Semileptonic Decays in Off-shell Top Production with bb4l

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based on: [**TJ**, Nason '15], [**TJ**, Lindert, Nason, Oleari, Pozzorini '16], [Ferrario Ravasio, **TJ**, Nason, Oleari '18], [Ferrario Ravasio, **TJ**, Nason, Oleari '19], [Herwig, **TJ**, Nachman '19], [Ferrario Ravasio, **TJ** '21], [**TJ**, Lindert, Pozzorini 'XY]

Semileptonic Decays in Off-shell Top Production with bb4l

- Motivations:
  - Why top quark? Because it's a versatile probe of the SM and a window to NP.
    - a.) Coloured object that b.) decays electroweakly and c.) couples strongly to the Higgs boson
  - Why top quark at LHC? Because "several hundred million tops produced" ...
    - ...implies 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!

Correspondingly we have: NLO QCD, NNLO QCD, NLO EW, NNLO QCD+NLO EW, analytic resummations, NLO QCD+PS and NNLO QCD+PS

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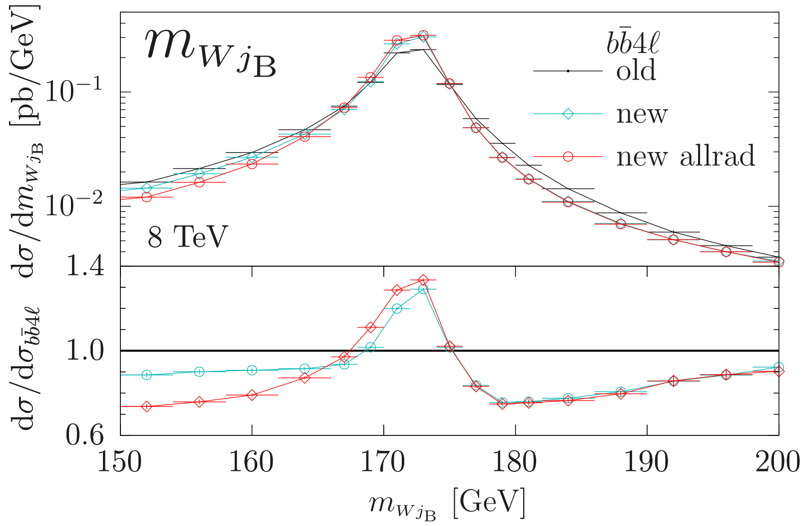
  - Why top quark at LHC? Because "several hundred million tops produced" ...
    - ...implies theory will soon lag behind the experiment.
    - ...means it is major background in many other LHC analyses.
  - But do we also need off-shell effects?
    - They modify shapes of spectra used for measurements of top properties,
    - and allow the inclusion of quantum interferences between different production modes and radiation from production and decay

There is: NLO QCD, NLO EW and NLO QCD+PS in the dileptonic channel

Off-shell effects in $t\bar{t}$: bb4l

- Off-shell effects distort the top mass shape and other distributions



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

  - Potentially affecting m_t and y_t measurements
- Proper treatment of interference required
  - To describe the data
  - And if you have it, you can try measuring Γ_t in tails

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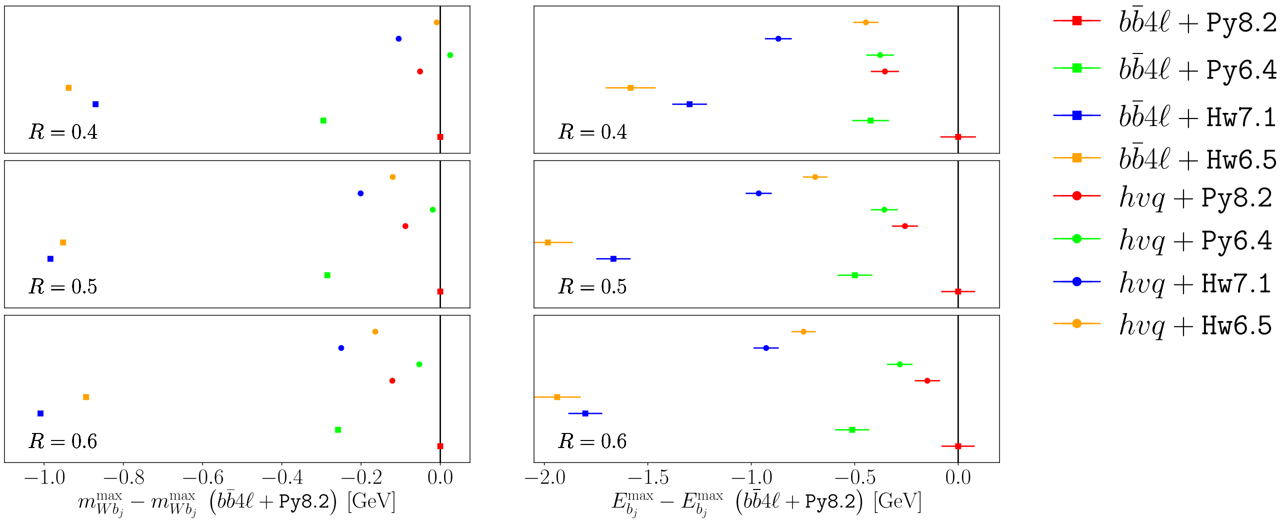

[Ferrario Ravasio, **TJ**, Nason, Oleari '18, '19], [ATL-PHYS-PUB -2021-042]

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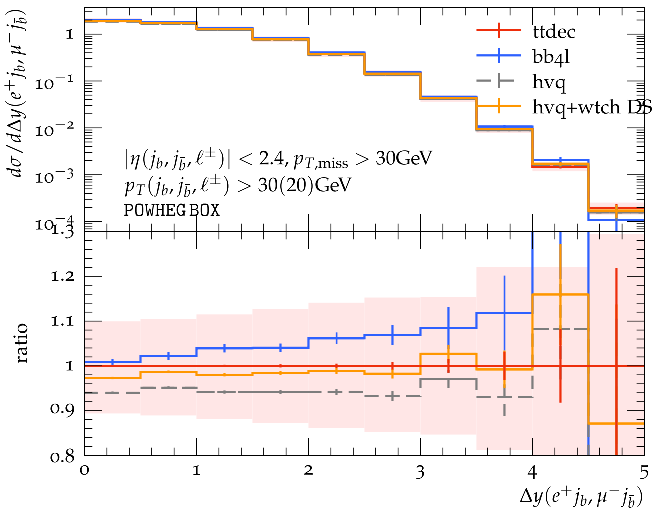

[Ferrario Ravasio, **TJ** '21]

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Off-shell effects in $t\bar{t}$: bb41

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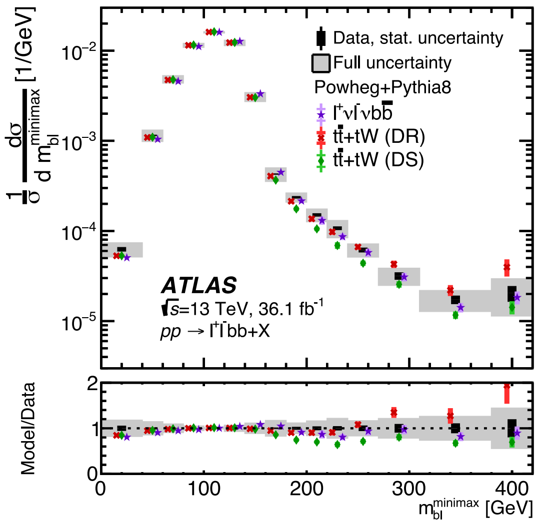

