Resonance-aware NLOPS matching for off-shell $tt + tW$ production with semileptonic decays

Tomáš Ježo

Institute of Theoretical Physics
University of Münster

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], [**TJ**, Lindert, Pozzorini '23]

Universität Münster

TOP 2024
23/09/24

top 2024

Resonance-aware NLOPS matching for off-shell $tt + tW$ production with semileptonic decays

- 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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    - ...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

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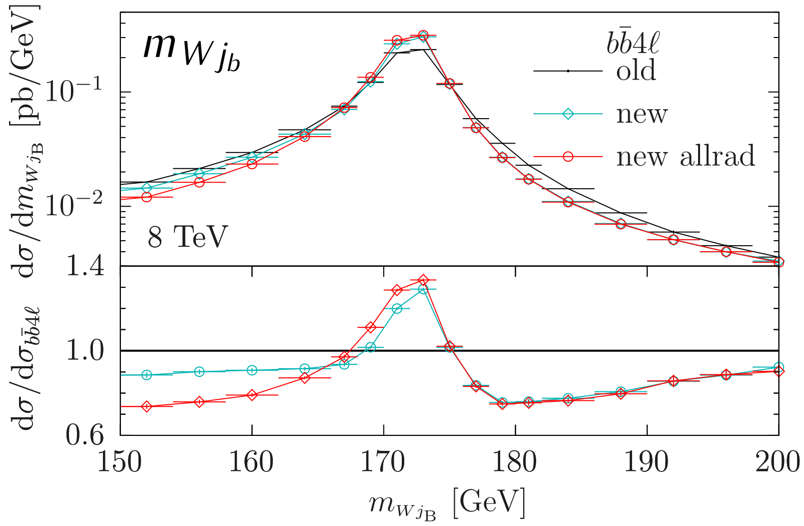

[**TJ**, Nason '15],
[**TJ**, Lindert, Nason, Oleari, Pozzorini '16]

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  - To describe the data
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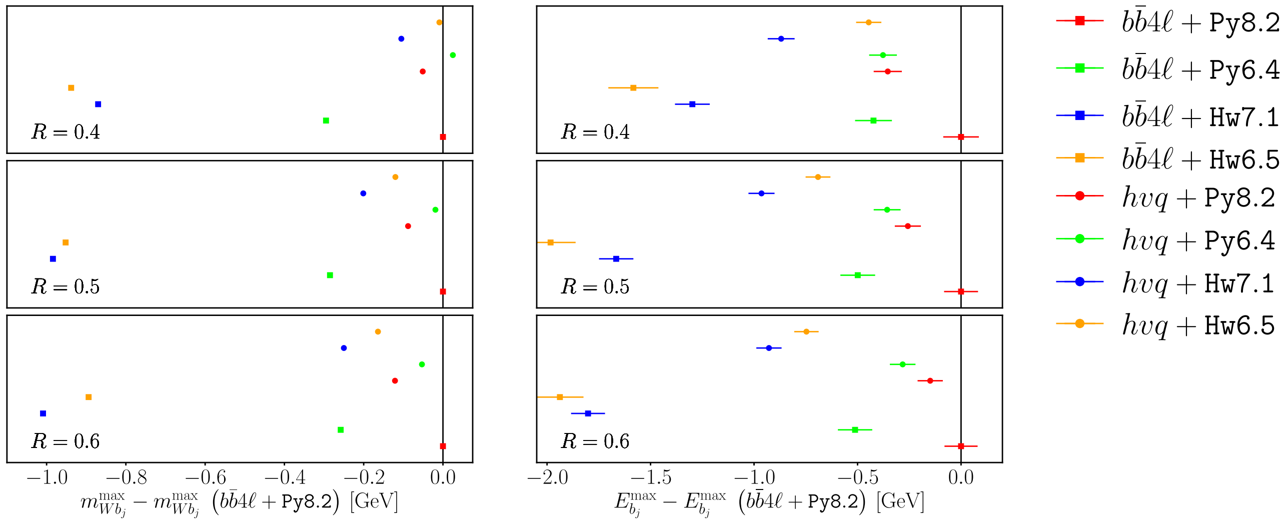

[Ferrario Ravasio, **TJ**, Nason, Oleari '18, '19], [ATL-PHYS-PUB -2021-042]

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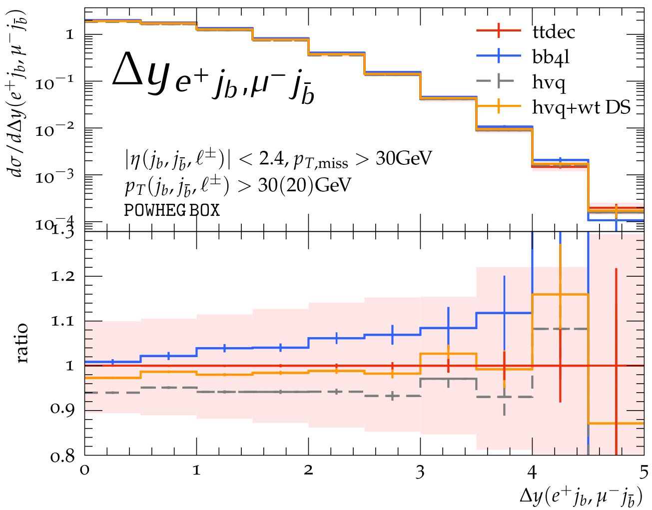

[Ferrario Ravasio, **TJ** '21]

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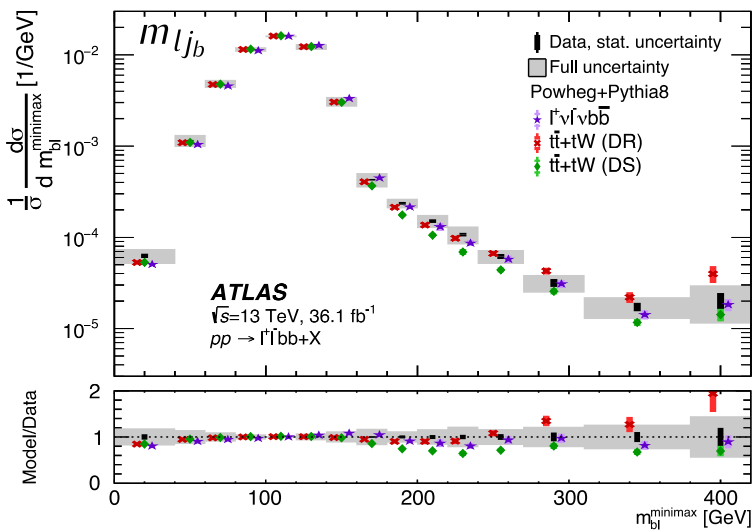

[PRL 121, 152002]

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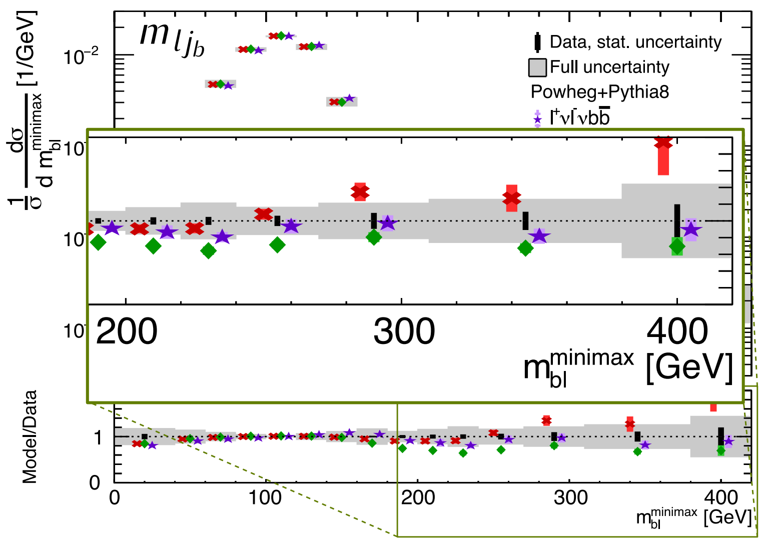

