

Modelling $t\bar{t}W^\pm$ final states in the POWHEG-BOX

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CERN – LHC TOP WG Meeting

20. May 2021

Based on Phys. Rev. D **103** 094014



Outline

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

- the need for high precision
- Anatomy of higher-order corrections

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

- The POWHEG method in a nutshell
- Inclusive signature
- Two same-sign leptons

Summary & Outlook

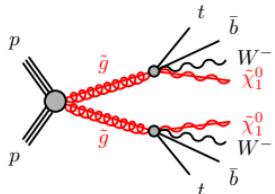
Motivations for $t\bar{t}W$ at the LHC

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]

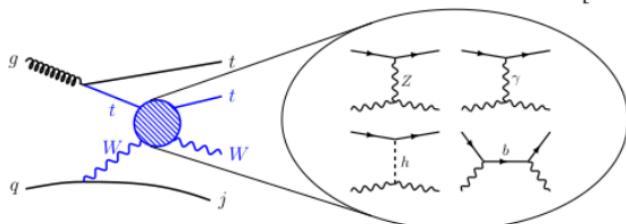
[ATLAS, arXiv:1706.03731]

[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

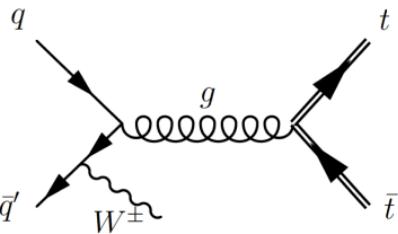
[ATLAS, arXiv:2007.14858]

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

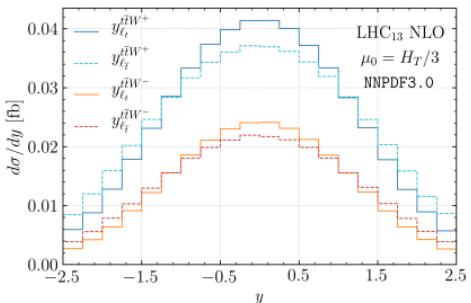
Top quarks are produced highly polarized

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



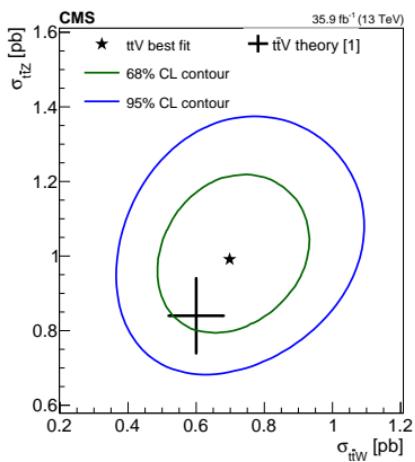
		8 TeV	13 TeV	14 TeV
$t\bar{t}$	$\sigma(\text{pb})$	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^\pm$	$\sigma(\text{fb})$	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$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

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

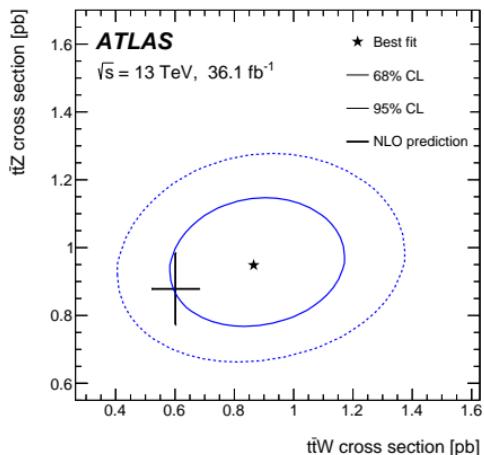
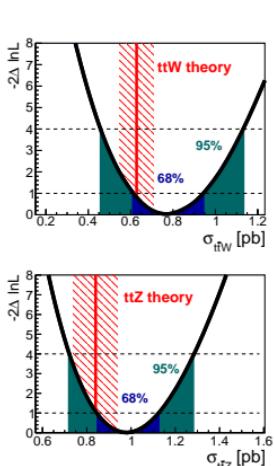
[Maltoni et al., arXiv:1406.3262]

