Theory perspectives on $t\bar{t}+X$
$(X = H, W, Z, b\bar{b}, \ldots)$

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$t\bar{t} + X$: a powerful physics case

- $t\bar{t} + X$ processes ($X = V, H, b\bar{b}, \ldots$) crucial role in Run II physics
  - ▷ $t\bar{t}H/W/Z/\gamma$: measure top-quark properties
  - ▷ $t\bar{t} + b\bar{b}, W/Z$: backgrounds to Higgs ($t\bar{t}H$) and new-physics searches
- Distinctive yet challenging signatures
  - ▷ $t\bar{t} + H, W, Z$: rare modes, achievable at Run 2
  - ▷ $t\bar{t} + b\bar{b}$, $t\bar{t}$+jets: large, complex multiparticle QCD backgrounds
  - ▷ soon to be limited by theoretical systematic uncertainty
  - ▷ vaste theoretical effort to provide state-of-the-art predictions
    - ↪ **NLO QCD and EW corrections**
    - ↪ **interface with NLO parton-shower Monte Carlo generators**
- All $t\bar{t} + X$ channels play a role in the measurement of $t\bar{t} + H$

↪ main focus of $t\bar{t}H/tH$ subgroup of HXSWG → YR4

↪ excerpt of results and ideas presented in this talk:
thanks to my co-conveners [S. Guindon, C. Neu, S. Pozzorini],
and all working-group participants!

Theory progress $t\bar{t} + X$

- **$\mathbf{t\bar{t}H}$**
  - **NLO QCD corrections**
    Beenakker et al., hep-ph/0107081, hep-ph/0211352
    Dawson et al., hep-ph/0211438, hep-ph/030508
  - **NLO QCD+EW corrections**
    Frixione et al., arXiv:1407.0823, arXiv:1504.03446
    Zhang et al., arXiv:1407.1110
  - **$\mathbf{b\bar{b}l^+l^-\nu\bar{\nu}H}$, NLO QCD corrections**
    Denner et al., arXiv:1506.07448
  - **Beyond NLO QCD, soft-gluon resummation**
    Kulesza et al., arXiv:1509.02780
    Broggio et al., arXiv:1510.0191
  - **$\mathbf{t\bar{t}H + j}$, NLO QCD corrections**
    van Deurzen et al., arXiv:1307.8437

Theory progress $t\bar{t} + X$

- **$\mathbf{t\bar{t}b\bar{b}}$**
  - **NLO QCD corrections**

    Bredenstein et al., arXiv:0905.0110, arXiv:1001.4006
    Bevilacqua et al. arXiv:0907.4723
- **$\mathbf{t\bar{t}V}$** $(V = W, Z, \gamma)$
  - **NLO QCD corrections**

    Melnikov et al., arXiv:1102.1967 ($t\bar{t}\gamma$)
    Hirschi et al. arXiv:1103.0621 ($t\bar{t}\gamma, Z, W$)
    Lazopoulos et al. arXiv:0804.2220 ($t\bar{t}Z$)
    Kardos et al. arXiv:1111.0610 ($t\bar{t}Z$),
    Campbell et al. arXiv:1204.5678 ($t\bar{t}W$)
  - **NLO QCD+EW corrections**

    Frixione et al.arXiv:1504.03446 ($t\bar{t}VV$)
  - **Beyond NLO QCD, soft-gluon resummation**

    Broggio et al., arXiv:1702.00800 ($Zb\bar{b}$)
- **$\mathbf{t\bar{t}VV}$** $(V = W, Z, \gamma)$
  - **NLO QCD corrections**

    Kardos et al., arXiv:1408.0278 ($t\bar{t}\gamma\gamma$)
    Maltoni et al., arXiv:1507.05640 ($t\bar{t}VV$, $V = W, Z, \gamma$)
    van Deurzen et al., arXiv:1509.02077 ($t\bar{t}\gamma\gamma$)

Theory progress, NLO QCD+Parton Shower

- **$t\bar{t}H$**

  MG5_aMC@NLO, Frederix et al., arXiv:1104.5613, arXiv:1610.07922
  PowHel, Garzelli et al., arXiv:1108.0387, arXiv:1610.07922
  POWHEG BOX, Hartanto et al., arXiv:1501.04498, arXiv:1610.07922
  OpenLoops+SHERPA, Cascioli et al., arXiv:1610.07922
  HERWIG7: Reuschle et al., arXiv:1610.07922

- **tH**

  MG5_aMC@NLO, Demartin et al., arXiv:1504.00611

- **$t\bar{t}b\bar{b}$**

  PowHel, Kardos et al., arXiv:1303.6291, arXiv:1610.07922
  OpenLoops+SHERPA, Cascioli et al., arXiv:1309.5912, arXiv:1610.07922
  MG5_aMC@NLO, Frederix et al., arXiv:1610.07922

- **$t\bar{t}V$** $(V = W, Z)$

  PowHel, Garzelli et al. arXiv:1111.1444, arXiv:1208.2665, arXiv:1610.07922
  OpenLoops+SHERPA, Cascioli et al., arXiv:1610.07922
  MG5_aMC@NLO, Frixione et al., arXiv:1610.07922

arXiv:1610.07922 $\longrightarrow$ LHC Higgs XS Working Group, Yellow Report 4
($t\bar{t}H/tH$ section)

Highlights from TH progress

Through $t\bar{t}+X$ processes following the $t\bar{t}H$ lead:

- $t\bar{t}H$

↪ NLO QCD+EW, parton-level accuracy

↪ NLO QCD+PS, understanding accuracy at PS-level

- $t\bar{t}b\bar{b}$: many layers of complexity

↪ 5F $t\bar{t}$+jets vs 4F $t\bar{t}+b\bar{b}$ revisited

↪ 4F $t\bar{t}+b\bar{b}$ recommended but need further studies

↪ $t\bar{t}b\bar{b}$: NLO+PS, comparison of MC generators

↪ Off-shell effects: signal (NLO) and signal-background interference (LO)

