

# $WbWb$ production with POWHEG BOX RES

Tomáš Ježo

University of Zürich

Based on:

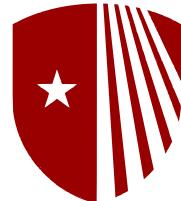
TJ, Nason [*arXiv:1509.09071*]

TJ, Lindert, Nason, Oleari, Pozzorini [*arXiv:1607.04538*]

ATLAS Higgs & B-tagging Workshop  
Simons Center for Geometry and Physics  
5 September 2017

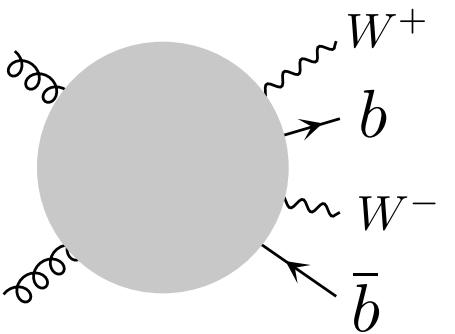


Universität  
Zürich<sup>UZH</sup>

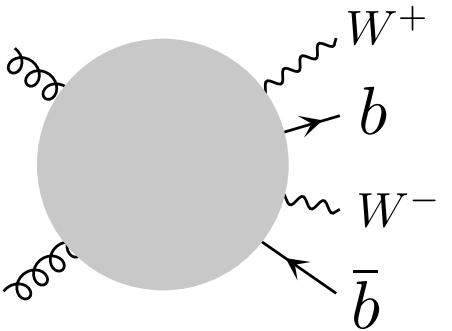


Stony Brook  
University

# $W^+ b W^- \bar{b}$ production



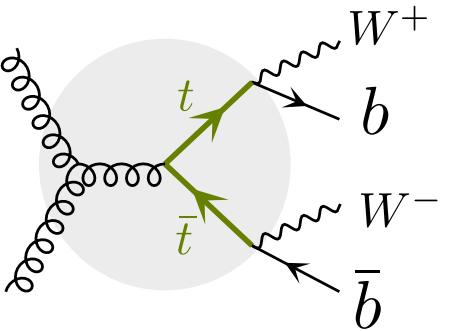
# $W^+ b W^- \bar{b}$ production



- Important background in Higgs and BSM studies
  - ▶ Les Houches wishlist: background to  $H \rightarrow W^+ W^-$
- Dominated by top-pair production
  - ▶ Top mass determination
- Includes single top topologies
  - ▶ Separation of  $Wt$  and  $t\bar{t}$  production



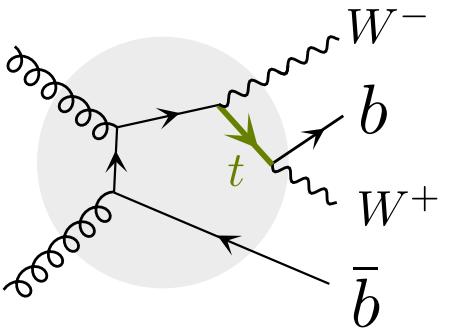
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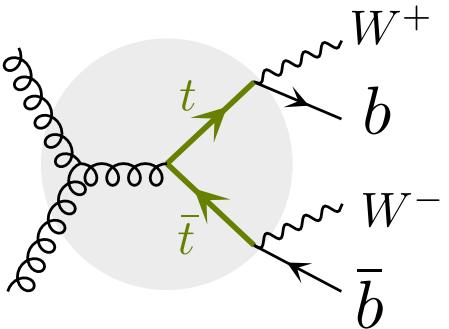
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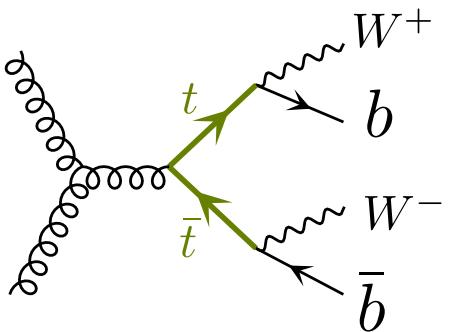
# $W^+ b W^- \bar{b}$ production @ NLO+PS



- $W^+ W^- b\bar{b}$  @ NLO QCD with  $W$  leptonic decays
  - ▶ [Bevilacqua et al.; 2010], [Denner et al.; 2010, 2012],  
 [Heinrich et al.; 2013], [Frederix et al.; 2013],  
 [Cascioli et al.; 2013]
- $W^+ W^- b\bar{b}$  @ NLO+PS with  $W$  leptonic decays
  - ▶ [Garzelli et al.; 2014]
  - ▶ [TJ, Lindert, Nason, Oleari, Pozzorini; 2016]



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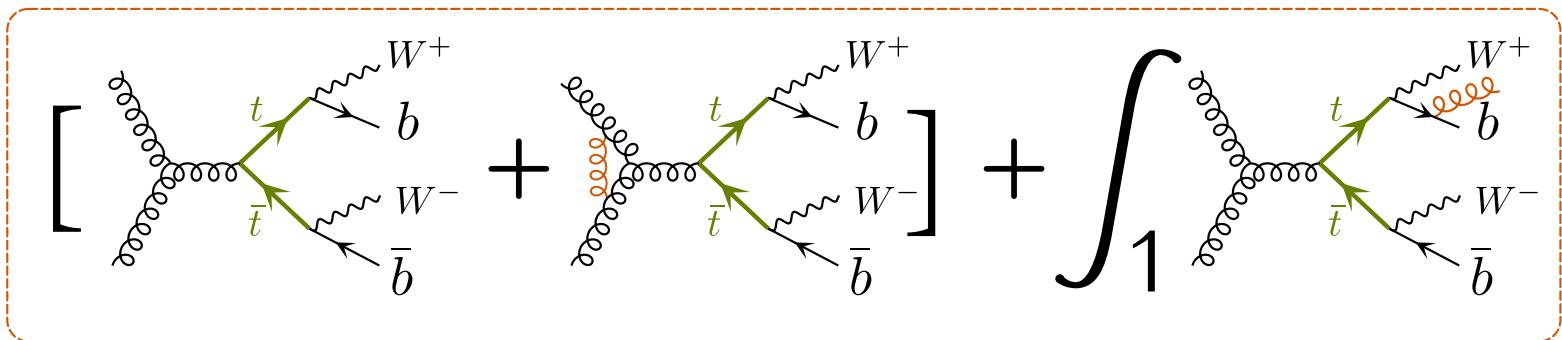


$$d\sigma = \overline{B}(\Phi_B) d\Phi_B \left[ \Delta(q_{\text{cut}}) + \sum_{\alpha} \Delta(k_T^{\alpha}) \frac{R_{\alpha}(\Phi_{\alpha}(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)} d\Phi_{\text{rad}} \right]$$

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



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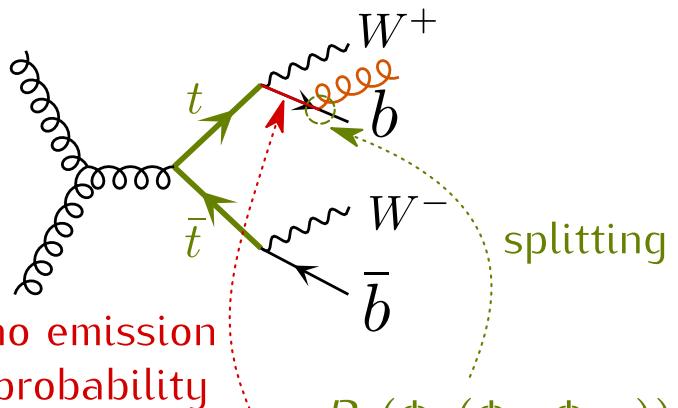


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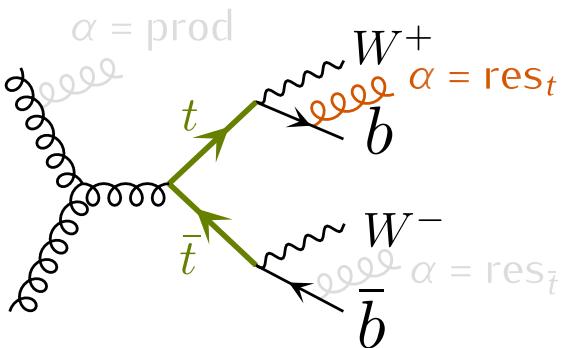


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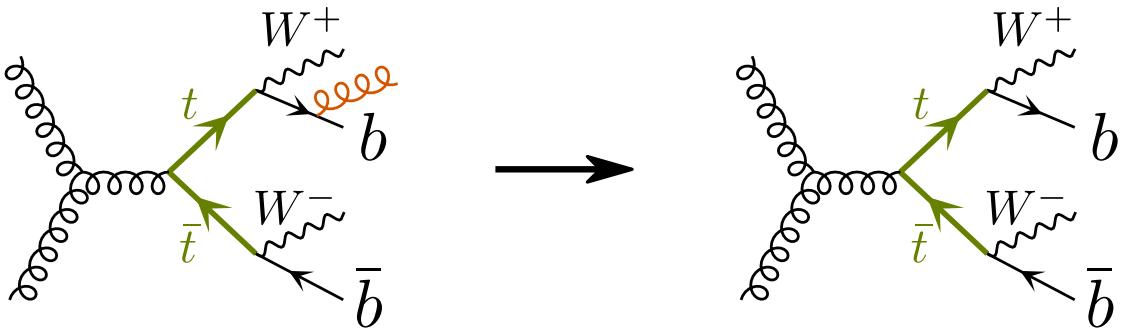


$$d\sigma = \overline{B}(\Phi_B) d\Phi_B \left[ \Delta(q_{\text{cut}}) + \sum_{\alpha} \Delta(k_T^\alpha) \frac{R_\alpha(\Phi_\alpha(\Phi_B, \Phi_{\text{rad}}))}{B(\Phi_B)} d\Phi_{\text{rad}} \right]$$

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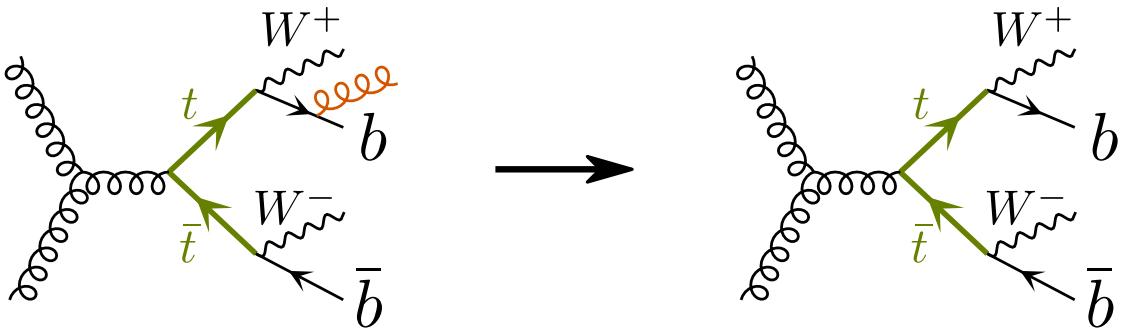


