Resonance aware NLO+PS in POWHEG for top-pair and single-top physics

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work in collaboration with:

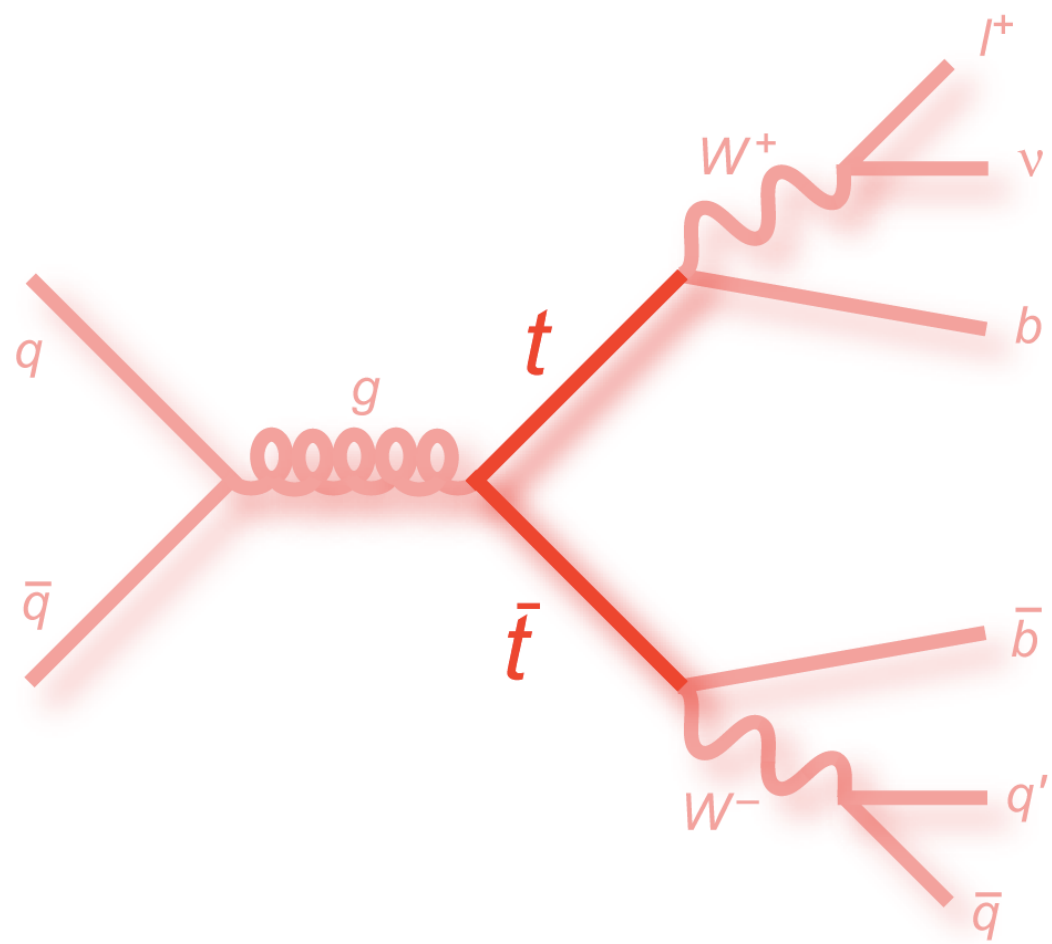
T. Ježo, P. Nason, C. Oleari, S. Pozzorini

based on [Ježo, Nason; '15] & [Ježo, JML, Nason, Oleari, Pozzorini; '16]

QCD@LHC

Zurich, 23th August 2016

Top-pair production and decay



@ NLO+PS

NLO QCD [Bernreuther, Brandenburg, Si; '04, Melnikov, Schulze;'09, Campbell, Ellis; '15] **[Bevilacqua, Czakon, van. Hameren, Papadopoulos, Worek; '11, Denner, Dittmaier, Kallweit, Pozzorini; '11+'12, Heinrich, Maier, Nisius, Schlenk, Winter; '14, Frederix '14, Cascioli, Kallweit, Maierhfer, Pozzorini; '14]**

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NLO EW [Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth; '94, Bernreuther, Fuecker, Si; '06+'08, Kühn, Scharf, Uwer; '07,+'15, Hollik, Pagani; '07, Pagani, Tsinikos, Zaro,; '16] **[Bernreuther, Si;'10] [Denner, Pellen '16]**

NLO QCD+PS [Frixione, Nason, Webber, '03, Frixione, Nason, Ridolfi; '07] **[Campbell, Ellis, Nason, Re, '15] [Garzelli, Kardos, Trocsanyi; '14]**

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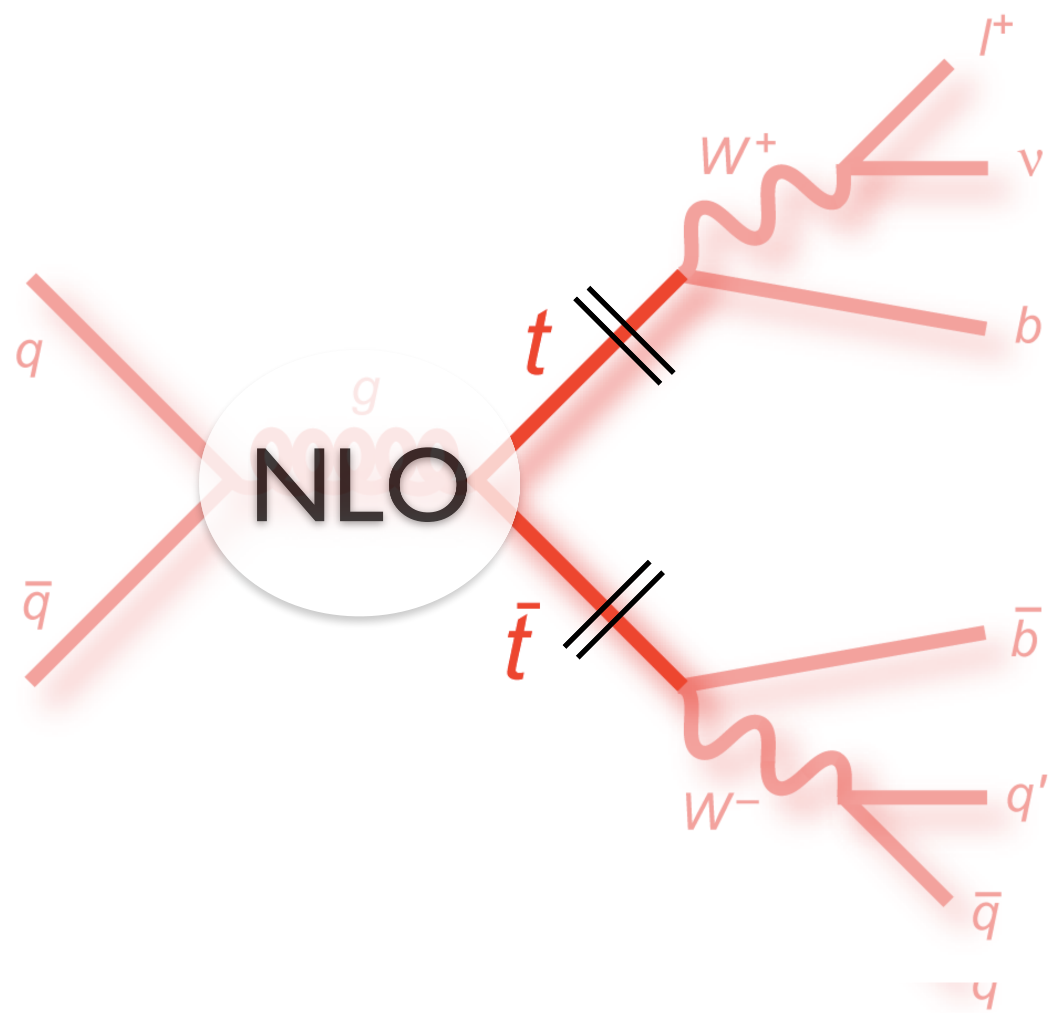

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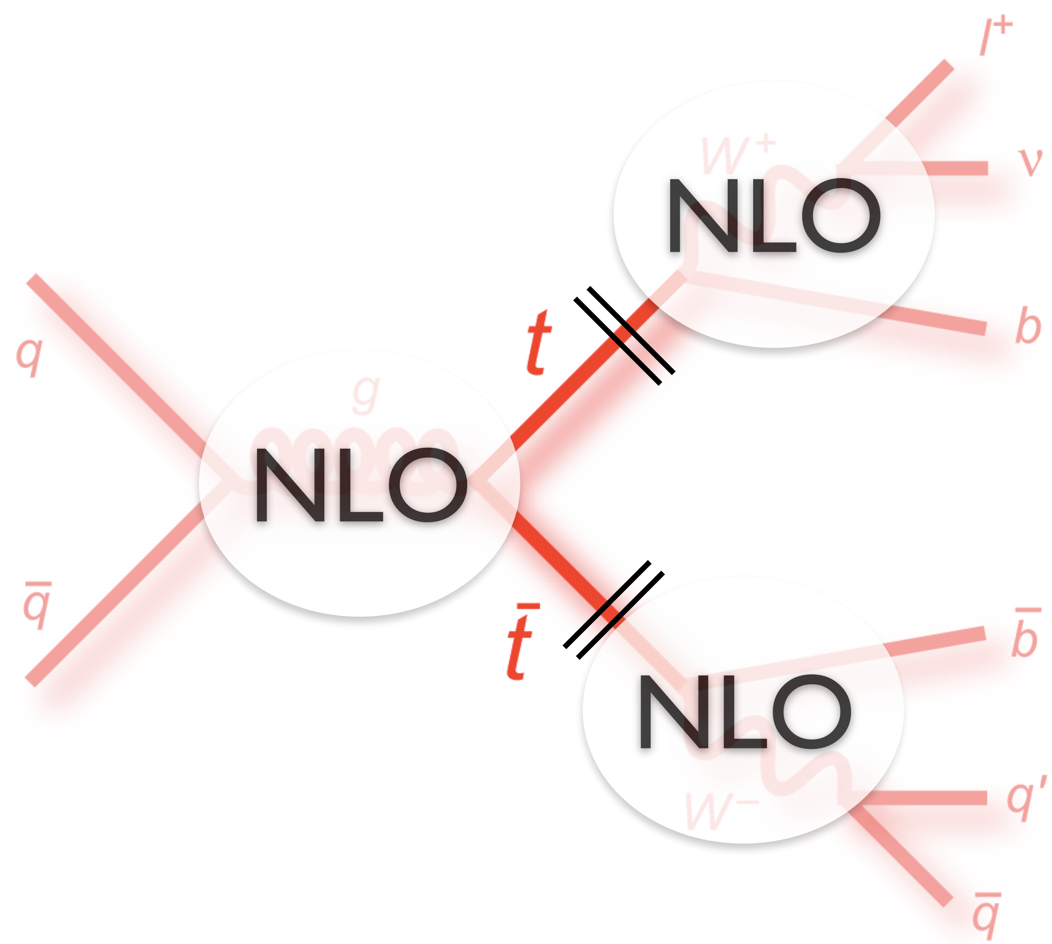

