Resonance-aware NLOPS matching for off-shell top-pair plus tW production with semileptonic decays

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based on 2307.15653
(in collaboration with T. Jezo, S. Pozzorini)

University of Sussex

Science & Technology Facilities Council | UK Research and Innovation

HP2
Turin, 10th Sep 2024

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University of Sussex

on

NLO+PS predictions for
top-pair and Wt production and decay

Universität Zürich UZH

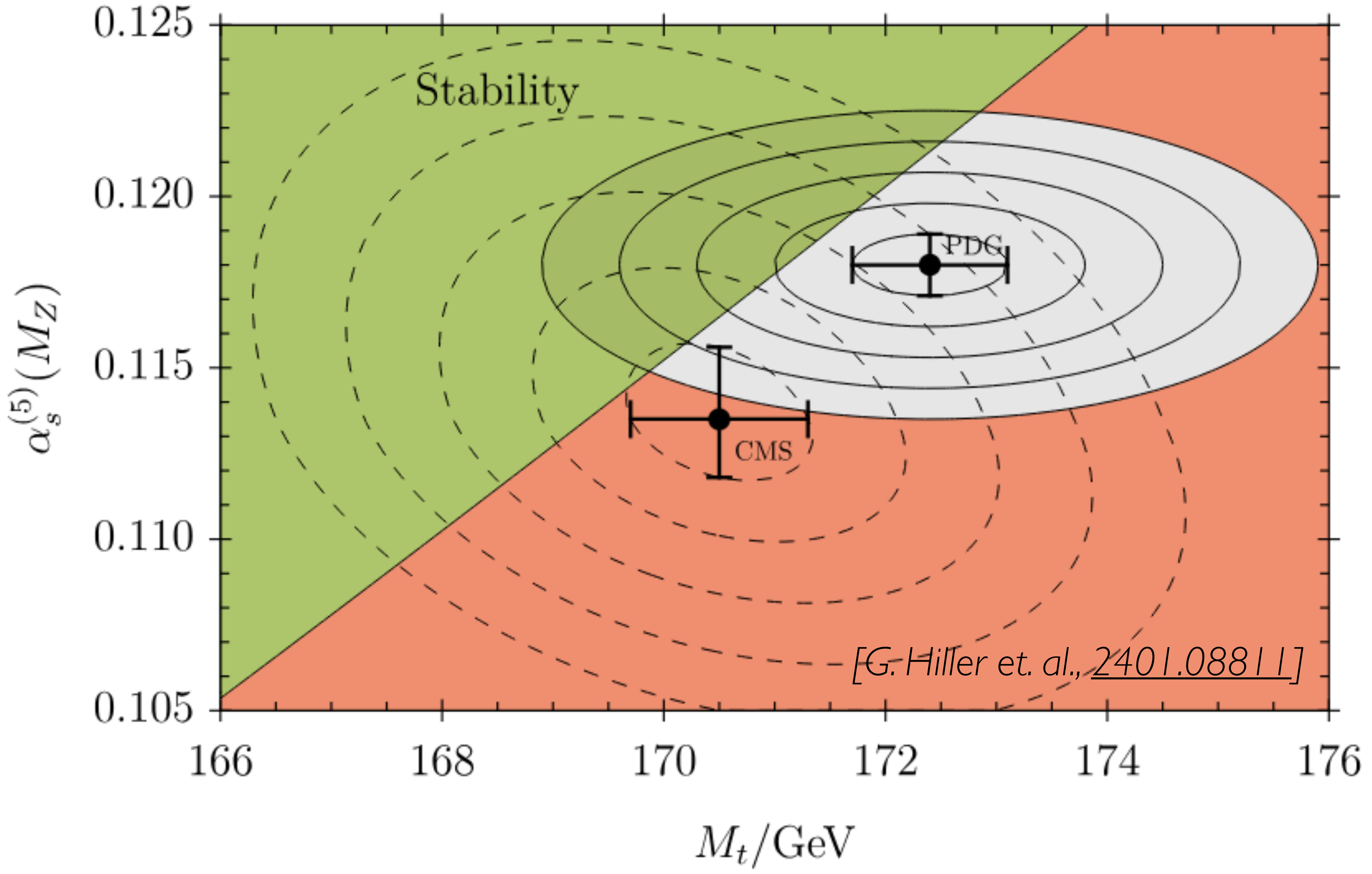
Jonas M. Lindert

work in collaboration with:
T.Ježo, P. Nason, C. Oleari, S. Pozzorini
based on [Ježo, Nason; '15] & [Ježo, JML, Nason, Oleari, Pozzorini; '16]

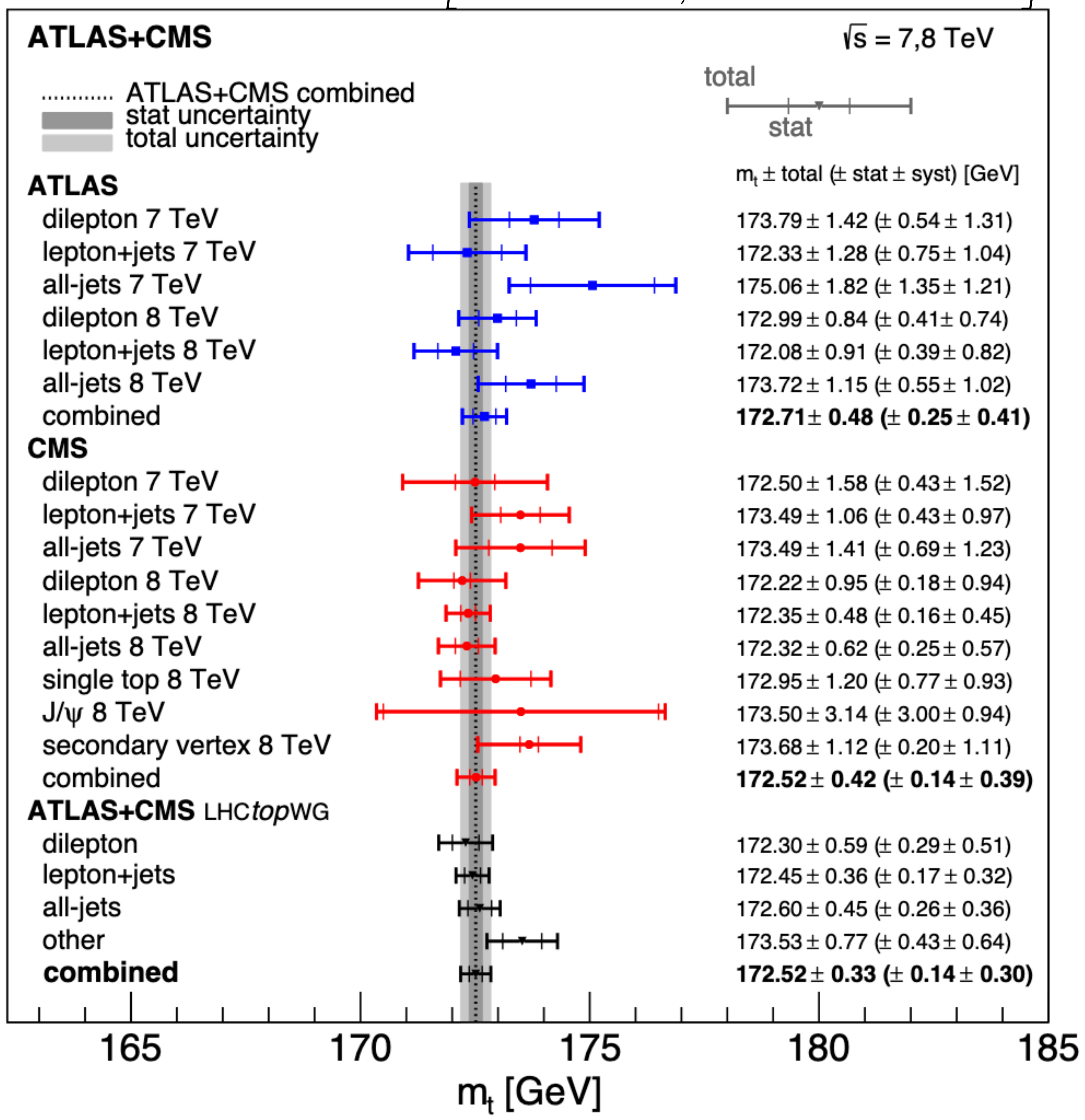
HP2
Buenos Aires, 8th September 2016

Turin, 10th Sep 2024

The fate of the Universe



[ATLAS+CMS; arXiv:2402.08713]



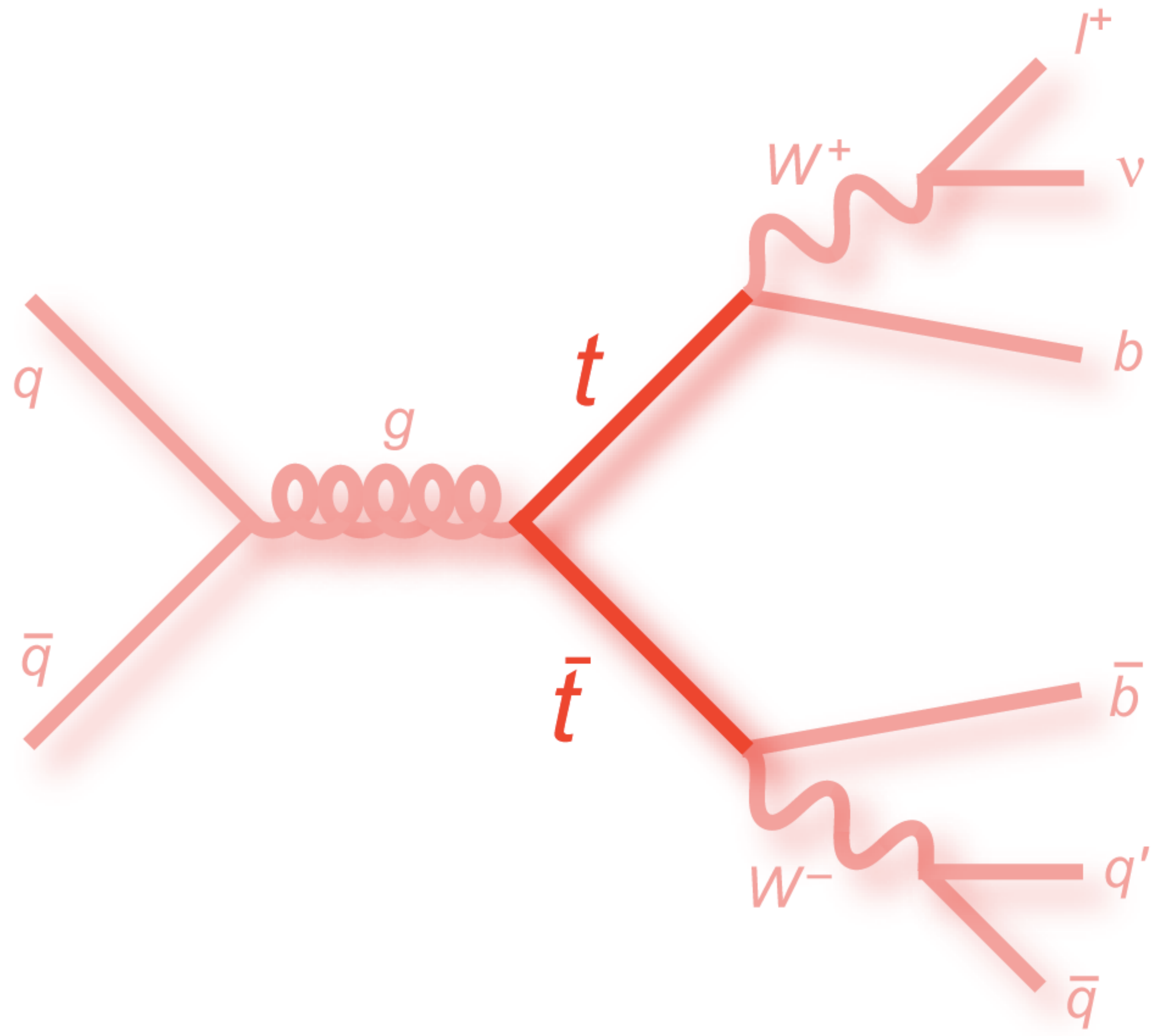
- top-mass measurements at the LHC via combination of different strategies:
  - total x-section, tt+jet, kinematic reconstruction, kinematic edges,….

