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TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Precision predictions for pp → ttγ

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Plan

- Motivation for $t\bar{t}\gamma$
- Status of theoretical predictions for $t\bar{t}\gamma$
- NWA vs. off-shell effects ⇨ $t\bar{t}$
- Results for $t\bar{t}\gamma$ ⇨ di-lepton channel
- Predictions for $t\bar{t}\gamma/t\bar{t}$ ⇨ di-lepton channel
- Summary: $t\bar{t}$ & $t\bar{t}j$ & $t\bar{t}\gamma$ & $t\bar{t}Z$ ⇨ di-lepton ✓
- Outlook: $t\bar{t}$ & $t\bar{t}j$ & $t\bar{t}V$, $V=\gamma, Z, H, W^+$ & W^- ⇨ di-lepton & lepton-jet ✗

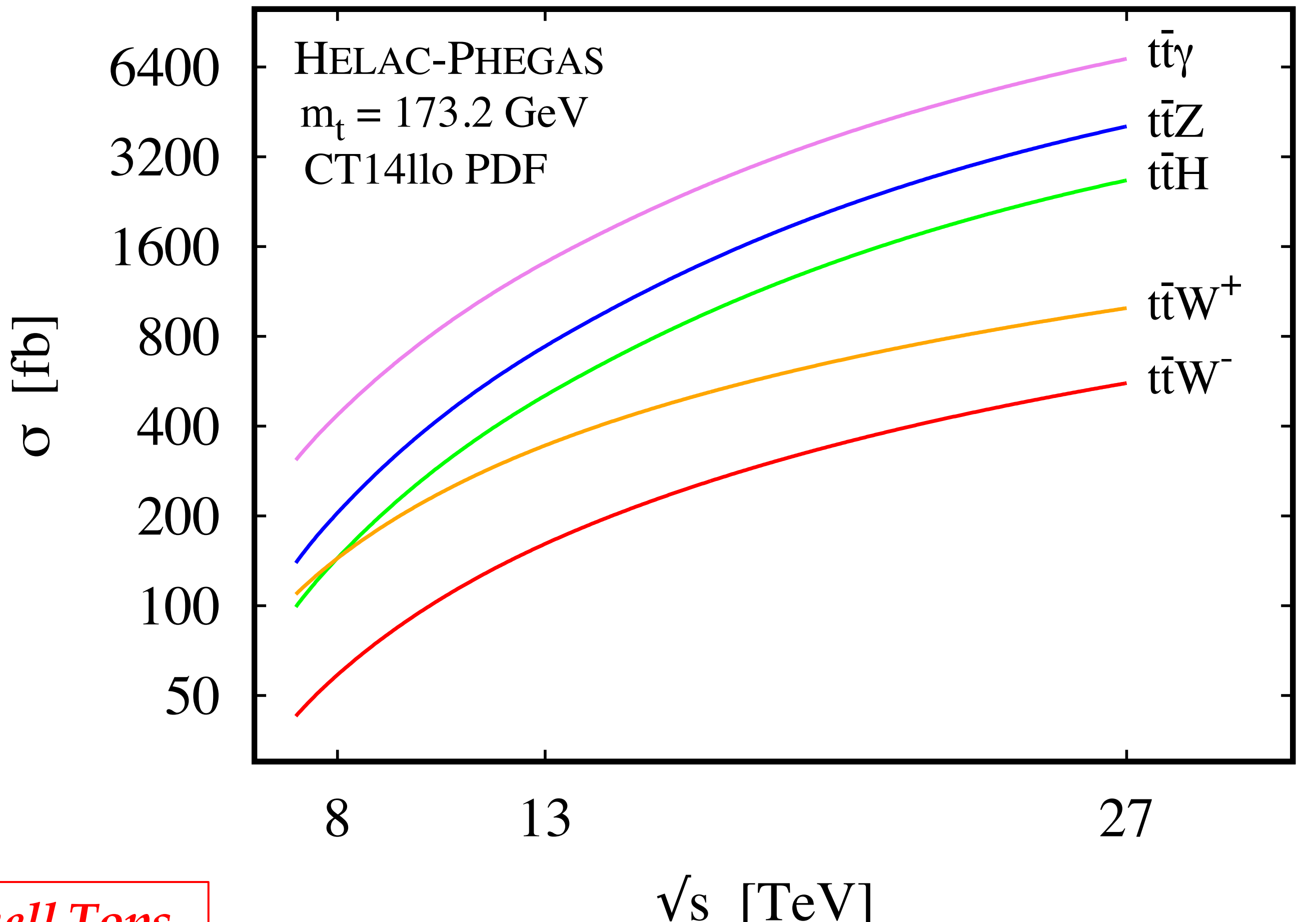
Collaborators:

- *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⁺ & ttW⁻ @ LHC

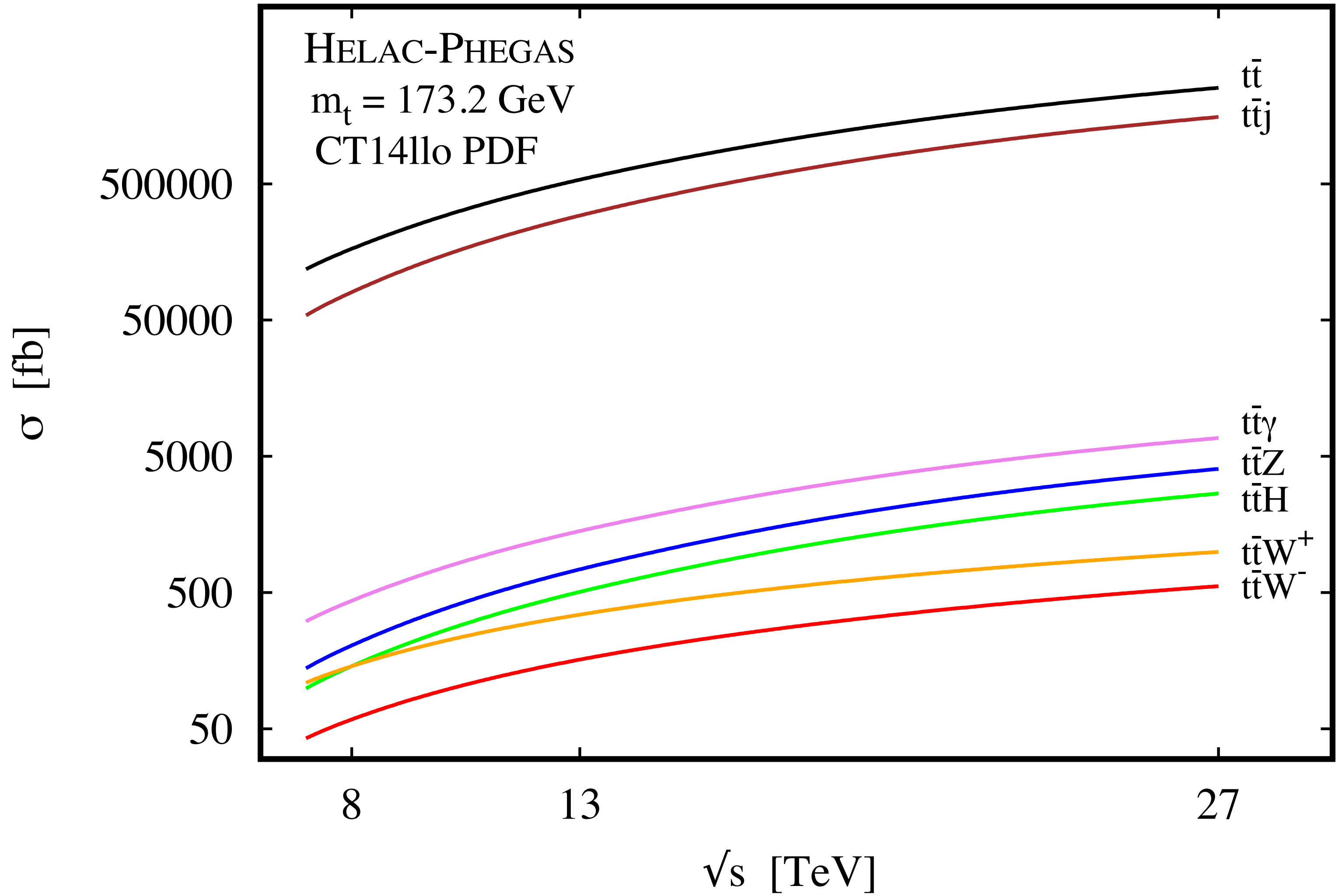


On-shell Tops

tt & tt+X @ LHC

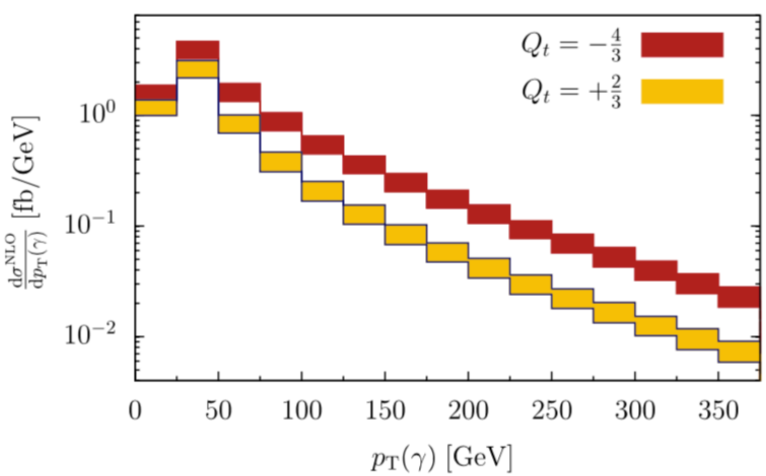
On-shell Tops

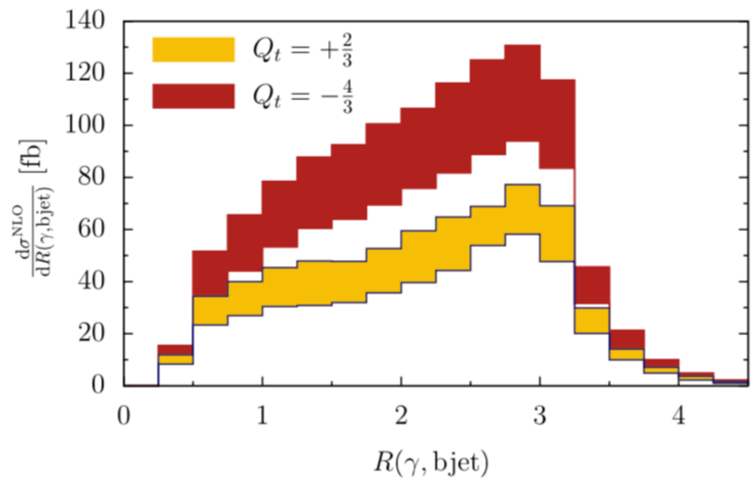
tt, ttj, ttγ, ttZ, ttH, ttW⁺ & ttW⁻ @ LHC



