On the $\mathrm{t\bar{t}}\gamma/t\bar{t}$ cross section ratio at the LHC

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

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Outline

Introduction

- Motivations for $t\bar{t}\gamma$ at LHC
- Towards higher precision

Predictions for $t\bar{t}\gamma$ with `HELAC-NLO`

- total and differential cross sections
- impact of scale choice

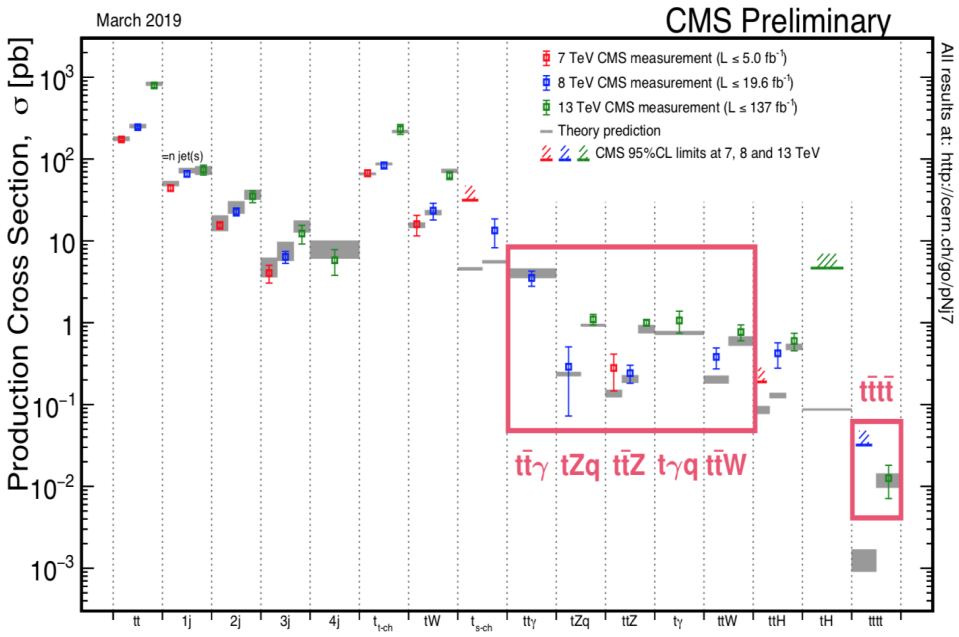
The $t\bar{t}\gamma/t\bar{t}$ cross section ratio as a precision observable

- kinematical correlations
- estimate of theory uncertainties

Introduction

In the absence of convincing evidence for new resonances effects, precise measurements of SM observables are key to look for effects of New Physics (NP) at the LHC

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



As luminosity increases, LHC allows to probe associated $t\bar{t}$ channels with more precision (and provide insights into NP)

Let's focus on the $t\bar{t}\gamma$ channel

↪ See talk by Joscha Knolle

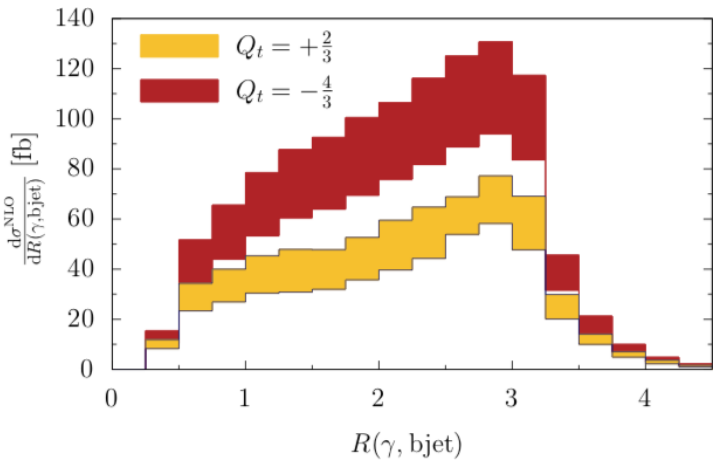
Motivations for $t\bar{t}\gamma$ at LHC

Probe of the top quark charge

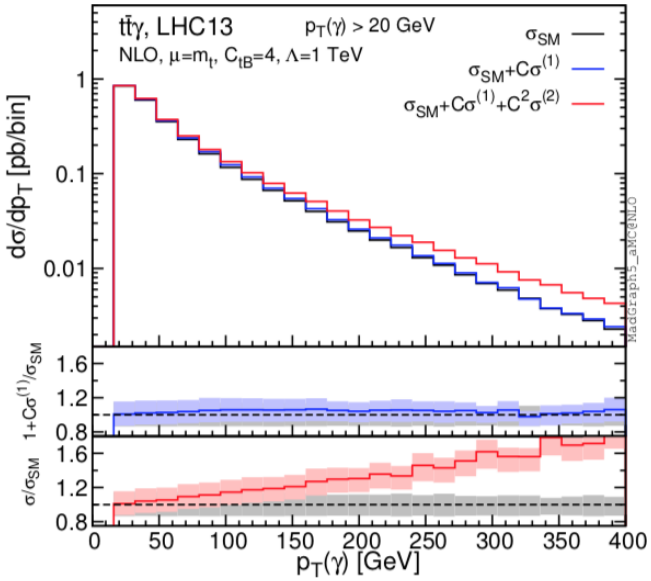
$\hookrightarrow \quad \sigma_{t\bar{t}\gamma} \sim Q_t^2$

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: 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
- First results @ LHC 13 TeV
  ATLAS Collaboration, arXiv:1812.01697 [hep-ex]

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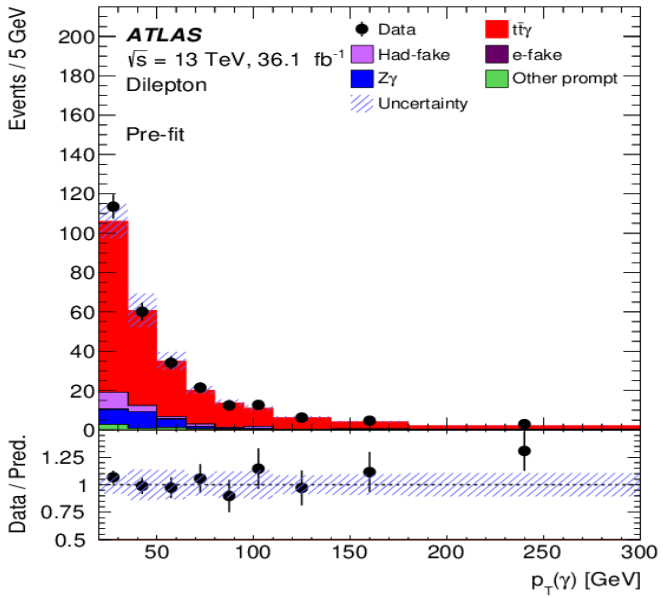


