H_T/4) = (1.93 \pm 0.06) \cdot 10^{-3} \qquad (3\%)$$

- Best predictions with dynamical scale choice

$$R(\mu_0 = H_T/4, p_{T,\gamma} > 25\ \text{GeV}) = (4.62 \pm 0.06\ [\text{scales}] \pm 0.02\ [\text{PDFs}]) \cdot 10^{-3}$$
$$R(\mu_0 = H_T/4, p_{T,\gamma} > 50\ \text{GeV}) = (1.93 \pm 0.06\ [\text{scales}] \pm 0.02\ [\text{PDFs}]) \cdot 10^{-3}$$

# Differential cross section ratios – $t\bar{t}\gamma/t\bar{t}$

[Bevilacqua,Hartanto,Kraus,Weber,Worek '19]




Correlation reduces uncertainties:

$$\text{e.g. } \Delta\phi_{\ell\ell} \approx 3 : \quad \underbrace{\mathcal{O}(50\%)}_{abs(m_t/2)} \to \underbrace{\mathcal{O}(20\%)}_{abs(H_T/4)} \quad \Leftrightarrow \quad \underbrace{\mathcal{O}(30\%)}_{rat(m_t/2)} \to \underbrace{\mathcal{O}(3\%)}_{rat(H_T/4)}$$

# Conclusions

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## 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 $t\bar{t}\gamma$ completed
  - 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

## Precise predictions for cross section ratios

arXiv:1809.08562

- $t\bar{t}\gamma$ and $t\bar{t}$ are strongly correlated!
- Ratios are very precise

## Outlook:

- Comparison with NWA approximation
- Anomalous top-quark couplings

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