$t\bar{t}H/tH$: Theory Summary

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/LHCHXSWGTTH`

The 18$^{\text{th}}$Workshop of the LHC Higgs Working Group

CERN, December 1, 2021

Brief summary of group's theory activities

Main focus: theoretical modelling of background and signal, among the largest residual systematic uncertainties in $t\bar{t}H + tH$ analyses

- ***$t\bar{t} + b$* jets** [bckgr. to $t\bar{t}H(b\bar{b})$] – **wrapping up + outlook**
  - ↪ Comparison of NLO PS MC → Converged on new recommendation
    Used in recent analyses. Will be documented in a WG note + publication.
  - ↪ Study of **off-shell effects** in fully decayed $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}b\bar{b}$ including NLO QCD corrections. ↪ Denner et al. arXiv:2008.00918, Bevilacqua et al., arXiv:2105.08404
- ***$t\bar{t}W$*** [bckgr. to $t\bar{t}H$(multileptons)] – **several new studies**
  - ↪ Tension between data and theoretical predictions:
    $\lambda_{t\bar{t}W}^{2lSS} = 1.56^{+0.30}_{-0.28}$ and $\lambda_{t\bar{t}W}^{3l} = 1.68^{+0.30}_{-0.28}$
  - ↪ Investigated impact of higher-order QCD and EW corrections.
  - ↪ Improved modelling of fiducial signatures including parton-shower and off-shell effects.
- ***$t\bar{t}H/tH$*** – **looking ahead**
  - ↪ Aim for default NLO QCD+EW in all PS event generators.
  - ↪ Include new elements in theoretical studies: off-shell effects, STXS, anomalous couplings (e.g. C$\not{P}$), EFT interpretation.
  - ↪ Towards NNLO QCD to bring further perturbative stability.

$t\bar{t}W$: 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:

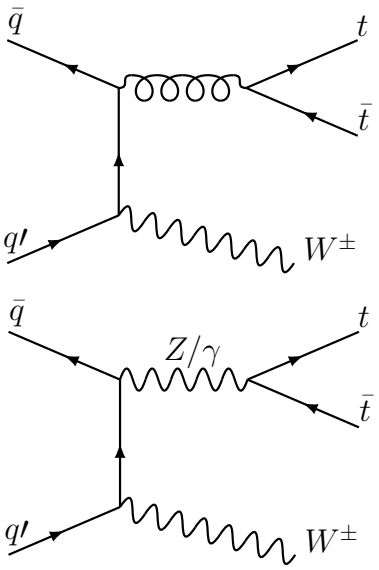
- [Frederix, Tsinikos, arXiv:2004.09552] - aMC@NLO
- [Buddenbrock et al., arXiv:2009.00032] - aMC@NLO+FxFx
- [ATL-PHYS-PUB-2020-024] - aMC@NLO+FxFx and SHERPA
- [Frederix, Tsinikos, arXiv:2108.07826] - aMC@NLO+FxFx

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

$t\bar{t}W$: large NLO 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: $O(\alpha_s^3\alpha) + O(\alpha_s^2\alpha^2) + O(\alpha_s\alpha^3) + O(\alpha^4)$

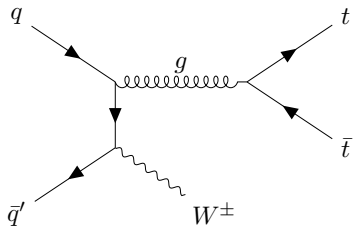
$\downarrow$ Leading effect

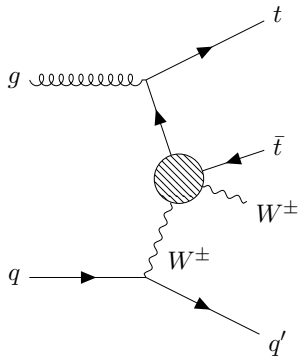
$\downarrow$ Main sub-leading effect ($\sim 6\%$)

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:





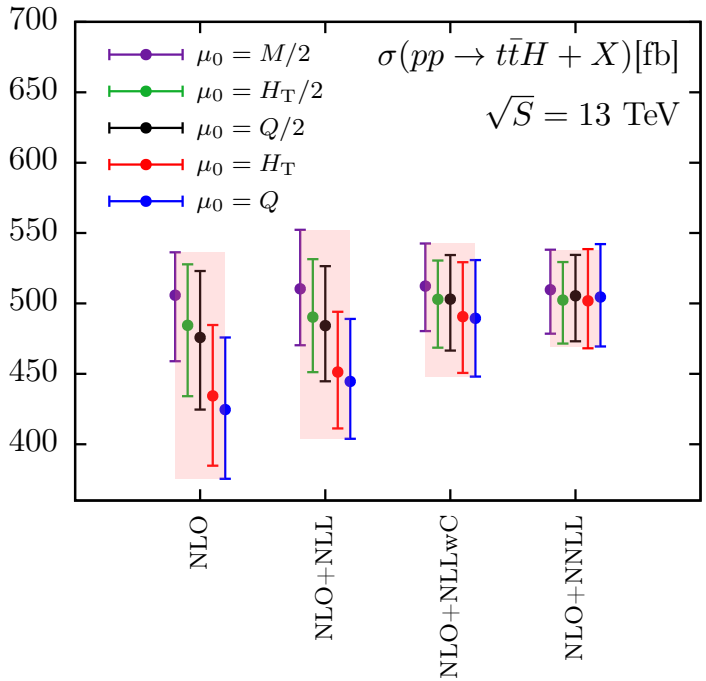
Tree level processes:

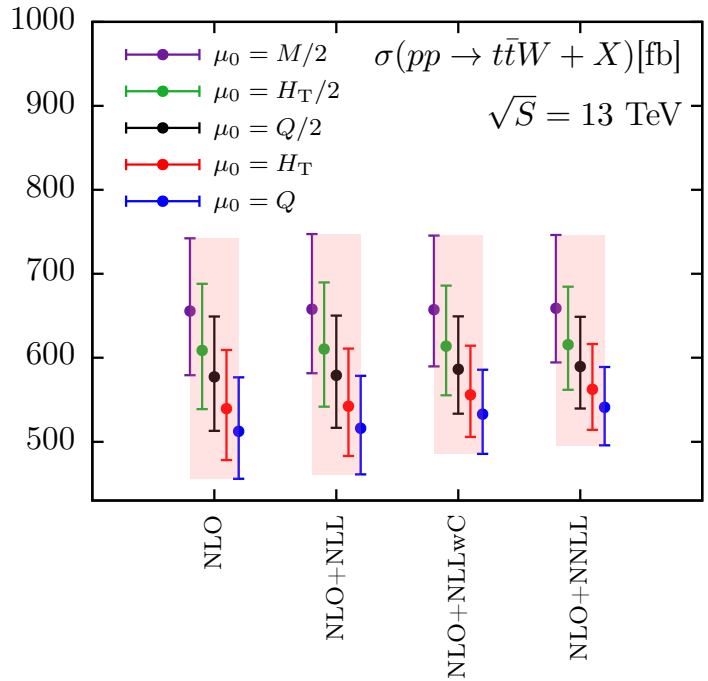
subject to non negligible h.o. effects

$t\bar{t}W$: 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.

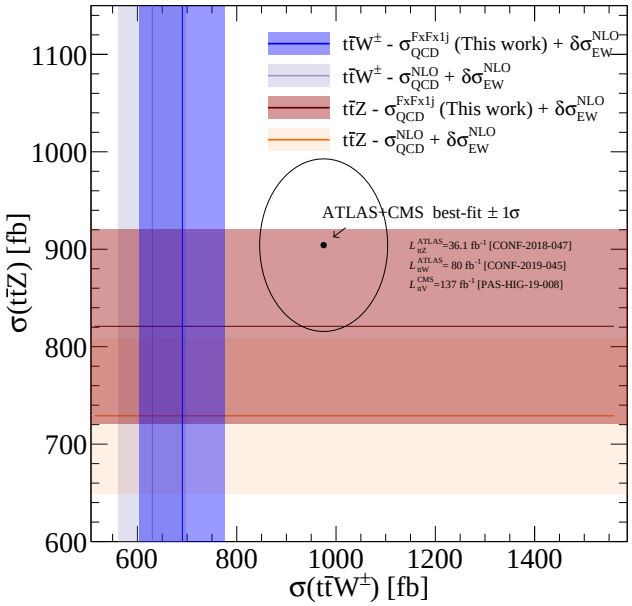
↪ Estimate of theoretical uncertainty → envelope:

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

↪ Indication of large NNLO QCD corrections?

$t\bar{t}W$: NLO QCD + Jet merging +EW

[Buddenbrock, Ruiz, Mellado '20]