Experimental Status at the LHC – I

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



CMS, arXiv:1711.02547

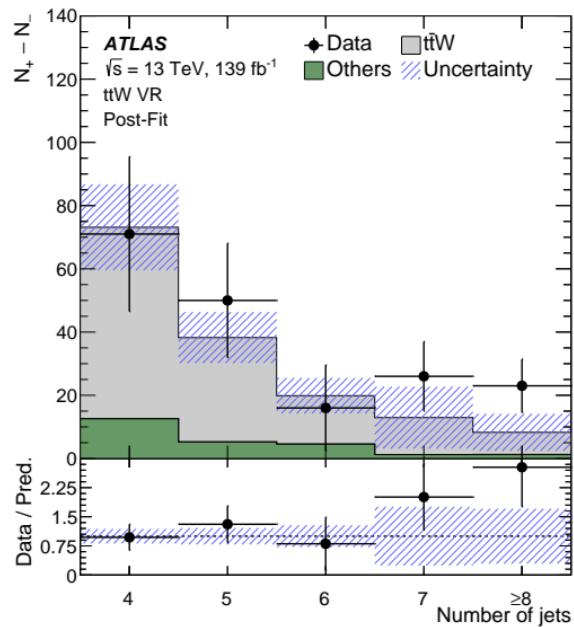
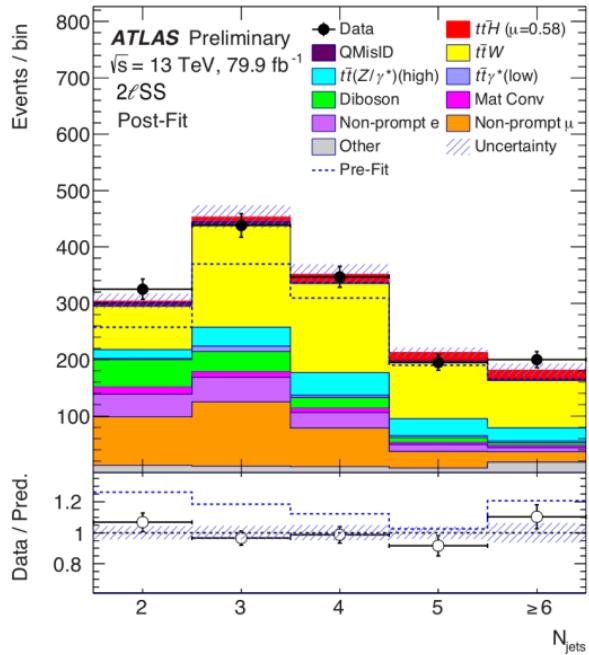


ATLAS, arXiv:1901.03584

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

Experimental Status at the LHC – II

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 $\sim 1.3 - 1.7$ 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 decay, spin correlations
- NLO QCD + EW: complete off-shell
→ (non-) resonant diagrams, finite width-effects
 - [Bevilacqua, Bi, Hartanto, MK, Nasufi, Worek'20 ('21)]
 - [Denner and Pelliccioli'20] [Denner and Pelliccioli'21]

