Latest Developments in POWHEG

Tomáš Ježo
University of Zürich

In collaboration with:
P. Nason *[arXiv:1509.09071]*
J. Lindert, P. Nason, C. Oleari, S. Pozzorini *[arXiv:1607.04538]*

LHC TOP WG meeting
21 November 2016

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Resonance aware NLO+PS & top-pair production at the LHC

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Outline

- NLO+PS matching for processes with radiating intermediate resonances
  - Problem: real/born on-shellness mismatch
    - Cancellation of IR singularities
    - Hardest emission Sudakov
  - Solution: resonance aware NLO+PS matching
    - Resonance virtualities preserving $\mathcal{R} \leftrightarrow \mathcal{B}$ mapping
    - Generalized FKS subtraction

- Generator for top-pair and Wt associated production at the LHC
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

- Study the impact of:
  - Resonance aware NLO+PS matching
  - Non-resonant and interference effects
  - Radiative corrections in top-decays

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Resonance aware NLO+PS

- In a typical calculation of a $2 \to n$ scattering process at NLO

$$\sigma_{\mathrm{NLO}} = \int_n (\mathcal{B} + \mathcal{V}) + \int_{n+1} \mathcal{R}$$

Resonance aware NLO+PS

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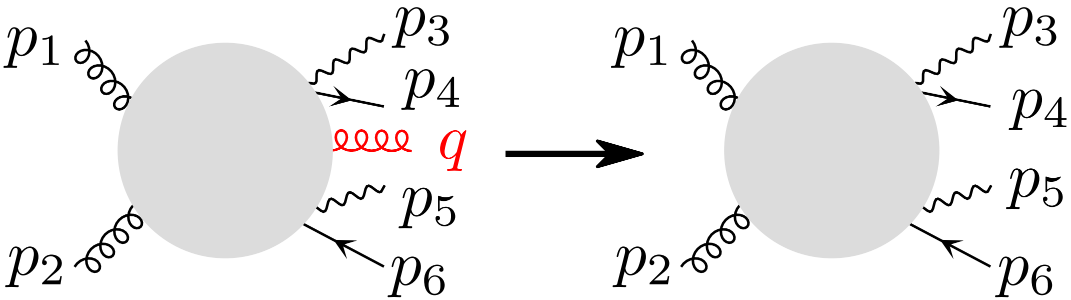
separately divergent

Resonance aware NLO+PS

- A typical calculation of a $2 \to n$ scattering process at NLO ...

$$\sigma_{\text{NLO}} = \int_n (\mathcal{B} + \mathcal{V}) + \int_{n+1} \mathcal{R}$$

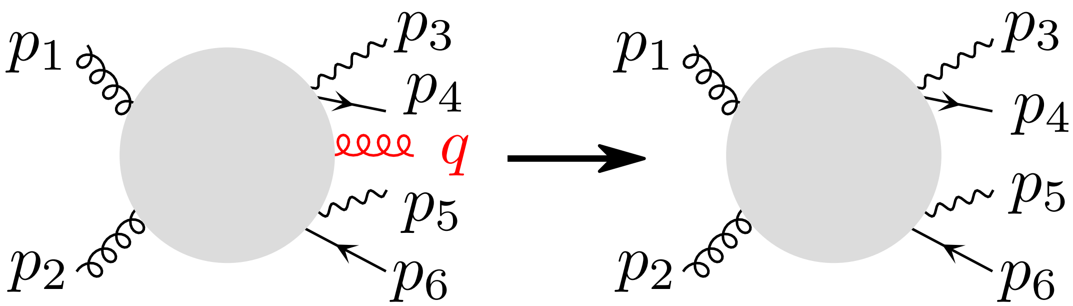
- ... will employ a mapping between $n+1$ (real) and n (Born) phase space



  - Treatment of IR singularities
  - Calculation of the hardest emission Sudakov

Resonance aware NLO+PS

- ... will employ a mapping between $n+1$ (real) and n (Born) phase space



- Such that when q becomes soft or collinear with p_i

$$\{p_1, p_2, \ldots, q\} \to \{p_1, p_2, \ldots\}$$

$$\{p_1, \ldots, p_i, \ldots, q\} \to \{p_1, \ldots, p_i + q, \ldots\}, i > 2$$

- In FKS for *emitter* i and any *emitted* momentum
  - $\vec{p}_i$ preserved
  - Recoiling system boosted along $\vec{p}_i$

Resonance aware NLO+PS

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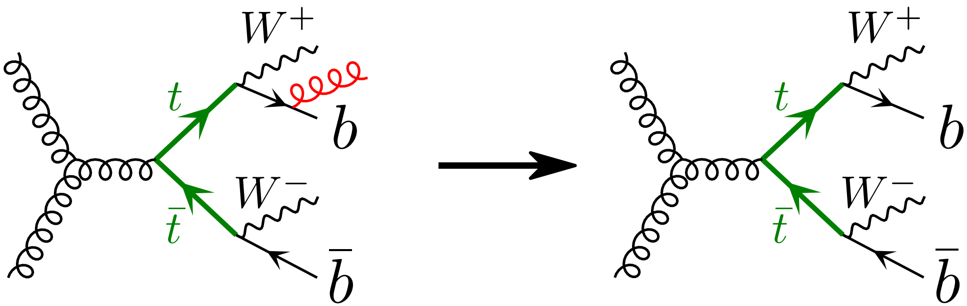

- In FKS
  - b direction preserved
  - $W^+W^-\bar{b}$ system boosted along $\vec{p}_b$
- In general
  - Resonance virtualities not preserved

$$p_t^2(\Phi_{n+1}) \neq p_t^2(\Phi_n)$$

Resonance aware NLO+PS

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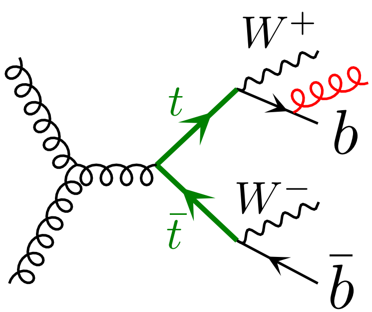
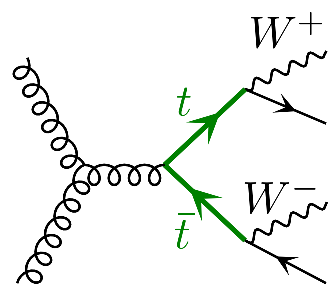
  - Resonance virtualities not preserved, $p_t^2(\Phi_{n+1}) \neq p_t^2(\Phi_n)$

- This leads to real/born on-shellness mismatch



$1/[(p_t^2(\Phi_{n+1}) - m_t^2)^2 + m_t^2\Gamma_t^2]$



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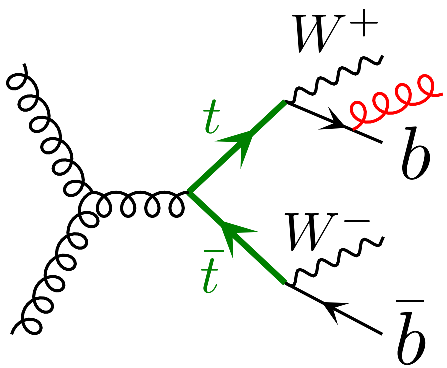
  - If $p_t^2(\Phi_{n+1}) = m_t^2$



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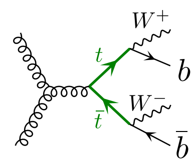

$1/[(p_t^2(\Phi_{n+1}) - m_t^2)^2 + m_t^2\Gamma_t^2]$ $\qquad$ $1/[(p_t^2(\Phi_n) - m_t^2)^2 + m_t^2\Gamma_t^2]$

large $\mathcal{R}/\mathcal{B}$

Resonance aware NLO+PS

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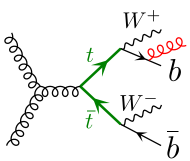

