Off-shell effects in $\mathrm{t\bar{t}} + \gamma/\mathrm{Z}$ production at the LHC

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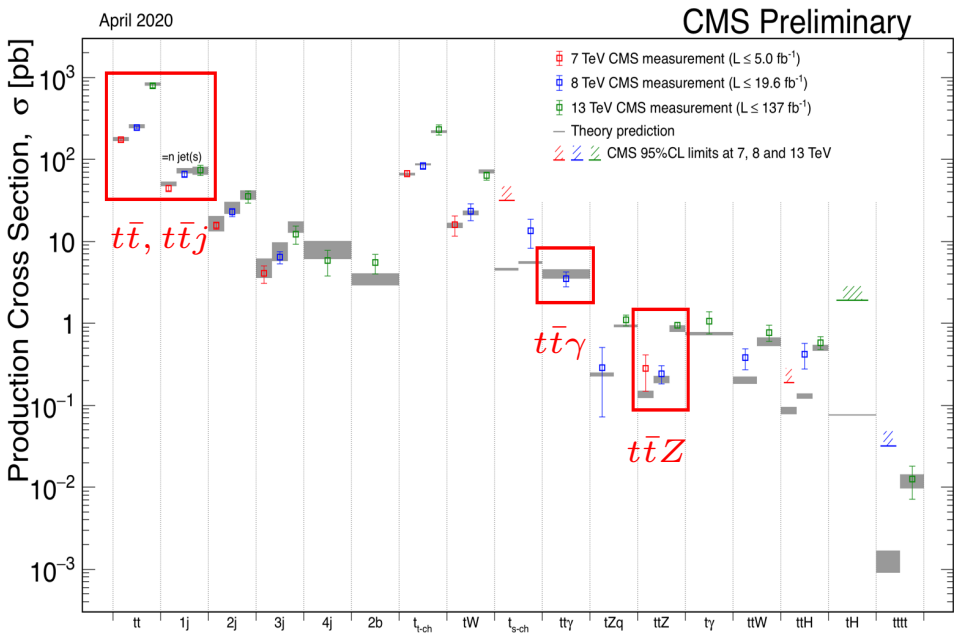
In collaboration with H. B. Hartanto, M. Kraus, T. Weber and M. Worek

Based on: arXiv:1803.09916 [hep-ph] arXiv:1809.08562 [hep-ph]
arXiv:1907.09359 [hep-ph] arXiv:1912.09999 [hep-ph]

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



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined

As luminosity increases, LHC allows to probe associated $t\bar{t}$ channels with more precision

We'll focus on $t\bar{t} + \gamma$ and $t\bar{t} + Z(Z \to \nu\bar{\nu})$ production at Run II of the LHC

Motivations

$\mathrm{t\bar{t}\gamma}$

- **Direct probe of top quark electric charge** Melnikov *et al.* '11 ...

$\hookrightarrow$ $\sigma_{t\bar{t}\gamma} \sim Q_t^2$, while indirect through other processes

- **Probe of the effective $\mathrm{t\bar{t}\gamma}$ interaction** Baur *et al.* '05 *Aguilar Saavedra '09*

$\hookrightarrow$ - dimension-six SM EFT Schulze *et al.* '16 Maltoni *et al.* '16 ...
- top-quark anomalous couplings ...

- **Irreducible background to direct BSM searches**

$\mathrm{t\bar{t}Z}$

- **Direct probe of ttZ coupling** Rontsch and Schulze '15 ...

$\hookrightarrow$ search for deviations from SM expectations

- **Dark Matter searches at LHC ($\mathrm{t\bar{t}} + \mathrm{E_T^{miss}}$)** Arina *et al.* '16 Haisch *et al.* '16

$\hookrightarrow$ in several models, DM couples preferentially to top quarks

- **Background to searches for rare processes**

$\hookrightarrow$ *e.g.* search of same-sign leptons + jets + E_T^{miss}

Predictions for $t\bar{t}\gamma/Z$ at LHC: state of the art

$t\bar{t}\gamma$

- **NLO QCD & EW: on-shell, inclusive** Duan *et al.* '09,'11,'16 Maltoni *et al.* '16
  - ↪ top quarks undecayed: general idea about size of NLO corrections
- **NLO QCD: on-shell, with radiative decays** Melnikov, Scharf and Schulze '11
  - ↪ QCD corrections to production and decays, with spin correlations and γ radiation from decays
- **NLO QCD: on-shell, with PS effects** Kardos and Trocsanyi '14
  - ↪ top decays in PS, no spin correlations, only direct-photon contribution
- **NLO QCD: complete off-shell** G.B, Hartanto, Kraus, Weber and Worek '18
  - ↪ resonant and non-resonant diagrams, interferences and finite-width effects (dilepton channel)

$t\bar{t}Z$

- **NLO QCD: on-shell, inclusive** Lazopoulos *et al.* '08
- **NLO QCD: on-shell, with NLO decays** Röntsch and Schulze '14
- **NLO QCD & EW: on-shell, with PS effects** Kardos *et al.* '12 Frixione *et al.* '15
- **NLO QCD & EW + NNLL** Kulesza *et al.* '18, '20 Broggio *et al.* '17, '19
- **NLO QCD: complete off-shell** G.B, Hartanto, Kraus, Weber and Worek '19

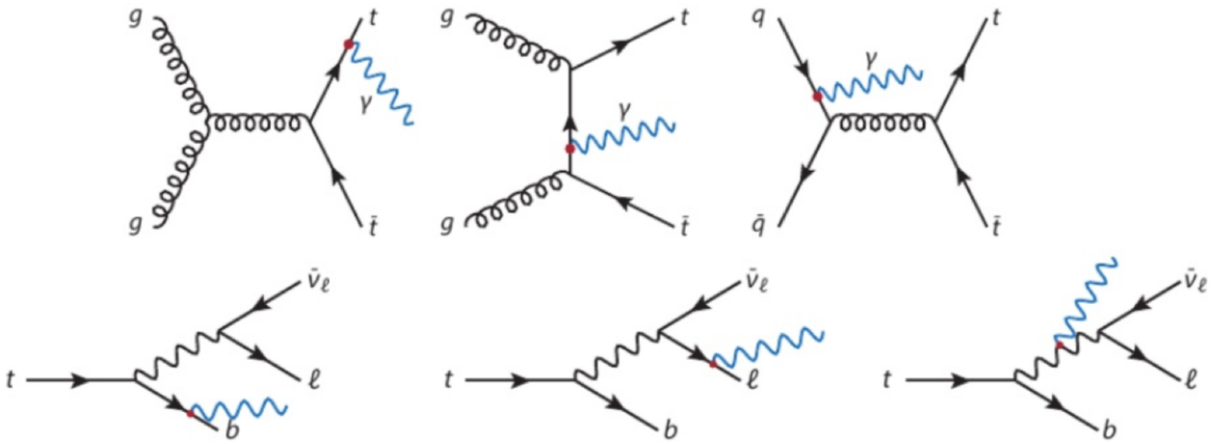
Narrow Width Approximation

Based on the narrow-width limit:

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

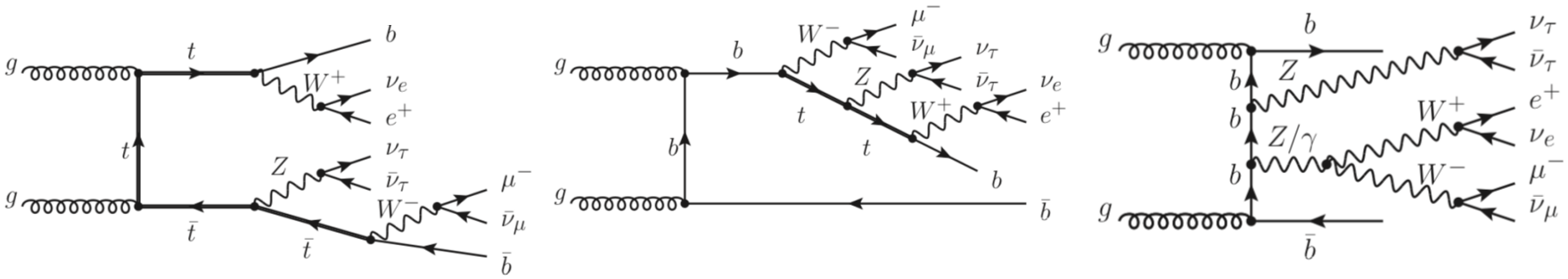
- cross section factorizes into on-shell $t\bar{t}\ (+X)$ *production* $\otimes$ *decays*
  $\hookrightarrow$ only *double-resonant* diagrams are retained
- non-factorizable contributions are suppressed by powers of $\Gamma_t/m_t = \mathcal{O}(1\%)$ for *sufficiently inclusive* observables
- huge simplification, but several contributions have to be put together to account for all resonant structures...

e.g. $t\bar{t}\gamma$



Beyond NWA

Representative Feynman diagrams for the case of $t\bar{t}Z(Z \to \nu\bar{\nu})$:

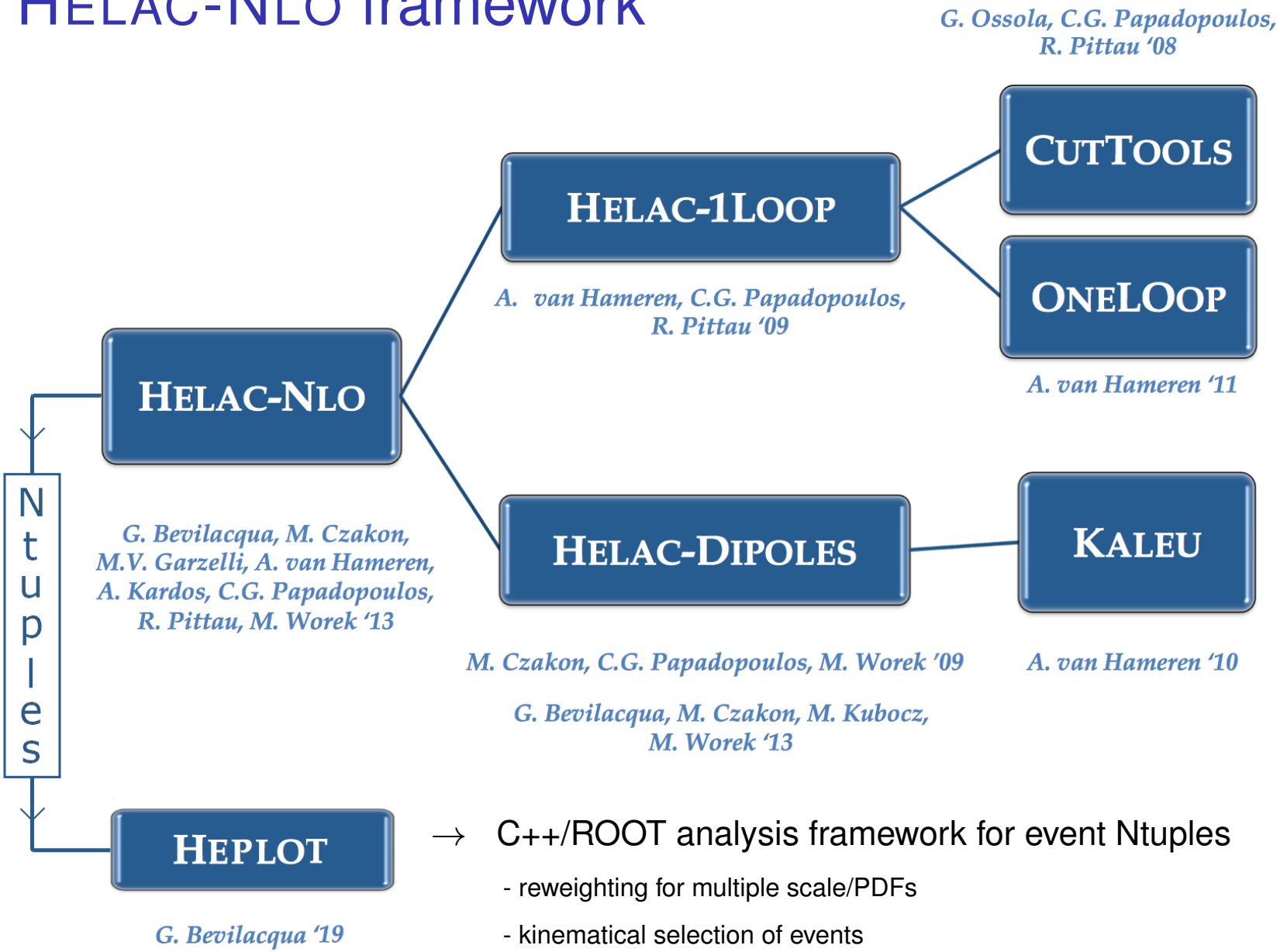


double-resonant (DR) single-resonant (SR) non-resonant (NR)

- all resonant and non-resonant contributions are taken into account
- most complete calculation of ME's at fixed perturbative order
- computationally demanding: $\mathcal{O}(10)$ increase in complexity w.r.t. NWA

"Off-shell effects" $=$ finite-width effects for tops and W's
$+$ SR + NR
$+$ interferences among DR, SR, NR

The HELAC-NLO framework



→ C++/ROOT analysis framework for event Ntuples

- reweighting for multiple scale/PDFs
- kinematical selection of events
- histogramming tools