- many techniques rely on kinematic information of top decay products

➡ need realistic MC modelling

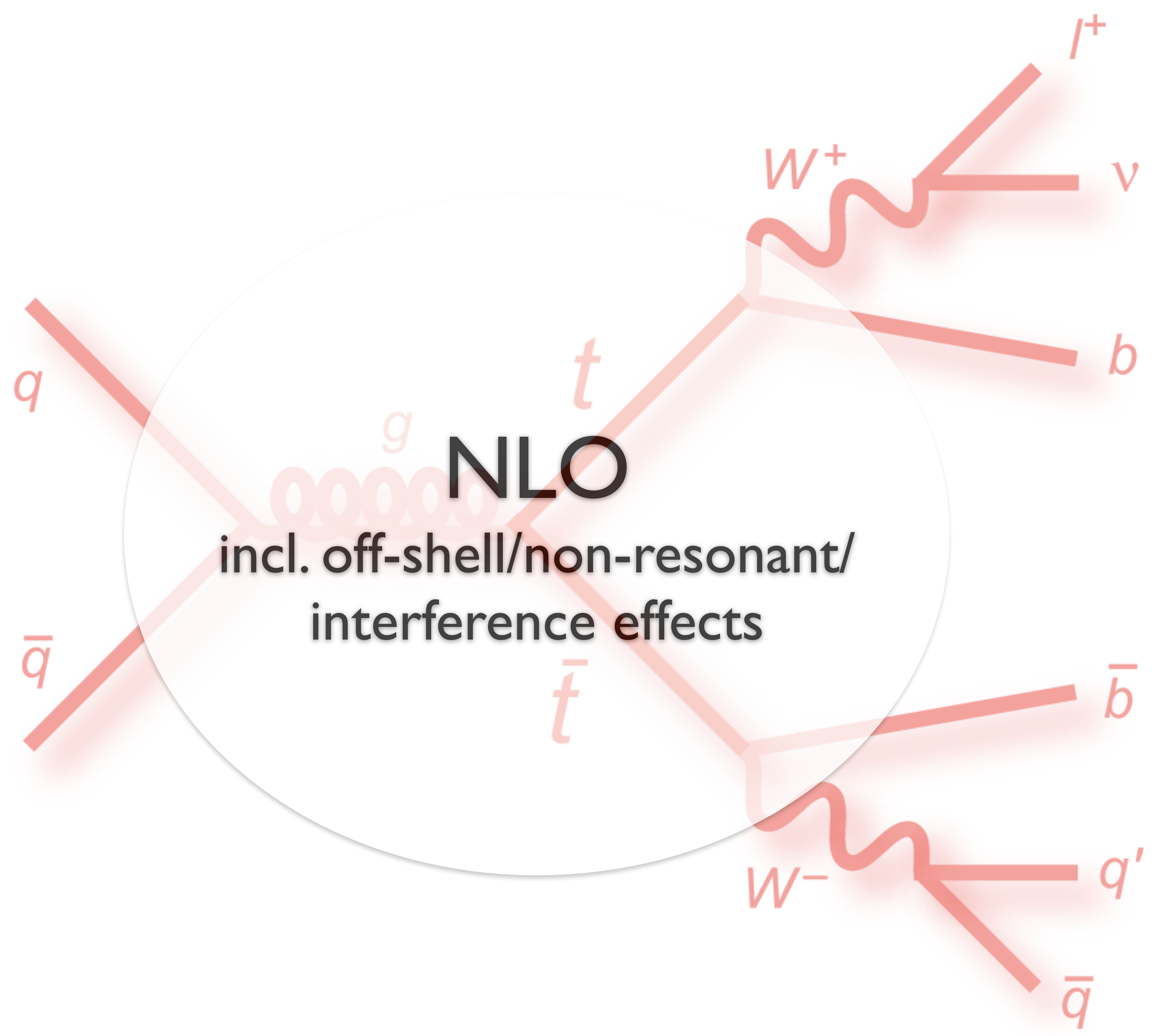
- Also: tt ubiquitous background, QCD laboratory, anomalous coupling, etc.…

Top-pair production and decay



@ NLO+PS

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**, including quantum corrections to top propagators and off-shell top-decay chains thanks to POWHEG-BOX-RES
- **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

What's new?

[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

    $$(\Phi_{\rm B}, \Phi_{\rm rad}) \longleftrightarrow \Phi_{\rm R}^{(\alpha)}$$ from FKS mappings

  - IR cancellation spoiled

    ⟹ **severe efficiency problem!**

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

    emission probability

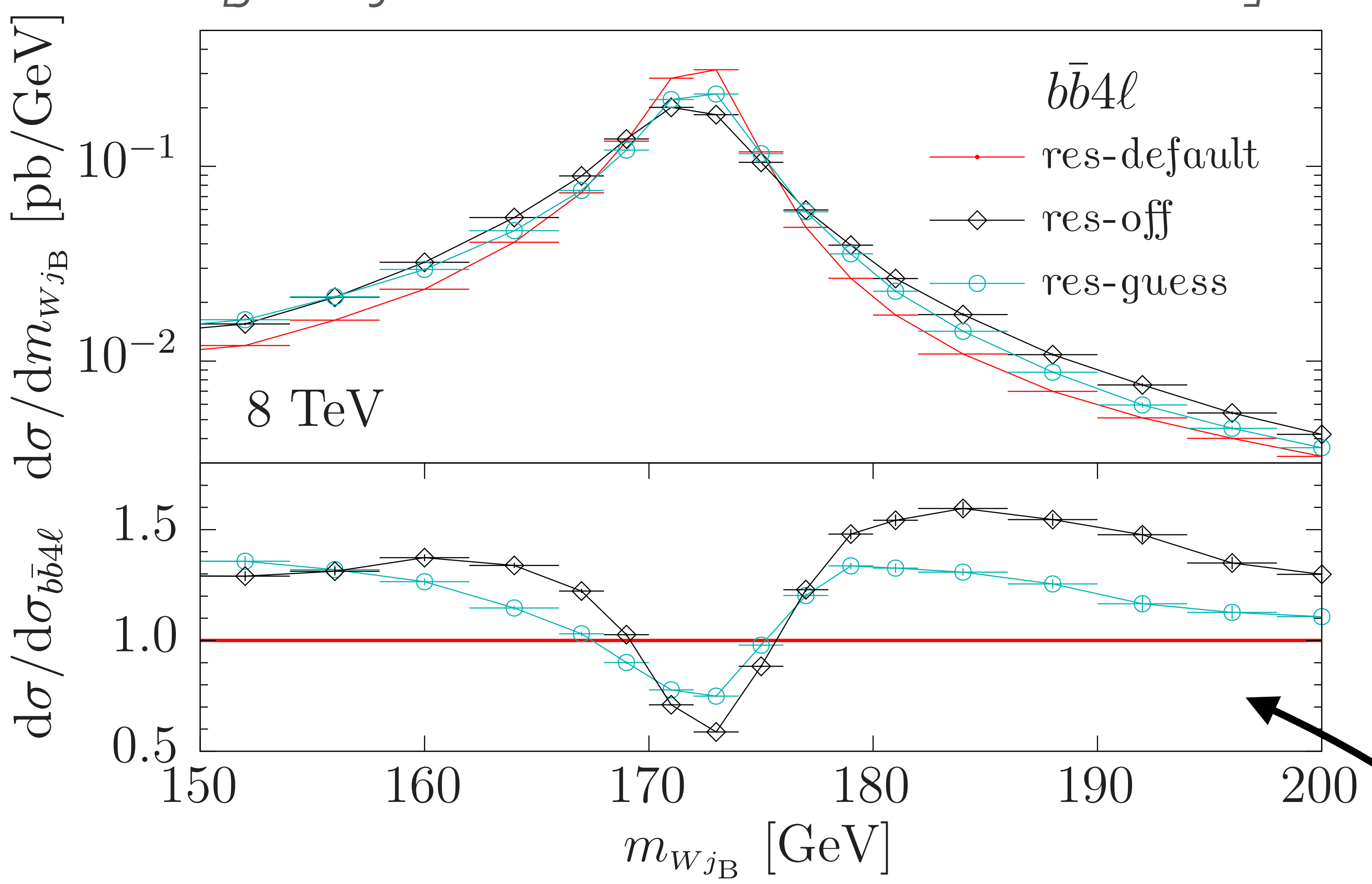
    Sudakov form-factor generated from uncontrollable R/B ratios:

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

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

    ⟹ **expect uncontrollable distortion of important kinematic shapes!**

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



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!***

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

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

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

original kinematic projectors

✓ **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

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

✓ **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

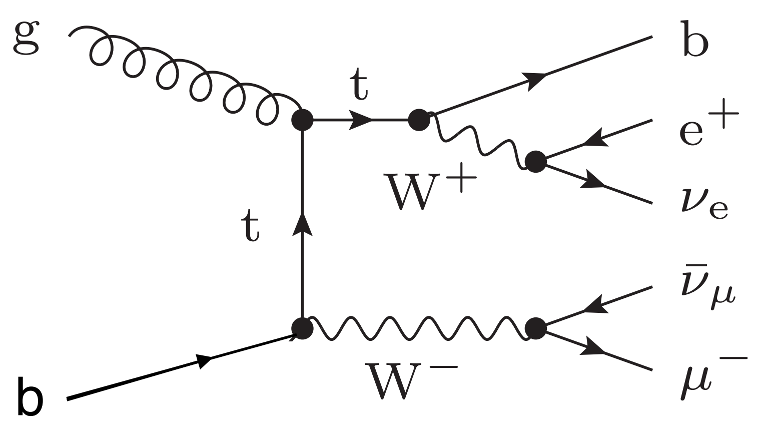
✓ **PS**:

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

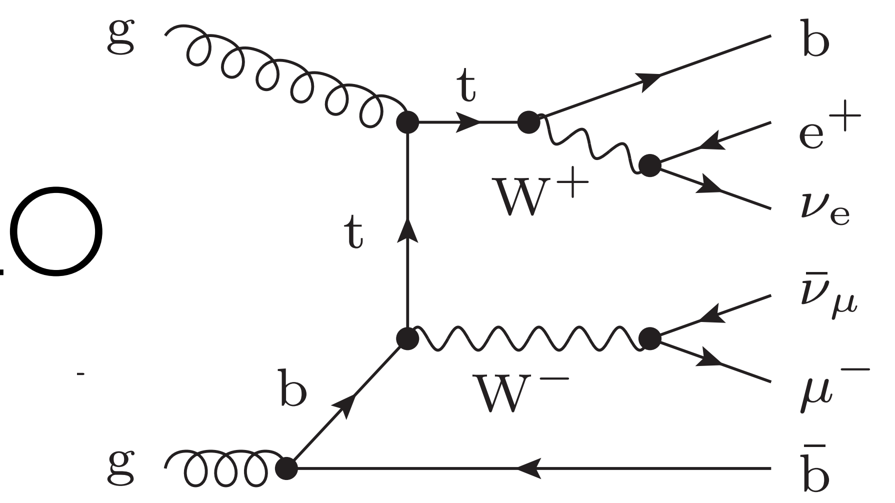
Key advantage I: Interplay between top-pair and Wt

