Modeling uncertainties of $t\bar{t}W^{\pm}$ signatures

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Outline

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

- the need for high precision
- state of the art

Modeling of $t\bar{t}W$

- on-shell $t\bar{t}W^{\pm}$ with parton showers
- full off-shell results
- A first comparison of both approaches

Summary & Outlook

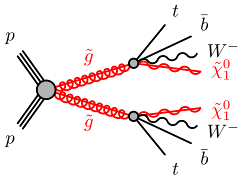
Motivations for $t\bar{t}W$ at the LHC

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]

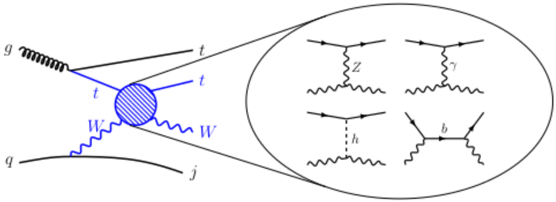
[ATLAS, arXiv:1706.03731]

[CMS, arXiv:1605.03171]

[CMS, arXiv:1704.07323]

- anomalous top-quark couplings, EFT interpretations

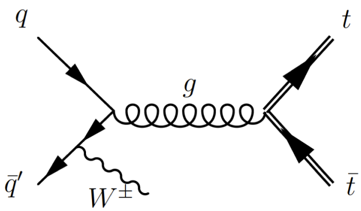
[Dror et al, arXiv:1511.03674]



- **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

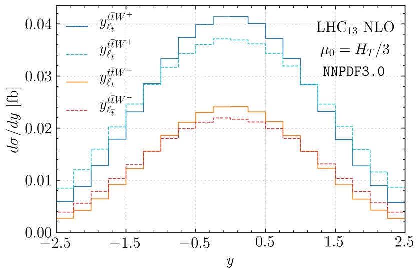


Top quarks are produced highly polarized

- large charge asymmetries of top decay products

Symmetric gg channel only opens up at NNLO

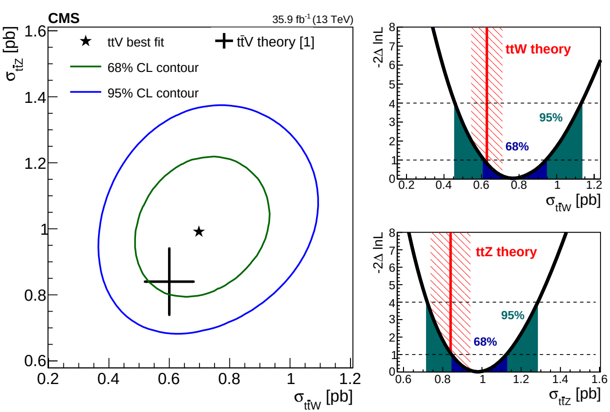
LO: $q\bar{q}'$ **NLO:** $q\bar{q}' + qg$ **NNLO:** $q\bar{q}' + qg + gg$



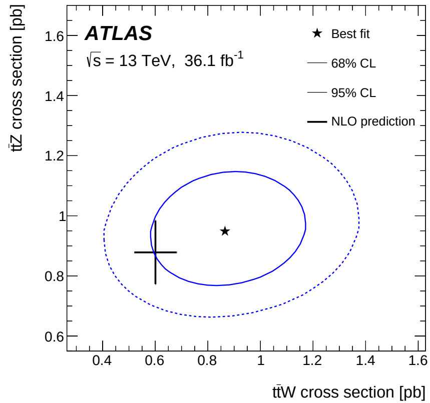
		8 TeV	13 TeV	14 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$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

[Bevilacqua, Bi, Hartanto, MK, Nasufi, Worek'21] [Maltoni et al., arXiv:1406.3262]

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



CMS, arXiv:1711.02547

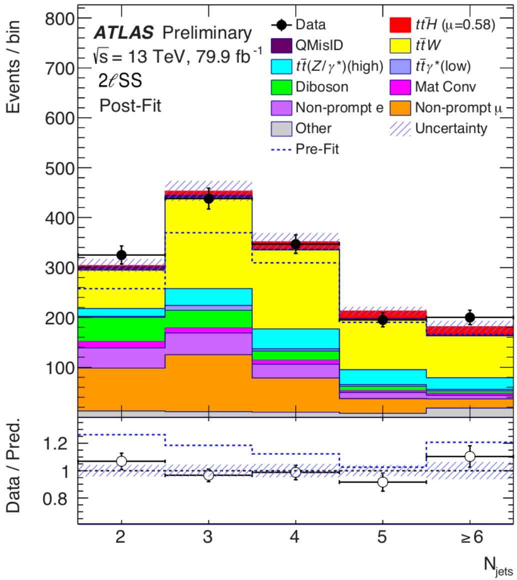


ATLAS, arXiv:1901.03584

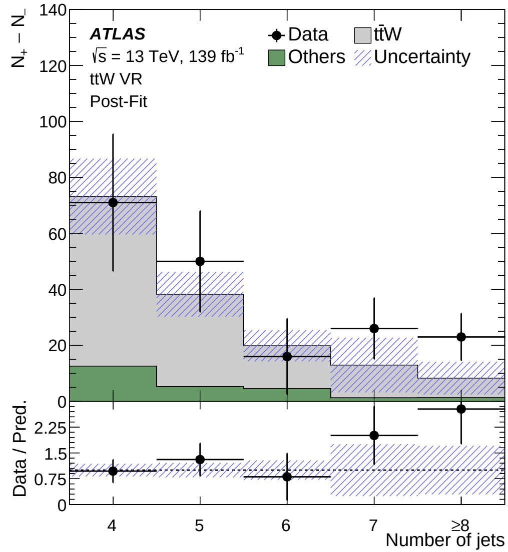
Both experiments see an excess of $t\bar{t}W$ events wrt to the Standard Model

