On the QCD modelling of $t\bar{t}W^{\pm}$ signatures

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Radcor & LoopFest
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Outline

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

- the need for high precision
- state of the art

on-shell $t\bar{t}W$ – parton showers

- Inclusive signature
- Two same-sign leptons

off-shell $t\bar{t}W$ – multi-leptons

- Size of NLO QCD corrections
- off-shell vs. Narrow-width approximation

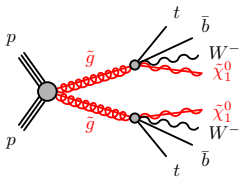
Summary & Outlook

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

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

- Irreducible background to BSM searches

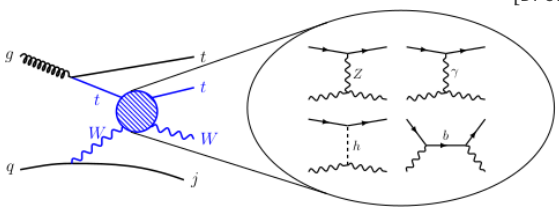
e.g. SUSY



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

- anomalous top-quark couplings, EFT interpretations

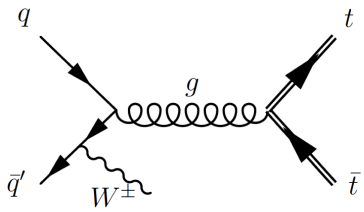
[Dror et al, arXiv:1511.03674]



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

[ATLAS,arXiv:2007.14858]

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

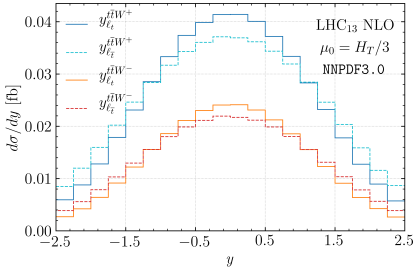


Top quarks are produced highly polarized

- 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:** $q\bar{q}' + qg + gg$

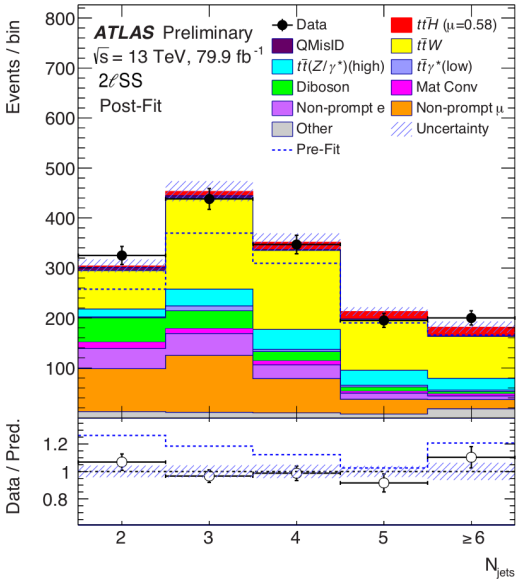


		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$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

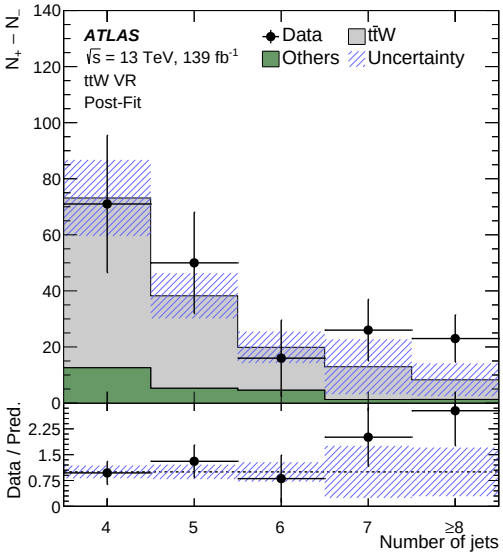
[Bevilacqua, Bi, Hartanto, MK, Nasufi, Worek'21]

