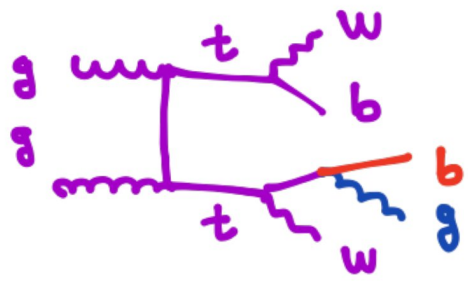
$pp \to W^+W^-b\bar{b}$ at the LHC

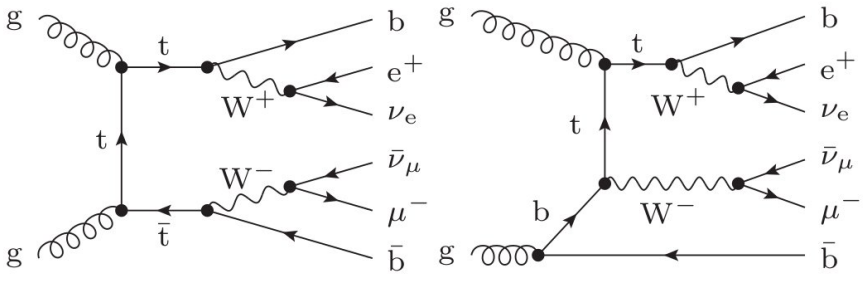
★ measurement of the top-mass: at the LHC likely to be achieved from combination of different strategies: total x-section, $t\bar{t}$ + jet, leptonic spectra, $b\ell$ endpoint and distribution,...

[see *e.g.* TOP LHC Working Group]



- some techniques rely on looking into the kinematics of visible particles from top-decay
- important that simulations are as accurate as possible, and associated uncertainties are quantified

★ $t\bar{t}$ vs. tW: by including decays with massive b, unified treatment of $t\bar{t}$ and tW:



- " $t\bar{t}$ " $\to WWbb$: 2 resolved b-jets
- " Wt " $\to WWb$: veto on second b-jet
- arbitrary cuts on the other objects

★ jet-vetoes: used in many searches where $t\bar{t}$ is a background (*e.g.* $H \to W^+W^-$):

- vetoes can also act on decay products (*e.g.* b-jet veto)

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important to have a fully-consistent NLO+PS simulation of $W^+W^-b\bar{b}$

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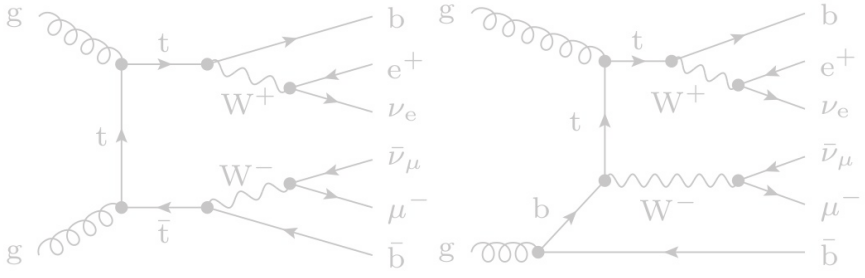

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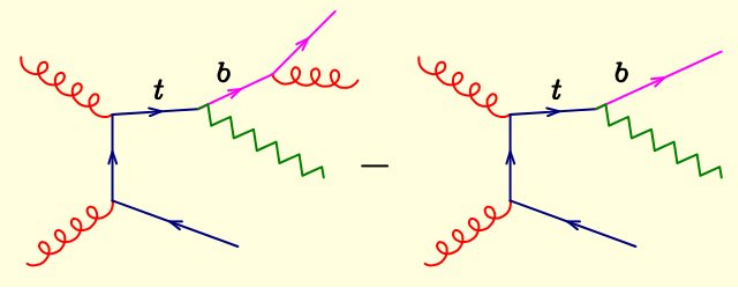
NLO+PS & intermediate resonances

The problem, in a nutshell:



$$d\sigma = d\Phi_{\rm rad}\bar{B}(\Phi_B)\frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}\times \exp\left[-\int\frac{R(\Phi_B,\Phi_{\rm rad})}{B(\Phi_B)}d\Phi_{\rm rad}\right]$$