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 decy, spin correlations

- NLO QCD + EW: complete off-shell

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

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

[Denner and Pellicciolі'20] [Denner and Pellicciolі'21]

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek'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]

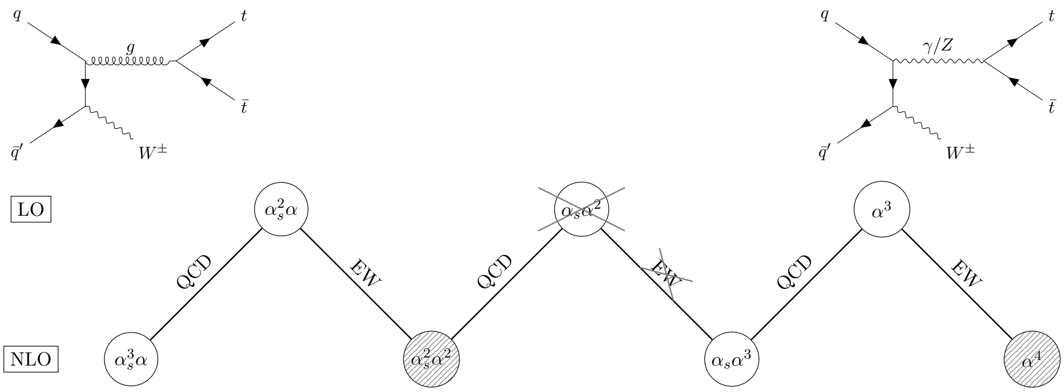
NLO + parton shower

- 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] [Frederix and Tsinikos'21]

Complete NLO QCD + EW corrections – I

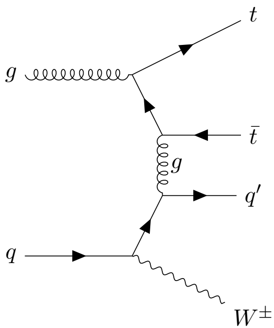


Perturbative corrections

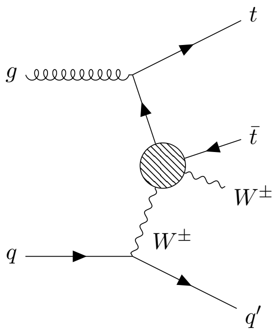
- $\mathcal{O}(\alpha_s^3\alpha)$ – (50%) dominant NLO QCD corrections
- $\mathcal{O}(\alpha_s^2\alpha^2)$ – (−4%) mixed QCD-EW corrections
- $\mathcal{O}(\alpha_s\alpha^3)$ – (10%) NLO QCD corrections **!!!**
- $\mathcal{O}(\alpha^4)$ – sub per mill NLO EW corrections

[Frederix et al arXiv:1711.02116]

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

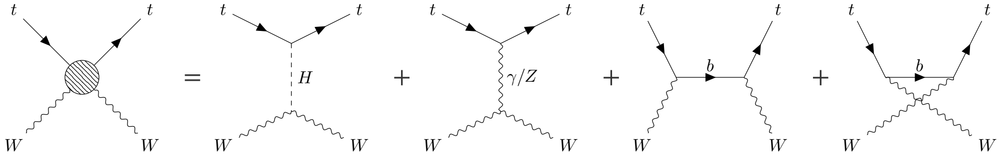


QCD



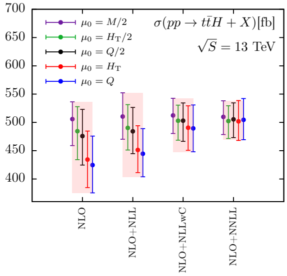
EW

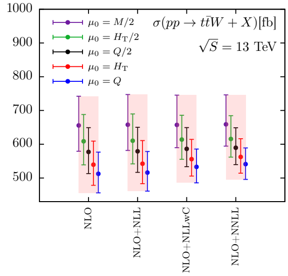
- $tW \longrightarrow tW$ **scattering**



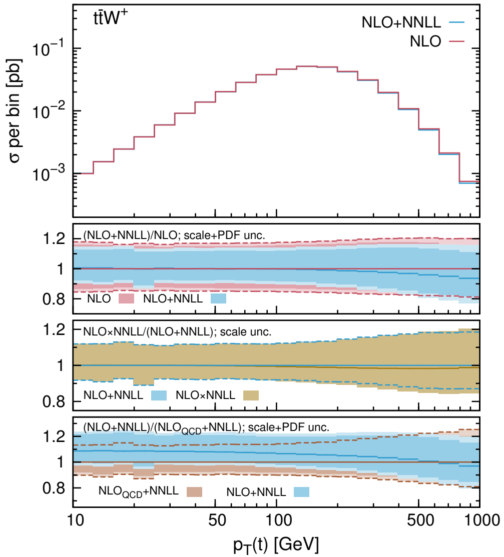
Soft-gluon Resummation

- Soft-gluon resummation @ NNLL
- no gg channel for $t\bar{t}W^{\pm}$
- Scale dependence of total cross sections
  - significant reduction for $t\bar{t}H/t\bar{t}Z$
  - marginal impact on $t\bar{t}W^{\pm}$
- Impact of resummation: $K_{NNLL} \lesssim 1.06$
- Small impact on diff. distributions