[Maltoni et al., arXiv:1406.3262]

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

Theory status

NLO fixed order

- NLO QCD + EW: inclusive production [Hirschi et al'11, Maltoni et al'15]

→ stable top-quarks [Frixione et al'15, Frederix et al'17]

- NLO QCD: on-shell decay × production [Campbell and Ellis'12]

→ QCD corrections to production and decy, spin correlations

- NLO QCD + EW: complete off-shell

→ (non-) resonant diagrams, finite width-effects

[Bevilacuqa, Bi, Hartanto, MK, (Nasufi), Worek'20 ('21)]

[Denner and Pelliccioli'20] [Denner and Pelliccioli'21]

NLO + resummation

-NLO+NNLL QCD + EW: inclusive production [Li et al'14, Broggio et al'16]

→ stable top-quarks [Broggio et al'19, Kulesza et al'18'20]

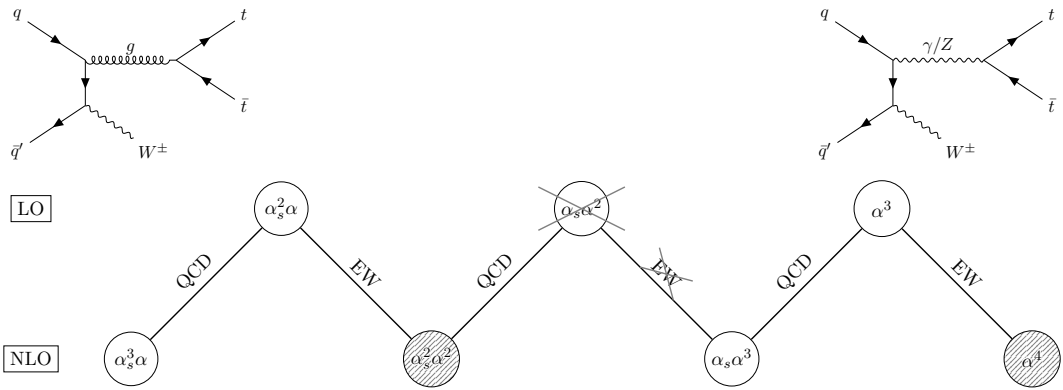
NLO + parton shower

- NLO+PS QCD + EW: on-shell [Garzelli et al'12, Maltoni et al'14'15]

→ top decays at LO [Frederix and Tsinikos'20] [Febres Cordero, MK, Reina'21]

- Multi-jet merging [von Buddenbrock et al'20, ATLAS'20]

Anatomy of higher-order corrections



Perturbative corrections

- $\mathcal{O}(\alpha_s^3\alpha)$ – (50%) dominant NLO QCD corrections
- $\mathcal{O}(\alpha_s^2\alpha^2)$ – (−4%) mixed QCD-EW corrections
- $\mathcal{O}(\alpha_s\alpha^3)$ – (10%) NLO QCD corrections
- $\mathcal{O}(\alpha^4)$ – sub per mill NLO EW corrections [Frederix et al arXiv:1711.02116]

on-shell $t\bar{t}W$ – parton showers

Generator comparison

[Febres Cordero, MK, Reina arXiv:2101.11808]

	POWHEG-BOX	MG5_aMC@NLO	Sherpa
$\mathcal{O}(\alpha_s^3\alpha)$	POWHEG	MC@NLO	MC@NLO
$\mathcal{O}(\alpha_s\alpha^3)$	POWHEG	MC@NLO	tree-level merg.
Decay	spin/no spin	MadSpin	spin-density mat.
Shower	Pythia8	Pythia8	CS shower