- $\Phi_B \to (\Phi_B, \Phi_{\rm rad})$ mapping doesn't preserve virtuality
  $\Rightarrow R/B$ can become large also far from collinear singularity, but it shouldn't
- POWHEG radiation should have a well-defined resonance assignment, otherwise the shower will not preserve invariant masses, distorting the BW shape.
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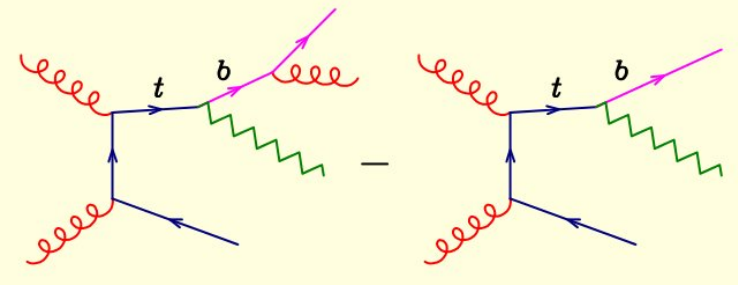

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- Issues first addressed, for $pp \to b\bar{b} + 4$ leptons production, in the narrow-width approximation [Campbell,Ellis,Nason,ER '14]
- POWHEG BOX RES: general solution and new framework [Jezo,Nason '15]
  - applied to 4F t-channel single-top and $pp \to b\bar{b} + 4$ leptons (full exact NLO) [Jezo,Nason '15; Jezo,Lindert,Nason,Oleari,Pozzorini '16]
  - in the MC@NLO matching scheme, 4-f t-channel single-top [Frederix et al. '16]

intermediate resonances in NLO+PS w/ POWHEG

1. complete matrix elements for $W^+W^-b\bar{b}$: need to project each partonic subprocess onto all possible "resonance histories":
   - each contribution should be dominated by a single resonance history:

$$B = \sum_{f_b} B_{f_b}, \quad \text{where} \quad B_{f_b} \equiv \frac{P^{f_b}(\Phi_B)}{\sum_{f_b'} P^{f_b'}(\Phi_B)} B(\Phi_B)$$

$P^{f_b}(\Phi_B)$ (products of) Breit-Wigner functions $\Leftrightarrow$ resonance history f_b

   - for real contributions, split also according to compatible FKS regions

     $\Rightarrow$ a term R_{α_r} is dominant if the collinear partons of region α_r have the smallest k_T, and the corresponding resonance history is the closest to its mass shell.

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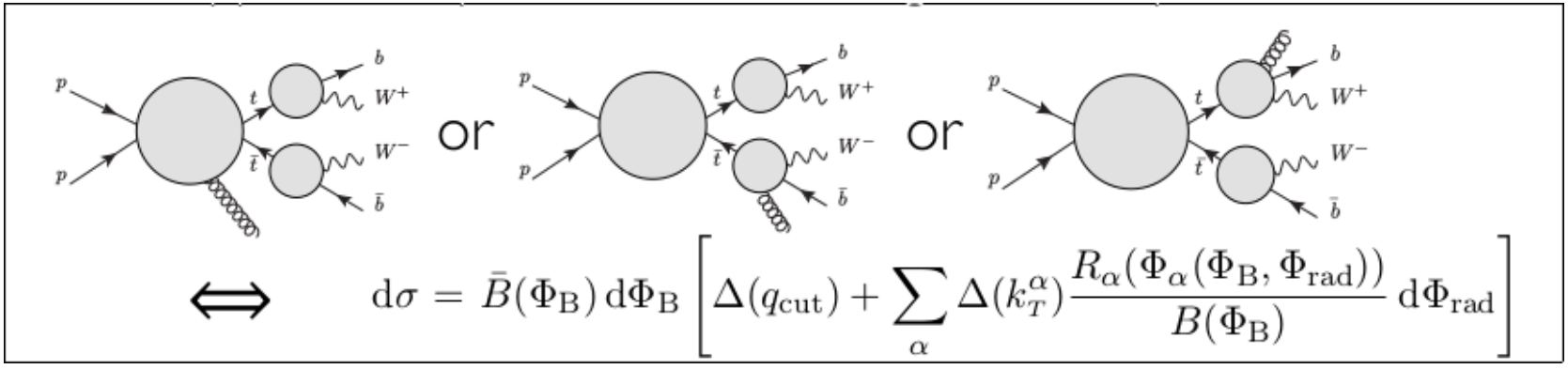
2. each term (Born-like and real) is attributed to an unique resonance history
   - virtuality-preserving mappings between Φ_B and $(\Phi_B, \Phi_{\mathrm{rad}})$ can be used
   - `POWHEG` radiation(s) can now be assigned to a resonance
   - (& other technical but crucial subtleties...)