- $t\bar{t}$+jets,

↪ NLO QCD+PS, with merging

- $t\bar{t}+V$, $t\bar{t}+VV$ $(V=W,Z)$

↪ NLO QCD+EW, parton-level accuracy

↪ NLO QCD+PS

- $t\bar{t}+\gamma\gamma$

$t\bar{t}H$, NLO QCD+EW corrections

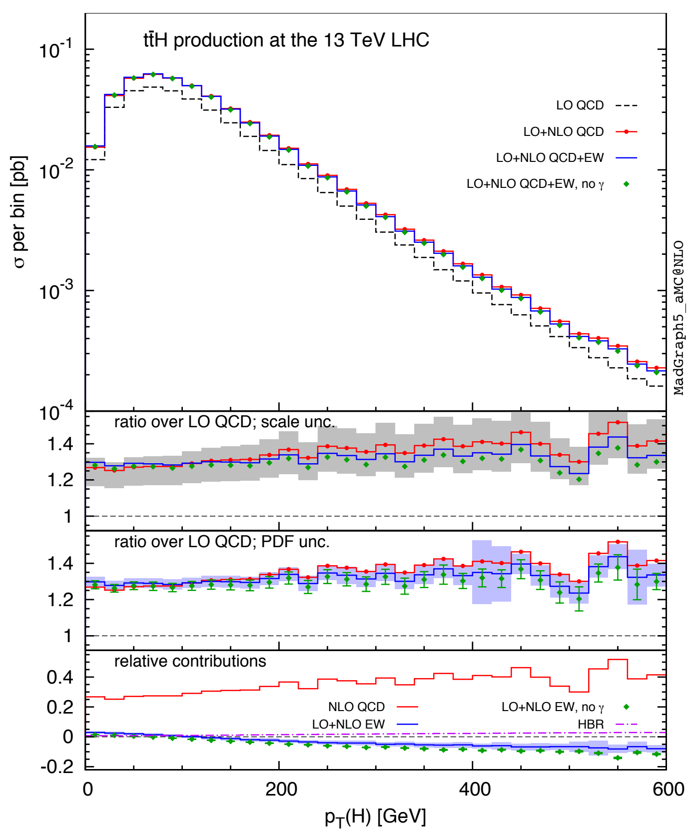
At 13 TeV, for $M_H = 125$ GeV,

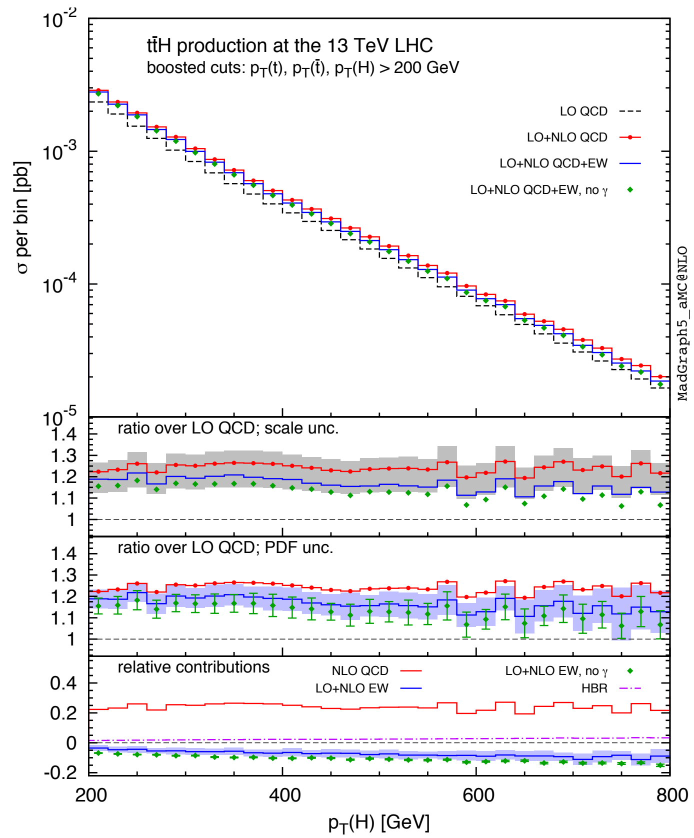
$$\sigma^{NLO}_{QCD+EW}[\text{fb}] = 507.1^{+5.7\%}_{-9.2\%}(\text{scale}) \pm 3.6\%(\text{PDF} + \alpha_s)$$

where

$$\sigma^{NLO}_{QCD+EW} = \sigma^{NLO}_{QCD} + \delta\sigma_{EW} = K\sigma^{LO}_{QCD} + \delta\sigma_{EW}$$

with $K = \sigma^{NLO}_{QCD}/\sigma^{LO}_{QCD} = 1.25$ and $\delta_{EW} = \delta\sigma_{EW}/\sigma^{NLO}_{QCD} = 1.7\%$.

