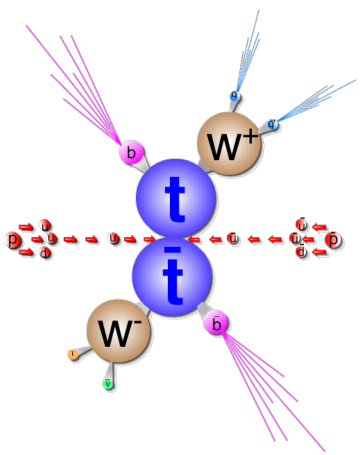
Off-shell vs on-shell modelling of top quarks in photon associated production

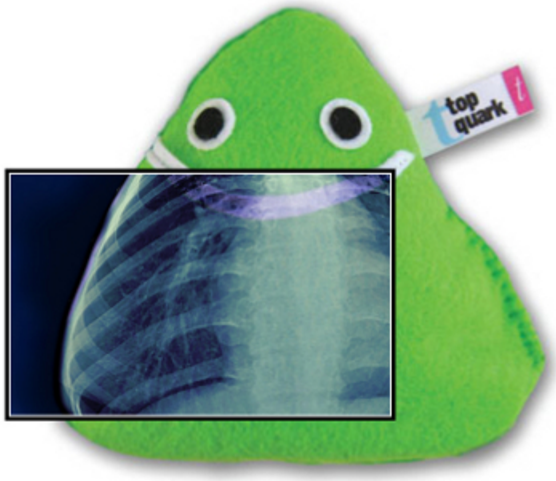


Malgorzata Worek

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

13th International Workshop on Top Quark Physics (TOP 2020), 14-18 September 2020
virtually hosted by IPPP Durham on Zoom

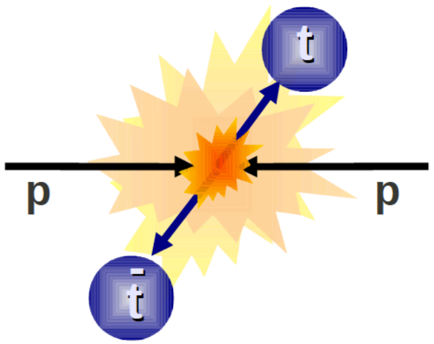
Outline

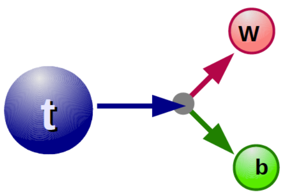


ttγ ⇨ di-lepton channel

<u>Questions:</u>

- Size of NLO QCD corrections ⇨ $\sigma_{t\bar{t}\gamma}\,,\, d\sigma_{t\bar{t}\gamma}/dX$
- Reduction of theoretical uncertainties ⇨ $t\bar{t}\gamma/t\bar{t}$
- Applicability of the NWA ⇨ *Importance of off-shell effects*
- Photon emission in production & decays

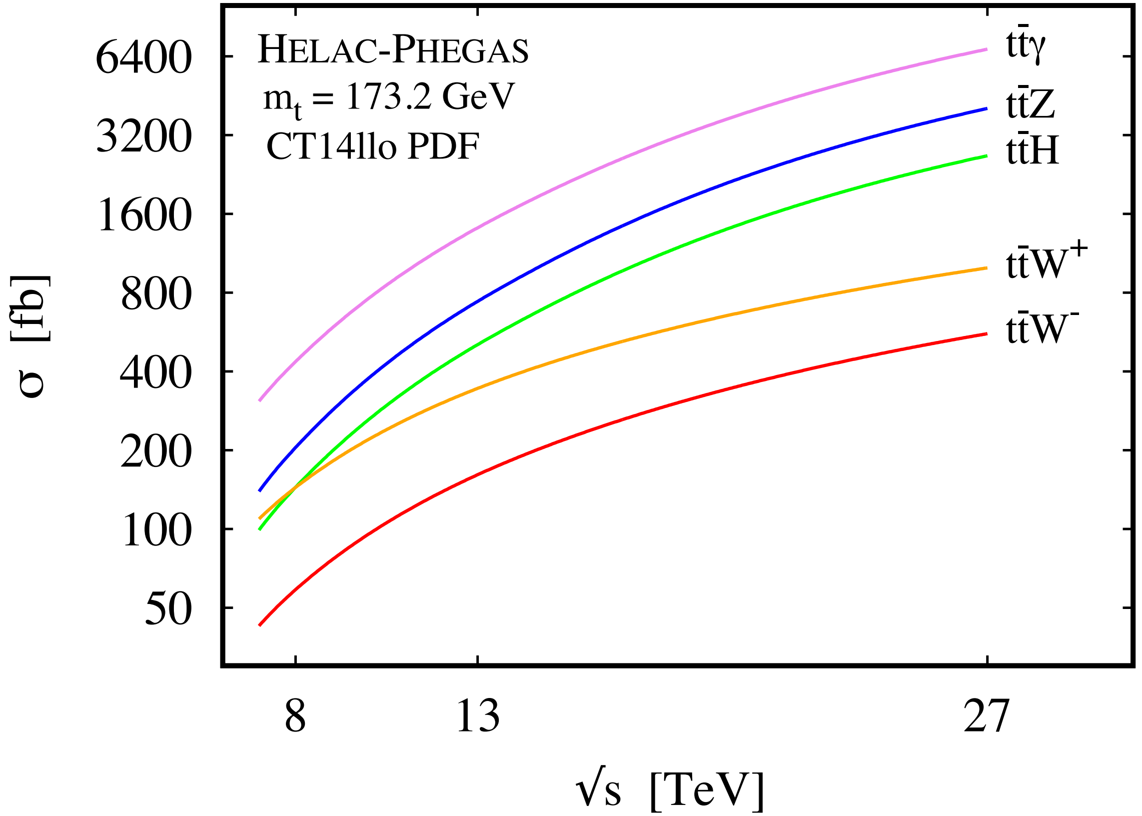




What about other processes ?

- NNLO theoretical predictions only for ***tt*** ⇨ di-lepton channel
- Besides ***tt*** more exclusive final states can be accessed @ LHC

$t\bar{t}\gamma, t\bar{t}Z, t\bar{t}H, t\bar{t}W^+, t\bar{t}W^-$ @LHC



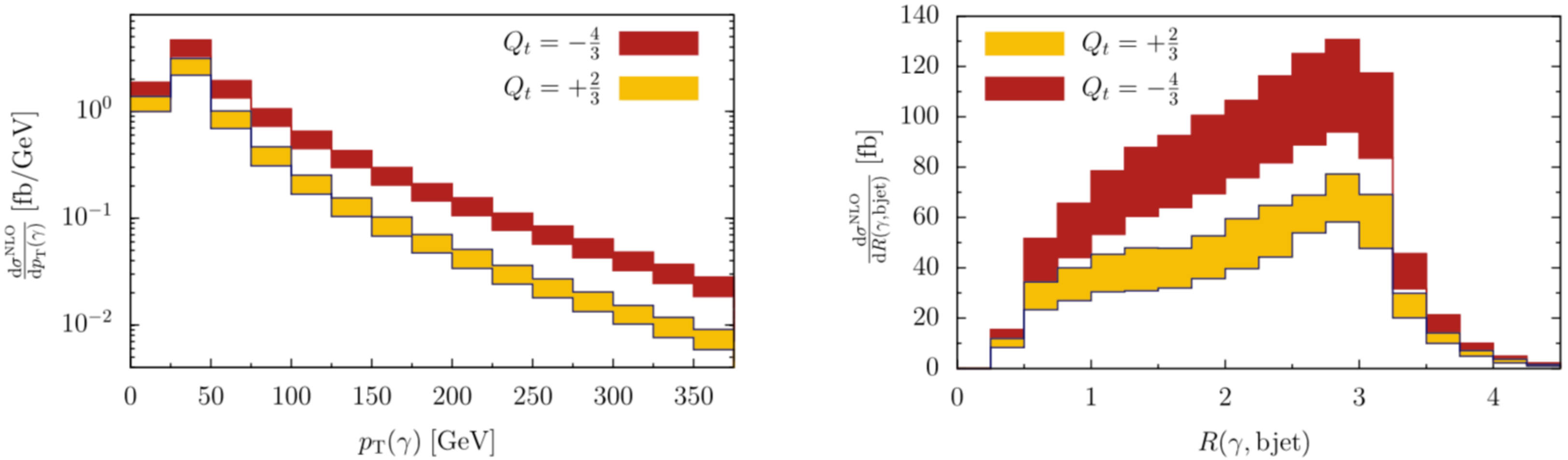
Stable top quarks

HELAC-PHEGAS

Cafarella, Papadopoulos, Worek '09

Motivations For ttγ

- ***ttV*** cross sections much smaller than ***tt(j)***
- ***Information on couplings*** ⇨ ***γ, Z, H, W^+ & W^-***
- ***$\sigma_{tt\gamma}$*** direct way to measure ***top quark charge @ LHC*** ⇨ ***$\sigma_{tt\gamma} \sim Q_t^2$ @ LHC***
- ***$Q_t = +⅔$ with CL ≥ 5σ @ LHC*** ⇨ Indirectly from ***$Q_t = Q_W - Q_{b\text{-}jet}$*** in ***tt***
- ***Exotic physics scenarios*** ⇨ top-like quarks with ***$Q_t \neq +⅔$***



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

Melnikov, Schulze, Scharf '11

Motivations For ttγ

- ***Probe the strength and the structure of ttγ vertex*** ⇰ SM + contributions from dimension-six effective operators ⇰ Constrains on anomalous couplings

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

Aguilar-Saavedra '09
Schulze, Soreq '16

- Measure ***cross section ratio*** (also differential ratios)

$$\mathcal{R} = \frac{\sigma_{pp\to t\bar{t}\gamma}}{\sigma_{pp\to t\bar{t}}}$$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

  - More stable against radiative corrections
  - Reduced scale dependence ⇰ Various uncertainties cancel in ratio
  - Enhanced predictive power ⇰ Interesting to probe new physics @ LHC

- Top quark charge ***asymmetry, differential top quark charge asymmetries***, …
- Lepton charge asymmetry

Aguilar-Saavedra, Alvarez, Juste, Rubbo '14
Maltoni, Pagani, Tsinikos '16
Aguilar-Saavedra '18

Theoretical Predictions For $t\bar{t}\gamma$

- NLO corrections for stable top quarks ⇨ General idea about size of NLO corrections. Can not provide reliable description of top quark decay products and radiation pattern