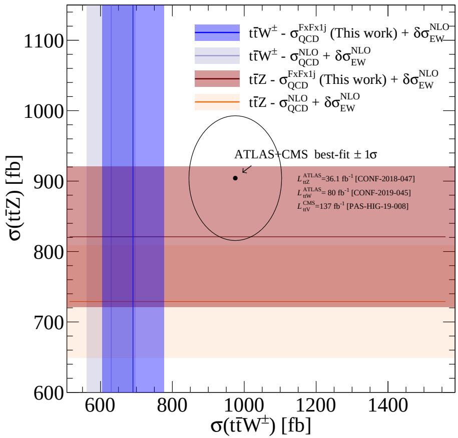


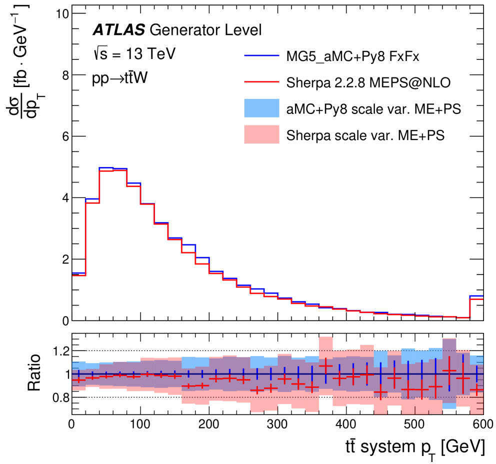
[Kulesza et al. arXiv:2001.03031]



[Broggio et al arXiv:1907.04343]

Multi-jet merging



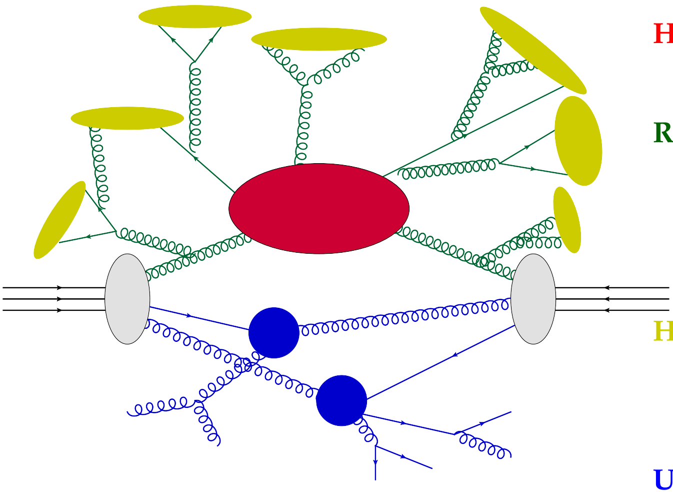


[von Buddenbrock et al arXiv:2009.00032] [ATL-PHYS-PUB-2020-024]

- FxFx NLO vs. MEPS@NLO multi-jet merging → consistent schemes
- multi-jet merging improves slightly tension with LHC measurements

on-shell $t\bar{t}W$ – parton showers

Modelling of hadron collisions



Event generators have to be improved once data becomes more precise!

Incoming protons

- Parton distribution functions

Hard interaction

- LO, NLO, NNLO predictions

Radiation

- Parton shower
- Resonance decays
- Matching to NLO, NNLO

Hadronization

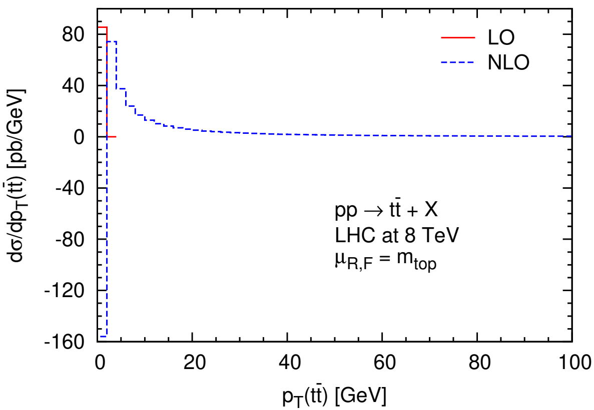
- Phenomenological models
- Hadronic decays

Underlying event

- Multi parton interactions

Beyond Leading order

Why fixed-order calculations are not always enough:



✓ NLO normalization

✗ large logarithms – e.g $\log(p_T^2(t\bar{t})/\hat{s})$

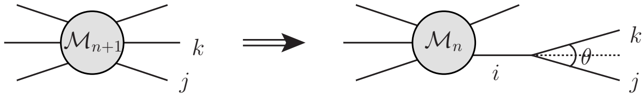
✗ simulates only few final state partons

✗ Needs a bridge to hadronization

Parton showers can improve all these points!

Parton shower - collinear factorization

- Higher-order QCD matrix elements factorize in the collinear limit



$$|M_{n+1}|^2 d\Phi_{n+1} \approx |M_n|^2 d\Phi_n \frac{dt}{t}\frac{\alpha_s}{2\pi} P_{ij}(z)\, dz\, d\phi \qquad (\star)$$

- t: evolution variable – e.g k_T, angle θ, virtuality Q^2, ...
- z: momentum fraction of the emitted parton
- P_{ij}: Altarelli-Parisi splitting kernels

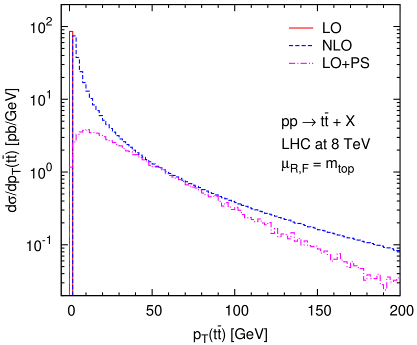
- For infinite many emissions Eq. ($\star$) yields

$$\sigma^{\text{LO+PS}} = \int d\Phi_n B(\Phi_n) \left[\Delta(t_0, t_{\max}) + \sum_{ij} \int_{t_0}^{t_{\max}} \frac{dt}{t}\frac{\alpha_s}{2\pi} \int dz P_{ij}(z) \Delta(t, t_{\max}) \right]$$

with the **Sudakov form factor**

$$\Delta(t_0, t_{\max}) = \exp\left[- \int_{t_0}^{t_{\max}} \frac{dt}{t}\frac{\alpha_s}{2\pi} \int dz P_{ij}(z) \right]$$