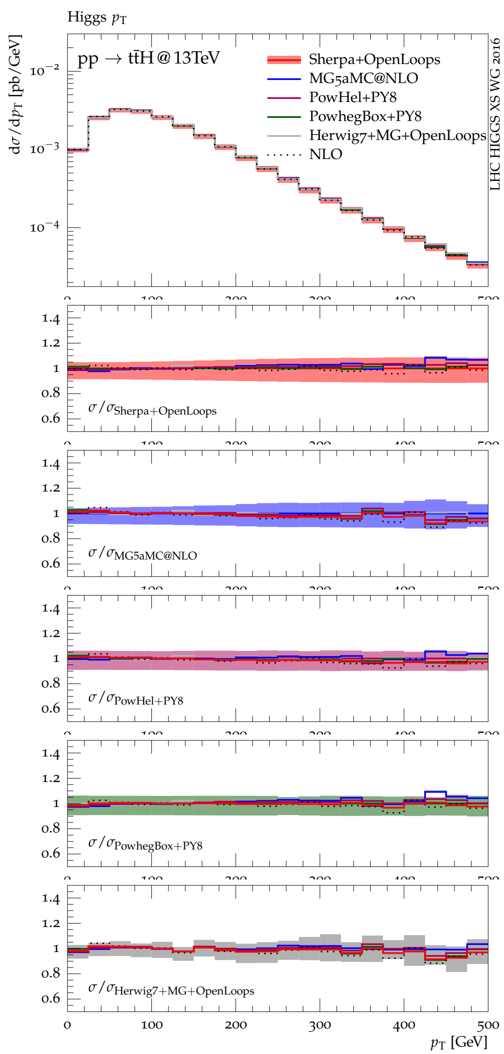


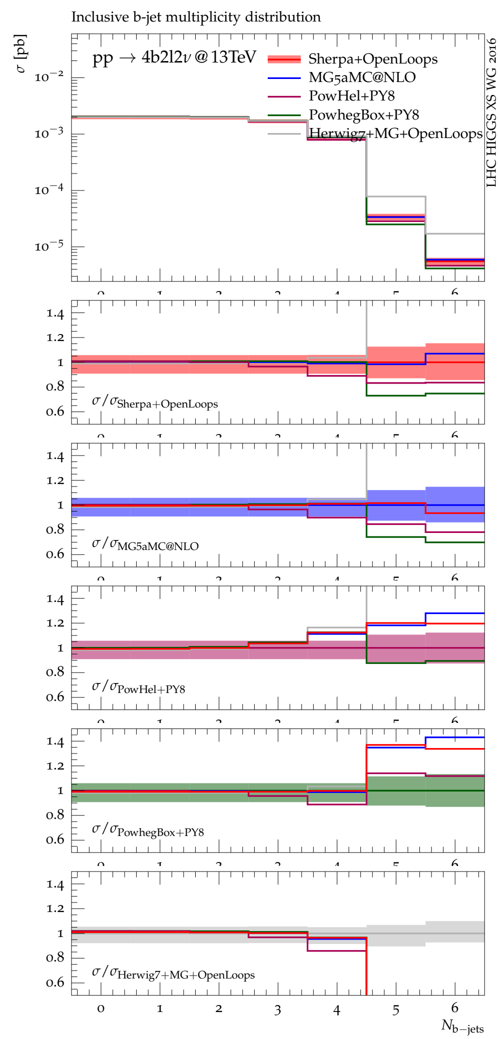


Frixione et al., arXiv:1504.03446

$t\bar{t}H(H \to b\bar{b})$, validation of NLO QCD+PS

5 different NLO PS-MC compared!





Comparison with and w/o top decays,

$t \to b e^+ \nu_e$

$\bar{t} \to \bar{b} \mu^- \nu_\mu$

Proved very good compatibility within scale uncertainty

$N_{\text{b-jets}} > 4$

↪ shower effects

↪ more meaningful to investigate in the context of specific experimental analyses.

see YR4 - $t\bar{t}H/tH$ section, arXiv:1610.07922

$t\bar{t} + b$ jets, NLO QCD

Accuracy of theoretical predictions and reliable estimate of their uncertainty still problematic, but progress is being made.

- NLO QCD calculation reduces uncertainty from $\approx 80\%$ to $\approx 20 - 30\%$
  [Bredenstein et al., arXiv:0905.0110, arXiv:1001.4006, Bevilacqua et al., arXiv:0907.4723]
- NLO QCD+PS poses new questions

▷ **5F t$\bar{\textbf{t}}$+jets** ($m_b = 0$, $N_f = 5$) [PowHel, Kardos et al., arXiv:1303.6291]

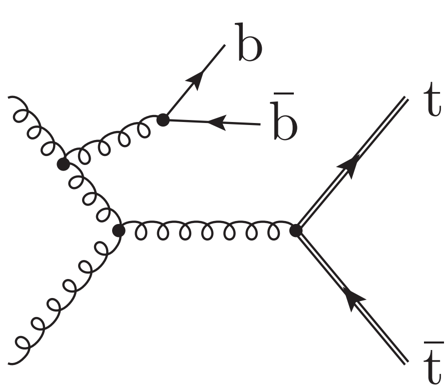
↪ NLO matrix elements cannot describe $g \to b\bar{b}$

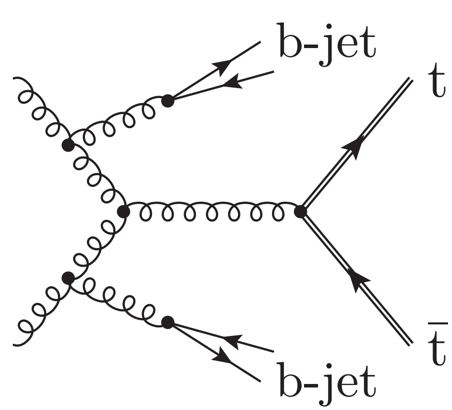
↪ $m_{b\bar{b}} > \xi_m 2m_b$ and $p_T^b > \xi_T m_b$ cuts introduced to mimic m_b effects.

▷ **4F t$\bar{\textbf{t}}$b$\bar{\textbf{b}}$** ($m_b \neq 0$, $N_f = 4$) [OpenLoops+SHERPA, Cascioli et al., arXiv:1309.5912; MG5_aMC@NLO, Frederix et al.]

