Top quarks in POWHEG

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EPIPHANY

Top quarks in POWHEG

- Motivations:
  - Why top quark? Because it's a versatile probe of the SM.
    - It will teach us about the Higgs sector of the SM.
    - Further improvements expose great theoretical challenges.
  - Why top quark at LHC? Because "a few hundred million tops on tape" ...
    - ...imply theory will soon lag behind the experiment.
    - ...means it is major background in many other LHC analyses.
    - Precise simulation of top quark production and decay at LHC imperative!

POWHEG processes with tops, page 1

- top pair
  - `hvq`: [Frixione, Nason, Ridolfi '07]
  - `ttb_NLO_dec`: top decay in NWA + LO rwgt, [Campbell, Ellis, Nason, Re '14]
  - `bb4l`: 4FNS, off-shell dileptonic channel, [**TJ**, Lindert, Nason, Oleari, Pozzorini '16]
  - `ttJ_MiNNLO`: NNLO QCD, [Mazzitelli, Monni, Nason, Re, Wiesemann, Zanderighi '20, '21]
  - `bb4l-sl`: 4FNS, off-shell semileptonic channel, [**TJ**, Lindert, Pozzorini '23]
- top pair + jets
  - `ttbarj`: [Alioli, Moch, Uwer '11]
  - `ttbb`: 4FNS, [**TJ**, Lindert, Moretti, Pozzorini '18]

† unless otherwise stated: NLO QCD corrections; top decays à la Madspin [Frixione et al. '07]

POWHEG processes with tops, page 2

- single top
  - `ST_sch`, `ST_tch`: s- & t-channel, [Alioli, Nason, Oleari, Re '09]
  - `ST_wtch_DR`, `ST_wtch_DS`: tW, [Re '10]
  - `ST_tch_4f`: t-channel, 4FNS, [Frederix, Re, Torrielli '12]
  - `t-mg`: t-channel, off-shell leptonic channel, [**TJ**, Nason '15]
- $t\bar{t} + H$ (`ttH`): [Hartanto, Jäger, Reina, Wackeroth '15]
- $t\bar{t} + W$ (`Wtt_dec`): [Febres Cordero, Kraus, Reina '21]
- $t\bar{t} + Z$, $t\bar{t} + l\bar{l}$ (`ttZ, ttll`): [Ghezzi, Jäger, Lopez Portillo Chavez, Reina, Wackeroth '21]
- $t\bar{t} + t\bar{t}$ (`fourtops`): [**TJ**, Kraus '21]
- $\gamma/Z/Z'/W' \to t\bar{t}$ (`PBZp`): [Bonciani, **TJ**, Klasen, Lyonnet, Schienbein '15], [Altakach, **TJ**, Klasen, Lang, Schienbein '20]

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POWHEG processes with tops, today's highlights

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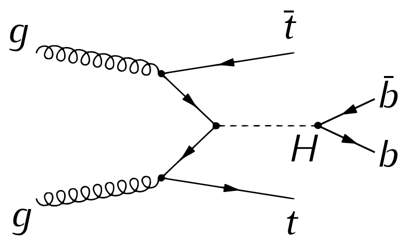
$t\bar{t} + b$ jets

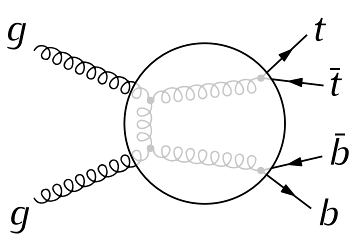
$t\bar{t} + b$ jets for dummies

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

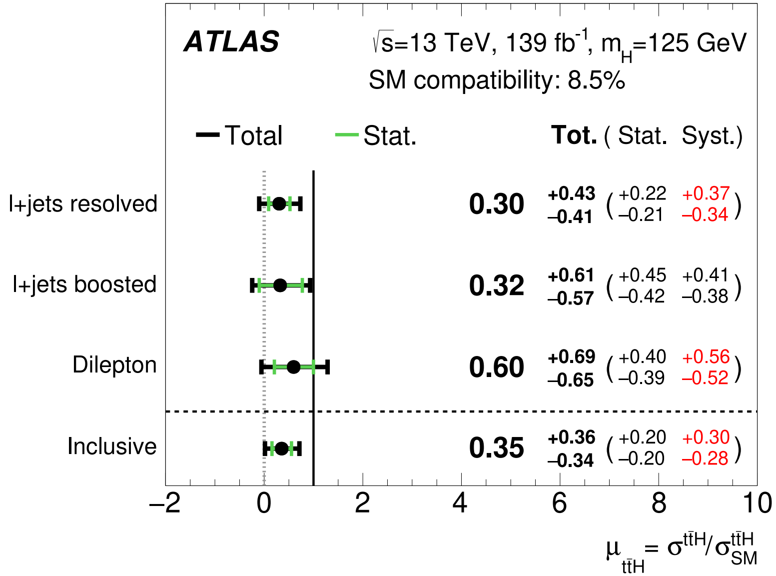
signal



background



ATLAS [JHEP 06 (2022) 097]



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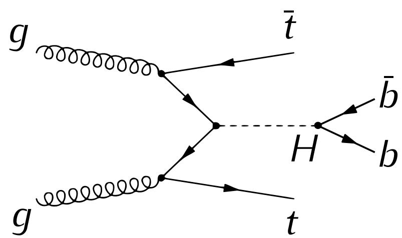

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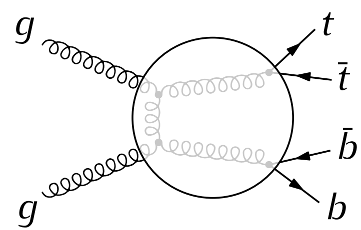

- How do we get $t\bar{t} + b$-jets?
  - From an inclusive $t\bar{t}$?
  - 5FNS multi-jet merged?
  - Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?

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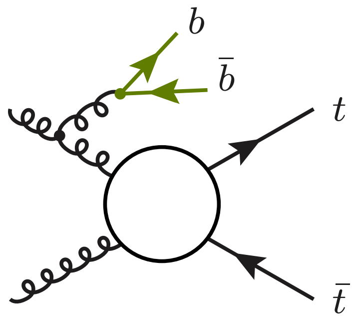
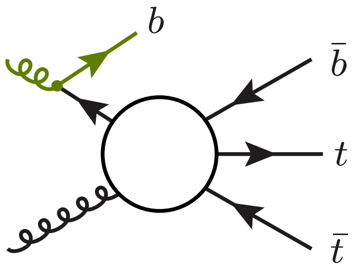


$gg \to t\bar{t}g$ + FS splittings



$\bar{b}g \to t\bar{t}\bar{b}$ + IS splittings

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

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- How do we get $t\bar{t} + b$ jets?
  - From an inclusive $t\bar{t}$? Not event LO accuracy!
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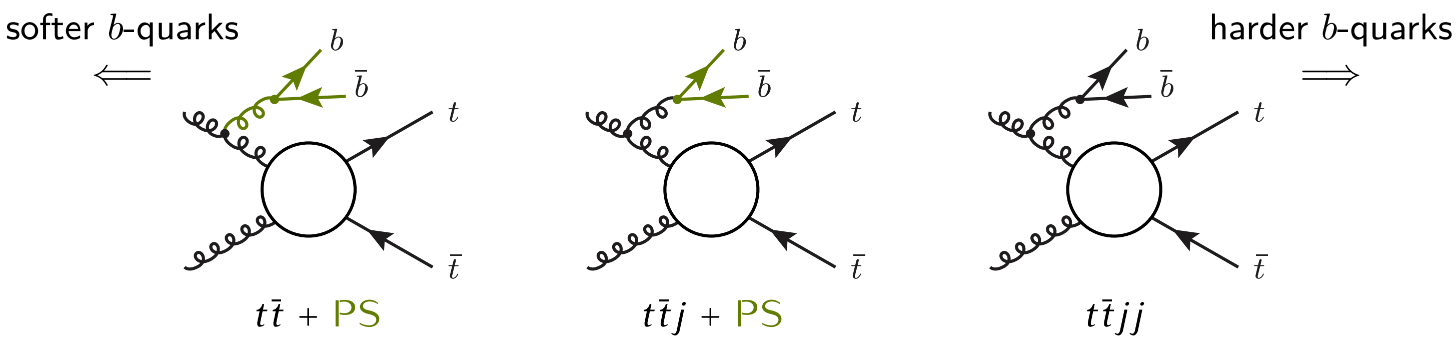

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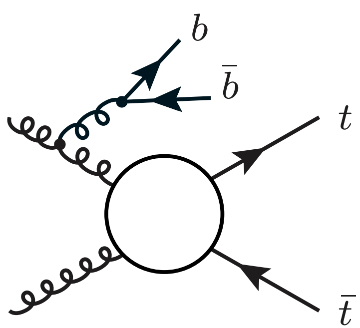
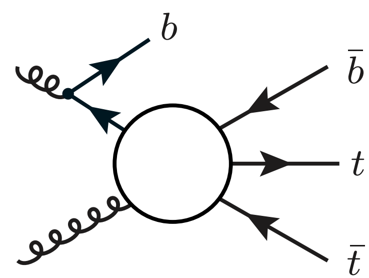
- How do we get $t\bar{t} + b$ jets?
  - From an inclusive $t\bar{t}$? Not event LO accuracy!
  - 5FNS multi-jet merged? $b\bar{b}$ pairs still mostly from PS! (see backup)
  - Explicit $t\bar{t}b\bar{b}$, alternatively matched to PS?

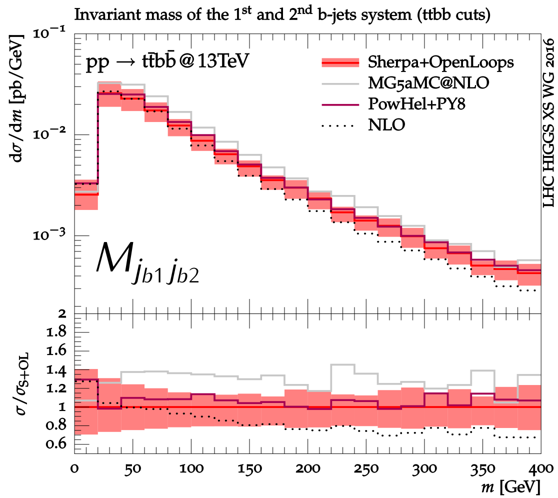


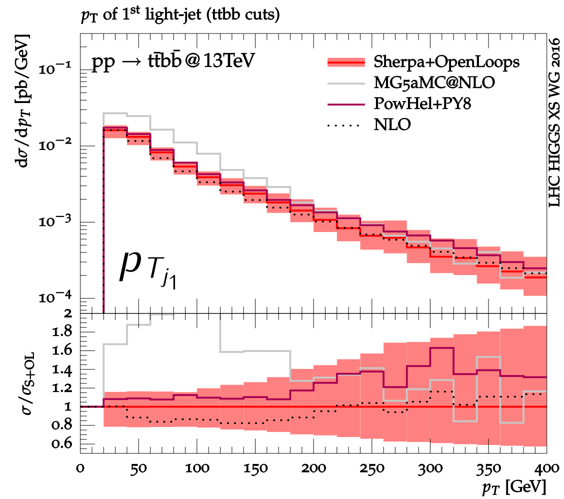


- $\sigma_{t\bar{t}b\bar{b}} \propto \alpha_S^4(\mu_R) \Rightarrow$ scale uncertainity: $\sim 80\%$ @ LO, $20-30\%$ @ NLO

$t\bar{t} + b$ 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`

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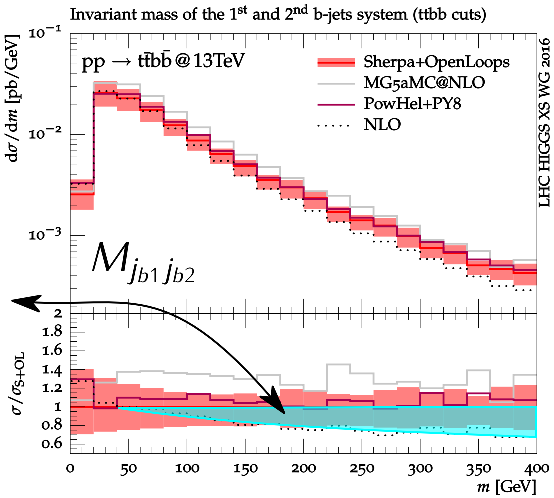
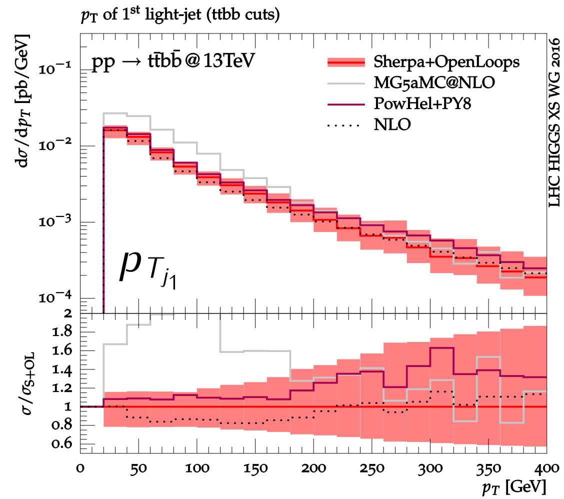