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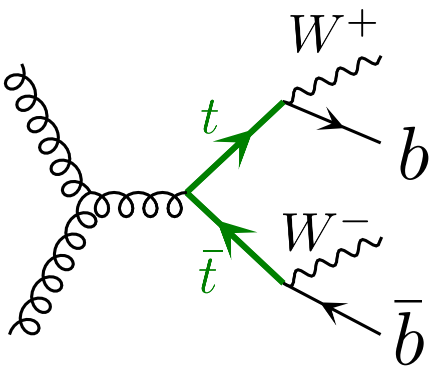

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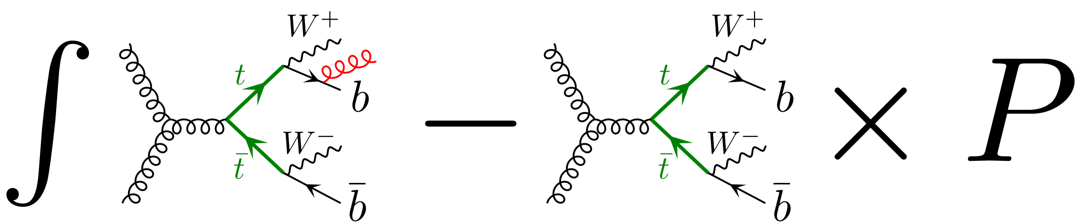
- This leads to real/born on-shellness mismatch causing
  - Poor convergence



  - Distortion of radiation observables

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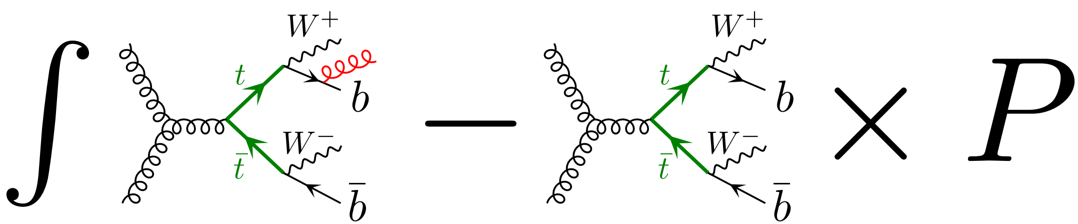

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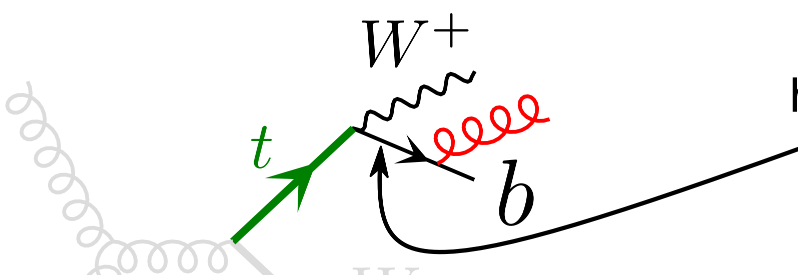
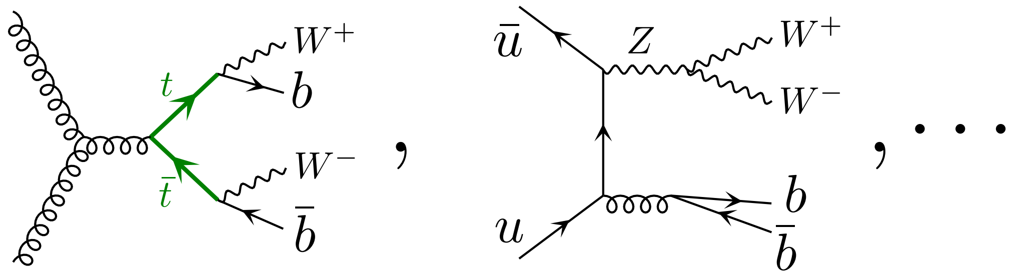


hardest emission Sudakov off due to large $\mathcal{R}/\mathcal{B}$

Resonance aware NLO+PS

- Solution: [Campbell, Elliss, Nason, Re 2014]
  - Use mapping preserving resonance virtualities
- But there is a catch: [TJ, Nason 2015]
  - Same final state realized through different *resonance histories* requiring different mappings (and different reference frames)



  - All contributions must be integrated over regions dominated by a single *resonance history*
  - FKS subtraction needs generalizing
    - Standard FKS requires that the soft limit is taken in the same frame for all singular regions

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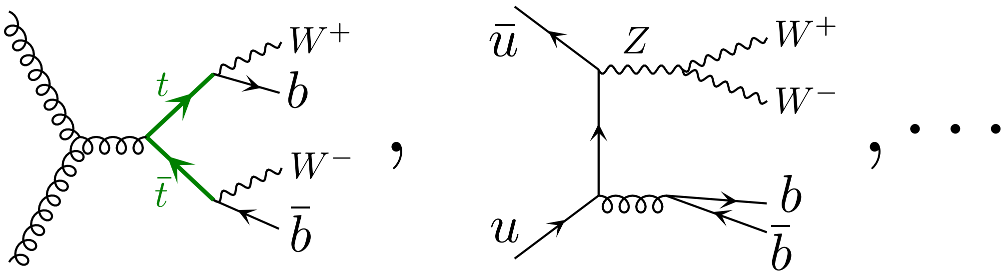


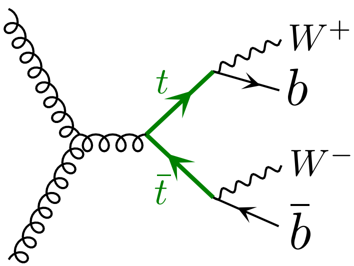
  - All contributions must be integrated over regions dominated by a single *resonance history*
  - FKS subtraction needs generalizing
- Alternative solution based on a re-mapping of the phase space also available [Frederix, Frixione, Papanastasiou, Prestel, Torrielli 2016]

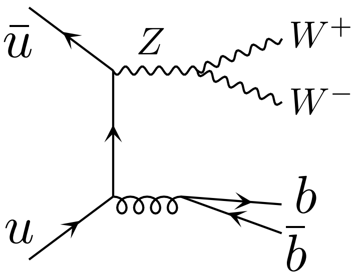
Resonance aware NLO+PS

- All contributions must be integrated over regions dominated by a single resonance history
  - Contributions with Born kinematics:

$$\mathcal{B}_{t\bar{t}} = \frac{P_{t\bar{t}}}{P_{t\bar{t}}+P_Z}\mathcal{B} \qquad P_{t\bar{t}} = \frac{m_t^4}{(s^2_{W^+b}-m_t^2)^2+\Gamma_t^2 m_t^2} \times \frac{m_t^4}{(s^2_{W^-\bar{b}}-m_t^2)^2+\Gamma_t^2 m_t^2}$$

$$\mathcal{B}_Z = \frac{P_Z}{P_{t\bar{t}}+P_Z}\mathcal{B} \qquad P_Z = \frac{m_Z^4}{(s^2_{W^+W^-}-m_Z^2)^2+\Gamma_Z^2 m_Z^2}$$





  - Contributions with real kinematics: the separation nested with the separation into singular rgions

Resonance aware NLO+PS

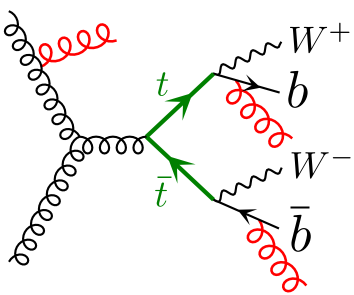
- Bonus:
  - Resonance aware formalism allows us to further improve the POWHEG radiation formula

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

$$\Updownarrow$$

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

  - We can attach radiation to each resonance in a single event (`allrad` scheme)
    - Requires keeping track of multiple matching scales for subsequent shower



Resonance aware NLO+PS

- NLO+PS matching for processes with radiating intermediate resonances

  - Problem: real/born on-shellness mismatch
    - Problematic cancellation of IR singularities leading to poor convergence
    - Large $\mathcal{R}/\mathcal{B}$ ratio in the hardest emission Sudakov leading to distortion of radiation observables

