Deutsche Forschungsgemeinschaft

NLO Off-Shell ttγ Production with HELAC-NLO

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Plan

- ⌘ Motivation for $t\bar{t}\gamma$
- ⌘ Status of theoretical predictions for $t\bar{t}\gamma$ @ LHC
- ⌘ NWA vs. off-shell effects
- ⌘ NWA vs. off-shell effects → Applications: m_t from $t\bar{t}j$ @ LHC
- ⌘ Top-quark off-shell effects with **HELAC–NLO**
- ⌘ Results for $t\bar{t}\gamma$ in di-lepton channel
- ⌘ Summary & Outlook

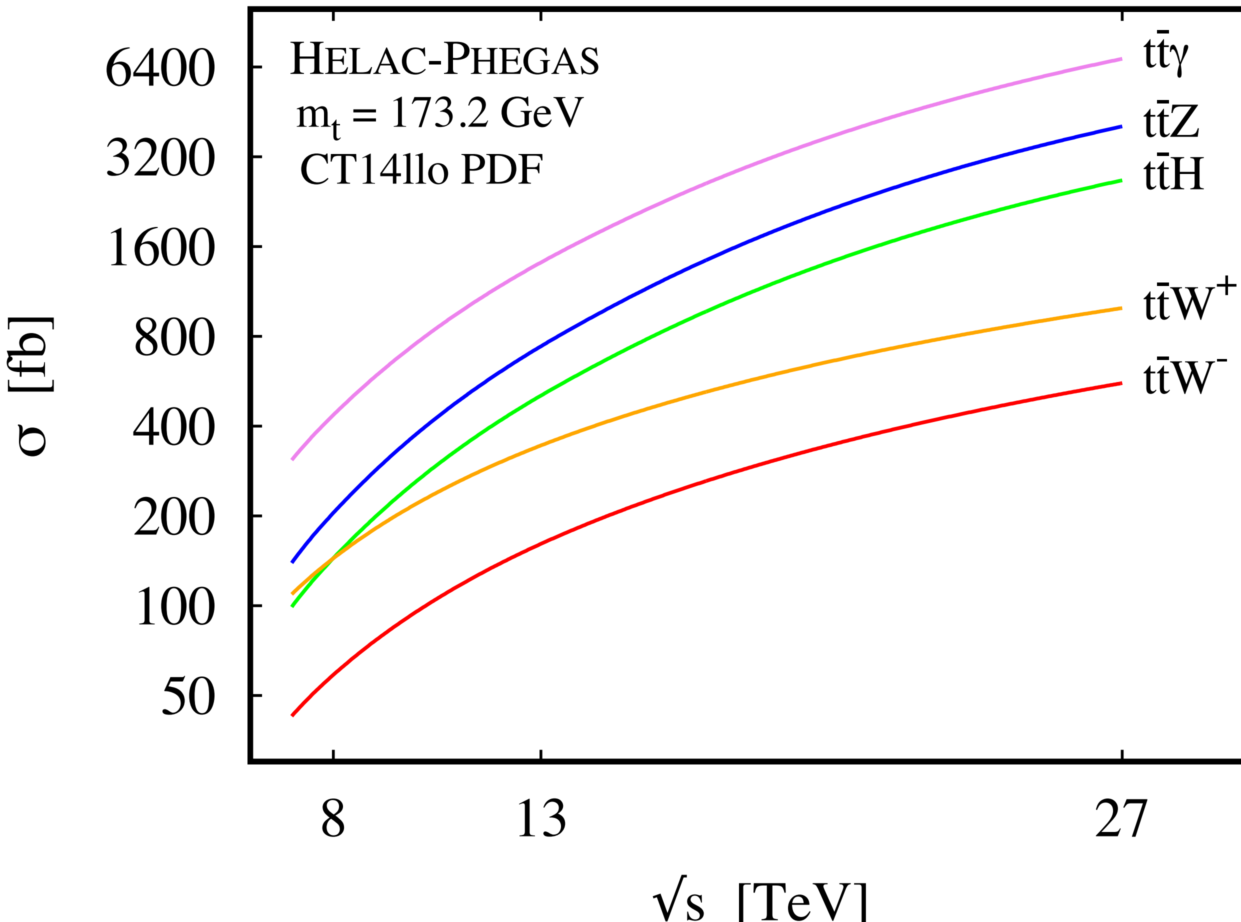
Collaborators:

G. Bevilacqua (University of Debrecen)
H. B. Hartanto (University of Durham)
M. Kraus (Humboldt University of Berlin)
T. Weber (RWTH Aachen University)

Motivations For ttγ

⌘ Besides $t\bar{t}, t\bar{t}j$ more exclusive final states can be accessed @ LHC

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

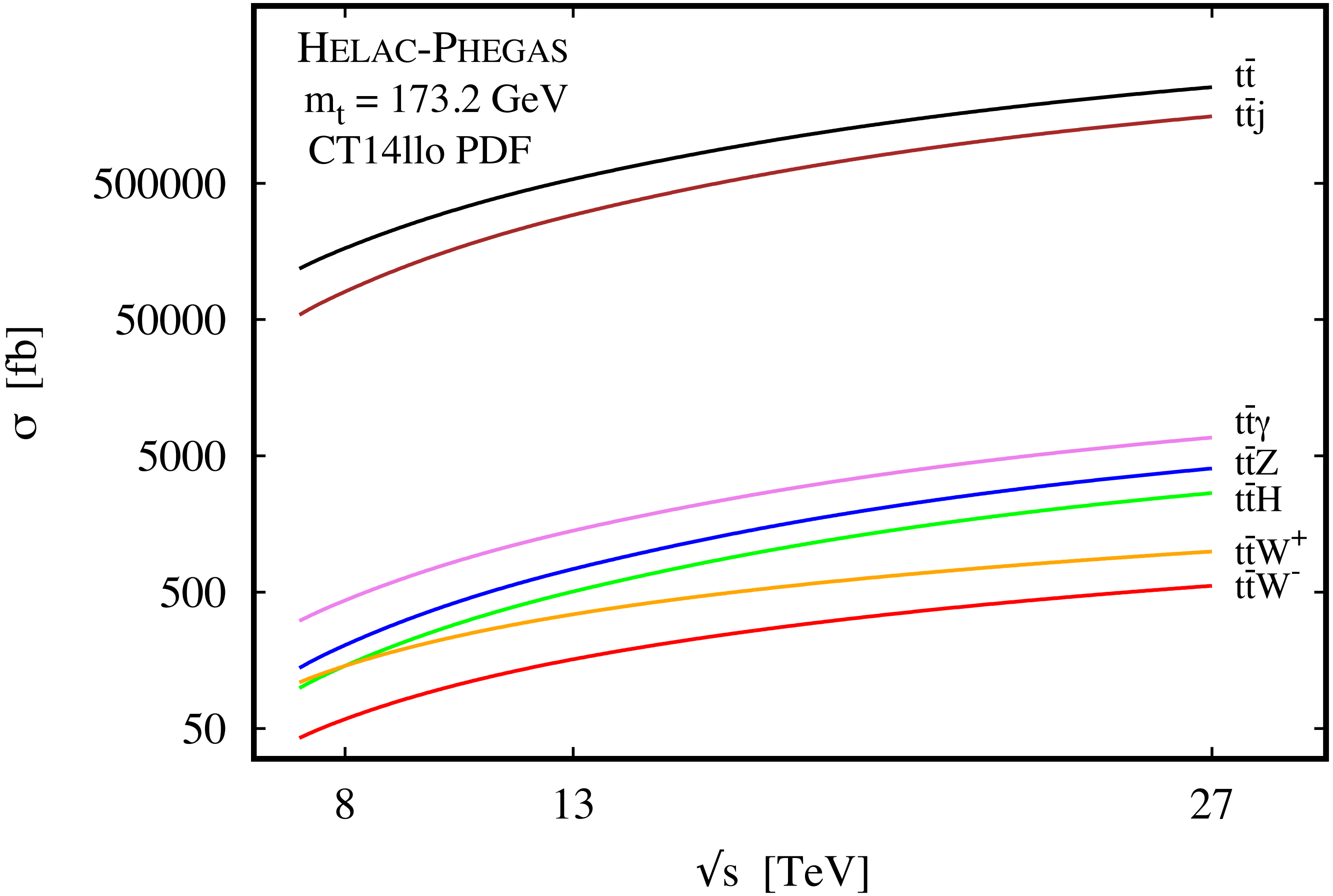


On-shell production

Motivations For ttγ

⌘ Besides $t\bar{t}, t\bar{t}j$ more exclusive final states can be accessed @ LHC

