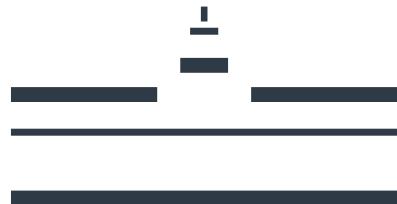


$t\bar{t} + b$ -jets and $t\bar{t}W$ as $t\bar{t}H$ backgrounds

Tomáš Ježo

ITP, University of Münster
SFB 1225 isoQuant

Higgs 2023, 27.11.

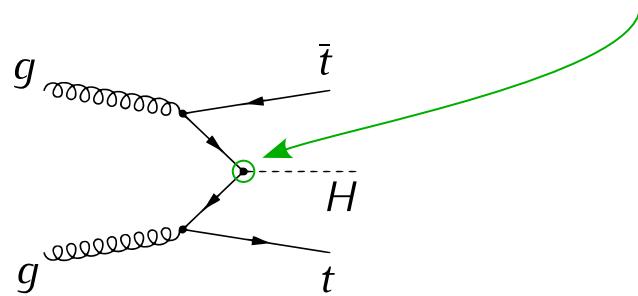


Universität
Münster



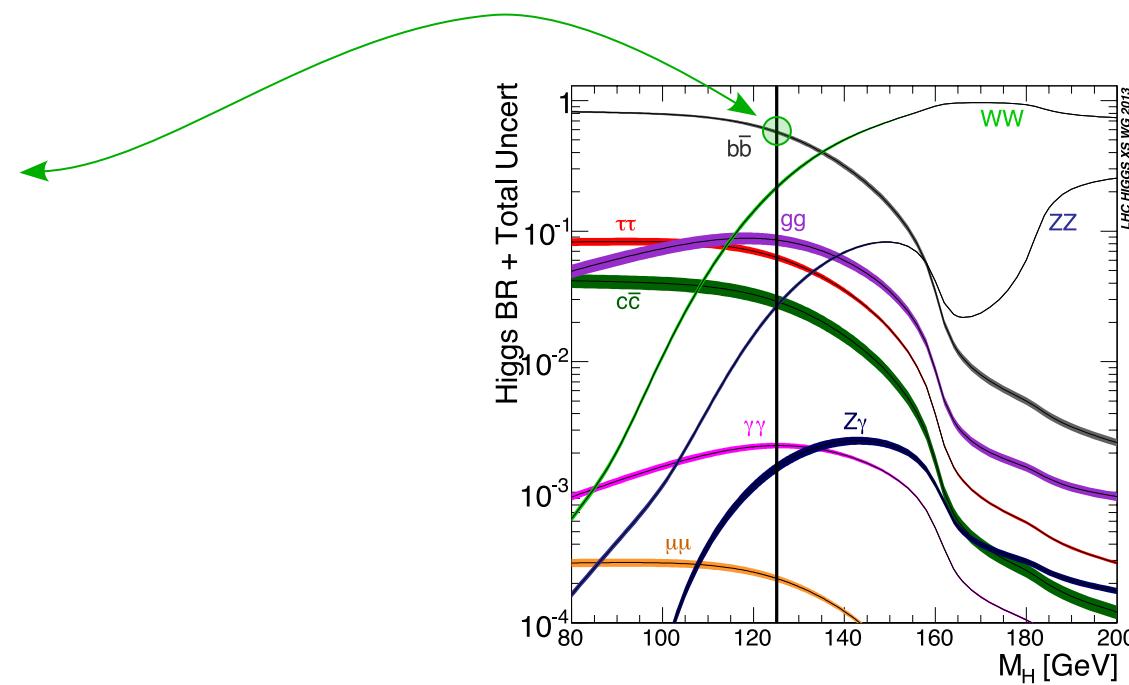
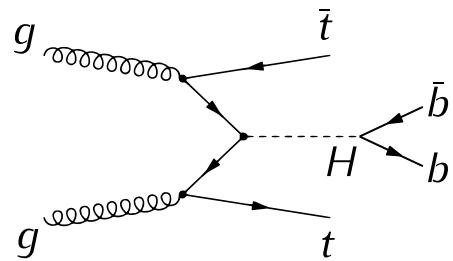
$t\bar{t}H$ at the LHC

- $t\bar{t}H$: Direct probe of top-quark Yukawa coupling



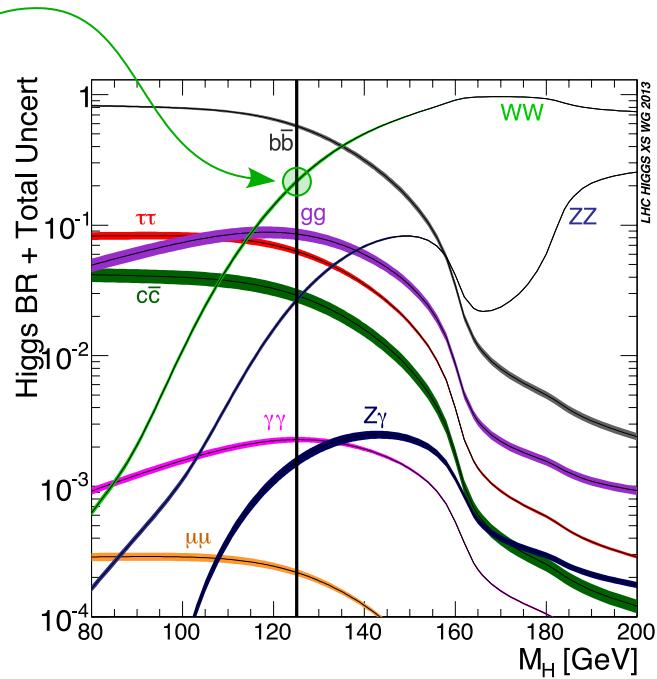
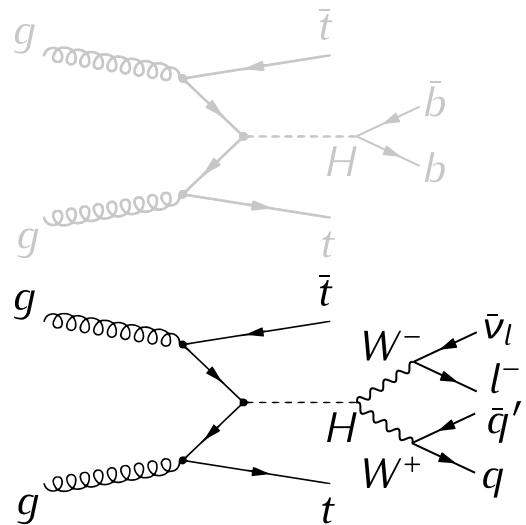
$t\bar{t}H$ at the LHC

- The usual suspects:



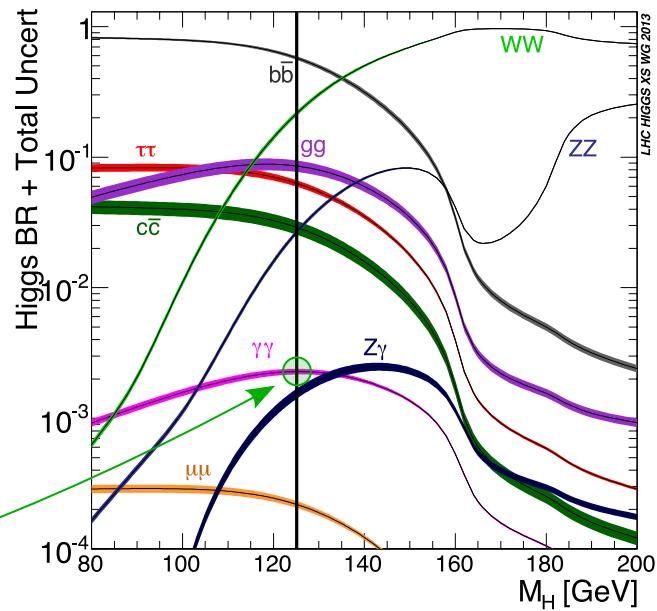
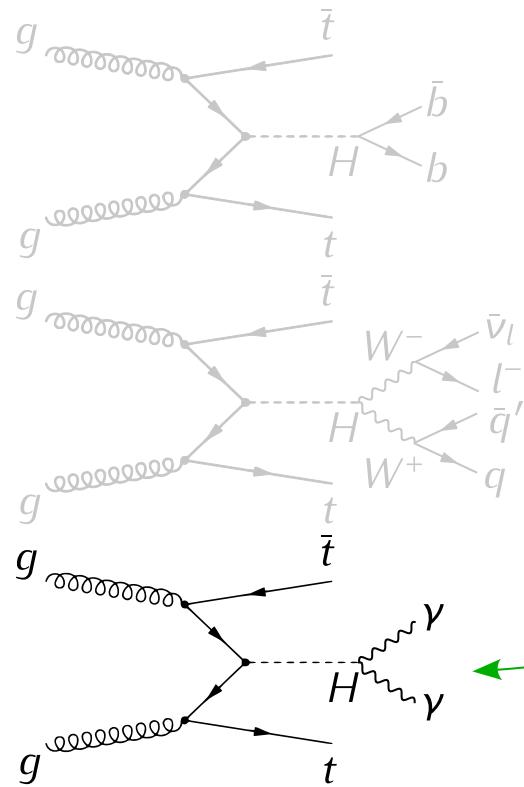
$t\bar{t}H$ at the LHC

- The usual suspects:



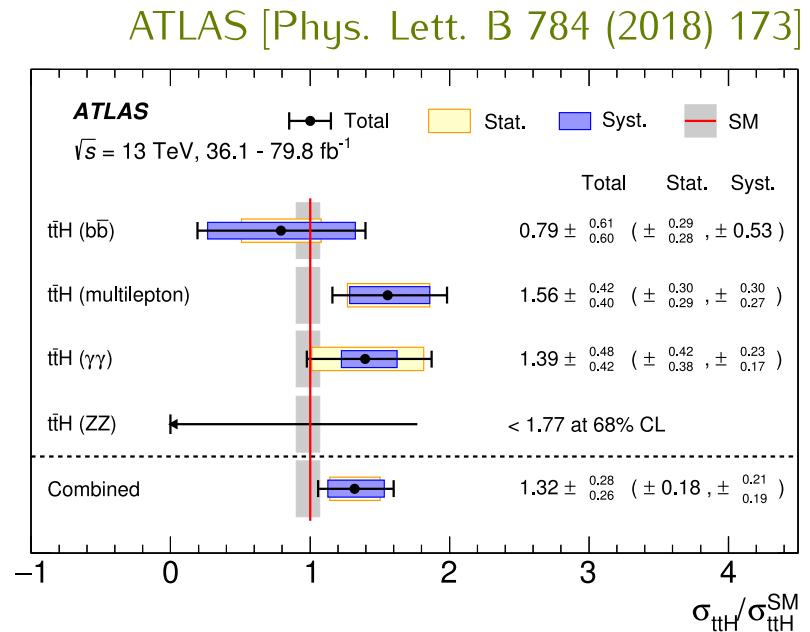
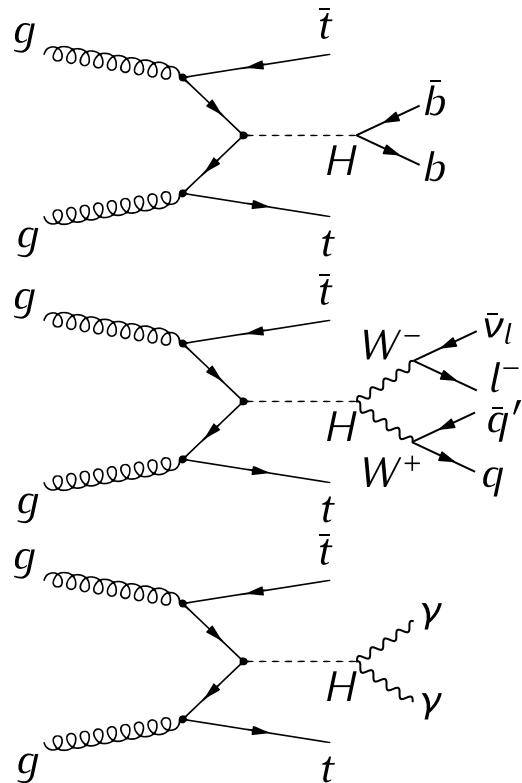
$t\bar{t}H$ at the LHC

- The usual suspects:



