A detailed comparison of QCD modelling

$pp \to t\bar{t}W^{\pm}$ production

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Outline

Motivations for $t\bar{t}W^{\pm}$ at the LHC

Recent theory advances:

- EW corrections, NNLL resumation
- off-shell effects, multi-jet merging,...

Open Questions

- Production of $t\bar{t}W^{\pm}$
- Decay of (polarized) top-quarks

Summary

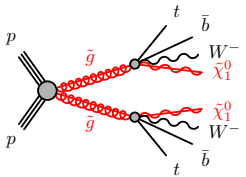
Motivations for $t\bar{t}W^{\pm}$ at the LHC

Motivations for $t\bar{t}W^{\pm}$ at the LHC

$t\bar{t}W^{\pm}$ offers one of the rarest and most complex signatures in the SM

- Irreducible background to BSM searches

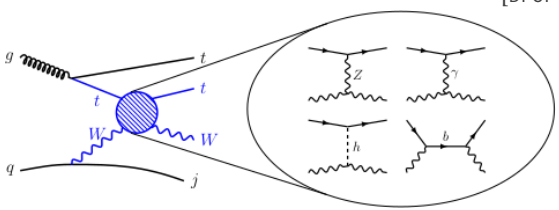
e.g. SUSY



[ATLAS, arXiv:1602.09058]
[ATLAS, arXiv:1706.03731]
[CMS, arXiv:1605.03171]
[CMS, arXiv:1704.07323]

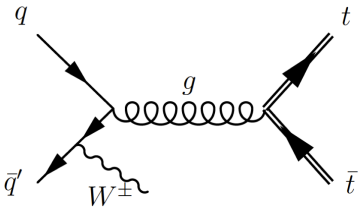
- anomalous top-quark couplings, EFT interpretations

[Dror et al., arXiv:1511.03674]



- **Dominant background for SM $t\bar{t}H$ and $t\bar{t}t\bar{t}$ multi-lepton signatures**

[ATLAS,arXiv:2007.14858]



Top quarks are produced highly polarized

- large charge asymmetries of top decay products

Symmetric gg channel only opens up at NNLO

LO: $q\bar{q}'$ **NLO:** $q\bar{q}' + qg$ **NNLO:** $q\bar{q}' + qg + gg$

		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$
	$A_c^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$

[Maltoni et al., arXiv:1406.3262]

Theoretical Status at the LHC

NLO fixed-order

- NLO QCD + EW - inclusive production
  - stable top quarks

  Hirschi et al.'11 Maltoni et al.'15
  Frixione et al.'15 Frederix et al.'17
- NLO QCD - onshell production × decay
  - NLO in prod. and decay, spin correlations

  Campbell and Ellis'12
- NLO QCD - complete off-shell
  - resoant and non-resonant diagrams, interferences and finite-width effects