Predictions for $t\bar{t}\gamma$ at $\sqrt{s} = 13$ TeV

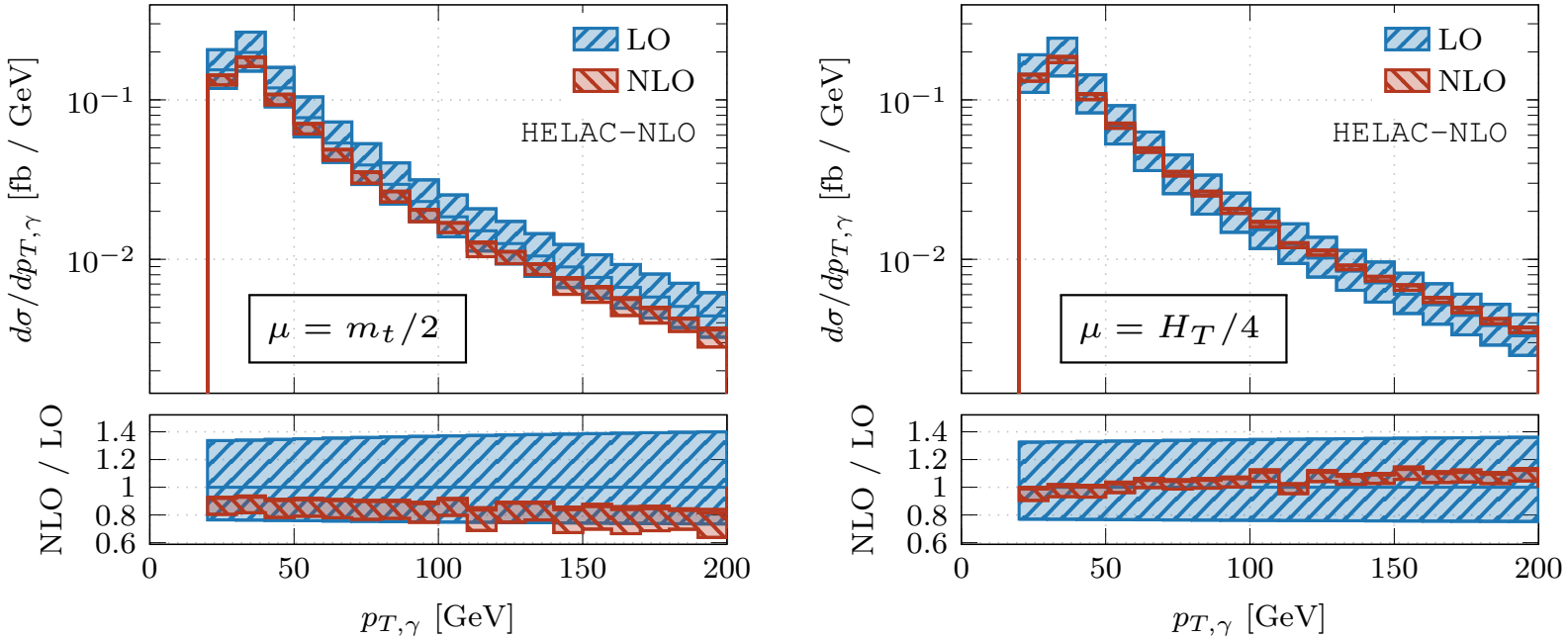
Predictions for off-shell $t\bar{t}\gamma$

$pp \to t\bar{t}(\gamma) \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu\gamma$ @ 13 TeV

-dilepton channel-

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

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



Dynamical scale $\mu_R = \mu_F = H_T/4$ improves perturbative stability

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

Comparative analysis of different approaches of $t\bar{t}\gamma$ modeling in progress

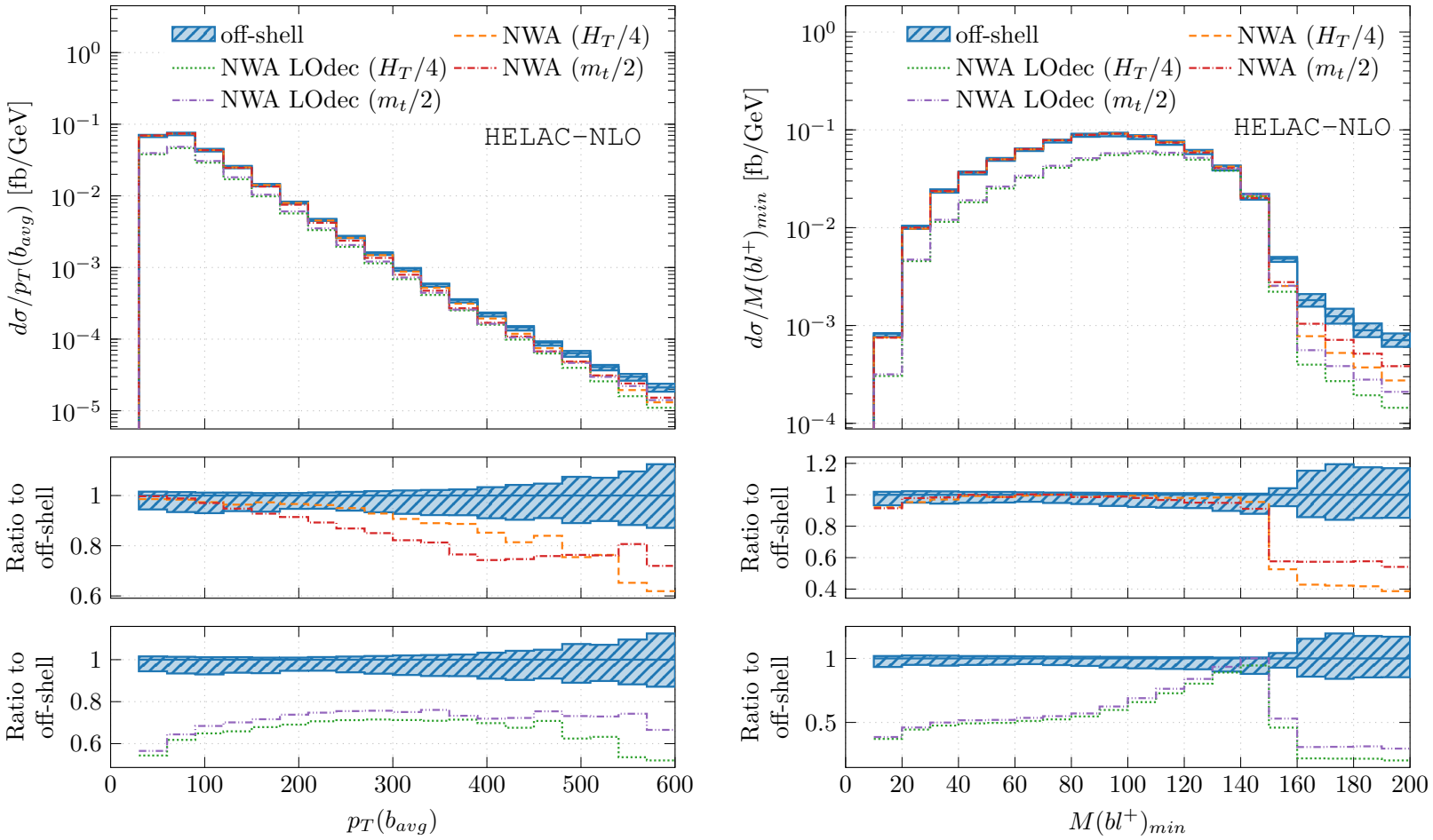
ATLAS-CONF-2019-042

$t\bar{t}\gamma$: off-shell vs on-shell

Impact of off-shell effects
and radiative decays

$pp \to t\bar{t}(\gamma) \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu\gamma$ @ 13 TeV
-dilepton channel-

