bb4l generator

Tomáš Čežo

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

Theory-Experimental Top Quark Mass Workshop
29/01/25

$b\bar{b}4l \leftrightarrow t\bar{t} + tW$ in dilepton channel

- 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

$b\bar{b}4l \leftrightarrow t\bar{t} + tW$ in dilepton channel

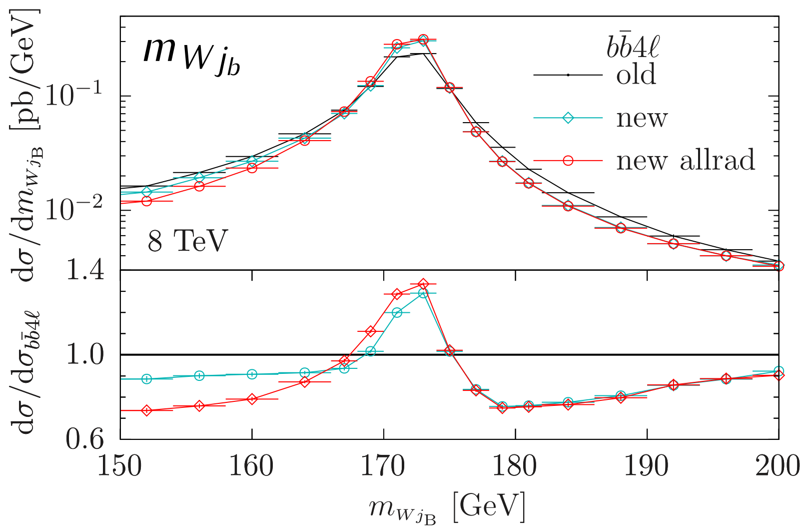
- Motivations:
  - Why top quark? Because it's a versatile probe of the SM and a window to NP.
    - a.) Coloured object that b.) decays electroweakly and c.) couples strongly to the Higgs boson
  - Why top quark at LHC? Because "several hundred million tops produced" …
    - …implies theory will soon lag behind the experiment.
    - …means it is major background in many other LHC analyses.
  - 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

Do we need off-shell effects?

Do we need off-shell effects?

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



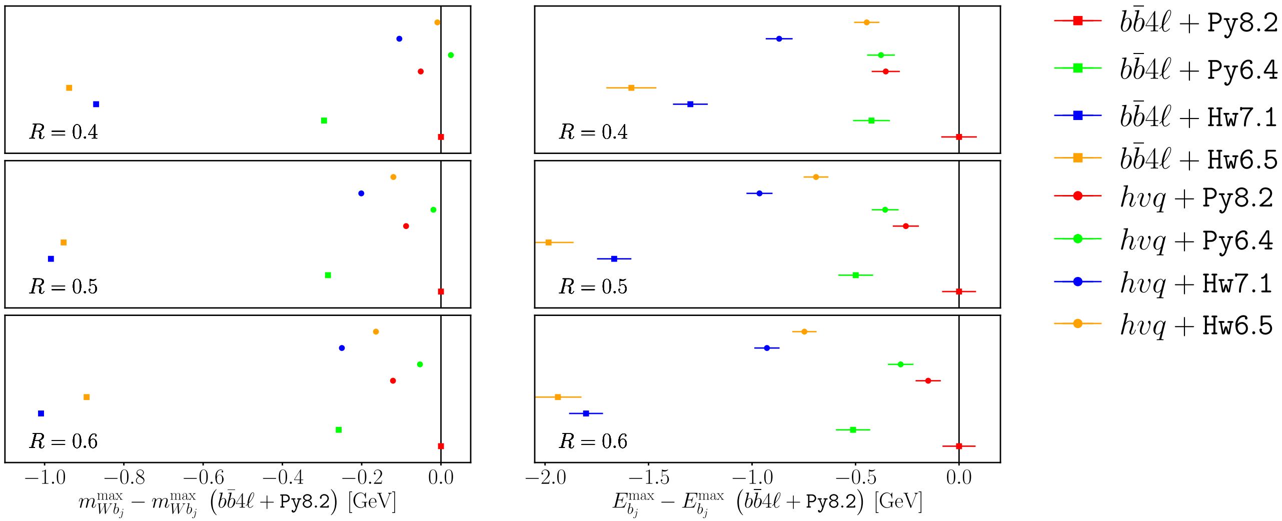
[**TJ**, Nason '15],
[**TJ**, Lindert, Nason, Oleari, Pozzorini '16]

  - 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

Do we need off-shell effects?

- Off-shell effects distort the top mass shape and other distributions
  - Potentially affecting $\boldsymbol{m_t}$ and y_t measurements

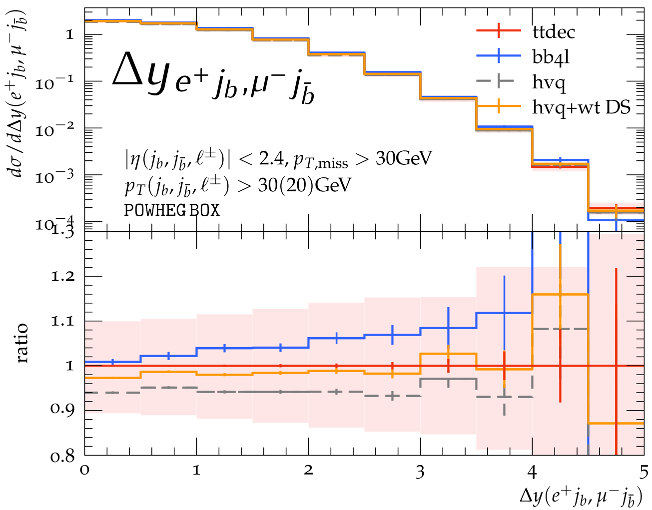


[Ferrario Ravasio, **TJ**, Nason, Oleari '18, '19], [ATL-PHYS-PUB -2021-042]

- Proper treatment of interference required
  - To describe the data
  - And if you have it, you can try measuring Γ_t in tails

Do we need off-shell effects?

