new MCs: bb4l theory

UNIVERSITY
OF SUSSEX

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Workshop on top quark mass measurements
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"new" MCs: bb4l theory

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An NLO+PS generator for $t\bar{t}$ and Wt production and decay including non-resonant and interference effects

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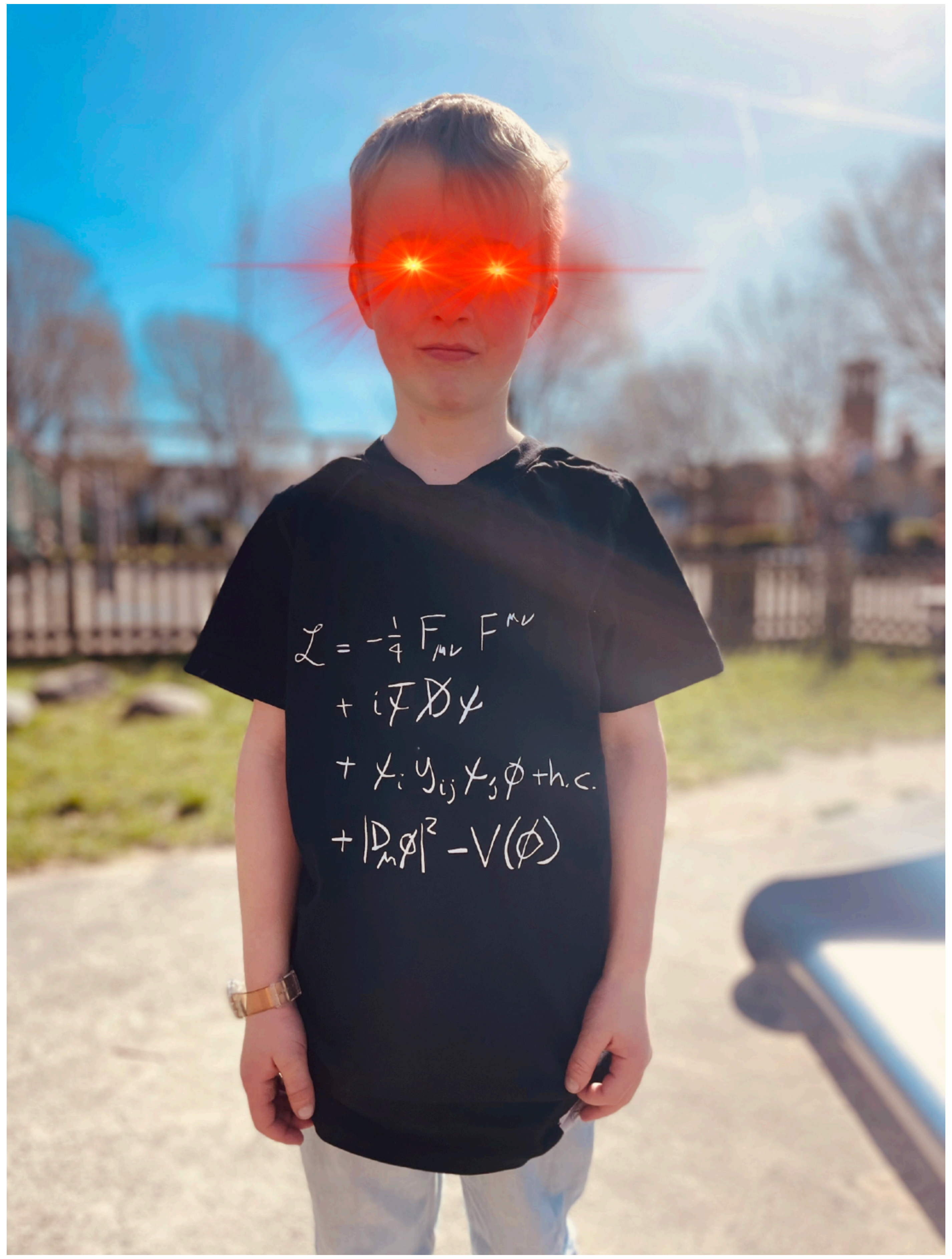
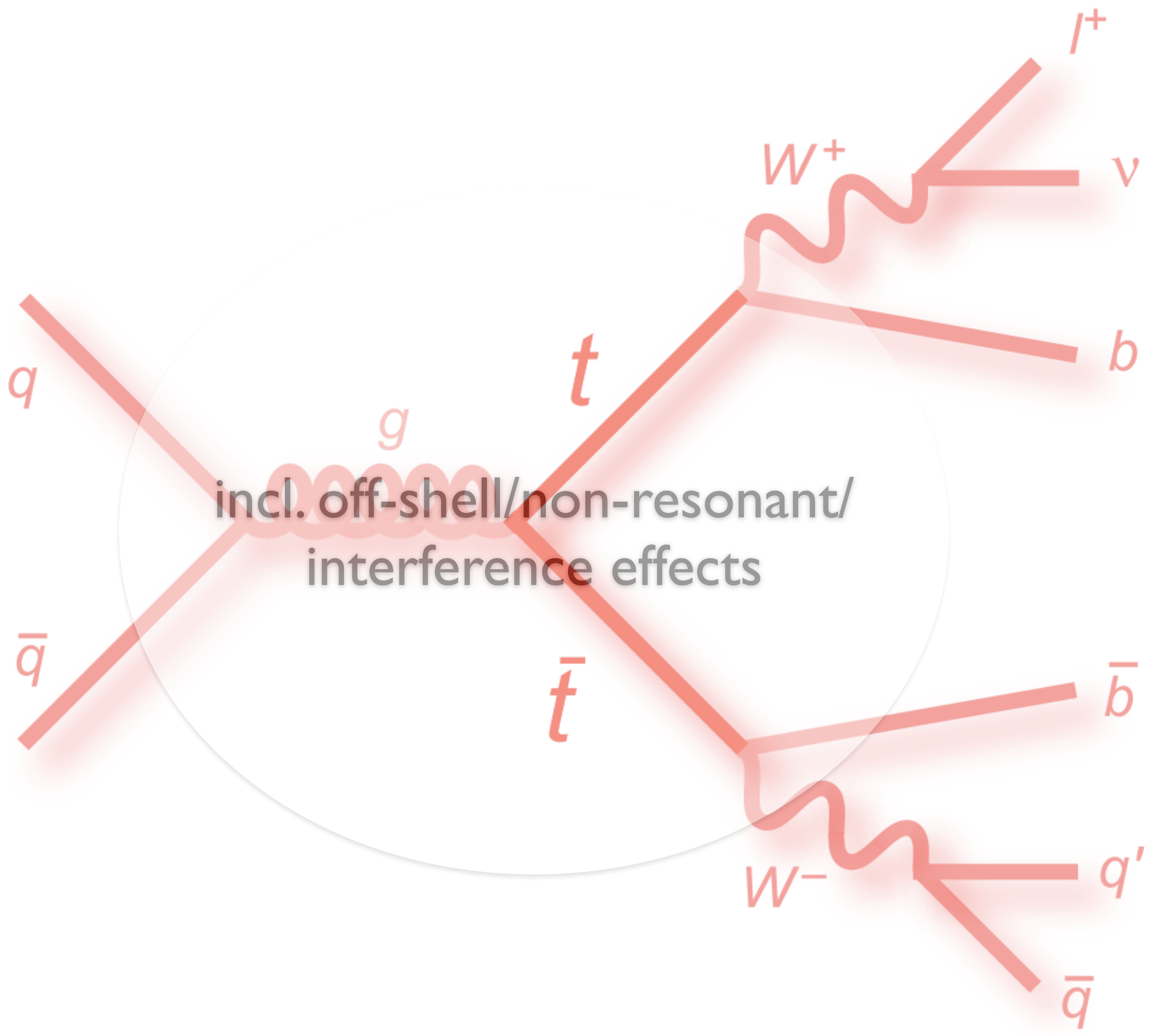


Top-pair production and decay



@ NLO+PS

bb4l

[Jezo, JML, Nason, Oleari, Pozzorini, '16]

Physics features:

- exact **non-resonant** / **off-shell** / **interference** / **spin-correlation** effects at NLO
- **consistent NLO+PS treatment of top resonances and off-shell top-decay chains** thanks to POWHEG-BOX-RES
- **top propagators including consistent quantum corrections** in well-defined (on-shell) renormalisation scheme
- **unified treatment of top-pair and Wt** production with interference at NLO
- access to phase-space regions with **unresolved b-quarks** and/or jet vetoes

bb4l-dl/-sl

[T. Jezo, JML, S. Pozzorini, 2307.15653]

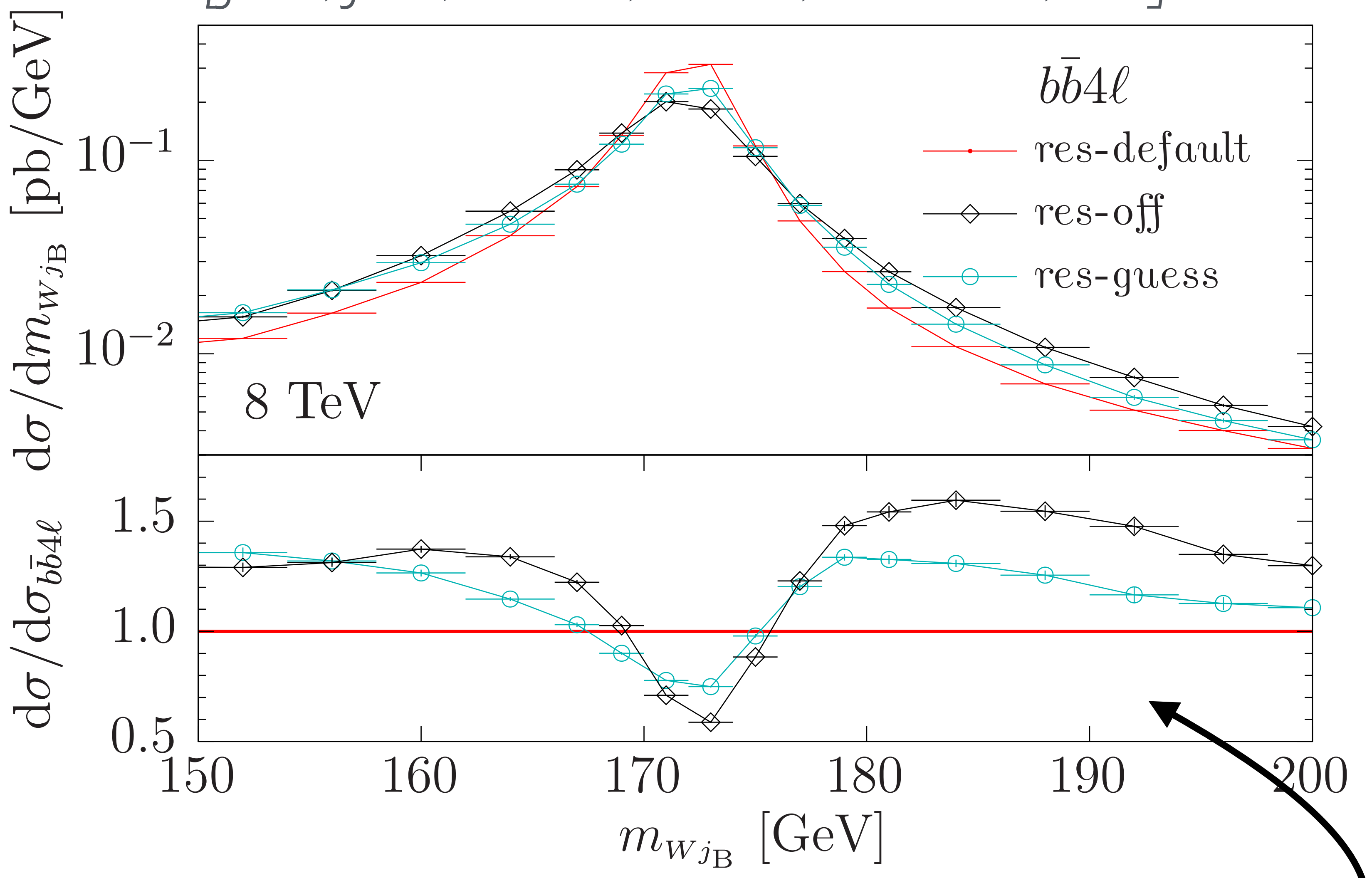
- Consistent inverse-width expansion
- Matrix-element based resonance histories
- **Semi-leptonic decays**

Resonance-unaware NLOPS matching in POWHEG

- Already at **NLO**:
  - FKS (and similar CS) subtraction does not preserve virtuality of intermediate resonances
  - Real (R) and Subtraction-term (S~B) with different virtuality of intermediate resonances
  - IR cancellation spoiled

  $\Longrightarrow$ **severe efficiency problem!**

[Jezo, JML, Nason, Oleari, Pozzorini, '16]



emission probability

- More severe problems at **NLO+PS**:
  - in POWHEG: $$\mathrm{d}\sigma = \bar{B}(\Phi_\mathrm{B})\,\mathrm{d}\Phi_\mathrm{B}\left[\Delta(q_\mathrm{cut}) + \sum_{c\in\mathcal{C}}\Delta(k_{\mathrm{T},c})\,\frac{R_c(\Phi_{\mathrm{R},c})}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_{\mathrm{rad},c}\right]$$

    Sudakov form-factor generated from uncontrollable R/B ratios:

    $$\Delta\left(\Phi_B, p_\mathrm{T}\right) = \exp\left\{-\sum_\alpha \int_{k_\mathrm{T}>p_\mathrm{T}} \frac{R(\Phi_\mathrm{R}^{(\alpha)})}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_\mathrm{rad}^{(\alpha)}\right\}$$

  - also subsequent radiation by the **PS** itself reshuffles internal momenta and does in general not preserve the virtuality of intermediate resonances.

