Modelling uncertainties of $t\bar{t}W$ multilepton signatures

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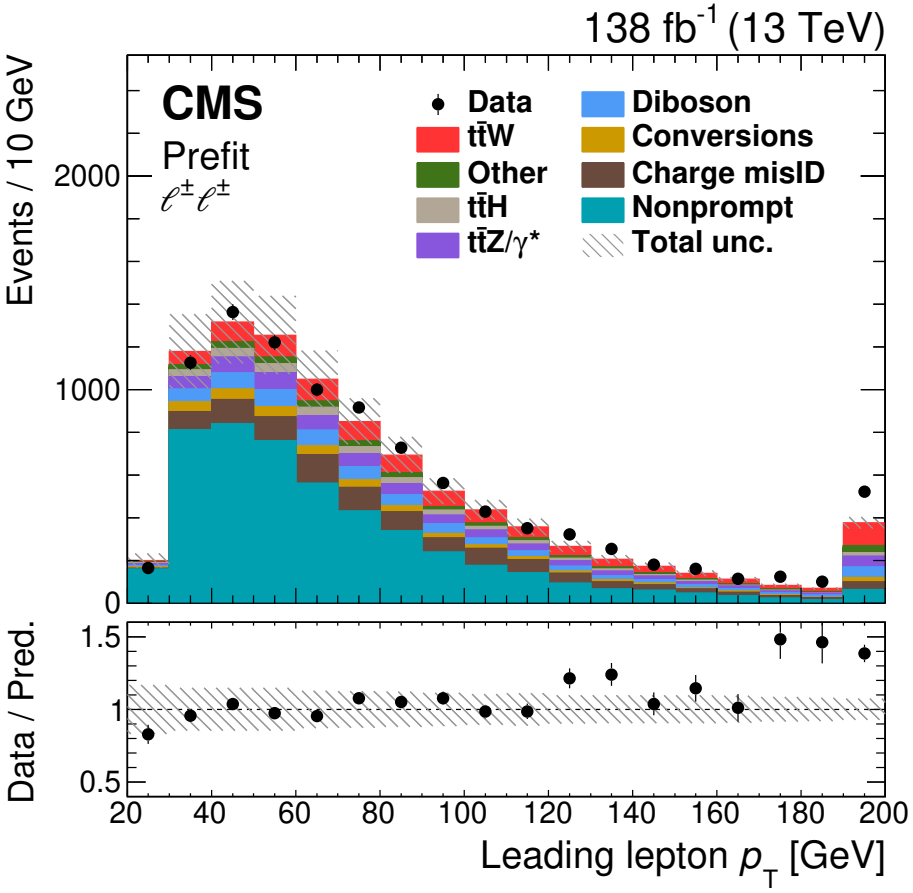
$t\bar{t}W$ modelling in light of $t\bar{t}H$ measurements

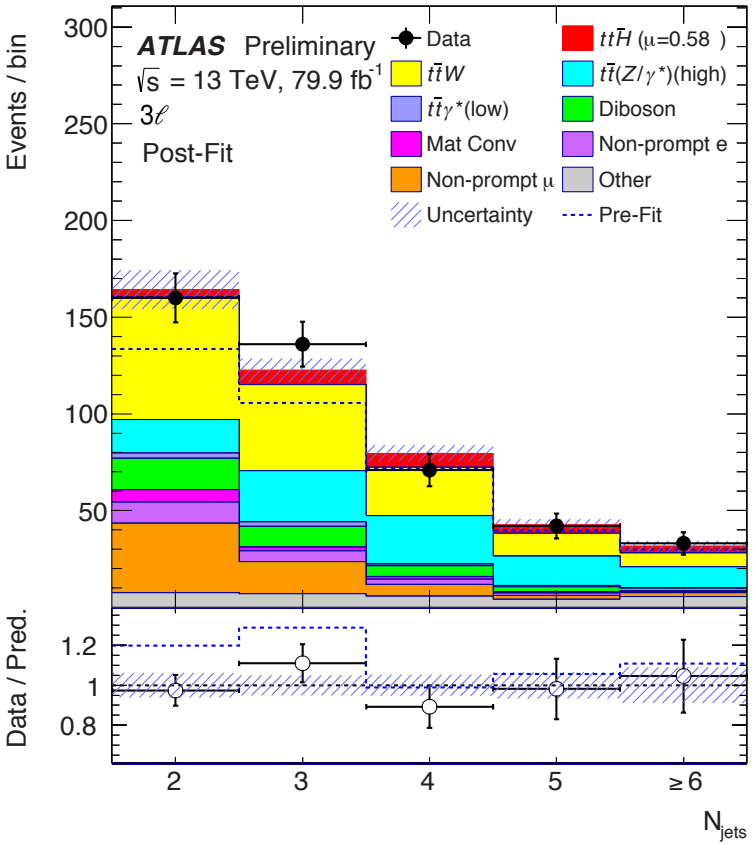
Joint session of LHC Top and Higgs working groups

December 9, 2022

[CMS-TOP-21-011, arXiv:2208.06485]



[ATLAS-CONF-2019-045]



↪ **Multilepton signature, $2lSS$ and $3l$ important in measurements of $t\bar{t}H$** production ($H \to WW^*, ZZ^*, \tau^+\tau^-$)

↪ $t\bar{t}W^{\pm}$background shows **largest data vs theory discrepancies in multilepton signatures**. Normalization factors:

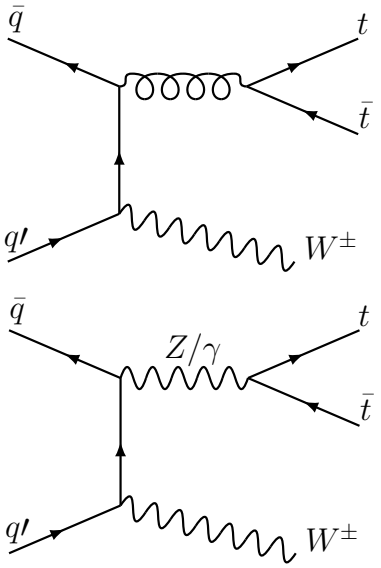
$$\lambda^{2lSS}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28} \text{ and } \lambda^{3l}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$$

How to improve the modelling of multilepton signatures?

Towards a better modelling of multilepton signatures – Recent theoretical developments –

- **Fixed-order higher-order corrections to full signature** $(3l)$
  - ↪ **NLO QCD for fully decayed final states**: assess off-shell effects.
    - – [Bevilacqua et al., arXiv:2005.09427, 2012.01363]
    - – [Denner et al., arXiv:2007.12089]
  - ↪ **NLO QCD+EW for fully decayed final states**
    - – [Denner et al., arXiv:2102.03246]
- **NLO+parton shower QCD, including dominant $O(\alpha_s^3\alpha_e)$ and $O(\alpha_s\alpha^3)$, LO spin-correlation in decays, jet merging**
  - – [Frederix, Tsinikos, arXiv:2004.09552] - aMC@NLO
  - – [Buddenbrock et al., arXiv:2009.00032] - aMC@NLO+FxFx
  - – [ATL-PHYS-PUB-2020-024] - aMC@NLO+FxFx and SHERPA
  - – [Frederix, Tsinikos, arXiv:2108.07826] - aMC@NLO+FxFx
  - ↪ [Febres Cordero, Kraus, Reina, arXiv:2101.11808] - POWHEG BOX
- **Comparing/combining NLO QCD+PS vs NLO QCD off-shell**
  - ↪ [Bevilacqua et al., arXiv:2109.15181]

$Wt\bar{t}$: large NLO (real) corrections



LO_{QCD}: $O(\alpha_s^2\alpha)$
NLO_{QCD}: $O(\alpha_s^3\alpha)$

$\Downarrow$ QCD+EW

LO: $O(\alpha_s^2\alpha) + O(\alpha^3)$

NLO: $O(\alpha_s^3\alpha) + O(\alpha_s^2\alpha^2) + O(\alpha_s\alpha^3) + O(\alpha^4)$

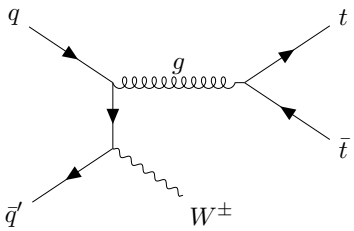
$\downarrow$ Leading effect

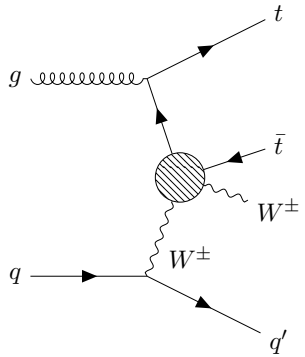
$\downarrow$ Main sub-leading effect ($\sim 6\%$)

σ[fb]	LO_{QCD}	$\text{LO}_{\text{QCD}} + \text{NLO}_{\text{QCD}}$	LO	LO + NLO	$\frac{\text{LO+NLO}}{\text{LO}_{\text{QCD}}+\text{NLO}_{\text{QCD}}}$
$\mu = H_T/2$	$363^{+24\%}_{-18\%}$	$544^{+11\%}_{-11\%}\,(456^{+5\%}_{-7\%})$	$366^{+23\%}_{-18\%}$	$577^{+11\%}_{-11\%}\,(476^{+5\%}_{-7\%})$	1.06 (1.04)

[Frederix, Pagani, Zaro, '17] (number in parenthesis obtained with extra jet veto)

Large impact of qg radiative processes:

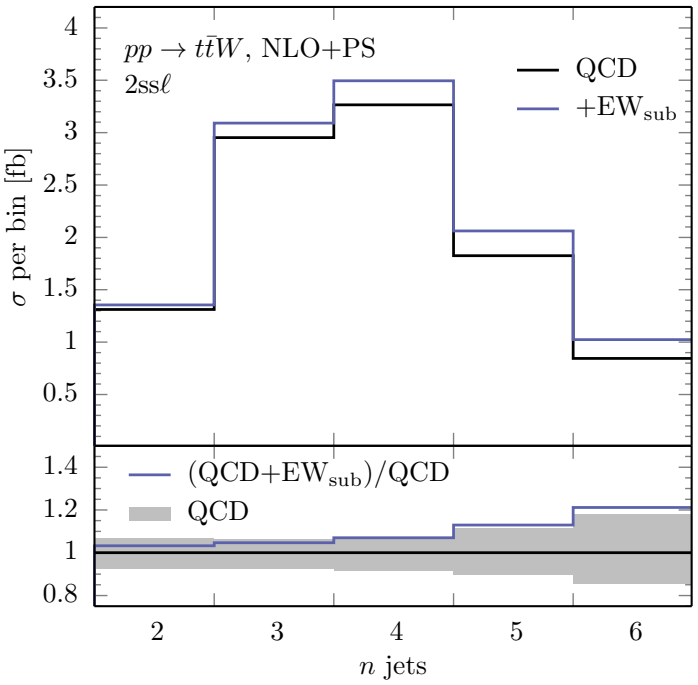


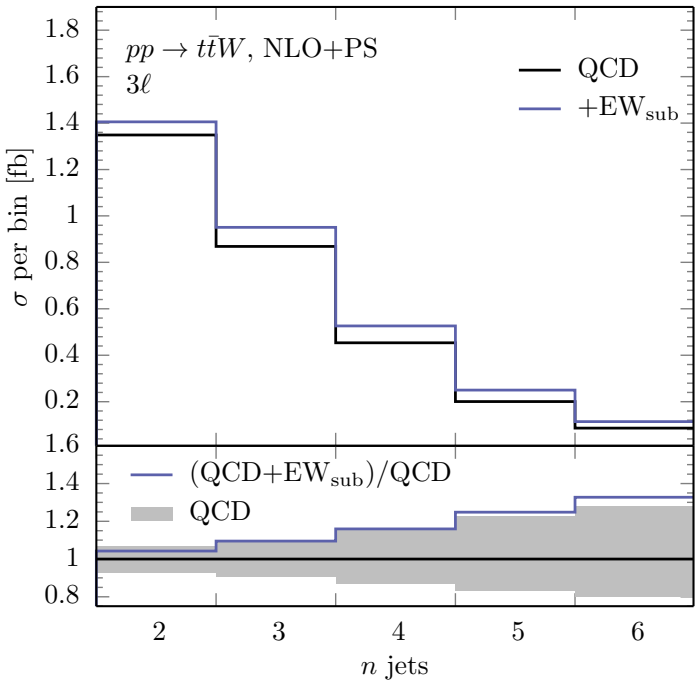


Tree level processes:

subject to non negligible h.o. effects

[Frederix, Tsinikos, '20 - aMC@NLO+Madspin, using Pythia8]





↪ Visible effects from subleading-EW on $2lSS$ and $3l$ distributions.

↪ $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ are $O(\alpha_s)$ corrections to QCD+EW born: can be consistently included in NLO QCD PS Monte Carlo.

↪ Visible effects from spin-correlation effects in decays.

↪ Important to validate NLO QCD PS Monte Carlo frameworks (aMC@NLO, POWHEG BOX, SHERPA).

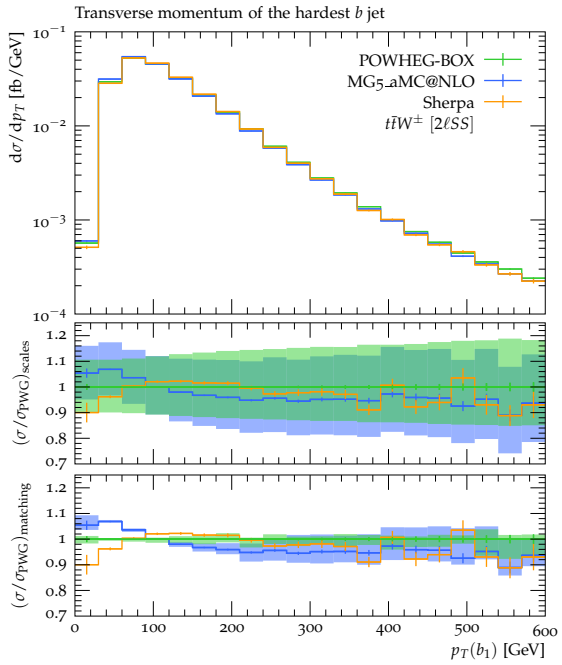
↪ Important to compare NLO+PS to fully off-shell fixed-order calculations.

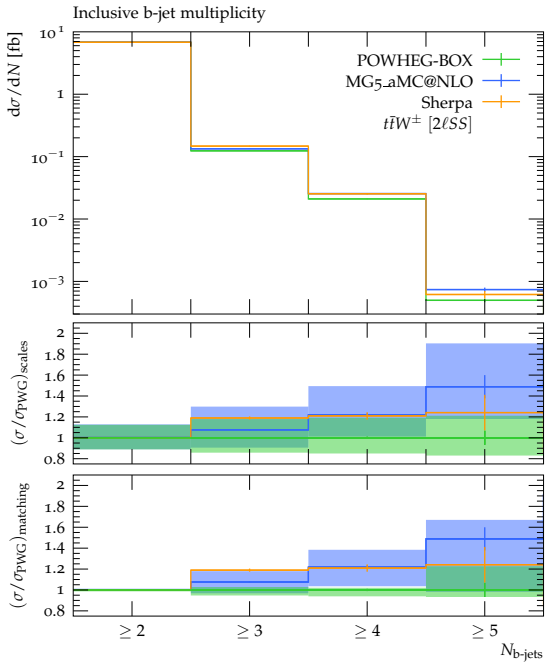
Comparison of different NLO PS frameworks