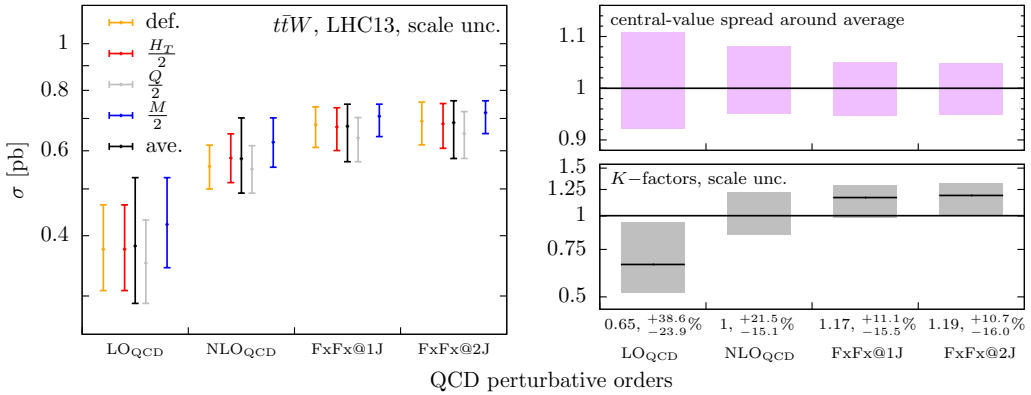


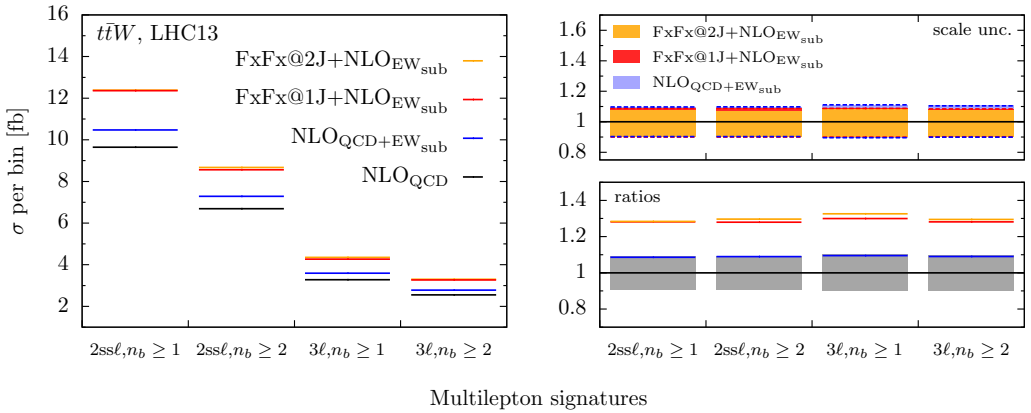
$\sqrt{s} = 13$ TeV

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

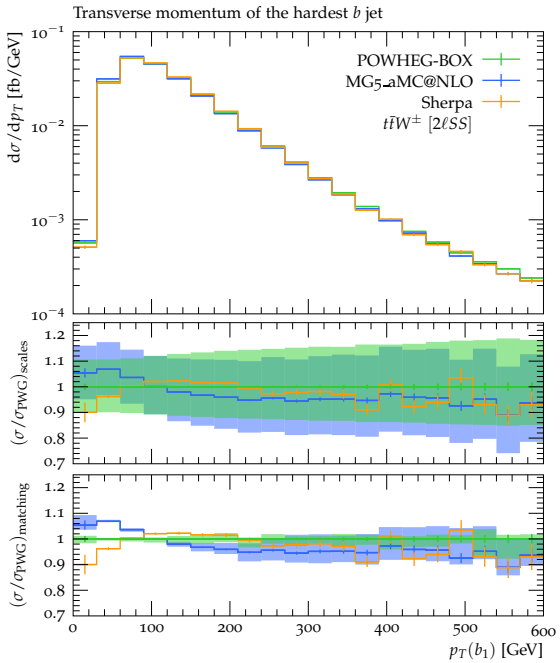
Strong indication that NNLO QCD corrections could bring better agreement with SM predictions.

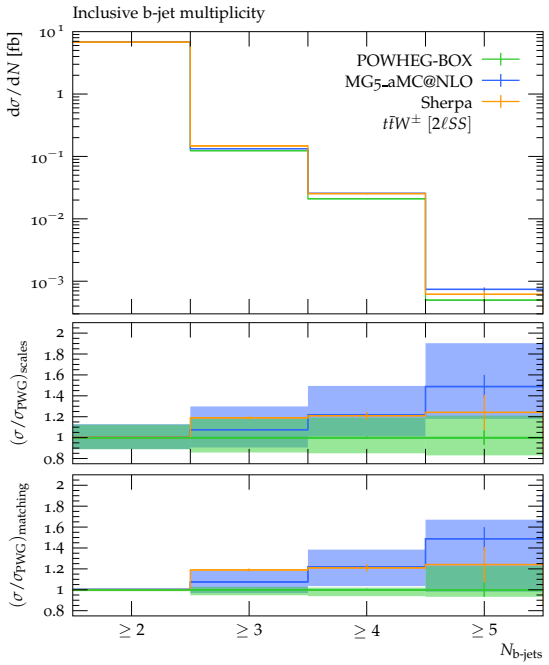
$t\bar{t}W$: Comparison of different NLO PS frameworks