[PRL 121, 152002]

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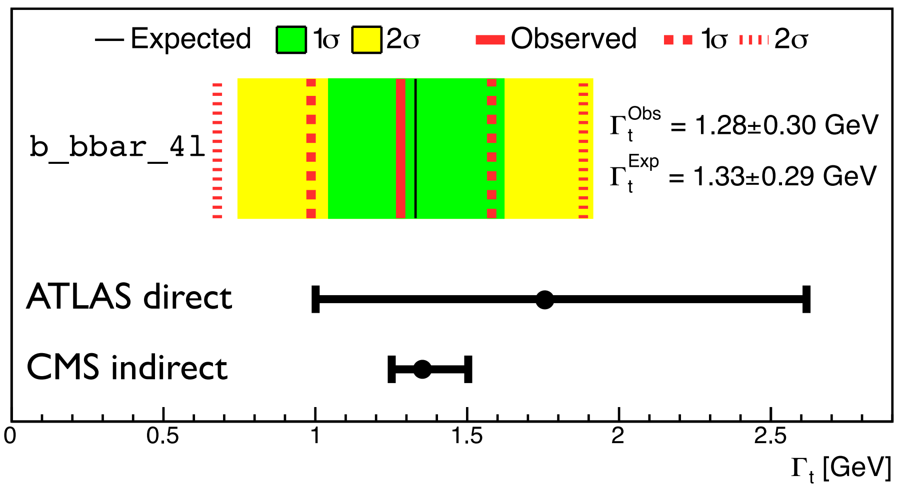
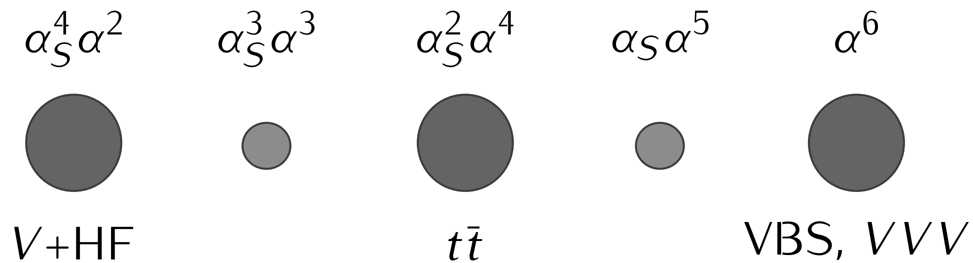


[Herwig, **TJ**, Nachman '19]

Semileptonic $t\bar{t}$

- Consider the signature $pp \to \ell^{\pm}\nu jjb\bar{b}$ at LO



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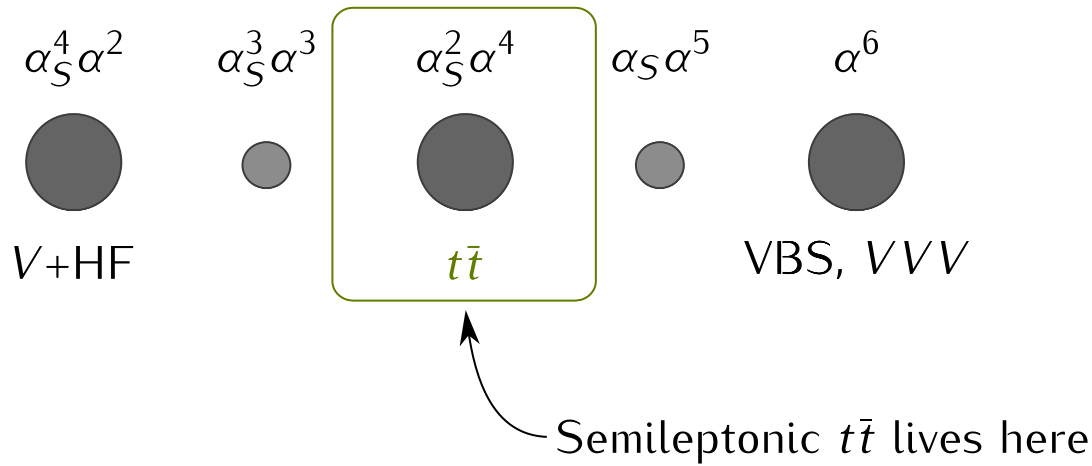

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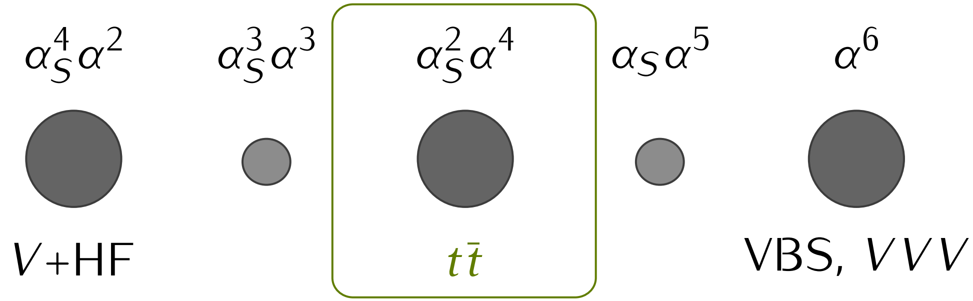
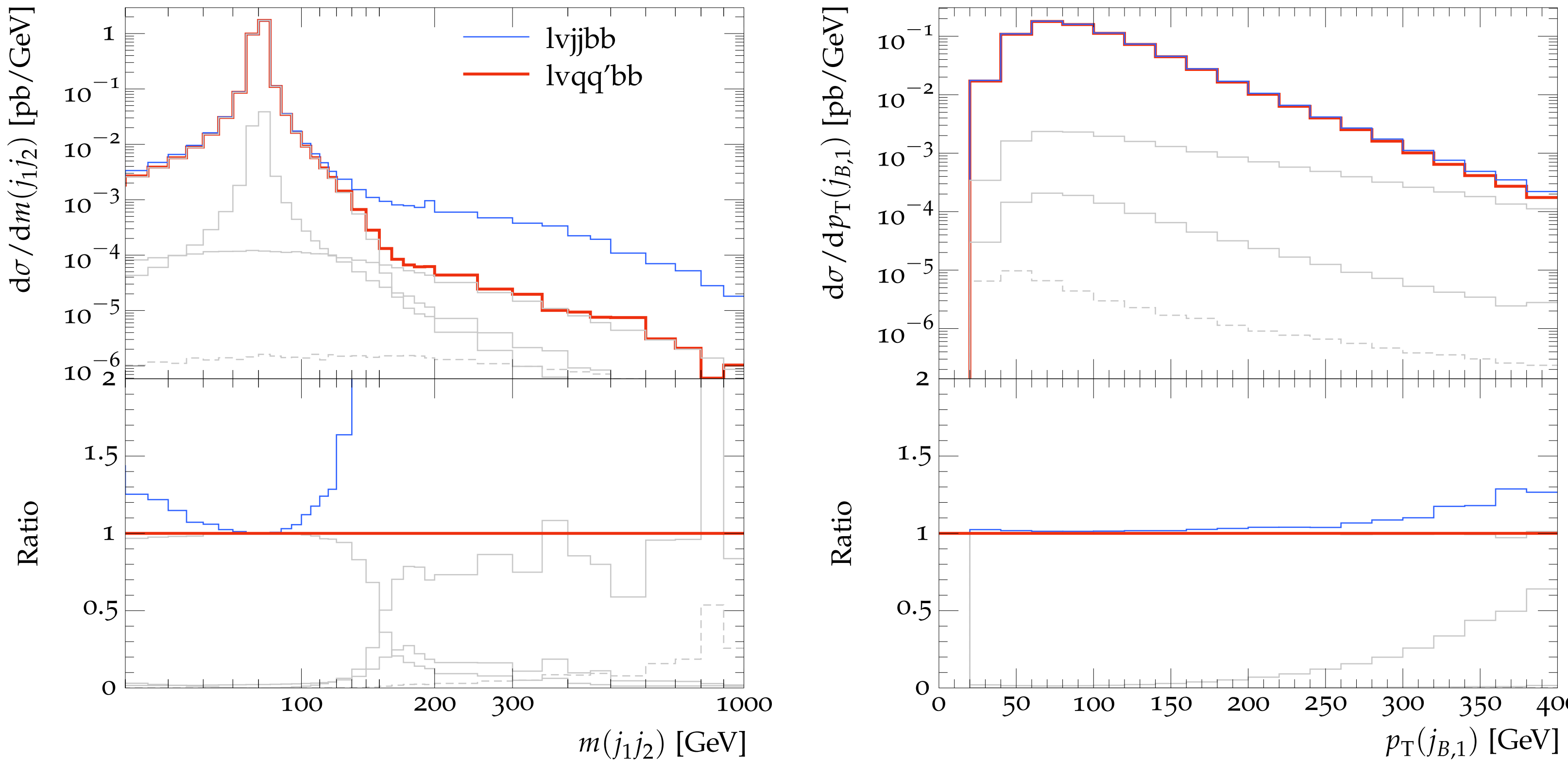