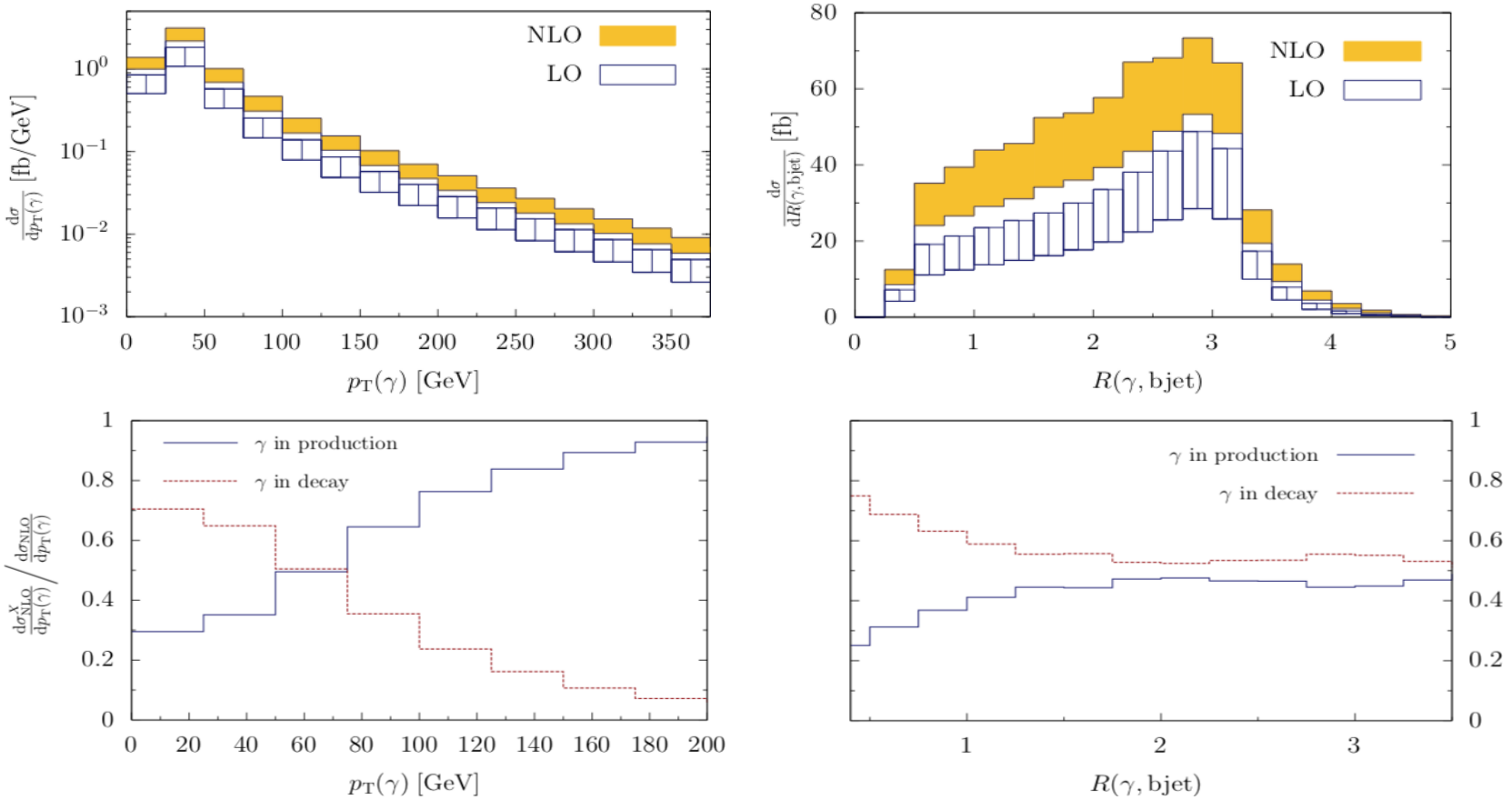
Theory

- NLO QCD/EW
  Duan *et al* '09,'11; Maltoni, Pagani and Tsinikos '15; Duan *et al* '16
- NLO QCD $\rightarrow$ radiative decays
  Melnikov, Scharf and Schulze '11
- NLO+PS $\rightarrow$ LO decays in PS
  Kardos and Trocsanyi '14
- NLO QCD $\rightarrow$ off-shell, dilepton channel
  G.B, Hartanto, Kraus, Weber and Worek '18

Narrow Width Approximation

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

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



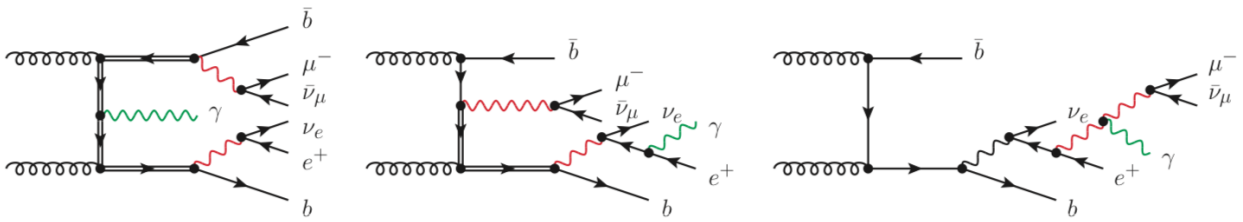
Contributions from γ in production and decay are comparable in size:

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

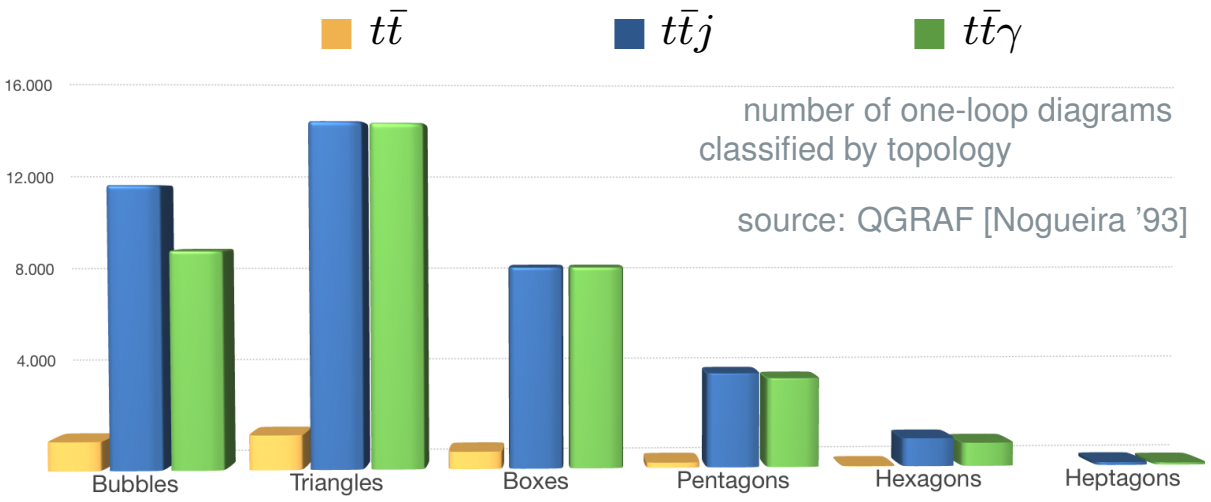
Beyond NWA

We release the approximation of intermediate on-shell tops

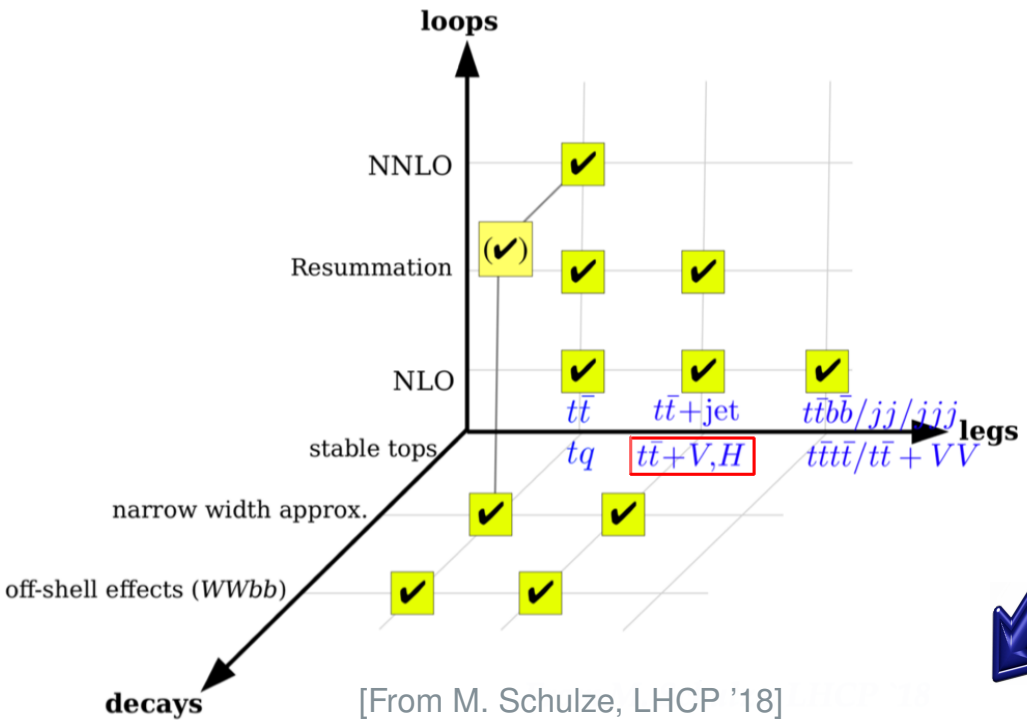
$\hookrightarrow$ include *finite-width* + *single-resonant* + *non-resonant* contributions ("off-shell effects").