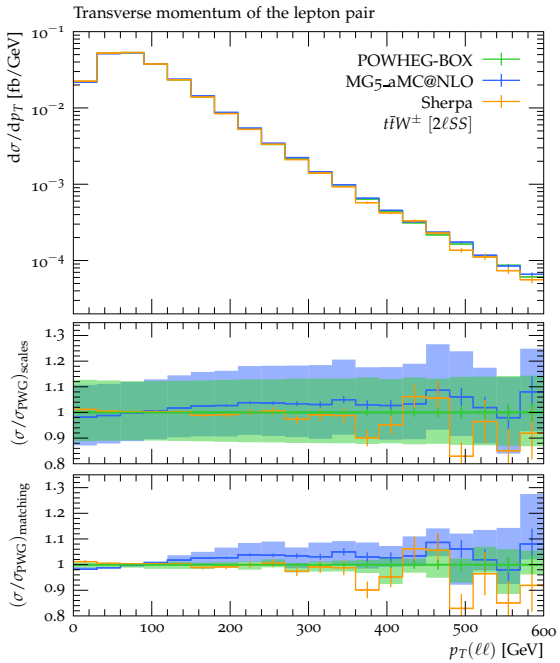
[Febres Cordero, Kraus, Reina, arXiv:2101.11808]

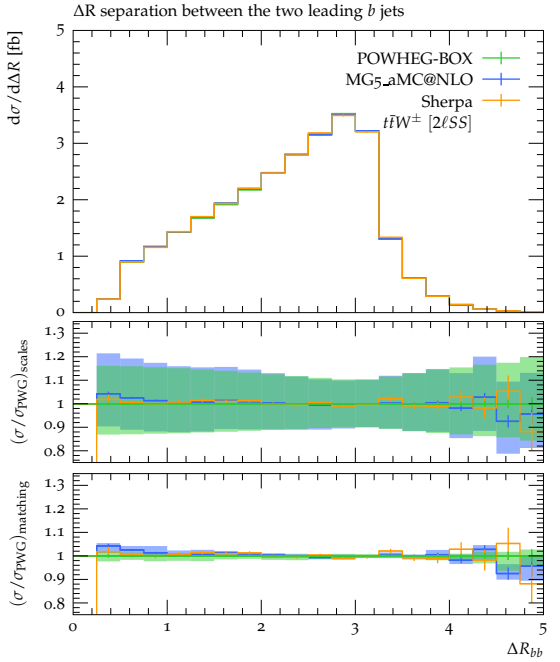
- ↪ Considered POWHEG BOX, MG5_aMC@NLO, and SHERPA.
- ↪ First publically available POWHEG BOX implementation → now being tested by ATLAS/CMS.
- ↪ $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ included (one-loop via NLOX).
- ↪ **Scale and PS uncertainties considered**:
  - $\mu_R = \mu_F = \mu_0 = H_T/2$ - 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)

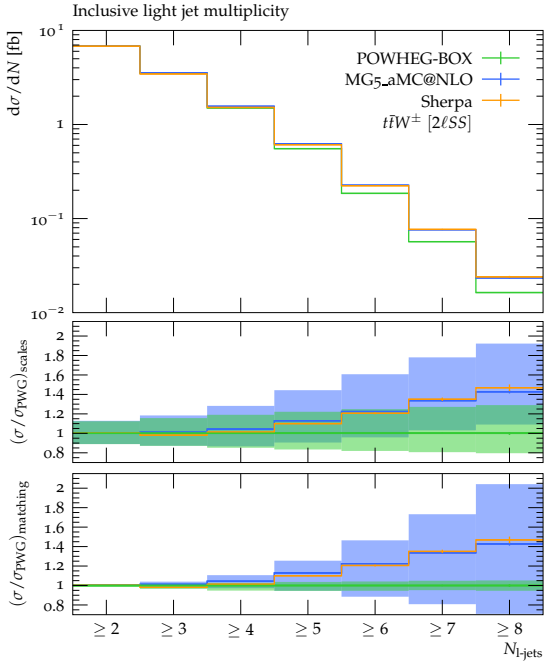
Use as baseline for further estimate of theoretical uncertainty/systematics.