- Dominant contribution: semileptonic $t\bar{t}$ (with tops and Ws on-shell)
  - $pp \to \ell^{\pm}\nu q\bar{q}'b\bar{b}$ with $q\bar{q}' = \{u\bar{d}, c\bar{s}\}$ or $q\bar{q}' = \{d\bar{u}, s\bar{c}\}$
  - Also includes: tW, t- and s-channel t+jets, VBF-W+jets

Semileptonic $t\bar{t}$

- leading order, 13 TeV LHC, results from `Sherpa/OpenLoops`



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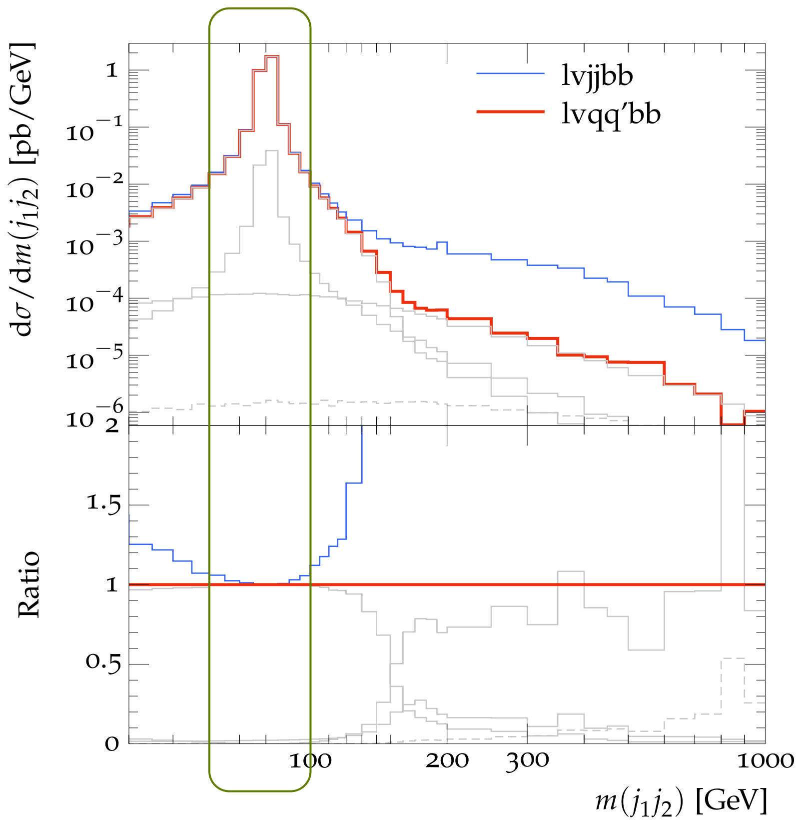

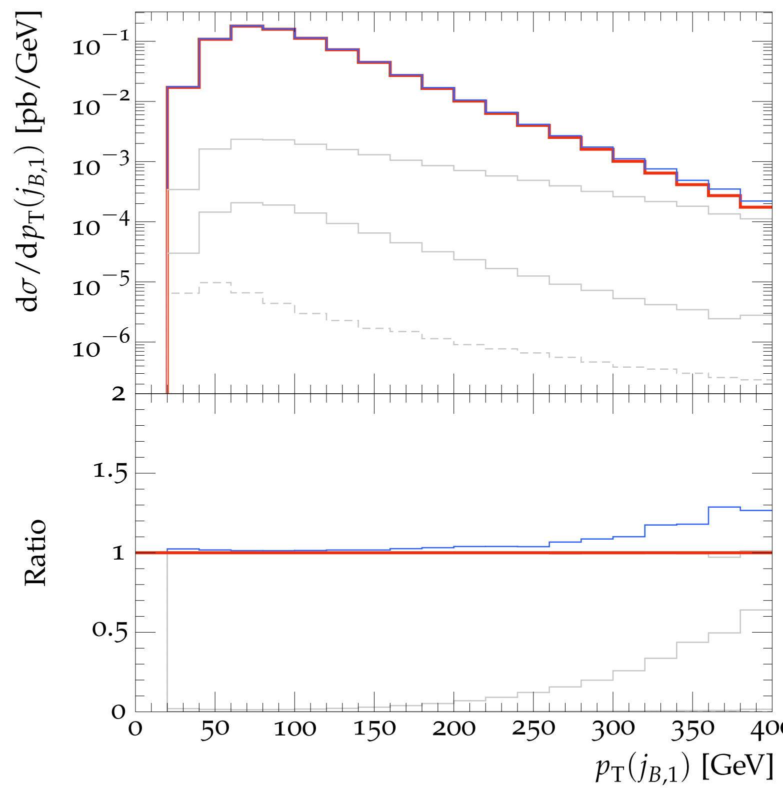

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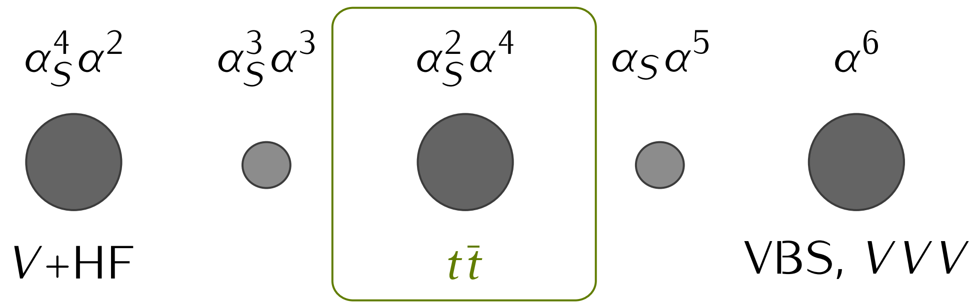