LO + Parton shower



- ✓ more realistic description in the low p_T region
- ✗ only LO accurate
- ✗ high p_T region reliably described only by NLO calculation

Combining NLO calculation and parton shower: NLO+PS matching

- ✓ avoid double counting
- ✓ preserve NLO accuracy
- popular methods:
  - MC@NLO [Frixione, Webber hep-ph/0204244]
  - POWHEG [Nason hep-ph/0409146]

Also: Merging matched calculation for different multiplicities ($t\bar{t} + 0j$, $t\bar{t} + 1j$, $t\bar{t} + 2j$, ...) → NOT discussed in this talk.

The POWHEG method in a nutshell – I

- Start from NLO fixed-order cross section

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

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

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

- $F(\Phi_{n+1})$ to a large extend arbitary

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

- Standard choices in the POWHEG-BOX

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

- one step parton shower approximation

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

$$+ \int d\Phi_{n+1} R_h(\Phi_{n+1})$$

- Inclusive NLO and infrared finite cross section

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

- **Modified** Sudakov form factor

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

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

Comparative analysis: Two same-sign leptons

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

Not addressed in this study:

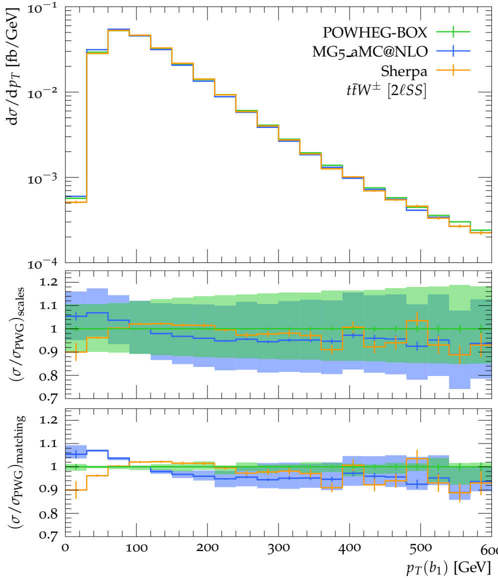
- Effects from Multi-parton interactions
- Hadronization effects

Fiducial observables - Uncertainties

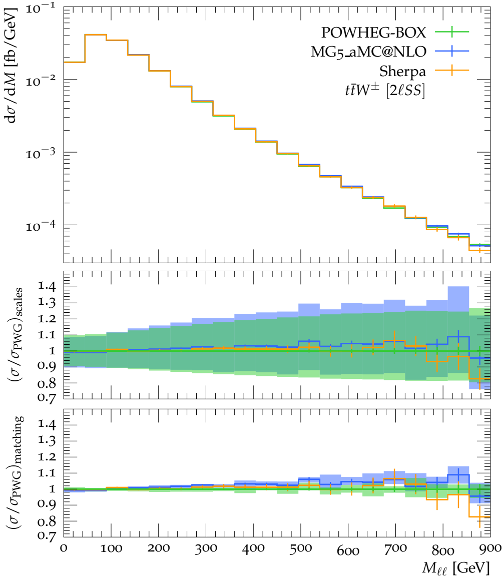
two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]

Transverse momentum of the hardest b jet



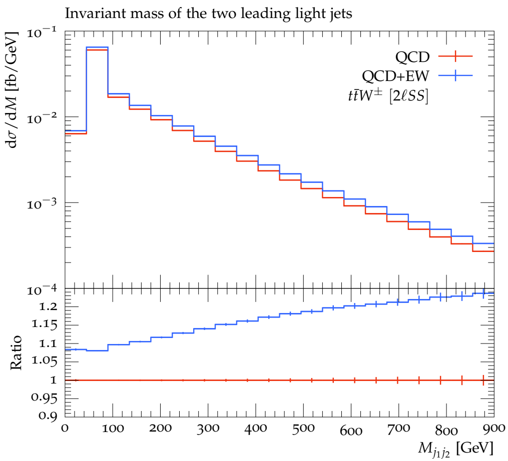
Invariant mass of the lepton pair

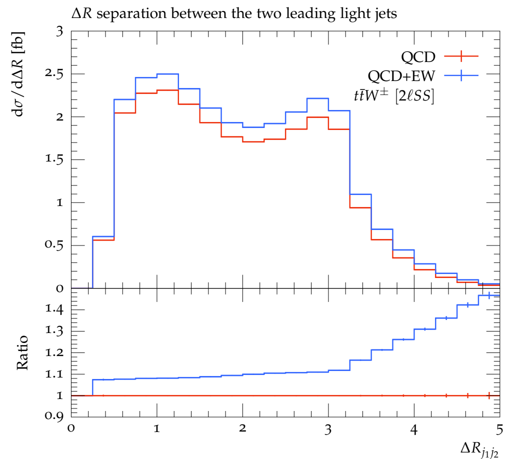


Good agreement within uncertainties

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]