5FS

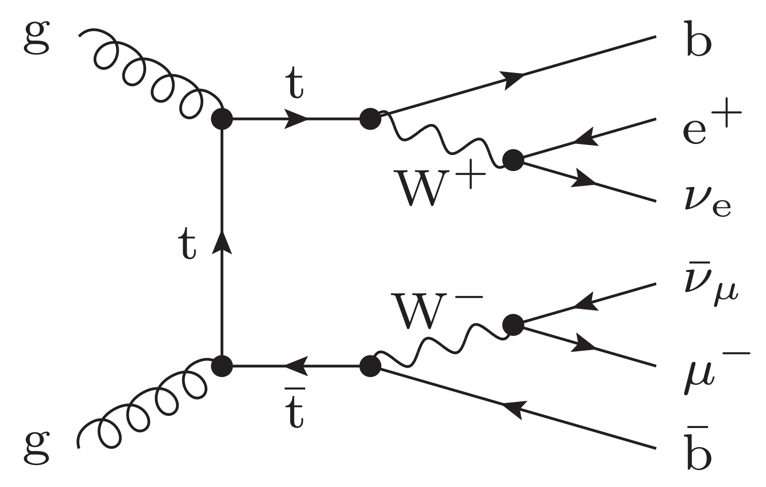
LO



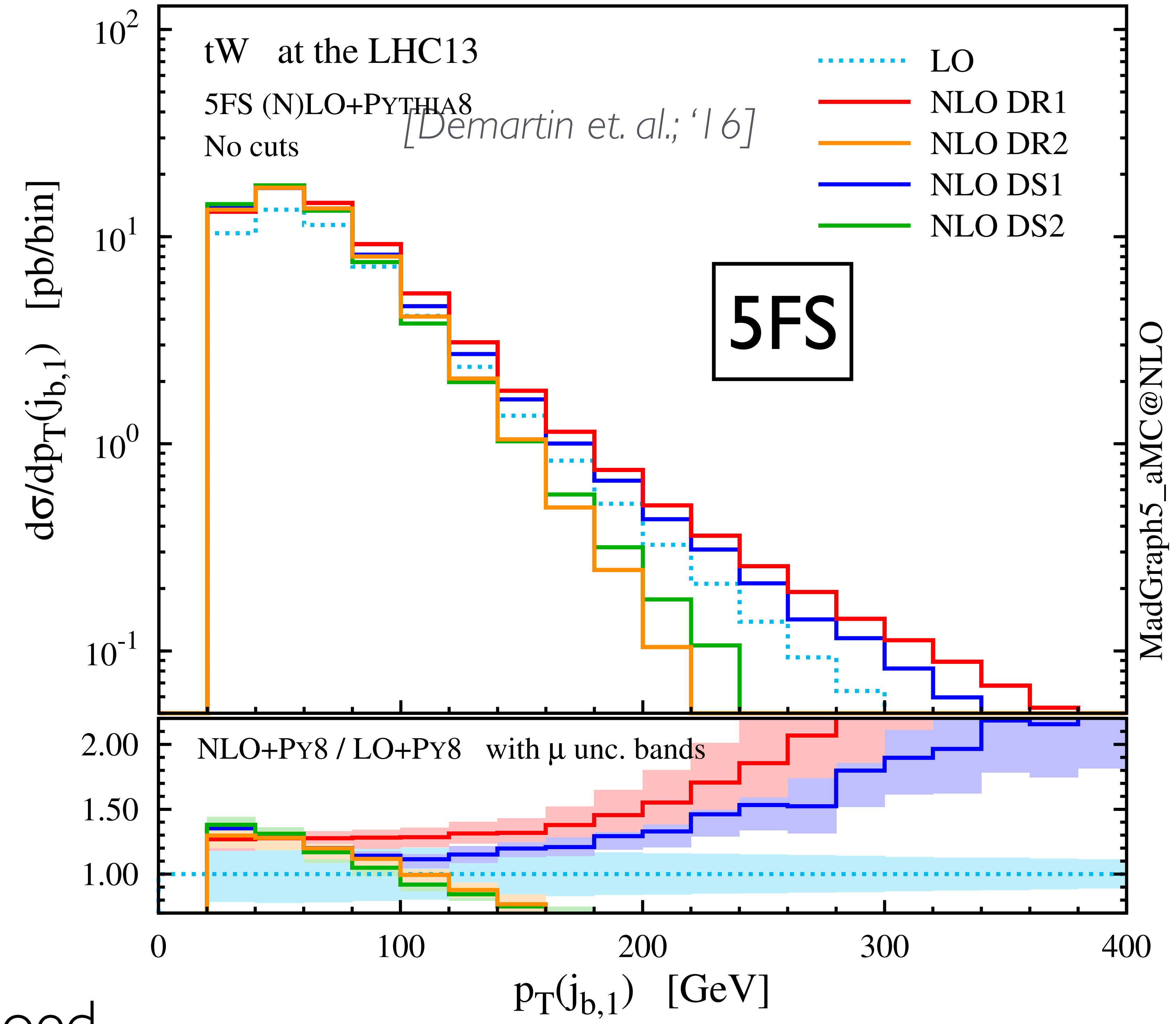
NLO



same finale state!

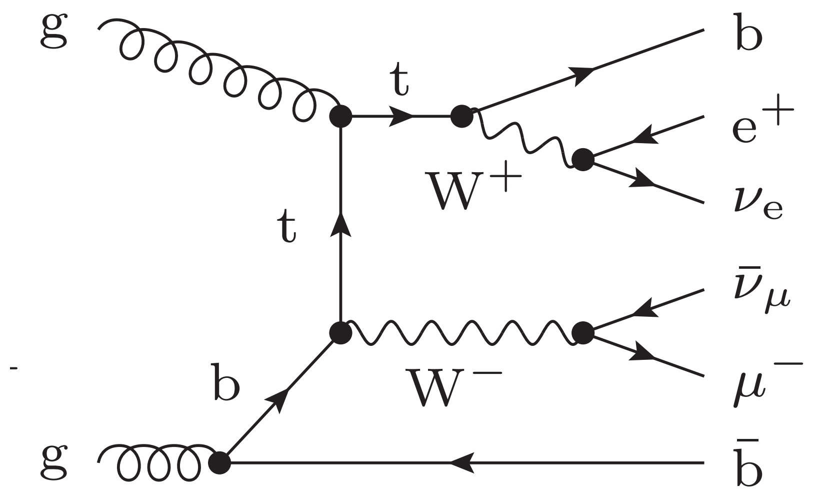


- **NLO corrections to Wt swamped by LO tt+decay**
- requires ad-hoc subtraction prescription: (Diagram Removal = DR vs. Diagram Subtraction = DS)
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

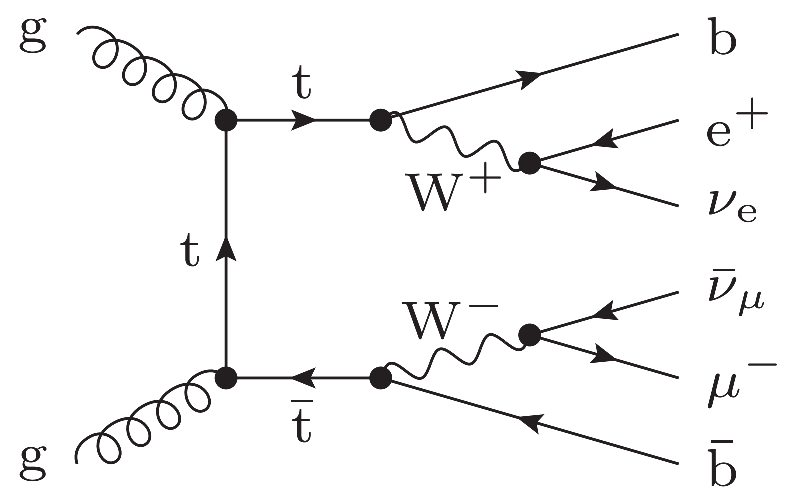


4FS

LO



Wt



$t\bar{t}$

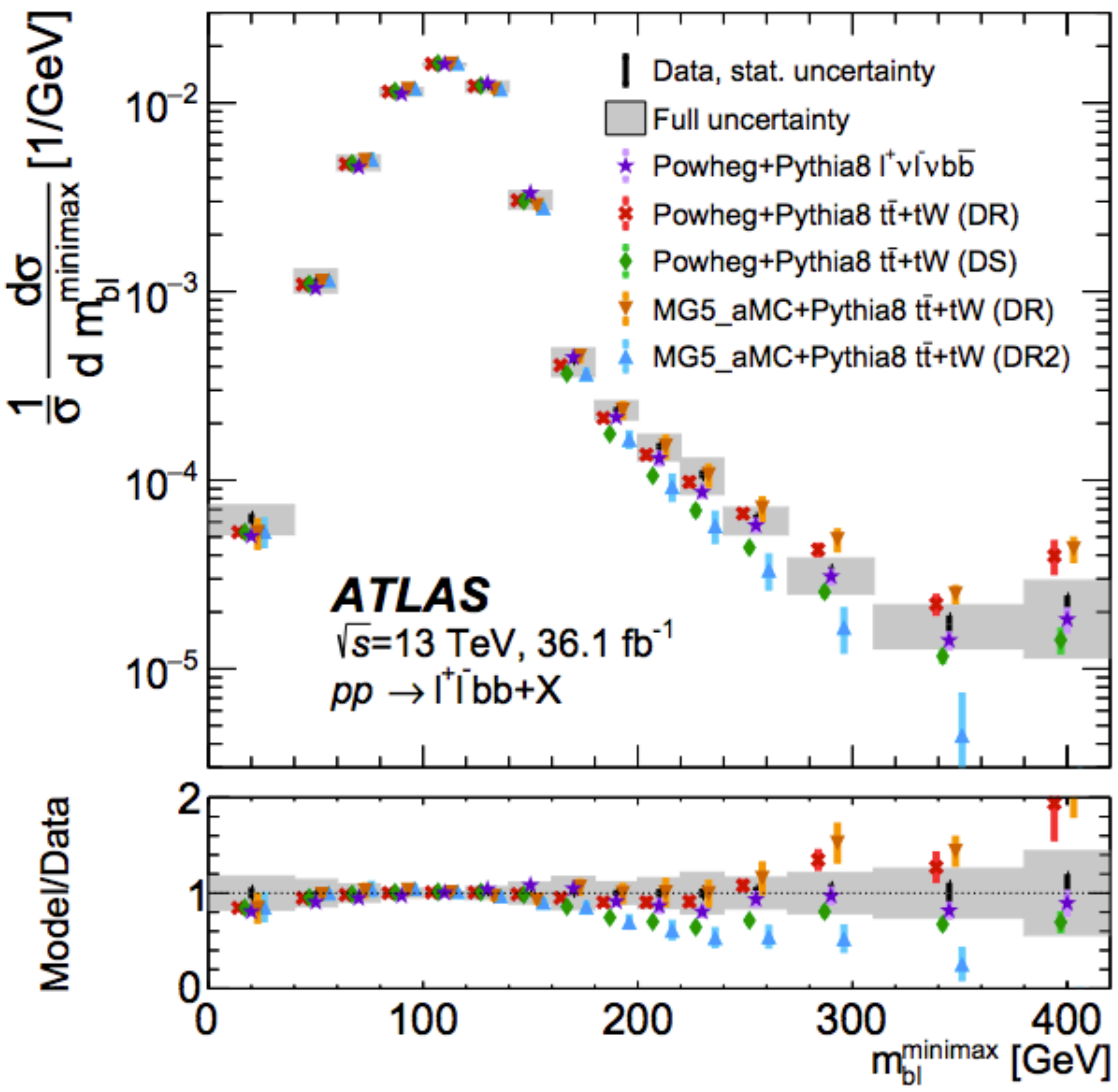
same finale state!

- **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



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

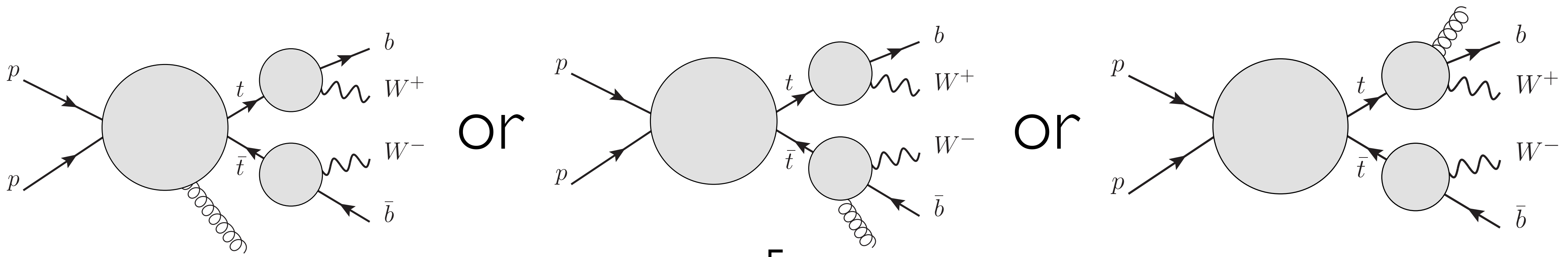
For $t\bar{t}$ (double-resonant) at LO: $m_{b\ell}^{\text{minimax}} < \sqrt{m_t^2 - m_W^2}$

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

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

Key advantage II: Multiple-radiation scheme

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

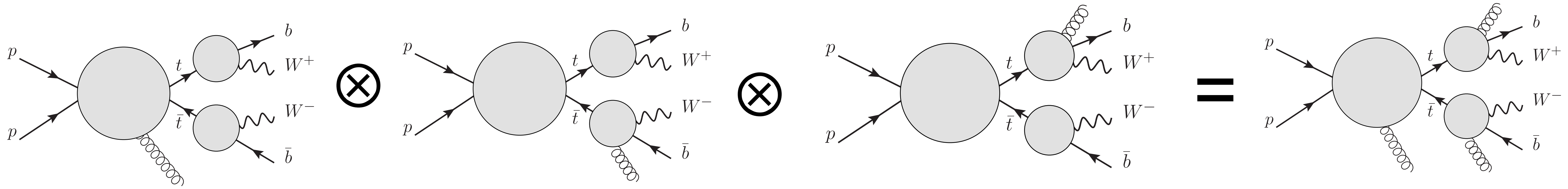


$$\Longleftrightarrow \qquad \mathrm{d}\sigma = \bar{B}(\Phi_{\mathrm{B}})\,\mathrm{d}\Phi_{\mathrm{B}} \left[\Delta(q_{\mathrm{cut}}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_{\mathrm{B}}, \Phi_{\mathrm{rad}}))}{B(\Phi_{\mathrm{B}})}\,\mathrm{d}\Phi_{\mathrm{rad}}\right]$$

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**: . *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: $\mathrm{d}\sigma_{\mathrm{prod}\times\mathrm{dec}} = \mathrm{d}\sigma \frac{\mathrm{d}\Gamma}{\Gamma}$, **where** $\Gamma = \int_{\mathrm{dec}} \mathrm{d}\Gamma$

This hold to all orders!

