

Progress towards a theory recommendation for $t\bar{t}W$

On behalf of the $t\bar{t}H/tH$ working group

Theory conveners: S. Pozzorini, L. Reina → **M. Worek, M. Zaro**

Exp. conveners: J. McFayden (ATLAS), S. Sanchez Cruz (CMS)

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGTTTH>

WG1 Fall Meeting

October 5, 2021

Brief summary of group's activities

Focus on: Theoretical modelling of $t\bar{t}bb$ and $t\bar{t}W$ backgrounds among largest residual systematic uncertainties in $t\bar{t}H$ analyses

- $t\bar{t} + b$ jets [bckgr. to $t\bar{t}H(bb)$]

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 - ↪ Comparison of NLO PS MC → Converging on final recommendation: Will be presented at the General Meeting (Dec. 1-3) and documented in a publication and a WG note.
 - ↪ ATLAS and CMS: working at **comparison of updated POWHEG BOX and SHERPA setups, based on WG recommendations**. Comparing uncertainty treatment between experiments.
 - ↪ Study of **off-shell effects** in fully decayed $pp \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}b\bar{b}$ including NLO QCD corrections [[Denner et al.](#), arXiv:2008.00918, [Bevilacqua et al.](#), arXiv:2105.08404]

↪ See **Worek's talk**

- $t\bar{t}W$ [bckgr. to $t\bar{t}H$ (multileptons, in particular [2lSS](#) and [3l](#))]

- $t\bar{t}W$ [bckgr. to $t\bar{t}H$ (multileptons, in particular [2lSS](#) and [3l](#))
 - ↪ Tension between data and theoretical predictions:
 $\lambda_{t\bar{t}W}^{2lSS} = 1.56_{-0.28}^{+0.30}$ and $\lambda_{t\bar{t}W}^{3l} = 1.68_{-0.28}^{+0.30}$
 - ↪ ATLAS and CMS: incorporating **new POWHEG BOX ttW implementation** in ATLAS/CMS generator framework. Include generated samples in Rivet comparisons.

↪ Several new theoretical developments.

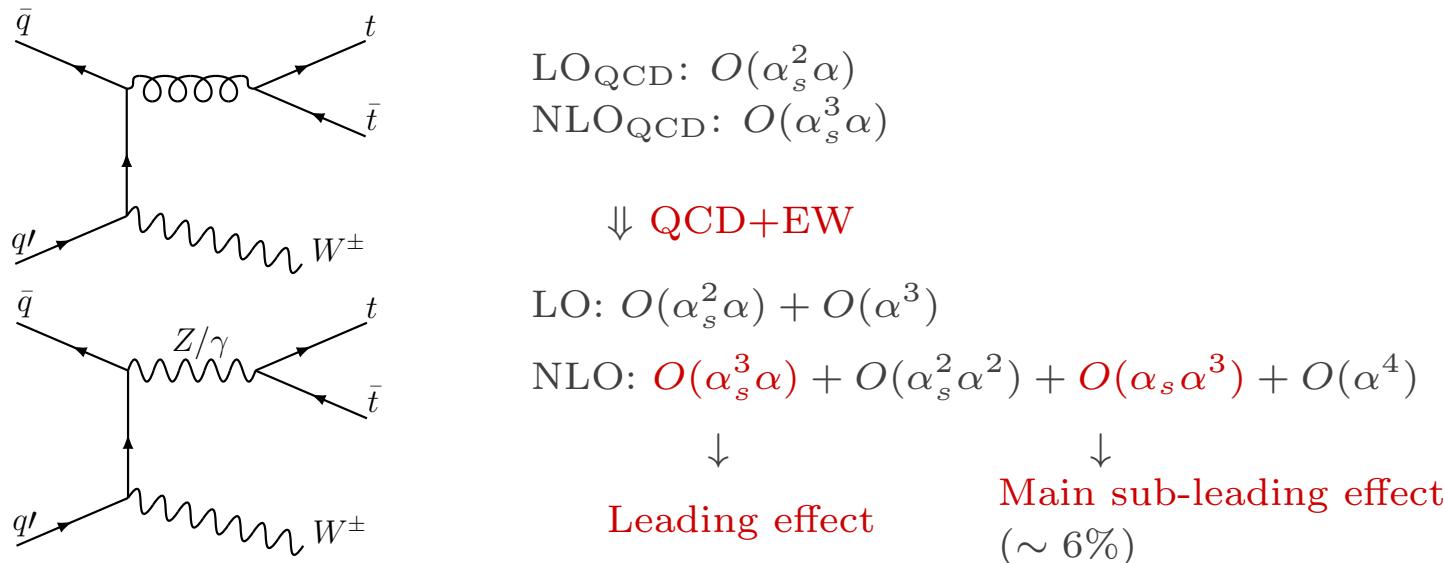
- ↪ **NLO QCD+EW** points to large EW corrections from t -channel Higgs exchange. Frederix, Pagani, Zaro arXiv:1711.02116, Frederix, Tsinikos arXiv:2004.09552
- ↪ **NLO+NNLL QCD** underline importance of higher-order QCD corrections. Broggio et al. arXiv:1907.04343, Kulesza et al. arXiv:2001.03031
- ↪ Study of **multi-jet** merging. Buddenbrock et al. arXiv:2009.00032, Frederix, Tsinikos arXiv:2108.07826
- ↪ **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