"double-splitting"



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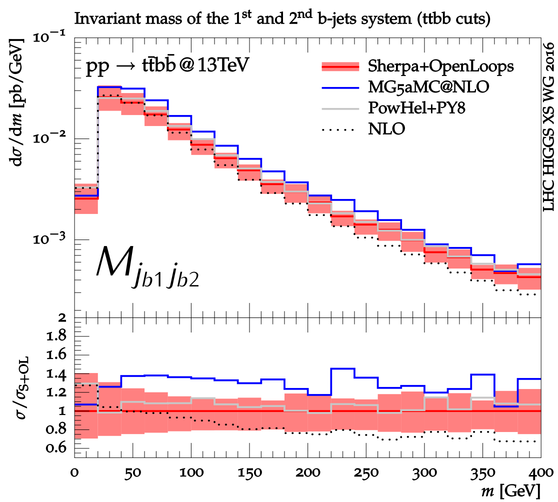

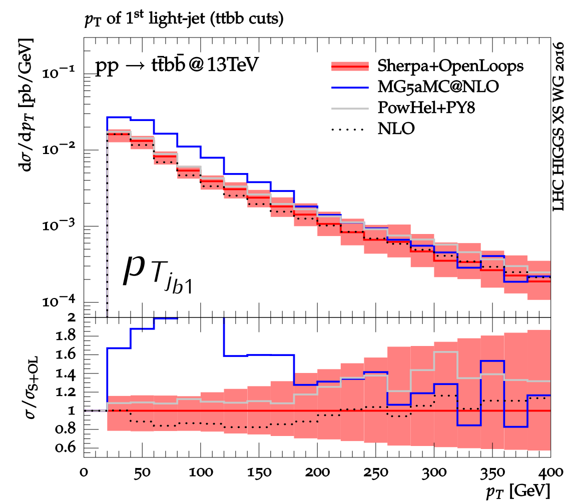

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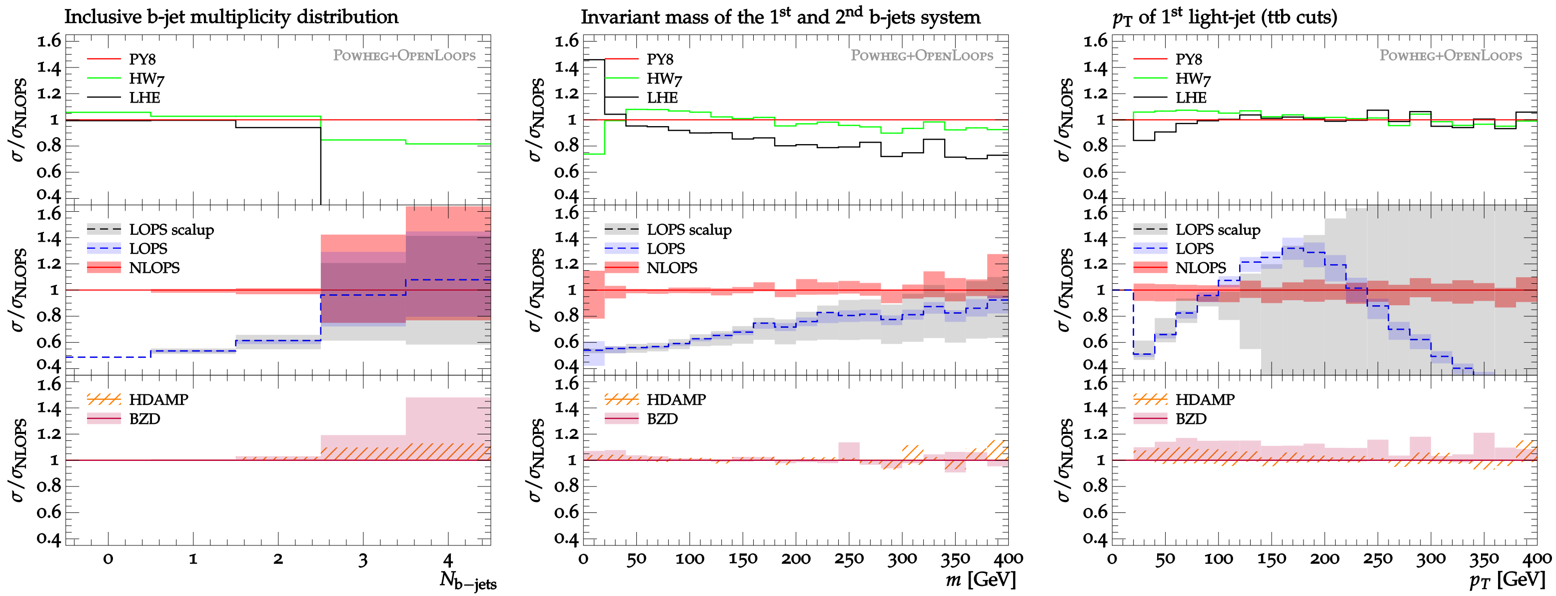
$t\bar{t} + b$ jets matched to PS

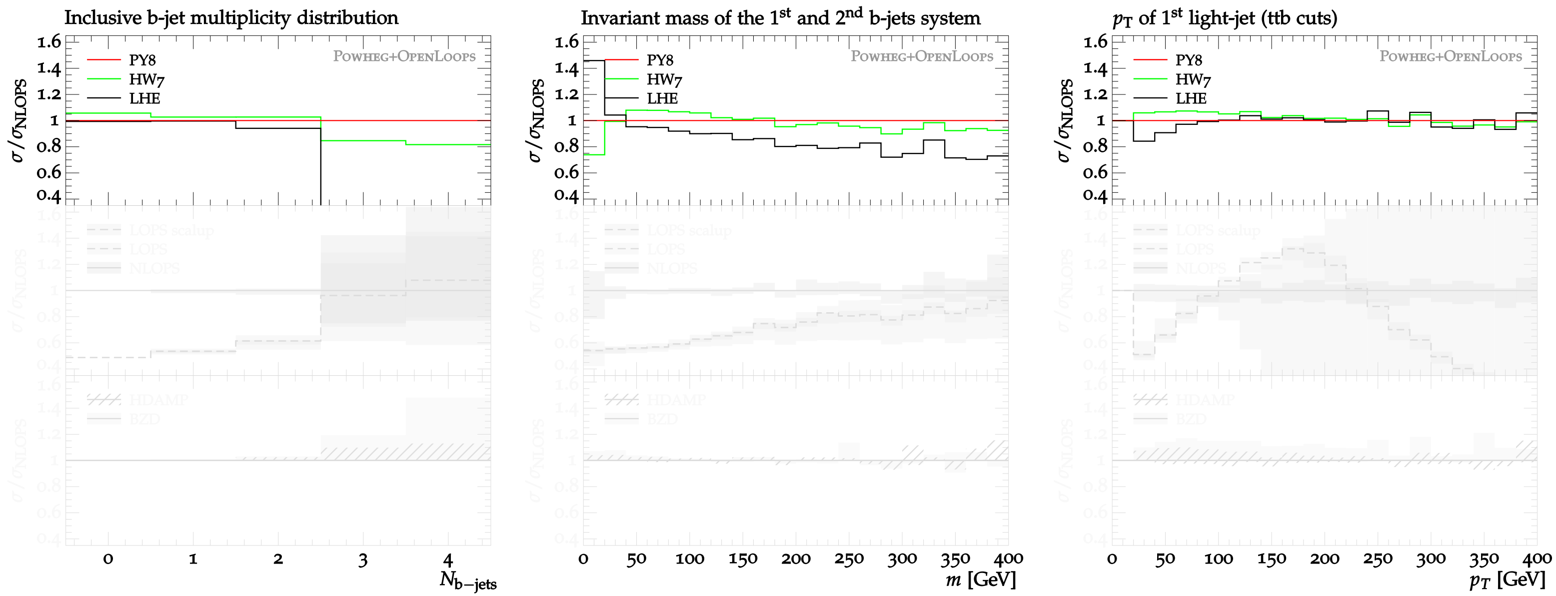
[**TJ** et al.'18]



- NLO+PS matched with `Pythia 8.2`
- NLO+PS matched with `Herwig 7.1` (angular ordered)
- LHE level (NLO + Sudakov suppressed harded emission)
- LO+PS (`Pythia 8.2`), `scalup` $\in \{H_T/4, \boldsymbol{H_T/2}, H_T\}$
- LO+PS (`Pythia8.2`), `weightGluonToQuark` $\in \{2, \mathbf{4}, 6, 8\}$, `renormMultFac` $\in \{0.1, \mathbf{1}, 10\}$
- NLO+PS (`Pythia8.2`), `weightGluonToQuark` $\in \{2, \mathbf{4}, 6, 8\}$, `renormMultFac` $\in \{0.1, \mathbf{1}, 10\}$
- NLO+PS (`Pythia8.2`), $h_{\text{damp}} \in \{H_T/4, \boldsymbol{H_T/2}, H_T\}$
- NLO+PS (`Pythia8.2`), $h_{\text{bzd}} \in \{\mathbf{2}, 5, 10\}$

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

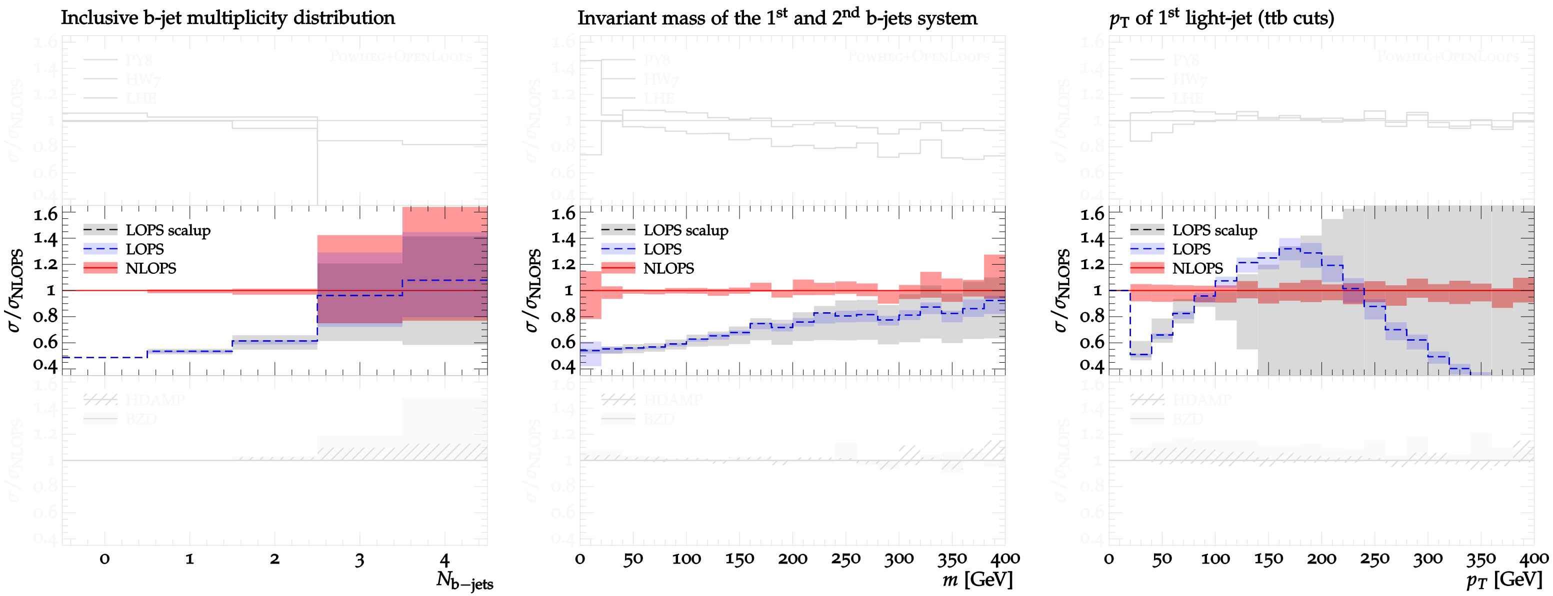
[TJ et al.'18]