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

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

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

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

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

NWA limit: $\Gamma_r \to 0$

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

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

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

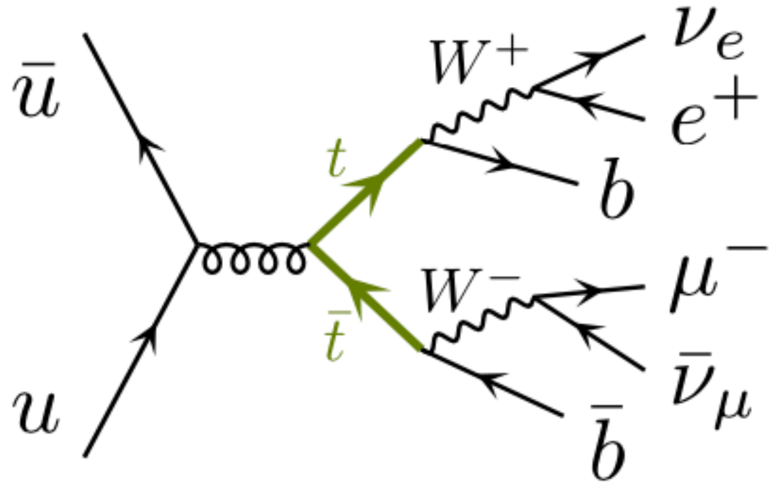
$$R^{(\mathrm{hard})}_{h,c}(\Phi_\mathrm{R})\Big|_{\mathrm{exp}} = \left(\prod_{r\in\mathcal{R}} \frac{\Gamma_{r,\mathrm{NLO}}}{\Gamma_{r,0}}\right) R^{(\mathrm{hard})}_{h,c}(\Phi_\mathrm{R})$$

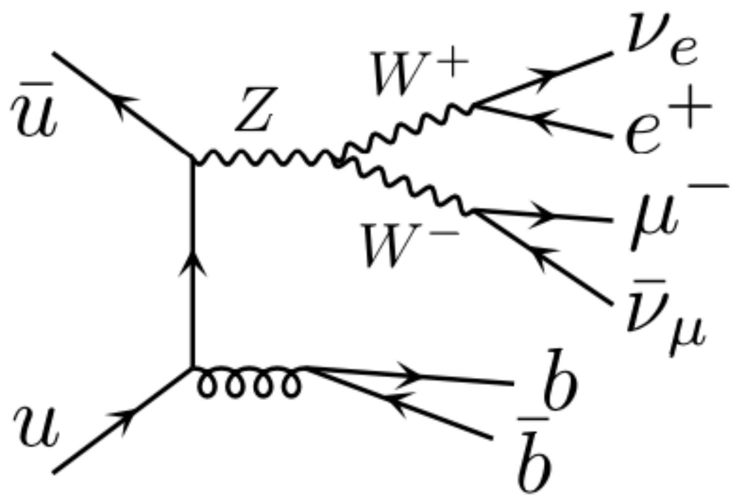
$$\frac{\sigma_{\mathtt{bb4l-sl}}}{\sigma_{\mathtt{hvq+ST}}}\Bigg|_{\mathrm{no}\ 1/\Gamma_t\ \mathrm{expansion}} = 1.074 \qquad \text{vs.} \qquad \frac{\sigma_{\mathrm{bb4l-sl}}}{\sigma_{\mathrm{hvq+ST}}}\Bigg|_{\mathrm{with}\ 1/\Gamma_t\ \mathrm{expansion}} = 1.012$$

Matrix element-based resonance histories

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

kinematics-based resonance histories



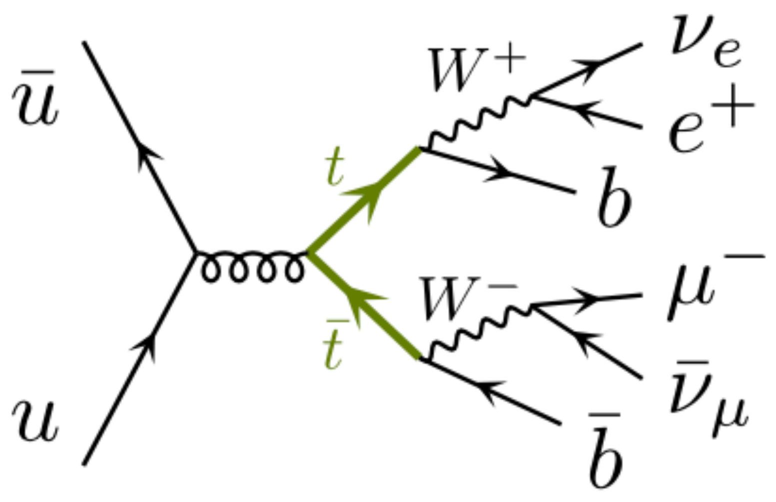


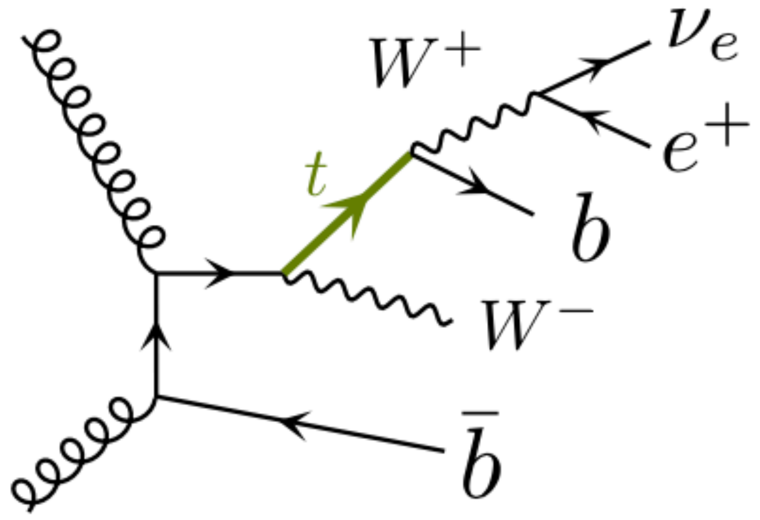
$$P_1 = \frac{m_t^4}{(s-p_t^2)^2+m_t^2\Gamma_t^2} \times \frac{m_t^4}{(s-p_{\bar{t}}^2)^2+m_t^2\Gamma_t^2} \times \cdots$$

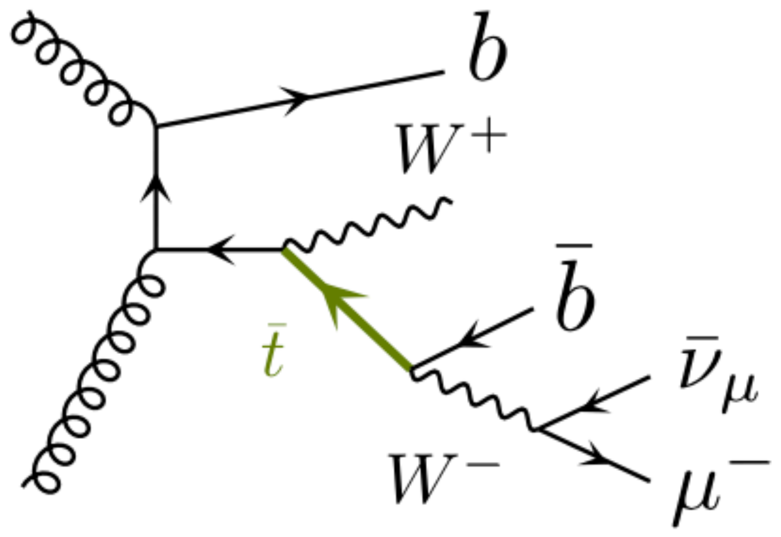
$$P_2 = \frac{m_Z^4}{(s-p_Z^2)^2+m_Z^2\Gamma_Z^2} \times \cdots$$

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

Matrix element-based resonance histories







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

$P_2 = B_{tW^+}$

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

squared-ME in pole approximation

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

$$\rho^{(\mathrm{hist})}_{t\bar{t}}(\Phi_\mathrm{B})\big|_\mathrm{ME} = |\mathcal{A}_{t\bar{t}}|^2 \qquad \rho^{(\mathrm{hist})}_{\bar{t}W^+}(\Phi_\mathrm{B})\big|_\mathrm{ME} = |\mathcal{A}_{\bar{t}W^+}|^2 \qquad \rho^{(\mathrm{hist})}_{tW^-}(\Phi_\mathrm{B})\big|_\mathrm{ME} = |\mathcal{A}_{tW^-}|^2$$