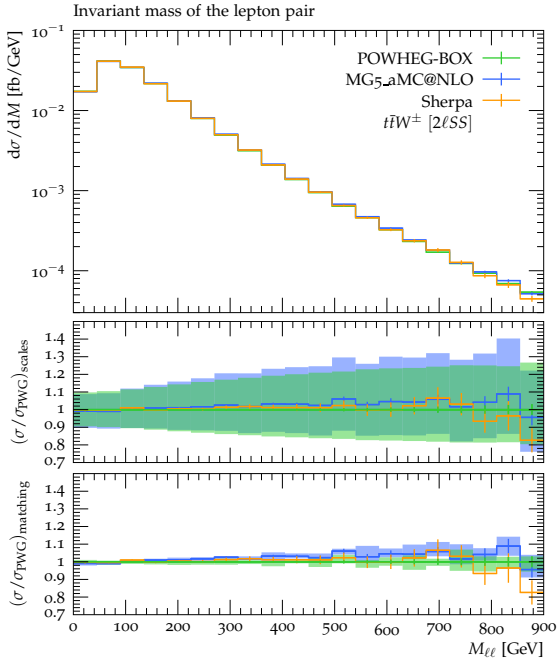








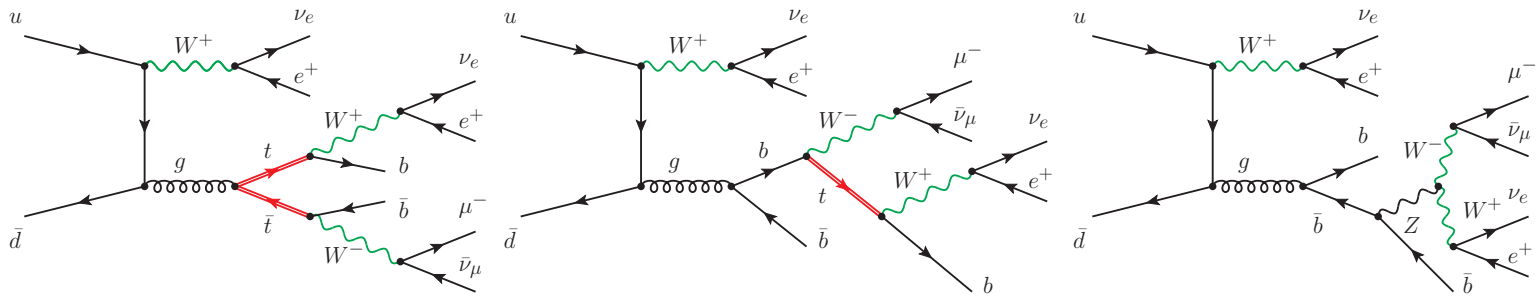


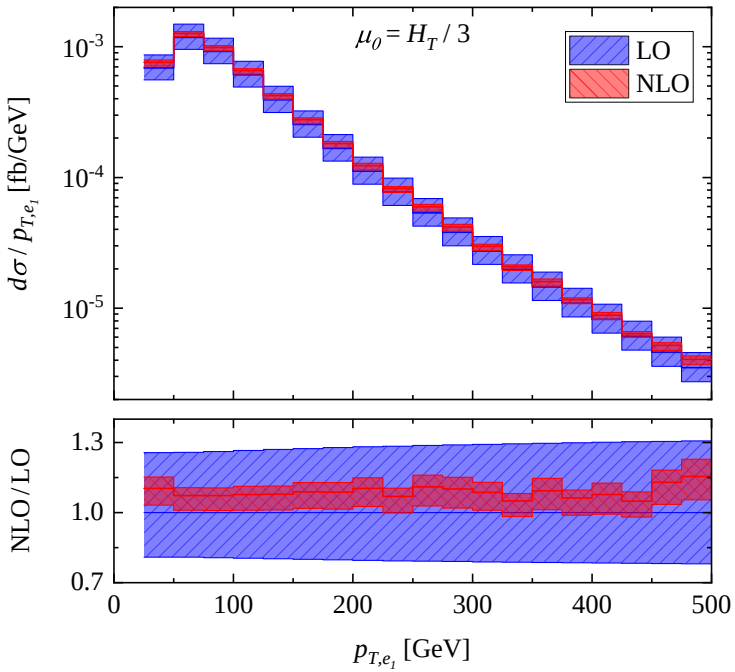


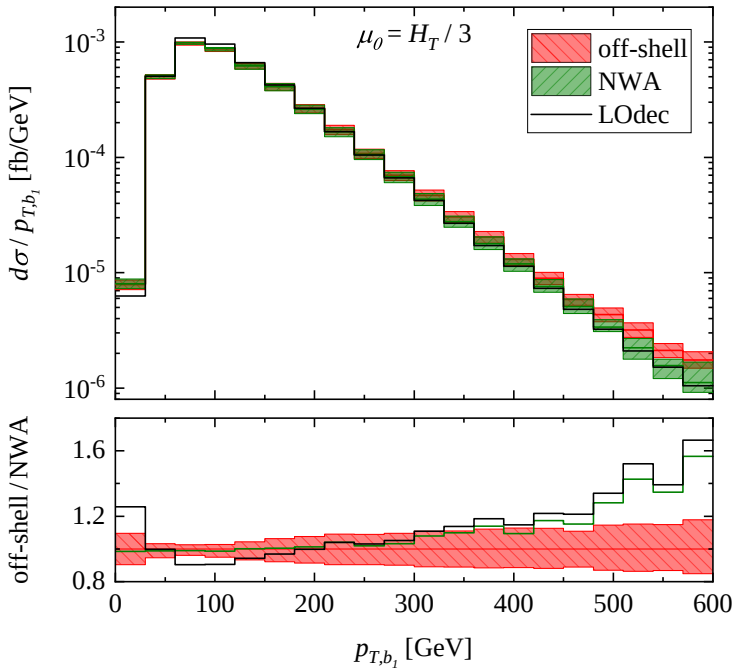
Good agreement within theoretical uncertainties