- Off-shell effects distort the top mass shape and other distributions
  - Potentially affecting m_t and y_t measurements

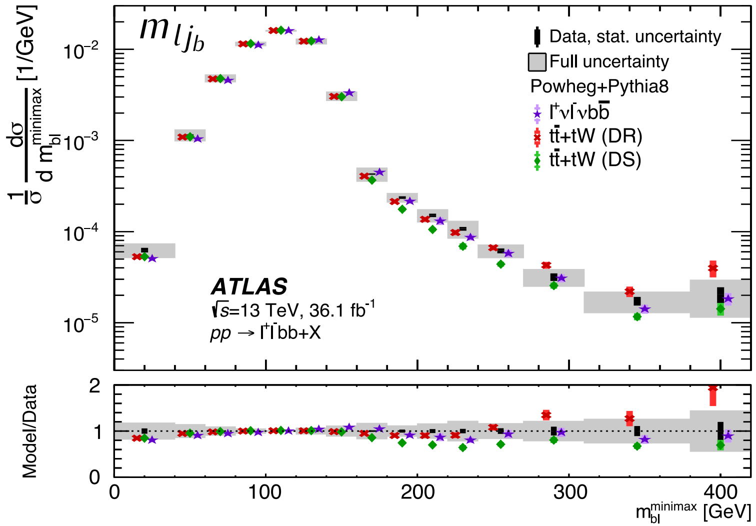


[Ferrario Ravasio, **TJ** '21]

- Proper treatment of interference required
  - To describe the data
  - And if you have it, you can try measuring Γ_t in tails

Do we need off-shell effects?

- Off-shell effects distort the spectra used for measurements of top properties
  - Potentially affecting m_t and y_t measurements
- Proper treatment of interference required
  - To describe the data

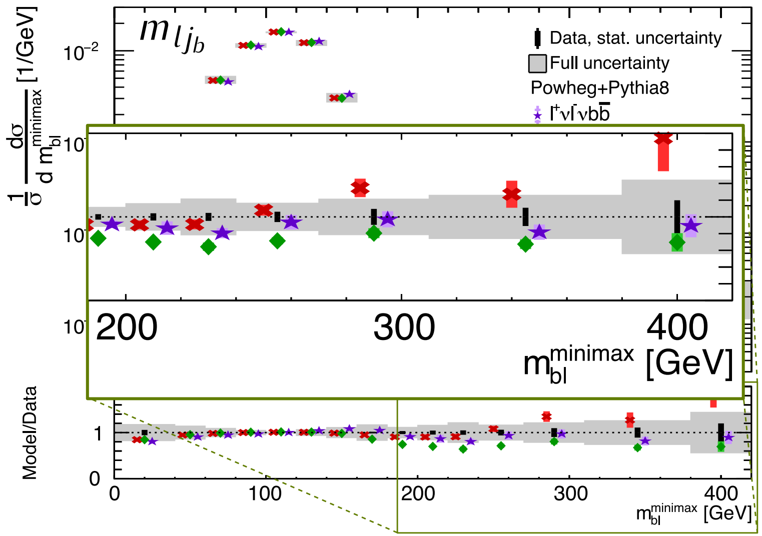


[**PRL** 121, 152002]

- And if you have it, you can try measuring Γ_t in tails

Do we need off-shell effects?

- Off-shell effects distort the spectra used for measurements of top properties
  - Potentially affecting m_t and y_t measurements
- Proper treatment of interference required
  - To describe the data

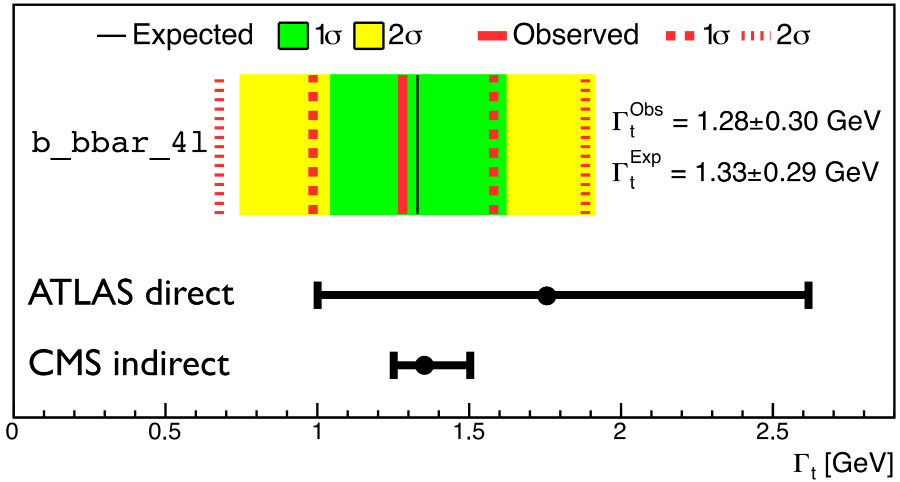


[**PRL** 121, 152002]

- And if you have it, you can try measuring Γ_t in tails

Do we need off-shell effects?

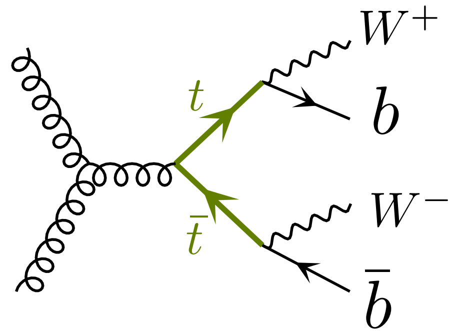
- Off-shell effects distort the spectra used for measurements of top properties
  - Potentially affecting m_t and y_t measurements
- Proper treatment of interference required
  - To describe the data
  - And if you have it, you can try measuring Γ_t in tails