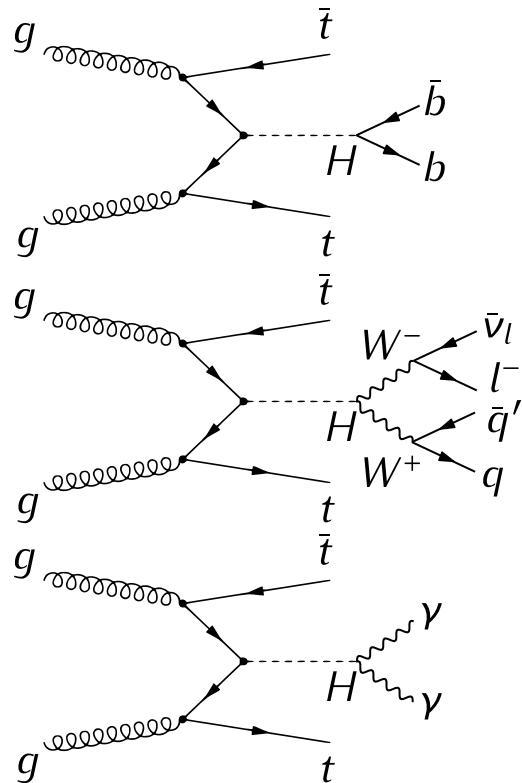
$t\bar{t}H$ at the LHC

- Observation of $t\bar{t}H$ in a combination of channels:

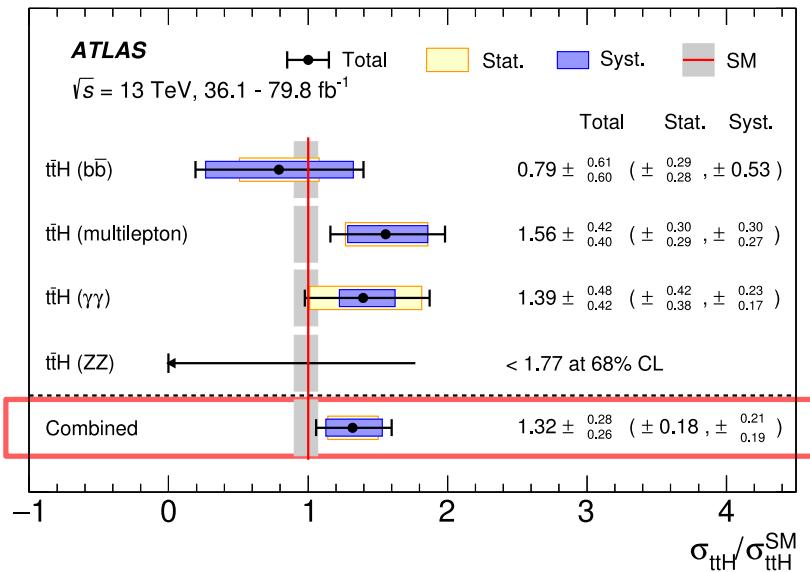


$t\bar{t}H$ at the LHC

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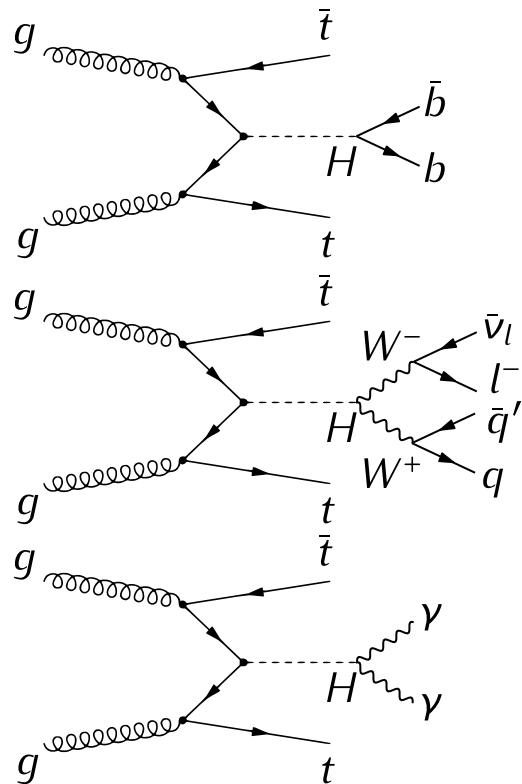


ATLAS [Phys. Lett. B 784 (2018) 173]



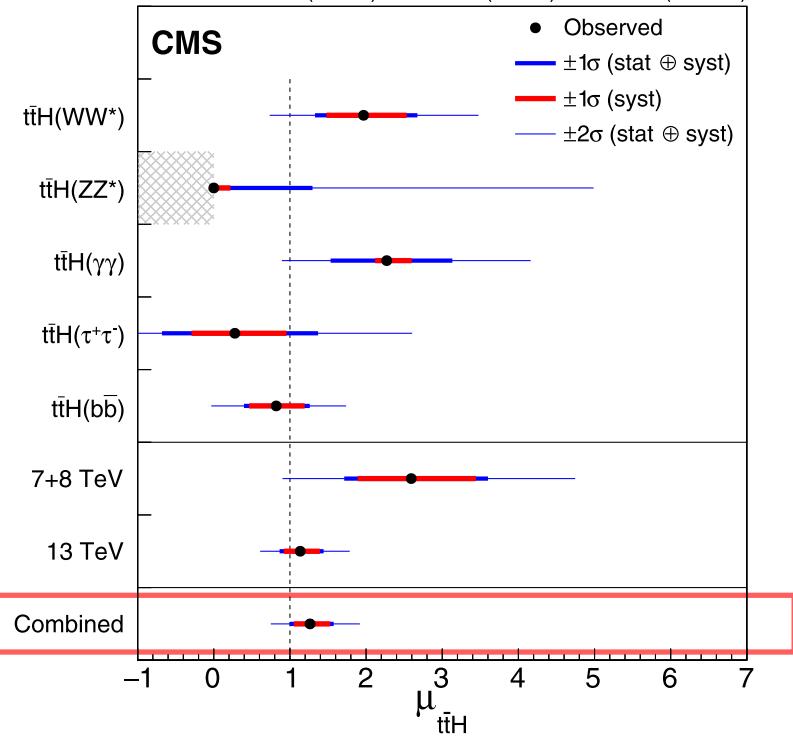
$t\bar{t}H$ at the LHC

- Observation of $t\bar{t}H$ in a combination of channels:



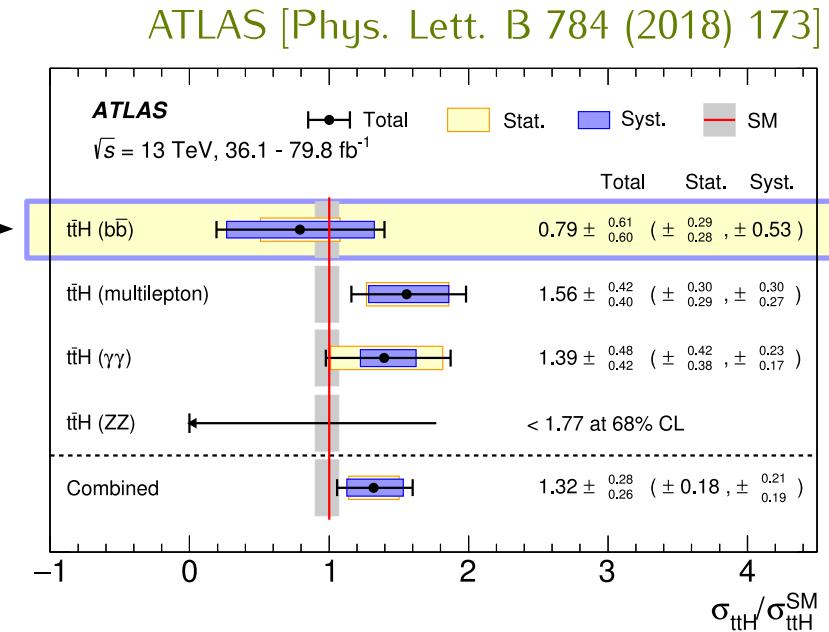
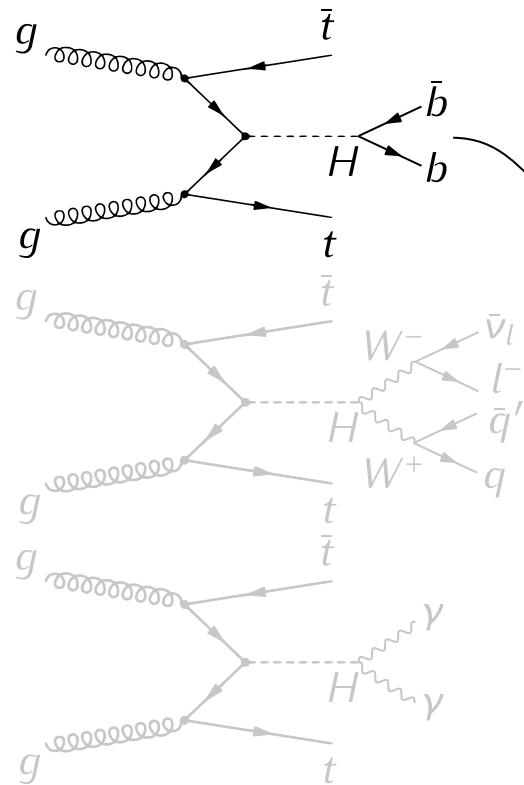
CMS [Phys. Rev. Lett. 120, 231801]

$5.1 \text{ fb}^{-1} (7 \text{ TeV}) + 19.7 \text{ fb}^{-1} (8 \text{ TeV}) + 35.9 \text{ fb}^{-1} (13 \text{ TeV})$



$t\bar{t}H$ at the LHC

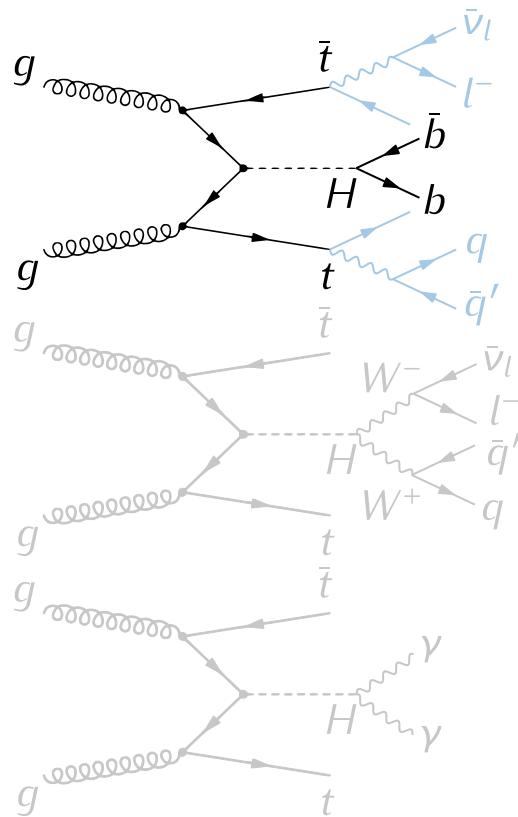
- $t\bar{t}H, H \rightarrow b\bar{b}$:



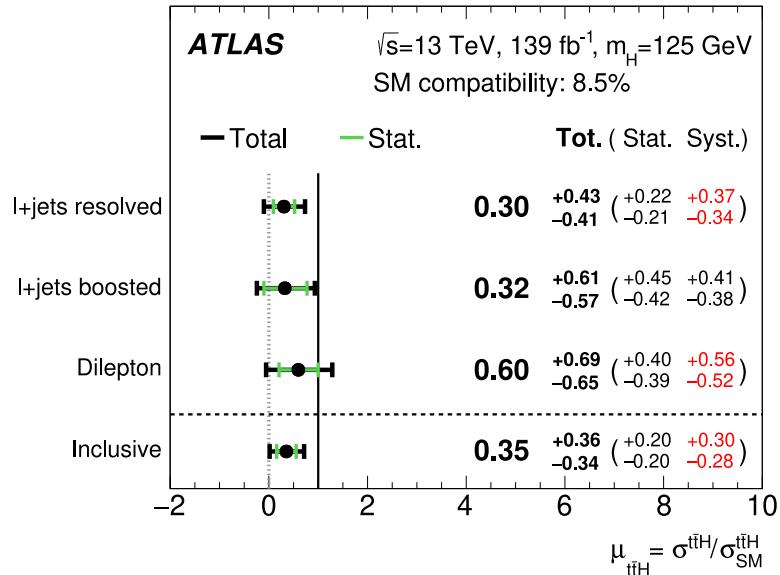
Systematics dominated!