  $\Longrightarrow$ **expect uncontrollable distortion of important kinematic shapes!**

Resonance-aware NLOPS matching in POWHEG-RES

Rigorous solution to all these issues within POWHEG-BOX-RES according to *[Ježo, Nason; '15]*

Idea: ***preserve invariant mass of intermediate resonances at all stages!***

✓ **NLO**:

- Split phase-space integration into regions dominated by a single **resonance history**
- within a given resonance history **modify FKS mappings**, such that they *always* preserve intermediate resonances
  - ⟹ R and S~B *always* with same virtuality of intermediate resonances
  - ⟹ IR cancellation restored

✓ **NLO+PS**:

- R and B related via modified FKS mappings
  - ⟹ R/B ratio with fixed virtuality of intermediate resonances
  - ⟹ Sudakov form-factor preserves intermediate resonances

✓ **PS**:

- pass information about resonance histories to the shower (via extension of LHE)
- tell **PS to respect intermediate resonances** (available in Pythia8)

$$\bar{B}_h(\Phi_\mathrm{B}) = \omega_h^{(\mathrm{hist})}(\Phi_\mathrm{B})\,\bar{B}(\Phi_\mathrm{B})$$

$$\omega_{h,c}(\Phi_\mathrm{R}) = \rho_{h,c}(\Phi_\mathrm{R})\left[\sum_{h'\in\mathcal{H}}\sum_{c'\in\mathcal{C}(h')}\rho_{h',c'}(\Phi_\mathrm{R})\right]^{-1}$$

$$\rho_{h,c}^{(\mathrm{hist})}(\Phi_\mathrm{R}) = \prod_{r\in\mathcal{R}(h,c)}\frac{M_r^4}{(q_{\mathrm{R},r}^2 - M_r^2)^2 + \Gamma_r^2 M_r^2}$$

original kinematic projectors

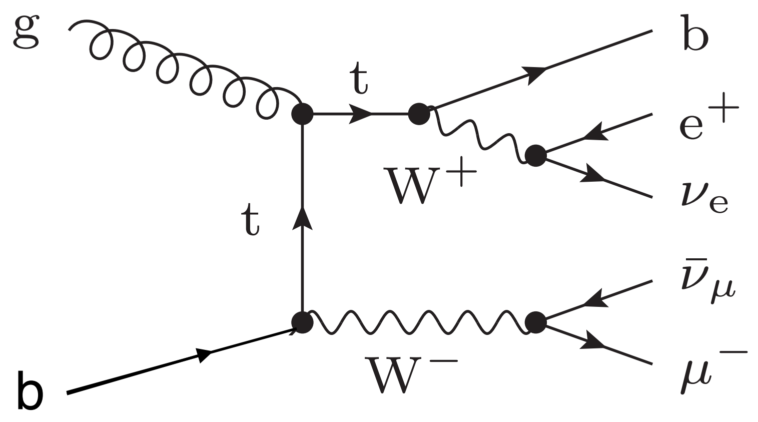
$$d\sigma = \sum_{h\in\mathcal{H}}\bar{B}_h(\Phi_\mathrm{B})\,d\Phi_\mathrm{B}\left[\Delta_h(q_\mathrm{cut}) + \sum_{c\in\mathcal{C}(h)}\Delta_h(k_{\mathrm{T},c})\,\frac{R_{h,c}(\Phi_{\mathrm{R},c})}{B_h(\Phi_\mathrm{B})}\,d\Phi_{\mathrm{rad},c}\right]$$

Interplay between top-pair and Wt

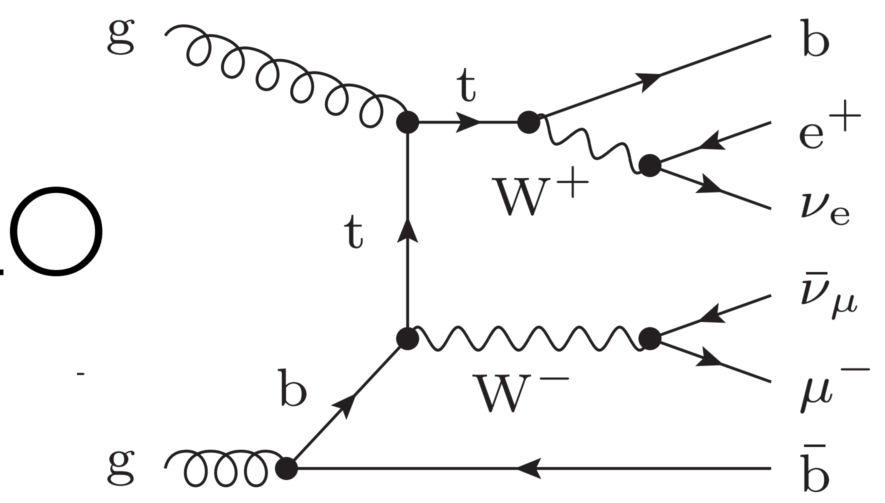
same finale state!

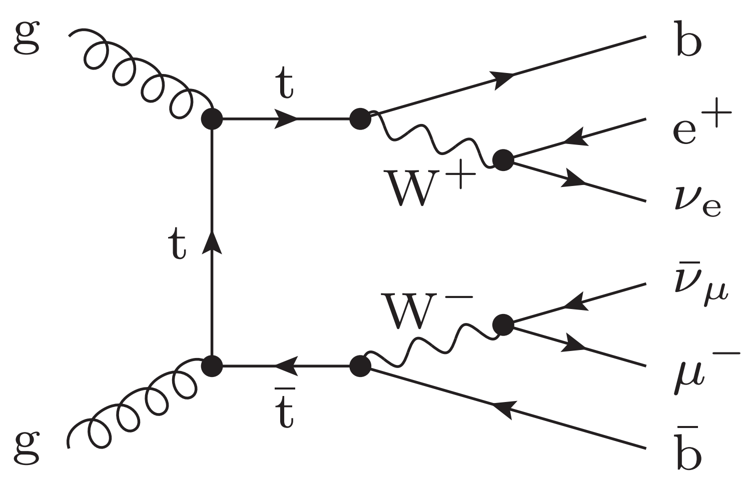
5FS

LO

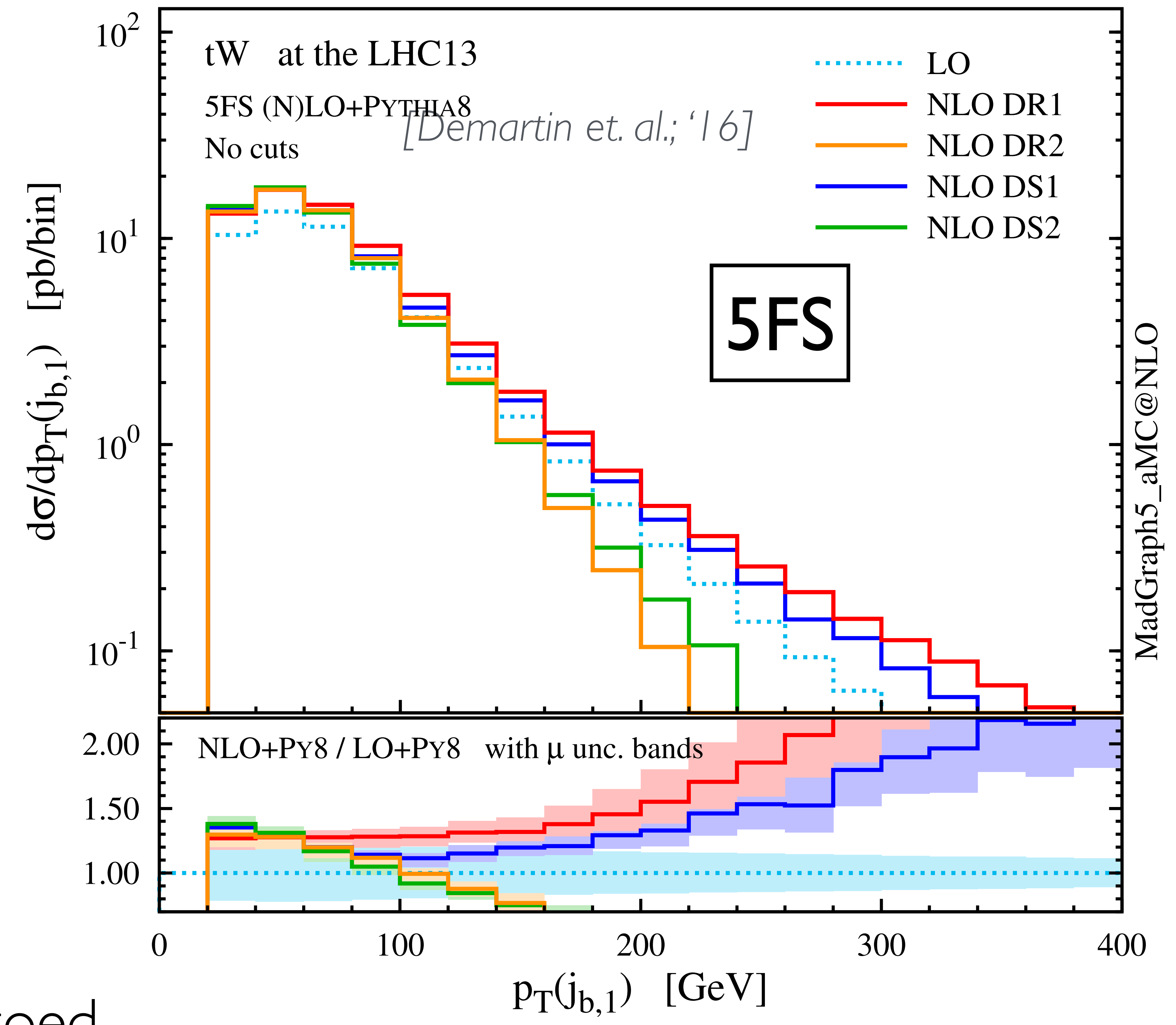


NLO



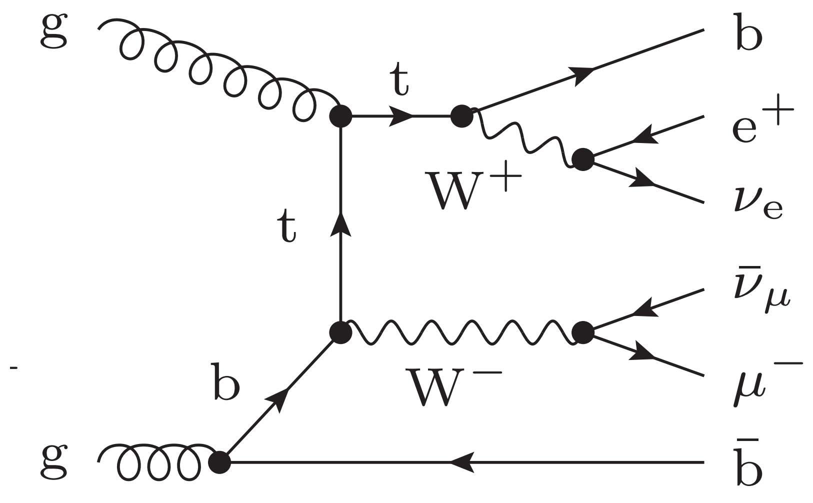


- **NLO corrections to Wt swamped by LO tt+decay**
- requires ad-hoc subtraction prescription:
  (Diagram Removal = DR vs. Diagram Subtraction = DS)
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

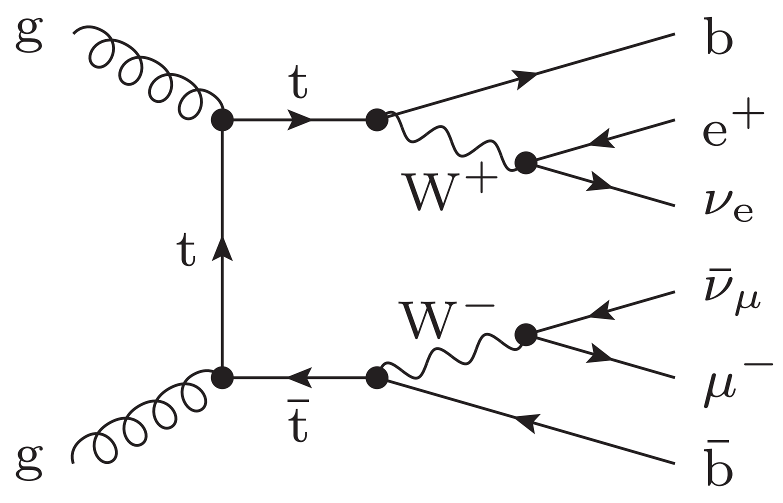


4FS

LO



Wt



$t\bar{t}$

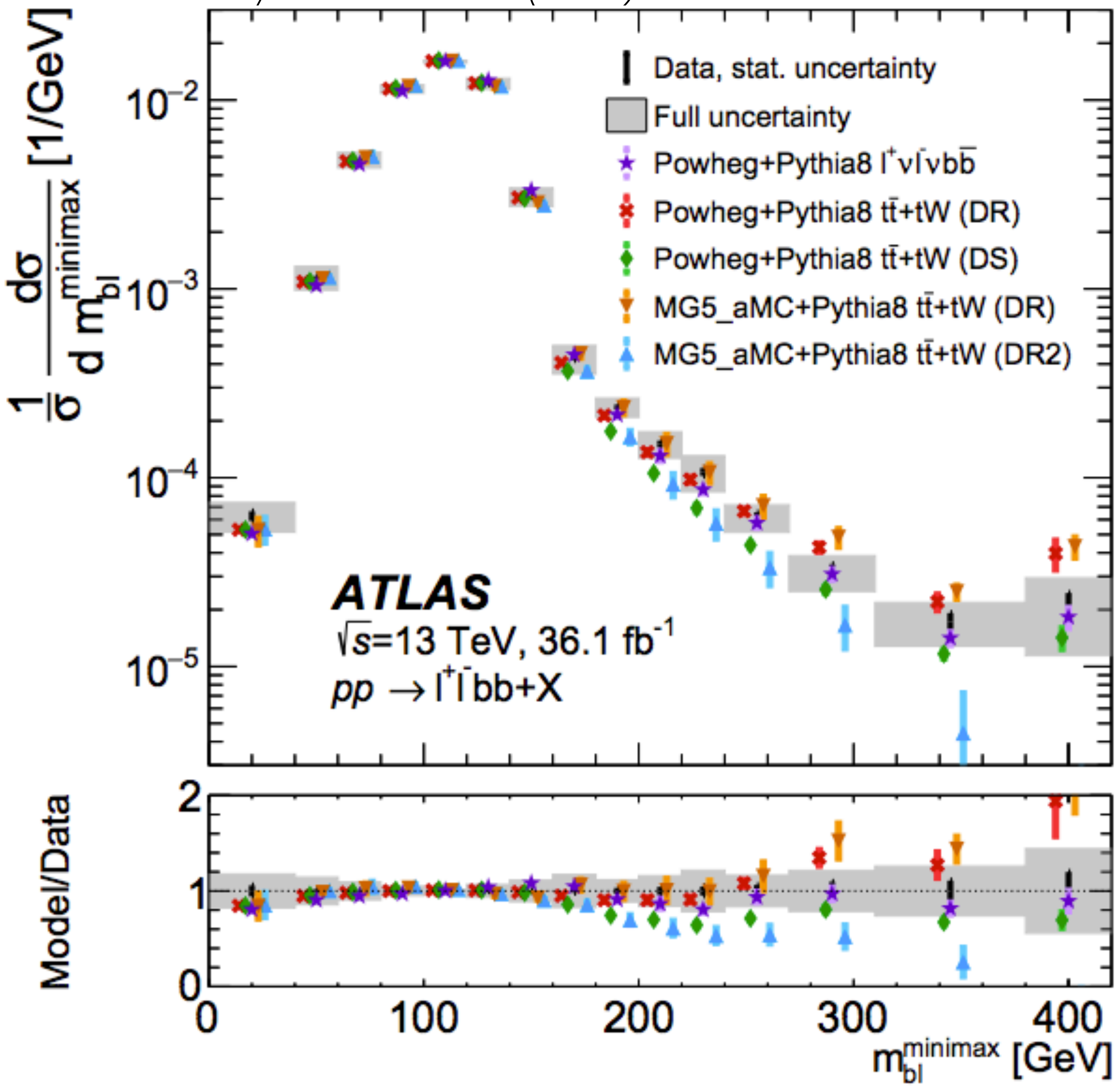
same finale state!