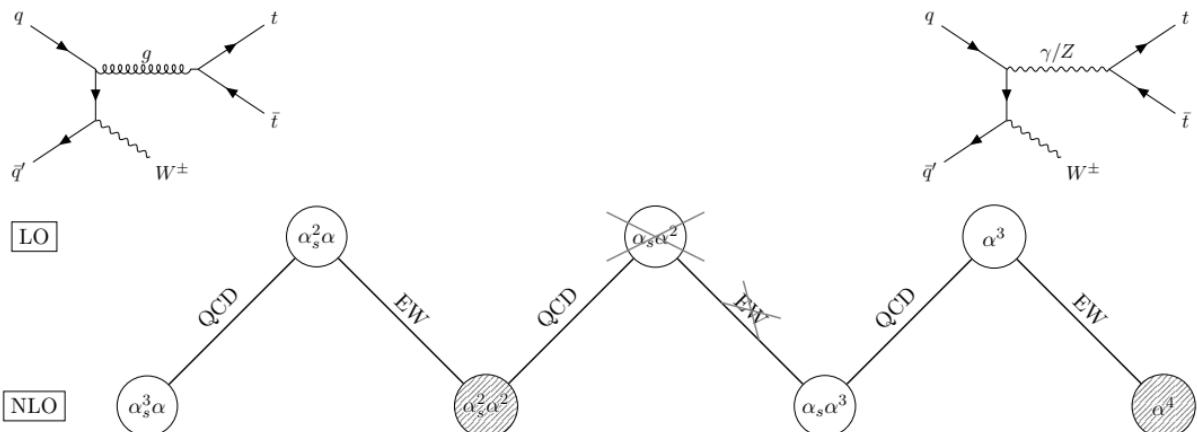
NLO + resummation

- 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 – I



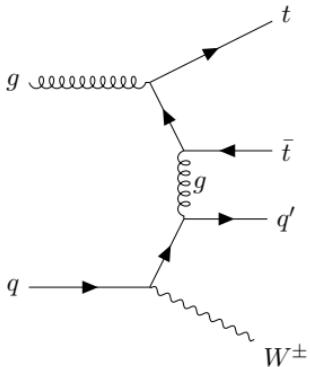
Perturbative corrections

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

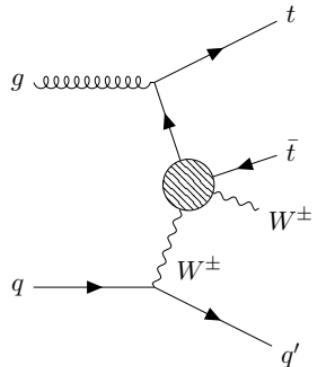
[Frederix et al arXiv:1711.02116]

Anatomy of higher-order corrections – II

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

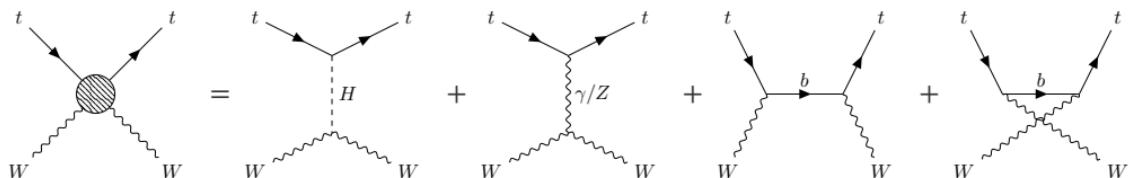


QCD



EW

- $tW \rightarrow tW$ scattering



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

The POWHEG method in a nutshell – I

- Start from NLO fixed-order cross section

$$\sigma^{\text{NLO}} = \int d\Phi_n \left[B(\Phi_n) + V(\Phi_n) \right] + \int d\Phi_{n+1} R(\Phi_{n+1})$$

- Split real radiation in *soft* and *hard* contributions

$$R(\Phi_{n+1}) = \underbrace{F(\Phi_{n+1})R(\Phi_{n+1})}_{\equiv R_s(\Phi_{n+1})} + \underbrace{\left[1 - F(\Phi_{n+1})\right]R(\Phi_{n+1})}_{\equiv R_h(\Phi_{n+1})}$$

- Standard choices in the POWHEG-BOX

$$F(\Phi_{n+1}) = F_{\text{damp}}(\Phi_{n+1}) F_{\text{bornzero}}(\Phi_{n+1})$$

$$F_{\text{damp}}(\Phi_{n+1}) = \frac{h_{\text{damp}}^2}{h_{\text{damp}}^2 + p_T^2} , \quad F_{\text{bornzero}}(\Phi_{n+1}) = \Theta \left(h_{\text{bornzero}} - \frac{R(\Phi_{n+1})}{P_{ij}(\Phi_r) \otimes B(\Phi_n)} \right)$$

The POWHEG method in a nutshell – II

- one step parton shower approximation

$$\sigma^{\text{NLO+PS}} = \int d\Phi_n \bar{B}(\Phi_n) \underbrace{\left[\Delta(\Phi_n, p_T^{\min}) + \int d\Phi_r \frac{R_s(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p_T) \right]}_{=1} + \int d\Phi_{n+1} R_h(\Phi_{n+1})$$

- Inclusive NLO and infrared finite cross section

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_r R_s(\Phi_n)$$

- **Modified** Sudakov form factor

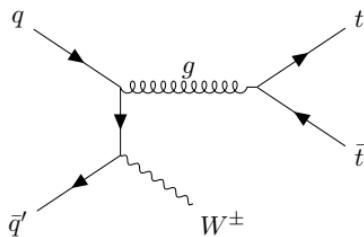
$$\Delta(\Phi_n, p_T) = \exp \left(- \int d\Phi_r \frac{R_s(\Phi_n, \Phi_r)}{B(\Phi_n)} \Theta(k_T(\Phi_n, \Phi_r) - p_T) \right)$$