- ↪ **New POWHEG BOX implementation** Febres Cordero et al., arXiv:2101.11808
Enables comparison of NLO PS Monte Carlo event generators, including dominant $O(\alpha_s^3 \alpha_e)$ and $O(\alpha_s \alpha^3)$ and LO spin-correlation in decays:
 - [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**
as well as [$O(\alpha_s^3 \alpha)$ and no spin correlations]
 - [Garzelli et al., arXiv:1208.2665] - **PowHel**
- ↪ Comparison between **NLO QCD+PS vs NLO QCD off-shell**. Bevilacqua et al., arXiv:2109.15181

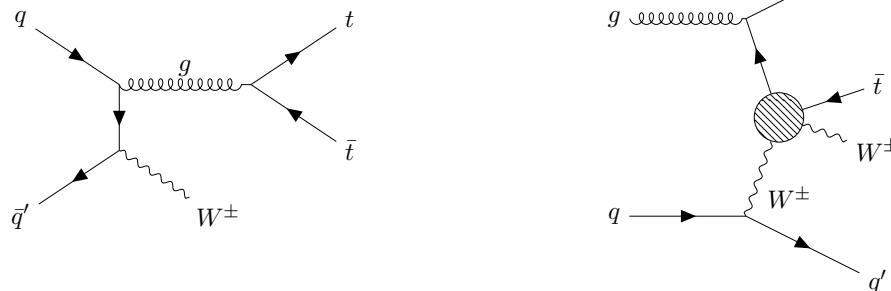
$Wt\bar{t}$: large NLO (real) corrections



$\sigma [\text{fb}]$	LO _{QCD}	LO _{QCD} + NLO _{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)

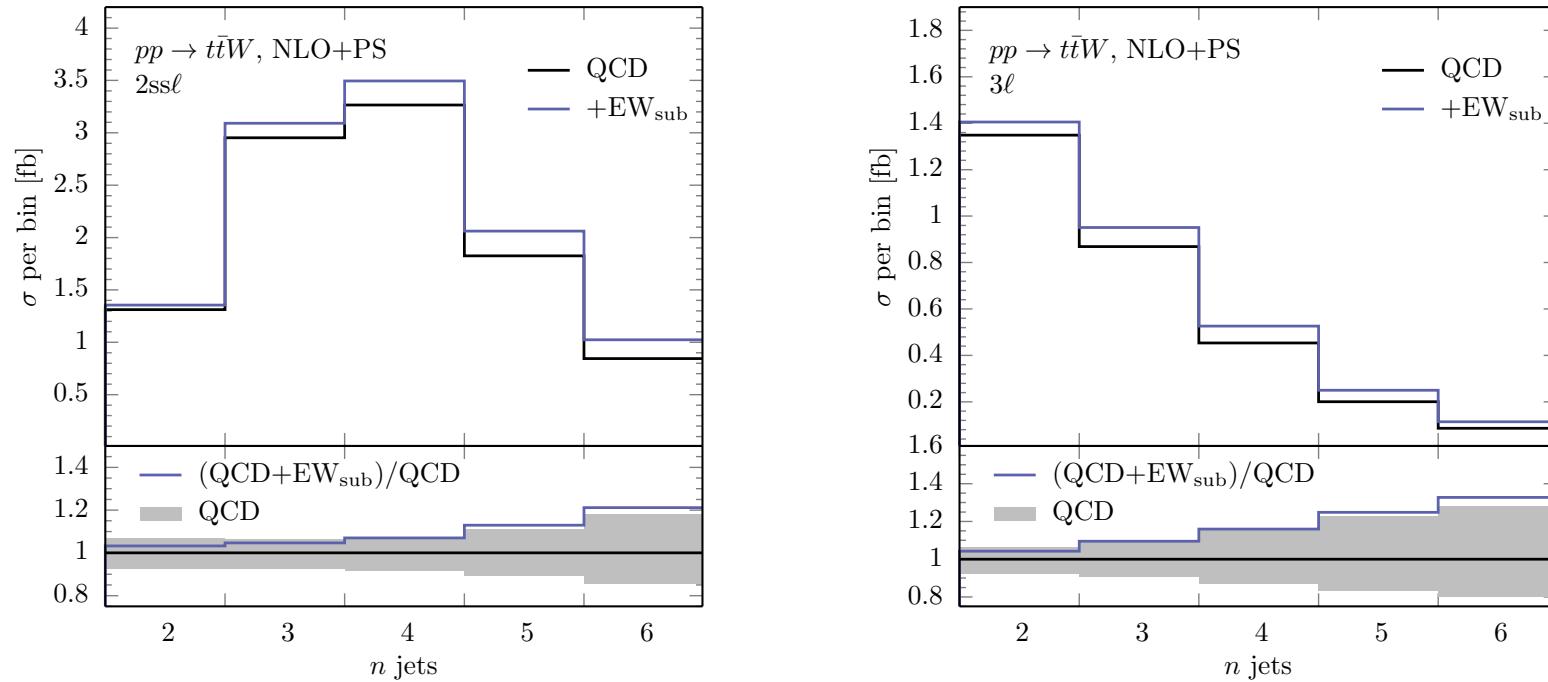
[Frederix, Pagani, Zaro, '17] (number in parenthesis obtained with extra jet veto)