$t\bar{t}W$: 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)

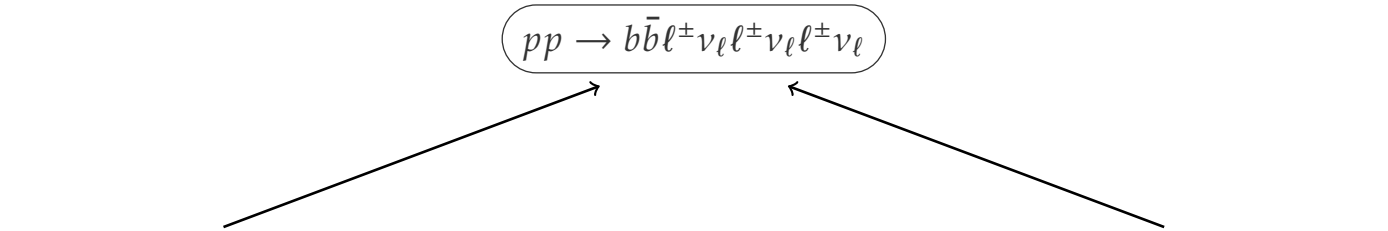
↪ Off-shell: uncertainty below 10% independently of scale choice (fixed/dynamic).

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

$t\bar{t}W$: 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?

$t\bar{t}W$: 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**:

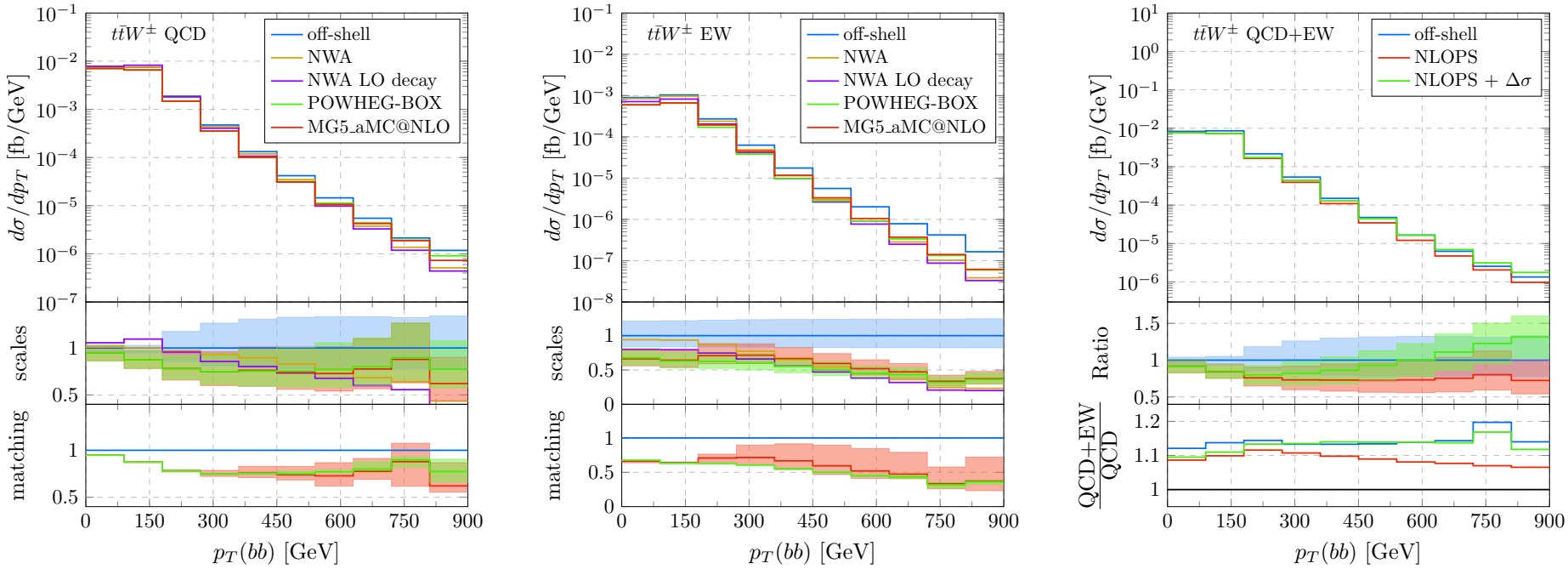
- $\mu_R = \mu_F = \mu_0 = E_T/3$- 7-point variation by factor of 2 (cross-check at fixed scale $\mu_R = \mu_F = \mu_0 = m_t + M_W/2$)
- PS effects studied by variation of ($\xi_{\rm damp}$,$\xi_{\rm bornzero}$) in `POWHEG BOX` and μ_Q in `aMC@NLO`.