- **unified treatment of top-pair and Wt including interference**
- Wt enhanced in phase-space regions where one b becomes unresolved/vetoed
- requires off-shell WWbb calculation (with massive b's)

Interference effects between top-pair and Wt production

"Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector"

Phys. Rev. Lett. 121 (2018) 152002

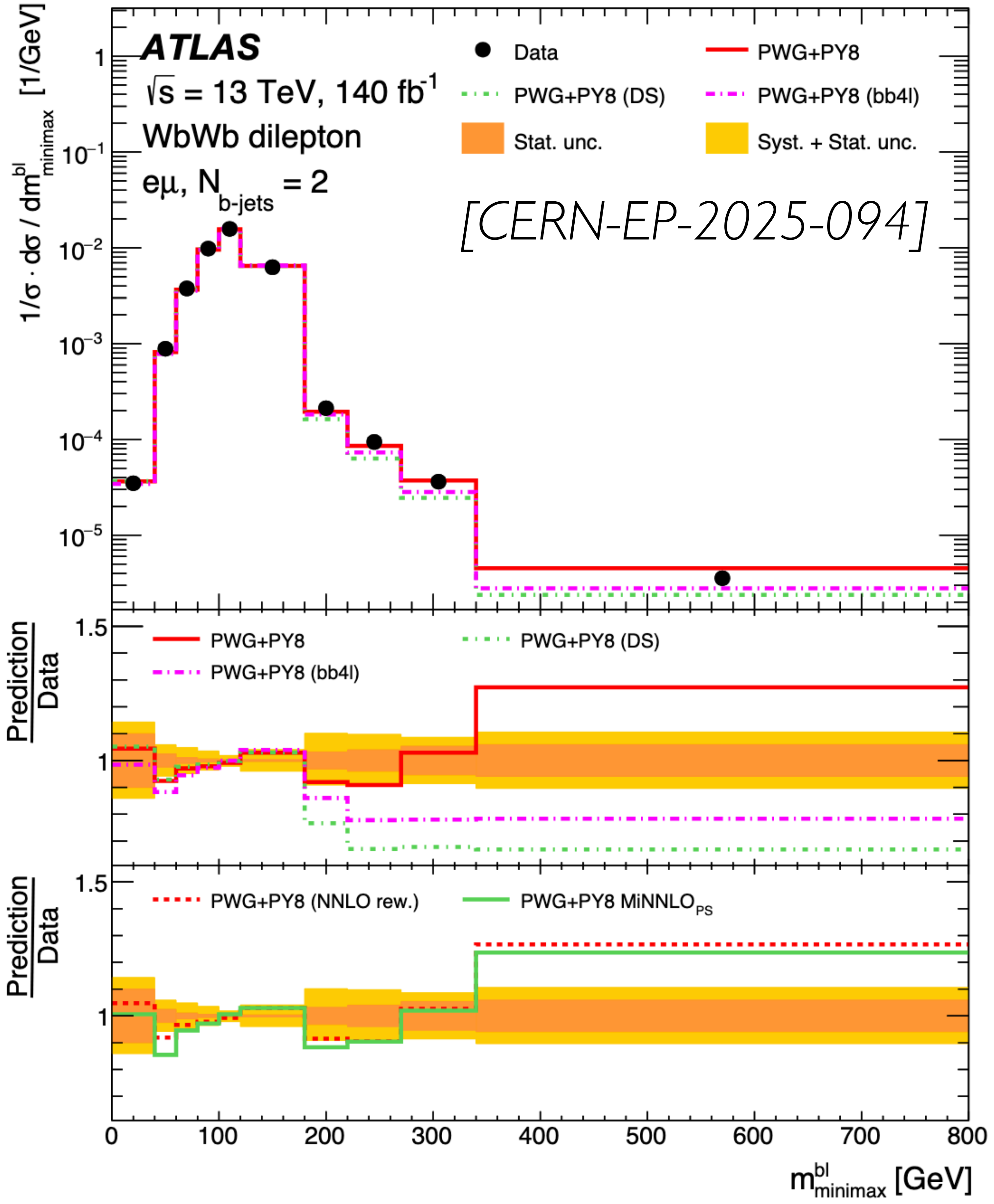


$$m_{b\ell}^{\text{minimax}} \equiv \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

For tt (double-resonant) at LO: $m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$

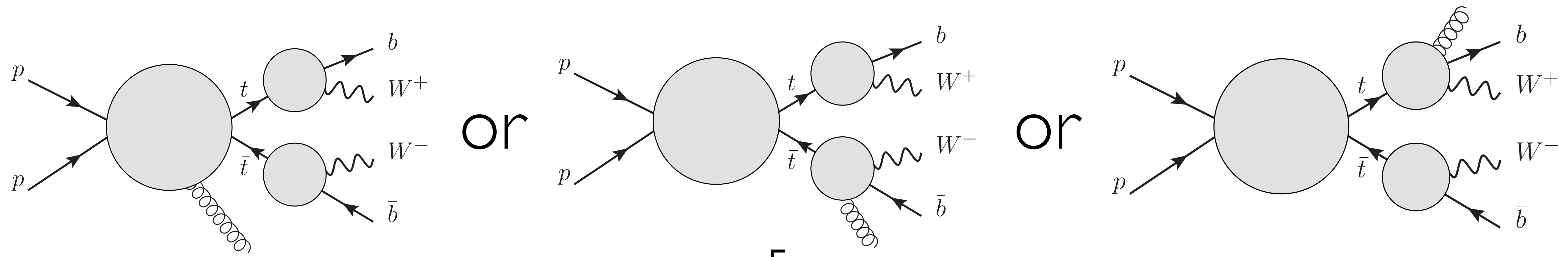
→ sensitivity to off-shell effects/ tt-Wt interference beyond endpoint

→ measure top width *[Herwig, Jezo, Nachman, '19]*



Multiple-radiation scheme

- In traditional approach only hardest radiation is generated by POWHEG:

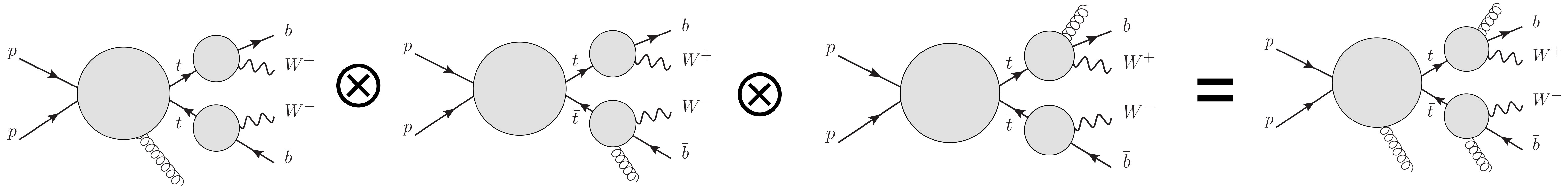


$$\Longleftrightarrow \qquad \mathrm{d}\sigma = \bar{B}(\Phi_\mathrm{B})\,\mathrm{d}\Phi_\mathrm{B}\left[\Delta(q_\mathrm{cut}) + \sum_\alpha \Delta(k_T^\alpha)\frac{R_\alpha(\Phi_\alpha(\Phi_\mathrm{B},\Phi_\mathrm{rad}))}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_\mathrm{rad}\right]$$

BUT: for top-pair (or single-top) production and decay, emission from production is almost always the hardest.

➡ emission off decays are mostly generated by the shower.

- **Multiple-radiation scheme (allrad)**: . *introduced in [Campbell, Ellis, Nason, Re; '15]*
  - keep hardest overall emission and additionally hardest emission from any of *n* decaying resonances.
  - merge emissions into a single radiation event with several radiated partons (up to *n+1*)



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

Consistent inverse-width expansion at NLO

[Jezo, JML, Pozzorini, 2307.15653]

NWA: $$\mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma\frac{\mathrm{d}\Gamma}{\Gamma}\,, \quad \textbf{where} \quad \Gamma = \int_{\mathrm{dec}} \mathrm{d}\Gamma$$

This factorisation holds to all orders!

and ensures: $$\int_{\mathrm{dec}} \mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma$$

Naive NLO expansion of NWA: $$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1\,, \qquad \mathrm{d}\Gamma_{\mathrm{NLO}} = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_1\,, \qquad \Gamma_{\mathrm{NLO}} = \Gamma_0 + \Gamma_1$$

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

spurious

[Melnikov, Schulze, '09]

Consistent NLO expansion of NWA: $$\mathrm{d}\sigma_{\mathrm{NLO}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1\,, \qquad \mathrm{d}\Gamma_{\mathrm{NLO}} = \mathrm{d}\Gamma_0 + \mathrm{d}\Gamma_1\,, \qquad \frac{1}{\Gamma_{\mathrm{NLO}}} \to \frac{1}{\Gamma_0}\left(1 - \frac{\Gamma_1}{\Gamma_0}\right)$$

$$\int_{\mathrm{dec}} \mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma_0 + \mathrm{d}\sigma_1$$

Generalise to multiple resonances: $$\mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \left[\mathrm{d}\sigma_0 + \sum_r \left(\mathrm{d}\sigma_0\frac{\mathrm{d}\Gamma_{r,1}}{\mathrm{d}\Gamma_{r,0}} - \mathrm{d}\sigma_0\frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) + \mathrm{d}\sigma_1\right]\left(\prod_{r\in\mathcal{R}}\frac{\mathrm{d}\Gamma_{r,0}}{\Gamma_{r,0}}\right)$$

$$\mathrm{d}\sigma_{\mathrm{spurious}} = \mathrm{d}\sigma^{\mathrm{NLO}}_{\mathrm{prod}\times\mathrm{dec}} - \mathrm{d}\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \delta\kappa_{\mathrm{spurious}}\,\mathrm{d}\sigma^{\mathrm{LO}}_{\mathrm{prod}\times\mathrm{dec}}$$

E.g.: $$\delta\kappa^{t\bar{t}+X}_{\mathrm{spurious}} \simeq -2\,\frac{\mathrm{d}\sigma_1}{\mathrm{d}\sigma_0}\frac{\Gamma_{t,1}}{\Gamma_{t,0}} \simeq +17\%\,\frac{\mathrm{d}\sigma_1}{\mathrm{d}\sigma_0}\;!$$

Consistent inverse-width expansion at NLOPS

Start from fNLO in NWA: $$d\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{prod}\times\mathrm{dec}} = \left[d\sigma_0 + \sum_r \left(d\sigma_0 \frac{d\Gamma_{r,1}}{d\Gamma_{r,0}} - d\sigma_0 \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) + d\sigma_1\right] \left(\prod_{r\in\mathcal{R}} \frac{d\Gamma_{r,0}}{\Gamma_{r,0}}\right)$$

NWA limit: $\Gamma_r \to 0$

fNLO for off-shell computation: $$d\sigma^{\mathrm{NLO_{exp}}}_{\mathrm{off-shell}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right) \left[d\sigma^{\mathrm{NLO}}_{\mathrm{off-shell}} - \left(\sum_{r\in\mathcal{R}} \frac{\Gamma_{r,1}}{\Gamma_{r,0}}\right) d\sigma^{(0)}_{\mathrm{off-shell}}\right]$$

$\boxed{\text{use } \Gamma_{r,\mathrm{NLO}} \text{ in ME}}$

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

$$R^{(\mathrm{hard})}_{h,c}(\Phi_R)\Big|_{\mathrm{exp}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right) R^{(\mathrm{hard})}_{h,c}(\Phi_R)$$

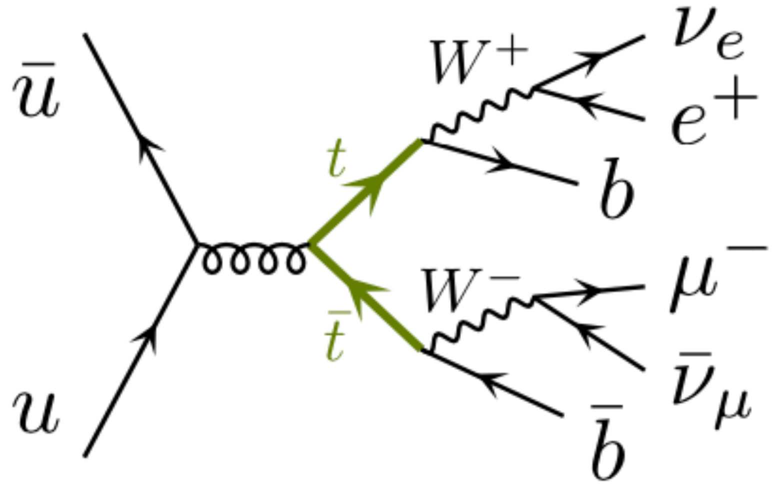
$$\frac{\sigma_{\mathtt{bb4l-sl}}}{\sigma_{\mathtt{hvq+ST}}}\Bigg|_{\text{no } 1/\Gamma_t \text{ expansion}} = 1.074 \qquad \text{vs.} \qquad \frac{\sigma_{\mathrm{bb4l-sl}}}{\sigma_{\mathrm{hvq+ST}}}\Bigg|_{\text{with } 1/\Gamma_t \text{ expansion}} = 1.012$$

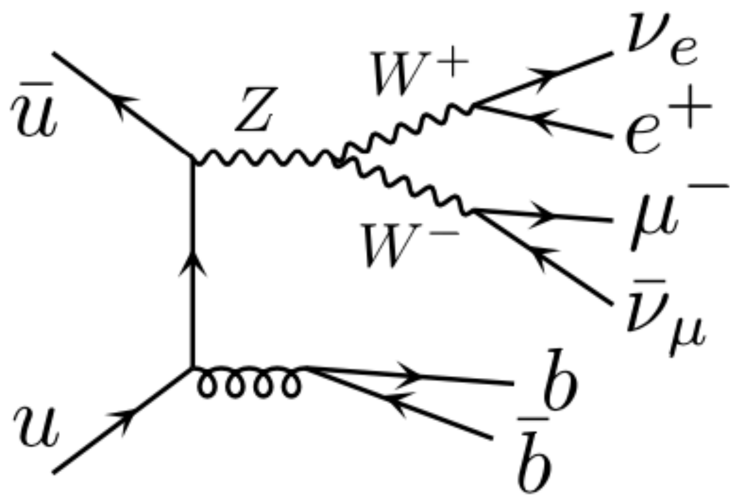
$\Longrightarrow$ **can also induce important shape effects!**

Born resonance history projectors

$$\rho_{h,c}^{(\mathrm{hist})}(\Phi_{\mathrm{R}}) = \prod_{r\in\mathcal{R}(h,c)} \frac{M_r^4}{(q_{\mathrm{R},r}^2 - M_r^2)^2 + \Gamma_r^2 M_r^2}$$

kinematics-based
(used in 1607.04538)