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

NLOPS with POWHEG

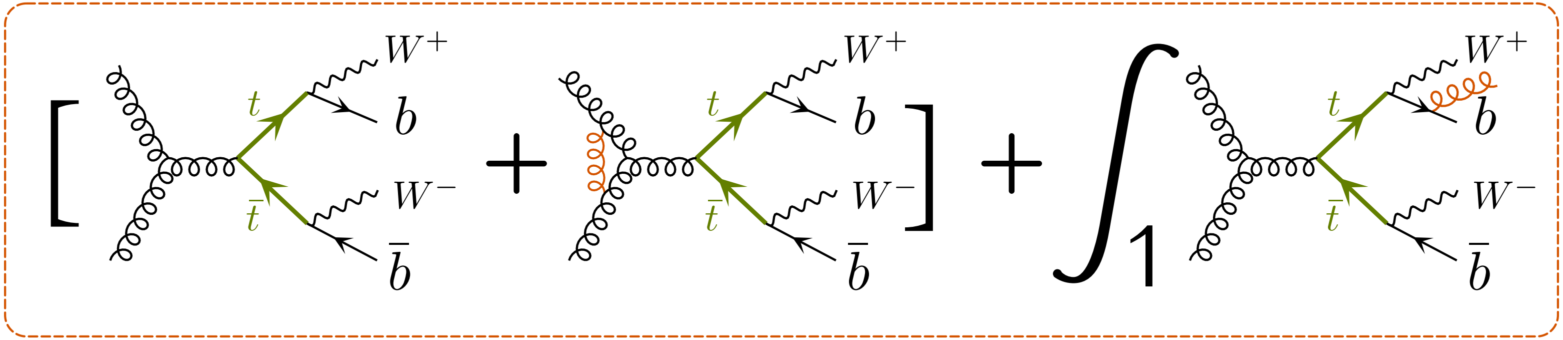
POWHEG Parton Shower Matching



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

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

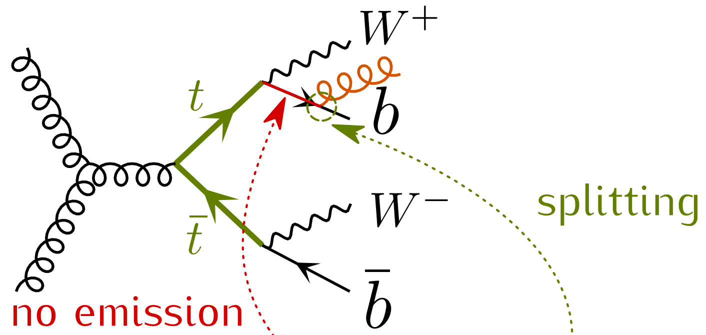
POWHEG Parton Shower Matching



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

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

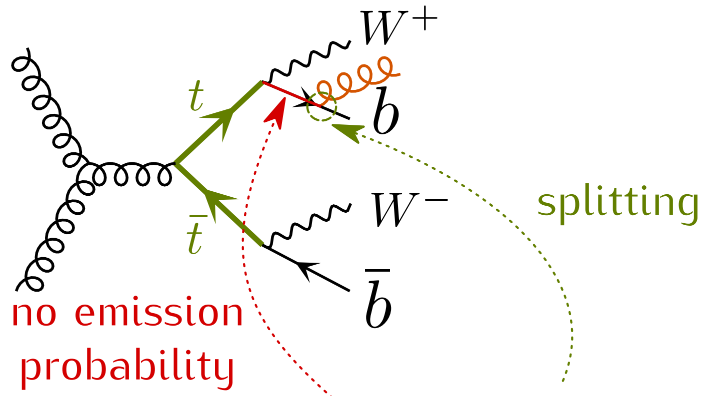
POWHEG Parton Shower Matching



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

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

POWHEG Parton Shower Matching



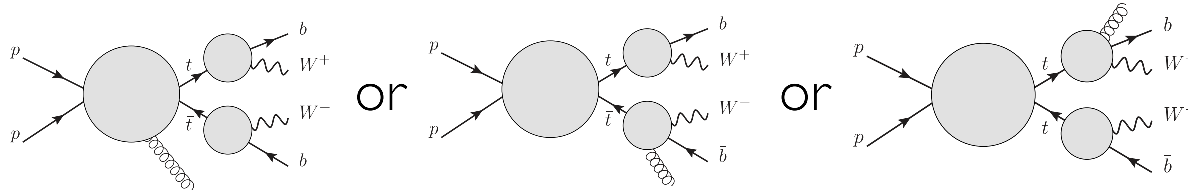
$$\mathrm{d}\,\sigma = \overline{B}(\Phi_B)\,\mathrm{d}\,\Phi_B \left[\Delta(q_{\mathrm{cut}}) + \sum_\alpha \Delta(k_T^\alpha)\,\frac{R_\alpha(\Phi_\alpha(\Phi_B,\Phi_{\mathrm{rad}}))}{B(\Phi_B)}\,\mathrm{d}\,\Phi_{\mathrm{rad}}\right]$$

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

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

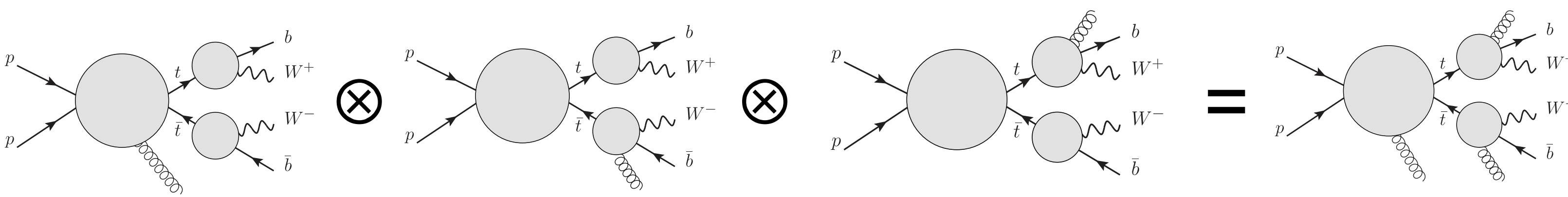
Recent improvement: resonance awareness

- Traditional matching:



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

- Multiple radiation scheme:



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

† 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`)

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

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

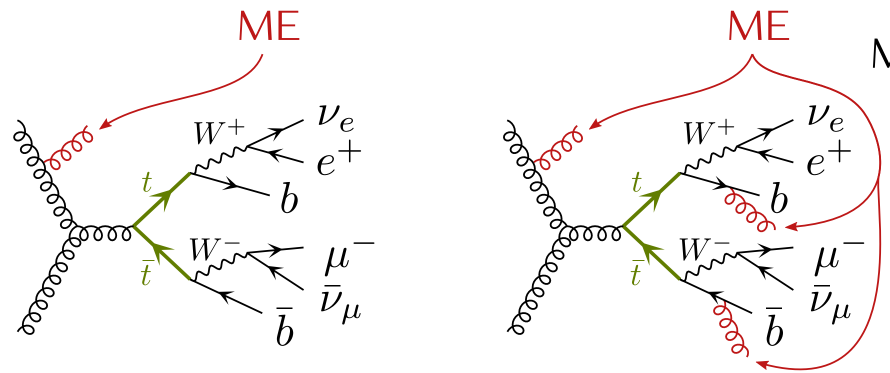
- We published a MC event generator `POWHEG BOX RES/bb4l`
  - Implementing process $pp \to l^+ \nu_l \ell^- \bar{\nu}_\ell b\bar{b}$ up to $\mathcal{O}(\alpha_S^2 \alpha^4 \times \alpha_S)$, l, ℓ different
  - ME in 4FNS ($m_b > 0$) but 5FNS PDFs also possible (CGN '98 matching)
  - Matching to PS using 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

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



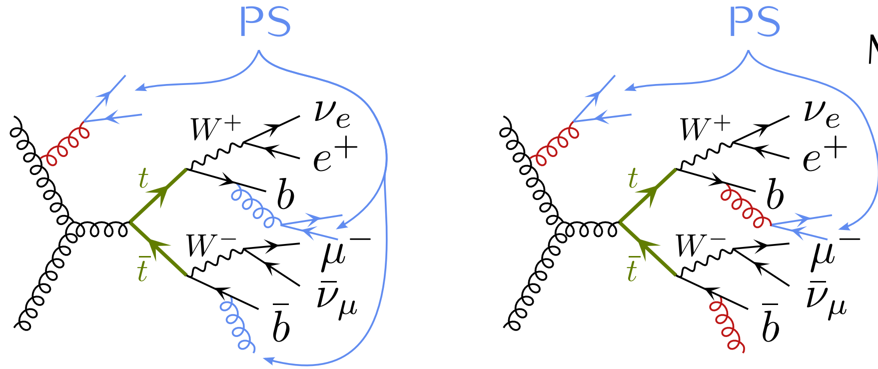
Multiple-radiation-improved NLOPS (`allrad`)

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

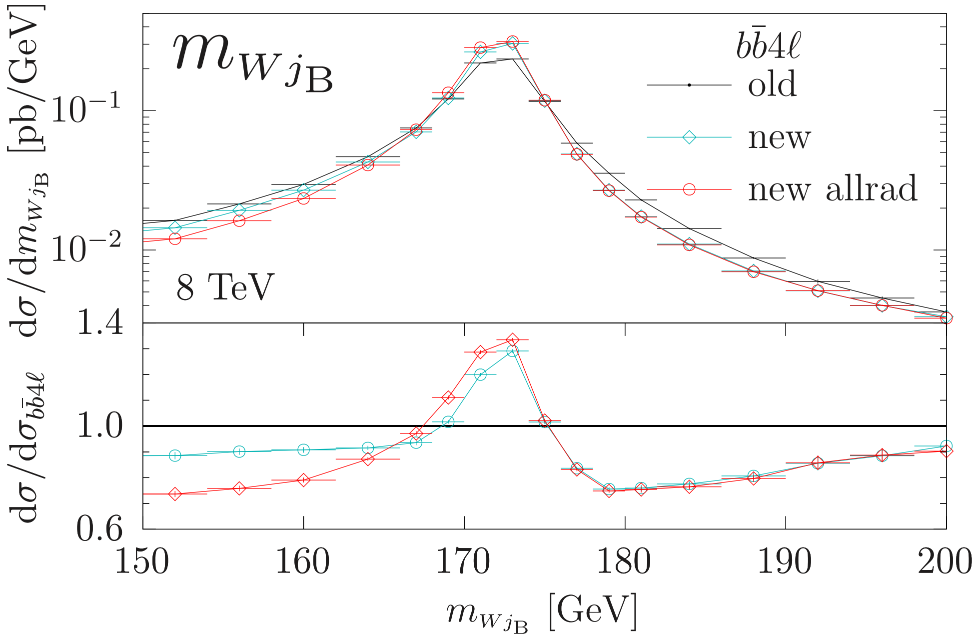


Multiple-radiation-improved NLOPS (allrad)