↪ NLO matrix element describe first $g \to b\bar{b}$ splitting

↪ NLO accuracy for any $N_b \geq 1$ observable



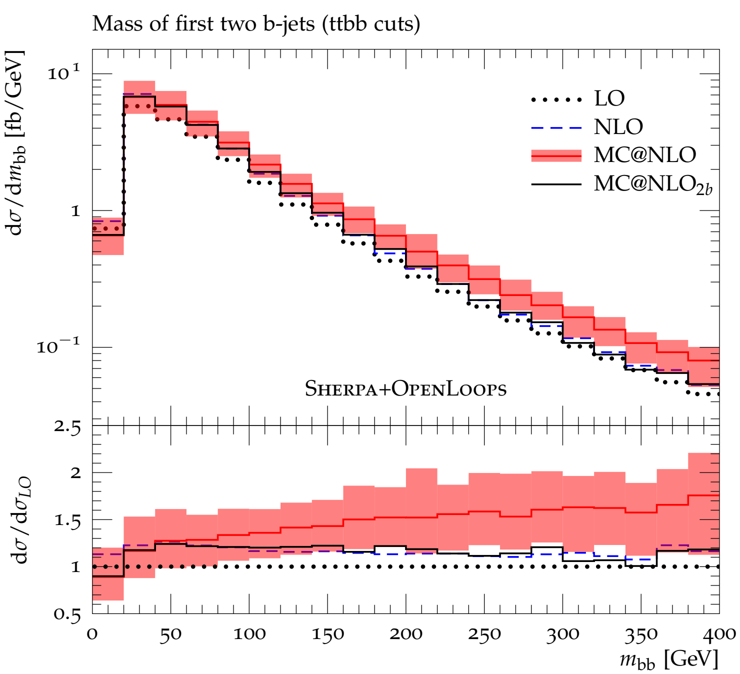


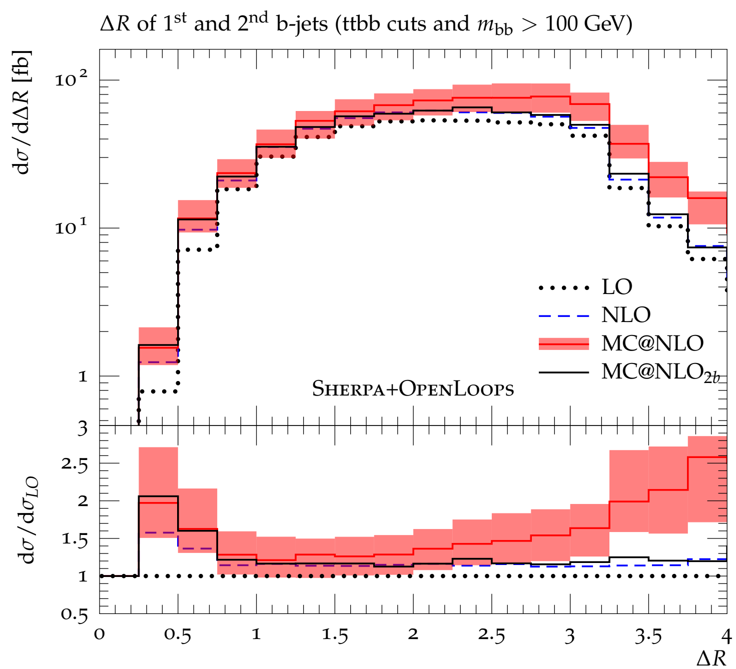
Interesting to notice that:

	ttb	ttbb	ttbb($m_{\mathrm{bb}} > 100$)
σ_{LO}[fb]	$2644^{+71\%+14\%}_{-38\%-11\%}$	$463.3^{+66\%+15\%}_{-36\%-12\%}$	$123.4^{+63\%+17\%}_{-35\%-13\%}$
σ_{NLO}[fb]	$3296^{+34\%+5.6\%}_{-25\%-4.2\%}$	$560^{+29\%+5.4\%}_{-24\%-4.8\%}$	$141.8^{+26\%+6.5\%}_{-22\%-4.6\%}$
$\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$	1.25	1.21	1.15
σ_{MC}[fb]	$3313^{+32\%+3.9\%}_{-25\%-2.9\%}$	$600^{+24\%+2.0\%}_{-22\%-2.1\%}$	$181.0^{+20\%+8.1\%}_{-20\%-6.0\%}$
$\sigma_{\mathrm{MC}}/\sigma_{\mathrm{NLO}}$	1.01	1.07	1.28
$\sigma^{\mathrm{2b}}_{\mathrm{MC}}$[fb]	3299	552	146
$\sigma^{\mathrm{2b}}_{\mathrm{MC}}/\sigma_{\mathrm{NLO}}$	1.00	0.99	1.03

[Cascioli et al., arXiv:1309.5912]

Large enhancement in Higgs-boson region due to $g \to b\bar{b}$ (from PS).





From the ongoing discussion within $t\bar{t}H/tH$ WG

- In experimental analyses $t\bar{t}+b\bar{b}$ obtained as ($\hookrightarrow$see Maria's talk):
  - ▷ 5F $t\bar{t}$+ jets (light/c/b) ($m_b = 0$)
    extracting and reweighing $t\bar{t}+1b$, $t\bar{t}+2b$, $t\bar{t}+B$, ... samples with 4F $t\bar{t}+b\bar{b}$ NLO calculation: prone to several correlated systematic errors.
  - ▷ 4F $t\bar{t}+b\bar{b}$ ($m_b \neq 0$): $t\bar{t}+b$, $t\bar{t}+2b$, etc. well defined.
- WG recommendation: use NLO PS MC to produce 4F $t\bar{t}+b\bar{b}$ samples for $t\bar{t}+b$ jets, and $t\bar{t}$+jets for everything else.
- Caveat: this assumes the validity of 4F calculation in all regimes and over the entire phase space. What else?
- **Proper 5F calculation** of $t\bar{t}+b$ should be structured as:
  - ▷ tree level: $bg \to t\bar{t}+b$
  - ▷ $+\,O(\alpha_s)$ QCD virtual corrections
  - ▷ $+\,O(\alpha_s)$ QCD real corrections (including $gg \to t\bar{t}+b\bar{b}$, $m_b \neq 0$)
  - ▷ initial state $\ln(m_b^2/M^2)$ resummed
  - ▷ not yet consistently implemented in NLO PS MC

$t\bar{t} + b$ jets,comparison of NLO Monte Carlo simulations

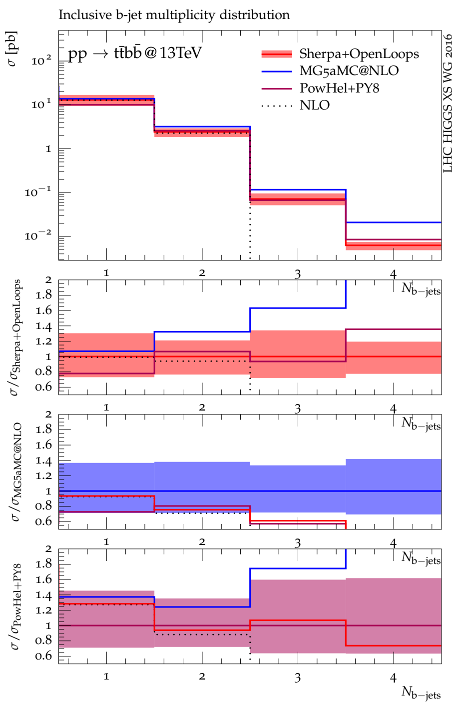
[Full details at: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalTtbb]

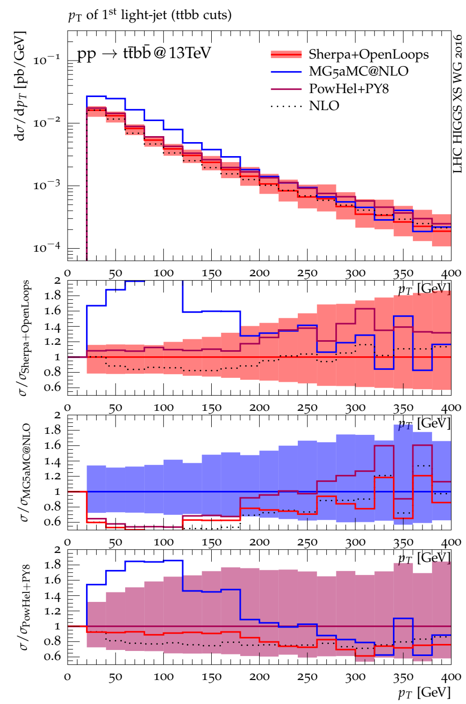
- Comparing different matchings:
  - ▷ `SHERPA+OpenLoops` [Höche et al.] and [Cascioli et al.] (4F, $m_b > 0$)
  - ▷ `Madgraph5_aMC@NLO+PYTHIA8.2` [Frederix et al.] (4F, $m_b > 0$)
  - ▷ `PowHel+PYTHIA8.2` [Garzelli et al.] (5F, $m_b = 0$, $m_{bb} > 2m_b$, $p_{T,b} > m_b$)

