NLO QCD corrections to off-shell $\mathrm{t\bar{t}}\gamma$ production at the LHC

Giuseppe Bevilacqua

MTA-DE Particle Physics Research Group, Debrecen

HP2 Workshop

Albert-Ludwigs-Universität Freiburg

October 1, 2018

Work in collaboration with H. B. Hartanto, M. Kraus, T. Weber and M. Worek

arXiv:1803.09916 + arXiv:1809.08562 [hep-ph]

Outline

Motivations for $t\bar{t}\gamma$ at LHC

- the need for high precision
- state of the art

Predictions for $t\bar{t}\gamma$ at LHC 13 TeV with HELAC−NLO

- total cross sections, differential distributions
- dominant theoretical uncertainties

The $t\bar{t}\gamma/t\bar{t}$ cross section ratio at LHC 13 TeV

- analysis of correlations between $t\bar{t}\gamma$ and $t\bar{t}$
- estimate of theoretical uncertainties

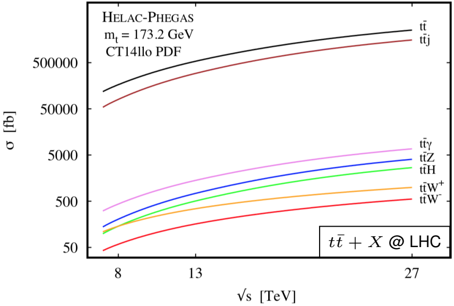
Summary and outlook

Introduction

In the absence of convincing evidence for new resonances effects, precise measurements of the properties of SM particles are key to look for effects of New Physics at the LHC.

This is especially true for the top quark, where NP effects are expected to be more prominent due to its large mass scale

The LHC provides a unique opportunity for testing the properties of the top quark (and providing insights into NP) via abundant production of $t\bar{t}$ pairs.



- top-quark mass, charge
- spin correlations
- charge asymmetries
- top-quark EW couplings

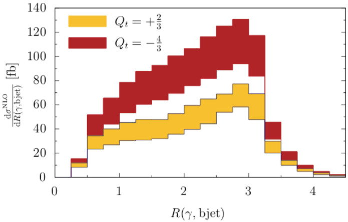
Motivations for $t\bar{t}\gamma$

Probe of the top quark charge

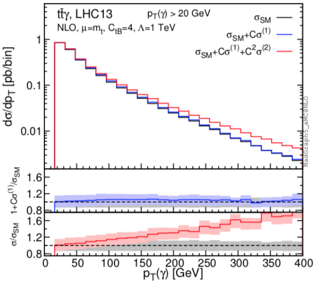
$\hookrightarrow \quad \sigma_{t\bar{t}\gamma} \sim Q_t^2$ @ LHC

Indirect from $t\bar{t}$:
$Q_t = Q_W - Q_b$

Melnikov, Scharf and Schulze '11



Bessidskaia Bylund, Maltoni *et al.* '16



Probe of the effective $tt\gamma$ interaction

$\hookrightarrow$ dimension-six SMEFT

$\hookrightarrow$ top quark anomalous couplings

Baur *et al.* '05, Aguilar Saavedra '09
Schulze *et al.*'16, Maltoni *et al.* '16 ...

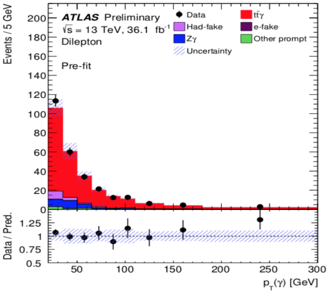
Also: $t\bar{t}\gamma \rightarrow$ irreducible background in direct BSM searches

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

Experiment

- First evidence: CDF @ Tevatron
  CDF Collaboration '11
- Observation: ATLAS @ LHC 7 TeV
  ATLAS Collaboration '15
- Measurements: ATLAS/CMS @ LHC 8 TeV
  ATLAS and CMS Collaborations '17

