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Cross section ratios as a precision tool for ttγ

Malgorzata Worek

Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Plan

- ⌘ Motivation for ***ttγ***
- ⌘ Status of theoretical predictions for ***ttγ***
- ⌘ NWA vs. off-shell effects → ***tt & ttj***
- ⌘ Results for ***ttγ*** in di-lepton channel
- ⌘ Predictions for ***ttγ/tt***
- ⌘ Summary & Outlook

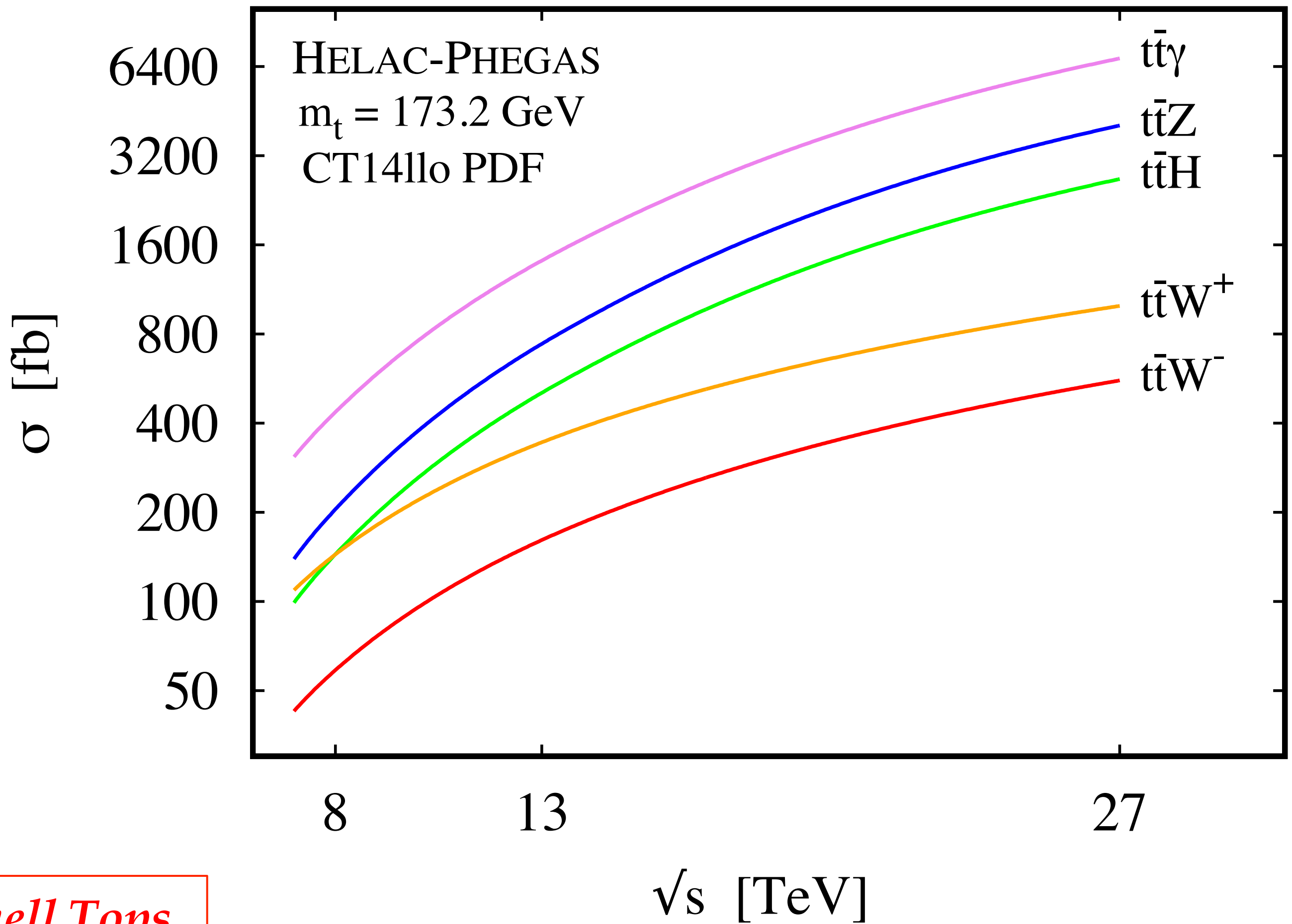
Collaborators:

- *G. Bevilacqua (University of Debrecen, Hungary)*
- *H. B. Hartanto (University of Durham, UK)*
- *M. Kraus (Florida State University, USA)*
- *T. Weber (RWTH Aachen University, Germany)*

Motivations For ttγ

⌘ Besides ***tt & ttj*** more exclusive final states can be accessed @ LHC

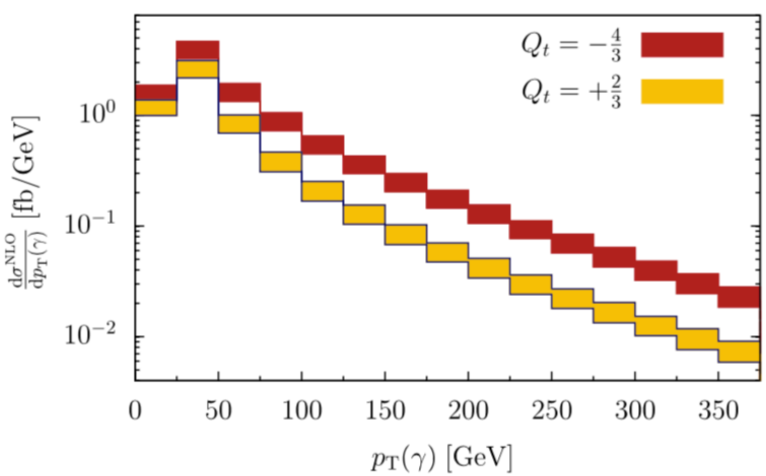
ttγ, ttZ, ttH, ttW± @ LHC

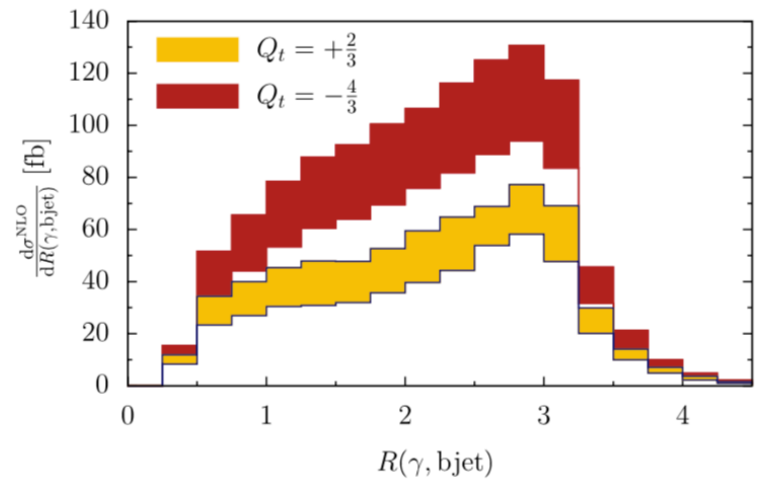


On-shell Tops

Motivations For ttγ

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





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

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

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

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***, …

Aguilar-Saavedra, Alvarez, Juste, Rubbo '14

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

⌘ NLO corrections for on-shell top quarks → General idea about size of NLO corrections. Can not provide reliable description of top quark decay products and radiation pattern

- ★ *NLO QCD* — *Duan, Ma, Zhang, Han, Guo, Wang '09 '11*; *Maltoni, Pagani, Tsinikos '15*
- ★ *NLO electroweak* — *Duan, Zhang, Wang, Song, Li '16*