  - ***NLO QCD***
  - ***NLO electroweak***

  Duan, Ma, Zhang, Han, Guo, Wang '09 '11
  Hirschi, Frederix, Frixione, Garzelli, Maltoni '11
  Maltoni, Pagani, Tsinikos '15
  Duan, Zhang, Wang, Song, Li '16

- For more realistic studies decays are needed

  - ***NLO QCD for $t\bar{t}\gamma$ + PS*** ⇨ Top decays in parton shower approximation, omitting photon emission in PS evolution & omitting tt spin correlations

    Kardos, Trocsanyi '14

  - ***NLO QCD in NWA*** ⇨ NLO QCD corrections to top production & decays & no QCD corrections to hadronic decays of W-bosons & photon emission of top quark and of top quark decay product & tt spin correlations @ NLO included

    Melnikov, Schulze, Scharf '11

  - ***NLO QCD complete off-shell effects of top quarks*** ⇨ resonant & non-resonant diagrams, interferences and off-shell effects of the top quarks

    Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20

NWA & Off-Shell Effects

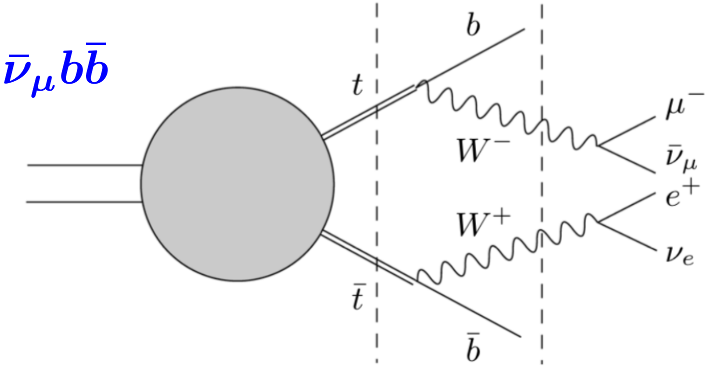
- ***Complete off-shell effects***
  - Off-shell top quarks are described by Breit-Wigner propagators
  - Double-, single- as well as non-resonant top-quark contributions are included
  - All interference effects consistently incorporated at the matrix element level

- ***NWA***
  - Works in the limit ⇨ $\Gamma_t/m_t \to 0$

$\Gamma_t = 1.35159$ GeV	$m_t = 173.2$ GeV	$\Gamma_t/m_t \approx 0.008$

  - Incorporates only double resonant contributions
  - Restricts the unstable top quarks (W gauge bosons) to ***on-shell states***

$$pp \to t\bar{t} \to W^+W^-b\bar{b} \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$$



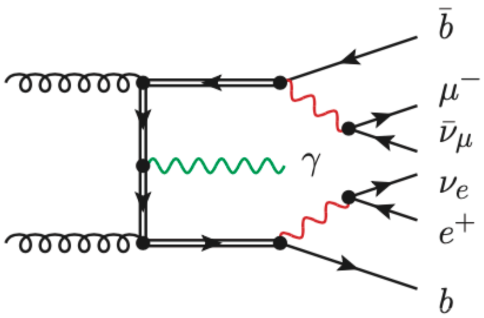
$$d\sigma^{\rm NWA}_{t\bar{t}} = d\sigma_{t\bar{t}}\, d\mathcal{B}_{t\to be^+\nu_e}\, d\mathcal{B}_{\bar{t}\to\bar{b}\mu^-\bar{\nu}_\mu}$$

$$d\sigma^{\rm NWA}_{t\bar{t}\gamma} = d\sigma_{t\bar{t}\gamma}\, d\mathcal{B}_{t\to be^+\nu_e}\, d\mathcal{B}_{\bar{t}\to\bar{b}\mu^-\bar{\nu}_\mu} + d\sigma_{t\bar{t}}\left(d\mathcal{B}_{t\to be^+\nu_e\gamma}\, d\mathcal{B}_{\bar{t}\to\bar{b}\mu^-\bar{\nu}_\mu} + d\mathcal{B}_{t\to be^+\nu_e}\, d\mathcal{B}_{\bar{t}\to\bar{b}\mu^-\bar{\nu}_\mu\gamma}\right)$$

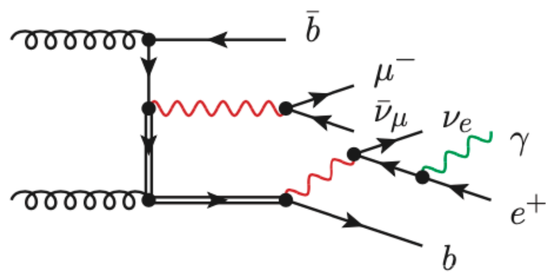
NWA & Off-Shell Effects

$pp \to t\bar{t}\gamma$

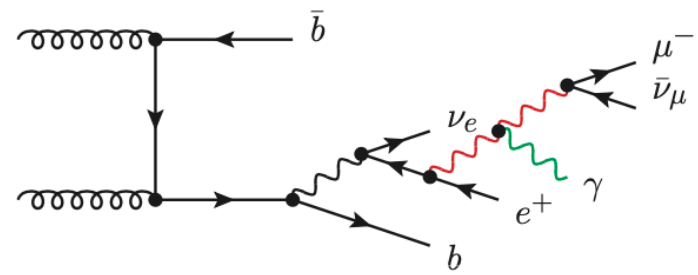
- Feynman Diagrams ⇨ *628* @ *LO* for gg channel versus *38* in NWA
- *8* diagrams with photon in production and *30* in decay stage



two top-quark resonances



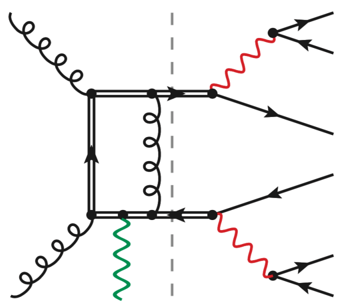
one top-quark resonance

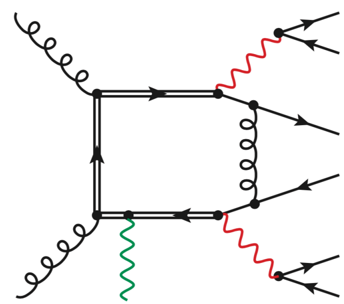


no top-quark resonances

- NLO ⇨ *4348* real emission *& 36032* @ *1-loop* for gg channel
- Most complicated ⇨ *90* heptagons *& 958* hexagons

ttγ in NWA
up to pentagons





ttγ full
up to heptagons

$$pp \to t\bar{t}\gamma + X \ @ \ \mathcal{O}(\alpha_s^3\alpha^5)$$

How Good Is the NWA ?

- Should be accurate for sufficiently inclusive observables
- Off-shell effects for integrated fiducial σ_{tt+X} ⇨ ***at few % level*** @ NLO in QCD

• ***tt*** ***(di-lepton)***	*Denner, Dittmaier, Kallweit, Pozzorini '11 '12* *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11* *Frederix '14* *Heinrich, Maier, Nisius, Schlenk, Winter '14* *Denner, Pellen '16 (EW+QCD)* *Jezo, Lindert, Nason, Oleari, Pozzorini '16 (PS)*
• ***tt*** ***(lepton+jets)***	*Denner, Pellen '18*
• ***ttH*** ***(di-lepton)***	*Denner, Feger '15* *Denner, Lang, Pellen, Uccirati '17 (EW+QCD)*
• ***ttj*** ***(di-lepton)***	*Bevilacqua, Hartanto, Kraus, Worek '16 '18*
• $tt\gamma$ ***(di-lepton)***	*Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19 '20*
• $ttZ,\ Z \to \nu_l \nu_l$ ***(di-lepton)***	*Bevilacqua, Hartanto, Kraus, Weber, Worek '19*
• $ttW^{\pm}$ ***(di-lepton)***	*Bevilacqua, Bi, Hartanto, Kraus, Worek '20* *Denner, Pelliccioli '20*
• ***ttbb*** ***(di-lepton)***	*Denner, Lang, Pellen '20*

$tt\gamma$

Questions:

- Size of NLO QCD corrections ⇨ $\sigma_{t\bar{t}\gamma}$, $d\sigma_{t\bar{t}\gamma}/dX$
- Reduction of theoretical uncertainties ⇨ $t\bar{t}\gamma/t\bar{t}$
- Applicability of the NWA ⇨ ***Importance of off-shell effects***
- Photon emission in production & decays

$t\bar{t}\gamma$ with dynamical scale ¼ H_T

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

$pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

PDF	$p_{T,b}$	σ^{LO} [fb]	δ_{scale}	σ^{NLO} [fb]	δ_{scale}	δ_{PDF}	$\mathcal{K} = \frac{NLO}{LO}$
CT	25	10.68	+3.54 (33%) −2.49 (23%)	11.19	+0.16 (1%) −0.54 (5%)	+0.32 (3%) −0.35 (3%)	1.05
	30	9.58	+3.18 (33%) −2.24 (23%)	9.93	+0.14 (1%) −0.54 (5%)	+0.28 (3%) −0.31 (3%)	1.04
	35	8.44	+2.80 (33%) −1.97 (23%)	8.69	+0.12 (1%) −0.50 (6%)	+0.25 (3%) −0.27 (3%)	1.03
	40	7.32	+2.45 (33%) −1.71 (23%)	7.50	+0.11 (1%) −0.45 (6%)	+0.22 (3%) −0.23 (3%)	1.02
MMHT	25	11.59	+4.22 (36%) −2.88 (25%)	11.29	+0.16 (1%) −0.57 (5%)	+0.24 (2%) −0.22 (2%)	0.97
	30	10.38	+3.78 (36%) −2.58 (25%)	10.02	+0.13 (1%) −0.58 (6%)	+0.22 (2%) −0.19 (2%)	0.97
	35	9.12	+3.33 (36%) −2.26 (25%)	8.77	+0.11 (1%) −0.54 (6%)	+0.19 (2%) −0.17 (2%)	0.96
	40	7.90	+2.89 (37%) −1.96 (25%)	7.57	+0.09 (1%) −0.48 (6%)	+0.16 (2%) −0.15 (2%)	0.96
NNPDF	25	10.78	+3.82 (35%) −2.62 (24%)	11.62	+0.17 (1%) −0.58 (5%)	+0.16 (1%) −0.16 (1%)	1.08
	30	9.65	+3.42 (35%) −2.34 (24%)	10.31	+0.14 (1%) −0.58 (6%)	+0.14 (1%) −0.14 (1%)	1.07
	35	8.48	+3.01 (35%) −2.05 (24%)	9.02	+0.12 (1%) −0.53 (6%)	+0.12 (1%) −0.12 (1%)	1.06
	40	7.34	+2.61 (36%) −1.78 (24%)	7.79	+0.10 (1%) −0.48 (6%)	+0.11 (1%) −0.11 (1%)	1.06