G.B., Kraus, Hartanto, Weber and Worek, arXiv:1912.09999 [hep-ph]



$\sigma_{\text{NLO, NWA}} = 7.33$ fb $\leftrightarrow$ $\sigma_{\text{NLO, NWA (LO decays)}} = 4.63$ fb

Predictions for off-shell $t\bar{t}\gamma$

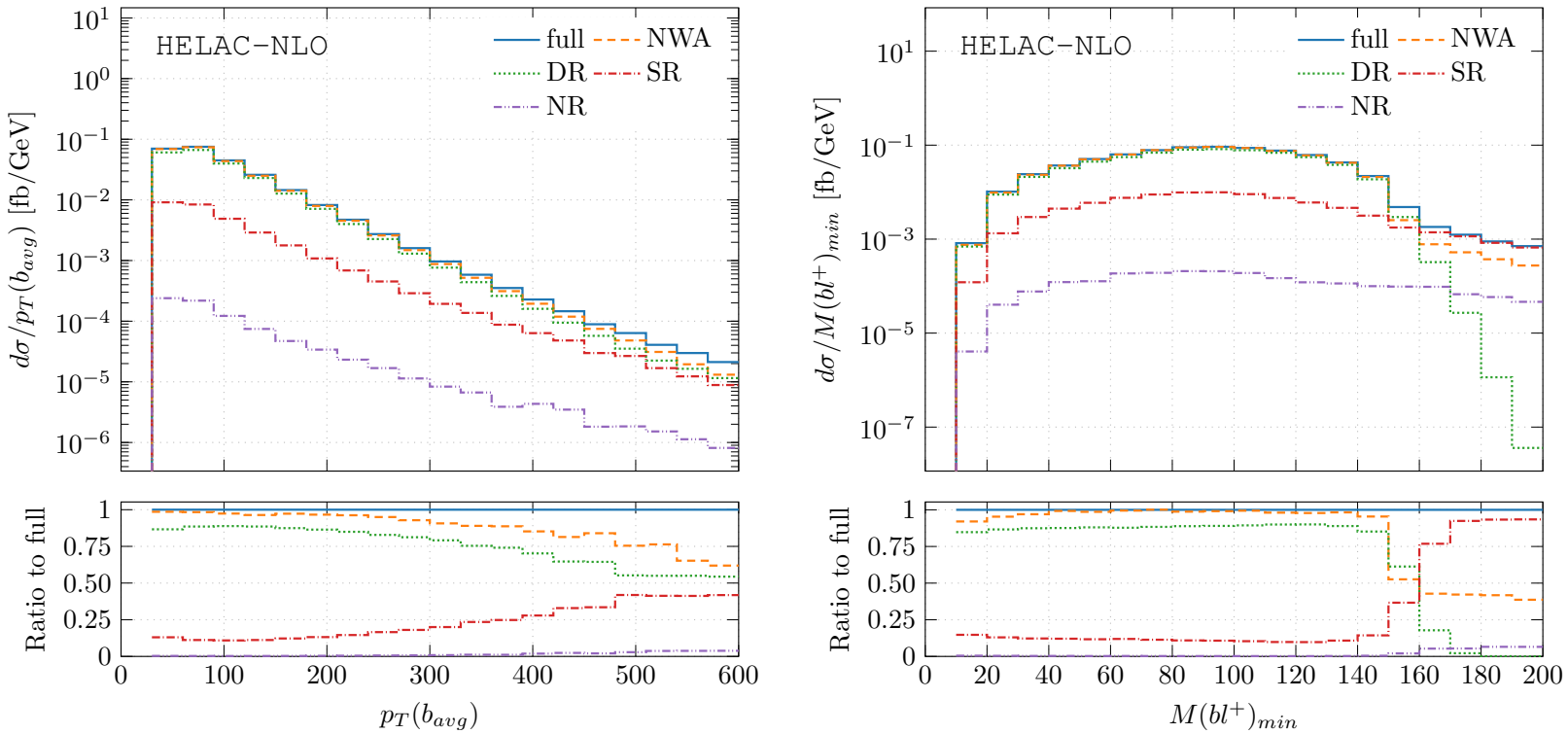
Analysis of Double-, Single- and Non-Resonant phase space regions

Kauer and Zappenfeld '01 ...

$pp \to t\bar{t}(\gamma) \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu\gamma$ @ 13 TeV

-dilepton channel-

G.B., Kraus, Hartanto, Weber and Worek, arXiv:1912.09999 [hep-ph]



DR $\to$ $|M(t) - m_t| < n\,\Gamma_t \quad \wedge \quad |M(\bar{t}) - m_t| < n\,\Gamma_t \qquad (n = 15)$

NR $\to$ $|M(t) - m_t| > n\,\Gamma_t \quad \wedge \quad |M(\bar{t}) - m_t| > n\,\Gamma_t$

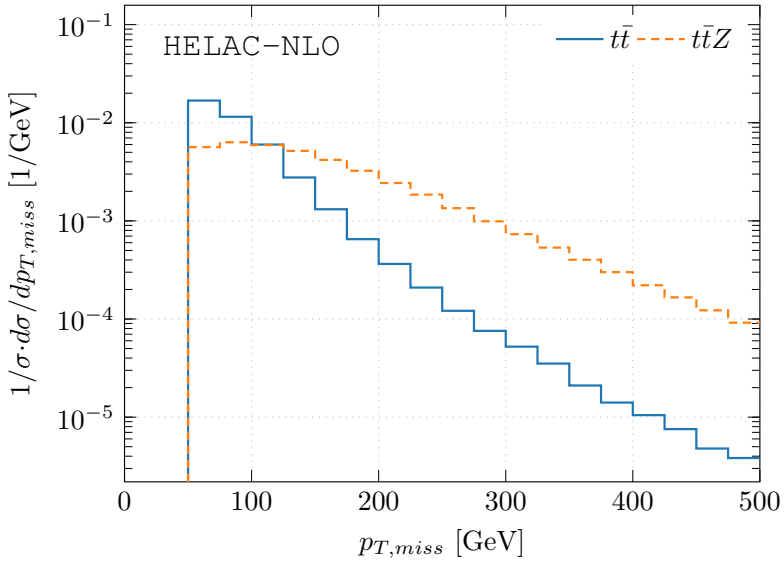
SR $\to$ full $-$ (DR $+$ NR)