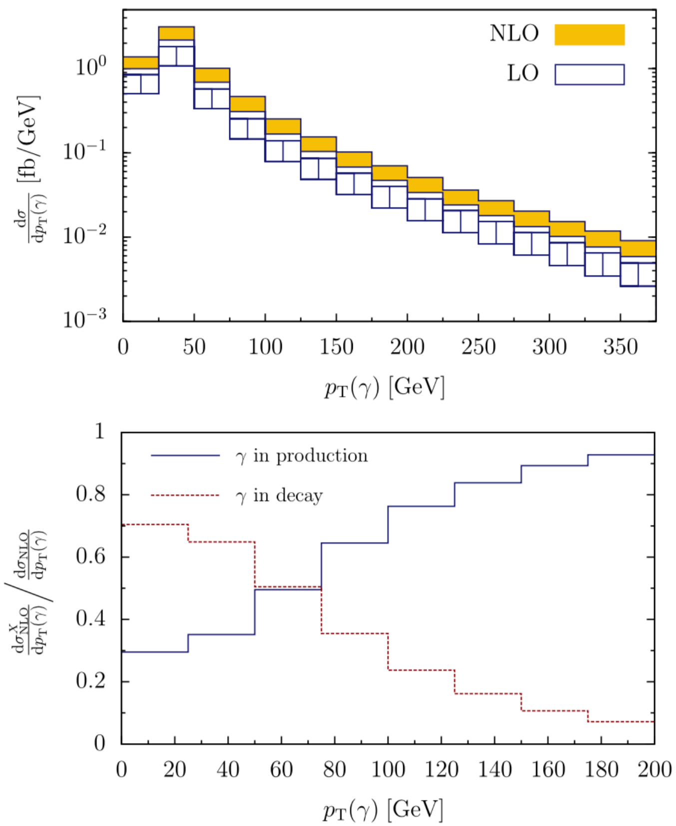
⌘ For more realistic studies decays are needed

- ★ *NLO QCD for on-shell top quarks + PS* → Top decays in parton shower approximation, omitting photon emission in PS evolution & omitting $t\bar{t}$ spin correlations *Kardos, Trocsanyi '14*
- ★ *NLO QCD in NWA* → NLO QCD corrections to top production & decays, photon emission of top quark and of top quark decay product & $t\bar{t}$ spin correlations 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

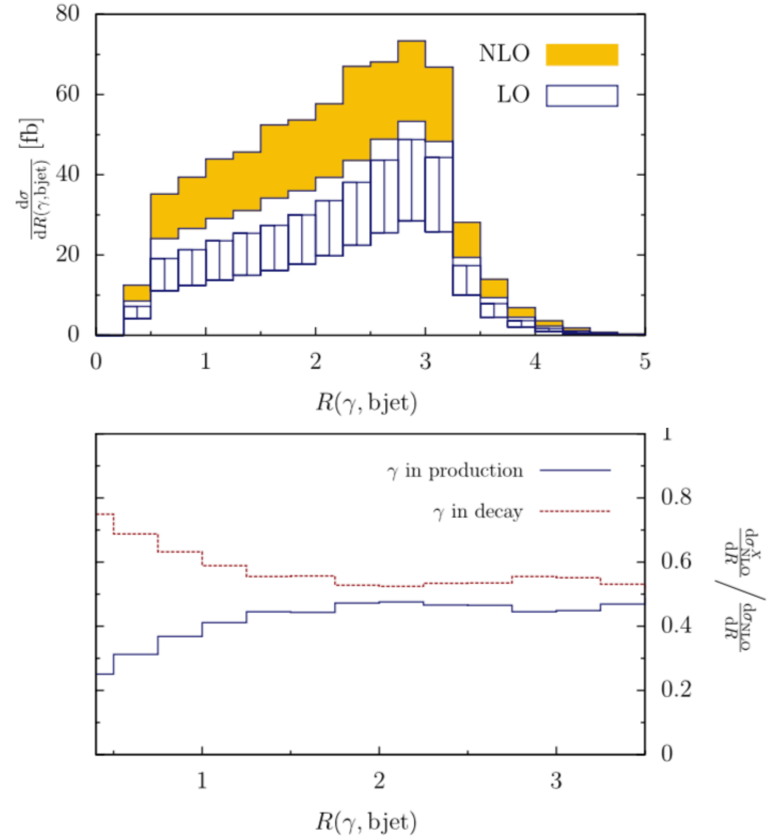
Bevilacqua, Hartanto, Kraus, Weber, Worek '18

ttγ in NWA @ LHC

Melnikov, Schulze, Scharf '11



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



⌘ Large fraction of isolated photons comes from radiative decay of tops

$\sigma^{\text{NLO}} = 138$ fb	$\sigma^{\text{NLO}}_{\gamma-\text{Prod.}} = 60.9$ fb	$\sigma^{\text{NLO}}_{\gamma-\text{Dec.}} = 77.2$ fb

How Good Is NWA ?

Off-shell Tops

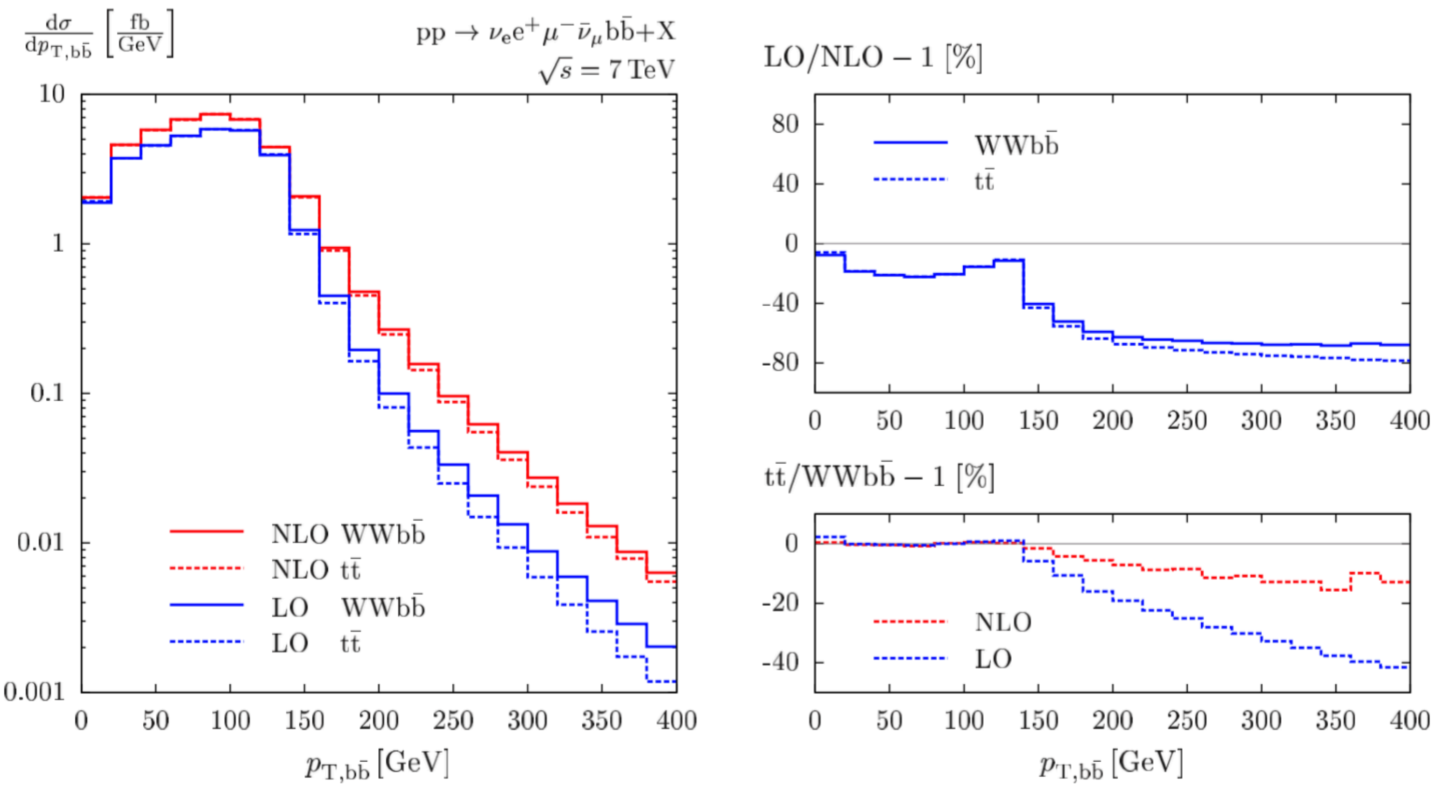
- In NWA tops are restricted to on-shell states
- Approximation is controlled by the ratio $\Gamma_t / m_t \approx 0.8\%$
- Should be accurate for sufficiently inclusive observables
- ***Off-shell effects for integrated σ_{tt} @ few % level @ NLO in QCD***

tt (di-lepton)	*Denner, Dittmaier, Kallweit, Pozzorini '11 '12* *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11* *Denner, Pellen '16 (EW)* *Jezo, Lindert, Nason, Oleari, Pozzorini '16 (PS)*
tt (semi-leptonic)	*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*
ttγ (di-lepton)	*Bevilacqua, Hartanto, Kraus, Weber, Worek '18 '19*