  Bevilacqua, Bi, Hartanto, MK, Worek'20
  Denner and Pelliccioli'20

NLO + Resummation

- NLO +NNLL QCD + EW
  - stable top-quarks

  Li et al.'14 Broggio et al.'16
  Broggio et al.'19 Kulesza et al.'18'20

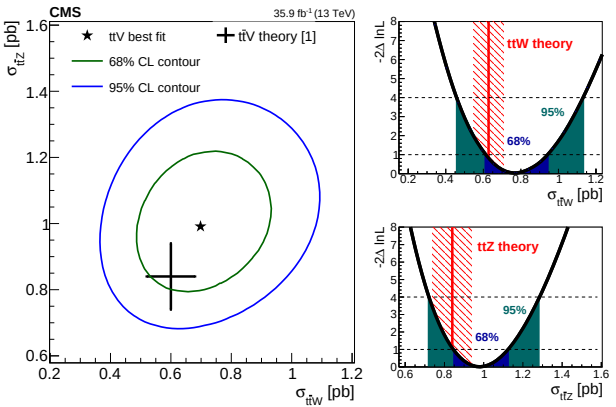
NLO + Parton Shower

- NLO + PS QCD + EW
  - top decays @ LO

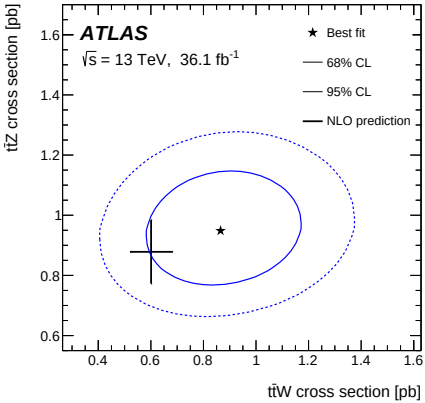
  Garzelli et al.'12 Maltoni et al.'14'15
  Frederix and Tsinikos'20
- NLO + PS multi-jet merging
  - top decays @ LO

  von Buddenbrock et al.'20
  ATLAS simulation'20

inclusive $t\bar{t}W^{\pm}$ and $t\bar{t}Z$ cross section measurements at $\sqrt{s} = 13$ TeV



CMS, arXiv:1711.02547

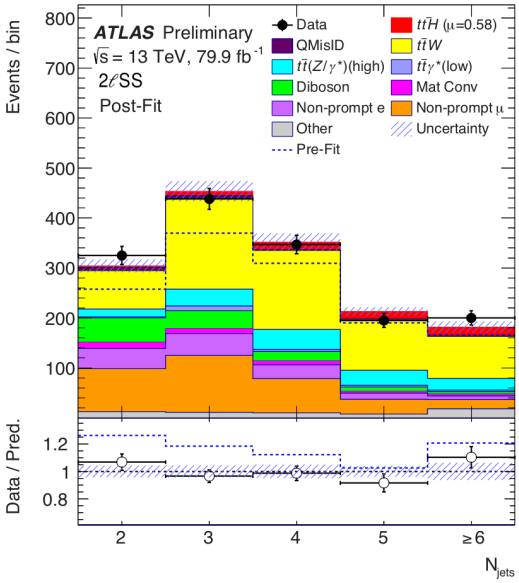


ATLAS, arXiv:1901.03584

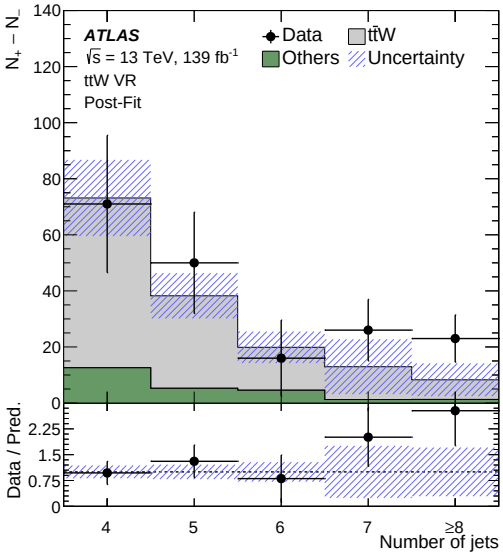
Both experiments see an excess of $t\bar{t}W$ events wrt to the Standard Model

[ATLAS-CONF-2019-045]

Dominant background for SM $t\bar{t}H$ and $t\bar{t}t\bar{t}$ multi-lepton signatures



