

$t\bar{t}H/tH$: theory summary

Theory conveners: S. Pozzorini, L. Reina

Exp. conveners: M. Moreno Llacer (ATLAS), J. Thomas-Wilsker (CMS)

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

The 17th Workshop of the LHC Higgs Working Group

CERN, November 9, 2020

Activity since last LHC Higgs WG Workshop

Theoretical modelling of background modes among largest residual systematic uncertainties in $t\bar{t}H$ analyses

Focus on two main background modes:

- $t\bar{t} + b$ jets [bckgr. to $t\bar{t}H(b\bar{b})$]
 - ▷ Since YR4: several important developments:
 - ↪ Extensive comparison of NLOPS MC (aMC@NLO, POWHEG BOX+OpenLoops, SHERPA+OpenLoops): focus on understanding sizable differences, especially in the behavior of light-jet radiation.
 - ↪ New insights from NLO QCD calculation of $t\bar{t}b\bar{b} + j$: differences due to mismodelling of 1st shower emission. → [Boccioni et al.](#), arXiv:1907.13624
 - ↪ Agreed on two-step *theoretical tuning* of (μ_R, μ_{sh}) :
 - Adapt μ_R in NLO $t\bar{t}b\bar{b}$ to match extra jet emission in NLO $t\bar{t}b\bar{b} + j$.
 - Adapt NLO matching parameters (e.g. μ_{sh}) to avoid sizable deviations from NLO $t\bar{t}b\bar{b} + j$ for extra radiation.
 - ▷ Converging on final recommendation: **Will be documented in a publication and a WG note.**
 - ↪ Reduced MC differences.
 - ↪ Significant enhancement of $t\bar{t}b\bar{b}$ XS (about 50% wrt YR4).

Stay tuned!

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

- ▷ Disagreement between data and theoretical predictions:

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

- ▷ **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

- ↪ **NLO QCD for fully decayed final states** now available: assess off-shell effects. Bevilacqua et al. arXiv:2005.09427, Denner et al. arXiv:2007.12089

- ↪ **New Powheg-Box implementation** Febres Cordero et al., in progress

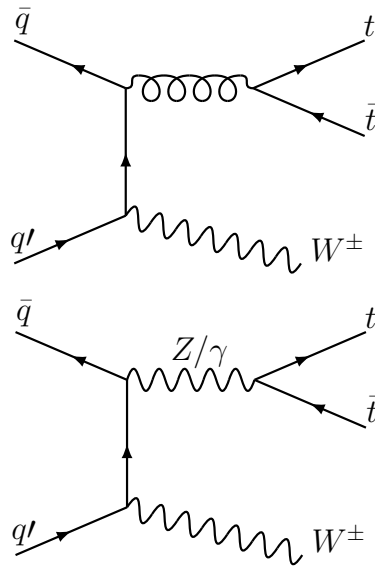
Enables comparison of NLO PS Monte Carlo event generators, including dominant $O(\alpha_s^3\alpha_e)$ and $O(\alpha_s\alpha^3)$ and LO spin-correlation in decays:

- [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

as well as [$O(\alpha_s^3\alpha)$ and no spin correlations]

- [Garzelli et al., arXiv:1208.2665] - PowHel

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



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

↓ QCD+EW

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

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

↓

Leading effect

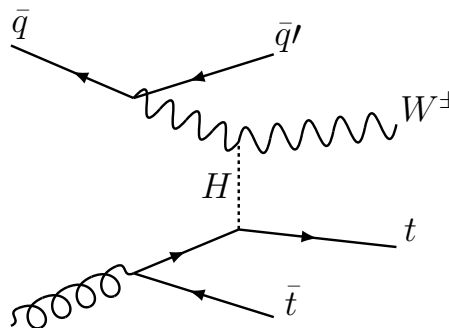
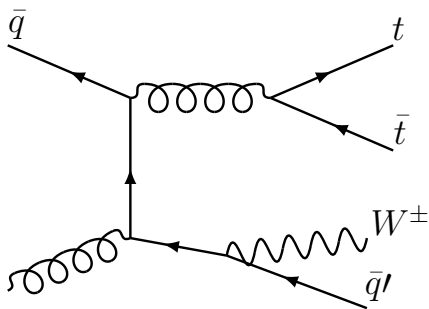
↓

