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Off-shell $t\bar{t}\gamma$ Production

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Loops & Legs in QFT, 29 April – 4 May 2018, St. Goar, Germany

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

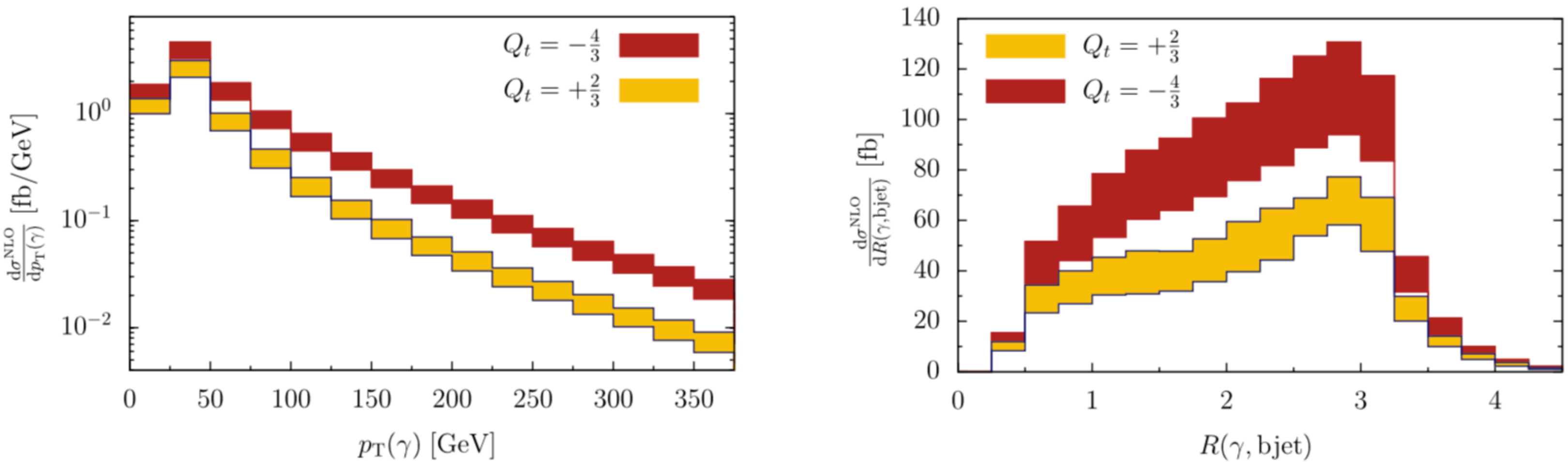
⌘ Besides $t\bar{t}, t\bar{t}j$ more exclusive final states can be accessed @ LHC

⌘ Their 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 structure of the ttγ vertex → SM + contributions from dimension-six effective operators

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

Aguilar-Saavedra '09

⌘ Constrains on anomalous couplings

⌘ Measure cross section ratio (also of various differential distributions)

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

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

$t\bar{t}\gamma$ @ LHC

- **First evidence: CDF @ TeVatron**

  CDF Collaboration '11

- **Observation: ATLAS @ LHC$_{7\,\mathrm{TeV}}$**

  ATLAS Collaboration '15

- **Measurements: ATLAS & CMS @ LHC$_{8\,\mathrm{TeV}}$**

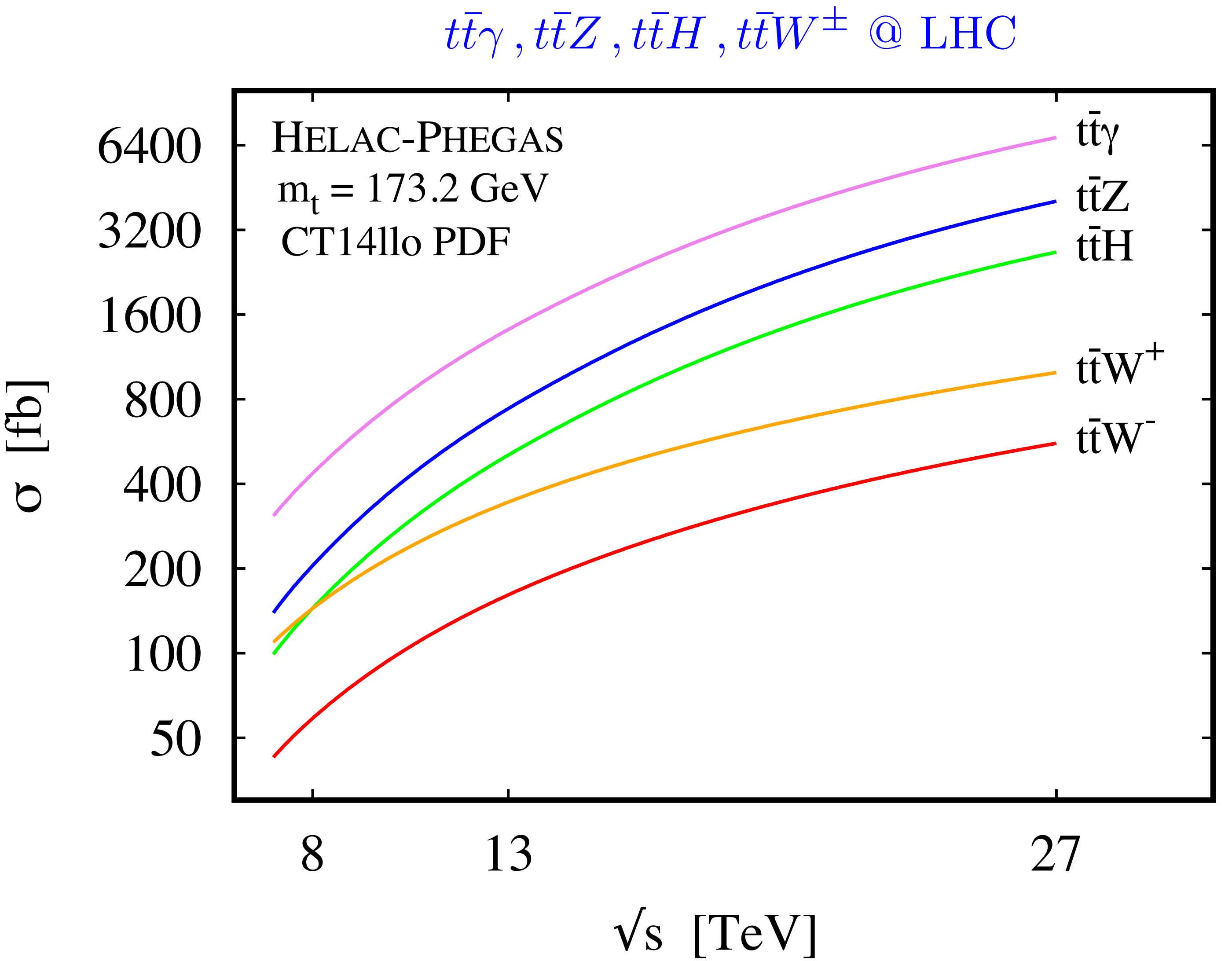
  ATLAS Collaboration '17
  CMS Collaboration '17