ATLAS-CONF-2019-045



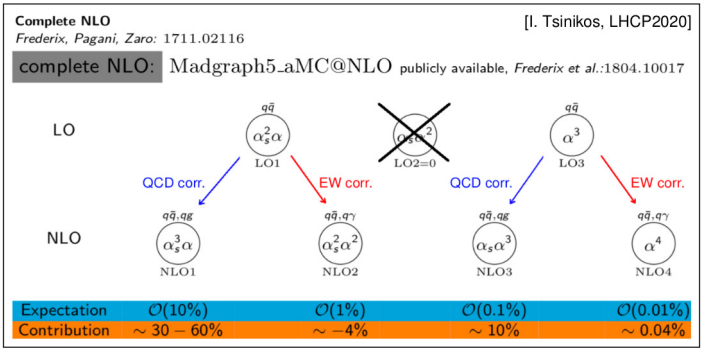
ATLAS, arXiv:2007.14858

A significant normalisation of the $t\bar{t}W$ background ~ 1.7 is necessary

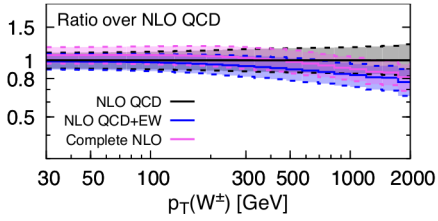
Recent advances in theory

EW corrections for stable top-quarks

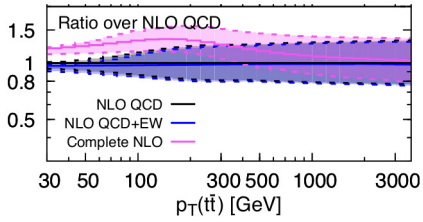
Surprisingly large corrections



13 TeV



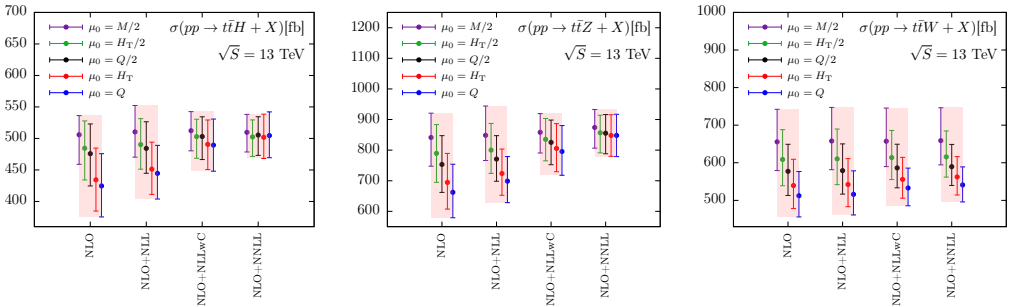
100 TeV



[Frederix,Pagani,Zaro arXiv:1711.02116]

NNLL Resummation

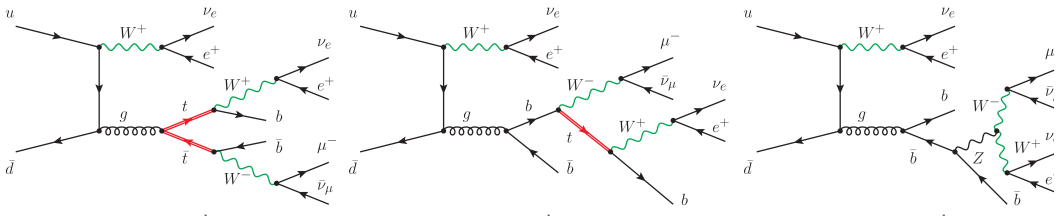
- Soft-gluon resummation
- no gg channel for $t\bar{t}W^{\pm}$
- Scale dependence significantly reduced for $t\bar{t}H$ and $t\bar{t}Z$
- Marginal impact on $t\bar{t}W^{\pm}$
  - **Is this a hint that NNLO is needed?**



[Kulesza et al. arXiv:2001.03031]

Beyond stable tops

- off-shell contributions to $t\bar{t}W^+$



Double resonant Single resonant Non-resonant

- Narrow-width approximation (NWA)

$$\frac{1}{(p^2 - m_t^2)^2 + m_t^2\Gamma_t^2} \to \frac{\pi}{m_t\Gamma_t}\delta(p^2 - m_t^2) + \mathcal{O}\left(\frac{\Gamma_t}{m_t}\right)$$

Keeps only double resonant contributions

- How large are these effects at the differential level?
- What is the impact of QCD corrections on the top decay?