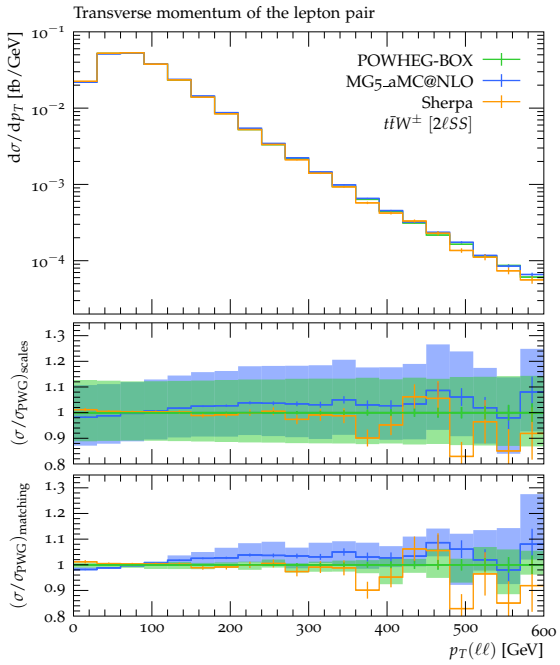
[Febres Cordero, Kraus, Reina, arXiv:2101.11808]

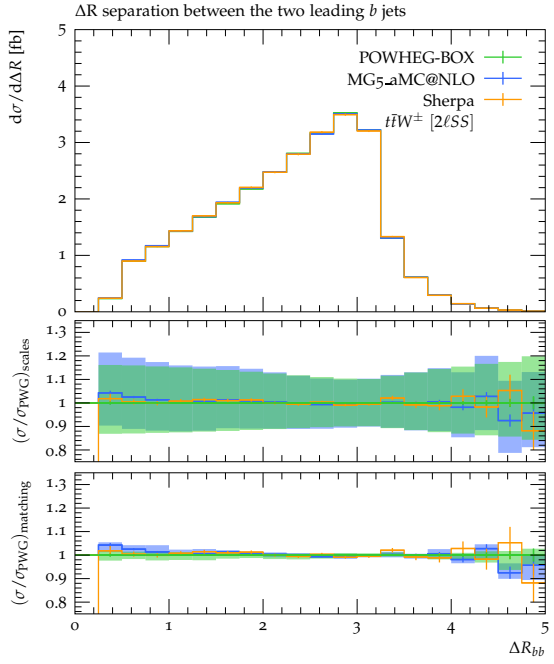
- ↪ Considered POWHEG BOX, MG5_aMC@NLO, and SHERPA.
- ↪ First publically available POWHEG BOX implementation → now being tested by ATLAS/CMS.
- ↪ $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ included (one-loop via NLOX).
- ↪ **Scale and PS uncertainties considered**:
  - $\mu_R = \mu_F = \mu_0 = H_T/2$ - 7-point variation by factor of 2.
  - PS effects studied by variation of (ξ_{damp},ξ_{bornzero}) in POWHEG BOX and μ_Q in aMC@NLO.
- ↪ Keeping **LO spin correlations** [Frixione et al. hep-ph/0702198]
- ↪ **Signature: 2lSS+jets**:
  - $p_T(l) > 15$ GeV, $|\eta(l)| < 2.5$ GeV
  - $p_T(j) > 25$ GeV, $|\eta(j)| < 2.5$ GeV, anti-k_T with $R = 0.4$
  - $N_{\text{b-jets}} \geq 2$, $N_{\text{jets}} \geq 2$
  - Using PYTHIA 8.303 (No MPI, No hadronization)

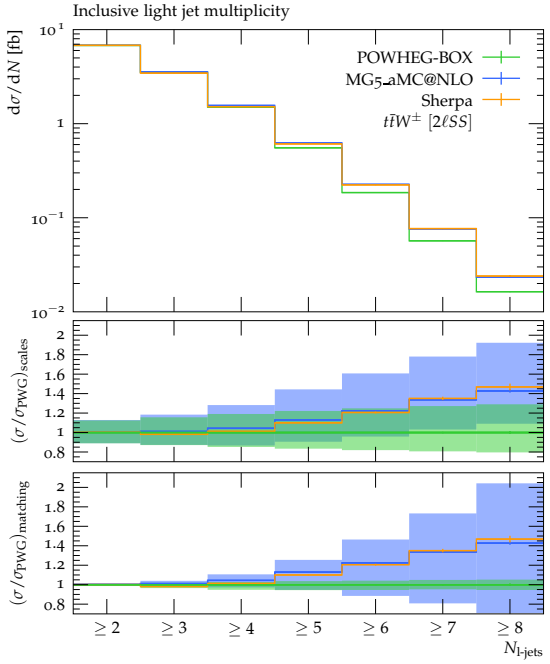
Use as baseline for further estimate of theoretical uncertainty/systematics.