Two comparative analyses

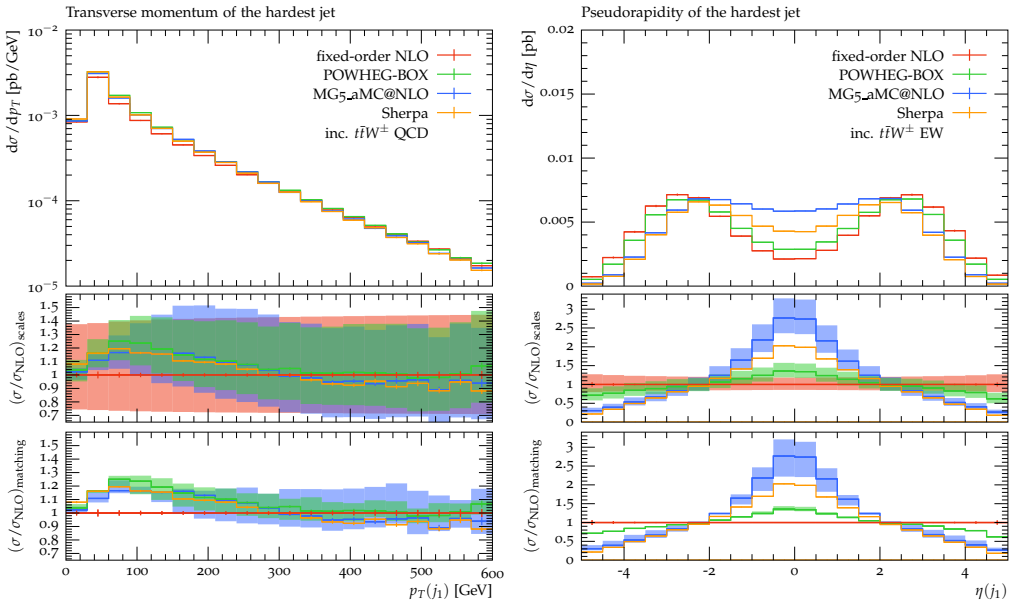
- Stable top quarks – Fully inclusive
- Unstable top quarks – Two same-sign leptons

$$
\begin{aligned}
&p_T(\ell) > 15\ \text{GeV}\,, \qquad |\eta(\ell)| < 2.5\,,\\
&p_T(j) > 25\ \text{GeV}\,, \qquad |\eta(j)| < 2.5\,,\\
&N_{l\text{-jets}} \geq 2\,, \qquad N_{b\text{-jets}} \geq 2\,,\\
&\text{anti–}k_T\,, \qquad R = 0.4
\end{aligned}
$$

Inclusive observables - QCD vs. EW

stable tops

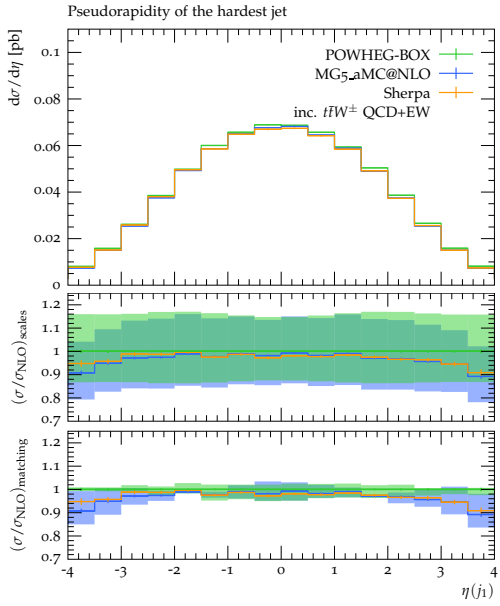
[Febres Cordero, MK, Reina arXiv:2101.11808]