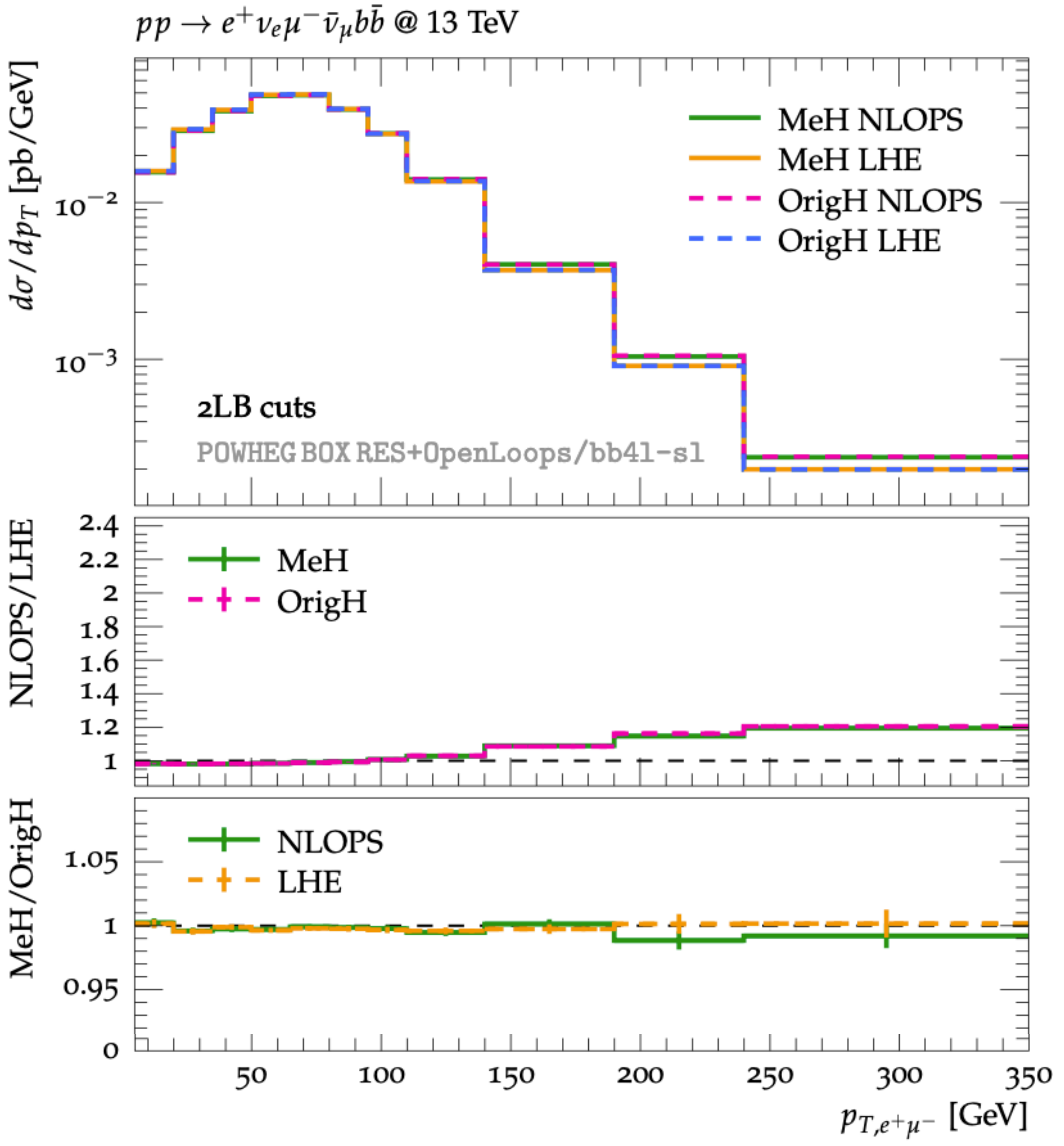
**illustration courtesy of T. Jezo*

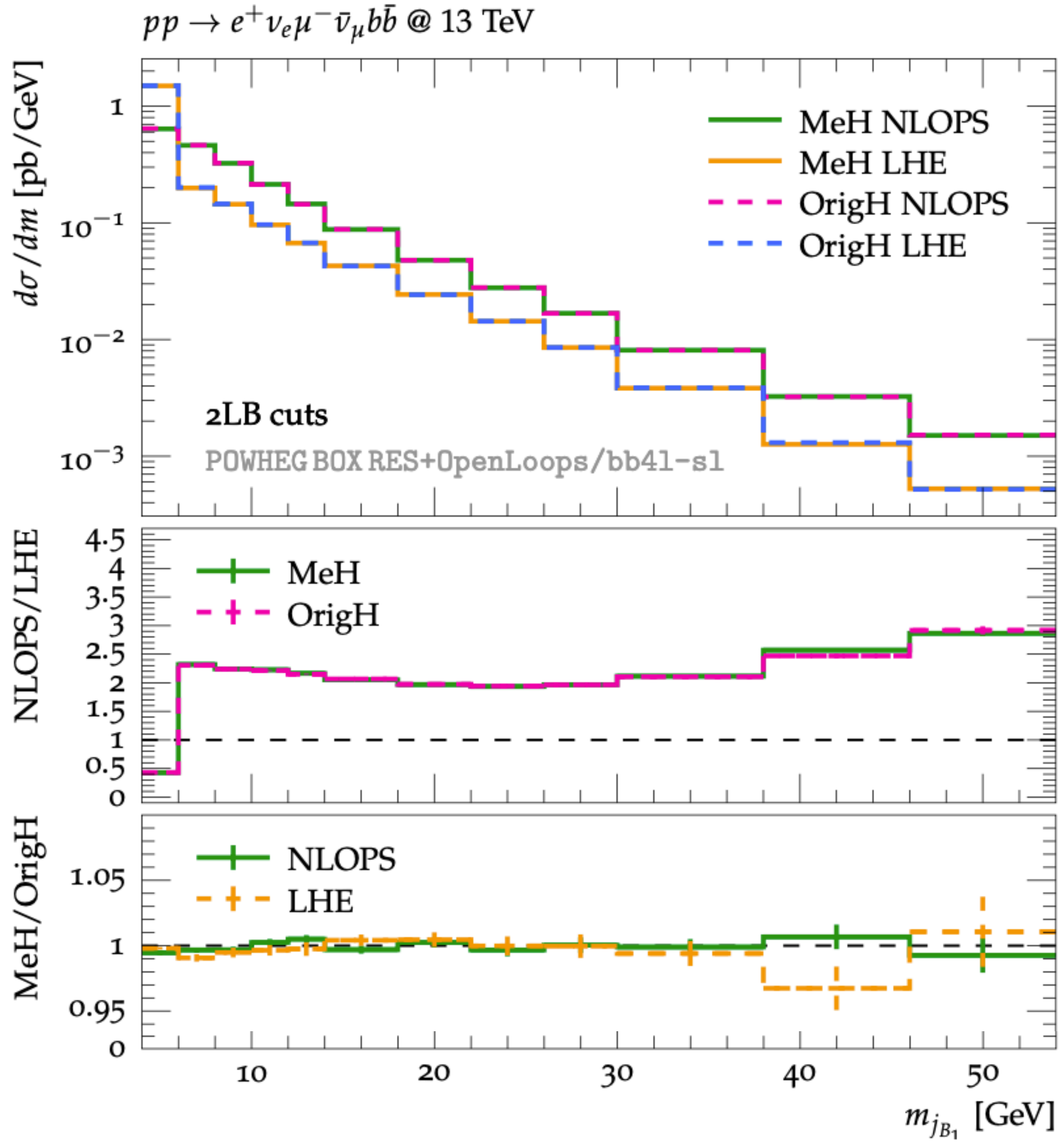
Matrix element-based resonance histories

		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%

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

Different resonance history projectors agree at <1% level!





Matrix element-based resonance histories

Naive $\rho^{(\mathrm{hist})}_{t\bar t}(\Phi_\mathrm{B})\Big|_{\mathrm{naive}} = W_t(p_t)W_t(p_{\bar t})$ $\quad \rho^{(\mathrm{hist})}_{\bar t W^\pm}(\Phi_\mathrm{B})\Big|_{\mathrm{naive}} = \frac{\chi\, m_t^2}{E^2_{\mathrm{T},b}} W_t(p_{\bar t})$ $\quad W_t(p) = \frac{M_t^4}{(p^2-M_t^2)^2+\Gamma_t^2 M_t^2}$

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

ME

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

ME'

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

ME''

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

	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%	

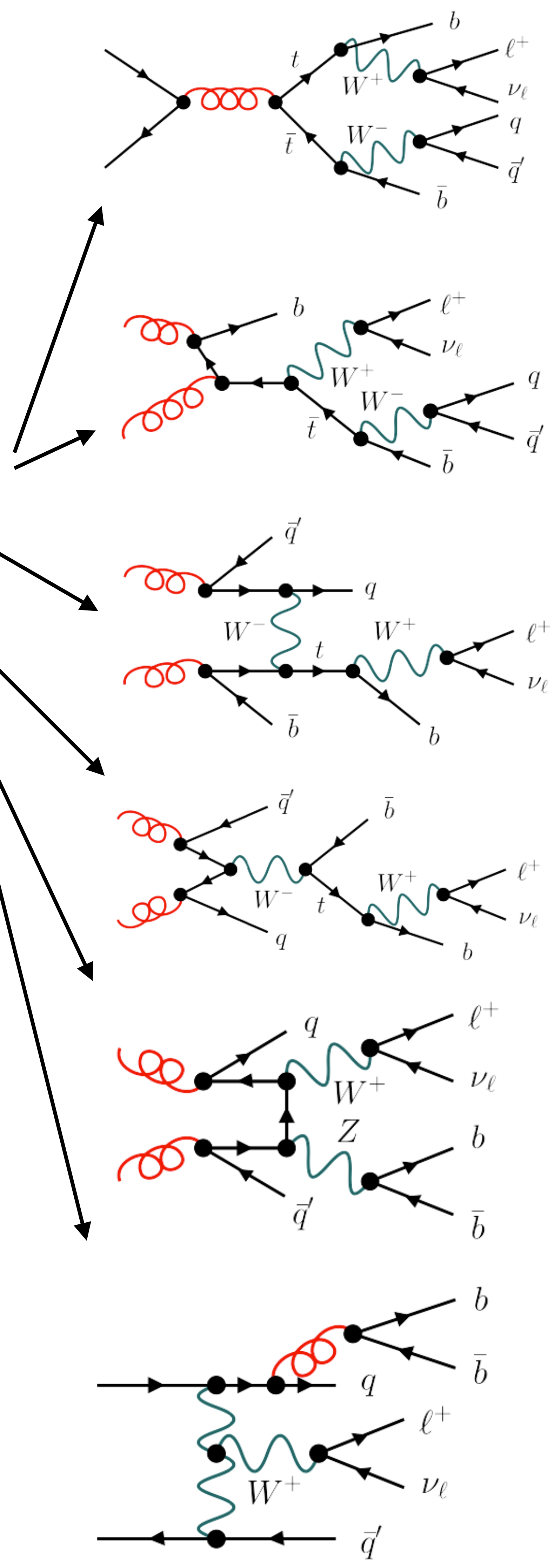
$$\sigma_{t\bar t} = \lim_{\xi_t \to 0}\left(\xi_t^2\, \sigma_{\mathrm{bb4l}}\Big|_{\Gamma_t \to \xi_t \Gamma_t}\right)$$

Might open the door to **tt vs tW separation**. Similar to "matrix-element methods". [Kondo, '88]
However, remember: here separation at LO + Real