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

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

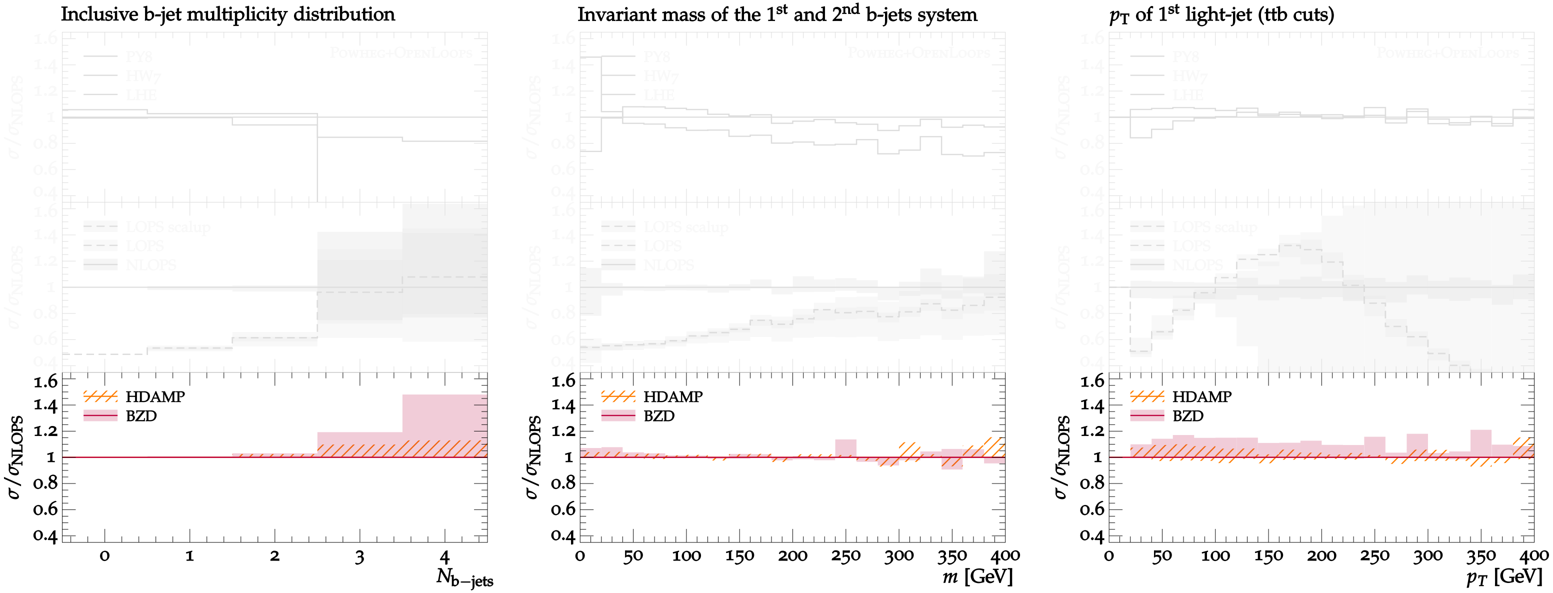
[TJ et al.'18]



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

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

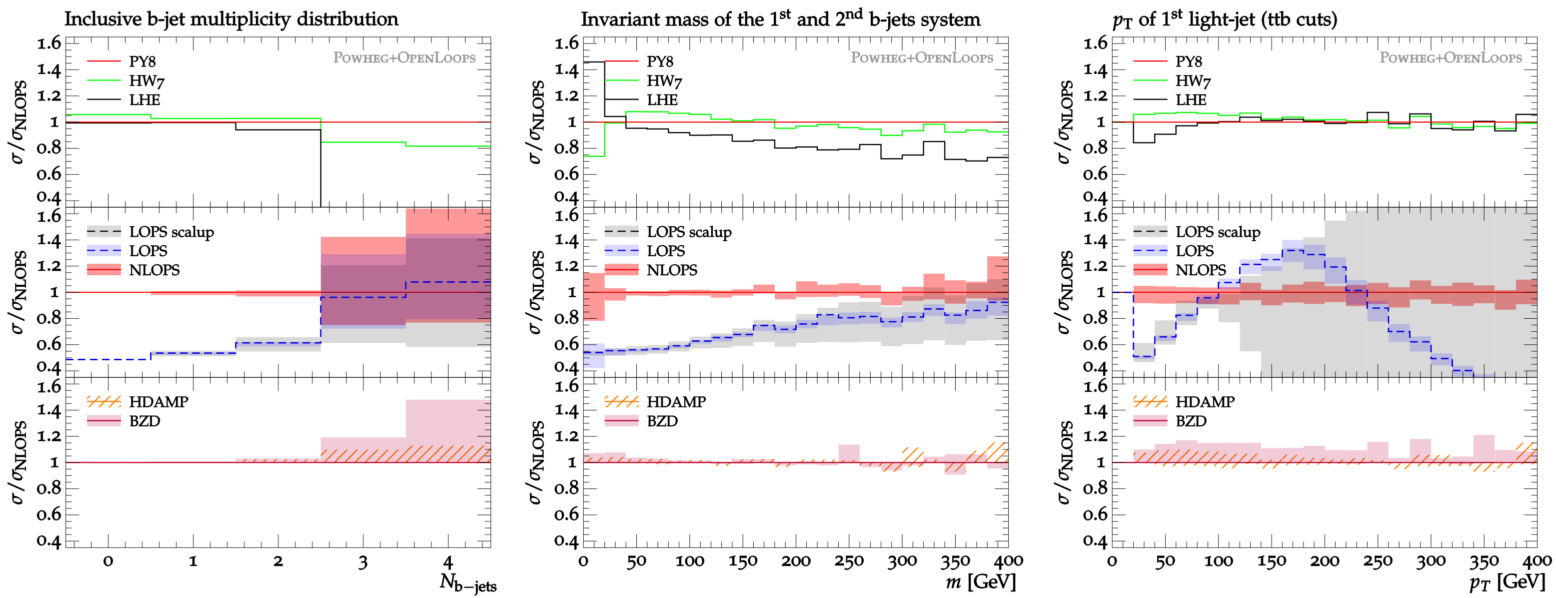
[TJ et al.'18]



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

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

[TJ et al.'18]

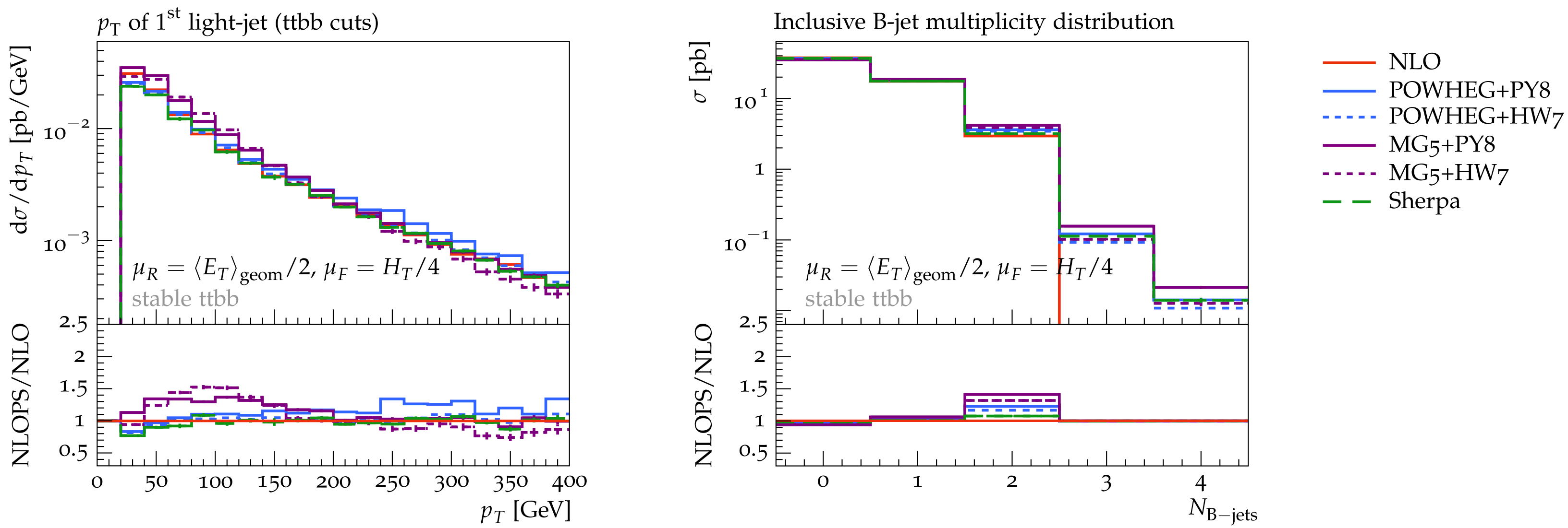


- We failed to find a way of reaching MG5_MC@NLO+PY8 prediction in POWHEG
  - Hints at conceptual differences in how the shower starting scales are treated

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

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

- Reduction of the renormalization scale $\mu_R \to \mu_R/2$ in NLOPS $t\bar{t}b\bar{b}$ codes inspired by a calculation with an extra light jet [Buccioni et al. '19] :

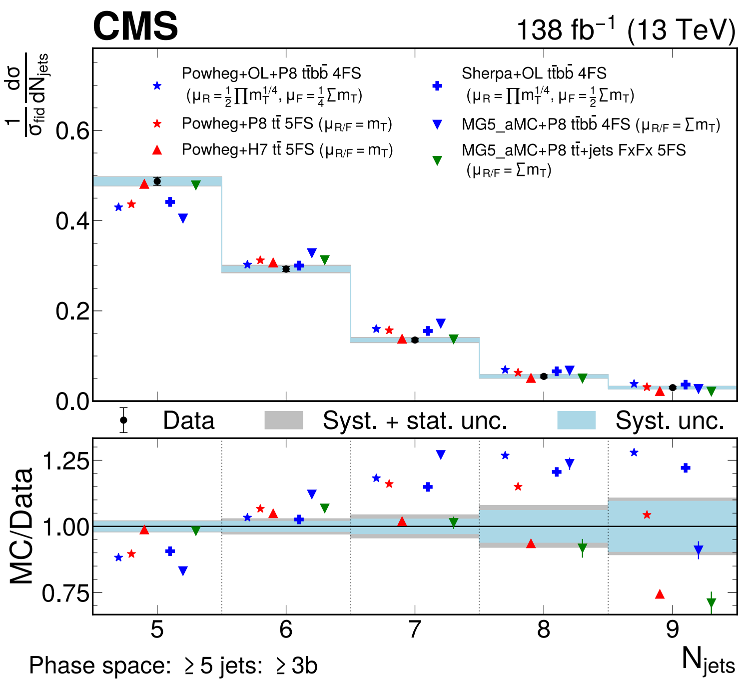


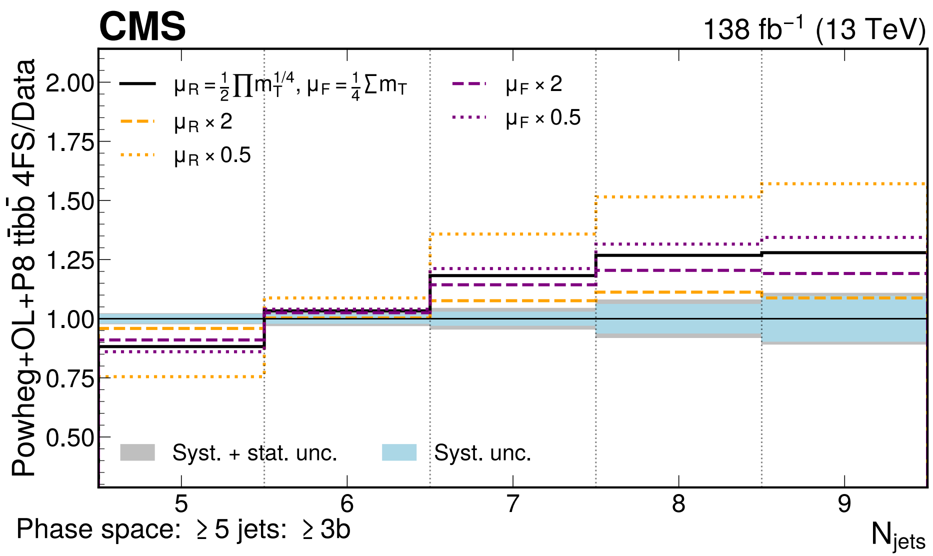
  - Reduces the spread in the predictions for the light jet spectrum significantly, but not in the b jet multiplicity

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

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

- New measurement:





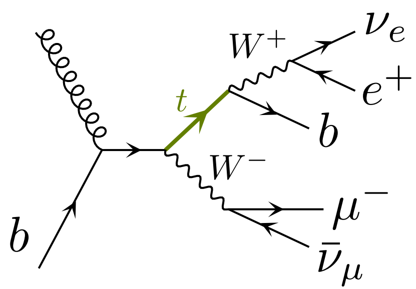
  - Can it provide further input for theory?