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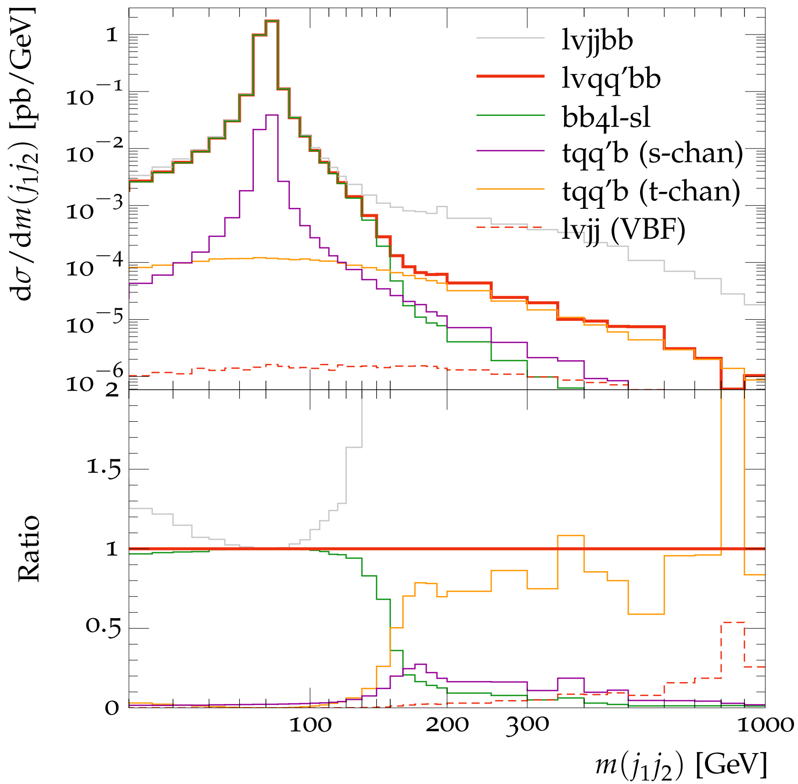
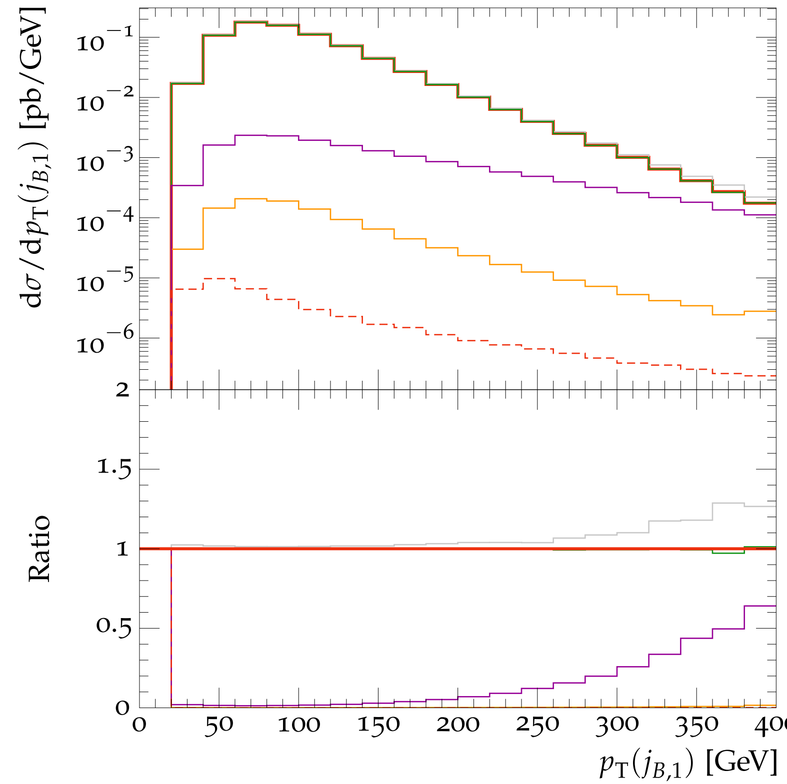
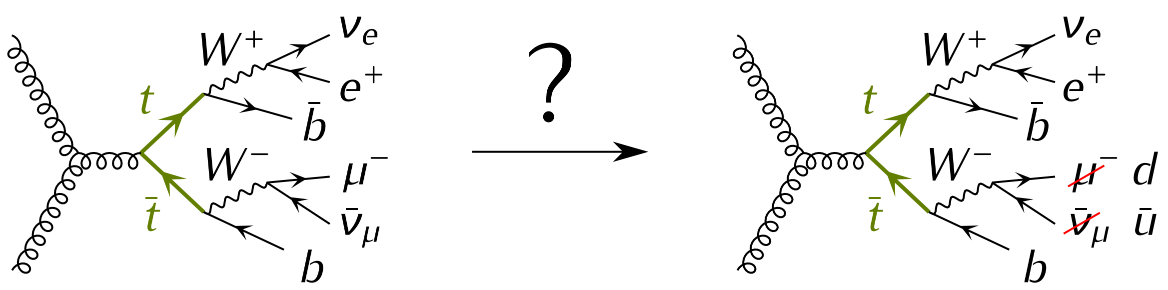




Semileptonic $t\bar{t}$ from dileptonic $t\bar{t}$?

- Semileptonic channel: **eight** legs, **six** coloured = very high complexity at NLO QCD
- Leptonic ($pp \to \ell^{\pm}\nu_{\ell} l^{\mp}\nu_{l} b\bar{b}$) vs. semileptonic ($pp \to \ell^{\pm}\nu_{\ell} q\bar{q}' b\bar{b}$)



$$d\sigma(\text{"bb4l - sl"}) = d\sigma(\text{bb4l})\frac{\text{BR(SL)}}{\text{BR(DL)}}$$

- Only leptonic topologies in semileptonic channel ≡ dropping some off-shell effects
  - tW and the $tt - tW$ interference is still included, but not t+jets

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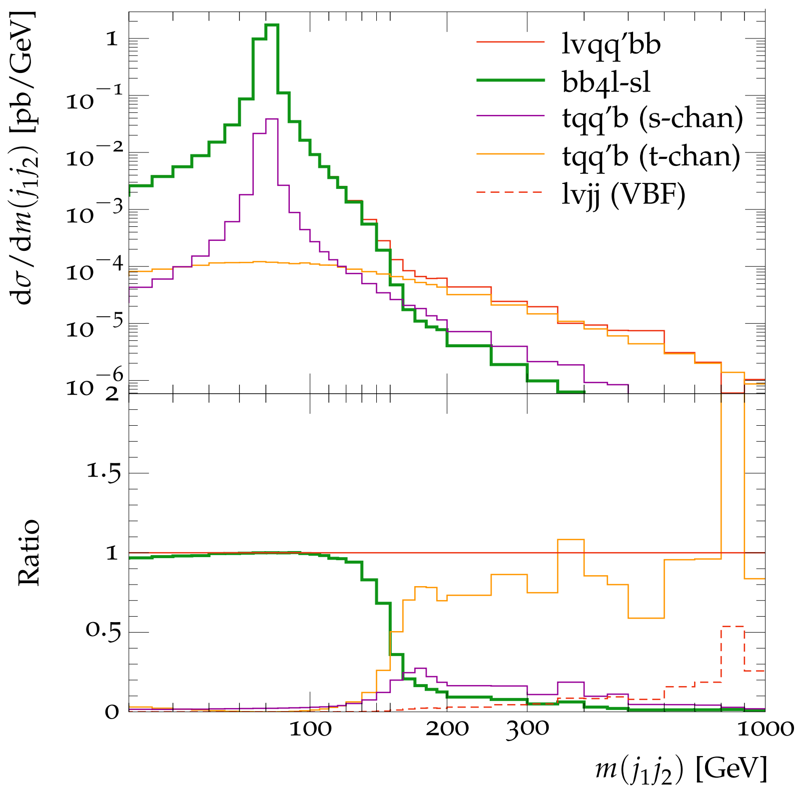