Compare with other benchmark calculations: off-shell $t\bar{t}$ and $t\bar{t}j$



Towards higher precision



[From M. Schulze, LHCP '18]

improving accuracy

improving final state shaping

At present, the best theoretical accuracy available for offshell $t\bar{t}\gamma$ production is NLO QCD. NNLO is out of reach.

$\hookrightarrow$ Concentrate on observables which can help reducing the theoretical uncertainties: cross section ratios

The cross section ratio

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

$$\boxed{\mathcal{R} = \frac{\sigma(pp \to b\bar{b}WW\gamma)}{\sigma(pp \to b\bar{b}WW)}} \qquad [p_T(\gamma) > 25 \text{ GeV}]$$

Advantages:

- Experiment $\to$ more accurate measurement

  $\hookrightarrow$ common systematics cancel in $\mathcal{R}$

  (e.g. b-tagging efficiency, luminosity ...)

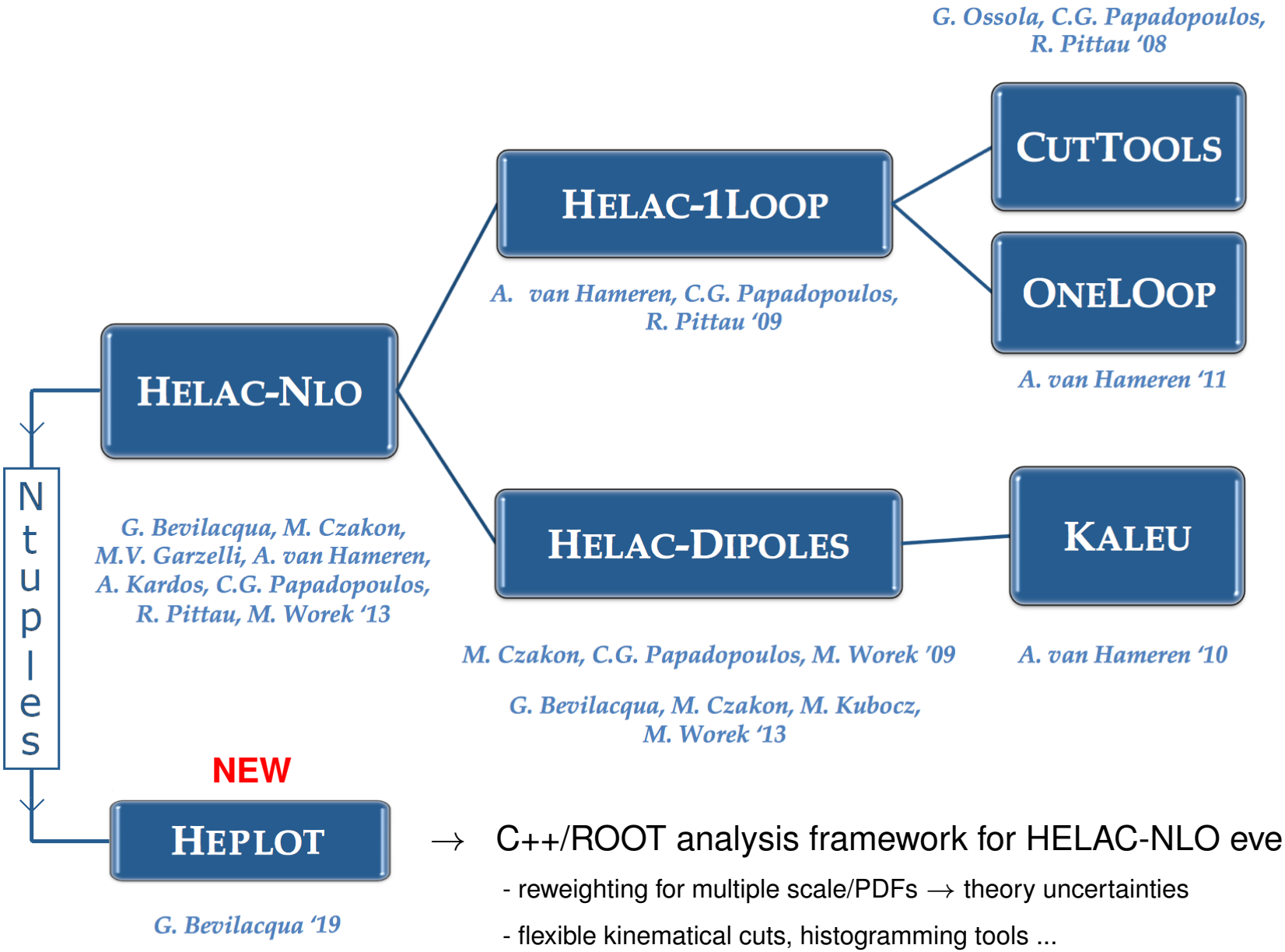
- Theory $\to$ more accurate prediction (?)

  $\hookrightarrow$ theory uncertainties on $\mathcal{R}$ (dominated by scale variation) can be dramatically reduced *if* 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 $t\bar{t}$ production ?

The HELAC-NLO framework



→ C++/ROOT analysis framework for HELAC-NLO events

- reweighting for multiple scale/PDFs → theory uncertainties
- flexible kinematical cuts, histogramming tools ...

Absolute predictions for $t\bar{t}\gamma$

Setup - LHC 13 TeV

Basic settings

- Dilepton channel: $\boxed{pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X}$
- All leptons and quarks (except top) massless $\to$ 5-Flavor scheme

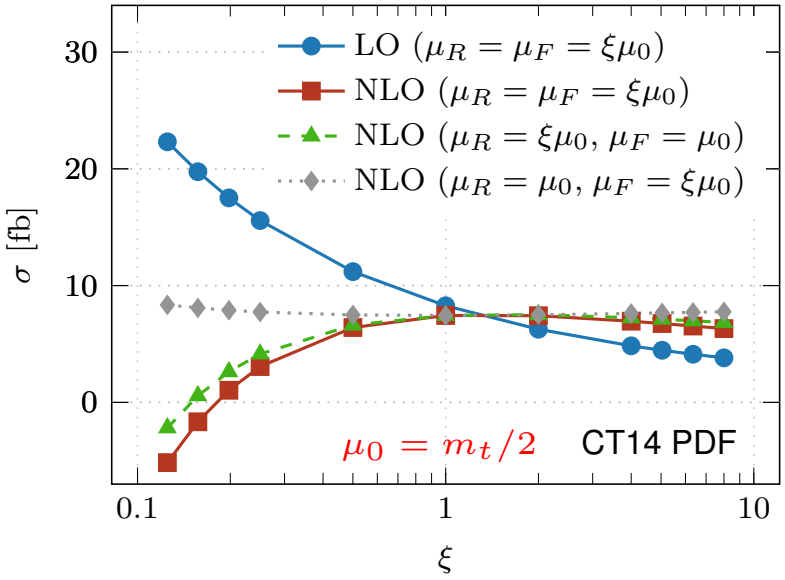
Kinematics

- exactly two b-jets $+$ one photon $+$ two charged leptons $+$ $\not{p}_T$
- Photon isolation: $\sum_i E_{T,i}\Theta(R - R_{\gamma,i}) \leq E_{T,\gamma}\left(\frac{1-\cos(R)}{1-\cos(R_{\gamma k})}\right), \quad R_{\gamma k} = 0.4$
  [Frixione '98]
- Cuts:

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

Total cross sections

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

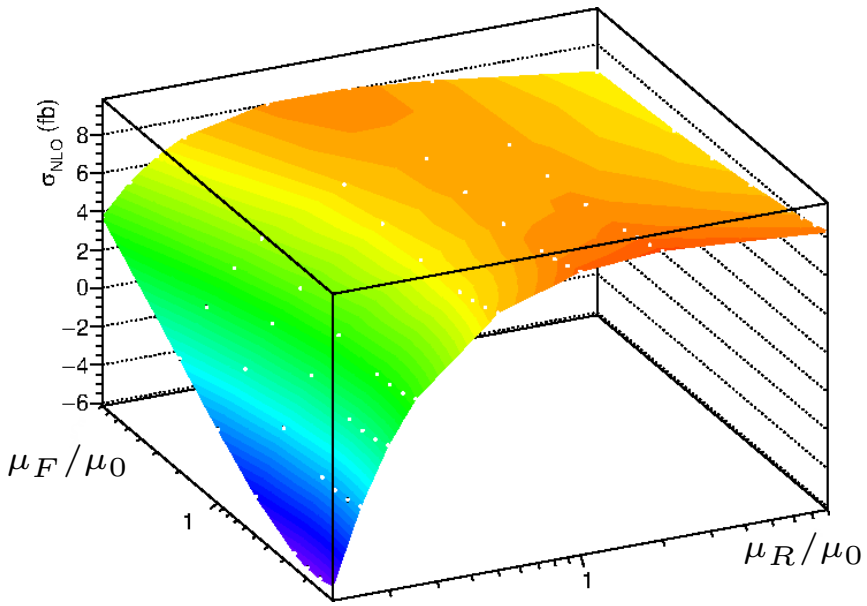


- scale uncertainties driven by μ_R variation

- 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 (total cross section)