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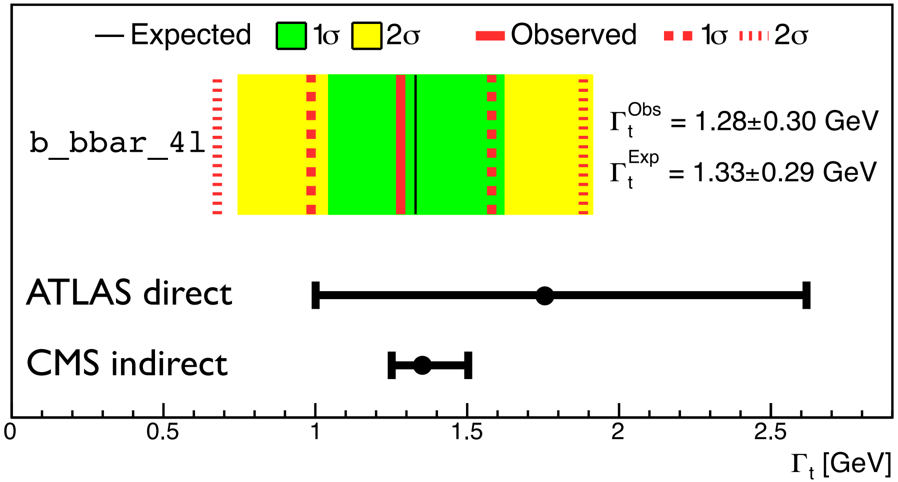
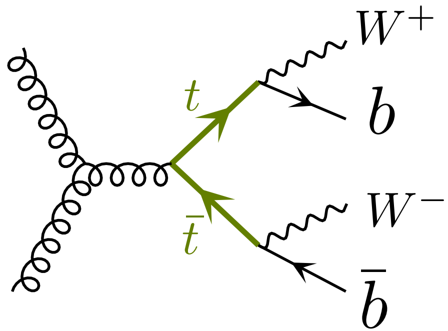


[Herwig, **TJ**, Nachman '19]

NLOPS with POWHEG

POWHEG Parton Shower Matching



$$\mathrm{d}\,\sigma = \overline{B}(\Phi_B)\,\mathrm{d}\,\Phi_B \left[\Delta(q_{\mathrm{cut}}) + \sum_\alpha \Delta(k_T^\alpha)\frac{R_\alpha(\Phi_\alpha(\Phi_B,\Phi_{\mathrm{rad}}))}{B(\Phi_B)}\,\mathrm{d}\,\Phi_{\mathrm{rad}}\right]$$

$$\text{with } \Delta(k_T^\alpha) = \exp\left[-\int_{k_T^\alpha > q_{\mathrm{cut}}} \frac{R_\alpha(\Phi_\alpha(\Phi_B,\Phi_{\mathrm{rad}}))}{B(\Phi_B)}\,\mathrm{d}\,\Phi_{\mathrm{rad}}\right]$$

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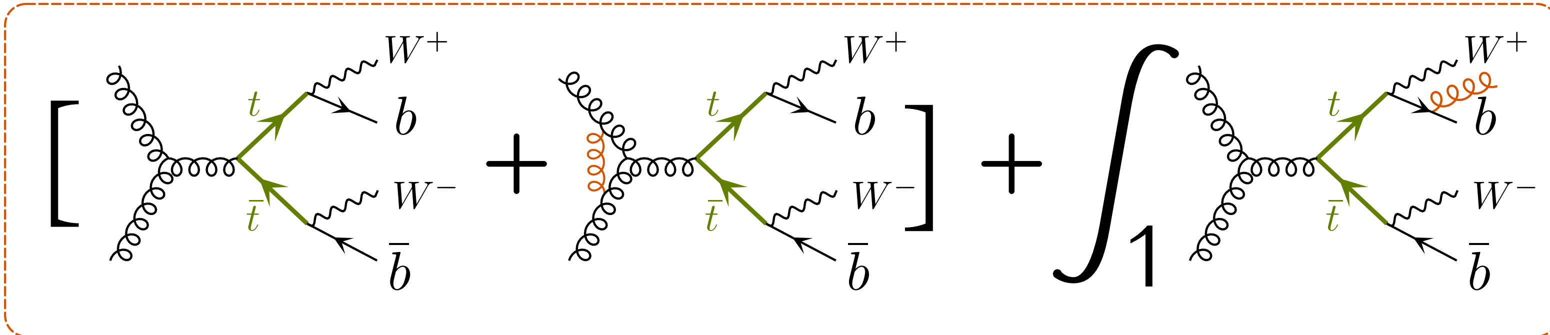

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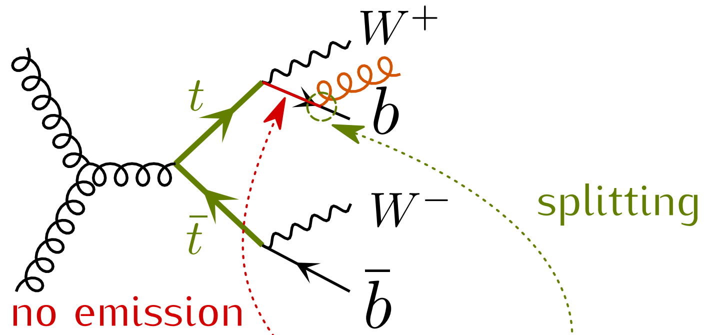

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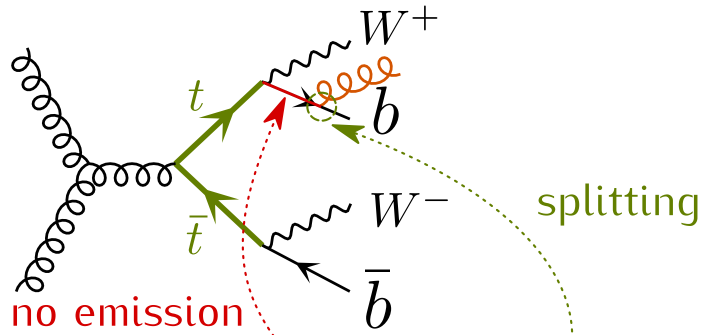

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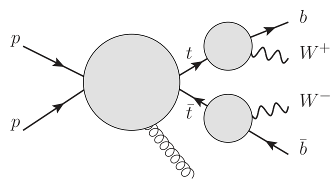
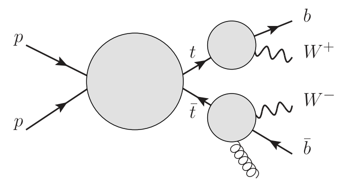
- Such an event can be passed on to any parton shower with p_T veto
  - p_T veto interface standardized (`scalup`)
  - Pythia, Herwig, ...

Recent improvement: resonance awareness

- Traditional matching:



or



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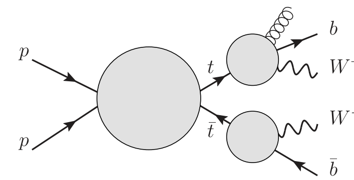

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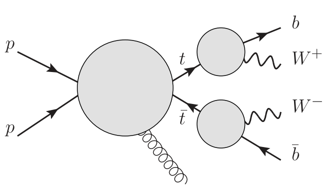
- Multiple radiation scheme:



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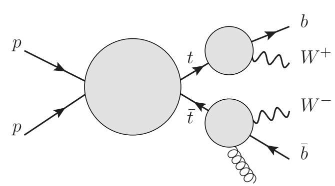

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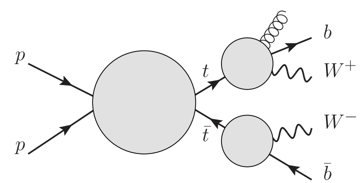

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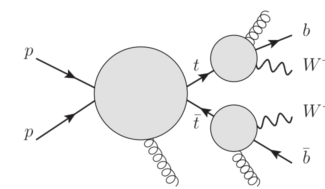

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† figure inspired by J. Lindert

bb41

bb4l: $pp \to l^+ \nu_l \ell^- \bar{\nu}_\ell b\bar{b}$ @ NLO+PS

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

- 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
- Two important developments
  - POWHEG style matching for processes with resonances possible
  - Modelling of emission in the decay with exact matrix element

Traditional NLOPS

Multiple-radiation-improved NLOPS (`allrad`)

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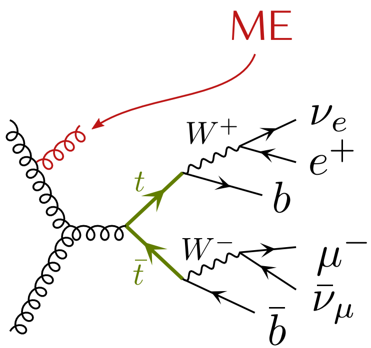