Motivations For ttγ

- ✽ ***ttV*** cross sections much smaller than ***tt(j)***
- ✽ Information on couplings ⇨ ***γ & Z & H & W⁺ & 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 $\boldsymbol{Q_t \neq +⅔}$





Tops in NWA

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

Melnikov, Schulze, Scharf '11

Motivations For $t\bar{t}\gamma$

- ***Probe the strength and the structure of $t\bar{t}\gamma$ 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 '19

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

- Top quark and leptonic charge asymmetry
- Differential asymmetries, …

Aguilar-Saavedra, Alvarez, Juste, Rubbo '14
Maltoni, Pagani, Tsinikos '16
Bergner, Schulze '19

Theoretical Predictions For ttγ

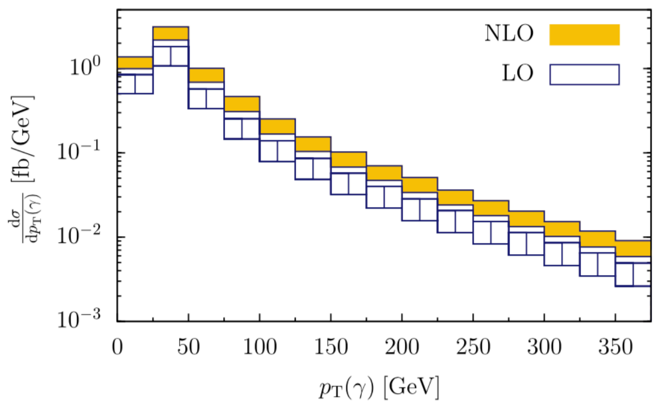
- NLO corrections for on-shell top quarks ⇨ General idea about size of NLO corrections. Can not provide reliable description of top quark decay products and radiation pattern
  - ***NLO QCD*** — *Duan, Ma, Zhang, Han, Guo, Wang '09 '11*; *Maltoni, Pagani, Tsinikos '16*
  - ***NLO electroweak*** — *Duan, 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*
  - ***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*

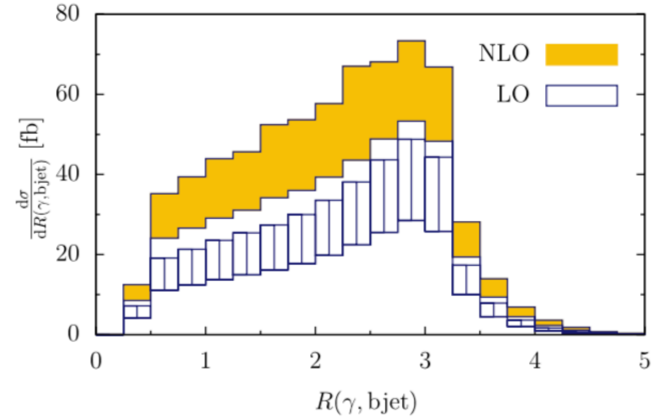
ttγ in NWA @ LHC

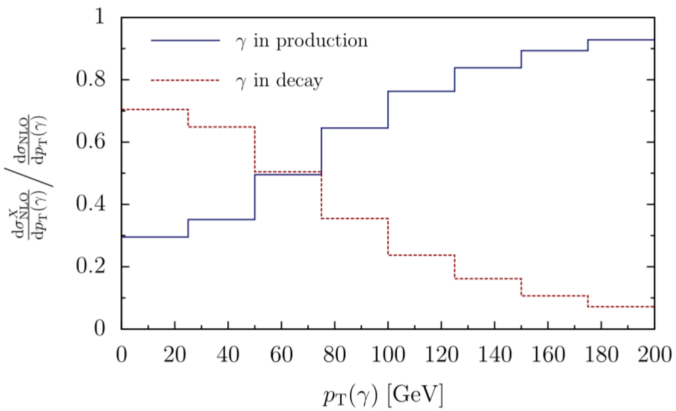
Tops in NWA

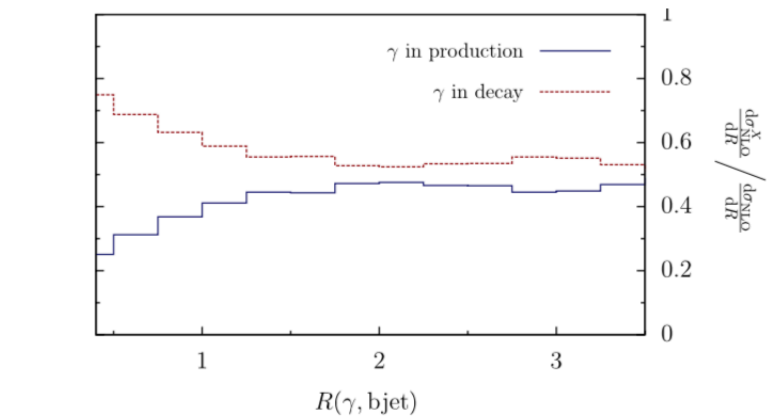
Melnikov, Schulze, Scharf '11

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

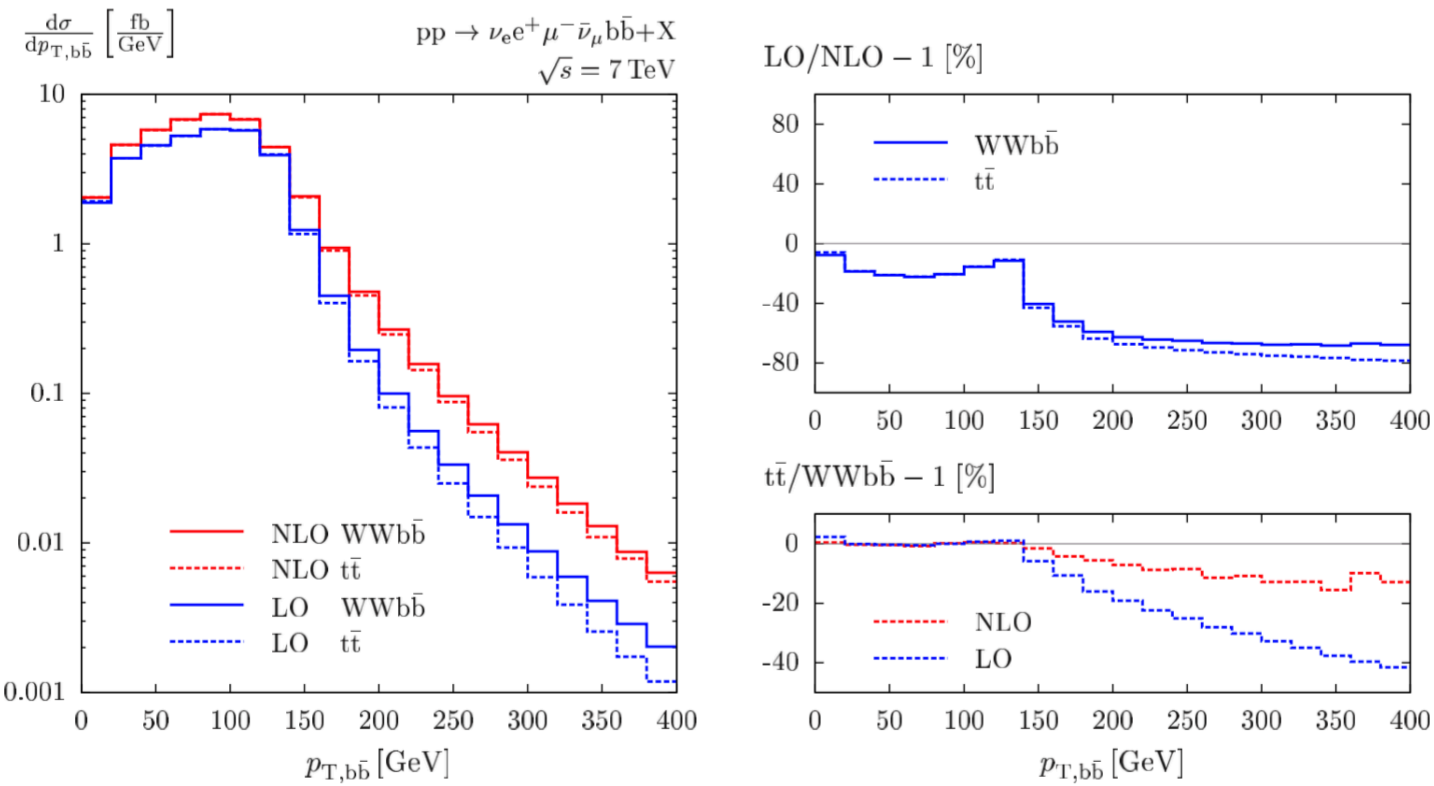
- ✽ In NWA tops are restricted to on-shell states
- ✽ Approximation is controlled by the ratio ⇨ $\Gamma_t/m_t \approx 0.8\%$
- ✽ Should be accurate for sufficiently inclusive observables
- ✽ ***Off-shell effects for integrated σ_{tt} @ few % level @ NLO in QCD***