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

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

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

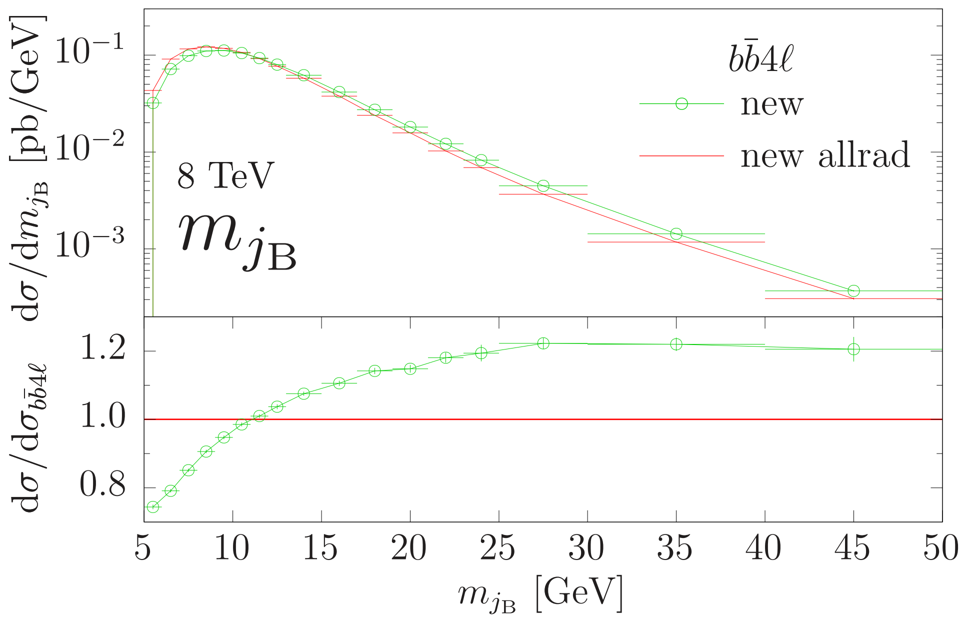


- old: non-resonance aware
- new: resonance aware
- new allrad: resonance aware, up to three emissions

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

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

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



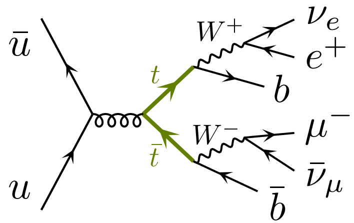
- old: non-resonance aware
- new: resonance aware
- new allrad: resonance aware, up to three emissions

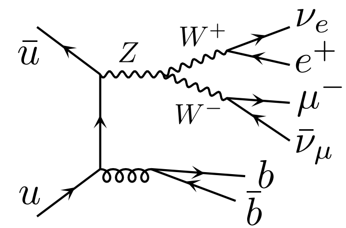
Beyond `bb41`

Resonance history projector uncertainties

[TJ, Lindert, Pozzorini '23]

bb4l:



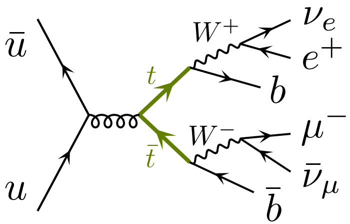


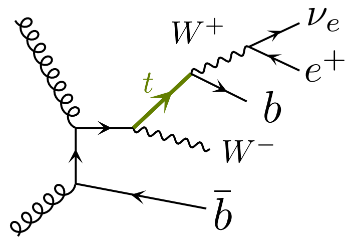
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

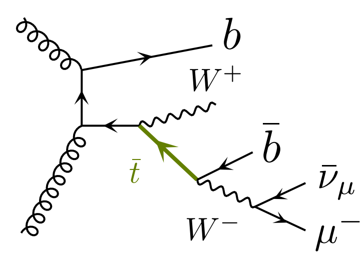
$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

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

bb4l-dl:







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

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

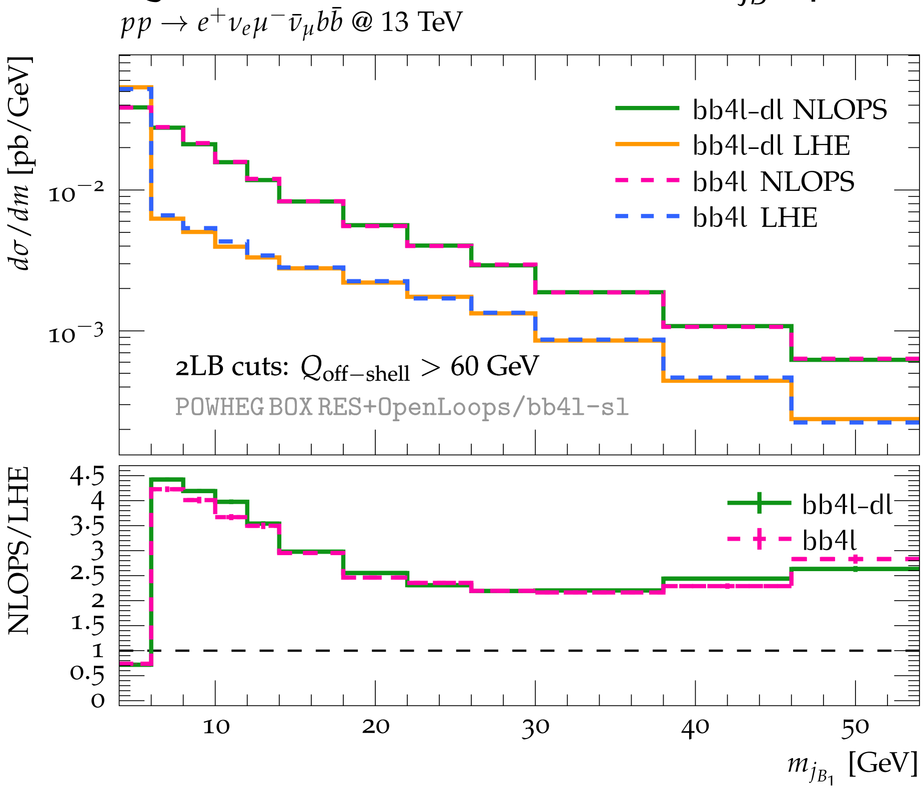
$$P_3 = B_{\bar{t}W^-}$$

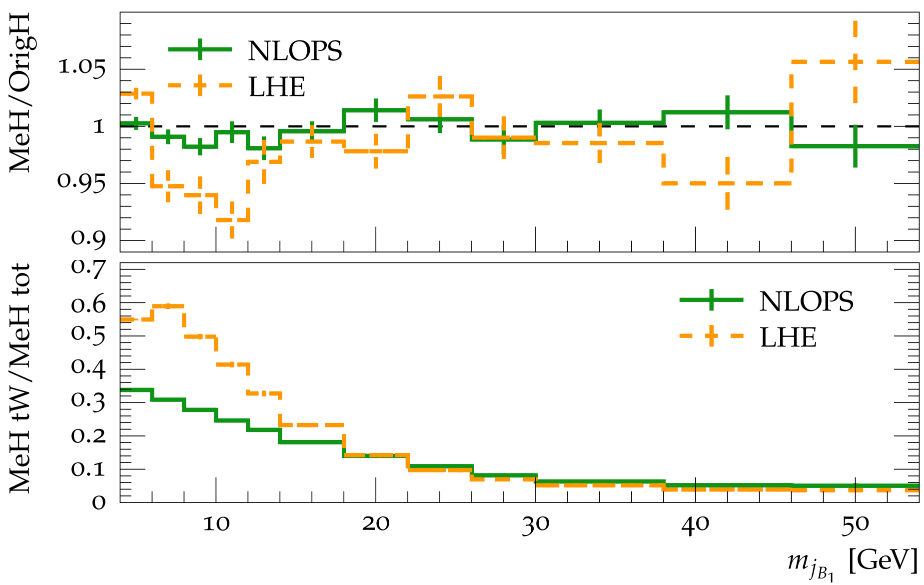
$$d\sigma = \frac{P_1}{P_1+P_2+P_3} d\sigma + \frac{P_2}{P_1+P_2+P_3} d\sigma + \frac{P_3}{P_1+P_2+P_3} d\sigma$$

Resonance history projector uncertainties

[TJ, Lindert, Pozzorini '23]

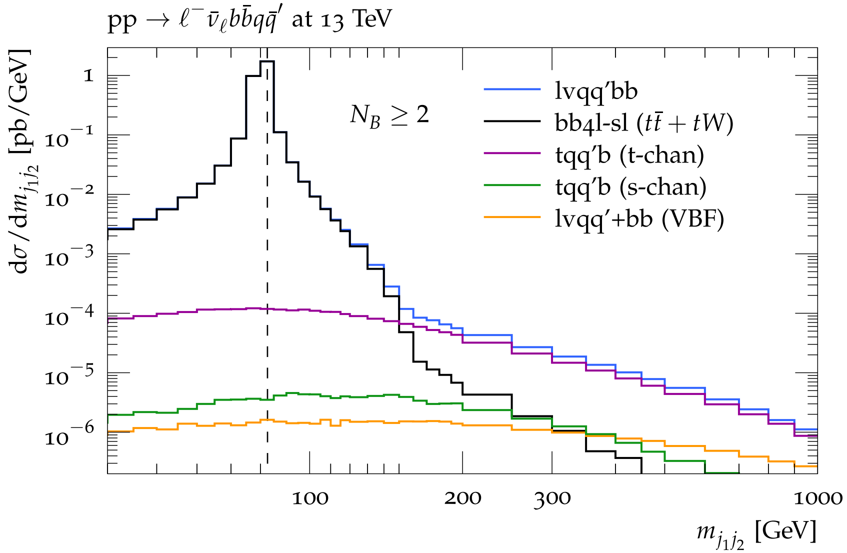
- Different resonance history projector prescriptions agree extremely well, the worst agreement we found was in m_{j_B} spectrum:

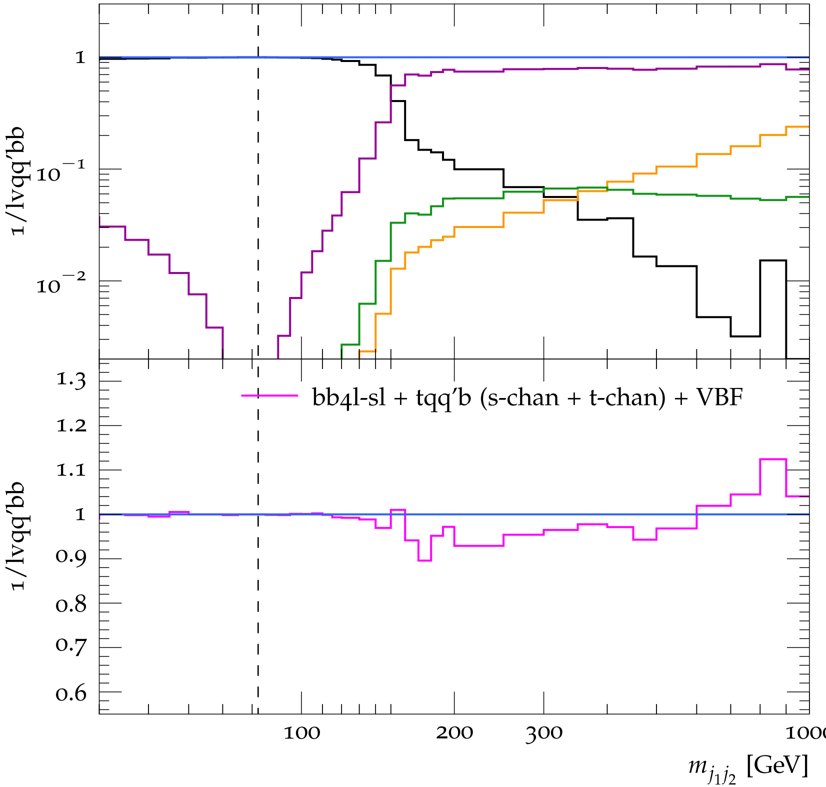




Semileptonic channel: bb4l-sl approximation
[TJ, Lindert, Pozzorini '23]