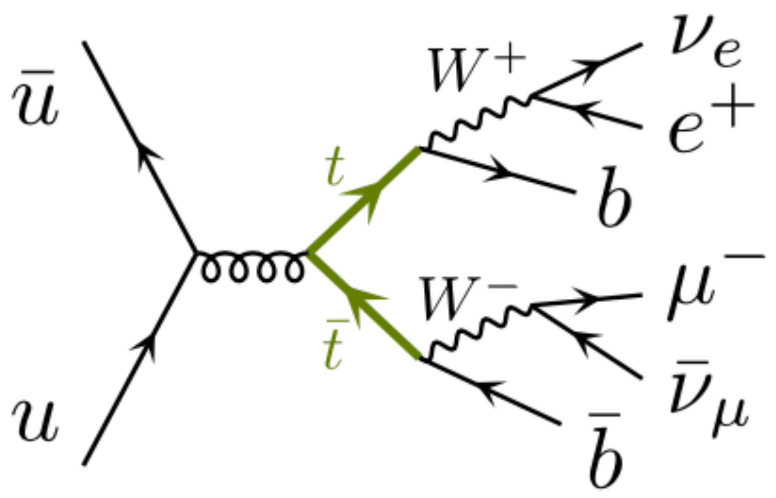


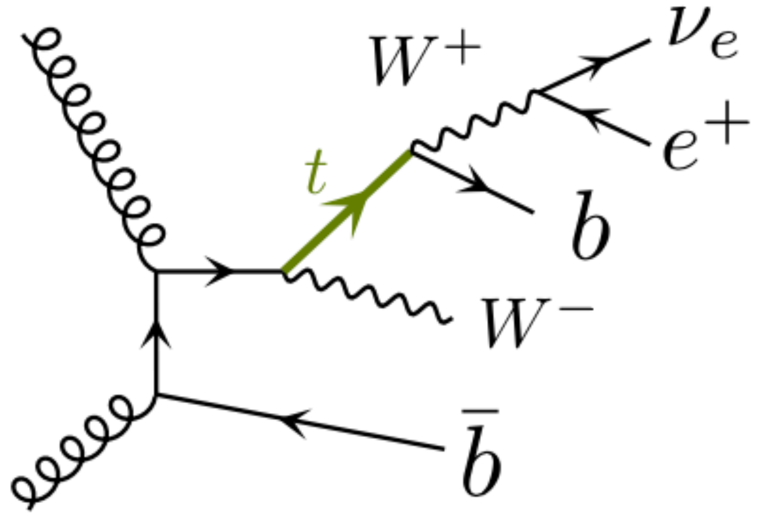
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

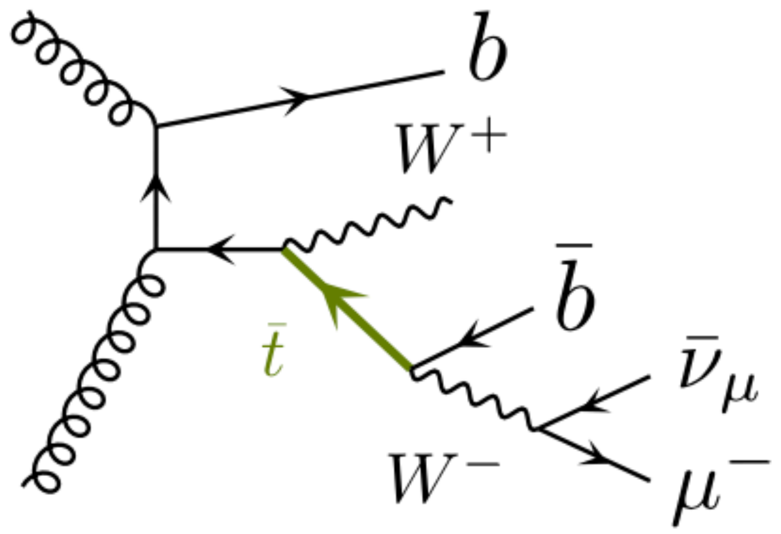
$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

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

matrix element-based
(new in 2307.15653)







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

$P_2 = B_{\bar{t}W^+}$

$P_3 = B_{tW^-}$

squared LO matrix elements in pole approximation

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

e.g.: $\rho_{t\bar{t}}^{(\mathrm{hist})}(\Phi_{\mathrm{B}})\big|_{\mathrm{ME}} = |\mathcal{A}_{t\bar{t}}|^2 \quad \rho_{\bar{t}W^+}^{(\mathrm{hist})}(\Phi_{\mathrm{B}})\big|_{\mathrm{ME}} = |\mathcal{A}_{\bar{t}W^+}|^2 \quad \rho_{tW^-}^{(\mathrm{hist})}(\Phi_{\mathrm{B}})\big|_{\mathrm{ME}} = |\mathcal{A}_{tW^-}|^2$

Real resonance history projectors

kinematics-based
(used in 1607.04538)

$$\rho_{h,c}(\Phi_{\mathrm{R}}) = \rho^{(\mathrm{hist})}_{h,c}(\Phi_{\mathrm{R}})\, \rho^{(\mathrm{coll})}_{c}(\widetilde{\Phi}_{\mathrm{rad},c})$$

collinear weights, e.g.:

$$\rho^{(\mathrm{coll})}_{c}(\Phi_{\mathrm{rad},c}) = \left[\frac{E_i^2 E_j^2}{(E_i+E_j)^2}(1-\cos\theta_{ij})\right]^{-b}$$

kinematic resonance weights:

$$\rho^{(\mathrm{hist})}_{h,c}(\Phi_{\mathrm{R}}) = \prod_{r\in\mathcal{R}(h,c)} \frac{M_r^4}{(q^2_{\mathrm{R},r}-M_r^2)^2+\Gamma_r^2 M_r^2}$$

matrix element-based
(new in 2307.15653)

$$\rho^{(\mathrm{hist})}_{h,c}(\Phi_{\mathrm{R}})\big|_{\mathrm{ME}} = \rho^{(\mathrm{hist})}_{h}(\widetilde{\Phi}_{\mathrm{B},c})\big|_{\mathrm{ME}}$$

R → B mapping

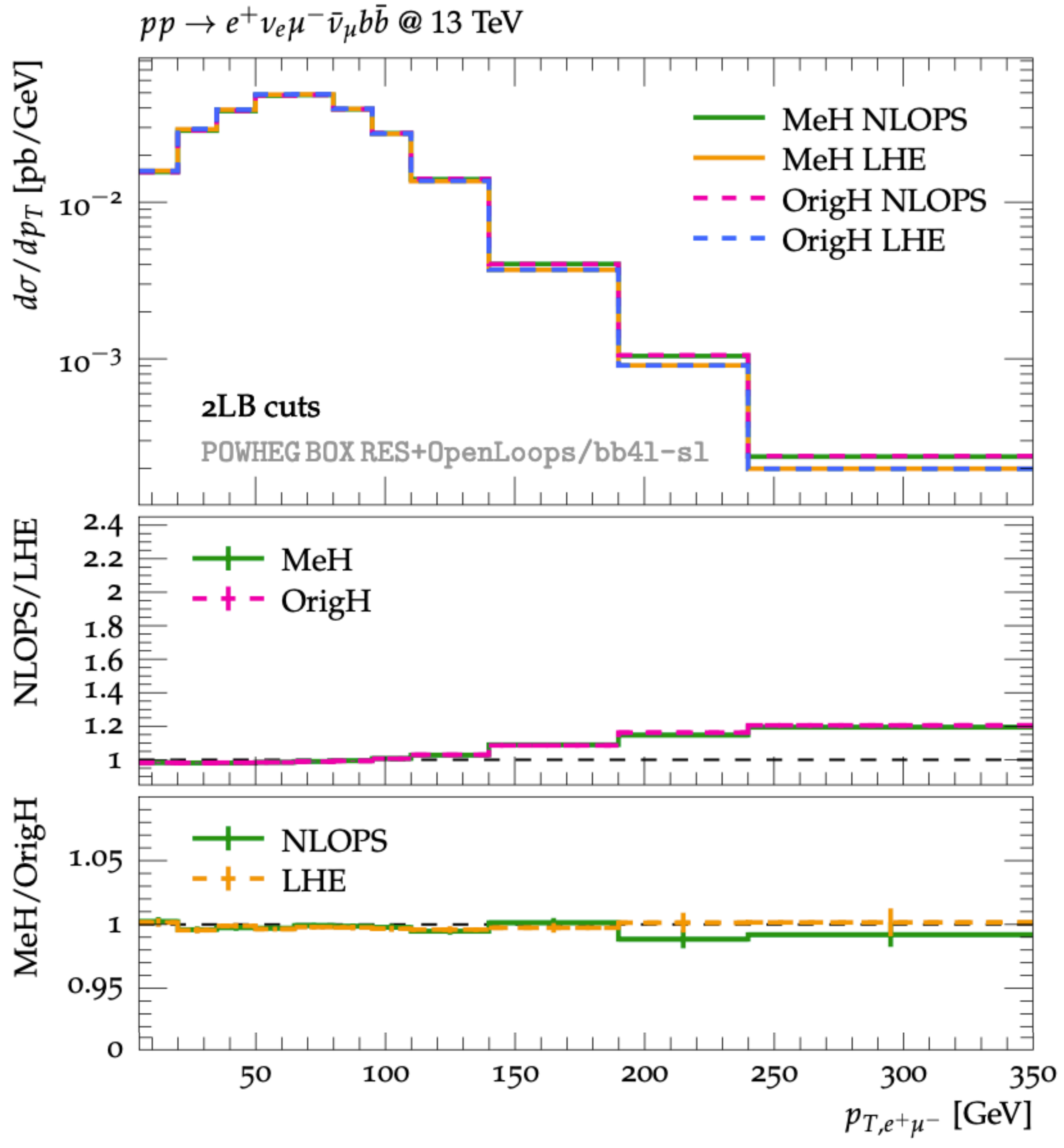
- defined in a way that preserves the virtuality of the top quarks and the invariant mass of the virtual b quark in IS $g \to b\bar{b}$ splittings
- preserve relative probabilities of $t\bar{t}$ and tW histories

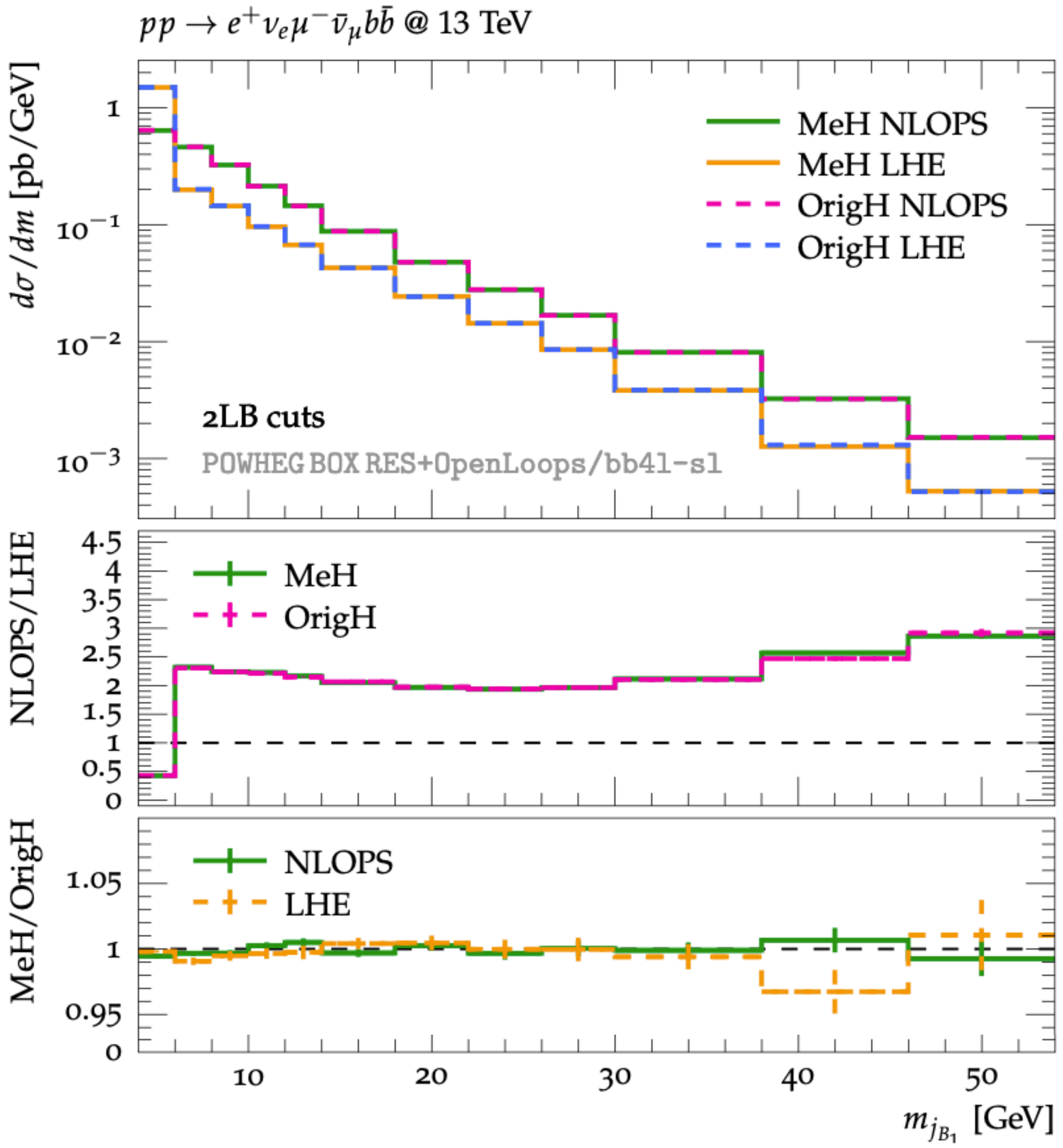
Old vs. New

		inclusive phase space	2LB cuts	2LB + off-shell cuts
LHE	OrigH	9.672(4)	4.422(3)	0.1908(6)
LHE	MeH	9.653(3)	4.411(2)	0.1912(4)
LHE	tW fraction	4.31%	3.86%	43.0%
NLOPS	OrigH	9.672(4)	4.419(3)	0.3515(8)
NLOPS	MeH	9.653(3)	4.408(2)	0.3502(5)
NLOPS	tW fraction	4.31%	3.86%	23.3%

$$Q_{\text{off-shell}} = \max\left\{|Q_t - m_t|, |Q_{\bar{t}} - m_t|\right\} > 60\,\text{GeV}$$

- Kinematic-based (OrigH) and matrix element-based (MeH) resonance history projectors agree at <1% level!
- this indicates small small systematic uncertainty related to ambiguity in resonance history definition





$t\bar{t}$ vs. tW resonance histories

[2307.15653]

Naive: $\rho^{(\text{hist})}_{t\bar{t}}(\Phi_\text{B})\Big|_\text{naive} = W_t(p_t)W_t(p_{\bar{t}})$

$\rho^{(\text{hist})}_{\bar{t}W^+}(\Phi_\text{B})\Big|_\text{naive} = \frac{\chi\, m_t^2}{E^2_{\text{T},b}}\, W_t(p_{\bar{t}})$

tuneable

IS $g \to b\bar{b}$

kinematic resonance weights: $W_t(p) = \frac{M_t^4}{(p^2 - M_t^2)^2 + \Gamma_t^2 M_t^2}$

ME-based: $\mathcal{A}_\text{full} = \mathcal{A}_{t\bar{t}} + \mathcal{A}_{\bar{t}W^+} + \mathcal{A}_{tW^-} + \mathcal{A}_\text{rem}$