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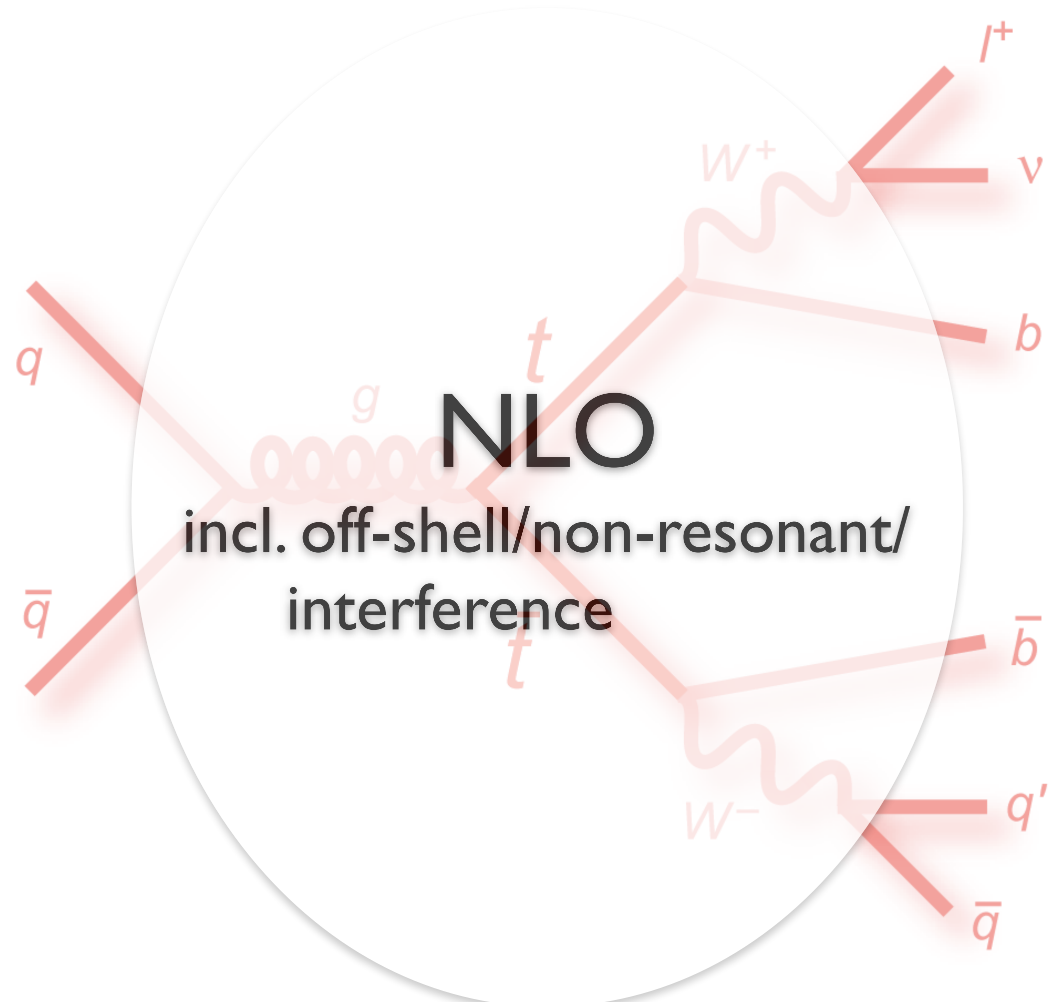

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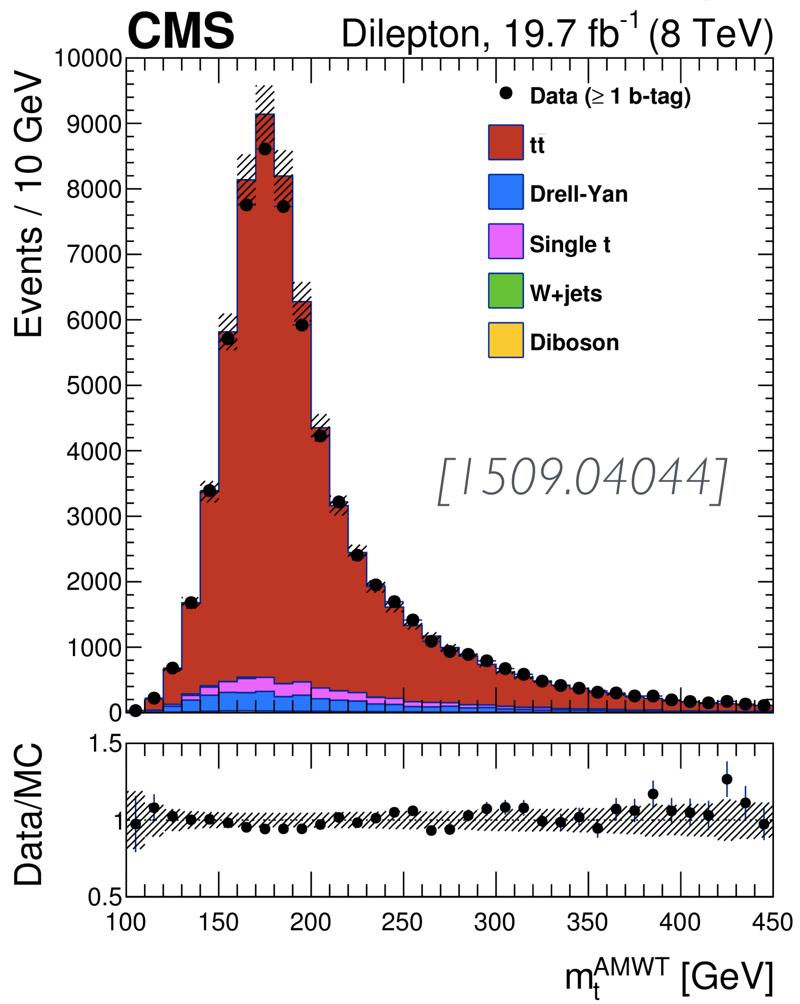
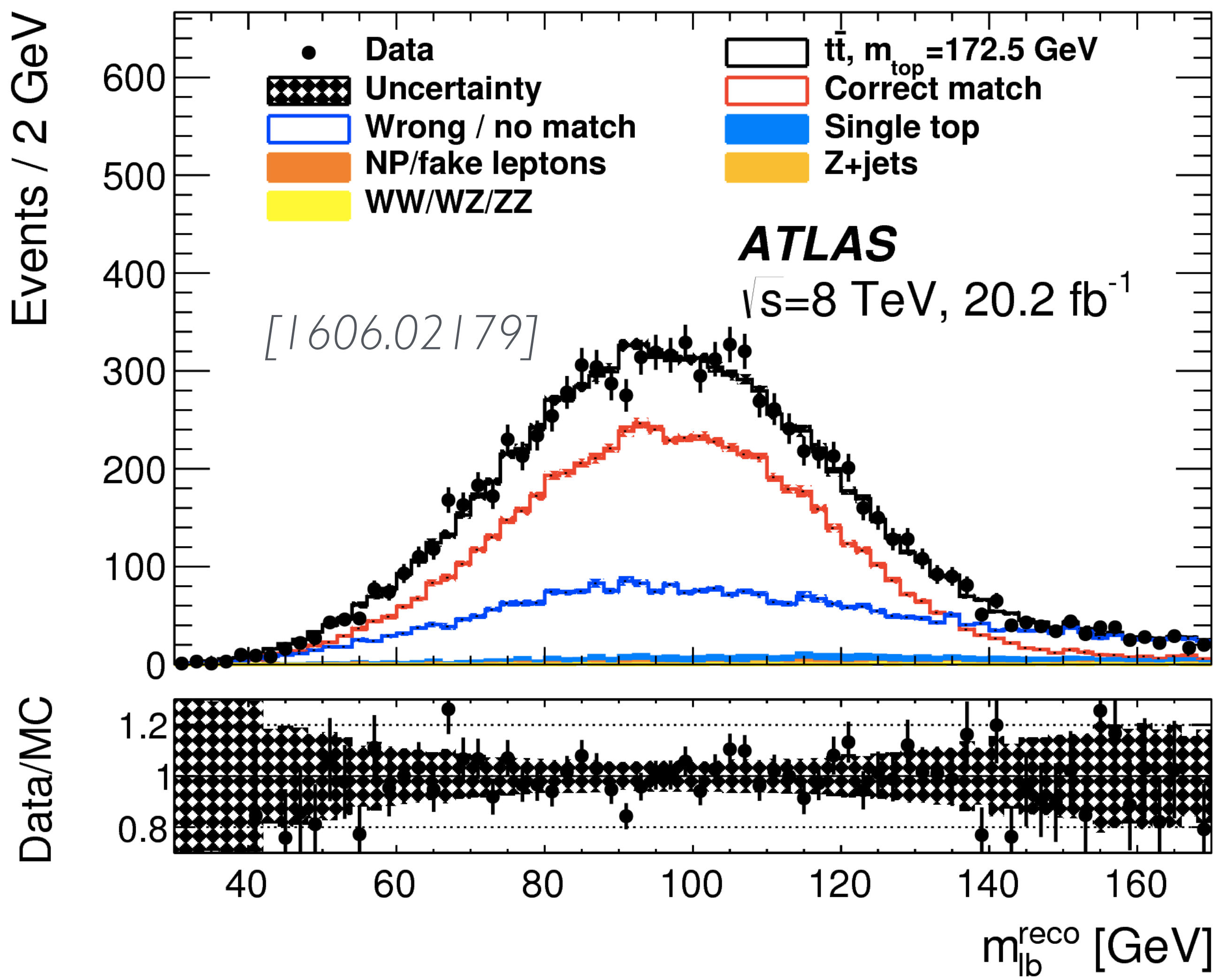
Phenomenological relevance: precision top-quark mass measurements

via reconstruction using analytical distributions derived from simulated samples



mtop = 172.82 ± 0.19 (stat) ± 1.22 (syst) GeV

via template fit of lepton-b-jet invariant mass



mtop = 172.99 ± 0.41 (stat) ± 0.74 (syst) GeV

- these kinematic measurements strongly rely on MC modelling!
- NLO+PS generator for off-shell top-pair production and decay employs well defined (on-shell) top-quark mass input parameter!