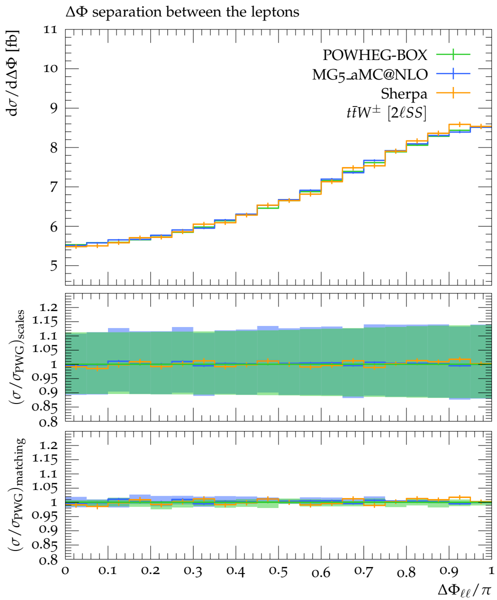


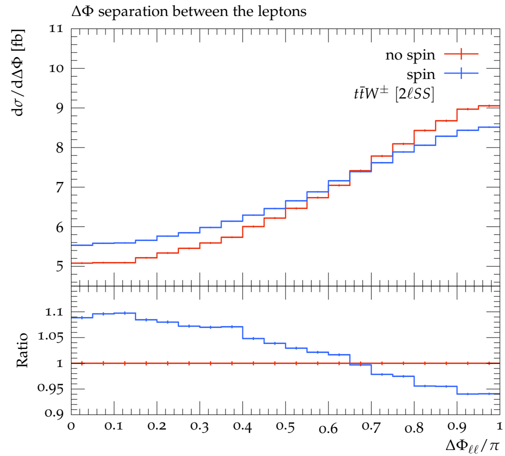
- EW contribution sizeable if sensitive to forward jets
- For most observables: flat +10% correction

Fiducial observables - Polarization effects

two same-sign leptons

[Febres Cordero, MK, Reina arXiv:2101.11808]

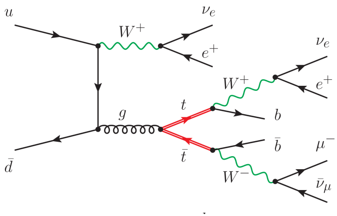




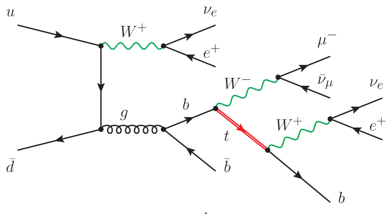
- Polarization effects modify shape by 10%
- Stronger effects for $t\bar{t}W^{+}$ and $t\bar{t}W^{-}$ separately

Beyond stable top quarks

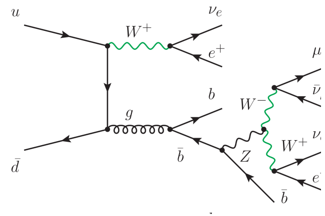
- full off-shell contributions to $t\bar{t}W^+$



Double resonant



Single resonant



Non-resonant

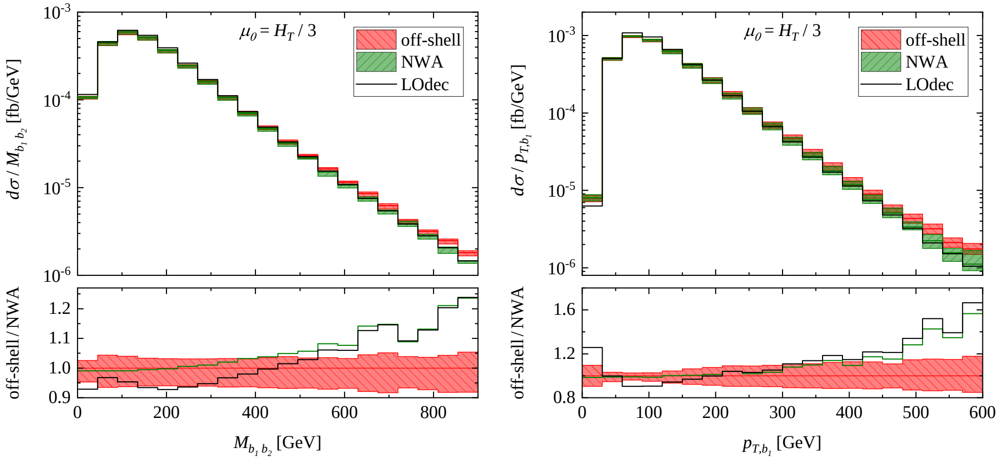
- Narrow-width approximation (NWA)

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

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



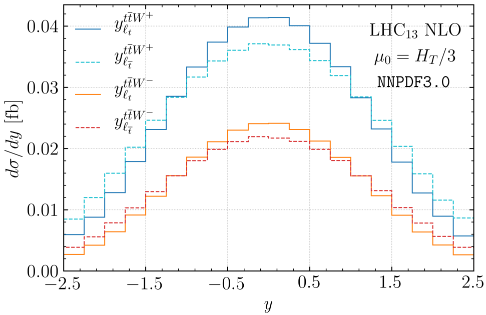
- Large off-shell effects in the tails of the distributions
- Differences between NWA and $\text{NWA}_{\text{LOdec}}$ are $\mathcal{O}(10\%)$ in the bulk

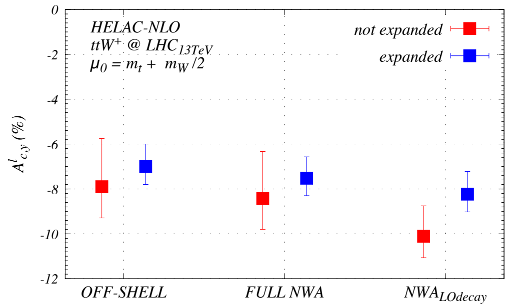
[Bevilacqua, Bi, Hartanto, MK, Worek, arXiv:2005.09427]

off-shell $t\bar{t}W$ - Charge Asymmetry

Leptonic charge asymmetry

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





- Decay modelling has large impact on charge asymmetry

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

Comparison of different approaches

Comparison of different approaches

How to model multilepton final states?

$$pp \to b\bar{b}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}\ell^{\pm}\nu_{\ell}$$

fixed-order

- top decay at NLO
- exact spin correlations
- double, single and non-resonant contributions or NWA
- only one extra parton

parton showers

- Additional radiation
- Hadronization
- More flexible
- NLO only for production
- LO spin correlations

How compatible are the different descriptions?