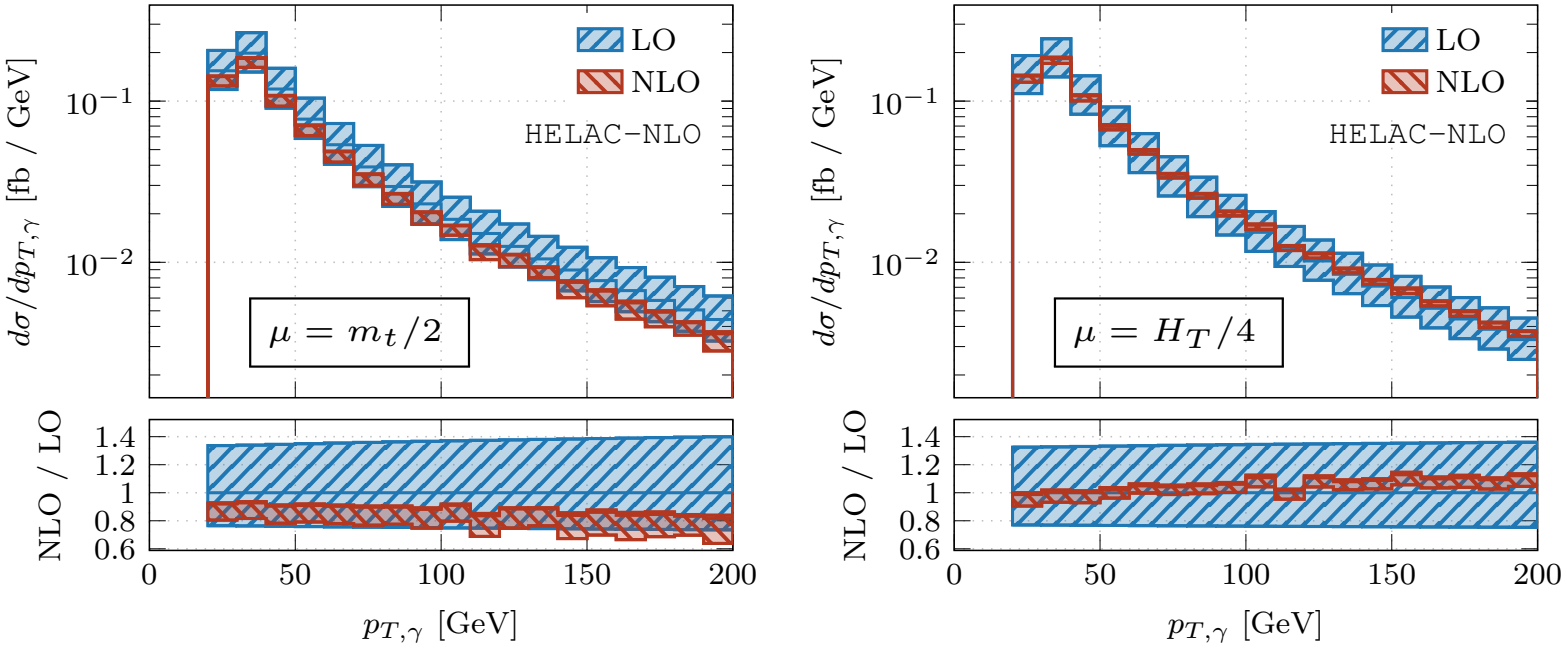


Differential cross sections

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]



Dynamical scale $\mu = H_T/4$ improves perturbative stability

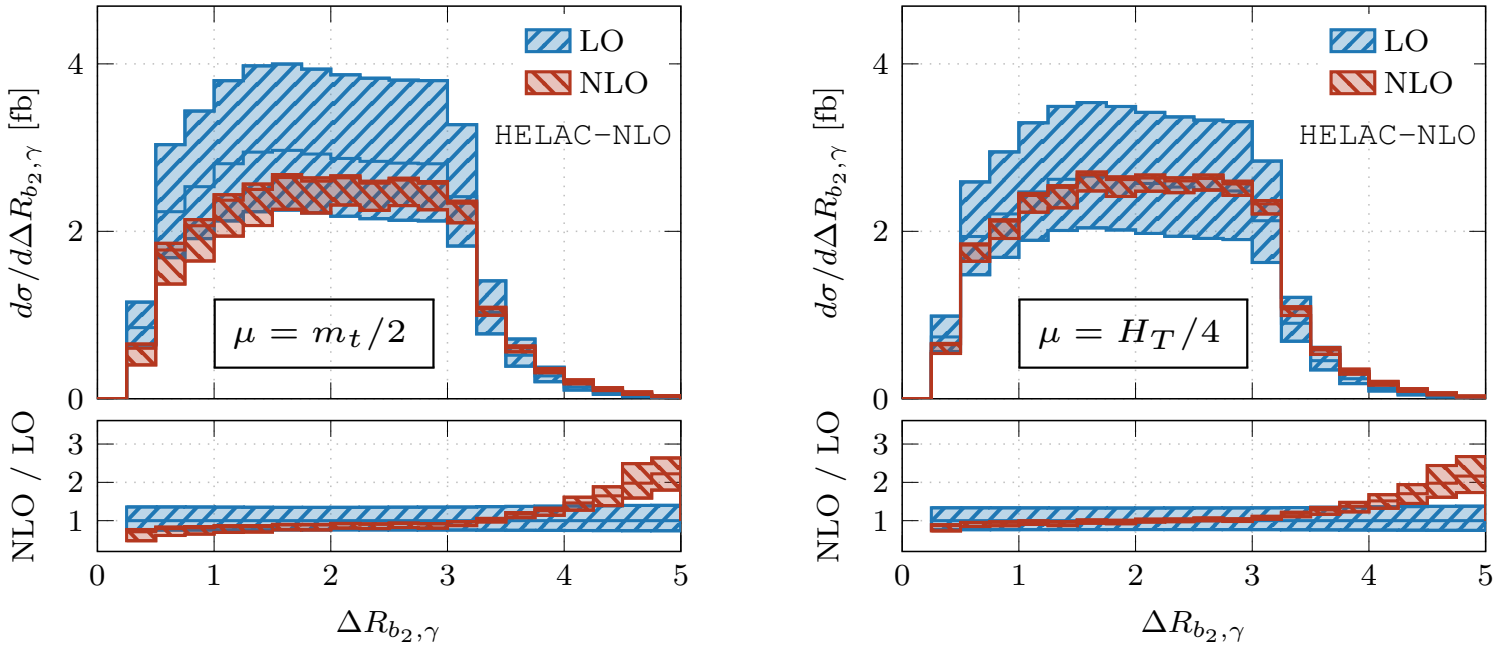
$$H_T = \sum_{i=\{b,\bar{b},\ell^\pm,\gamma\}} p_{T_i} + \not{p}_T$$