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.**

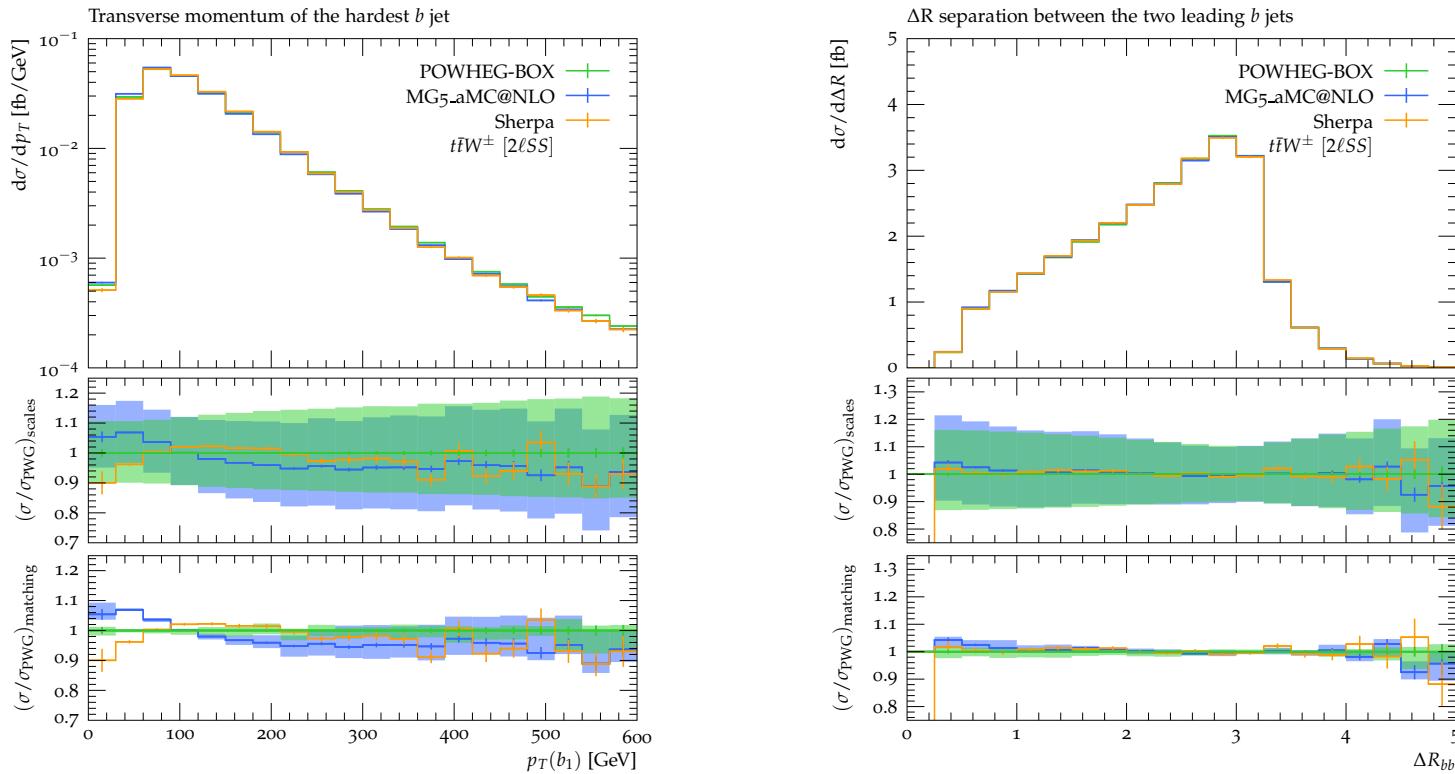
Comparison of different NLO PS frameworks

[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 $(\xi_{\text{damp}}, \xi_{\text{bornzero}})$ 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)