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

Multi-lepton signature

- 3 lepton final states

$$p_T(j) > 25 \text{ GeV} \,, \qquad |\eta(j)| < 2.5 \,,$$
$$p_T(\ell) > 25 \text{ GeV} \,, \quad |\eta(\ell)| < 2.5 \,, \quad \Delta R(\ell\ell) > 0.4 \,, \quad \Delta R(\ell j) > 0.4$$

- Jets defined via anti-k_T jet algorithm with $R = 0.4$
- b jets are defined as jets having a b parton inside
- Required at least $2b$ jets
- Parton shower: Pythia8

Not addressed in this study:

- Effects from Multi-parton interactions
- Hadronization effects

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

- **full off-shell**

$$\sigma^{\text{NLO}}_{\text{off-shell}} = 1.58^{+0.05\ (3\%)}_{-0.10\ (6\%)}\ \text{fb}$$

- **NWA**

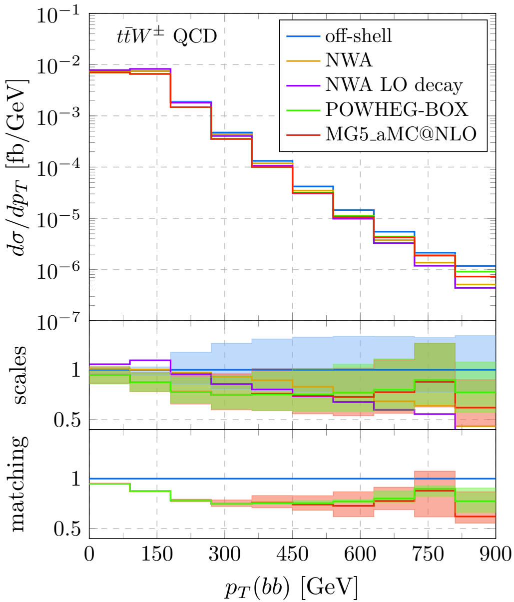
$$\sigma^{\text{NLO}}_{\text{NWA}} = 1.57^{+0.05\ (3\%)}_{-0.10\ (6\%)}\ \text{fb}\ , \qquad \sigma^{\text{NLO}}_{\text{NWA LOdec}} = 1.66^{+0.17\ (10\%)}_{-0.17\ (10\%)}\ \text{fb}\ ,$$

  - QCD corrections in top decay negative $\to -5\%$
  - subtle interplay between scale variation in prod. and decay

- **Parton shower**

$$\sigma^{\text{NLO+PS}}_{\text{PWG}} = 1.40^{+0.16\ (11\%)}_{-0.15\ (11\%)}\ \text{fb}\ , \qquad \sigma^{\text{NLO+PS}}_{\text{MG5}} = 1.40^{+0.16\ (11\%)}_{-0.15\ (11\%)}\ \text{fb}\ ,$$

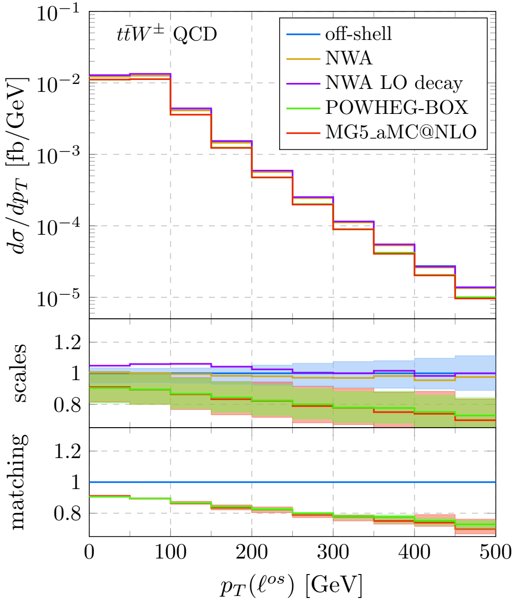
  - similar uncertainties as NWA LOdec
  - 11% reduction due to multiple emissions in top decays!



- Large single-resonant $pp \to tWWb$ contribution in the tail
- top decay @ NLO QCD important for the bulk of the distribution
- Large shower corrections

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

$pp \to t\bar{t}W^{\pm}$ QCD - III



- NWA reproduces distribution obtained with full off-shell effects
- top decay only has minor influence for low p_T
- Shower based results have different shapes

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

$pp \to t\bar{t}W^{\pm}$ EW - I

- **full off-shell**

$$\sigma^{\rm NLO}_{\rm off\text{-}shell} = 0.206^{+0.045\ (22\%)}_{-0.034\ (17\%)}\ {\rm fb}$$