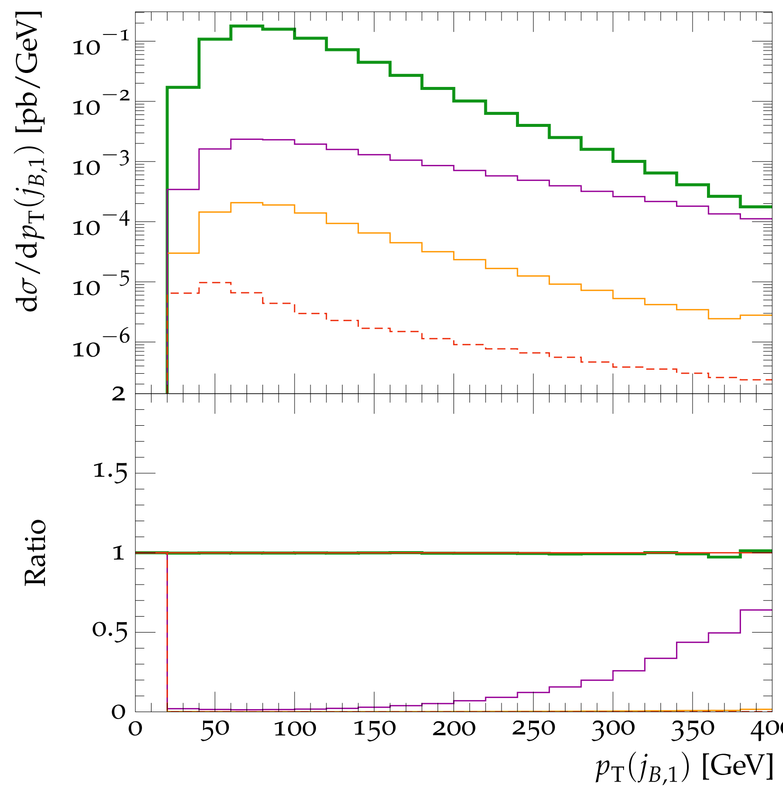

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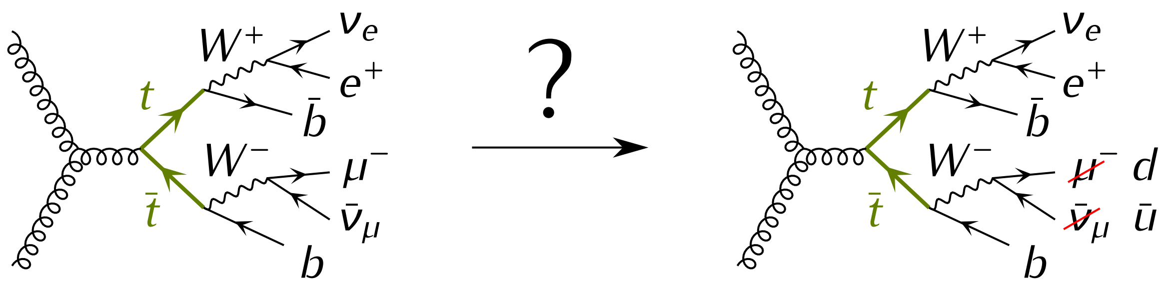

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bb4l-sl

- Semileptonic $t\bar{t}$ NLO+PS predictions from `bb4l`:
  - Read in `bb4l` LHE files with `allrad`
  - Relabel W^+ or W^- decay products and attach an emission

$$d\sigma = \bar{B}_{\mathtt{bb4l-sl}}(\Phi_B)\, d\Phi_B \prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\mathrm{ISR}}} \left[\Delta_\alpha^{\mathtt{bb4l}}(q_{\mathrm{cut}}) + \Delta_\alpha^{\mathtt{bb4l}}(k_T^\alpha) \frac{R_\alpha^{\mathtt{bb4l}}(\Phi_\alpha(\Phi_B, \Phi_{\mathrm{rad}}^\alpha))}{B^{\mathtt{bb4l}}(\Phi_B)}\, d\Phi_{\mathrm{rad}}^\alpha \right]$$

$$\times \left[\Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(q_{\mathrm{cut}}) + \Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(k_T^{\alpha_W}) \frac{R_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_{\alpha_W}(\Phi_B, \Phi_{\mathrm{rad}}^{\alpha_W}))}{B^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_B)} d\Phi_{\mathrm{rad}}^{\alpha_W} \right]$$

  - Shower with `Pythia8` as normal with an extra veto in W decay

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bb4l

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emission from W^- or W^-

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Numerical results

- Our setup:
  - LHC 13 TeV, NNPDF31_nlo_as_0118, $m_t = 172.5$ GeV, $m_b = 4.75$ GeV
  - `hdamp` $= m_t$, $\mu_r = \mu_f = m_t^{\dagger}$
  - $R = 0.5$ anti-k_T jets, $p_T > 25$ GeV, $|\eta| < 2.5$
  - W^+ leptonic, W^- hadronic
  - Compare `bb4l` vs `bb4l-sl` and for an adequate comparison we need to:
    - distinguish $\bar{u}$, d and b, $\bar{b}$ jets (using MC truth partonic content)
    - require that all tagged top decay products be separated by $\Delta R = 0.5$
    - construct correctly flavour-matched objects (MC truth)
  - Employ 2×2 different selection criteria
    - W^-: $W^- \equiv j_{\bar{u}} + j_d$, W^+: $W^+ \equiv e^+ + \bar{\nu}_e$
    - $N_b = 1$, $N_b \leq 2$

† not an optimal scale choice, we use it for technical reasons

Numerical results

- However, it is not enough to:
  - distinguish $\bar{u}$, d and b, $\bar{b}$ jets (using MC truth partonic content)
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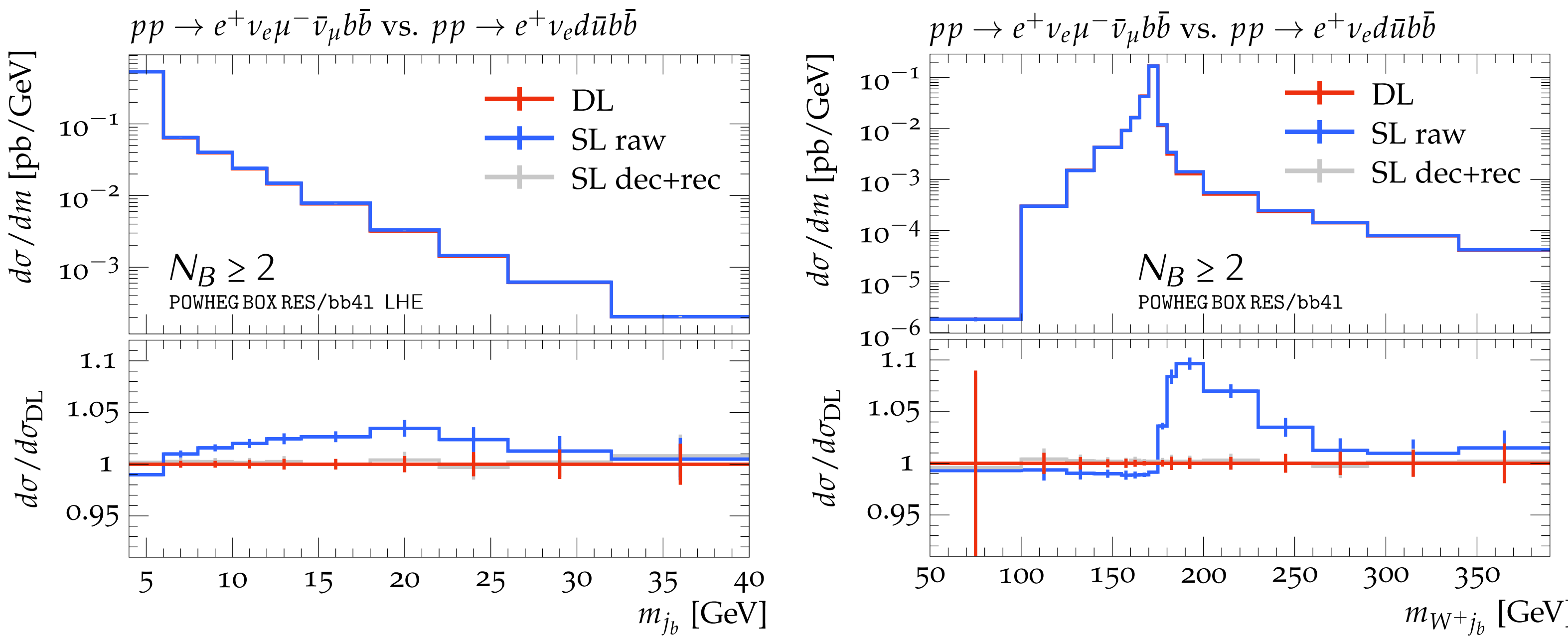