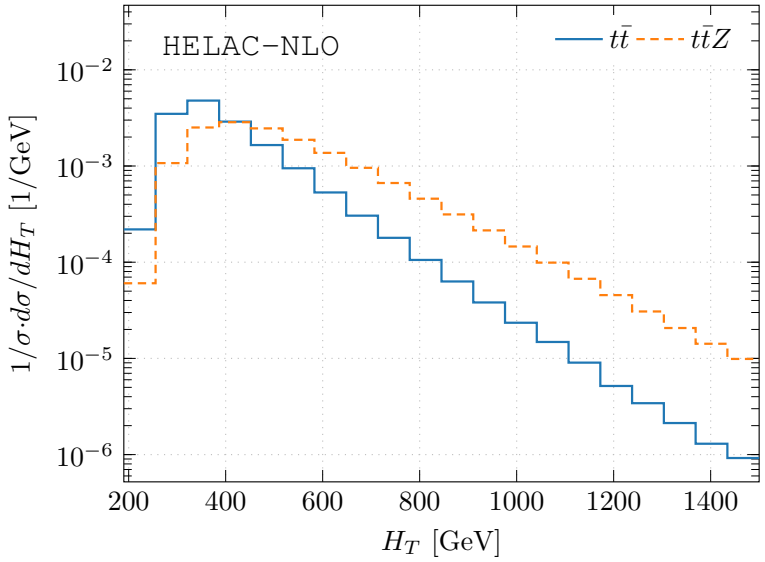
Predictions for $t\bar{t}Z(Z \to \nu\bar{\nu})$ at $\sqrt{s} = 13$ TeV

$t\bar{t} + E_T^{miss}$

While leading to the same *visible* final state, off-shell $t\bar{t}$ and $t\bar{t}Z(Z \to \nu\bar{\nu})$ have pretty different kinematics

[distributions normalized to one]





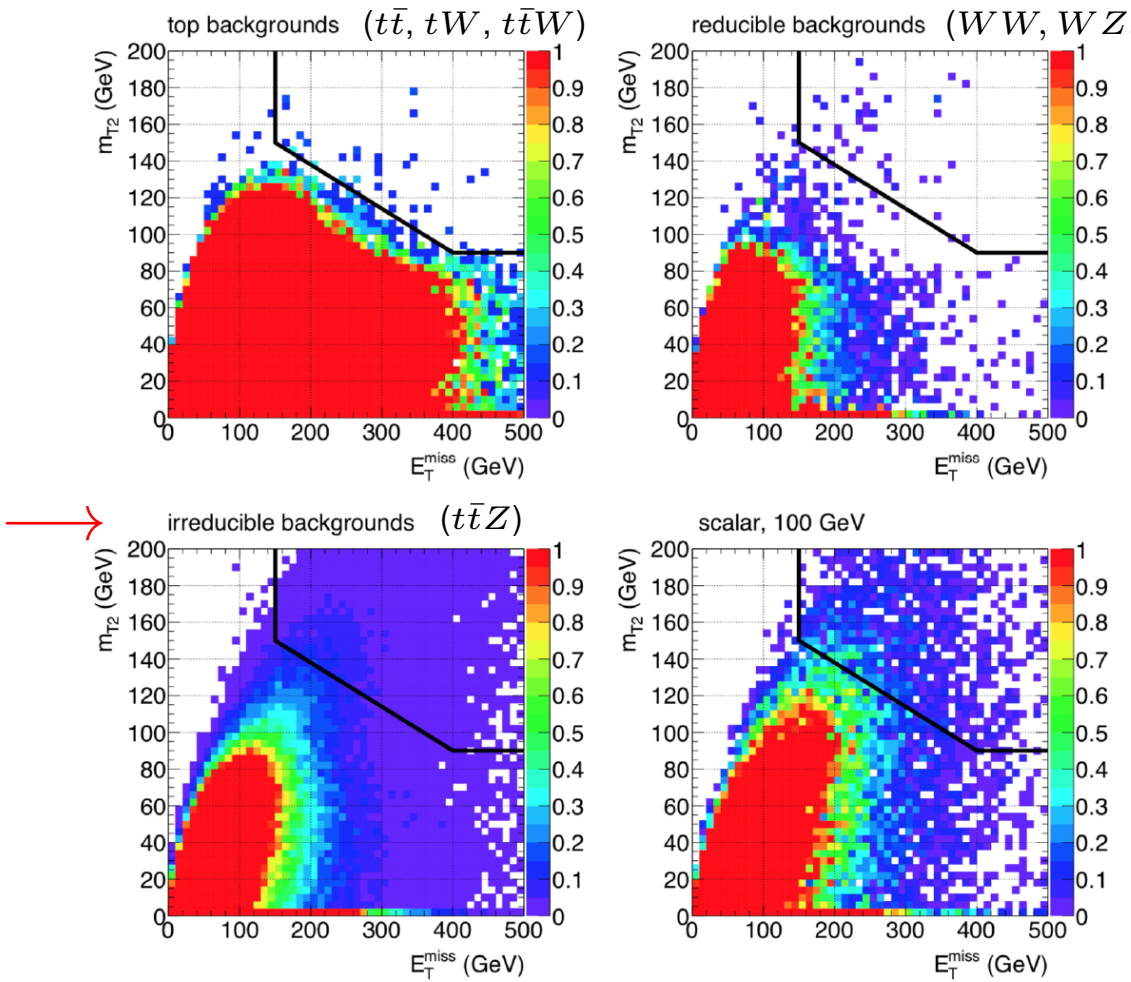
G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]

$t\bar{t}Z$ populates high p_T^{miss} regions which are important for BSM studies. However $t\bar{t}$ dominates over $t\bar{t}Z(Z \to \nu\bar{\nu})$ by several orders of magnitude (at *inclusive* level).

$\hookrightarrow$ Is it important to strive for higher accuracy in $t\bar{t}Z$? Yes!

Determining the CP nature of spin-0 mediators in $t\bar{t}$ + DM production

Haisch, Pani and Polesello, arXiv:1611.09841 [hep-ph]



- Distribution of events in the (E_T^{miss}, m_{T2}) plane for the different backgrounds and for one example of DM signal $[M_\phi = 100 \text{ GeV} \ , \ M_\chi = 1 \text{ GeV}]$

- The area in the upper right corner above the black line is the region selected in the analysis

