Parton shower effects in $t\bar{t}W^{\pm}$ at NLO QCD

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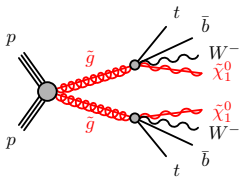
Motivations for $t\bar{t}W^{\pm}$ at the LHC

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

- Irreducible background to BSM searches

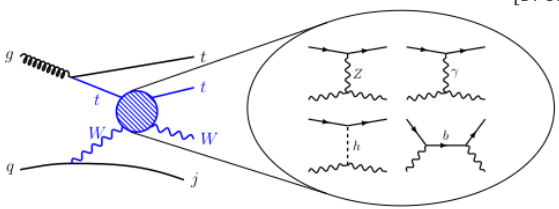
e.g. SUSY



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

- anomalous top-quark couplings, EFT interpretations

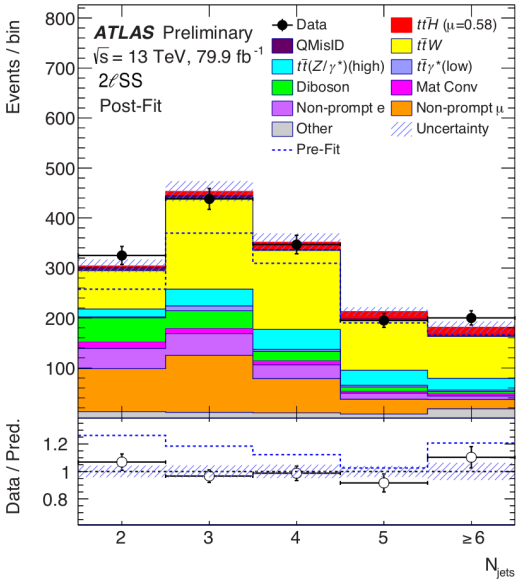
[Dror et al, arXiv:1511.03674]



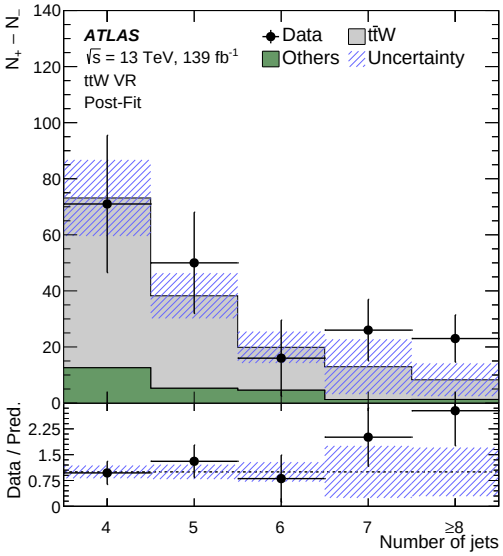
- **Dominant background for SM $t\bar{t}H$ and $t\bar{t}t\bar{t}$ multi-lepton signatures**

[ATLAS,arXiv:2007.14858]

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]

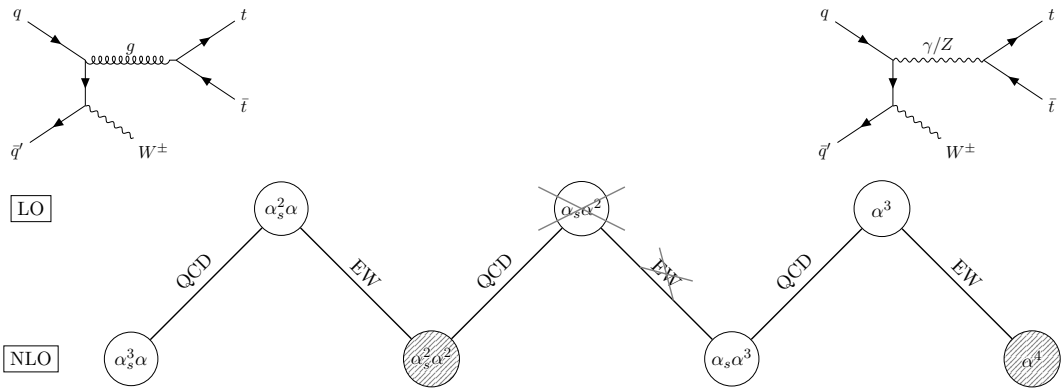
NLO + parton shower

- 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]