$t\bar{t}$ off-shell

Off-shell tops at LHC

- Consider production of a top quark in association with a W boson

tW associated production @ LO



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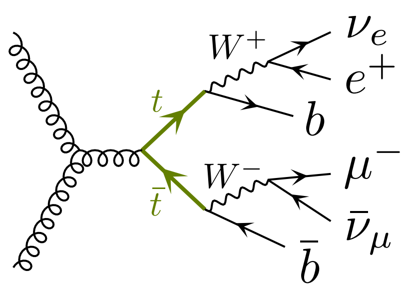

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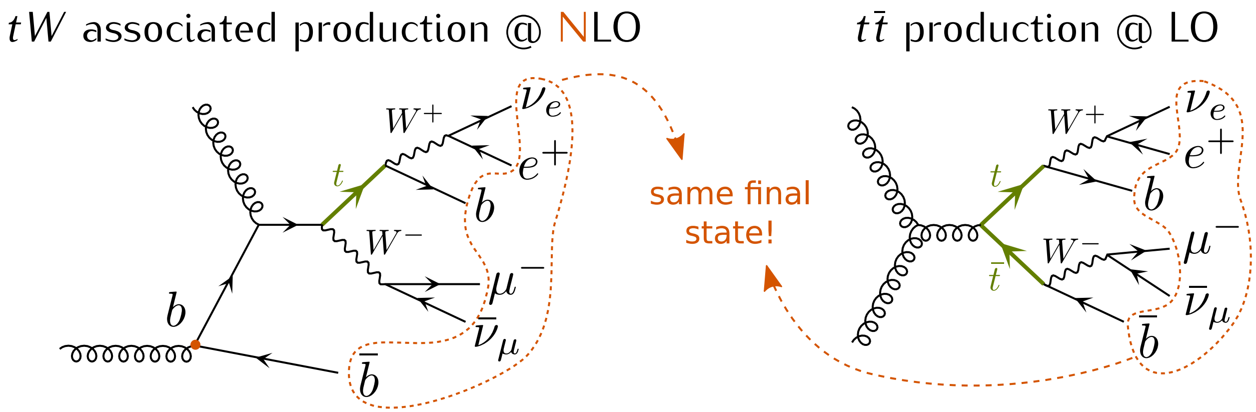

Off-shell tops at LHC

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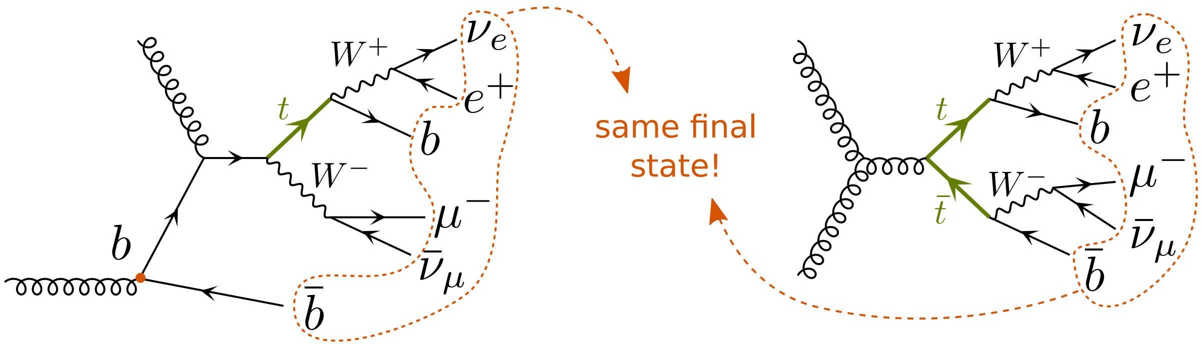
tW associated production @ NLO $\qquad\qquad$ $t\bar{t}$ production @ LO



- Modelling the tW process at NLO on its own:
  - ▹ Perturbative convergence of tW "spoiled" ($\sigma_{tW} \sim 0.1\sigma_{t\bar{t}}$)
  - ▹ $t\bar{t}$ contribution is often removed using ad-hoc schemes

$$\mathcal{M} = \mathcal{M}^{tW} + \mathcal{M}^{t\bar{t}} \qquad \mathcal{R}^{\mathrm{DR}} = \frac{|\mathcal{M}^{tW}|^2}{2s} \qquad \mathcal{R}^{\mathrm{DS}} = \frac{|\mathcal{M}^{tW}+\mathcal{M}^{t\bar{t}}|^2 - \mathcal{C}}{2s}$$

Our calculation: $pp \to l^+ \nu_l \ell^- \bar{\nu}_\ell b\bar{b}$ @ NLO+PS

- We published a MC event generator `POWHEG BOX RES/bb4l`
  - Implementing process $pp \to l^+ \nu_l \ell^- \bar{\nu}_\ell b\bar{b}$ up to $\mathcal{O}(\alpha_S^2 \alpha^4 \times \alpha_S)$, l, ℓ different
  - ME in 4FNS ($m_b > 0$) but 5FNS PDFs also possible (CGN '98 matching)
  - Matching to PS using the resonance-aware version of the POWHEG method
- Lessons learned:
  - Virtualities of resonances must be preserved
  - ME description of the hardest emission in decay is important
  - Quantum interference of tt and tW observable at the LHC!
  - NEW: Uncertainties due to choice of resonance history projectors small
  - NEW: Dilepton topologies sufficient to describe semileptonic case

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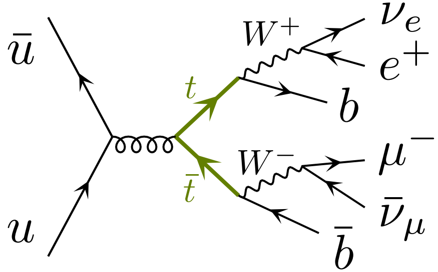
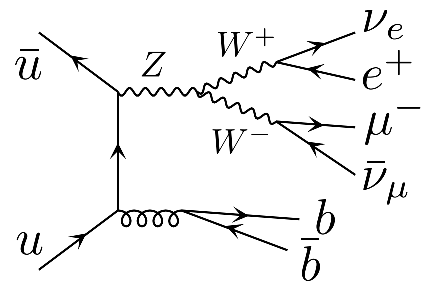
Resonance aware NLO+PS

[TJ, Nason '15]

- Preserving resonance virtualities involves:
  - Reformulating the $n \to n+1$ mapping: global recoil $\to$ resonance contained recoil
  - Splitting up the phase space





$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$

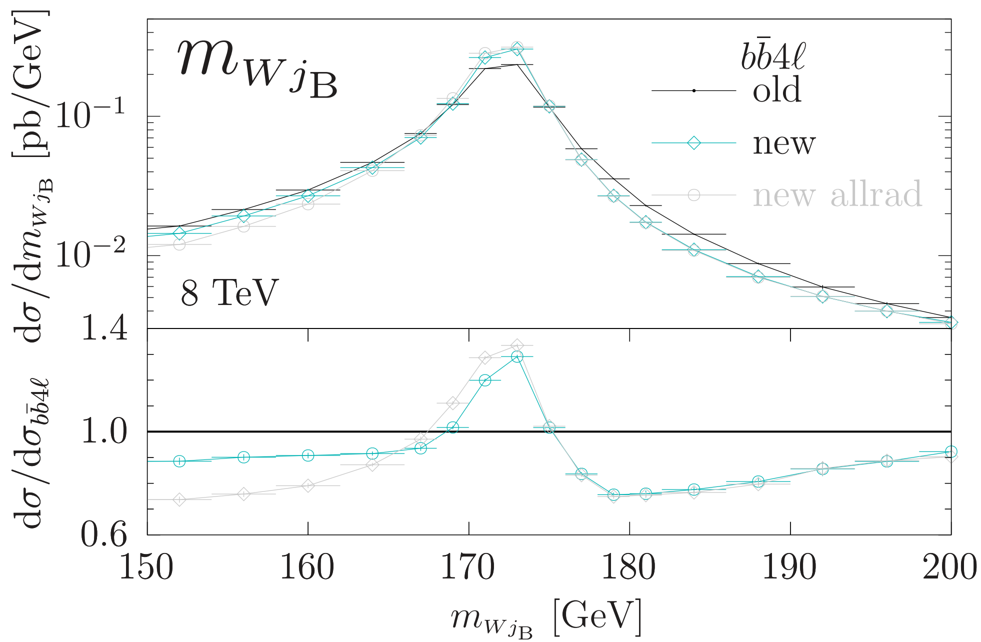
$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

  - Generalizing the subtraction scheme

Resonance aware NLO+PS

[TJ, Nason '15], [TJ, Lindert, Nason, Oleari, Pozzorini '16]

- Three NLO+PS "top mass" predictions, same amplitudes used differently
  - old: resonance virtualities not preserved
  - new: resonance virtualities preserved, only one emission kept
  - new allrad: resonance virtualities preserved, all emission kept

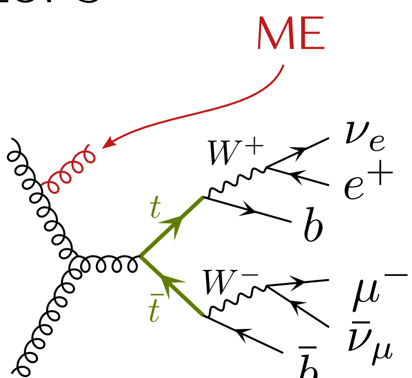


Resonance aware NLO+PS

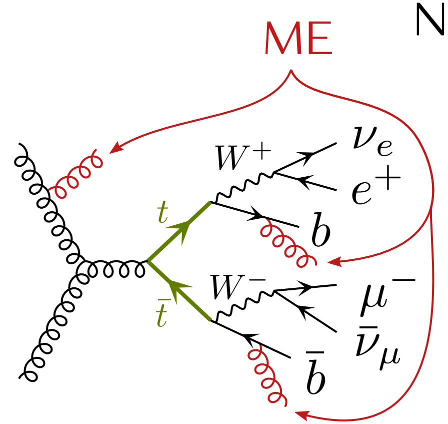
[TJ, Nason ’15]

- Matrix Element description of hardest emission in decay based on:
  - Factorization of production and decay processes in NWA
  - Phase space separation
  - Extended Les Houches interface

Traditional NLOPS



Multiple-radiation-improved NLOPS (`allrad`)



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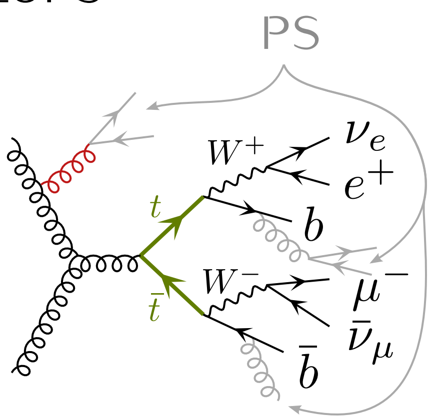
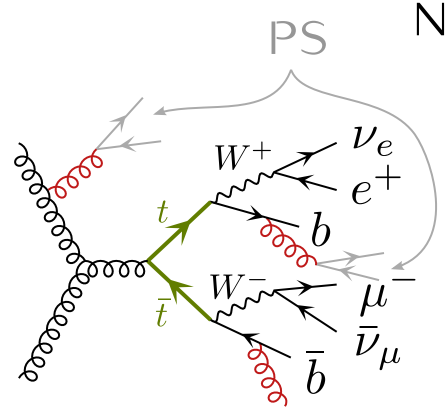