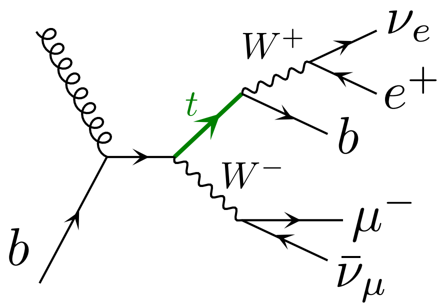
  - Solution: resonance aware POWHEG method
    - Integration over regions dominated by one resonance history
    - Resonance virtualities preserving $\mathcal{R} \leftrightarrow \mathcal{B}$ mapping
    - Generalized FKS subtraction
    - Improved multiple-radiation scheme (`allrad`)

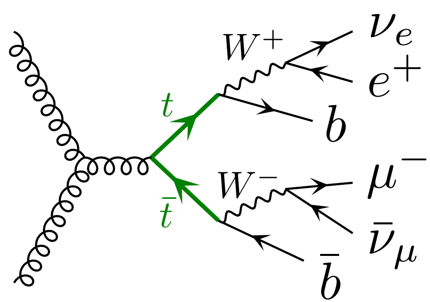
  - Publicly available as a part of the `POWHEG BOX RES` code

Top-pair and Wt @ LHC

➤ Production of top-pair and associated Wt; top decaying leptonically

- 5F scheme, @LO





- Different processes
  - ❧ Different final state
  - ❧ Different power of α_S

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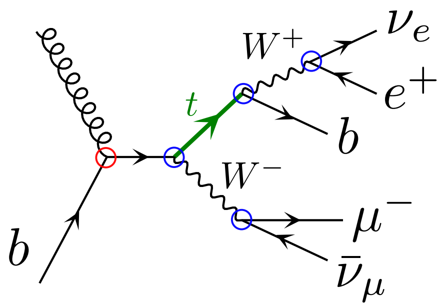

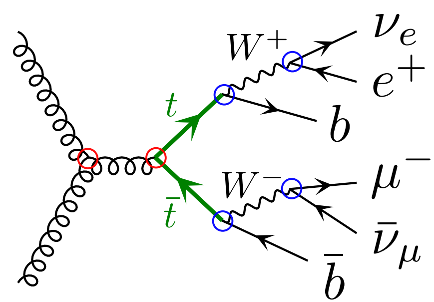

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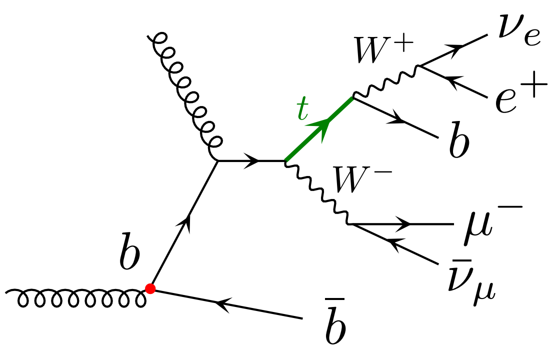

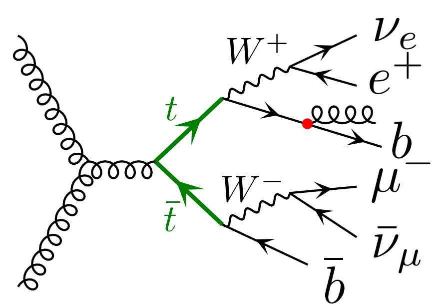

- Different processes
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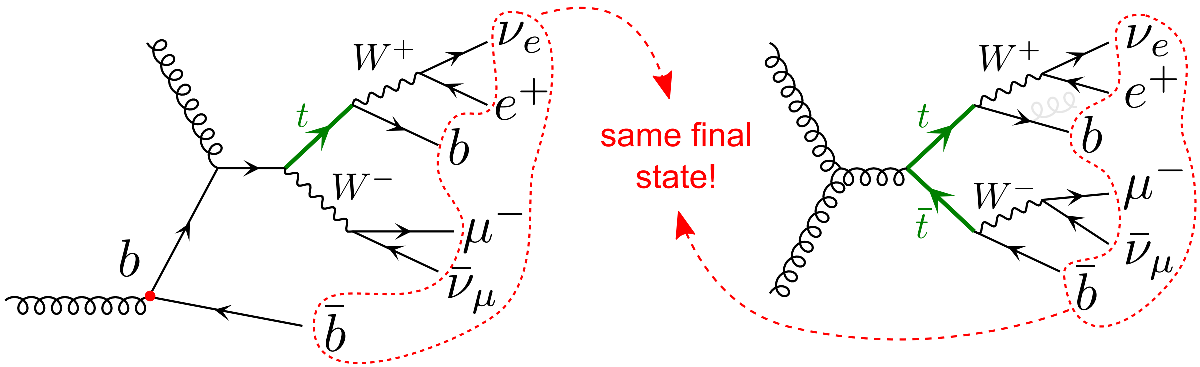
Top-pair and Wt @ LHC

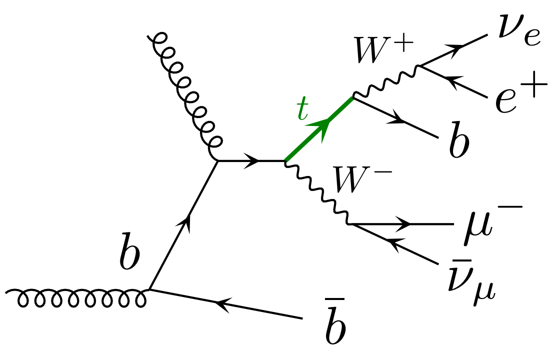
- ➤ Production of top-pair and associated Wt; top decaying leptonically
  - ➢ 5F scheme, Wt @NLO, top-pair @LO

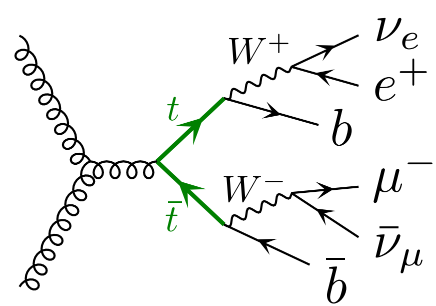


- ➢ Same processes
  - ❧ Real correction to Wt production includes top-pair topology

Top-pair and Wt @ LHC

- Production of top-pair and associated Wt; top decaying leptonically
  - 4F scheme, @LO

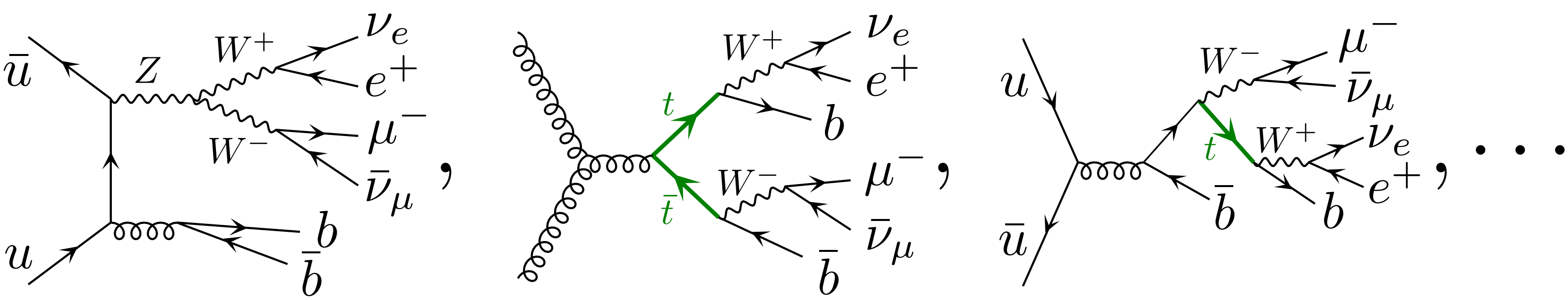




  - Same processes
    - Constitutes unified treatment for Wt and top-pair production