Illustration of the resonance matching problem

- In a traditional off-shell NLO+PS calculation:
  subtraction, matching and PS do not see/preserve intermediate resonances
- any (necessary) reshuffling/recoil might distort kinematic shapes!

Problem in POWHEG language

- 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

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

  - IR cancellation spoiled

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

- More severe problems at **NLO+PS**:
  - in POWHEG: $\mathrm{d}\sigma = \bar{B}(\Phi_\mathrm{B})\,\mathrm{d}\Phi_\mathrm{B} \left[\Delta(q_\mathrm{cut}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_\mathrm{B}, \Phi_\mathrm{rad}))}{B(\Phi_\mathrm{B})}\,\mathrm{d}\Phi_\mathrm{rad} \right]$

    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 POWHEG

Rigorous solution to all these issues within POWHEG 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

$$(\Phi_B, \Phi_{rad}) \overset{\text{RES}}{\longleftrightarrow} \Phi_R^{(\alpha)}$$

  ⟹ 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

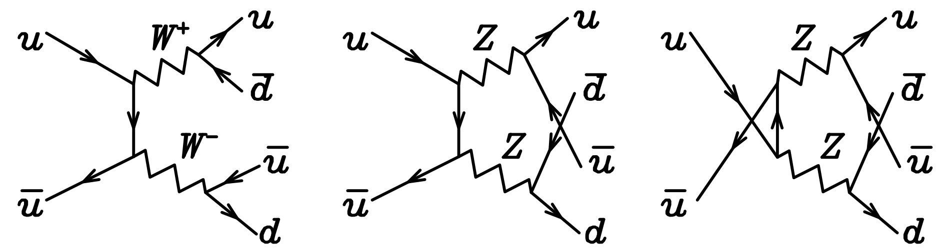
✓ **PS**:

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

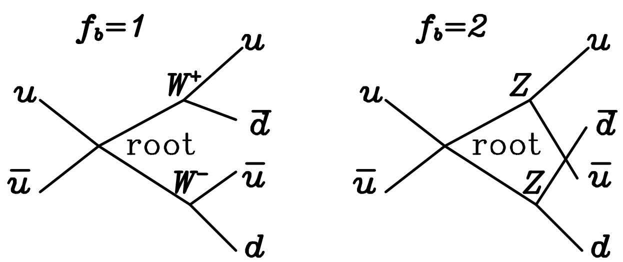
Resonance histories

This approach is rigorous up to the point that assignment of resonance histories requires a prescription.

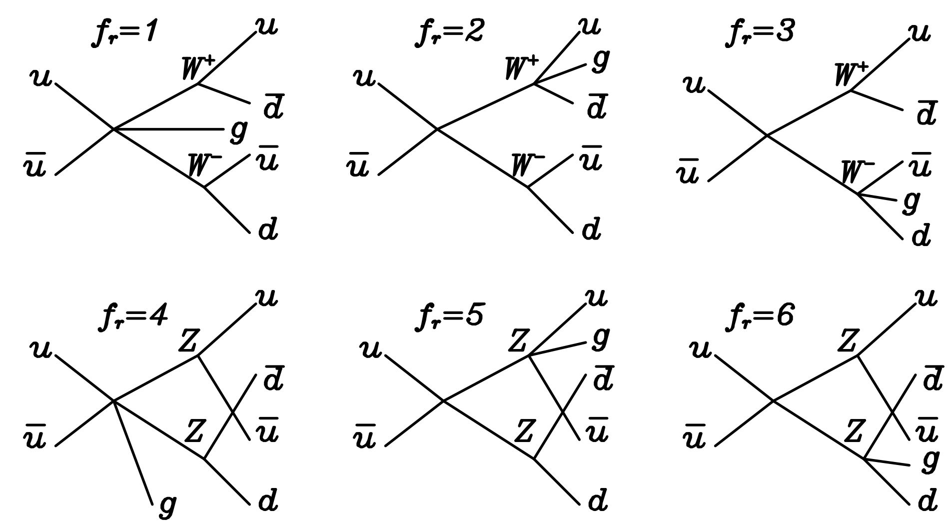
Example: $u\bar{u} \to u\bar{d}\bar{u}d$ @ $\mathcal{O}(\alpha^4)$



LO



NLO



Projection onto resonance histories f_b and f_r based on kinematic proximity:

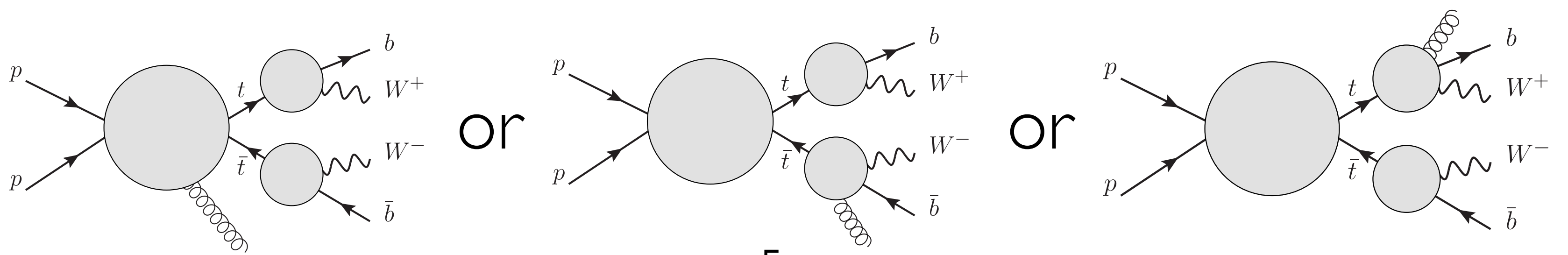
$$B_{F_b} = \sum_{f_b \in T(F_b)} B_{f_b}, \qquad B_{f_b} = \Pi_{f_b} B_{F_b}$$

$$\Pi_{f_b} = \frac{P^{f_b}}{\sum_{f'_b \in T(F_b(f_b))} P^{f'_b}}, \qquad P^{f_b} = \prod_{i \in \mathrm{Nd}(f_b)} \frac{M_i^4}{(s_i - M_i^2)^2 + \Gamma_i^2 M_i^2}$$

(similar for R: separation into resonance structures and *compatible* FKS singular regions)

Multiple-radiation scheme

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

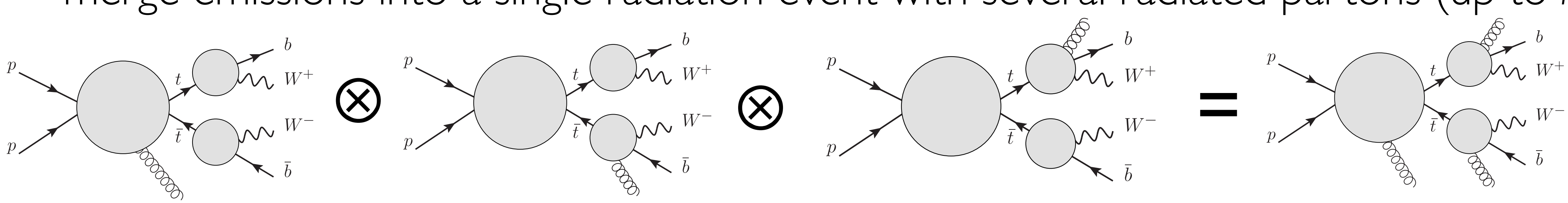


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \left[\Delta(q_{\rm cut}) + \sum_\alpha \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\rm rad}))}{B(\Phi_B)}\, d\Phi_{\rm rad} \right]$$

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*)

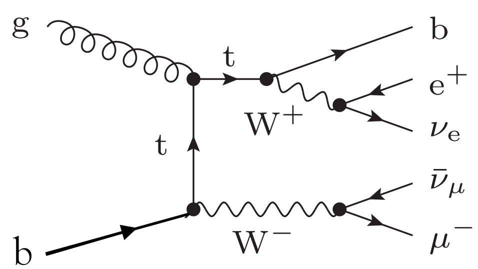


$$\Longleftrightarrow \qquad d\sigma = \bar{B}(\Phi_B)\, d\Phi_B \prod_{\alpha=\alpha_b,\alpha_{\bar{b}},\alpha_{\rm ISR}} \left[\Delta_\alpha(q_{\rm cut}) + \Delta_\alpha(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi^\alpha_{\rm rad}))}{B(\Phi_B)}\, d\Phi^\alpha_{\rm rad} \right]$$

Interplay between top-pair and Wt single-top production

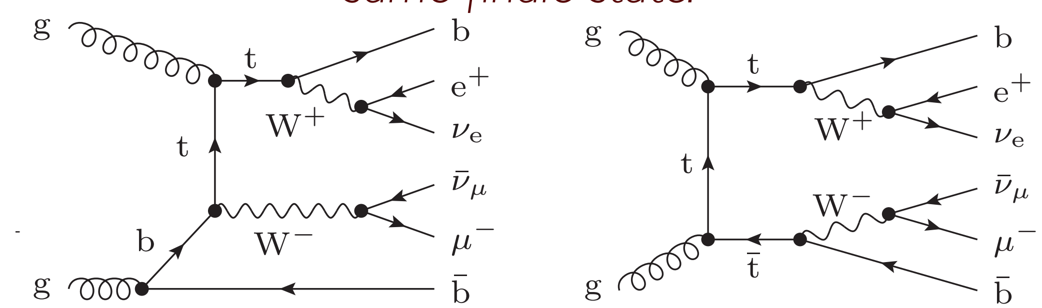
5FS

LO

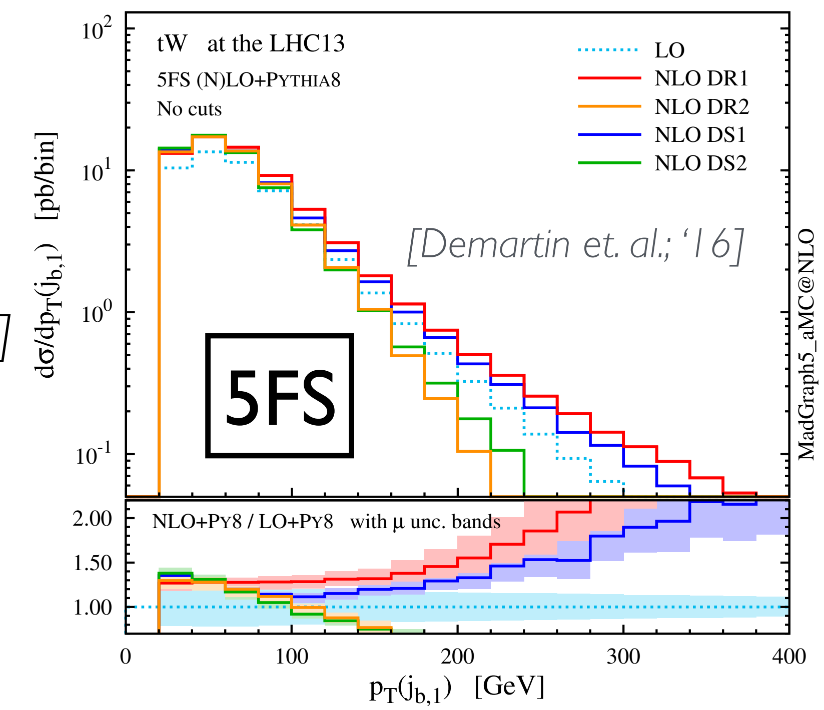


same finale state!