↪ 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)

$t\bar{t}W$: Combining PS and off-shell effects



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

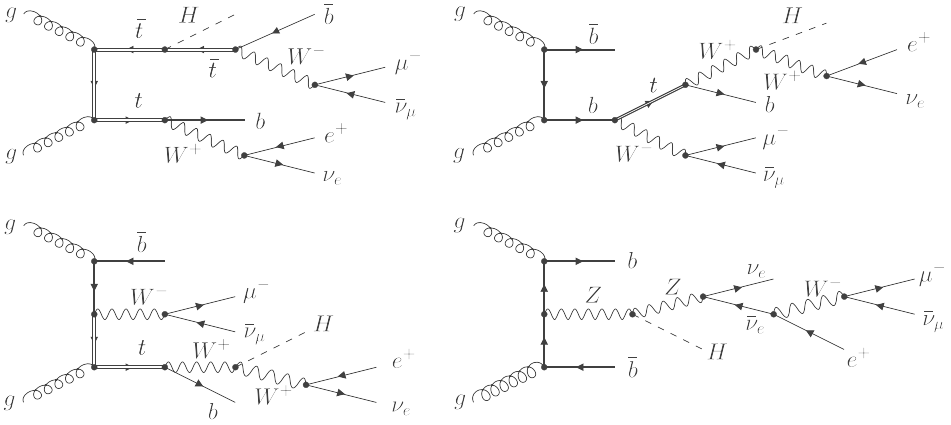
↪ PS effects affects broader region of PS, in particular low p_T regions

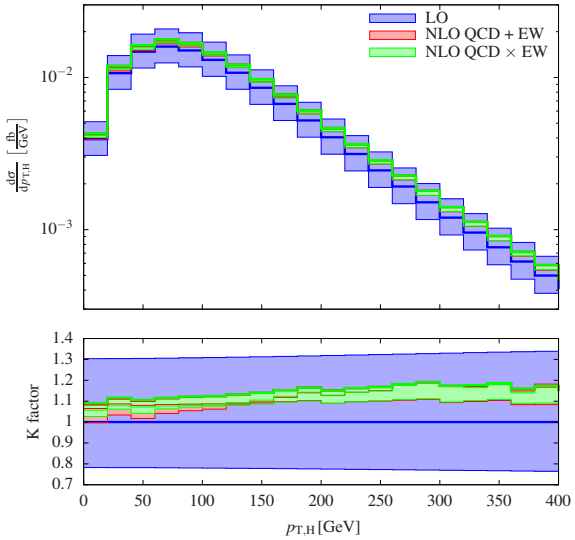
Compensate for tail effects by combining two approaches:

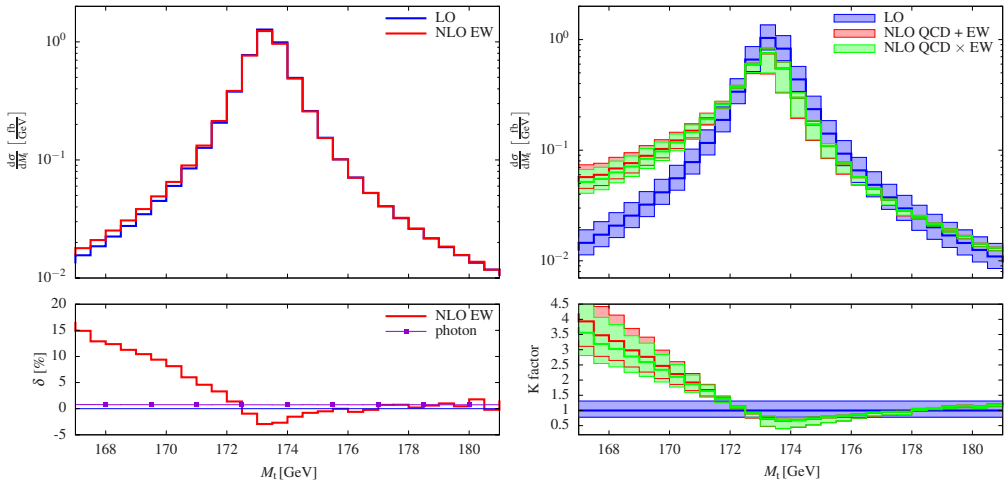
$$\frac{d\sigma^{\text{th}}}{dX} = \frac{d\sigma^{\text{NLO+PS}}}{dX} + \frac{d\Delta\sigma_{\text{off-shell}}}{dX} \quad \text{with} \quad \frac{d\Delta\sigma_{\text{off-shell}}}{dX} = \frac{d\sigma^{\text{NLO}}_{\text{off-shell}}}{dX} - \frac{d\sigma^{\text{NLO}}_{\text{NWA}}}{dX}$$