Main sub-leading effect
 (~ 6%)

$\sigma[\text{fb}]$	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)

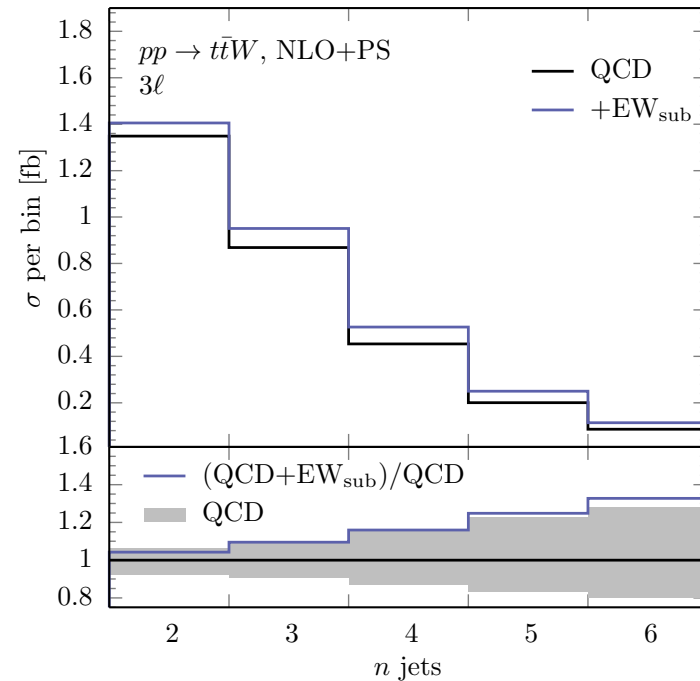
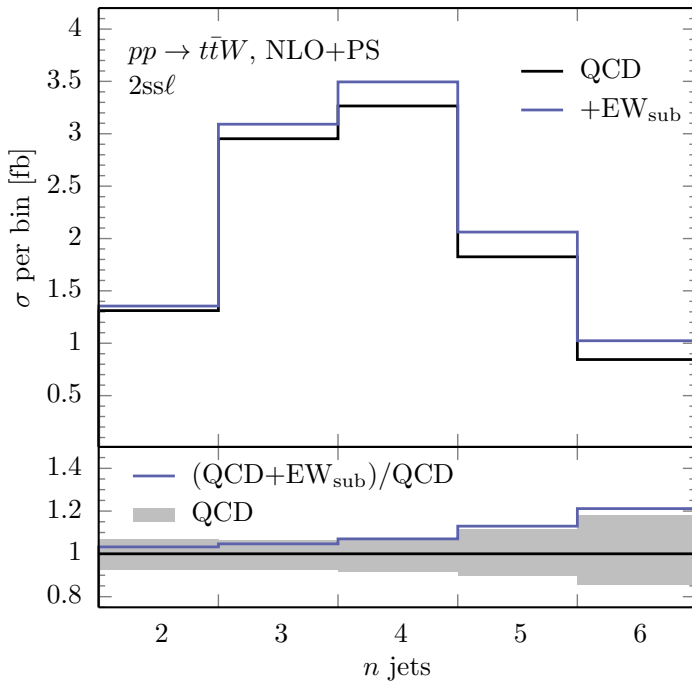
[Frederix, Pagani, Zaro, '17] (number in parenthesis obtained with extra jet veto)

Large impact of qg radiative processes:



Tree level processes:
 subject to non negligible
 h.o. effects

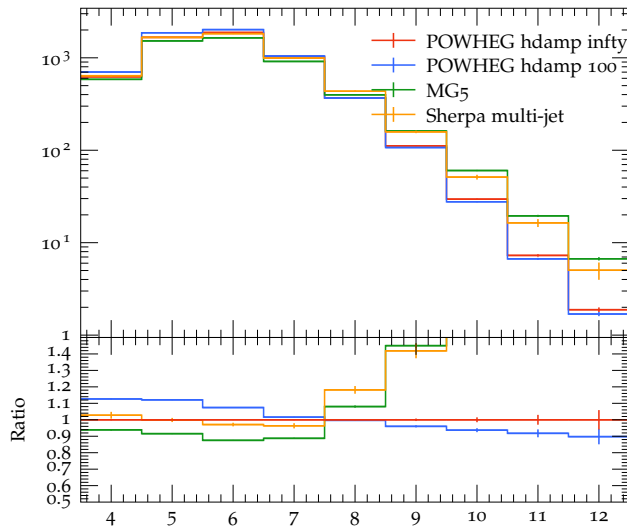
[Frederix, Tsinikos, '20 - aMC@NLO+Madspin, using Pythia 8]



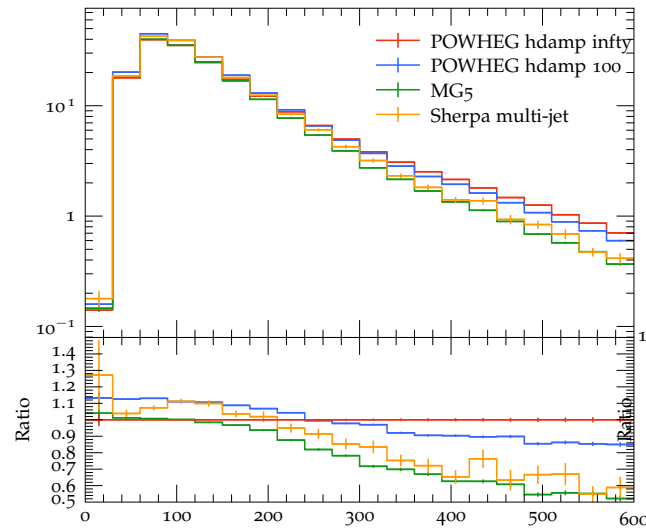
- Visible effects from subleading-EW on $2lSS$ and $3l$ distributions.
- $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ are $O(\alpha_s)$ corrections to QCD+EW born: can be consistently included in NLO QCD PS Monte Carlo.
- Important to validate within other NLO QCD PS Monte Carlo frameworks (Powheg-Box, Sherpa).

Preliminary - Comparison of different NLO PS framework

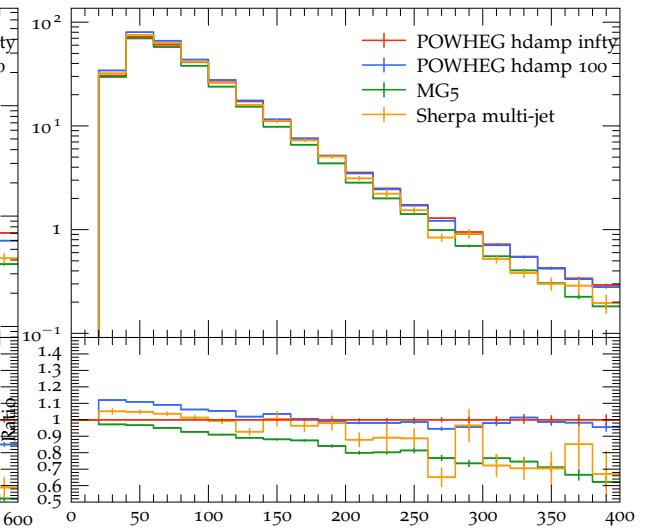
[Febres Cordero, Kraus, Reina - POWHEG BOX - in progress]



N_{jet}



p_T^{j1}



p_T^{j2}

↪ $O(\alpha_s^3\alpha)$ and $O(\alpha_s\alpha^3)$ included (one-loop via NLO).