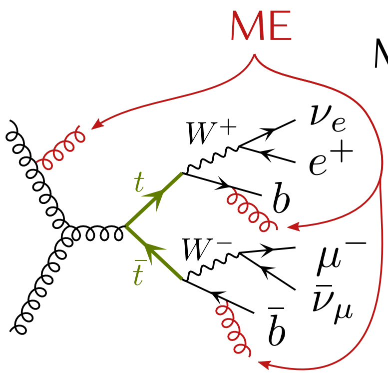

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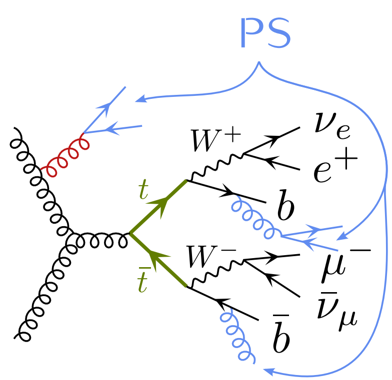

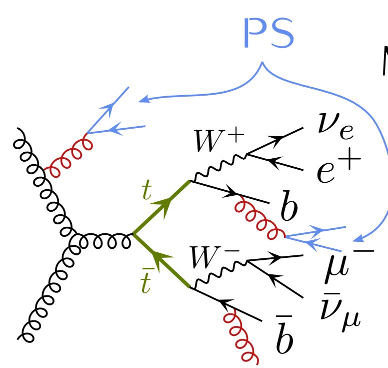

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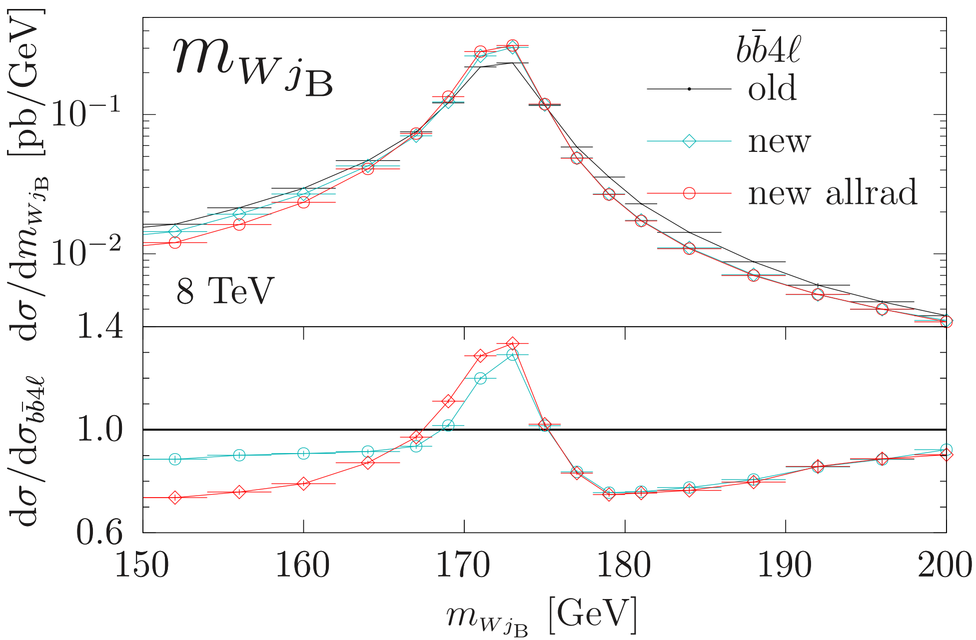


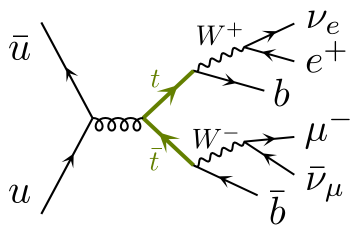
- old: non-resonance aware
- new: resonance aware
- new allrad: resonance aware, up to three emissions

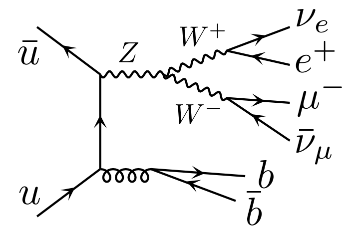
Beyond `bb41`

Resonance history projector uncertainties

[TJ, Lindert, Pozzorini '23]

bb4l:



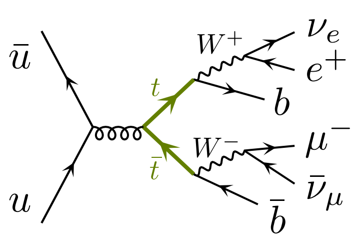


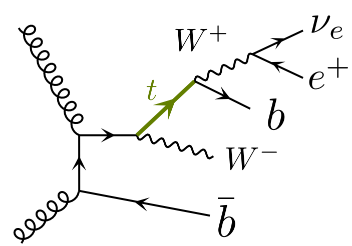
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

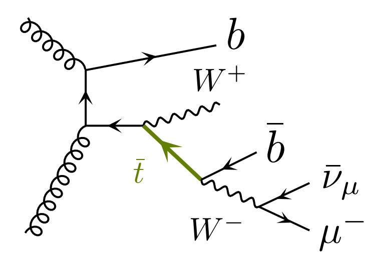
$$d\sigma = \frac{P_1}{P_1+P_2}\, d\sigma + \frac{P_2}{P_1+P_2}\, d\sigma$$

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

bb4l-dl:







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

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

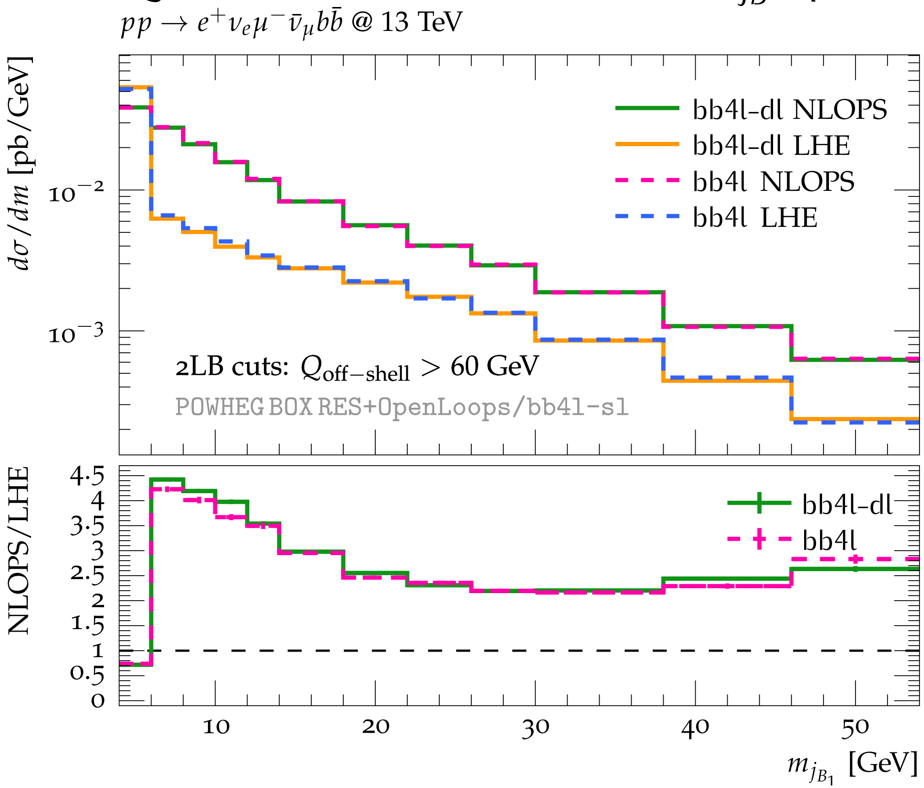
$$P_3 = B_{\bar{t}W^-}$$

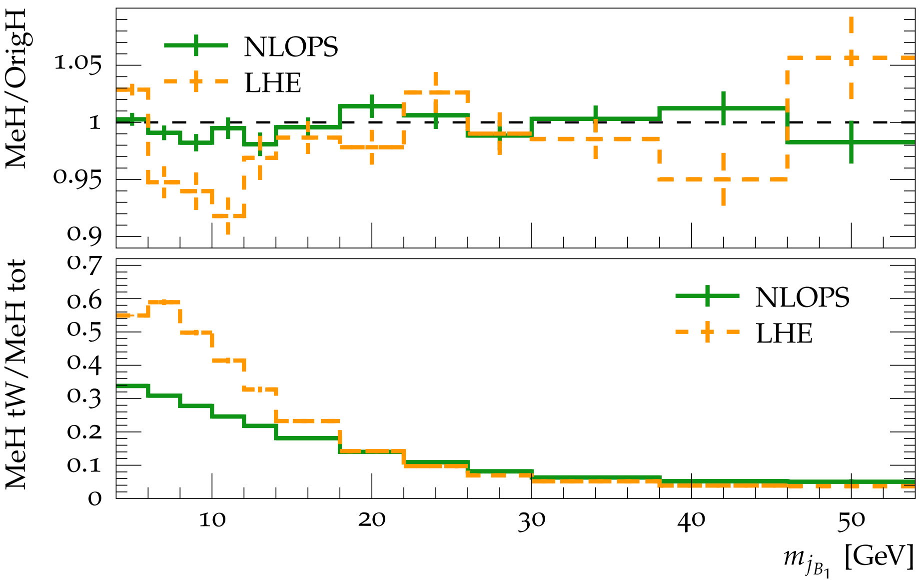
$$d\sigma = \frac{P_1}{P_1+P_2+P_3}\, d\sigma + \frac{P_2}{P_1+P_2+P_3}\, d\sigma + \frac{P_3}{P_1+P_2+P_3}\, d\sigma$$