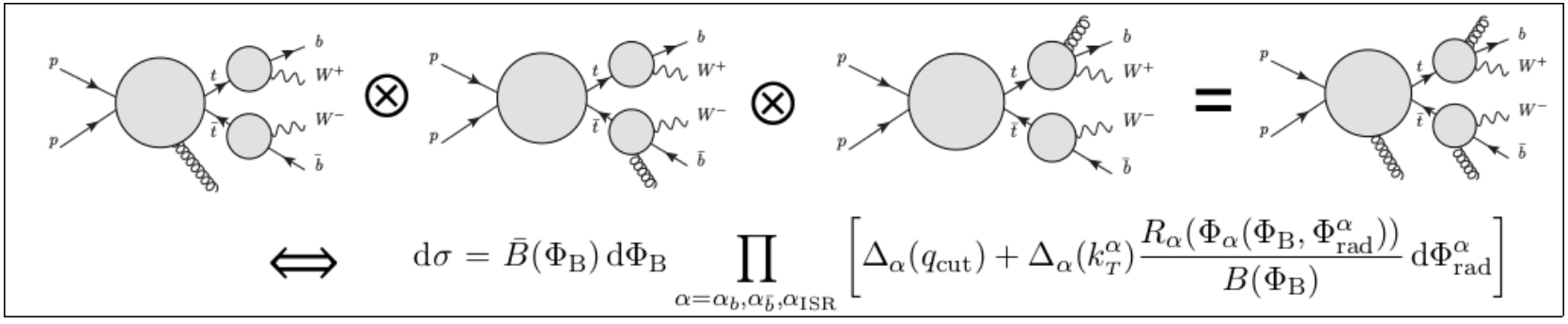
POWHEG-BOX framework

"multiplicative POWHEG": keep multiple emissions before showering [☜]

- by default POWHEG is additive: keeps only the hardest emission
- for heavy-pair production and decay, emissions from decay are rarely the hardest. Hence, with default POWHEG, they would be mostly generated by the shower
- keep hard radiation and the emissions from all decaying resonances, then merge them into a single radiation phase space with several radiated partons, up to one for each resonance

POWHEG-BOX framework





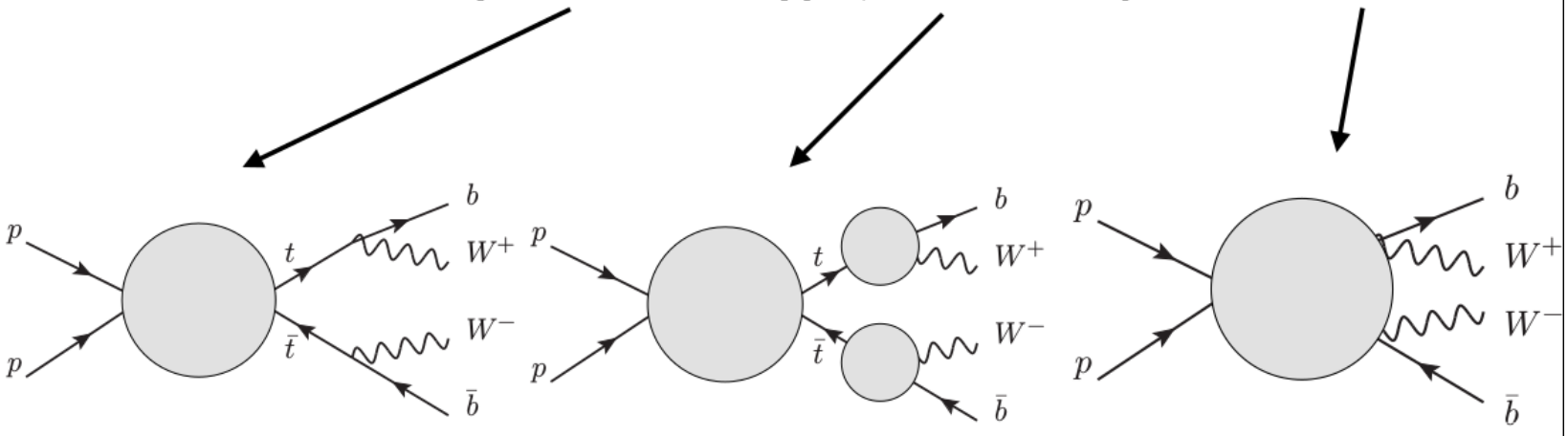
- in the above case, the interface to parton shower becomes more complicated.
  - for results in published results, brute-force approach (iterate shower untill all veto conditions respected)
  - more recently: `PowhegHooksBB4L.h`, `Pythia8` UserHook, dedicated for vetoes in presence of resonance decays adapted from `PowhegHooks` [Jezo,Seidel,Nachman; April '17]