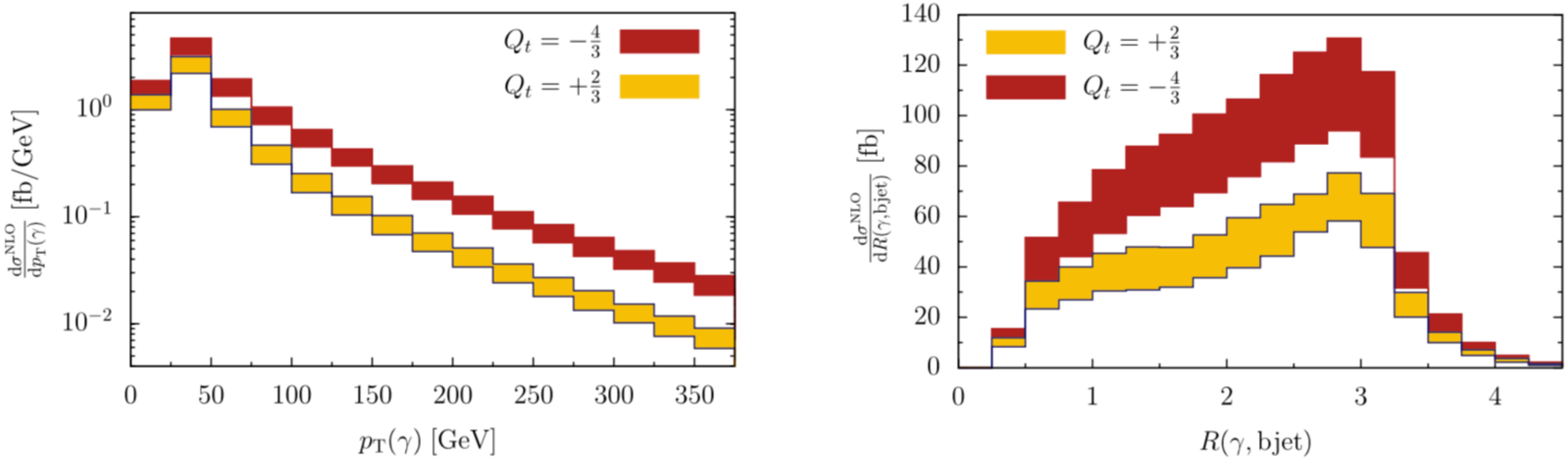
$t\bar{t}\,, t\bar{t}j\,, t\bar{t}\gamma\,, t\bar{t}Z\,, t\bar{t}H\,, t\bar{t}W^{\pm}$ @ LHC



On-shell production

Motivations For ttγ

- ⌘ $t\bar{t}V$ cross sections much smaller → Information on couplings to $\gamma, H, Z, W^{\pm}$
- ⌘ $t\bar{t}\gamma$ direct way to measure top quark charge $Q_t \longrightarrow \sigma_{t\bar{t}\gamma} \sim Q_t^2$ @ LHC
- ⌘ $Q_t = +\frac{2}{3}$ with CL $\geq 5\sigma$ @ LHC → Indirectly from $Q_t = Q_W - Q_{b-jet}$ in $t\bar{t}$
- ⌘ Test exotic physics scenarios: top-like quarks with $Q_t = -4/3$



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

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

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, …

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 patter from decays

- ★ **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

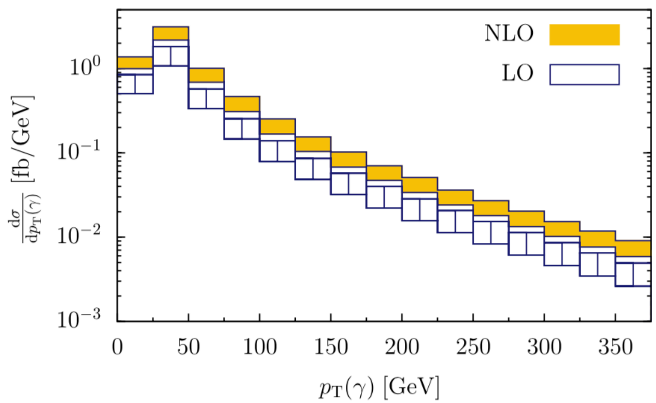
- ★ **NLO QCD for on-shell top quarks + PS** → Top decays in parton shower approximation, omitting photon emission in PS evolution & omitting tt spin correlations *Kardos, Trocsanyi '14*

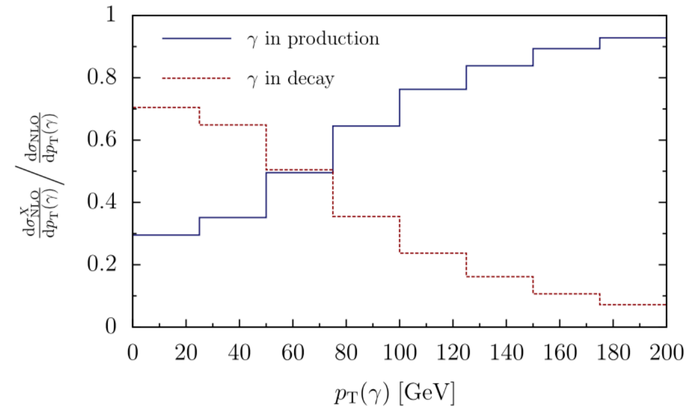
- ★ **NLO QCD in NWA** → NLO QCD corrections to top production & decays, photon emission of top quark and of top quark decay product & tt spin correlations included
  Melnikov, Schulze, Scharf '11

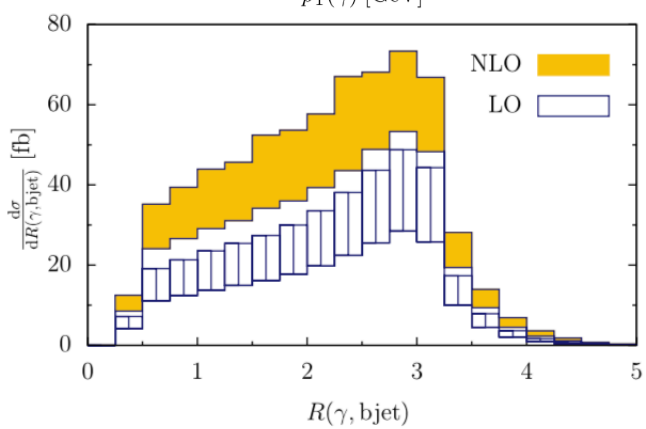
ttγ in NWA @ LHC

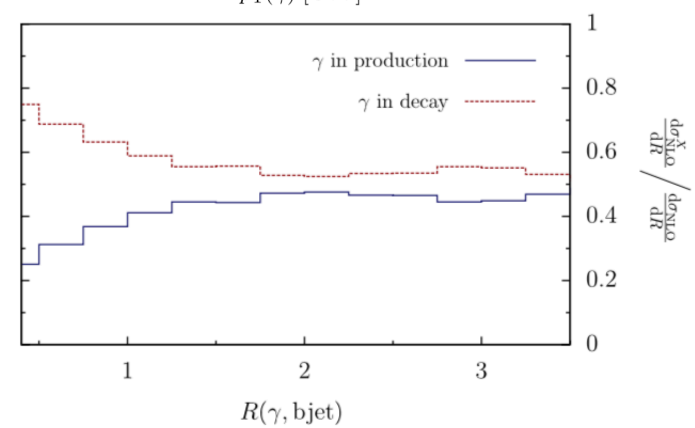
Melnikov, Schulze, Scharf '11

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









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

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

How Good Is NWA?