Differential cross sections

Focus on observables relevant for BSM searches

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

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



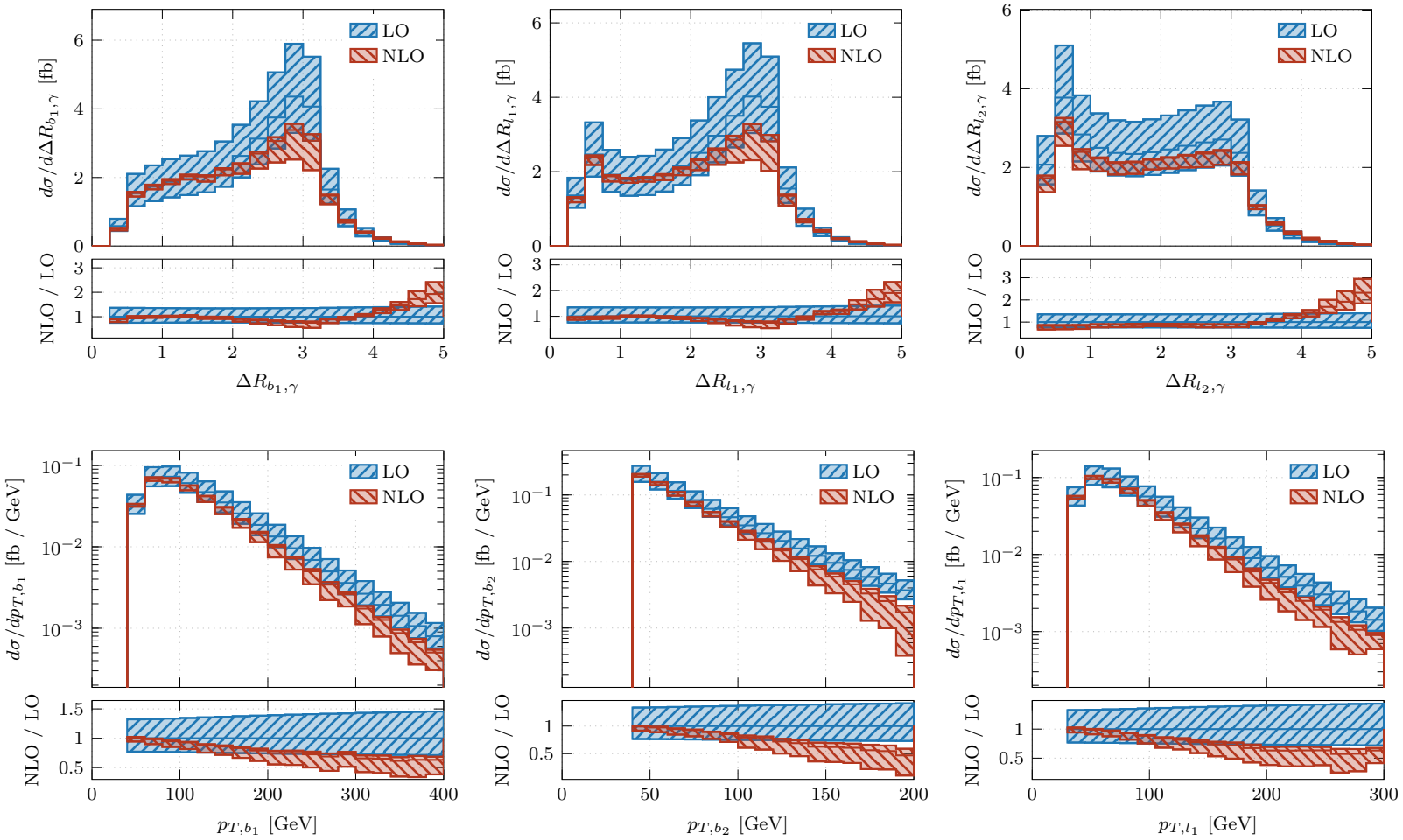
Important shape distortions starting at $\Delta R_{b_2,\gamma} \approx 4$

$\hookrightarrow$ genuine NLO effect: initial-state γ radiation from qg channel

Similar behaviour observed for other observables...

A collection of distributions based on the scale choice $\mu_R = \mu_F = m_t/2$

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



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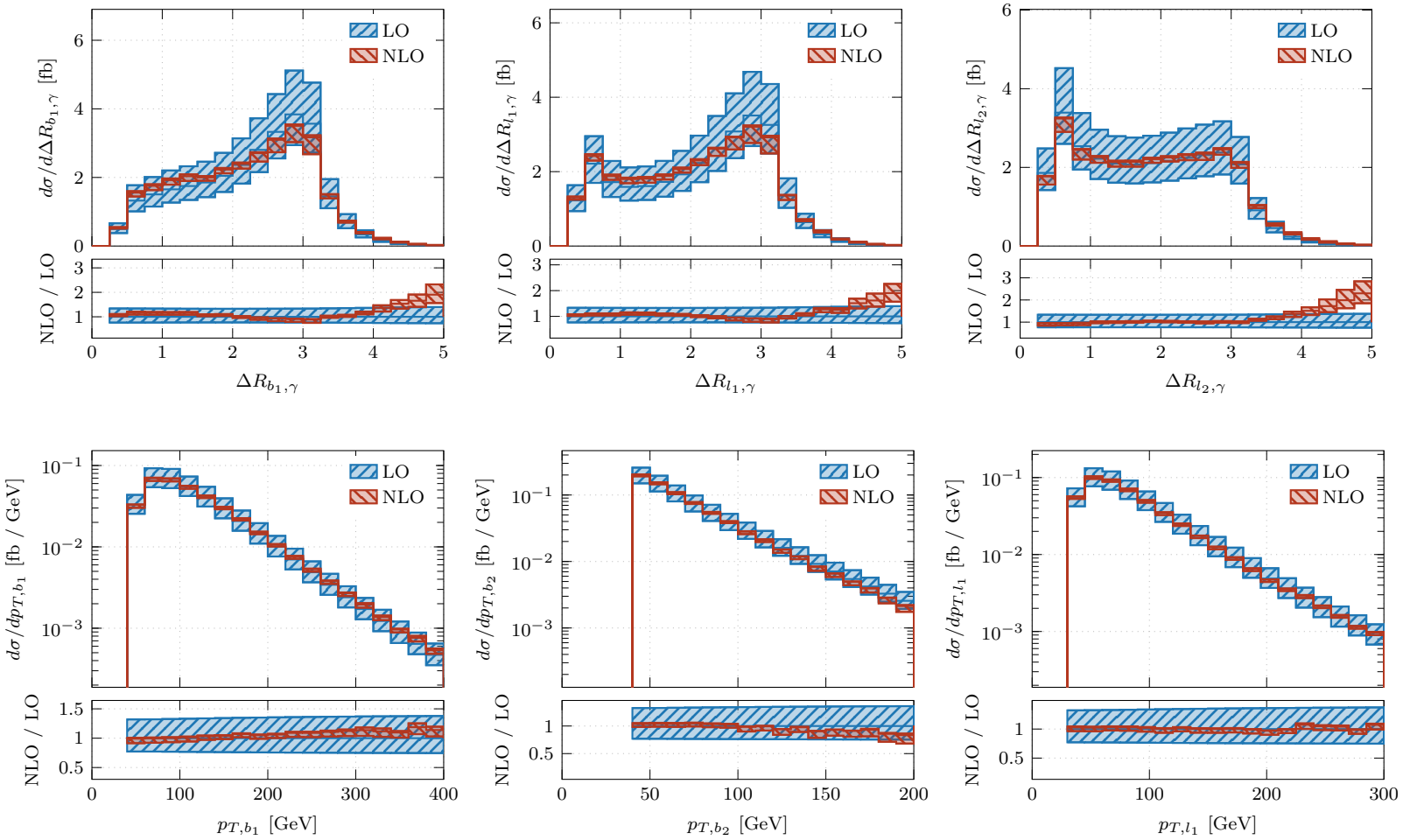
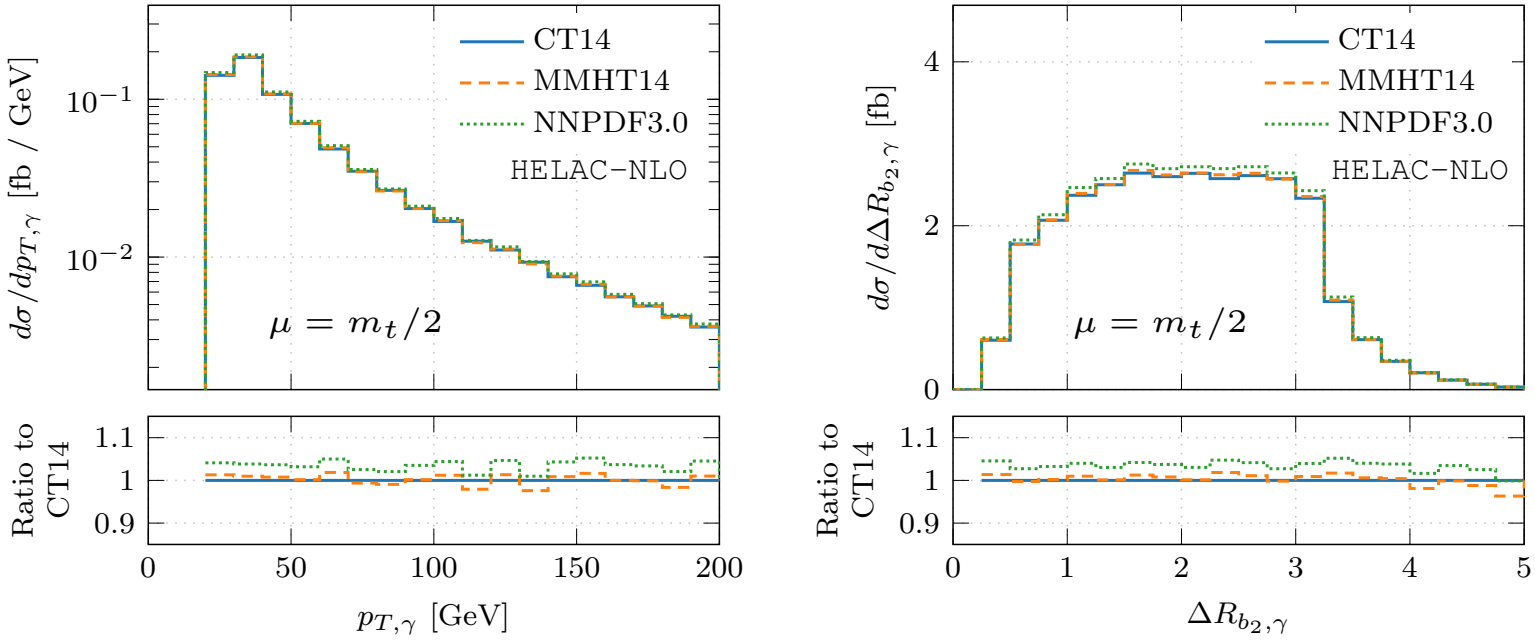