- **NWA**

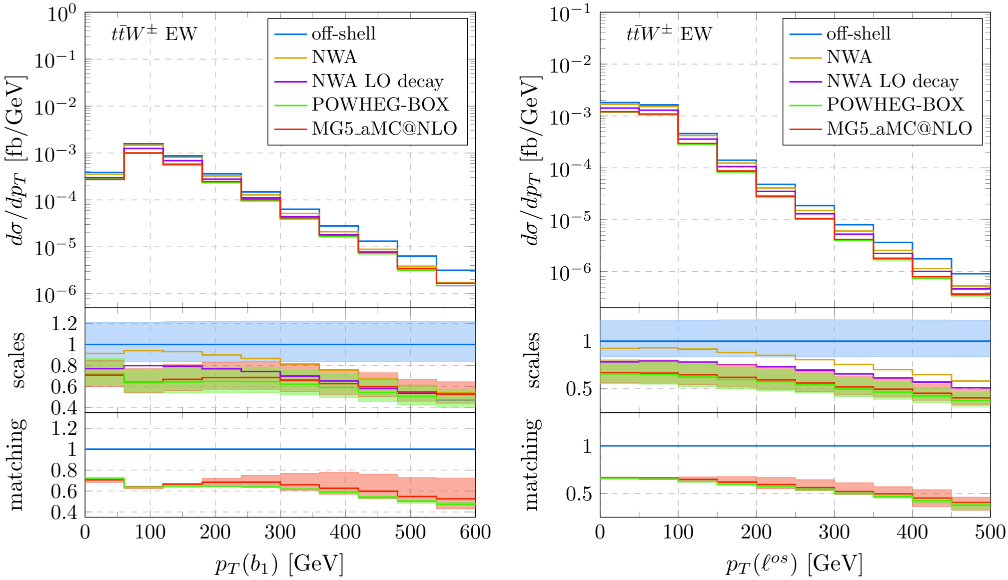
$$\sigma^{\rm NLO}_{\rm NWA} = 0.190^{+0.041\ (22\%)}_{-0.031\ (16\%)}\ {\rm fb}\ , \qquad \sigma^{\rm NLO}_{\rm NWA\ LOdec} = 0.162^{+0.035\ (22\%)}_{-0.026\ (16\%)}\ {\rm fb}\ ,$$

  - QCD corrections in top decay positive $\to +17\%$
  - scale variation dominanted by qg initial state processes
  - 8% difference wrt full off-shell due to $WW \to WW$ contributions!

- **Parton shower**

$$\sigma^{\rm NLO+PS}_{\rm PWG} = 0.133^{+0.028\ (21\%)}_{-0.021\ (16\%)}\ {\rm fb}\ , \qquad \sigma^{\rm NLO+PS}_{\rm MG5} = 0.136^{+0.028\ (21\%)}_{-0.022\ (16\%)}\ {\rm fb}\ ,$$

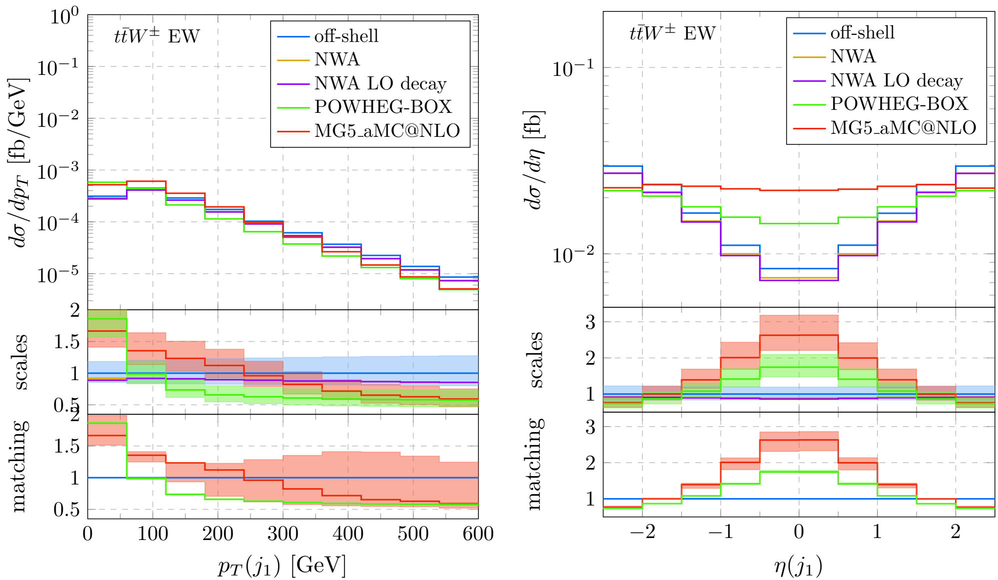
  - similar uncertainties as NWA and full off-shell
  - Reduction due to multiple emissions in top decays!
  - significantly smaller than full off-shell prediction!



Effects more extreme for the EW production mode

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

$pp \to t\bar{t}W^{\pm}$ EW - III



Effects more extreme for the EW production mode

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

Combination of approaches

- In the absence of full off-shell @ NLO+PS can we do something more?

What do we have at hand?

