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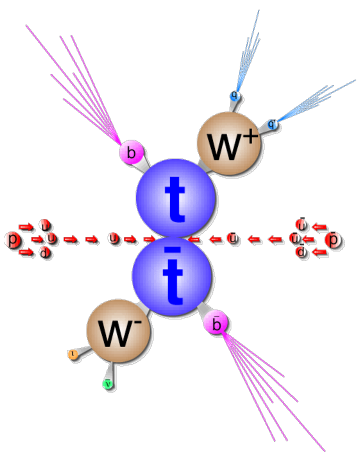
Project B1b: Precision top-quark physics at the LHC



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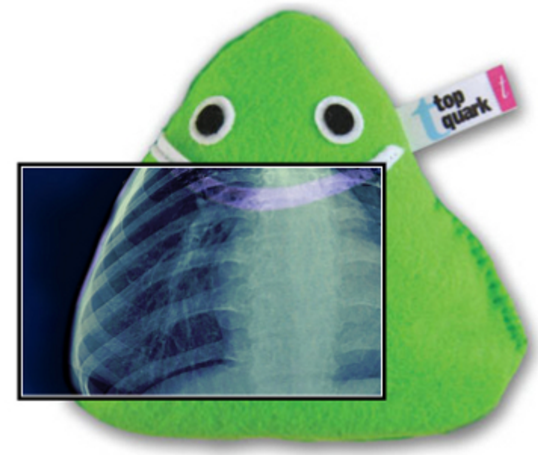
Outline



- Introduction
- Status of theoretical predictions ⇨ **QCD**
- State-of-the-art (fixed order) theoretical predictions for:

$$pp \to t\bar{t}, t\bar{t}\gamma, t\bar{t}W^{\pm}, t\bar{t}Z$$

- Modeling of top quark production & decays ⇨ *top quark in di-lepton channel*
  - NWA
  - Off-shell top quark effects

Papers in Project B1b (so far…)

NNLO

1. *NNLO QCD corrections to leptonic observables in top-quark pair production and decay*
   - ***Czakon***, Mitov, Poncelet
   - arXiv: 2008.11133

2. *Higher order corrections to spin correlations in top quark pair production at the LHC*
   - Behring, ***Czakon***, Mitov, Papanastasiou, Poncelet
   - ***Phys. Rev. Lett. 123 (2019) 082001***

NLO

1. *The simplest of them all:* $t\bar{t}W^{\pm}$ *at NLO accuracy in QCD*
   - Bevilacqua, ***Bi***, Hartanto, Kraus, ***Worek***
   - ***JHEP 08 (2020) 043***

2. *Off-shell vs on-shell modelling of top quarks in photon associated production*
   - Bevilacqua, Hartanto, Kraus, ***Weber, Worek***
   - ***JHEP 2003 (2020) 154***

3. *Towards Constraining Dark Matter at the LHC: Higher order QCD predictions for* $pp \to t\bar{t} + p_T^{miss}$
   - Bevilacqua, Hartanto, Kraus, Weber, ***Worek***
   - ***JHEP 1911 (2019) 001***

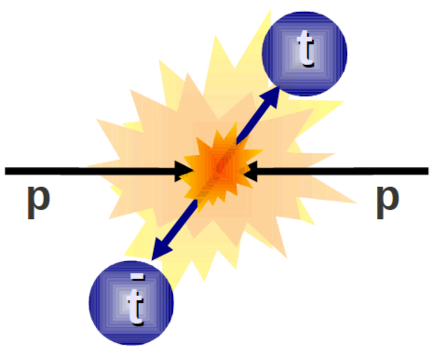
Why top quark is special

- Infrared structure of QCD ⇨ Precision physics
  - Extract SM parameters as precisely as possible ⇨ α_s & m_t
  - Constraining gluon PDFs
  - Verify couplings to other particles ⇨ $\gamma, H, Z, W^{\pm}$

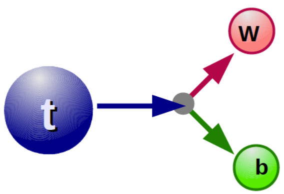
- Background process to various SM studies ⇨ *Higgs boson*

- Window to New Physics
  - Direct searches ⇨ Main background to many BSM scenarios
  - Indirect searches ⇨ Precision tests of properties, rare decays, various top quark production modes

Production



Decays

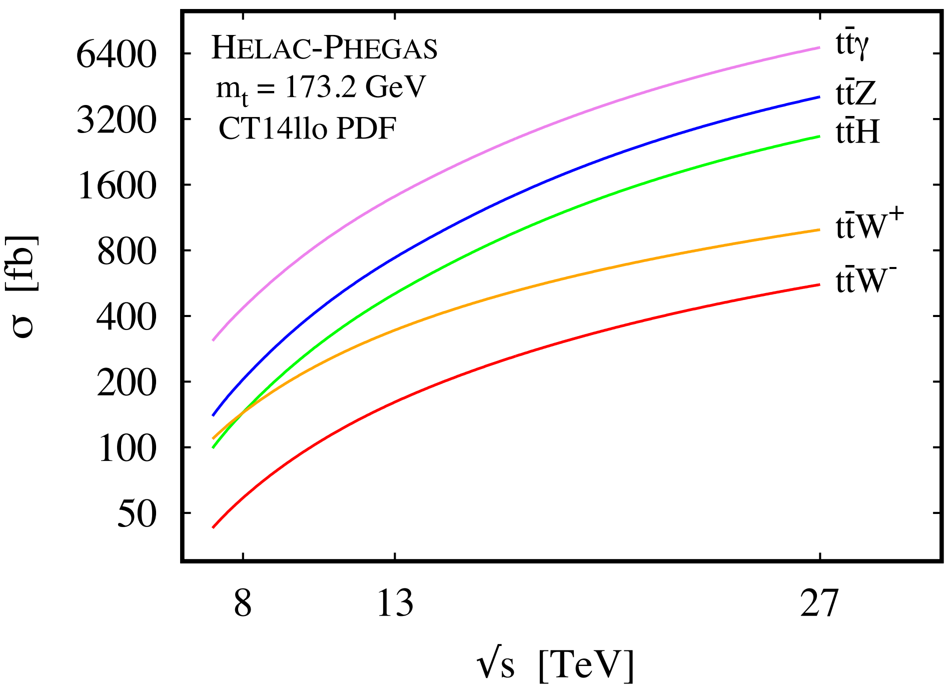


Intrinsic properties

tt(j) & ttV

- NNLO in NWA ⇨ ***tt*** di-lepton channel
- NLO with off-shell top quarks ⇨ ***tt, ttj*** di-lepton channel
- Besides ***tt(j)*** more exclusive final states can be accessed @ LHC

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



Stable top quarks

HELAC-PHEGAS

Cafarella, Papadopoulos, Worek '09

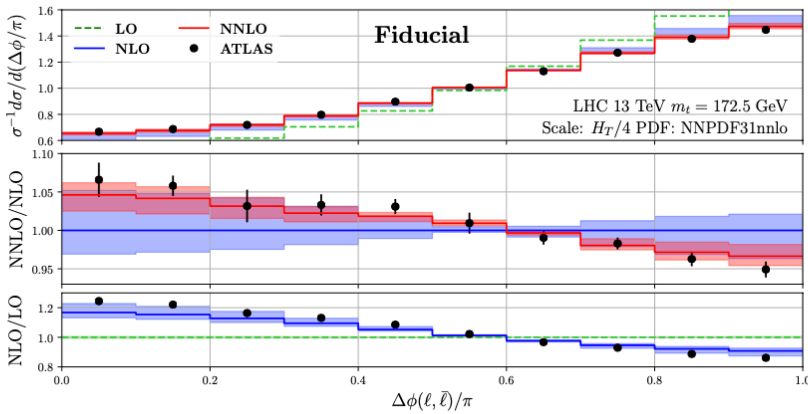
Top-Quark Pair Production & Decays

Normalized differential *tt* cross-section ⇨ Azimuthal opening angle between two leptons