ME

$\rho^{(\text{hist})}_{t\bar{t}}(\Phi_\text{B})\big|_\text{ME} = |\mathcal{A}_{t\bar{t}}|^2\,,$

$\rho^{(\text{hist})}_{\bar{t}W^\pm}(\Phi_\text{B})\big|_\text{ME} = |\mathcal{A}_{\bar{t}W^\pm}|^2$

ME'

$\rho^{(\text{hist})}_{t\bar{t}}(\Phi_\text{B})\big|_{\text{ME}'} = |\mathcal{A}_\text{full}|^2 - |\mathcal{A}_{\bar{t}W^+}|^2 - |\mathcal{A}_{\bar{t}W^+}|^2$

$\rho^{(\text{hist})}_{\bar{t}W^\pm}(\Phi_\text{B})\big|_{\text{ME}'} = |\mathcal{A}_{\bar{t}W^\pm}|^2\,,$

ME''

$\rho^{(\text{hist})}_{t\bar{t}}(\Phi_\text{B})\big|_{\text{ME}''} = |\mathcal{A}_{t\bar{t}}|^2\,,$

$\rho^{(\text{hist})}_{\bar{t}W^\pm}(\Phi_\text{B})\big|_{\text{ME}''} = |\mathcal{A}_{\bar{t}W^\pm}|^2\,,$

$\rho^{(\text{hist})}_\text{rem}(\Phi_\text{B})\big|_{\text{ME}''} = |\mathcal{A}_\text{full}|^2 - |\mathcal{A}_{t\bar{t}}|^2 - |\mathcal{A}_{\bar{t}W^+}|^2 - |\mathcal{A}_{tW^-}|^2$

LO

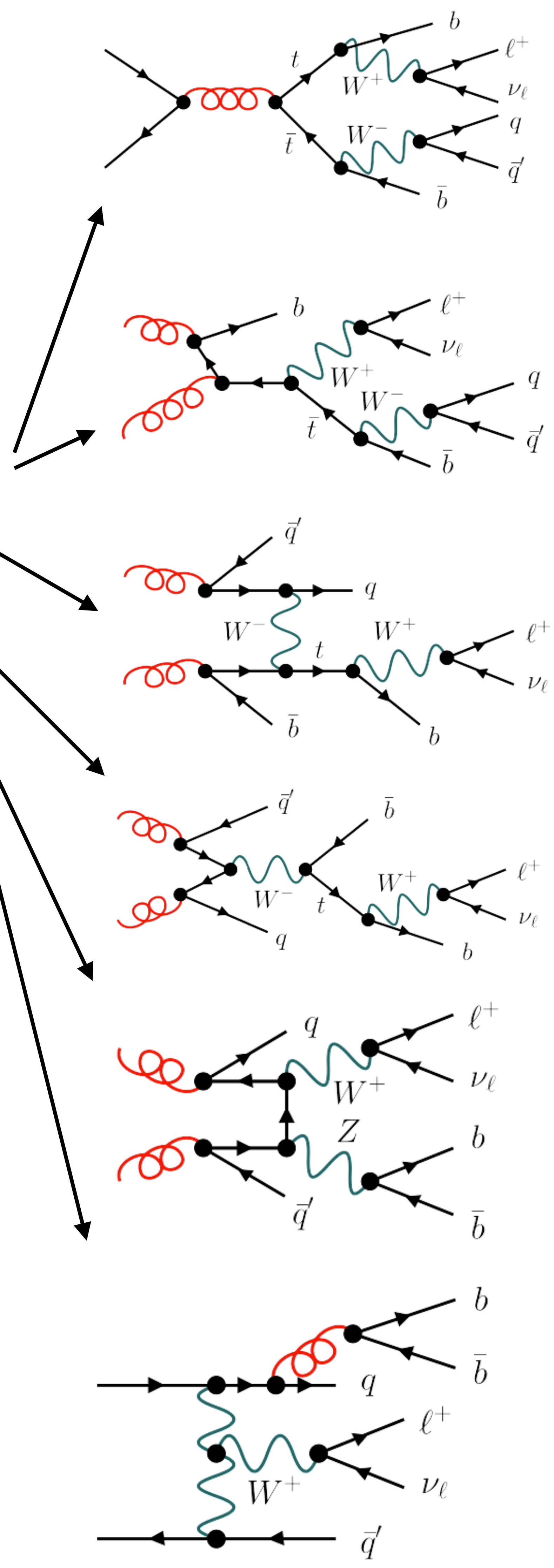
	naive		matrix-element–based			extrapolation
	$\chi = 1$	$\chi = 0.1$	ME	ME$'$	ME$''$	$\Gamma_t \to 0$
$t\bar{t}$	90.6%	95.3%	94.2%	93.7%	95.3%	96.0%
tW	9.4%	4.7%	5.8%	6.3%	6.2%	4.0%
rem					− 1.5%	

$\sigma_{t\bar{t}} = \lim_{\xi_t \to 0} \left(\xi_t^2\, \sigma_\text{bb4l}\Big|_{\Gamma_t \to \xi_t \Gamma_t} \right)$

Semi-leptonic $t\bar{t}$

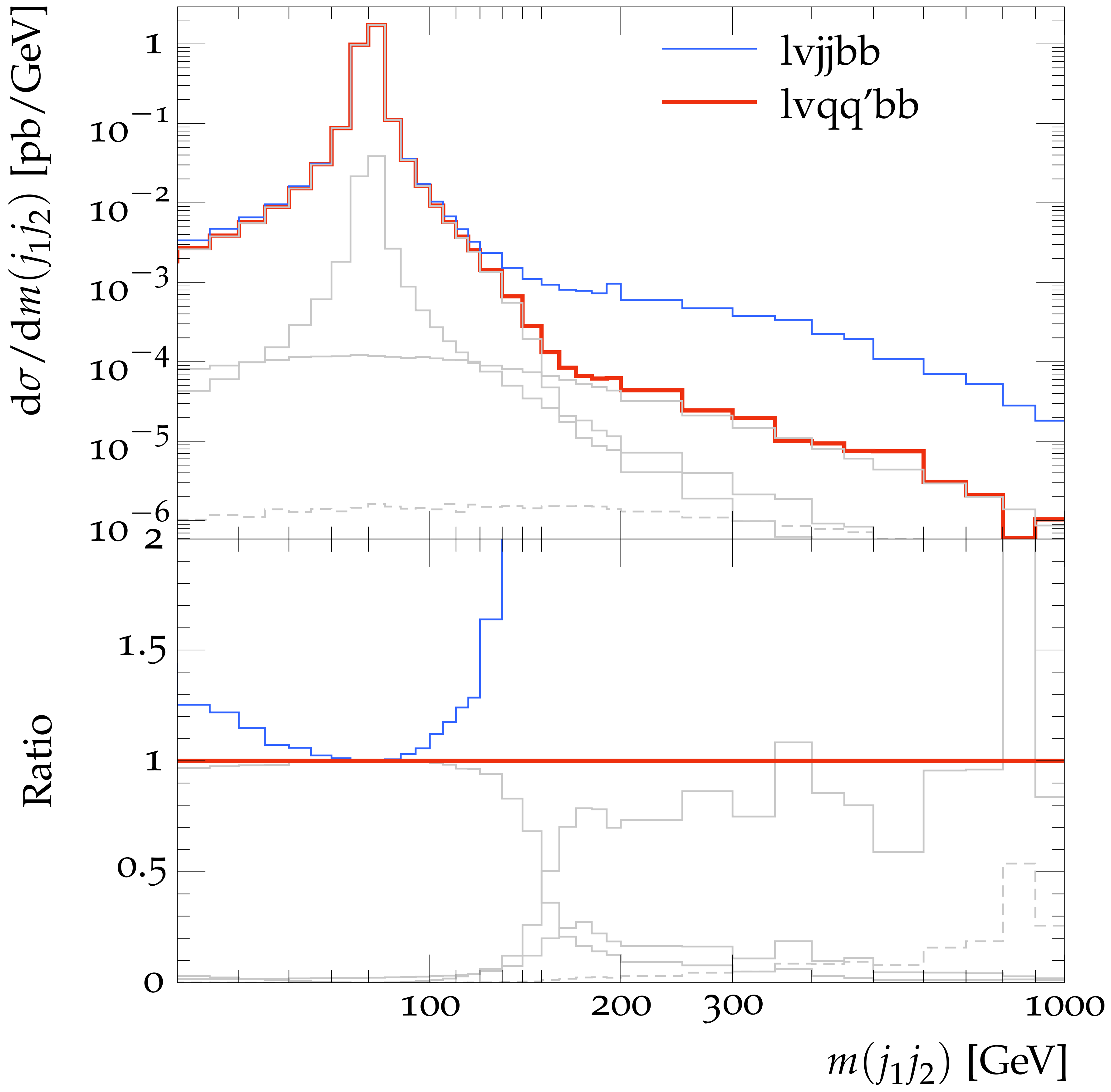
$$pp \to \ell^{\pm}\nu_{\ell} jjb\bar{b}$$

$\alpha_S^n\alpha^m$	dominant subprocesses	type	order
$\alpha_S^4\alpha^2$	$W^{\pm}b\bar{b} + 2$ jets	V+HF	NNLO
$\alpha_S^3\alpha^3$	tiny interference		
$\alpha_S^2\alpha^4$	$t\bar{t} + tWb$	$t\bar{t} + tW$	4FNS LO
	$gq \to tq'\bar{b} + 1$ jet	t-chanel single-top	4FNS NLO
	$q\bar{q}' \to t\bar{b} + 2$ jets	s-chanel single-top	NNLO
	$W^{\pm}Z + 2$ jets with $Z \to b\bar{b}$	VV	NNLO
	$W^{\pm}jj + 2$ b-jets	VBF	NNLO
$\alpha_S^1\alpha^5$	tiny interference		
α^6	$W^{\pm}Zjj$ with $Z \to b\bar{b}$	VBS	LO
	$W^{\pm}ZV$ with $Z \to b\bar{b}$, $V \to jj$	VVV	LO



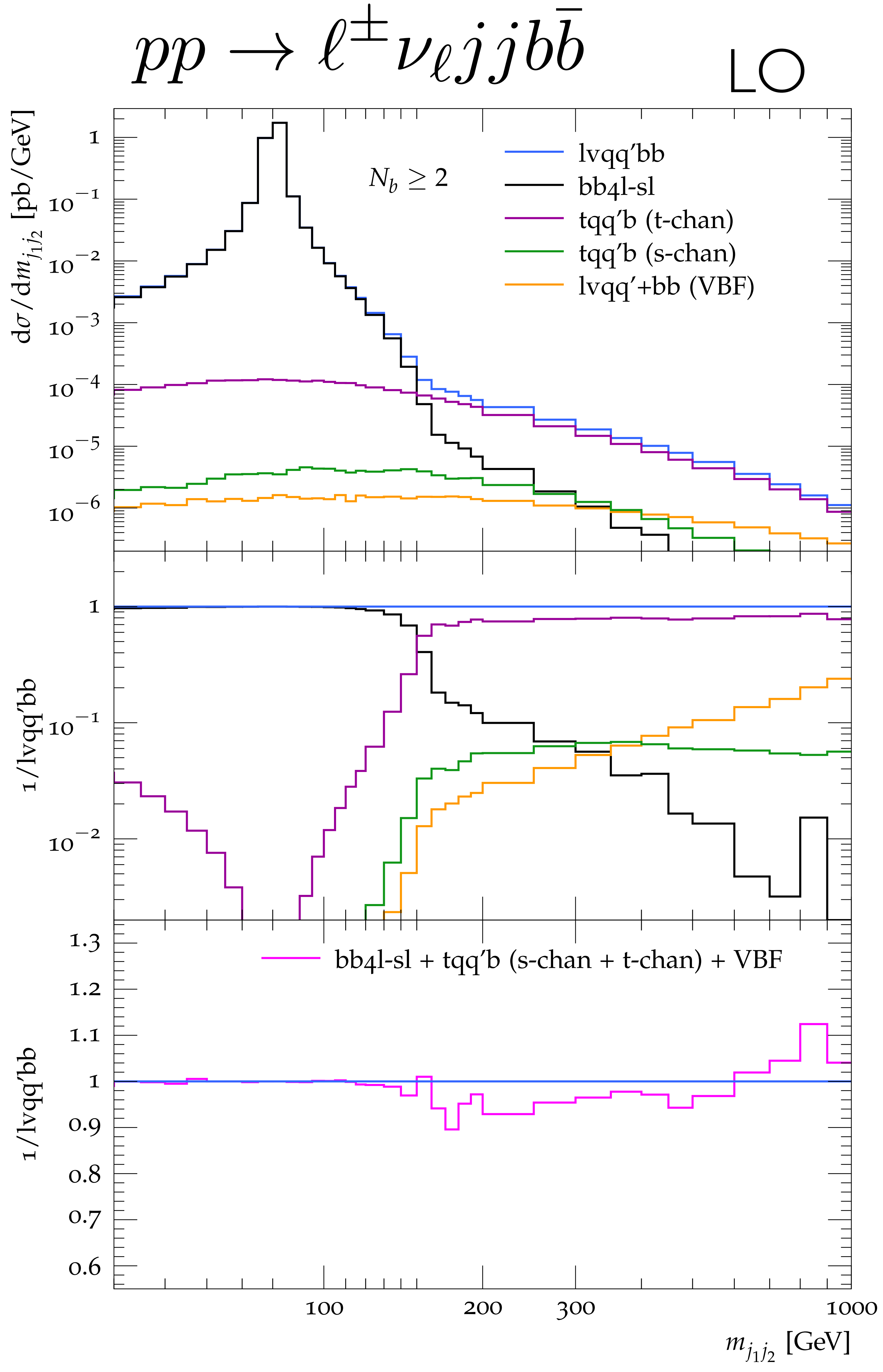
$$pp \to \ell^{\pm}\nu_{\ell} jjb\bar{b}$$

LO

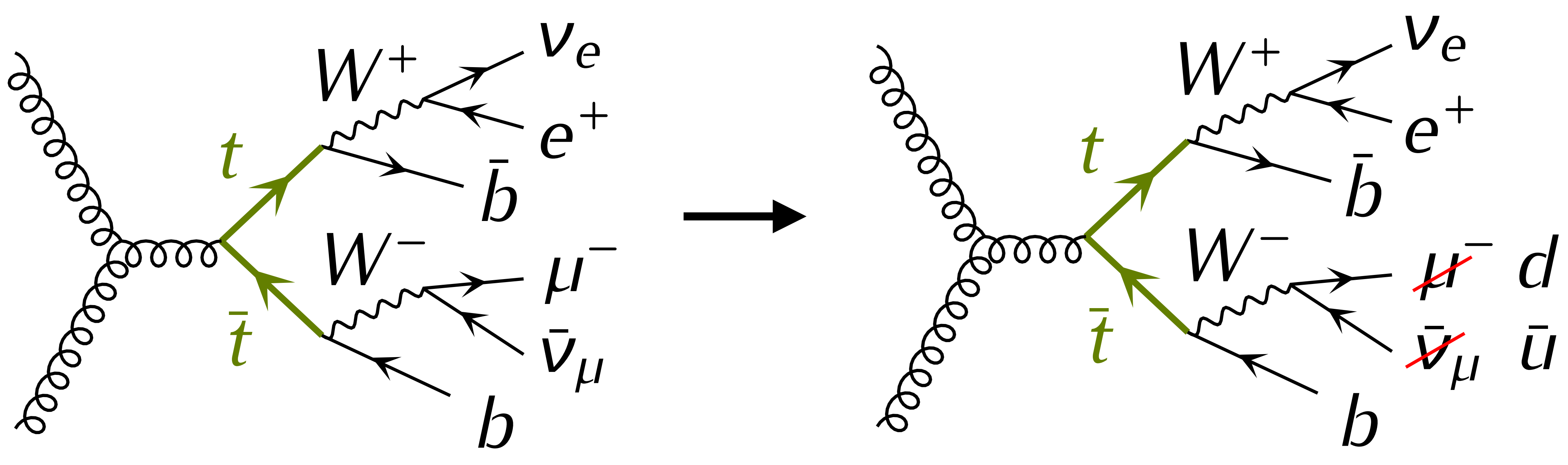


Full NLO QCD computation for $pp \to \ell^{\pm}\nu_{\ell} q\bar{q}' b\bar{b}$: [Denner, Pellen; '17]