- For now due to small statistics only $\sigma_{t\bar{t}\gamma}$ → semi-leptonic channel

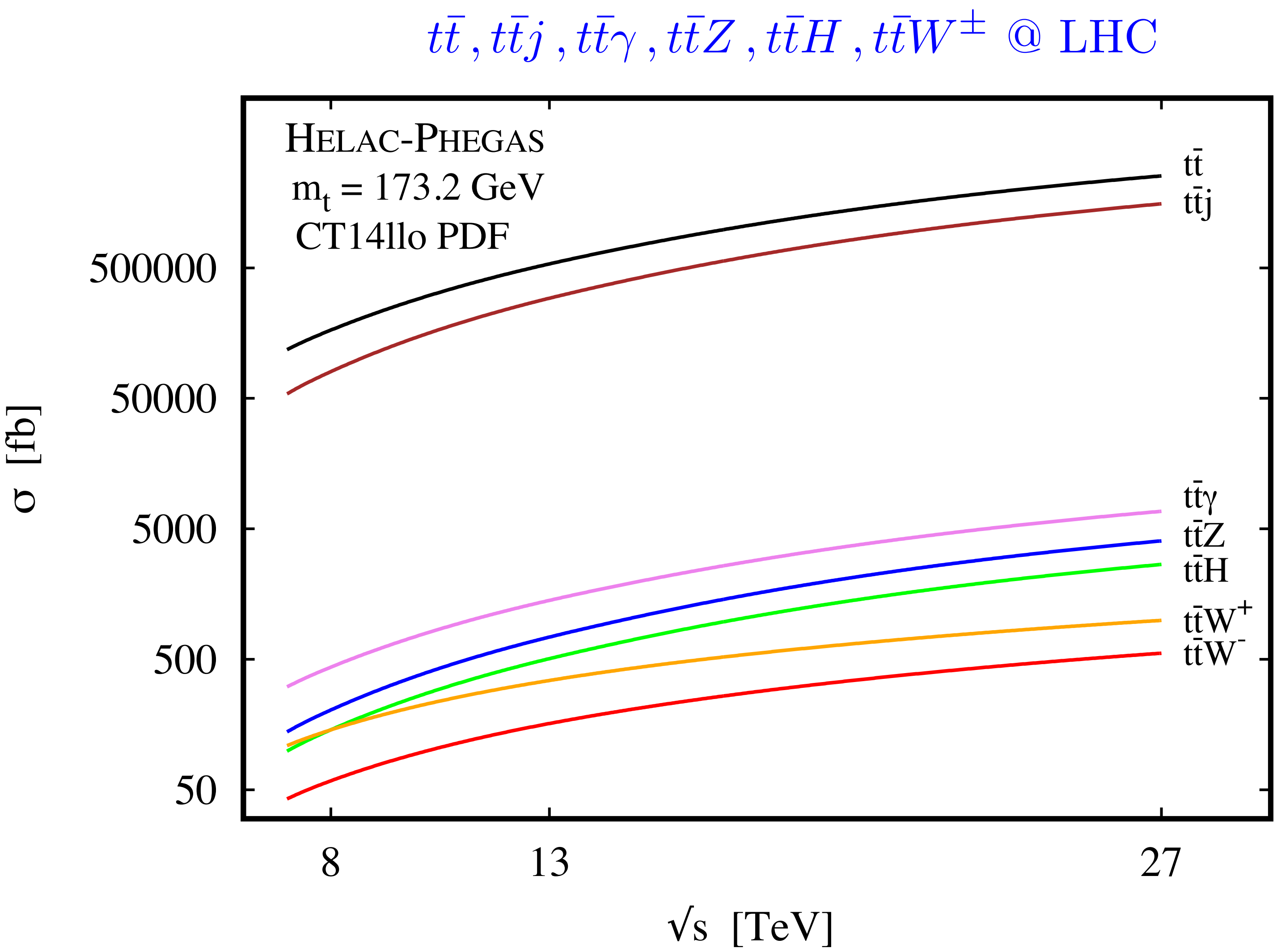
- LHC Run 2 @ 13 TeV, HL-LHC @ 14 TeV, HE-LHC @ 27 TeV, …

- More exclusive observables, various properties of top quarks, ratio(s) …

ttγ @ LHC


$t\bar{t}\gamma\,, t\bar{t}Z\,, t\bar{t}H\,, t\bar{t}W^{\pm}$ @ LHC
HELAC-PHEGAS
m_t = 173.2 GeV
CT14llo PDF
$t\bar{t}\gamma$
$t\bar{t}Z$
$t\bar{t}H$
$t\bar{t}W^+$
$t\bar{t}W^-$
6400
3200
1600
800
400
200
100
50
σ [fb]
8
13
27
√s [TeV]

ttγ @ 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
HELAC-PHEGAS
m_t = 173.2 GeV
CT14llo PDF
$t\bar{t}$
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$t\bar{t}Z$
$t\bar{t}H$
$t\bar{t}W^{+}$
$t\bar{t}W^{-}$
500000
50000
5000
500
50
σ [fb]
8
13
27
√s [TeV]