Top quarks in NWA di-lepton channel

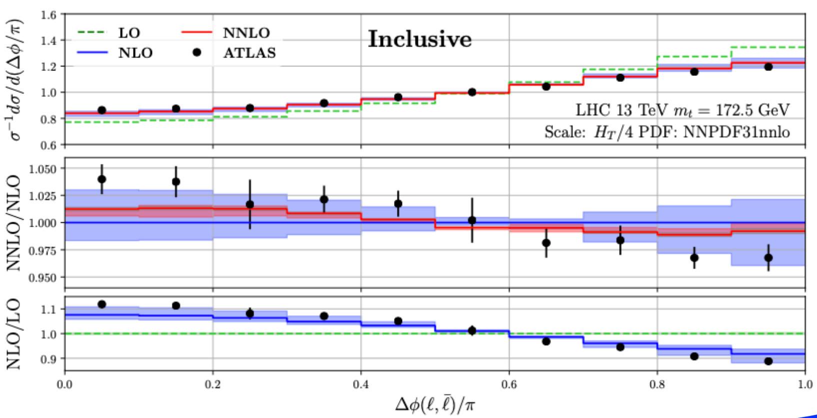
agreement

Behring, Czakon, Mitov, Papanastasiou, Poncelet '19



Inclusive ⇨ does not assume any selection cuts

Fiducial ⇨ based on the ATLAS selection cuts



Proper modeling of top-quark production & decay essential

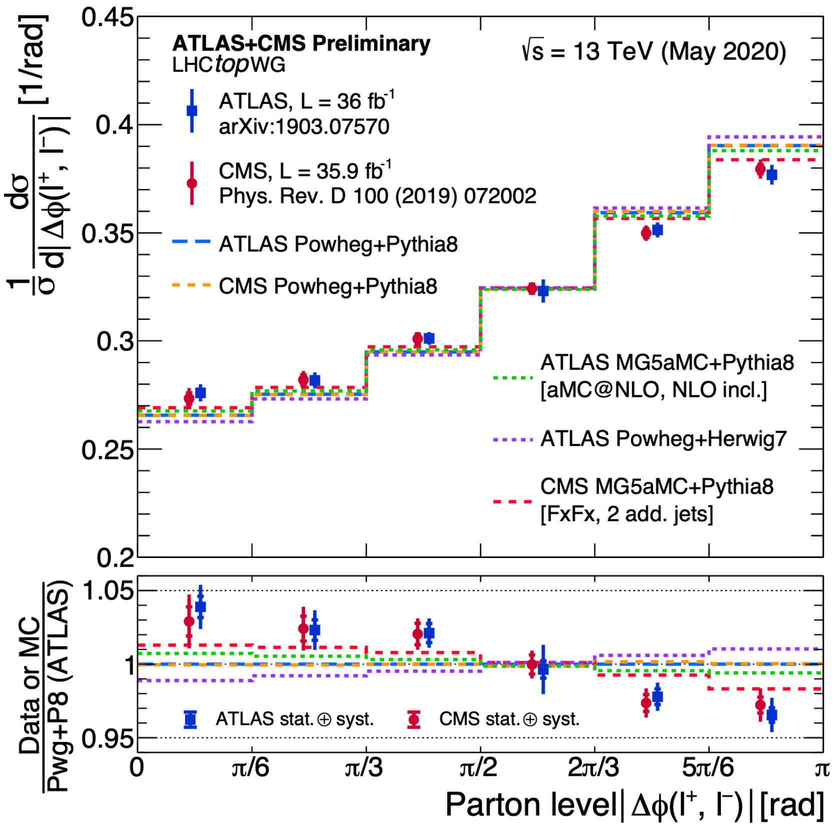
tension

Top-Quark Pair Production & Decays

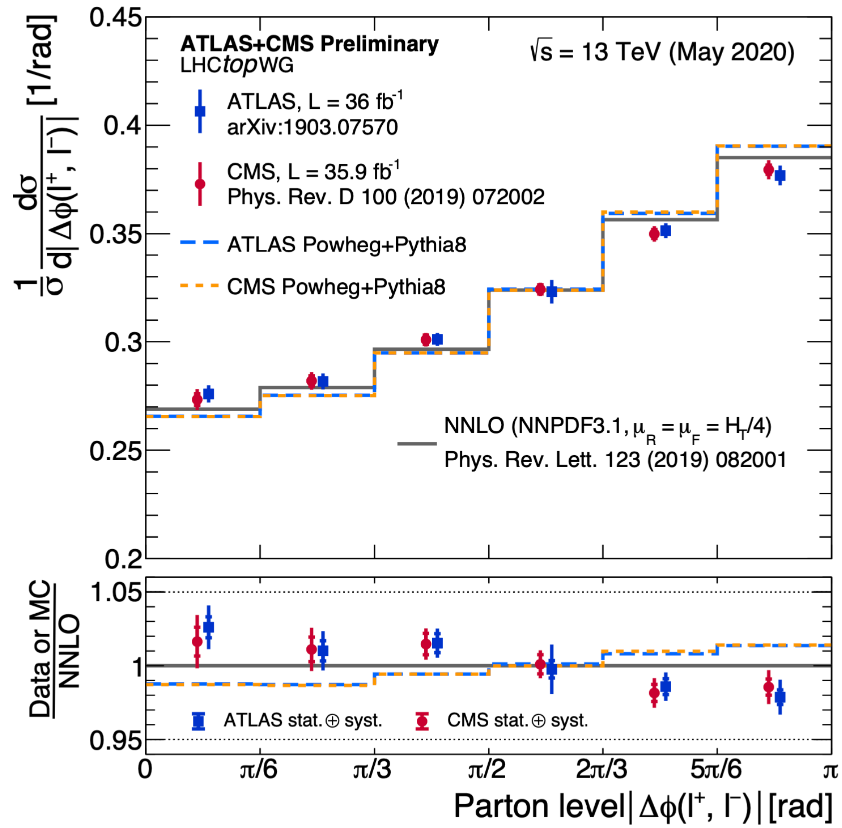
Normalized differential tt cross-section

⇨ *Azimuthal opening angle between two leptons*

LHCtopWG



Comparison to Powheg & Mad-Graph5_aMC@NLO

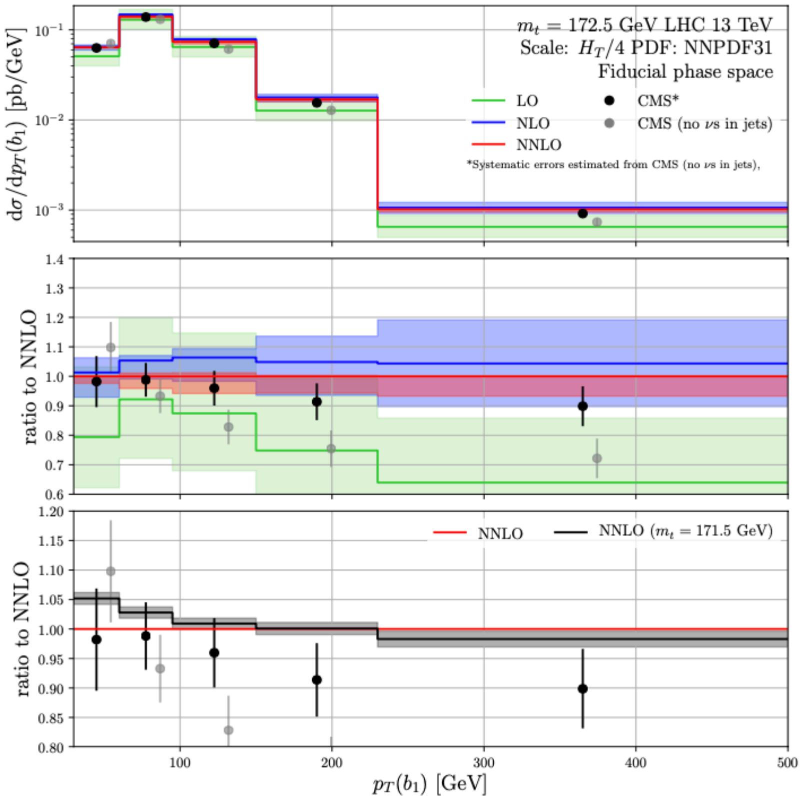


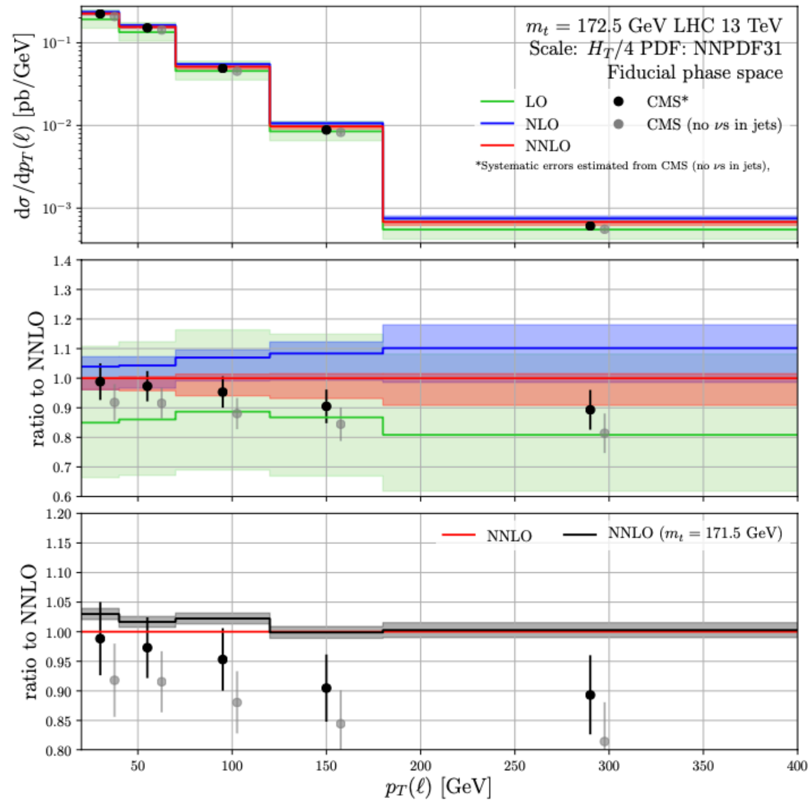
Comparison to NNLO QCD predictions in the NWA