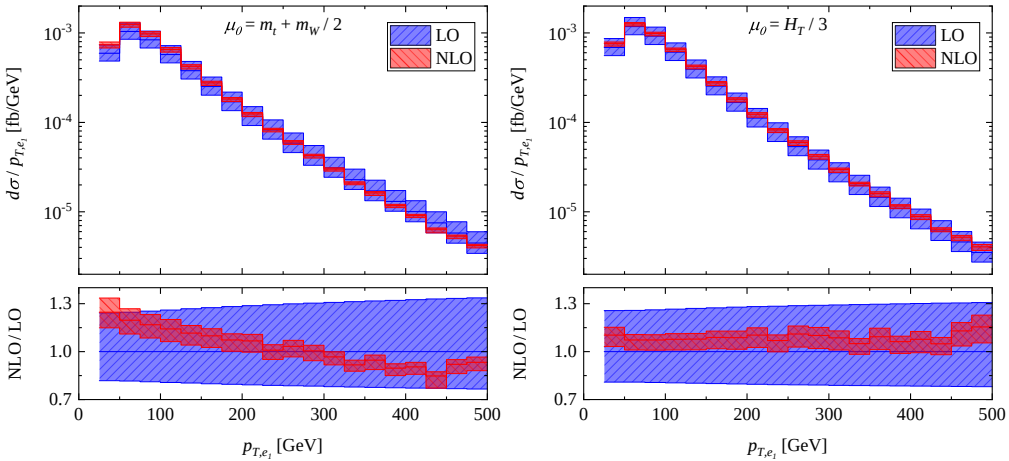
Impact of radiative top decays in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV

Modelling Approach	σ^{LO} [ab]	σ^{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 ($\mu_0 = H_T/3$)	$115.1^{+30.4\,(26\%)}_{-22.4\,(19\%)}$	$124.2^{+4.1\,(3\%)}_{-7.7\,(6\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = m_t + m_W/2$)		$127.0^{+14.2\,(11\%)}_{-13.3\,(10\%)}$
$\text{NWA}_{\text{LOdecay}}$ ($\mu_0 = H_T/3$)		$130.7^{+13.6\,(10\%)}_{-13.2\,(10\%)}$

- The full NWA reproduces the off-shell computation excellently
- NLO QCD corrections to the decay reduce the scale uncertainty

[Bevilacqua, Bi, Hartanto, MK, Worek, arXiv:2005.09427]

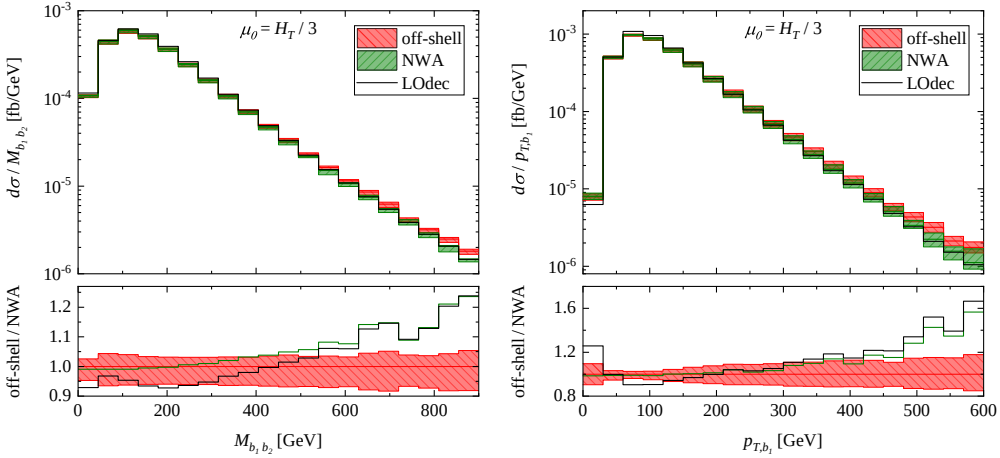
Impact of NLO QCD corrections in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV



- Dynamic scales gives better perturbative convergence
- Uncertainties are below 10% independently of scale choice

[Bevilacqua, Bi, Hartanto, MK, Worek, arXiv:2005.09427]