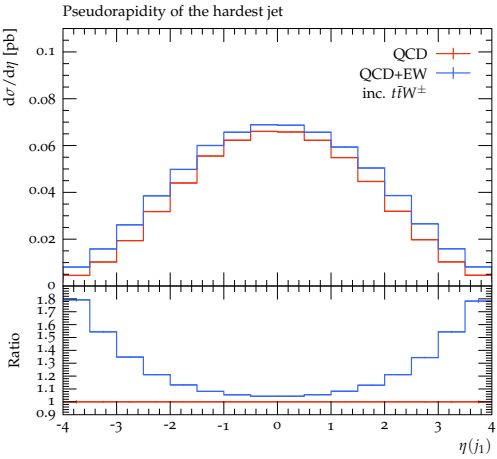


- Good agreement between generators for inc. $t\bar{t}W^{\pm}$ QCD
- Strong matching scheme dependence for inc. $t\bar{t}W^{\pm}$ EW

Inclusive observables – QCD+EW

[Febres Cordero, MK, Reina arXiv:2101.11808]



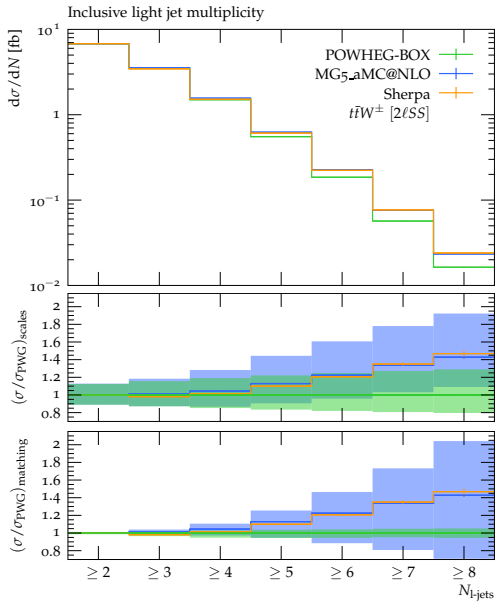


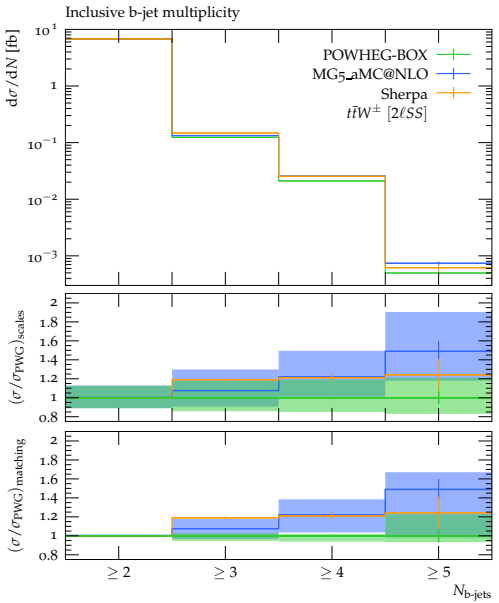
Mild impact once combined

Fiducial observables - Uncertainties

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]