Implementation

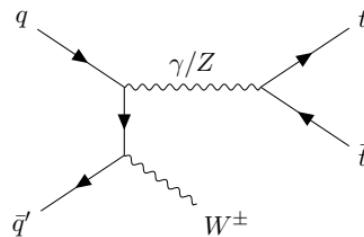
[Febres Cordero, MK, Reina arXiv:2101.11808]

We have implemented in the POWHEG-BOX

- NLO QCD corrections for $t\bar{t}W^\pm$



QCD born – $\mathcal{O}(\alpha_s^2 \alpha)$



EW born – $\mathcal{O}(\alpha^3)$

- Virtual matrix elements from NLOX [Honeywell et al. arXiv:1812:11925]
- All tree-level matrix elements from MG4/aMC@NLO
- Included LO spin-correlated top-quark decays [Frixione et al. hep-ph/0702198]

Let's compare it to other generators!

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

$$p_T(\ell) > 15 \text{ GeV} , \quad |\eta(\ell)| < 2.5 ,$$

$$p_T(j) > 25 \text{ GeV} , \quad |\eta(j)| < 2.5 ,$$

$$N_{l\text{-jets}} \geq 2 , \quad N_{b\text{-jets}} \geq 2 ,$$

$$\text{anti-}k_T , \quad R = 0.4$$

Uncertainties

$$H_T = \sum_{i \in \text{final state}} \sqrt{m_i^2 + p_{T,i}^2}$$

POWHEG-BOX

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

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

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

MG5_aMC@NLO

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

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

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

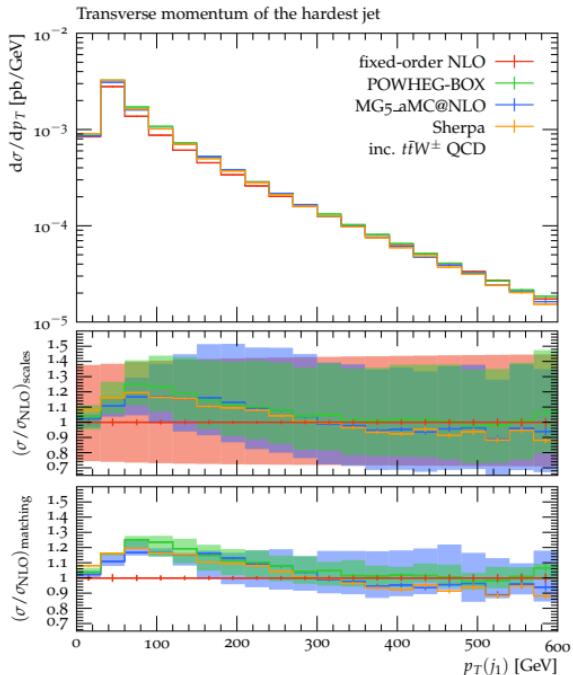
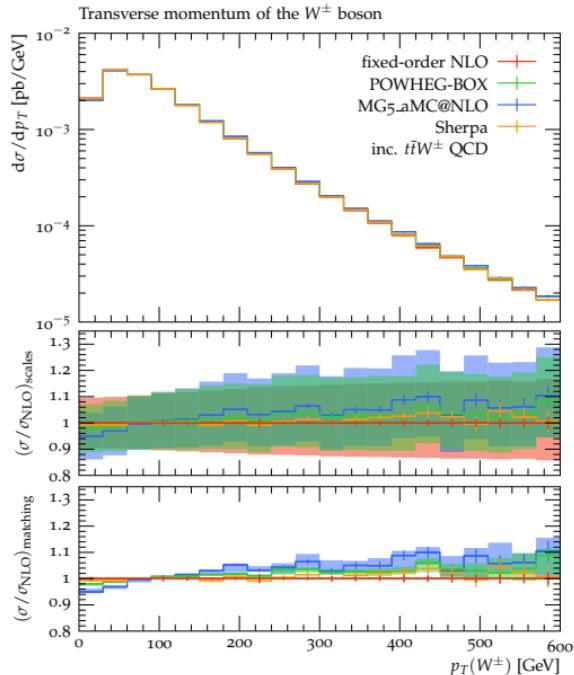
Sherpa

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

Inclusive observables – QCD

stable top quarks

[Febres Cordero, MK, Reina arXiv:2101.11808]