NLO

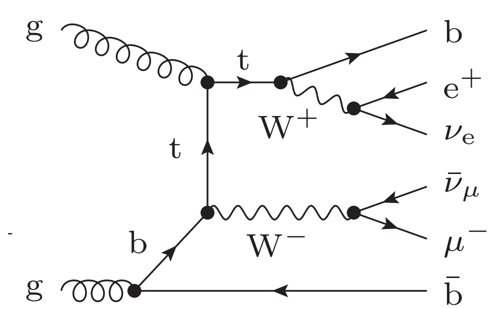


- NLO corrections to Wt swamped by LO $t\bar{t}$+decay
- requires ad-hoc subtraction prescription: DRI, DRII, DSI, DSII
- NLO+PS for Wt available in MC@NLO *[Frixione, et. al.; '08]*, POWHEG *[Re; '11]* and Madgraph_aMC@NLO *[Demartin et. al.; '16]*

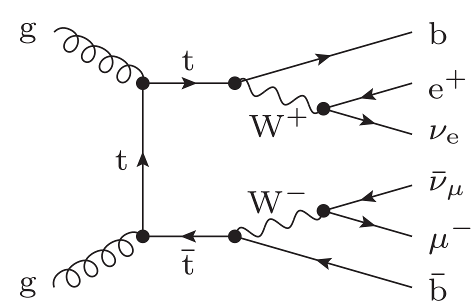


4FS

LO



Wt



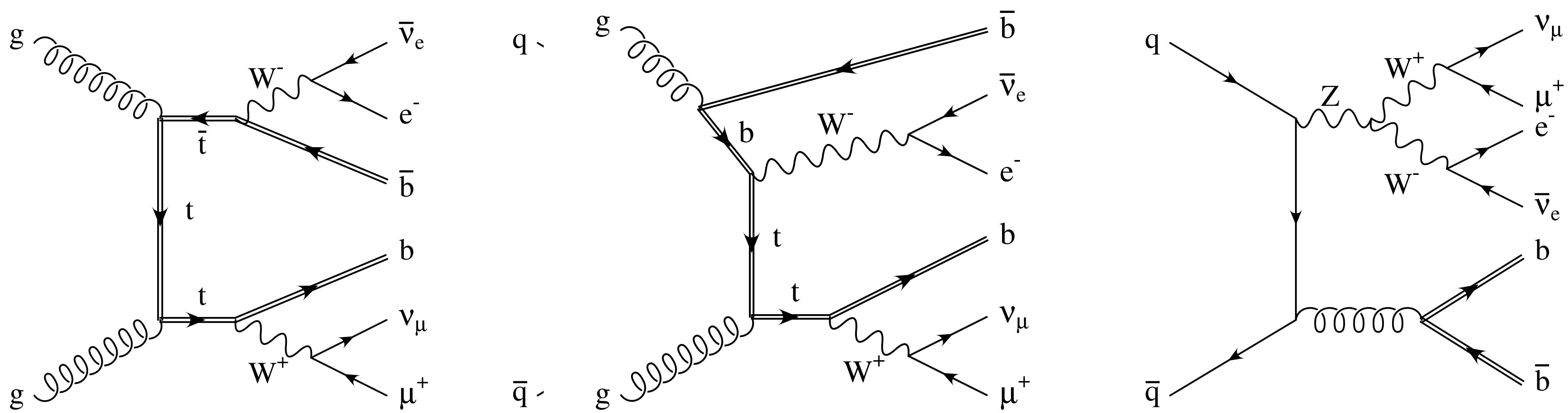
$t\bar{t}$

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)

The new bb4l generator

- We consider the full process $pp \to b\bar{b}e^+\nu_e\mu^-\bar{\nu}_\mu$ with massive b's (**4F scheme**)
- Implemented in the **POWHEG-BOX-RES** framework
- All matrix elements from **OpenLoops** (B, B_{ij}, $B_{\mu\nu}$, V, R, color-flow)



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

Efficiency study

		resonance aware	resonance unaware
NLO cross section	rel. accuracy (*)	0,11%	0,79%
efficiency of generation of radiation	vetos per event	750	15000
speed of event generation	events per hour	1500	200

⟹ factor of ~7 improvement in convergence/efficiency/speed!

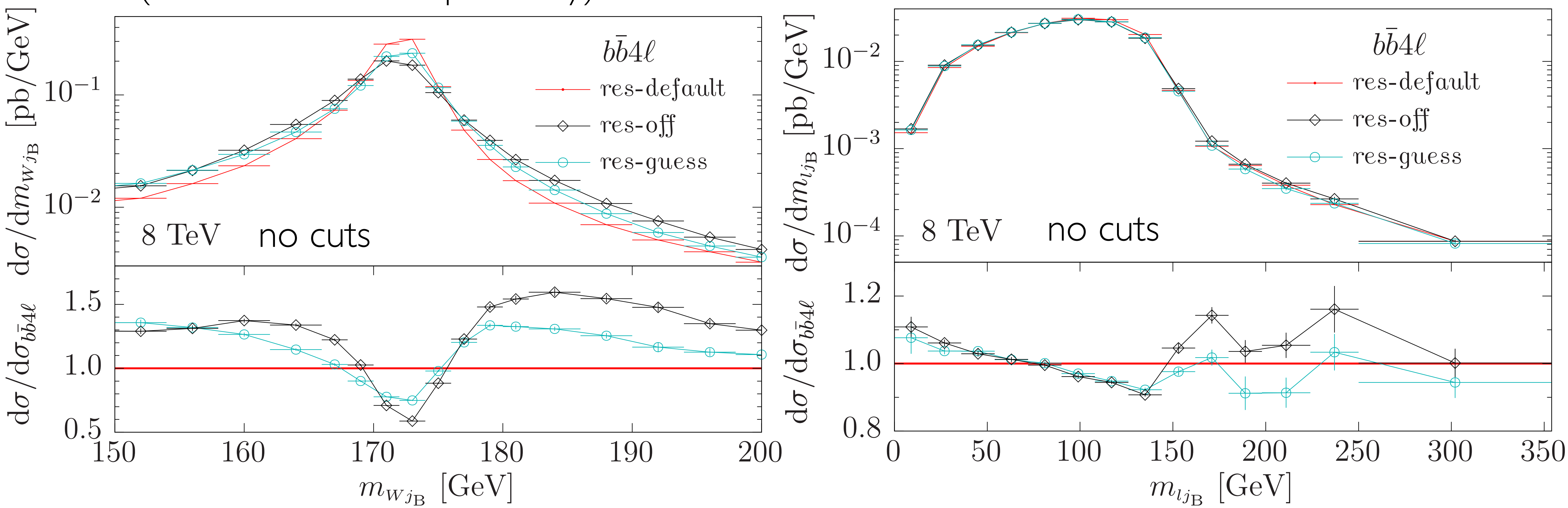
(*) NLO POWHEG setup

- stage 1: ncalls=80k, itmx=2
- stage 2: ncalls=100k, itmx=4
- nrun = 64

(typical setup for small cluster/blade)

Results: top-resonance

- default: resonance aware matching & multiple-radiation scheme
- off: resonance unaware matching
- guess: resonance unaware matching but kinematic guess off resonance structure before PS (based on kinematic proximity)