POWHEG-BOX framework

Top-pair production in POWHEG

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

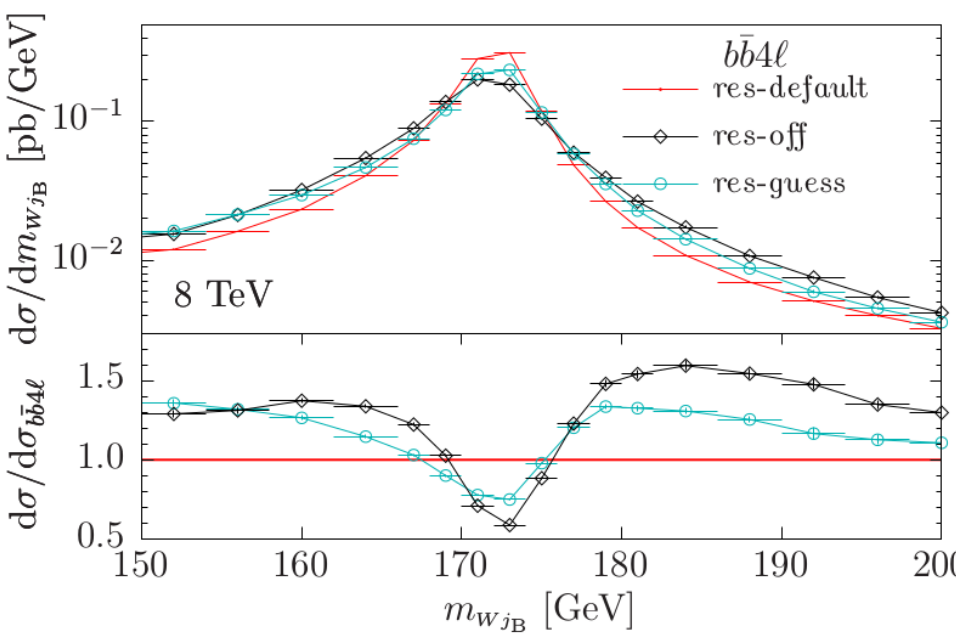
[Frixione, Nason, Ridolfi; '07] *[Campbell, Ellis, Nason, Re; '15]* *[Ježo, JML, Nason, Oleari, Pozzorini; '16]*