Resonance history projector uncertainties

[TJ, Lindert, Pozzorini '23]

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

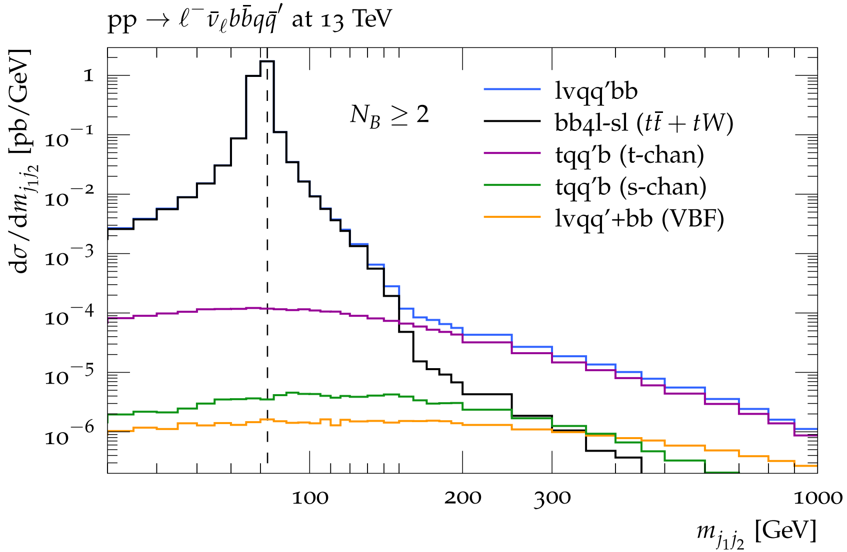


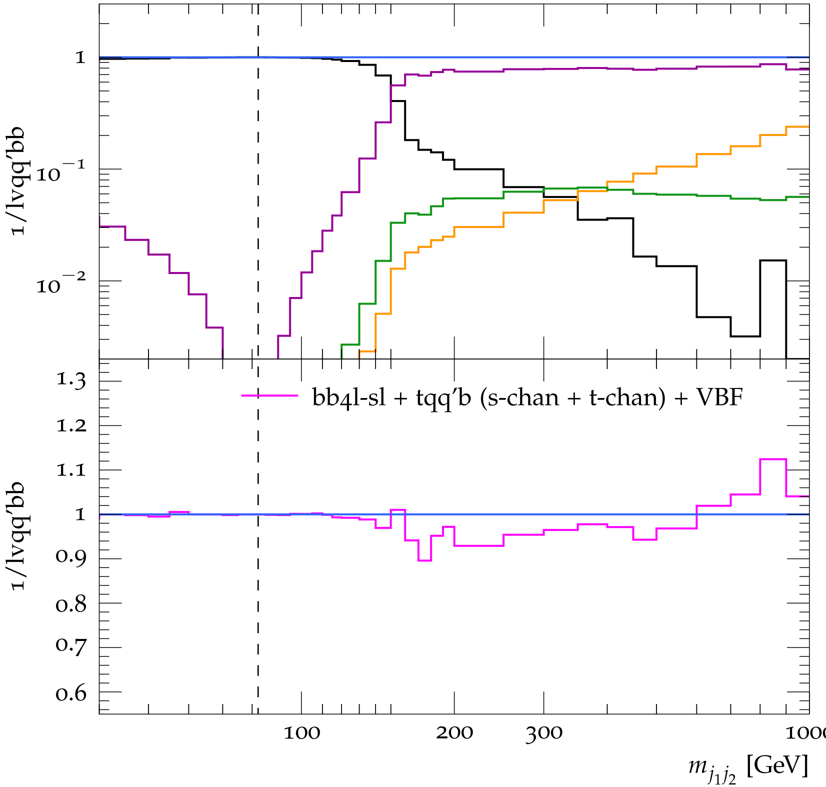


Semileptonic channel: bb4l-sl approximation

[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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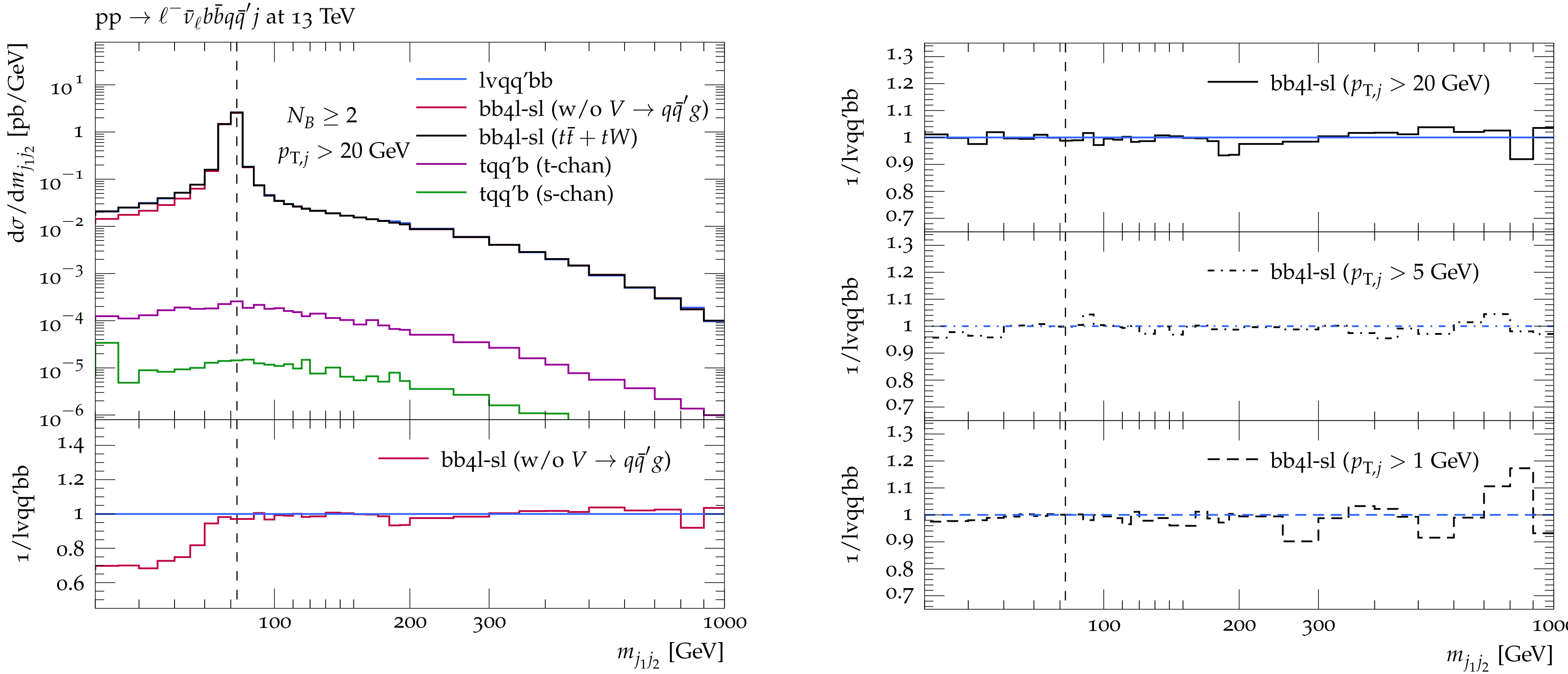
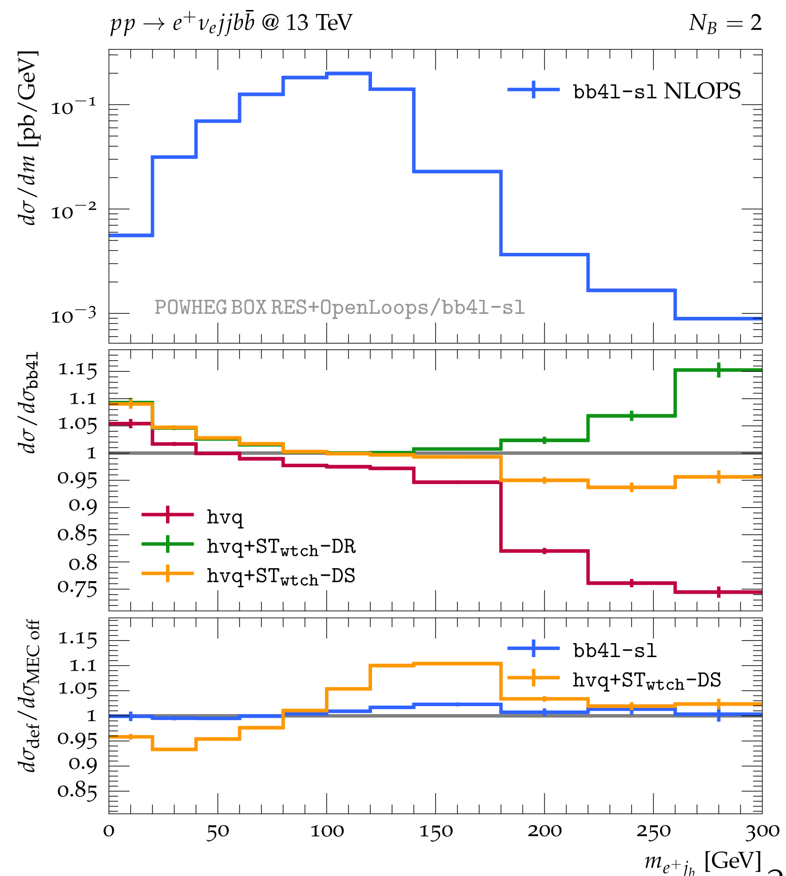