Semi-leptonic $t\bar{t}$

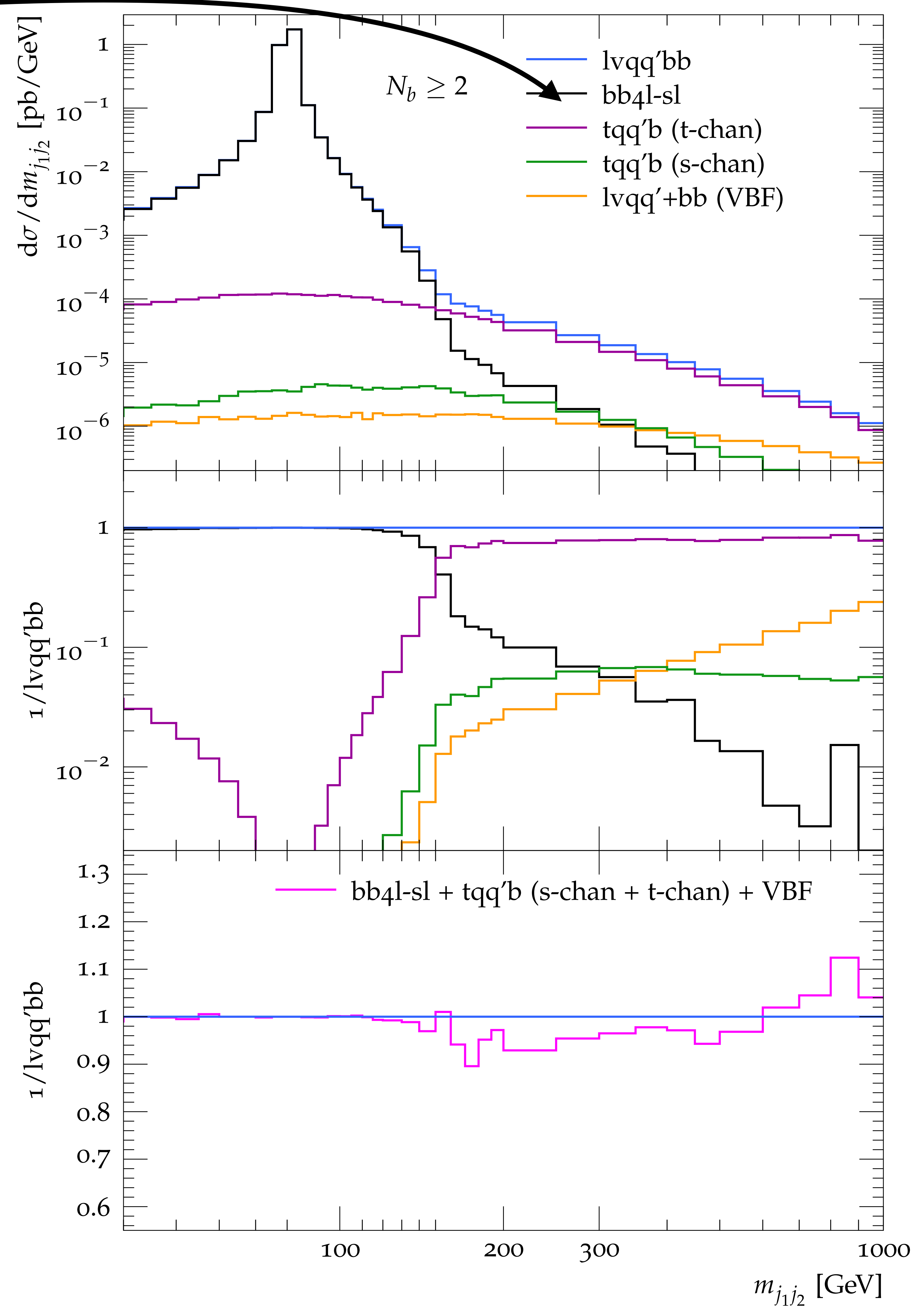


Semi-leptonic $t\bar{t}$: bb4l-sl



$$pp \to \ell^\pm \nu_\ell \ell'^\mp \nu_{\ell'} b\bar{b} \Big|_{\ell'^\mp \nu_{\ell'} \to q\bar{q}'} \longrightarrow pp \to \ell^\pm \nu_\ell q\bar{q}' b\bar{b}$$

$pp \to \ell^\pm \nu_\ell jjb\bar{b}$ LO



- In this approximation we drop some off-shell/interference effects
- But: $t\bar{t}$, Wt and $t\bar{t}$-Wt interference is retained!
- POWHEG emission based on "allrad" approach:

$$d\sigma_{\mathtt{bb4l-sl}} = d\sigma_{\mathtt{bb4l-dl}}\, K_{W_{\rm had}} \left[\Delta_{W_{\rm had}}(q_{\rm cut}) + \sum_{c \in \mathcal{C}(W_{\rm had})} \Delta_{W_{\rm had}}(k_{{\rm T},c}) \frac{R_{\rm DPA}(\Phi_{{\rm R},c})}{B_{\rm DPA}(\Phi_{\rm B})} d\Phi_{{\rm rad},c} \right]$$

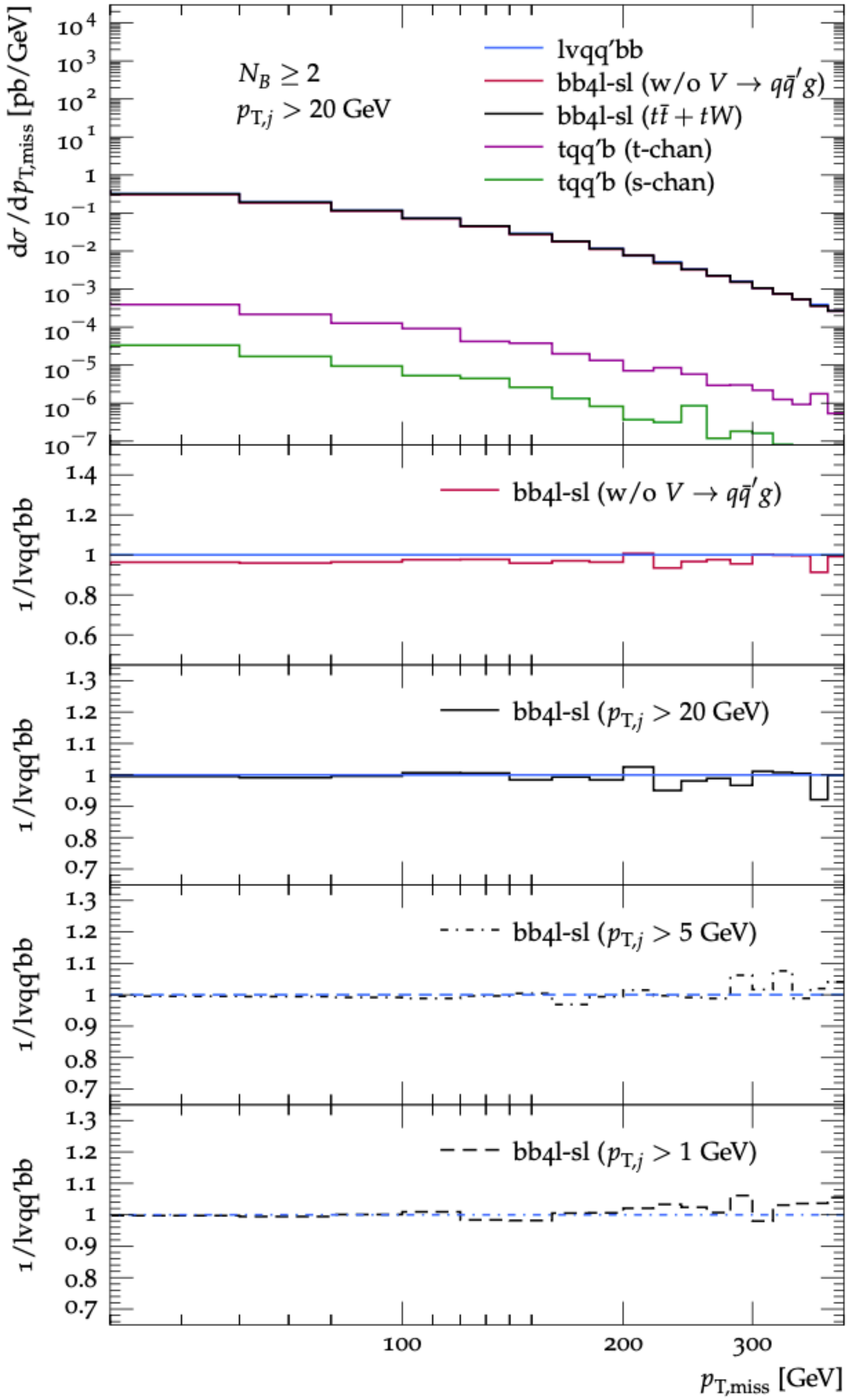
$$K_{W_{\rm had}} = \frac{\mathrm{BR}(W \to jj)}{\mathrm{BR}_{\mathtt{bb4l}}(W \to l\nu)}$$

$$pp \to W^\pm(\to \ell^\pm \nu) W^\mp(\to q\bar{q}') b\bar{b}$$
$$pp \to W^\pm(\to \ell^\pm \nu) W^+(\to q\bar{q}' g) bb$$

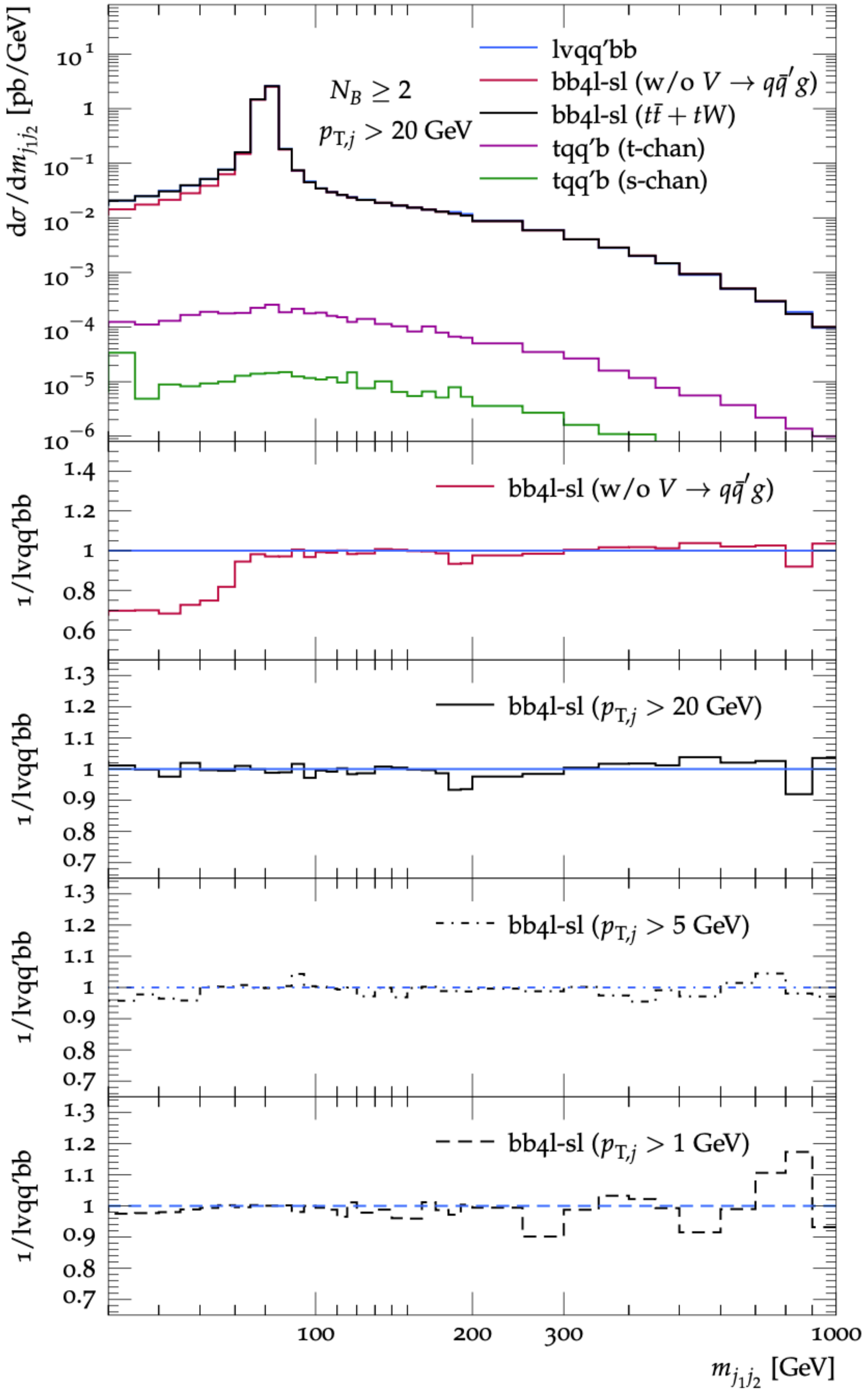
- Note: can also be used for full hadronic decays!