Top-Quark Pair Production & Decays

Fiducial PS
CMS cuts

Czakon, Mitov, Poncelet '20





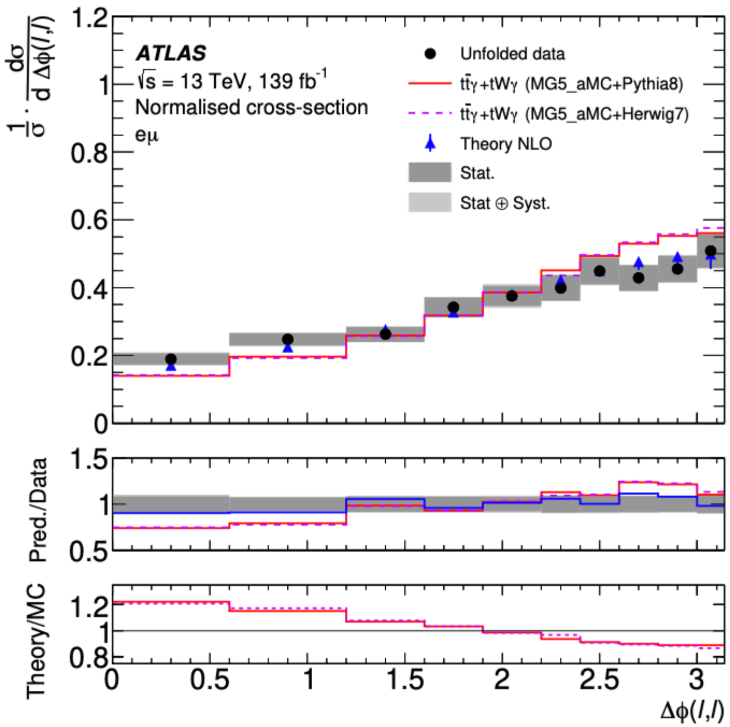
- *p_T of b-jet & lepton* ⇨ Difference between two data sets ⇨ With and without neutrinos from semileptonic B-decays
- All observables strongly affected ⇨ Overall normalization & shape

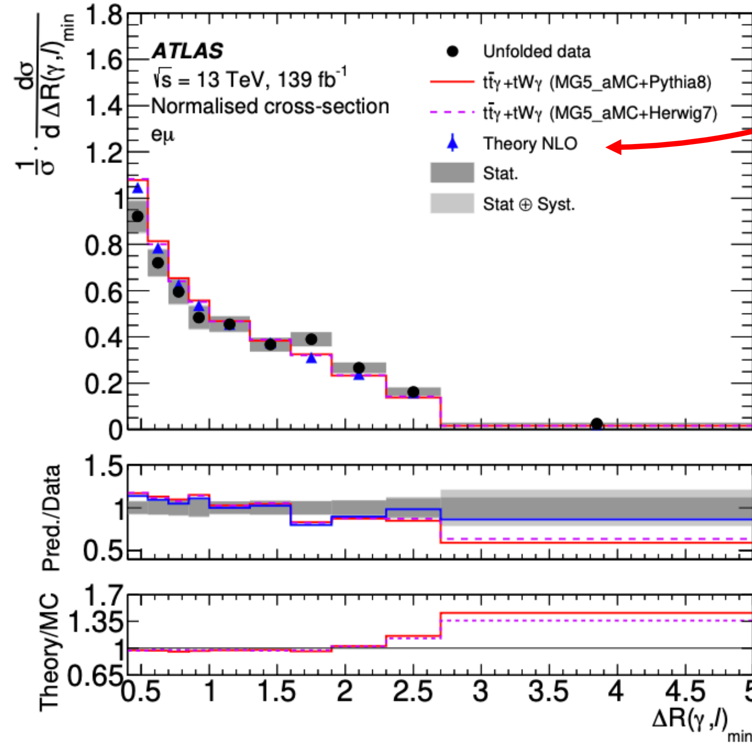
Combined $t\bar{t}\gamma$ + $tW\gamma$ Production & Decays

eμ channel

ATLAS Collaboration '20
JHEP 09 (2020) 049

HELAC-NLO





Predictions	$p_T(\gamma)$ χ^2/ndf	$p_T(\gamma)$ p-value	$\lvert\eta(\gamma)\rvert$ χ^2/ndf	$\lvert\eta(\gamma)\rvert$ p-value	$\Delta R(\gamma,\ell)_{min}$ χ^2/ndf	$\Delta R(\gamma,\ell)_{min}$ p-value	$\Delta\phi(\ell,\ell)$ χ^2/ndf	$\Delta\phi(\ell,\ell)$ p-value	$\lvert\Delta\eta(\ell,\ell)\rvert$ χ^2/ndf	$\lvert\Delta\eta(\ell,\ell)\rvert$ 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

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 matrix element level

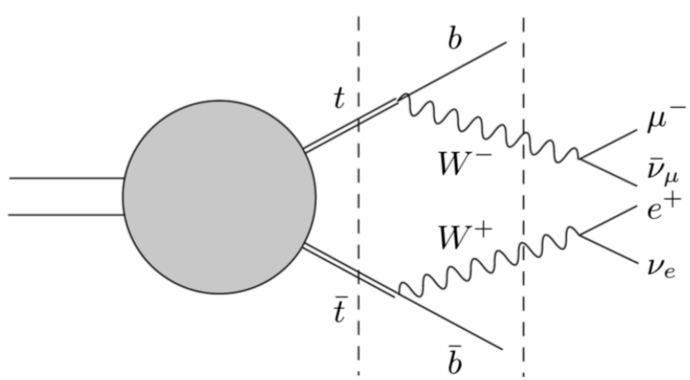
NWA

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

$$\Gamma_t = 1.35159 \text{ GeV}, \; m_t = 173.2 \, \text{GeV}, \; \Gamma_t/m_t \approx 0.008$$

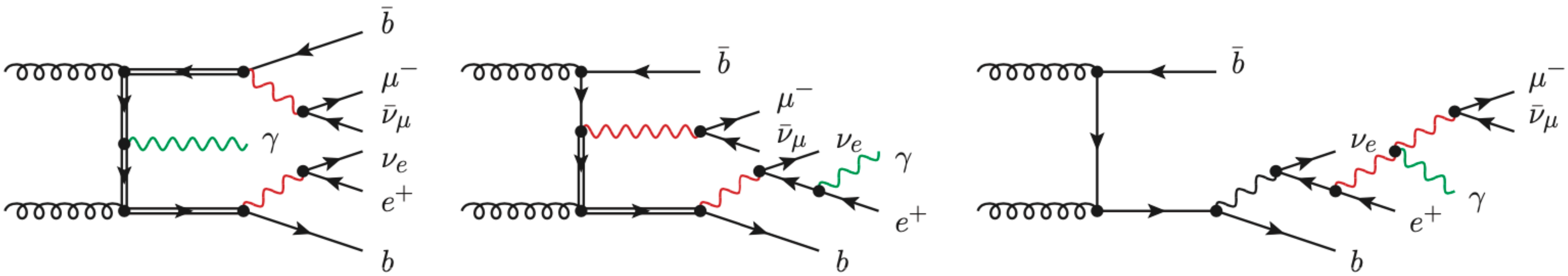
- Incorporates only double resonant contributions
- Restricts the unstable top quarks (W gauge bosons) to on-shell states

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



NWA & Off-Shell Effects

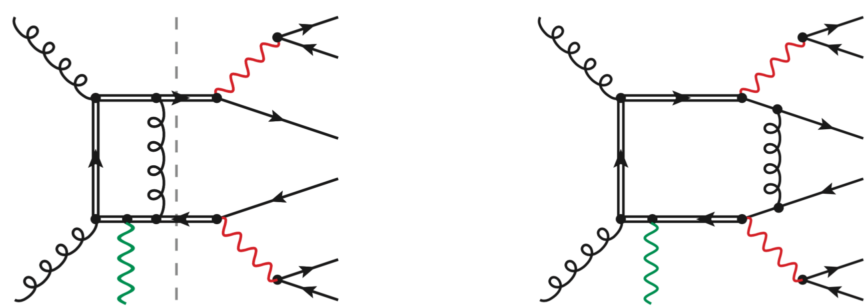
- Feynman Diagrams ⇨ *628* @ *LO* for gg channel versus *38* in NWA
- *8* diagrams with photon in production and *30* in decay stage



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

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

How Good Is the NWA ?