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- In standard formulation of the POWHEG method:
  - ▶  $n+1 \leftrightarrow n$  mapping **doesn't preserve** top virtuality
  - ▶ Leading to **unphysical suppression** away from collinear singularities
  - ▶ Only **one hardest emission** is kept

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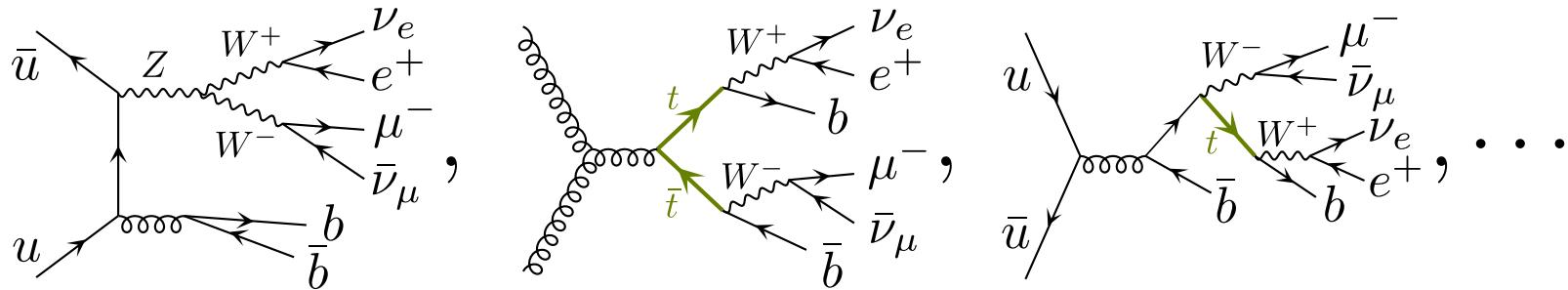
- In new “resonance-aware” formulation of the POWHEG method:
  - ▶  $n+1 \leftrightarrow n$  mapping preserves top virtuality
  - ▶ No unphysical distortions of the top line shape
  - ▶ Keeps multiple emissions: from production and each resonance



# $t\bar{t} + Wt$ event generator

- Process

- ▶  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$  @ NLO QCD ( $pp \rightarrow W^+ b W^- \bar{b}$ ,  $W \rightarrow \text{leptons}$ )



- ▶ Born, real and virtual matrix elements by [OpenLoops](#)
- ▶ 4 flavour number scheme
  - ▷ Unified description of  $t\bar{t}$  and  $Wt$  production
  - ▷ Effects of  $b$ -quark mass included
  - ▷ Phase space with unresolved  $b$ -quarks accessible



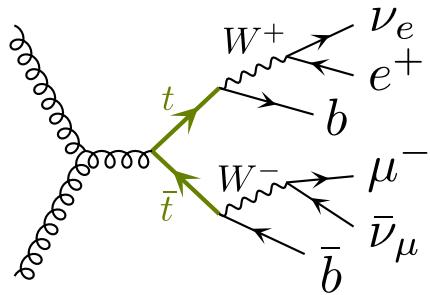
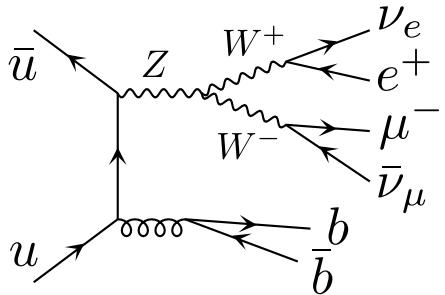
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- NLO+PS generator

- ▶ Implements resonance aware POWHEG method
- ▶ Employs 2 resonance histories



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- NLO+PS generator
  - ▶ Implements resonance aware POWHEG method
  - ▶ Employs 2 resonance histories ( $t(W^+ b)\bar{t}(W^- \bar{b})$ ,  $Z(W^+ W^-)b\bar{b}$ )
- Shower Monte Carlo
  - ▶ Standard LHE interface not sufficient (separate scalup required each resonance)
  - ▶ Pythia8: PowhegHooksBB4L class publicaly available
  - ▶ Herwig7: coming soon



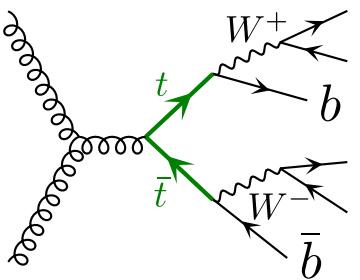
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- Shower Monte Carlo
  - ▶ Pythia8 interface available, Herwig7 coming soon
- Implementation
  - ▶ Resonance aware POWHEG method: **POWHEG BOX RES**
  - ▶ Process implementation: **b\_bbar\_4l** or **bbar4l**
  - ▶ Publicly available <http://powhegbox.mib.infn.it/>



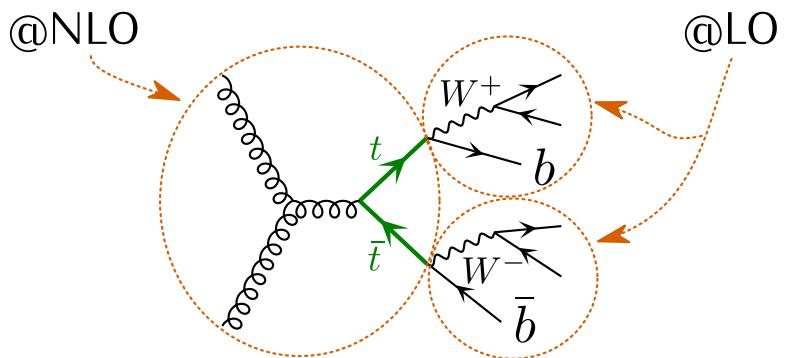
# POWHEG $t\bar{t}$ NLO+PS generators

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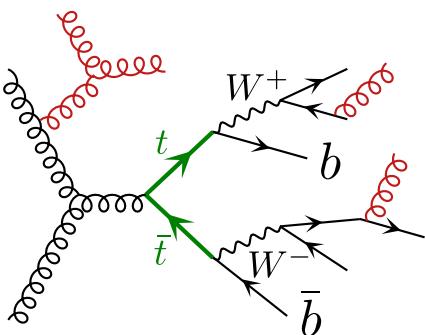


- ▶  $t\bar{t}$  production at NLO
- ▶ No NLO corrections in decays (radiation from  $b$  only by PS)
- ▶ Spin correlations and off shell effects approximate
- ▶ Includes hadronic  $W$  decays
- ▶ No  $Wt$  contribution



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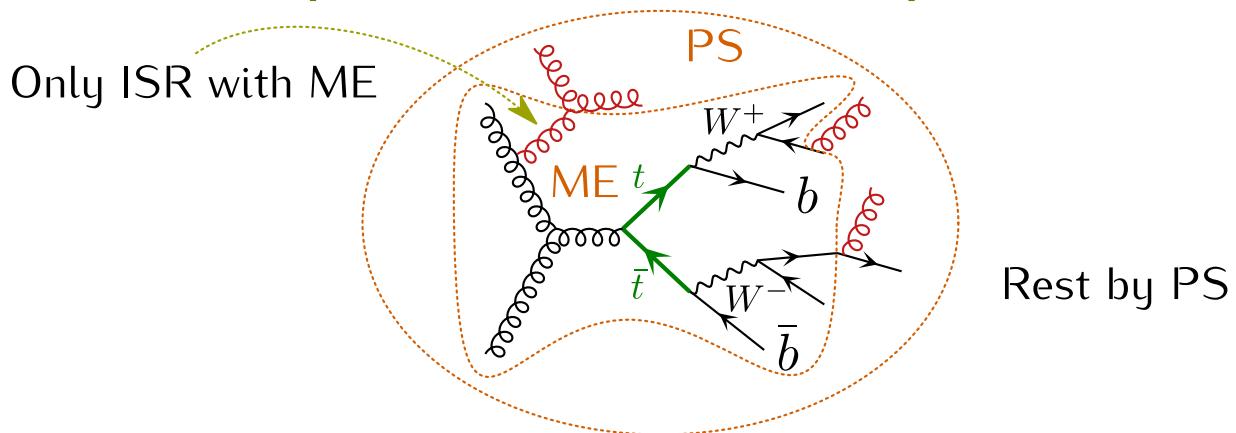


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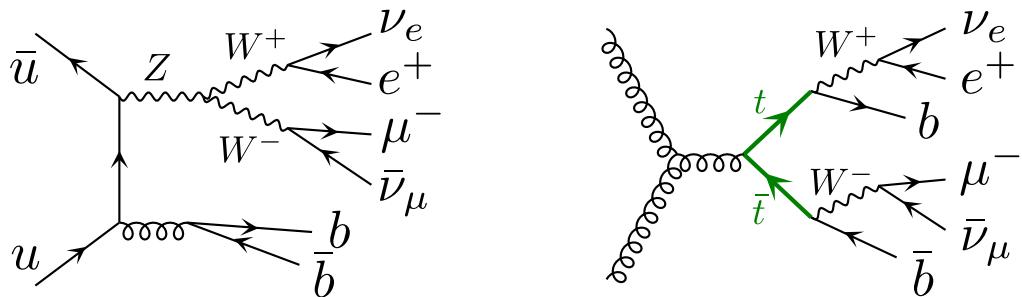


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- POWHEL/Wbb [Garzelli, Kardos, Trócsányi, 2014]