⌘ In NWA tops are restricted to on-shell states

⌘ Approximation is controlled by the ratio $\Gamma_t/m_t \approx 0.8\%$

⌘ Contributions from diagrams involving two top-quark resonances

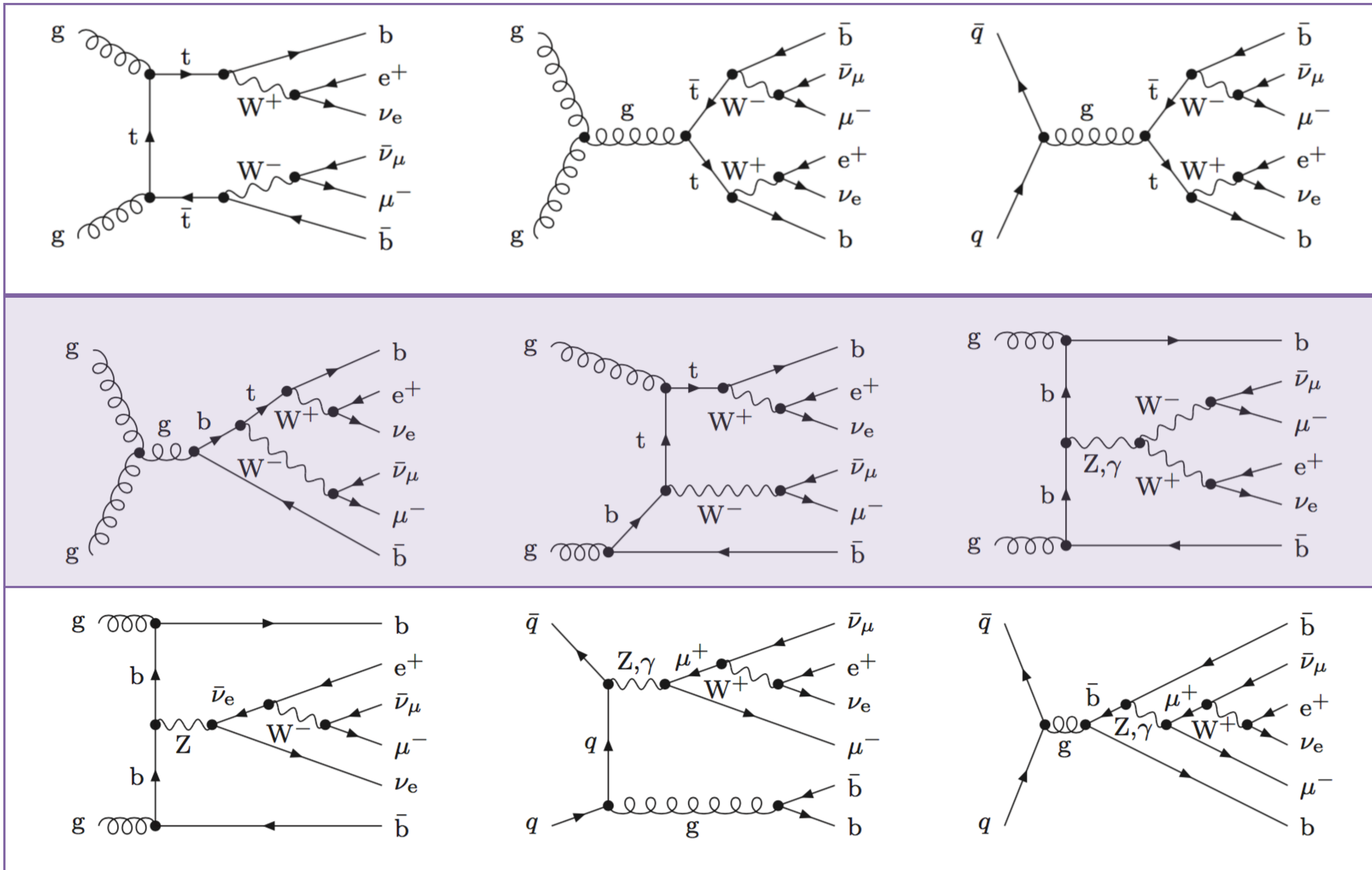
⌘ Should be accurate for sufficiently inclusive observables

⌘ Indeed → **Off-shell effects for σ at few % level @ NLO in QCD**

tt (di-lepton)	*Denner, Dittmaier, Kallweit, Pozzorini '11 '12* *Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '11*
tt (semi-leptonic)	*Denner, Pellen '18*
ttH (di-lepton)	*Denner, Feger '15*
ttj (di-lepton)	*Bevilacqua, Hartanto, Kraus, Worek '16 '18*
ttγ (di-lepton)	*Bevilacqua, Hartanto, Kraus, Weber, Worek '18*

NWA vs. Off-Shell Effects

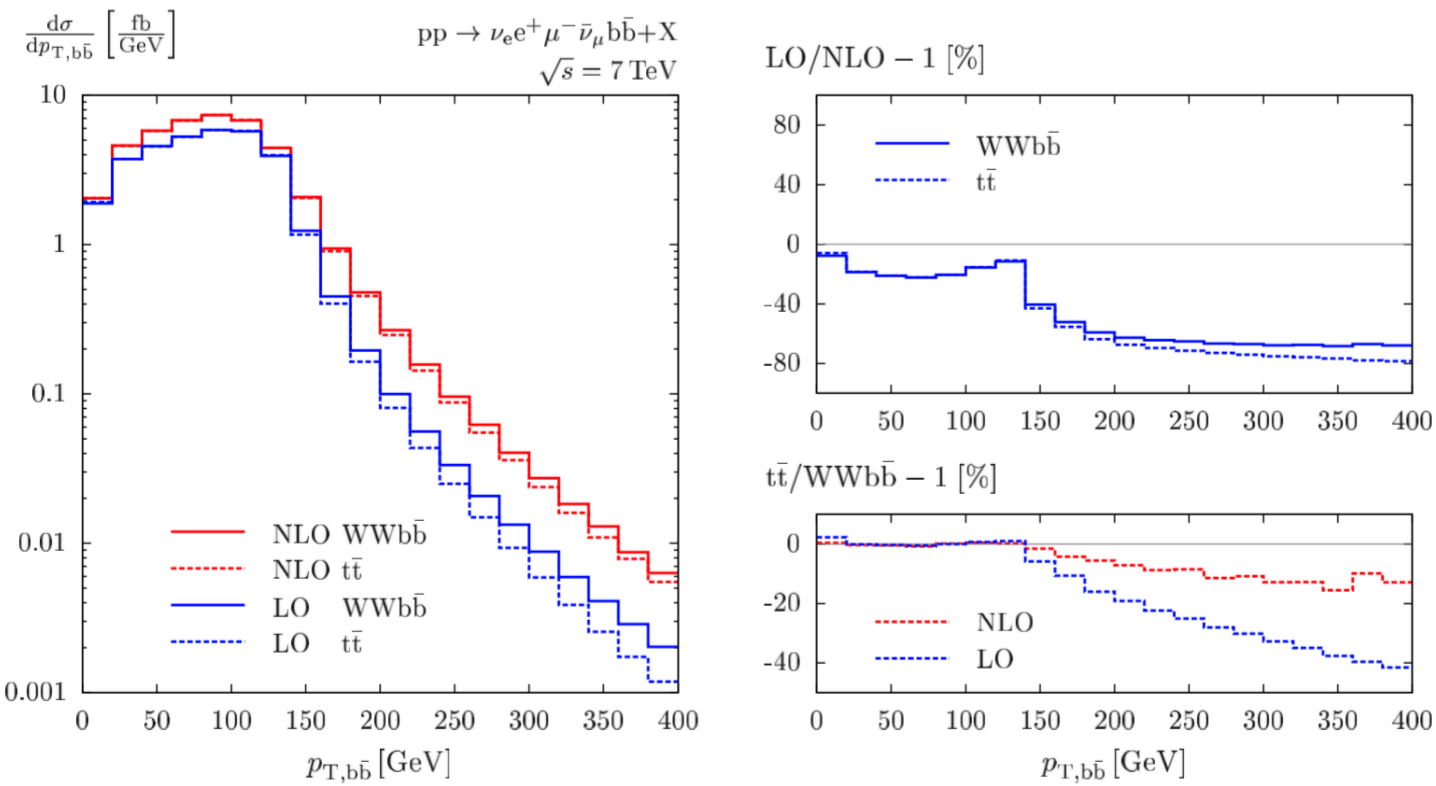
$\mathbf{pp \to t\bar{t}}$



Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

NWA vs. Off-Shell Effects

- Off-shell results vs. results with (spin-correlated) NWA
- Tens of per cent in phase-space regions where $t\bar{t}$ suppressed as signal
- Important as background to **Higgs and BSM searches**