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*	✓
ttZ (di-lepton)	*Bevilacqua, Hartanto, Kraus, Weber, Worek '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***



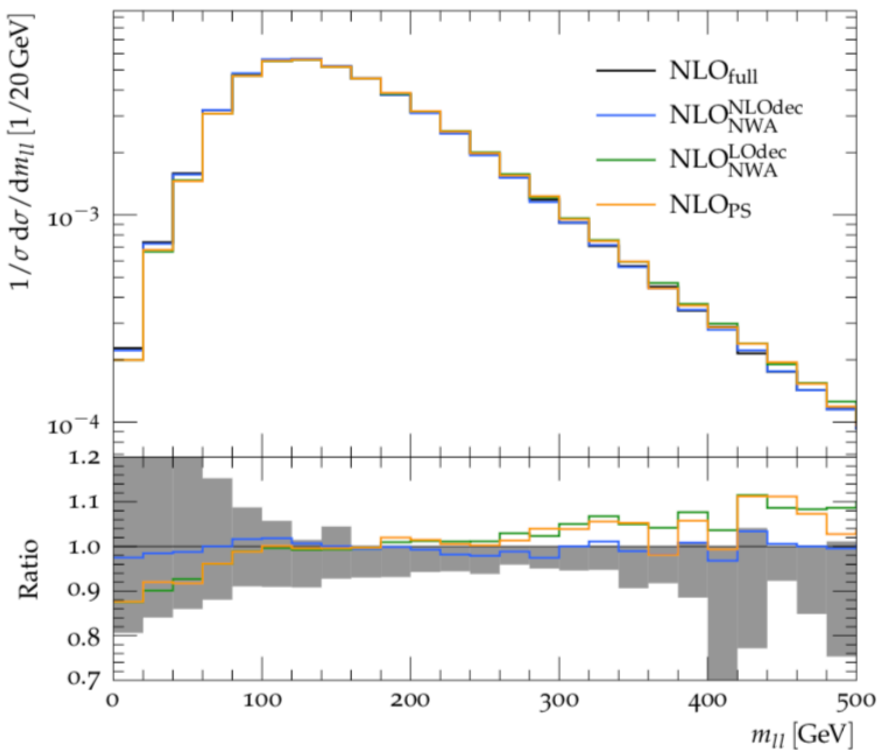
Denner, Dittmaier, Kallweit, Pozzorini, Schulze '12