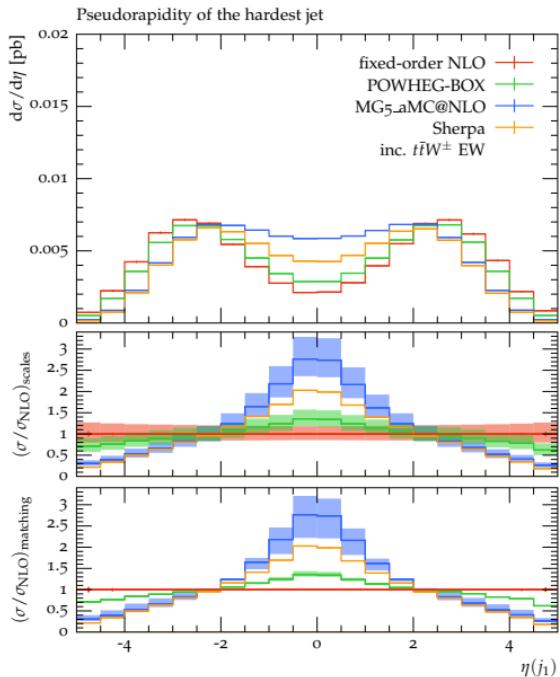
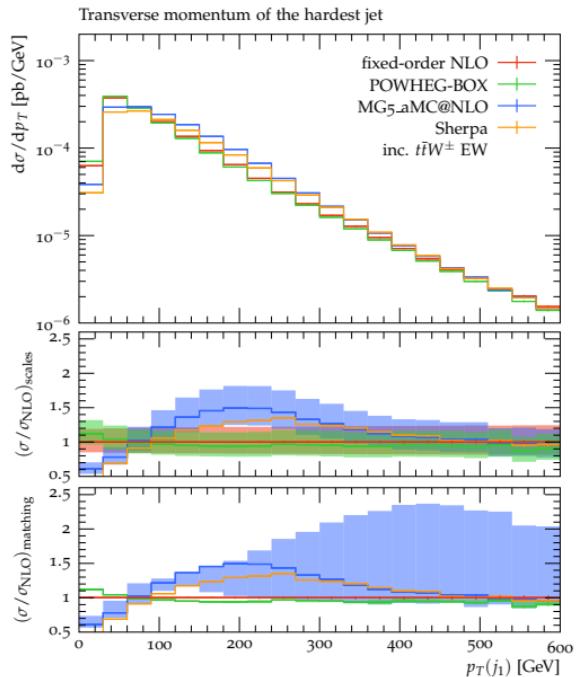


Good agreement between all generators and fixed-order

Inclusive observables – EW

stable top quarks

[Febres Cordero, MK, Reina arXiv:2101.11808]

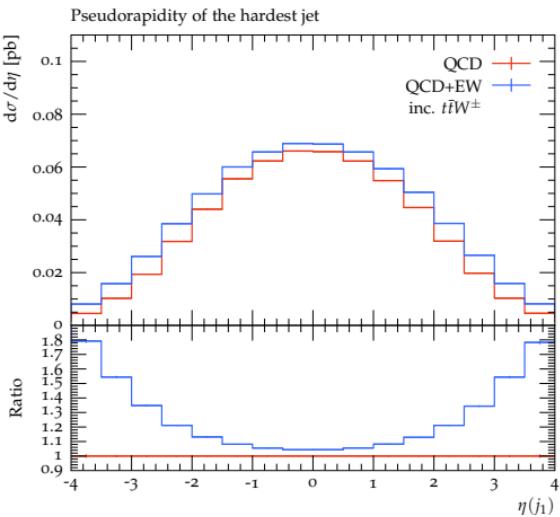
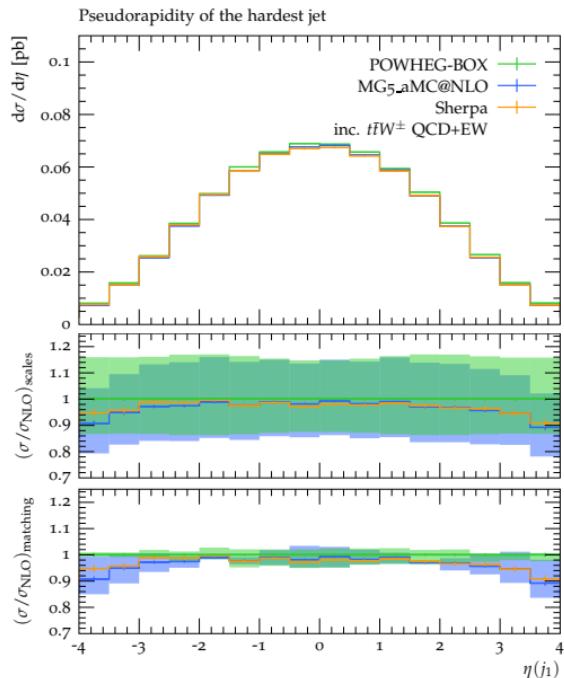