Semileptonic channel

[TJ, Lindert, Pozzorini '23]

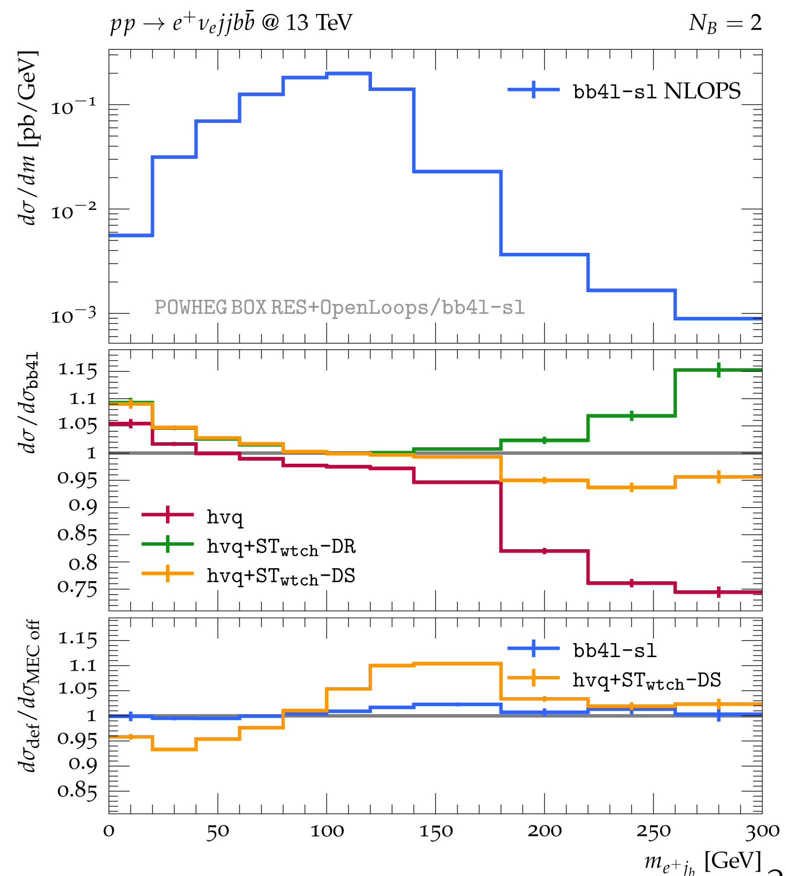
- NEW!: semileptonic decay channel
  - relies on an approximation assuming hadronic W is not far off shell ($\pm$20 GeV) and on the multiple radiation scheme
  - implemented as a plugin to `bb4l-dl`
    - produce dileptonic sample
    - replace leptonic decay of one W for a hadronic decay
    - attach emission



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`
  - tW and $t\bar{t} - tW$ interference important
  - impact of SMC's Matrix Element Corrections (MEC) reduced
  - *inverse width correction* included

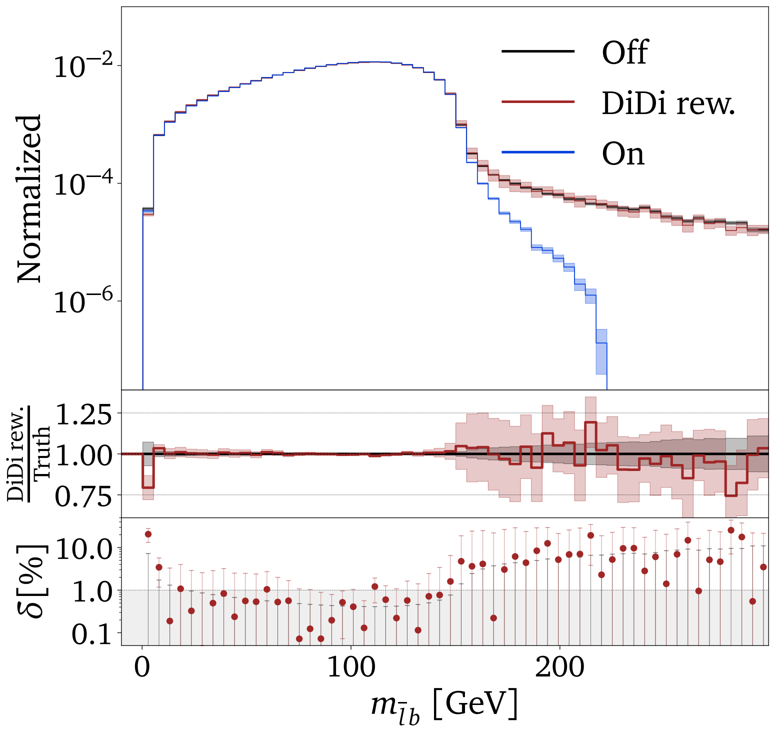


Other developments

Off-shell tops in dileptonic channel with ML

[Butter, **TJ**, Klasen, Kuschick, Palacios Schweitzer, Plehn ’23]

- Full off-shell over 2 orders of magnitude slower than approximate off-shell
- Could Machine Learning help?



- In a proof of concept study at LO, we show that combining direct diffusion neural network with a classifier leads to good results
- Training only requires 5M events and takes about a day
- DIDI rew. can be applied to an existing sample
- NLO is work in progress

Talk by M. Kuschick on Wed at 11:00!

Summary

Summary

- Off-shell effects needed to match the experimental precision

- For $t\bar{t} + tW$ production they are available at NLOPS in `POWHEG BOX RES`
  - Resonance virtualities must be preserved for POWHEG and shower emissions
  - Interference with subleading production modes need be included exactly
  - Shower approximations for hardest emission in decay not good enough

- New developments (`bb4l-dl` and `bb4l-sl`):
  - Matching uncertainties related to the resonance-aware formalism small
  - Semileptonic decay channel available in the bb4l-sl approximation
  - Inverse width correction needed for consistent comparison to inclusive calculations

Thank you!