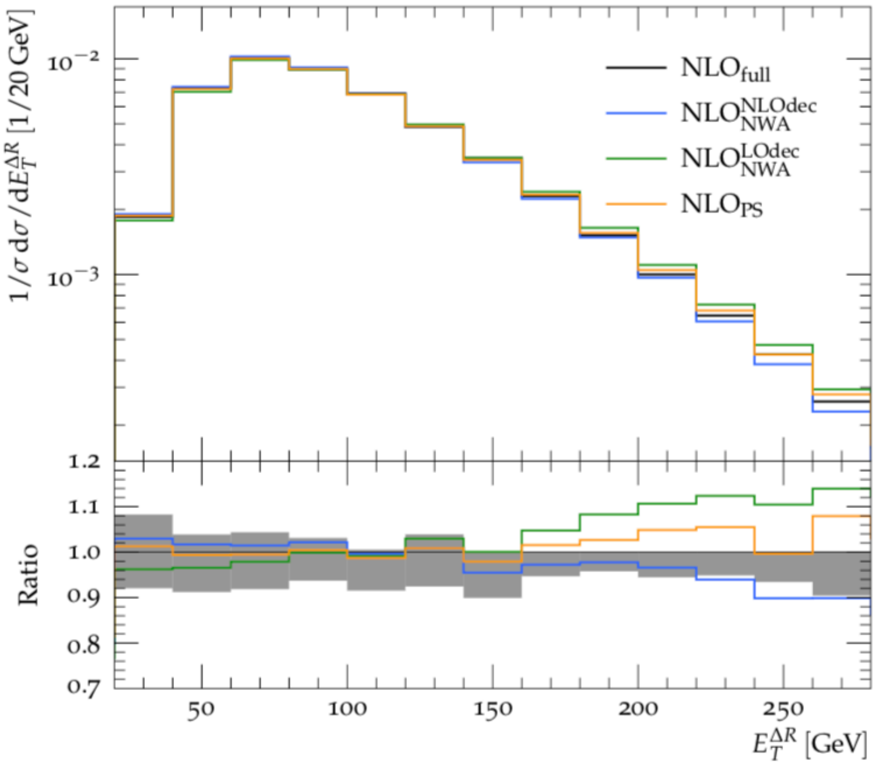
NWA & Off-Shell Effects

- Observables used for a recent top quark mass determination

Off-shell, NWA, PS

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



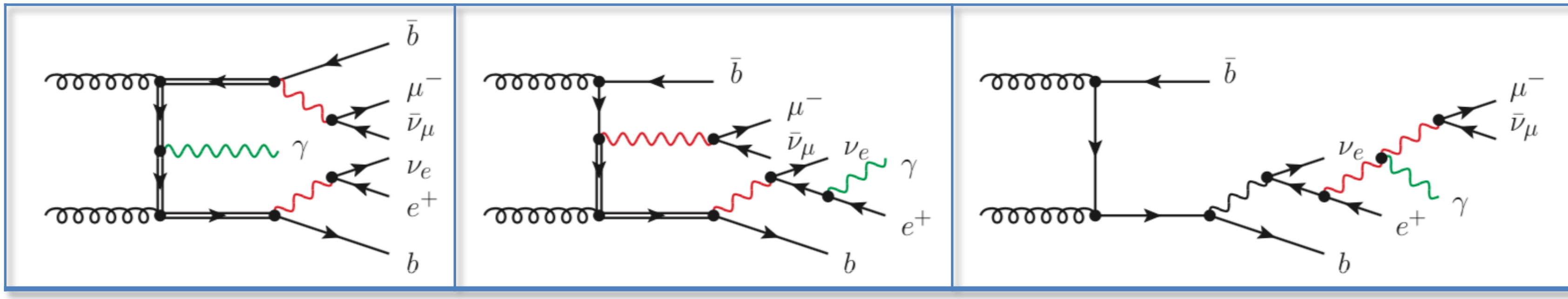


Heinrich, Maier, Nisius, Schlenk, Schulze, Scyboz, Winter '18

NWA & Off-Shell Effects

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

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

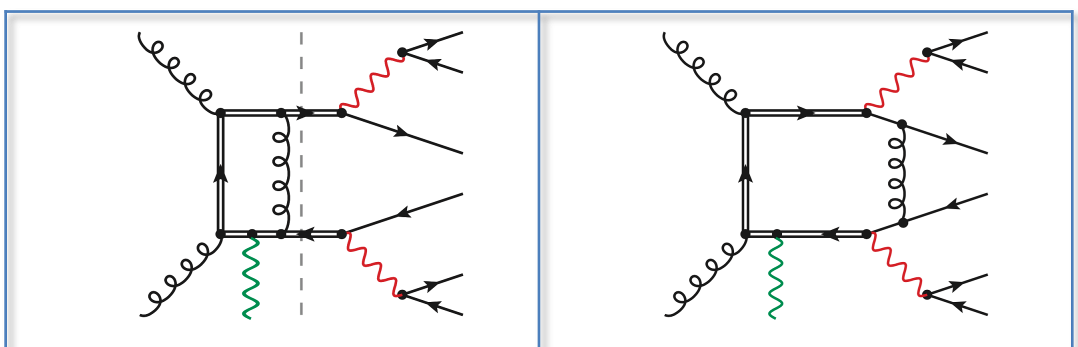


- NLO ⇨ ***4348 real emission & 36032 @ 1-loop for gg channel***

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

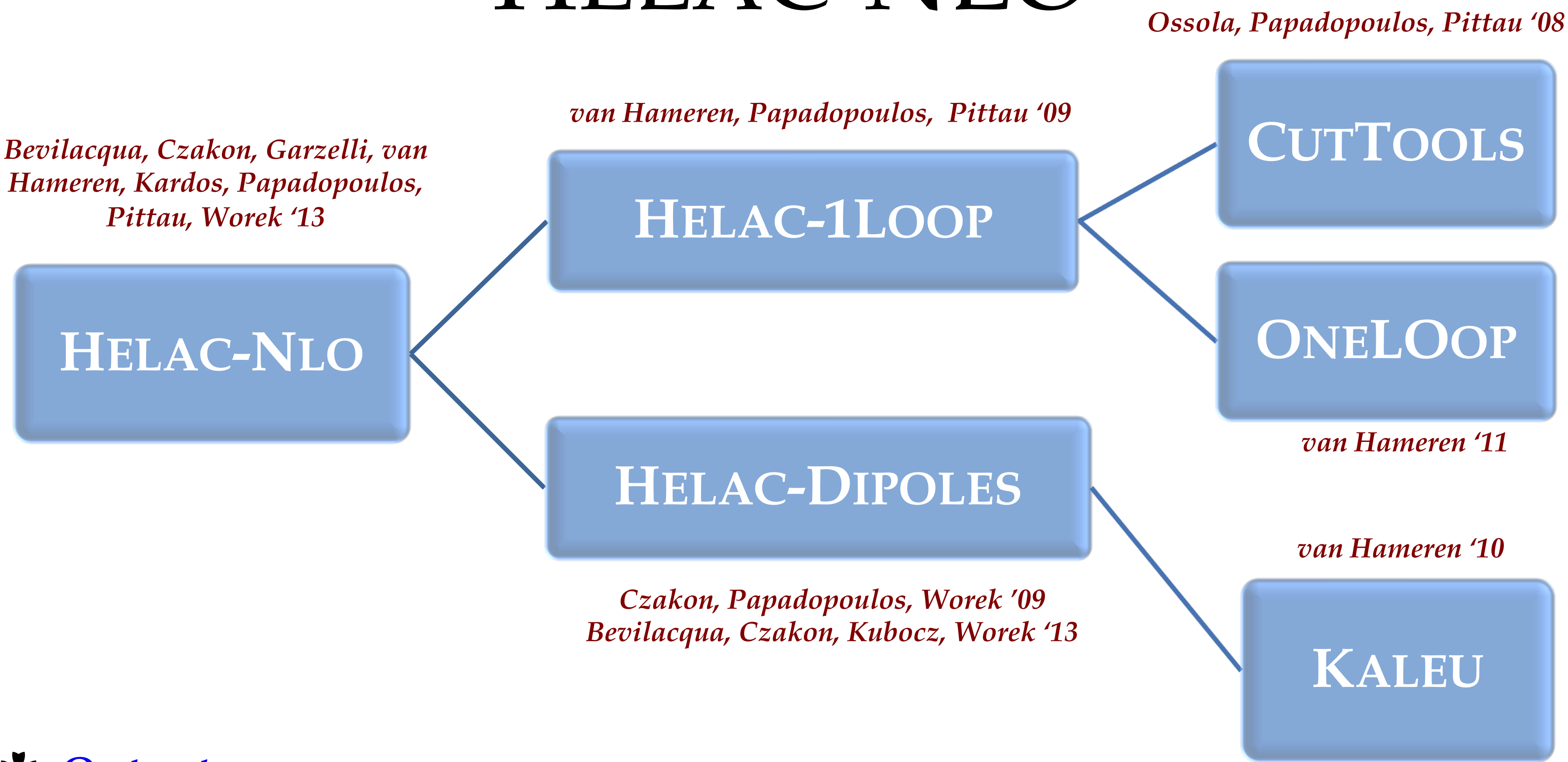
$t\bar{t}\gamma + X \;@\; \mathcal{O}(\alpha_s^3\alpha^5)$

ttγ in NWA up to pentagons



ttγ full up to heptagons

HELAC-NLO



- ***Output:***
  - Theoretical predictions 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 and/or factorization scales & PDFs can be changed

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

Setup for ttγ

✽ Different lepton generations

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

✽ 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: $p_T(\gamma) > 25 \ \mathrm{GeV}, |y_\gamma| < 2.5$

✽ 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%***

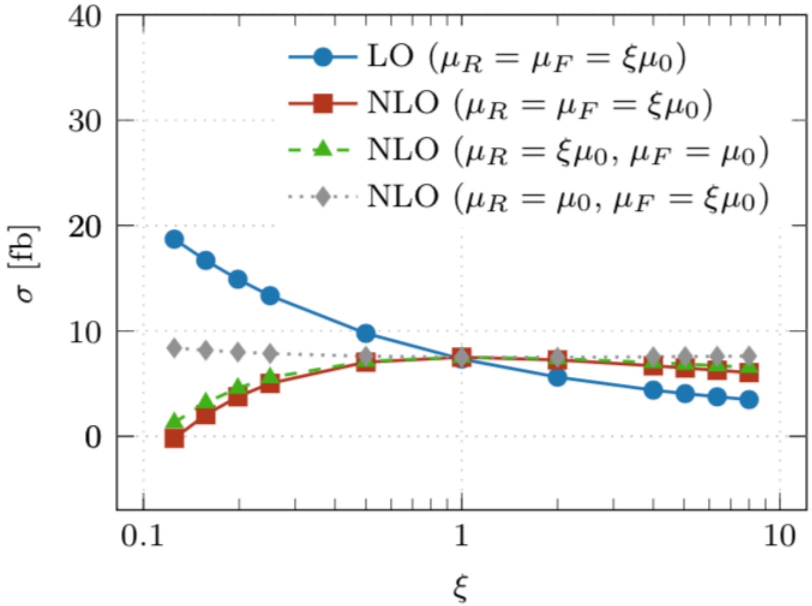
✽ Electroweak coupling in the G_μ scheme ⇨ account for some electroweak effects

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

$t\bar{t}\gamma$ with $\mu_0 = H_T/4$

Off-shell Tops

Bevilacqua, Hartanto, Kraus, Weber, Worek '18



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

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

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

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

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

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

- Positive & small ***NLO corrections of 2.5%***
- Theoretical uncertainties
  → ***33% @ LO & 6% @ NLO***

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

$t\bar{t}\gamma$ with $\mu_0=m_t/2$

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

PDF	$p_{T,b}$	σ^{LO} [fb]	δ_{scale}	σ^{NLO} [fb]	δ_{scale}	δ_{PDF}	$\mathcal{K}=\frac{NLO}{LO}$
CT	25	11.78	+4.10 (35%) −2.84 (24%)	11.16	+0.11 (1%) −1.18 (11%)	+0.32 (3%) −0.35 (3%)	0.95
	30	10.63	+3.71 (35%) −2.56 (24%)	9.89	+0.09 (1%) −1.15 (12%)	+0.29 (3%) −0.31 (3%)	0.93
	35	9.44	+3.31 (35%) −2.28 (24%)	8.65	+0.07 (1%) −1.09 (13%)	+0.25 (3%) −0.27 (3%)	0.92
	40	8.27	+2.92 (35%) −2.01 (24%)	7.45	+0.06 (1%) −1.01 (14%)	+0.22 (3%) −0.24 (3%)	0.90
MMHT	25	12.81	+4.90 (38%) −3.28 (26%)	11.26	+0.09 (1%) −1.24 (11%)	+0.24 (2%) −0.21 (2%)	0.88
	30	11.55	+4.43 (38%) −2.96 (26%)	9.97	+0.07 (1%) −1.21 (12%)	+0.21 (2%) −0.19 (2%)	0.86
	35	10.24	+3.95 (39%) −2.64 (26%)	8.71	+0.07 (1%) −1.14 (13%)	+0.18 (2%) −0.17 (2%)	0.85
	40	8.96	+3.47 (39%) −2.31 (26%)	7.50	+0.07 (1%) −1.06 (14%)	+0.16 (2%) −0.14 (2%)	0.84
NNPDF	25	11.86	+4.40 (37%) −2.97 (25%)	11.58	+0.10 (1%) −1.26 (11%)	+0.16 (1%) −0.16 (1%)	0.98
	30	10.68	+3.97 (37%) −2.68 (25%)	10.27	+0.08 (1%) −1.23 (12%)	+0.14 (1%) −0.14 (1%)	0.96
	35	9.47	+3.53 (37%) −2.38 (25%)	8.97	+0.07 (1%) −1.16 (13%)	+0.12 (1%) −0.12 (1%)	0.95
	40	8.27	+3.10 (38%) −2.09 (25%)	7.73	+0.07 (1%) −1.08 (14%)	+0.11 (1%) −0.11 (1%)	0.93