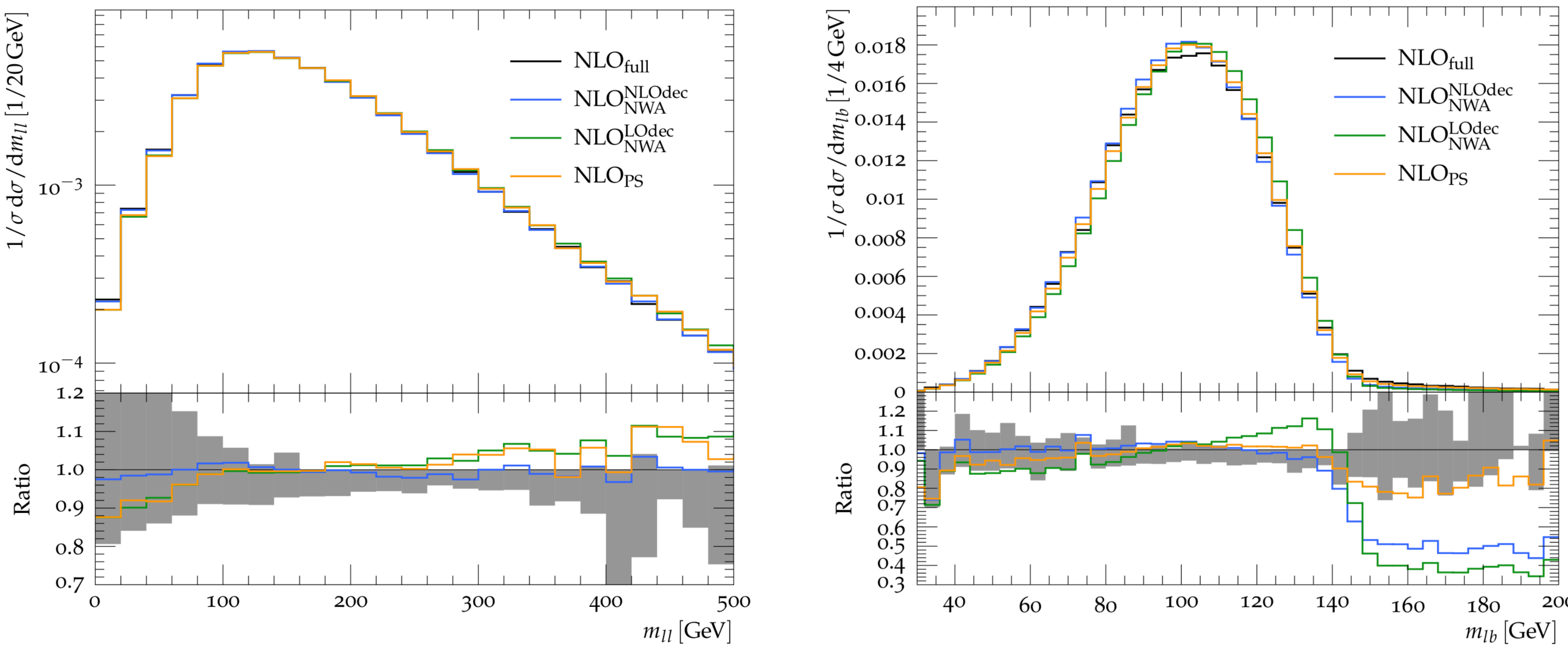


Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

NWA vs. Off-Shell Effects

⌘ Observables used for a recent top quark mass determination

$pp \to t\bar{t} \to \ell^+ \nu_\ell \mu^- \bar{\nu}_\mu b\bar{b}$ @ 13 TeV LHC

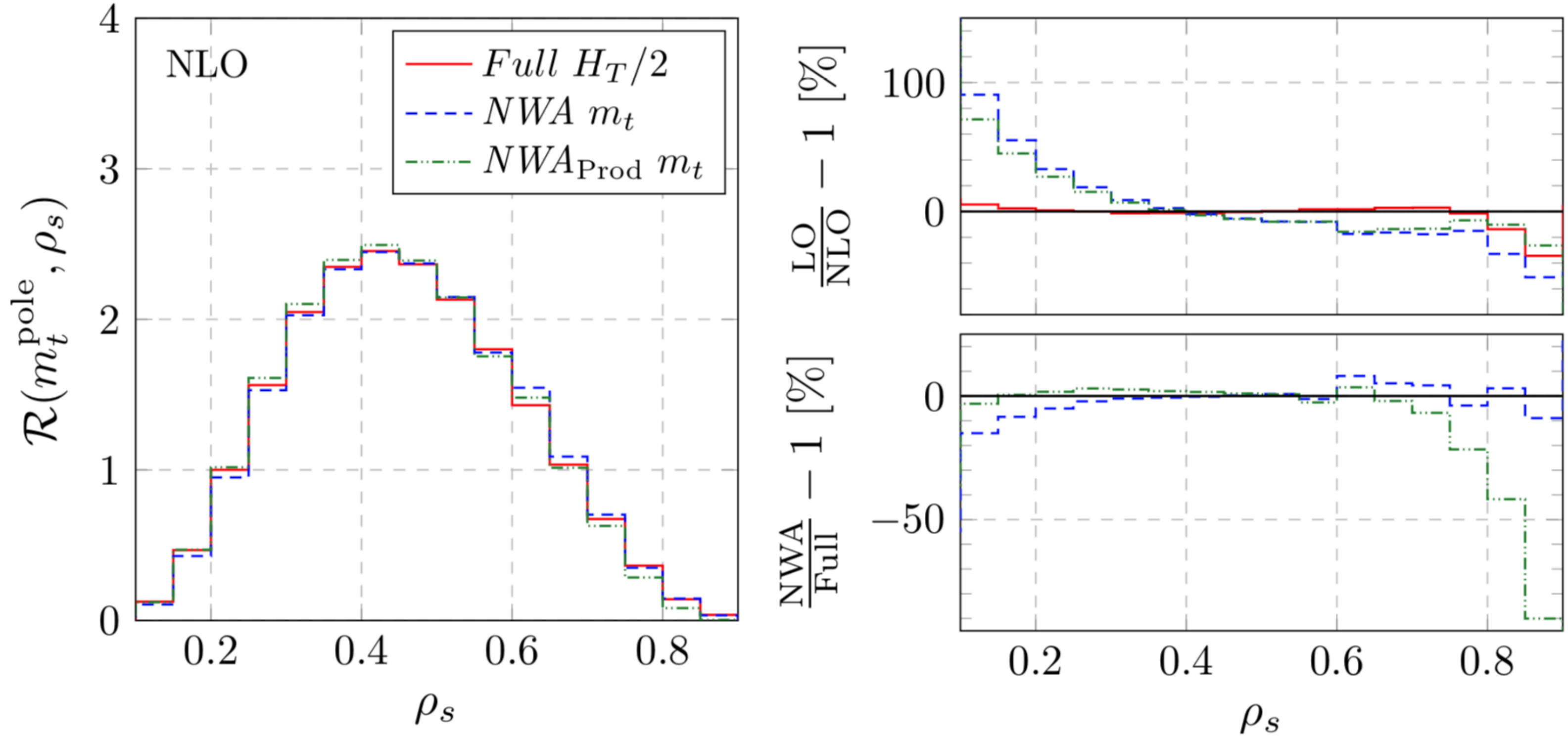


Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter '18

NWA vs. Off-Shell Effects

⌘ Observable used for a recent top quark mass determination

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



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

Bevilacqua, Hartanto, M. Kraus, M. Schulze, M. Worek '18

NWA vs. Off-Shell Effects

2.5 fb^{-1}

$pp \to t\bar{t}j \to \ell^+\nu_\ell\mu^-\bar{\nu}_\mu b\bar{b}j$ @ 13 TeV LHC

Theory, NLO QCD CT14 PDF	$m_t^{out} \pm \delta m_t^{out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{in} - m_t^{out}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.38 ± 1.34	1.04	0.40 (0.8σ)	-0.18
Full, $\mu_0 = E_T/2$	172.84 ± 1.33	1.05	0.39 (0.9σ)	$+0.36$
Full, $\mu_0 = m_t$	174.11 ± 1.39	1.07	0.37 (0.9σ)	-0.91
NWA, $\mu_0 = m_t$	175.70 ± 0.96	1.17	0.24 (1.2σ)	-2.50
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.93 ± 0.98	1.20	0.20 (1.3σ)	$+3.27$
5 bins				
Full, $\mu_0 = H_T/2$	173.15 ± 1.32	0.93	0.44 (0.8σ)	$+0.05$
Full, $\mu_0 = E_T/2$	172.55 ± 1.18	1.07	0.37 (0.9σ)	$+0.65$
Full, $\mu_0 = m_t$	173.92 ± 1.38	1.48	0.20 (1.3σ)	-0.72
NWA, $\mu_0 = m_t$	175.54 ± 0.97	1.38	0.24 (1.2σ)	-2.34
$NWA_{\text{Prod.}}$, $\mu_0 = m_t$	169.37 ± 1.43	1.16	0.33 (1.0σ)	$+3.83$

Bevilacqua, Hartanto, M. Kraus, M. Schulze, M. Worek '18

NWA vs. Off-Shell Effects

25 fb^{-1}

$pp \to t\bar{t}j \to \ell^+\nu_\ell\mu^-\bar{\nu}_\mu b\bar{b}j$ @ 13 TeV LHC

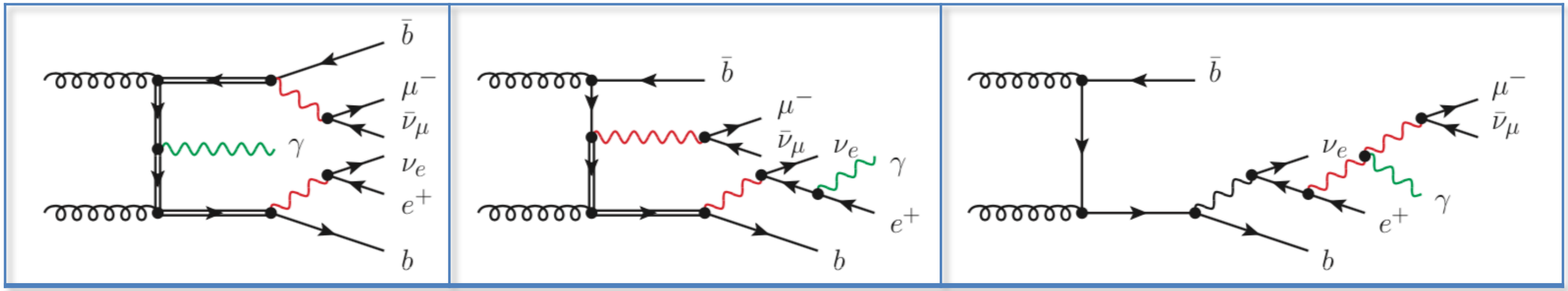
Theory, NLO QCD CT14 PDF	$m_t^{\text{out}} \pm \delta m_t^{\text{out}}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\text{in}} - m_t^{\text{out}}$ [GeV]
31 bins				
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$	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, M. Kraus, M. Schulze, M. Worek ‘18