NWA & Off-Shell Effects

Off-shell Tops

- Off-shell results vs. results with (spin-correlated) NWA
- ***Tens of per cent*** in phase-space regions where ***tt*** suppressed as signal
- Important as background to ***Higgs & BSM searches***



Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

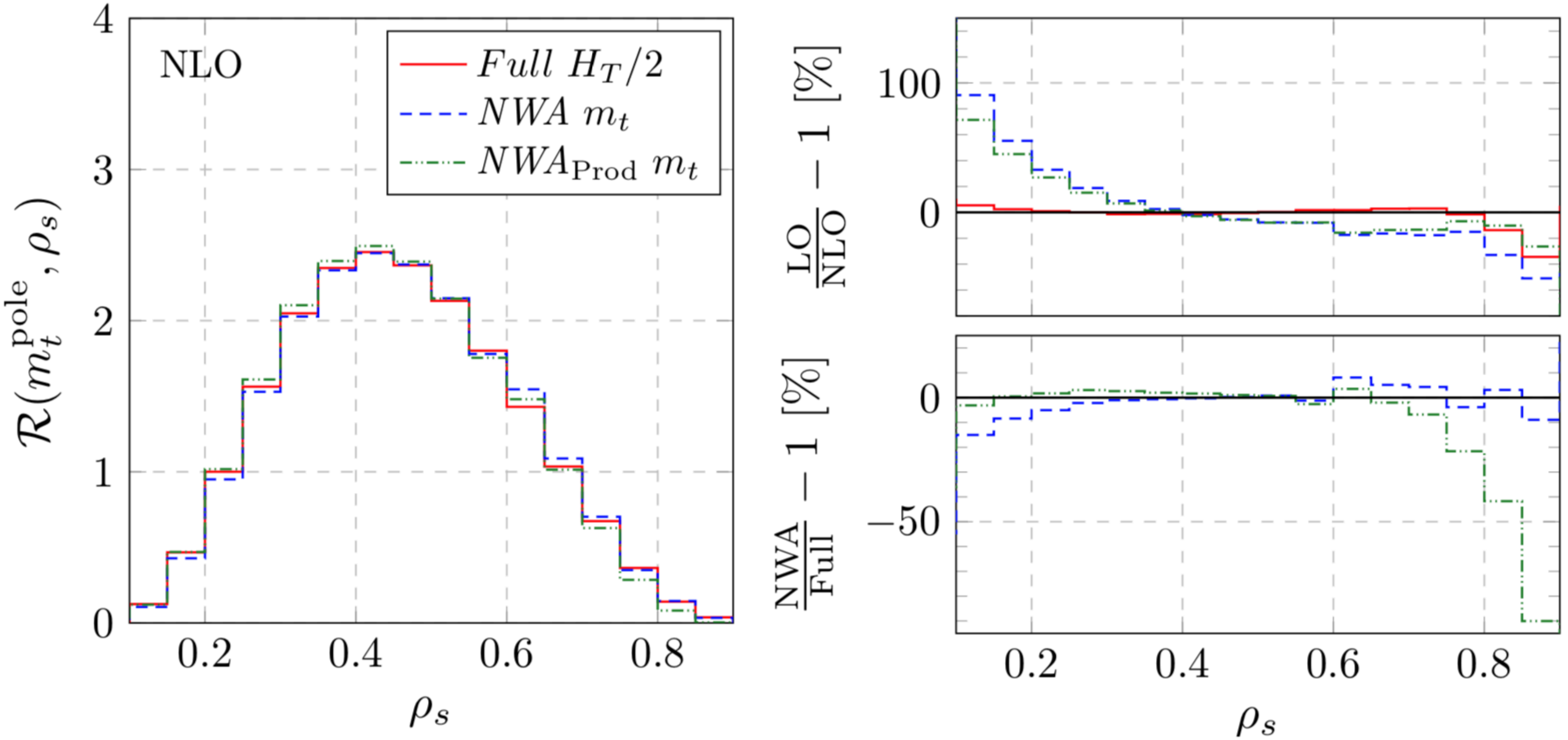
NWA & Off-Shell Effects

❖ Observable used for a recent ***top quark mass determination***

Off-shell, NWA

$pp \to t\bar{t}j \to e^+\nu_e\,\mu^-\bar{\nu}_\mu\,b\bar{b}\,j$ @ LHC$_{13\text{TeV}}$

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18



$$\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}j}} \frac{d\sigma_{t\bar{t}j}}{d\rho_s}(m_t^{\text{pole}}, \rho_s) \qquad \rho_s = \frac{2m_0}{M_{t\bar{t}j}}$$

Alioli, Fernandez, Fuster, Irles, Moch, Uwer, Vos '13

NWA & Off-Shell Effects

25 fb^{-1}

$pp \to t\bar{t}j \to e^+\nu_e\, \mu^-\bar{\nu}_\mu\, b\bar{b}\, j$ @ LHC$_{13\text{TeV}}$

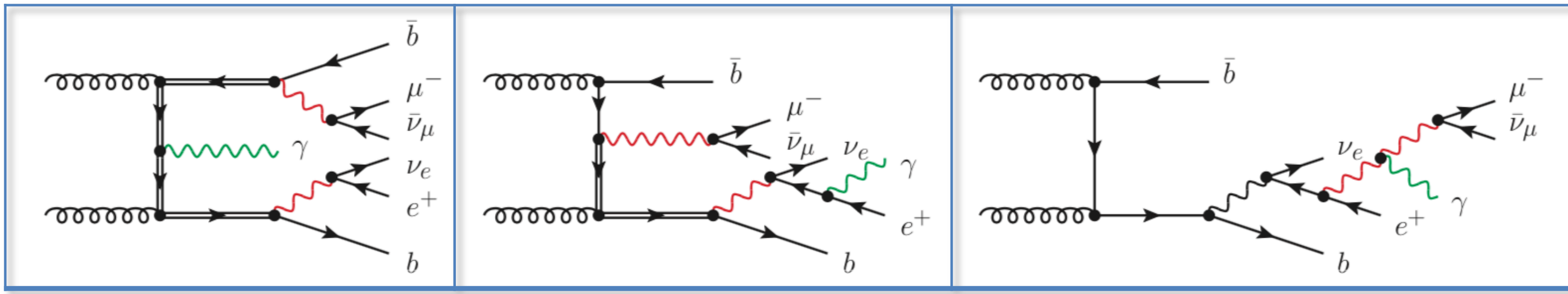
Theory, NLO QCD CT14 PDF	$m_t^{\text{out}} \pm \delta m_t^{\text{out}}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\text{in}} - m_t^{\text{out}}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	173.76 ± 0.40	1.87	0.003 (3.0σ)	−0.56
NWA, $\mu_0 = m_t$	175.65 ± 0.31	2.99	$7 \cdot 10^{-8}$ (5.4σ)	−2.45
NWA$_{\text{Prod.}}$, $\mu_0 = m_t$	169.59 ± 0.30	3.10	$2 \cdot 10^{-8}$ (5.6σ)	+3.61
5 bins				
Full, $\mu_0 = H_T/2$	173.08 ± 0.40	0.94	0.44 (0.8σ)	+0.12
Full, $\mu_0 = E_T/2$	172.48 ± 0.38	1.58	0.18 (1.3σ)	+0.72
Full, $\mu_0 = m_t$	173.75 ± 0.40	6.76	$2 \cdot 10^{-5}$ (4.3σ)	−0.55
NWA, $\mu_0 = m_t$	175.49 ± 0.30	5.31	$2 \cdot 10^{-4}$ (3.7σ)	−2.29
NWA$_{\text{Prod.}}$, $\mu_0 = m_t$	169.39 ± 0.47	3.42	$8 \cdot 10^{-3}$ (2.6σ)	+3.81