Generator details

- Process
  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @ NLO QCD



  - Born, real and virtual matrix elements by `OpenLoops`
  - 4F scheme
    - Unified description of top-pair and Wt production
    - Effects of b-quark mass included
    - Phase space with unresolved b-quarks accessible

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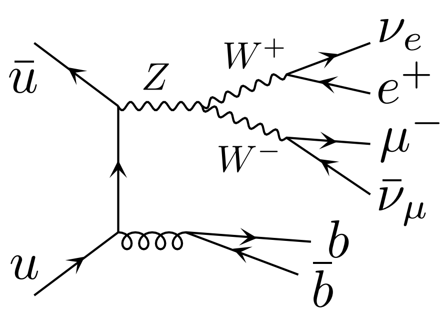
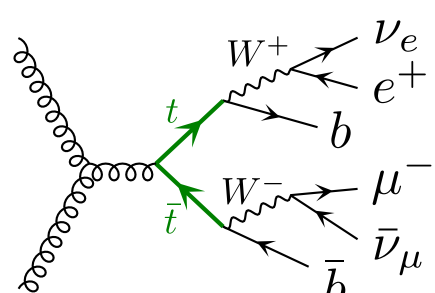
- NLO+PS generator
  - Implements resonance aware POWHEG method
  - Employs 2 resonance histories





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  - $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @ NLO QCD
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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 for each resonance)
  - `Pythia8`: "simplified" `PowhegHooks` class available
  - `Herwig7`: work in progress

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see Silvia's talk tomorrow

Generator details

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- Shower Monte Carlo
  - `Pythia8` interface available, `Herwig7` interface work in progress

- Implementation
  - Resonance aware POWHEG method: `POWHEG-BOX-RES`
  - Process implementation: `b_bbar_4l` or $b\bar{b}4l$
  - Publicly available http://powhegbox.mib.infn.it/

Results

- Study the impact of:
  - Resonance aware NLO+PS matching: by comparing different `b_bbar_4l` results [TJ, Lindert, Nason, Oleari, Pozzorini 2016]
    - **res-default**: resonance treatment switched on (`allrad`)
    - **res-off**: resonance treatment switched off
    - **res-guess**: attempt at improving **res-off** by reconstructing the resonance information just before the shower
  - Non-resonant and interference effects: by comparing against `ttb_NLO_dec` [Campbell, Elliss, Nason, Re 2014]
    - both implement resonance aware NLO+PS & `allrad`
    - `b_bbar_4l`: all diagrams for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
    - `ttb_NLO_dec`: top-pair production and decay @NLO with NWA
  - Radiative corrections in top-decays: by comparing against `hvq`
    - `hvq`: top-pair production @NLO, decay @LO, resonance aware NLO+PS matching not required (no emission from within the top resonance) [Frixione, Nason, Ridolfi 2007]

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    - hvq: top-pair production @NLO, decay @LO, resonance aware NLO+PS matching not required (no emission from within the top resonance) [Frixione, Nason, Ridolfi 2007]

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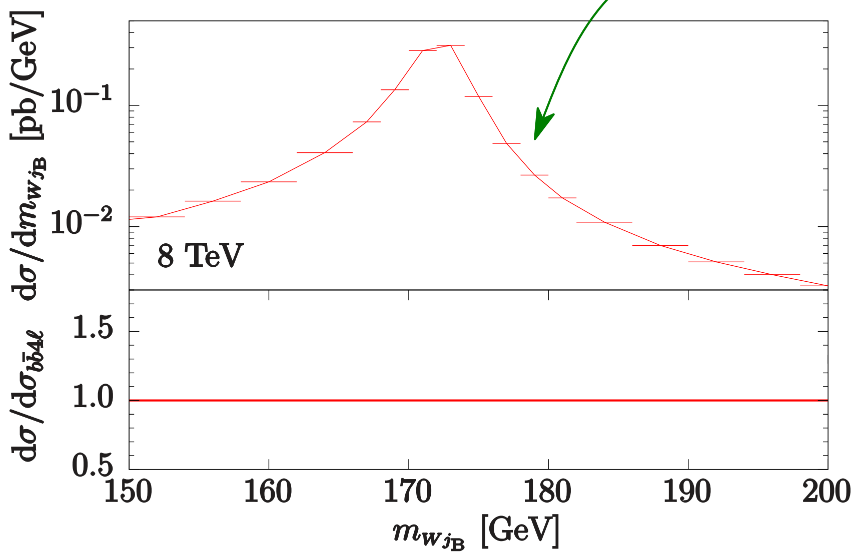
    - `ttb_NLO_dec`: top-pair production and decay @NLO with NWA
  - Radiative corrections in top-decays: by comparing against hvq
    - hvq: top-pair production @NLO, decay @LO, resonance aware NLO+PS matching not required (no emission from within the top resonance) [Frixione, Nason, Ridolfi 2007]

Impact of "resonance awareness"

- $W j_B$ mass
  - res-default legend line — **res-default**: resonance aware NLO+PS, `allrad` scheme

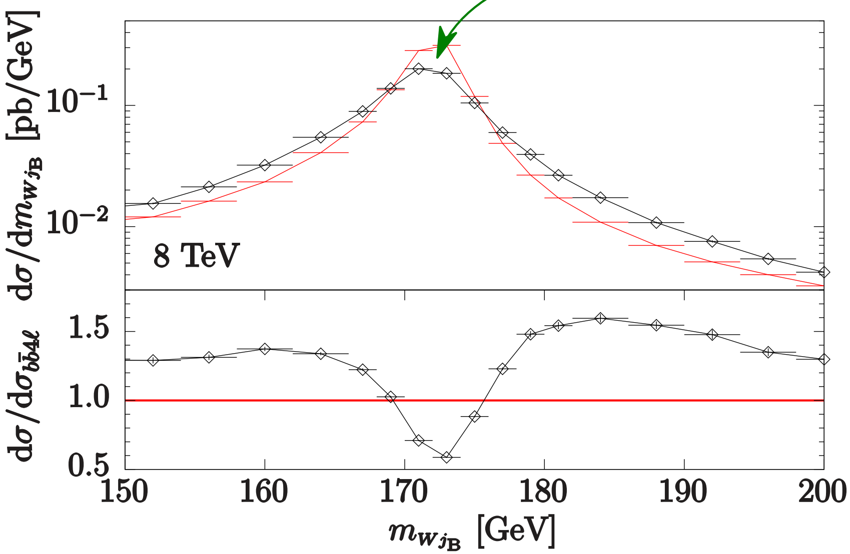
our best prediction



Impact of "resonance awareness"

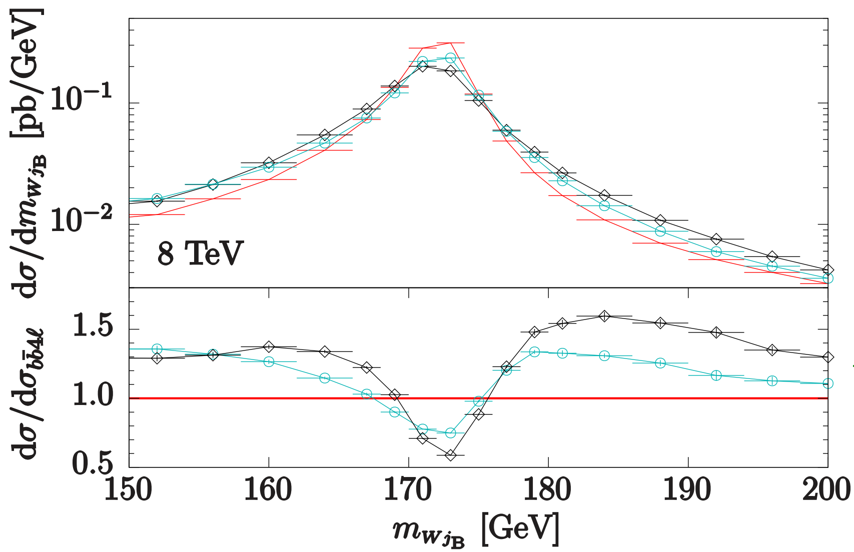
- $W j_B$ mass
  - **res-default**: resonance aware NLO+PS, `allrad` scheme
  - **res-off**: resonance aware NLO+PS switched off

considerably wider peak



Impact of "resonance awareness"