ATLAS-CONF-2018-048

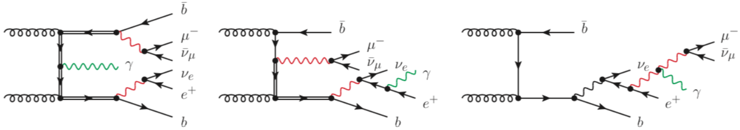


Theory

- NLO QCD $\rightarrow$ stable top quarks
  Duan, Guo, Han, Ma, Wang and Zhang '09,'11; Maltoni, Pagani and Tsinikos '15
- NLO EW $\rightarrow$ stable top quarks
  Duan, Zhang, Wang, Song and Li '16
- NLO QCD $\rightarrow$ NWA: radiative decays + spin correlations
  Melnikov, Scharf and Schulze '11
- NLO QCD + PS (PowHel) $\rightarrow$ LO top decays in PS
  Kardos and Trocsanyi '14

NLO predictions of $t\bar{t}\gamma$ have been so far restricted to on-shell tops

$t\bar{t}\gamma$: the Narrow Width Approximation



[double-resonant] [single-resonant] [non-resonant]

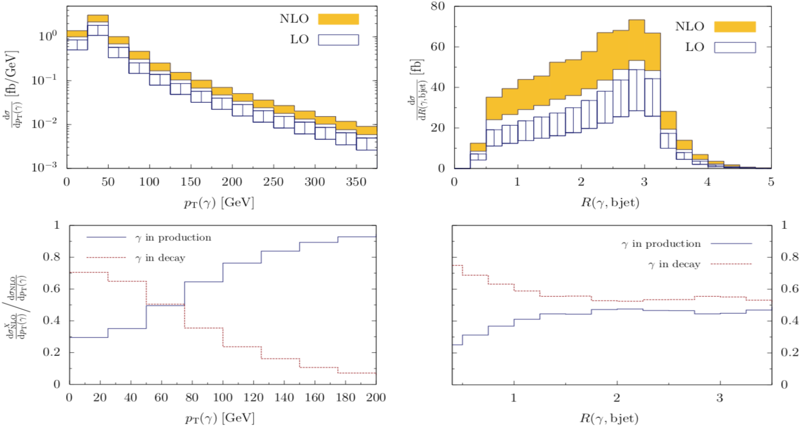
NWA: $$\frac{1}{(p_t^2-m_t^2)^2+m_t^2\Gamma_t^2} \overset{\Gamma_t \to 0}{\sim} \frac{\pi}{m_t\Gamma_t}\,\delta(p_t^2-m^2)+\mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

- only the dominant *double-resonant* contributions are retained
- cross section factorizes into ”top-quark production $\otimes$ decays”
- the photon can originate at the *production* ($t\bar{t}\gamma \to$ ...) or at the *decay* stage ($t \to bW\gamma$)
- sufficiently accurate for *inclusive* observables: $\Gamma_t/m_t \sim 0.8\%$

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

$pp \to b\bar{b}\ell^+\nu_\ell jj\gamma$ @ 14 TeV

Melnikov, Scharf and Schulze, arXiv:1102.1967 [hep-ph]



Contributions from photon radiation in the decay stage are important

$$\sigma_{\text{NLO}} = 138.1 \text{ fb} = \underbrace{60.9}_{\gamma-Prod} + \underbrace{77.2}_{\gamma-Decay} \text{ fb}$$

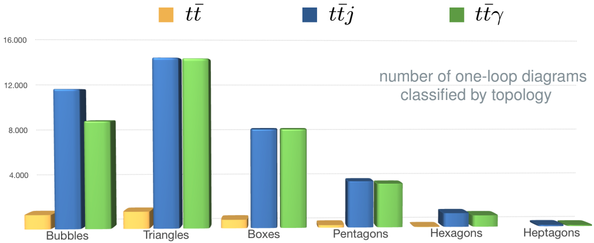
Beyond NWA

To further improve the accuracy of fixed-order predictions, one needs to release the approximation of intermediate top quarks produced on-shell.