Semi-leptonic $t\bar{t}$: bb4l-sl

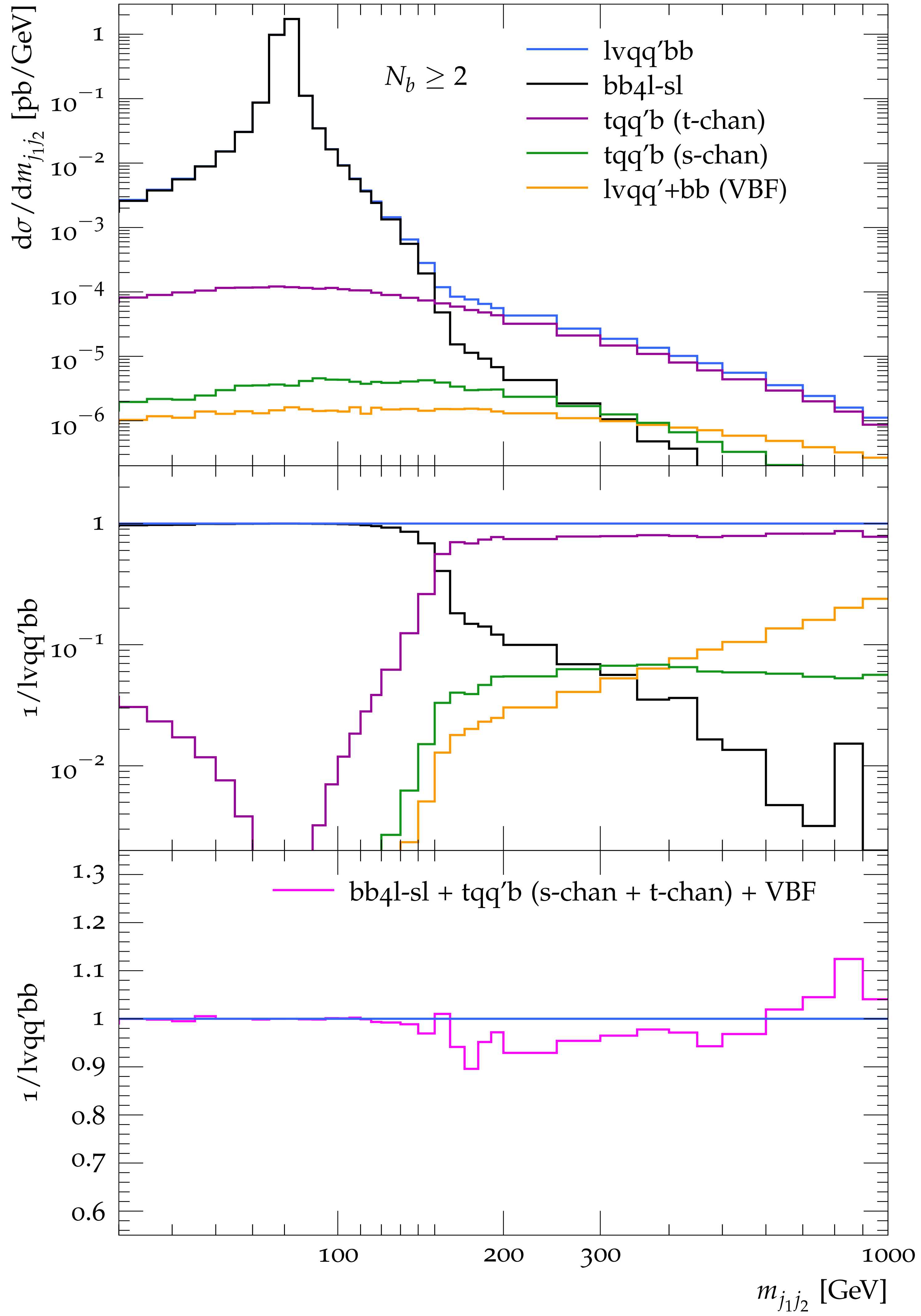
$pp \to \ell^\pm \nu_\ell q \bar{q}' b\bar{b} j$ + 1j



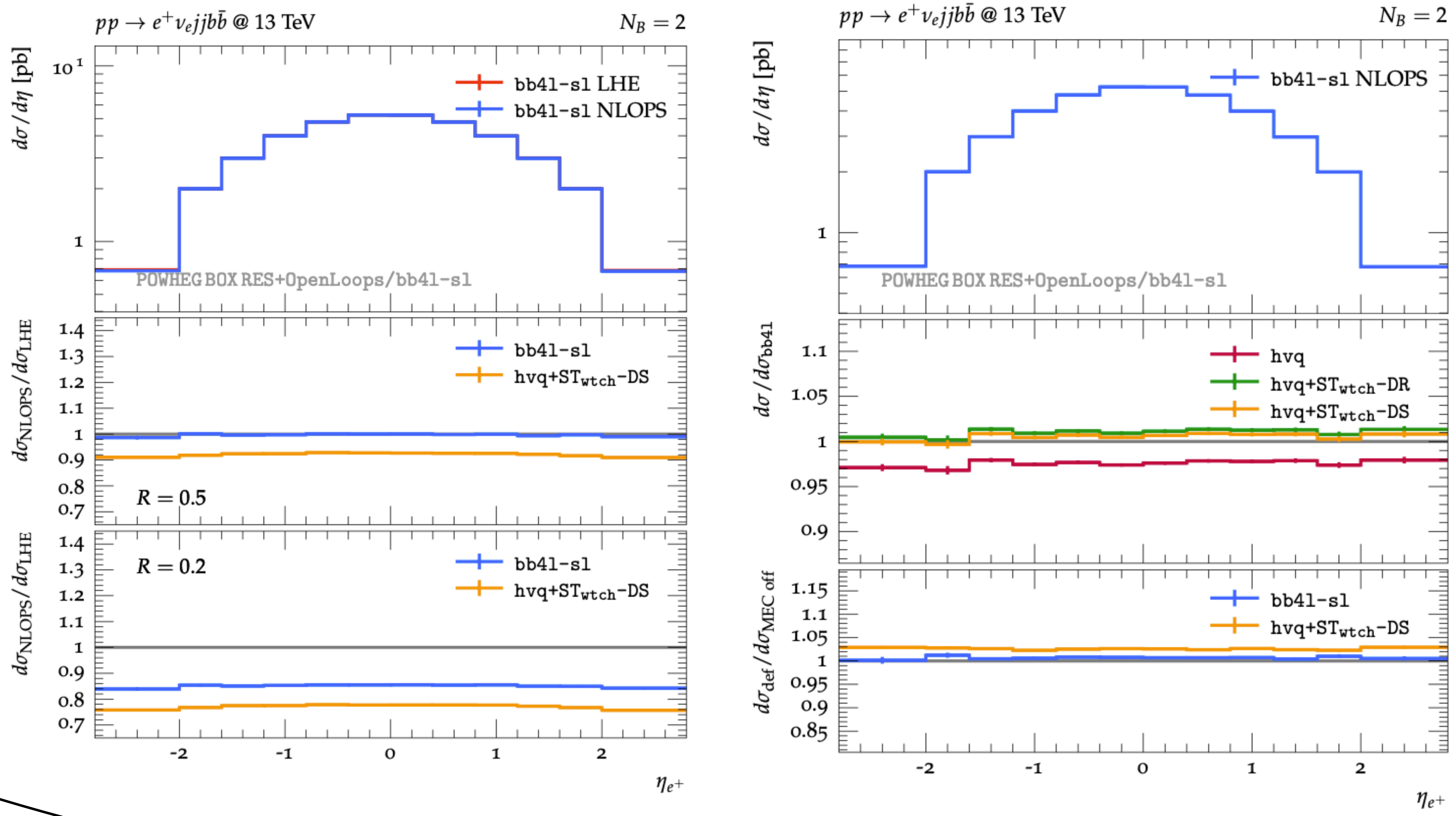
$pp \to \ell^\pm \nu_\ell q \bar{q}' b\bar{b} j$ + 1j



$pp \to \ell^\pm \nu_\ell j j b\bar{b}$ LO

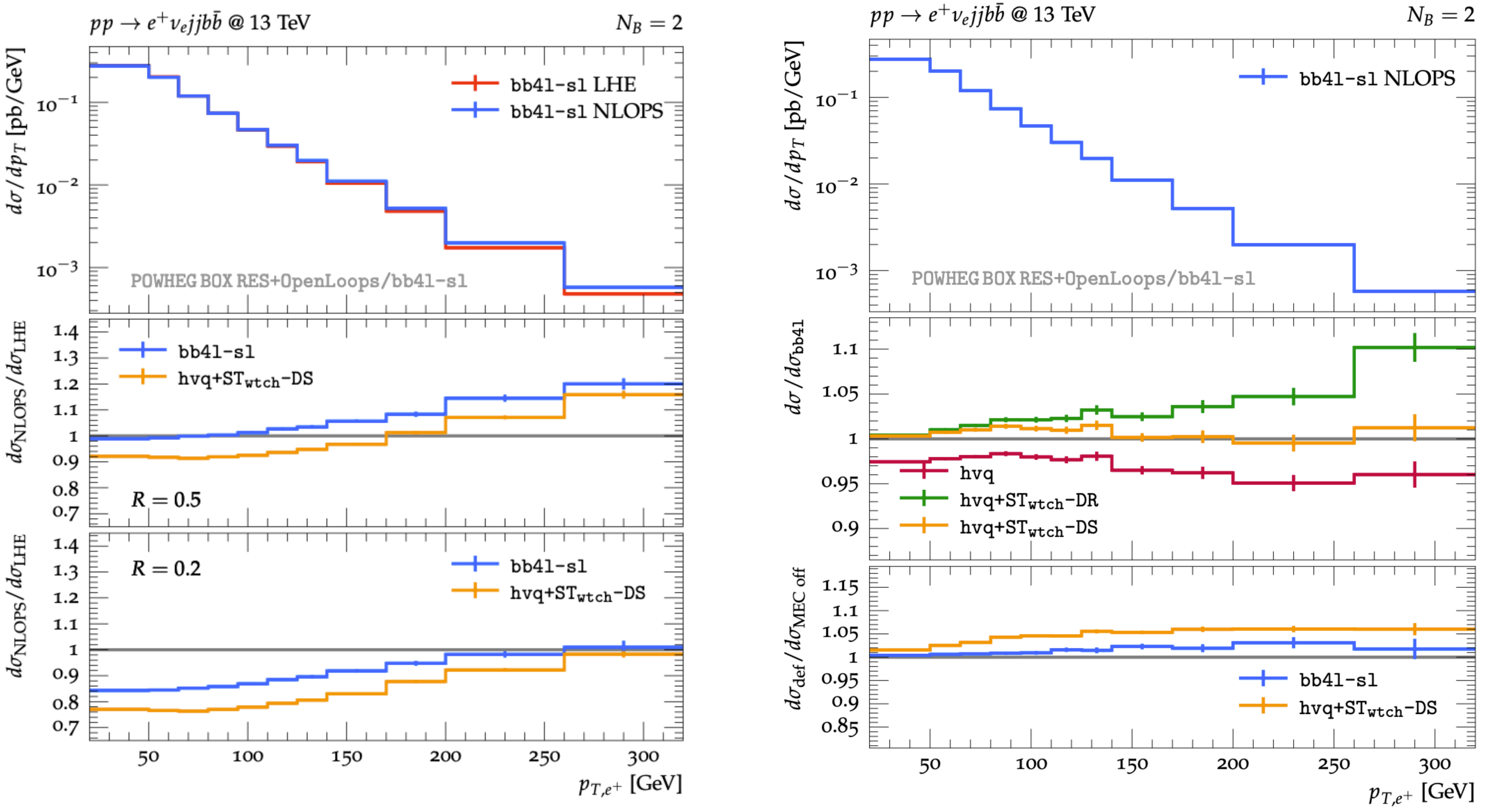


bb4l-sl vs. on-shell top-pair plus single-top



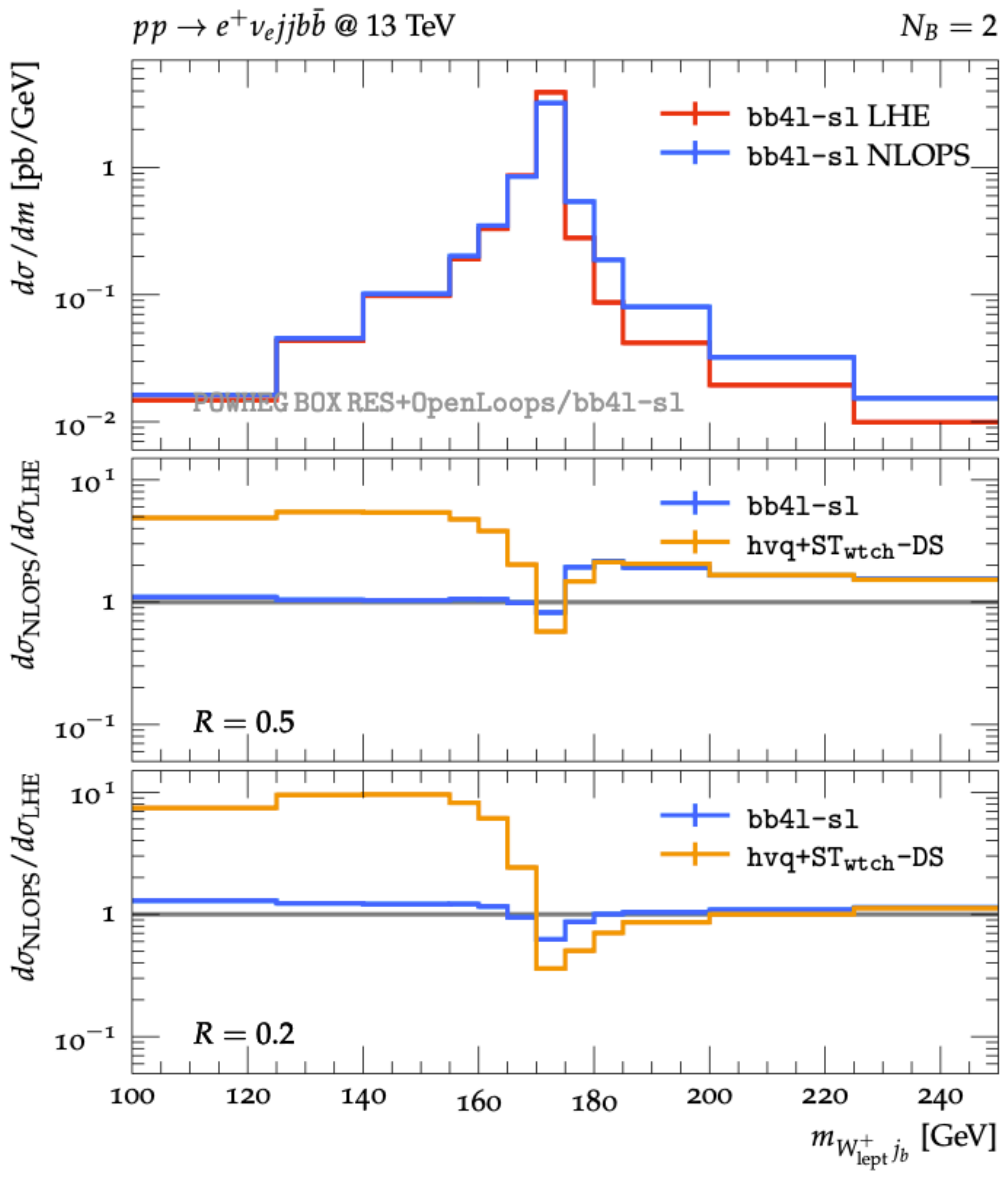
- Accidentally small shower effects in bb4l
- Percent-level agreement between bb4l and hvq+ST!
- O(1%) difference: tt-Wt interference + genuine off-shell