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

- ★ **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

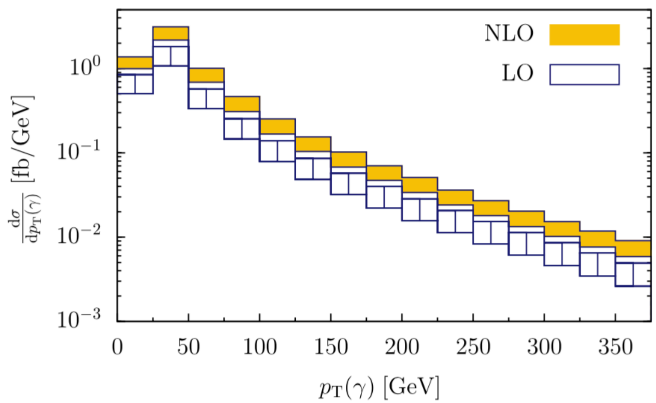
- ★ **NLO QCD for on-shell top quarks + PS** → Top decays in parton shower approximation, omitting photon emission in PS evolution & omitting $t\bar{t}$ spin correlations *Kardos, Trocsanyi '14*

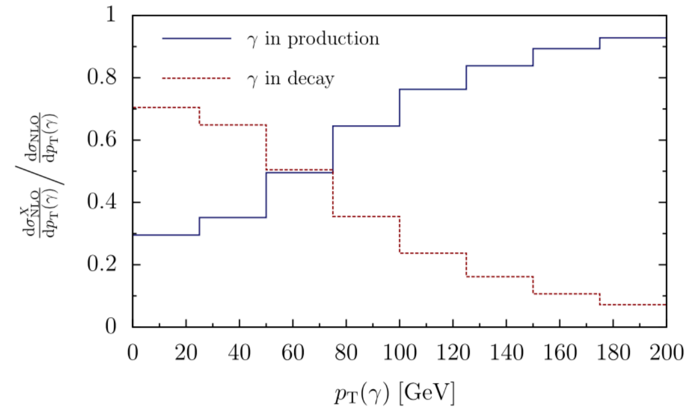
- ★ **NLO QCD in NWA** → NLO QCD corrections to top production & decays, photon emission of top quark decay product & $t\bar{t}$ spin correlations included *Melnikov, Schulze, Scharf '11*

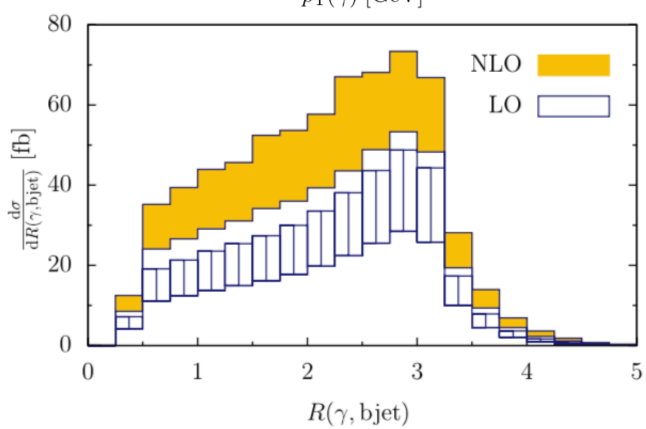
ttγ in NWA @ LHC

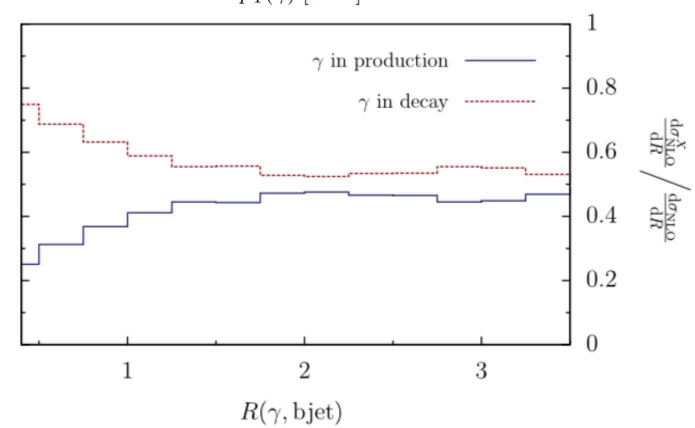
Melnikov, Schulze, Scharf '11

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









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

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

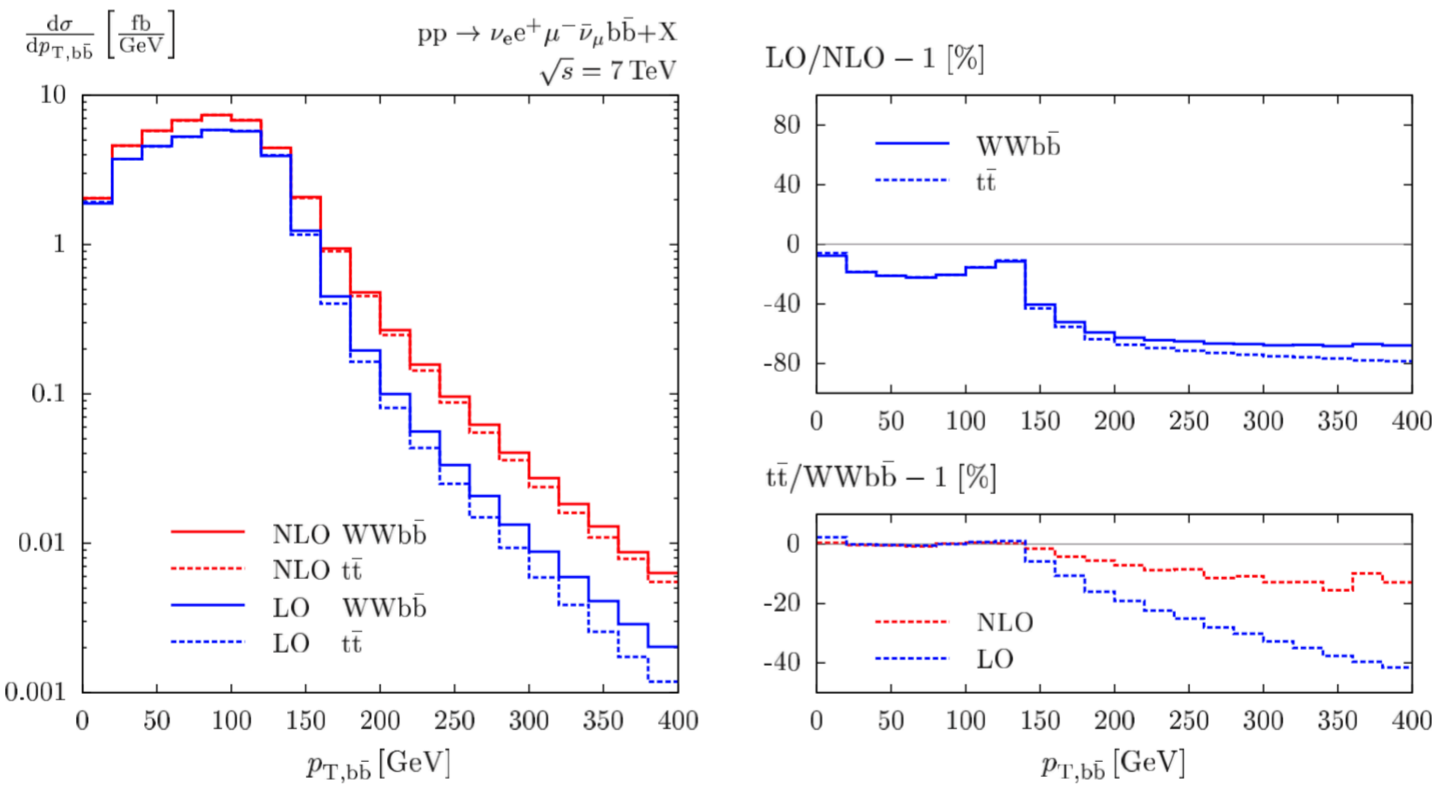
How Good Is NWA?