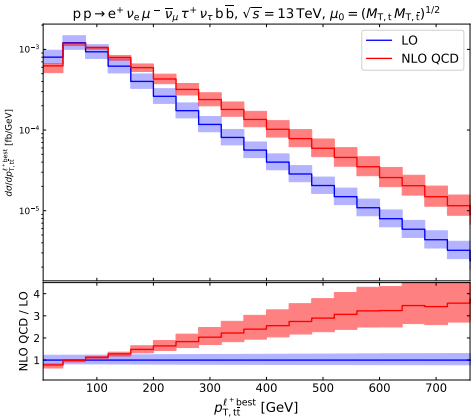
Impact of radiative top decays in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV

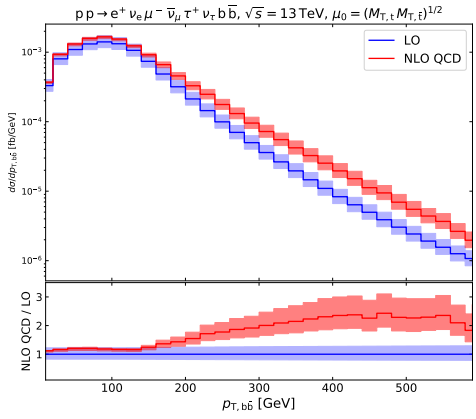


- Large off-shell effects in the tails of the distributions
- Differences between NWA and $\text{NWA}_{\text{LOdec}}$ are $\mathcal{O}(10\%)$ in the bulk

[Bevilacqua, Bi, Hartanto, MK, Worek, arXiv:2005.09427]

Impact of radiative corrections in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV

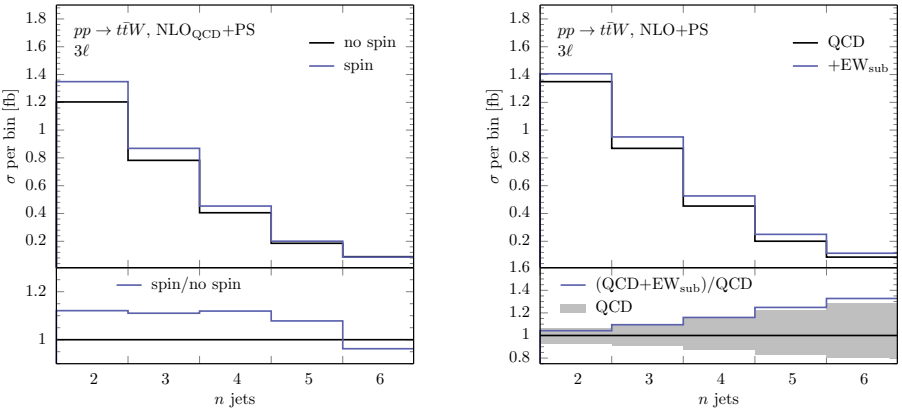




- Large recoil effects from additional QCD radiation
- LO effect ~ LO uncertainties

[Denner, Pelliccioli, arXiv:2007.12089]

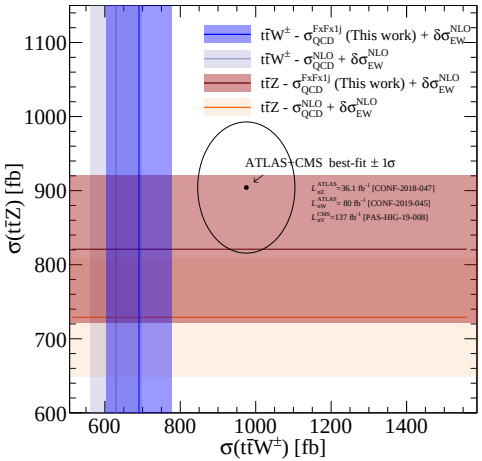
on-shell $t\bar{t}W$@ NLO matched to parton shower