Backup

Inverse width correction

[TJ, Lindert, Pozzorini '23]

- Needed for consistency of production and off-shell cross sections:

$$\int_{\mathrm{dec}} \mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma \qquad \text{where} \quad \mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma \frac{\mathrm{d}\Gamma}{\Gamma} \quad \text{and} \quad \Gamma = \int_{\mathrm{dec}} \mathrm{d}\Gamma$$

- Naive calculations in NWA deviate:

$$\text{with} \quad \begin{aligned} \mathrm{d}\sigma_{\mathrm{NLO}} &= \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1 \\ \mathrm{d}\Gamma_{\mathrm{NLO}} &= \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_1 \\ \Gamma_{\mathrm{NLO}} &= \Gamma_0 + \Gamma_1 \end{aligned}$$

$$\mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 \frac{\mathrm{d}\Gamma_0}{\Gamma_{\mathrm{NLO}}} + \mathrm{d}\sigma_1 \frac{\mathrm{d}\Gamma_0}{\Gamma_{\mathrm{NLO}}} + \mathrm{d}\sigma_0 \frac{\mathrm{d}\Gamma_1}{\Gamma_{\mathrm{NLO}}}$$

$$\int_{\mathrm{dec}} \mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 \int_{\mathrm{dec}} \frac{\mathrm{d}\Gamma_{\mathrm{NLO}}}{\Gamma_{\mathrm{NLO}}} + \mathrm{d}\sigma_1 \int_{\mathrm{dec}} \frac{\mathrm{d}(\Gamma_{\mathrm{NLO}} - \Gamma_1)}{\Gamma_{\mathrm{NLO}}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1 - \mathrm{d}\sigma_1 \frac{\Gamma_1}{\Gamma_{\mathrm{NLO}}}$$

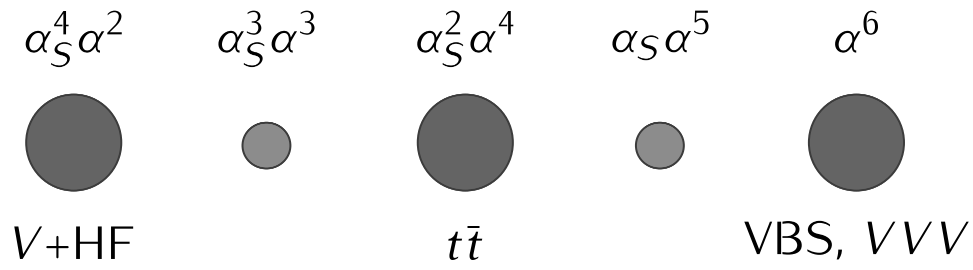
- Unless we expand inverse of the width: $\frac{1}{\Gamma_{\mathrm{NLO}}} \to \frac{1}{\Gamma_0}\left(1 - \frac{\Gamma_1}{\Gamma_0}\right)$

- Also fully off-shell calculations need *inverse width correction*:

$$\bar{B}_h(\Phi_{\mathrm{B}})\Big|_{\mathrm{exp}} = \left(\prod_{r\in\mathcal{R}(h)} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right)\left[\bar{B}_h(\Phi_{\mathrm{B}}) - \left(\sum_{r\in\mathcal{R}(h)} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) B_h(\Phi_{\mathrm{B}})\right]$$

Semileptonic $t\bar{t}$

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



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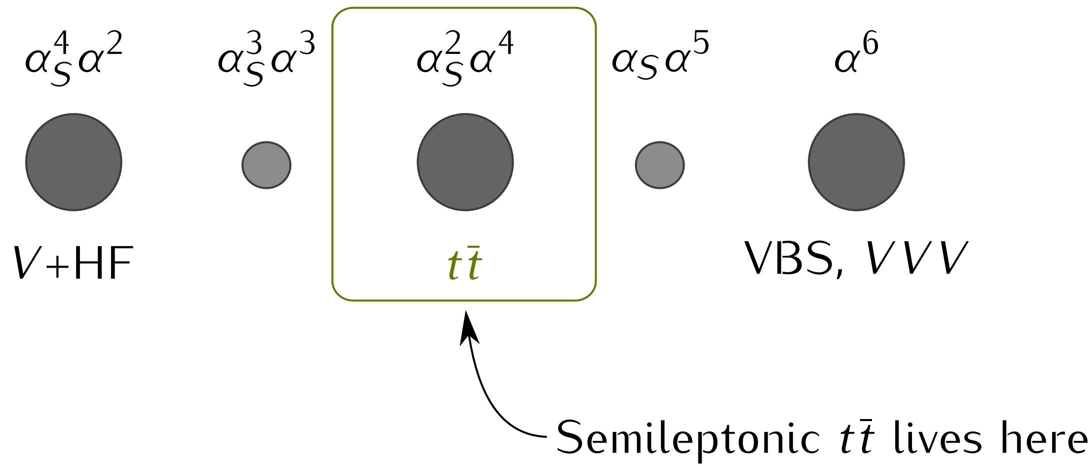
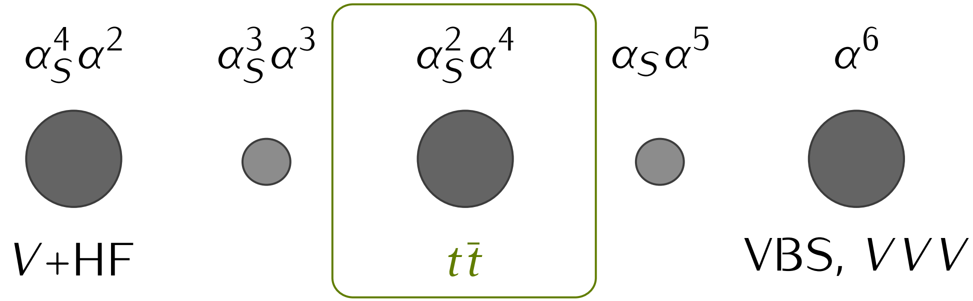


Semileptonic $t\bar{t}$

WWU MÜNSTER

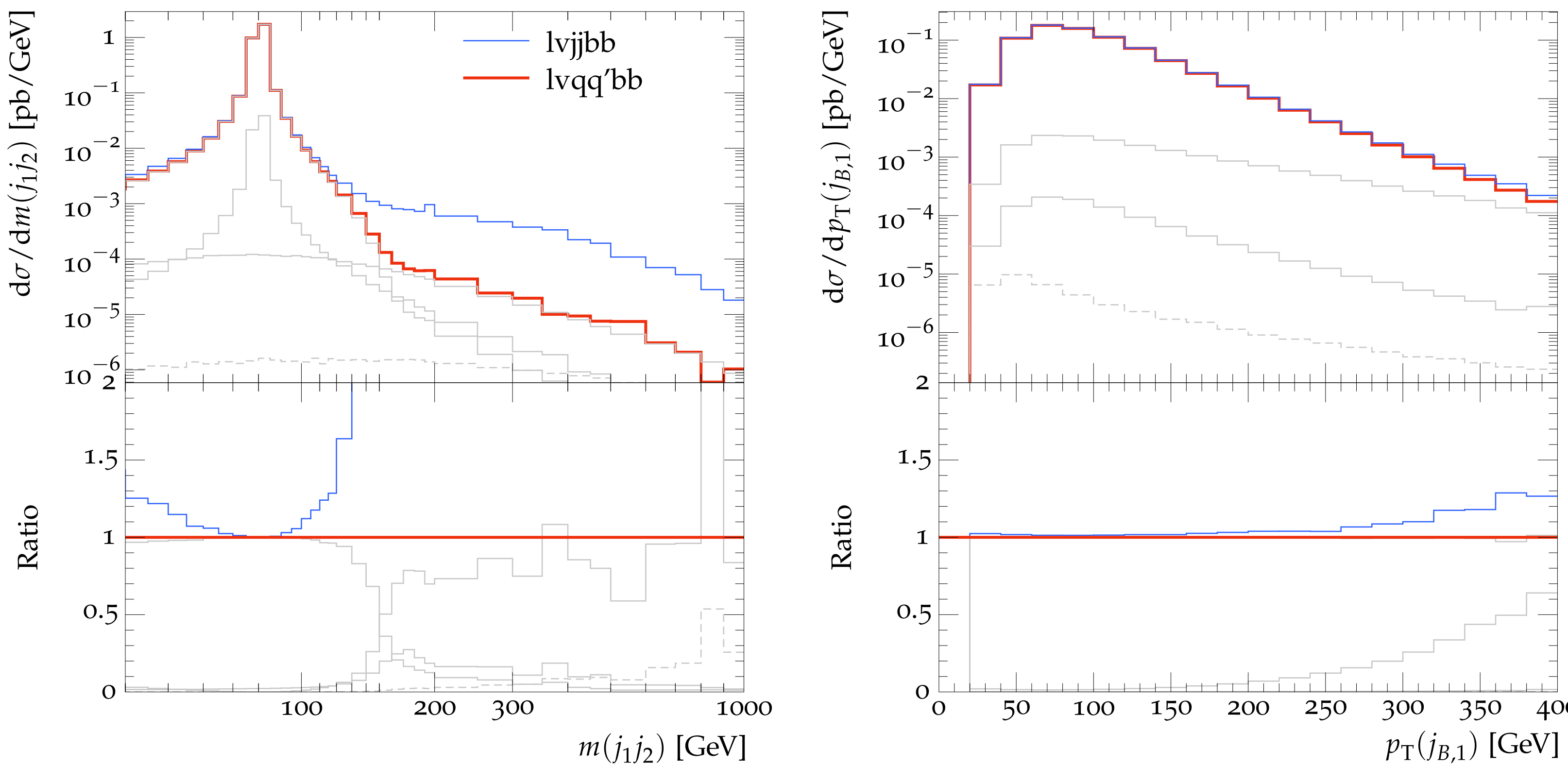
- Consider the signature $pp \to \ell^{\pm}\nu jjb\bar{b}$ at LO