- General setup: not just a choice of parameters
  - ▷ consistent HF treatment: $N_f = 4$ vs $N_f = 5 \rightarrow \alpha_s$, PDF
  - ▷ control source of b quarks: matrix element, parton shower, top decays $\hookrightarrow$ exclude some of these sources (e.g: switch off top decays, ...)
  - ▷ consistent b-jet definition
  - ▷ ...

- Coherent treatment of theoretical uncertainty
  - ▷ $\mu_R =< E_T >_{\text{geom}}$, $\mu_F = \mu_Q = H_T/2$
  - ▷ scale, PDF dependence
  - ▷ shower scale dependence ($\mu_Q = H_T/2$ vs $\mu_Q = f(\xi)\sqrt{\hat{s}}$, $0.1 < f(\xi) < 0.25$ vs $h_{damp} \approx= H_T/2, \ldots$)

$t\bar{t} + b$ jets, NLO+PS, from YR4





↪ switch off top decays, hadronization, UE

↪ To better compare the effect of

- different matchings
- different parton showers
- different flavor scheme

[$t\bar{t}H/tH$ working group, YR4, arXiv:1610.07922]

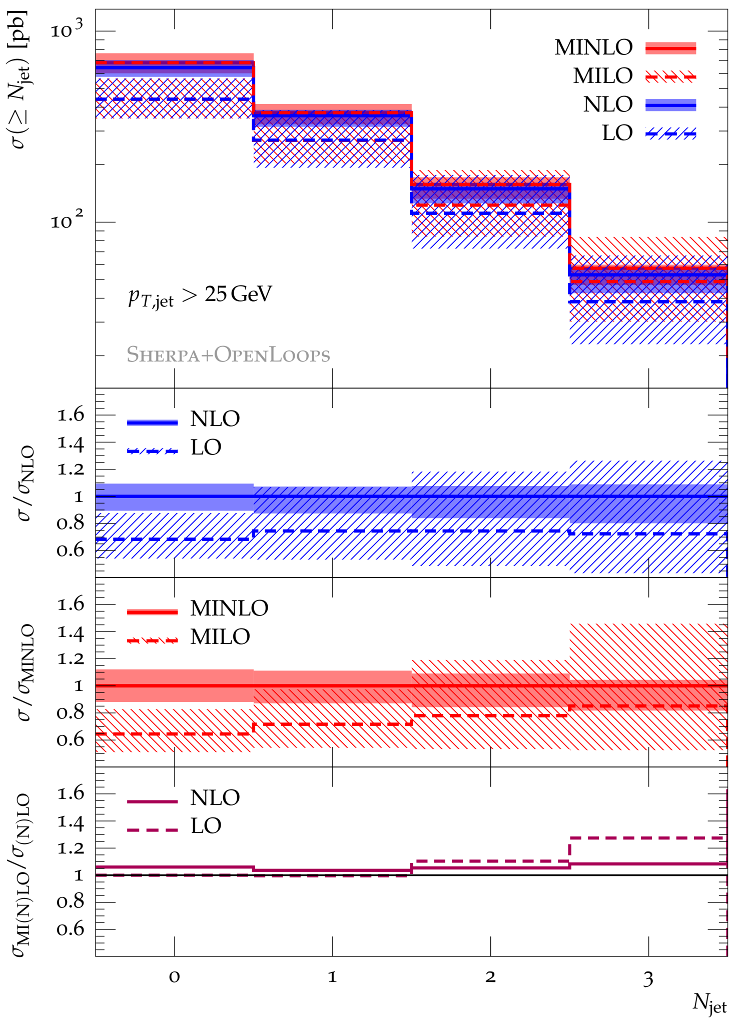
Discrepancies emerge that will have to be understood if we want to resolve the very large systematic uncertainties that affects experimental analyses
↪ **This is becoming a limiting factor** → see ATLAS and CMS talks

Moving forward:

▷ Dedicated collaboration on NLO+PS $t\bar{t} + b$ jets in the context of the HXSWG

▷ `Madgraph5_aMC@NLO` 2.5.3 now allows for $\mu_Q = H_T/2$ → ongoing comparison

$t\bar{t}$+jets at NLO+PS [Höche et al. arXiv:1607.06934]



NLO+PS: Openloops+Sherpa

scale choice and uncertainties:
MINLO method [Hamilton, et al, 12]:
improved convergence for multi-scale processes through NLO+NLL CKKW resummation

Large NLO/LO, nice MINLO convergence
↪ can aim for $t\bar{t}$+multijets at the 10% precision level

Off-shell signal-background interference, LO

$pp \to t(bl^+\nu)\bar{t}(\bar{b}jj)H(b\bar{b})$ at LO [Denner, Feger, Scharf, arXiv:1412.5290]

- ▷ include all possible channels with/without top and Higgs resonances
- ▷ include all QCD and EW contributions to matrix elements and interferences

matrix-element order	$O(\alpha_s^3\alpha)$	$O(\alpha_s^2\alpha^2)$	$O(\alpha_s\alpha^3)$	$O(\alpha^4)$
$t\bar{t}H(b\bar{b})$ signal			×	×
$t\bar{t}b\bar{b}$ background		×	×	×
full process $(l^+\nu + 2j + 4b)$	×	×	×	×

- ▷ Results for 13 TeV LHC:
  - → negligible $t\bar{t}H$ signal-background interference
  - → significant -8% interference between QCD and EW contributions to $t\bar{t}b\bar{b}$ background (from W exchange in t-channel)
  - → significant +11% enhancement in $t\bar{t}b\bar{b}$ background from diagrams without top resonances