NWA vs. Off-Shell Effects

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

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

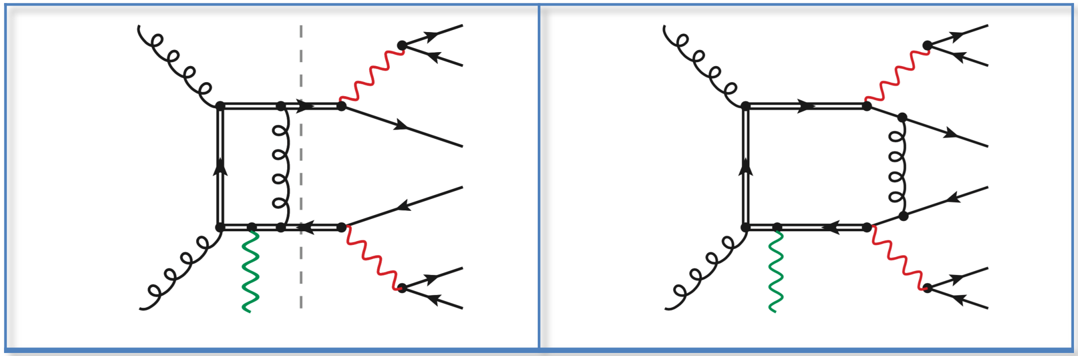


⌘ NLO → **4348 real emission & 36032 @ 1-loop for gg channel**

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

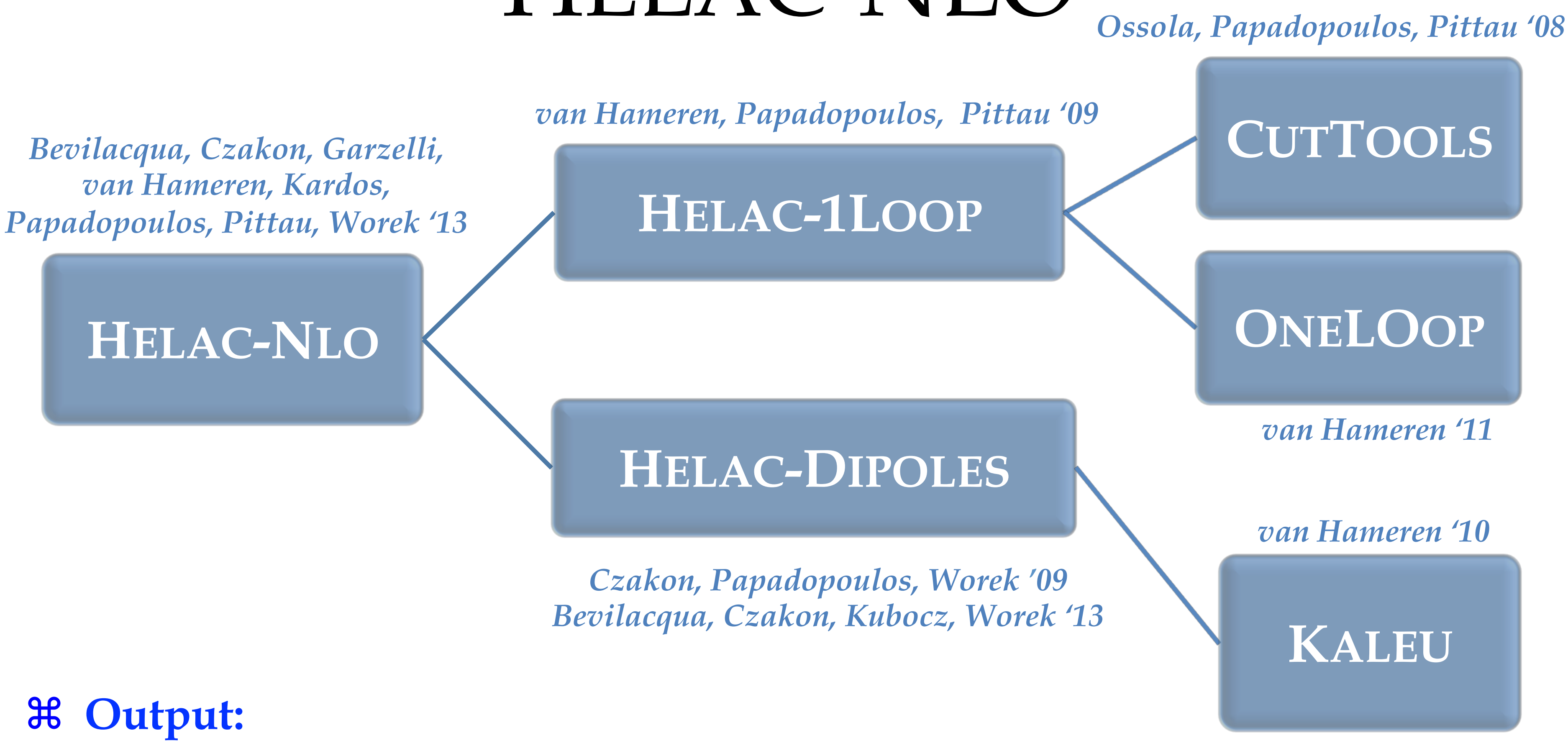
$t\bar{t}\gamma + X$ @ $\mathcal{O}(\alpha_s^3\alpha^5)$

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
- ✧ renormalisation or factorisation scale and PDF set can be changed

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

Setup for ttγ

⌘ Different lepton generations $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma + X$

⌘ $\gamma^* \to \ell^\pm\ell^\mp$ interference effects neglected → **Per-mille level @ LO**

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

⌘ Requirement: exactly two b-jets, one photon, two charged leptons & p_T^{miss}

⌘ Photon: $p_T(\gamma) > 25$ GeV, $|y_\gamma| < 2.5$ *Frixione '98*

⌘ Isolation condition for photon: $\sum_i E_{T,i}\,\Theta(R - R_{\gamma i}) \le E_{T,\gamma}\left(\frac{1-\cos(R)}{1-\cos(R_{\gamma j})}\right)$

★ Reject event if condition not fulfilled for all $R \le R_{\gamma j}$ with $R_{\gamma j} = 0.4$

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

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

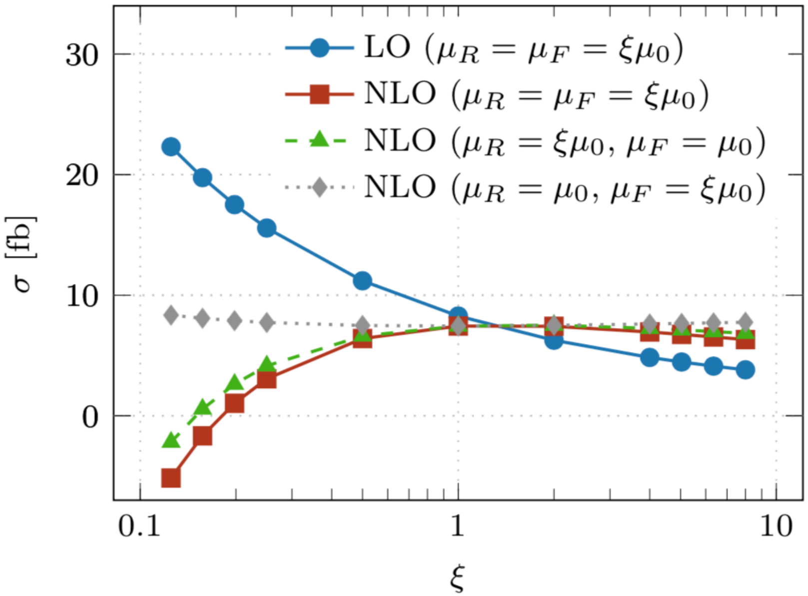
⌘ Kinematics-independent & kinematic-dependent scale: $\mu_0 = m_t/2, H_T/4$

ttγ - Fixed Scale

LHC @ 13 TeV

$\mu_0 = m_t/2, \text{CT14}$

Bevilacqua, Hartanto, Kraus, Weber, Worek '18



$$\sigma^{\text{LO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\text{CT14}, \mu_0 = m_t/2) = 8.27 \,^{+2.92\,(35\%)}_{-2.01\,(24\%)}\ \text{fb}$$

$$\sigma^{\text{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\text{CT14}, \mu_0 = m_t/2) = 7.44 \,^{+0.07\,(\ 1\%)}_{-1.03\,(14\%)}\ \text{fb}$$

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

$$\sigma^{\text{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\text{MMHT14}, \mu_0 = m_t/2) = 7.49\ \text{fb}$$

$$\sigma^{\text{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\text{NNPDF3.0}, \mu_0 = m_t/2) = 7.72\ \text{fb}$$