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$$\frac{d\sigma^{\text{NLO+PS}}}{dX} \left\{ \begin{array}{l} \bullet\ \text{Many non-trivial kinematic effects} \\ \bullet\ \text{Corrections beyond fixed-order} \\ \bullet\ \text{Hadronization} \end{array} \right.$$

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- Corrections beyond fixed-order
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$$\frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX} \left\{ \right.$$

- Double resonant contributions
- top decay @ NLO QCD
- exact spin correlations

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- Double resonant contributions
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- exact spin correlations

$$\frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} \left\{ \right.$$

- Double, single + non-resonant contributions
- top decay @ NLO QCD
- finite width effects

Combination of approaches

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$$\frac{d\sigma^{\text{NLO+PS}}}{dX}$$

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- top decay @ NLO QCD
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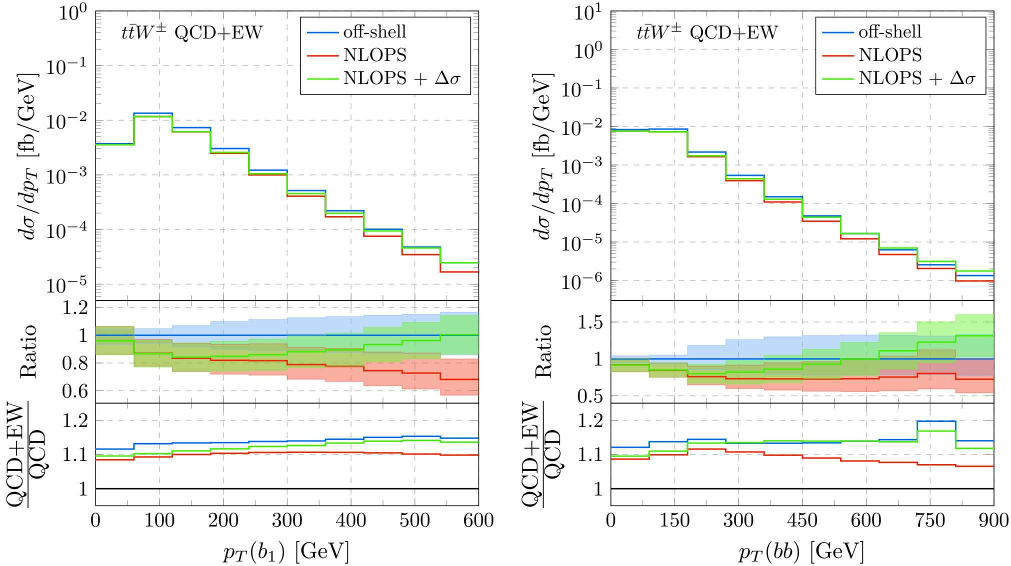
$$\frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX}$$

- Double, single + non-resonant contributions
- top decay @ NLO QCD
- finite width effects

Combine predictions via

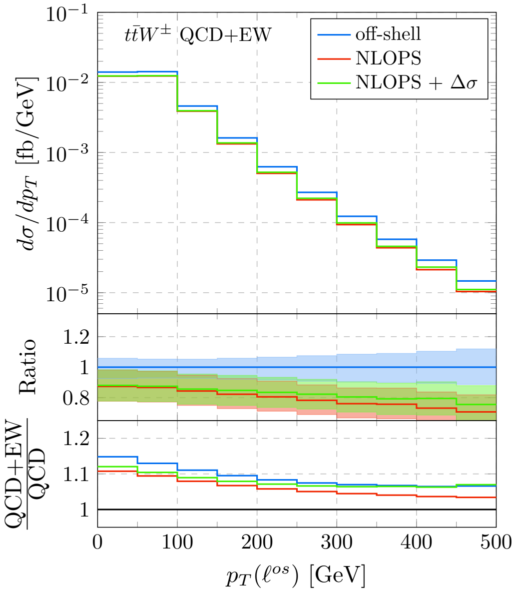
$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLO+PS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX}, \qquad \frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}$$



Sizable corrections for the tail of distributions

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

$pp \longrightarrow t\bar{t}W^{\pm}$ QCD+EW - II



- EW part receives sizable corrections
- overall minor impact as single-res. contributions are small
- Sizable shape differences between predictions

[Bevilacqua, Bi, Febres Cordero, Hartanto, MK, Nasufi, Reina, Worek arXiv:2109.15181]

Summary & Outlook

Summary

Phenomenology of $pp \to t\bar{t}W^{\pm}$ at the LHC

- Much progress has been made in recent months
- Comparison of fixed-order and NLO+PS presented
  - Difficult to say which is the *better* one
  - each has advantages and disadvantages
- We proposed a simple combination to get the best of both worlds!
  - full off-shell at NLO+PS would be great to have!

Where do we go from here?

- Two same-sign leptons:
  - NLO QCD corrections for $W \to q\bar{q}'$ are inevitable
- Multi-lepton signatures:
  - NNLO QCD and full NWA for $pp \to t\bar{t}W^{\pm}$ are necessary

Backup

The POWHEG method in a nutshell – I

- Start from NLO fixed-order cross section

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

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

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

- $F(\Phi_{n+1})$ to a large extend arbitary

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

- Standard choices in the POWHEG-BOX

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

The POWHEG method in a nutshell – II

- one step parton shower approximation

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

$$+ \int d\Phi_{n+1} R_h(\Phi_{n+1})$$

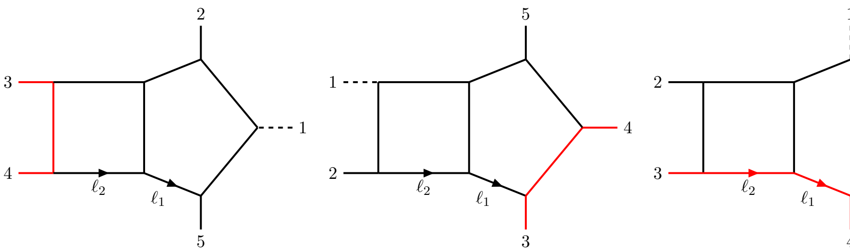
- Inclusive NLO and infrared finite cross section

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

- **Modified** Sudakov form factor

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

Planar master integrals



(a) $I_1(\vec{v})$ (b) $I_2(\vec{v})$ (c) $I_3(\vec{v})$

Number of master integrals per topology

$$\dim(I_1) = 128\,, \qquad \dim(I_2) = 117\,, \qquad \dim(I_3) = 139\,.$$