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

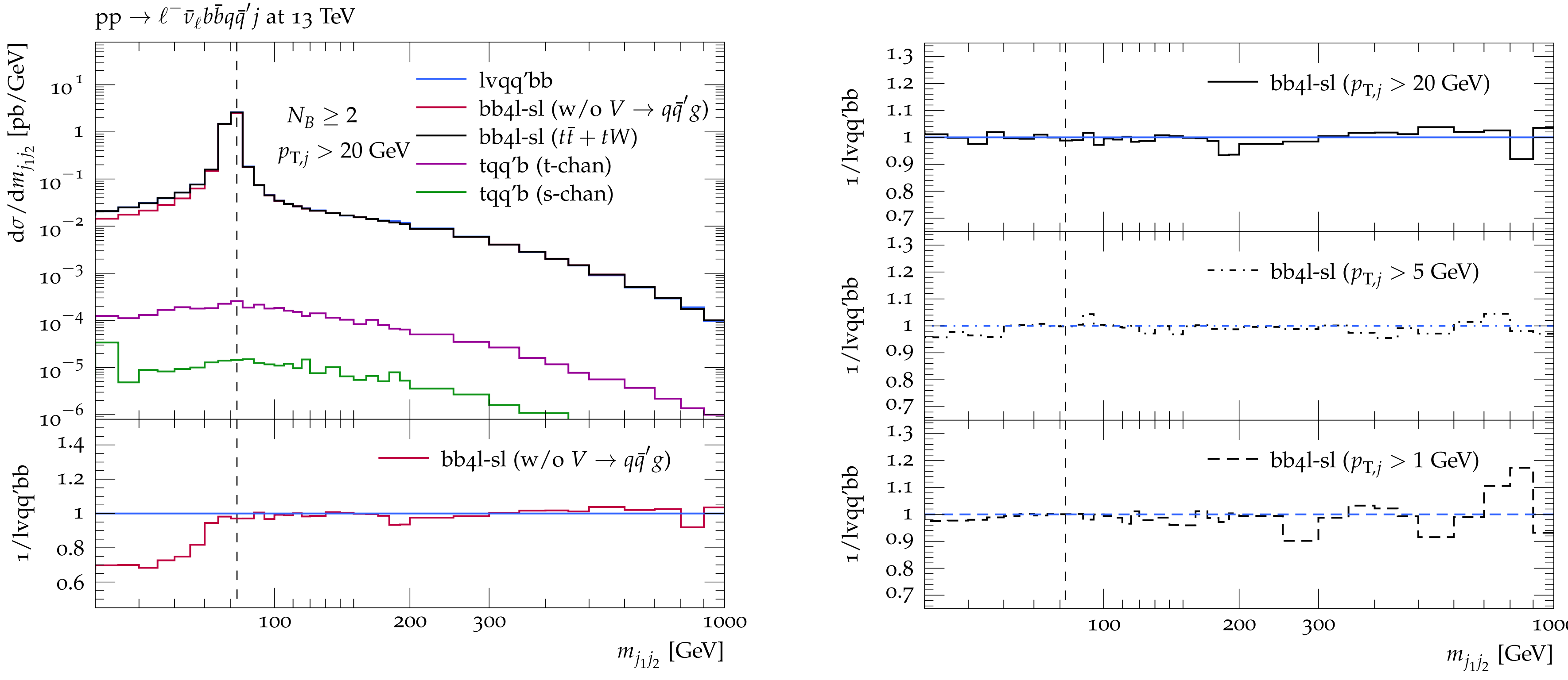




Semileptonic channel: bb4l-sl approximation

[TJ, Lindert, Pozzorini '23]

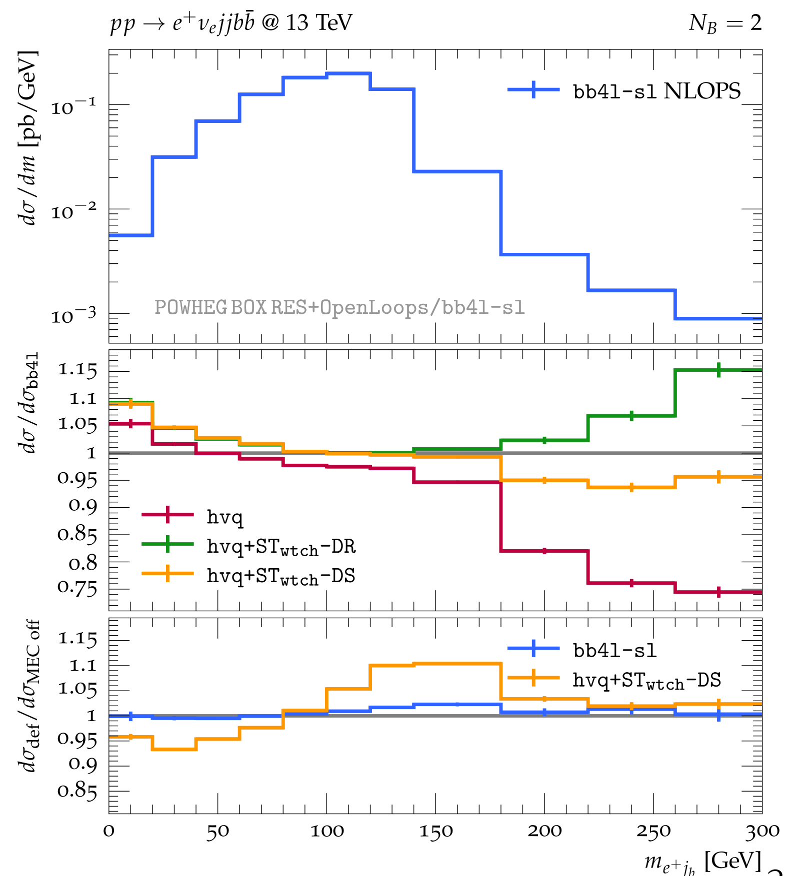
- ME of semileptonic decay channel much more difficult to evaluate, can we simplify?
  - Yes, by considering only dileptonic topologies:



Semileptonic channel

[TJ, Lindert, Pozzorini '23]