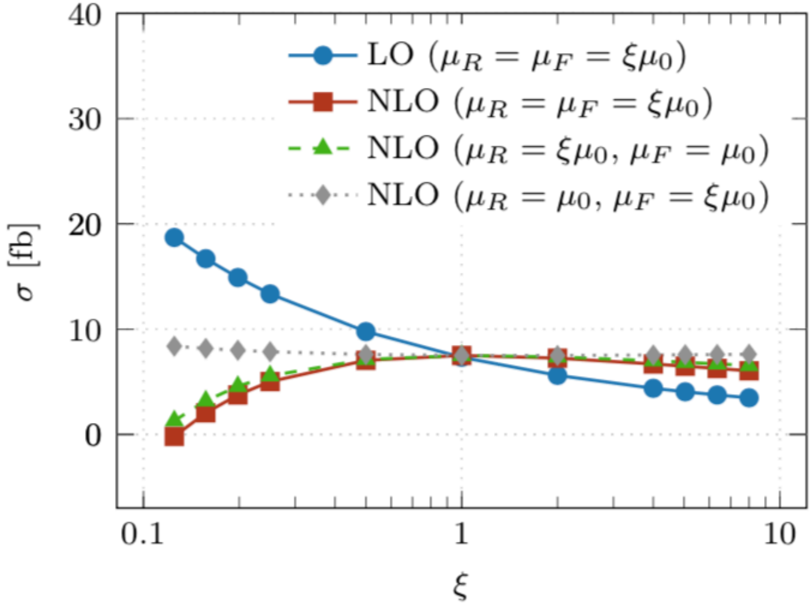
- ⌘ @ LO: **gg channel** dominates **79%, qq channel** follows with **21%**
- ⌘ Negative & moderate **NLO corrections of 10%**
- ⌘ Theoretical uncertainties → **35% @ LO & 14% @ NLO** ↓ **2.5**
- ⌘ After Symmetrisation → **30% at LO** and **7% at NLO** ↓ **4.3**

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

ttγ - Dynamical Scale

LHC @ 13 TeV

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



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$$H_T = p_{T,e^+} + p_{T,\mu^-} + p_{T,b_1} + p_{T,b_2} + p_T^{\text{miss}} + p_{T,\gamma}$$

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

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

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

- ⌘ Positive & small **NLO corrections of 2.5%**
- ⌘ Theoretical uncertainties → **33% @ LO & 6% @ NLO** ↓ **5.5**
- ⌘ After symmerisation → **28% at LO** & **4% at NLO** ↓ **7**

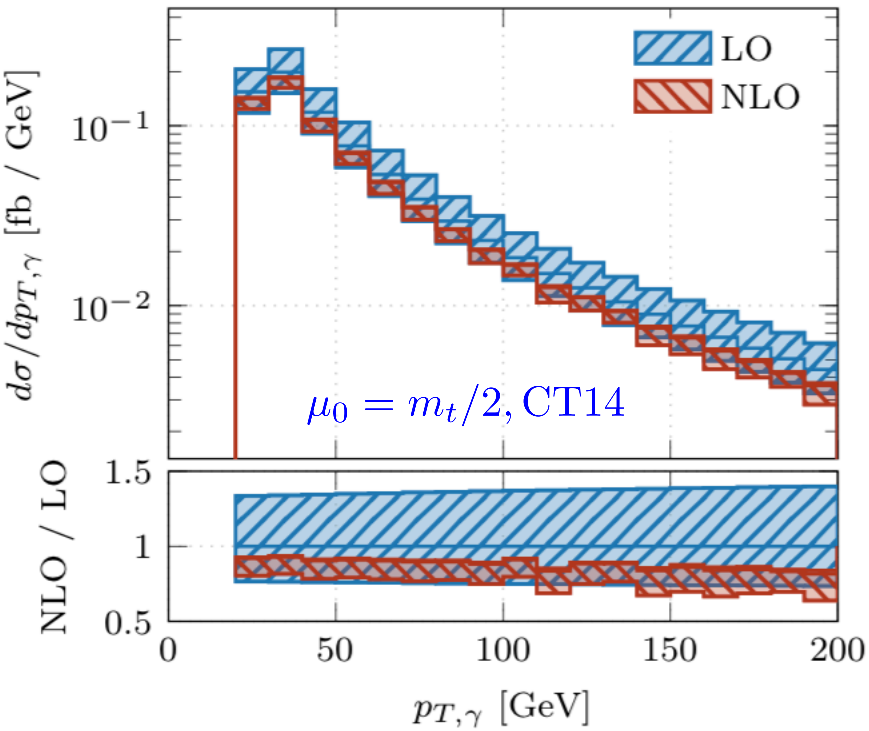
$$\sigma^{\text{NLO}}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}(\text{CT14}, \mu_0 = m_t/2) = 7.44\ ^{+0.07\,(\ 1\%)}_{-1.03\,(14\%)}\ [\text{scales}]\ ^{+0.05\,(1\%)}_{+0.28\,(4\%)}\ [\text{PDF}]\ \text{fb}\,.$$

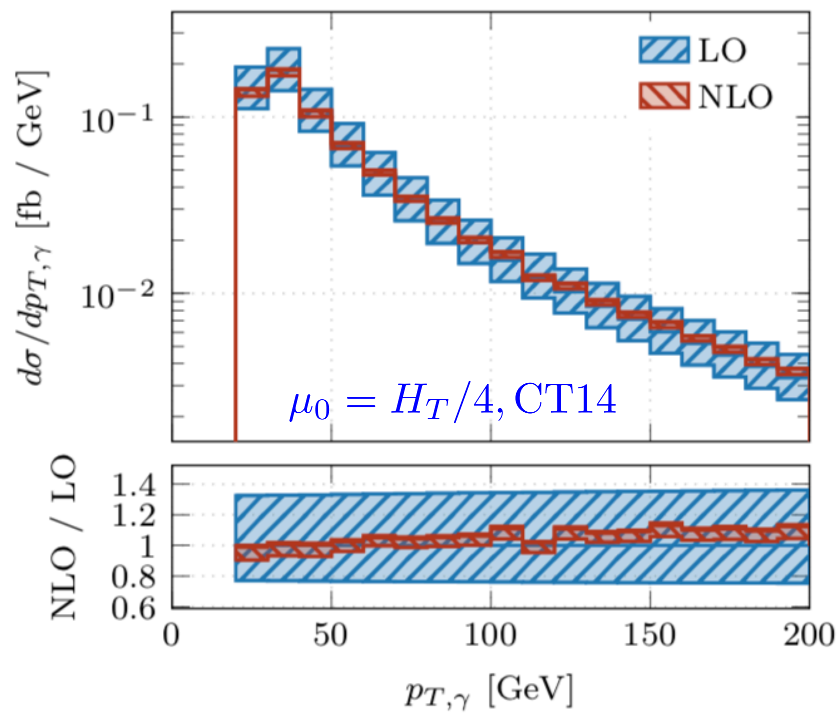
ttγ - Distributions

⌘ Observable relevant for BSM searches: $p_T(\gamma)$

LHC @ 13 TeV

Bevilacqua, Hartanto, Kraus, Weber, Worek '18





⌘ **Differential K-factor** varying only **from −8% to −18%**

⌘ Theoretical Error **up to ±22%**

⌘ **Positive corrections up to 13%**

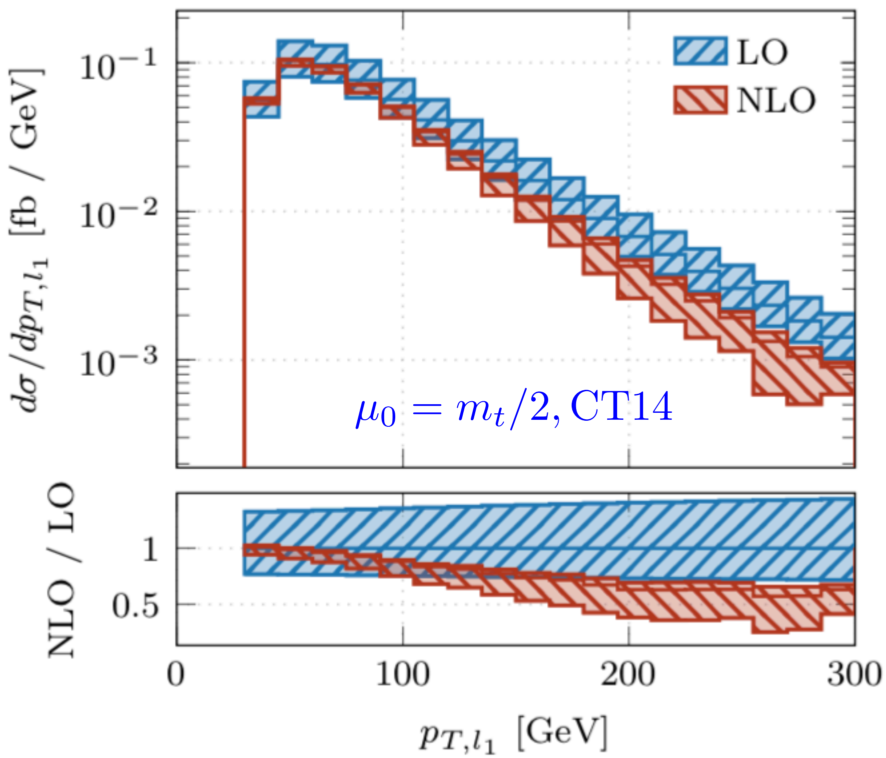
⌘ NLO error bands within the LO error band → **Error up to ±8%**