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18

NWA & Off-Shell Effects

- Feynman Diagrams → ***628 @ LO for gg channel***

$t\bar{t}\gamma + X \ @ \ \mathcal{O}(\alpha_s^2\alpha^5)$

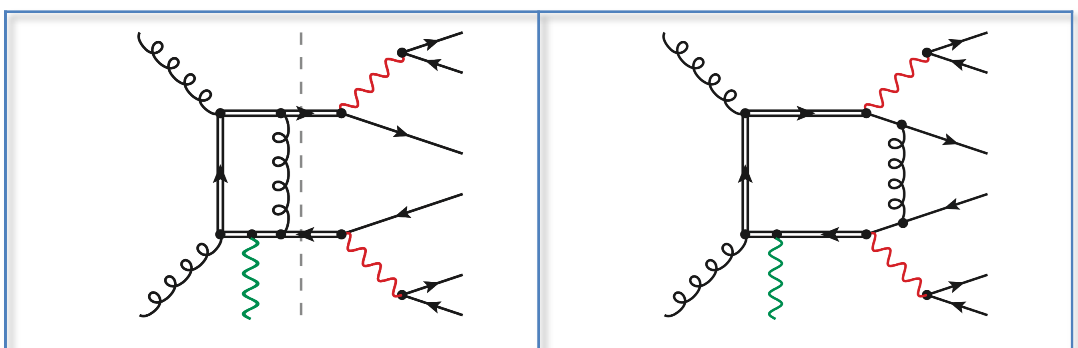


- NLO → ***4348 real emission & 36032 @ 1-loop for gg channel***

- Most complicated → ***90 heptagons & 958 hexagons***

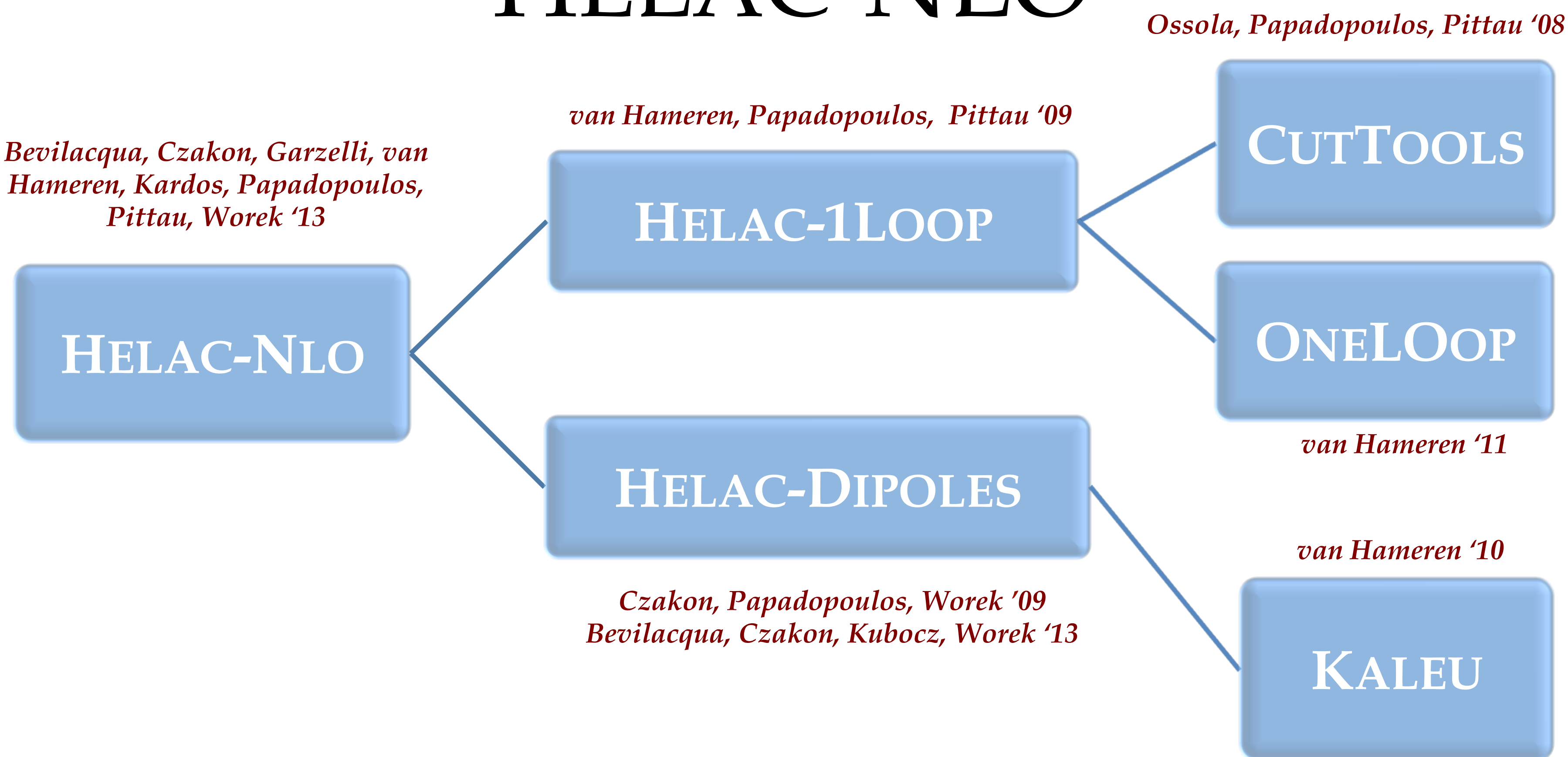
$t\bar{t}\gamma + X \ @ \ \mathcal{O}(\alpha_s^3\alpha^5)$

ttγ in NWA up to pentagons



ttγ full up to heptagons

HELAC-NLO



⌘ **Output:**

- ❖ theoretical predictions are stored in the form of the **Ntuples Event Files**
- ❖ modified **Les Houches & ROOT Event 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

Setup for ttγ

⌘ Different lepton generations

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

⌘ Interference effects neglected → ***Per-mille level @ LO***

⌘ Contribution from b quarks in the initial state neglected → ***Effect < 0.1% @ LO***

⌘ ***2 b-jets, one photon, two charged leptons & p_T^{miss}***

⌘ Photon: $p_T(\gamma) > 25 \text{ GeV}, |y_\gamma| < 2.5$

⌘ Isolation condition for photon → Reject event if $R \leq R_{\gamma j}$ with $R_{\gamma j} = 0.4$

Frixione '98

$$\sum_i E_{T,i}\,\Theta(R - R_{\gamma i}) \leq E_{T,\gamma}\left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})}\right)$$