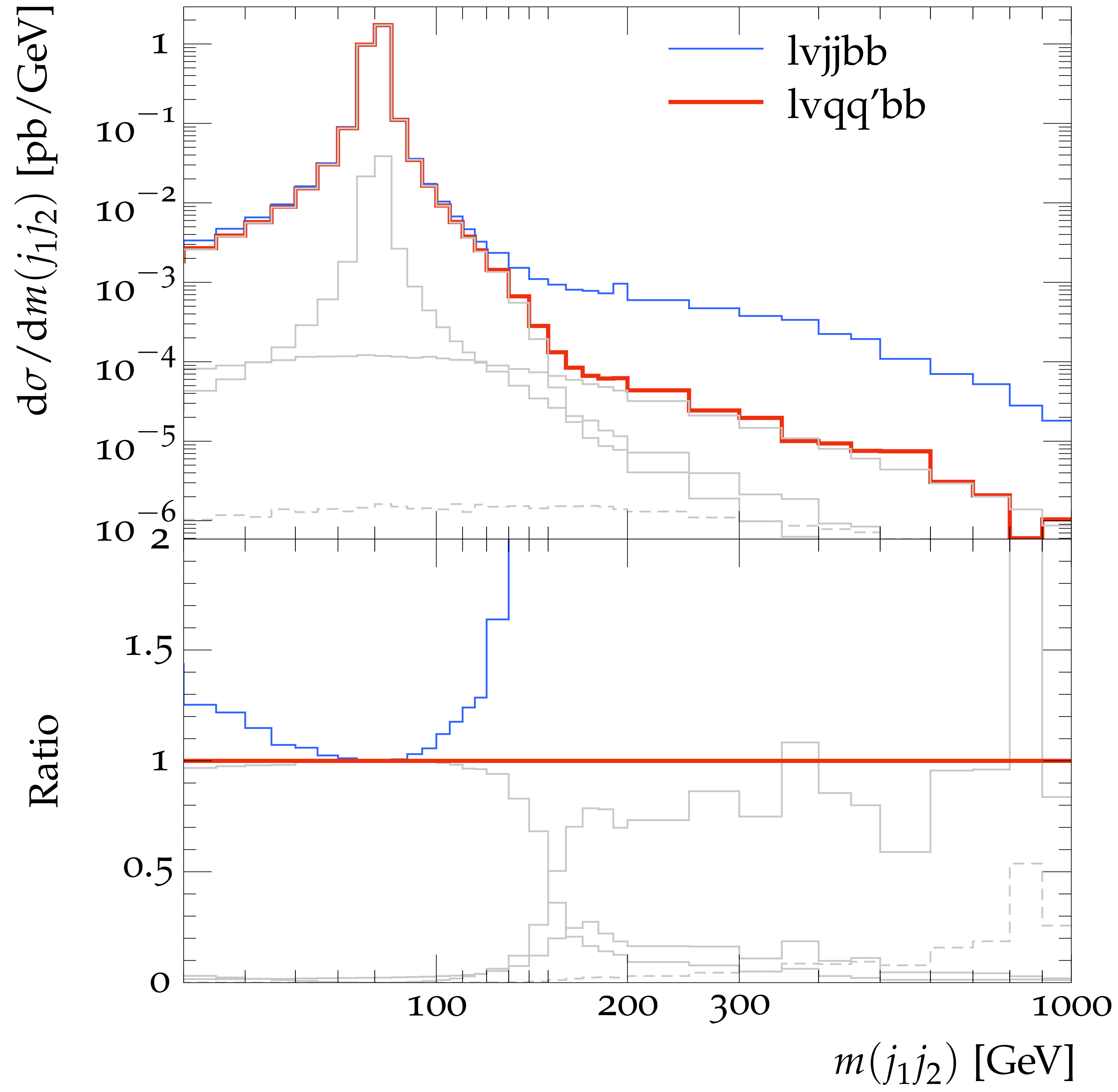
Semi-leptonic $t\bar{t}$

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

$\alpha_S^n\alpha^m$	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

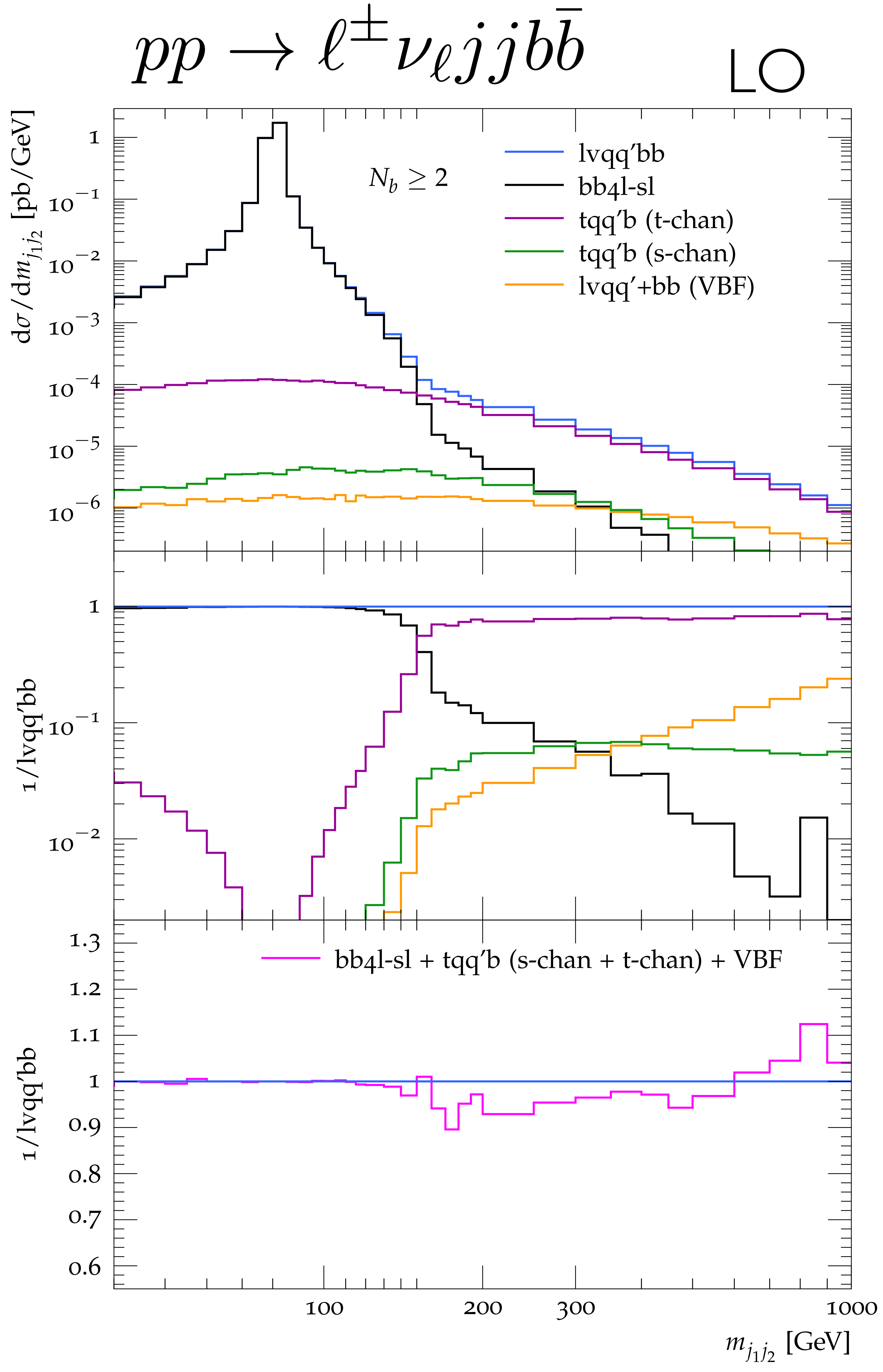


$$pp \to \ell^{\pm}\nu_\ell jjb\bar{b}$$

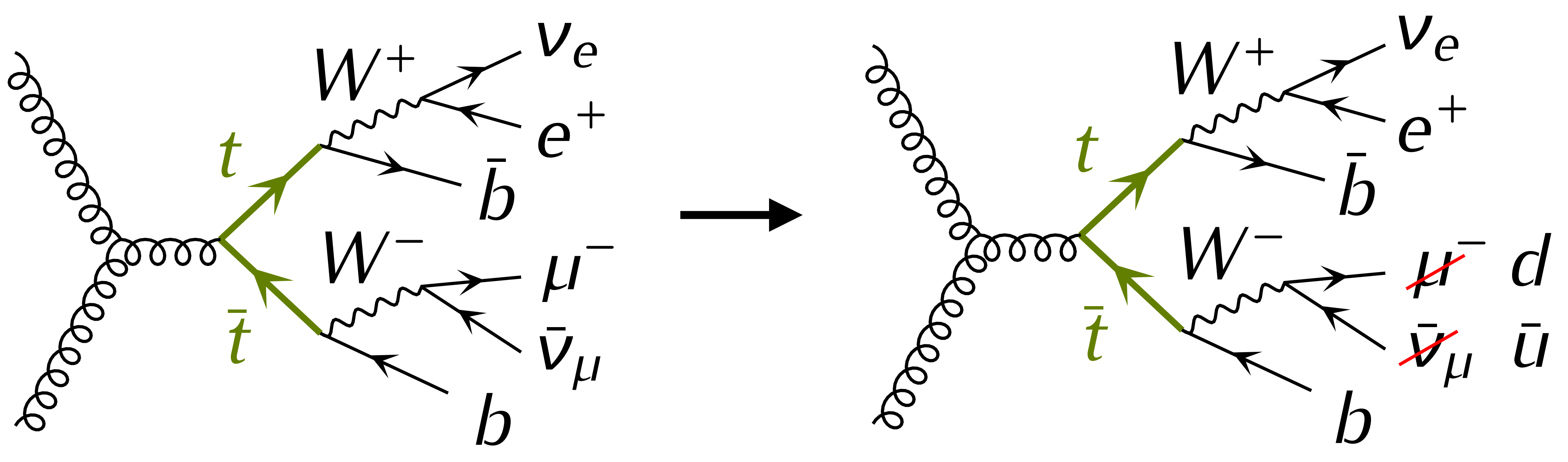


Full NLO QCD computation for $pp \to \ell^{\pm}\nu_\ell q\bar{q}'b\bar{b}$: [Denner, Pellen; '17]

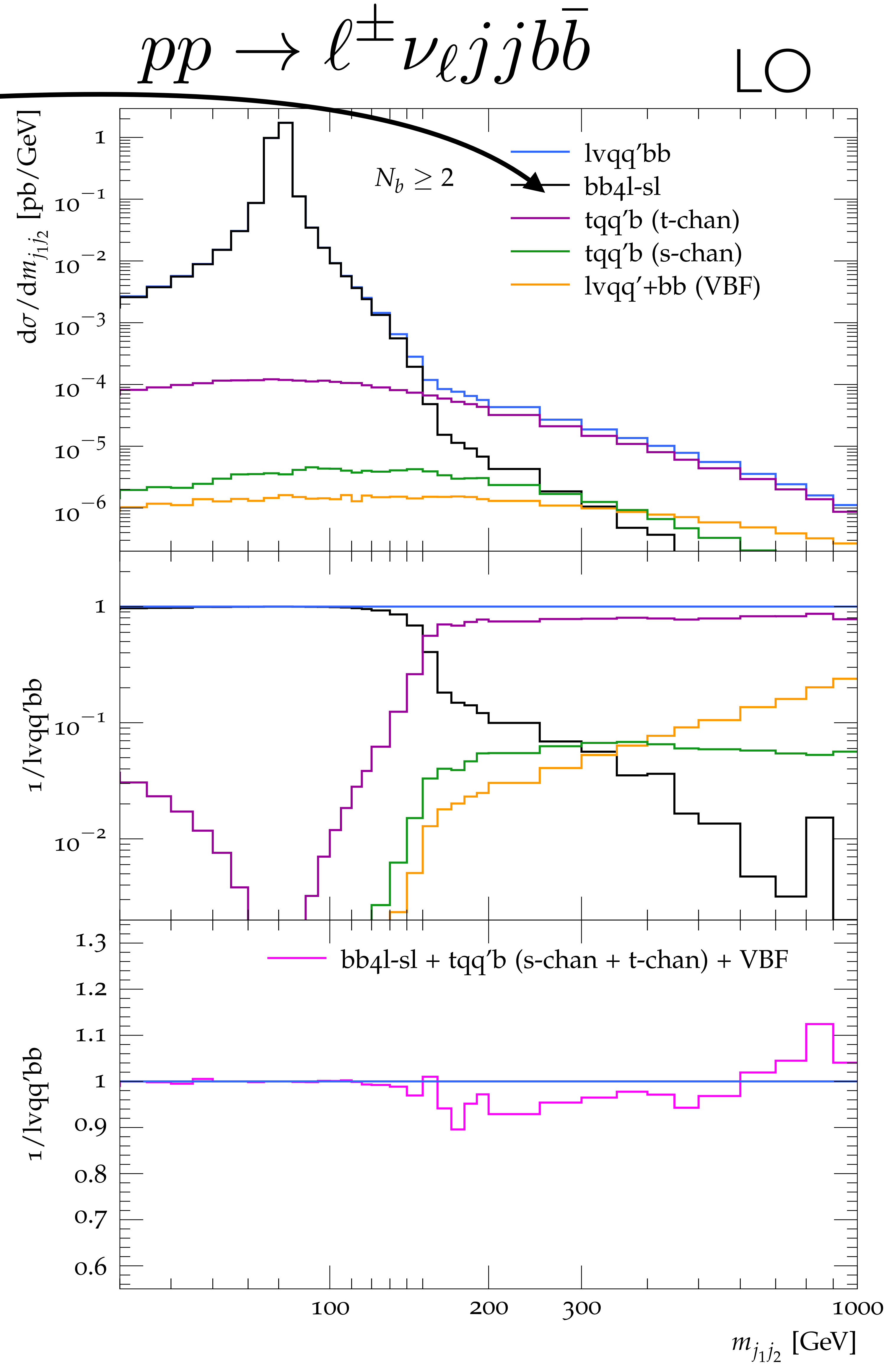
Semi-leptonic $t\bar{t}$



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



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



- In this approximation we drop some off-shell/interference effects
- But: tt, wt and tt-wt interference is retained!
- POWHEG emission based on "allrad" approach:

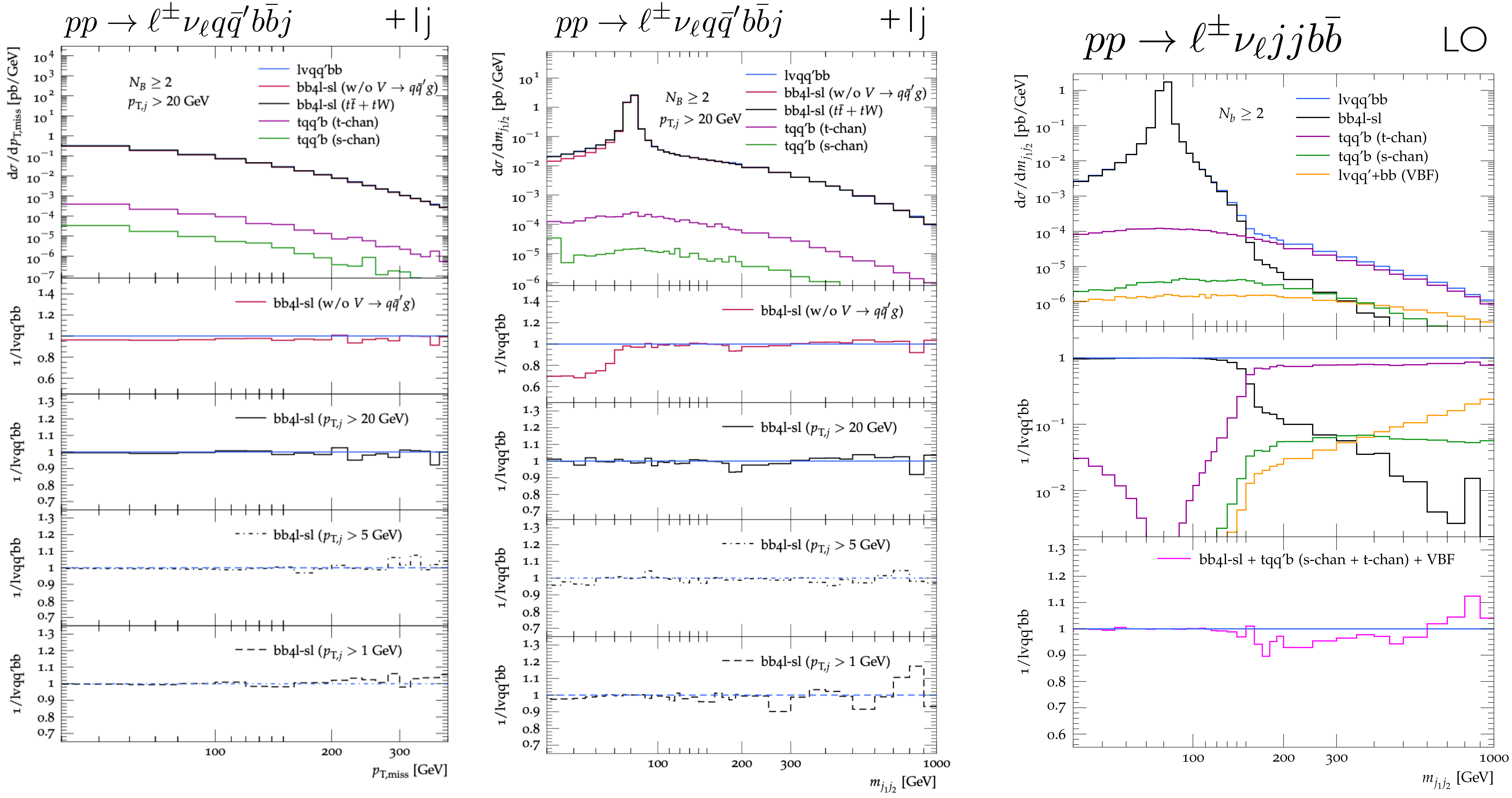
$$d\sigma_{\texttt{bb4l-sl}} = d\sigma_{\texttt{bb4l-dl}}\, K_{W_{\text{had}}} \left[\Delta_{W_{\text{had}}}(q_{\text{cut}}) + \sum_{c \in \mathcal{C}(W_{\text{had}})} \Delta_{W_{\text{had}}}(k_{\text{T},c}) \frac{R_{\text{DPA}}(\Phi_{\text{R},c})}{B_{\text{DPA}}(\Phi_{\text{B}})} d\Phi_{\text{rad},c}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