Stability w.r.t. $p_{T,b}$ cut

- NLO QCD corrections stable against $p_{T,b}$ cut
- CT14 PDF uncertainties similar/smaller than difference between various PDF sets
- Similar results for $p_{T,\gamma}$ *cut*

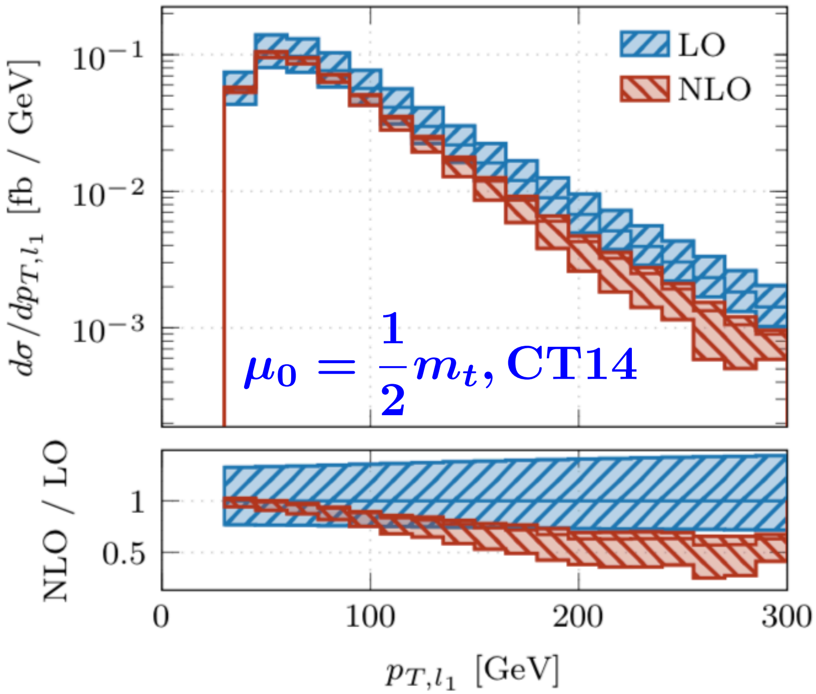
$$H_T = p_{T,\,e^+} + p_{T,\,\mu^-} + p_{T,\,j_b} + p_{T,\,j_b} + p_T^{miss} + p_{T,\,\gamma}$$

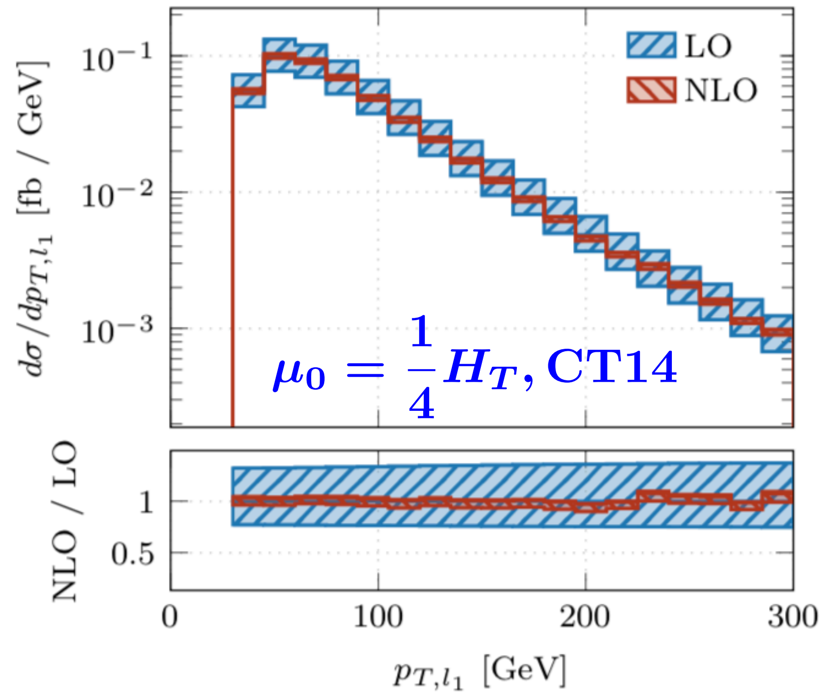
$t\bar{t}\gamma$ with dynamical scale ¼ H_T

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma \text{ @ LHC}_{13\text{TeV}}$$





- NLO Corrections up to ***- 43%***
- Theoretical uncertainties up to ***± 56%***

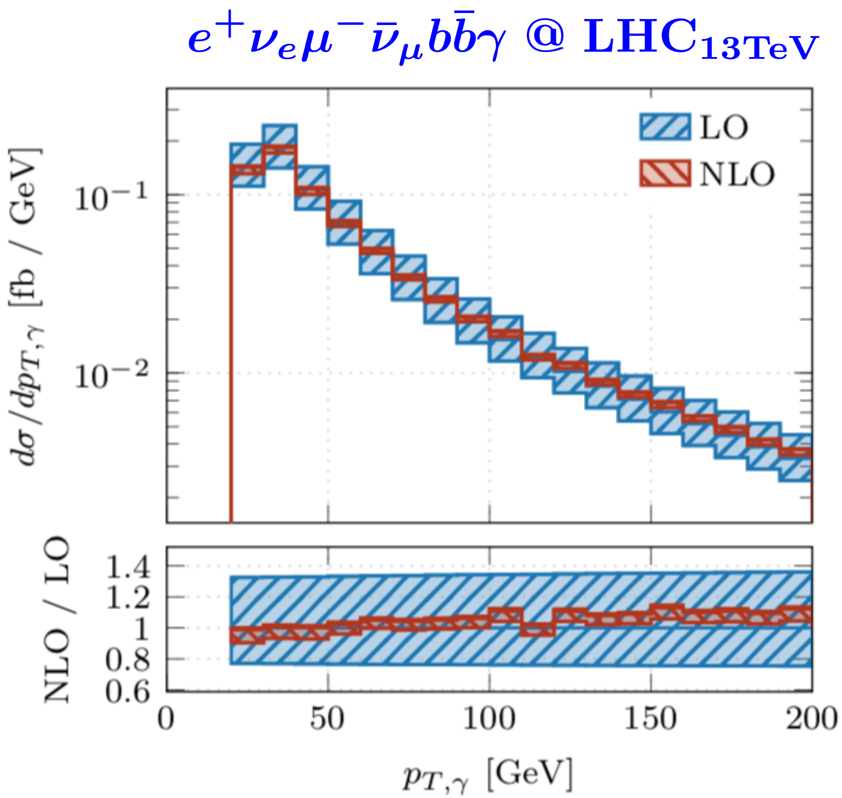
- NLO Corrections up to ***+ 8%***
- Error reduced down to ***± 7%***

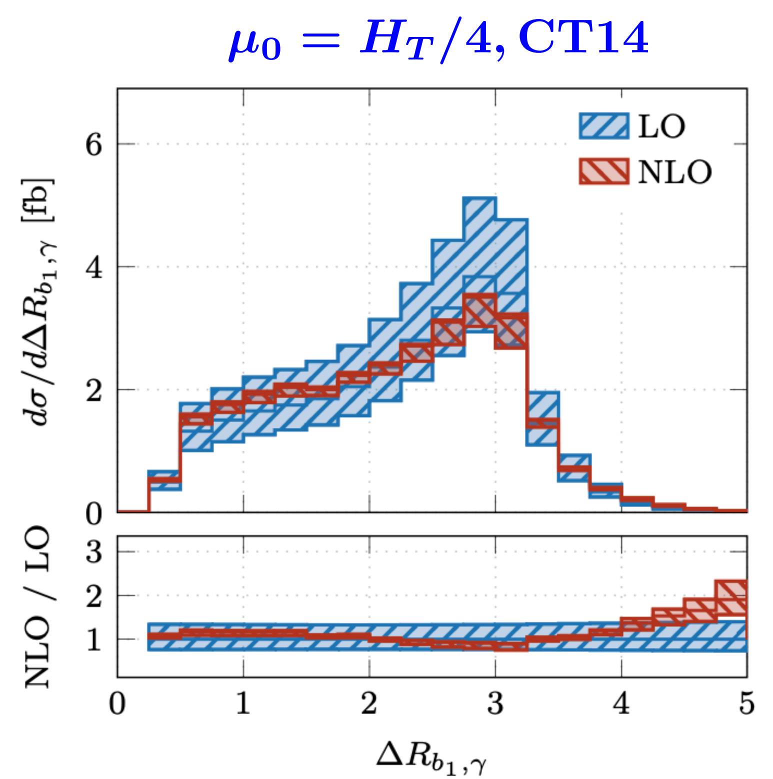
Dynamical scale very effective in stabilizing perturbative convergence !
Provides smaller theoretical error !

$t\bar{t}\gamma$ with dynamical scale ¼ H_T

HELAC-NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18





- *Positive NLO corrections up to 13%*
- NLO error bands within LO
- Theoretical error up to ± *8%*

Not all differential K-factors are flat even with μ_0 = ¼ H_T !