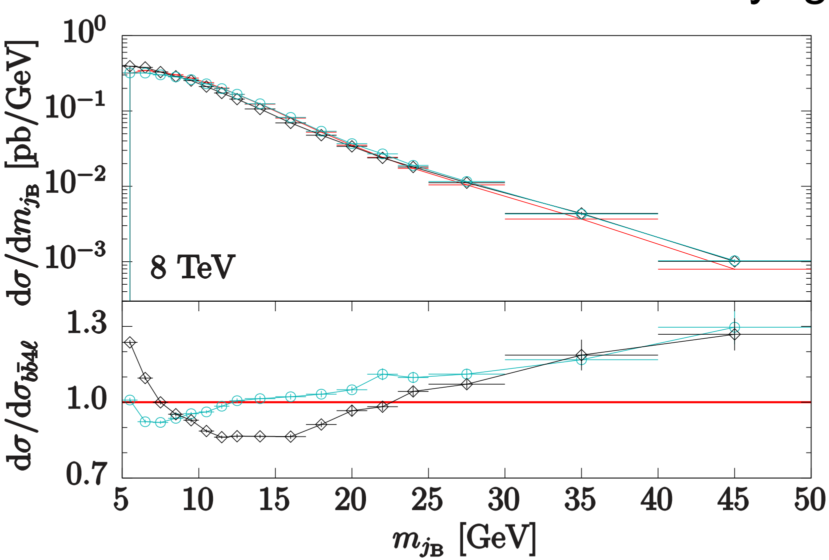
- Wj_B mass
  - **res-default**: resonance aware NLO+PS, `allrad` scheme
  - **res-off**: resonance aware NLO+PS switched off
  - **res-guess**: resonance aware NLO+PS swtched off, resonance history "guessed" before showering

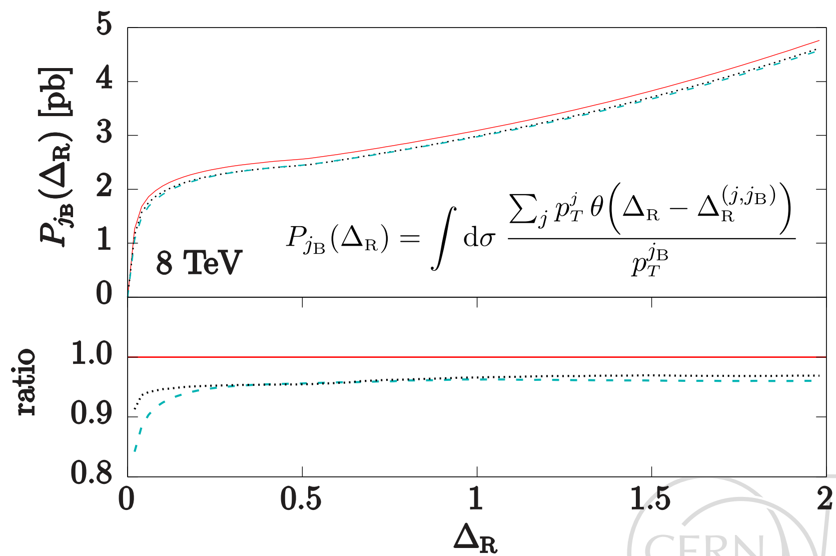


guessing the resonance history does not help

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 swtched 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 swtched off, resonance history "guessed" before showering

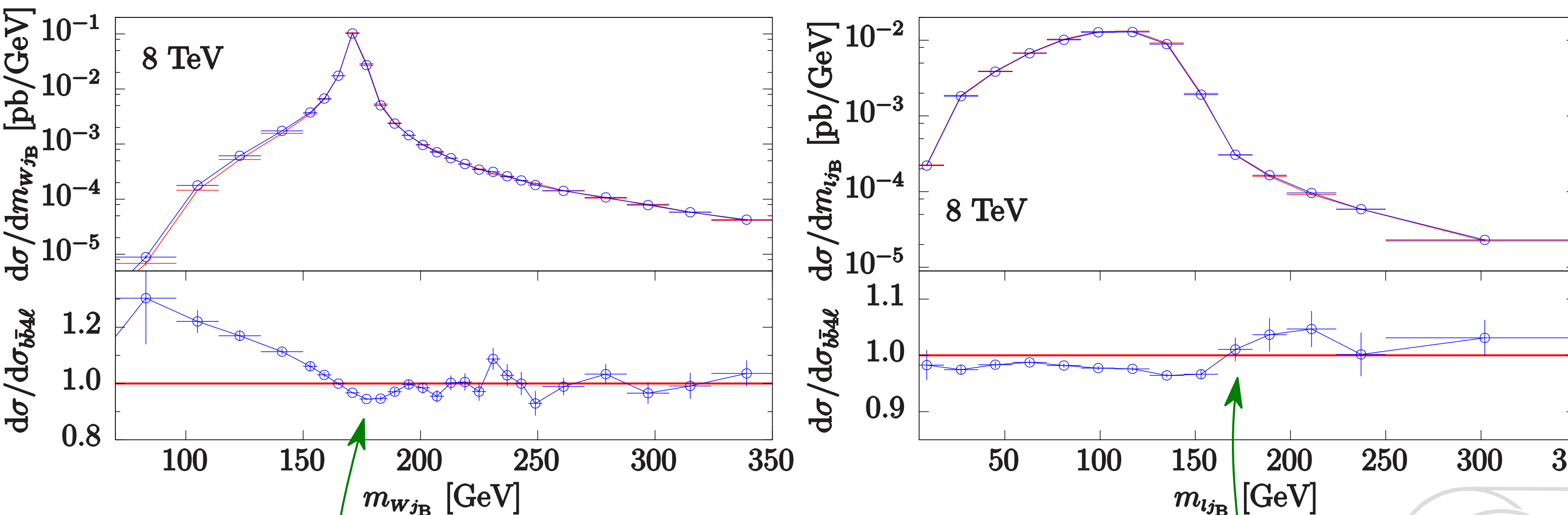
- In conclusion, the resonance aware NLO+PS ...
  - yields a narrower peak for the reconstructed top distribution;
  - predicts more hadronic activity aroudn the B hadron;
  - offers a considerable speed up both in the integration and event generation (not discussed in this talk, please ask).

- Moreover, the traditional approach ...
  - cannot be fixed by reconstructing the resonance history of the event after the hardest emission has already been generated.