Some technical details for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}\gamma$:

- LO: 628 diagrams for the gg channel @ $\mathcal{O}(\alpha^5 \alpha_s^2)$
- Real: 4348 diagrams for the gg channel @ $\mathcal{O}(\alpha^5 \alpha_s^3)$
- Virtual: 36032 one-loop diagrams for the gg channel @ $\mathcal{O}(\alpha^5 \alpha_s^3)$

$\hookrightarrow$ Compare with related benchmark processes: off-shell $t\bar{t}$ and $t\bar{t}j$



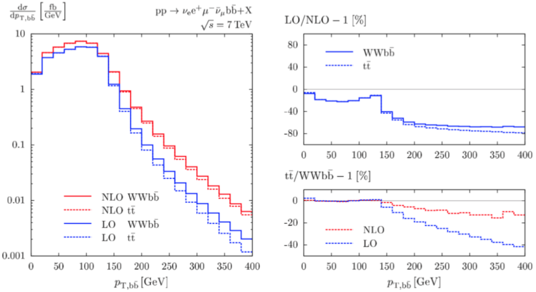
source: QGRAF [Nogueira '93]

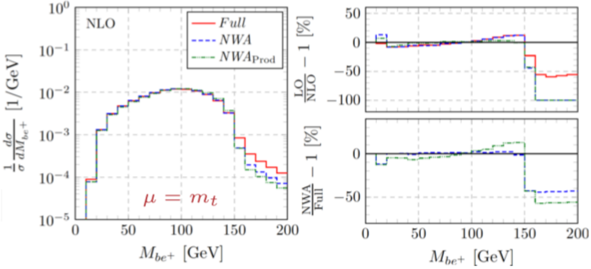
Off-shell effects can reach tens of percents in tails

↪ Examples:

Off-shell $t\bar{t}$ @ LHC

Denner, Dittmaier, Kallweit, Pozzorini and Schulze, arXiv:1203.6803 [hep-ph]

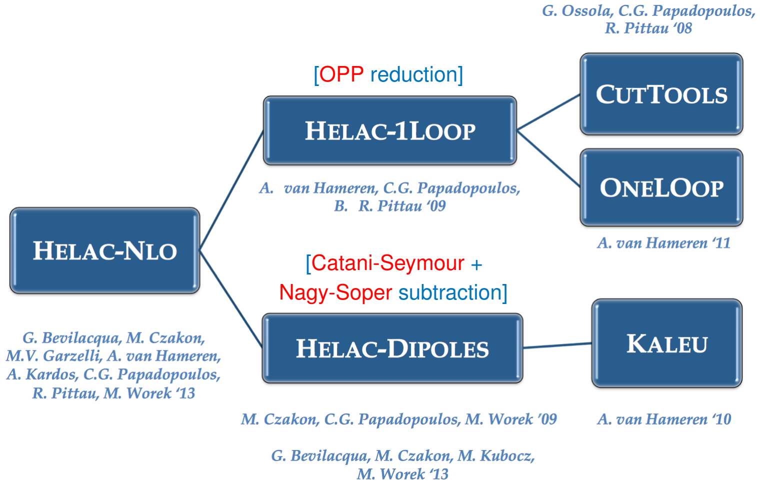




Off-shell $t\bar{t}j$ @ LHC

G.B, Hartanto, Kraus, Schulze and Worek, arXiv:1710.07515 [hep-ph]

The HELAC-NLO framework



- Functionality extended to produce Ntuples of events
- Recomputing for different scales + PDFs is not practical $\rightarrow$ use re-weighting