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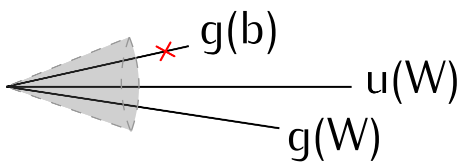
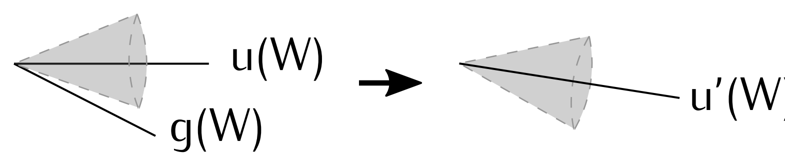
- We also introduce decontamination and recombination prescriptions:

decontamination = parton removal

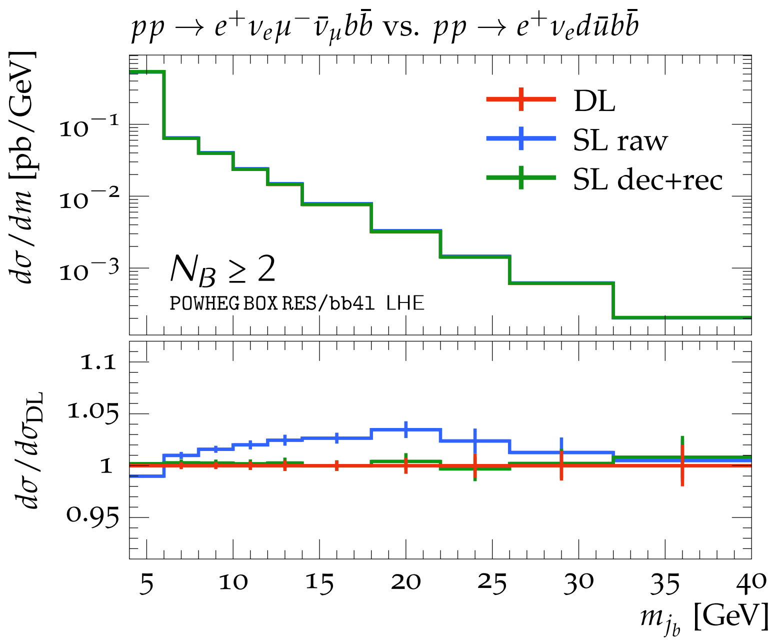


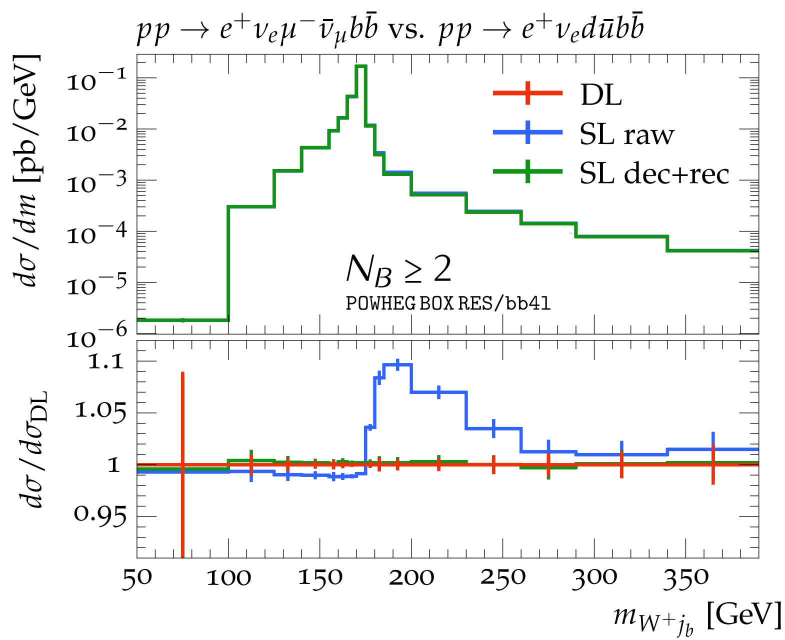
recombination = merging of partons



Numerical results

- Legend:
  - **DL**: dileptonic channel; **SL**: semileptonic channel
  - **dec only**: only W and b jet decontamination
  - **dec+rec**: both W and b jet decontamination and recombination





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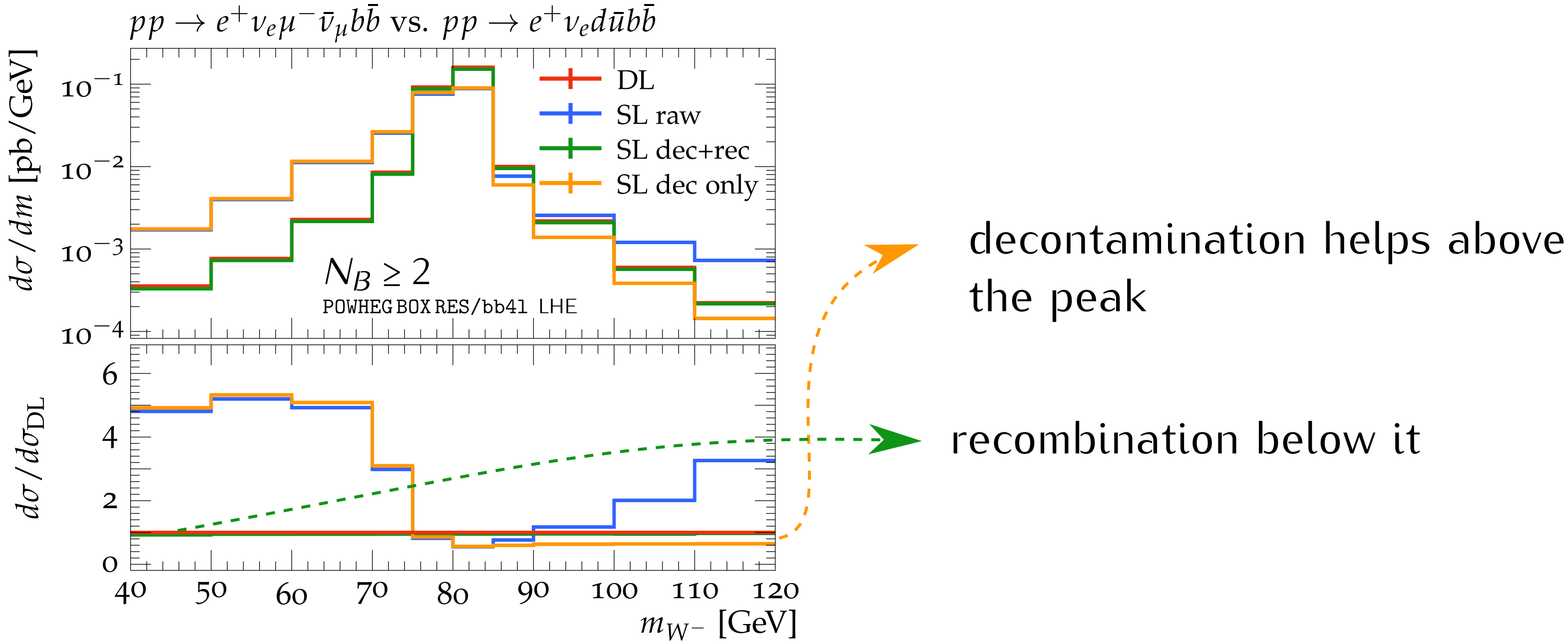