Non-resonant and interference effects

UZH

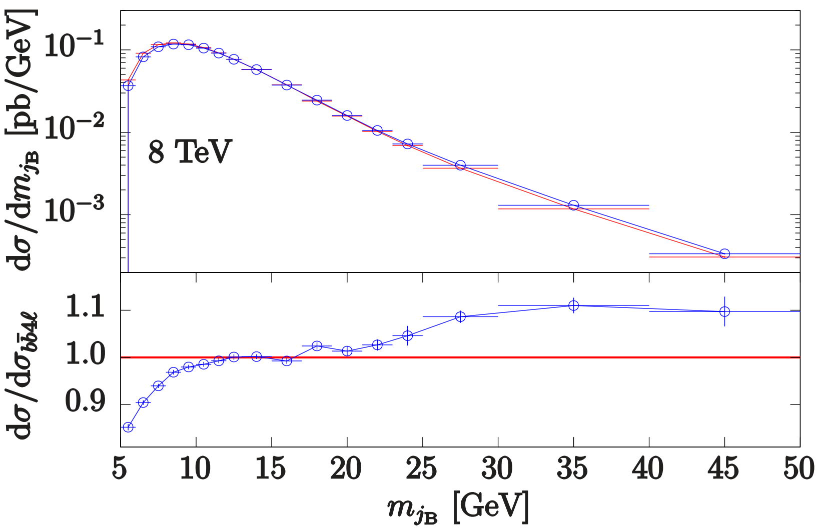
- Wj_B and lj_B mass
  - `b_bbar_4l`: all diagrams for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
  - `ttb_NLO_dec`: top-pair prod. and decay @NLO with NWA
  - both: resonance aware NLO+PS, `allrad` scheme

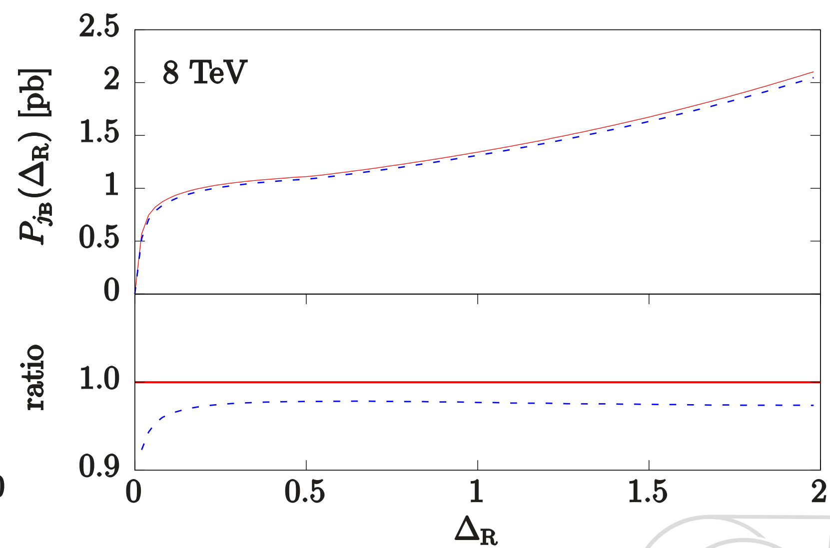


we observe a remarkable agreement

Non-resonant and interference effects

- j_B mass and profile
  - b_bbar_4l: all diagrams for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$
  - ttb_NLO_dec: top-pair prod. and decay @NLO with NWA
  - both: resonance aware NLO+PS, allrad scheme

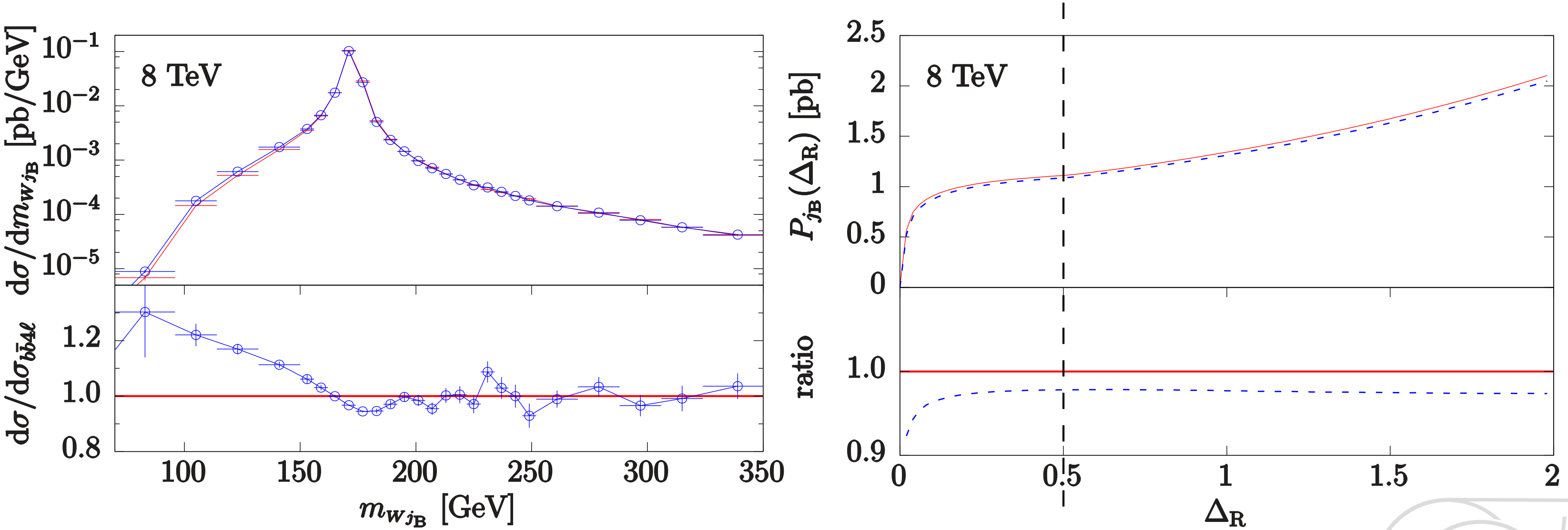




b_bbar_4l yields slightly wider b jets

Non-resonant and interference effects

- Wj_B mass and j_B profile
  - b_bbar_4l: all diagrams for $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$
  - ttb_NLO_dec: top-pair prod. and decay @NLO with NWA
  - both: resonance aware NLO+PS, allrad scheme



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

Non-resonant and interference effects

- Summary
  - `b_bbar_4l`: all diagrams for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
  - `ttb_NLO_dec`: top-pair prod. and decay @NLO with NWA
  - both: resonance aware NLO+PS, `allrad` scheme

- In conclusion, the non-resonant and interference effects...
  - can lead to a considerably different b jet structure;
  - but do not seem relevant for the reconstructed top mass spectrum for usual values of Δ_R.

- Also ...
  - matrix elements in `ttb_NLO_dec` much less computationally costly to evaluate;
  - hadronic W decays unfeasible unless using NWA.

Non-resonant and interference effects

- Summary
  - `b_bbar_4l`: all diagrams for $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
  - `ttb_NLO_dec`: top-pair prod. and decay @NLO with NWA
  - both: resonance aware NLO+PS, `allrad` scheme

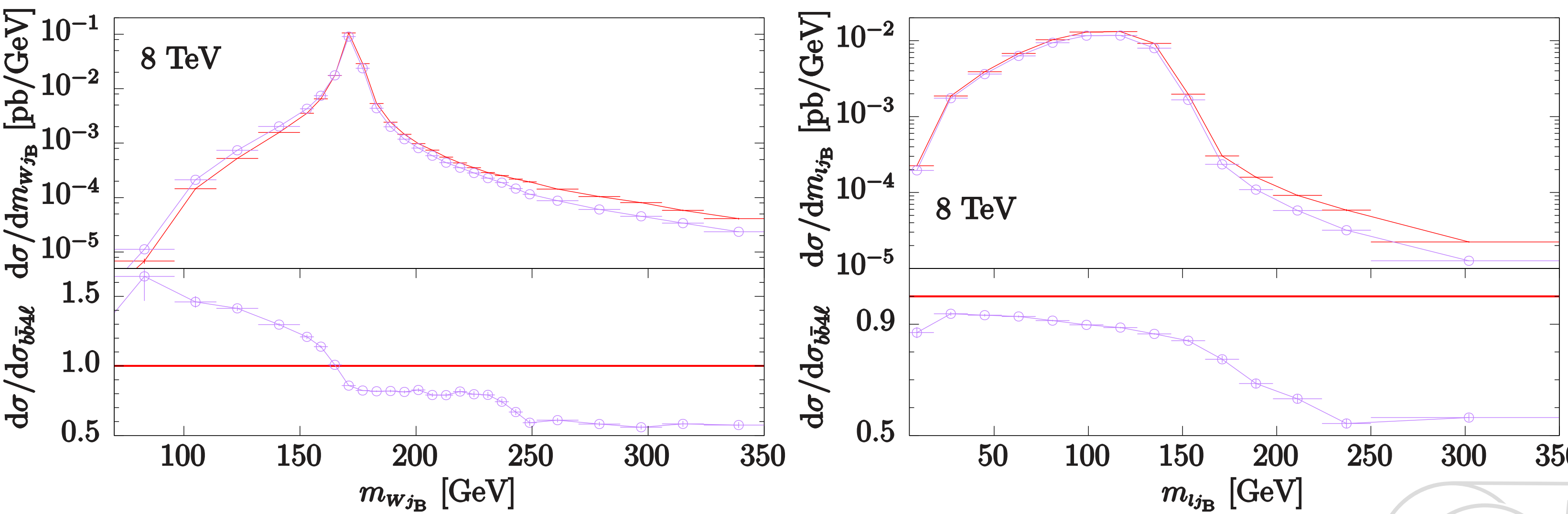
- In conclusion, the non-resonant and interference effects...
  - can lead to a considerably different b jet structure;
  - but do not seem relevant for the reconstructed top mass spectrum for usual values of Δ_R.