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

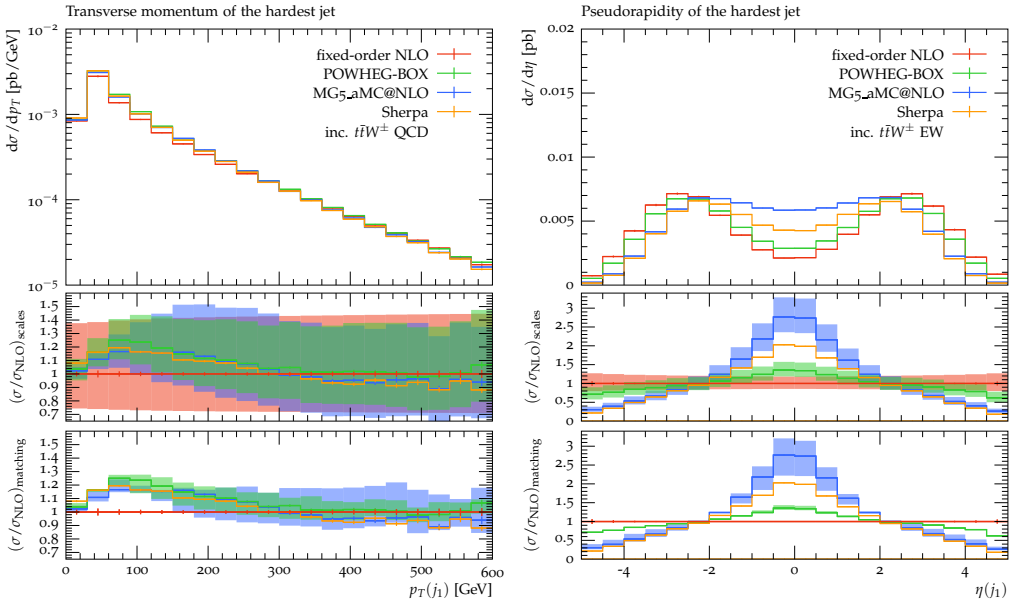
- Stable top quarks – Fully inclusive
- Unstable top quarks – Two same-sign leptons

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

Inclusive observables - QCD vs. EW

stable tops

[Febres Cordero, MK, Reina arXiv:2101.11808]

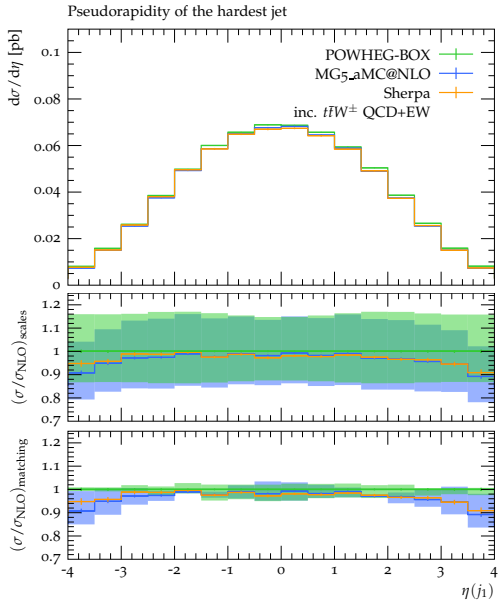


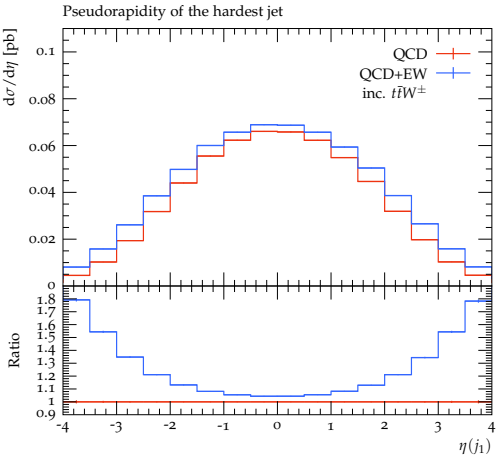
- Good agreement between generators for inc. $t\bar{t}W^{\pm}$ QCD
- Strong matching scheme dependence for inc. $t\bar{t}W^{\pm}$ EW

Inclusive observables – QCD+EW

stable tops

[Febres Cordero, MK, Reina arXiv:2101.11808]