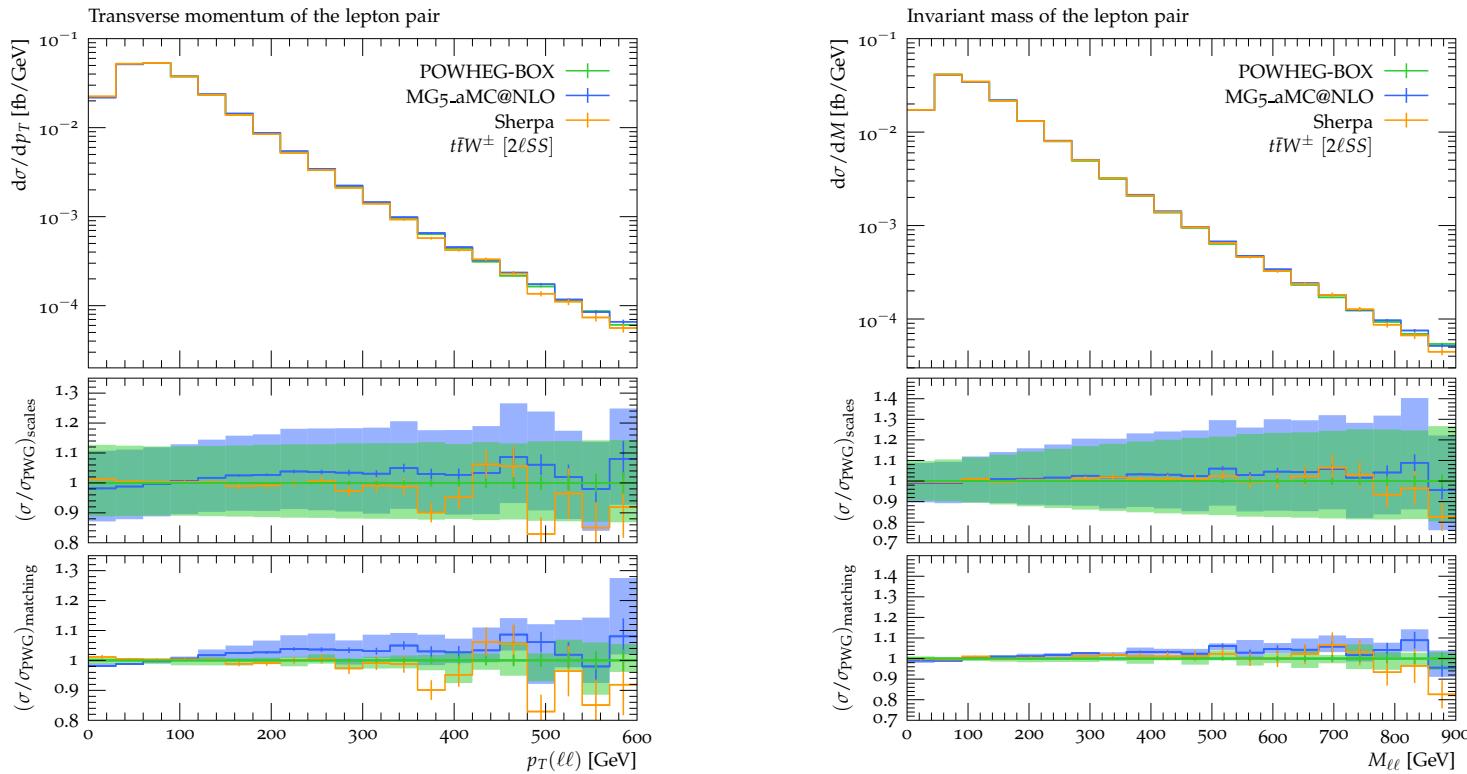
Use as baseline for further estimate of theoretical uncertainty/systematics.

Comparison of different NLO PS frameworks



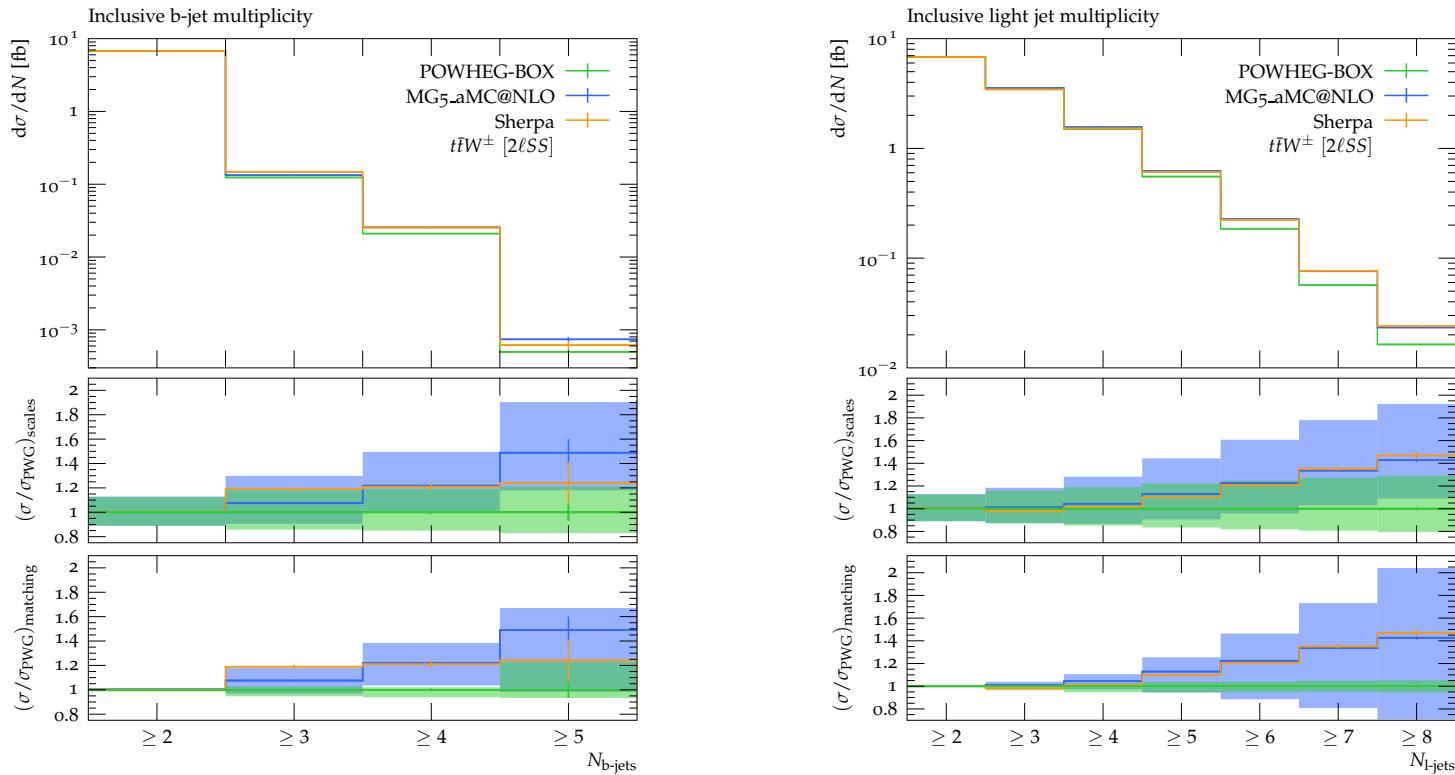
Small shape differences at the beginning of the p_T spectrum