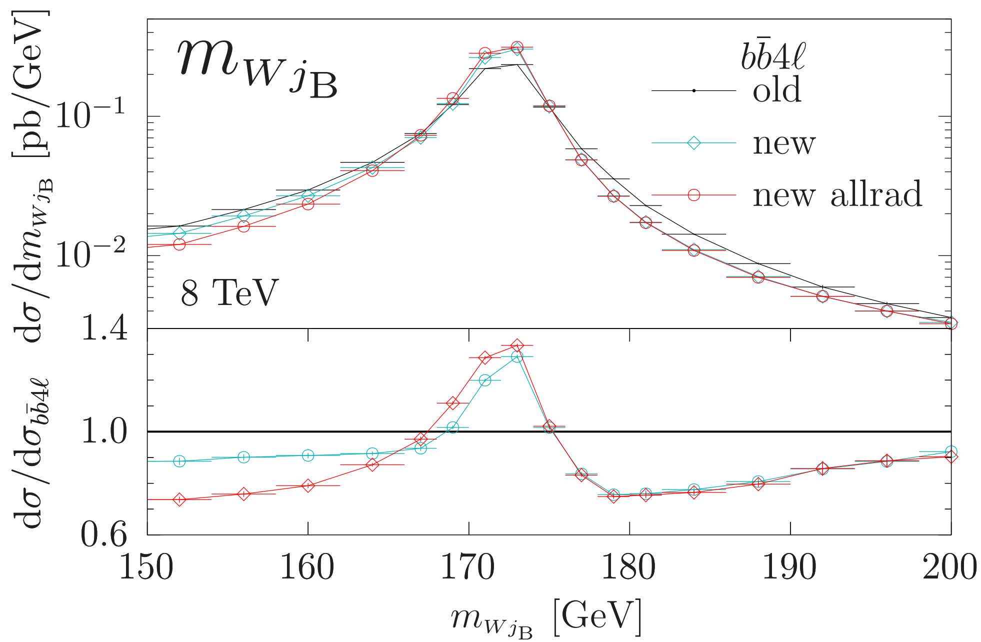
Multiple-radiation-improved NLOPS (`allrad`)



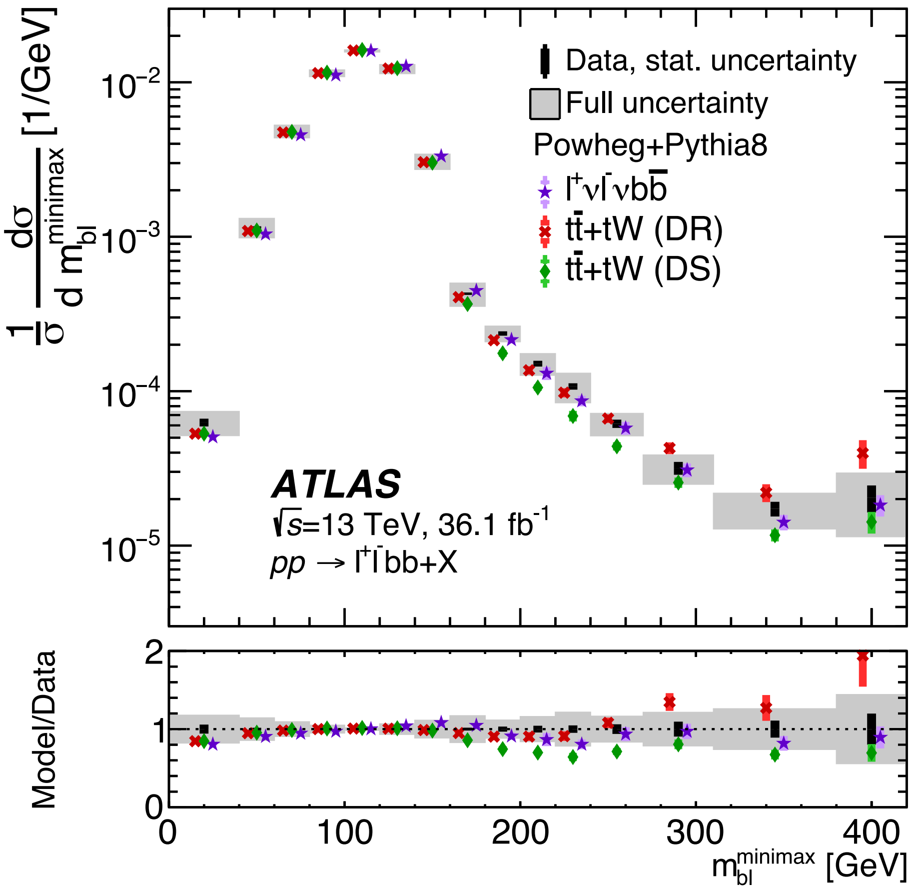
Resonance aware NLO+PS

[TJ, Nason '15], [TJ, Lindert, Nason, Oleari, Pozzorini '16]

- Three NLO+PS "top mass" predictions, same amplitudes used differently
  - old: resonance virtualities not preserved
  - new: resonance virtualities preserved, only one emission kept
  - new allrad: resonance virtualities preserved, all emission kept



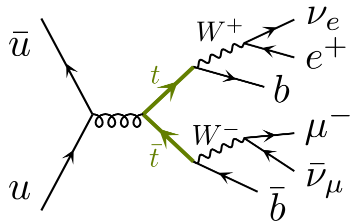
Quantum interference of tt and tW

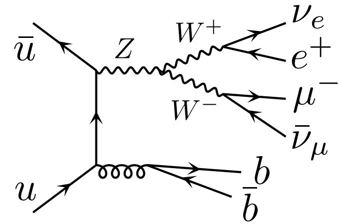


- [**PRL** 121, 152002]: Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector
- Calculation of $\ell^+ \nu_\ell l^- \bar{\nu}_l b\bar{b}$ which naturally includes both describes data better than any other combination of $t\bar{t}$ and tW

Improved resonance history projectors

[TJ, Lindert, Pozzorini '23]

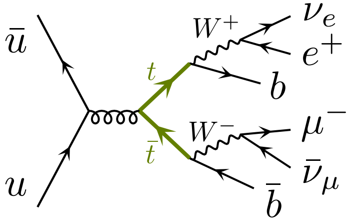


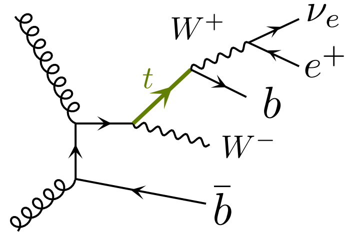


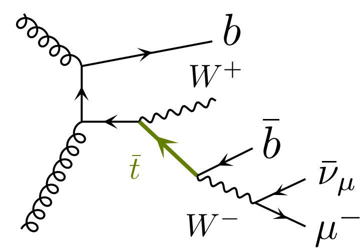
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$







$$P_1 = B_{t\bar{t}}$$

$$P_2 = B_{tW^+}$$

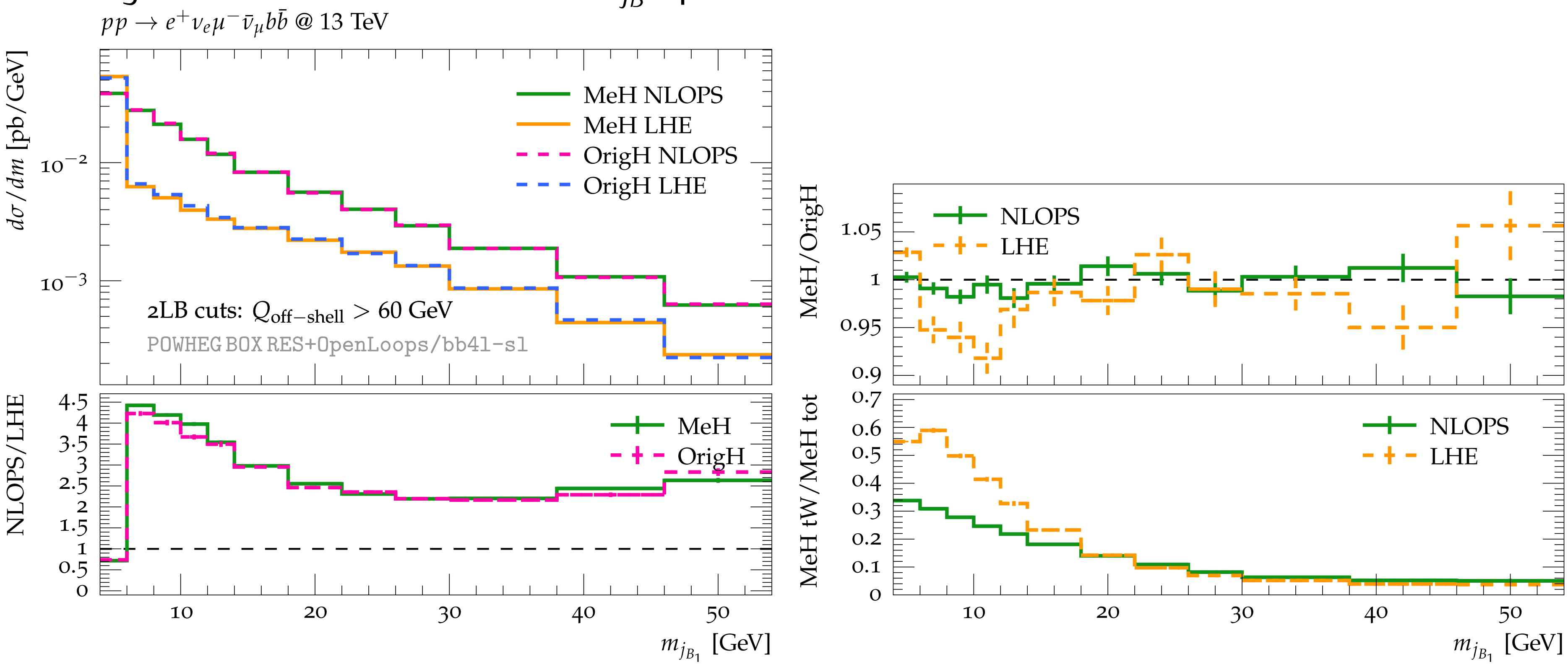
$$P_3 = B_{\bar{t}W^-}$$

$$d\sigma = \frac{P_1}{P_1+P_2+P_3} d\sigma + \frac{P_2}{P_1+P_2+P_3} d\sigma + \frac{P_3}{P_1+P_2+P_3} d\sigma$$

Improved resonance history projectors

[TJ, Lindert, Pozzorini '23]

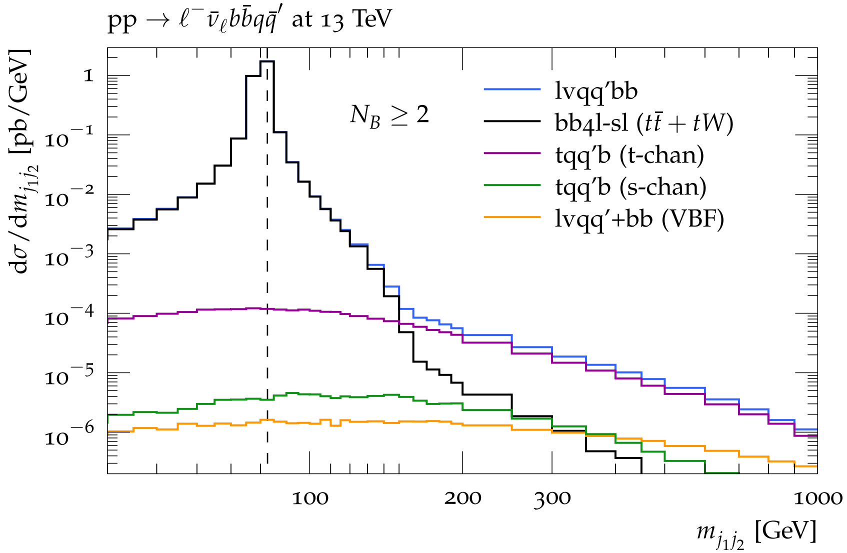
- Different resonance history projector prescriptions agree extremely well, the worst agreement we found was in m_{j_B} spectrum:

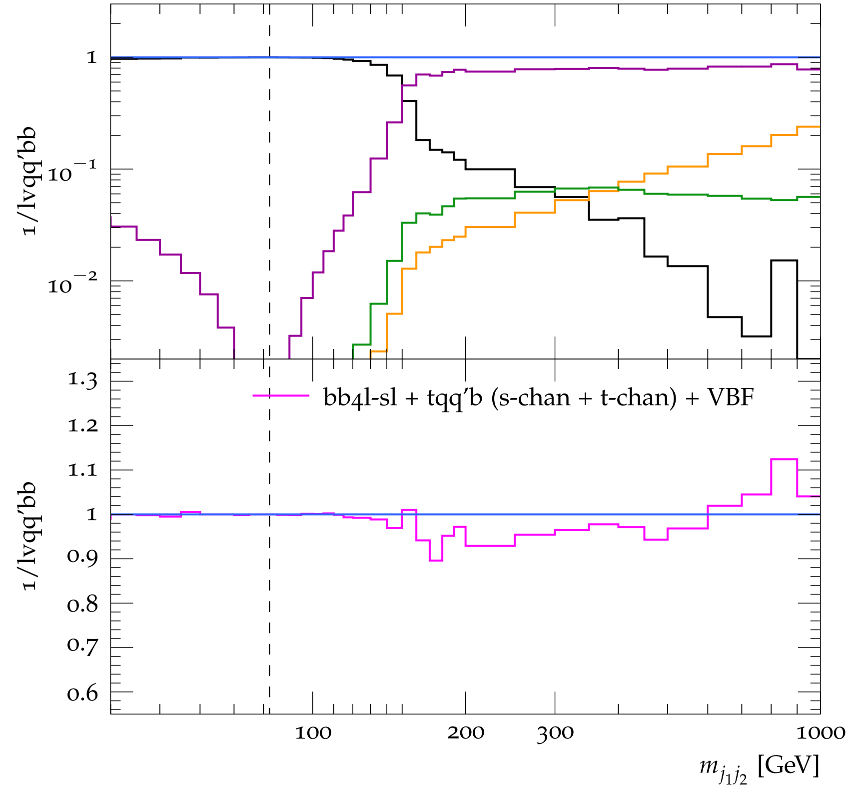


Semileptonic channel: bb4l-sl approximation

[TJ, Lindert, Pozzorini '23]