$t\bar{t}\gamma/t\bar{t}$

- Fiducial integrated $\sigma_{tt\gamma}$ with dynamical scale ⇨ th. error of ± *6%*
- Fiducial differential $d\sigma_{tt\gamma}/dX$ ⇨ th. error ± *(10% - 30%)*
- Can we decrease theoretical error even further for ***ttγ*** without going to NNLO ?
- ***Answer is yes !***

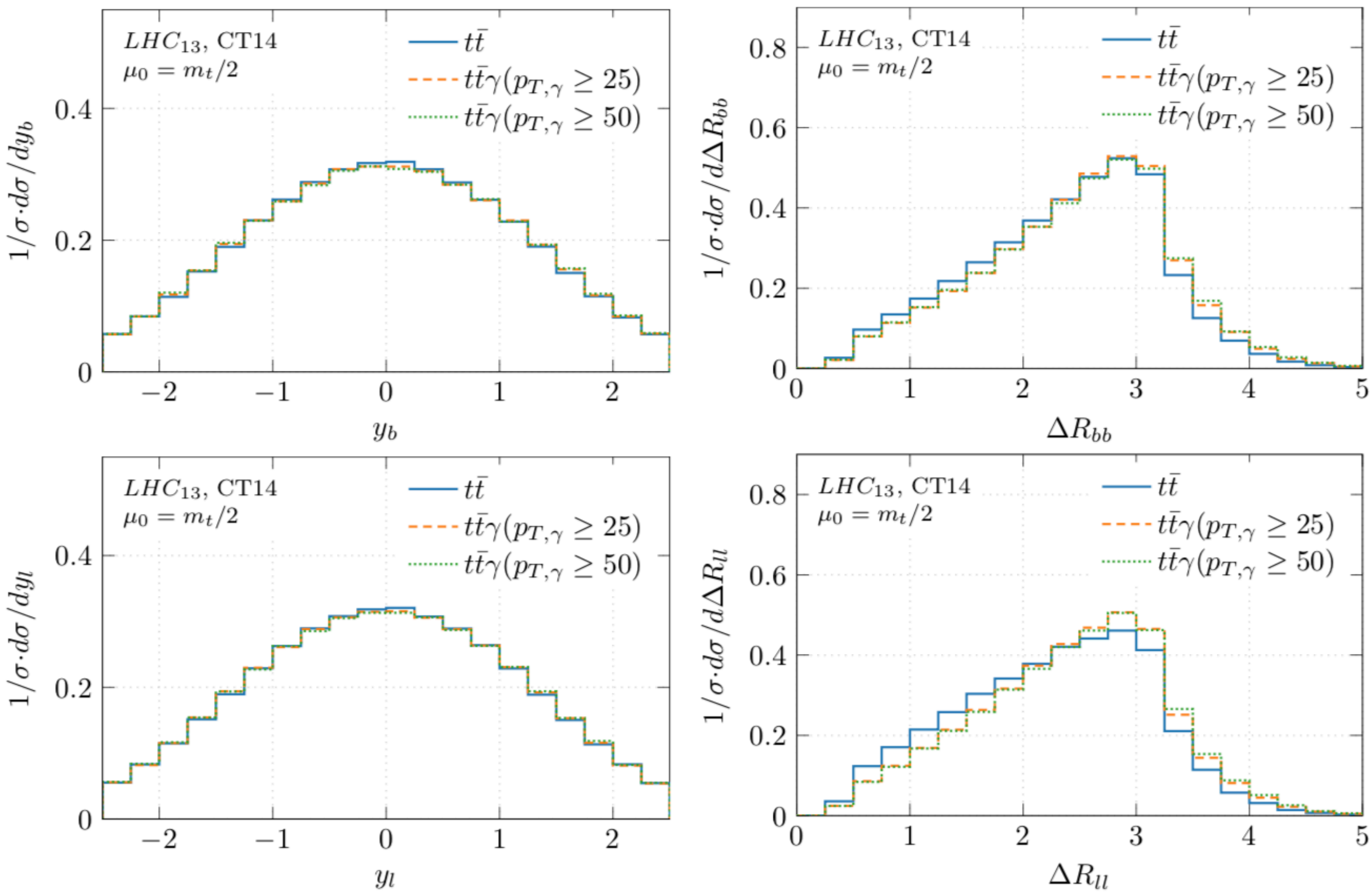
$$\mathcal{R} = \frac{\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}$$	$$\mathcal{R}_X = \left(\frac{d\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{dX}\right)\left(\frac{d\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}{dX}\right)^{-1}$$

- $\sigma_{tt\gamma}/\sigma_{tt}$ we have ± *(1% - 3%)* ⇨ Differential cross section ratios ± *(1% - 6%)*
- ***High precision comparable to NNLO QCD results for top quark physics !***
- Processes need to be correlated ⇨ top quark pair production excellent candidate
- Similar dynamical scale choice need to be implemented for μ_1 *&* μ_2 !

$t t\gamma$ & $t t$

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$



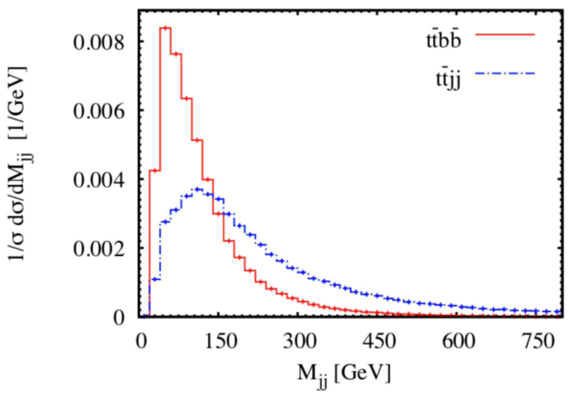
Bevilacqua, Hartanto, Kraus, Weber, Worek '19

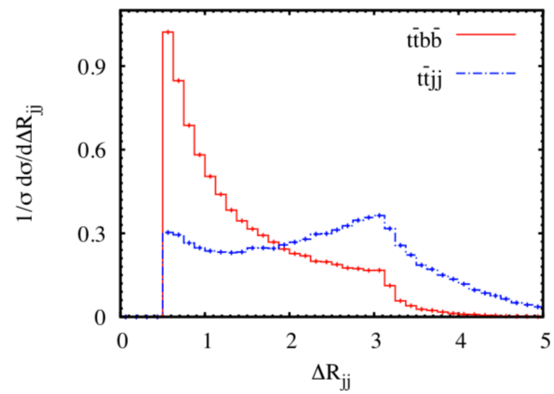
ttbb & ttjj

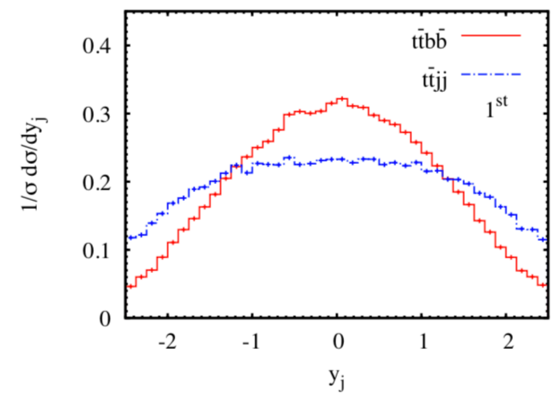
Stable top quarks

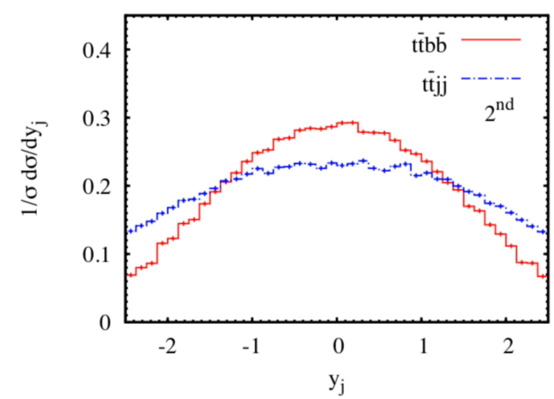
$t\bar{t}b\bar{b}$ & $t\bar{t}jj$ @ LHC$_{8\mathrm{TeV}}$

HELAC-NLO









- Different jet kinematics makes the ***ttbb*** and ***ttjj*** processes uncorrelated in several observables

- *Scale uncertainty is not significantly reduced when taking ratio of cross sections*

Bevilacqua, Worek '14

ttγ/tt

$$\mathcal{R} = \frac{\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}$$

HELAC-NLO

$$\mathcal{R}\,(\mu_0 = m_t/2, \mathrm{CT14}, p_{T,\gamma} > 25\,\mathrm{GeV}) = (4.56 \pm 0.25) \cdot 10^{-3}\,(5\%)\,,$$

$$\mathcal{R}\,(\mu_0 = H_T/4, \mathrm{CT14}, p_{T,\gamma} > 25\,\mathrm{GeV}) = (4.62 \pm 0.06) \cdot 10^{-3}\,(1\%)\,,$$

$$\mathcal{R}(\mu_0 = m_t/2, \mathrm{CT14}, p_{T,\gamma} > 50\,\mathrm{GeV}) = (1.89 \pm 0.16) \cdot 10^{-3}\,(8\%)\,,$$

$$\mathcal{R}(\mu_0 = H_T/4, \mathrm{CT14}, p_{T,\gamma} > 50\,\mathrm{GeV}) = (1.93 \pm 0.06) \cdot 10^{-3}\,(3\%)\,.$$

- *Uncertainties stable against $p_{T,\gamma}$ cut ⇨ 25 GeV increased to 50 GeV*
- Our best NLO QCD predictions with dynamical scale choice:

$$\mathcal{R}\,(\mu_0 = H_T/4, \mathrm{CT14}, p_{T,\gamma} > 25\,\mathrm{GeV}) = (4.62 \pm 0.06\,[\mathrm{scales}] \pm 0.02\,[\mathrm{PDFs}]) \cdot 10^{-3}$$

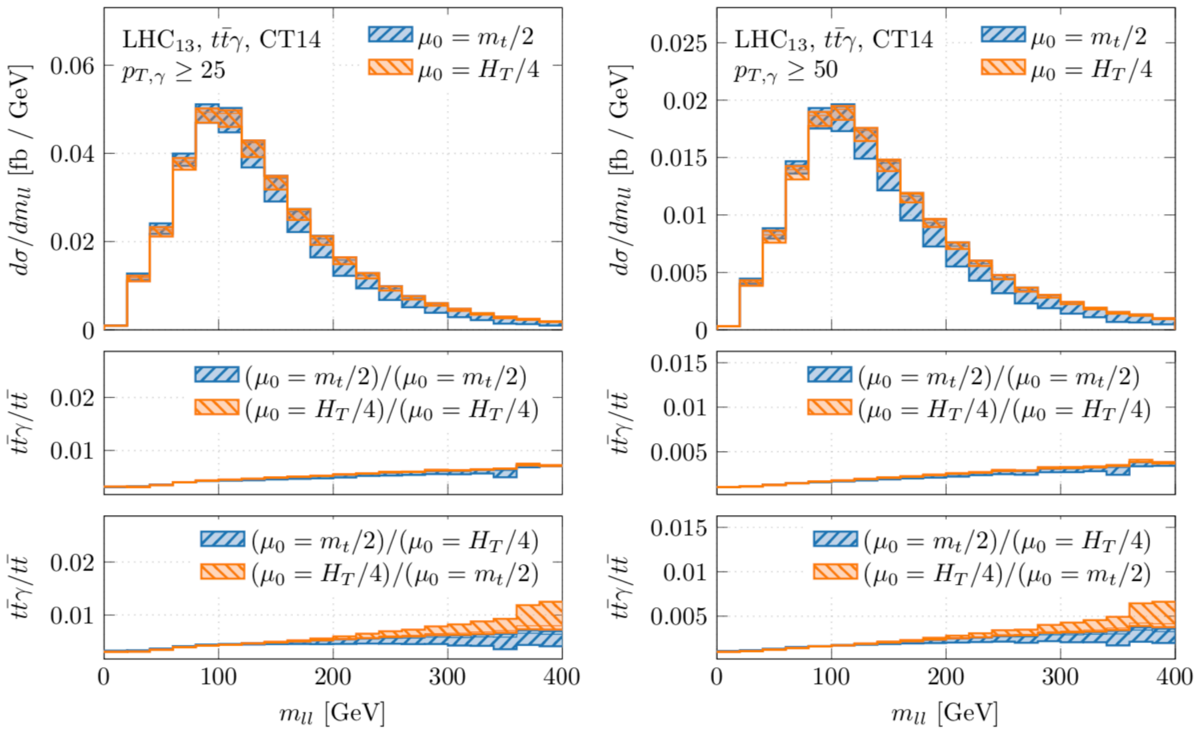
$$\mathcal{R}(\mu_0 = H_T/4, \mathrm{CT14}, p_{T,\gamma} > 50\,\mathrm{GeV}) = (1.93 \pm 0.06\,[\mathrm{scales}] \pm 0.02\,[\mathrm{PDFs}]) \cdot 10^{-3}\,,$$