more in Silvia's talk tomorrow

- Also ...
  - matrix elements in `ttb_NLO_dec` much less computationally costly to evaluate;
  - hadronic W decays unfeasible unless using NWA.

Impact of radiative corrections in top decays

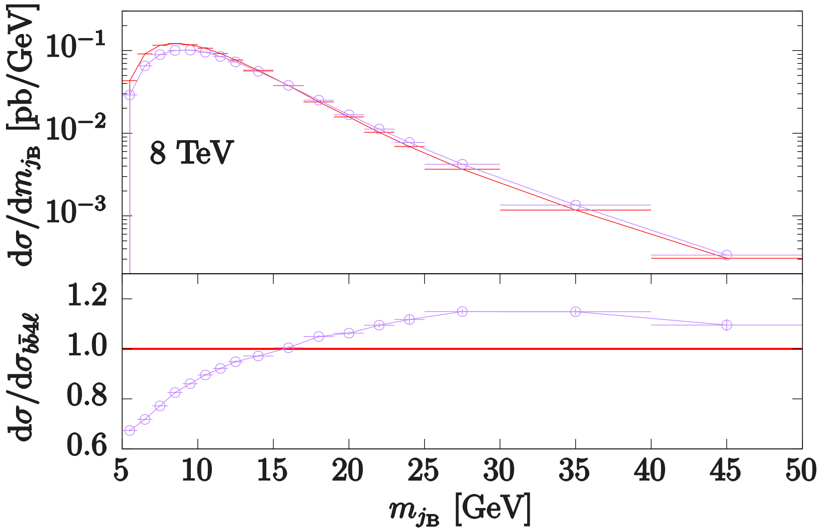
- Wj_B and lj_B mass
  - b_bbar_4l: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @NLO, allrad scheme
  - hvq: top-pair production @NLO, decay @LO

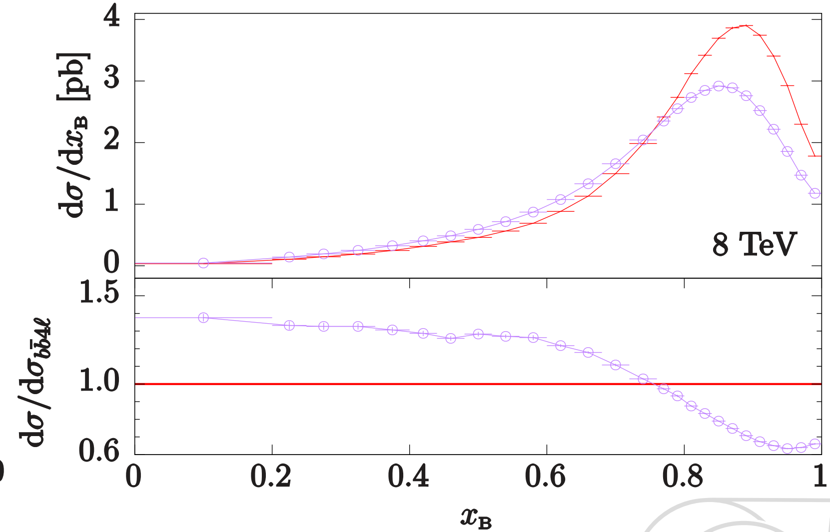


we observe drastic differences, even a shift in the reconstructed top mass peak

Impact of radiative corrections in top decays

- j_B mass and B fragmentation function
  - b_bbar_4l: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @NLO, allrad scheme
  - hvq: top-pair production @NLO, decay @LO



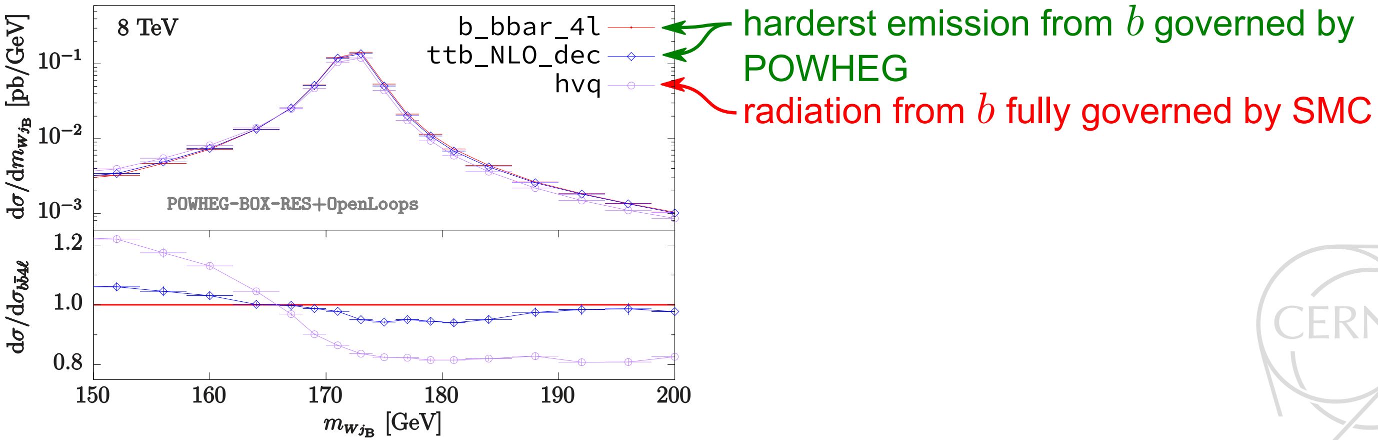


hvq predicts narrower b jets and softer B fragmentation function

Impact of radiative corrections in top decays

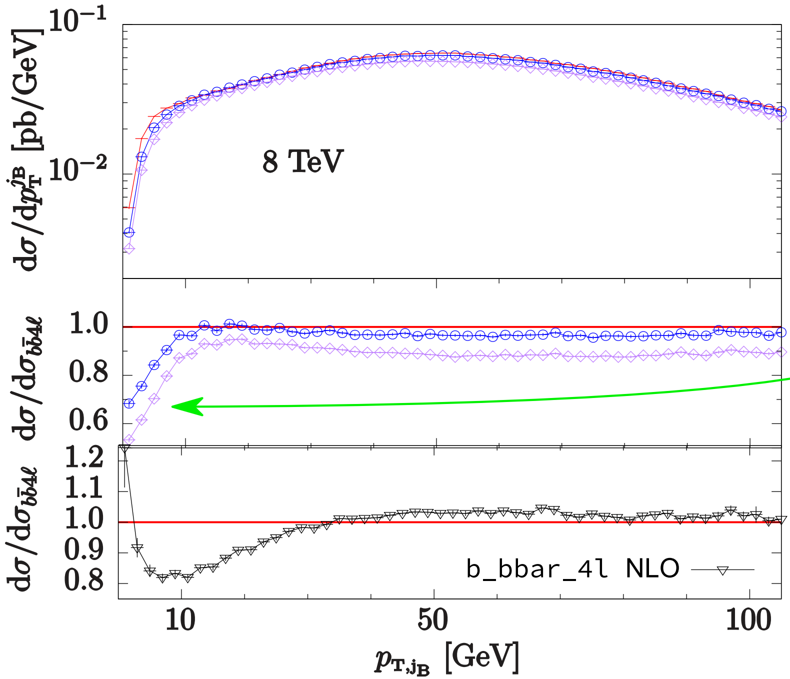
- Summary
  - b_bbar_4l: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ @NLO, allrad scheme
  - hvq: top-pair production @NLO, decay @LO

- In conclusion, radiative corrections in top decays have dramatic impact both on ...
  - b jet related observables;
  - and observables constructed from b jets.