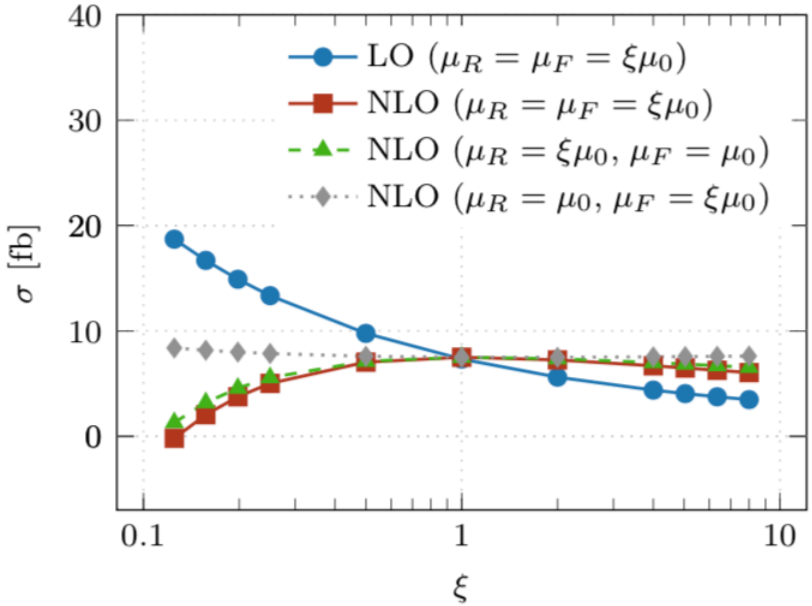
⌘ For hard photon $\alpha = \alpha(0) = 1/137$ → ***Predictions decreased by 3%***

⌘ Electroweak coupling in the G_μ scheme → account for some electroweak effects

⌘ Kinematics-independent & kinematic-dependent scale: $\mu_0 = m_t/2, H_T/4$

ttγ with H_T

Bevilacqua, Hartanto, Kraus, Weber, Worek '18



$$\mu_R \neq \mu_F,\ 0.5 < \mu_R/\mu_F < 2$$

$$\mu_0 = H_T/4, \mathrm{CT14}$$

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

$$\sigma^{\mathrm{LO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\mathrm{CT14}, \mu_0 = H_T/4) = 7.32\ ^{+2.44\,(33\%)}_{-1.71\,(23\%)}\ \mathrm{fb}\,,$$

$$\sigma^{\mathrm{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\mathrm{CT14}, \mu_0 = H_T/4) = 7.50\ ^{+0.10\,(1\%)}_{-0.46\,(6\%)}\ \mathrm{fb}\,.$$

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

⌘ Positive & small ***NLO corrections of 2.5%***

⌘ Theoretical uncertainties
→ ***33% @ LO & 6% @ NLO***

$$\sigma^{\mathrm{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\mathrm{CT14}, \mu_0 = m_t/2) = 7.44\ ^{+0.07\,(\ 1\%)}_{-1.03\,(14\%)}\ [\mathrm{scales}]\ ^{+0.05\,(1\%)}_{+0.28\,(4\%)}\ [\mathrm{PDF}]\ \mathrm{fb}\,.$$

$t\bar{t}\gamma$ with H_T

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

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

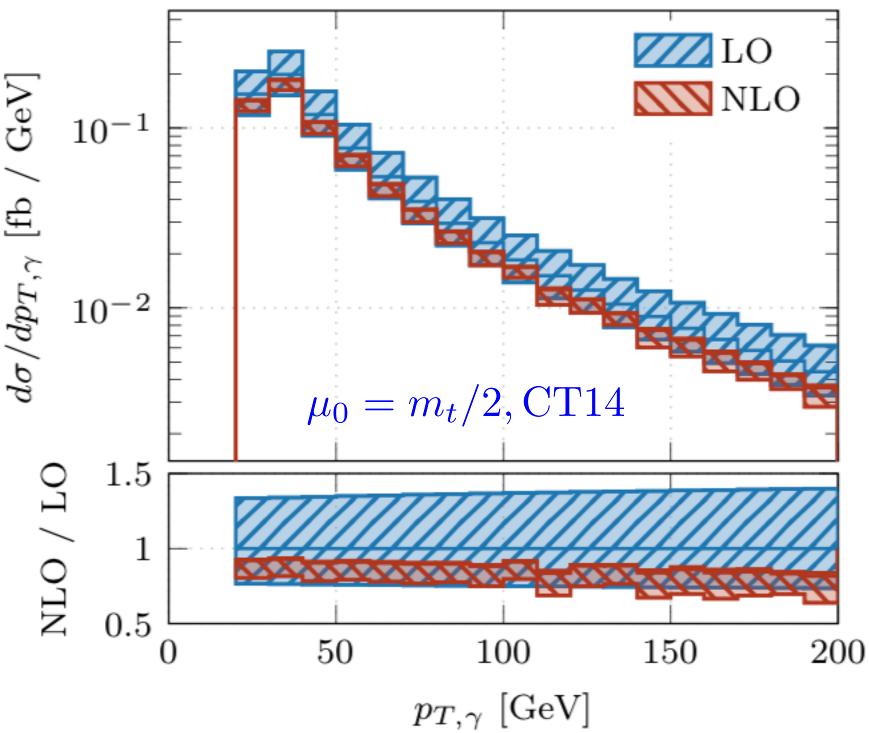
- NLO QCD corrections stable against $p_{T,b}$ cut
- CT14 PDF uncertainties similar/smaller than difference between various PDF sets
- Similar results for $p_{T,\gamma}$ ***cut***

$t\bar{t}\gamma$ with m_t & H_T

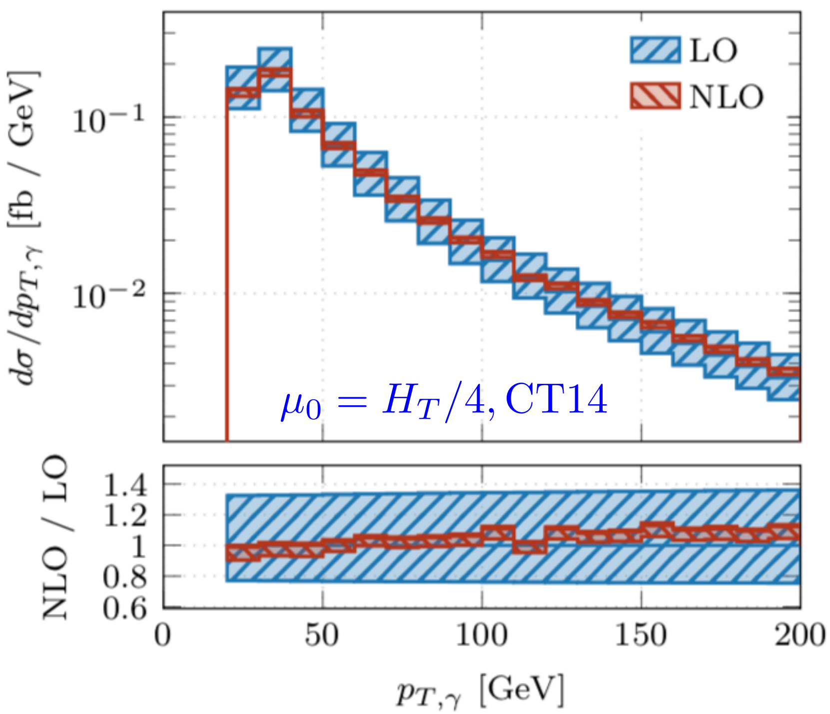
$p_T(\gamma)$

LHC$_{13\ TeV}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18



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



- ⌘ ***Negative NLO corrections up to 18%***
- ⌘ Theoretical error up to ***± 22%***