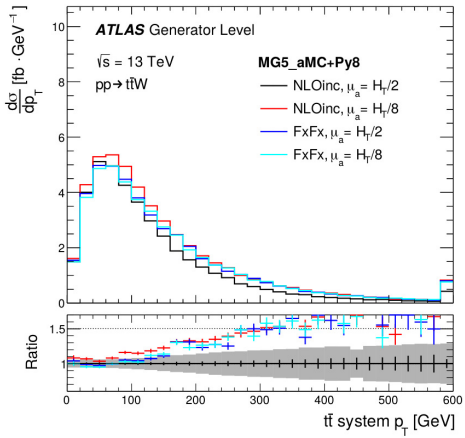
- Spin correlations increase low jet-multiplicty
- Subleading EW contributions increase high jet-multiplicty
- Effects also visible in other observables
- Top-quark decay modelled at LO (MadSpin)

[Frederix, Tsinikos, arXiv:2004.09552]

on-shell $t\bar{t}W$@ NLO multi-jet merging



[Buddenbrock et al. arXiv:2009.00032]



[ATL-PHYS-PUB-2020-024]

- Slight improvement on the total cross section
- Severe corrections to differential distributions

Open Questions

All these studies leave us with the following questions:

Q1: Given all the recent progress what is the best way to move forward?

- Do we ultimately need an off-shell $t\bar{t}W^{\pm}$ @ NLO+PS?

Q2: Are the studied effects the bulk of higher-order corrections or are we still missing **important** higher-order contributions?

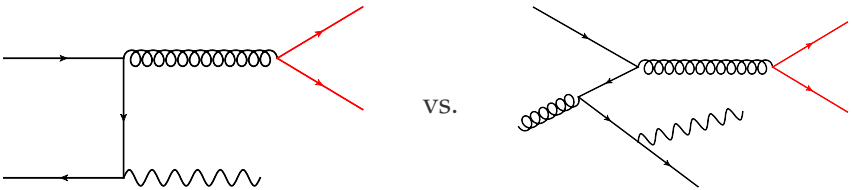
- Do we ultimately need $t\bar{t}W^{\pm}$ @ NNLO?

Q3: Given the sizeable impact of off-shell effects and NLO corrections to the top decay; How well are these effects captured by standard event generators?

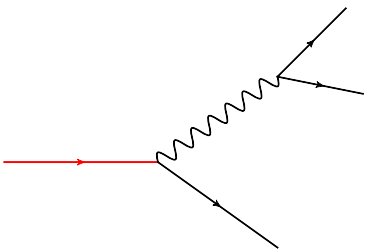
Divide and conquer

The QCD modelling of $t\bar{t}W^{\pm}$ can be roughly divided into two parts

- Modelling of the **production** of the $t\bar{t}W^{\pm}$ final state

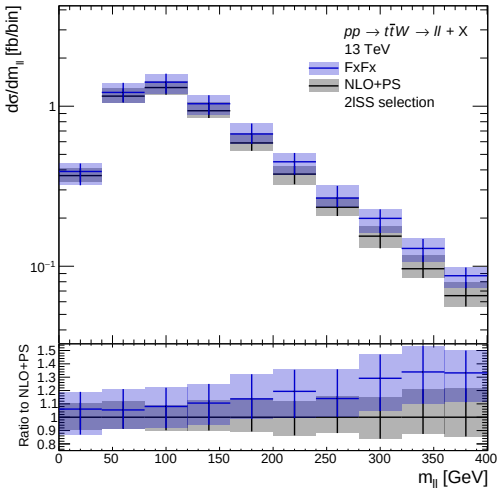


- Modelling of the **decay** of the $t\bar{t}W^{\pm}$ final state



Modelling of the production of $t\bar{t}W^{\pm}$

- **No gg channel at NLO for $t\bar{t}W^{\pm}$**
  - Might be sensitive to modelling of initial-state radiation
- Include QCD rad. via multi-jet merging
  - $t\bar{t}W^{\pm}$ and $t\bar{t}W^{\pm} + j$ @ NLO
  - $t\bar{t}W^{\pm} + jj$ and $t\bar{t}W^{\pm} + jjj$ @ LO
- Recent studies with MG5_aMC + FxFx:
  - [arXiv:2009.00032]
  - [ATL-PHYS-PUB-2020-024] (also Sherpa)
- Study multi-jet merging with: Sherpa + MEPS@NLO
- Focus on fiducial observables: b-jets, leptons, missing p_T