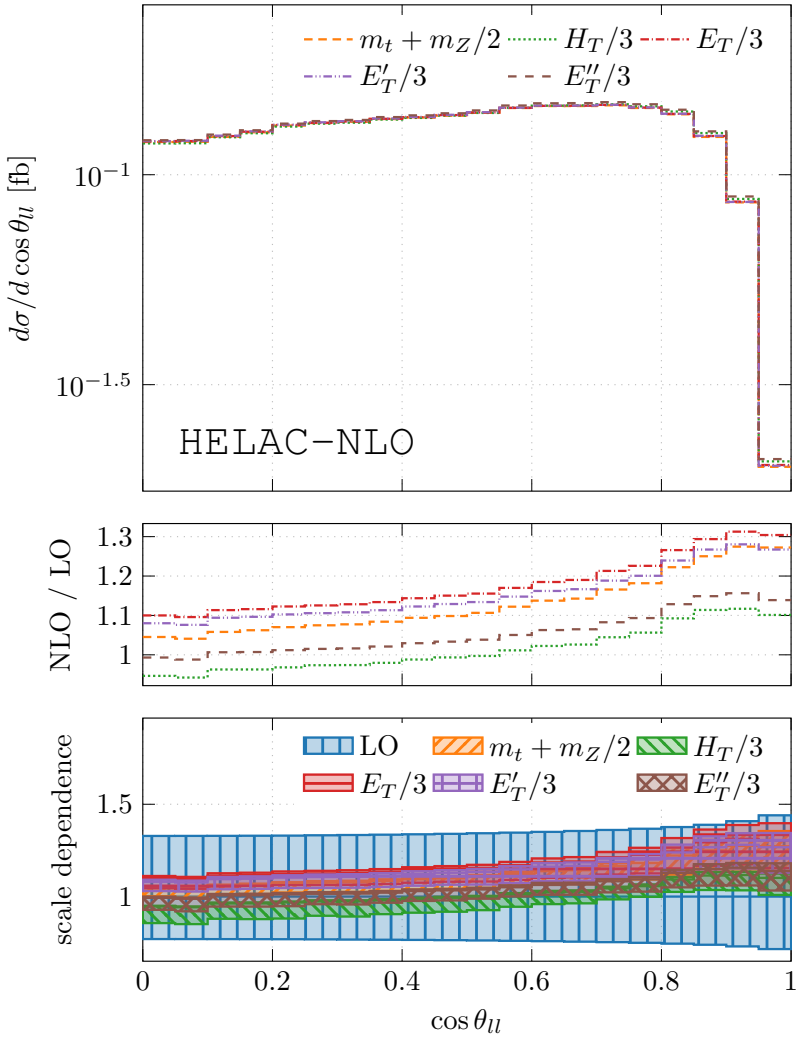
$$m_{\mathrm{T2}}^2(\vec{p}_{\mathrm{T}}^{\,\ell_i}, \vec{p}_{\mathrm{T}}^{\,\ell_j}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) \equiv \min_{\vec{q}_{\mathrm{T}}^{\,1}+\vec{q}_{\mathrm{T}}^{\,2}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left\{ \max\left[m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\ell_i}, \vec{q}_{\mathrm{T}}^{\,1}), m_{\mathrm{T}}^2(\vec{p}_{\mathrm{T}}^{\,\ell_j}, \vec{q}_{\mathrm{T}}^{\,2}) \right] \right\}$$

- With 300 fb^{-1}, assuming 20% systematics for SM backgrounds, it should be possible to resolve the (pseudo-)scalar nature of the mediator up to mass ≈ 200 GeV

- Discovery reach depends on syst. uncertainty of SM backgrounds, dominated by $t\bar{t}Z$

Off-shell $t\bar{t}Z(Z \to \nu\bar{\nu})$: differential cross sections

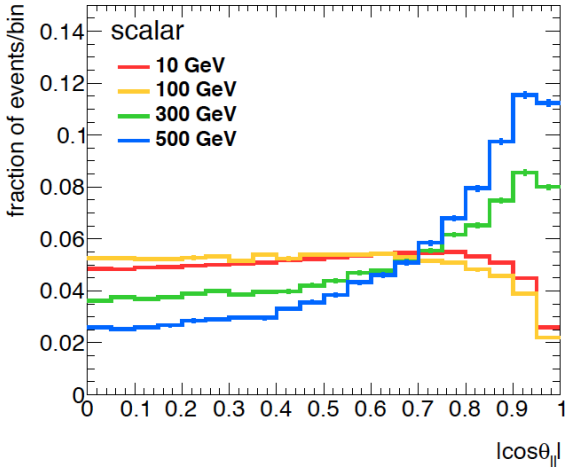
G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]



$$\cos\theta_{ll} = \tanh(\Delta y_{ll}/2)$$

- Sensitive to the nature of DM mediator

Haisch *et al.* '16



- Differential K-factors far from constant!

- $\mu = m_t + m_Z/2$: $+4\% \leftrightarrow 27\%$
- $\mu = H_T/3$: $-5\% \leftrightarrow 10\%$
- $\mu = E''_T/3$: $-1\% \leftrightarrow 14\%$

Summary

- Achieving the highest precision for $t\bar{t} + V$ requires to include non-resonant, finite-width and interference effects.
- Systematic comparisons between predictions at different levels of accuracy (on-shell vs off-shell) are important to assess the reliability of various approximations
- We have computed predictions for a variety of *off-shell* $t\bar{t} + X$ processes (dilepton channel) with the package HELAC-NLO:

  - $pp \to t\bar{t} + \gamma$ - $pp \to t\bar{t} + Z$
  - $pp \to t\bar{t} + j$ - $pp \to t\bar{t} + W^{\pm}$ NEW! arXiv:2005.09427 [hep-ph]

- Our predictions are available in the form of ROOT Ntuples. We can provide them along with a user-friendly software to extract physical results for your analysis. If interested, contact us!

A Zoom meeting room is available for further discussions.

Please find the details on next slide $\to$

Details of Zoom Meeting room (May 25, 16:30-17:00 CERN time)

Topic: Giuseppe Bevilacqua's Zoom Meeting

Date, Time: May 25, 2020 04:30 PM Paris

Click here to join

(same password of this parallel session)

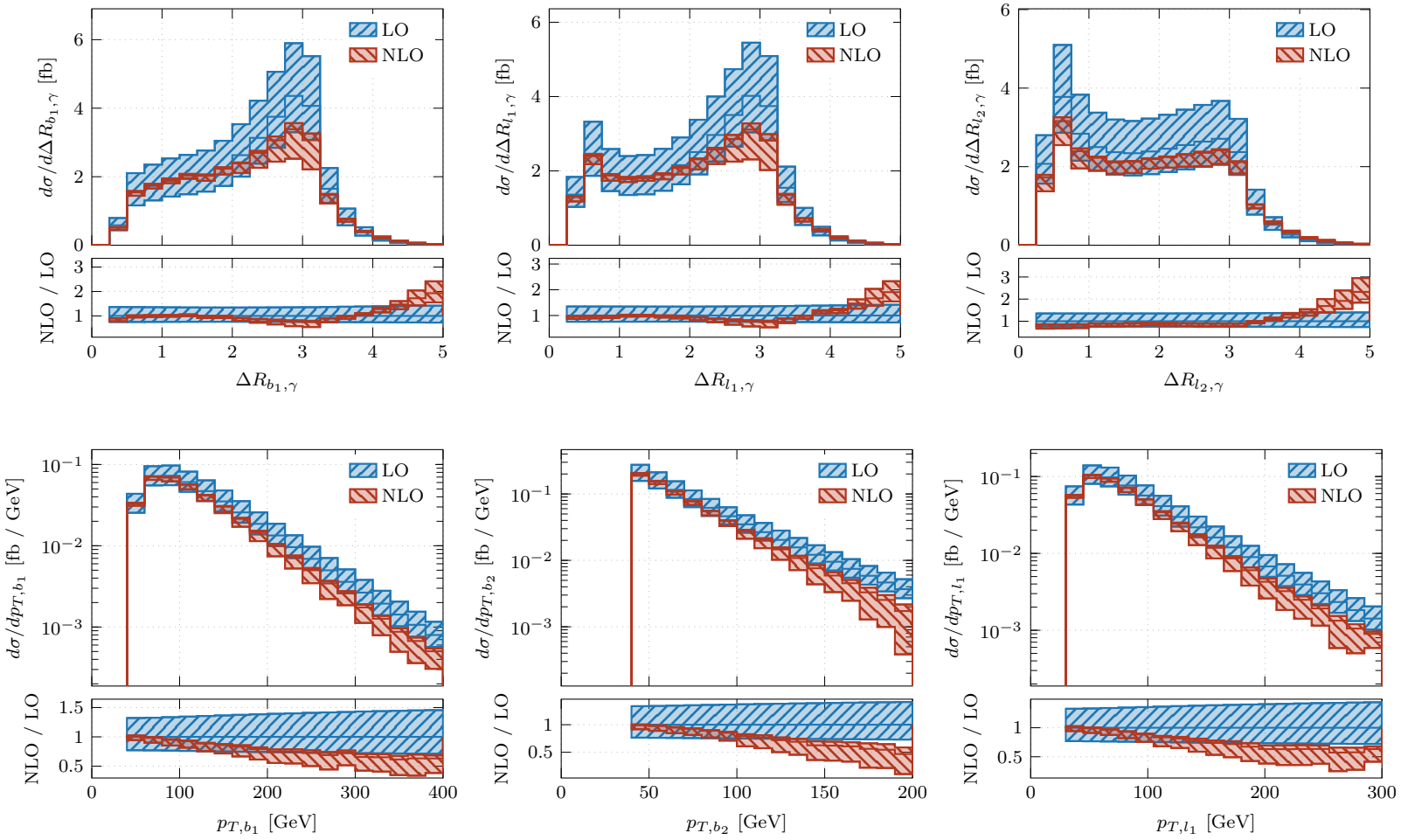
In case of problems, just email me
(giuseppe.bevilacqua_AT_science.unideb.hu)