Differential cross sections

Impact of different PDF sets:

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



↪ Global estimate of theoretical uncertainties for the absolute $t\bar{t}\gamma$ predictions:

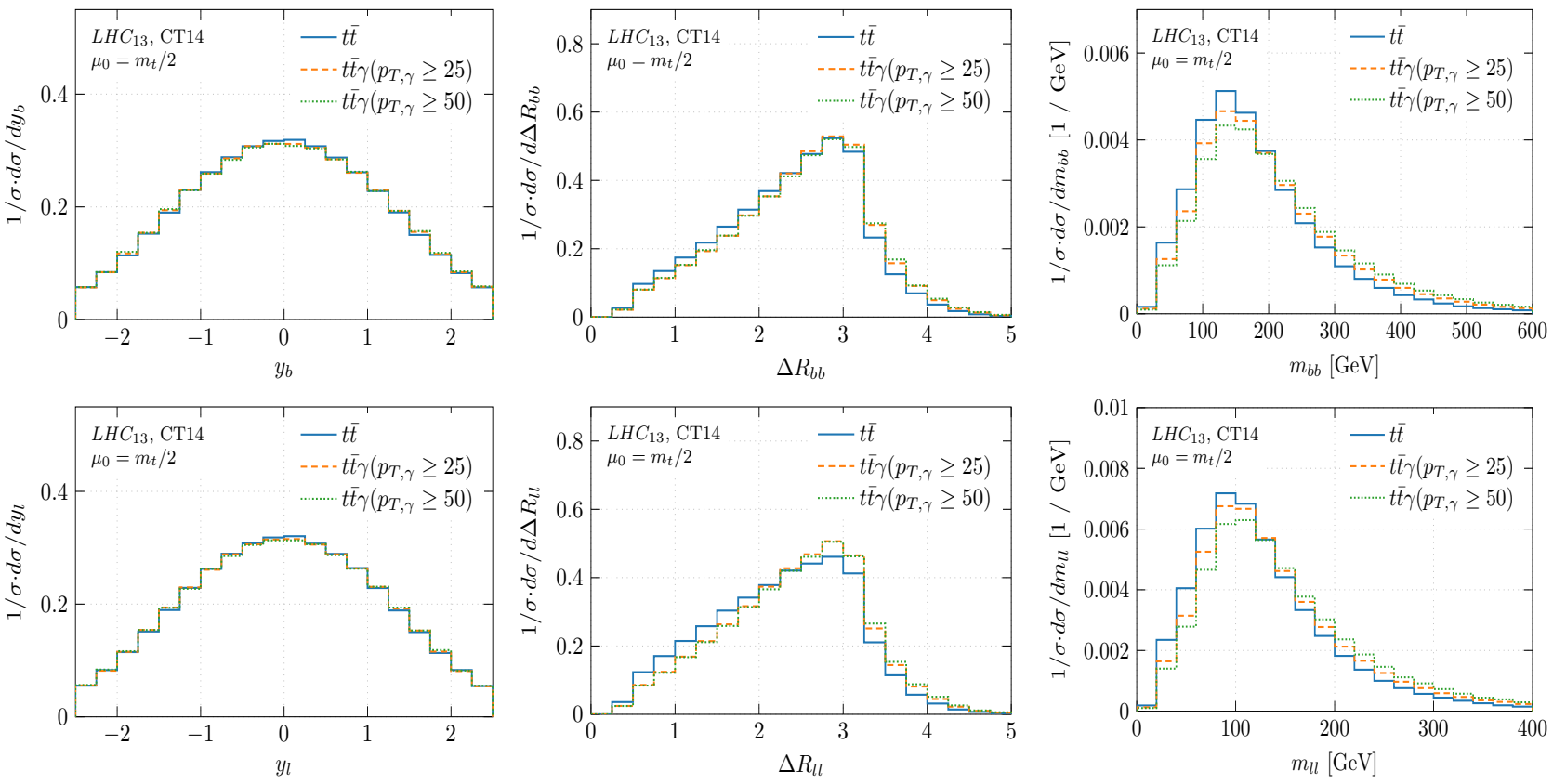
$$\sigma_{\text{NLO}}\,(\mu = m_t/2) \;=\; (\mathbf{7.4} \pm \mathbf{1.0}^{\,[\text{scale}]} \pm \mathbf{0.3}^{\,[\text{PDF}]})\ \text{fb}$$
$$\sigma_{\text{NLO}}\,(\mu = H_T/4) \;=\; (\mathbf{7.5} \pm \mathbf{0.5}^{\,[\text{scale}]} \pm \mathbf{0.3}^{\,[\text{PDF}]})\ \text{fb}$$

The $t\bar{t}\gamma$ / $t\bar{t}$ cross section ratio

Looking for correlations

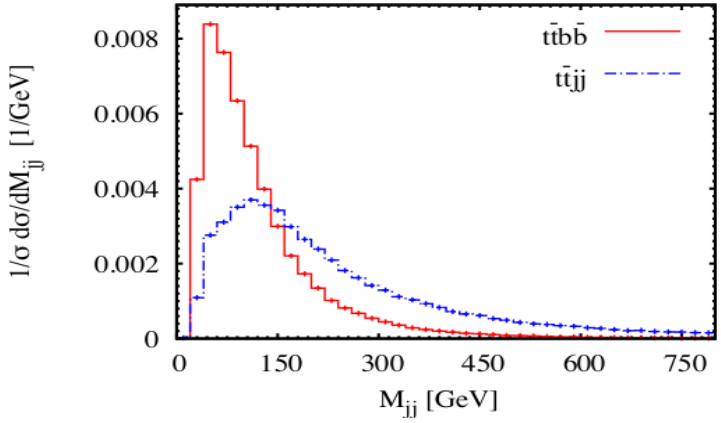
$t\bar{t}\gamma$ vs $t\bar{t}$ @ LHC : distributions normalized to unit