Predictions for $t\bar{t}\gamma$ production at LHC 13 TeV

Setup for LHC 13 TeV

Final state and parameters

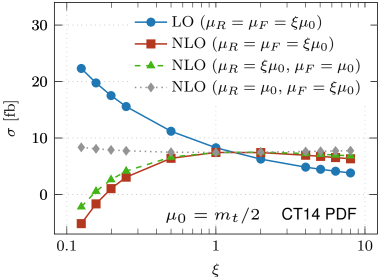
- Fully leptonic decay channel: $\boxed{pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}\gamma + X}$
- All leptons and light quarks (including bottom) massless $\to$ 5F scheme
- Top quark (pole mass): $m_t = 173.2$ GeV
- Complex Mass Scheme: $m_t^2 \to m_t^2 - i\, m_t\, \Gamma_t$
  [Denner *et al.* '99, '05]

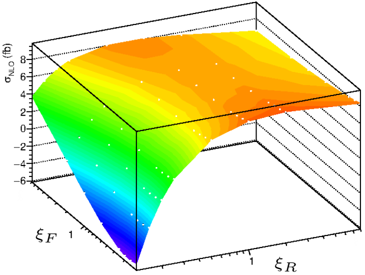
Kinematics

- exactly two b-jets , one photon , two charged leptons , missing p_T
- cuts: $p_{T\,\ell} > 30$ GeV $\quad p_{T\,b} > 40$ GeV $\quad \not{p}_T > 20$ GeV $\quad p_{T,\gamma} > 25$ GeV
  $\Delta R_{bb} > 0.4 \quad \Delta R_{\ell\ell} > 0.4 \quad \Delta R_{\ell b} > 0.4$
  $|y_\ell| < 2.5 \quad |y_b| < 2.5 \quad |y_\gamma| < 2.5$
- photon isolation condition: $\sum_i E_{T,i}\Theta(R - R_{\gamma,i}) \leq E_{T,\gamma}\left(\frac{1-\cos(R)}{1-\cos(R_{\gamma k})}\right), \quad R_{\gamma k} = 0.4$
  [Frixione '98]
- for the hard photon $\alpha = \alpha(0) = 1/137 \to$ predictions decreased by 3%

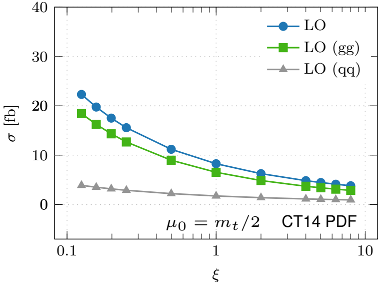
Total cross sections

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]





- at LO: $gg \sim 79\%$, $q\bar{q} \sim 21\%$,
- negative NLO corrections: -10%
- scale uncertainties: 35% @ LO
  $\hookrightarrow$ 14% @ NLO
- estimate of non-factorizable contrib. via $\Gamma_t \to 0$ limit: 2.5% @ NLO