Large discrepancies between different generators

Inclusive observables – QCD+EW

stable top quarks

[Febres Cordero, MK, Reina arXiv:2101.11808]

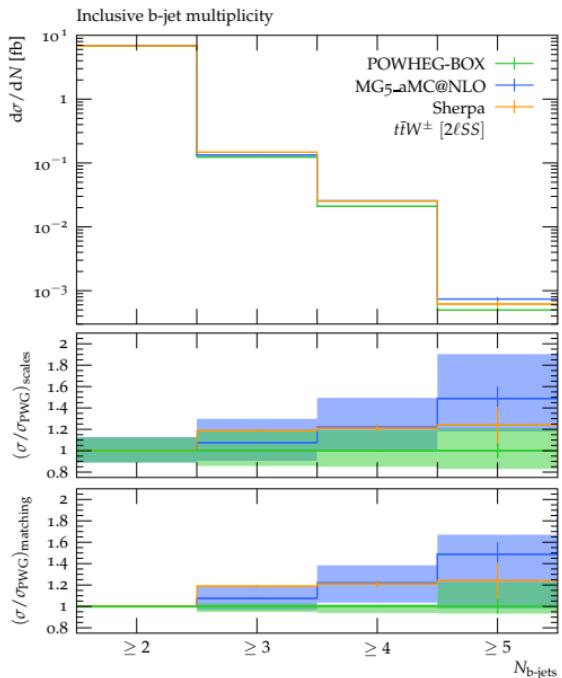
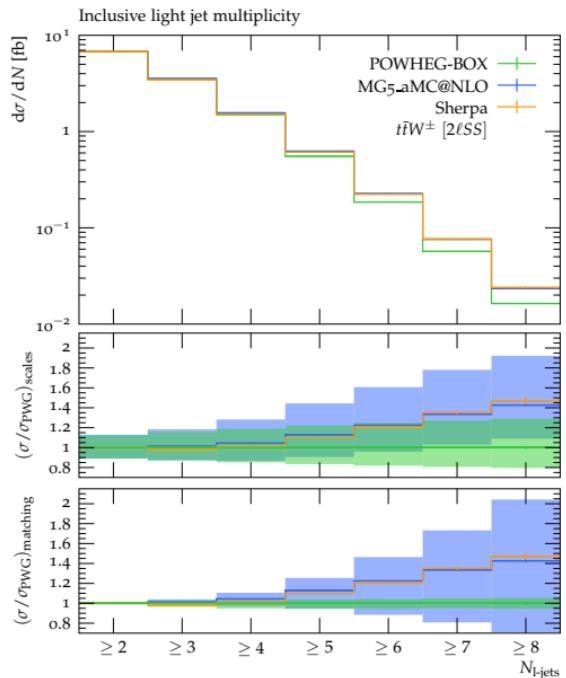


Mild impact once combined

Fiducial observables - Uncertainties

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]