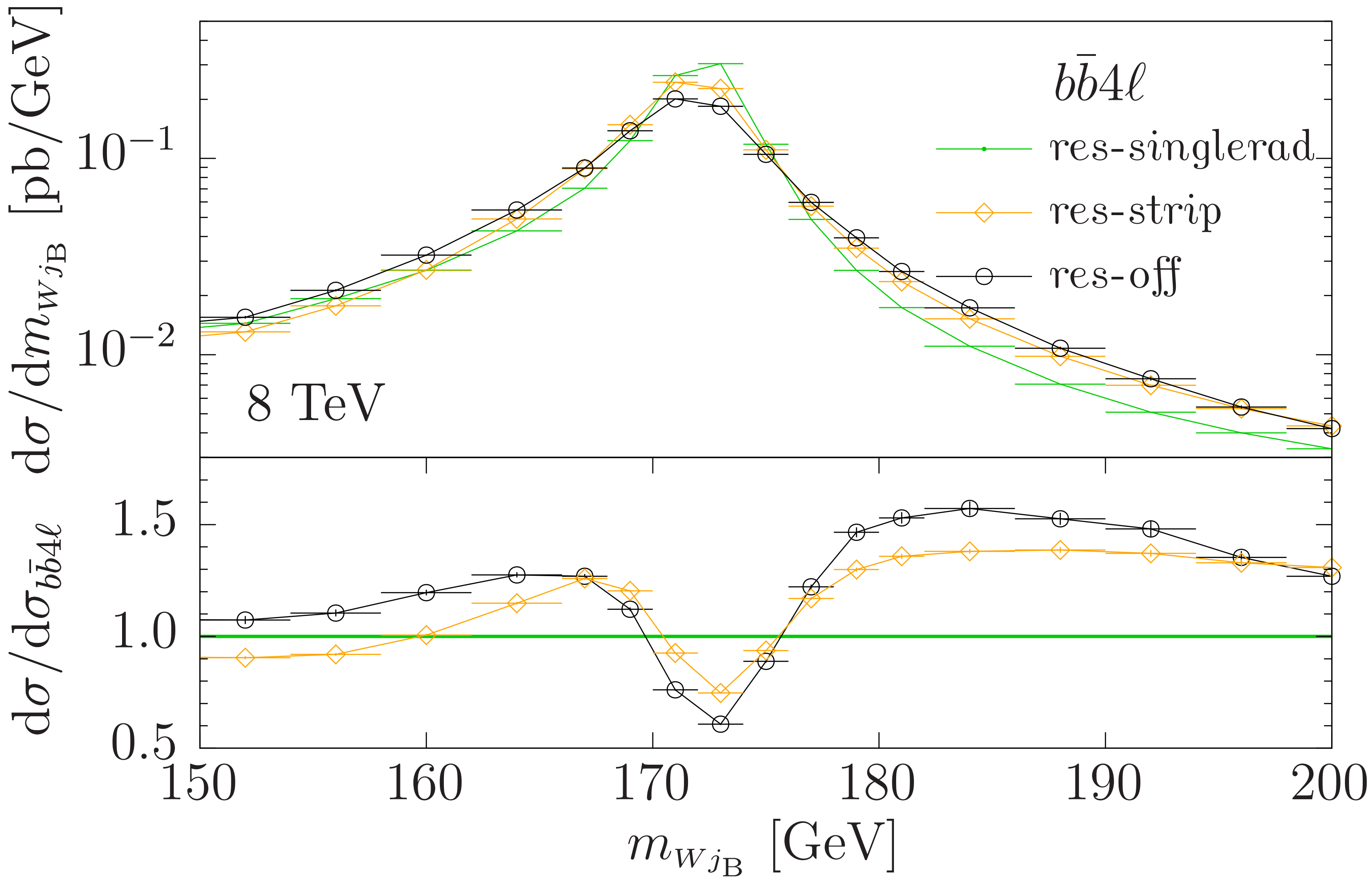
$\Longrightarrow$ resonance unaware matching yields distortions of important kinematic shapes

$\Longrightarrow$ control of these shapes crucial for **precise top-mass measurements!**

$\Longrightarrow$ resonance assignment based on kinematic proximity with standard matching not sufficient

Impact of PS momentum reshuffling

- res-singlerad: resonance aware matching & single-radiation scheme
- res-strip: resonance aware matching, but resonance information not passed to PS
- res-off: resonance unaware matching



⟹ res-strip in-between res-singlerad and res-off

⟹ both effects important:

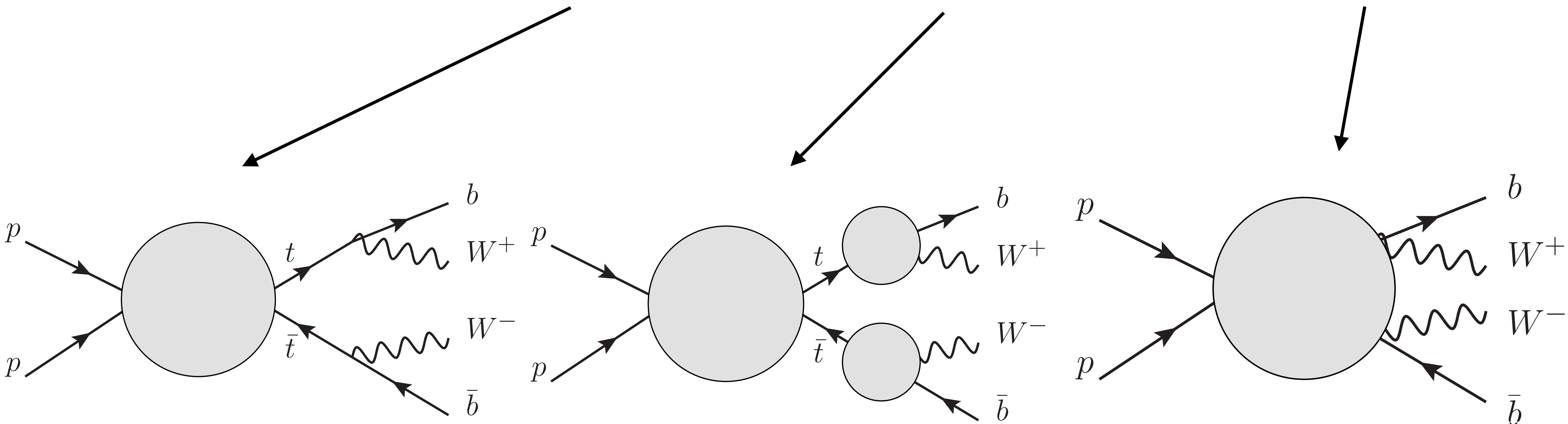
I) first emission governed by resonance preserving R/B

II) PS reshuffling preserves the resonance masses

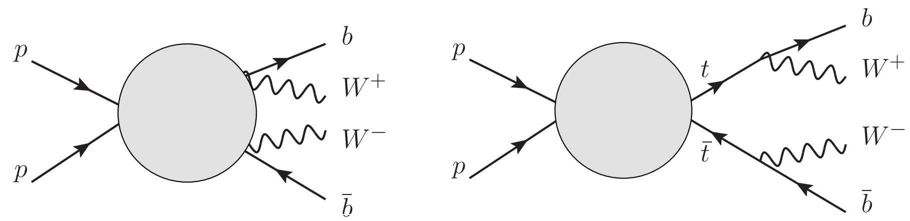
Compare different treatment of top off-shellness

label	$t\bar{t}$ NLOPS	$t\bar{t}$+decay NLOPS	$b\bar{b}4\ell$ NLOPS-RES
NLO matrix elements	$\mathrm{t\bar{t}}$	$\mathrm{t}(\to \mathrm{e}^+\nu_\mathrm{e}\mathrm{b})\bar{\mathrm{t}}(\to \mu^-\bar{\nu}_\mu\bar{\mathrm{b}})$	$\mathrm{b\bar{b}e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$
decay accuracy	LO+PS	NLO+PS	NLO+PS
NLO radiation	single	multiple	multiple
spin correlations	approx.	exact	exact
off-shell $t\bar{t}$ effects	BW smearing	LO $\mathrm{b\bar{b}}4\ell$ reweighting	exact
Wt & non-resonant effects	no	LO $\mathrm{b\bar{b}}4\ell$ reweighting	exact

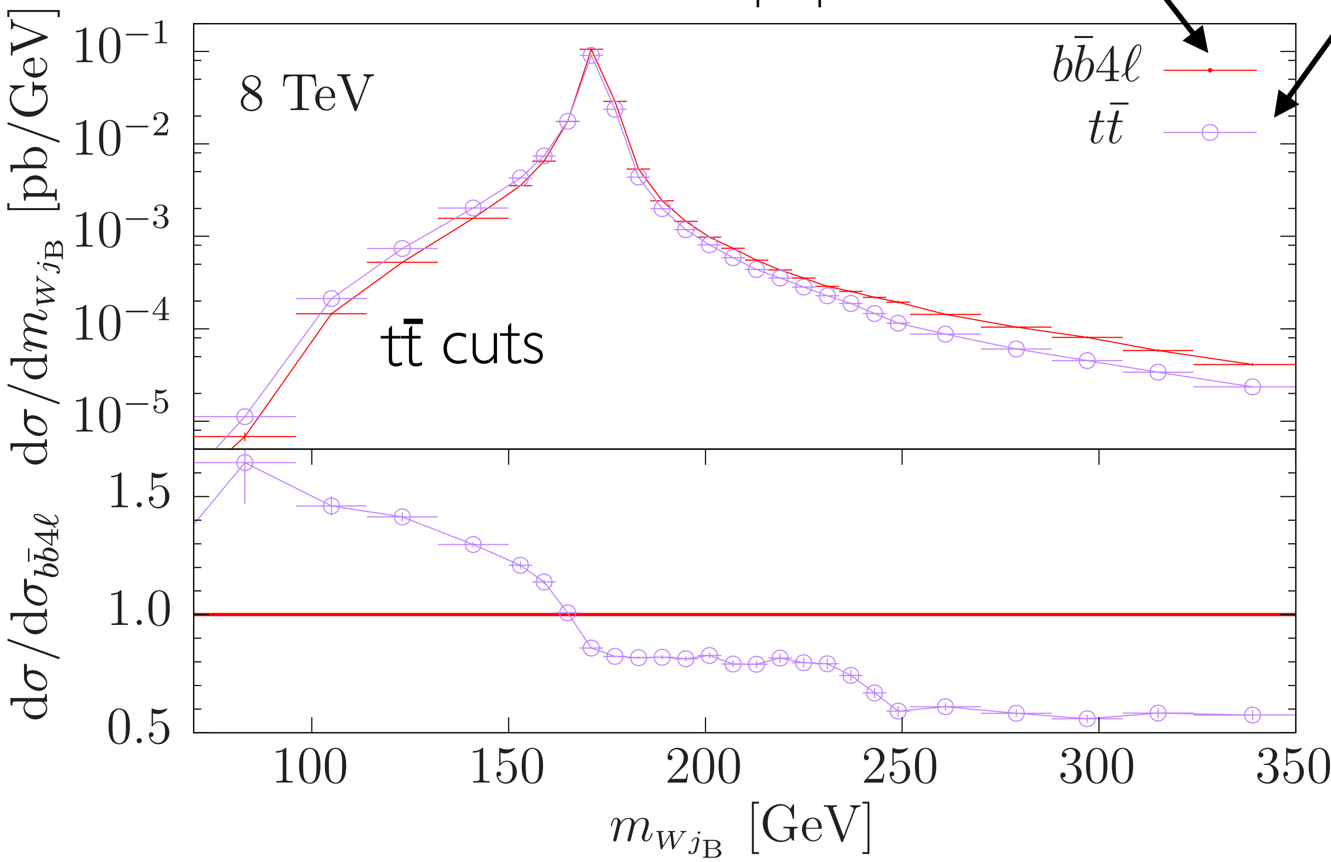
. [Frixione, Nason, Ridolfi; '07] *[Campbell, Ellis, Nason, Re; '15]* *[Ježo, JML, Nason, Oleari, Pozzorini; '16]*