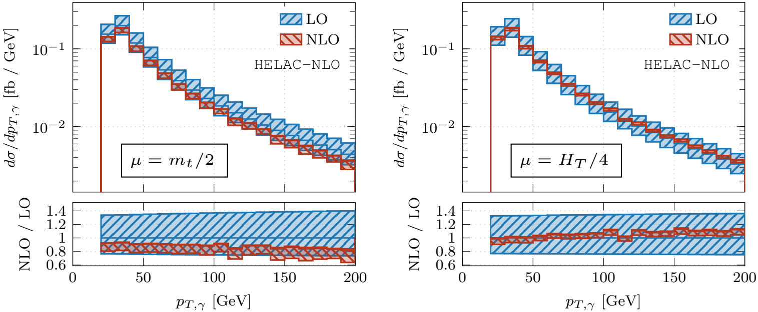


Differential cross sections

Focus on observables relevant for BSM searches

1. Transverse momentum of the photon: $p_{T,\gamma}$

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



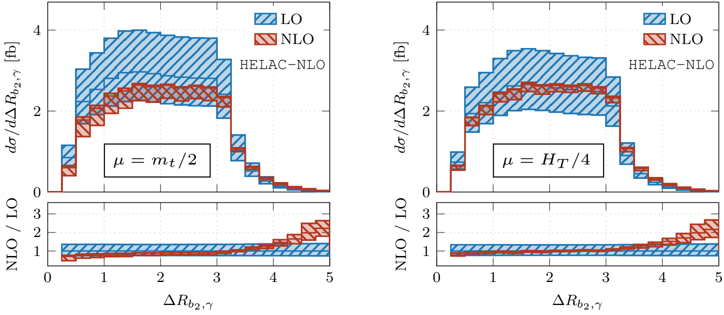
- Scale uncertainties via envelope: $\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \{(2,1), (0.5,1), (1,2), (1,1), (1,0.5), (2,2), (0.5,0.5)\}$
- Differential K-factor varies from -8% to -18% in plotted range
- Dynamical scale $\mu = H_T/4$ helps to improve perturbative stability

Differential cross sections

Focus on observables relevant for BSM searches

2. Separation between photon and 2^{nd} hardest b-jet: $\Delta R_{b_2,\gamma}$

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



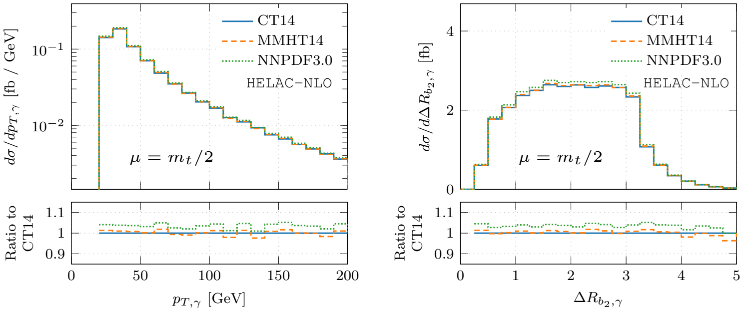
- Severe shape distortions for $\Delta R_{b_2,\gamma} > 4$ are genuine NLO effects
  $\hookrightarrow$ initial-state γ radiation from qg channel

- Similar effect observed for other ΔR observables

Differential cross sections

Impact of different PDF sets on $p_{T,\gamma}$ and $\Delta R_{b_2,\gamma}$

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



$\hookrightarrow$ Global estimate of theoretical uncertainties $[p_{T,\gamma} \geq 25$ GeV] :

$$\sigma_{\text{NLO}}\,(\mu = m_t/2) \;=\; (\mathbf{7.4} \pm \mathbf{1.0}\,^{\text{[scale]}} \pm \mathbf{0.3}\,^{\text{[PDF]}})\ \text{fb}$$

$$\sigma_{\text{NLO}}\,(\mu = H_T/4) \;=\; (\mathbf{7.5} \pm \mathbf{0.5}\,^{\text{[scale]}} \pm \mathbf{0.3}\,^{\text{[PDF]}})\ \text{fb}$$

The $t\bar{t}\gamma$ / $t\bar{t}$ cross section ratio at LHC 13 TeV

The ratio

Instead of considering the *absolute* $t\bar{t}\gamma$ cross section, normalize to $t\bar{t}$

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

Advantages

- Experiment: more accurate measurement

  $\hookrightarrow$ common systematics cancelled in the ratio
  (e.g. b-jet reconstruction efficiency, luminosity ...)