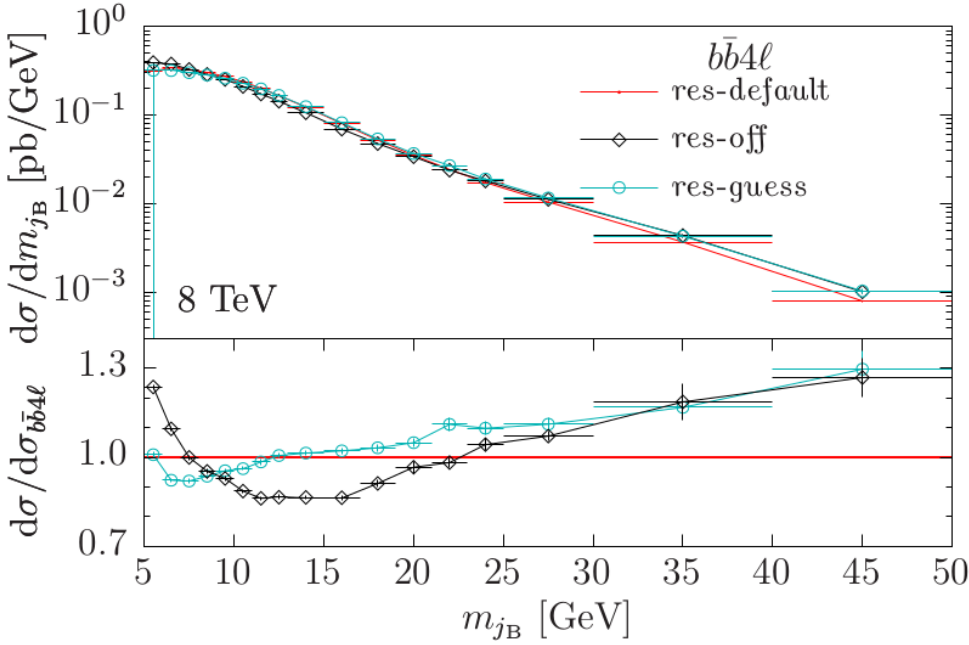


(*) dedicated Wt generators available

$WWbb$ at NLO+PS: results I

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

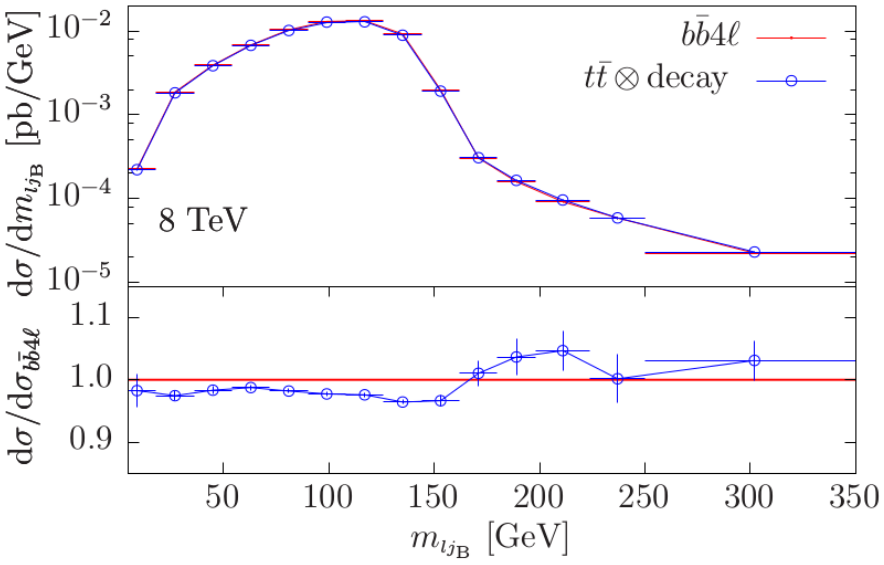


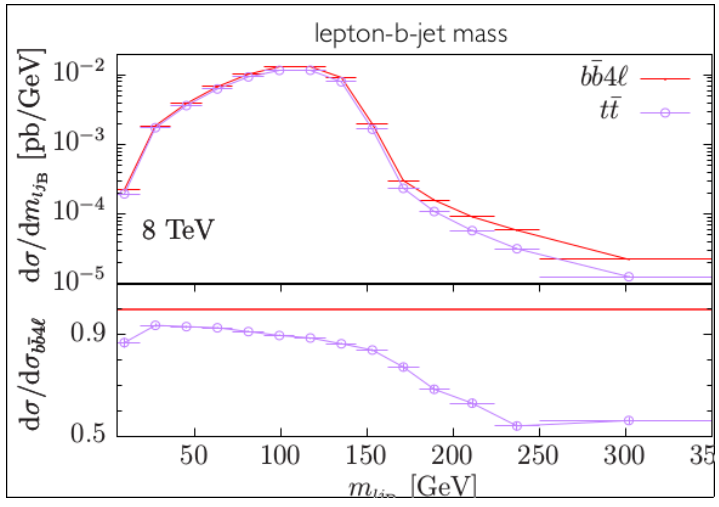


- no cuts.
- "res-default": resonance-aware, "res-off": not-resonance-aware, "res-guess": guess resonance history a posteriori, using event kinematics
- left: important effects both from information made available to parton-showering, but also from generating radiation using resonance history
- right: less radiation close to B in "res-off". Distorsion of b-jet mass ("expected" to be at $m^2 \approx E_b \Gamma_t$, *i.e.* $m_j \simeq 8$ GeV)