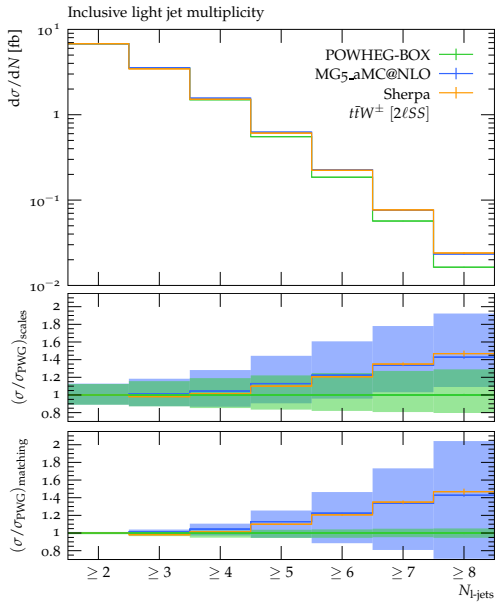


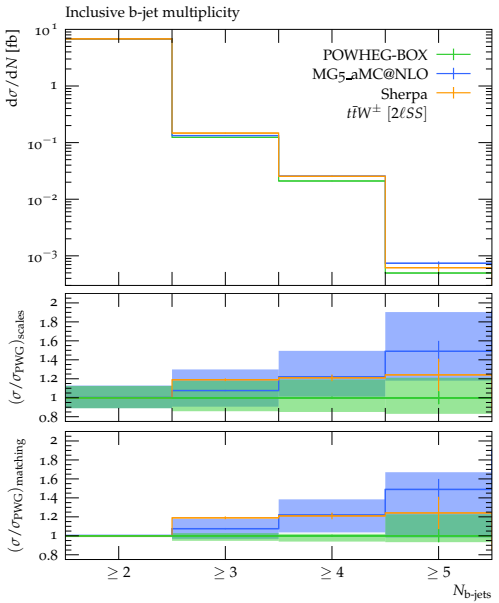
Mild impact once combined

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

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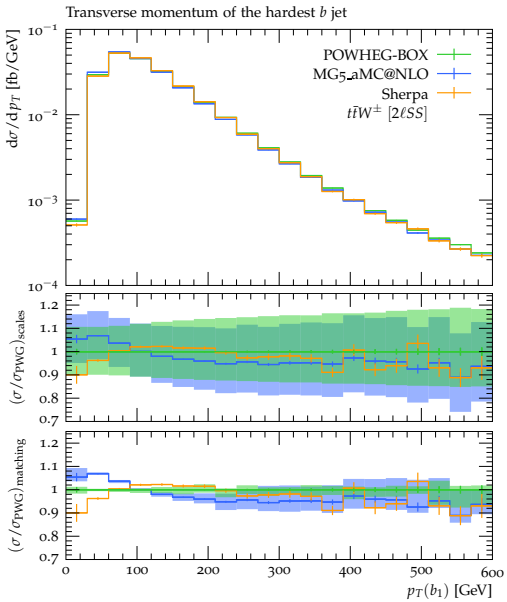
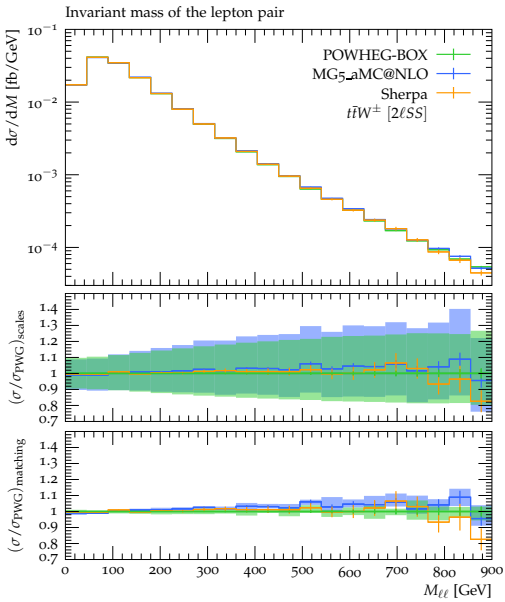
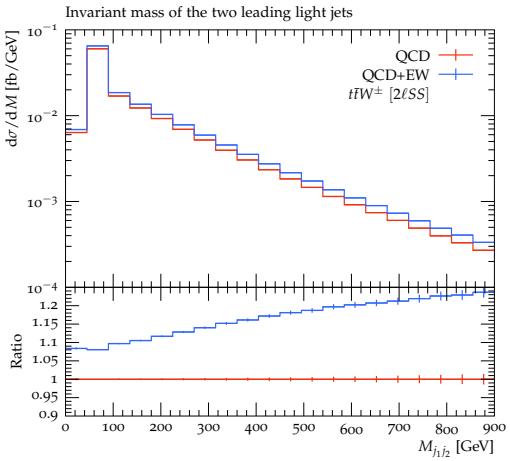