- Theory: more accurate prediction

  $\hookrightarrow$ theoretical uncertainties (dominated by scale variation) can be dramatically reduced provided the two processes are *correlated*

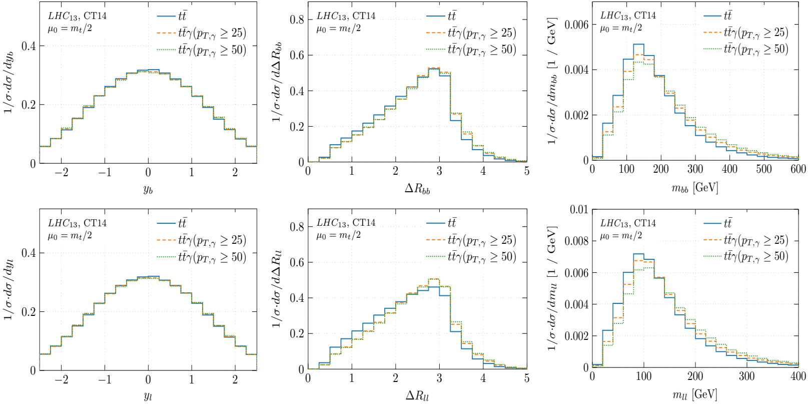
  Melnikov, Scharf, Schulze '11; Mangano, Rojo '12; G.B, Worek '14; Schulze, Soreq '16 ...

How strongly correlated are $t\bar{t}\gamma$ and $t\bar{t}$?

Looking for correlations

$t\bar{t}\gamma$ vs $t\bar{t}$ @ LHC : distributions normalized to unit

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1809.08562 [hep-ph]

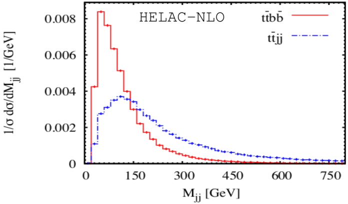


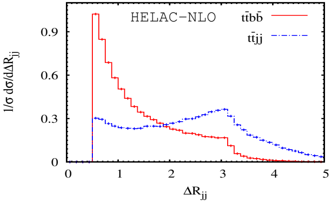
Kinematics of b-jets and leptons in $t\bar{t}\gamma$ and $t\bar{t}$ show correlations

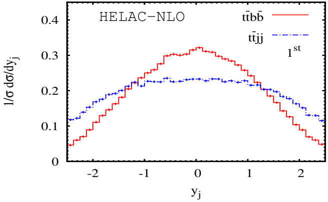
Compare to an example of *uncorrelated* processes: $t\bar{t}b\bar{b}$ vs $t\bar{t}jj$ @ LHC

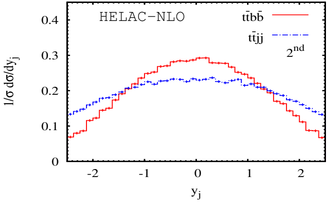
↪ see HP2 Workshop '14

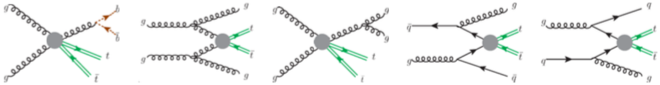
G.B. and Worek, arXiv:1403.2046 [hep-ph]





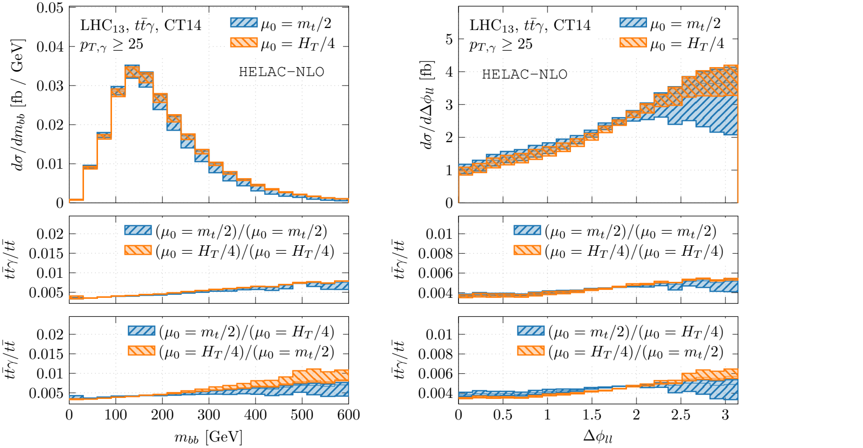






Differential cross section ratios

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1809.08562 [hep-ph]