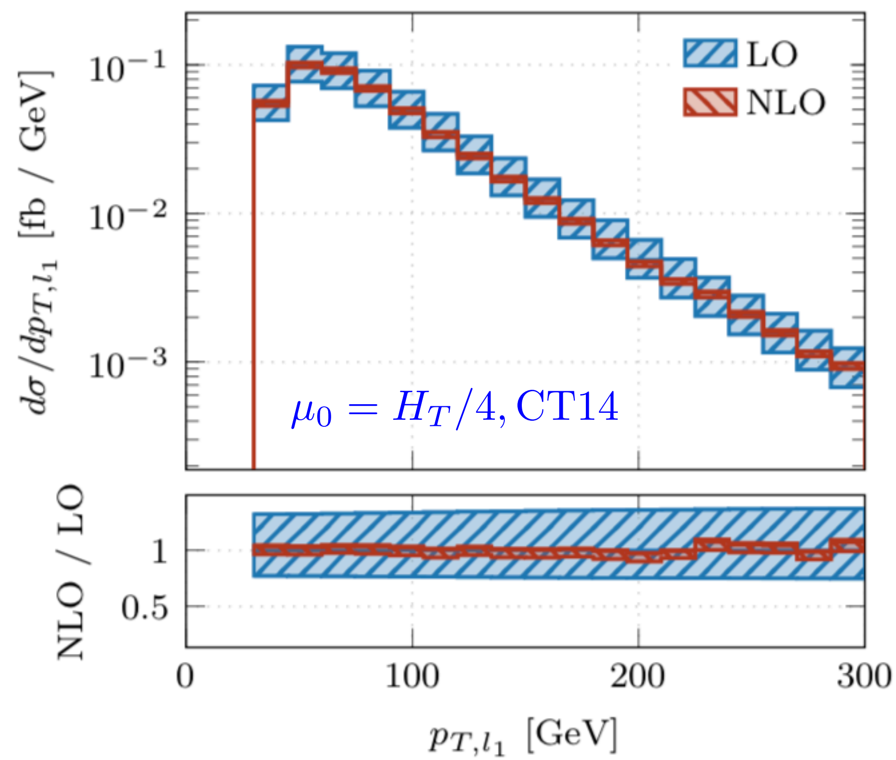
$t\bar{t}\gamma$ - Distributions

LHC @ 13 TeV

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$p_T(l_1)$





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

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

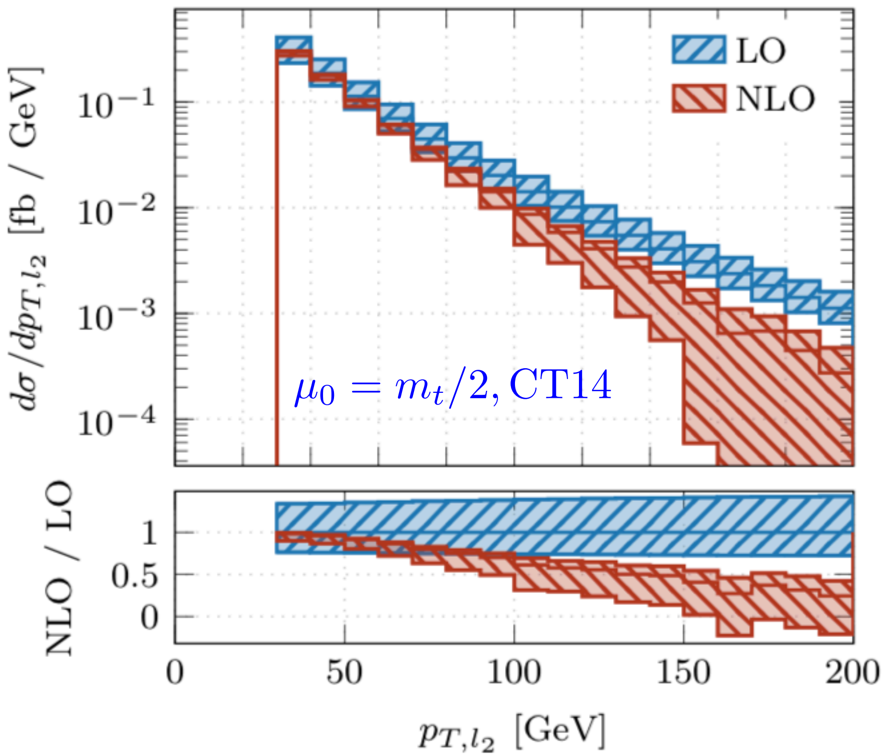
Dynamical scale very effective in stabilizing perturbative convergence.
Provides smaller theoretical error !
For all considered observables errors are below (±10% - ±30%) !

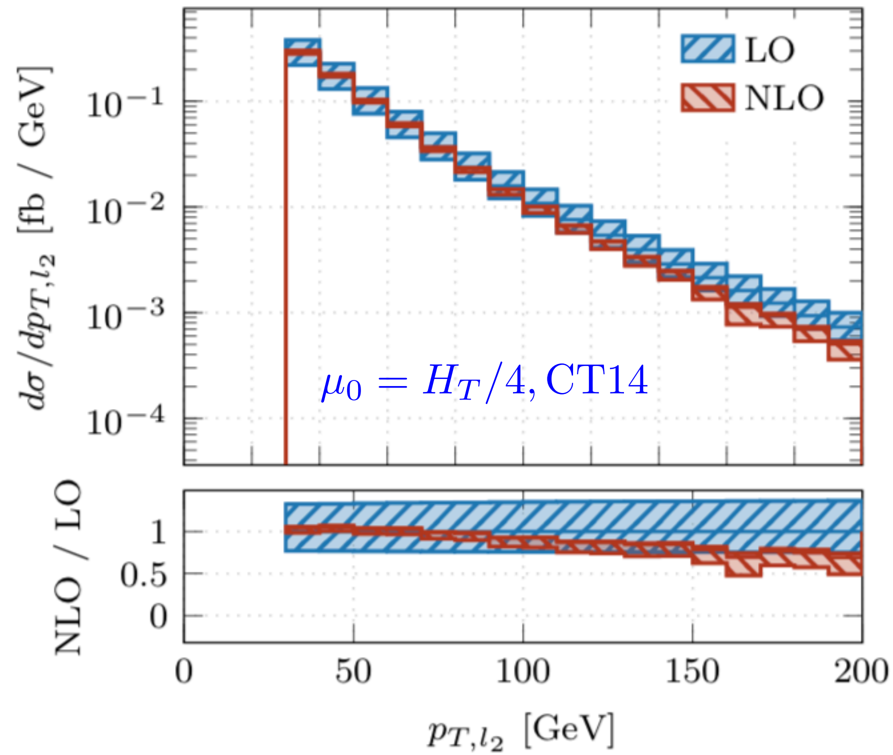
ttγ - Distributions

LHC @ 13 TeV

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$p_T(l_2)$





⌘ NLO Corrections up to **-76%**
⌘ Theoretical uncertainties up to **±186%**

⌘ NLO Corrections up to **-30%**
⌘ Error reduced down to **±31%**

Dynamical scale very effective in stabilizing perturbative convergence.
Provides smaller theoretical error !
For all considered observables errors are below (±10% - ±30%) !