$$K_{W_{\text{had}}} = \frac{\text{BR}(W \to jj)}{\text{BR}_{\texttt{bb4l}}(W \to l\nu)}$$

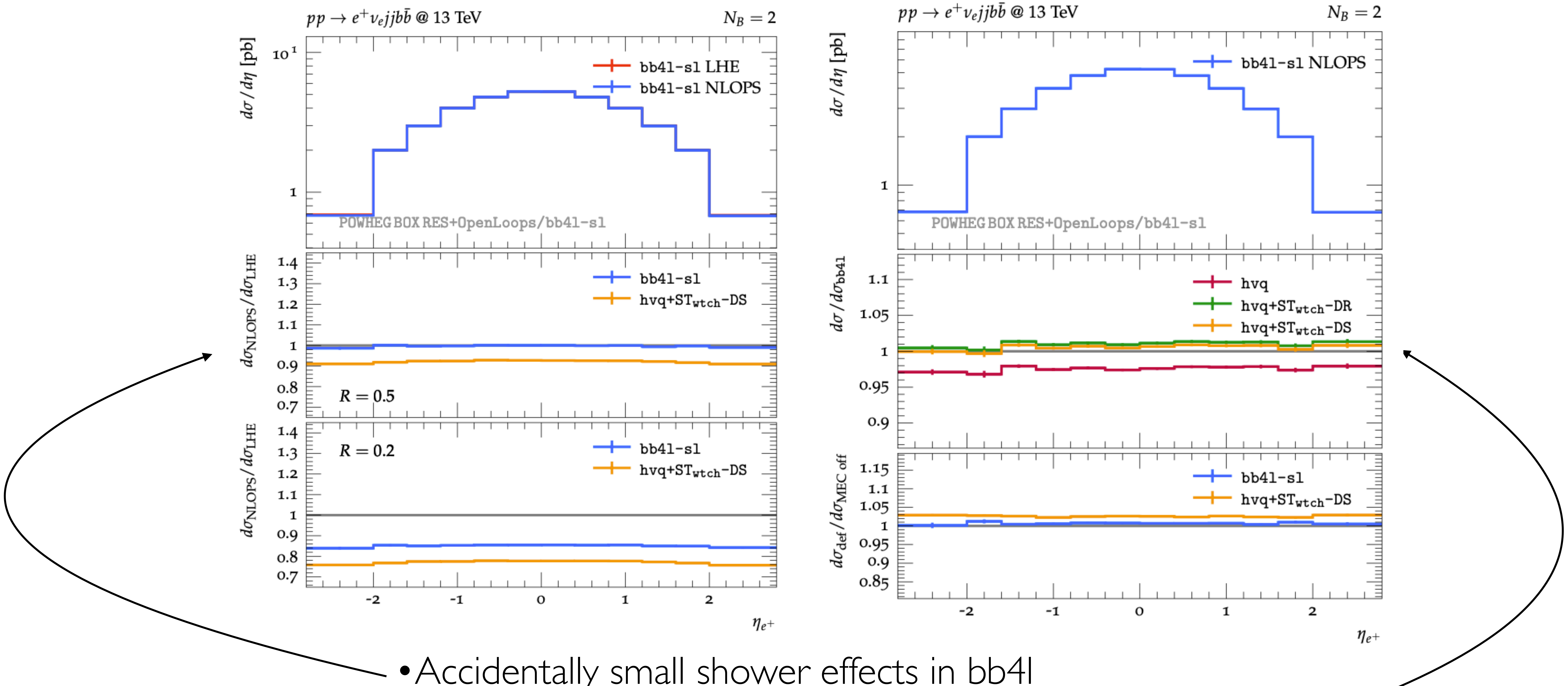
$$pp \to W^{\pm}(\to \ell^{\pm}\nu)W^{\mp}(\to q\bar{q}')b\bar{b}$$
$$pp \to W^{\pm}(\to \ell^{\pm}\nu)W^{+}(\to q\bar{q}'g)bb$$

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

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

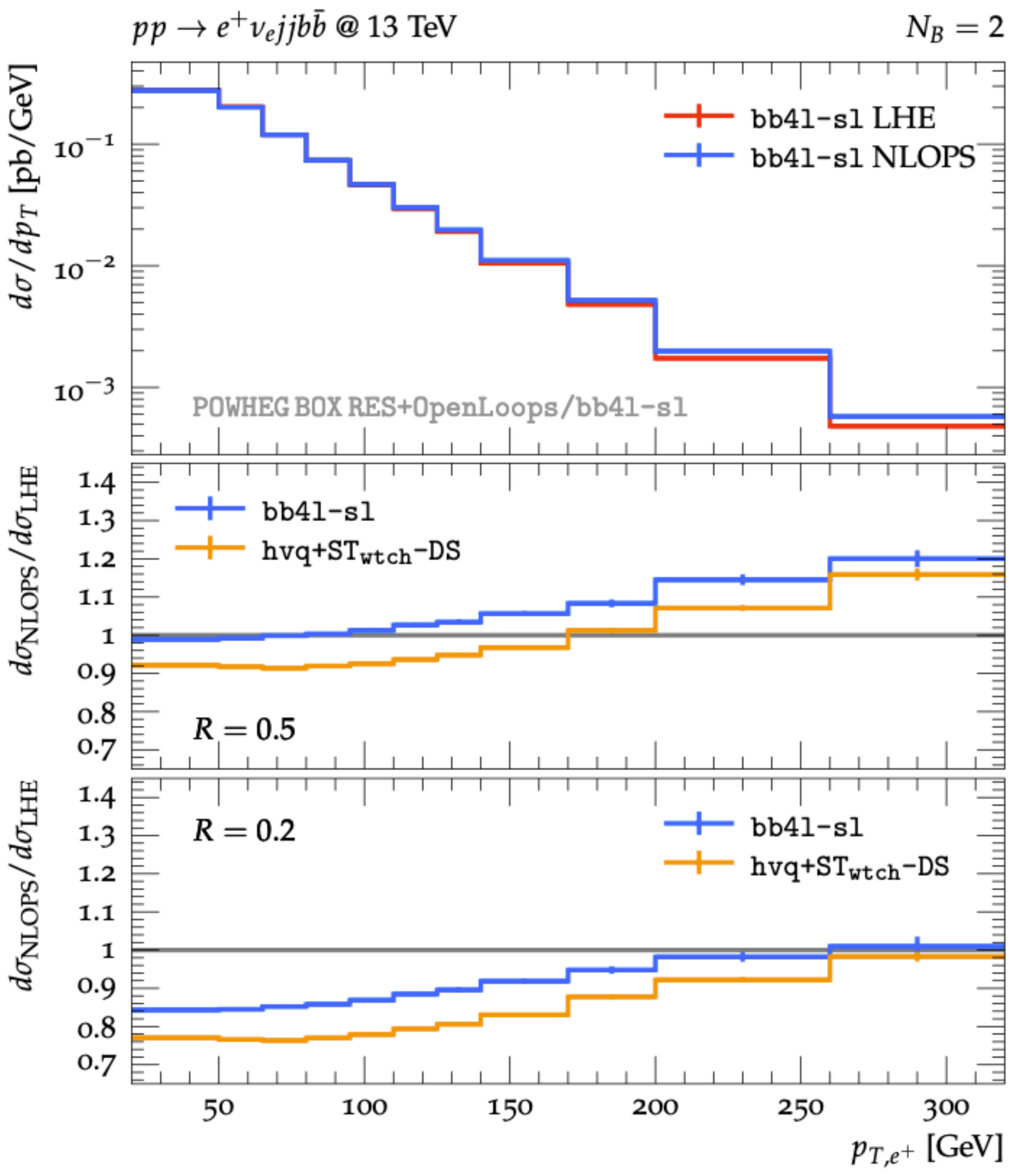


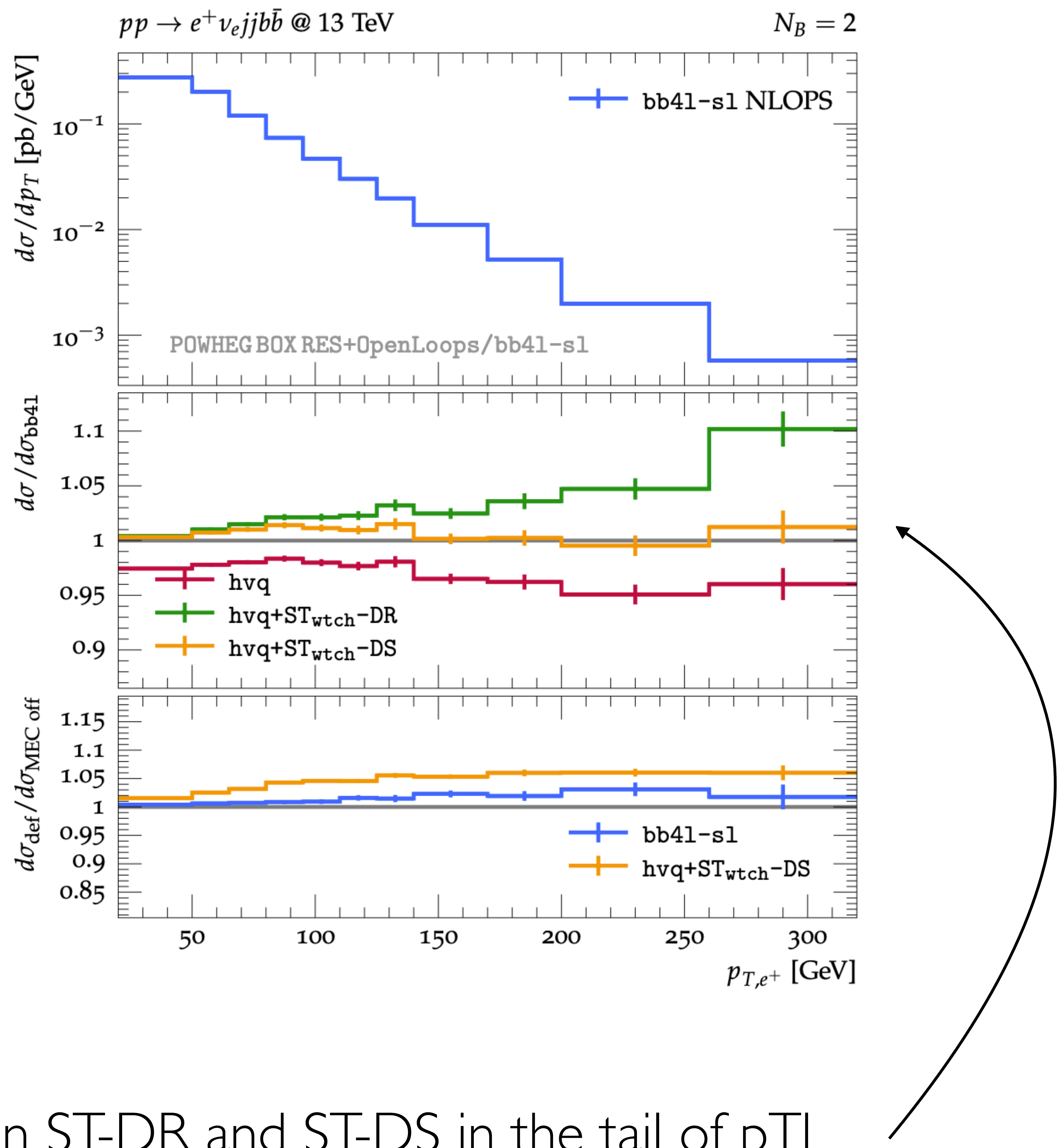
bb4l-sl vs. on-shell top-pair plus single-top