- Should be accurate for sufficiently inclusive observables
- Off-shell effects for integrated fiducial σ_{tt} ⇨ ***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*** *(di-lepton)*	*Bevilacqua, Bi, Hartanto, Kraus, Worek '20* *Denner, Pellicciolli '20*
• ***ttbb*** *(di-lepton)*	*Denner, Lang, Pellen '20*

Fiducial Cross Section for ttγ

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$_{\text{LOdecay}}$ ($\mu_0 = H_T/4$)		$4.63^{+0.44\,(9.5\%)}_{-0.52\,(11\%)}$

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%*** ⇨ $\mu_0 = \frac{1}{2}\, m_t$
- ***12%*** ⇨ $\mu_0 = \frac{1}{4}\, H_T$
- Theoretical uncertainties not underestimated for the full NWA

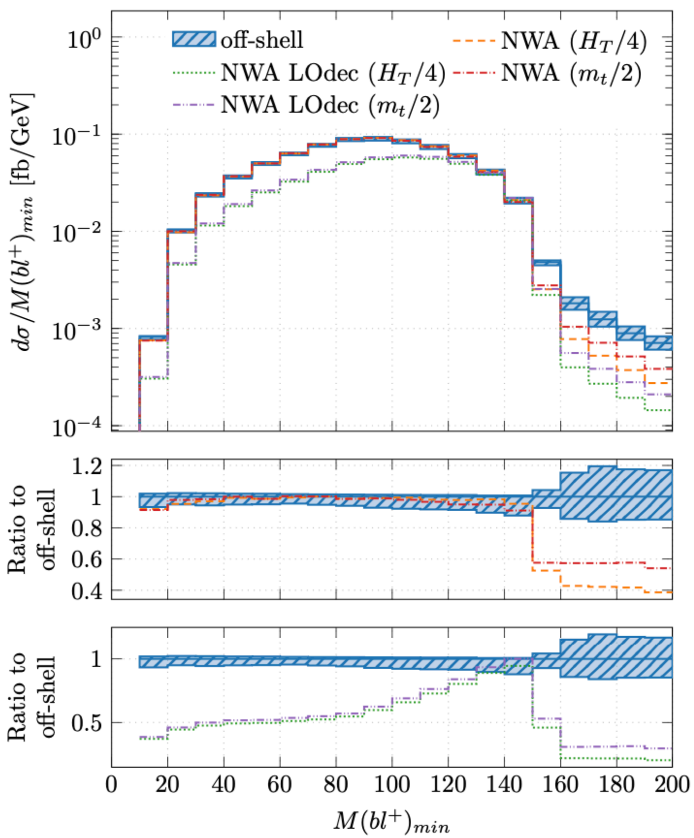
Bevilacqua, Hartanto, Kraus, Weber, Worek '20

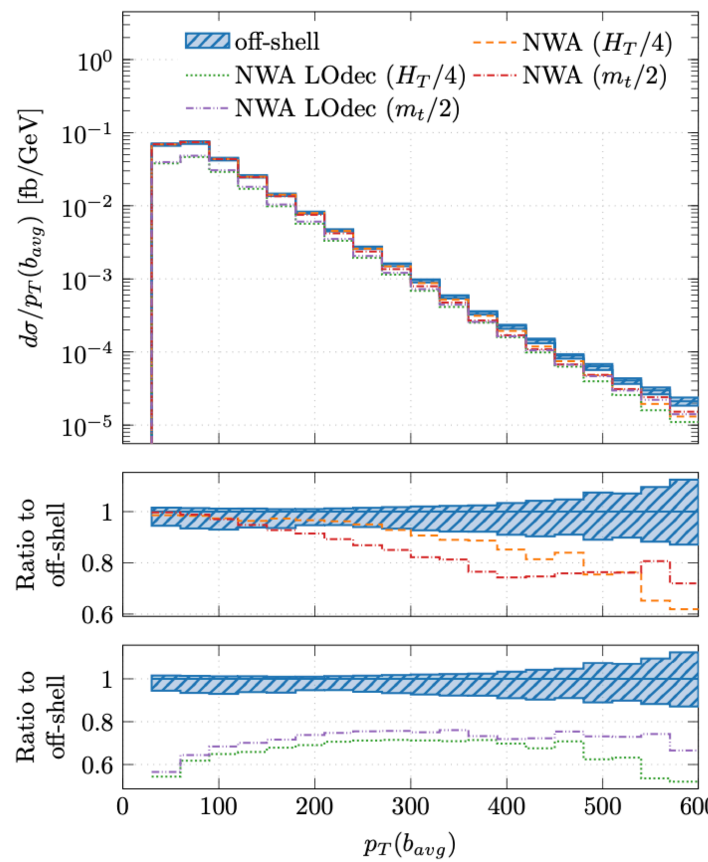
How Good Is the NWA ?

HELAC-NLO

- ***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***

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





Bevilacqua, Hartanto, Kraus, Weber, Worek '20

Various Phase-space Regions

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

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):***

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

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

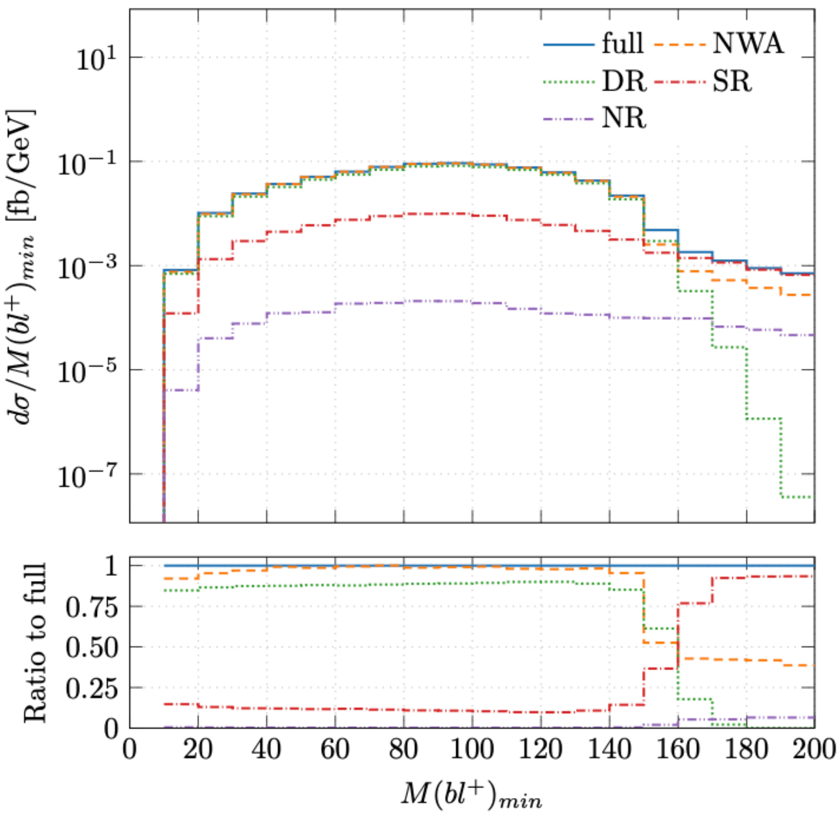
- ***Non-resonant region (NR):***

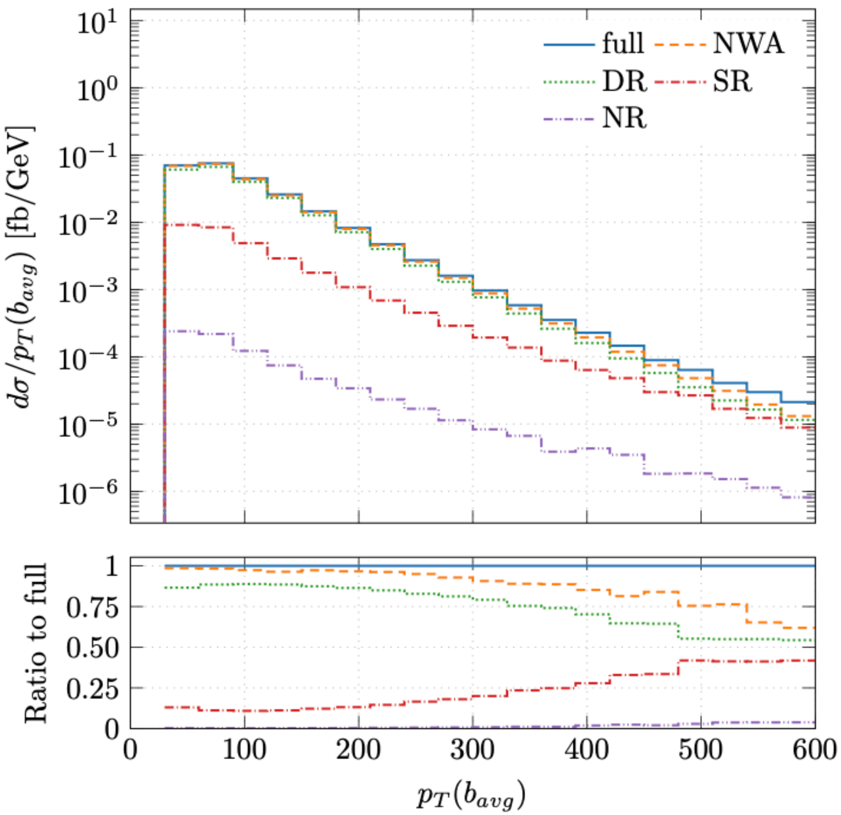
$$|M(t) - m_t| > n\,\Gamma_t\,, \quad \text{and} \quad |M(\bar{t}) - m_t| > n\,\Gamma_t$$