$t\bar{t}H$ at the LHC

- $t\bar{t}H, H \rightarrow b\bar{b}$:

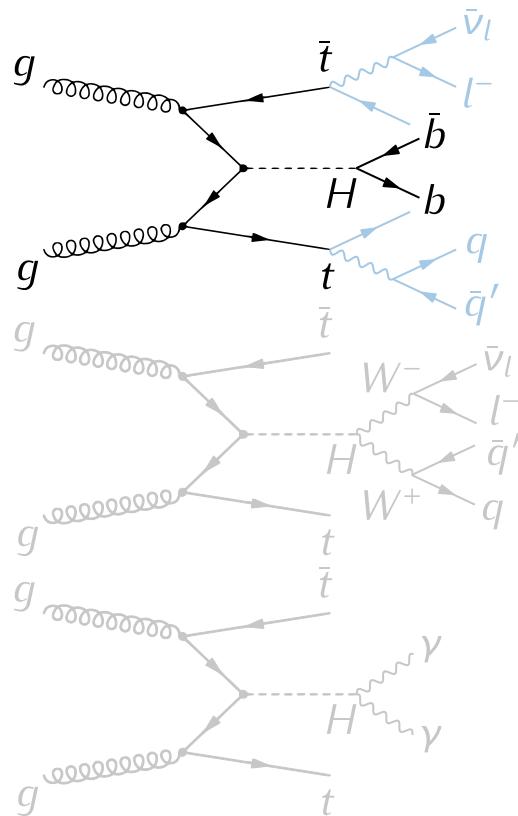


ATLAS [JHEP 06 (2022) 097]

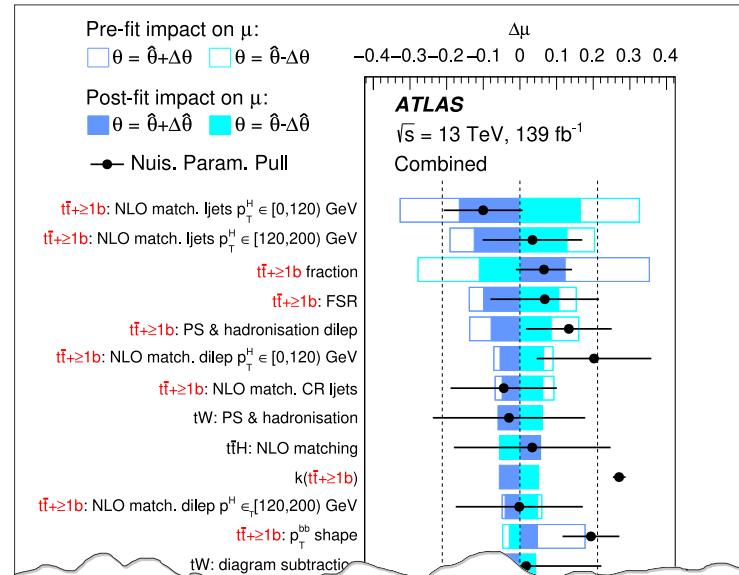


$t\bar{t}H$ at the LHC

- $t\bar{t}H, H \rightarrow b\bar{b}$:

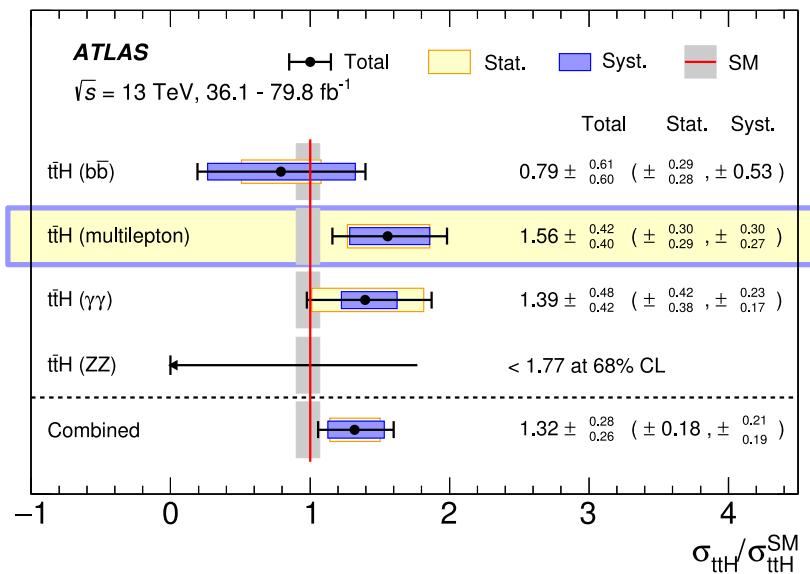
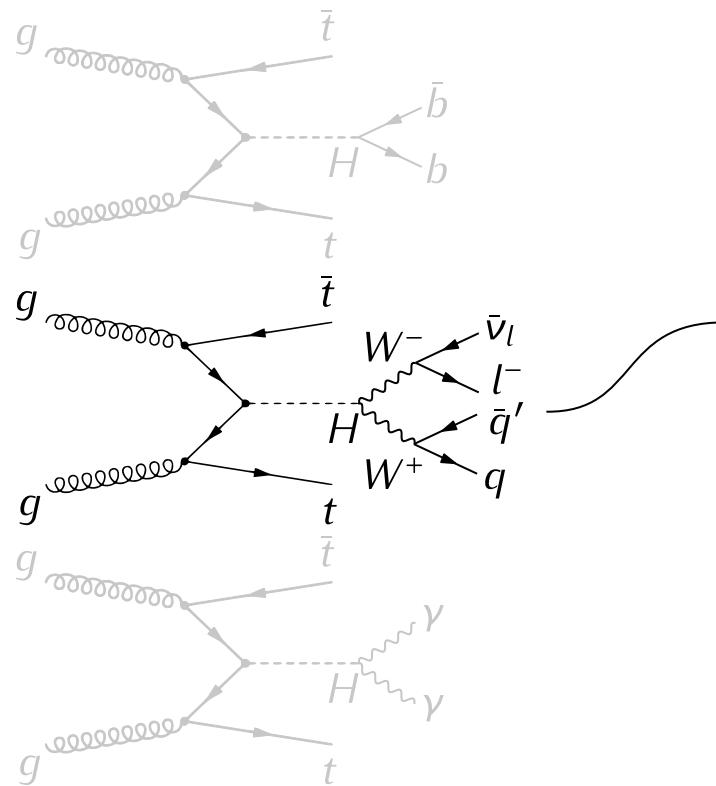


ATLAS [JHEP 06 (2022) 097]



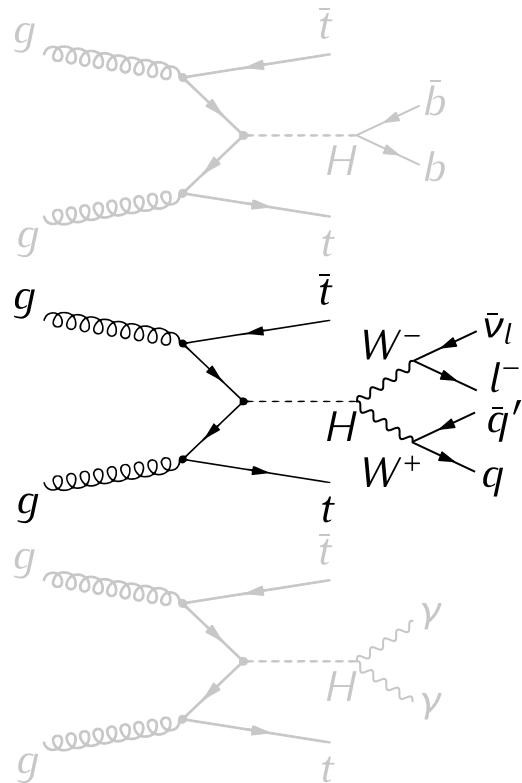
$t\bar{t}H$ at the LHC

- $t\bar{t}H, H \rightarrow W^+W^-$:



$t\bar{t}H$ at the LHC

- $t\bar{t}H, H \rightarrow W^+W^-:$



Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	-0.09
Jet energy scale and resolution	+0.18	-0.15
Non-prompt light-lepton estimates	+0.15	-0.13
Jet flavor tagging and τ_{had} identification	+0.11	-0.09
$t\bar{t}W$ modeling	+0.10	-0.09
$t\bar{t}Z$ modeling	+0.08	-0.07
Other background modeling	+0.08	-0.07
Luminosity	+0.08	-0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	-0.04
Fake τ_{had} estimates	+0.07	-0.07
Other experimental uncertainties	+0.05	-0.04
Simulation sample size	+0.04	-0.04
Charge misassignment	+0.01	-0.01
Total systematic uncertainty	+0.39	-0.30

$t\bar{t}H$ at the LHC

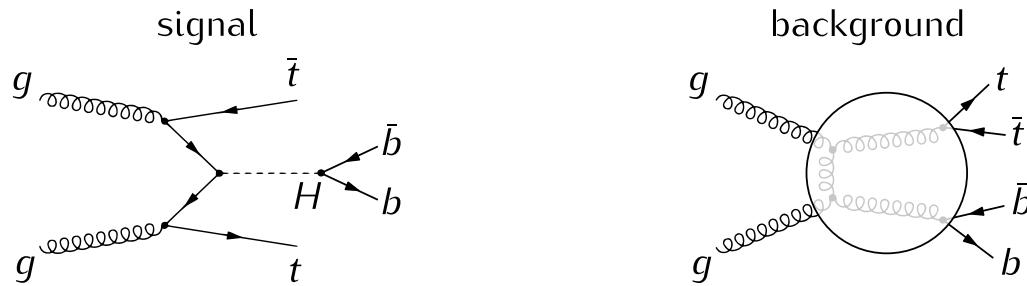
- $t\bar{t}H$ process at the LHC:
 - ▶ Observed in 2018! 
 - ▶ But theory uncertainties are in need of taming
 - ▶ Today's highlights:
 - ▷ $t\bar{t} + b$ -jets as a background to
 - $t\bar{t}H, H \rightarrow b\bar{b}$ largest cross section but troublesome theory uncertainty
 - ▷ $t\bar{t}W$ as a background to
 - $t\bar{t}H, H \rightarrow W^+ W^-$ most promising channel with great progress in theory modelling

$t\bar{t} + b$ jets

- Theory status:
 - ▶ NLO QCD ✓ [Berendstein et al. '08, '09, '10], [Bevilacqua et al. '09, '14], [Worek '11]
 - ▶ NLO+NLL QCD ✓ [van Beekveld et al. 'XY]
 - ▶ Parton shower matched ✓ [Kardos et al. '13], [Cascioli et al. '13], [Garzelli et al. '14], [Bevilacqua et al. '17], [TJ et al. '18]
 - ▶ Multi-jet merged ✓ [Hoeche et al. '14, '19]
 - ▶ Associated with an extra jet ✓ [Buccioni et al. '19]
 - ▶ With off-shell effects ✓ [Denner et al. '20], [Bevilacqua et al. '21, '22]

$t\bar{t} + b$ jets for dummies

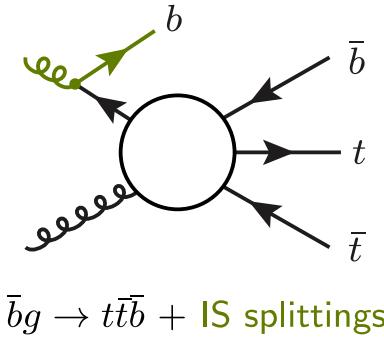
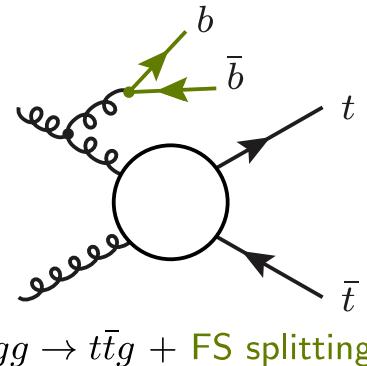
- Large $t\bar{t} + b$ -jets background and its theory uncertainties are bottleneck of $t\bar{t}H(b\bar{b})$ searches



- How do we get $t\bar{t} + b$ -jets?
 - ▶ From an inclusive $t\bar{t}$?
 - ▶ 5FNS multi-jet merged?
 - ▶ Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?

$t\bar{t} + b$ jets for dummies

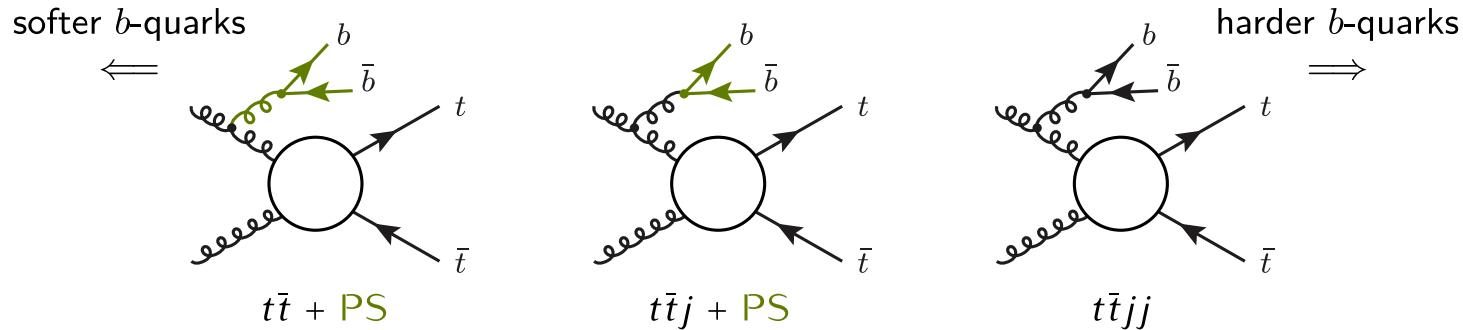
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- How do we get $t\bar{t} + b$ jets?
 - ▶ From an inclusive $t\bar{t}$?