[Buddenbrock et al. arXiv:2009.00032]

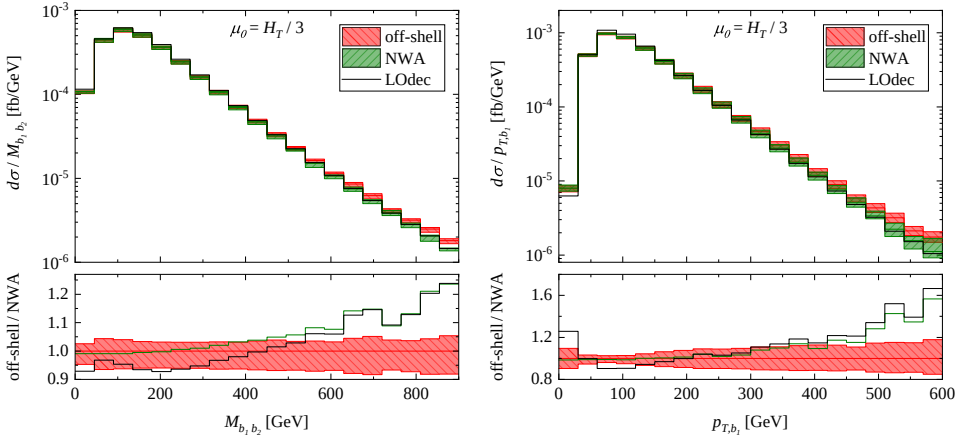
Question:

What is the impact of higher jet multiplicities on fiducial observables?

Modelling of the decay of $t\bar{t}W^{\pm}$

- QCD corrections to top decay can be sizeable $\sim \mathcal{O}(10\%)$

[arXiv:2005.09427]

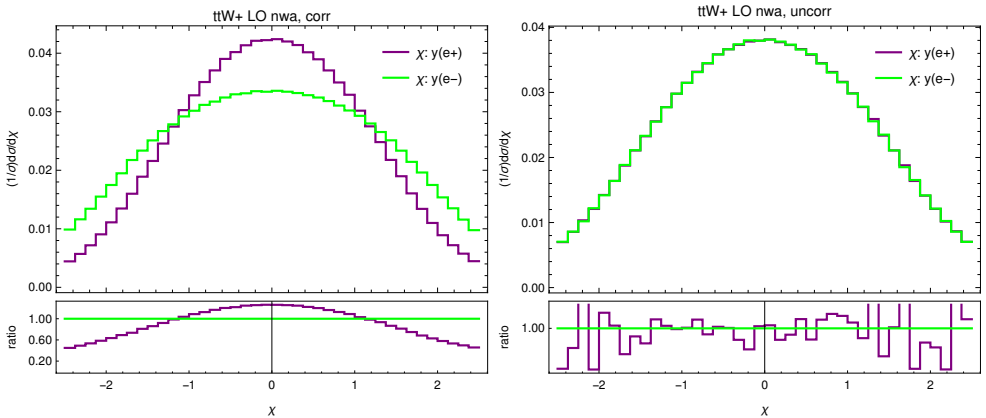


Question:

How much of these features are captured by standard event generators?

Modelling of the decay of $t\bar{t}W^{\pm}$

- QCD corrections to top decay can be sizeable $\sim \mathcal{O}(10\%)$
- Tops are **highly polarized**, spin correlations are sizeable



e^+ from top and e^- from anti-top

Question:

How much of these features are captured by standard event generators?

Summary

Summary

Study A: Production of $t\bar{t}W^{\pm}$

- Multi-jet merging to address impact of higher order QCD radiation
- Polarization effects in higher multiplicity predictions?

Study B: Decay of $t\bar{t}W^{\pm}$

- A detailed comparison of standard event generators with fixed-order NLO off-shell computation.
- How sizeabe are the differences?
- How well does the parton shower capture corrections to the top decay?

Goal:

Identify the critical effects for a proper modelling of the $t\bar{t}W^{\pm}$ process in a fiducial phase space volume