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

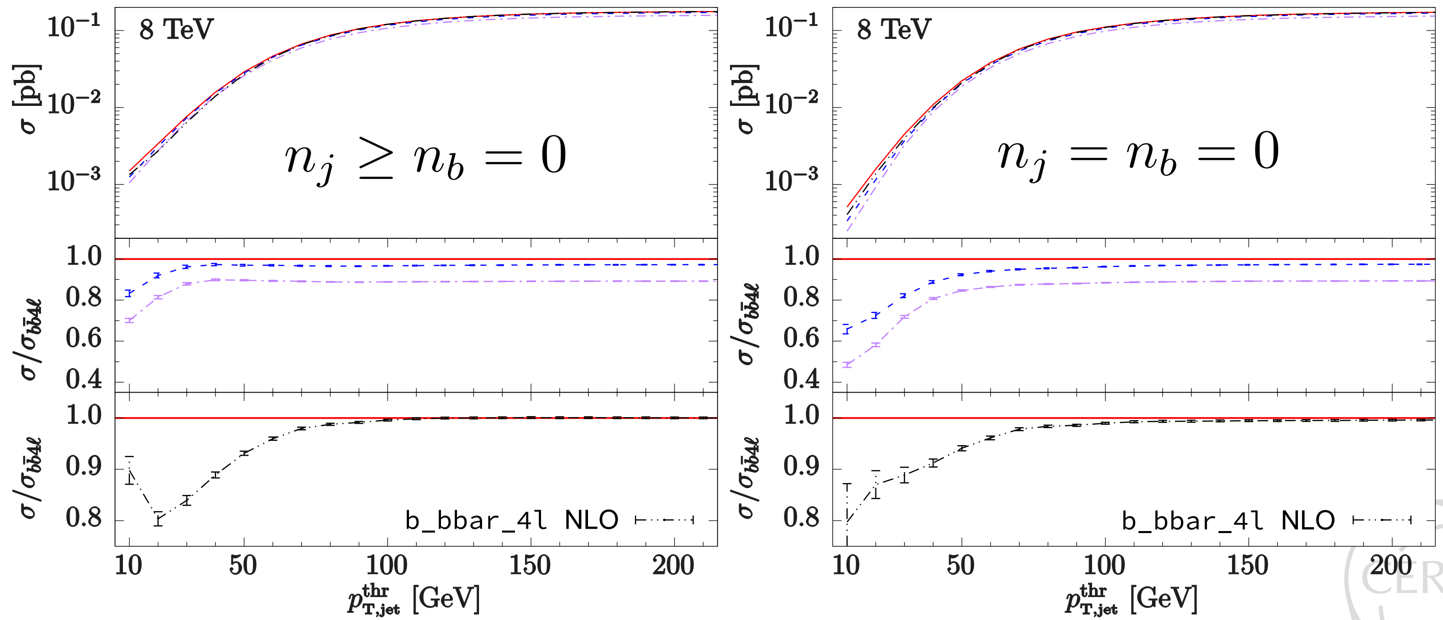


10% difference due to missing Wt contribution in hvq

Wt more important at small p_{T,j_B}

Jet vetoes and Wt contribution

- $\sigma = f(p_{T,\mathrm{jet}}^{\mathrm{thr}})$
  - b_bbar_4l: exact Wt
  - ttb_NLO_dec: Wt included via LO reweighting
  - hvq: no Wt



Jet vetoes and Wt contribution

- $\sigma = f(p_{T,\mathrm{jet}}^{\mathrm{thr}})$
  - b_bbar_4l: exact Wt
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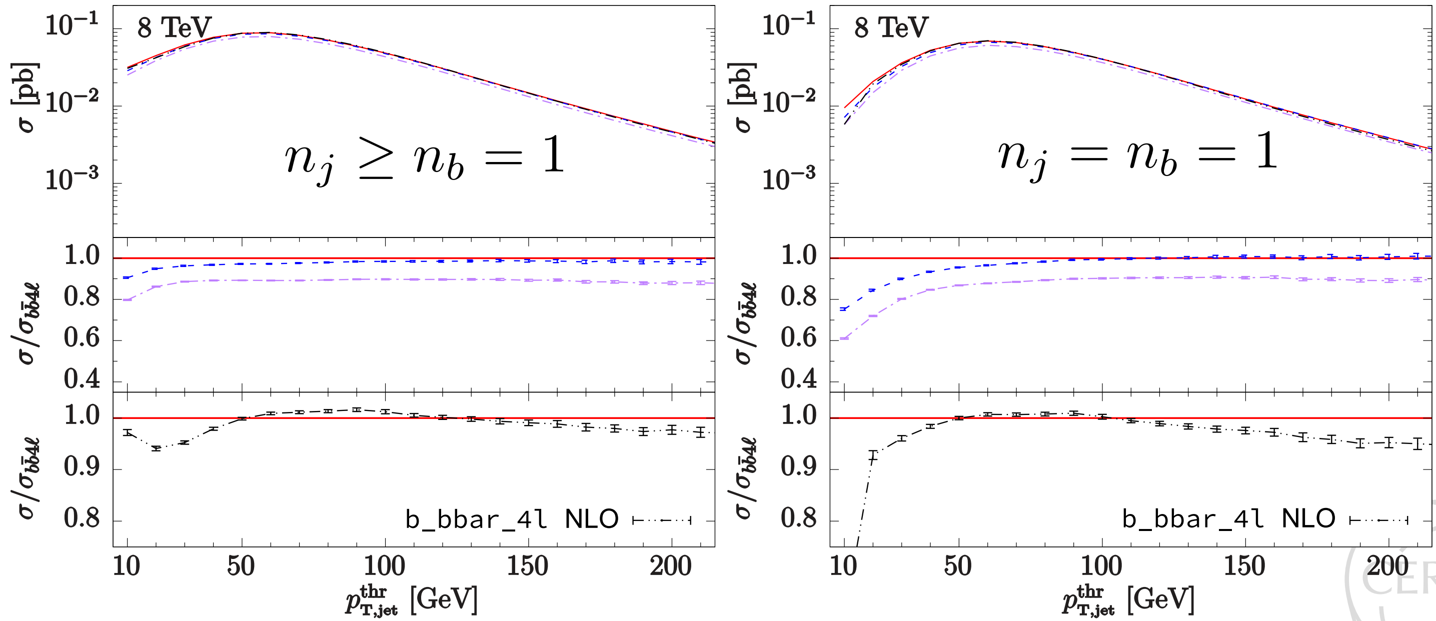

Jet vetoes and Wt contribution

- 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`.

Summary and Outlook

- `POWHEG BOX RES` implements a new resonance aware NLO+PS matching TJ, Nason 2015]
  - Born/real on-shelness mismatch solved
  - Studies of processes with intermediate radiating resonances feasible
  - So far: single-top t-channel 5FS, and top-pair & tW 4FS

- $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ 4FS [TJ, Lindert, Nason, Oleari, Pozzorini 2016]
  - Unified description of top-pair and tW production
    - Impact of the resonance treatment significant
    - Non-resonant and inteference effects important, but probably not relevant for top mass measurements
    - Impact of radiative corrections in top decays dramatic

- Systematic study of the impact of these effects on the top mass measurement well motivated
  - First results in the talk of Silvia Ferrario Ravasio tomorrow