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

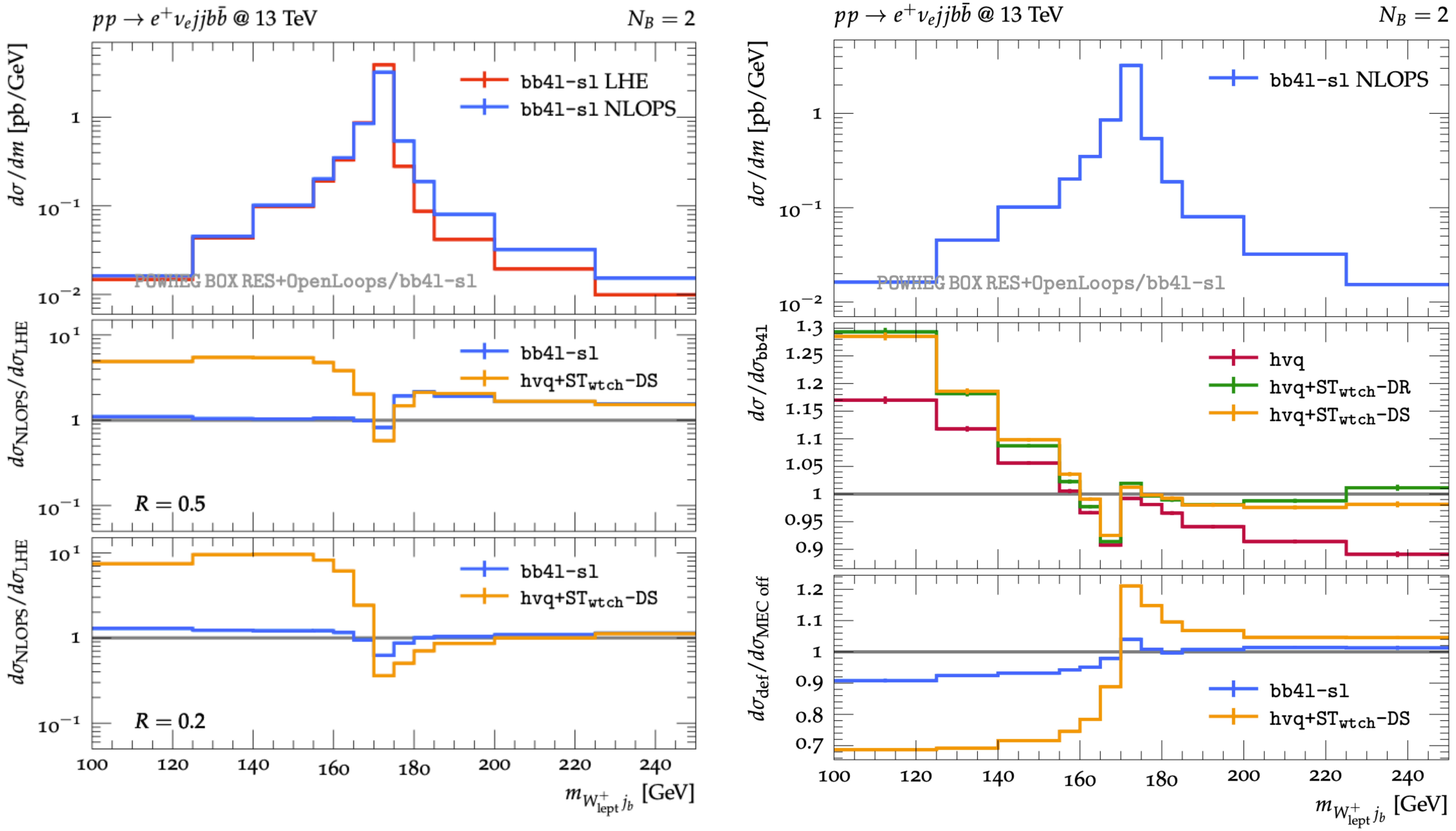
bb4l-sl vs. on-shell top-pair plus single-top





- 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

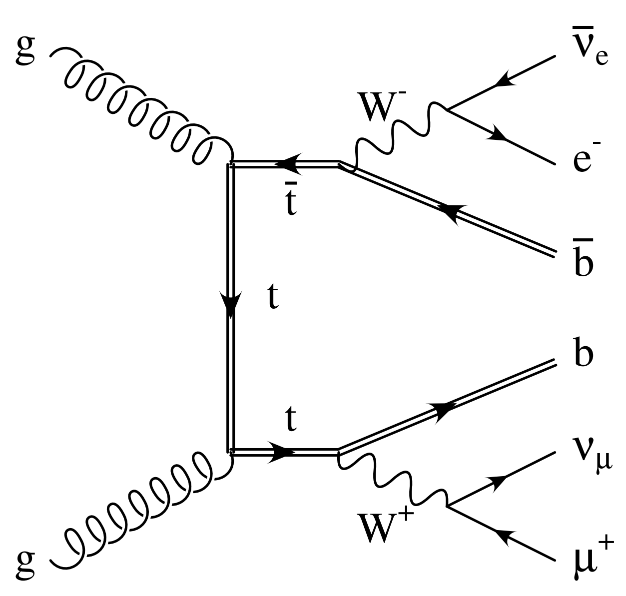
Conclusions

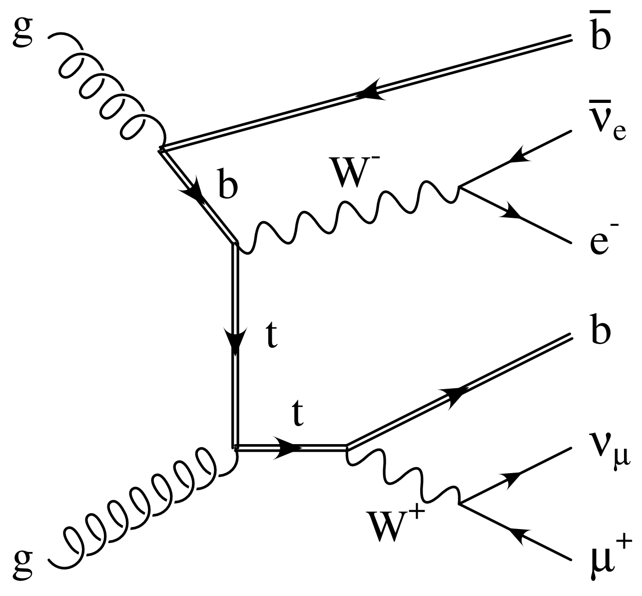
- Precision **NLOPS predictions for off-shell tt+Wt** crucial for top-mass measurements and backgrounds in searches.
- Resonance-aware matching mandatory
- Inverse-width expansion in off-shell fNLO and NLOPS computations ensures narrow-width limit. Numerical impact can be significant.
- Matrix-element 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

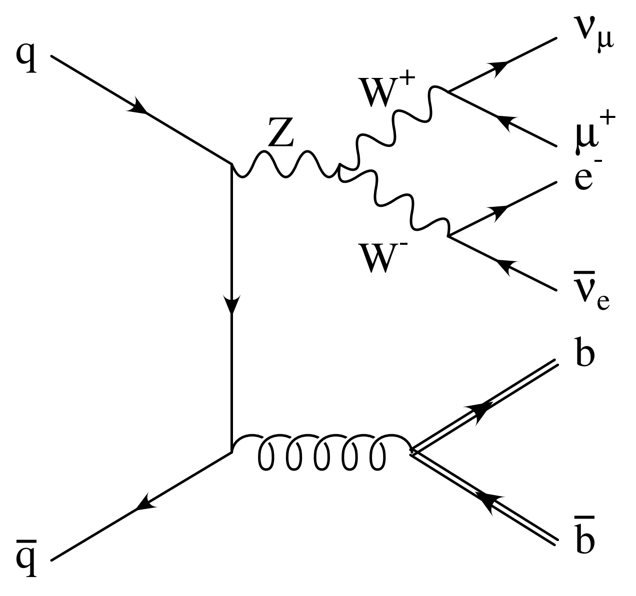
The resonance-aware bb4l generator

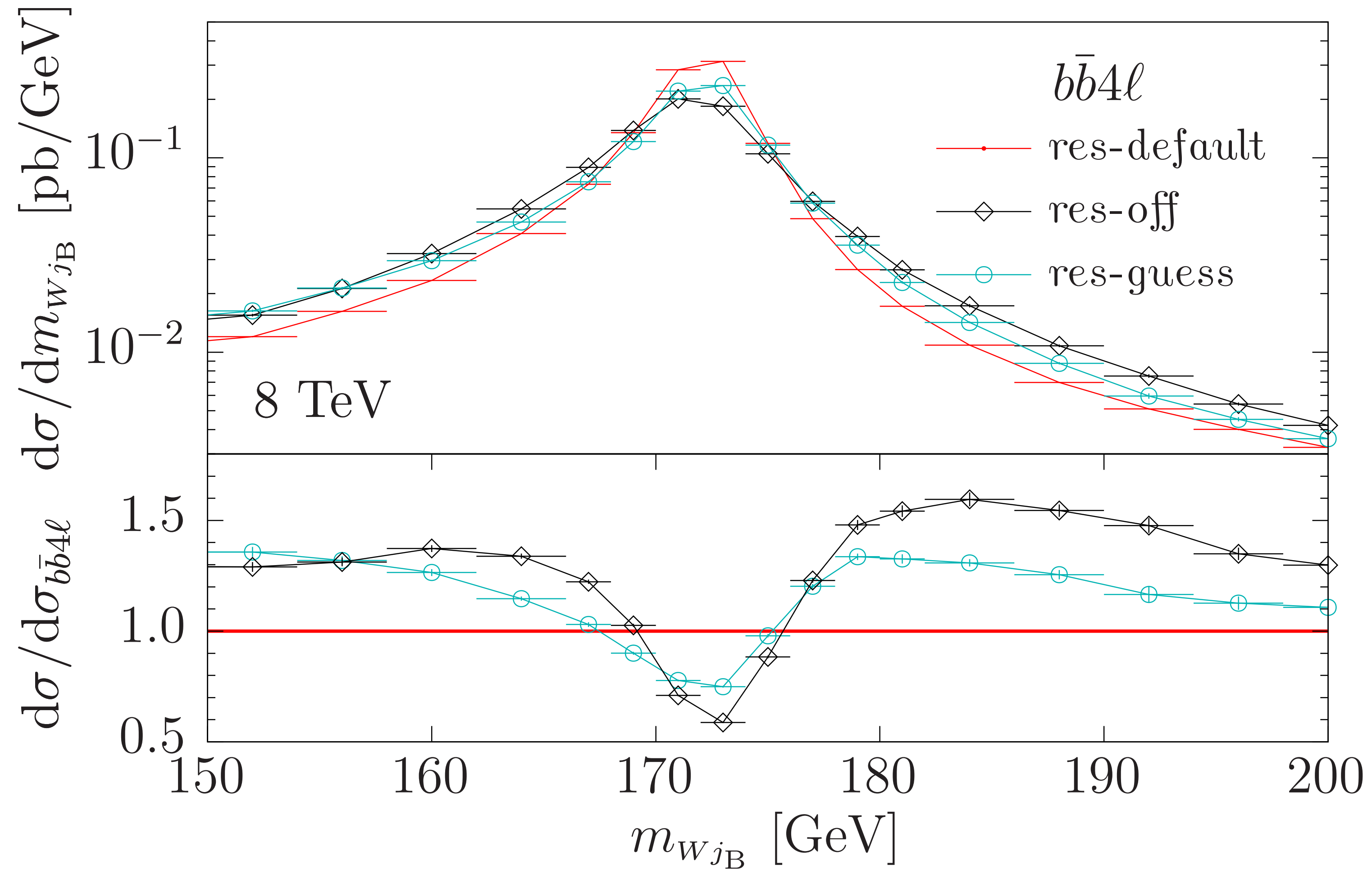
[Jezo, JML, Nason, Oleari, Pozzorini, '16]

- 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