$t\bar{t}H$: NLO QCD+EW off-shell production

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$







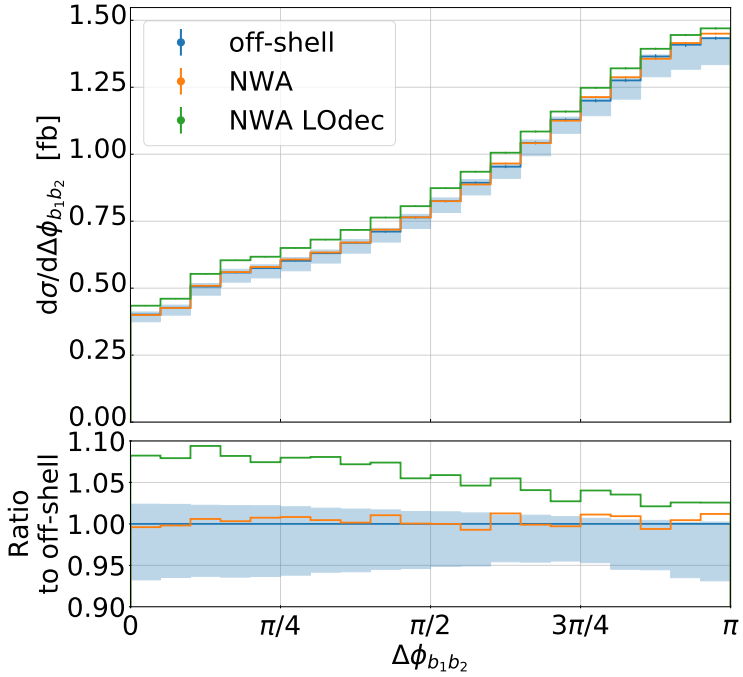
[Denner, et al., '17]

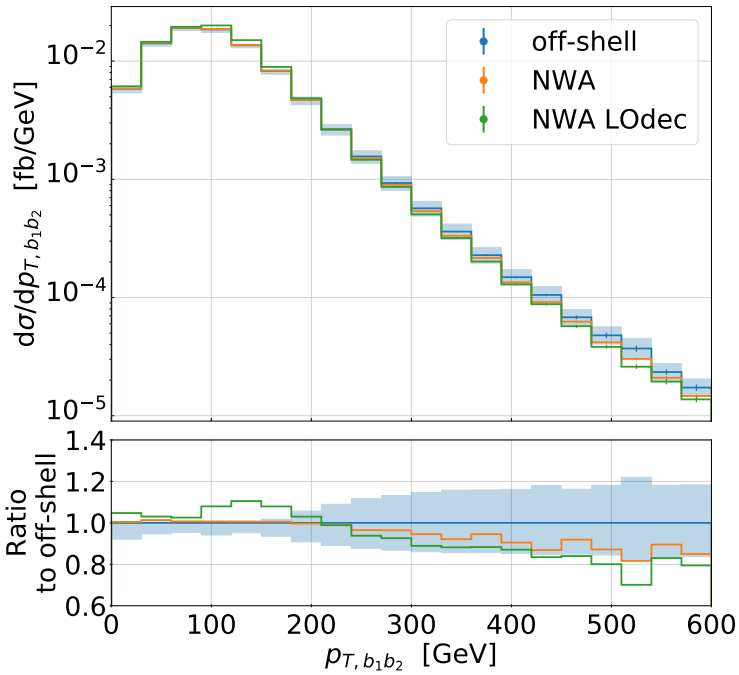
↪ NLO effects dominated by QCD corrections.

↪ EW non-negligible in specific regions: $\pm 15\%$.

↪ Off-shell effects can be large (see radiative tail in M_t distribution)

$t\bar{t}H$: NLO QCD off-shell production: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$





[Stremmer and Worek, '21]

↪ Thorough study of scale (5-10%) and PDF uncertainties (2-7%).

↪ Off-shell effects significant in distributions of dimensionfull observables.

↪ NLO QCD corrections to top decays visible beyond scale uncertainty.

Outlook and Future Work

- 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 ($t\bar{t}W + 2j$ with improved FxFx, ...)
- Time to revisit accuracy on $t\bar{t}H + tH$ signal considering:
  - ↪ NLO QCD+EW in all PS event generators.
  - ↪ New elements in theoretical studies: off-shell effects, STXS, sensitivity to anomalous couplings.
  - ↪ Higher-order QCD effects (NNLO).