Backup slides

Off-shell $t\bar{t}\gamma$: fixed vs dynamical scales

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

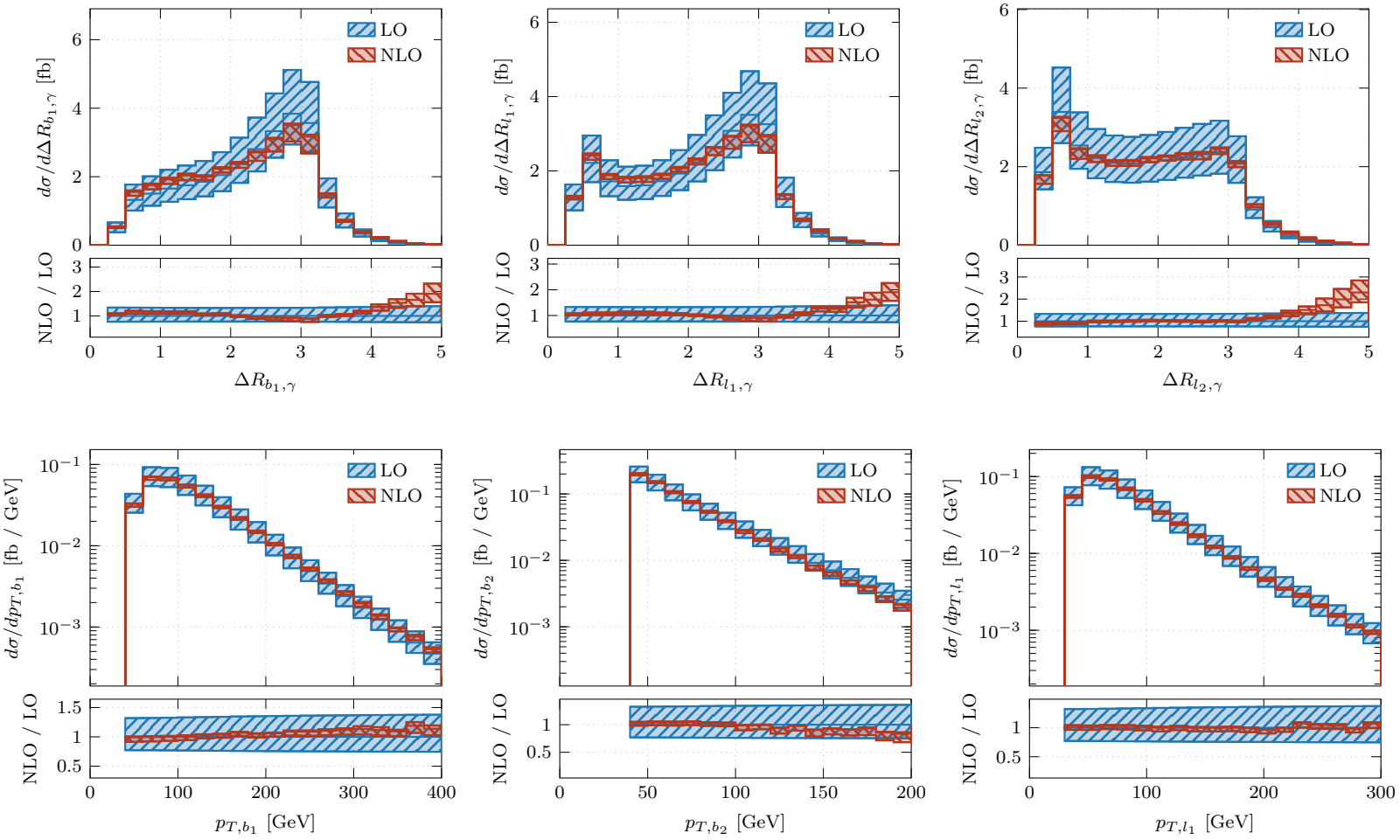
G.B., Hartanto, Kraus, Weber and Worek, arXiv:1803.09916 [hep-ph]



Off-shell $t\bar{t}\gamma$: fixed vs dynamical scales

A collection of distributions based on the scale choice $\mu_R = \mu_F = H_T/4$

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



Off-shell $t\bar{t}\gamma$: comparisons to Run II data

"Theory NLO" = off-shell $t\bar{t}\gamma$ (HELAC-NLO)

"Madgraph5" = double-resonant $t\bar{t}\gamma$ (LO)