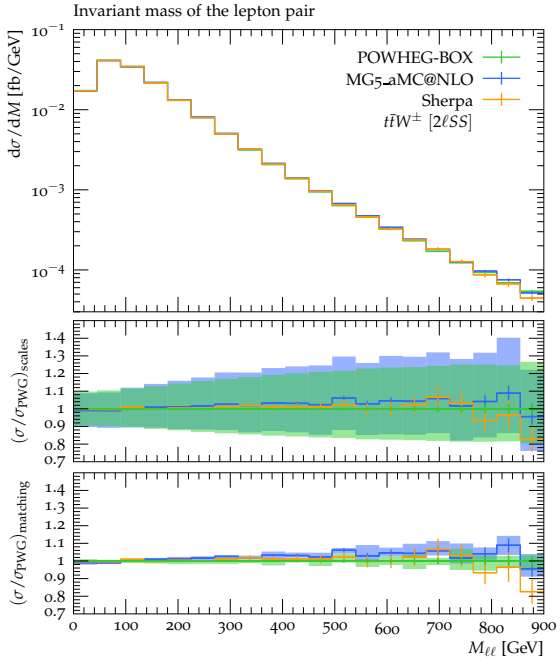








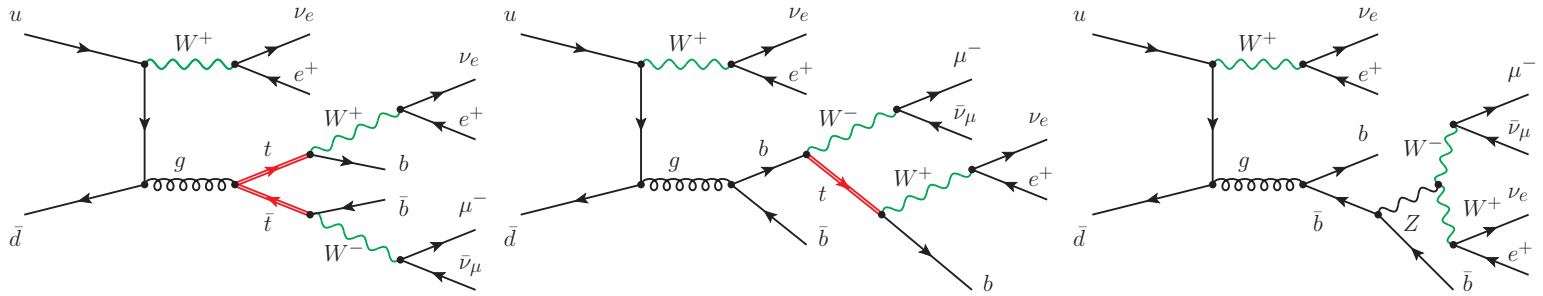


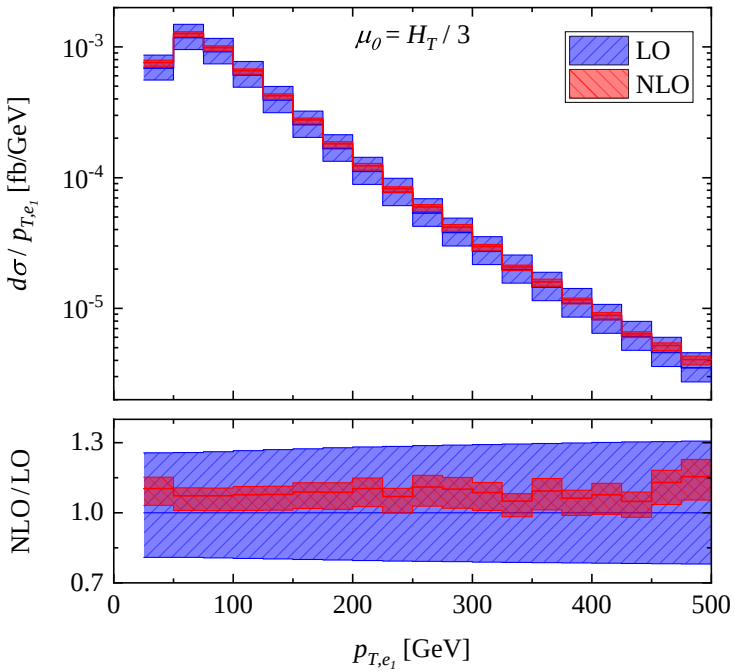


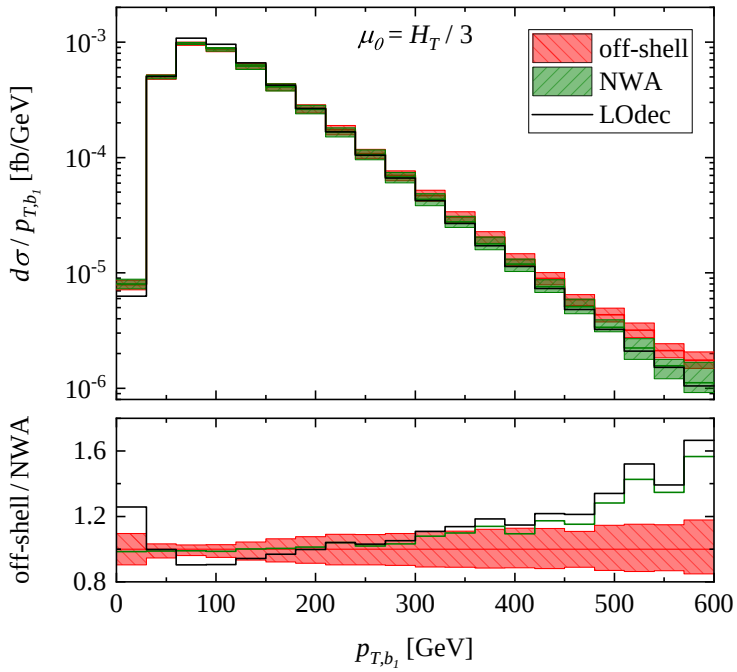
Overall good agreement within theoretical uncertainties that can now be quantified and used as a base to estimate residual modelling uncertainties