- ▶ 5FNS multi-jet merged?
- ▶ Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?

$t\bar{t} + b$ jets for dummies

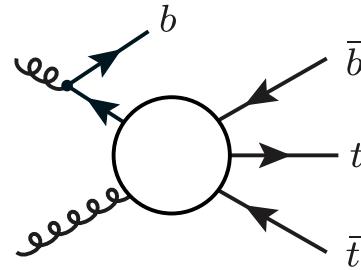
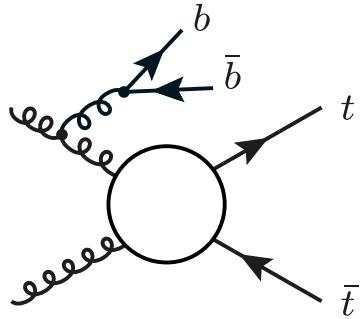
- Large $t\bar{t} + b$ -jets background and its theory uncertainties are bottleneck of $t\bar{t}H(b\bar{b})$ searches
- How do we get $t\bar{t} + b$ jets?
 - ▶ From an inclusive $t\bar{t}$? **Not event LO accuracy!**
 - ▶ 5FNS multi-jet merged?



- ▶ Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?

$t\bar{t} + b$ jets for dummies

- Large $t\bar{t} + b$ -jets background and its theory uncertainties are bottleneck of $t\bar{t}H(b\bar{b})$ searches
- How do we get $t\bar{t} + b$ jets?
 - ▶ From an inclusive $t\bar{t}$? **Not event LO accuracy!**
 - ▶ 5FNS multi-jet merged? **$b\bar{b}$ pairs still mostly from PS!** (see more later)
 - ▶ Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?



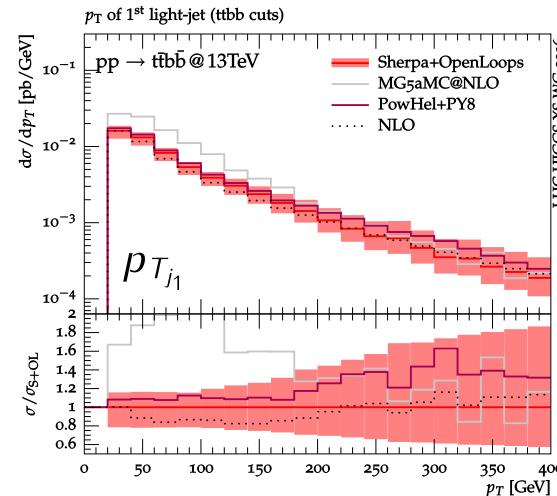
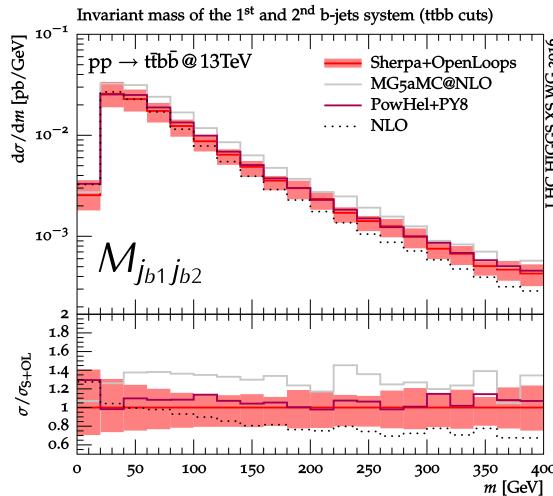
- $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R) \Rightarrow$ scale uncertainty: $\sim 80\% @ \text{LO}, 20 - 30\% @ \text{NLO}$

$t\bar{t} + b$ jets matched to PS

- Theory status:
 - ▶ NLO QCD ✓ [Berendstein et al. '08, '09, '10], [Bevilacqua et al. '09, '14], [Worek '11]
 - ▶ NLO+NLL QCD ✓ [van Beekveld et al. 'XY]
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$t\bar{t} + b$ jets matched to PS

- YR4 [arXiv:1610.07922]:

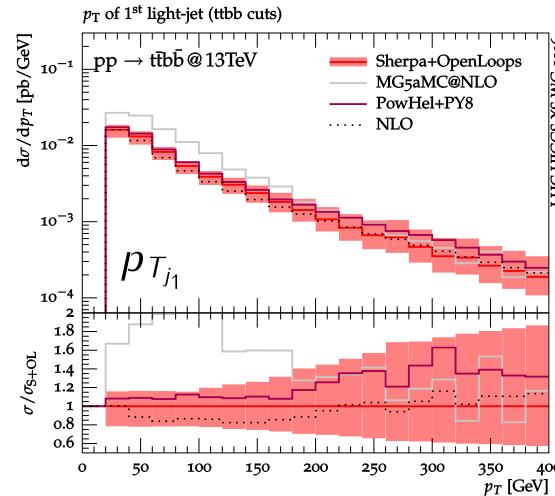
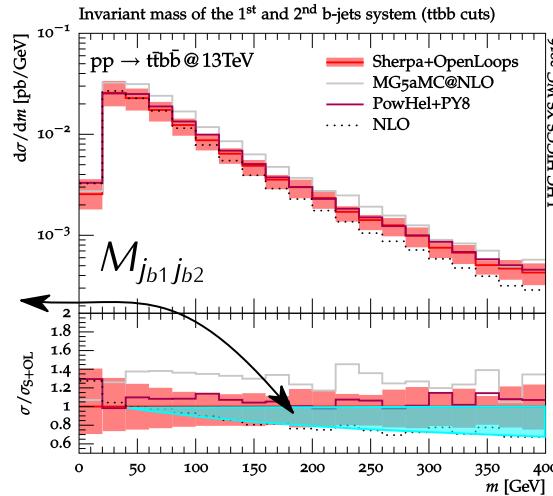


- Sherpa+OpenLoops vs. PowHel+PY8
 - ▶ Good agreement also in observables with large NLO+PS corrections
- Sherpa+OpenLoops vs. MG5_aMC@NLO+PY8
 - ▶ Sizable differences in NLO radiation pattern
 - ▶ Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$ +jet in MG5_aMC@NLO+PY8

$t\bar{t} + b$ jets matched to PS

- YR4 [arXiv:1610.07922]:

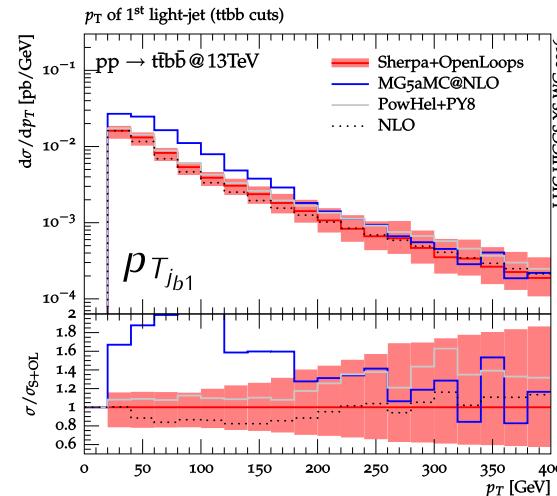
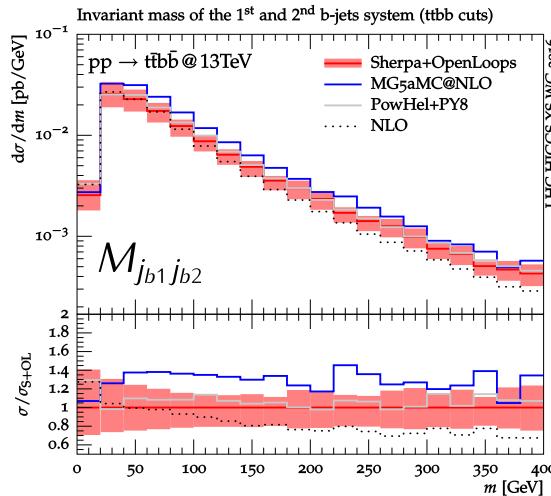
“double-splitting”



- Sherpa+OpenLoops vs. PowHel+PY8
 - ▶ Good agreement also in observables with large NLO+PS corrections
- Sherpa+OpenLoops vs. MG5_aMC@NLO+PY8
 - ▶ Sizable differences in NLO radiation pattern
 - ▶ Strong resummation-scale sensitivity of $t\bar{t}b\bar{b}$ +jet in MG5_aMC@NLO+PY8

$t\bar{t} + b$ jets matched to PS

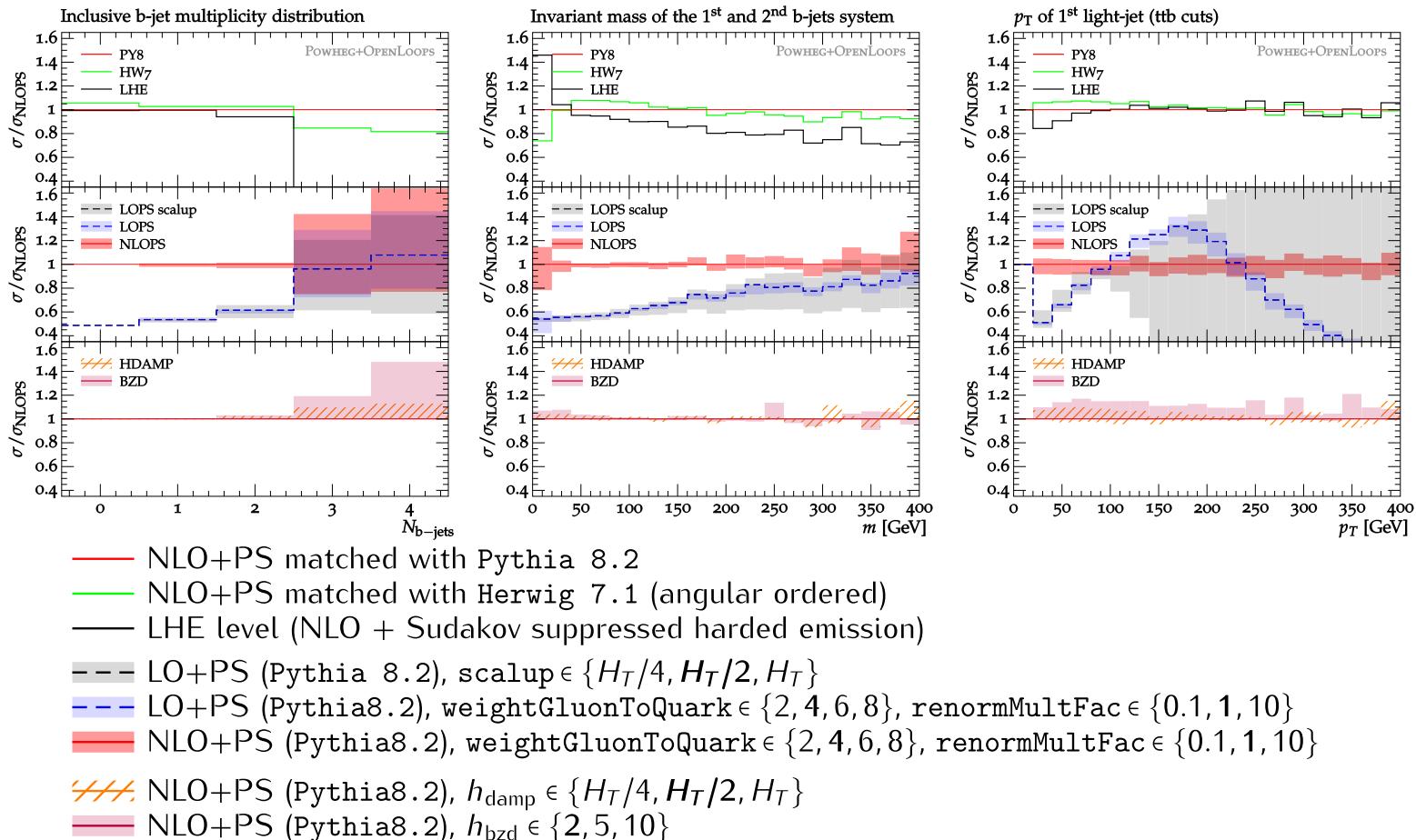
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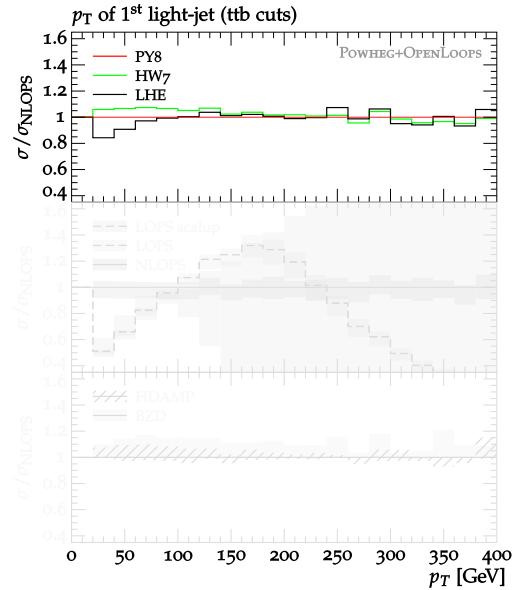
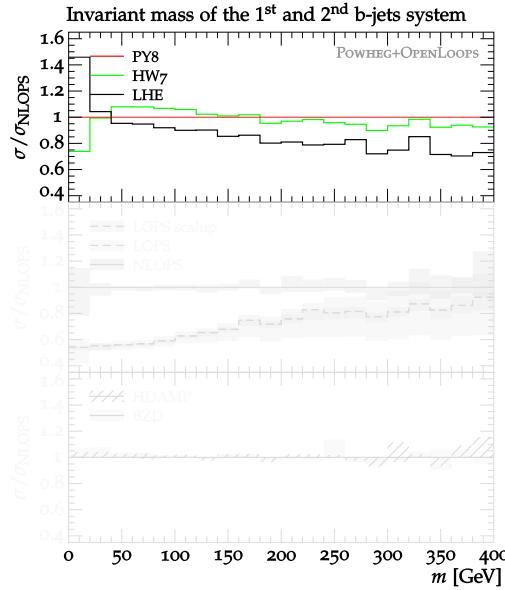
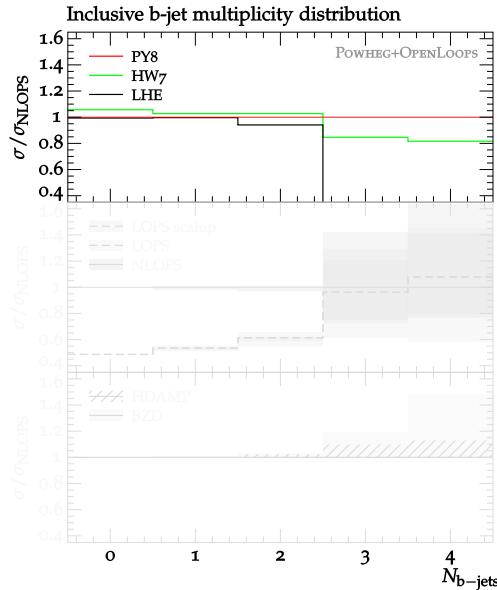
$t\bar{t} + b$ jets matched to PS