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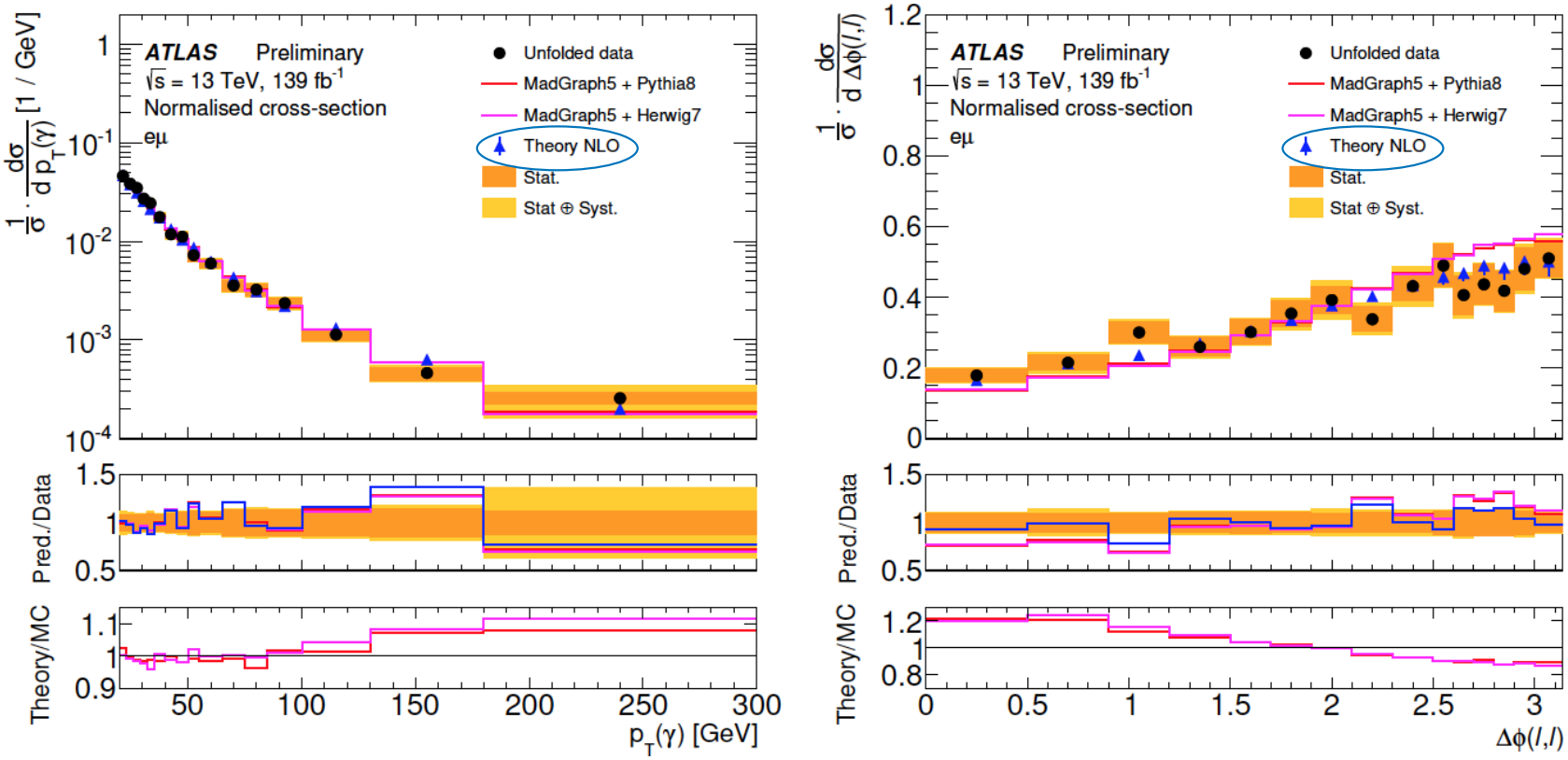


$$\sigma_{\text{exp}} = 44.2 \pm 0.9\,(\text{stat})^{+2.6}_{-2.4}\,(\text{syst})\ \text{fb} = 44.2 \pm 2.6\ \text{fb}$$

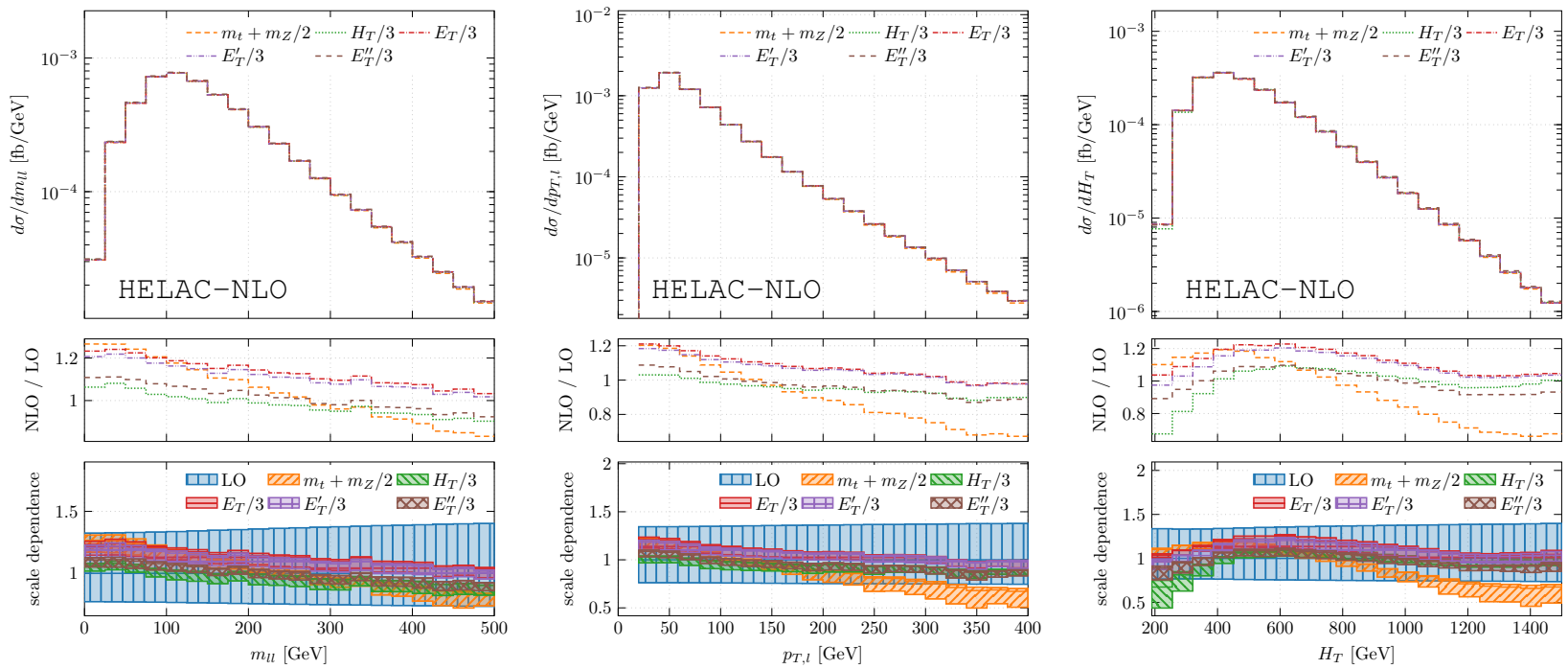
$$\sigma_{\text{Theory NLO}} = 39.50^{+0.56}_{-2.18}\,(\text{scale})^{+1.04}_{-1.18}\,(\text{PDF})\ \text{fb}$$

Off-shell $t\bar{t}Z(Z \to \nu\bar{\nu})$: differential cross sections

Checks on *dimensionful* observables

G.B, Hartanto, Kraus, Weber and Worek, arXiv:1907.09359 [hep-ph]

dilepton inv. mass | charged lepton's p_T | transverse energy (H_T)



- $\mu = \mathbf{m_t + m_Z/2}$ $\rightarrow$ NLO gets outside LO uncertainties
- $\mu = \mathbf{H_T/3, E_T/3, \ldots}$ $\rightarrow$ improves perturbative convergence