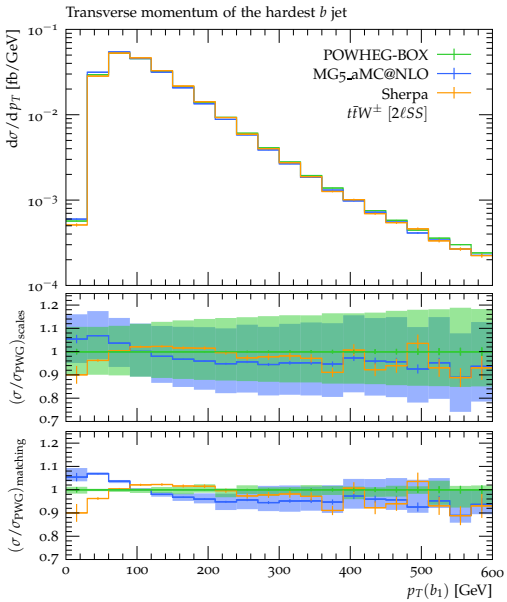


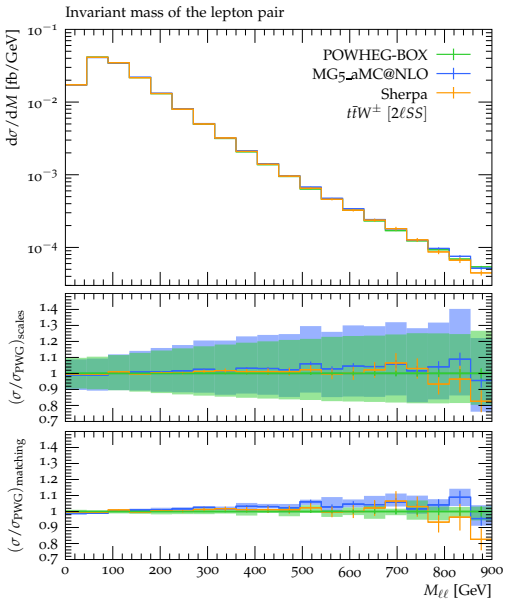
Good agreement within uncertainties

Fiducial observables - Uncertainties

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]



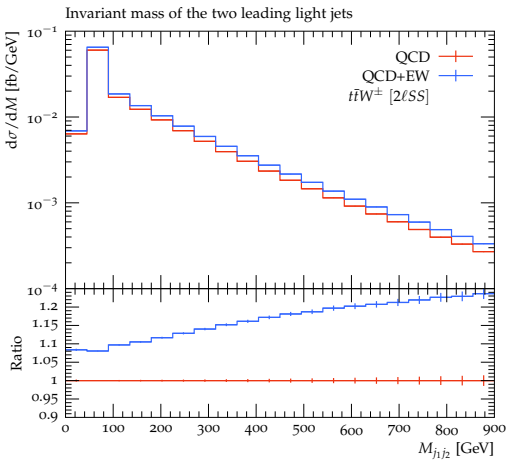


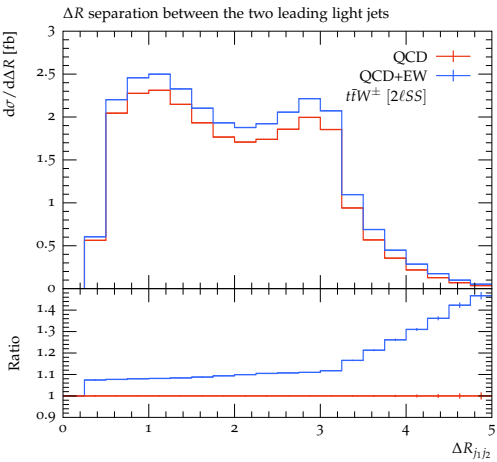
Good agreement within uncertainties

Fiducial observables - QCD vs. EW

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]