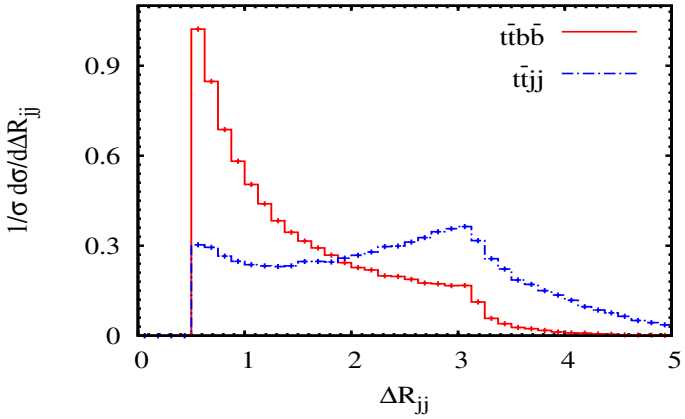
G.B., Hartanto, Kraus, Weber and Worek, arXiv:1809.08562 [hep-ph]

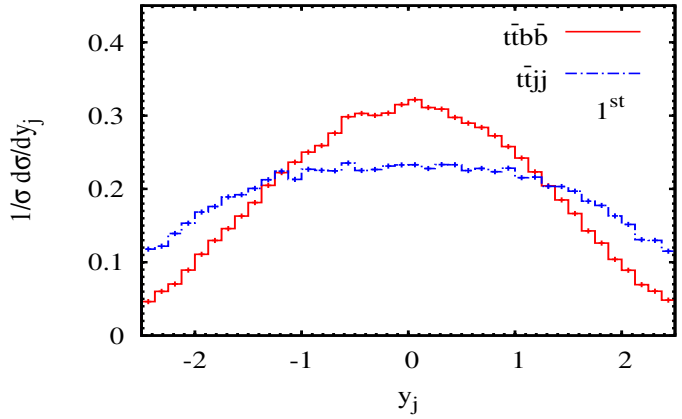


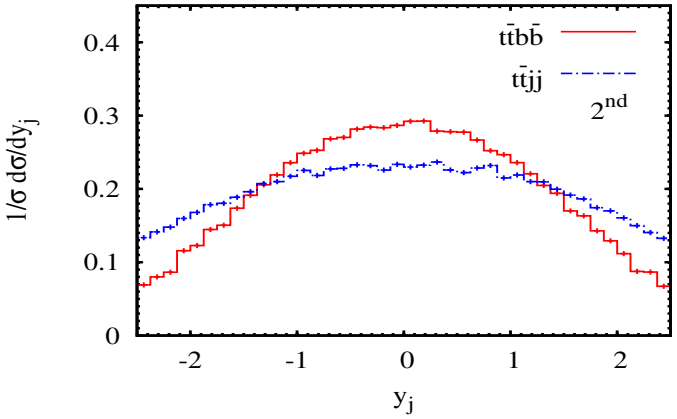
Compare to a case of uncorrelated processes: $t\bar{t}b\bar{b}$ vs $t\bar{t}jj$ @ LHC

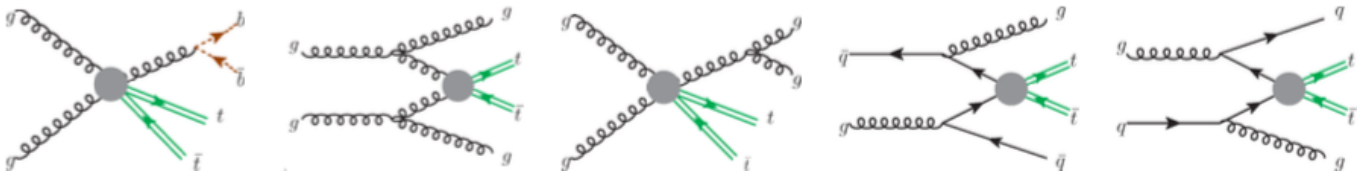
G.B. and Worek, arXiv:1403.2046 [hep-ph]



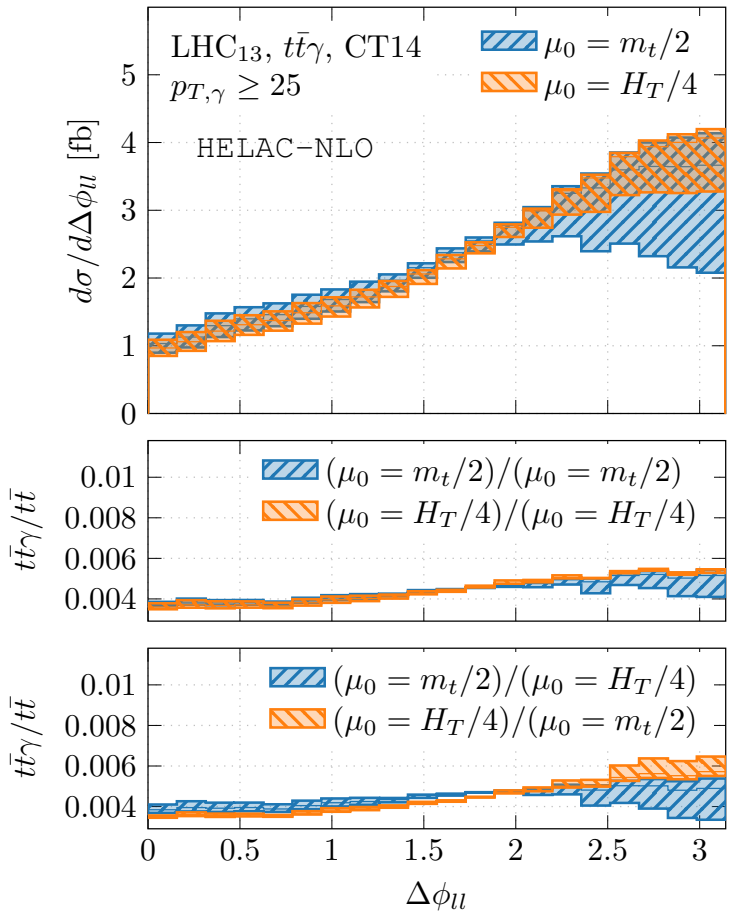








Differential cross section ratios

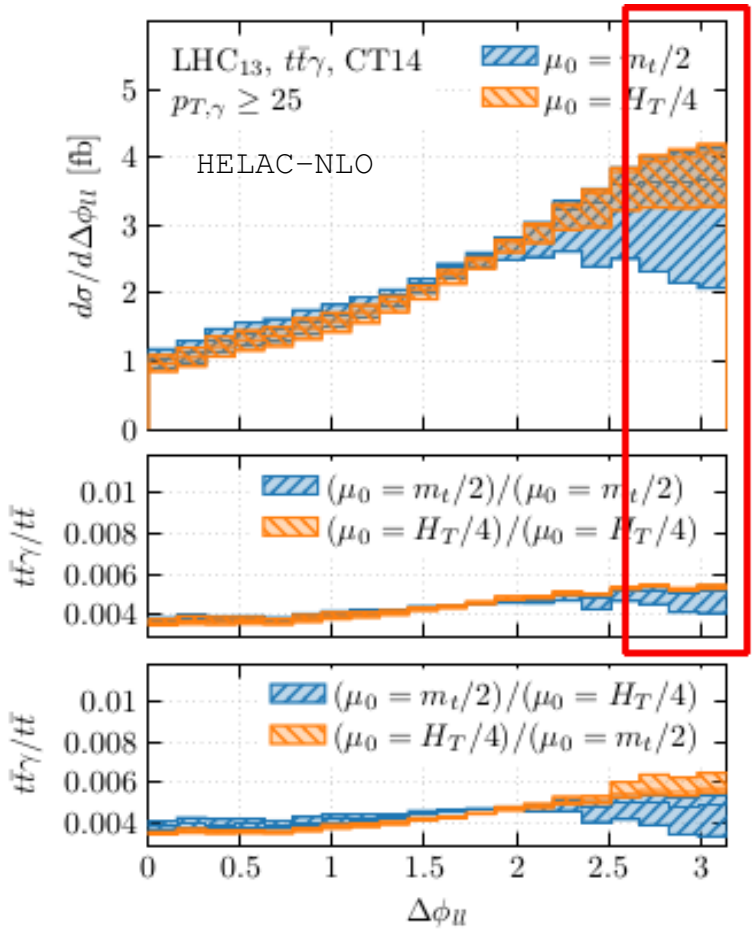


$\longrightarrow$ absolute $t\bar{t}\gamma$ prediction

$\longrightarrow$ correlated $t\bar{t}\gamma/t\bar{t}$ ratio

$\longrightarrow$ uncorrelated $t\bar{t}\gamma/t\bar{t}$ ratio (example)