Various Phase-space Regions

HELAC-NLO

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



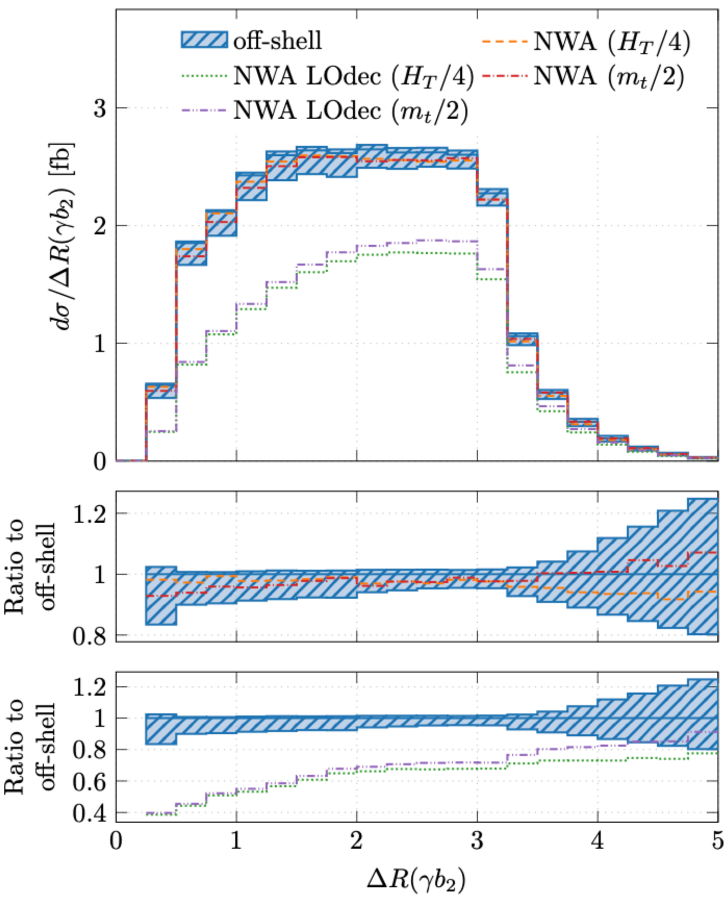


Bevilacqua, Hartanto, Kraus, Weber, Worek '20

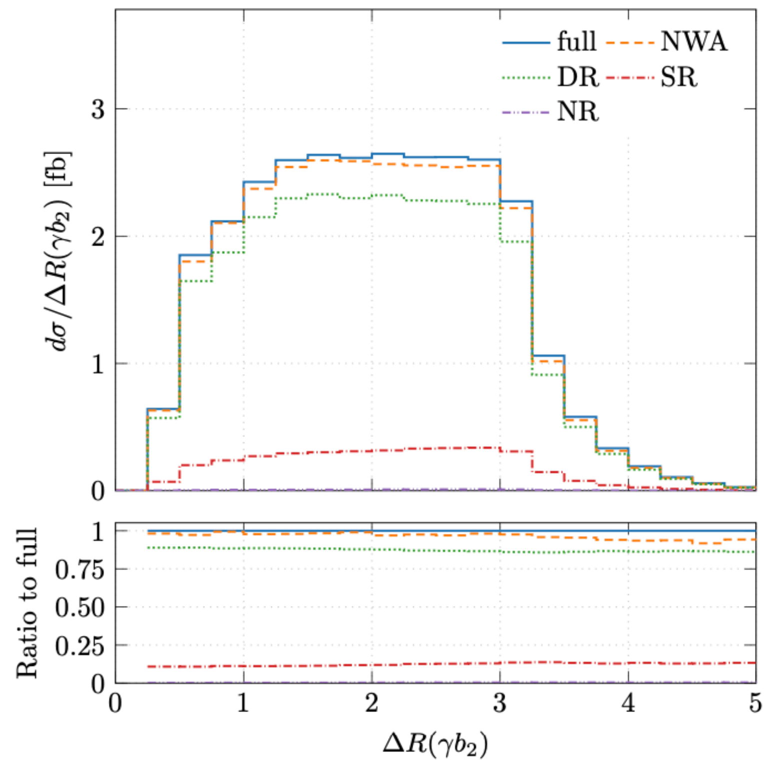
- ***Off-shell effects:***
  - High p_T region of various dimensionful observables
  - Vicinity of kinematical edges
  - Contribute up to ***50% − 60%***

Various Phase-space Regions

HELAC-NLO



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

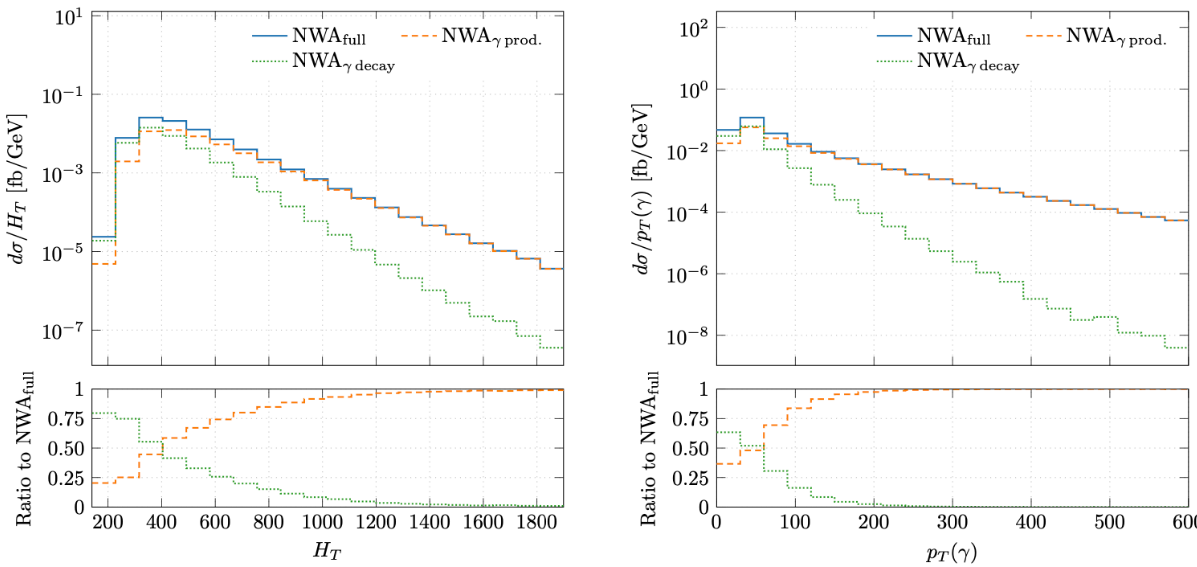


Bevilacqua, Hartanto, Kraus, Weber, Worek '20

- 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



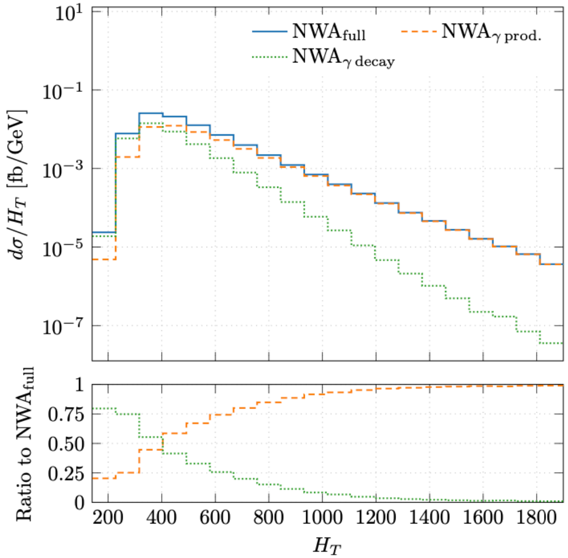
HELAC-NLO

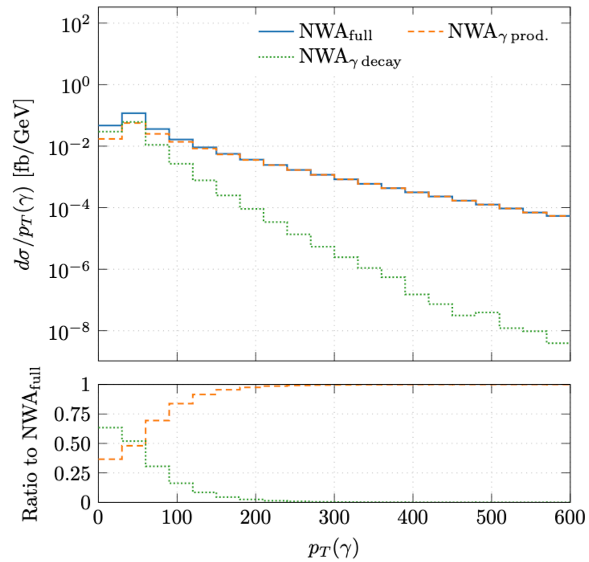
- Diverse picture
- Photon emission in decays can be reduced
  - ***H_T > 400 GeV***
  - ***$p_T(\gamma)$ > 50 GeV***

γ in Production & Decays ⇨ Differential Level

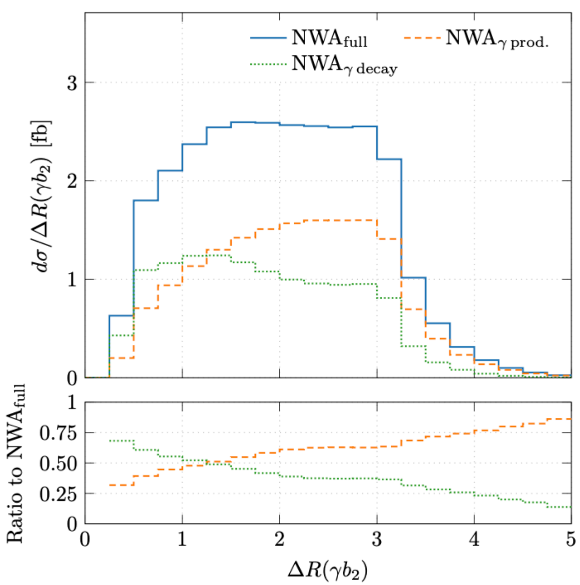
Bevilacqua, Hartanto, Kraus, Weber, Worek '20