$WWbb$ at NLO+PS: results II

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



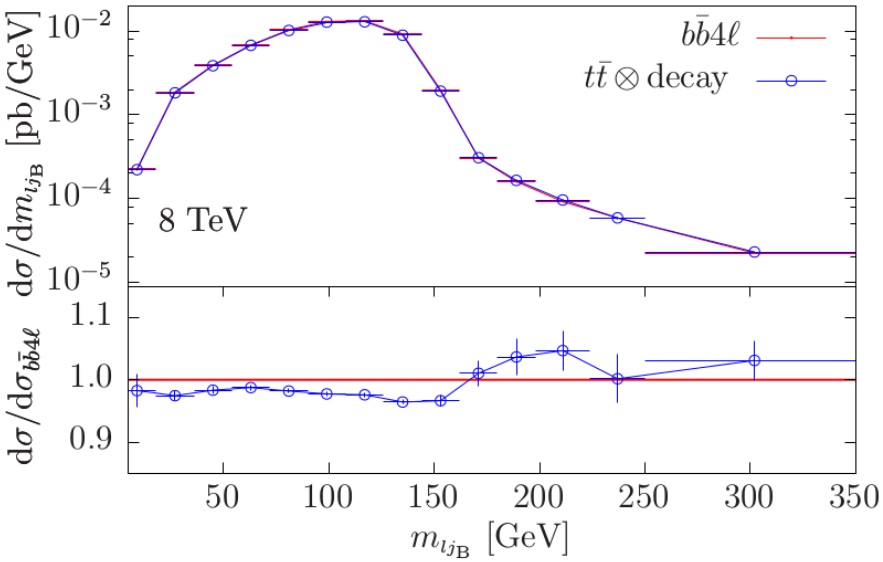


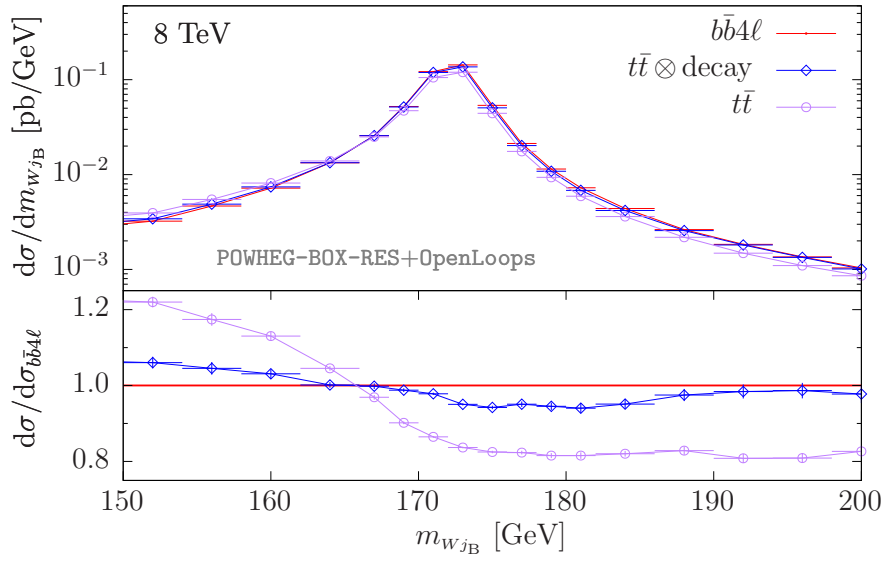
$t\bar{t}$ cuts.

- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- "tt": original generator [Frixione,Ridolfi,Nason '07]
- with these cuts: expect rad. in production and decay to factorize
- LEFT: Very good agreement ($< 5\%$) : serves also as a validation, since one result supports the choices made to obtain the other.
- RIGHT: missing proper description of decays