- 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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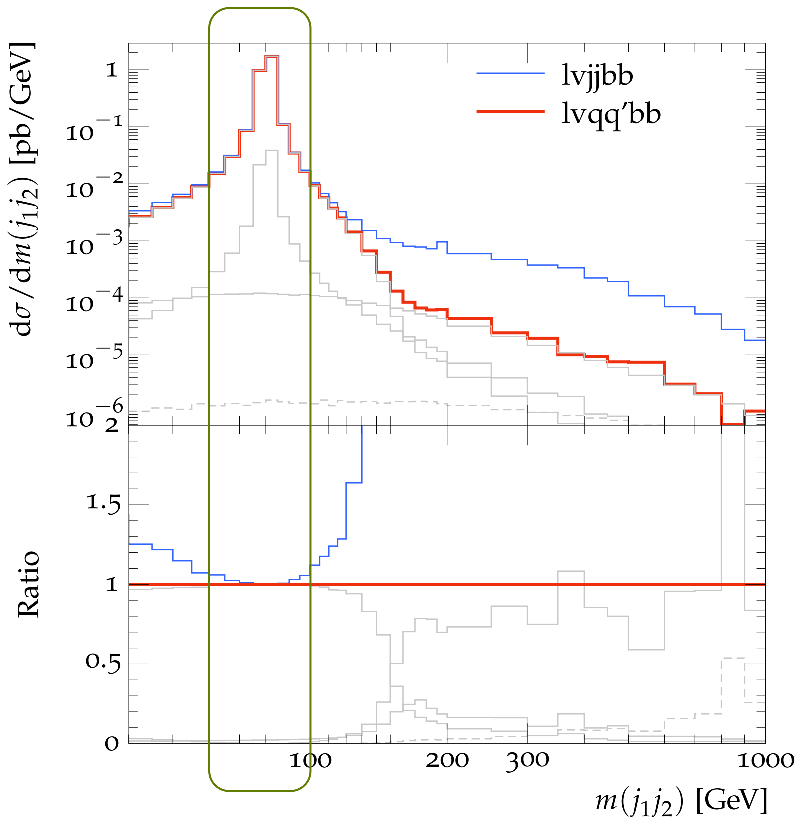

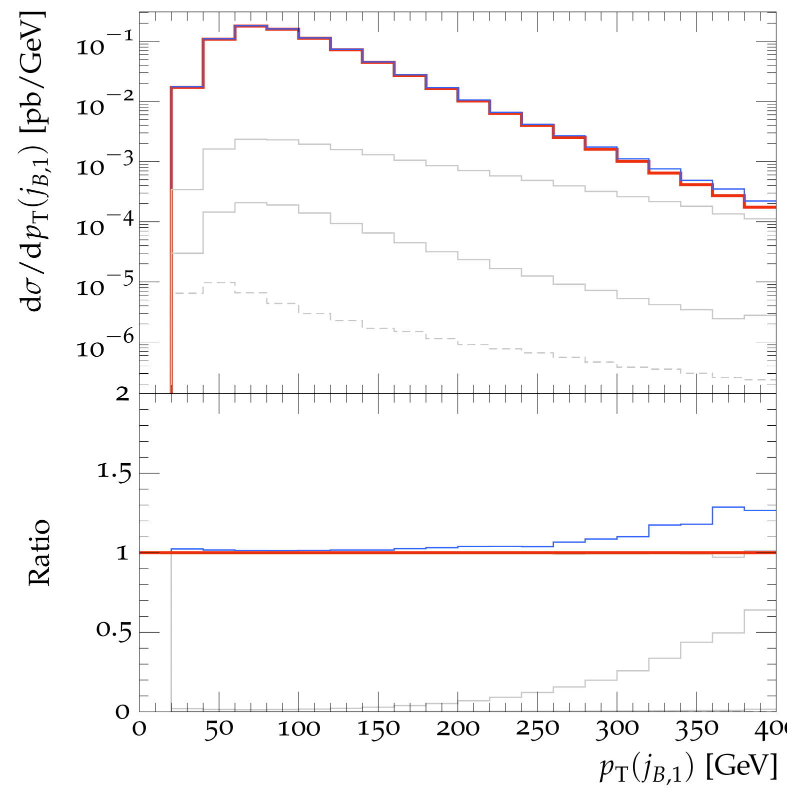

Semileptonic $t\bar{t}$

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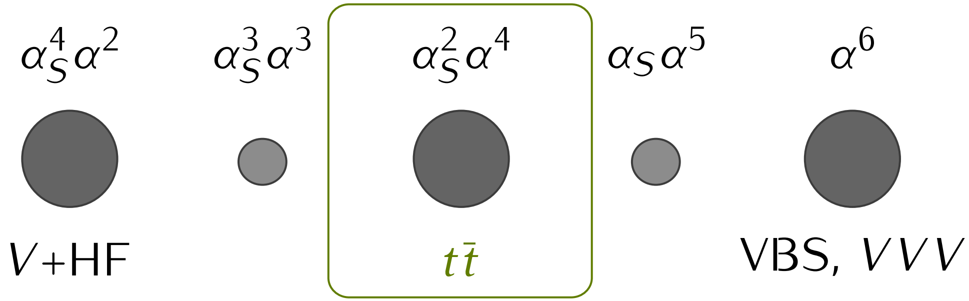

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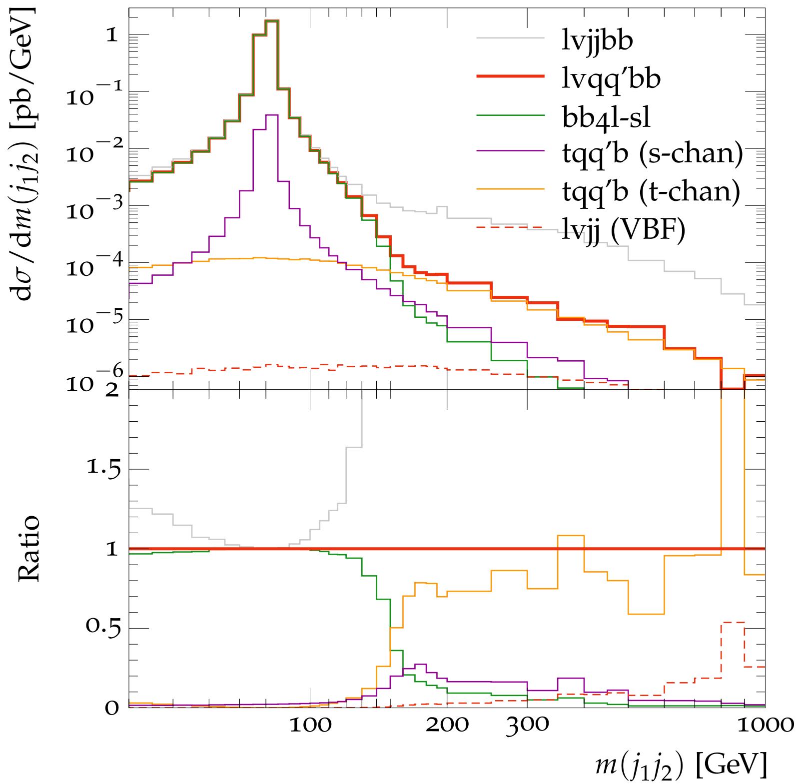
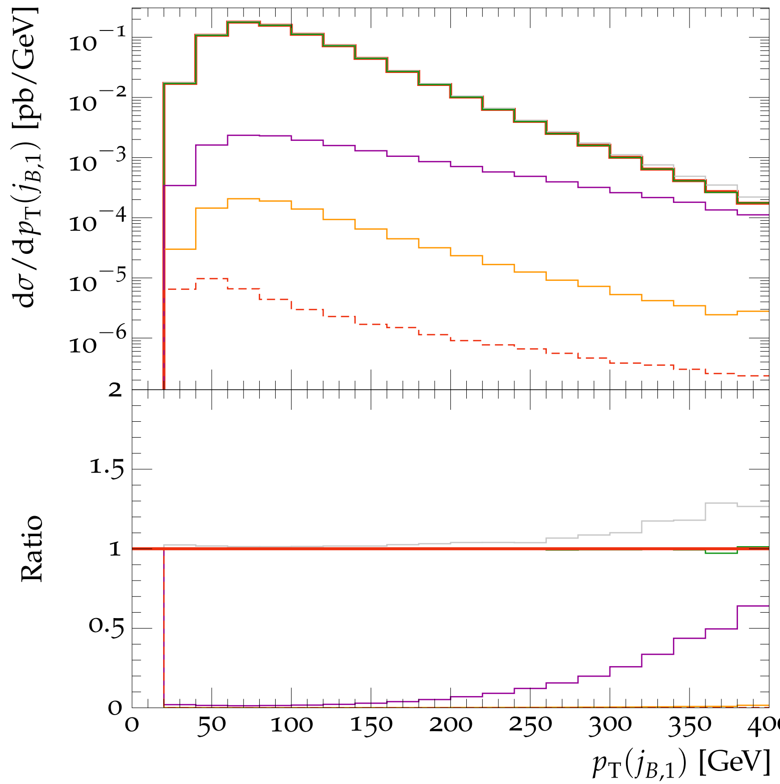
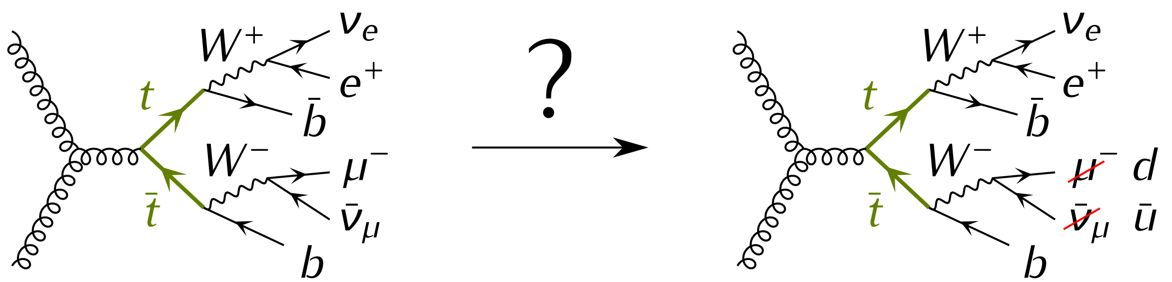