Off-shell Tops

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 $\mu_0 = H_T/4$

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

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

Off-shell Tops

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*

ttγ with μ_0=m_t/2 & μ_0=H_T/4

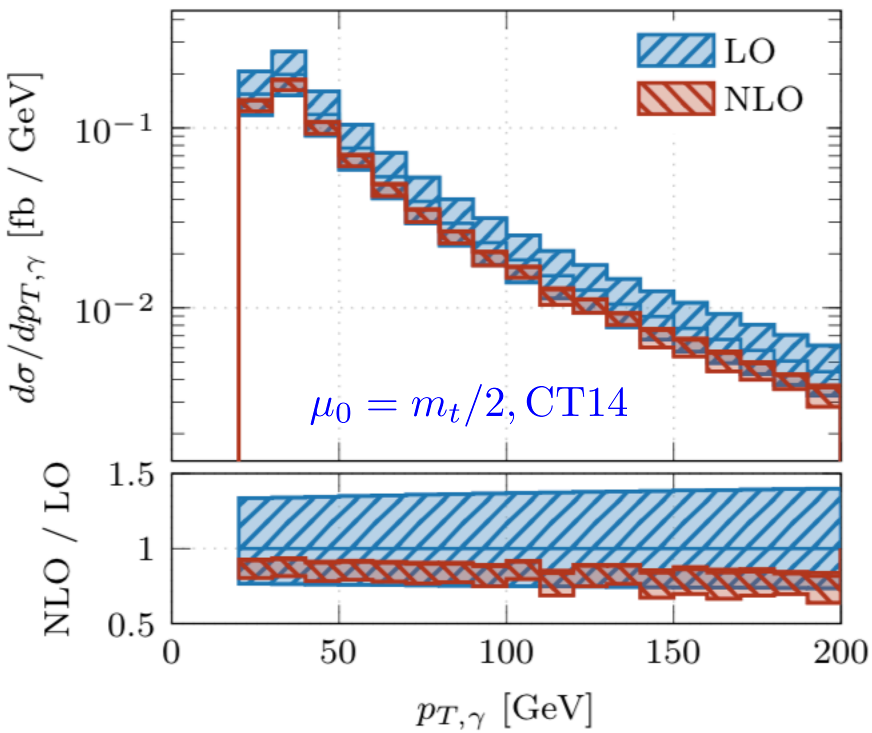
LHC$_{13\ TeV}$

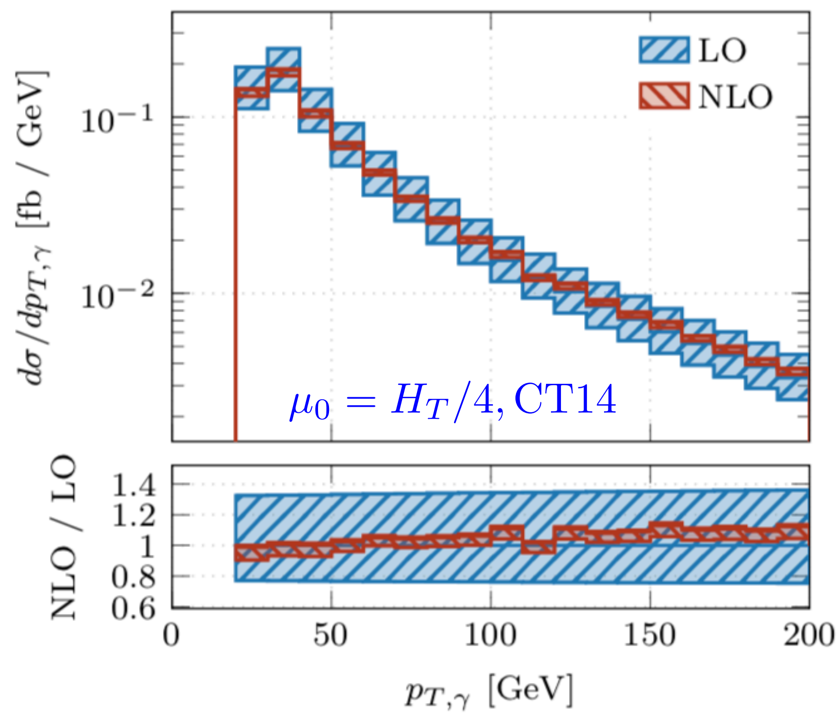
$p_T(\gamma)$

Off-shell Tops

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%*

ttγ with μ_0=m_t/2 & μ_0=H_T/4

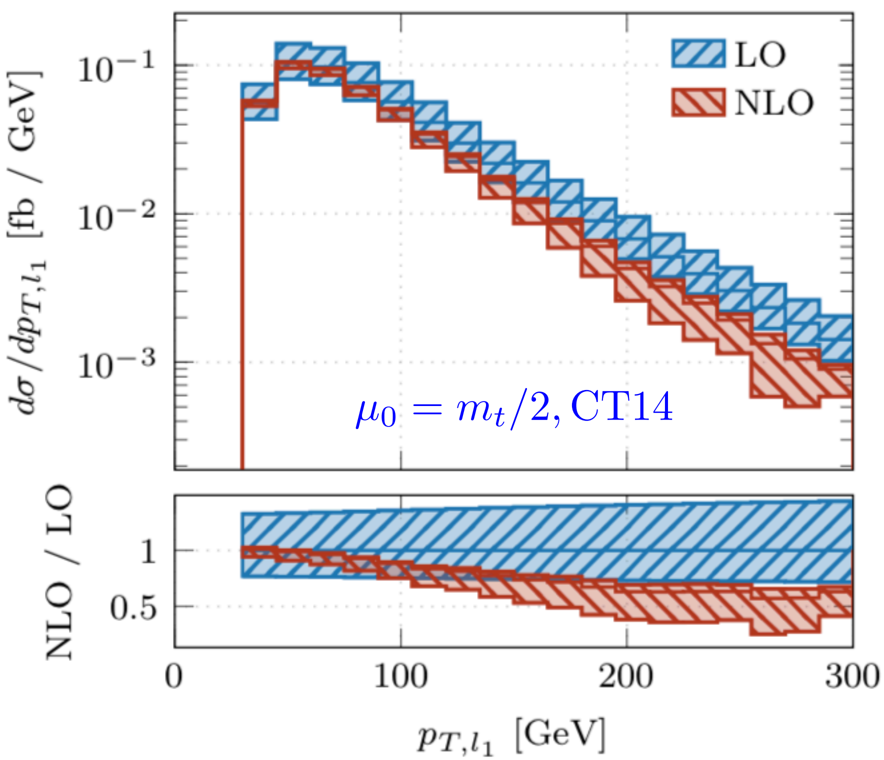
$p_T(l_1)$

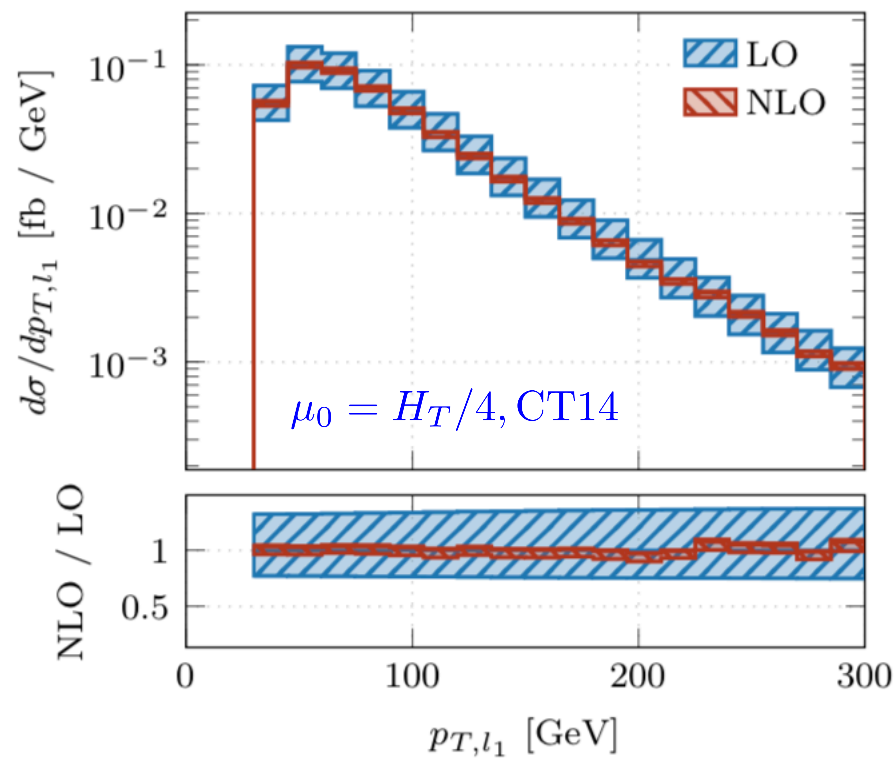
Off-shell Tops

$LHC_{13\ TeV}$

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 !

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

Off-shell Tops

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

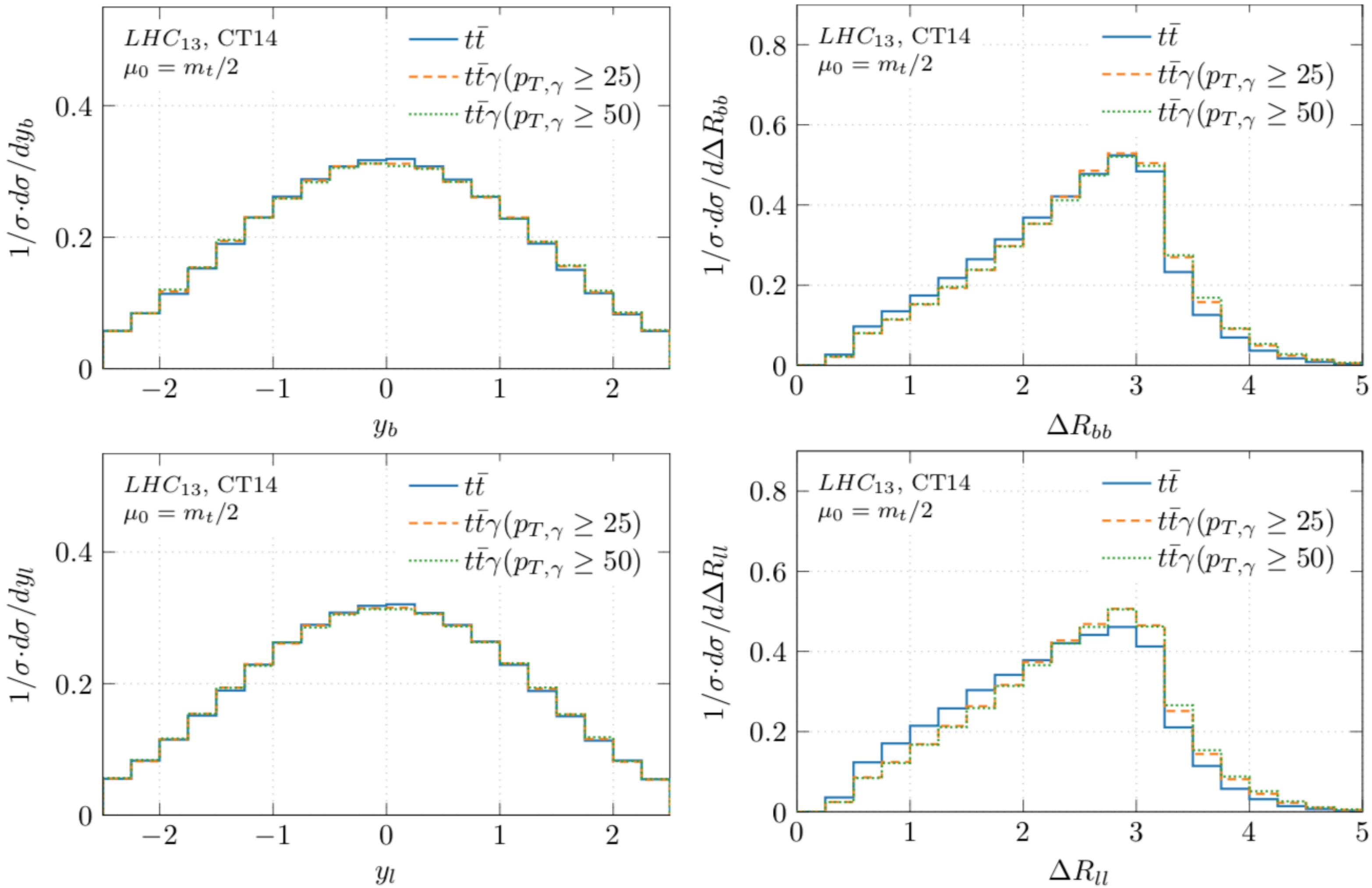
$$\left(\frac{\mu_1}{\mu_0}, \frac{\mu_2}{\mu_0} \right) = \{(2,2), (0.5, 0.5)\}$$