Considering off-shell effects

Off-shell fixed order NLO QCD calculation of $3l$ signature: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$







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

(See also: Denner, Pelliccioli, arXiv:2007.12089 and 2102.03246)

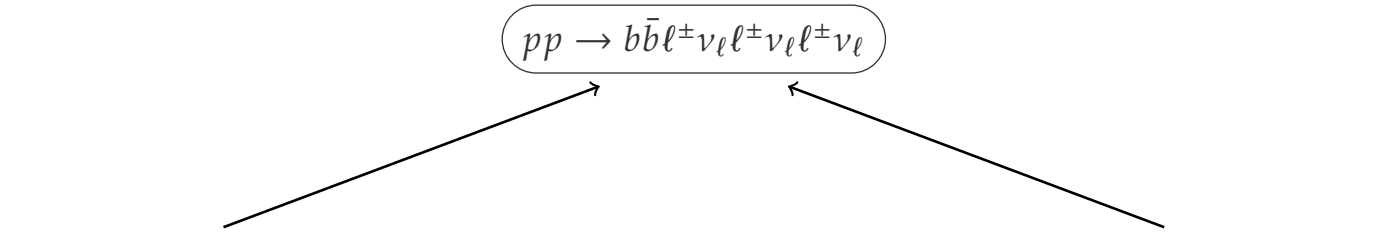
↪ Off-shell: uncertainty below 10% independently of scale choice (fixed/dynamic).

↪ Large off-shell effects in the tails of distributions.

Combining PS and off-shell effects

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

How to model leptonic final states?



fixed-order

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

parton showers

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

[From M. Kraus]

How compatible are the different descriptions?

Combining PS and off-shell effects

↪ Considered fixed-order NLO off-shell vs NLO QCD (POWHEG BOX, MG5_aMC@NLO)

↪ $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ on both sides.

↪ **Scale and PS uncertainties considered**:

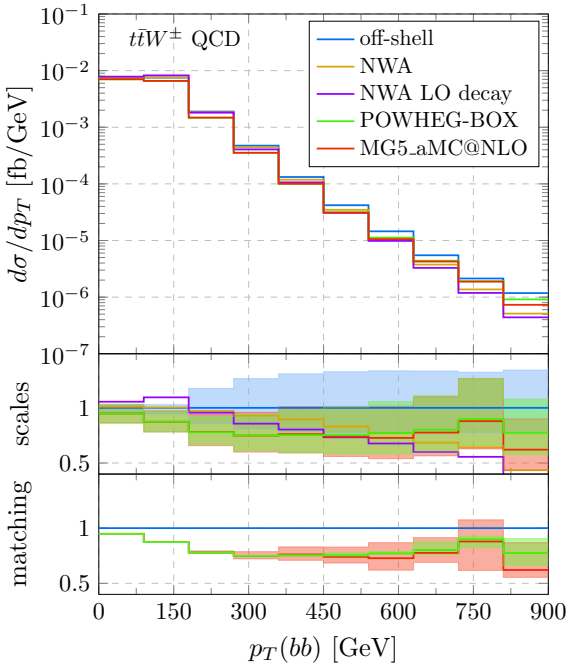
- $\mu_R = \mu_F = \mu_0 = E_T/3$- 7-point variation by factor of 2 (cross-check at fixed scale $\mu_R = \mu_F = \mu_0 = m_t + M_W/2$)
- PS effects studied by variation of ($\xi_{\rm damp}$,$\xi_{\rm bornzero}$) in POWHEG BOX and μ_Q in aMC@NLO.

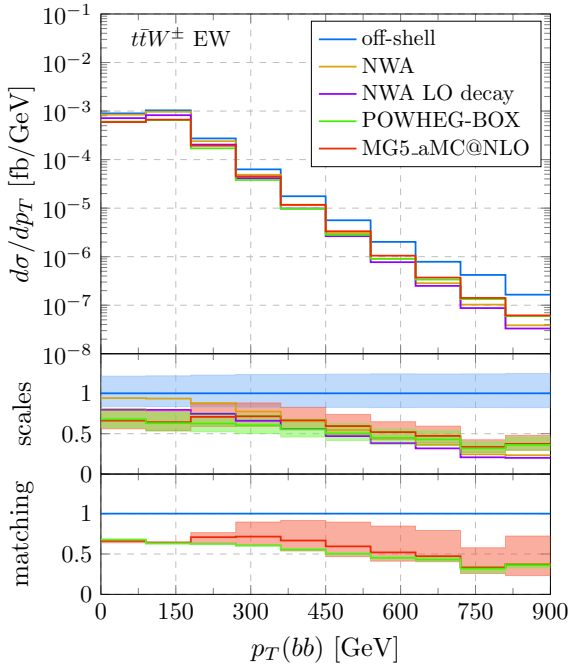
↪ Keeping **LO spin correlations** in NLO PS [Frixione et al. hep-ph/0702198]