Bevilacqua, Hartanto, Kraus, Weber, Worek '19

Differential Cross Section Ratio

Bevilacqua, Hartanto, Kraus, Weber, Worek '19

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ LHC$_{13\text{TeV}}$



HELAC-NLO

Theoretical uncertainties:

± (1% – 4%) dynamical scale

± (20% – 25%) fixed scale

- Should be compared to uncertainties for absolute differential cross section
  - ***up to ± 10% for μ_0 = ¼ H_T & up to ± 50% for μ_0 = ½ m_t***
- When different scales are used in numerator and denominator ***up to ± 60%***

Fiducial Cross Section for $t\bar{t}\gamma$

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ LHC$_{13\text{TeV}}$

Modelling Approach	σ^{LO} [fb]	σ^{NLO} [fb]
full off-shell ($\mu_0 = H_T/4$)	$7.32^{+2.45\,(33\%)}_{-1.71\,(23\%)}$	$7.50^{+0.11\,(1\%)}_{-0.45\,(6\%)}$
NWA ($\mu_0 = m_t/2$)	$8.08^{+2.84\,(35\%)}_{-1.96\,(24\%)}$	$7.28^{-0.99\,(13\%)}_{-0.03\,(0.4\%)}$
NWA ($\mu_0 = H_T/4$)	$7.18^{+2.39\,(33\%)}_{-1.68\,(23\%)}$	$7.33^{-0.43\,(5.9\%)}_{-0.24\,(3.3\%)}$
NWA$_{\gamma-\text{prod}}$ ($\mu_0 = m_t/2$)	$4.52^{+1.63\,(36\%)}_{-1.11\,(24\%)}$	$4.13^{-0.53\,(13\%)}_{-0.05\,(1.2\%)}$
NWA$_{\gamma-\text{prod}}$ ($\mu_0 = H_T/4$)	$3.85^{+1.29\,(33\%)}_{-0.90\,(23\%)}$	$4.15^{-0.12\,(2.3\%)}_{-0.21\,(5.1\%)}$
NWA$_{\gamma-\text{decay}}$ ($\mu_0 = m_t/2$)	$3.56^{+1.20\,(34\%)}_{-0.85\,(24\%)}$	$3.15^{-0.46\,(15\%)}_{+0.03\,(0.9\%)}$
NWA$_{\gamma-\text{decay}}$ ($\mu_0 = H_T/4$)	$3.33^{+1.10\,(33\%)}_{-0.77\,(23\%)}$	$3.18^{-0.31\,(9.7\%)}_{-0.03\,(0.9\%)}$
NWA$_{\text{LOdecay}}$ ($\mu_0 = m_t/2$)		$4.85^{+0.26\,(5.4\%)}_{-0.48\,(9.9\%)}$
NWA$_{\text{LOdecay}}$ ($\mu_0 = H_T/4$)		$4.63^{+0.44\,(9.5\%)}_{-0.52\,(11\%)}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Various approaches for the modelling of top quark production & decays

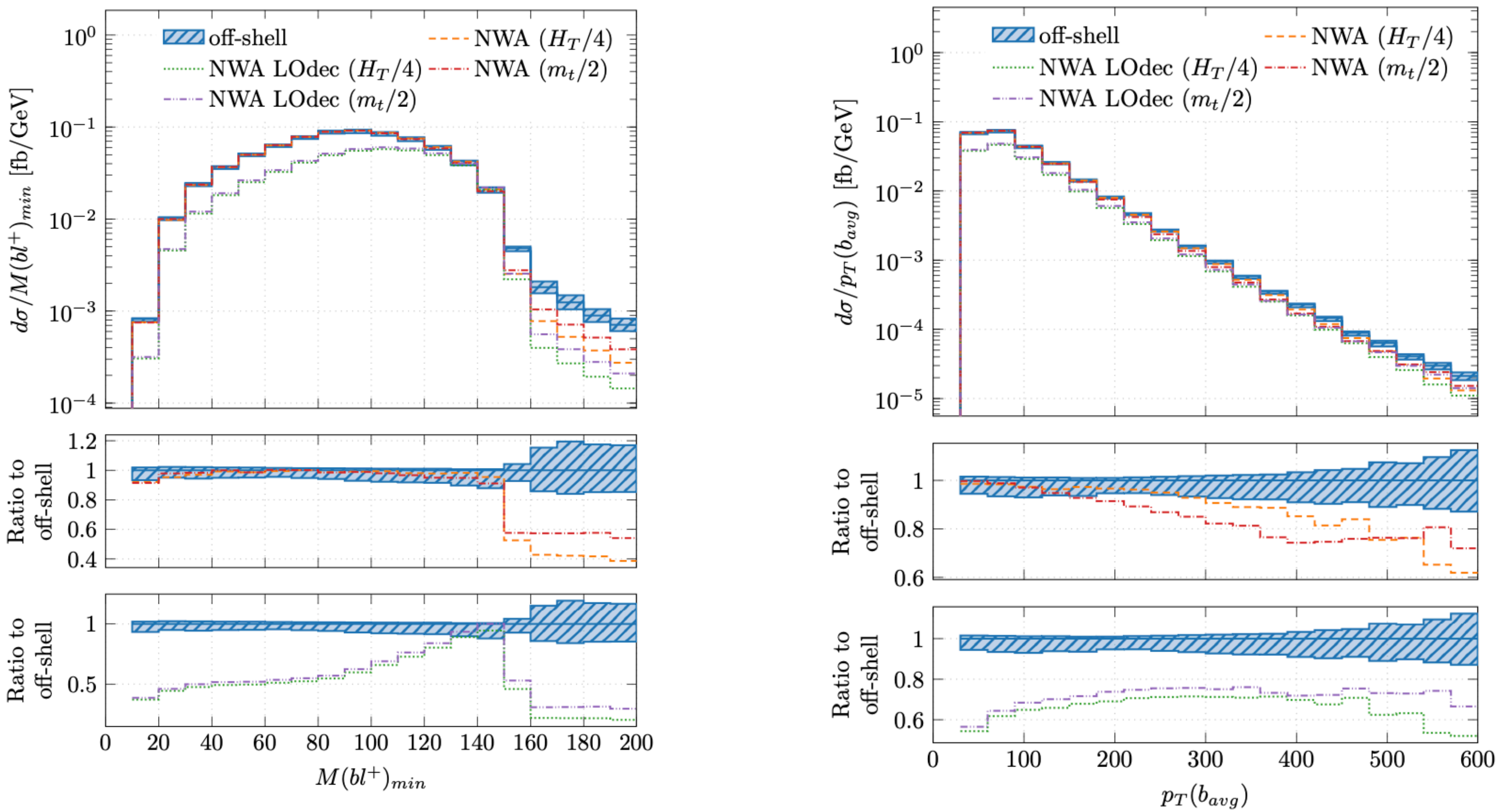
- Off-shell effects *3%*
- Consistent with $\Gamma_t / m_t \approx 0.8\%$
- *57%* ⇨ γ emitted in production
- *43%* ⇨ γ emitted in decay stage
- For $p_{T,b} > 25$ *GeV* it is *50%-50%*
- NLO QCD corrections to top quark decays are negative and not small
- *17%* ⇨ $\mu_0 = ½\, m_t$
- *12%* ⇨ $\mu_0 = ¼\, H_T$
- Theoretical uncertainties not underestimated for the full NWA

How Good Is the NWA ?

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ **@ LHC$_{13TeV}$**

- *Dimensionful* observables are sensitive to non-factorizable top quark corrections ⇨ *Tens of per cent* in specific phase-space regions
- *Kinematical edges & high p_T regions*