- ⌘ 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

- ⌘ 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**

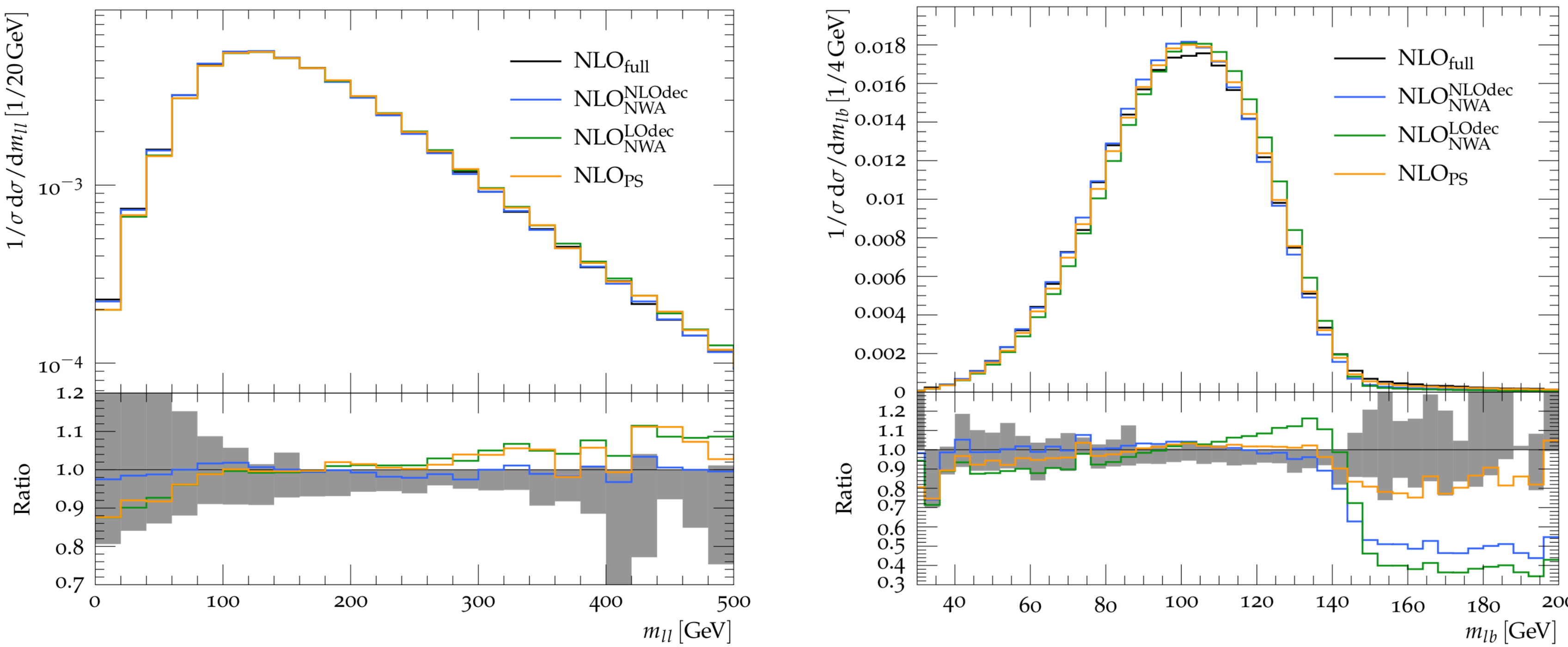


Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

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

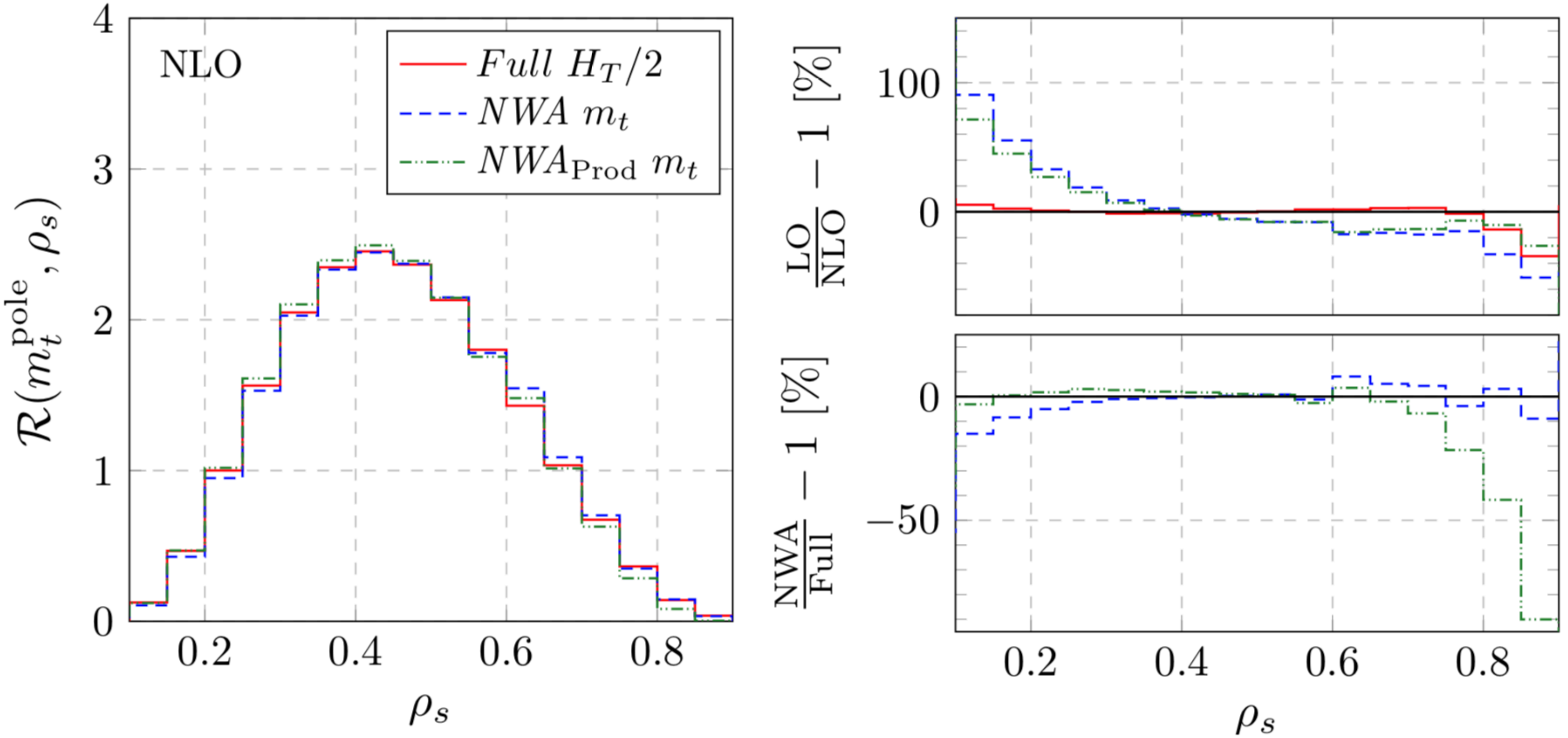


Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter '18

NWA vs. Off-Shell Effects

⌘ Observable used for a recent top quark mass determination

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



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

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	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [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
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	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