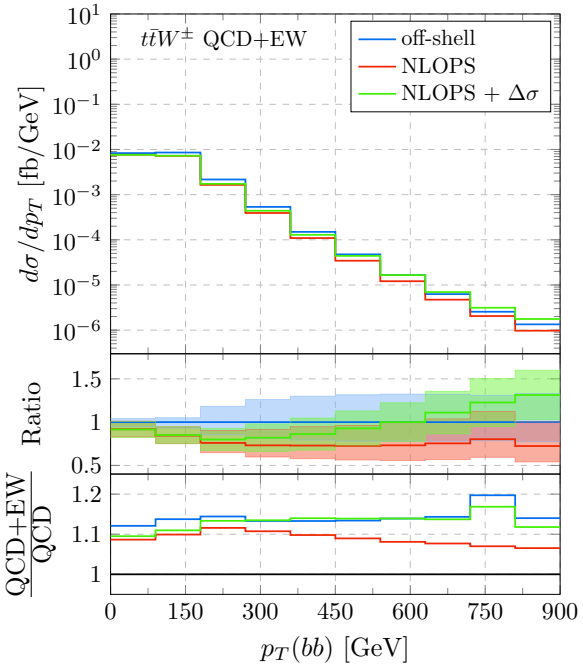
↪ **Signature: 3l**:

- $p_T(l) > 15$ GeV, $|\eta(l)| < 2.5$ GeV
- $p_T(j) > 25$ GeV, $|\eta(j)| < 2.5$ GeV, anti-k_T with $R = 0.4$
- $\Delta R(ll) > 0.4$, $\Delta R(lj_b) > 0.4$
- Using PYTHIA 8.303 (No MPI, No hadronization)

Combining PS and off-shell effects







↪ Off-shell effects very visible **in tails of distributions**: **PS misses single-resonant and non-resonant effects**.

↪ PS effects affects broader region of PS, in particular low p_T regions

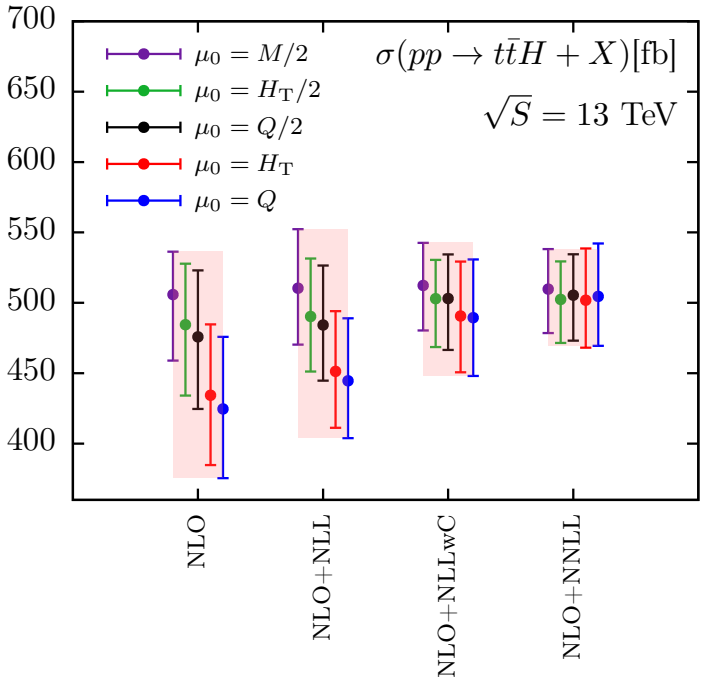
Compensate for tail effects by combining two approaches:

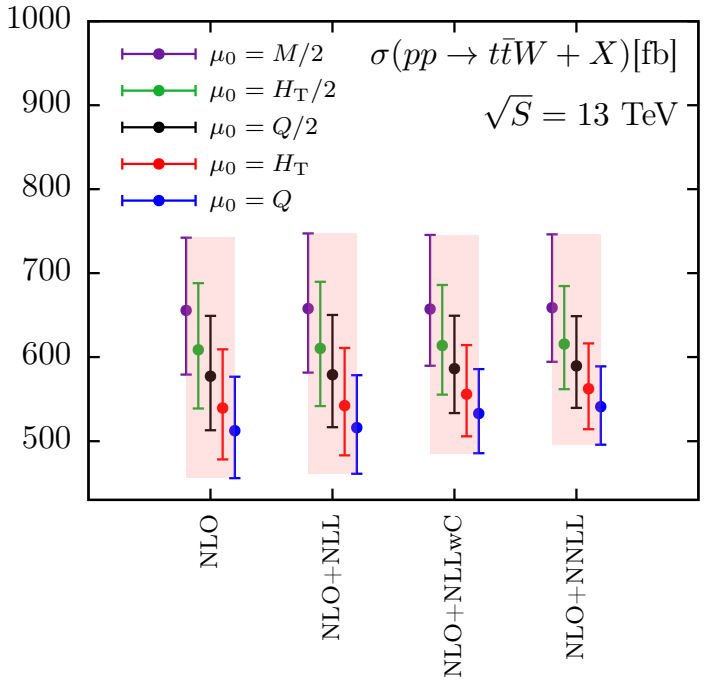
$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLO+PS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX} \quad \text{with} \quad \frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}$$

Estimating missing QCD orders: QCD NLO+NNLL

[Broggio, Ferroglia, Frederix, Pagani, Pecjak, Tsinikos, 19']

[Kulesza, Motyka, Schwartländer, Stebel, Theeuwes, 20']





↪ $t\bar{t}H$ stable wrt choice of central scale when including NLO+NNLL.