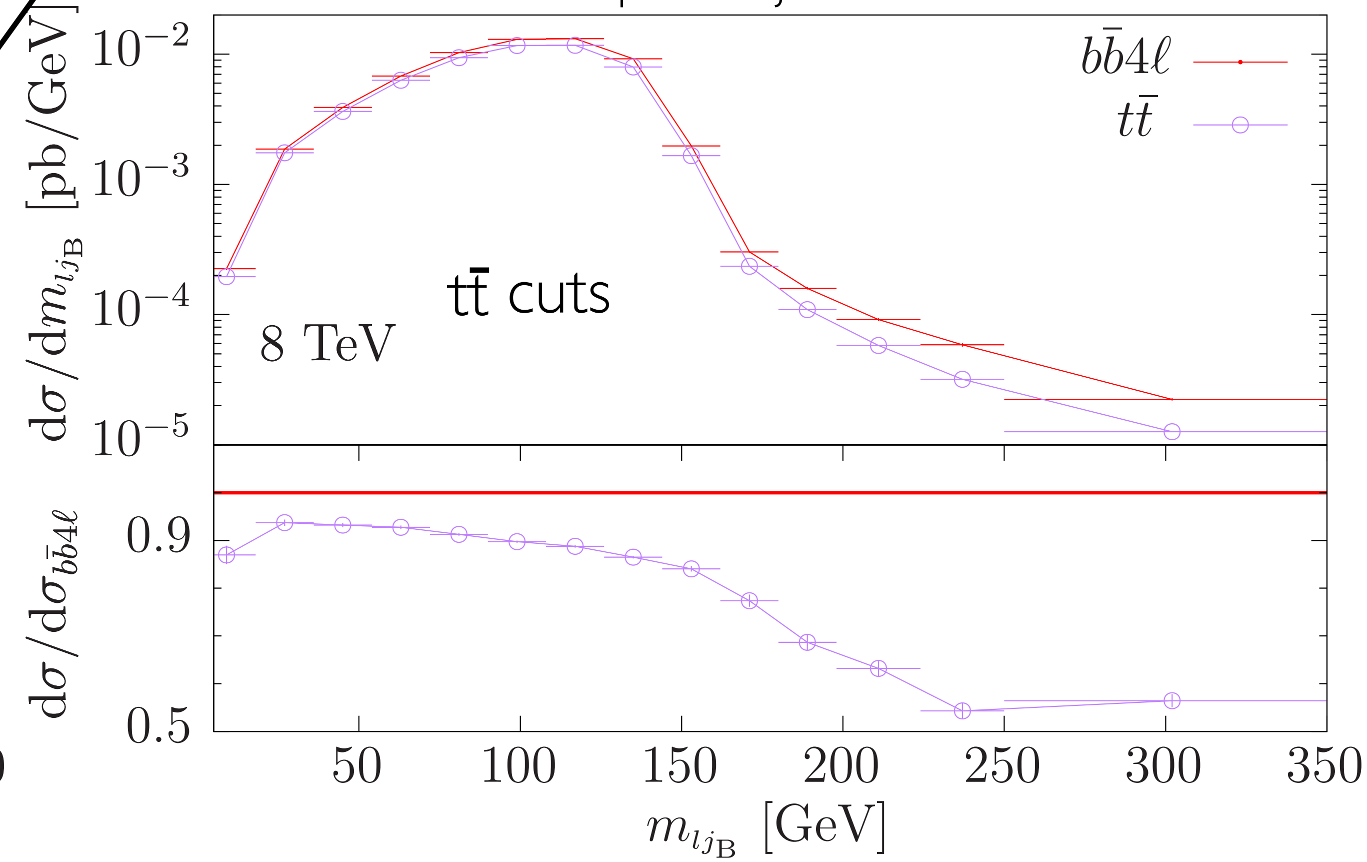
Results: on-shell $t\bar{t}$ vs. bb4l



reconstructed top-quark mass

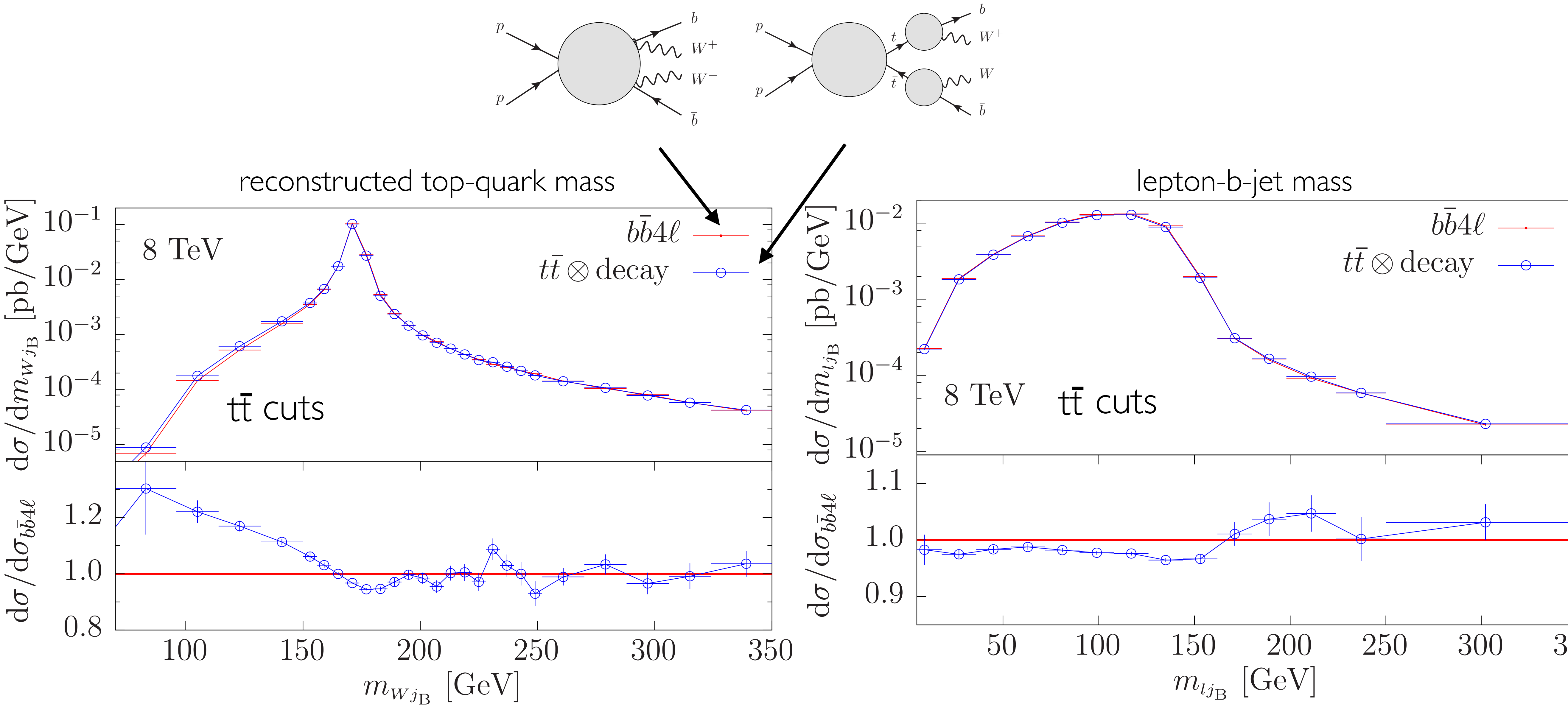


lepton-b-jet mass



- significant shape distortions around resonance with respect to on-shell calculation
- very relevant for top mass determination, see e.g. *[Heinrich, Maier, Nisius, Schlenk, Winter; '14]*
- average m_{Wj_B} roughly 500 MeV smaller in on-shell $t\bar{t}$ (in ±30 GeV around mtop)
- ~20-30% effects around the b-jet-lepton invariant mass edge

Results: tt̄⊗decay vs. bb4l

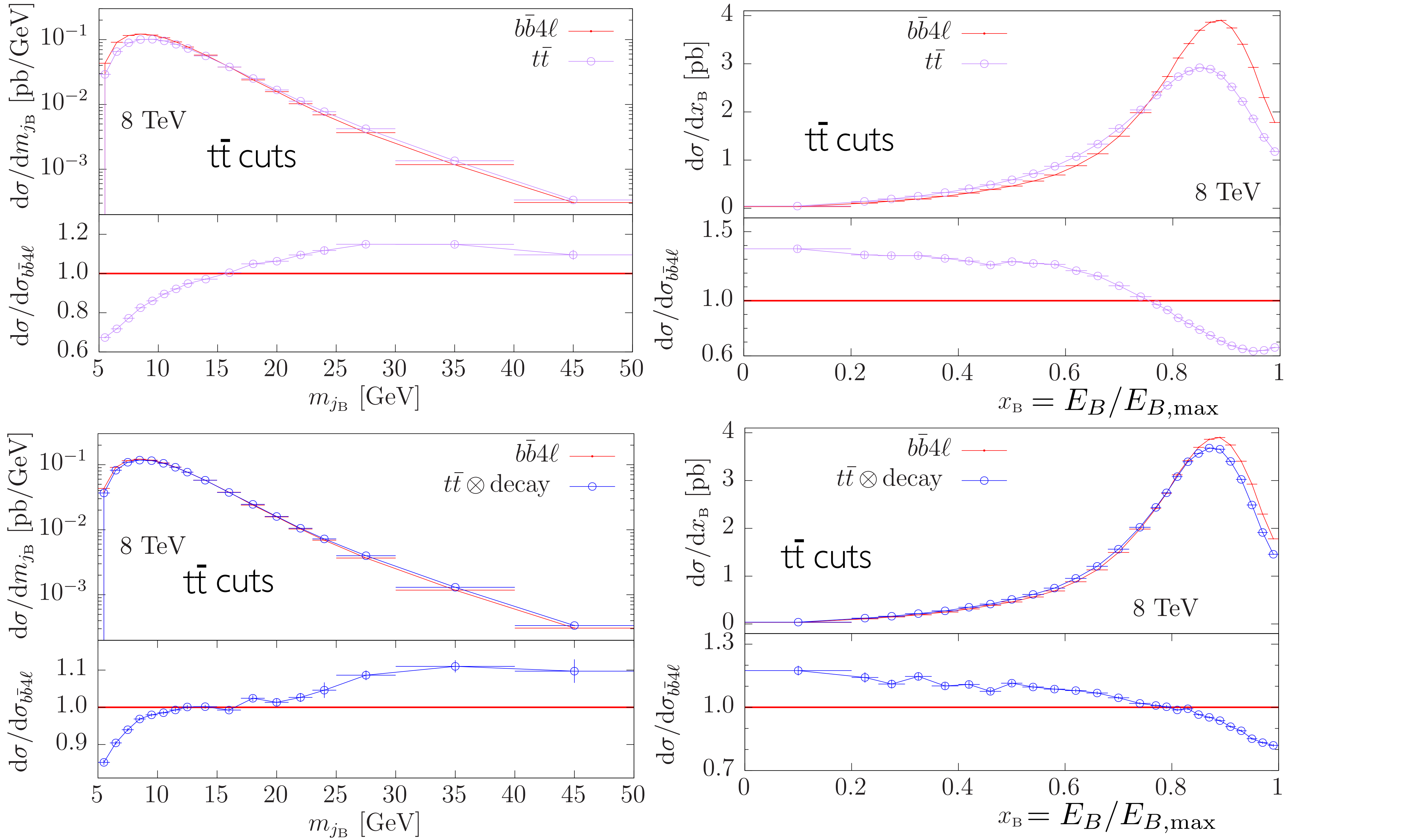


- very good agreement mostly <5% level between the two predictions
- the two calculations support each other (natural factorization of radiation between production and decay in tt⊗decay)
- average m_{Wj_B} roughly 100 MeV smaller in tt⊗decay (in ±30 GeV around mtop)