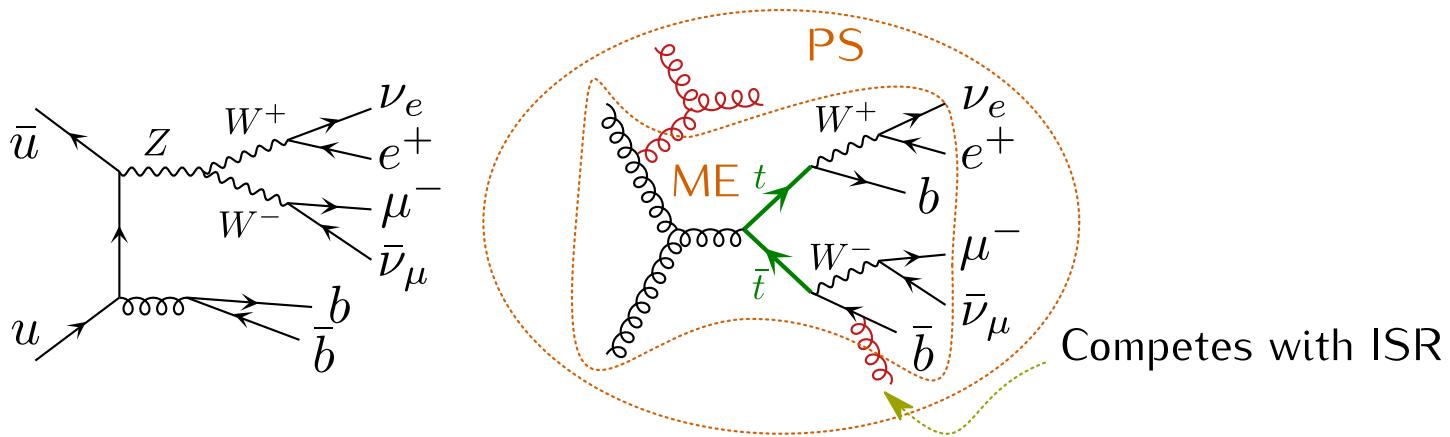


- ▶  $pp \rightarrow \ell^+\nu_\ell \ell^-\bar{\nu}_\ell b\bar{b}$  production at NLO
- ▶ Exact spin correlations and exact off shell effects
- ▶ Formally includes interference of radiation from production and decay
- ▶ Is not resonance aware
- ▶ No hadronic  $W$  decays



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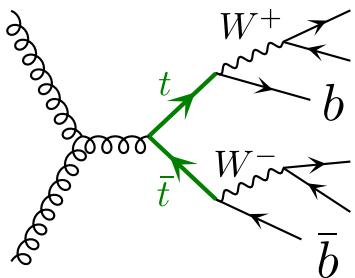


- ▶  $p\bar{p} \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b\bar{b}$  production at NLO
- ▶ Exact spin correlations and exact off shell effects
- ▶ Is **not** resonance aware
- ▶ No hadronic  $W$  decays
- ▶ Radiation from both production and resonances impossible



# POWHEG $t\bar{t}$ NLO+PS generators

- POWHEG-BOX/ttb\_NLO\_dec [Campbell, Ellis, Nason, Re, 2014]

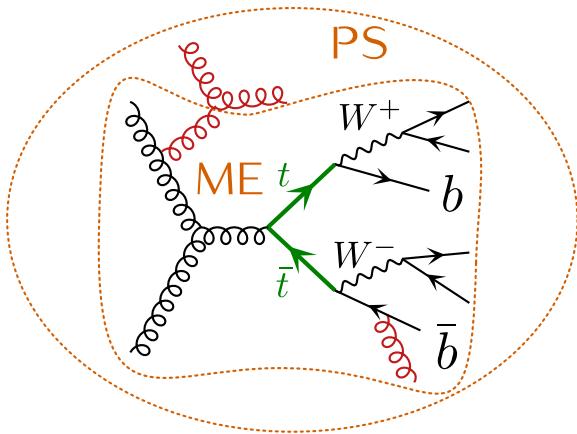


- ▶  $t\bar{t}$  production at NLO
- ▶ Includes NLO corrections in decays
- ▶ Exact spin correlations and LO exact off shell effects
- ▶ No interference of radiation from production and decay
- ▶ Includes hadronic  $W$  decays
- ▶  $Wt$  contribution at LO



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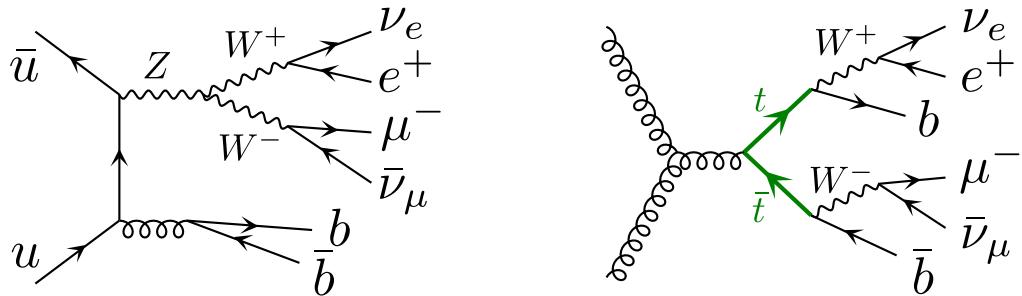


- ▶  $t\bar{t}$  production at NLO
- ▶ Includes NLO corrections in decays
- ▶ Exact spin correlations and LO exact off shell effects
- ▶ No interference of radiation from production and decay
- ▶ Includes hadronic  $W$  decays
- ▶  $Wt$  contribution at LO
- ▶ Makes radiation both from production and resonances possible (`allrad`)



# POWHEG $t\bar{t}$ NLO+PS generators

- POWHEG-BOX-RES/bb41 [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]

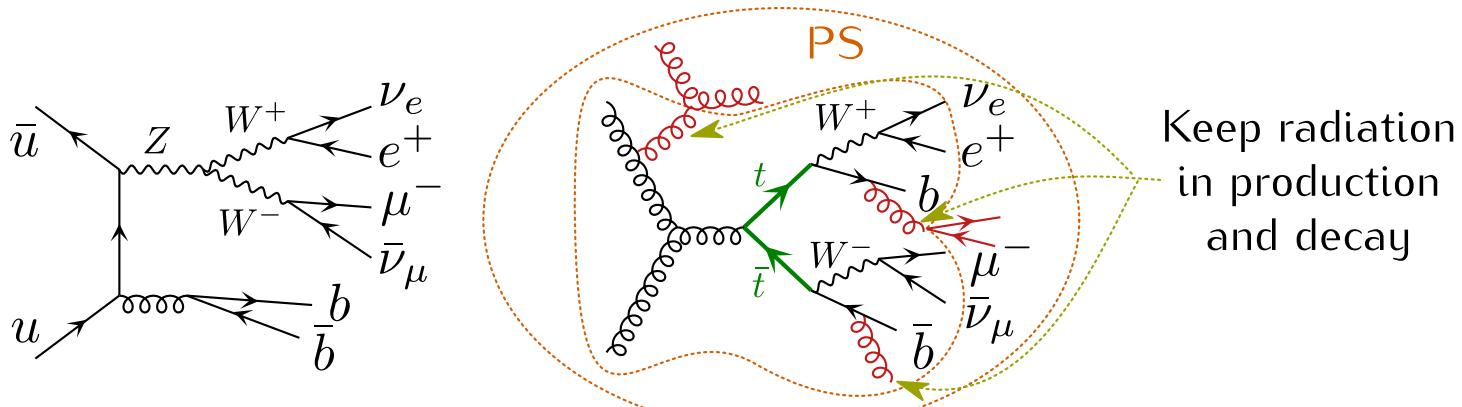


- ▶  $pp \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b \bar{b}$  production at NLO
- ▶ Is resonance aware
- ▶ Exact spin correlations\* and exact off shell effects
- ▶ Includes interference of radiation from production and decay
- ▶ Includes  $Wt$  contribution
- ▶ No hadronic decays



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  - ▶ Implements allrad
- POWHEG-BOX-RES/bb4l [TJ], Lindert, Nason, Oleari, Pozzorini, 2016]
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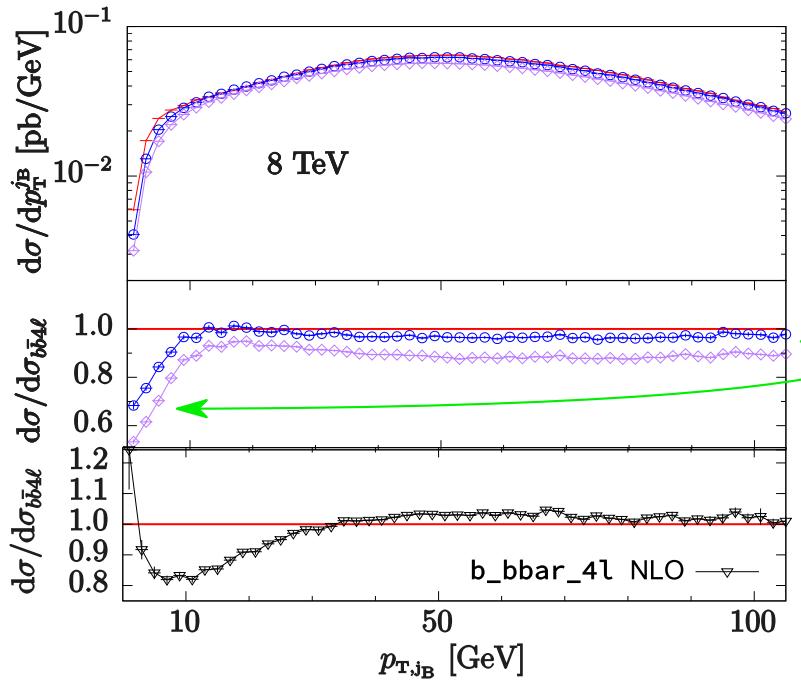
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POWHEG-BOX-V2  $t\bar{t}$



# Jet vetoes and $Wt$ contribution

- $j_B$  transverse momentum, no cuts
  - —●— b\_bbar\_4l: exact  $Wt$
  - —○— ttb\_NLO\_dec:  $Wt$  included via LO reweighting
  - —◇— hvq: no  $Wt$

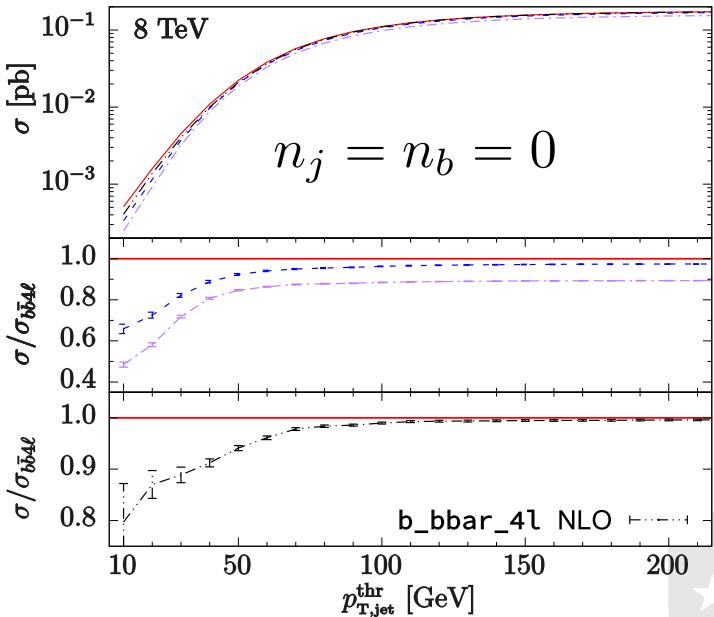
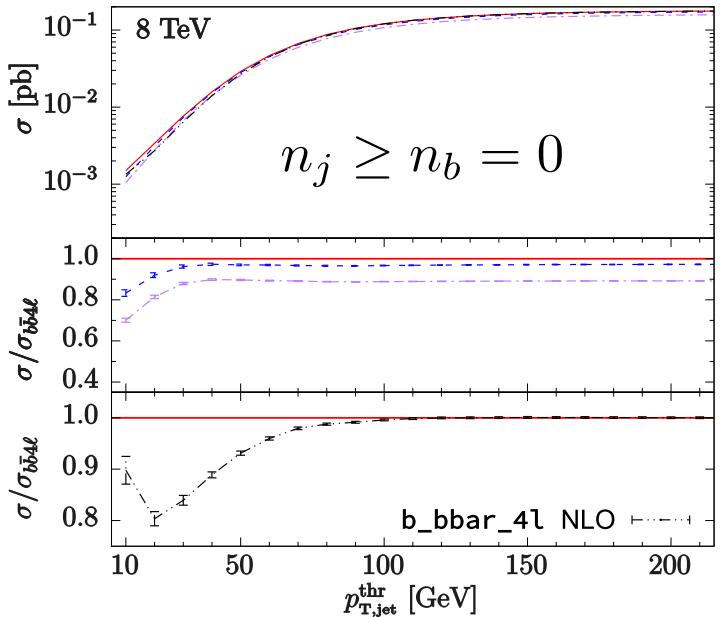