[TJ et al.'18]



$t\bar{t} + b$ jets matched to PS

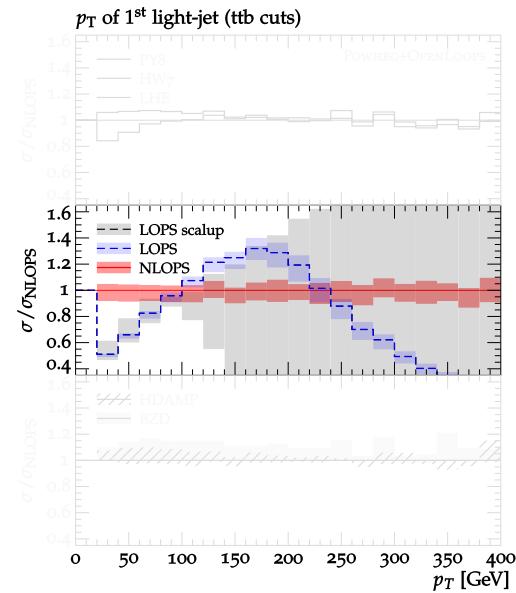
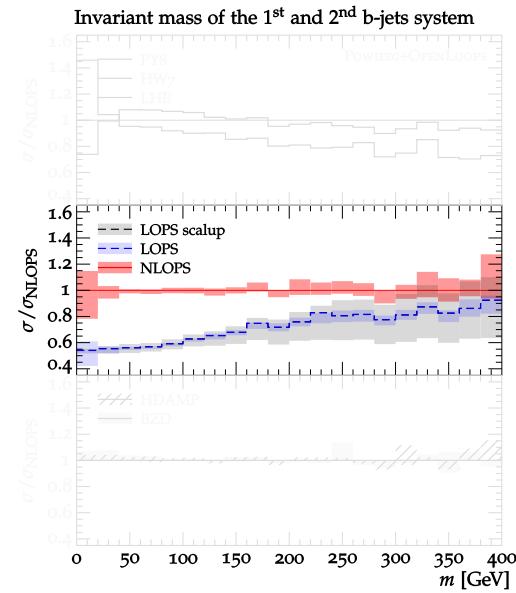
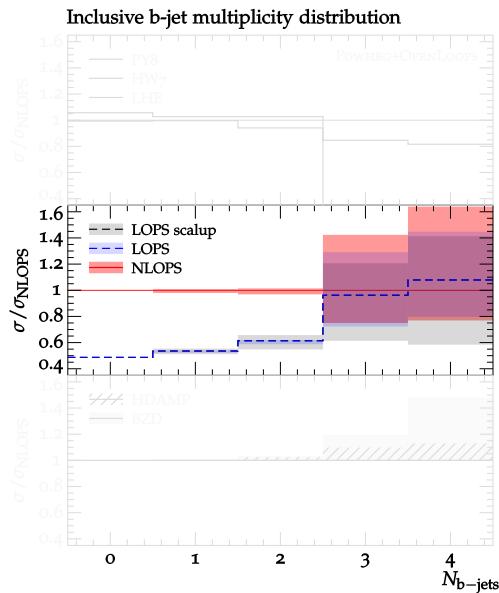
[TJ et al.'18]



- effect of the parton shower
 - small in the ttbar phase space, even for light-jet p_T
 - predictions with Pythia and Herwig in good agreement
 - shower starting scale and $g \rightarrow b\bar{b}$
 - hdamp and bornzerodamp

$t\bar{t} + b$ jets matched to PS

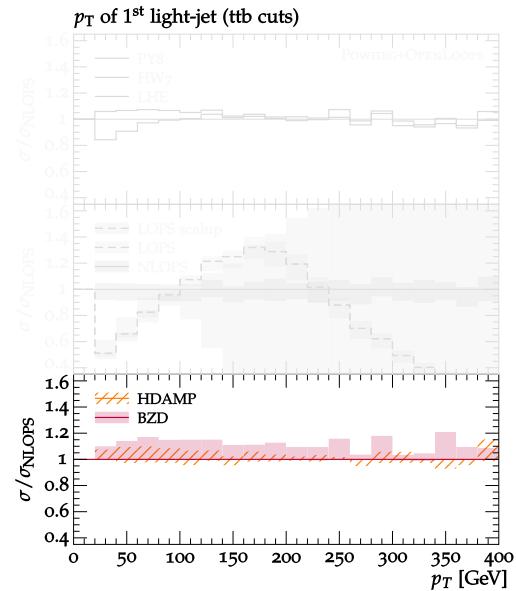
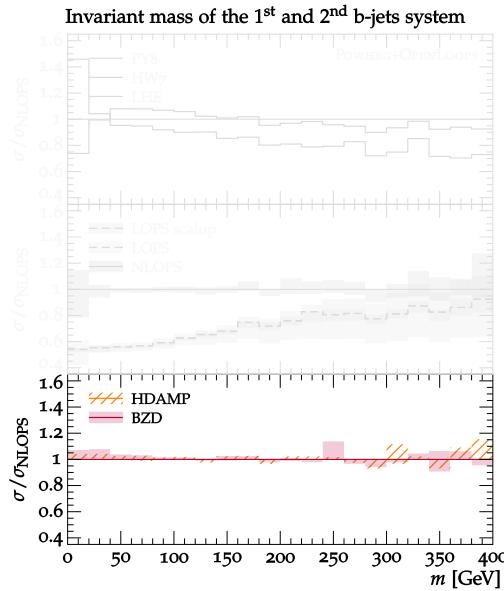
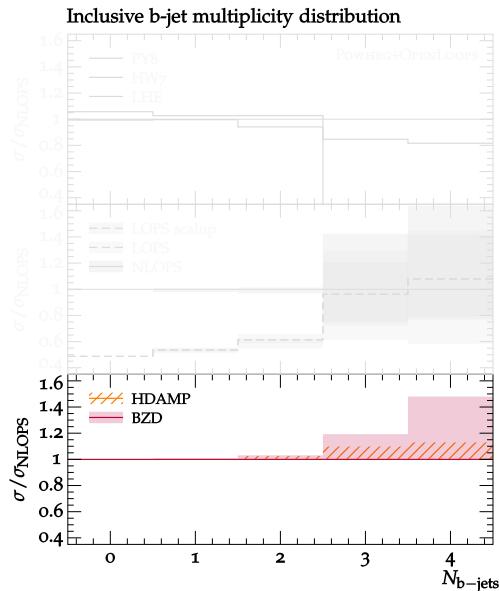
[TJ et al.'18]



- effect of the parton shower
- shower starting scale and $g \rightarrow b\bar{b}$
 - jet bins with $N_b \geq 3, 4$ show sizable variations
 - light-jet spectrum depend strongly on scalup
- hdamp and bornzerodamp

$t\bar{t} + b$ jets matched to PS

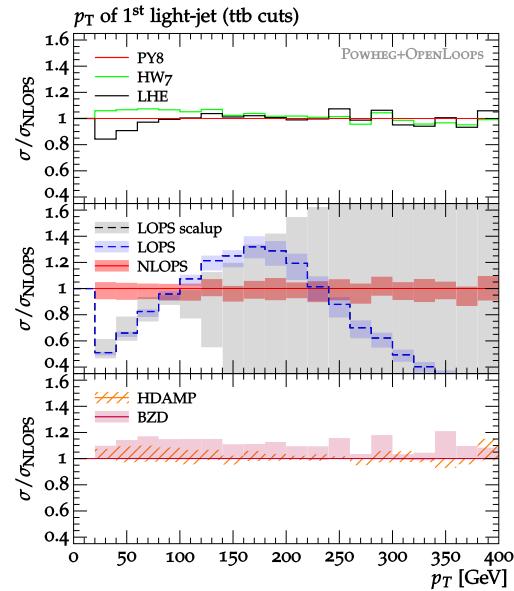
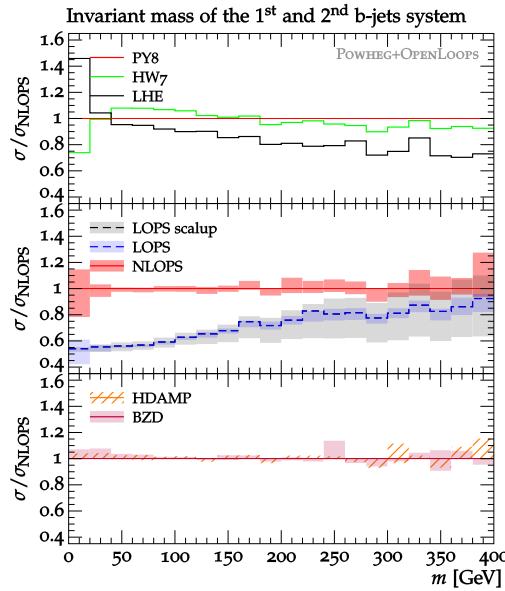
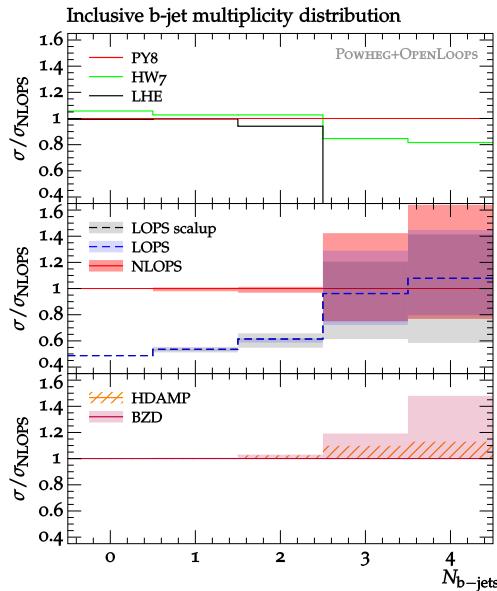
[TJ et al.'18]