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

ttγ & tt

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

Off-shell Tops

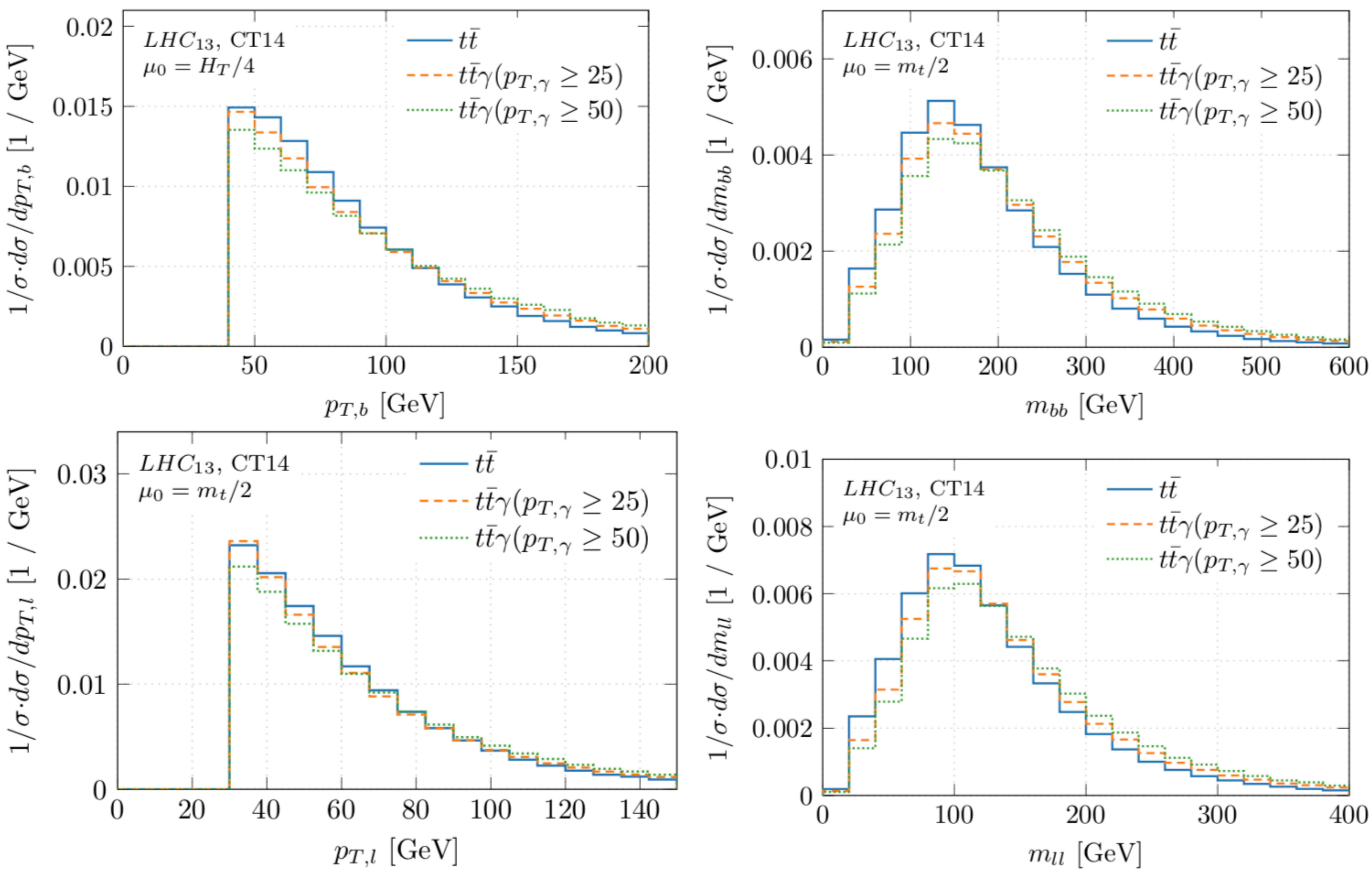


Bevilacqua, Hartanto, Kraus, Weber, Worek '19

ttγ & tt

Off-shell Tops

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



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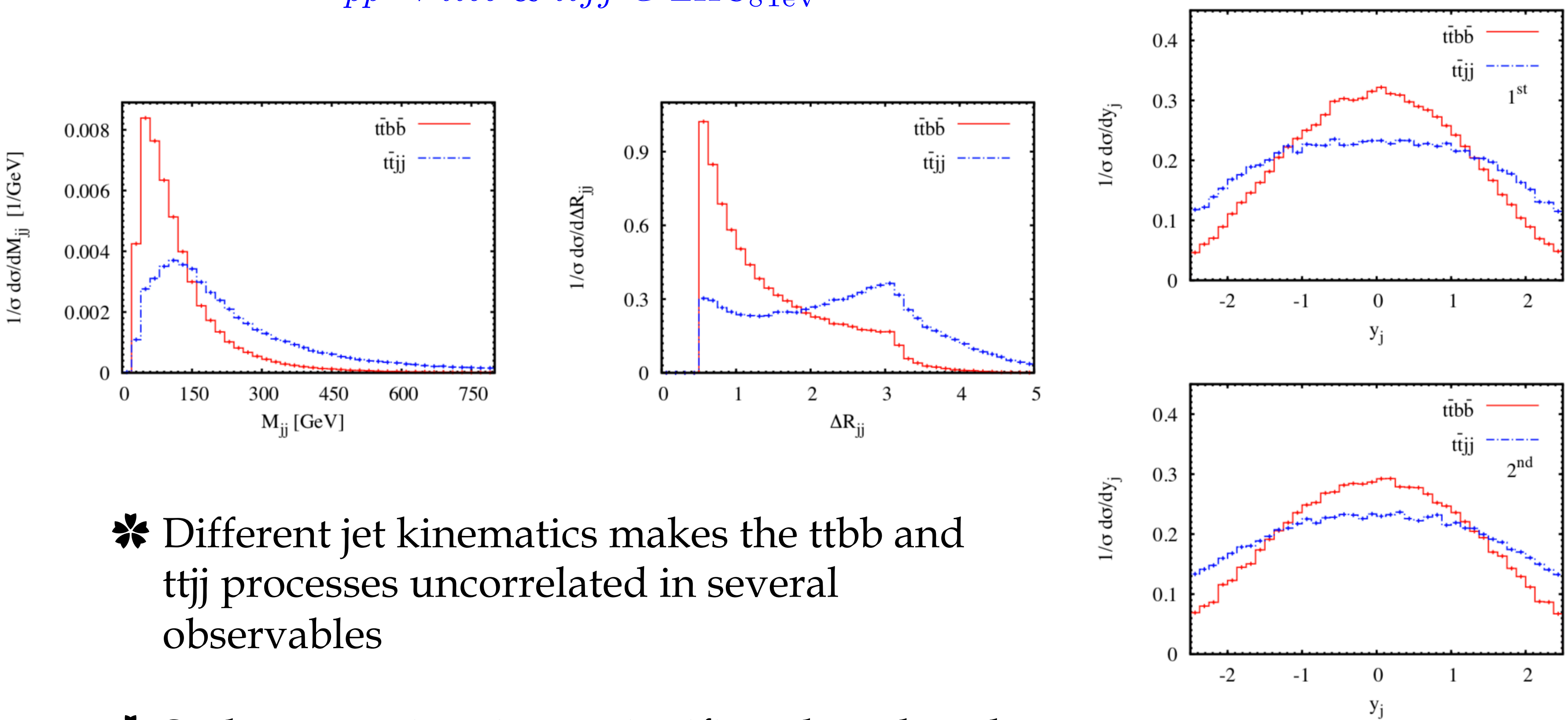
ttbb & ttjj

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



✽ 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

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

Off-shell Tops

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

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

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

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

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

✽ Our best NLO QCD predictions with dynamical scale choice:

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

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

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Differential Cross Section Ratio