Comparison of different NLO PS frameworks



Good agreement within uncertainties over the entire spectrum

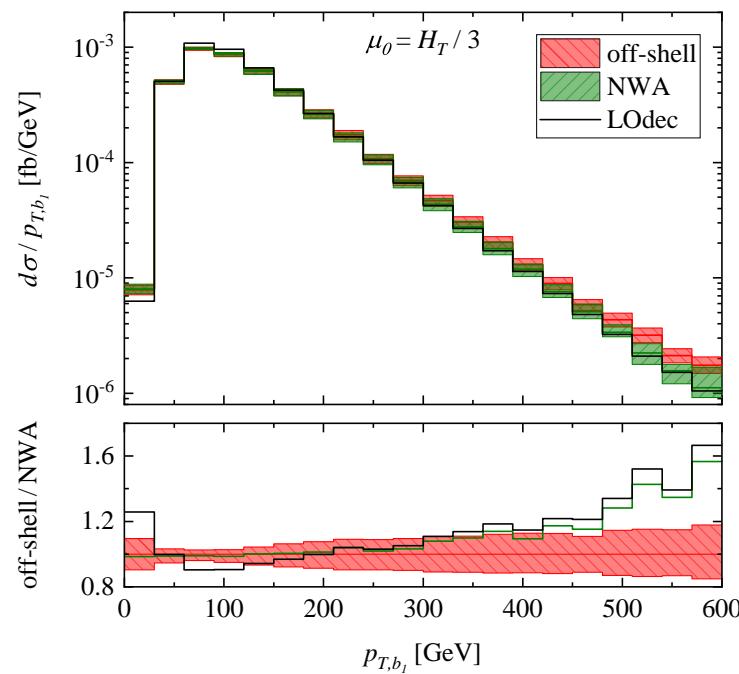
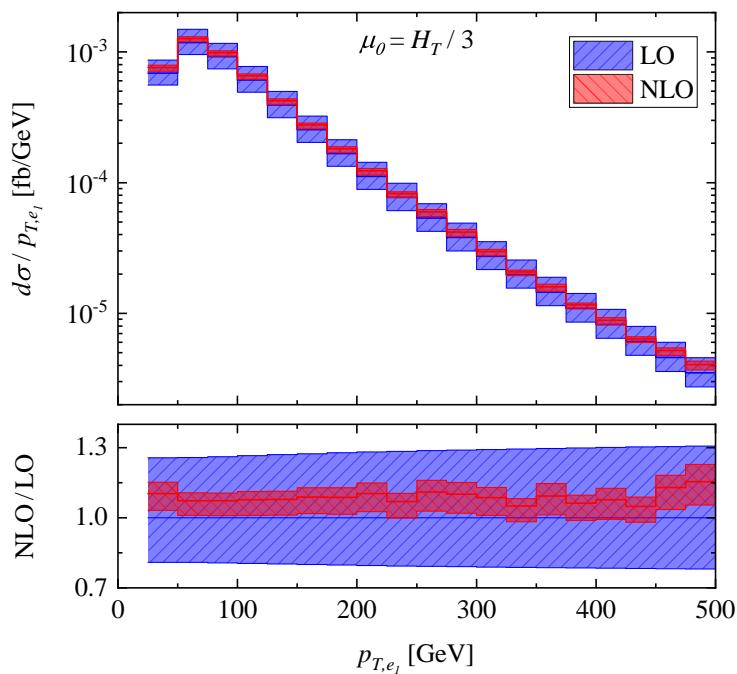
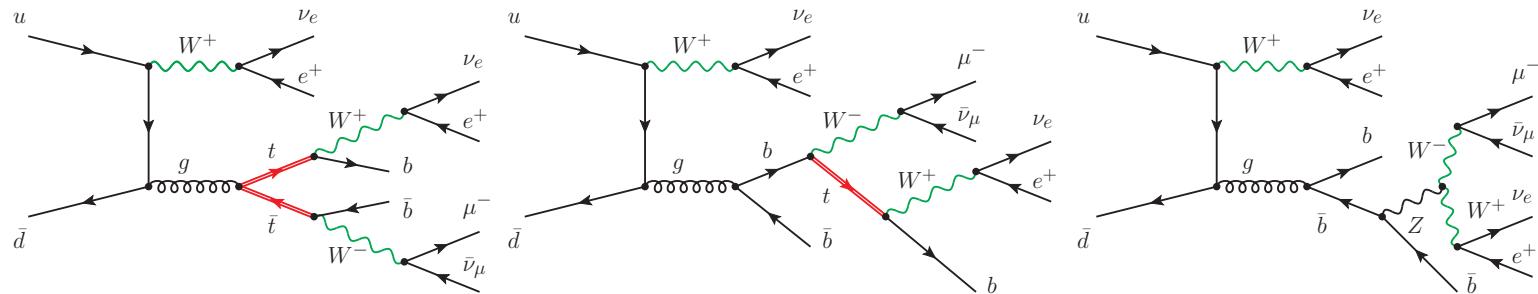
Comparison of different NLO PS frameworks