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

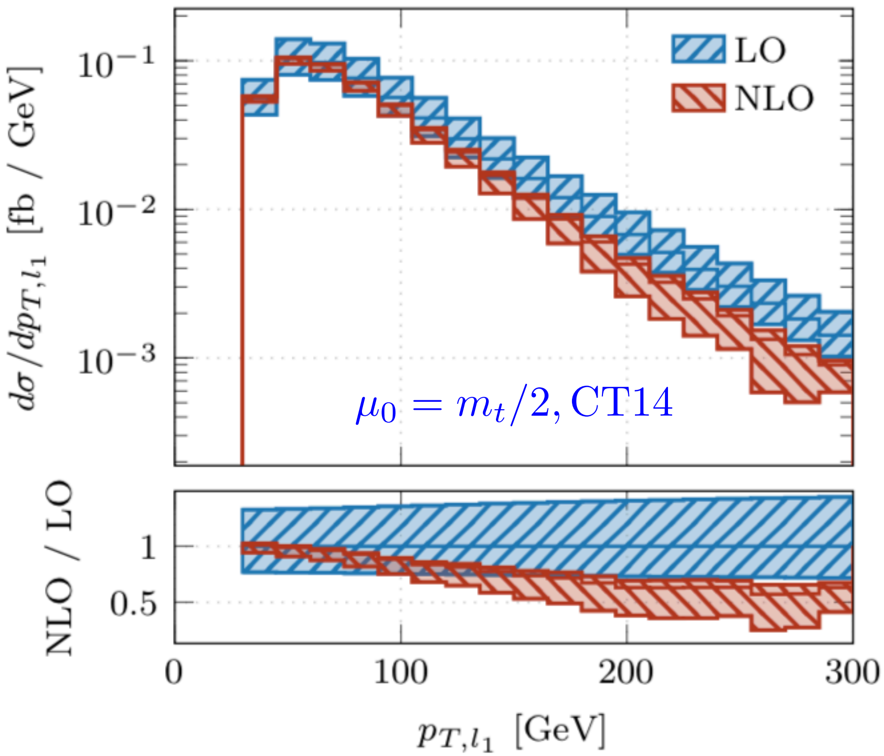
$t\bar{t}\gamma$ with m_t & H_T

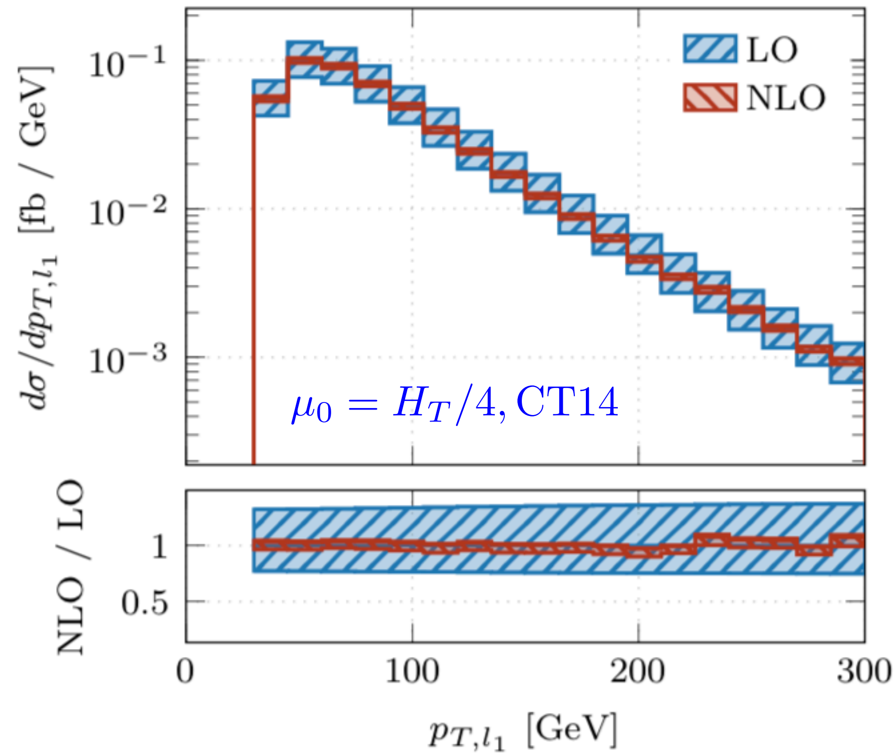
$p_T(l_1)$

$LHC_{13\ TeV}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

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





⌘ 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 !

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

⌘ For fiducial cross section with dynamical scale we have ***± 6%***

⌘ For ***differential distributions*** we have ***± (10% - 30%)***

⌘ Can we decrease theoretical error even further for ttγ ?

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

⌘ ***Answer is yes !*** → with ttγ/tt we have ***± (1% - 3%)*** for integrated cross section ratio

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

⌘ ***Differential cross section ratios ± (1% - 6%)***

⌘ High precision comparable to NNLO QCD results for top quark physics !

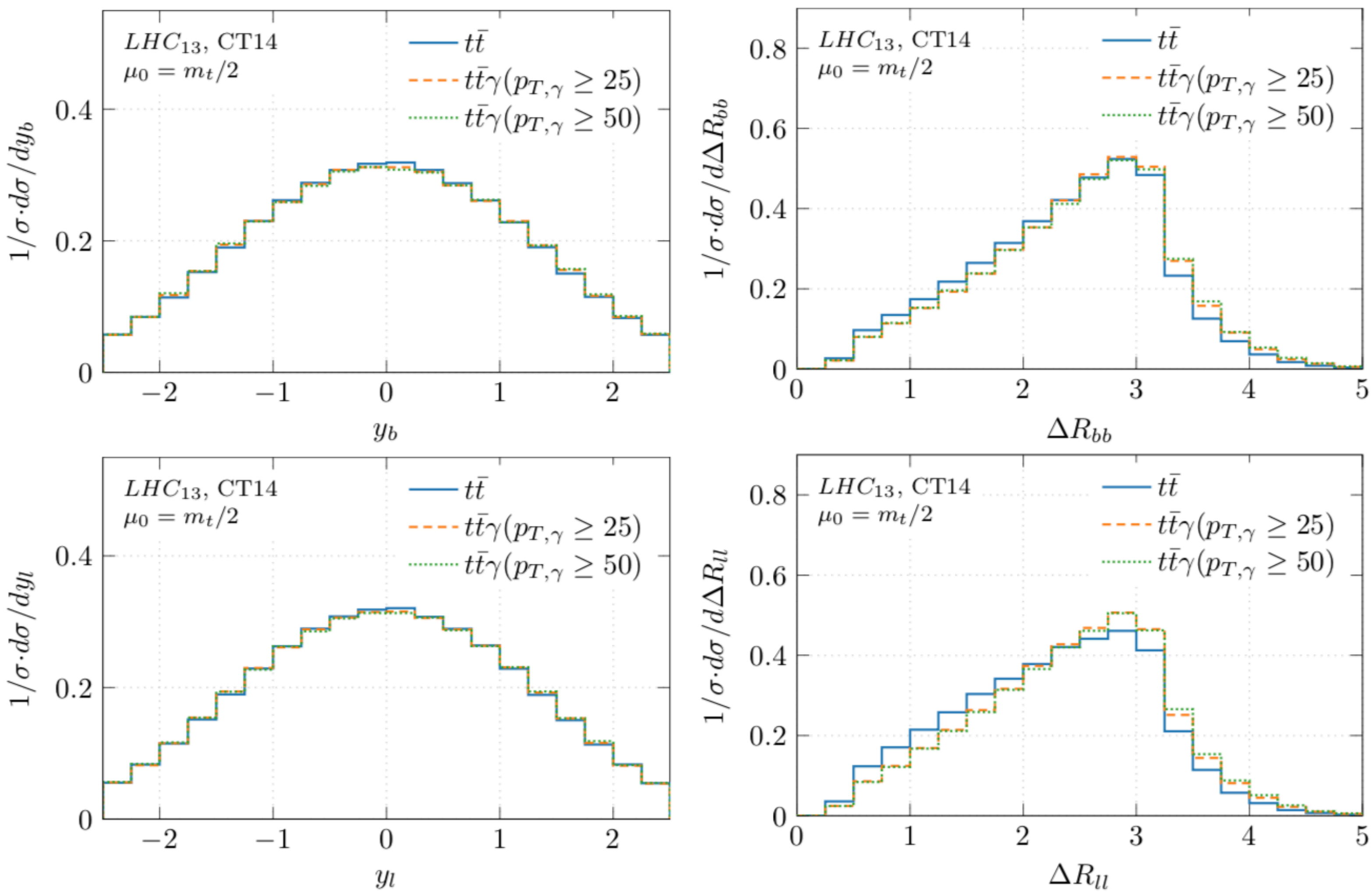
⌘ ***Processes need to be correlated*** → top quark pair production excellent candidate

$$\left(\frac{\mu_1}{\mu_0}, \frac{\mu_2}{\mu_0}\right) = \{(2,2), (0.5, 0.5)\}$$