- ME of semileptonic decay channel much more difficult to evaluate, can we simplify?
  - Yes, by considering only dileptonic topologies:





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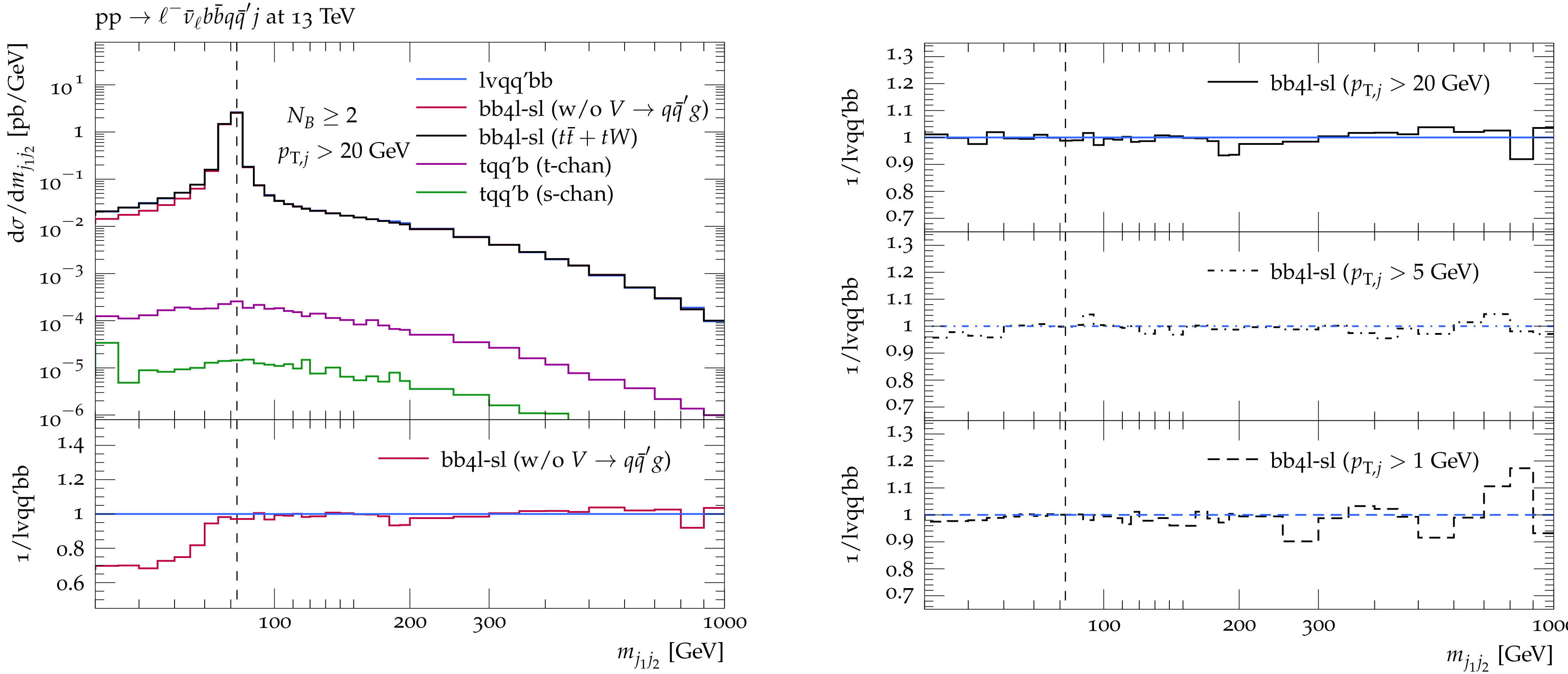
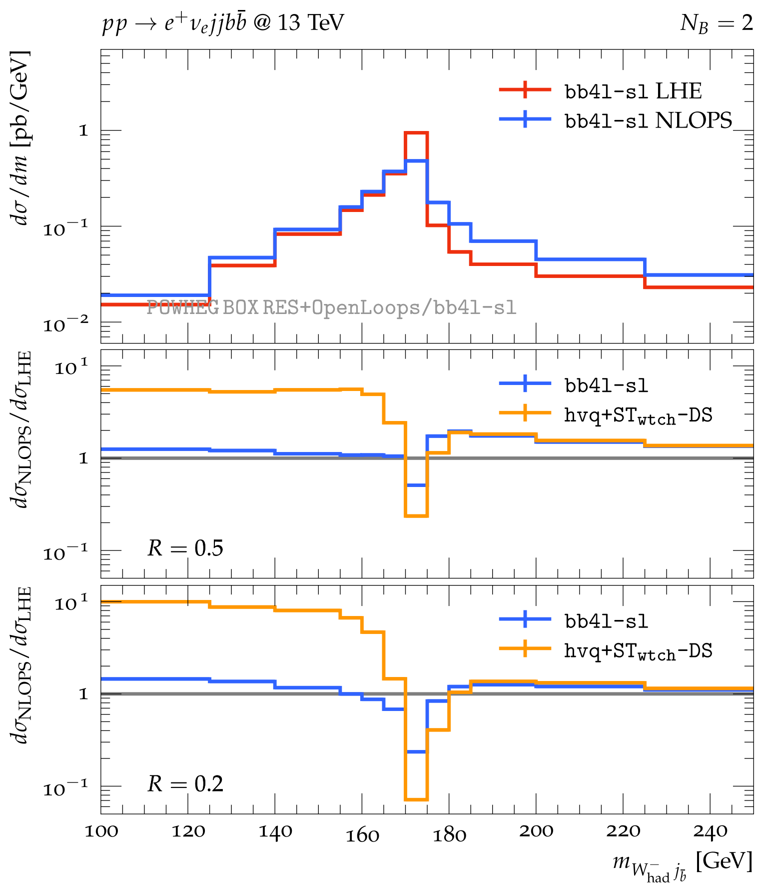


Semileptonic channel: `hvq` vs `bb4l-sl`

[TJ, Lindert, Pozzorini '23]

- top mass spectrum, approximate– vs. full–off-shell:
  - `bb4l-sl`: $t\bar{t} + tW$, full–off-shell
  - `hvq`: $t\bar{t}$, approx.–off-shell
  - $\mathtt{ST}_{\mathtt{wtch}}$-DS(DR): tW, approx.–off-shell +`Pythia8.2`
  - huge impact of the first emission in the decay; large shower uncertainties?
  - correction above peak due to ISR
  - impressive level of agreement, also thanks to MEC



Semileptonic channel: hvq vs bb4l-sl

[TJ, Lindert, Pozzorini '23]

- top mass spectrum, approximate– vs. full–off-shell:
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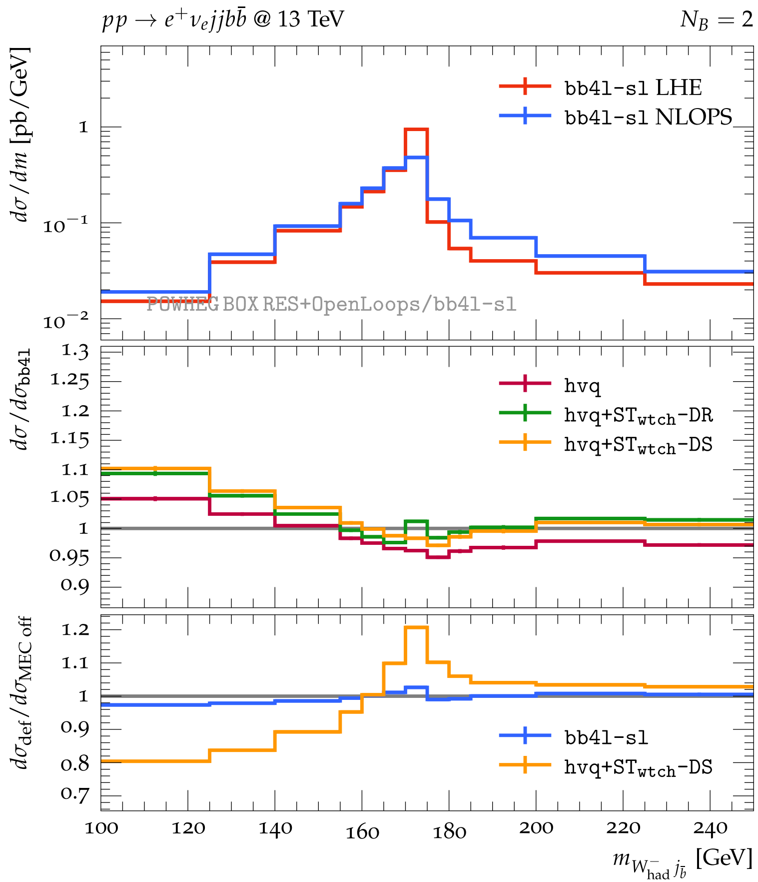
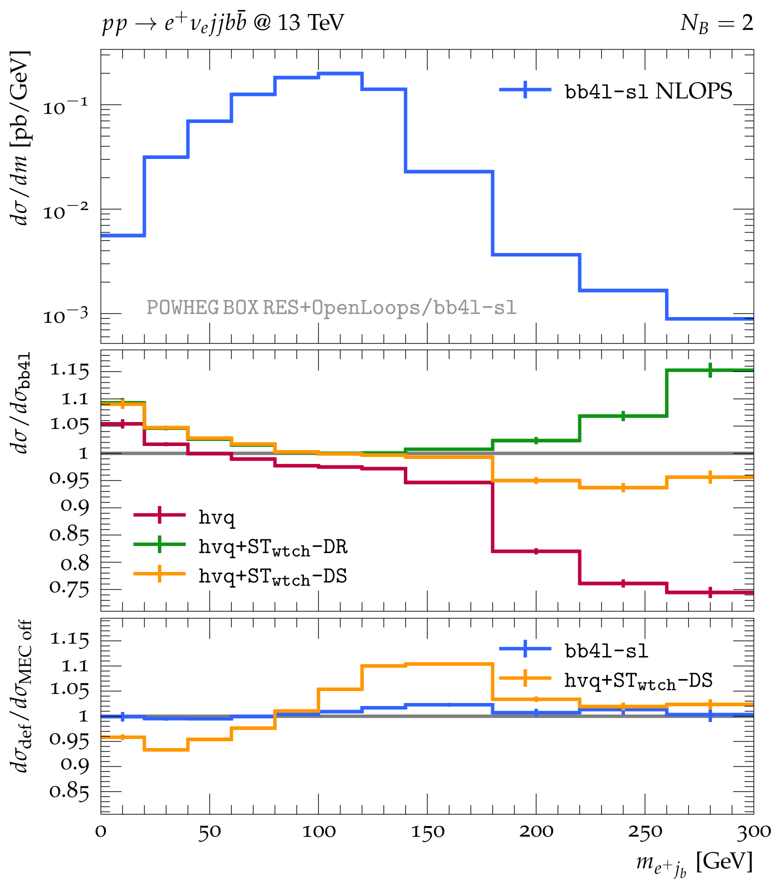


Semileptonic channel: hvq vs bb4l-sl

[TJ, Lindert, Pozzorini '23]

- lepton–b-jet mass, approximate– vs. full–off-shell:
  - bb4l-sl: $t\bar{t} + tW$, full–off-shell
  - hvq: $t\bar{t}$, approx.–off-shell
  - $\mathrm{ST_{wtch}}$-DS(DR): tW, approx.–off-shell

    +Pythia8.2
  - more stable with respect to shower corrections
  - tW and $t\bar{t} - tW$ interference important



Summary

Summary

- POWHEG is a great resource for top quark predictions matched to parton showers:
  - tops produced in pairs
    - alone
    - in association with light or heavy jets, with vector bosons, with another top pair
  - or produced singly
  - reaching up to NNLO QCD precision
  - most advanced decay modelling
  - including some BSM production channels
- Use cases:
  - $t\bar{t} + b$ jets
  - $t\bar{t}$ in the semileptonic channel off-shell

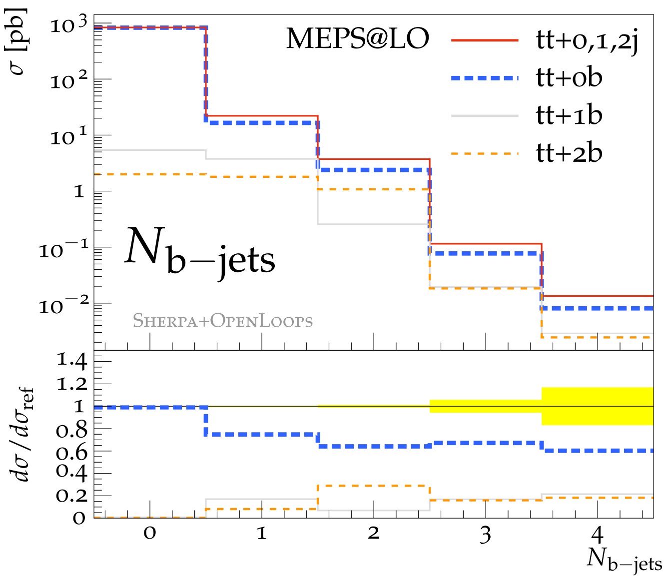
Thank you!