Cross Section Ratio(s) – ttγ/ tt

- ⌘ Can we decrease theoretical error even further for $t\bar{t}\gamma$?
- ⌘ For fiducial cross section with dynamical scale we have **±6%**
- ⌘ For differential distributions we have **(±10% - ±30%)**

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

- ⌘ **Answer is yes ! → with ttγ/tt we have ±1% - ±3% for absolute cross section ratio**
- ⌘ **Differential cross section ratios ±1% -± 6%**

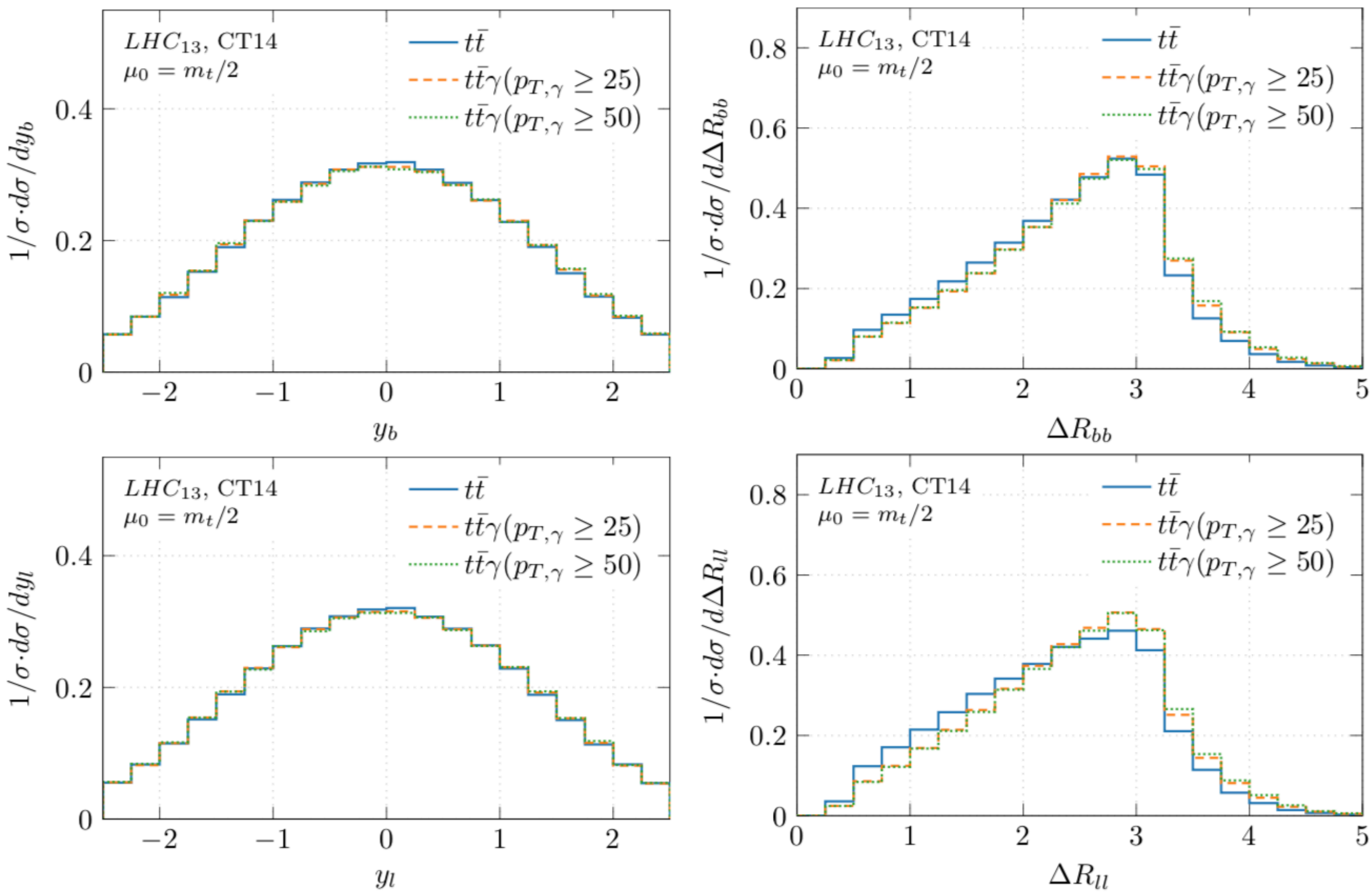
$$\mathcal{R}_X = \left(\frac{d\sigma^{\rm NLO}_{t\bar{t}\gamma}(\mu_1)}{dX}\right)\left(\frac{d\sigma^{\rm NLO}_{t\bar{t}}(\mu_2)}{dX}\right)^{-1}$$

- ⌘ 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 vs. tt



Bevilacqua, Hartanto, Kraus, Weber, Worek '18

Cross Section Ratio – ttγ/tt

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

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

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

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

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

⌘ Our best NLO QCD predictions with dynamical scale choice:

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

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

Differential Cross Section Ratio

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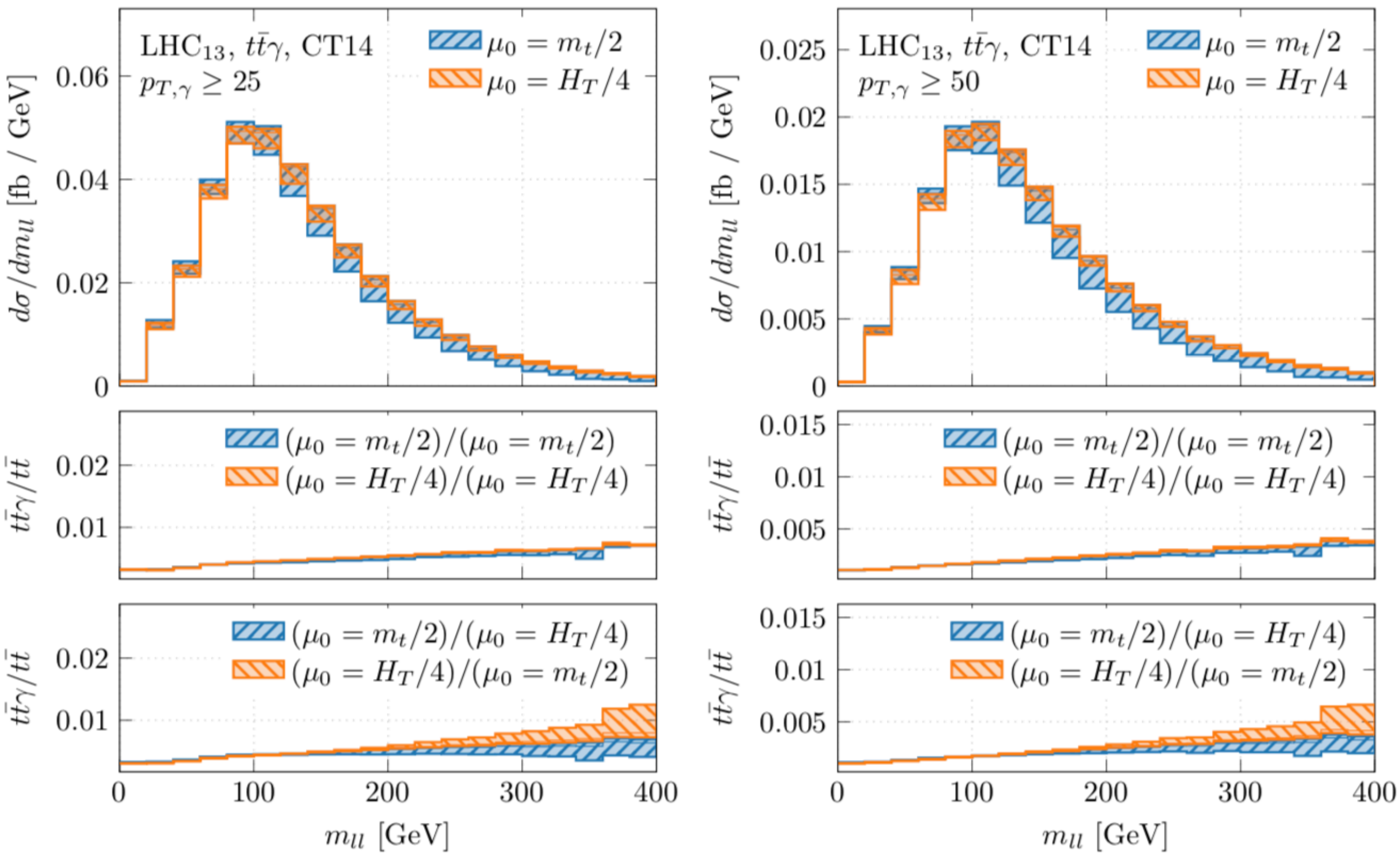

Theoretical uncertainties:

⌘ **±1% – ±4%** **dynamical scales**

⌘ **±20% – ±25%** **fixed scale choice**

⌘ Should be compared to uncertainties for absolute differential cross section

✧ **up to ±10%** for $\mathbf{\mu_0 = H_T/4}$ & **up to ±50%** for $\mathbf{\mu_0 = m_t/2}$

⌘ When different scales are applied to numerator and denominator **up to 40%-60%**

Summary & Outlook

- ⌘ The most precise NLO QCD theoretical predictions for $t\bar{t}\gamma$ in di-lepton channel

- ⌘ Complete description:
  - ✧ Photon emission from tops and top decay products
  - ✧ NLO corrections to production & decays
  - ✧ All non-resonant diagrams, interferences, and off-shell effects of top quarks included
  - ✧ Also non-resonant and off-shell effects due to finite W-boson width included
  - ✧ $t\bar{t}$ spin correlations

- ⌘ Relevant for BSM searches and studies of top quark properties

- ⌘ Dynamical scale choice important for fiducial cross sections !

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

- ⌘ **Next steps:**
  - ★ **Comparisons**: NWA vs. off-shell effects dedicated studies for $t\bar{t}\gamma$
  - ★ **Applications**: SM parameter extraction, disentangling and constraining anomalous couplings and more …