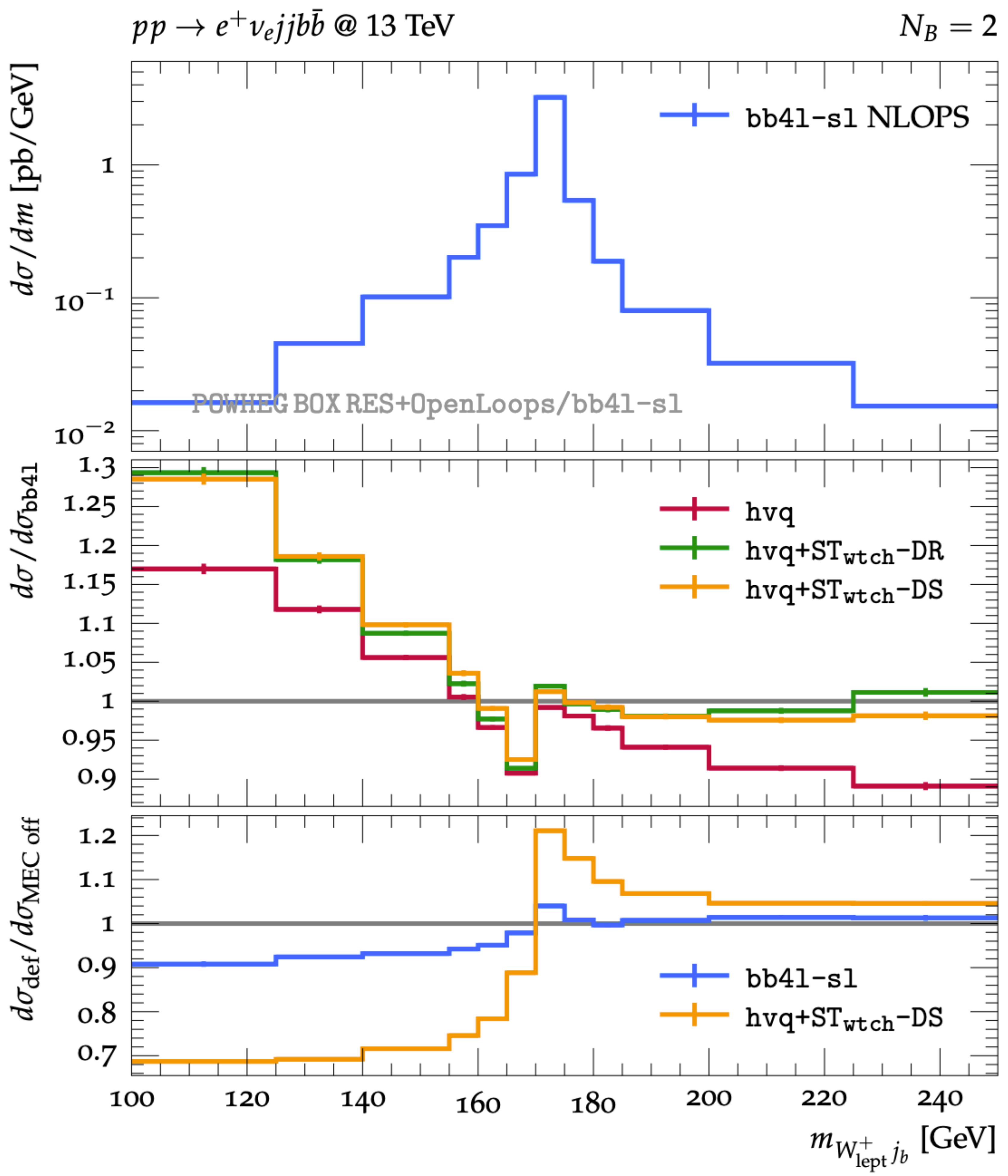
bb4l-sl vs. on-shell top-pair plus single-top



- Large differences between ST-DR and ST-DS in the tail of pTl
- bb4l agrees at O(1%) with ST-DS

bb4l-sl vs. on-shell top-pair plus single-top





- Control of reconstructed top-mass crucial for top-mass measurements
- Significantly **smaller shower effects (and MEC) in bb4l-sl compared to hvq+ST**

Ongoing Efforts

- Detailed uncertainty model for bb4l-dl (later bb4l-sl) based on intrinsic bb4l+PY8 uncertainties →Talk by Katharina

- Tunable ME histories / NNLO reweighting
  - $t\bar{t}$ @ NNLO+tW @ aNNLO, [Czakon, et. Al. '15] [Catani et.al. '19] [Kidonakis, Yamanaka; '21]
  - $b\bar{b}4\ell$ @ NNLO', [Buonocore, Grazzini, Kallweit, JML, Savoini; 2507.11410]

- bb4l-fh (full hadronic): same methodology as bb4l-sl

$$pp \to \ell^\pm \nu_\ell \ell'^\mp \nu_{\ell'} b\bar{b} \Big|_{\ell'^\mp \nu_{\ell'} \to q\bar{q}'} \text{x2} \longrightarrow pp \to q\bar{q}q'\bar{q}'b\bar{b}$$

→fully inclusive $t\bar{t}$ production and off-shell decays

- Threshold/resummation effects: *[Nason, Re, Rottoli; '25]*

Conclusions

- Precision **NLOPS predictions for off-shell tt+Wt** crucial for top-mass measurements and backgrounds in searches.
- Resonance-aware matching mandatory
- Inverse-width expansion in off-shell fNLO and NLOPS computations ensures narrow-width limit. Numerical impact can be significant.
- Matrix-element based projectors indicate small remaining systematics in RES method.
- Semi-leptonic tt x decay available in **bb4l-sl** approximation (valid for $|m_{j_1 j_2} - m_W| < 30\,\mathrm{GeV}$)
- percent-level agreement of bb4l-sl with hvq+ST in inclusive phase-space
- Crucial shape-effects and **reduced shower dependency** with bb4l-sl

Tuneable ME based projectors

ME-based: $$\mathcal{A}_{\rm full} = \mathcal{A}_{t\bar t} + \mathcal{A}_{\bar t W^+} + \mathcal{A}_{tW^-} + \mathcal{A}_{\rm rem}$$

$$\begin{aligned}
\rho^{\rm (hist)}_{t\bar t}(\Phi_{\rm B})\big|_{\rm ME'''}(\xi_{\rm int}, r_{\rm k}) &= r_{\rm k}\,|\mathcal{A}^{\rm (eff)}_{t\bar t}|^2\,,\\
\rho^{\rm (hist)}_{tW^\pm}(\Phi_{\rm B})\big|_{\rm ME'''}(\xi_{\rm int}, r_{\rm k}) &= |\mathcal{A}^{\rm (eff)}_{tW}|^2 \frac{|\mathcal{A}_{tW^\pm}|^2}{|\mathcal{A}_{tW^+}|^2 + |\mathcal{A}_{tW^-}|^2}\,,
\end{aligned}$$

$$\begin{aligned}
|\mathcal{A}^{\rm (eff)}_{t\bar t}|^2 &= |\mathcal{A}_{t\bar t}|^2 + \xi_{\rm int}|\mathcal{A}|^2_{\rm rem}\,,\\
|\mathcal{A}^{\rm (eff)}_{tW}|^2 &= |\mathcal{A}_{\bar t W^+}|^2 + |\mathcal{A}_{tW^-}|^2 + (1-\xi_{\rm int})|\mathcal{A}|^2_{\rm rem}\,,\\
&= |\mathcal{A}_{\rm full}|^2 - |\mathcal{A}_{t\bar t}|^2\,,\\
|\mathcal{A}|^2_{\rm rem} &= |\mathcal{A}_{\rm full}|^2 - |\mathcal{A}_{t\bar t}|^2 - |\mathcal{A}_{\bar t W^+}|^2 - |\mathcal{A}_{tW^-}|^2
\end{aligned}$$

Tuneable nuisance parameters:

- $\xi_{\rm int} \in [0,1]$: interference nuisance parameter corresponds to fraction of "interference" assigned to $t\bar t$ history.

  default: $\xi_{\rm int} = 0$ yields correct LO ratio $\sigma_{\rm tt}/\sigma_{W+W-b\bar b}$

- $r_{\rm k}$ mimics missing higher-order corrections to $|\mathcal{A}^{\rm (eff)}_{t\bar t}|^2/|\mathcal{A}^{\rm (eff)}_{tW}|^2$

  default: $r_{\rm k} = 1$

Idea: tune such (a) total cross section of the $t\bar t$ history agrees with inclusive $t\bar t$ @ NNLO.

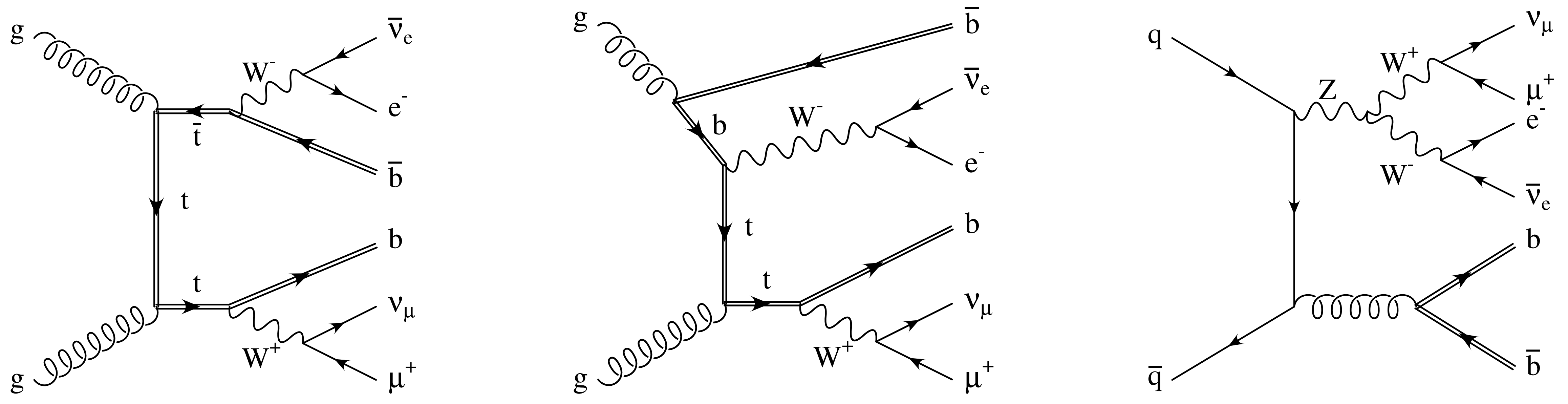
(b) $\Gamma_t \to 0$ limit agrees with the $t\bar t$ @ NNLO cross section.

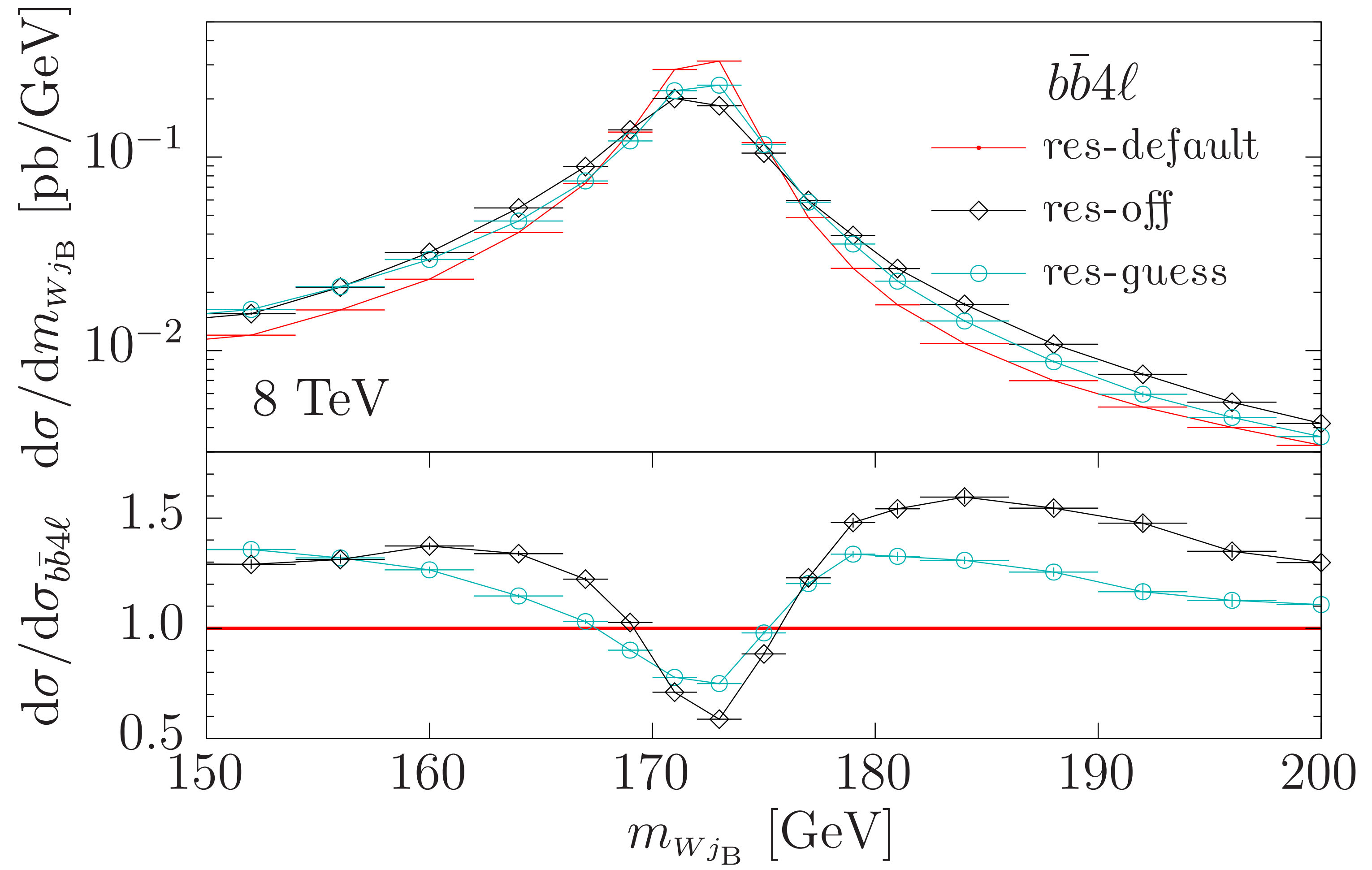
→work in progress

The resonance-aware bb4l generator

[Jezo, JML, Nason, Oleari, Pozzorini, '16]

- Full process $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ with massive b's (**4FS scheme**)
- Implemented in the **POWHEG-BOX-RES** framework





Physics features:

- exact **non-resonant** / **off-shell** / **interference** / **spin-correlation** effects at NLO
- unified treatment of **top-pair and Wt** production with interference at NLO
- access to phase-space regions with **unresolved b-quarks** and/or jet vetoes
- **consistent NLO+PS treatment of top resonances,** including quantum corrections to top propagators and off-shell top-decay chains

Standard POWHEG matching:

- Standard FKS/CS subtraction does not preserve virtuality of intermediate resonances → R and B (~S) with different virtualities.
- R/B enters POWHEG matching via generation of radiation and via Sudakov form-factor
  → **uncontrollable distortions**

Resonance-aware POWHEG matching: *[Jezo, Nason, '15]*

- Separate process in *resonances histories*
- Modified FKS mappings that retain virtualities