$NWA_{\rm Prod.}$, $\mu_0 = m_t$	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

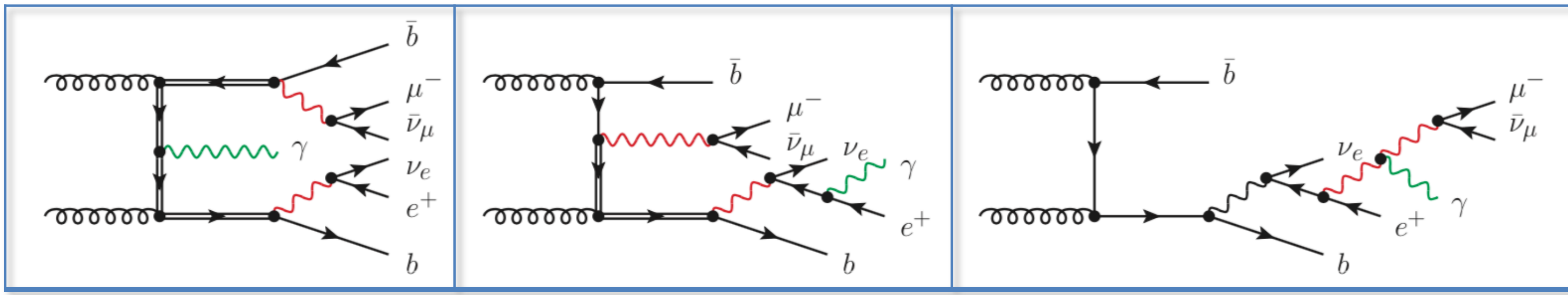
Theory, NLO QCD CT14 PDF	$m_t^{\rm out} \pm \delta m_t^{\rm out}$ [GeV]	Averaged χ^2/d.o.f.	Probability *p-value*	$m_t^{\rm in} - m_t^{\rm out}$ [GeV]
		31 bins		
Full, $\mu_0 = H_T/2$	173.09 ± 0.42	1.04	0.41 (0.8σ)	+0.11
Full, $\mu_0 = E_T/2$	172.45 ± 0.39	1.12	0.30 (1.0σ)	+0.75
Full, $\mu_0 = m_t$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

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

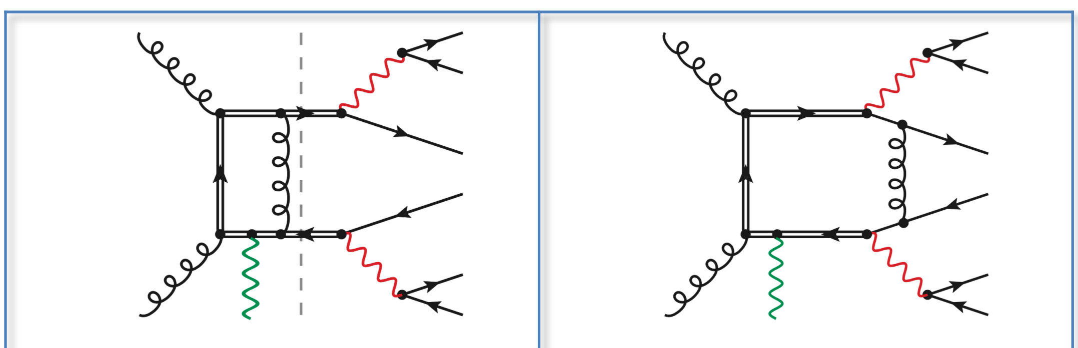


⌘ NLO → **4348 real emission & 36032 @ 1-loop for gg channel**

⌘ 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

Top Resonances

⌘ Putting simply $\Gamma_t \neq 0$ violates gauge invariance

⌘ Gauge-invariant treatment → **Complex Mass Scheme**

⌘ Γ_t → Incorporated into top mass via:

$$\mu_t^2 = m_t^2 - i\, m_t \Gamma_t$$

Denner, Dittmaier, Roth, Wackeroth '99
Denner, Dittmaier, Roth, Wieders '05

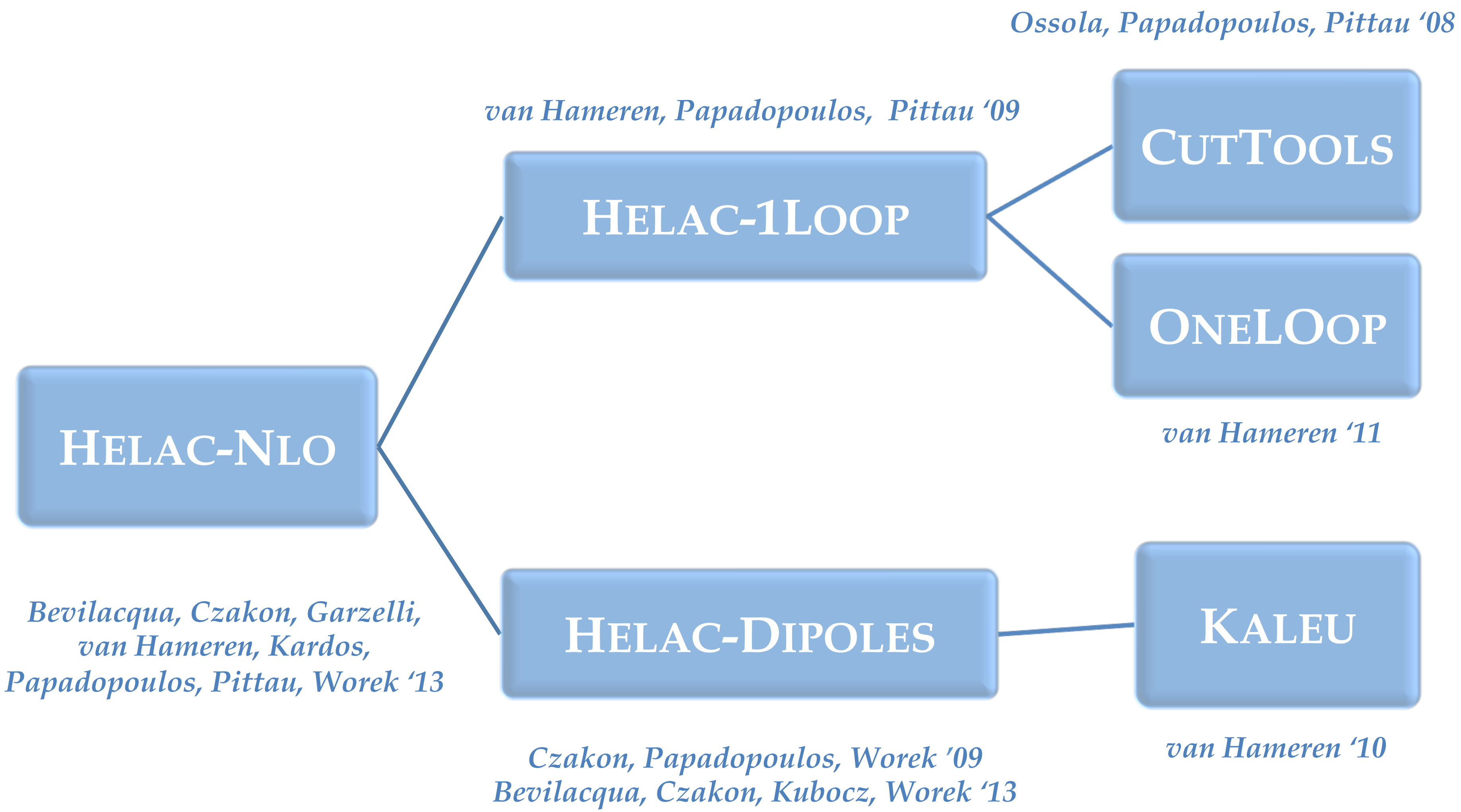
⌘ All matrix elements evaluated using complex masses

⌘ Another non trivial aspect → Evaluation of one-loop scalar integrals

⌘ Scalar integrals with complex masses → Supported e.g. by **ONELOOP**

van Hameren '11

HELAC-NLO


Ossola, Papadopoulos, Pittau '08
van Hameren, Papadopoulos, Pittau '09
CUTTOOLS
HELAC-1LOOP
ONELOOP
HELAC-NLO
van Hameren '11
Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek '13
HELAC-DIPOLES
KALEU
van Hameren '10
Czakon, Papadopoulos, Worek '09
Bevilacqua, Czakon, Kubocz, Worek '13

Setup

⌘ 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}

⌘ Inclusive cuts & $p_T(\gamma) > 25 \text{ GeV}$

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

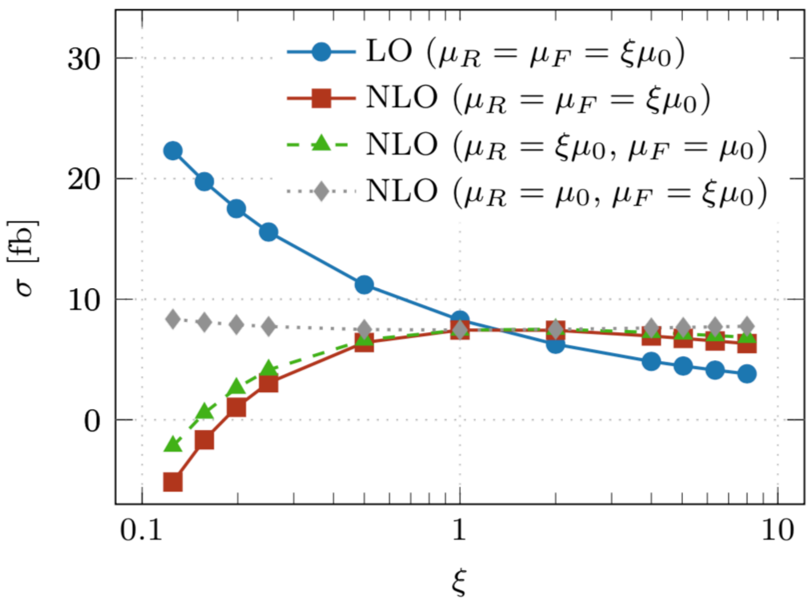
★ Reject event if condition not fulfilled for all $R \leq R_{\gamma j}$ with $R_{\gamma j} = 0.4$