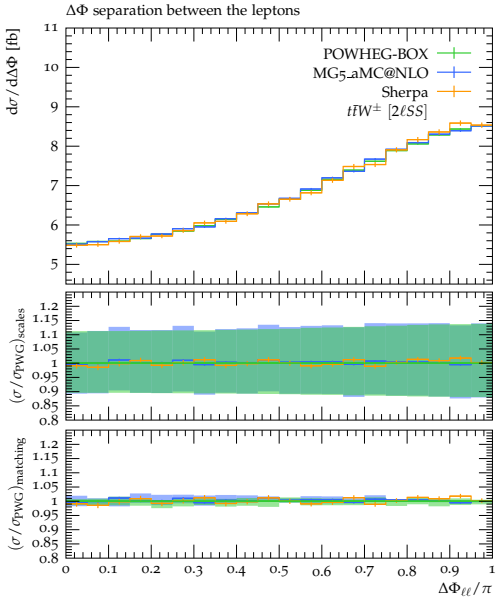


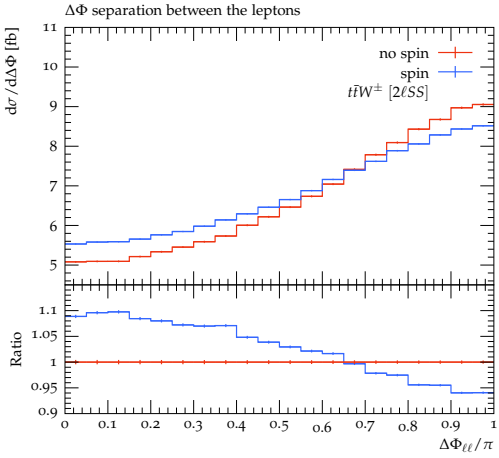
- EW contribution sizeable if sensitive to forward jets
- For most observables: flat +10% correction

Fiducial observables - Polarization effects

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]



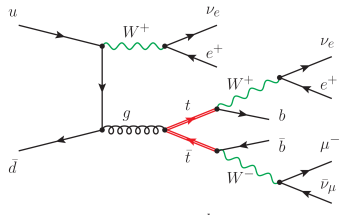


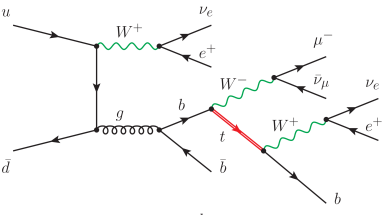
- Polarization effects modify shape by 10%
- Stronger effects for $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ separately

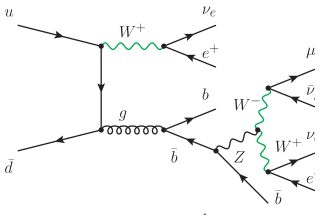
off-shell $t\bar{t}W$ – multi-leptons

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?

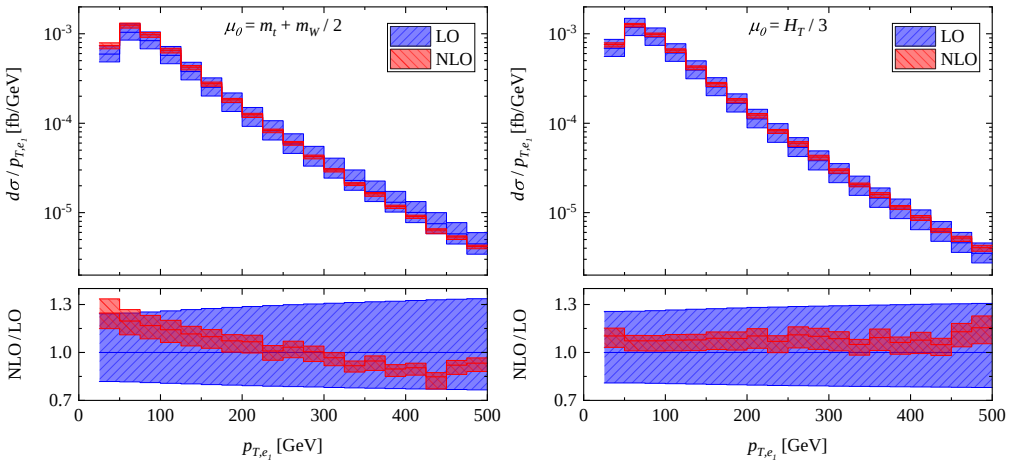
Impact of radiative top decays in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV

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]