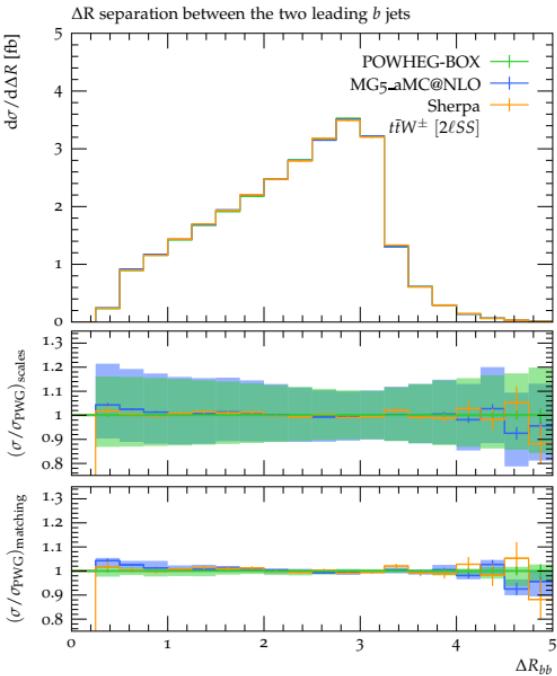
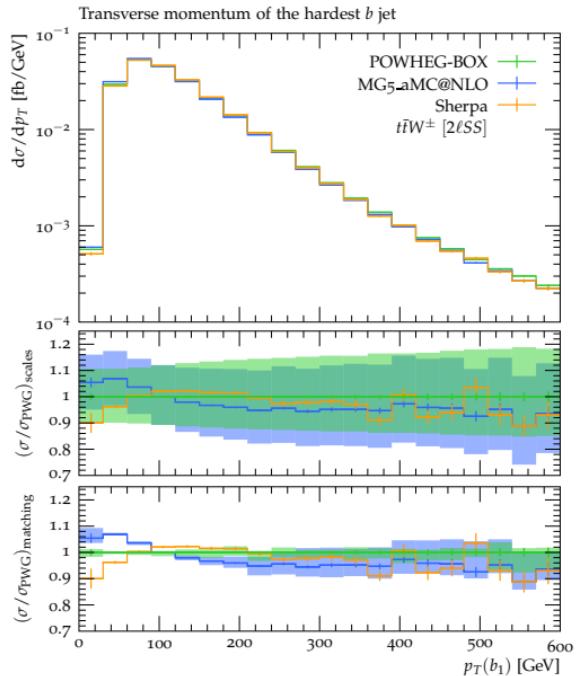


Good agreement within theoretical uncertainties

Fiducial observables - Uncertainties

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]

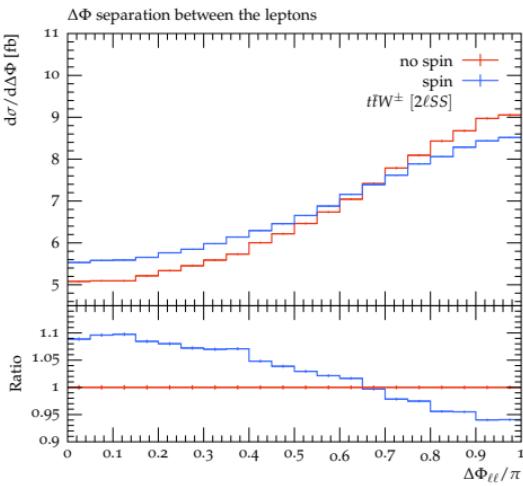
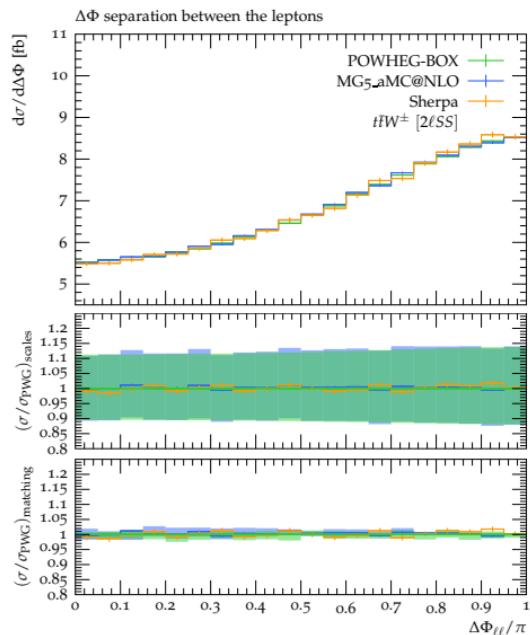


Small shape differences at the beginning of the p_T spectrum

Fiducial observables - Polarization effects

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]