Frixione '98

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

⌘ Kinematics-independent scales: $\mu_R = \mu_F = \mu_0 = m_t/2$

Scale Dependence



Bevilacqua, Hartanto, Kraus, Weber, Worek '18

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

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

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

- ⌘ @ LO: **gg channel** dominates **79%, qq channel** follows with **21%**
- ⌘ Photons are predominantly radiated off tops & top decay products
- ⌘ Negative & moderate **NLO corrections of 10%**
- ⌘ Theoretical uncertainties → **35% @ LO & 14% @ NLO** ↓ **2.5**

Cross Section Ratio

⌘ Assuming the same setup our ratio results @ LO & @ NLO

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

$$\mathcal{R} = \frac{\sigma^{\rm LO}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}}{\sigma^{\rm LO}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}}} = (4.94 \pm 0.08) \times 10^{-3}$$

$$\mathcal{R} = \frac{\sigma^{\rm NLO}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma}}{\sigma^{\rm NLO}_{pp\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}}} = (4.56 \pm 0.28) \times 10^{-3}$$

⌘ Errors from scale dependence assuming correlation of processes

⌘ Receives (negative) **NLO corrections → 8%. Scale uncertainties of $\mathcal{R}$ → 6%**

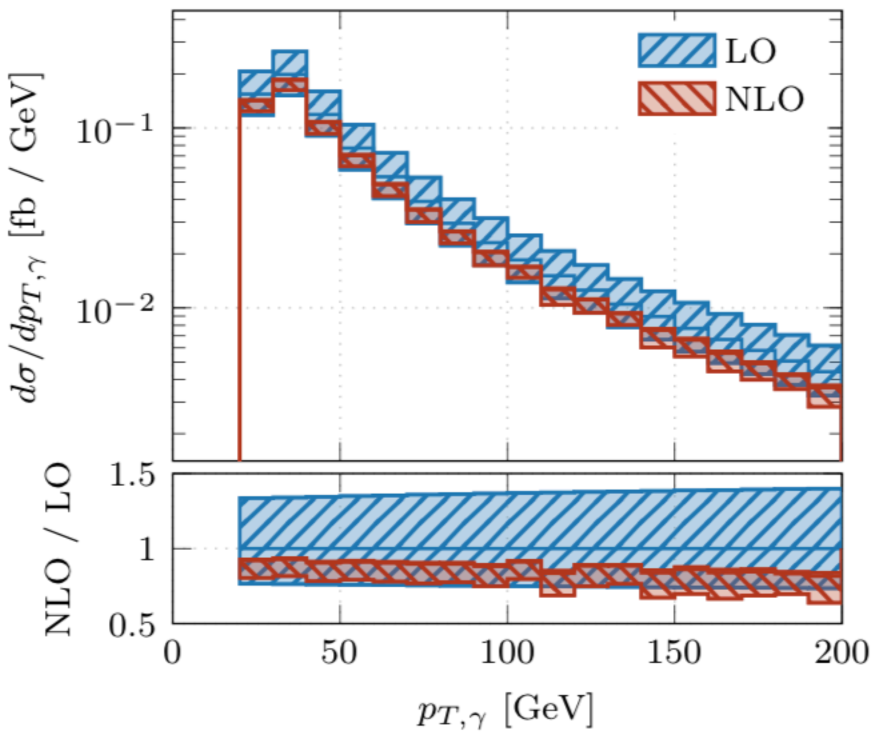
⌘ More stable against corrections, reduced error → Enhanced predictive power

⌘ Next step: $\mathcal{R} = \frac{d\sigma_{t\bar{t}\gamma}/dX}{d\sigma_{t\bar{t}}/dX}$ → Interesting observables to **probe BSM @ LHC**

Distributions

⌘ Crucial to study corrections to distributions

⌘ Two observables relevant for BSM searches: $p_T(\gamma)$ & $\Delta R(b_2, \gamma)$



⌘ $p_T(\gamma)$

⌘ Distribution, its scale dependence and differential K-factor

⌘ **Differential K-factor** varying only **from –8% to –18%** (in the plotted range)

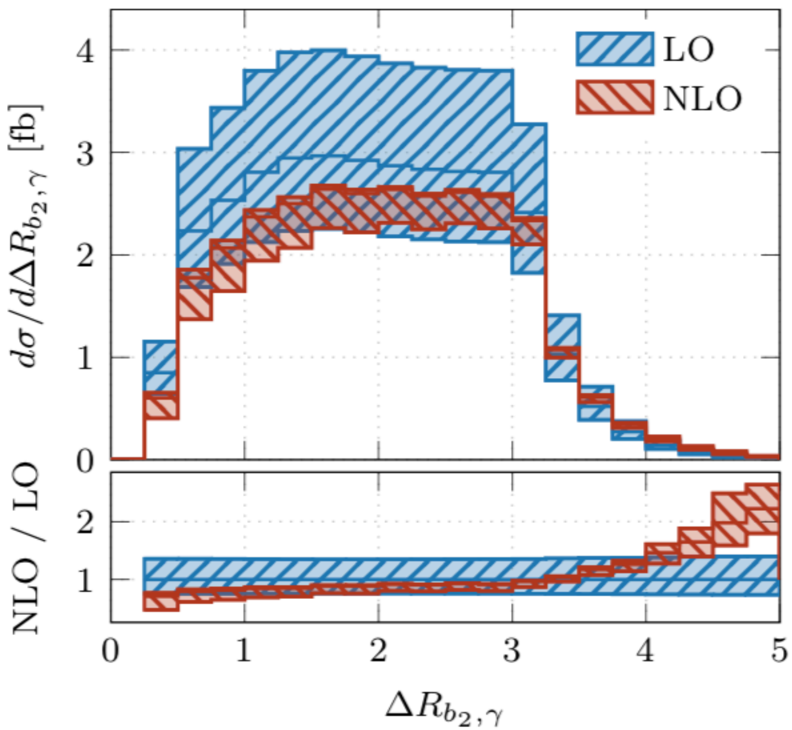
⌘ Quite stable against higher order corrections → Better suited for BSM searches