intermediate resonances in NLO+PS w/ POWHEG

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

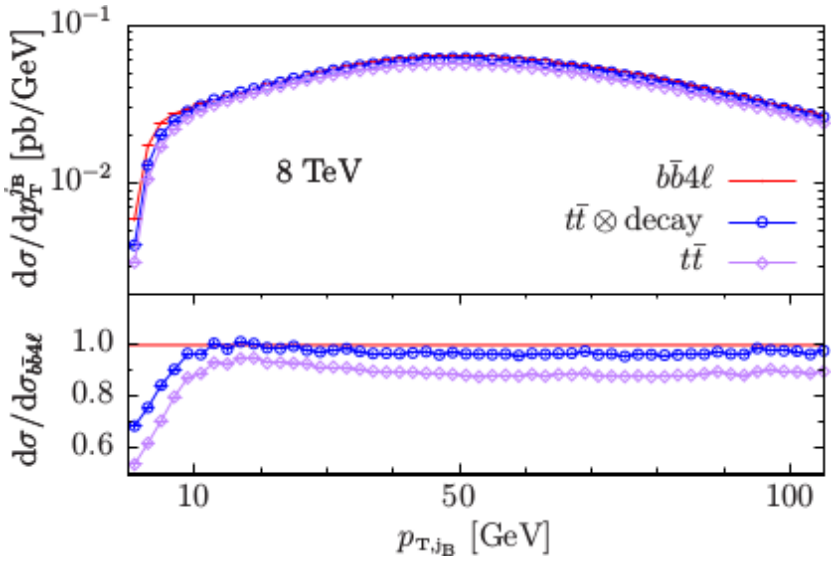




- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- left: $t\bar{t}$ cuts. Very good agreement: serves also as a validation, since one result supports the choices made to obtain the other.
- right: bigger differences with original $t\bar{t}$.

intermediate resonances in NLO+PS w/ POWHEG

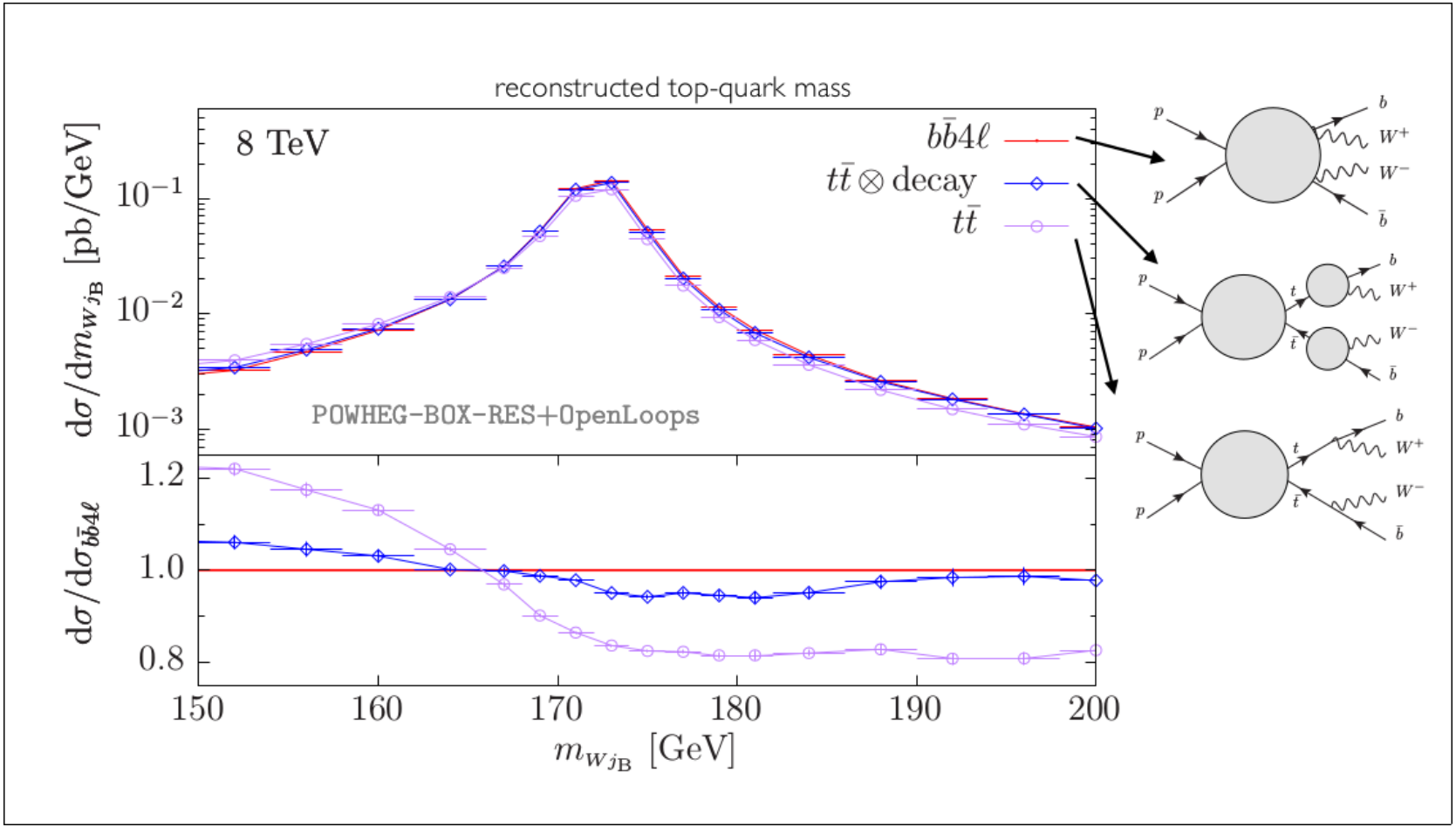
[Jezo,Lindert,Nason,Oleari,Pozzorini '16]