- effect of the parton shower
- shower starting scale and $g \rightarrow b\bar{b}$
- hdamp and bornzerodamp
 - h_{damp} dependence very small
 - h_{bzd} dependence small, except for light-jet spectrum

$t\bar{t} + b$ jets matched to PS

[TJ et al.'18]



- We failed to find a way of reaching MG5_MC@NLO+PY8 prediction in POWHEG
 - ▶ Hints at conceptual differences in how the shower starting scales are treated

$t\bar{t} + b$ jets multi-jet merged

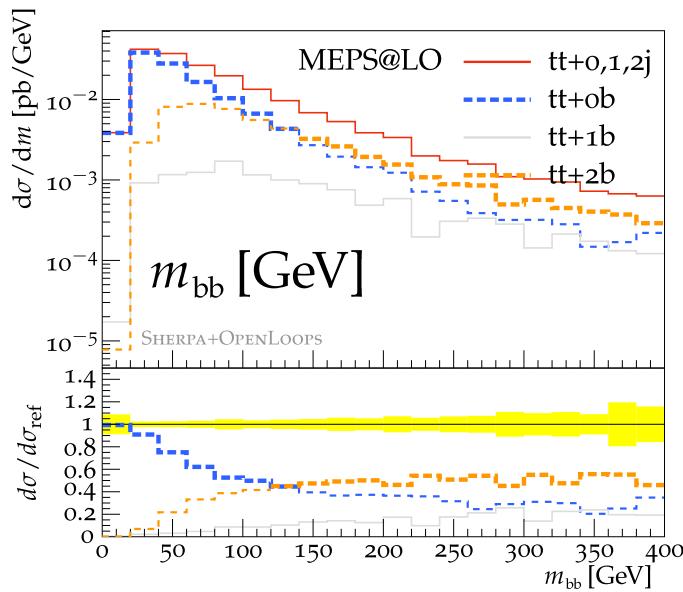
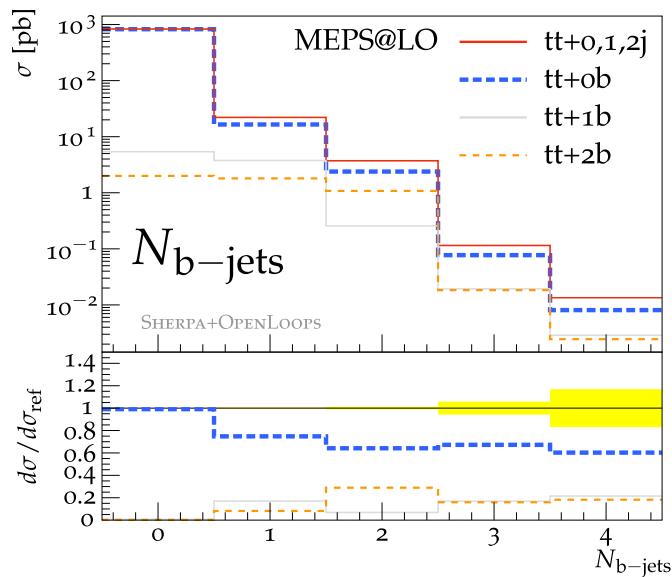
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- ▶ With off-shell effects ✓ [Denner et al. '20], [Bevilacqua et al. '21, '22]

$t\bar{t} + b$ jets multi-jet merged

[Höche et al.'14, '19]

- Multi-jet merged calculations in 5FNS naively promising:

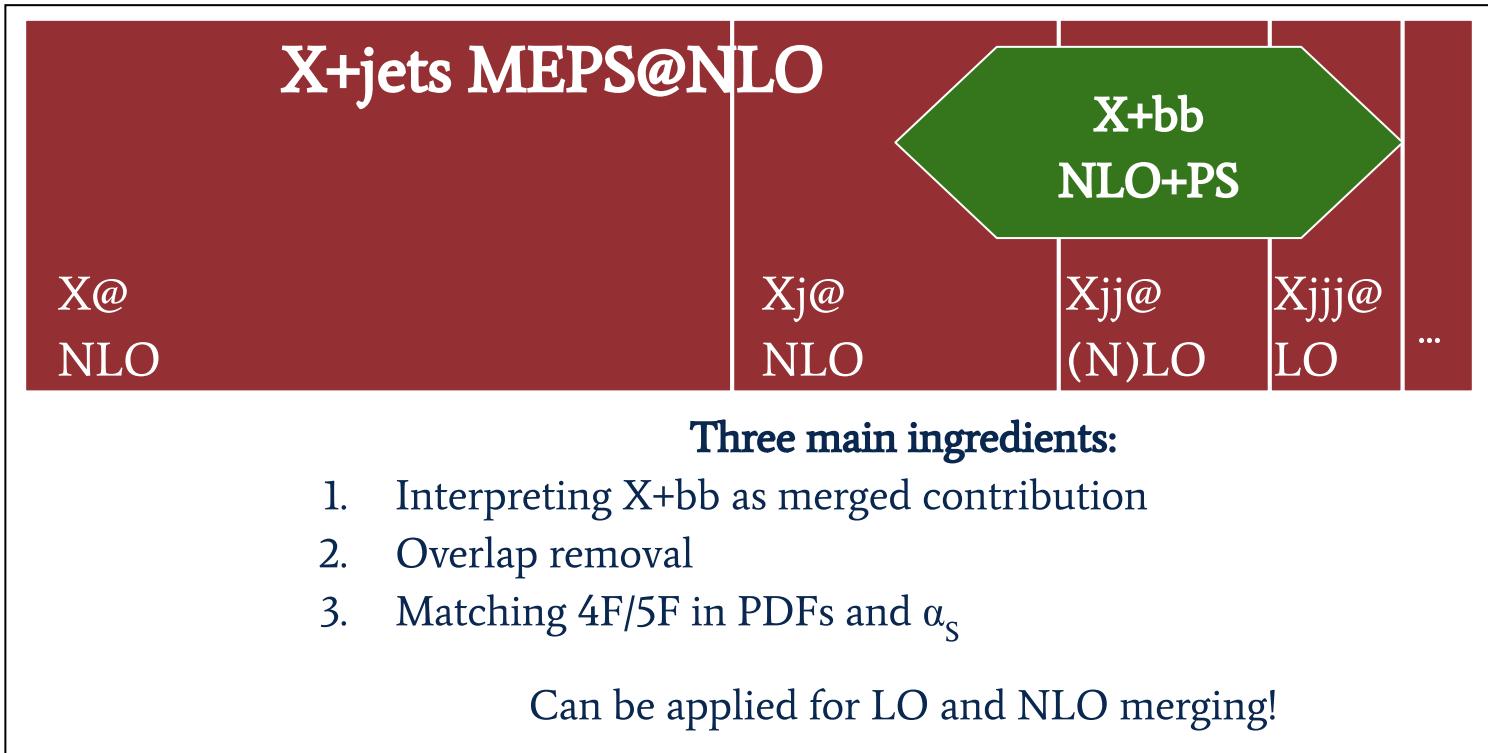


- ▶ But do not necessarily end up describing FS b 's using the matrix element

$t\bar{t} + b$ jets multi-jet merged

[Höche et al.'14, '19]

- Multi-jet merging in a variable flavour number scheme:



- ▶ Has yet to be applied to $t\bar{t} + b$ jets

$t\bar{t} + b$ jets in association with an extra jet

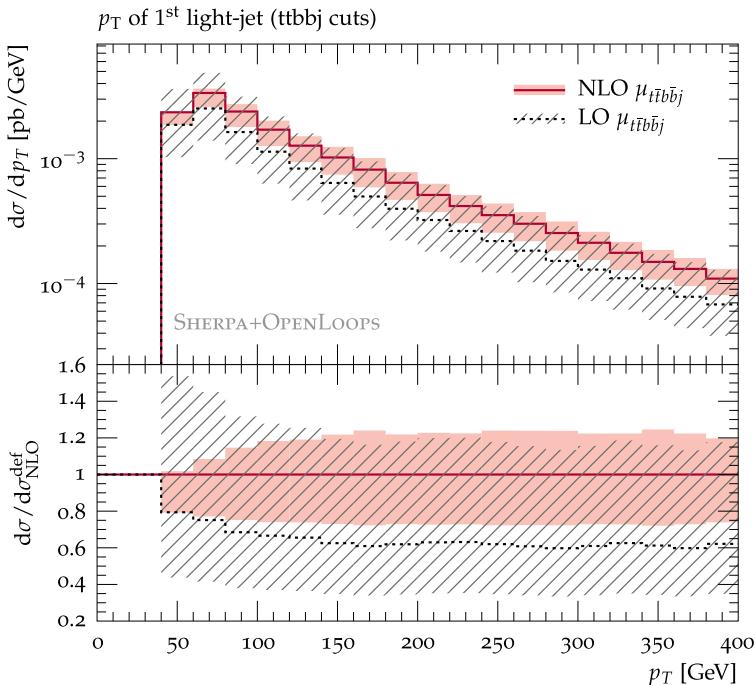
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$t\bar{t} + b$ jets in association with an extra jet

[Buccioni et al.'19]

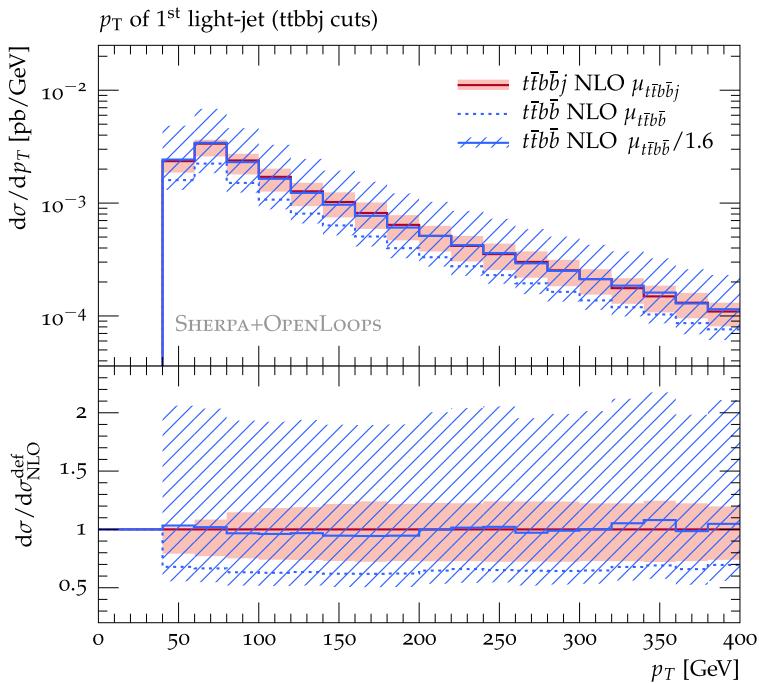
- 4FNS $t\bar{t}b\bar{b}j$ at NLO QCD:
 - ▶ Reduces perturbative uncertainties scale down to about $\pm 20\%$
 - ▶ Proposes a novel strategy for an optimal scale choice in the $t\bar{t}b\bar{b}$ process
 - ▶ Suggests using $t\bar{t}b\bar{b}j$ p_T spectra to tune $t\bar{t}b\bar{b}$ NLO+PS calculations to



$t\bar{t} + b$ jets in association with an extra jet

[Buccioni et al.'19]