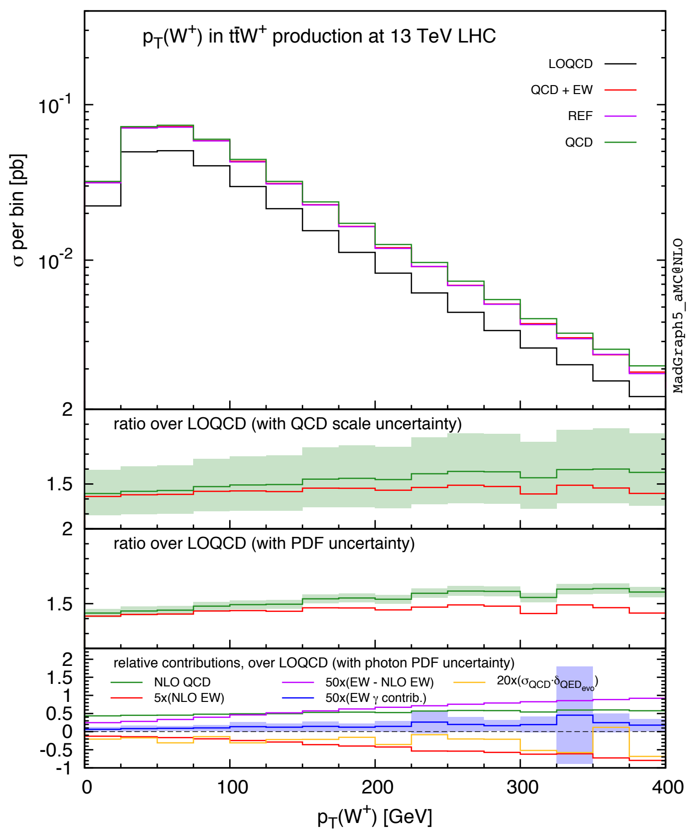
NLO QCD+EW corrections for $t\bar{t}+V$ $(V=W^{\pm},Z)$ production

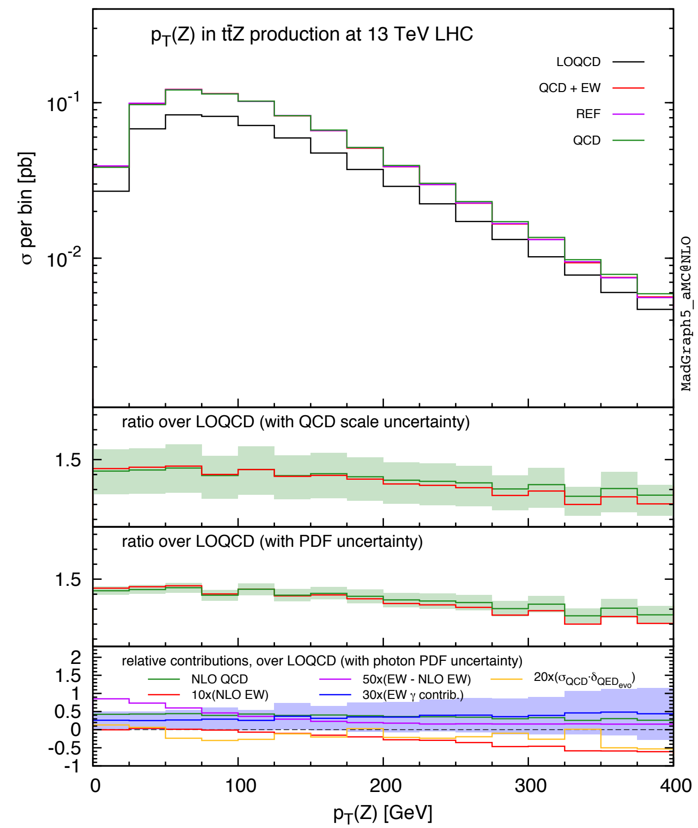
[Frixione, Hirschi, Pagani, Shao, Zaro, arXiv:1504.03446]

$$\sqrt{s}=13\ \text{TeV},\ K=\sigma^{NLO}_{QCD}/\sigma^{LO}_{QCD},\ \delta_{EW}=\delta\sigma_{EW}/\sigma^{NLO}_{QCD}$$

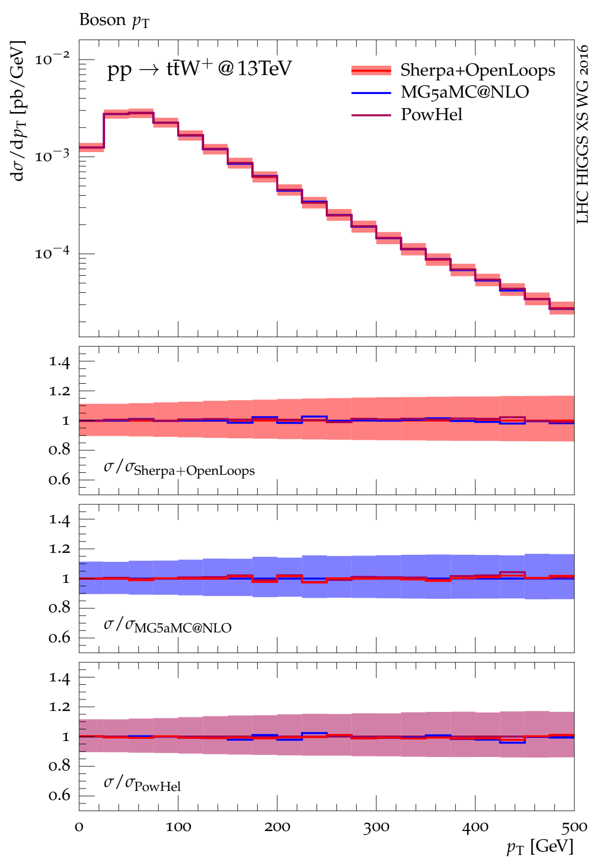
Process	$\sigma^{\rm NLO}_{\rm QCD}$	$\sigma^{\rm NLO}_{\rm QCD+EW}$	$K_{\rm QCD}$	$\delta_{\rm EW}[\%]$	Scale[%]		PDF[%]		$\alpha_S[\%]$	
$t\bar{t}Z$	841.3(1.6)	839.3(1.6)	1.39	−0.2	+9.6%	− 11.3%	+2.8%	− 2.8%	+2.8%	− 2.8%
$t\bar{t}W^+$	412.0(0.32)	397.6(0.32)	1.49	−3.5	+12.7%	− 11.4%	+2.0%	− 2.0%	+2.6%	− 2.6%
$t\bar{t}W^-$	208.6(0.16)	203.2(0.16)	1.51	−2.6	+13.3%	− 11.7%	+2.1%	− 2.1%	+2.9%	− 2.9%