⌘ ***Similar dynamical scale choice need to be implemented for μ_1 and μ_2 !***

ttγ & tt

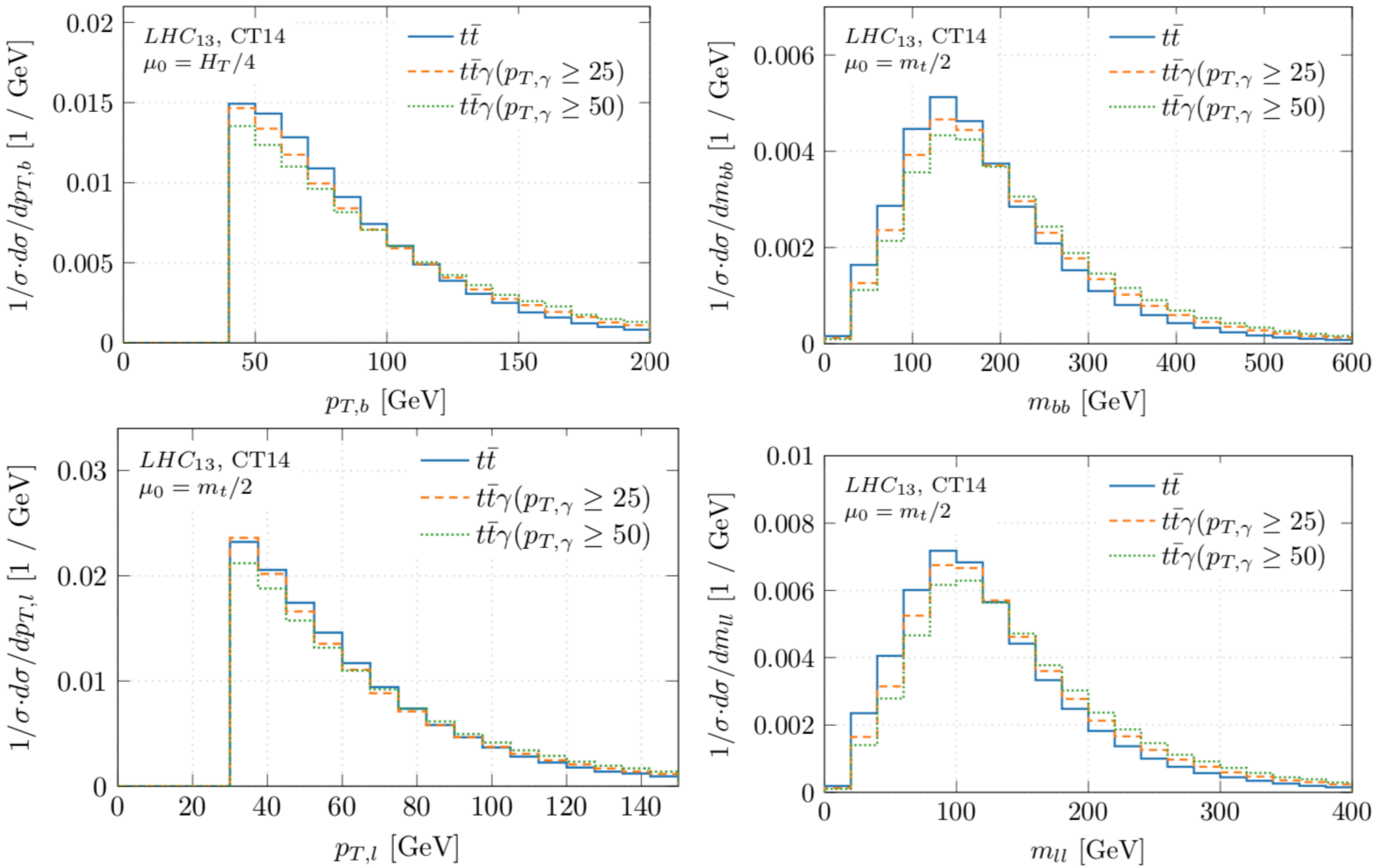
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC_{13TeV}}$



Bevilacqua, Hartanto, Kraus, Weber, Worek '18

ttγ & tt

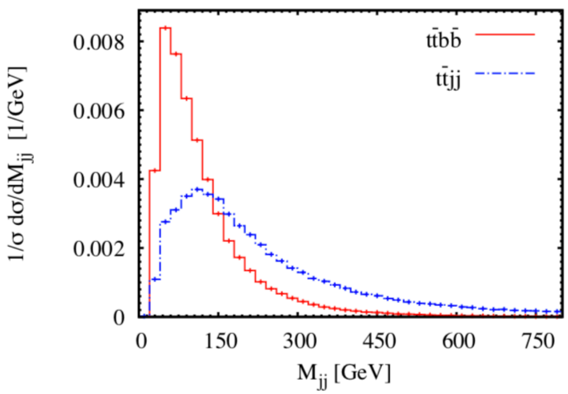
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ $\mathrm{LHC}_{13\mathrm{TeV}}$

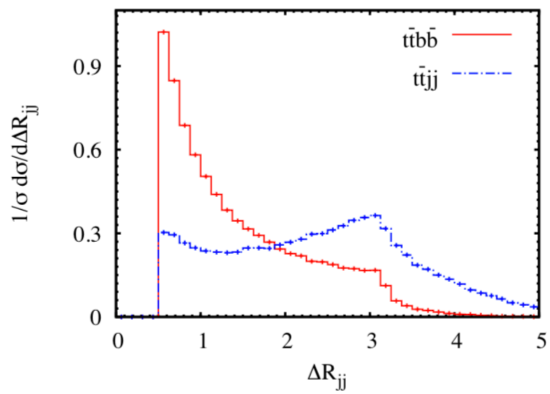


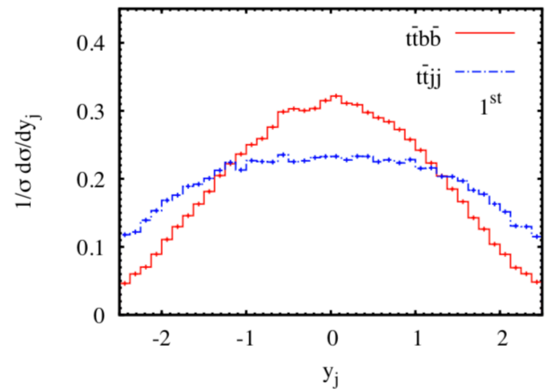
Bevilacqua, Hartanto, Kraus, Weber, Worek '18

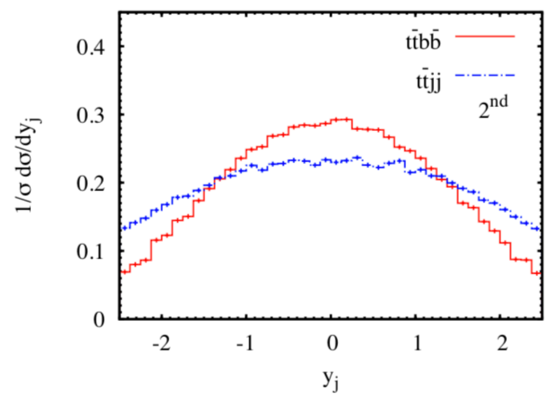
ttbb & ttjj

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









- ⌘ 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

On-shell Tops

$LHC_{8\ TeV}$

Bevilacqua, Worek '14

ttγ & tt

PDF set, $\mu_R = \mu_F = \mu_0$	$\sigma^{\text{NLO}}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}}$ [fb]	$\sigma^{\text{NLO}}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}$ [fb] $p_{T,\gamma} > 25$ GeV	$\sigma^{\text{NLO}}_{e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}$ [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, $\mu_0 = m_t/2$	$1695.0^{+18.4\,(1\%)}_{-153.3\,(9\%)}$	$7.718^{+0.078\,(1\%)}_{-1.102\,(14\%)}$	$3.195^{+0.054\,(2\%)}_{-0.550\,(17\%)}$