10% difference due to missing  $Wt$  contribution in hvq

$Wt$  more important at small  $p_{T,j_B}$

# Jet vetoes and $Wt$ contribution

- $\sigma = f(p_{T,\text{jet}}^{\text{thr}})$
- — b\_bbar\_4l: exact  $Wt$
- - - - ttb\_NLO\_dec:  $Wt$  included via LO reweighting
- - - - hvq: no  $Wt$



# Jet vetoes and $Wt$ contribution



## ► Summary

- — b\_bbar\_4l: exact  $Wt$
- - - - ttb\_NLO\_dec:  $Wt$  included via LO reweighting
- - - - hvq: no  $Wt$

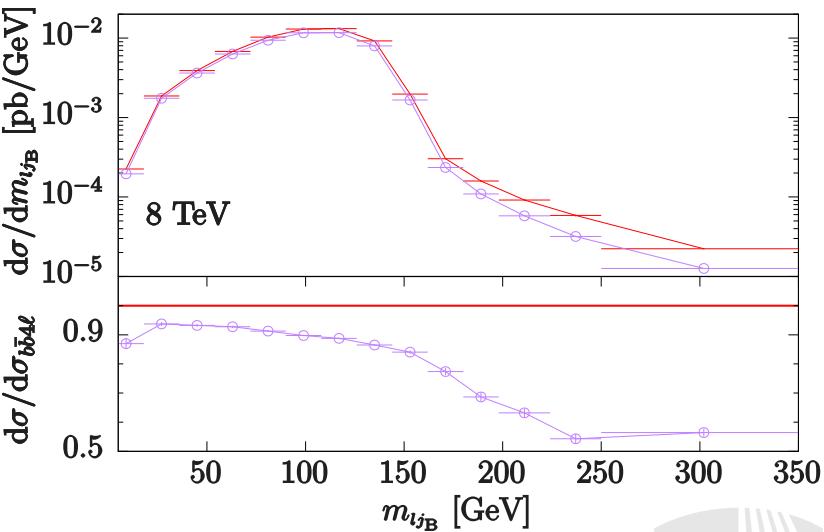
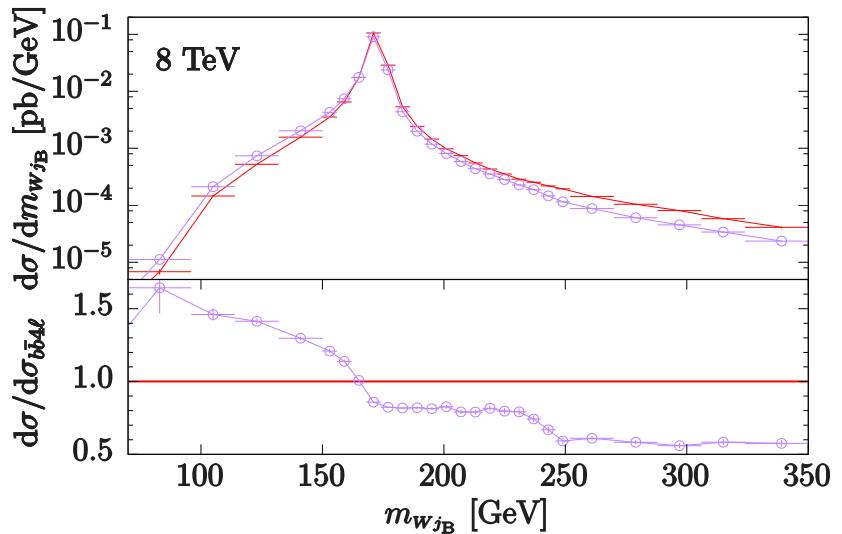
## ► In conclusion

- relative weight of the  $Wt$  contribution important at small values of  $b$  jet transverse momentum;
- jet-vetoed cross sections involve enhanced  $Wt$  contribution which are:
  - completely missing in hvq
  - significantly underestimated in ttb\_NLO\_dec.



# Impact of radiative corrections in top decays

- $Wj_B$  and  $lj_B$  mass
  -  b\_bbar\_4l:  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$ @NLO, allrad scheme
  -  hvq:  $t\bar{t}$  @NLO, decay @LO, no  $Wt$  contribution

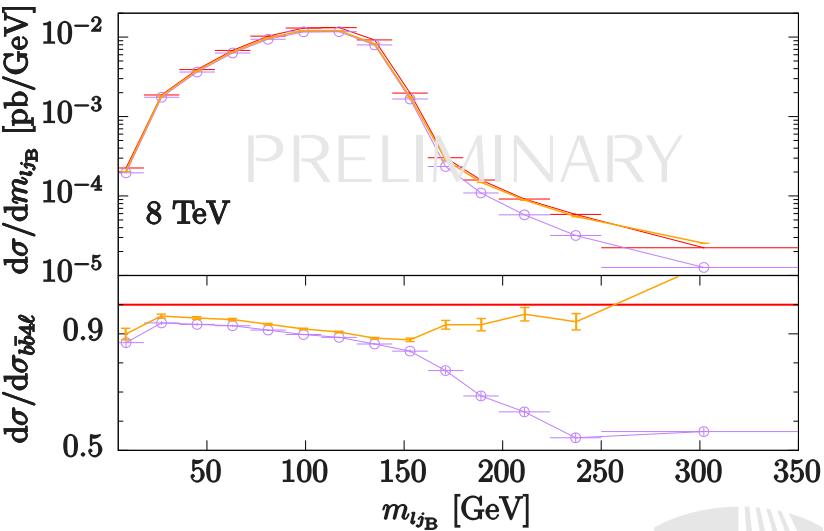
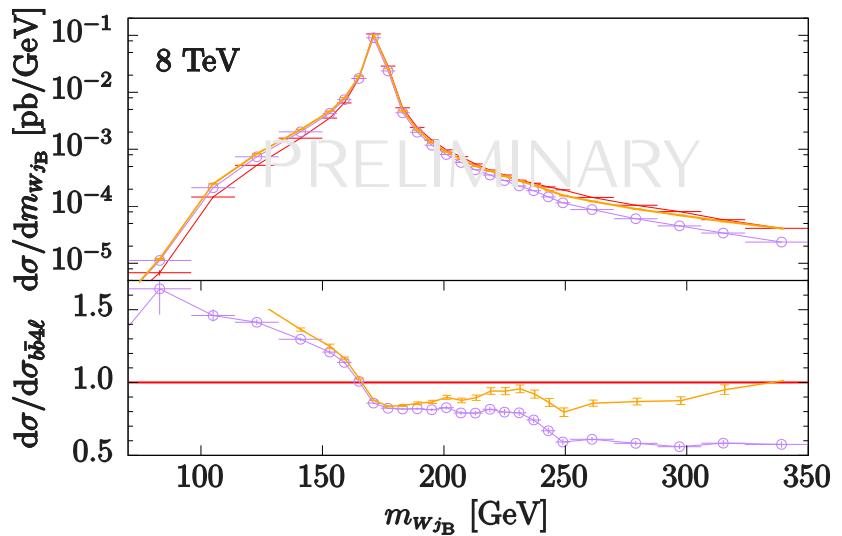


we observe a dramatic difference, even a shift in the reconstructed top mass peak

# Impact of radiative corrections in top decays



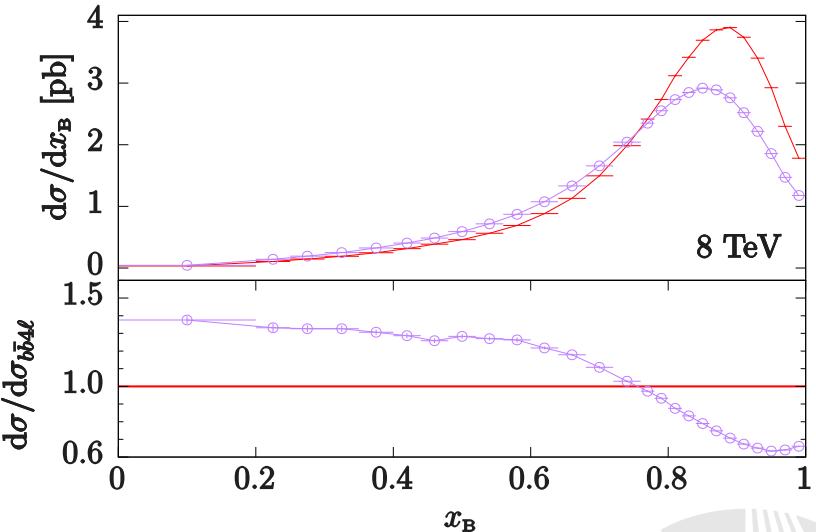
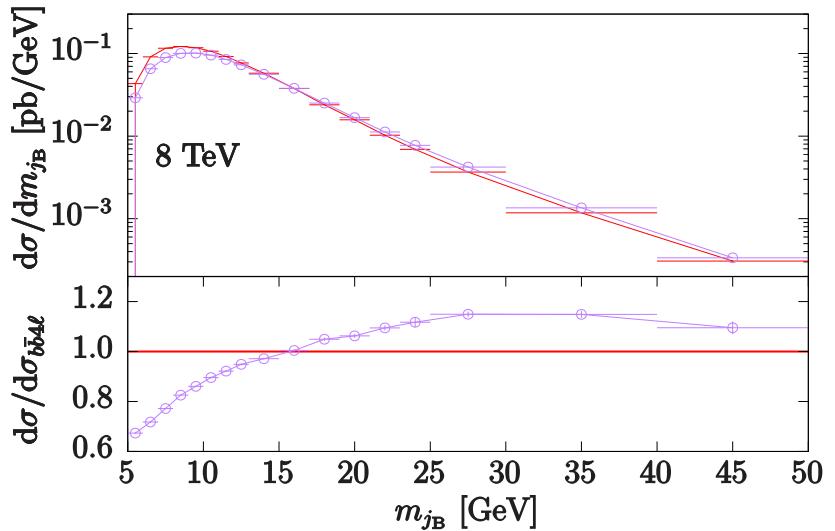
- $W j_B$  and  $l j_B$  mass
  - $b\bar{b}$ :  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$  @NLO, allrad scheme
  - $h v q$ :  $t\bar{t}$  @NLO, decay @LO, no  $Wt$  contribution
  - $h v q + ST\_wtch\_DR$ :  $t\bar{t}$  &  $Wt$  @NLO,  $t$  decay @LO



stacking  $Wt$  contribution on top of  $h v q$  improves  
the agreement, most notably for  $l j_B$  mass