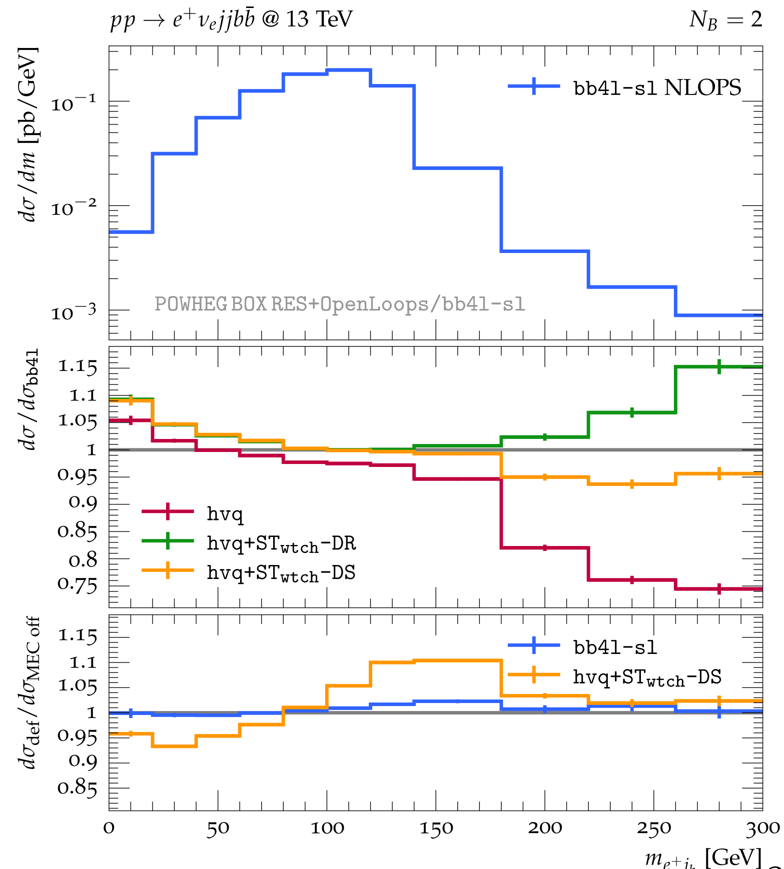
- NEW!: semileptonic decay channel
  - relies on an approximation assuming hadronic W is not far off shell ($\pm$20 GeV) and on the multiple radiation scheme
  - implemented as a plugin to `bb4l-dl`
    - produce dileptonic sample
    - replace leptonic decay of one W for a hadronic decay
    - attach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



Inverse width correction

[TJ, Lindert, Pozzorini '23]

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

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

- Naive calculations in NWA deviate:

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

with

$$\mathrm{d}\sigma_{\text{NLO}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1, \quad \mathrm{d}\Gamma_{\text{NLO}} = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_1, \quad \Gamma_{\text{NLO}} = \Gamma_0 + \Gamma_1$$

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

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

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

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

Inverse width correction

[TJ, Lindert, Pozzorini '23]

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

		inclusive phase space		$e^+\nu_e bbjj$ fiducial phase space			
				$R = 0.5$		$R = 0.2$	
		σ[pb]	$\frac{\sigma}{\sigma^{\text{NLOPS}}_{\texttt{bb4l-sl}}}$	σ[pb]	$\frac{\sigma}{\sigma^{\text{NLOPS}}_{\texttt{bb4l-sl}}}$	σ[pb]	$\frac{\sigma}{\sigma^{\text{NLOPS}}_{\texttt{bb4l-sl}}}$
`bb4l-sl`	NLOPS	57.56(2)	1	16.30(1)	1	14.639(9)	1
`bb4l-sl`	LHE	57.56(2)	1	16.33(1)	1.002	17.17(1)	1.173
`hvq` + $\texttt{ST}_{\texttt{wtch}}$`-DR`	NLOPS	56.892(8)	0.988	16.475(6)	1.011	14.780(6)	1.010
`hvq` + $\texttt{ST}_{\texttt{wtch}}$`-DR`	LHE	56.893(8)	0.988	17.754(7)	1.089	18.961(7)	1.295
`hvq` + $\texttt{ST}_{\texttt{wtch}}$`-DS`	NLOPS	56.859(8)	0.988	16.398(6)	1.006	14.667(6)	1.002
`hvq` + $\texttt{ST}_{\texttt{wtch}}$`-DS`	LHE	56.858(8)	0.988	17.746(7)	1.089	18.942(7)	1.294

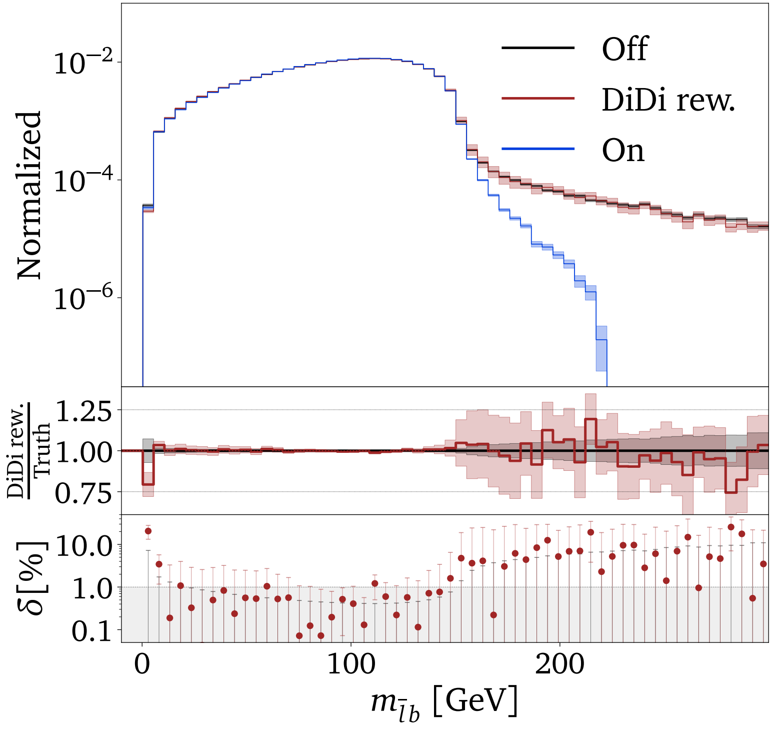
- Impressive agreement of `bb4l` with "on-shell" generators at NLOPS level once the Inverse width correction applied

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

See TOP2024 proceedings by M. Kuschick!

Summary

Summary

- Off-shell effects needed to match the experimental precision

- For $t\bar{t} + tW$ production they are available at NLOPS in the `bb4l` generator
  - 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!