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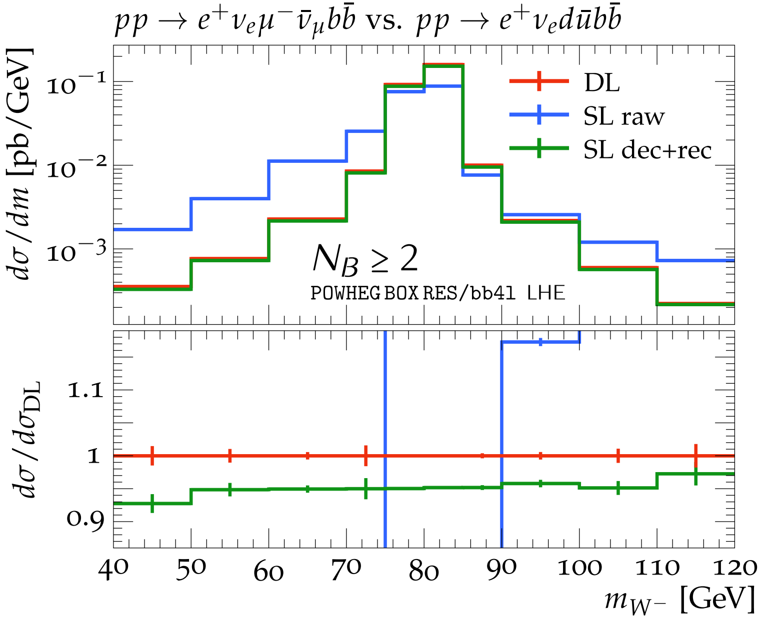
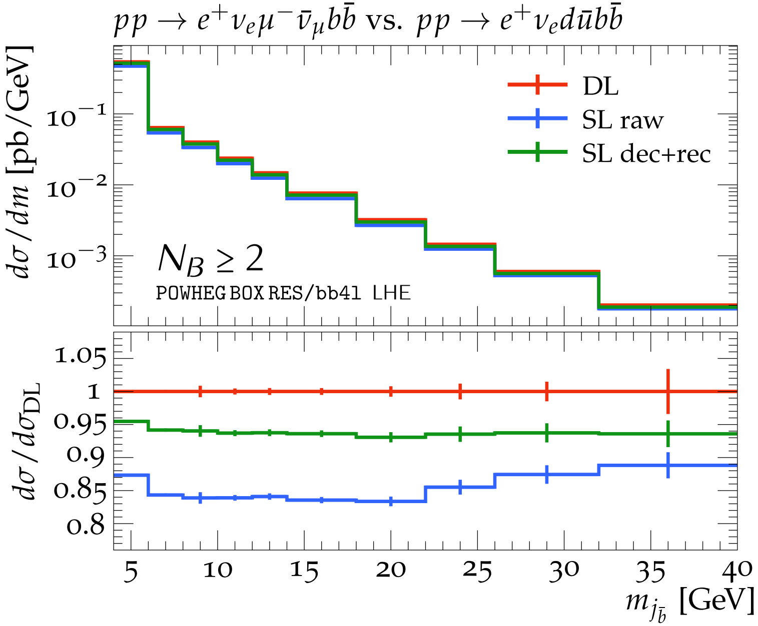
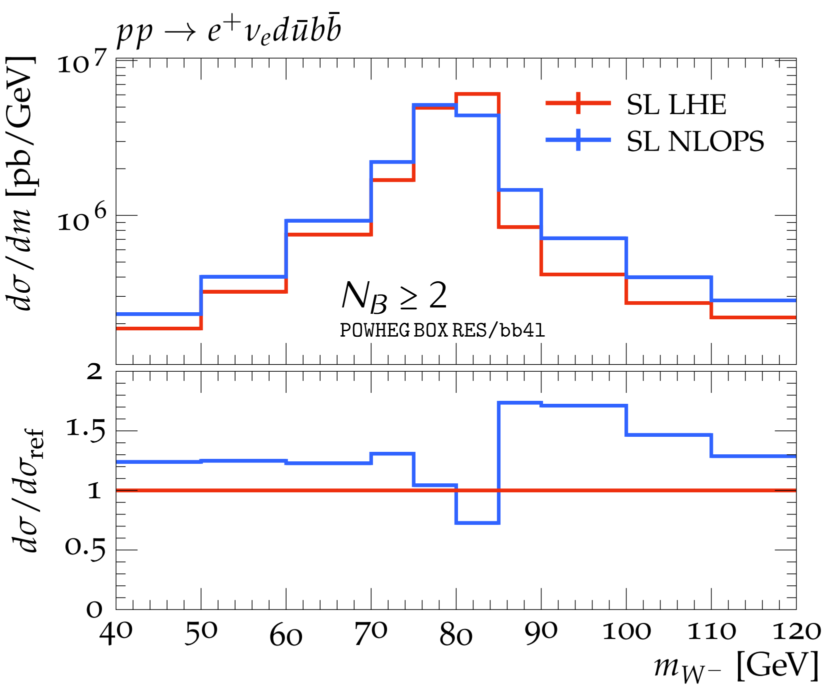
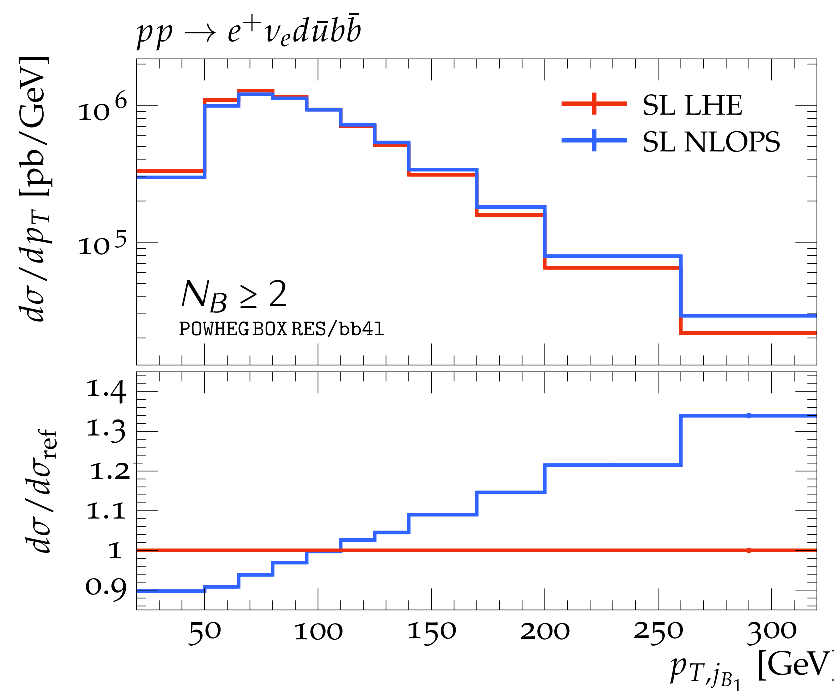