# Impact of radiative corrections in top decays

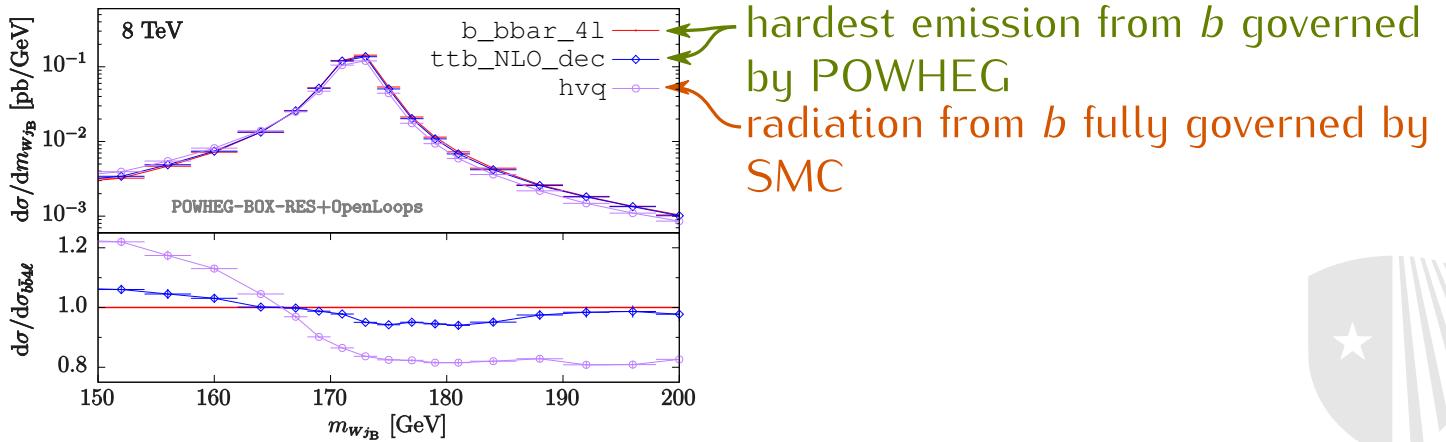
- $j_B$  mass and  $B$  fragmentation function
  -  b\_bbar\_4l:  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$  @NLO, allrad scheme
  -  hvq:  $t\bar{t}$  @NLO, decay @LO, no  $Wt$  contribution



hvq predicts narrower  $b$ -jets and softer  $B$  fragmentation function

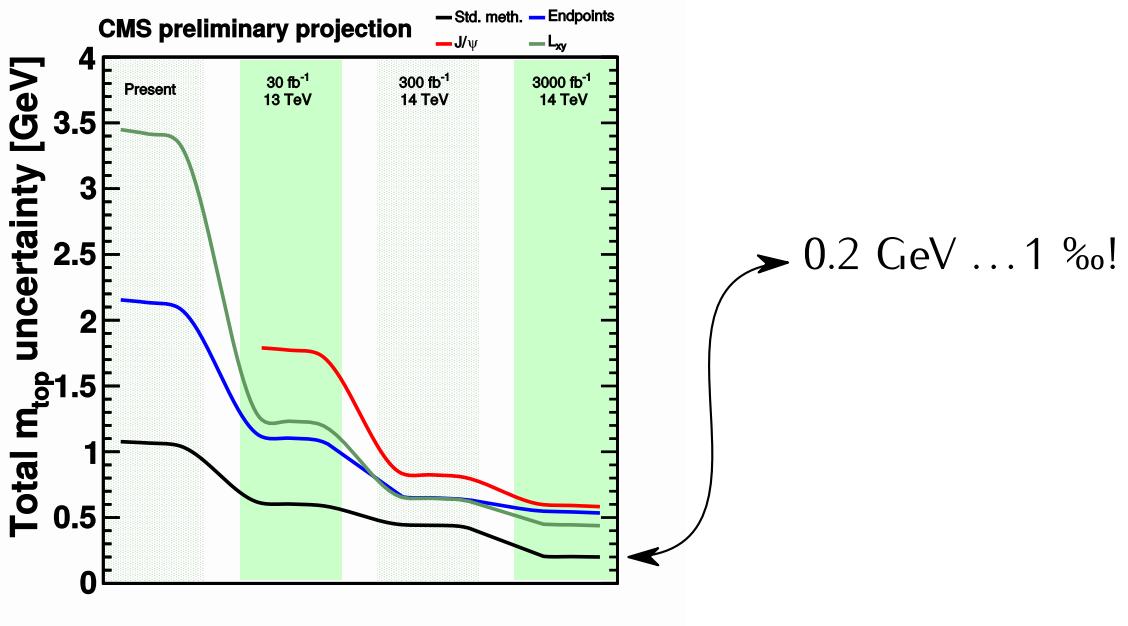
# Impact of radiative corrections in top decays

- Summary
  - ▶  b\_bbar\_4l:  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$ @NLO, allrad scheme
  - ▶  hvq:  $t\bar{t}$  @NLO, decay @LO, no  $Wt$  contribution
- In conclusion, radiative correctoins in top decays have dramatic impact both on ...
  - ▶  $b$ -jet related observables,
  - ▶ as well as observables constructed from  $b$ -jets.



# Impact on top mass determination

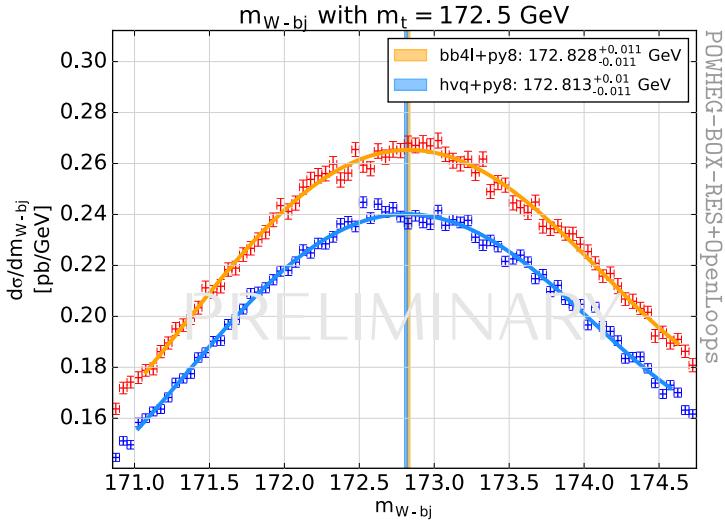
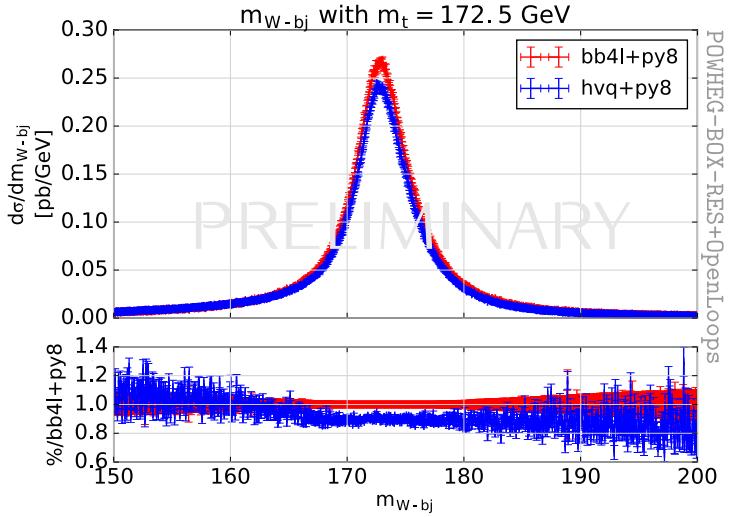
- Top-quark abundantly produced at LHC
- Most precise top-mass determinations based on top reconstruction from its decay products rely on MC event generators
- Projections suggest per mille precision
- Are our MCs precise enough?



# Impact on top mass determination

[Ferrario Ravasio, TJ, Nason and Oleari]

UZH



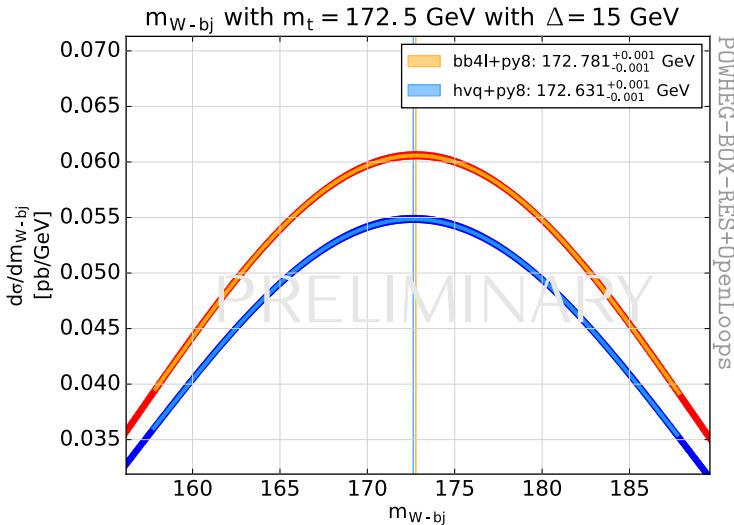
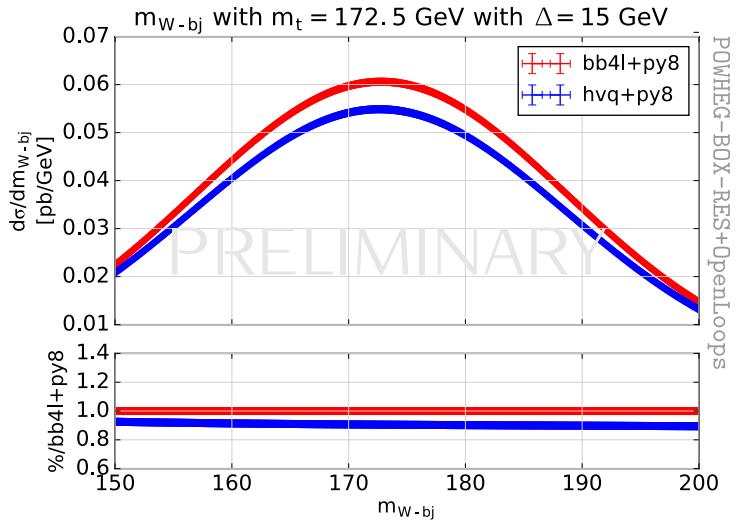
- Shower brings the two predictions closer together
- There's a shape difference, but is the peak shifted?
  - ▶ Polynomial fit of the invariant mass distribution reveals a peak shift of  $\sim 20 \text{ MeV}$