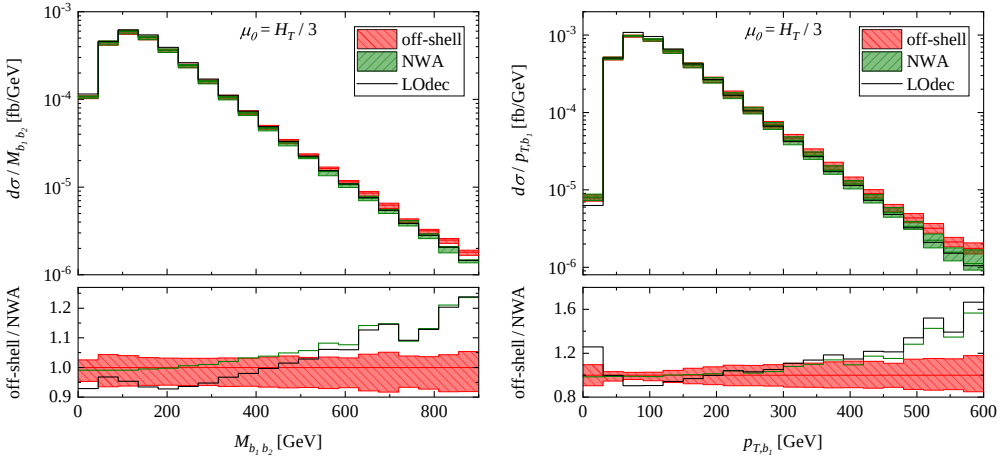
Impact of NLO QCD corrections in $pp \to e^+\nu_e e^-\bar{\nu}_e e^+\nu_e b\bar{b}$ @ $\sqrt{s} = 13$ TeV



- 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

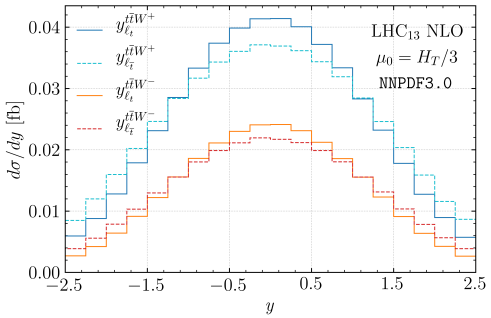


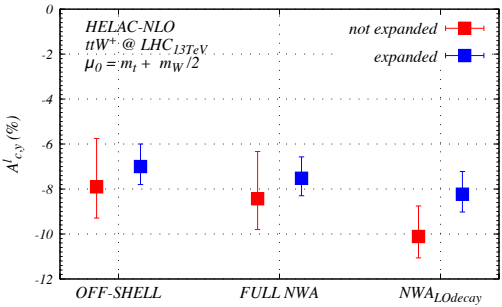
- Large off-shell effects in the tails of the distributions
- Differences between NWA and $\text{NWA}_{\text{LOdec}}$ are $\mathcal{O}(10\%)$ in the bulk

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

Leptonic charge asymmetry

$$A_c^\ell = \frac{\sigma^+_{\text{bin}} - \sigma^-_{\text{bin}}}{\sigma^+_{\text{bin}} + \sigma^-_{\text{bin}}}\,, \qquad \sigma^\pm_{\text{bin}} = \int \theta(\pm\Delta|y|)\,\theta_{\text{bin}}\,d\sigma\,, \qquad \Delta|y| = |y_{\ell_t} - y_{\ell_{\bar{t}}}|$$





- Decay modelling has large impact on charge asymmetry

[Bevilacqua, Bi, Hartanto, MK, Nasufi, Worek, arXiv:2012.01363]

Summary & Outlook

Summary

$t\bar{t}W^{\pm}$ production in the POWHEG-BOX

- NEW POWHEG-BOX generator for $t\bar{t}W^{\pm}$ at $\mathcal{O}(\alpha_s^3\alpha)$ and $\mathcal{O}(\alpha_s\alpha^3)$!
- Contribution at $\mathcal{O}(\alpha_s\alpha^3)$ very matching scheme dependent
  - only mild impact when physical signatures are considered
- Polarization effects can be sizable!
- Extensive comparision for inclusive and $2\ell SS$ signature

arXiv:2101.11808

off-shell $t\bar{t}W^{\pm}$ multi-lepton production

- non-resonant contributions sizeable in tails of distributions
- NLO QCD Corrections to decay important for
  - bulk of distributions
  - accurate description of charge asymmetry
- More details

arXiv:2005.09427 arXiv:2012.01363

Where do we go from here?