Off-shell Tops

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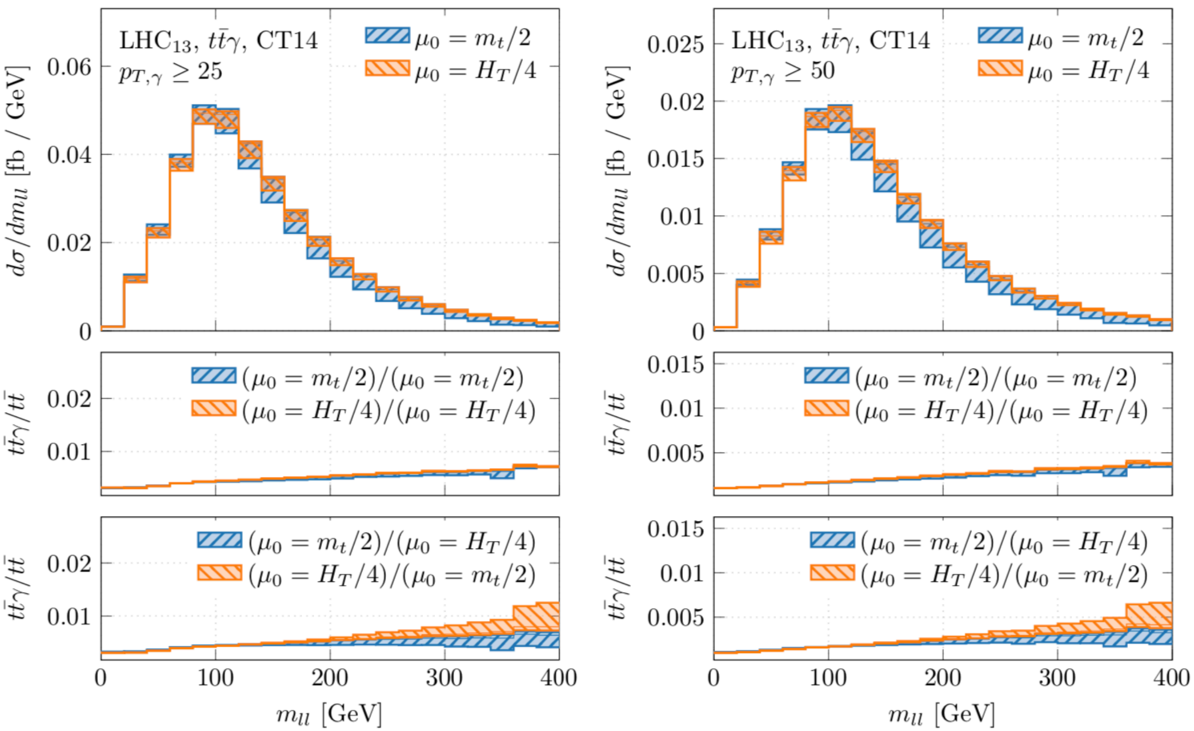


$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$ @ LHC$_{13\text{TeV}}$

Theoretical uncertainties:

± (1% – 4%) dynamical scale

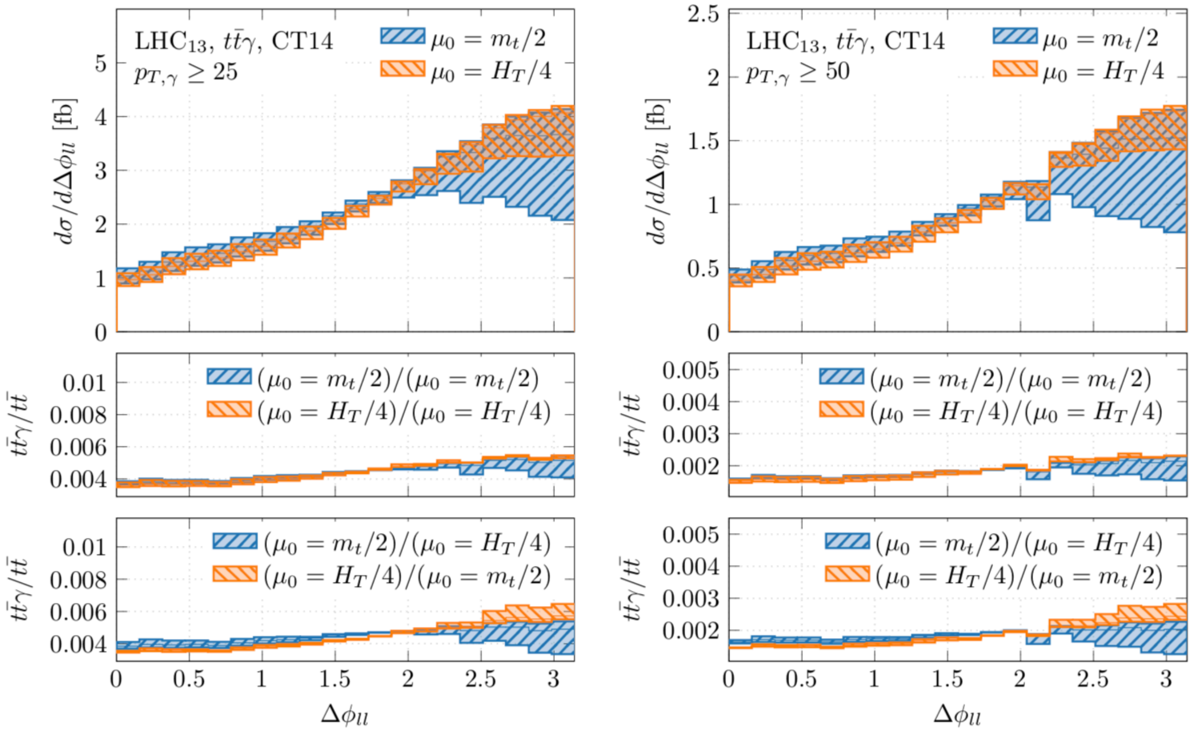
± (20% – 25%) fixed scale

- Should be compared to uncertainties for absolute differential cross section
  - ***up to ± 10% for $\mu_0 = H_T/4$ & up to ± 50% for $\mu_0 = m_t/2$***
- When different scales are used in numerator and denominator ***up to 60%***

Differential Cross Section Ratio

Bevilacqua, Hartanto, Kraus, Weber, Worek '19

Off-shell Tops



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

Off-shell Tops

- The most precise NLO QCD theoretical predictions for ***$t\bar{t}\gamma$*** in di-lepton channel
  - Complete off-shell effects for top quarks
  - ***Corrections to production & decays & tt spin correlations***
  - ***Photon emission of top quark and of top quark decay product***
  - ***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
- ***$t\bar{t}\gamma$*** relevant for BSM searches and studies of top quark properties
- Cross section ratio(s) increase precision without going to NNLO QCD !

Outlook

Off-shell Tops

- Similar results in di-lepton channel for
  - $pp \to tt$
  - $pp \to ttj$
  - $pp \to ttZ\ (Z \to \nu\nu)$
- Backgrounds for new physics searches, e.g. $pp \to tt + p_T^{miss}$
  - $pp \to tt$ & $pp \to ttZ\ (Z \to \nu\nu)$ ⇨ reducible & irreducible backgrounds
  - (some letter)MSSM, Dark Matter Models, Simplified Models, …
- Precise measurements of the top-quark fiducial cross sections
- Precise measurements of top-quark properties @ LHC ⇨ m_t & α_s & PDFs & …
- *Next steps:*
  - ***Comparisons**:* NWA vs. off-shell effects dedicated studies for $tt\gamma$
  - ***New processes:*** $pp \to ttW^+$ & $pp \to ttW^-$ ⇨ di-lepton
  - ***New processes:*** tt, ttj, ttV, $V = \gamma, H, Z, W^+$ & W^- ⇨ lepton+jet

Backup

SM parameters & Cuts for ttγ

$m_W = 80.385$ GeV,	$\Gamma_W = 2.0988$ GeV,
$m_Z = 91.1876$ GeV,	$\Gamma_Z = 2.50782$ GeV,
$\Gamma_t^{\rm LO} = 1.47848$ GeV,	$\Gamma_t^{\rm NLO} = 1.35159$ GeV,
$m_t = 173.2$ GeV,	$G_\mu = 1.166378 \times 10^{-5}$ GeV^{-2}.

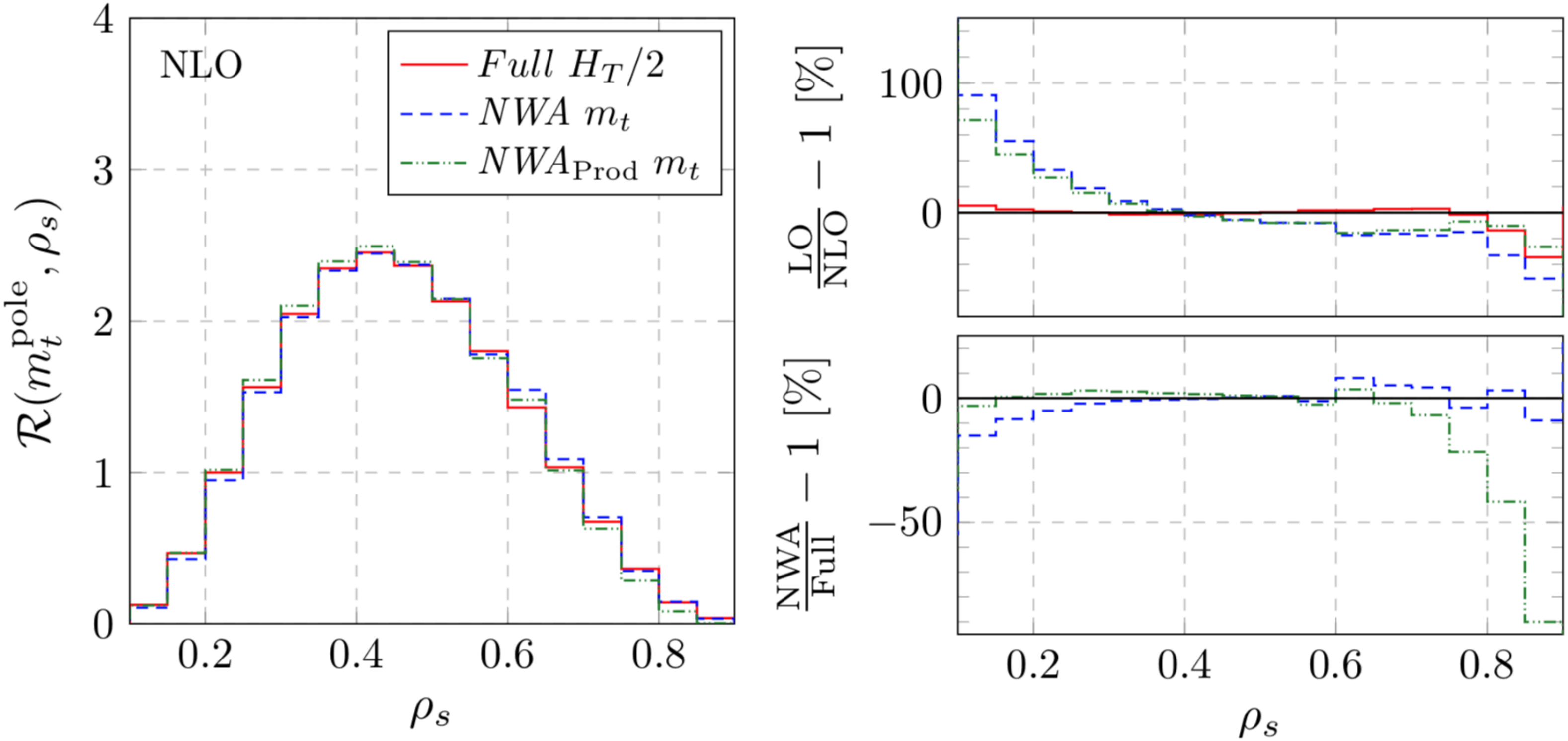
$p_{T,\ell} > 30$ GeV,	$\lvert y_\ell \rvert < 2.5$,	$\Delta R_{\ell\ell} > 0.4$,
$p_{T,b} > 40$ GeV,	$\lvert y_b \rvert < 2.5$,	$\Delta R_{bb} > 0.4$,
$p_T^{miss} > 20$ GeV,	$\Delta R_{\ell\gamma} > 0.4$,	$\Delta R_{\ell b} > 0.4$,