Differential cross section ratios



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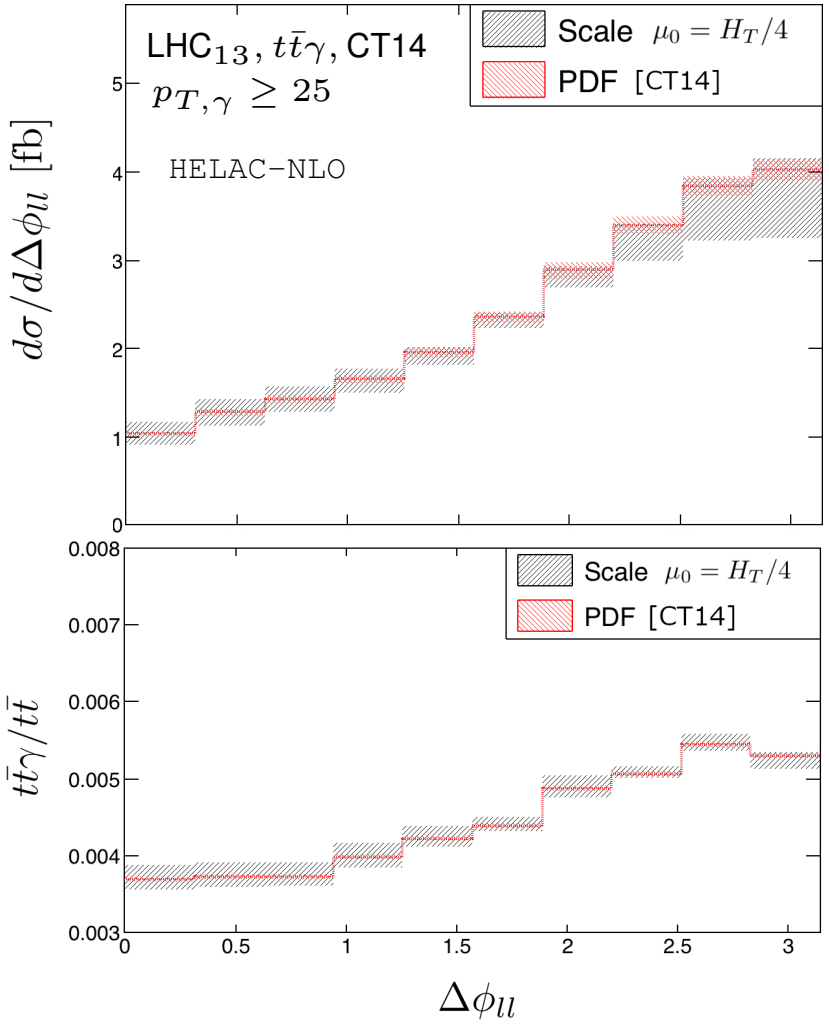
$\longrightarrow$ uncorrelated $t\bar{t}\gamma/t\bar{t}$ ratio (example)

Correlation reduces uncertainty bands

$$\Delta\phi_{ll} \approx 3 \; : \quad \underbrace{\mathcal{O}(50\%)}_{abs(m_t/2)} \rightarrow \underbrace{\mathcal{O}(20\%)}_{abs(H_T/4)} \Leftrightarrow \underbrace{\mathcal{O}(30\%)}_{rat(m_t/2)} \rightarrow \underbrace{\mathcal{O}(3\%)}_{rat(H_T/4)}$$

Differential cross section ratios

Comparing scale and PDF uncertainties at differential level:



$\longrightarrow$ absolute $t\bar{t}\gamma$ prediction

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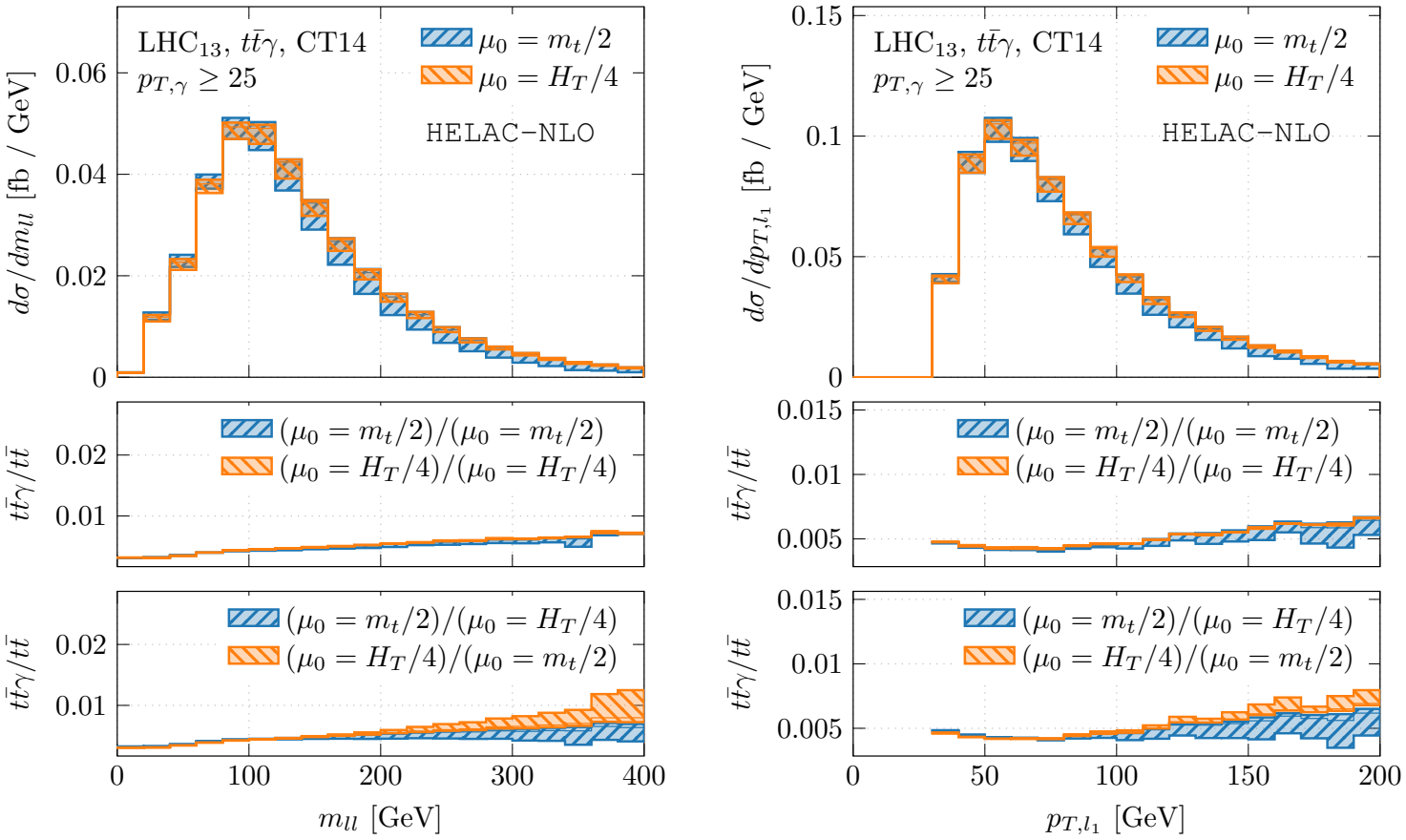
Differential cross section ratios

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



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

$$\mathcal{R}(\mu_0 = H_T/4) = (\mathbf{4.62} \pm \mathbf{0.06}\ ^{\text{[scale]}} \pm \mathbf{0.04}\ ^{\text{[PDF]}}) \cdot 10^{-3}$$

Summary

Based on the first NLO QCD calculation of off-shell $t\bar{t}\gamma$ production, we have presented precise predictions for the $t\bar{t}\gamma/t\bar{t}$ cross section ratio at the LHC:

- correlations between $t\bar{t}\gamma$ and $t\bar{t}$ production can help to constrain theoretical uncertainties
- the ratio observable has interesting potential for searches of BSM effects at the LHC

Our predictions are available in the form of ROOT Ntuples of events:

- a user-friendy tool, **`HEPlot`**, is now available to get predictions from HELAC-NLO events for arbitrary observables and scale/PDF choice
- we can provide Ntuples for off-shell $t\bar{t}$ & $t\bar{t}\gamma$ @ LHC 13 TeV (dilepton channel). If interested, contact us!
- other processes will be available soon... stay tuned!