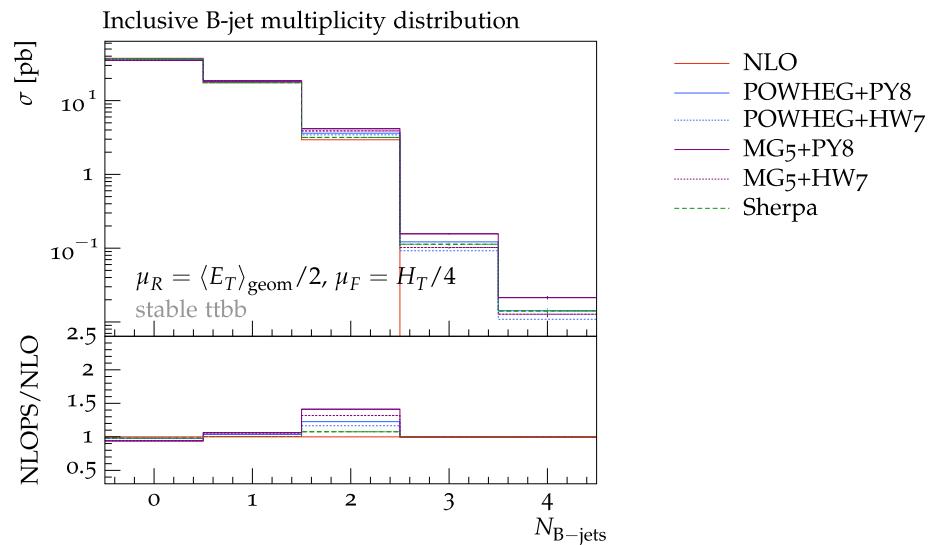
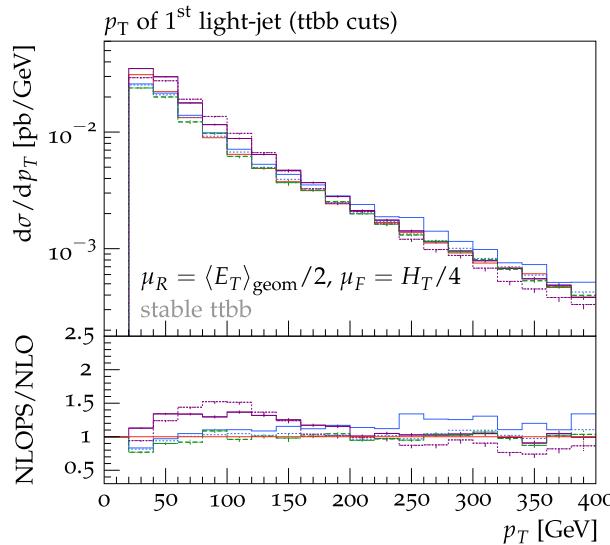
- 4FNS $t\bar{t}b\bar{b}j$ at NLO QCD:
 - ▶ Reduces perturbative uncertainties scale down to about $\pm 20\%$
 - ▶ Proposes a novel strategy for an optimal scale choice in the $t\bar{t}b\bar{b}$ process
 - ▶ Suggests using $t\bar{t}b\bar{b}j$ p_T spectra to tune $t\bar{t}b\bar{b}$ NLO+PS calculations to



$t\bar{t} + b$ jets & the HXWG $ttH/ttbb$ initiative

[Buccioni, Garzelli, TJ, Kardos, Lindert, Pozzorini, Reuschle, Siegert, Zaro 'XY]

- Reduction of the renormalization scale $\mu_R \rightarrow \mu_R/2$ in NLOPS $t\bar{t}b\bar{b}$ codes:

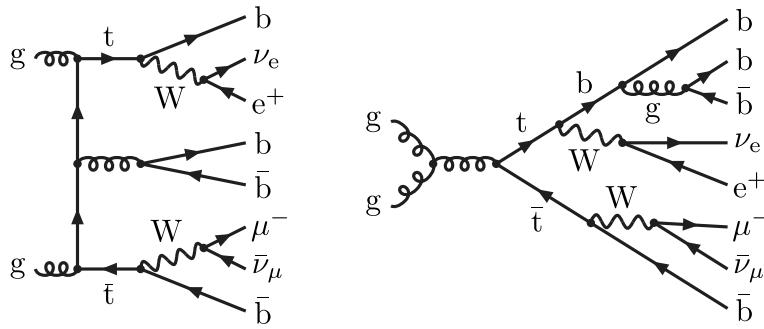


- Reduces the spread in the predictions for the light jet spectrum significantly, but not in the b jet multiplicity

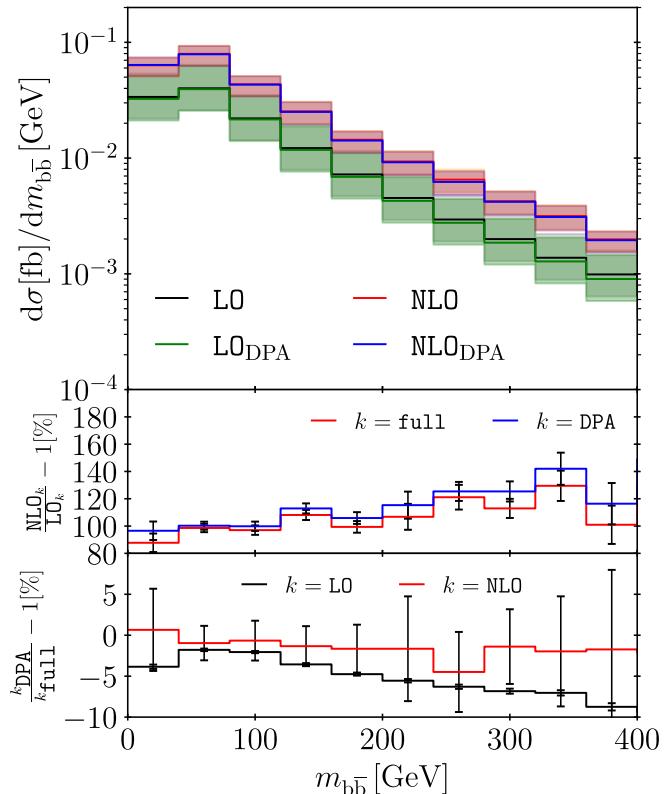
$t\bar{t} + b$ jets off-shell

[Denner et al.'20], [Bevilacqua et al.'21, '22]

- Full off-shell calculation of $pp \rightarrow \mu^- \nu_\mu e^+ \nu_e b\bar{b}b\bar{b}$:



- Impressive level of sophistication
- Includes interference with $t\bar{t}$
- But off-shell effects have limited impact on the observables relevant for $t\bar{t}H(\rightarrow b\bar{b})$
 - A couple percent agreement of off-shell and DPA



$t\bar{t}W^+(-)$

- Theory status:
 - ▶ NLO QCD ✓ [Badger et al. '10], [Campbell et al. '12]
 - ▶ NLO EW ✓ [Frixione et al. '15], [Dror et al. '15], [Frederix et al. '17, '18]
 - ▶ NLO+NLL QCD ✓ [Li et al. '14], [Broggio et al. '16, '19], [Kulesza et al. '18, '20]
 - ▶ Multi-jet merged ✓ [Buddenbrock et al. '20], [Frederix et al. '20]
 - ▶ Parton shower matched ✓ [Garzelli et al. '12], [Kardos et al. '14], [Maltoni et al. '14], [Frederix et al. '20], [Febres Cordero et al. '21]
 - ▶ With off-shell effects ✓ [Bevilacqua et al. '20, '21], [Denner et al. '20, '21] and in association with an extra jet ✓ [Bi et al. '23]
 - ▶ NNLO QCD ✓ [Buonocore et al. '23]

$t\bar{t}W^{+(-)}$ for dummies

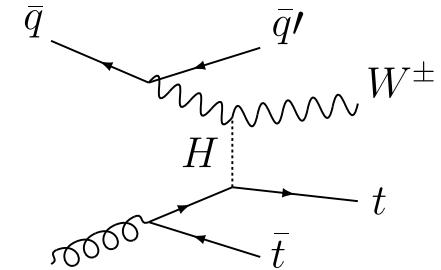
[Maltoni et al.'17]

- $pp \rightarrow t\bar{t}W$ process at “complete-NLO”:

$$\begin{aligned}\Sigma_{\text{NLO}}^{t\bar{t}W^\pm}(\alpha_s, \alpha) &= \alpha_s^3 \alpha \Sigma_{4,0}^{t\bar{t}W^\pm} + \alpha_s^2 \alpha^2 \Sigma_{4,1}^{t\bar{t}W^\pm} + \alpha_s \alpha^3 \Sigma_{4,2}^{t\bar{t}W^\pm} + \alpha^4 \Sigma_{4,3}^{t\bar{t}W^\pm} \\ &\equiv \Sigma_{\text{NLO}_1} + \Sigma_{\text{NLO}_2} + \Sigma_{\text{NLO}_3} + \Sigma_{\text{NLO}_4}\end{aligned}$$

NLO QCD NLO EW ???

$\delta [\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO ₂	-	-	-
LO ₃	0.8	0.9	1.1
NLO ₁	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
NLO ₂	-4.4 (-4.8)	-4.2 (-4.6)	-4.0 (-4.4)
NLO ₃	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
NLO ₄	0.02 (-0.02)	0.04 (-0.02)	0.05 (-0.01)



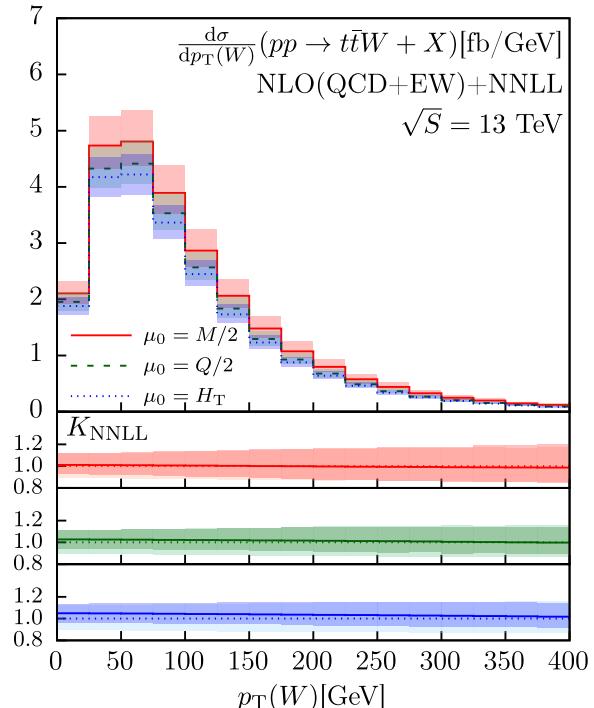
$tW \rightarrow tW$ scattering
contributing to NLO₃

Unexpectedly large
for formally subleading!

$t\bar{t}W^{+(-)}$ for dummies

[Li et al.'14], [Broggio et al.'16, '19], [Kulesza et al.'18, '20]

- $pp \rightarrow t\bar{t}W$ process at “complete-NLO”
 - ▶ Formally subleading contributions are counterintuitively large
- (N)NLL resummation also available
 - ▶ Inclusive NNLL K -factor is 0–6%, depending on the scale choice
 - ▶ Differentially the correction can go up to 20–30%



[Kulesza et al.'20]

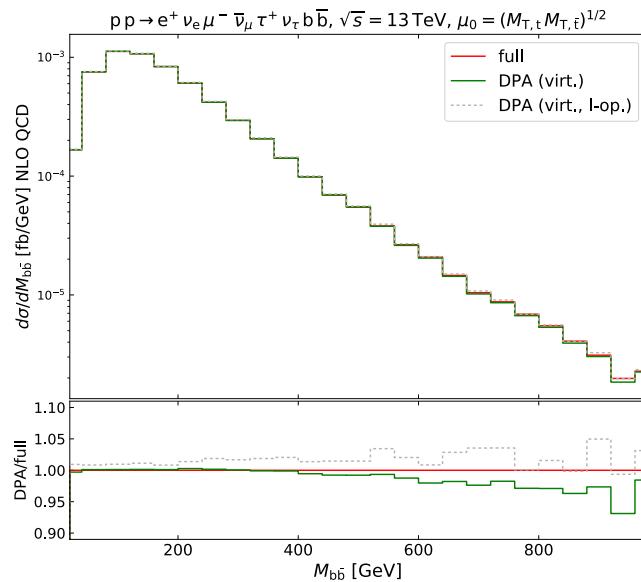
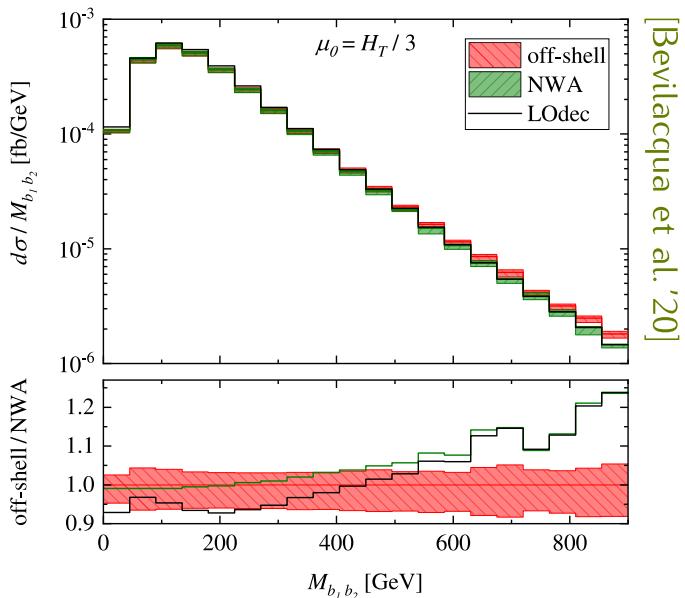
$t\bar{t}W^+(-)$ off-shell