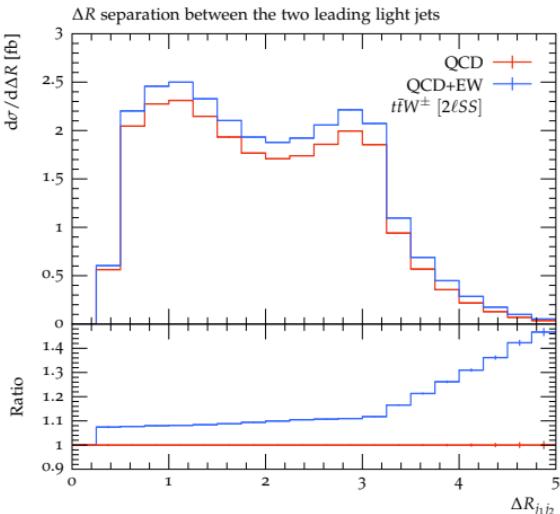
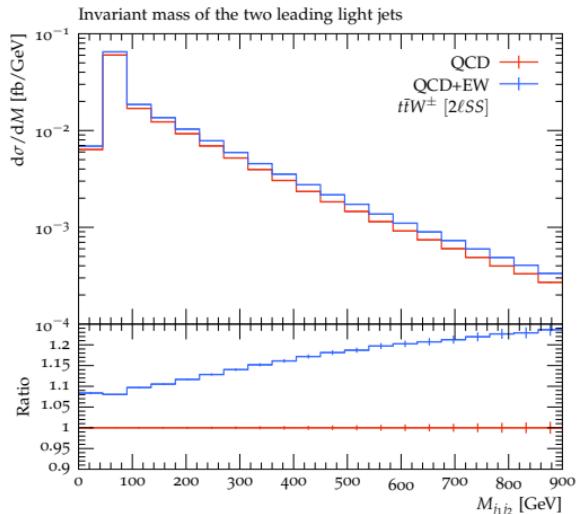


- Polarization effects modify shape by 10%
- Stronger effects for $t\bar{t}W^+$ and $t\bar{t}W^-$ separately

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

Summary & Outlook

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

- 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> NEW
- Contribution at $\mathcal{O}(\alpha_s \alpha^3)$ very dependent on matching scheme
 - only mild impact when physical signatures are considered
- Polarization effects can be sizable!
- Extensive comparison for inclusive and $2\ell SS$ signature

Phys. Rev. D **103** 094014

Summary & Outlook

Take home messages:

- Generators very consistent
→ no explanation for large normalization factors of ~ 1.7
- EW contribution at $\mathcal{O}(\alpha_s \alpha^3)$ is not an overall correction
- spin correlated decays are important!
- Everything seems highly dependent on *signature & phase space*

Where do we go from here?

- How well do parton showers account for corrections in polarized top decays?
- hadronic decays → NLO QCD corrections for $W \rightarrow q\bar{q}'$
- multi-lepton signatures → off-shell NLO QCD $t\bar{t}W^\pm$
→ on-shell NNLO QCD for $t\bar{t}W^\pm$

No universal answer

Backup

Decays in the POWHEG-BOX

[Frixione et al. hep-ph/0702198]

- Pick decay final state by hit-and-miss veto on density matrix elements

$$\rho_{ijk} = \text{Br}(W^+ \rightarrow X_i) \text{Br}(W^- \rightarrow \bar{X}_j) \text{Br}(W^+ \rightarrow X_k)$$

$$X_1 = e^+ \nu_e, \quad X_2 = \mu^+ \nu_\mu, \quad X_3 = \tau^+ \nu_\tau, \quad X_4 = u \bar{d}, \quad X_5 = c \bar{s}$$

- Start from on-shell $t\bar{t}W(j)$ phase space point and generate off-shell kinematics

$$\Phi_n^{OS} \rightarrow \Phi_n$$

- Sequence of $1 \rightarrow 2$ decays for $t \rightarrow Wb$ and $W \rightarrow \ell\nu$
 - 2 particle phase space has constant jacobian
 - generate decay momenta uniformly
- Compute upper bounding function

$$U_{\text{dec}} = \mathcal{N} \prod_{i=1}^2 \frac{|M(t_i \rightarrow Wb)|^2}{(p_i^2 - m_t^2)^2 + m_t^2 \Gamma_t^2} \prod_{j=1}^3 \frac{|M(W_j \rightarrow \ell\nu)|^2}{(p_j^2 - m_W^2)^2 + m_W^2 \Gamma_W^2}$$

- Hit-and-miss veto
 - Generate random number $r \in [0, U_{\text{dec}}]$
 - Accept event if

$$r \leq \frac{M_{\text{dec}}(\Phi_n, \Phi_{t \rightarrow b\ell\nu}, \Phi_{\bar{t} \rightarrow \bar{b}\ell\nu}, \Phi_{W \rightarrow \ell\nu})}{M_{\text{undec}}(\Phi_n^{OS})}$$