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

Distributions

⌘ Crucial to study corrections to distributions

⌘ Two observables relevant for BSM searches: $p_T(\gamma)$ & $\Delta R(b_2, \gamma)$



⌘ $\Delta R(b_2, \gamma)$

⌘ NLO corrections have strongly altered shape

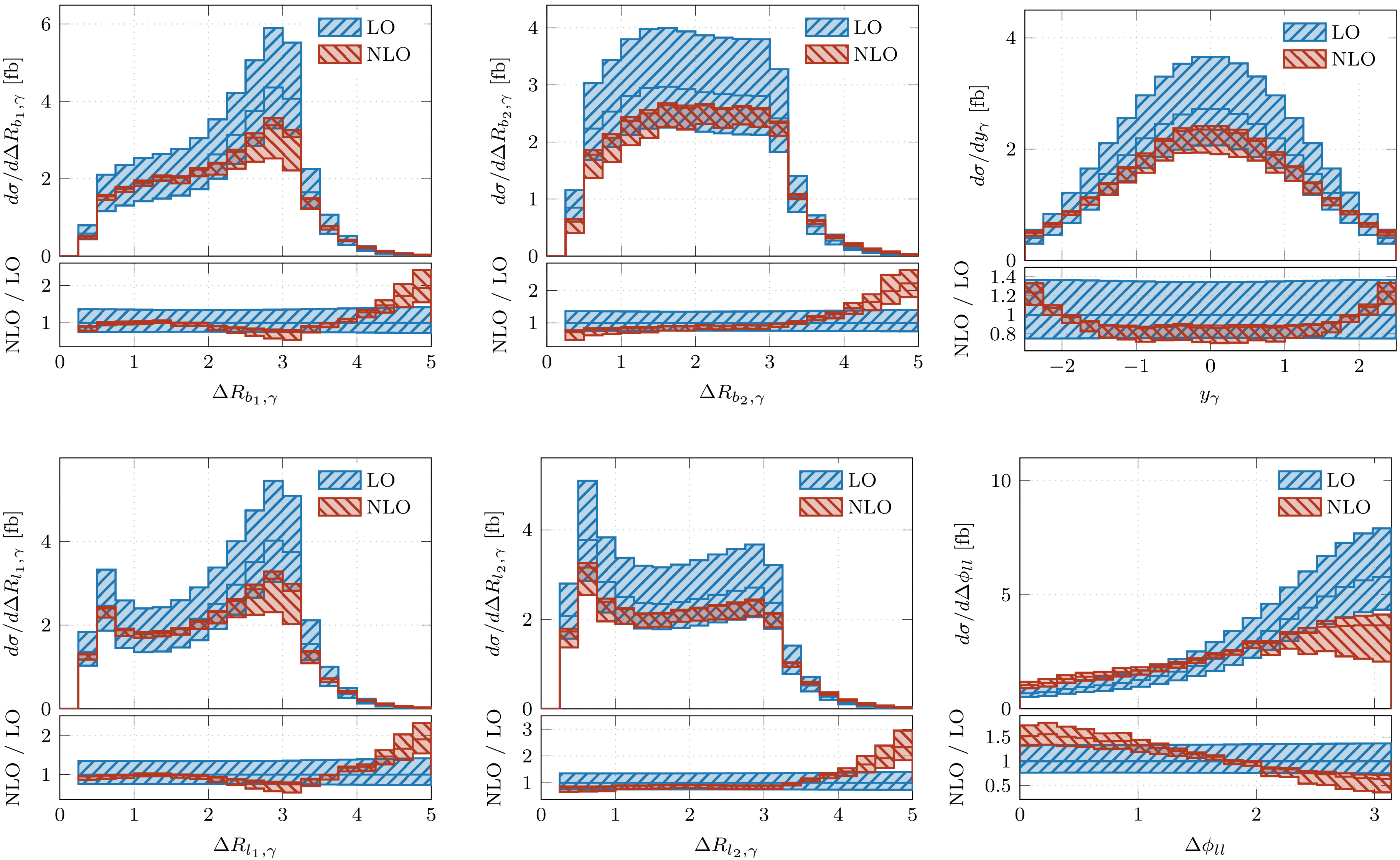
⌘ **Corrections from −29% to +122%**

⌘ **Distortion up to 150%**

⌘ Similar effects for other observables

Bevilacqua, Hartanto, Kraus, Weber, Worek '18

Distributions



Bevilacqua, Hartanto, Kraus, Weber, Worek '18

Summary & Outlook

⌘ NLO QCD to ttγ production @ LHC with complete off-shell effects completed

⌘ Complete description → Photon emission from tops & top decay products, NLO corrections to production & decays & tt spin correlations & off-shell effects

⌘ Relevant for (anomalous) couplings extraction

⌘ Relevant for BSM searches

★ $\mathcal{R} = \frac{\sigma_{t\bar{t}j}}{\sigma_{t\bar{t}}}$ & $\mathcal{R} = \frac{d\sigma_{t\bar{t}\gamma}/dX}{d\sigma_{t\bar{t}}/dX}$ & $p_T(\gamma)$ & $\Delta R(b_2, \gamma)$ & …

⌘ **Next steps:**

- ★ **Studies:** Various kinematics-dependent scales & PDF uncertainties
- ★ **Comparisons**: NWA vrs. off-shell effects
- ★ **Applications**: SM parameter extraction, disentangling and constraining anomalous couplings