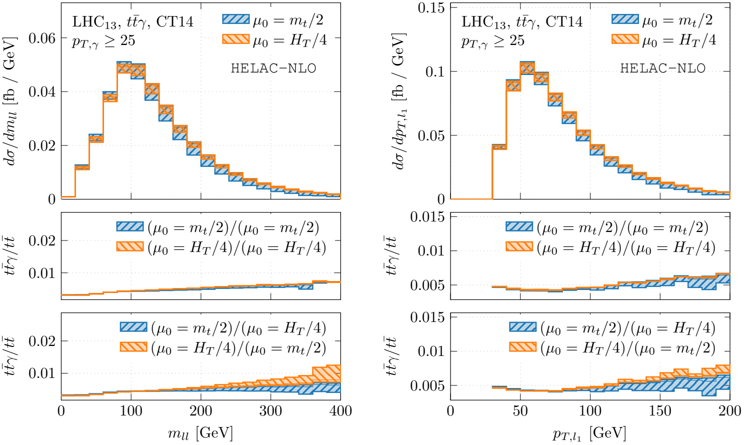


Using *correlated* scales in $t\bar{t}\gamma$ and $t\bar{t}$ helps to constrain uncertainty bands

- *e.g.* $\Delta\phi_{ll} \approx 3$: $\underbrace{\mathcal{O}(50\%)}_{\sigma_{tt\gamma}(m_t/2)} \rightarrow \underbrace{\mathcal{O}(20\%)}_{\sigma_{tt\gamma}(H_T/4)} \Leftrightarrow \underbrace{\mathcal{O}(30\%)}_{\mathcal{R}(m_t/2)} \rightarrow \underbrace{\mathcal{O}(3\%)}_{\mathcal{R}(H_T/4)}$

Differential cross section ratios

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1809.08562 [hep-ph]



$\hookrightarrow$ Global estimate of theoretical uncertainties $[p_{T,\gamma} \geq 25$ GeV] :

$$\mathcal{R}(\mu = m_t/2) = (\mathbf{4.56} \pm \mathbf{0.25}\ ^{\text{[scale]}} \pm \mathbf{0.02}\ ^{\text{[PDF]}}) \cdot 10^{-3}$$

$$\mathcal{R}(\mu = H_T/4) = (\mathbf{4.62} \pm \mathbf{0.06}\ ^{\text{[scale]}} \pm \mathbf{0.02}\ ^{\text{[PDF]}}) \cdot 10^{-3}$$

Summary and outlook

- First NLO predictions of $pp \to t\bar{t}\gamma$ with fully leptonic decays, including off-shell and non-resonant effects at $\mathcal{O}(\alpha^5\alpha_s^3)$
- Judicious dynamical scales quite effectively account for the multi-scale nature of the process
- NLO accuracy is important for a proper description of some observables relevant for BSM searches, e.g. $\Delta R_{b\gamma}$
- Correlations between $t\bar{t}\gamma$ and $t\bar{t}$ production can be exploited to constrain theoretical uncertainties
- The $t\bar{t}\gamma/t\bar{t}$ cross section ratio has interesting potential in searches for BSM effects
- Next steps:

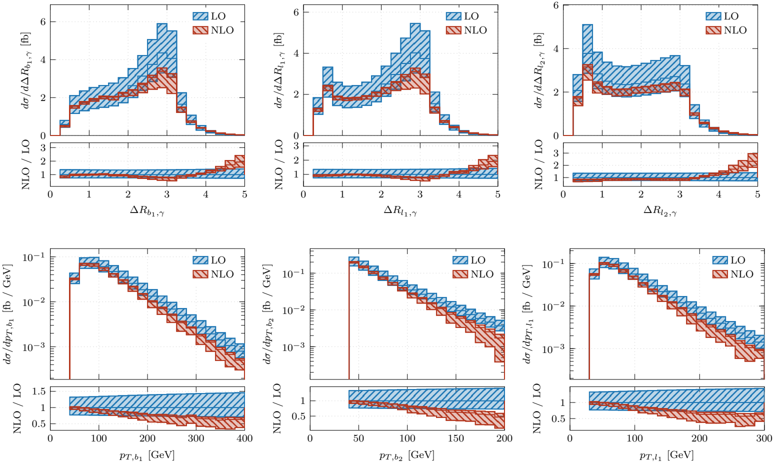
  - comparisons with NWA

  - pheno applications: SM parameter extraction,
    constraining anomalous couplings

Backup slides

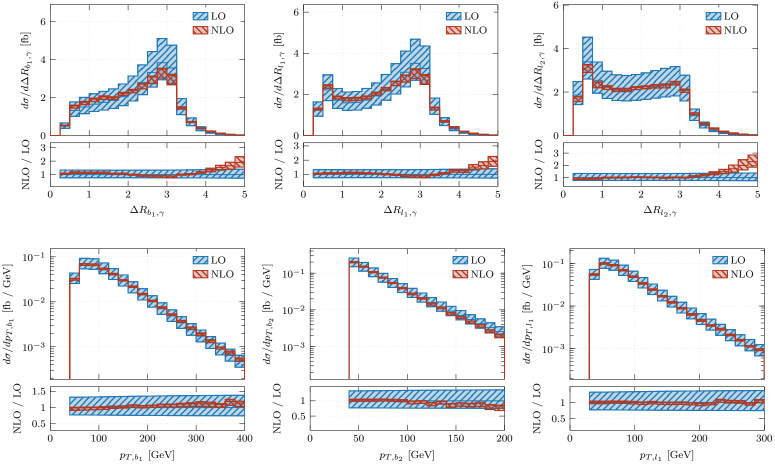
Differential cross sections for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$ at LHC 13 TeV, based on the scale choice $\mu_R = \mu_F = m_t/2$

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



Differential cross sections for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$ at LHC 13 TeV, based on the scale choice $\mu_R = \mu_F = H_T/4$

G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



NLO cross sections for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + X$ and $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$ at LHC 13 TeV, for various scale and PDF choices

(The errors refer to scale uncertainties)

PDF set, $\mu_R = \mu_F = \mu_0$	$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}}$ [fb]	$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}$ [fb] $p_{T,\gamma} > 25$ GeV	$\sigma^{\rm NLO}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}$ [fb] $p_{T,\gamma} > 50$ GeV
CT14, $\mu_0 = m_t/2$	$1629.4^{+18.4\,(1\%)}_{-144.7\,(9\%)}$	$7.436^{+0.074\,(1\%)}_{-1.034\,(14\%)}$	$3.081^{+0.050\,(2\%)}_{-0.514\,(17\%)}$
CT14, $\mu_0 = H_T/4$	$1620.5^{+21.6\,(1\%)}_{-118.8\,(7\%)}$	$7.496^{+0.099\,(1\%)}_{-0.457\,(6\%)}$	$3.125^{+0.040\,(1\%)}_{-0.142\,(4\%)}$
MMHT14, $\mu_0 = m_t/2$	$1650.5^{+17.0\,(1\%)}_{-152.7\,(9\%)}$	$7.490^{+0.080\,(1\%)}_{-1.081\,(14\%)}$	$3.093^{+0.053\,(2\%)}_{-0.535\,(17\%)}$
NNPDF3.0, $\mu_0 = m_t/2$	$1695.0^{+18.4\,(1\%)}_{-153.3\,(9\%)}$	$7.718^{+0.078\,(1\%)}_{-1.102\,(14\%)}$	$3.195^{+0.054\,(2\%)}_{-0.550\,(17\%)}$

Bevilacqua, Hartanto, Kraus, Weber and Worek, arXiv:1809.08562 [hep-ph]