Numerical results

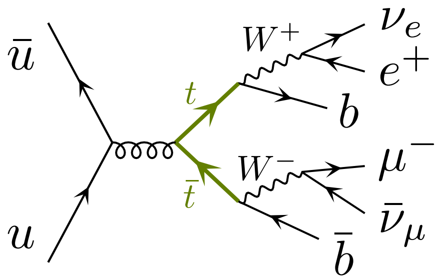
- Shower effects:
  - `bb4l-sl+Pythia8.2` (with `PowhegHooks` and `PowhegHooksBB4L-SL`)

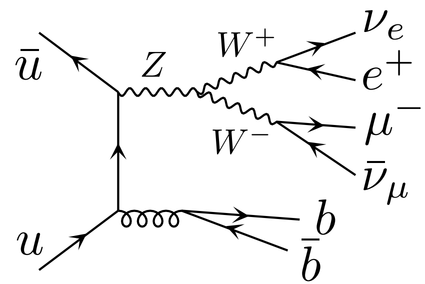




Resonance aware NLO+PS

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





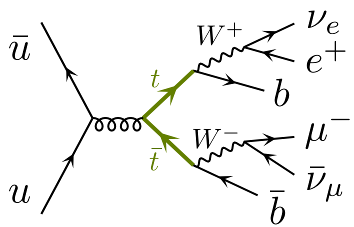
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

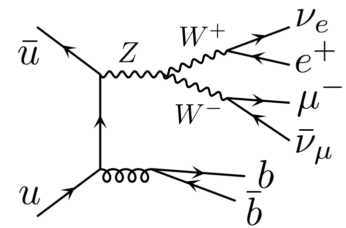
$$d\sigma = \frac{P_1}{P_1+P_2} d\sigma + \frac{P_2}{P_1+P_2} d\sigma$$

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

  - Generalizing the subtraction scheme

Improved resonance history projectors

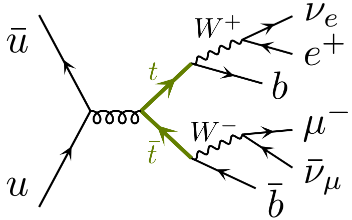


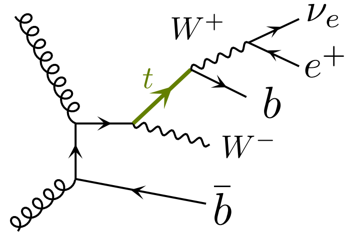


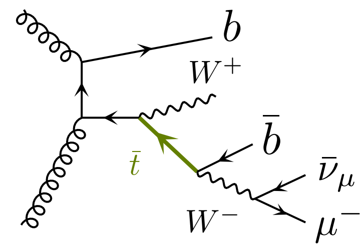
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

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

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







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

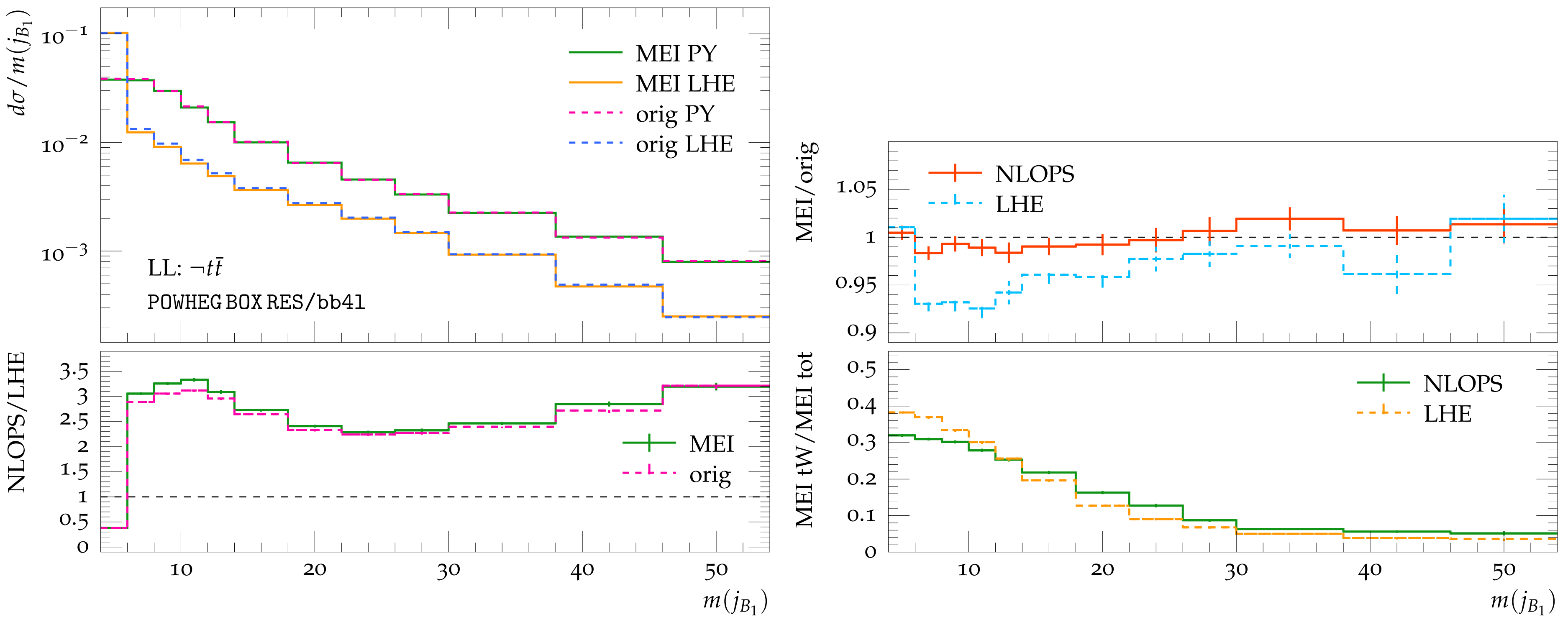
$$P_2 = B_{tW^+}$$

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

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

Improved resonance history projectors

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



Summary and outlook

WWU MÜNSTER

- Top quark plays a prominent role in the LHC physics program
- Experimental precision now sufficient to resolve off-shell effects in $t\bar{t}$ production
- **Leptonic channel**: available for a long time in `bb4l`
- **Semileptonic channel**
  - Now implemented in an approximation as a plugin to `bb4l`, publicaly available soon.
  - Still TODO: We're finalizing comparisons against `hvq`.
- Other developments:
  - Matching uncertainties due to the choice of resonance history projectors
- **Hadronic channel?**
  - The algorithm in `bb4l-sl` can redecay both Ws, but we still need to check whether this approximation is suitable