Bevilacqua, Hartanto, Kraus, Weber, Worek '20

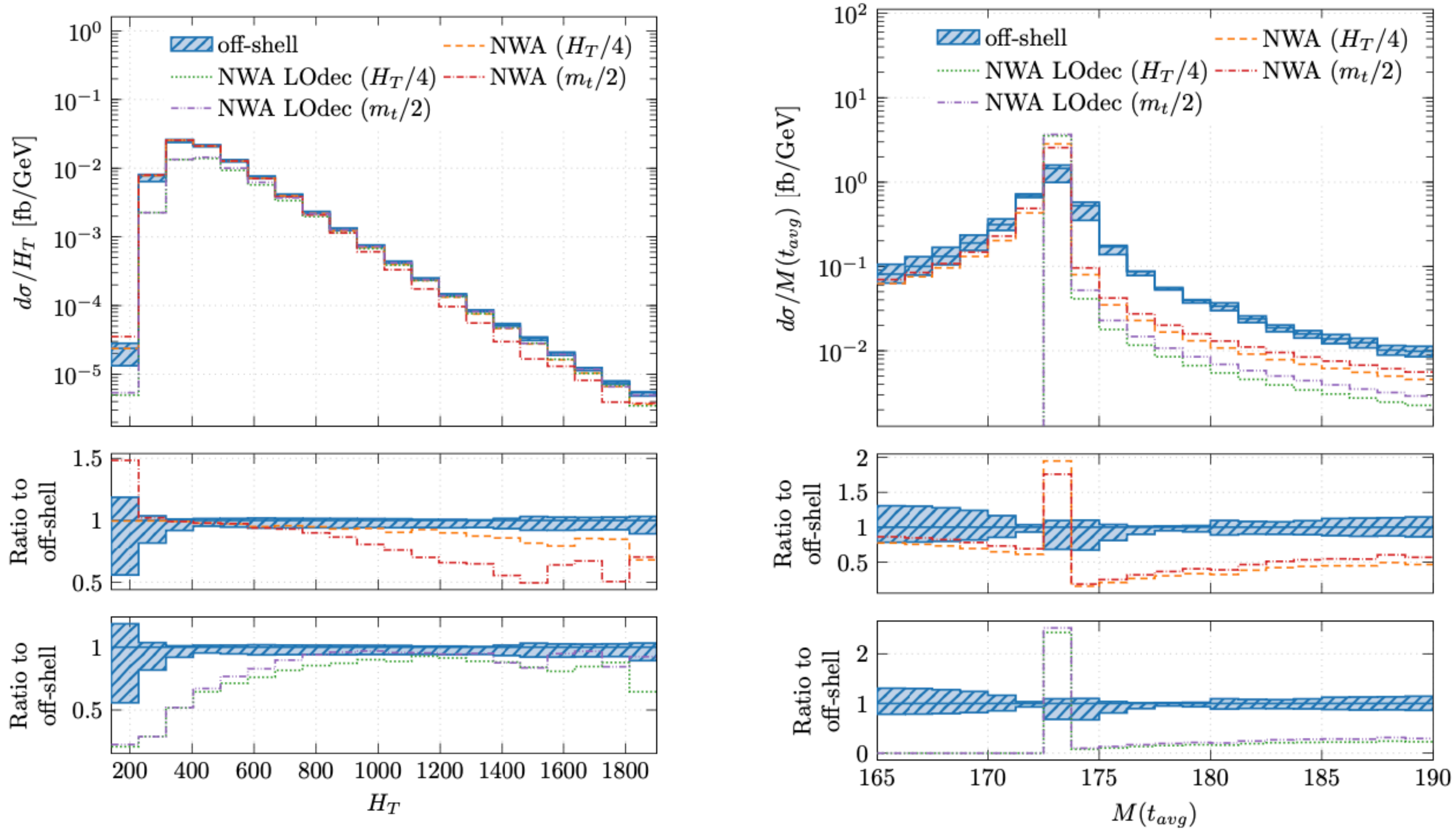
How Good Is the NWA ?

HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$

- *Dimensionful* observables are sensitive to non-factorizable top quark corrections ⇨ *Tens of per cent* in specific phase-space regions
- *Kinematical edges & high p_T regions*

MC truth



Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Various Phase-space Regions

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- 3 different resonance histories ⇨ Resolved jet at NLO gives 9 in total

$$
\begin{array}{llll}
\text{(i)} & t = W^+(\to e^+\nu_e)\, b & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\,, \\
\text{(ii)} & t = W^+(\to e^+\nu_e)\, b\gamma & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\,, \\
\text{(iii)} & t = W^+(\to e^+\nu_e)\, b & \text{and} & \bar{t} = W^-(\to \mu^-\bar{\nu}_\mu)\, \bar{b}\gamma
\end{array}
$$

- Compute for each history ***Q*** and pick the one that minimises the ***Q*** value

$$Q = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

- ***Double-resonant (DR):*** $|M(t) - m_t| < n\,\Gamma_t\,,$ and $|M(\bar{t}) - m_t| < n\,\Gamma_t$

- ***Two single-resonant regions (SR):***

$$|M(t) - m_t| < n\,\Gamma_t\,, \quad \text{and} \quad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

$$|M(t) - m_t| > n\,\Gamma_t\,, \quad \text{and} \quad |M(\bar{t}) - m_t| < n\,\Gamma_t$$

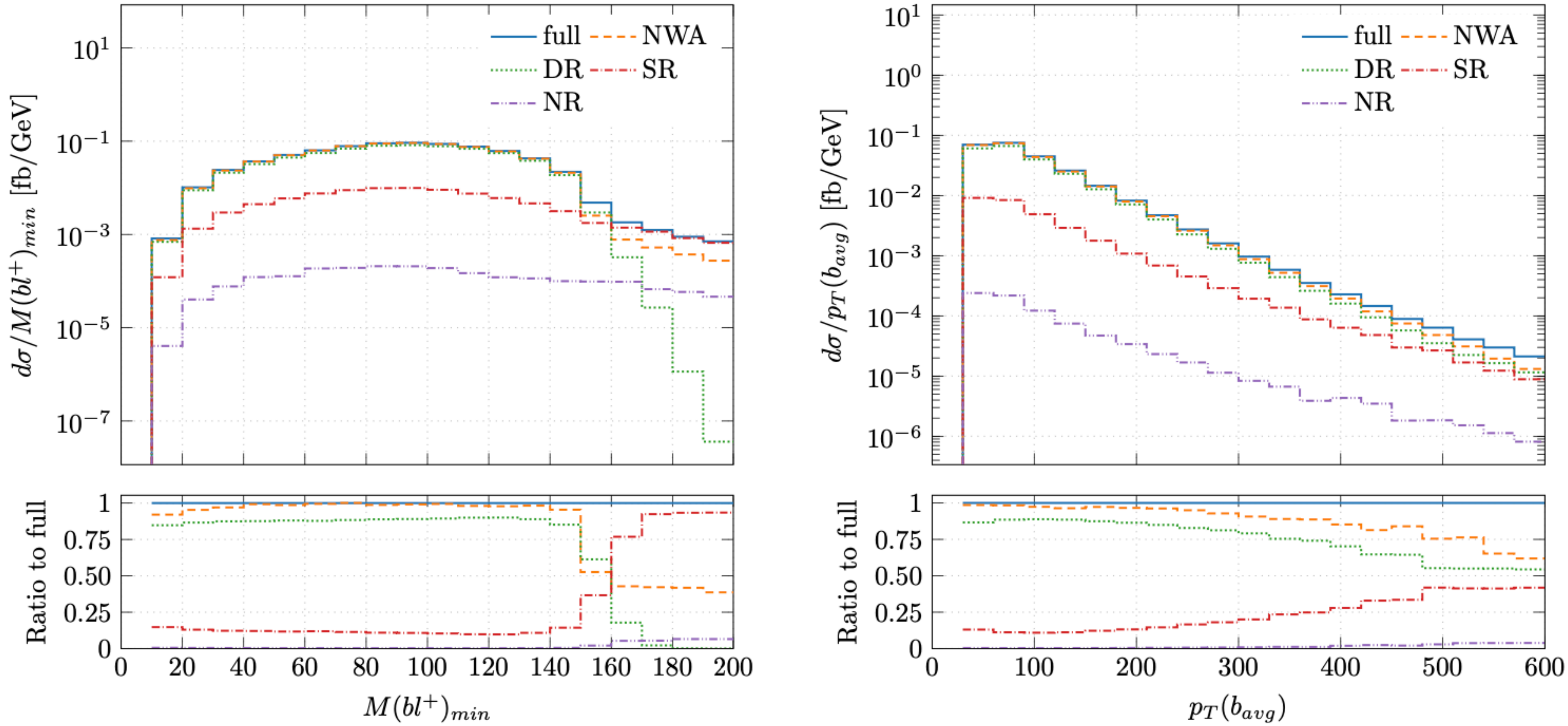
- ***Non-resonant region (NR):***

$$|M(t) - m_t| > n\,\Gamma_t\,, \quad \text{and} \quad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

Various Phase-space Regions

HELAC-NLO

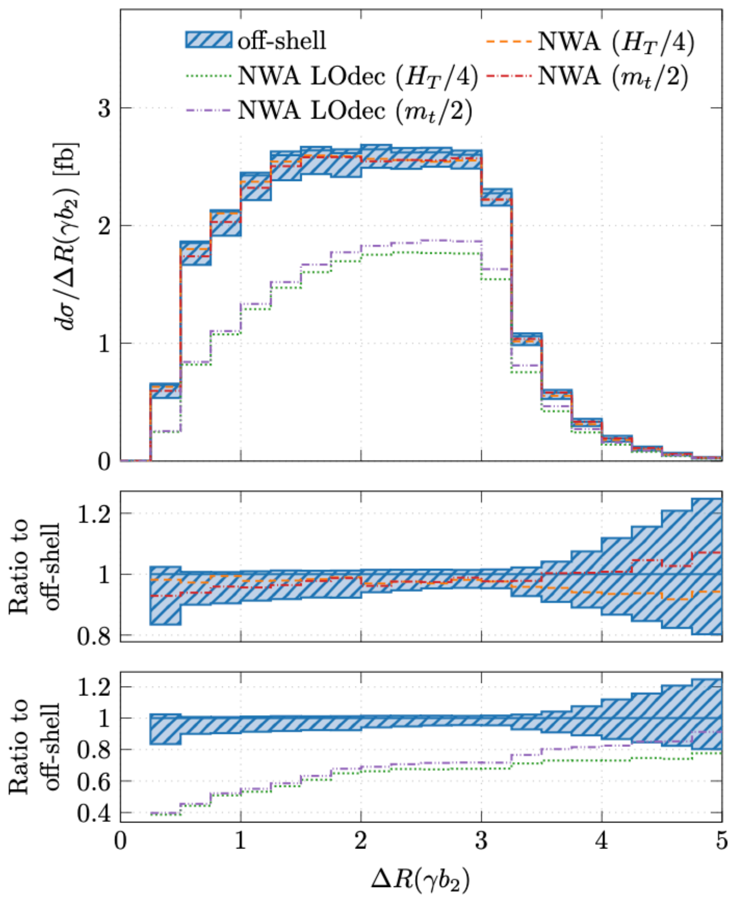
$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$