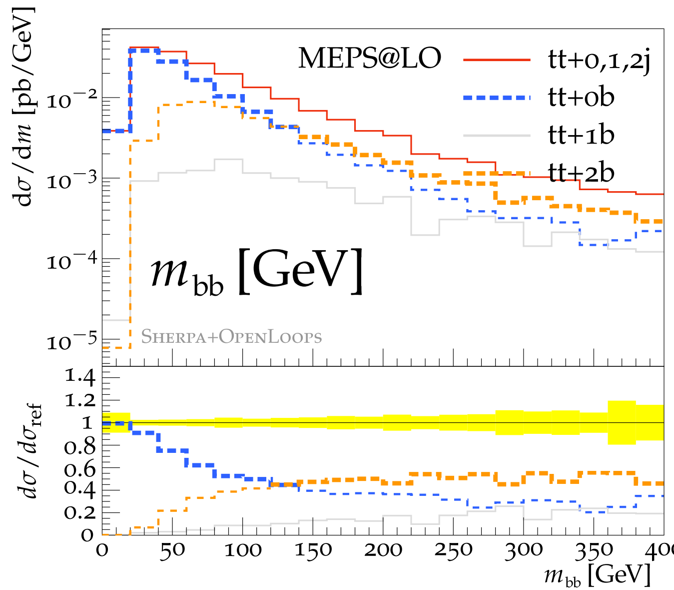
Backup

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

[Höche et al. '14, '19]

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

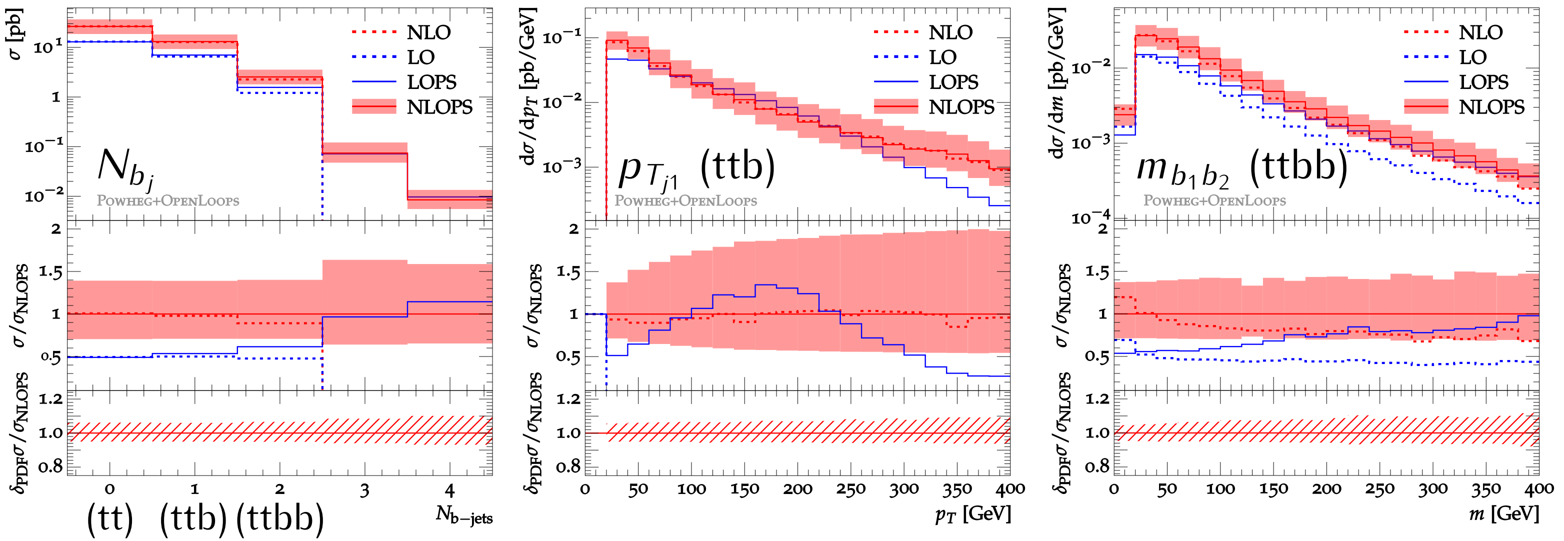




[TJ et al. '18]

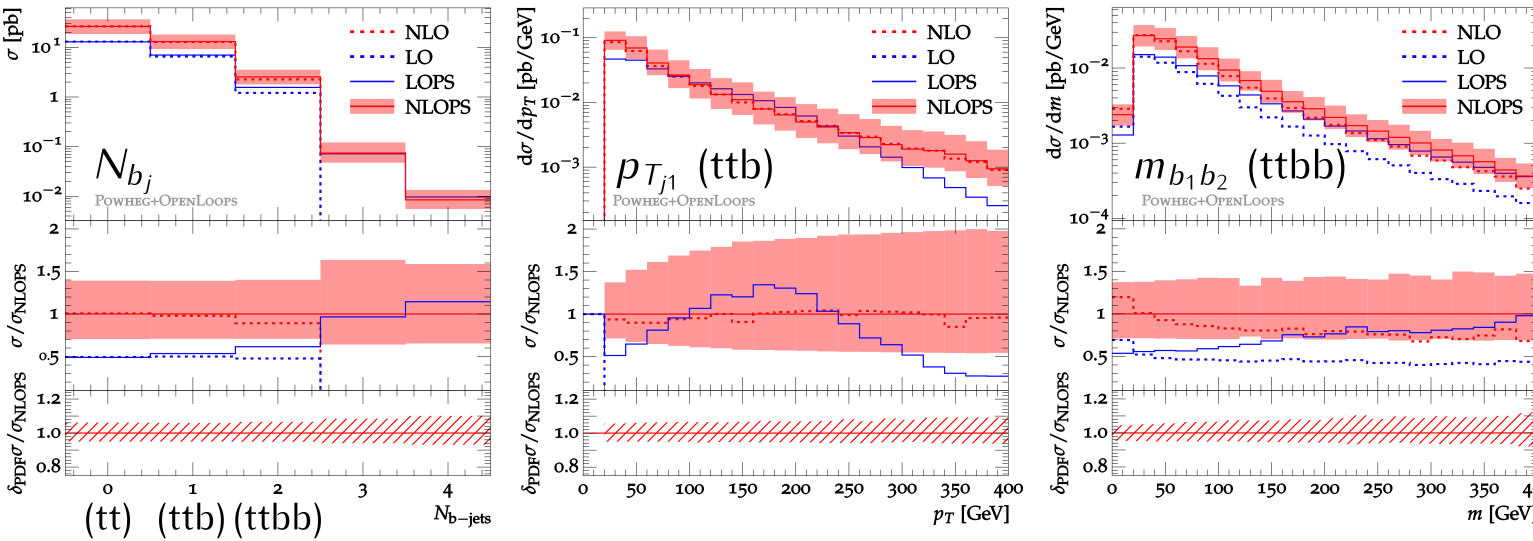
  - But do not necessarily end up describing FS b's using the matrix element

Perturbative uncertainties



- fixed order NLO
- fixed order LO
- LO+PS matched with `Pythia 8.2`
- NLO+PS matched with `Pythia 8.2`, 7 point scale variations
- NLO+PS matched with `Pythia 8.2`, PDF variations

Perturbative uncertainties

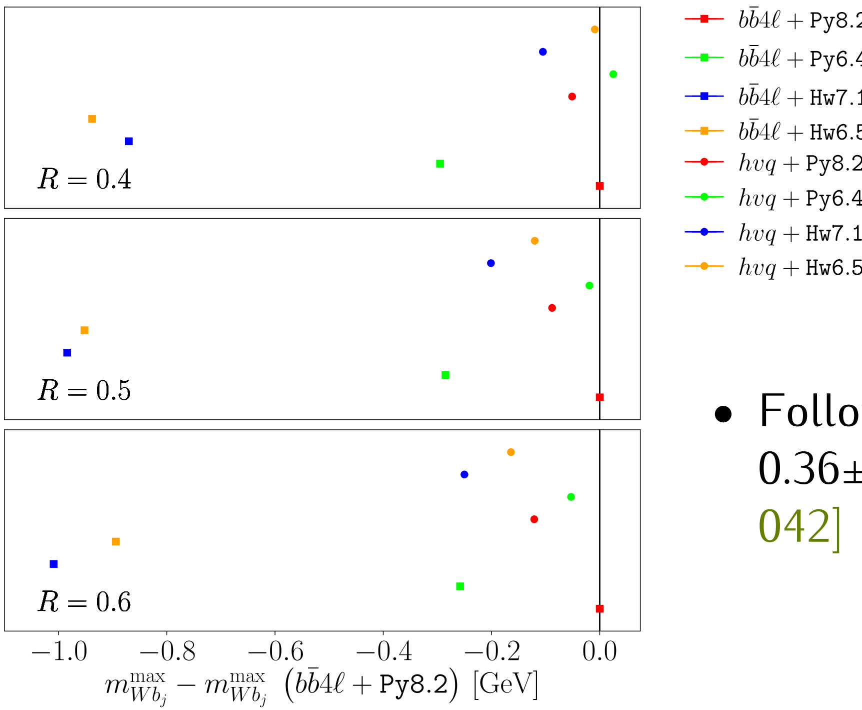


- shapes of distributions stable with respect to NLO QCD correctoins
- scale variations rather flat for inclusive observables
- PDF variations clearly subleading
- NLOPS corrections
  - ttb phase space: small
  - ttbb phase space: sizeable, i.e. ~ 27% in $M_{j_{b1} j_{b2}}$ above 100 GeV

Implications for top mass extractions

[Ferrario Ravasio, TJ, Nason, Oleari '18 & '19]

- Comprehensive study of mass shifts due to an upgrade of the $t\bar{t}$ generator:
  - Observables: Wb-jet mass, b-jet energy peak position, leptonic observables
  - NLO+PS generators: {`bb4l`, `ttbNLOdec`, `hvq`} + {Py6, Py8, Hw6, Hw7}