Good agreement within theoretical uncertainties

Considering off-shell effects

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



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

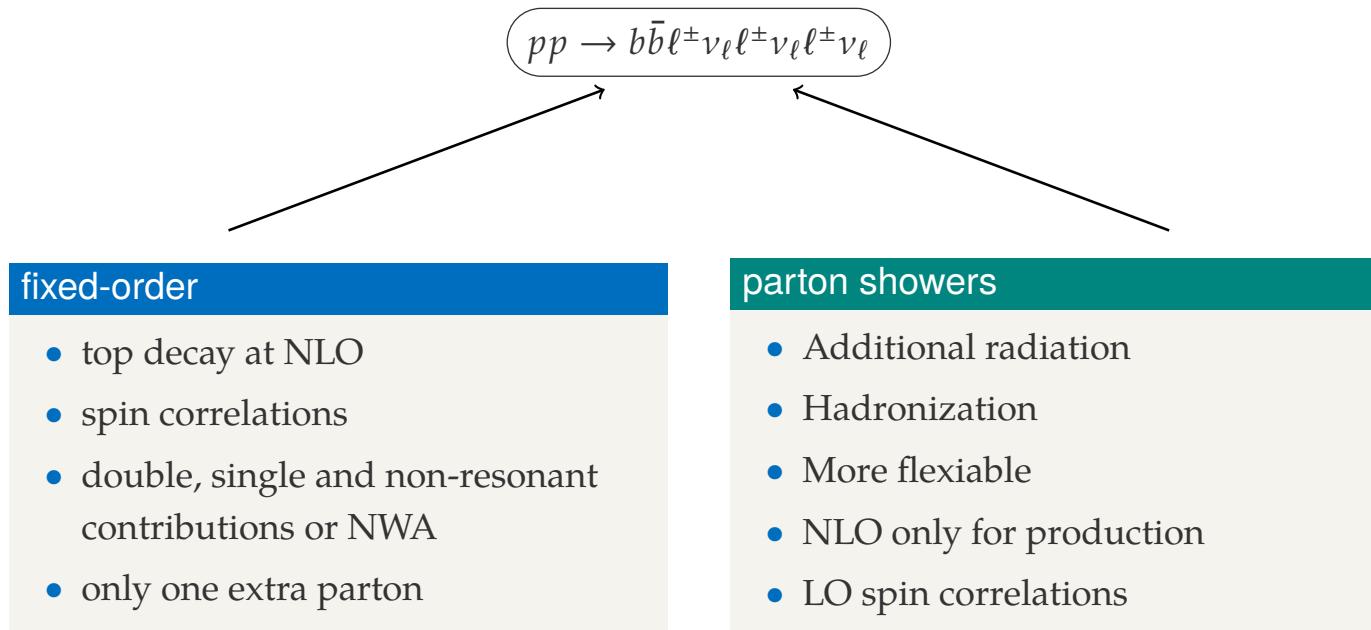
(See also: Denner, Pelliccioli, arXiv:2007.12089 and 2102.03246)

- ↪ 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?



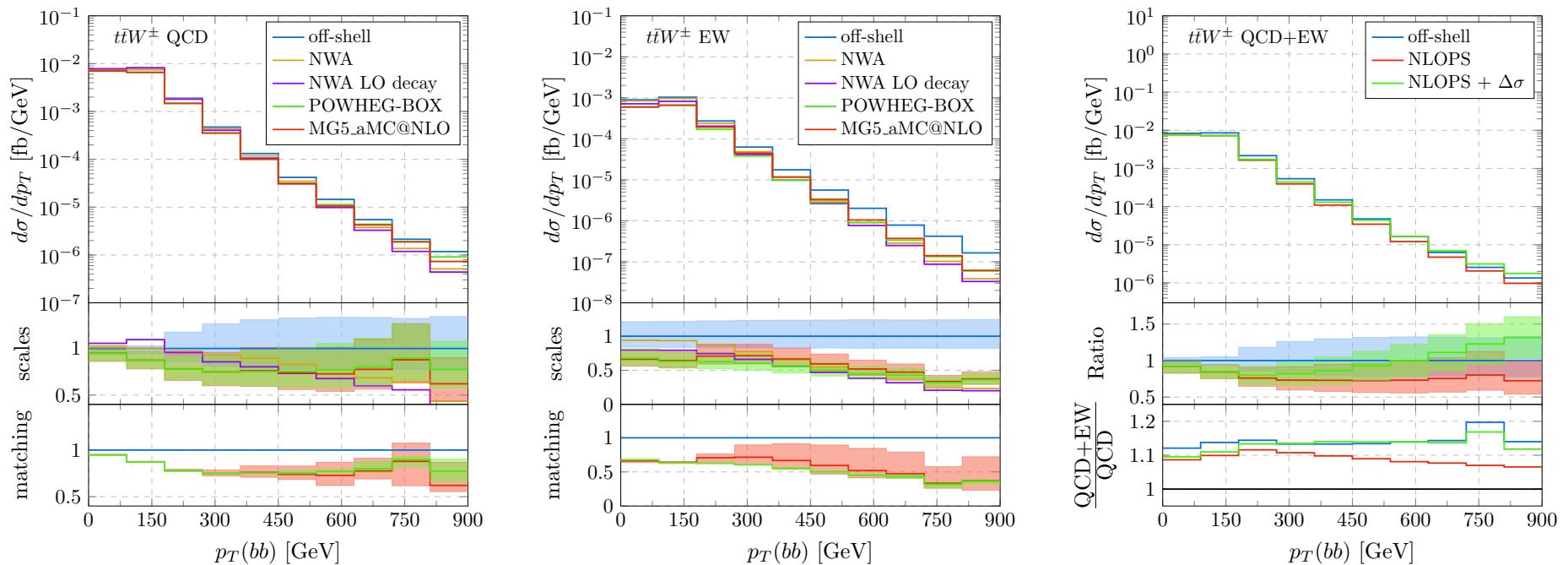
[From M. Kraus]