# Impact on top mass determination

[Ferrario Ravasio, TJ, Nason and Oleari]

UZH



- Repeat the exercise with distributions smeared with a gaussian weight

$$f(x) = \mathcal{N} \int dx' f(x') \exp \left[ -\frac{(x - x')^2}{2\Delta^2} \right]$$

- Polynomial fit now reveals a peak shift of  $\sim 150$  MeV



# $W^+ b W^- b$ with hadronic $W$ decays?



- Semileptonic and hadronic channel in ttb\_NLO\_dec:
  - ▶ Works remarkably well for  $Wb_j$  and  $lb_j$  mass
  - ▶ Underestimates  $Wt$  enriched jet-vetoed cross sections w.r.t. bb4l
- Semileptonic channel à la bb4l: [TJ, Lindert, Pozzorini]
  - ▶ OpenLoops MEs available, feasibility study upcoming
  - ▶ If MEs too slow, bb4l like topologies certainly feasible. Would this be good enough?
  - ▶ We do not foresee any complications in resonance-aware POWHEG matching
  - ▶ Timeline: ?
- Hadronic channel à la bb4l:
  - ▶ OpenLoops MEs currently beyond reach



# Summary

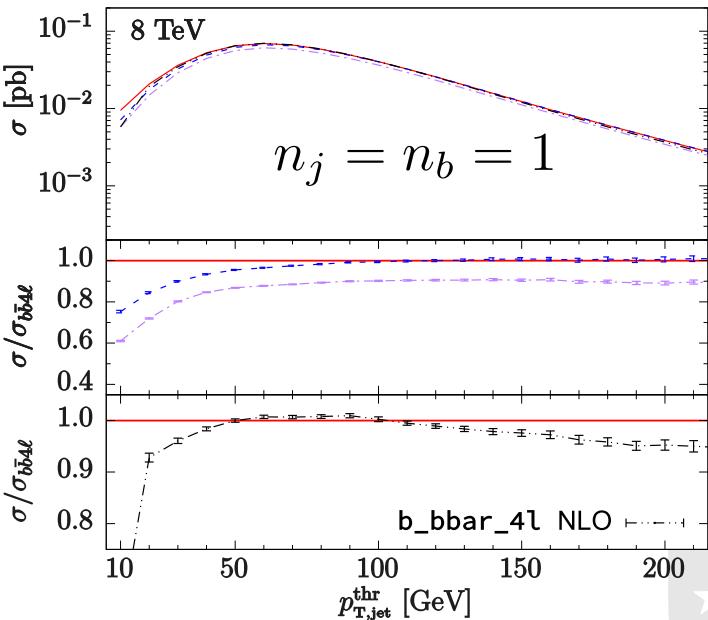
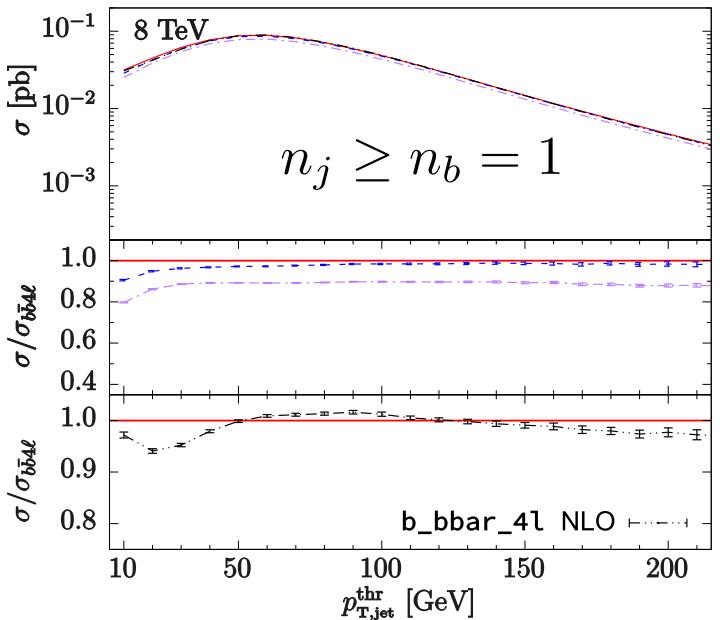
- $W^+ b W^- \bar{b}$  in leptonic channel:
  - ▶ NLO corrections to  $Wt$  in single top enriched regions important
  - ▶ Radiative corrections in top decays have large impact on  $b$ -jet observables
  - ▶ Preliminary: Impact on top mass determination not dramatic<sup>†</sup>
- $W^+ b W^- \bar{b}$  in semileptonic and hadronic channels:
  - ▶ Semileptonic channel à la bb4l seems feasible
  - ▶ Hadronic channel MEs out of reach
  - ▶ Meanwhile use `ttb_NLO_dec` as long as you avoid  $Wt$  enriched regions

<sup>†</sup> Shower Monte Carlo uncertainty (i.e. PY8  $\leftrightarrow$  HW7) not under control.



# Jet vetoes and $Wt$ contribution

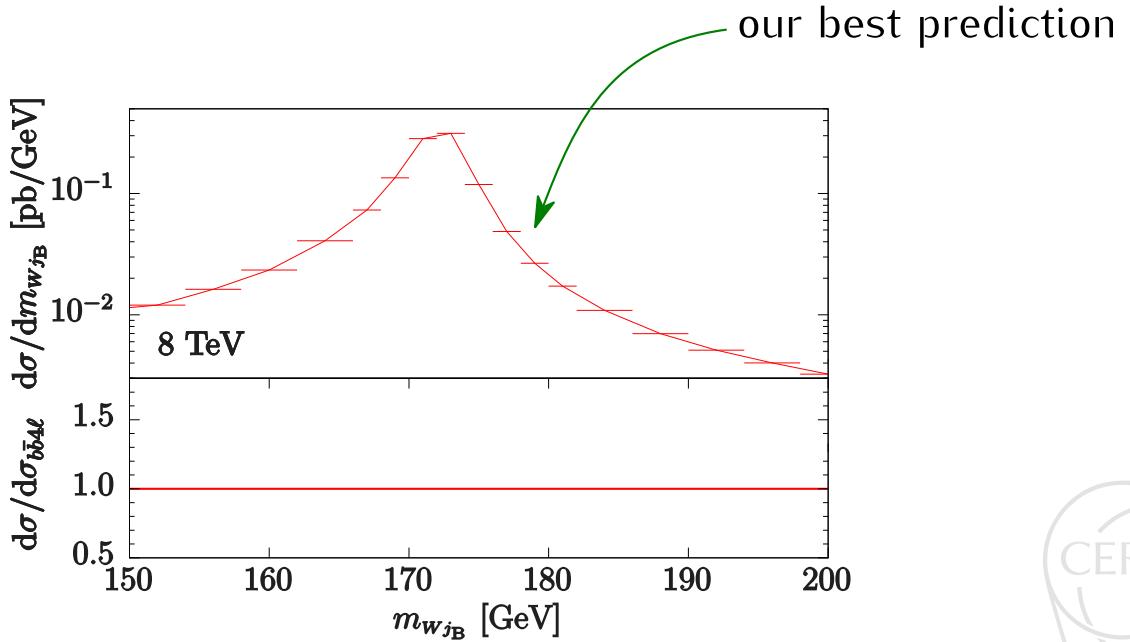
- $\sigma = f(p_{T,\text{jet}}^{\text{thr}})$
- — b\_bbar\_4l: exact  $Wt$
- - - - ttb\_NLO\_dec:  $Wt$  included via LO reweighting
- - · - hvq: no  $Wt$