↪ Keeping LO spin correlation [Frixione et al. hep-ph/0702198]

↪ Signature: 2lSS+jets:

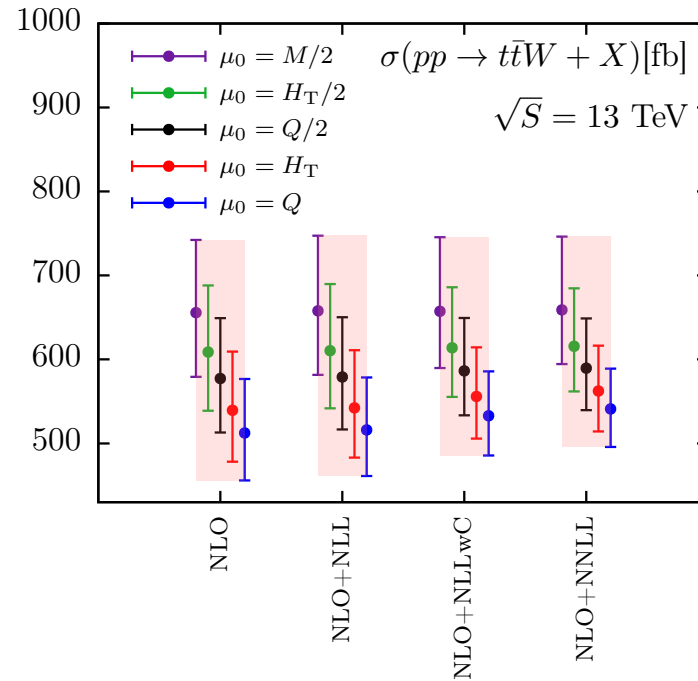
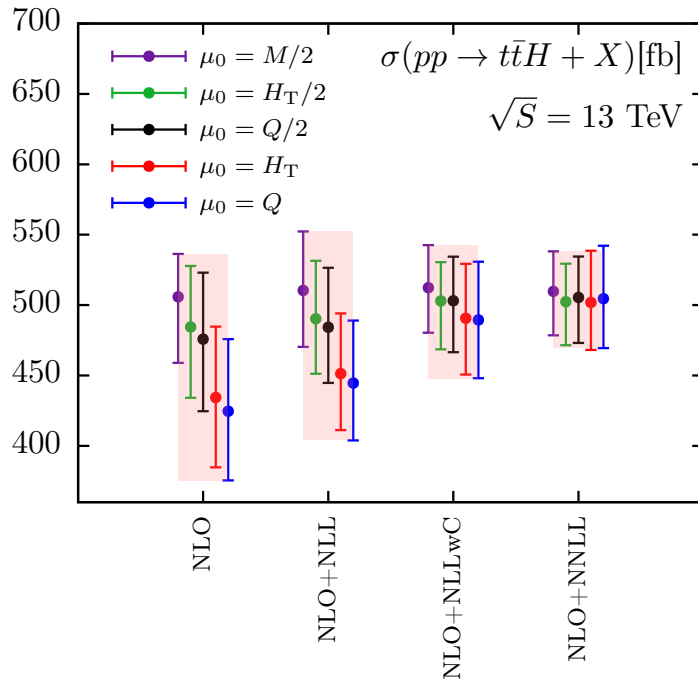
- $p_T(l) > 15$ GeV, $|\eta(l)| < 2.5$ GeV
- $p_T(j) > 25$ GeV, $|\eta(j)| < 2.5$ GeV, anti- k_T with $R = 0.4$
- $N_{b-jets} \geq 2$, $N_{jets} \geq 2$
- Using PYTHIA 8.303 (No MPI, No hadronization)

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

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:

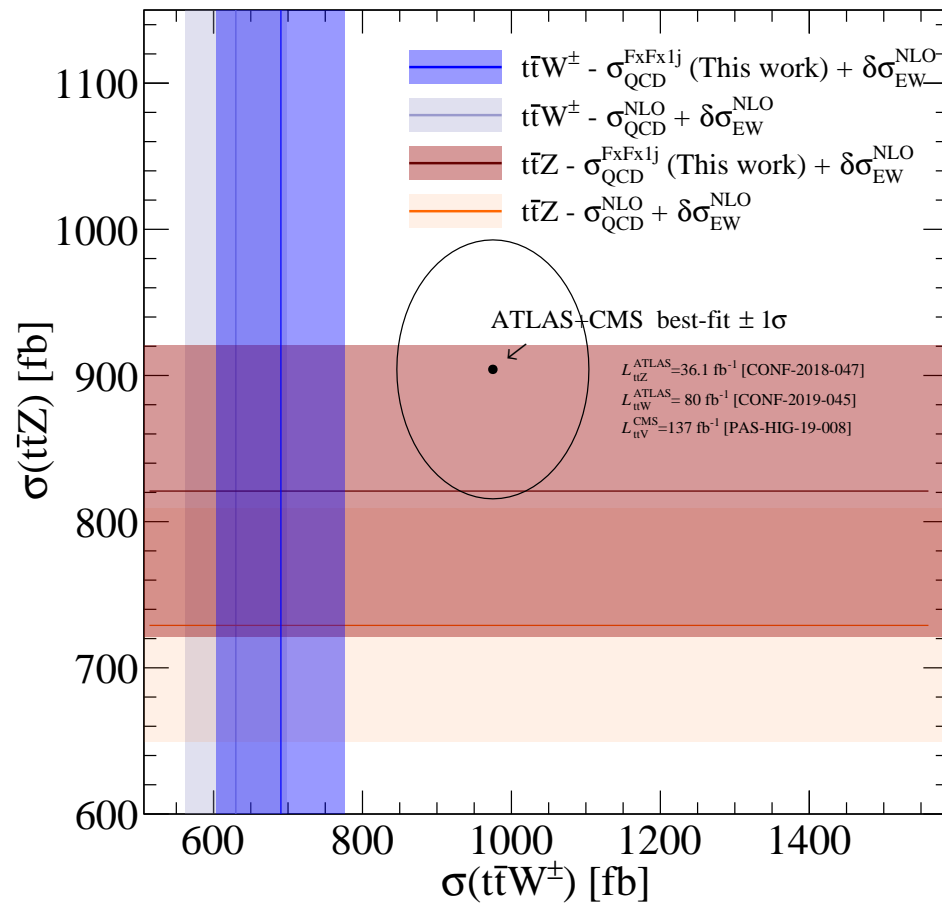
$$\sigma_{t\bar{t}W}^{\text{NLO+NNLL}} = 592^{+26.1\%+2.1\%}_{-16.2\%-2.1\%} \text{ fb}$$

↪ Indication of large NNLO QCD corrections?

NLO QCD + Jet merging +EW

[Buddenbrock, Ruiz, Mellado 29']

[ATLAS/CMS studies → see Maria's talk]



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

Light: NLO QCD+EW

Dark: NLO QCD+FxFX1j+ EW

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



Need to explore partial NNLO?

Moving Forward

- ▷ Finalize $t\bar{t}b\bar{b}$ study on theory systematics: will be documented in a publication and a WG note.
- ▷ Build on recent $t\bar{t}W$ studies to:
 - ↪ Update YR4 results for total rates and distributions.
 - ↪ Provide updated/new interfaces to NLO QCD PS Monte Carlo event generators.
 - ↪ Assess size of missing higher-order QCD corrections (NLO+NNLL, NLO QCD+jet merging, ...)
 - ↪ Assess impact of off-shell effects via NLO QCD calculations of fully decayed process.
- ▷ Next meeting will be announced through ttH/tH and WG1 mailing list.