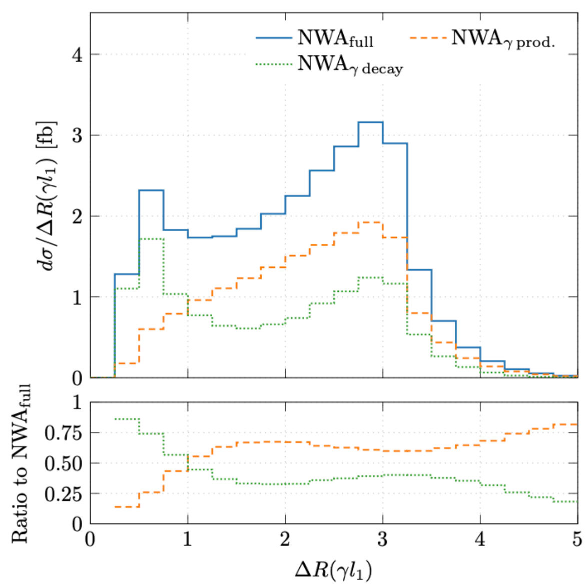
HELAC-NLO

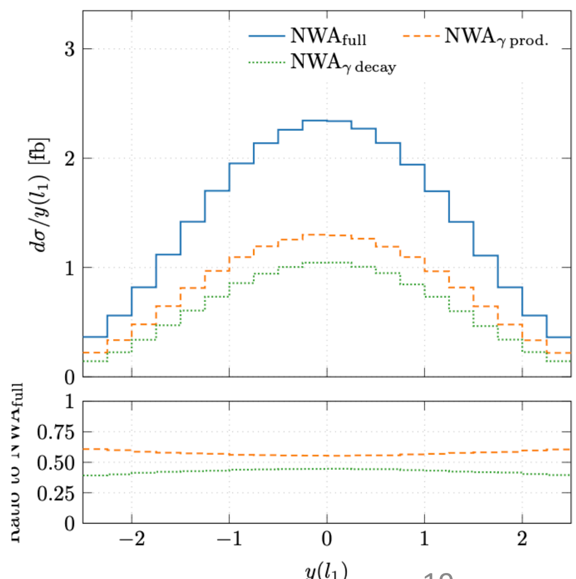




- Diverse picture
- Photon emission in decays can be reduced
  - *H_T > 400 GeV*
  - *$p_T(\gamma)$ > 50 GeV*







ttW with dynamical & fixed scale

HELAC-NLO

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

Bevilacqua, Bi, Hartanto, Kraus, Worek '20

$\mu_R = \mu_F = \mu_0 = m_t + m_W/2$							
PDF	$p_T(j_b)$	$\sigma^{\rm LO}$ [ab]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [ab]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\sigma^{\rm NLO}/\sigma^{\rm LO}$
NNPDF3.0	25	106.9	$+27.7$ (26%) -20.5 (19%)	123.2	$+6.3$ (5%) -8.7 (7%)	$+2.1$ (2%) -2.1 (2%)	1.15
	30	99.2	$+25.8$ (26%) -19.1 (19%)	113.1	$+5.4$ (5%) -7.8 (7%)	$+1.9$ (2%) -1.9 (2%)	1.14
	35	90.8	$+23.7$ (26%) -17.5 (19%)	102.6	$+4.7$ (5%) -6.8 (7%)	$+1.7$ (2%) -1.7 (2%)	1.13
	40	82.1	$+21.5$ (26%) -15.9 (19%)	92.0	$+4.0$ (4%) -6.1 (7%)	$+1.6$ (2%) -1.6 (2%)	1.12

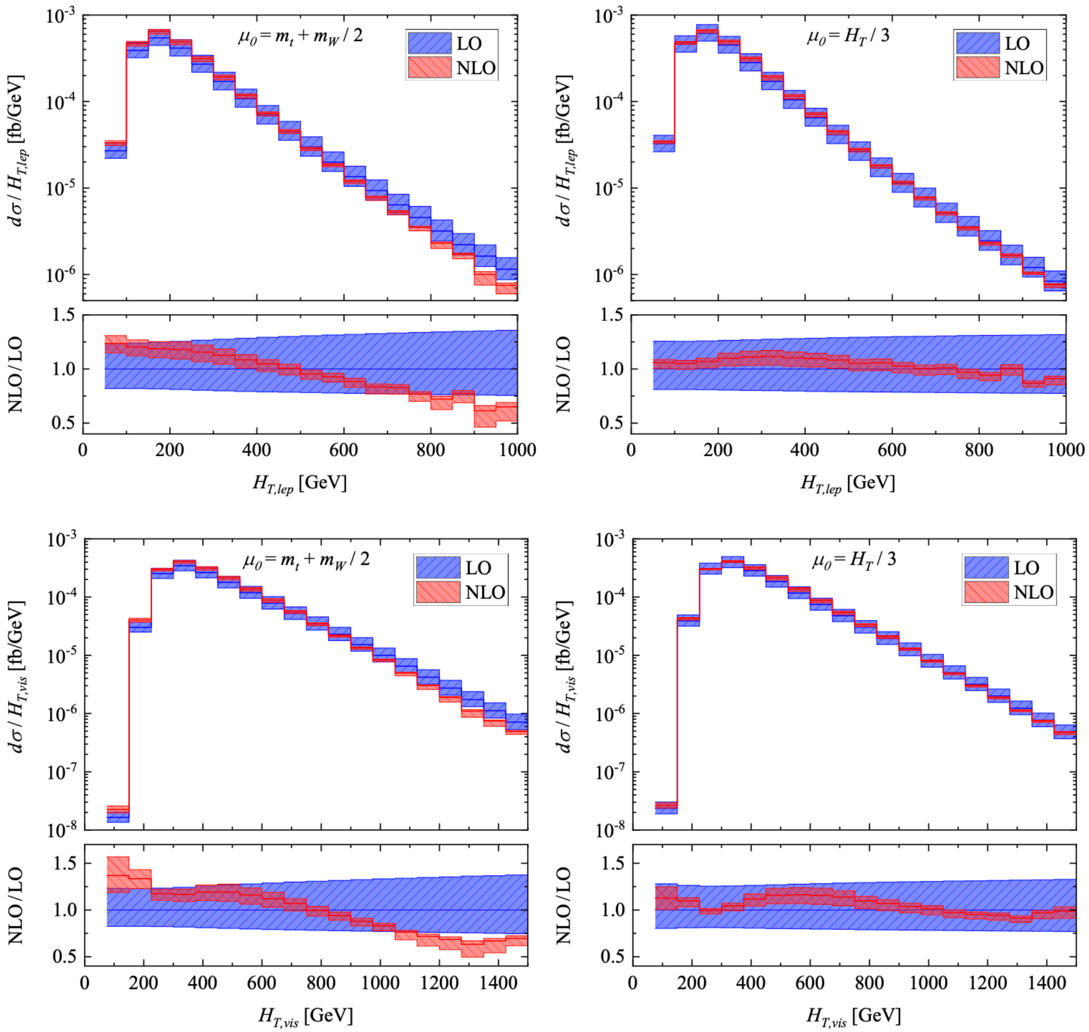
$\mu_R = \mu_F = \mu_0 = H_T/3$							
PDF	$p_T(j_b)$	$\sigma^{\rm LO}$ [ab]	$\delta_{\rm scale}$	$\sigma^{\rm NLO}$ [ab]	$\delta_{\rm scale}$	$\delta_{\rm PDF}$	$\sigma^{\rm NLO}/\sigma^{\rm LO}$
NNPDF3.0	25	115.1	$+30.5$ (26%) -22.5 (20%)	124.4	$+4.3$ (3%) -7.7 (6%)	$+2.1$ (2%) -2.1 (2%)	1.08
	30	106.5	$+28.2$ (26%) -20.8 (20%)	113.9	$+3.5$ (3%) -6.8 (6%)	$+1.9$ (2%) -1.9 (2%)	1.07
	35	97.0	$+25.7$ (27%) -18.9 (20%)	103.1	$+3.1$ (3%) -6.0 (6%)	$+1.7$ (2%) -1.7 (2%)	1.06
	40	87.2	$+23.2$ (27%) -17.0 (20%)	92.3	$+2.8$ (3%) -5.3 (6%)	$+1.5$ (2%) -1.5 (2%)	1.06