# Impact of “resonance awareness”

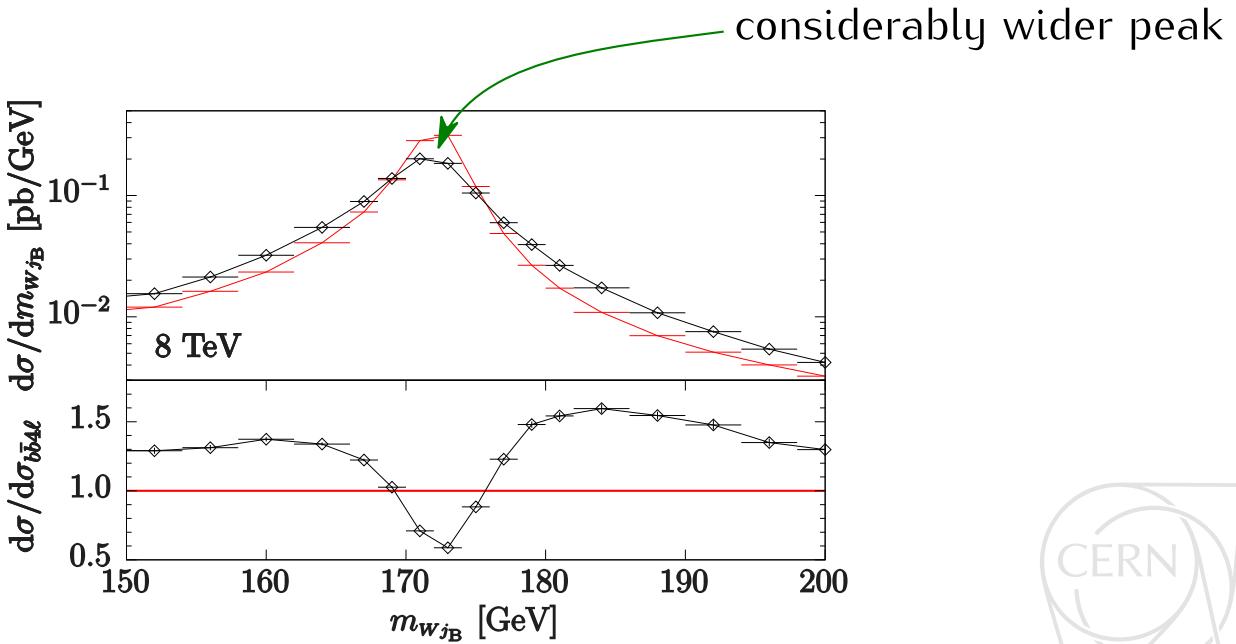
- $Wj_B$  mass

► —●— **res-default:** resonance aware NLO+PS, allrad scheme

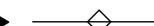


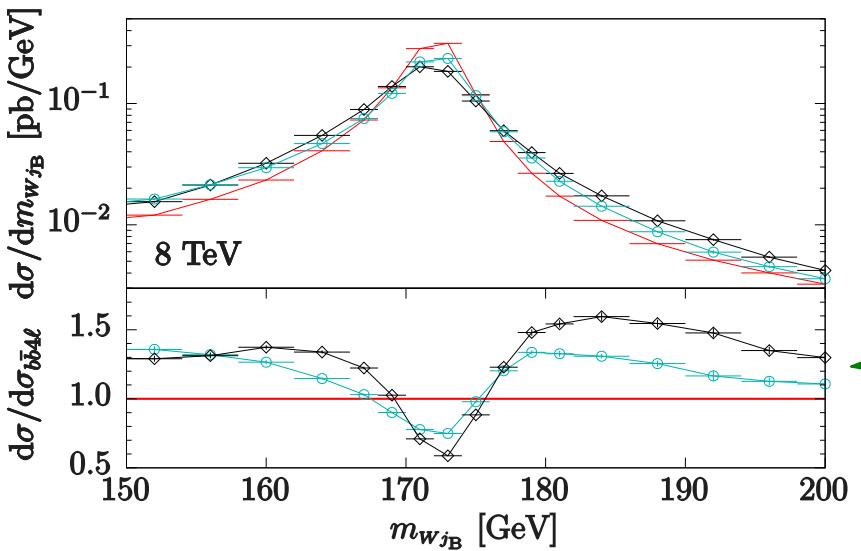
# Impact of “resonance awareness”

- $Wj_B$  mass
  - —●— **res-default:** resonance aware NLO+PS, allrad scheme
  - —◇— **res-off:** resonance aware NLO+PS switched off

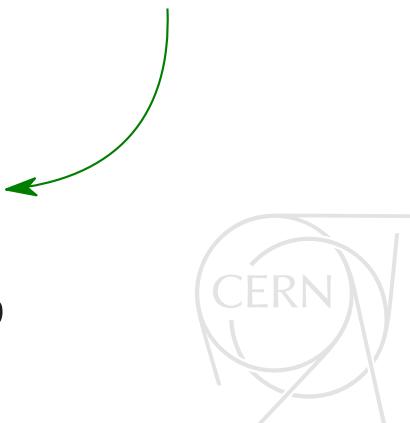


# Impact of “resonance awareness”

- $W j_B$  mass
  - ▶  **res-default:** resonance aware NLO+PS, allrad scheme
  - ▶  **res-off:** resonance aware NLO+PS switched off
  - ▶  **res-guess:** resonance aware NLO+PS switched off, resonance history “guessed” before showering



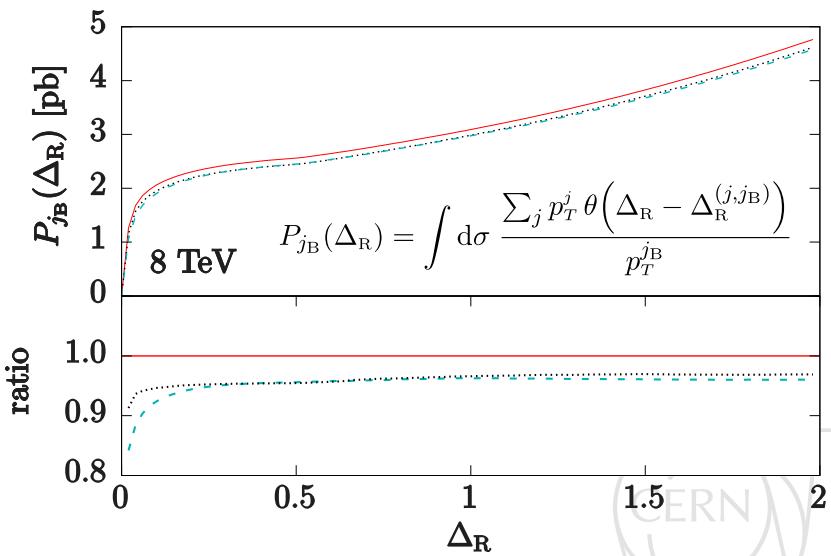
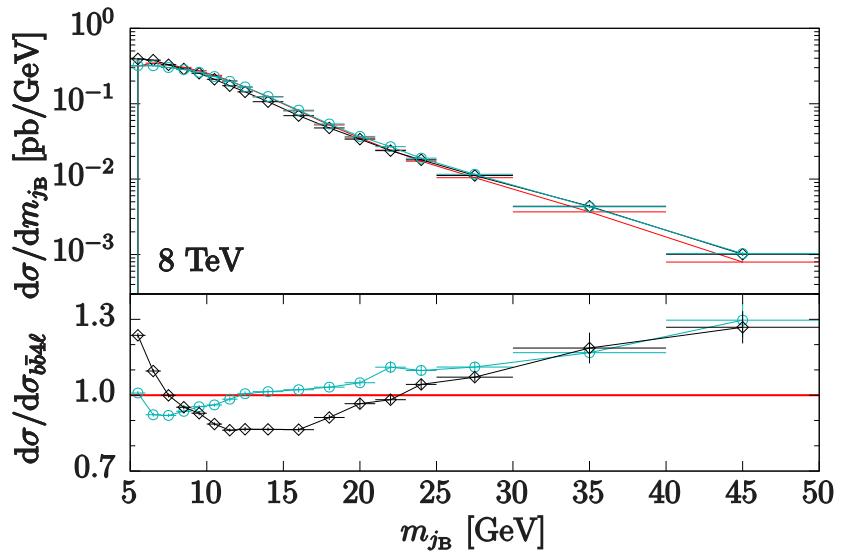
guessing the resonance history before shower does not help



# Impact of “resonance awareness”

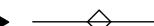
- $j_B$  mass and profile

- ▶  **res-default:** resonance aware NLO+PS, allrad scheme
- ▶  **res-off:** resonance aware NLO+PS switched off
- ▶  **res-guess:** resonance aware NLO+PS switched off, resonance history “guessed” before showering



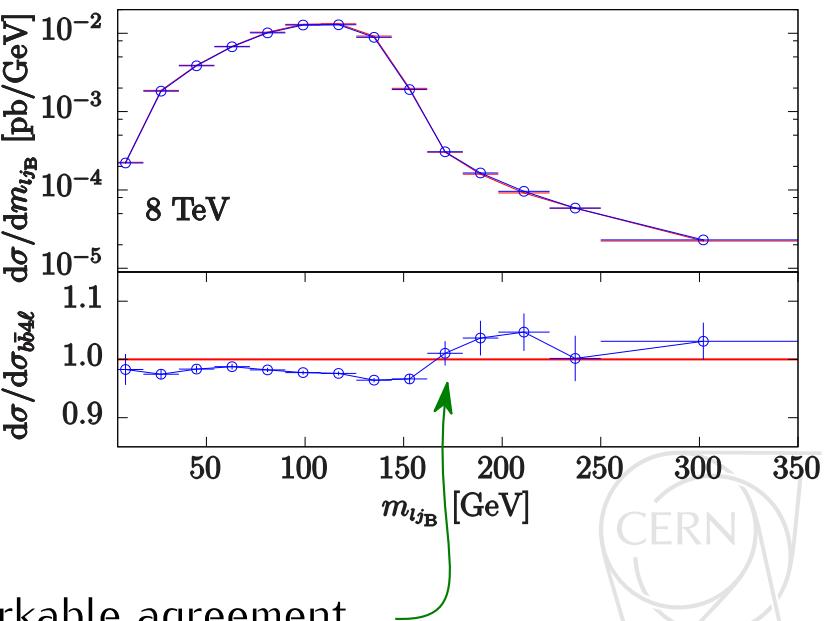
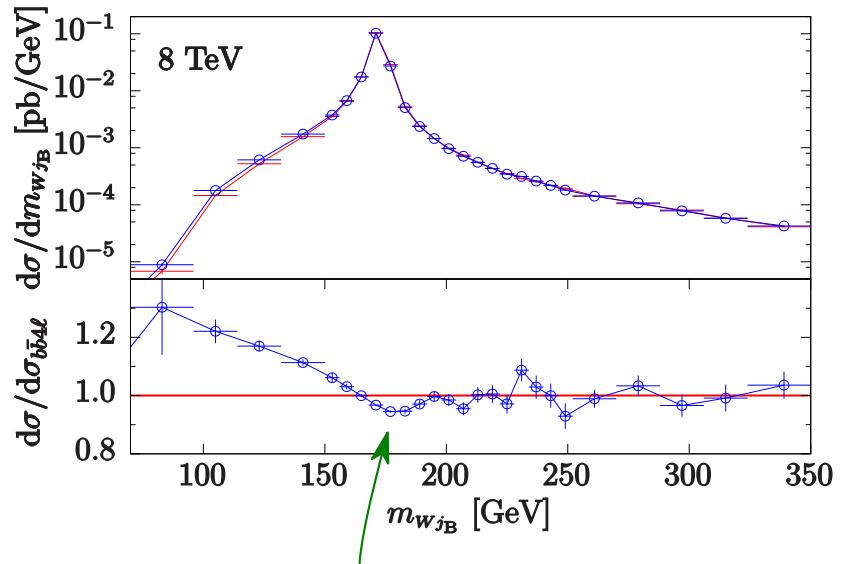
less activity around  $B$  hadron in **res-off**

# Impact of “resonance awareness”

- Summary
  - ▶  **res-default**: resonance aware NLO+PS, allrad scheme
  - ▶  **res-off**: resonance aware NLO+PS switched off
  - ▶  **res-guess**: resonance aware NLO+PS switched off, resonance history “guessed” before showering
- In conclusion, the resonance aware NLO+PS ...
  - ▶ ... yields a narrower peak for the reconstructed top mass distribution.
  - ▶ ... predicts more hadronic activity around the  $B$  hadron.
  - ▶ ... offers a considerable speed up both in the integration and generation.
- Moreover, the traditional approach ...
  - ▶ ... cannot be fixed by reconstructing the resonance history of the after the hardest emission has already been generated.