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 $(\xi_{\text{damp}}, \xi_{\text{bornzero}})$ 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

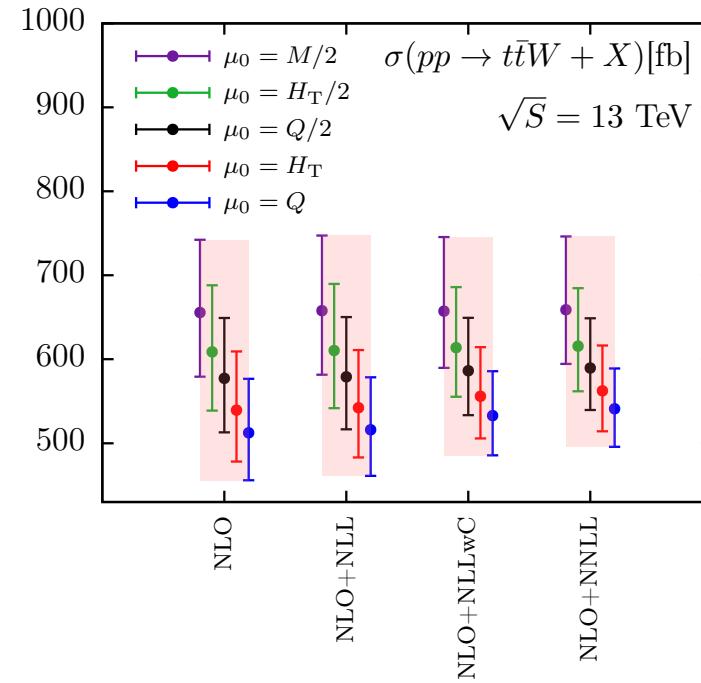
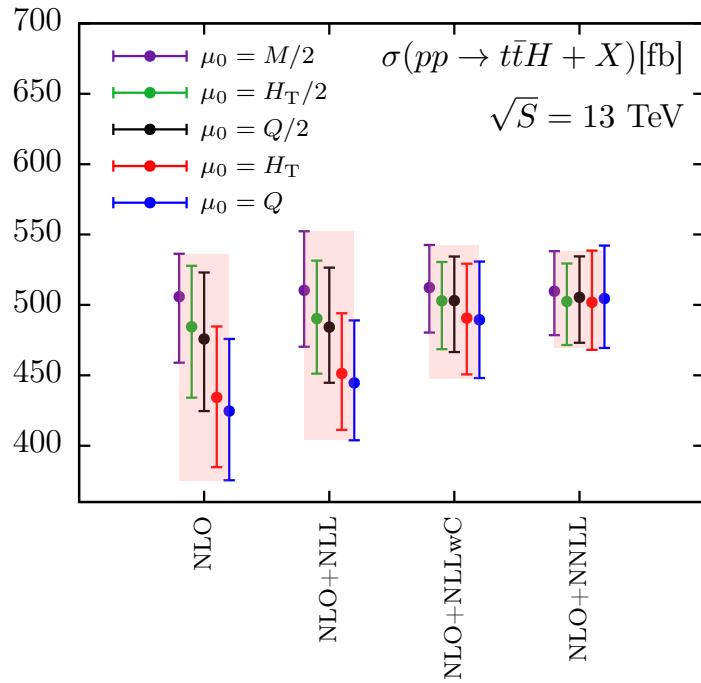
Compensate for tail effects by combining two approaches:

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

QCD NLO+NNLL

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

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

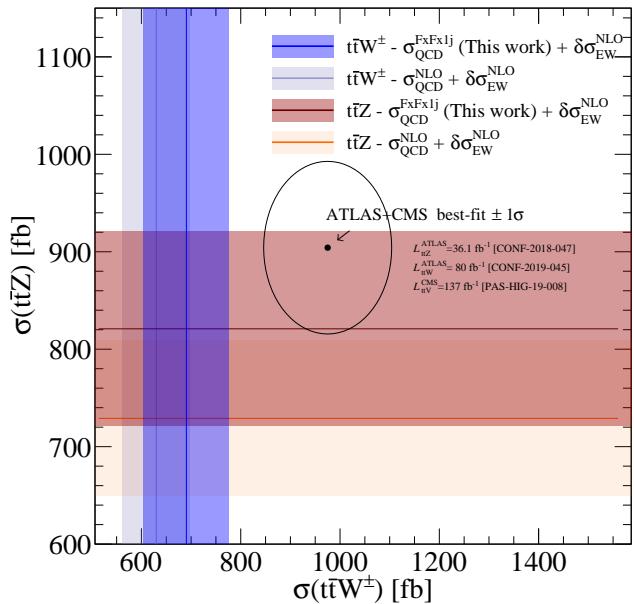


- ↪ $t\bar{t}H$ stable wrt choice of central scale when including NLO+NNLL.
 - ↪ $t\bar{t}W$ **still large scale dependence** even after including NLO+NNLL.
 - ↪ Estimate of theoretical uncertainty → envelope:
- $$\sigma_{t\bar{t}W}^{\text{NLO+NNLL}} = 592^{+26.1\% + 2.1\%}_{-16.2\% - 2.1\%} \text{ fb}$$
- ↪ Indication of large NNLO QCD corrections?

NLO QCD + Jet merging +EW

[Tsnikos, Rikkert '21]

[Buddenbrock, Ruiz, Mellado '20]



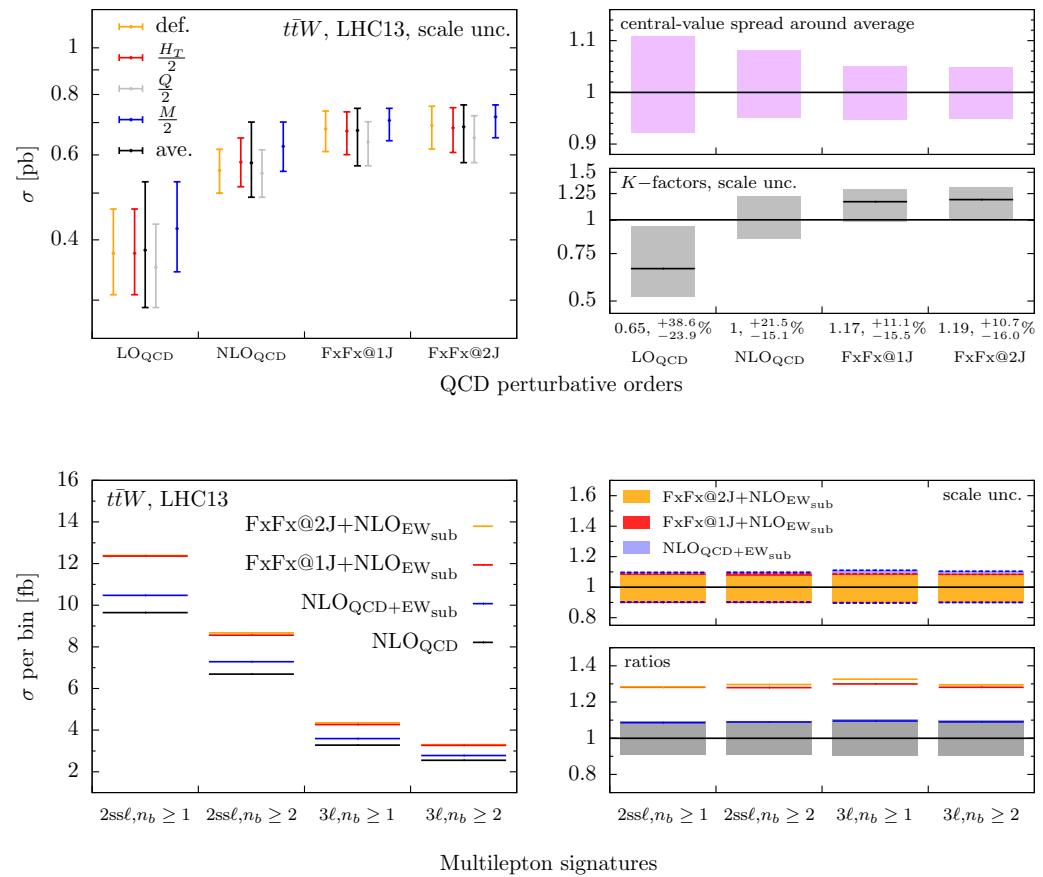
$\sqrt{s} = 13 \text{ TeV}$

Light: NLO QCD+EW

Dark: NLO QCD+FxFX1j+ EW

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

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



→ Tension partially resolved
 → Improved scale behavior

Outlook

- Finalize $t\bar{t}b\bar{b}$: publication and WG note.
- Present comprehensive study of $t\bar{t}W$ and first theory recommendation:
 - ↪ PS MC comparison
 - ↪ NLO PS vs off-shell studies
 - ↪ Approximate higher-order QCD effects
- Review results at one or more group meetings before December General Meeting.
- Discuss way forward and new studies.