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

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

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

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

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

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

⌘ Our best NLO QCD predictions with dynamical scale choice:

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

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

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Differential Cross Section Ratio

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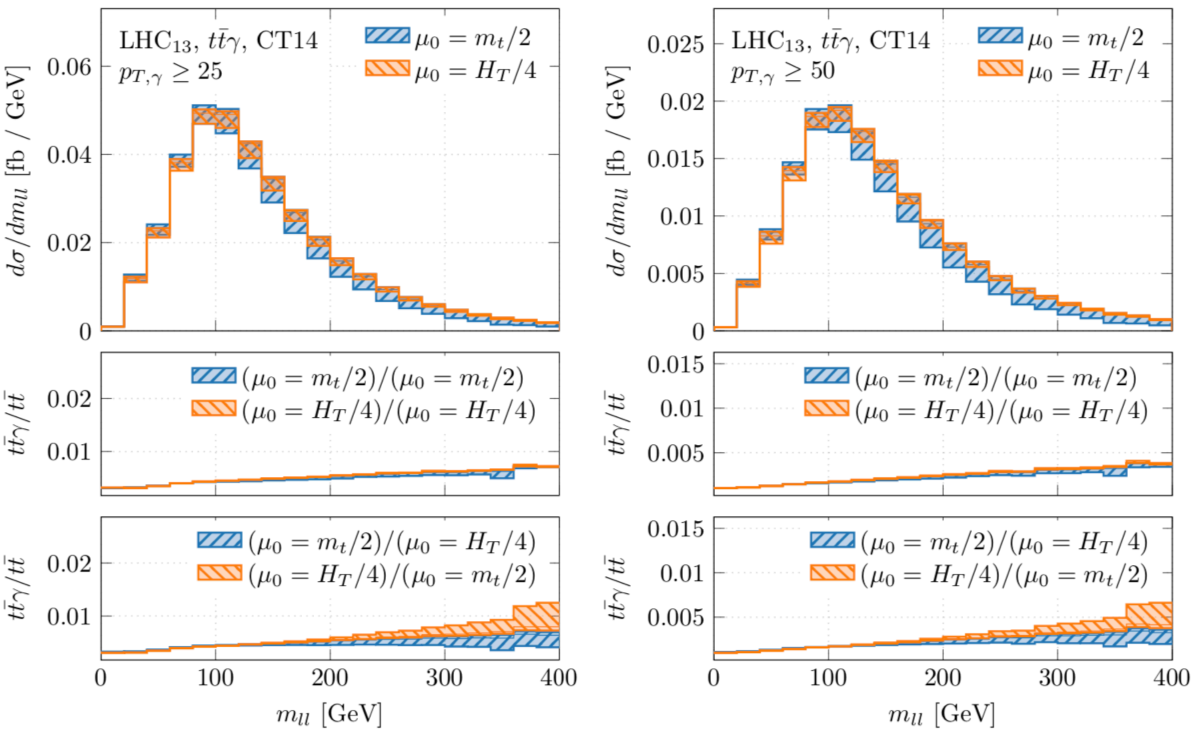


$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ LHC$_{13\text{TeV}}$

Theoretical uncertainties:

± (1% – 4%)
dynamical scale

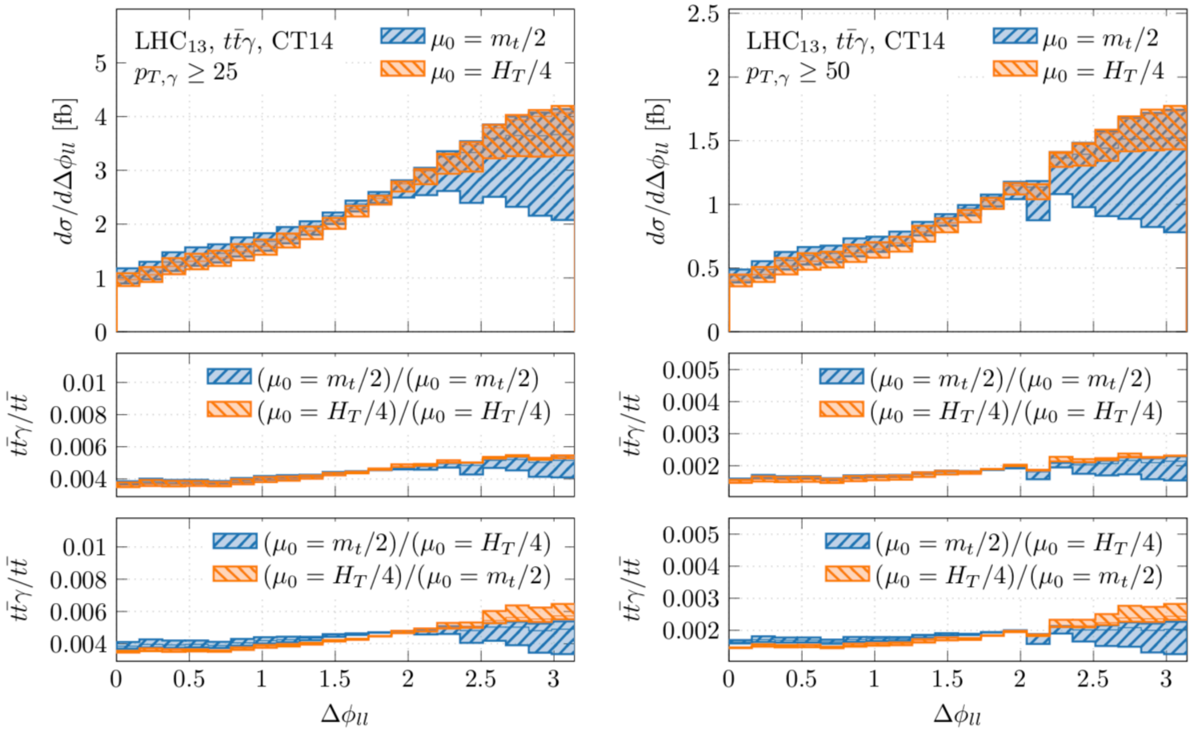
± (20% – 25%)
fixed scale

⌘ Should be compared to uncertainties for absolute differential cross section
- ❖ *up to ± 10% for* $\boldsymbol{\mu_0} = H_T/4$ & *up to ± 50% for* $\boldsymbol{\mu_0} = m_t/2$

⌘ When different scales are used in numerator and denominator ***up to 60%***

Differential Cross Section Ratio

Bevilacqua, Hartanto, Kraus, Weber, Worek '18



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

Theoretical uncertainties:

± (2% – 3%) dynamical scale

± (20% – 30%) fixed scale

⌘ Should be compared to uncertainties for absolute differential cross section

❖ ***up to ± 20% for $\mu_0 = H_T/4$ & up to ± 50% for $\mu_0 = m_t/2$***

⌘ When different scales are used in numerator and denominator ***up to 60%***

Summary & Outlook

⌘ The most precise NLO QCD theoretical predictions for ***ttγ*** in di-lepton channel
  - ❖ Complete off-shell effects for top quarks
  - ❖ Corrections to prodution & decays & tt spin correlations
  - ❖ Possibility of using kinematic-dependent scales

⌘ NLO QCD corrections stable against $p_{T,\gamma}$ *&* $p_{T,b}$ cut

⌘ CT14 PDF uncertainties similar/smaller than difference between various PDF sets

⌘ Uncertainties due to scale dependence dominant source of theoretical systematics

⌘ ***ttγ*** relevant for BSM searches and studies of top quark properties

⌘ Cross section ratio(s) increase precision without going to NNLO QCD !

⌘ ***Next steps:***
  - ❖ *Comparisons:* NWA vs. off-shell effects dedicated studies for ***ttγ***
  - ❖ *Applications:* SM parameter extraction, disentangling and constraining anomalous couplings and more …