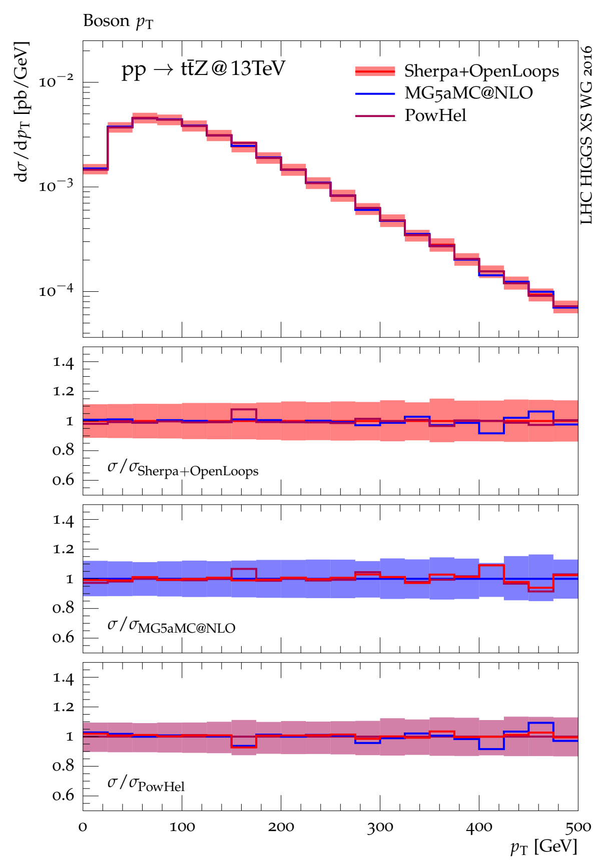
▷ inclusive cross section: NLO EW corrections ≪ NLO QCD uncertainty





Comparison of $t\bar{t} + V$ distributions at NLO QCD → YR4





↪ consistency among different generators at fixed order

NLO QCD corrections for $t\bar{t} + VV$ ($V = W^{\pm}, Z, H$) production

[Maltoni, Pagani, Tsinikos, arXiv:1507.05640 and YR4]

Heavy-Boson-Radiation (HBR) for $t\bar{t} + V$ processes

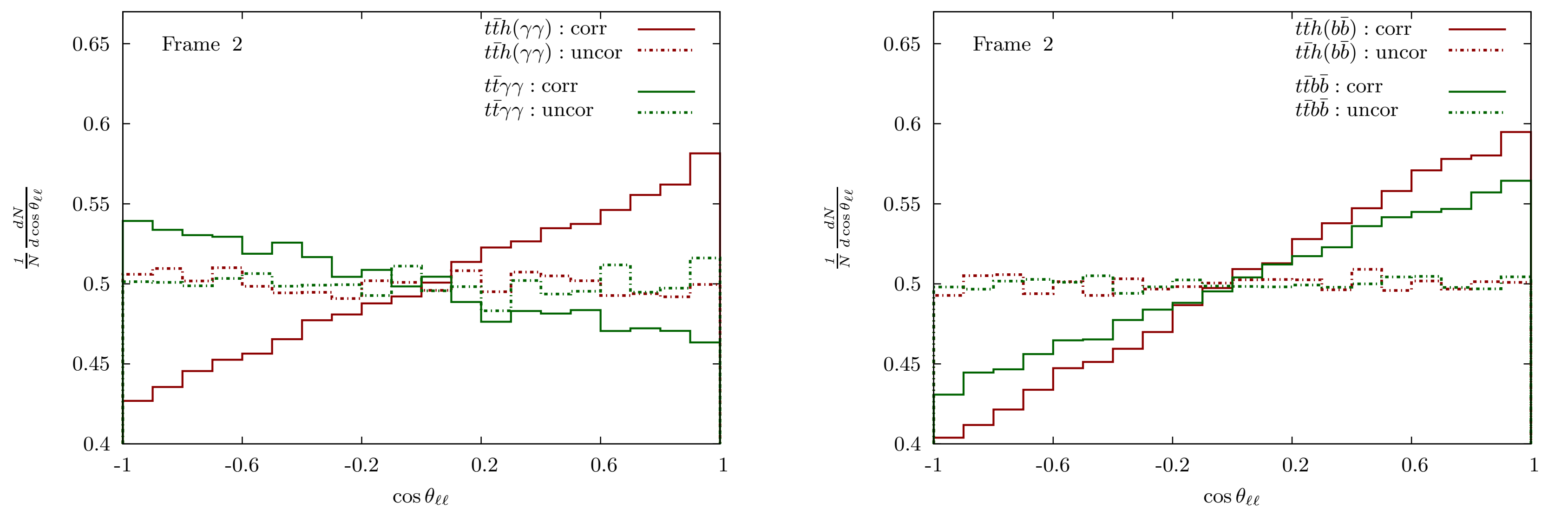
13 TeV σ [ab]	$t\bar{t}W^+Z$	$t\bar{t}W^-Z$	$t\bar{t}ZZ$
NLO QCD	$2705(3)^{+9.9\%}_{-10.6\%}{}^{+2.7\%}_{-2.7\%}$	$1179(2)^{+11.2\%}_{-11.2\%}{}^{+3.7\%}_{-3.7\%}$	$1982(2)^{+5.2\%}_{-9.0\%}{}^{+2.6\%}_{-2.6\%}$
LO	$1982(2)^{+28.4\%}_{-20.6\%}{}^{+3.3\%}_{-3.3\%}$	$839.4(6)^{+28.2\%}_{-20.5\%}{}^{+4.2\%}_{-4.2\%}$	$1611(1)^{+31.4\%}_{-22.1\%}{}^{+2.7\%}_{-2.7\%}$
K-factor	1.36	1.40	1.23
13 TeV σ [ab]	**$t\bar{t}W^+H$**	**$t\bar{t}W^-H$**	**$t\bar{t}ZH$**
NLO QCD	$1089(1)^{+1.8\%}_{-5.9\%}{}^{+2.6\%}_{-2.6\%}$	$493.0(5)^{+2.6\%}_{-6.4\%}{}^{+3.4\%}_{-3.4\%}$	$1535(2)^{+1.9\%}_{-6.8\%}{}^{+3.0\%}_{-3.0\%}$
LO	$997.0(9)^{+26.9\%}_{-19.8\%}{}^{+3.0\%}_{-3.0\%}$	$440.0(4)^{+26.9\%}_{-19.8\%}{}^{+3.8\%}_{-3.8\%}$	$1391(1)^{+32.2\%}_{-22.6\%}{}^{+2.8\%}_{-2.8\%}$
K-factor	1.09	1.12	1.10
13 TeV σ [ab]	**$t\bar{t}W^+W^-$**	**$t\bar{t}W^+W^-$ (4f)**	**$t\bar{t}HH$**
NLO QCD	–	$11500(10)^{+8.1\%}_{-10.9\%}{}^{+3.0\%}_{-3.0\%}$	$756.5(7)^{+1.1\%}_{-4.4\%}{}^{+3.3\%}_{-3.3\%}$
LO	$8380(5)^{+33.2\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$8357(5)^{+33.3\%}_{-23.1\%}{}^{+3.0\%}_{-3.0\%}$	$765.4(5)^{+31.8\%}_{-22.4\%}{}^{+2.9\%}_{-2.9\%}$
K-factor	–	1.38	0.99