ttW stable with respect to central scale choice in fiducial regions

ttW with dynamical scale

HELAC-NLO

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



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Fixed scale

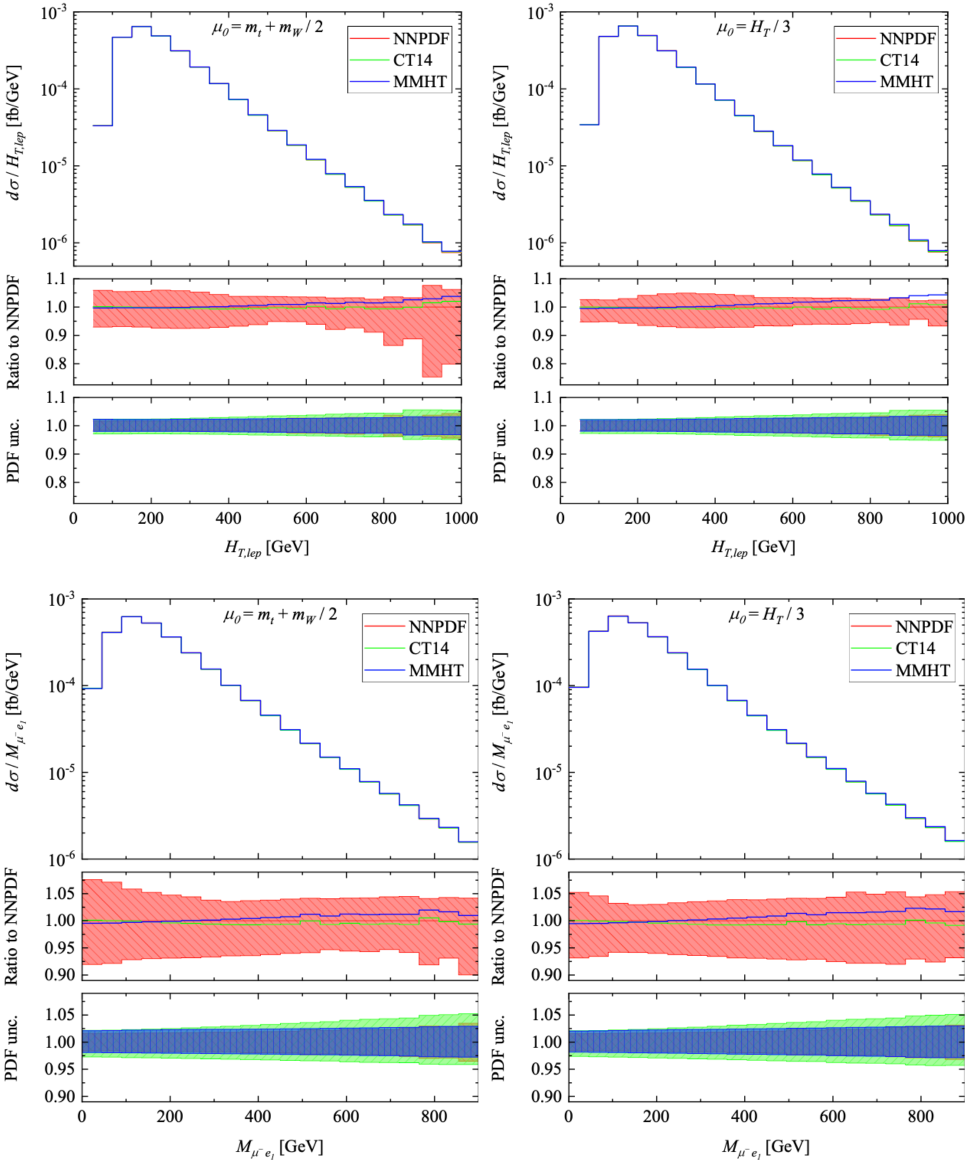
- NLO QCD ⇨ *+25%* up *-35%*
- Uncertainties ⇨ *15% − 20%*
- Perturbative instabilities in TeV regions

Dynamical scale

- NLO QCD ⇨ *±10%*
- Uncertainties ⇨ *5% − 10%*
- Stabilises tails and keeps NLO uncertainties bands within LO ones

ttW with dynamical scale

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



HELAC-NLO

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- PDF uncertainties ⇨ *5%*
- Negligible when contrasted with scale dependence
- Differences between results for various PDF sets are similar in size to internal PDF uncertainties
- For dynamical scale choice PDF uncertainties and scale dependence can be similar in high p_T regions

ttW with dynamical & fixed scale

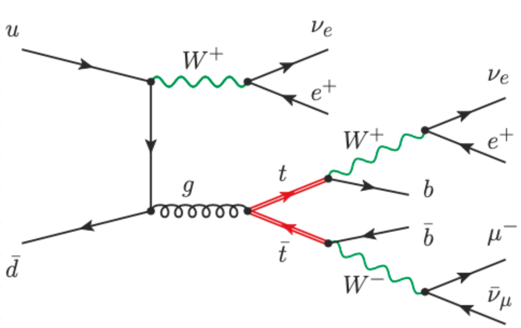
HELAC-NLO

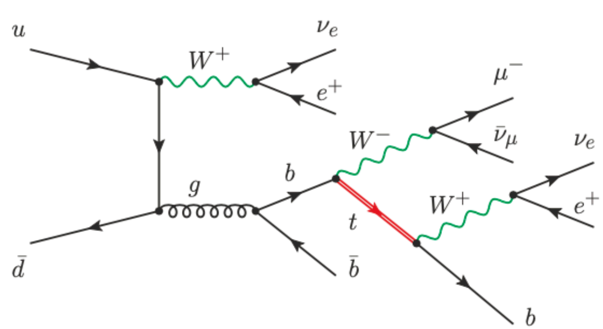
Bevilacqua, Bi, Hartanto, Kraus, Worek '20

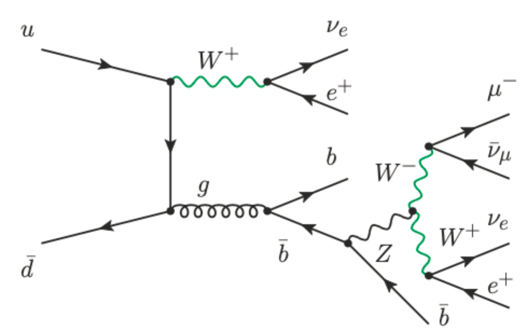
Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
NWA ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\rm NWA_{LOdecay}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

Results for various approaches for modelling of top quark production and decays

- Complete top-quark off-shell effects ⇨ ***0.2%***
- NLO QCD corrections to top-quark decays ⇨ ***3%*** for fixed scale ⇨ ***5%*** for dynamical scale
- Theoretical uncertainties are similar for off-shell case and NWA ⇨ ***6% − 7%***
- For $\rm NWA_{LOdecay}$ ⇨ Rise up to ***10% − 11%***







ttW with dynamical scale

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

HELAC-NLO

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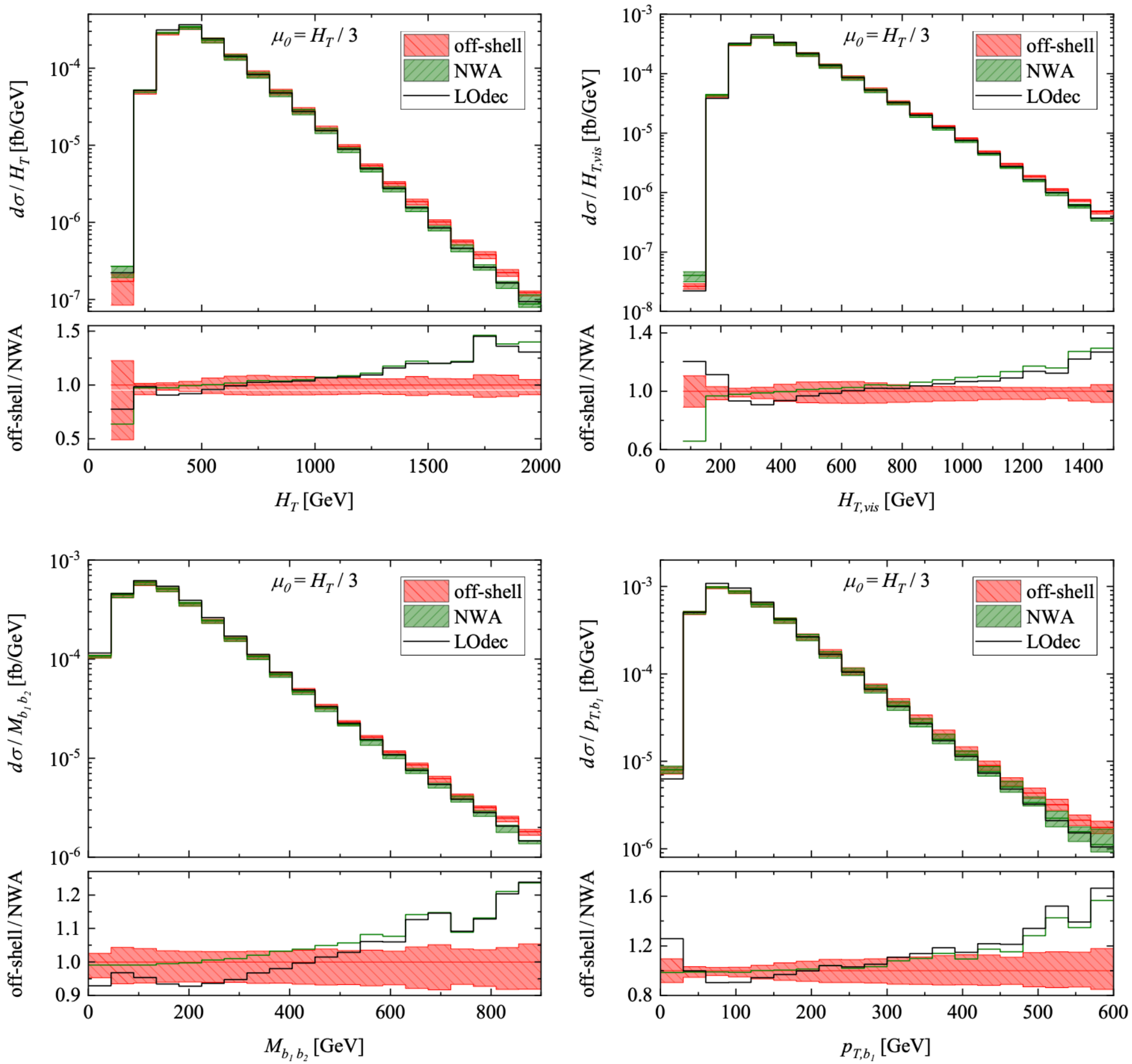