- How well do parton showers account for corrections in polarized top decays?
- Hadronic decays $\longrightarrow$ NLO QCD corrections for $W \longrightarrow q\bar{q}'$
- multi-lepton signatures $\longrightarrow$ NNLO QCD for $t\bar{t}W^{\pm}$

No universal answer

Backup

Uncertainties

POWHEG-BOX

$$\mu_R = \mu_F = \mu_0 = \frac{H_T}{2}$$

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \left\{(0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)\right\}$$

$$(h_{\text{damp}}, h_{\text{bornzero}}) = \left\{\left(\frac{H_T}{2}, 5\right), \left(\frac{H_T}{2}, 2\right), \left(\frac{H_T}{2}, 10\right), \left(\frac{H_T}{4}, 5\right), (H_T, 5)\right\}$$

MG5_aMC@NLO

$$\mu_R = \mu_F = \mu_0 = \frac{H_T}{2}$$

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0}\right) = \left\{(0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)\right\}$$

$$\mu_Q = \left\{\frac{H_T}{4}, \frac{H_T}{2}, H_T\right\}$$

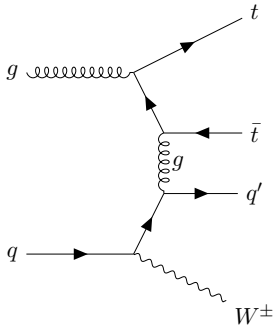
Sherpa

$$\mu_R = \mu_F = \mu_0 = \frac{H_T}{2}$$

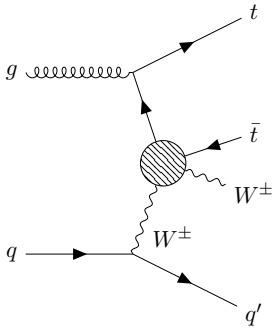
$$\mu_Q = \frac{H_T}{2}$$

Complete NLO QCD + EW corrections – II

- Origin of large QCD corrections at $\mathcal{O}(\alpha_s \alpha^3)$?

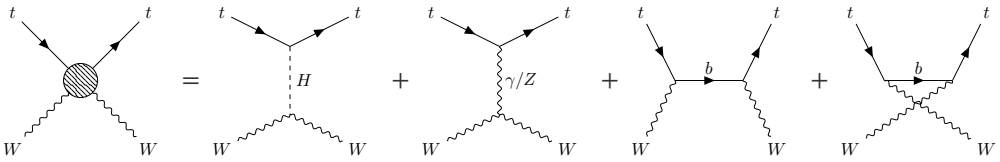


QCD



EW

- $tW \to tW$ **scattering**



How to determine which lepton comes from the top quark?

- For $t\bar{t}W^+$ there are 4 histories at LO

$$
\begin{aligned}
t &= e_1^+ \nu_{e,1} b \quad \text{and} \quad \bar{t} = \mu^- \bar{\nu}_\mu \bar{b} \\
t &= e_1^+ \nu_{e,2} b \quad \text{and} \quad \bar{t} = \mu^- \bar{\nu}_\mu \bar{b} \\
t &= e_2^+ \nu_{e,1} b \quad \text{and} \quad \bar{t} = \mu^- \bar{\nu}_\mu \bar{b} \\
t &= e_2^+ \nu_{e,2} b \quad \text{and} \quad \bar{t} = \mu^- \bar{\nu}_\mu \bar{b}
\end{aligned}
$$

- At NLO the extra jet has to be taken into account as well
- Pick history that minimizes

$$\mathbb{Q} = |M(t) - m_t| + |M(\bar{t}) - m_t|$$

- The lepton assignment is unique once a history is chosen