Bevilacqua, Hartanto, Kraus, Weber, Worek '20

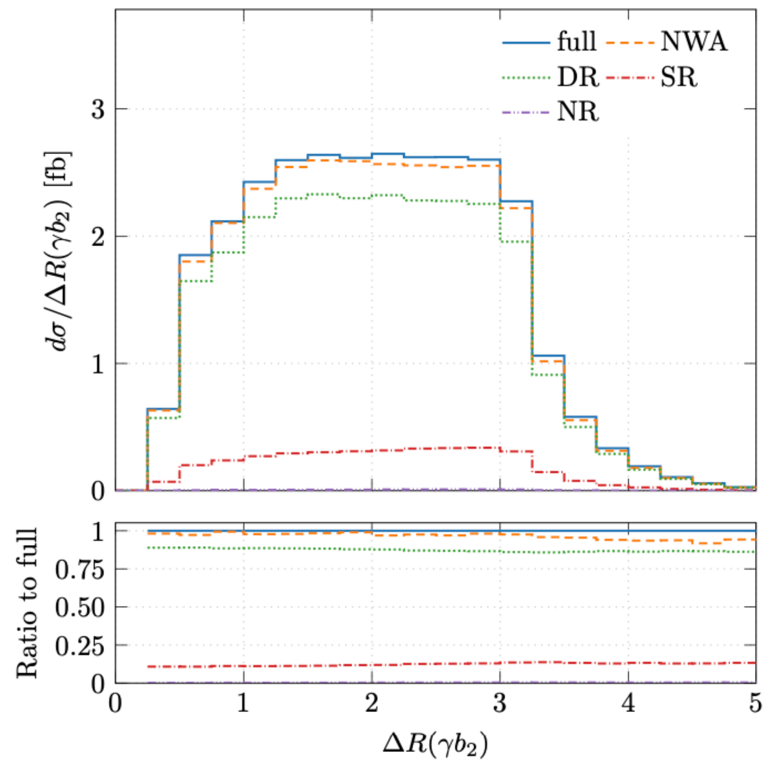
- ***Off-shell effects:***
  - High p_T region of various dimensionful observables
  - Vicinity of kinematical edges
  - Contribute up to ***50% − 60%***

Various Phase-space Regions



HELAC-NLO

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathbf{LHC_{13TeV}}$



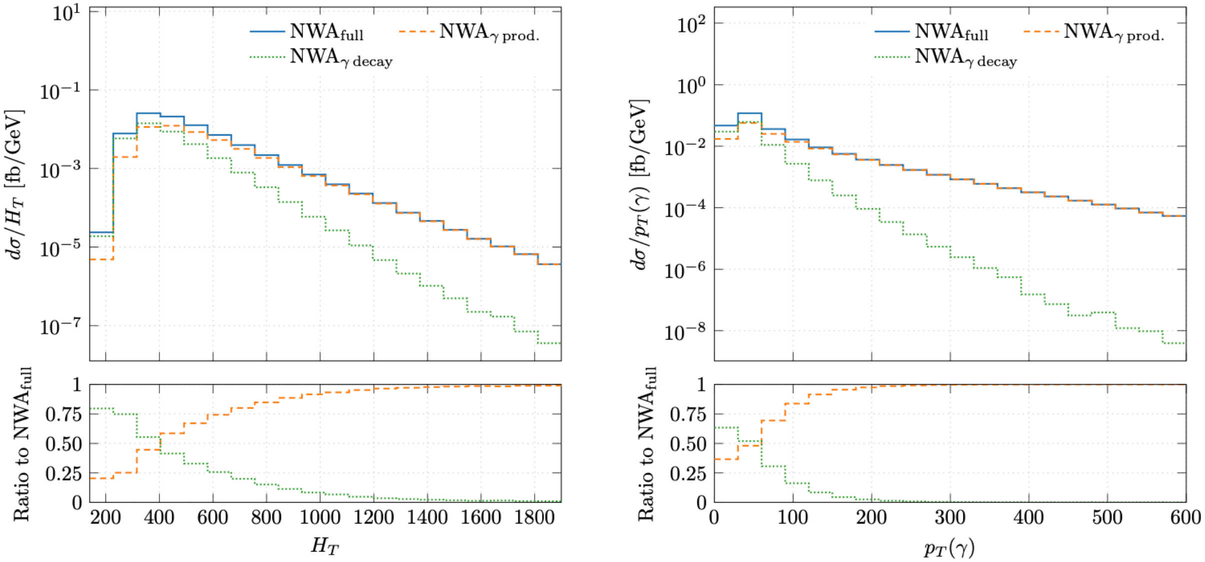
Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- Observables sensitive to top quark off-shell effects ⇨ Substantial contributions from single top quark process

- ***Dimensionless observables rather insensitive to top quark off-shell effects***

γ in Production & Decays ⇨ Differential Level

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

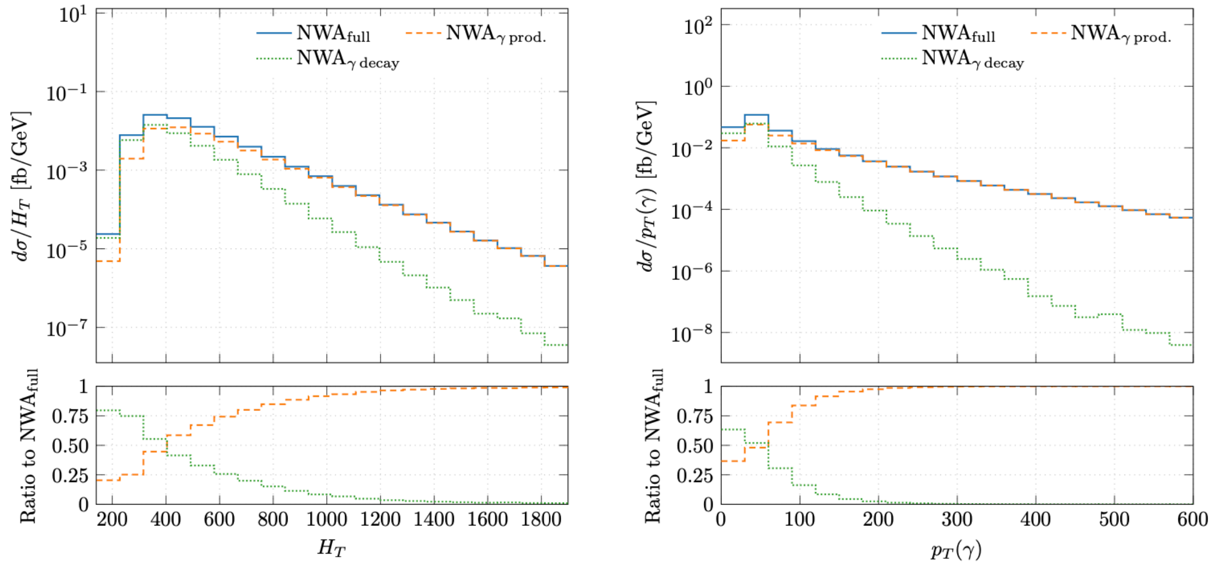


HELAC-NLO

- Diverse picture
- Photon emission in decays can be reduced
  - ***H_T > 400 GeV***
  - ***$p_T(\gamma)$ > 50 GeV***

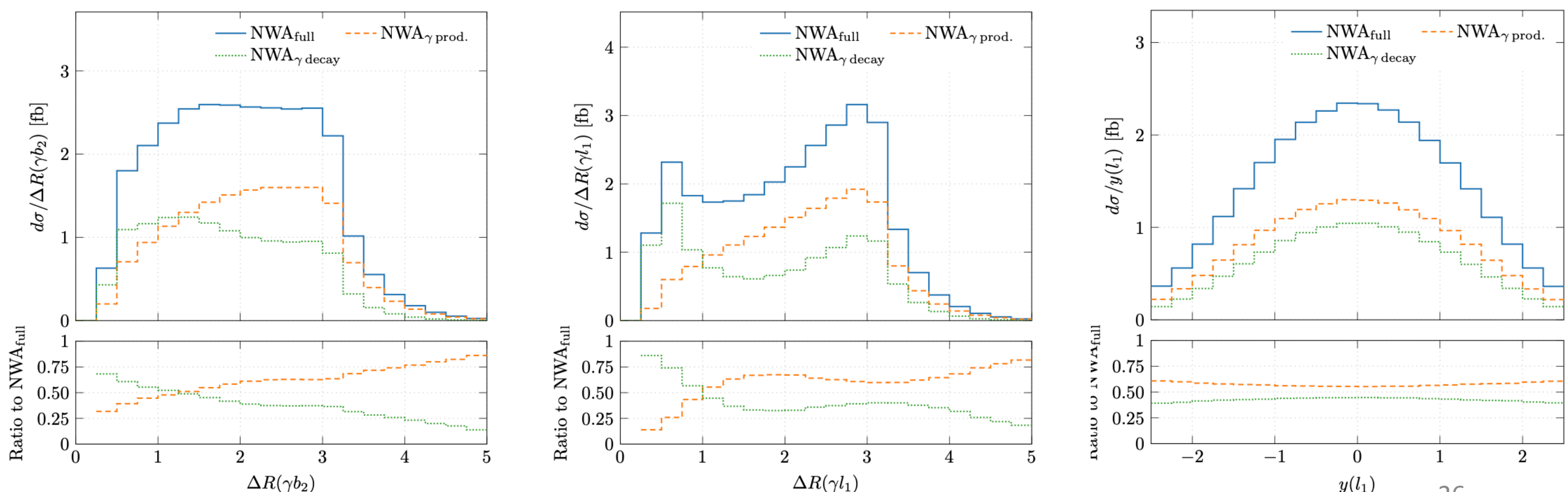
γ in Production & Decays ⇨ Differential Level

Bevilacqua, Hartanto, Kraus, Weber, Worek '20



HELAC-NLO

- Diverse picture
- Photon emission in decays can be reduced
  - H_T > 400 GeV
  - $p_T(\gamma)$ > 50 GeV



Summary

- ***Proper modeling of top quark production & decay essential already now in presence of inclusive cuts:***

- NLO QCD corrections to ***$tt\gamma$*** @ $\mathcal{O}(\alpha_s^3\alpha^5)$
  - At least full NWA or better yet complete off-shell effects for top quarks
    1. Corrections to production & decays ⇨ NLO ***tt*** spin correlations
    2. Possibility of using kinematic-dependent μ_R & μ_F scales
    3. Complete off-shell effects for top quarks

- ***Even more important for:***
  - Exclusive cuts & High luminosity measurements
  - New Physics searches & Might impact exclusion limits
  - SM parameter extraction

- Top quarks play important role in virtually every LHC analysis ⇨ ***SM & BSM***

- ***Lots of data, sophisticated analyses, precision measurements ⇨ Should be compared to state-of-the-art theoretical predictions***

- Our full off-shell ***$tt\gamma$*** results
  - Stored ⇨ ***Ntuples Files*** ⇨ ***Les Houches & ROOT Files***
  - Used by ATLAS Collaboration ⇨ ***JHEP 09 (2020) 049***

Backup Slides

$tt\gamma$

- Cuts on the transverse momenta and the rapidity of two recombined b-jets, which we assume to be always tagged