b-jet radiation properties

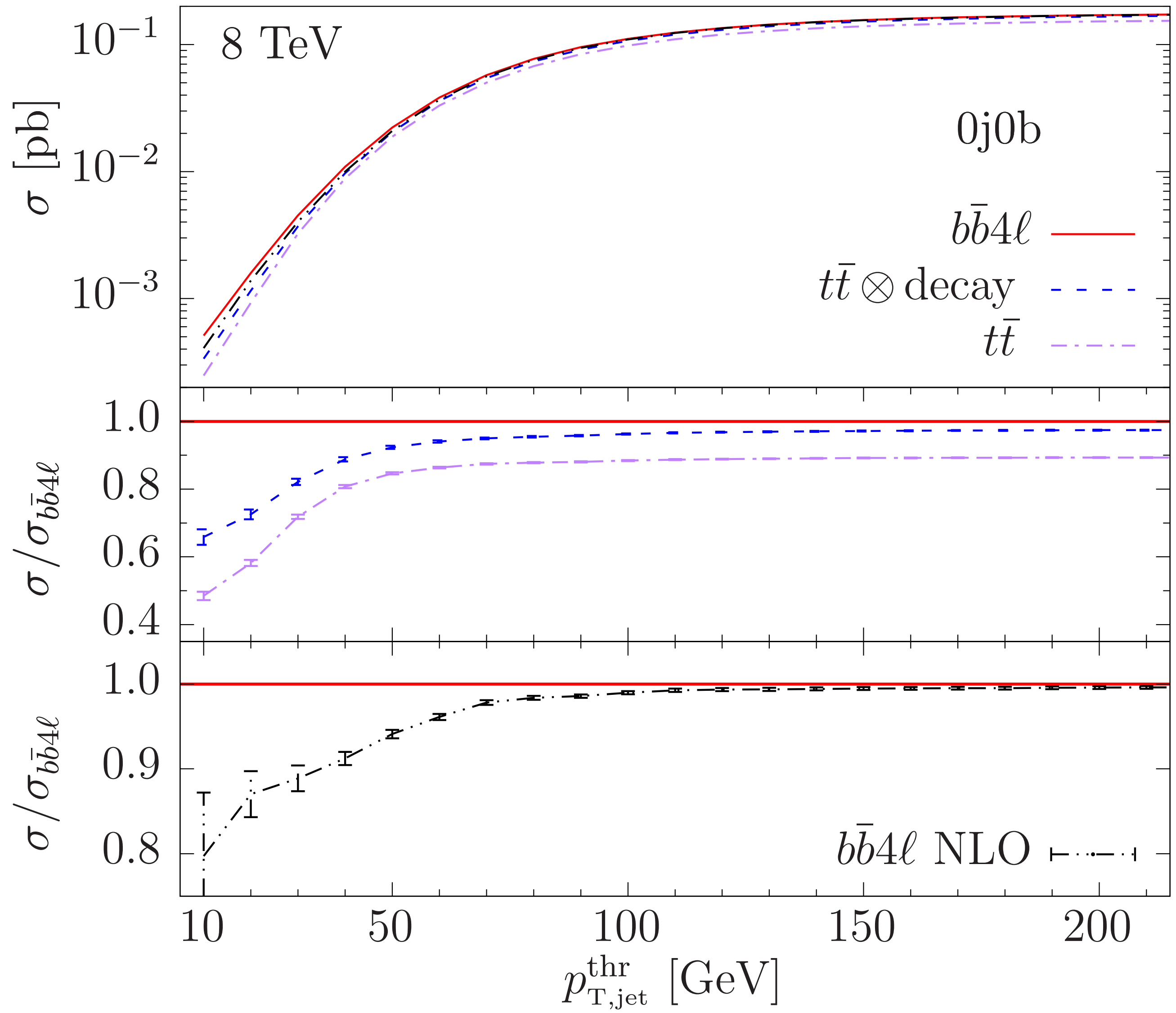
b-jet invariant mass

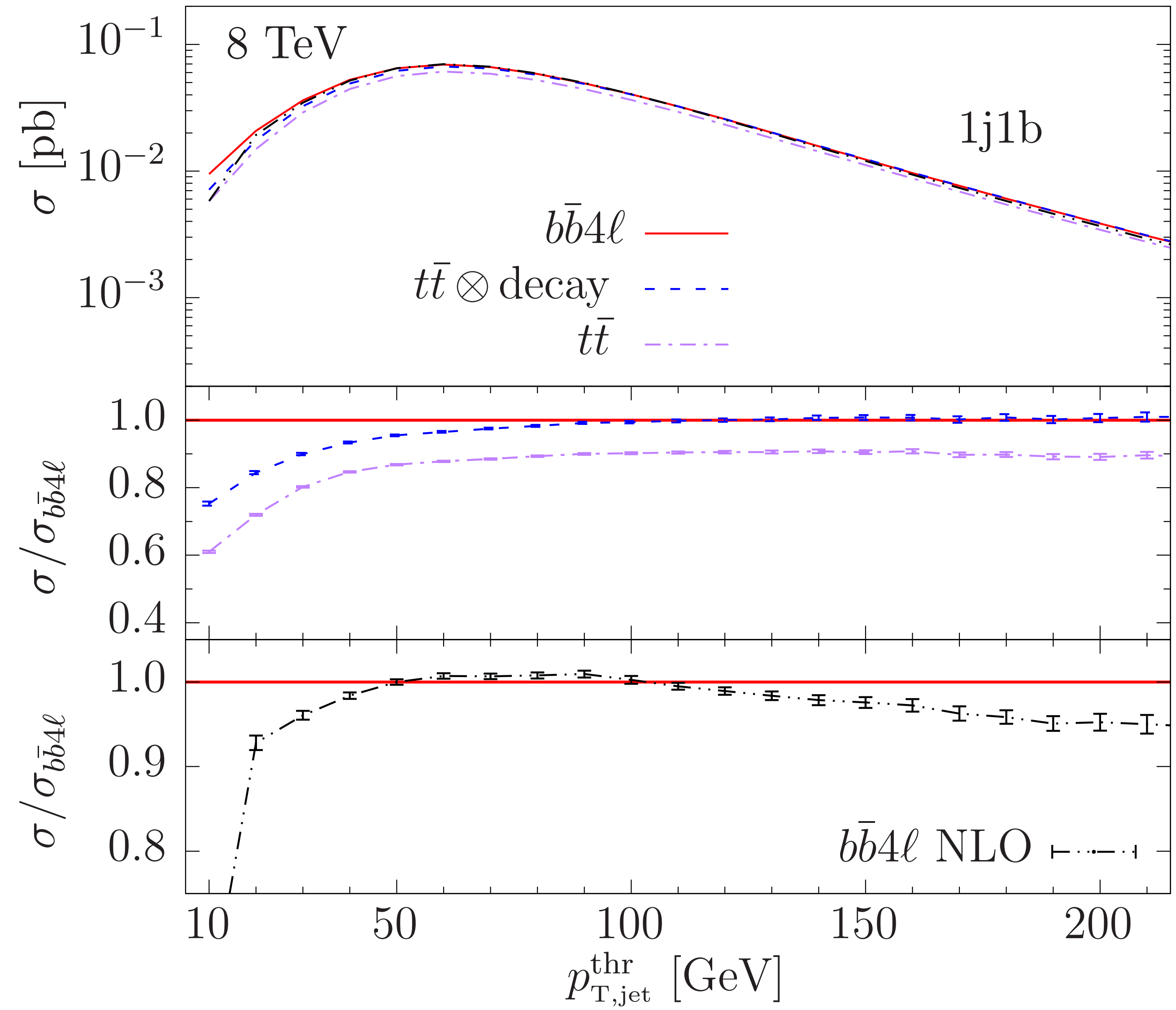
B-hadron fragmentation function

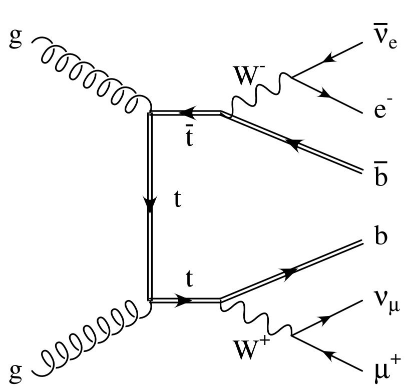


- narrower b-jets and harder B-fragmentation in bb̄4l
- due to reduced radiation from b's in bb̄4l

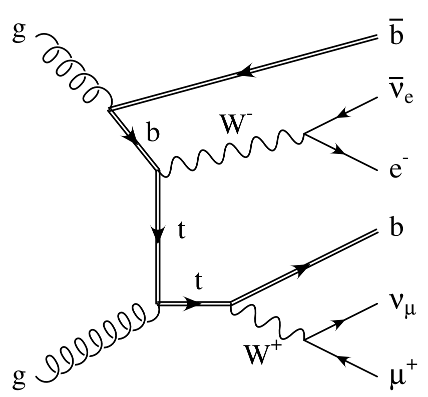
jet vetoes and single-top enriched observables





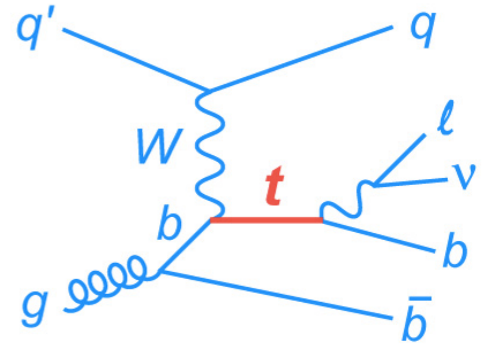


vs.