- Theory status:
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 - ▶ NLO EW ✓ [Frixione et al. '15], [Dror et al. '15], [Frederix et al. '17, '18]
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 - ▶ NNLO QCD ✓ [Buonocore et al. '23]

$t\bar{t}W^+(-)$ off-shell

[Bevilacqua et al.'20, Denner et al.'20]

- NLO QCD corrections to $pp \rightarrow e^+\nu_e\mu^-\bar{\nu}_\mu e^+\nu_e b\bar{b}$ and $pp \rightarrow e^-\bar{\nu}_e\mu^+\nu_\mu e^-\bar{\nu}_e b\bar{b}$:
 - Off-shell effects some observables appreciable



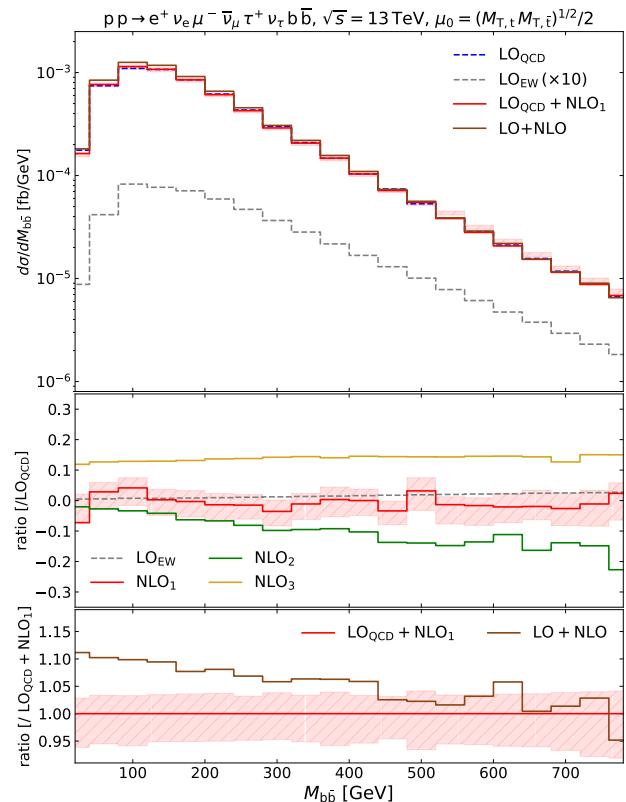
- But the size of the effect very much depends on what one compares to

$t\bar{t}W^+(-)$ off-shell

[Denner et al.'21]

- NLO QCD and EW corrections to $pp \rightarrow e^+ \nu_e \tau^+ \nu_\tau \mu^- \bar{\nu}_\mu b\bar{b}$:

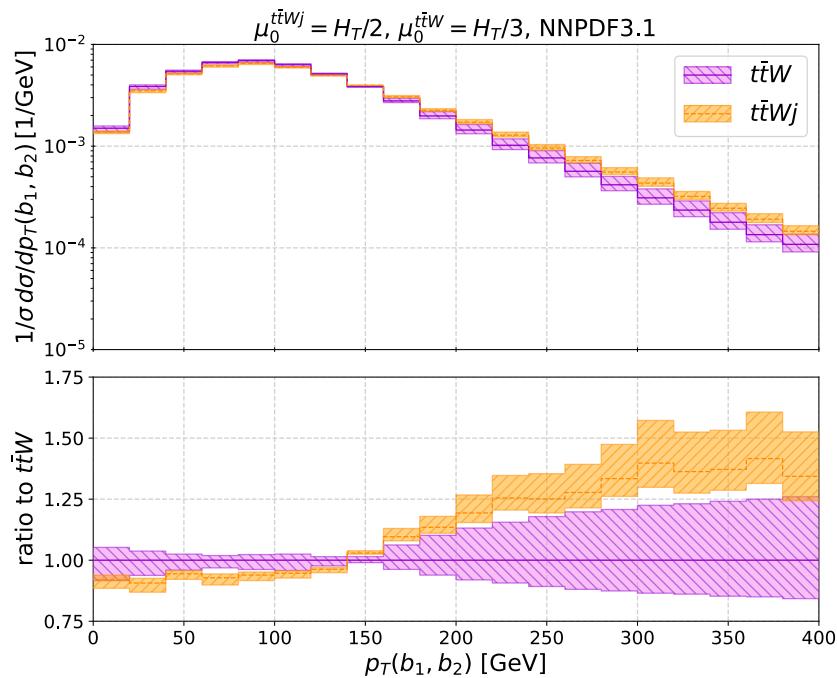
	$\mu_0^{(c)}$	
perturbative order	σ (fb)	ratio
LO _{QCD} ($\alpha_s^2 \alpha^6$)	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1
LO _{EW} (α^8)	$0.002164(1)^{+3.7\%}_{-3.6\%}$	0.010
NLO ₁ ($\alpha_s^3 \alpha^6$)	0.0147(6)	0.066
NLO ₂ ($\alpha_s^2 \alpha^7$)	-0.0122(3)	-0.055
NLO ₃ ($\alpha_s \alpha^8$)	0.0293(1)	0.131
LO _{QCD} +NLO ₁	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066
LO _{QCD} +NLO ₂	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945
LO _{EW} +NLO ₃	$0.03142(4)^{+22.2\%}_{-16.8\%}$	0.141
LO+NLO	$0.2554(7)^{+4.0\%}_{-6.5\%}$	1.151



$t\bar{t}W^{+(-)}j$ off-shell

[Bi et al.'23]

- NLO QCD to $pp \rightarrow e^+ \nu_e \tau^+ \nu_\tau \mu^- \bar{\nu}_\mu b\bar{b} j$:
 - ▶ In the phase space with one additional jet:
- $N_l = 1|1|1, \quad N_b = 2, \quad N_j \geq 1$
 $|y_{l|b|j}| \leq 2.5, \quad p_{T,l|b|j} > 25 \text{ GeV},$
 $\Delta R_{\text{all objects}} > 0.4$
- ▶ Distributions receive corrections beyond the scale uncertainty band



$t\bar{t}W^{+(-)}$ parton shower matched & off-shell effects

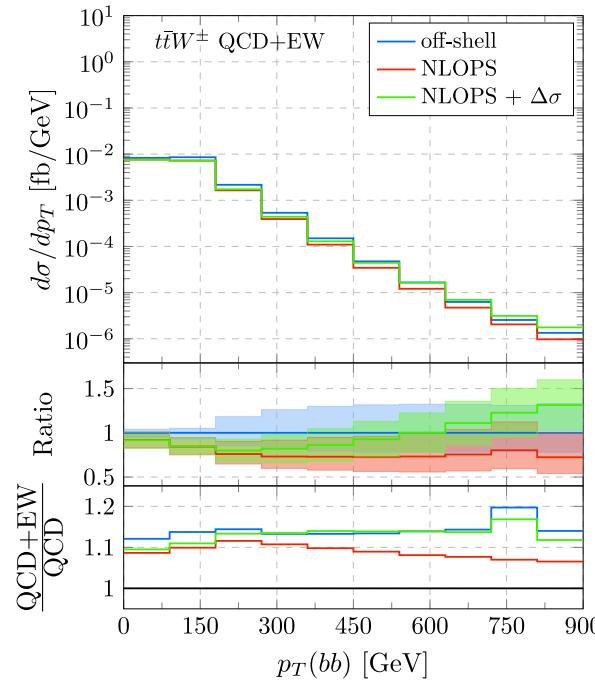
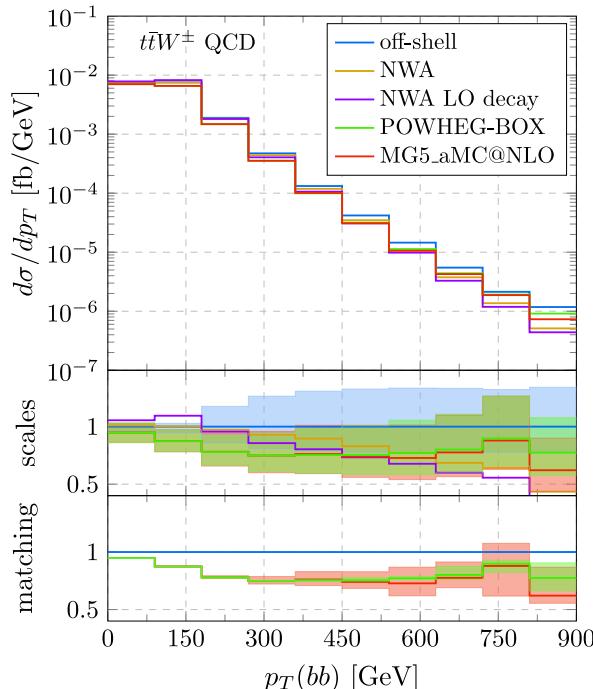
- Theory status:
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 - ▶ NNLO QCD ✓ [Buonocore et al. '23]

$t\bar{t}W^{+(-)}$ parton shower matched & off-shell effects

[Bevilacqua et al. '21]

- $pp \rightarrow t\bar{t}W$ at NLO PS with decays a la MadSpin combined with off-shell effects

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



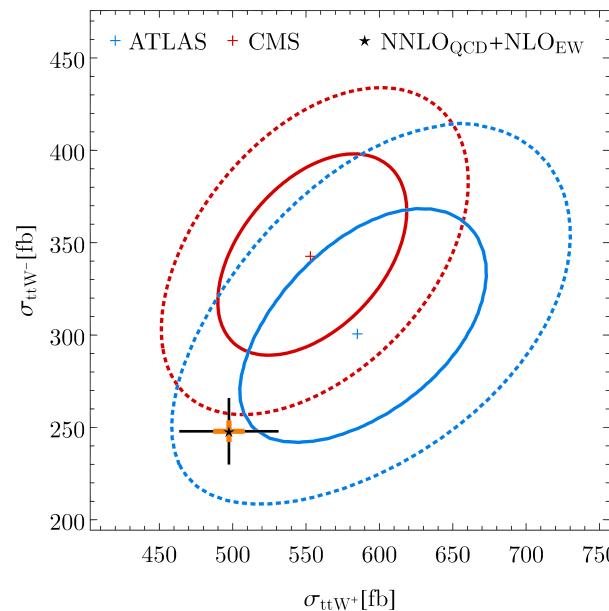
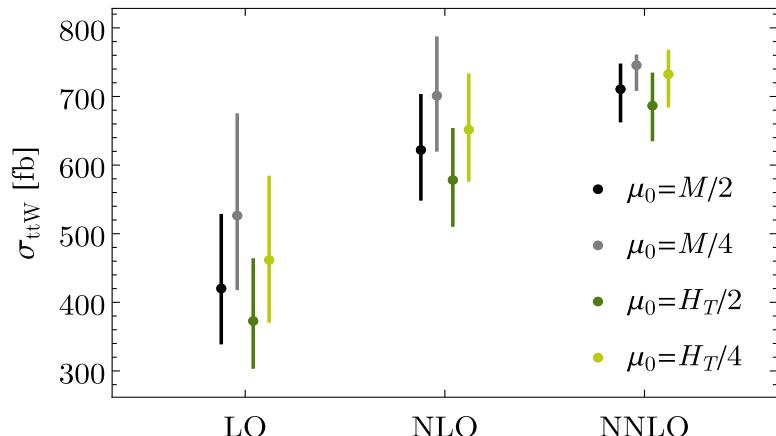
$t\bar{t}W^+(-)$ at NNLO QCD

- Theory status:
 - ▶ NLO QCD ✓ [Badger et al. '10], [Campbell et al. '12]
 - ▶ NLO EW ✓ [Frixione et al. '15], [Dror et al. '15], [Frederix et al. '17, '18]
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 - ▶ NNLO QCD ✓ [Buonocore et al. '23]

$t\bar{t}W^+(-)$ at NNLO QCD

[Buonocore et al.'23]

- NNLO QCD + NLO EW corrections now available:
 - ▶ Two loops calculated in two approximations: *soft-W approximation* and *massification*
 - ▶ Tension with ATLAS and CMS measurements alleviated but not resolved



Summary

- Provided perspective on $t\bar{t} + b$ jets and $t\bar{t}W$ production as backgrounds to $t\bar{t}H$ measurements
- $t\bar{t} + b$ jets:
 - ▶ Reminded of the modelling issues in event generators
 - ▶ Reviewed recent progress:
 - ▷ $t\bar{t}b\bar{b}$ in association with an extra jet
 - ▷ Off-shell effects in $t\bar{t}b\bar{b}$
 - ▷ Upcoming: variable flavour multi-jet merging
- $t\bar{t}W$:
 - ▶ Reviewed recent progress:
 - ▷ Off-shell calculations (NLO QCD & EW), also in association with an extra jet and combined with NLOPS calculations
 - ▷ NNLO QCD + NLO EW