$p_T(b) > 40$ GeV,	$\lvert y(b)\rvert < 2.5,$	$\Delta R(bb) > 0.4$

- Isolated hard photon

$p_T(\gamma) > 25$ GeV	$\lvert y(\gamma)\rvert < 2.5$

- Basic selection cuts for charged leptons to ensure that they are observed inside the detector and well separated from each other

$p_T(\ell) > 30$ GeV ,	$\Delta R(\ell\ell) > 0.4\,,$	$\lvert y(\ell)\rvert < 2.5$

- Charged leptons are well separated from the isolated photon and from b-jets

$\Delta R(\ell b) > 0.4\,,$	$\Delta R(\ell\gamma) > 0.4\,,$	$\Delta R(b\gamma) > 0.4$

Various Phase-space Regions

$e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- ***n* = 15** → Boundaries outside which effects of Γ_t in BW propagator < 1%
- DR region is set to for m_t = 173.2 GeV

$M(t) \in (152.9, 193.5)$ GeV	$M(\bar{t}) \in (152.9, 193.5)$ GeV

- Contributions at the integrated cross section level for these 3 regions

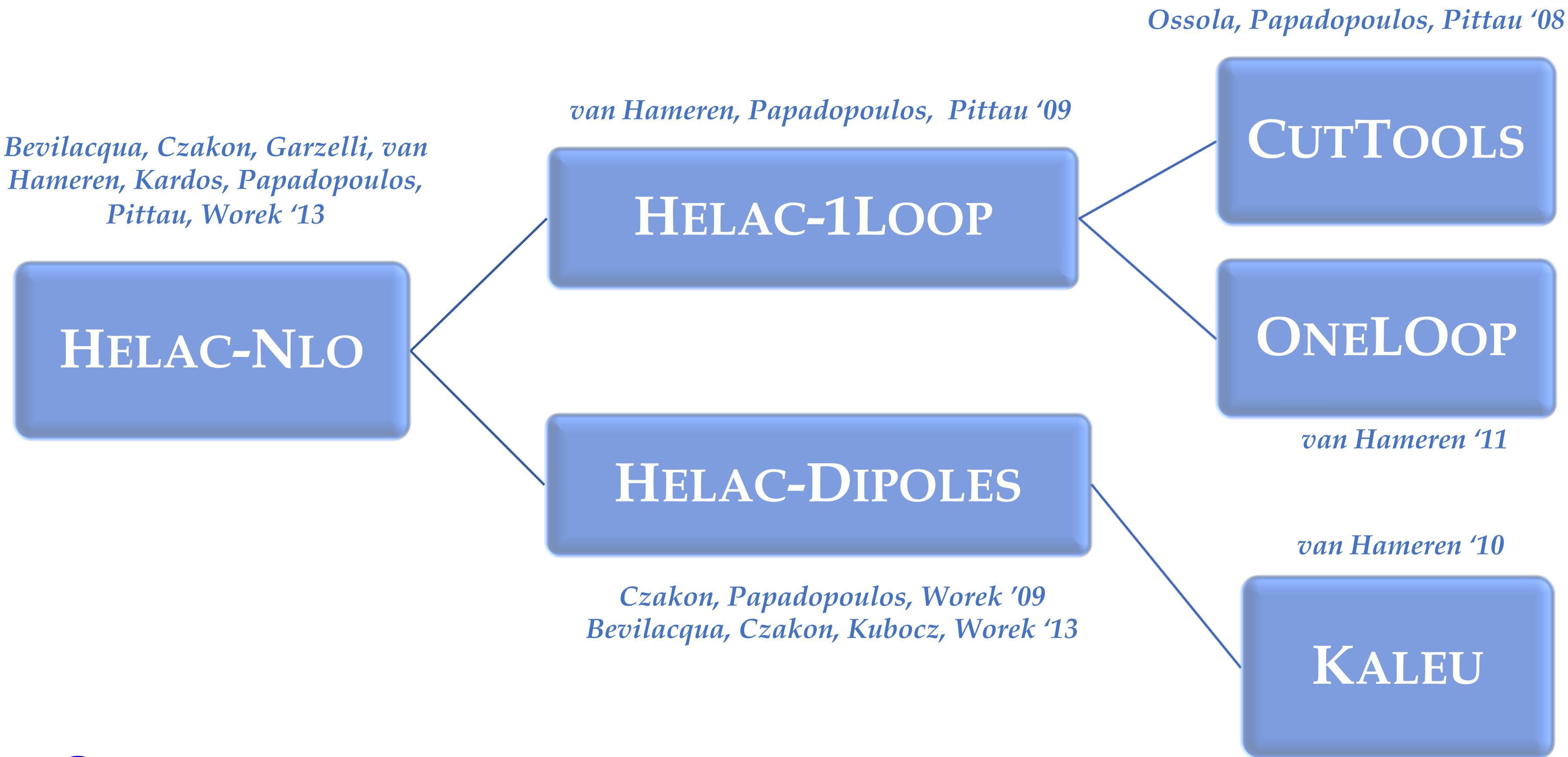
$\sigma^{\rm NLO}_{\rm DR} = 6.57$ fb ,	$\sigma^{\rm NLO}_{\rm SR} = 0.91$ fb ,	$\sigma^{\rm NLO}_{\rm NR} = 0.02$ fb

- DR contribution to full $\sigma_{t\bar{t}\gamma}$ → *88%* → SR comprises *12%* → NR only ***0.5%***
- Should we instead use ***n* = 5**

$$\sigma^{\rm NLO}_{\rm DR} = 4.82 \text{ fb}, \ \sigma^{\rm NLO}_{\rm SR} = 2.50 \text{ fb and } \sigma^{\rm NLO}_{\rm NR} = 0.18 \text{ fb}$$

- **DR = 64%, SR = 33%, NR = 3%**

HELAC-NLO



- **Output:**
  - theoretical predictions are stored in the form of the **Ntuples Files** and modified **Les Houches & ROOT Files**
  - kinematical cuts can be changed
  - new observables can be defined
  - renormalization or factorization scales and PDF sets can be changed

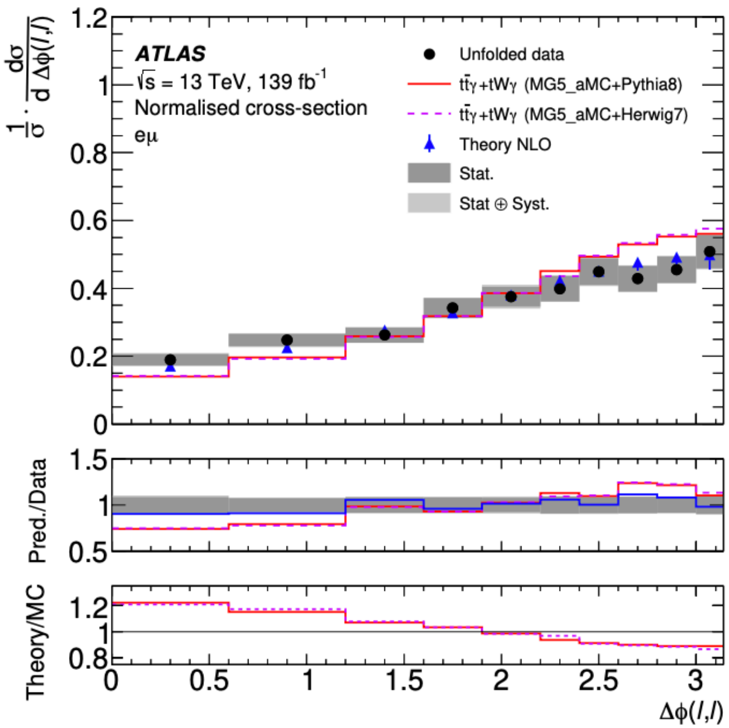
Bern, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre '14

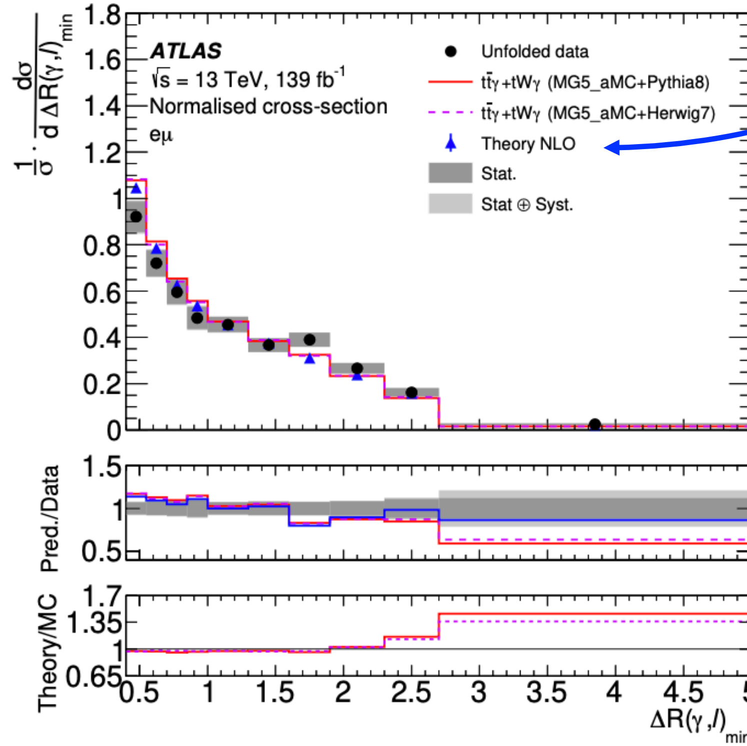
Combined ttγ + tWγ production

eμ channel

ATLAS Collaboration '20
JHEP 09 (2020) 049

HELAC-NLO





Predictions	$p_T(\gamma)$		$\lvert\eta(\gamma)\rvert$		$\Delta R(\gamma,\ell)_{\min}$		$\Delta\phi(\ell,\ell)$		$\lvert\Delta\eta(\ell,\ell)\rvert$	
	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value	χ^2/ndf	p-value
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+PYTHIA8)	6.3/10	0.79	7.3/7	0.40	20.1/9	0.02	30.8/9	<0.01	6.5/7	0.48
$t\bar{t}\gamma + tW\gamma$ (MG5_aMC+HERWIG7)	5.3/10	0.87	7.7/7	0.36	18.9/9	0.03	31.6/9	<0.01	6.8/7	0.45
Theory NLO	6.0/10	0.82	4.5/7	0.72	13.5/9	0.14	5.8/9	0.76	5.6/7	0.59