NWA & Off-Shell Effects

❖ Observable used for a recent ***top quark mass determination*** **Off-shell, NWA**

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

Bevilacqua, Hartanto, Kraus, Schulze, Worek '18



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

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

NWA & Off-Shell Effects

25 fb^{-1}

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

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

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ttγ & tt

Off-shell Tops

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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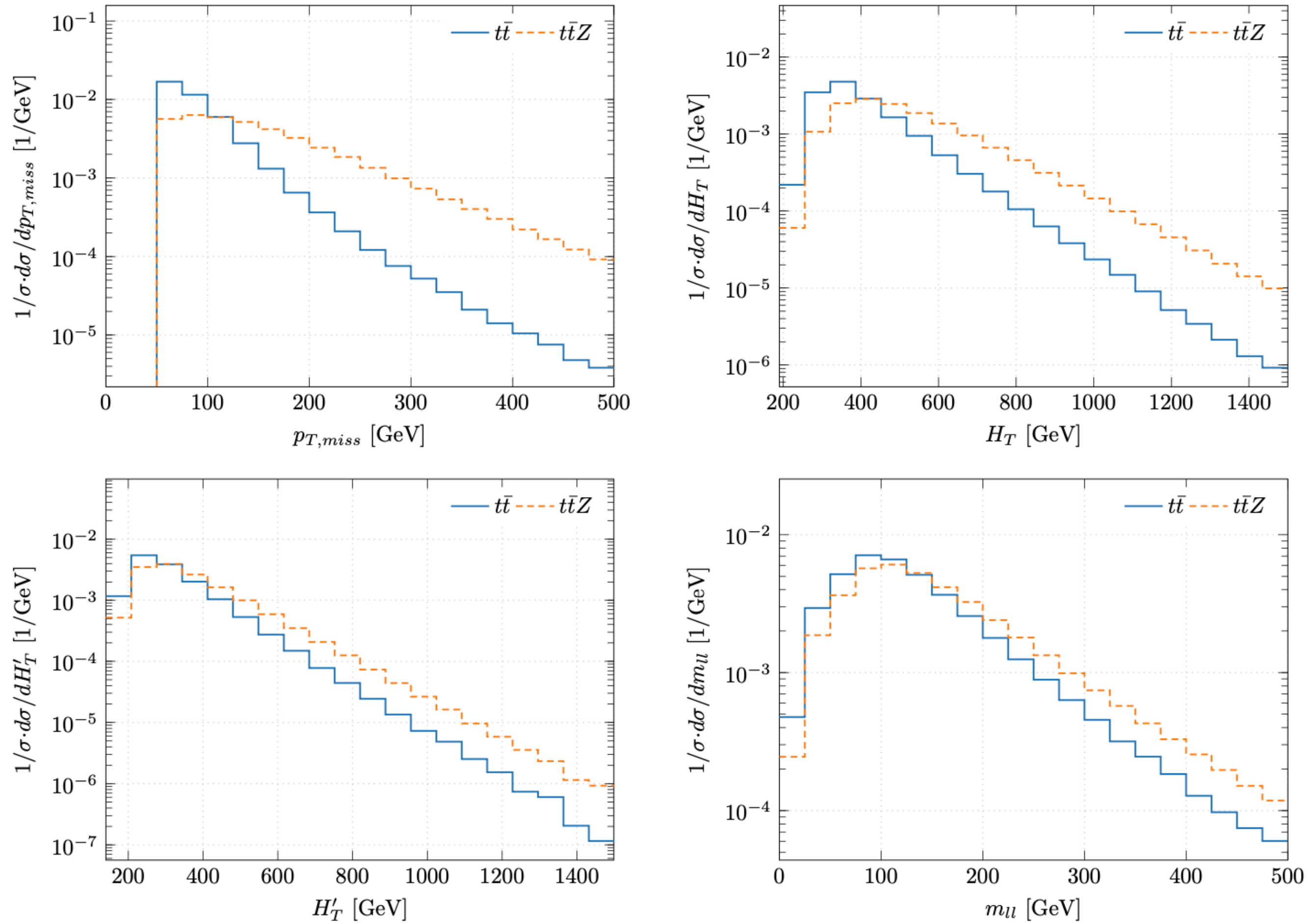
ttZ

✽ Normalized NLO differential cross sections

Off-shell Tops



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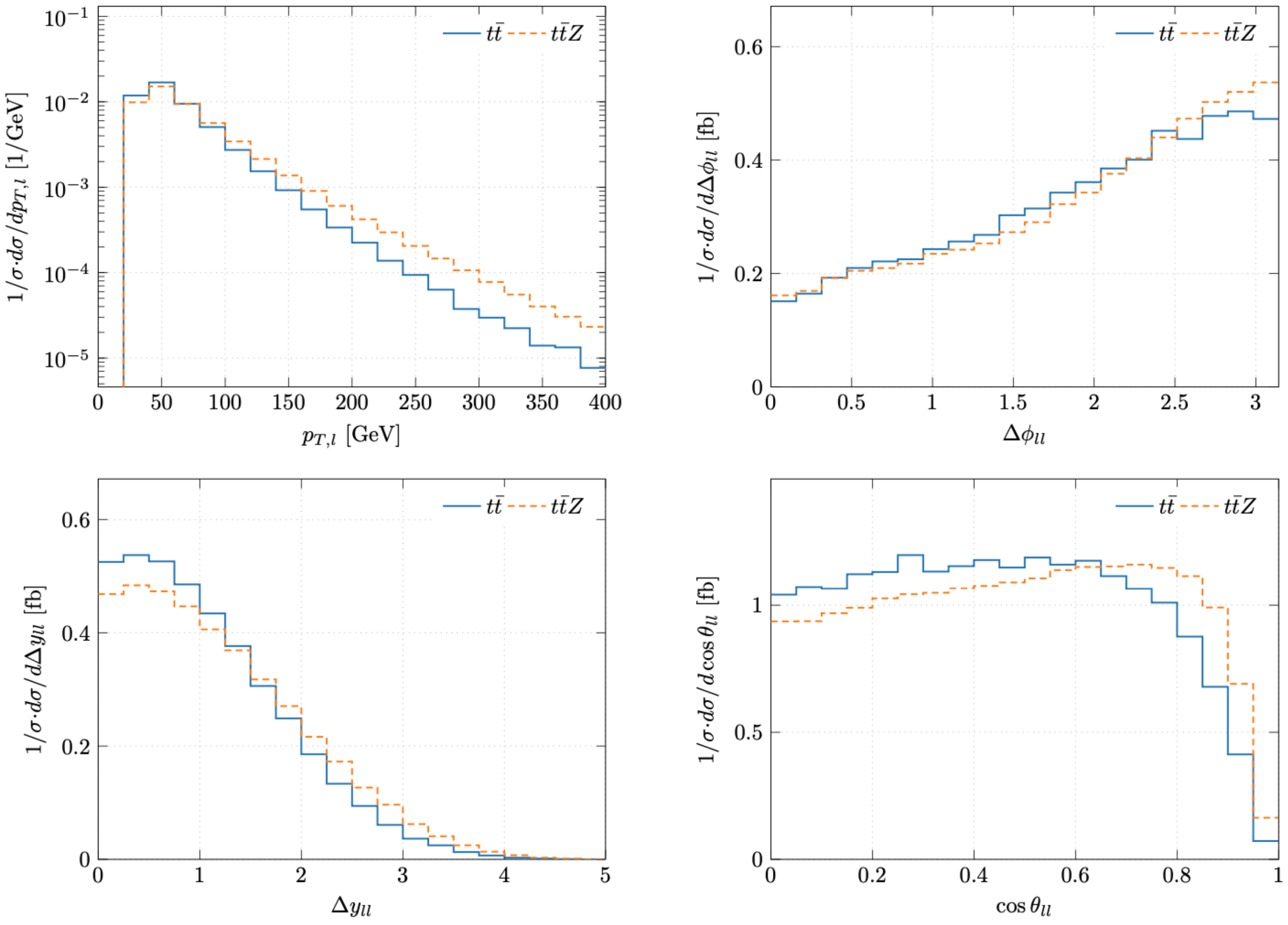
ttZ

Off-shell Tops

- Normalized NLO differential cross sections



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