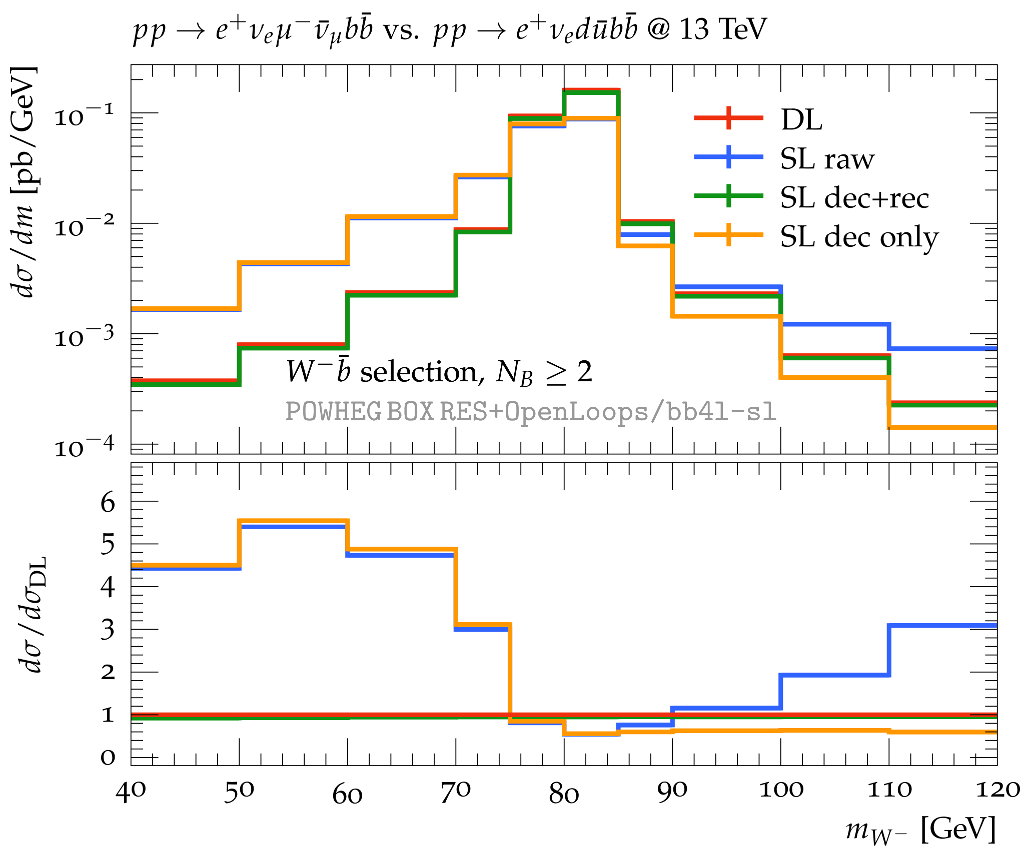


- Follow up by ATLAS reports a shift of 0.36±0.08 GeV [ATL-PHYS-PUB-2021-042]

Semileptonic channel: radiation in W decay

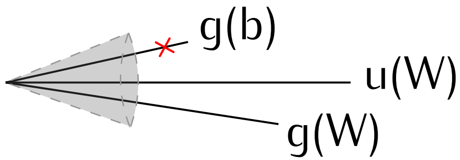
[TJ, Lindert, Pozzorini '23]

- W boson mass spectrum, dileptonic vs. semileptonic:

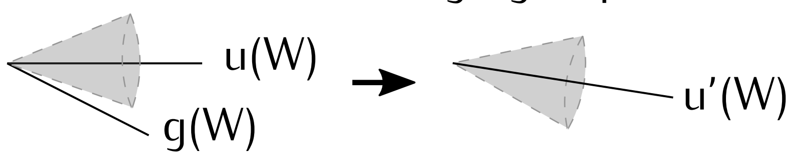


- DL: dileptonic channel
- SL raw: semileptonic channel
- SL dec+rec: SL + decontamination + recombination
- SL dec only: SL + decontamination

decontamination = parton removal



recombination = merging of partons



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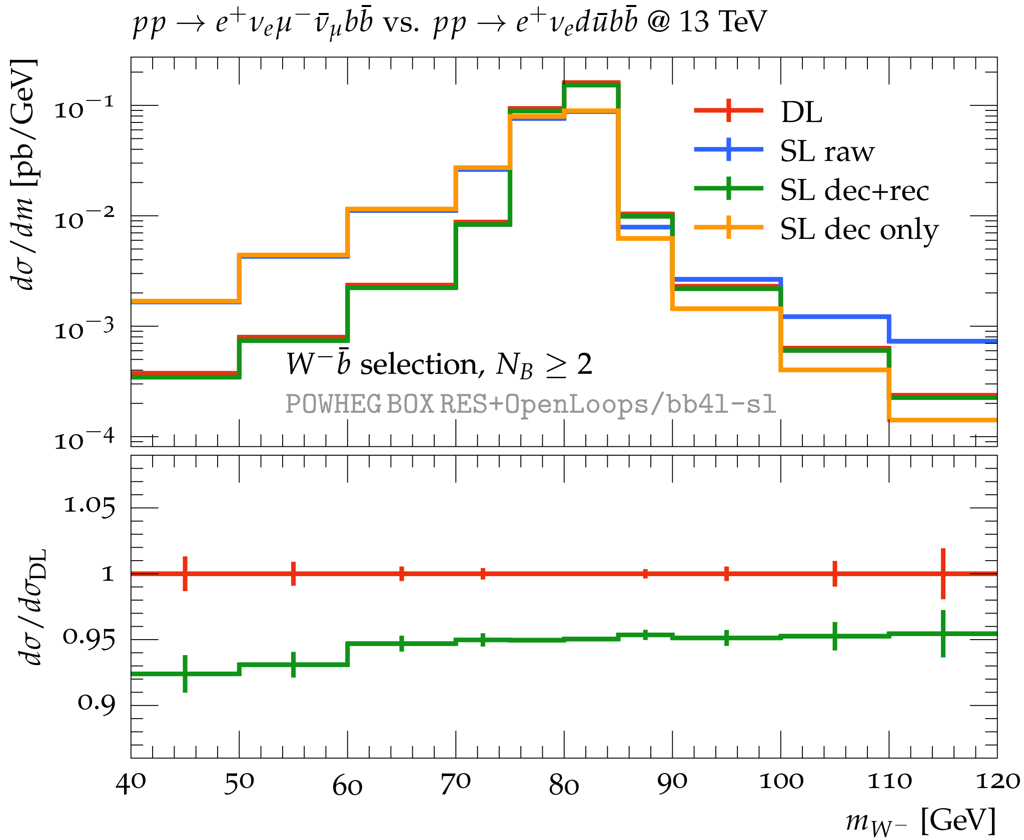

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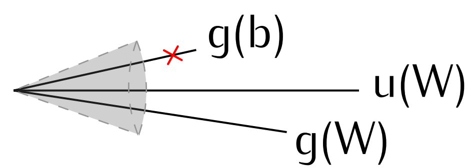

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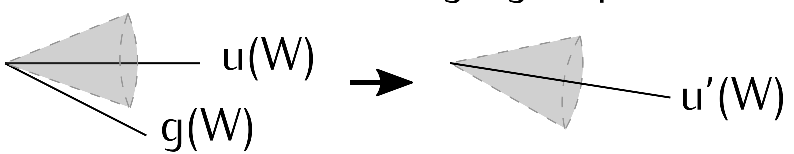

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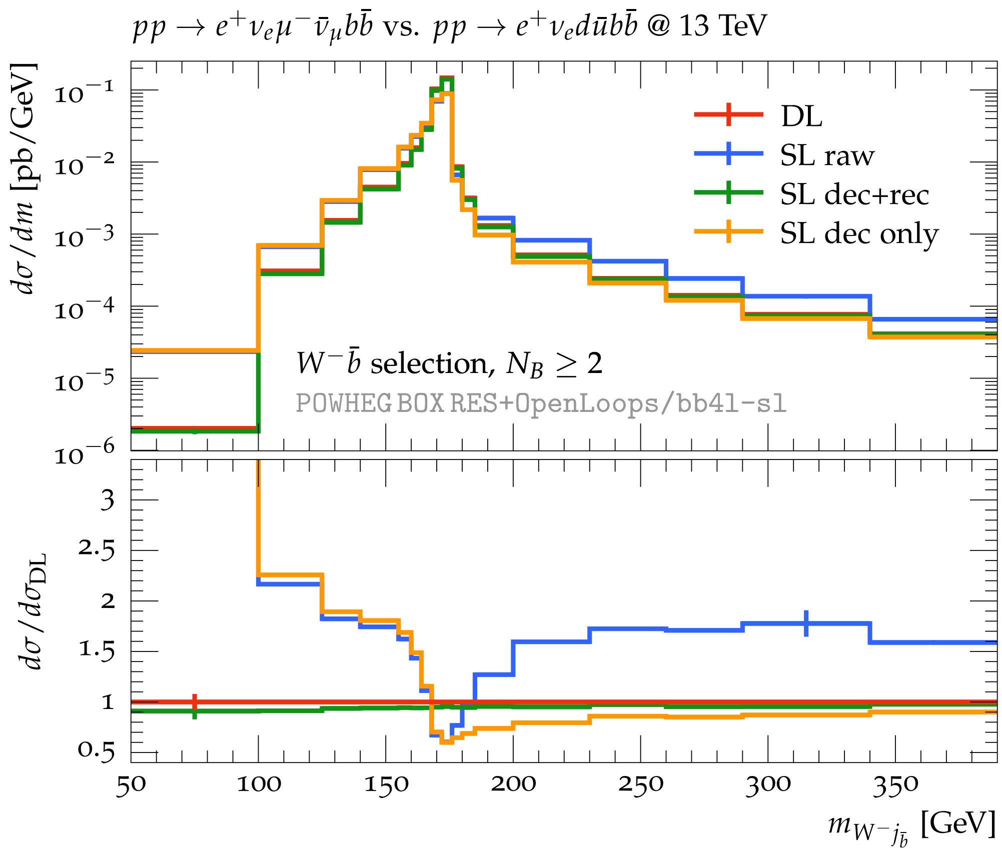

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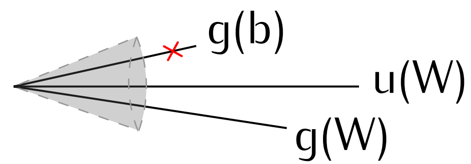

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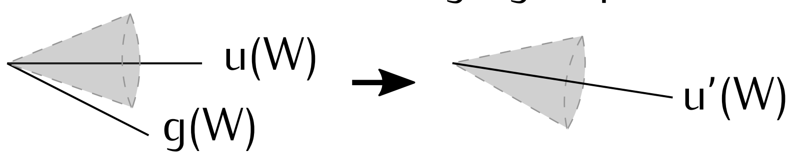

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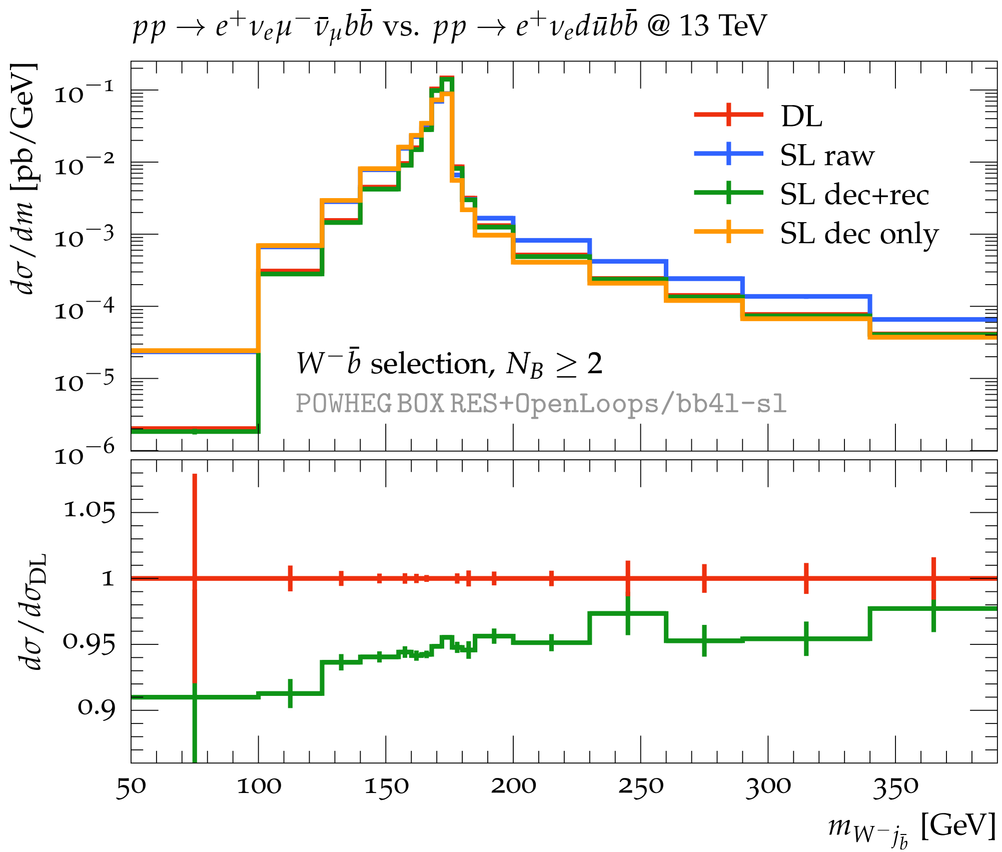

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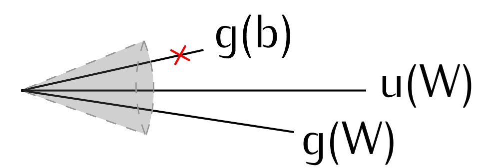

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