Semileptonic $t\bar{t}$ from dileptonic $t\bar{t}$?

- 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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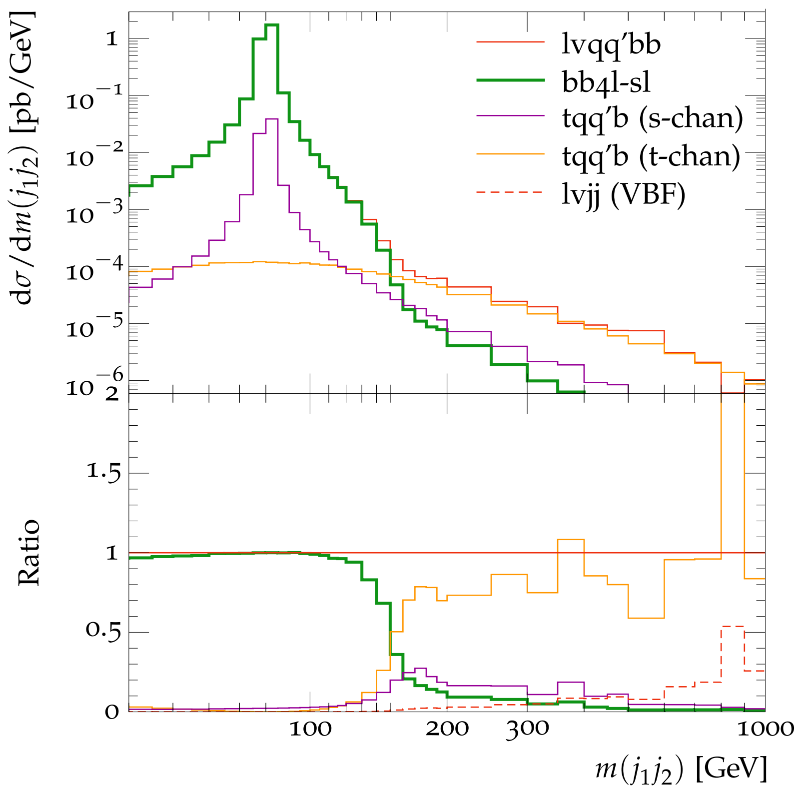

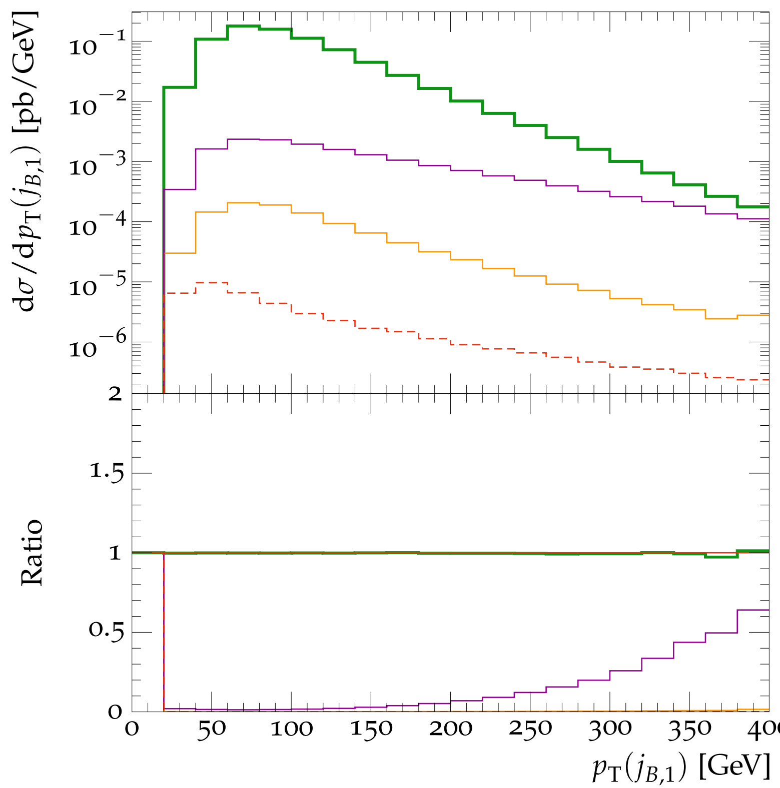

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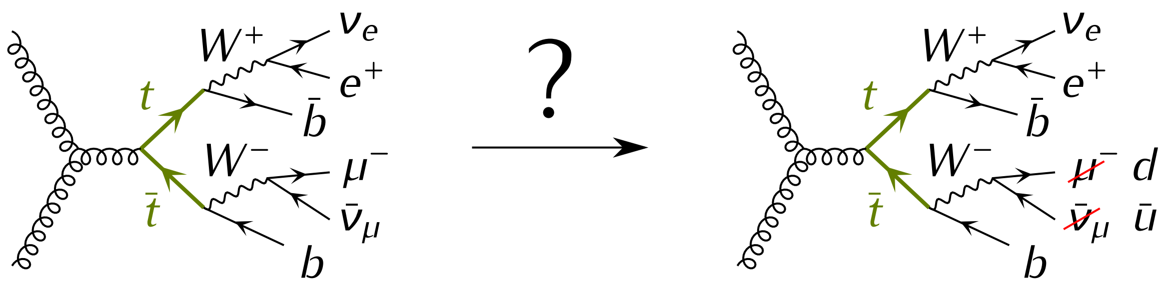

$$d\sigma(\text{"bb4l} - \text{sl"}) = d\sigma(\text{bb4l})\frac{\text{BR(SL)}}{\text{BR(DL)}}$$

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

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

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

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

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

bb4l-sl

- Semileptonic $t\bar{t}$ NLO+PS predictions from `bb4l`:
  - Read in `bb4l` LHE files with `allrad`
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$$\times \left[\Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(q_{cut}) + \Delta_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(k_T^{\alpha_W}) \frac{R_{\alpha_W}^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_{\alpha_W}(\Phi_B, \Phi_{rad}^{\alpha_W}))}{B^{pp\to\ell\nu_l q\bar{q}b\bar{b}}(\Phi_B)} d\Phi_{rad}^{\alpha_W} \right]$$

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

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

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- Semileptonic $t\bar{t}$ NLO+PS predictions from `bb4l`:
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bb4l

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

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

emission from W^- or W^-

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

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

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

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

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