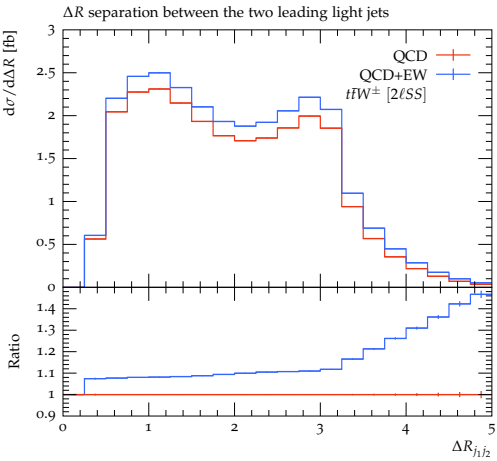


Good agreement within uncertainties

Fiducial observables - QCD vs. EW

[Febres Cordero, MK, Reina arXiv:2101.11808]





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

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 $\mathcal{O}(\alpha_s\alpha^3)$!

  http://powhegbox.mib.infn.it

- 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

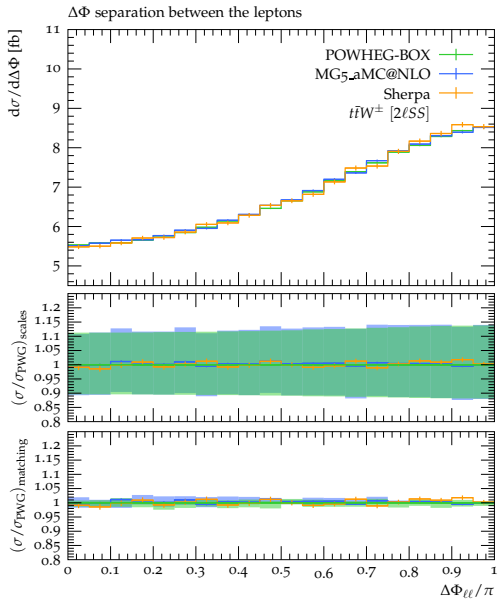
  Phys. Rev. D 103 094014

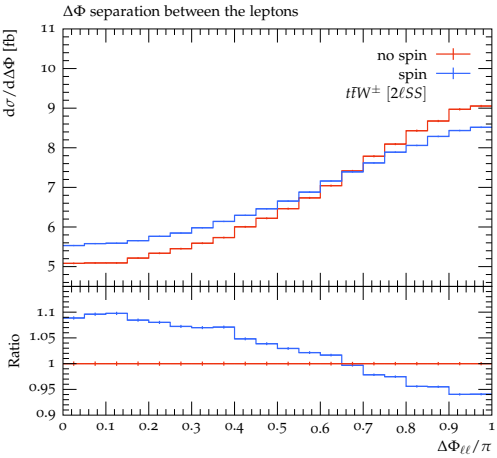
Outlook

- Detailed comparison with full off-shell $t\bar{t}W^{\pm}$ for multi lepton signatures

Backup

Polarization effects





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

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

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

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

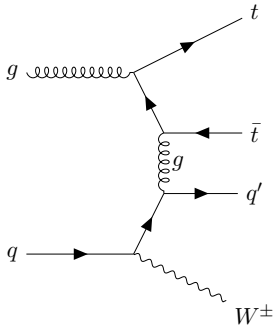
Sherpa

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

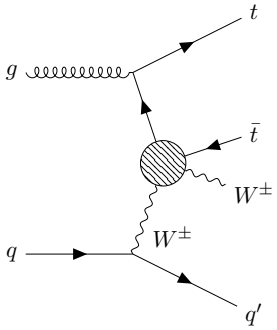
$$\mu_Q = \frac{H_T}{2}$$

Complete NLO QCD + EW corrections

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



QCD



EW

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