- "tt⊗decay": based on narrow-width [Campbell,Ellis,Nason,ER '14]
- no cuts. Clearly shows the "Wt" contribution, particularly relevant at small transverse momenta.

POWHEG-BOX framework

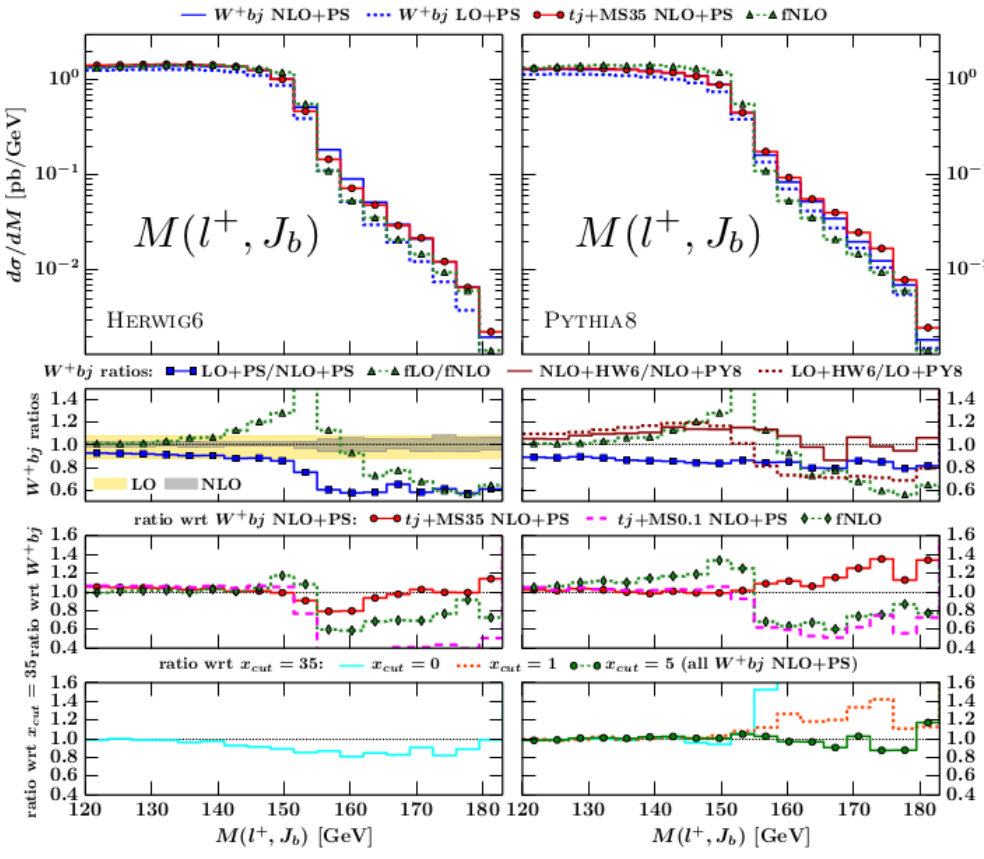
- summary plot:



- there's also an ongoing pheno study on top mass extraction

[Ferrario-Ravasio,Jezo,Nason,Oleari; in progress]

off-shell t-channel single-top production



- effect of resonance-aware matching also been studied in **MG_a@MC@NLO**
- application to t-channel single top

b-jet-lepton invariant mass

- large effects at the mass edge (and beyond)
- NLO+HW6/NLO+PY8 ~ 20%

[Frederix, Frixione, Papanastasiou, Prestel, Torrielli; '16]