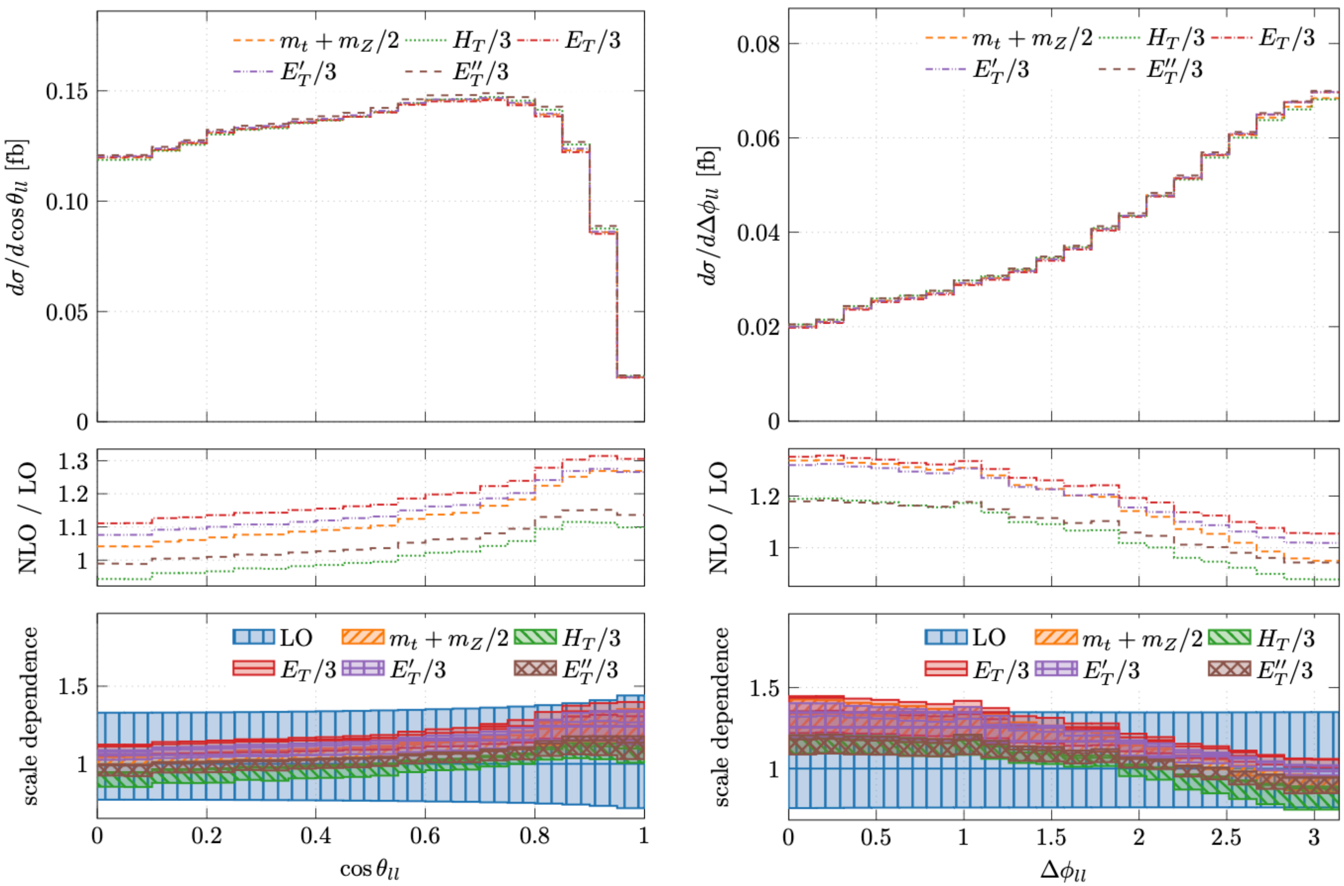
- Top-quark off-shell effects ***30% − 70%***
- Large discrepancies between full NWA description & $\mathrm{NWA_{LOdecay}}$
- Differences also in regions currently scrutinised by ATLAS & CMS experiments

ttZ ($Z \rightarrow \nu\nu$) with dynamical scale

HELAC-NLO

- Searches of new physics ⇨ $t\bar{t} + p_T^{miss}$
- New physics observables ⇨ p_T^{miss}, $\cos_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta y_{\ell\ell}$, H_T, E_T

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



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- Uncertainties reduced when going from LO to NLO
- Substantial non-flat K-factors

ttZ ($Z \to \nu\nu$) with dynamical scale

HELAC-NLO

- Searches of new physics ⇨ $t\bar{t} + p_T^{miss}$
- New physics observables ⇨ p_T^{miss}, $\cos_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta y_{\ell\ell}$, H_T, E_T

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

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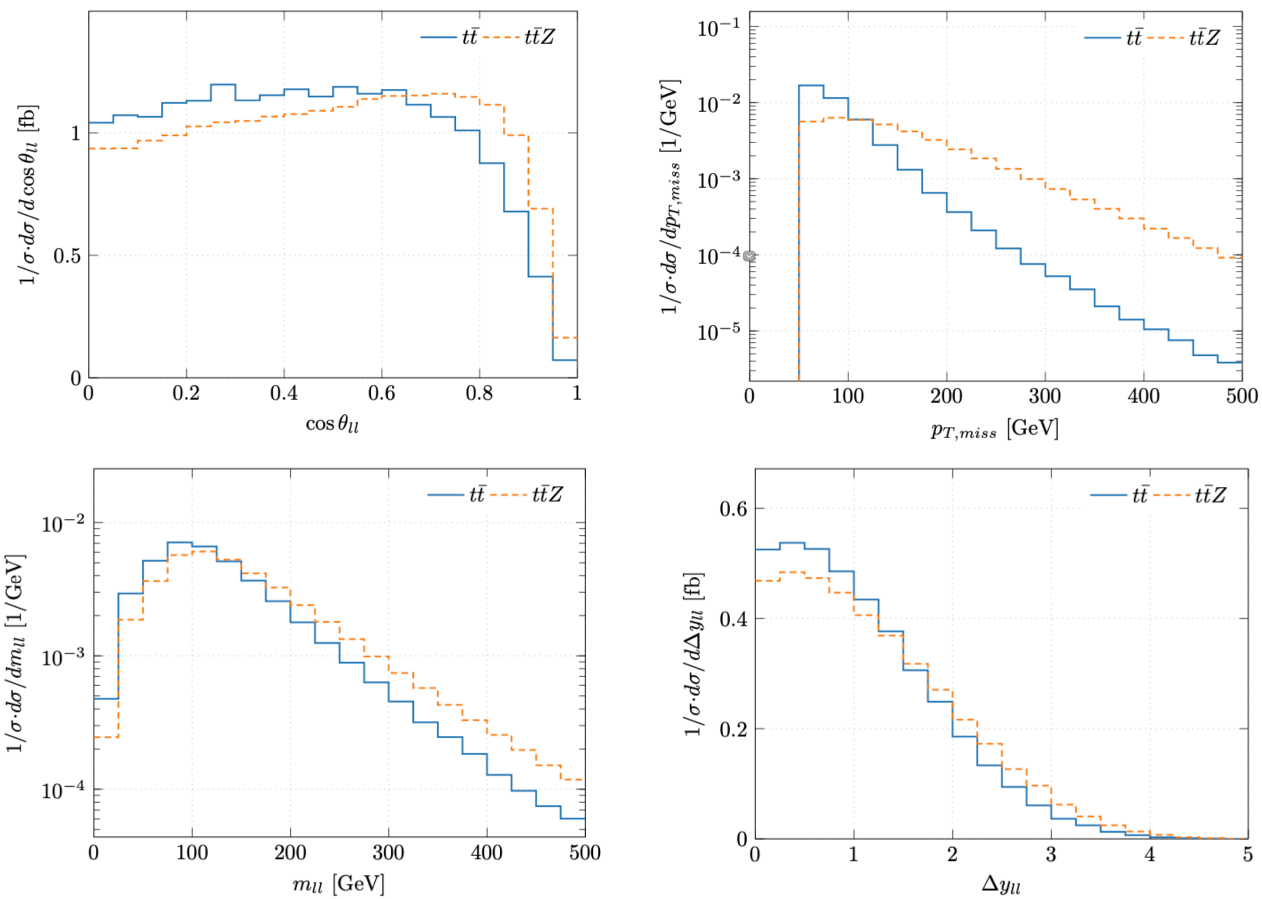

- Reducible and irreducible backgrounds
- tt production process does not exhibit long enough tails in p_T^{miss}
- Might impact exclusion limits

Summary

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

- NNLO QCD corrections to ***tt*** in NWA (di-lepton decay channel)

- NLO QCD corrections to ***ttV*** (top quarks in di-lepton channel)
  - Corrections to production & decays ⇨ NLO ***tt*** spin correlations
  - Possibility of using kinematic-dependent μ_R & μ_F scales
  - 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 results for ***tt, ttγ, ttZ, ttW***
  - Stored ⇨ ***Ntuples Files*** ⇨ ***Les Houches & ROOT Files***

Backup Slides

Various Phase-space Regions

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

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 $\sigma_{tt\gamma}$ → *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%