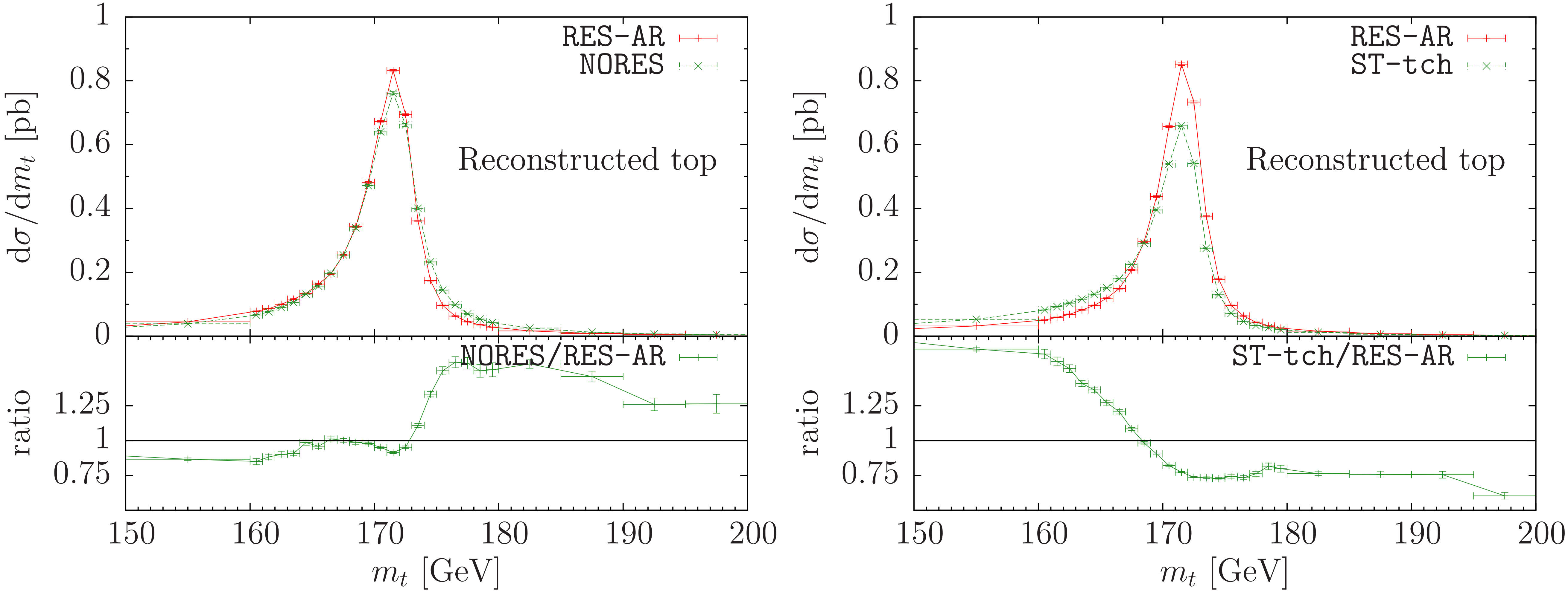


- for small jet thresholds Wt single-top reaches 40-50%
- tt⊗decay includes Wt only at LO and treats tops on-shell at NLO ⟹ overestimates radiation in Wt region
- 10-20% jet veto resummation effects
- important for any $t\bar{t}$ background with jet vetoes (e.g. $H \to W^+W^-$)

Single-top t-channel NLO+PS



[Ježo, Nason; '15]



- significant shape distortions in resonance unaware calculation and with respect to on-shell top calculation *[Alioli, Nason, Oleari, Re; '09]*

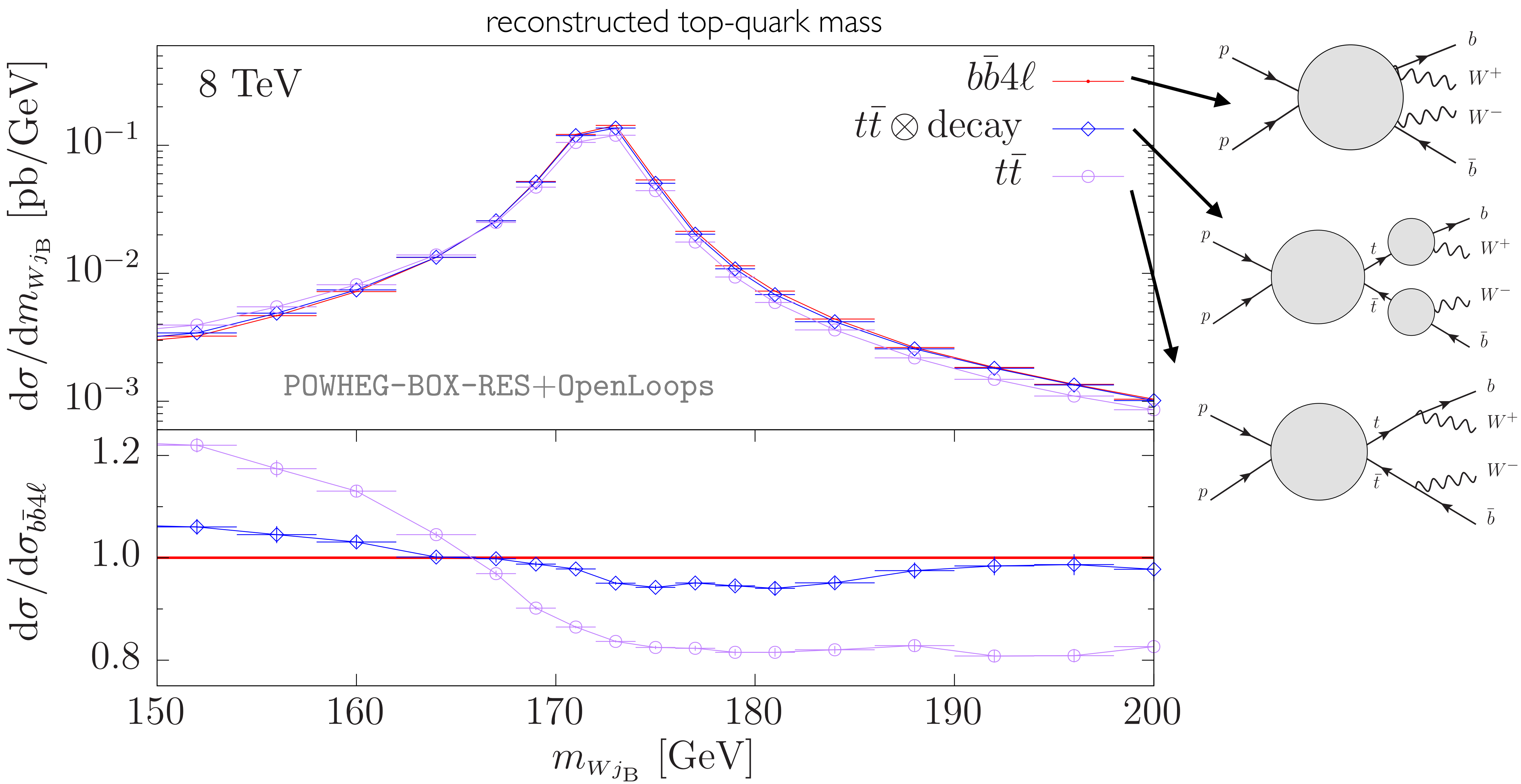
Conclusions

- Resonance-aware matching is pivotal for processes with intermediate resonances
- (quite) Rigorous solution within POWHEG by *[Ježo, Nason; '15]*
- New POWHEG framework: **POWHEG-BOX-RES** (http://powhegbox.mib.infn.it/)
  - resonance-aware subtraction and matching
  - automated generation of resonance histories and phase-space
  - on-the-fly scale and PDF variations / weights
  - process independent **POWHEG-BOX+OpenLoops** interface

- Phenomenology:
  - resonance-aware matching crucial for kinematic precision top-mass measurements
  - unified treatment of $t\bar{t}$ & Wt important for precision single-top physics and for modelling of $t\bar{t}$ backgrounds subject to jet vetoes.

- Outlook:
  - Detailed investigation of effects on top mass measurements
  - Hadronic top decays

Summary of the results



Backup slides

Setup

$$m_Z = 91.188\ \text{GeV}\,, \qquad \Gamma_Z = 2.441\ \text{GeV}\,,$$
$$m_W = 80.419\ \text{GeV}\,, \qquad \Gamma_W = 2.048\ \text{GeV}\,,$$
$$m_H = 125\ \text{GeV}\,, \qquad \Gamma_H = 4.03\times 10^{-3}\ \text{GeV}\,,$$
$$m_t = 172.5\ \text{GeV}\,, \qquad \Gamma_t = 1.329\ \text{GeV}\,,$$
$$m_b = 4.75\ \text{GeV}\,.$$

$$G_\mu = 1.16585\times 10^{-5}\ \text{GeV}^{-2}$$

Complex-mass-scheme: $\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \quad \text{for} \quad i = W, Z, t, H$

$$\sin\theta_W^2 = 1 - \cos\theta_W^2 = 1 - \frac{\mu_W^2}{\mu_Z^2}$$

For $t\bar{t}$ resonance histories: $\mu_\mathrm{R} = \mu_\mathrm{F} = \left[\left(m_t^2 + p_{T,t}^2\right)\left(m_{\bar{t}}^2 + p_{T,\bar{t}}^2\right)\right]^{\frac{1}{4}}$

For Z resonance histories: $\mu_\mathrm{R} = \mu_\mathrm{F} = \frac{\sqrt{p_Z^2}}{2}$

PDFs: MSTW2008NLO

$t\bar{t}$ cuts: at least one b- and one $\bar{\text{b}}$-jet with $p_T^j > 30\ \text{GeV}, \quad |\eta^j| < 2.5$

$$p_T^l > 20\ \text{GeV}, \qquad |\eta^l| < 2.5\,, \qquad p_T^\text{miss} > 20\ \text{GeV}$$

Kinematic guess

- res-singlerad: resonance aware matching & single-radiation scheme
- res-strip: resonance aware matching, but resonance information not passed to PS
- res-strip-guess: resonance aware matching, resonance information first stripped and then guessed (based on kinematic proximity) before passing to PS