$t\bar{t} + \gamma\gamma$: spin-correlation effects in top decays

Implemented at NLO+PS in `MG5_aMC@NLO`, `POWHEG BOX`, and `SHERPA`

- $\rightarrow$ only (NLO production)$\times$ (LO decay) accuracy
- $\rightarrow$ off-shell and non-resonant effects neglected $\rightarrow$ need off-shell studies

On top of discriminating SM (scalar) vs BSM (pseudoscalar) Higgs-boson (Artoisenet et al, arXiv:1212.3460),
can be very important in discriminating signal and background:



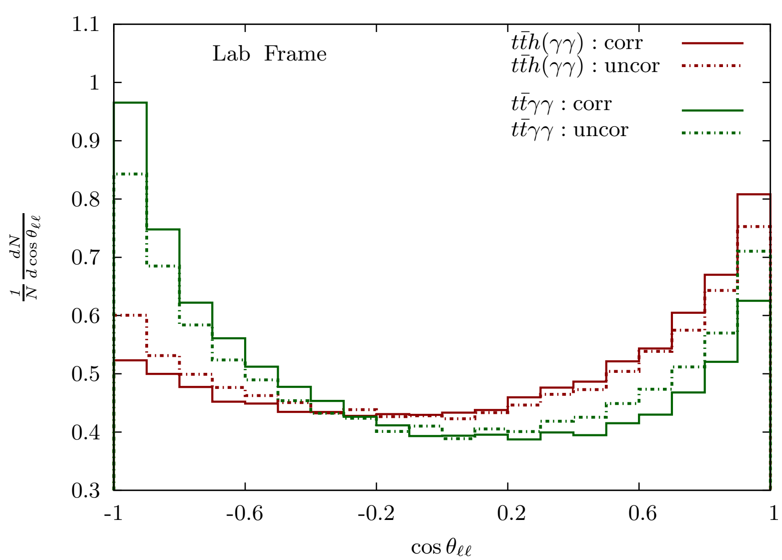
Biswas et al., arXiv:1403.1790

<u>Idea</u>: $t\bar{t}(\gamma\gamma)$ and $t\bar{t}H$ have different helicity structure in the chiral limit $m_t \rightarrow 0$ or $m_t/m_{t\bar{t}} \rightarrow 0$, and this main character is approximately preserved away form the chiral limit. Not so easily arguable for $t\bar{t}(b\bar{b})$.

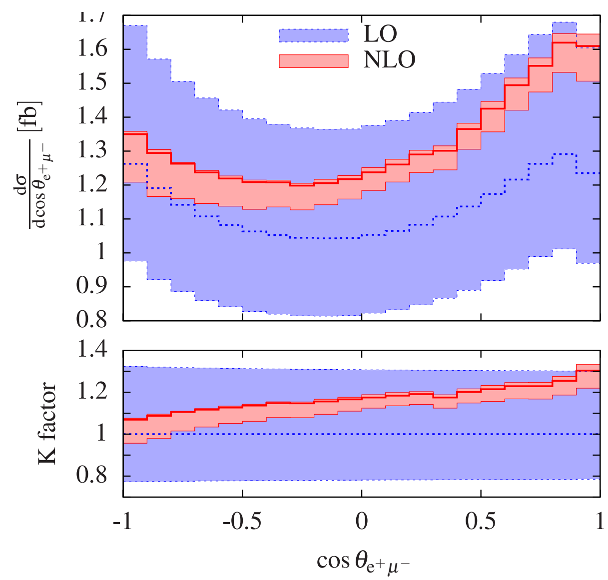
Off-shell $t\bar{t}H$ production and decay

$pp \to t(be^+\nu_e)\bar{t}(\bar{b}\mu^-\bar{\nu}_\mu)H$ at NLO in QCD [Denner, Feger, arXiv:1506.07448]

- include all non-resonant effects, off-shell effects, and interferences: NLO production <u>and</u> decay;
- full $2 \to 5$ NLO QCD calculation:
  RECOLA+COLLIER [Denner, Dittmaier, Hofer, Uccirati]
- effects of only 1% on NLO total cross section ($\approx \Gamma_t/m_t$);
- validate LO study of distributions:



Biswas et al., arXiv:1403.1790



Denner et al., arXiv:1506.07448

- validation with PS study [van Deurzen et al., arXiv:1509.02077]

Outlook

- **$t\bar{t}+X$ processes have gained a prominent role in Run II** LHC Higgs-physics analyses.
- **Lots of recent theoretical progress**:
  - ▷ $t\bar{t}H$: NLO QCD+EW, NLO QCD+PS
  - ▷ $t\bar{t}b\bar{b}$, NLO QCD+PS
  - ▷ $t\bar{t}+$ light jets, , NLO QCD+PS
  - ▷ Off-shell effects: signal (NLO) and signal-background interference (LO)
  - ▷ $t\bar{t}V$, $t\bar{t}VV$, NLO QCD+EW
  - ▷ Spin-correlation effects in top decays, and more ...
- **They are very challenging modes** to control. Building on existing experience, much needed progress will depend on
  - ▷ **validating state-of-the-art theoretical tools for Monte-Carlo simulations**, signal and **background**
  - ▷ **adopting validated tools** in experimental analyses.