↪ $t\bar{t}W$ **still large scale dependence** even after including NLO+NNLL.

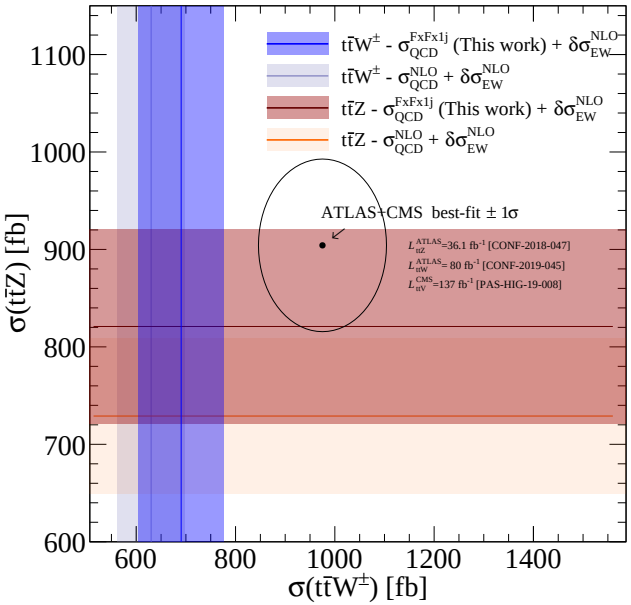
↪ Estimate of theoretical uncertainty → envelope:

$$\sigma_{t\bar{t}W}^{\text{NLO+NNLL}} = 592^{+26.1\%+2.1\%}_{-16.2\%-2.1\%}\ \text{fb}$$

↪ Indication of large NNLO QCD corrections?

NLO QCD + Jet merging +EW

[Buddenbrock, Ruiz, Mellado '20]

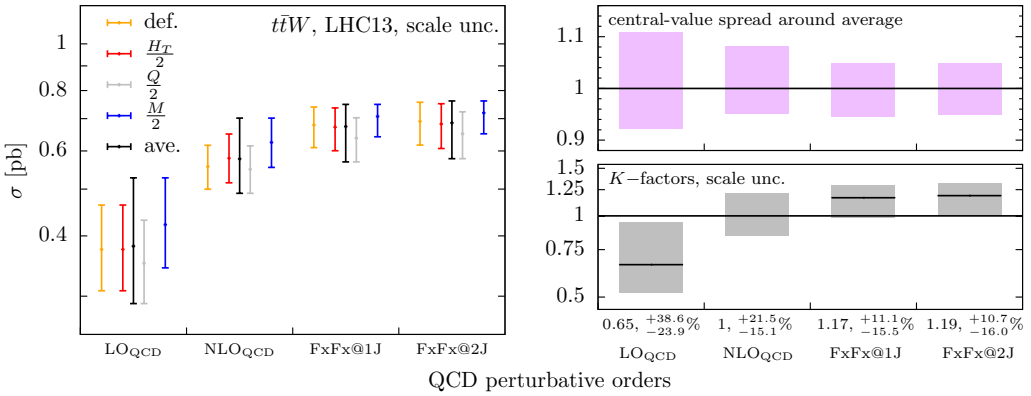


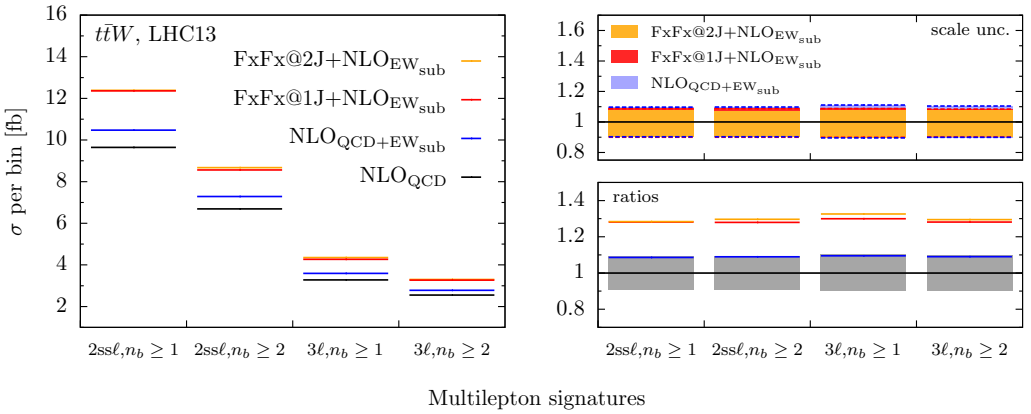
$\sqrt{s} = 13$ TeV

Light: NLO QCD+EW
Dark: NLO QCD+FxFX1j+ EW

↪ Moving in the right direction but still tension wrt ATLAS+CMS results.

[Tsnikos, Rikkert '21]





↪ Tension partially resolved
↪ Improved scale behavior

Strong indication that NNLO QCD corrections will bring better agreement with SM predictions.

Outlook

- Given all available theoretical studies we can provide well-motivated estimates of the theoretical accuracy on multilepton signatures based on:
  - ↪ PS MC comparison
  - ↪ NLO PS vs off-shell studies
  - ↪ Approximate higher-order QCD effects
- Comparison in fiducial volume is now possible and more reliable
- This discussion could most naturally and effectively happen within these WGs
- Considering summarizing the outcome in a note? Would it be useful?