# Non-resonant and interf. effects

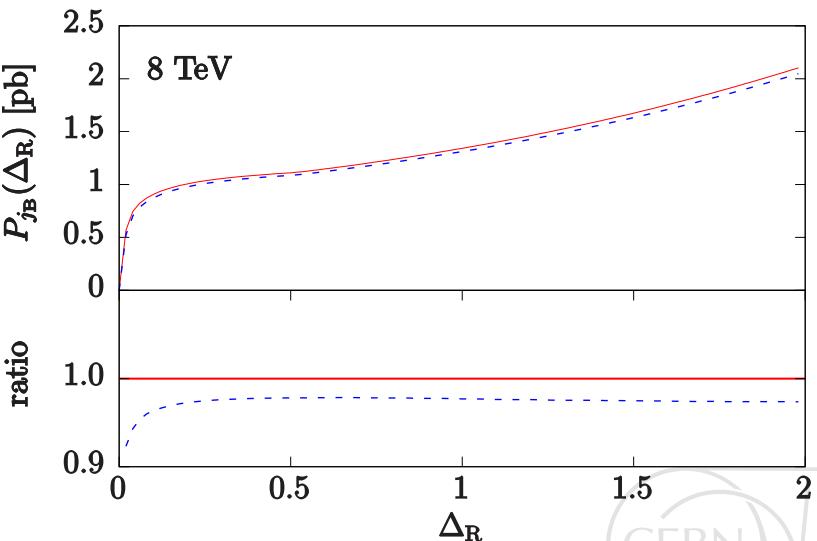
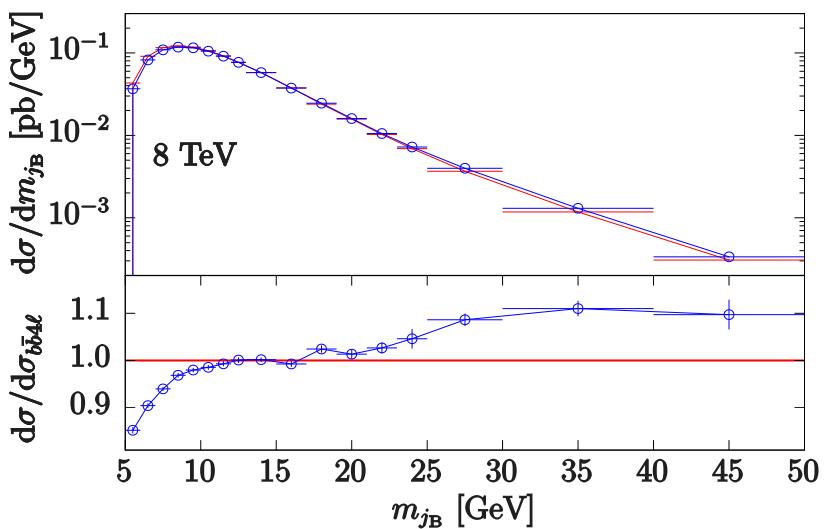
- $Wj_B$  and  $lj_B$  mass
  - ▶  b\_bbar\_4l: all diagrams for  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$
  - ▶  ttbar\_NLO\_dec:  $t\bar{t}$  production and decay @NLO with NWA
  - ▶ both: resonance aware NLO+PS, allrad scheme



we observe a remarkable agreement

# Non-resonant and interf. effects

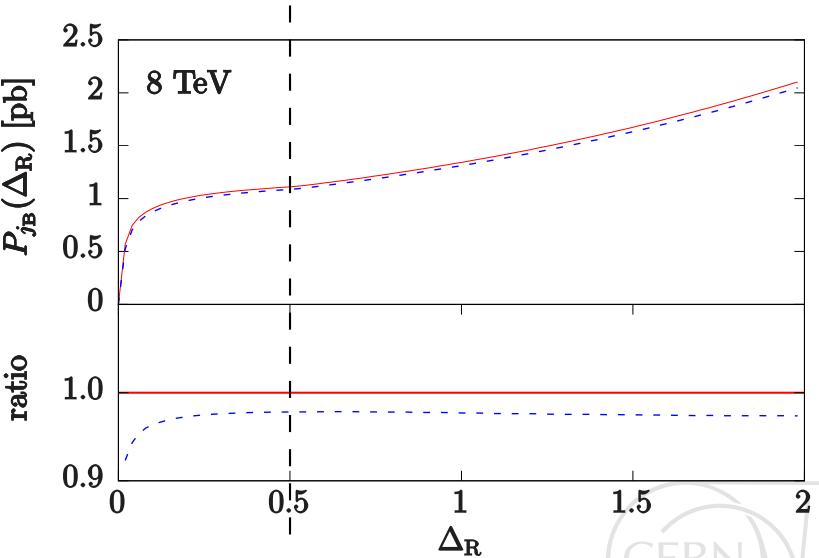
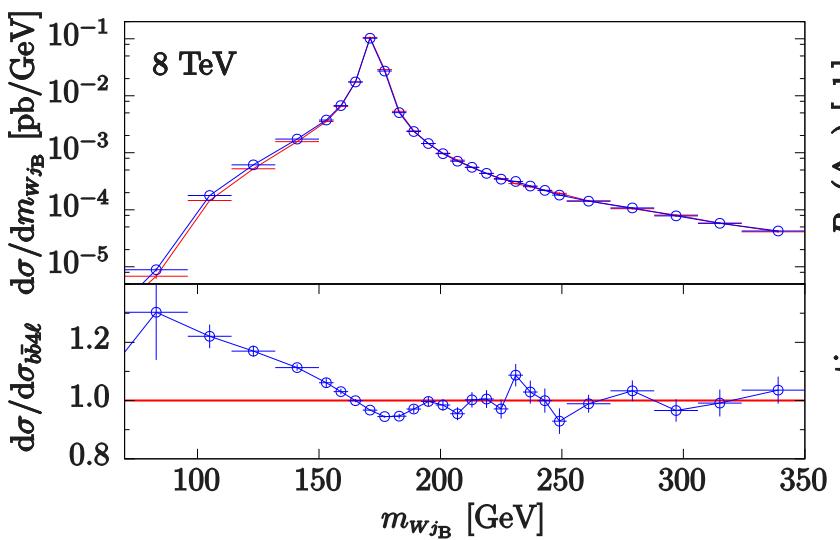
- $j_B$  mass and profile
  -  b\_bbar\_4l: all diagrams for  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_\ell b \bar{b}$
  -  ttbar\_NLO\_dec:  $t\bar{t}$  production and decay @NLO with NWA
  - both: resonance aware NLO+PS, allrad scheme



b\_bbar\_4l yields slightly wider  $b$  jets

# Non-resonant and interf. effects

- $Wj_B$  mass and  $j_B$  profile
  - ▶  b\_bbar\_4l: all diagrams for  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$
  - ▶  ttbar\_NLO\_dec:  $t\bar{t}$  production and decay @NLO with NWA
  - ▶ both: resonance aware NLO+PS, allrad scheme



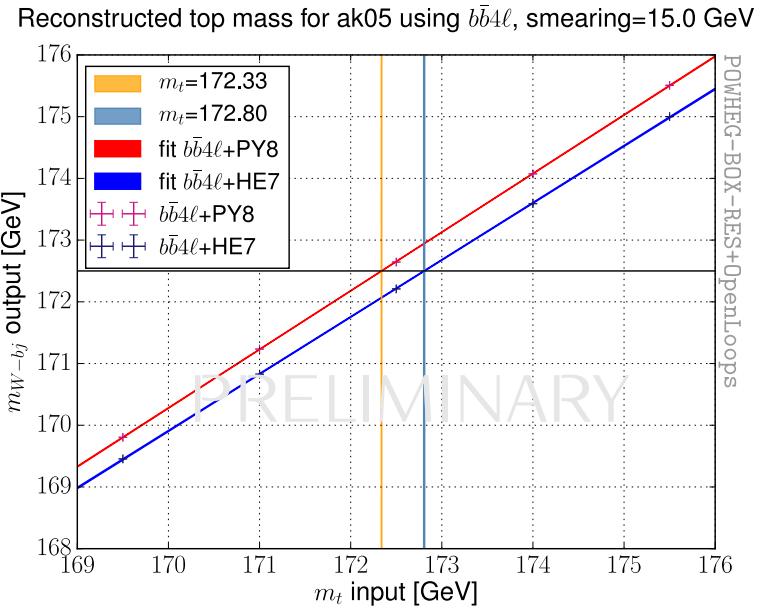
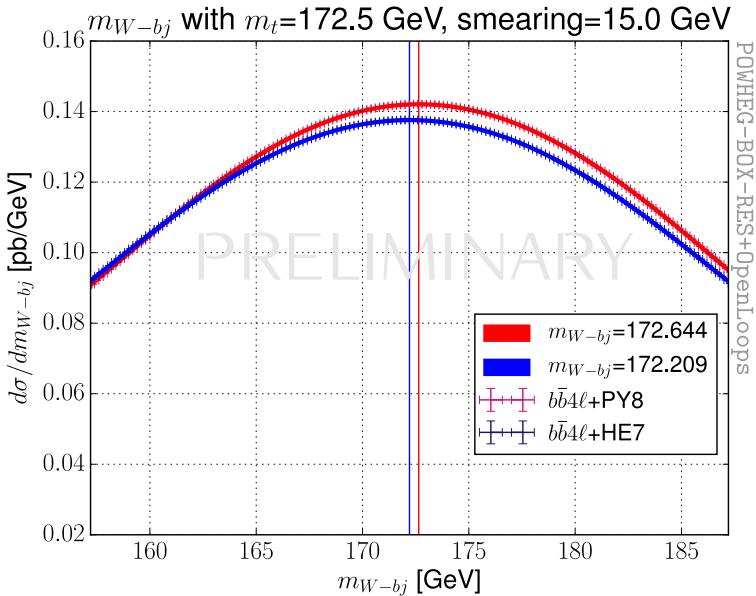
although differences in the jet profile significant, they are not sufficient to induce enough difference in the reconstructed mass

# Non-resonant and interf. effects

- Summary
  - ▶  b\_bbar\_4l: all diagrams for  $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_\ell b \bar{b}$
  - ▶  ttb\_NLO\_dec:  $t\bar{t}$  production and decay @NLO with NWA
  - ▶ both: resonance aware NLO+PS, allrad scheme
- In conclusion, the non-resonant and interf. effects ...
  - ▶ ... can lead to a considerably different  $b$ -jet profile
  - ▶ these, however, do not seem relevant for the reconstructed top mass for usual values of  $\Delta_R$ .
- Also ...
  - ▶ ... matrix elements in ttb\_NLO\_dec much easier to calculate.
  - ▶ ...  $t\bar{t}$  with hadronic  $W$  decays à la bb4l at the moment unfeasible unless using NWA.



# $m_{Wbj}$ : SMC dependence



- Left: polynomial fit reveals a peak shift of  $\sim 500$  MeV
- Right:
  - ▶ Dependence of the fitted peak position as a function of input top mass
  - ▶ We observe a fairly constant peak shift