# Heavy Flavour treatment in POWHEG

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# Outline

- Heavy quarks in massless approximation
- Heavy quark in massive approach
- $b$ quarks in top decay

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In jet production (`dijet`, `trijet`, Zj, Wj, Hjj, etc.):
$c$ and $b$ quarks always included in the massless approximation.

Mass effects accounted for in an approximate way.
Powheg cross section:

$$\begin{aligned} \mathrm{d}\sigma &= \bar{B}(\Phi_\mathrm{B})\left(\Delta(t_0) + \theta(t-t_0)\Delta(t)\frac{R(\Phi_\mathrm{B},\Phi_\mathrm{rad})}{B(\Phi_\mathrm{B})}\mathrm{d}\Phi_\mathrm{rad}\right)\mathrm{d}\Phi_\mathrm{B} \\ \bar{B}(\Phi_\mathrm{B}) &= B(\Phi_\mathrm{B}) + V(\Phi_\mathrm{B}) + \int R(\Phi_\mathrm{B},\Phi_\mathrm{rad})\mathrm{d}\Phi_\mathrm{rad} \\ \Delta(t) &= \exp\left[-\int_{t'>t}\frac{R(\Phi_\mathrm{B},\Phi'_\mathrm{rad})}{B(\Phi_\mathrm{B})}\mathrm{d}\Phi'_\mathrm{rad}\right] \qquad (1) \end{aligned}$$

- $\bar{B}$: $m_b, m_c = 0$;
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Controlled by `powheg.input` parameters:

- FSR: `charmthr` and `bottomthr` control the transverse momentum limit for $g \to q\bar{q}$ splittings involving charm and bottom in the generation of radiation.
- ISR: `charmthrpdf` and `bottomthrpdf` set the transverse momentum limit for inital charm and bottom in PDF's.

These parameters affect mainly the generation of radiation:

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No studies were ever performed to check for problems or sensitivity to these parameter.

- Much room for variation:
  - we may limit also scales in $c/b \to c/b + g$
  - we may use a smooth suppression instead of a sharp cut at threshold.
- Not much sensitivity expected from variations: `POWHEG` generates only the hardest radiation (transverse momenta down to heavy quark masses are Sudakov suppressed). Low scale splittings are more likely to take place in the subsequent shower.
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# Heavy quarks with full mass dependence

In `POWHEG` the real cross section is separated into contributions that are singular only in one region. For example, in the `Zj` generator, (real emission: $Z$ plus two light partons), we have

$$R = R_{\rm ISR} + R_{\rm FSR}$$

where

- $R_{\rm ISR}$ is singular when the transverse momentum (with respect to the beam) of a final state parton vanishes;
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Early POWHEG generator: hvq (2007) for $c$, $b$ and $t$.

Heavy quarks treated as heavy: no collinear singularities from heavy quark emissions were considered.
Only one singular region: $R_{\mathrm{ISR}}$.

In 2012: alternative treatment of radiation from heavy fermions (hvqaslight option), introduced in the framework of $W$ production with electroweak corrections (W_ew-BMNNP).
A phase space mapping appropriate to massive fermions was introduced, in order to separate out also a region $R_{\mathrm{FSR}\,q}$ for each massive quark $q$ that can radiate gluons.

In $R_{\mathrm{FSR}\,q}$ there is no true singularity in the collinear limit, since the mass of the quark acts as a collinear cutoff, but for large transverse momentum $R_{\mathrm{FSR}\,q}$ does become large in the collinear limit.

Used by default in Wbb_dec and Wbbj.

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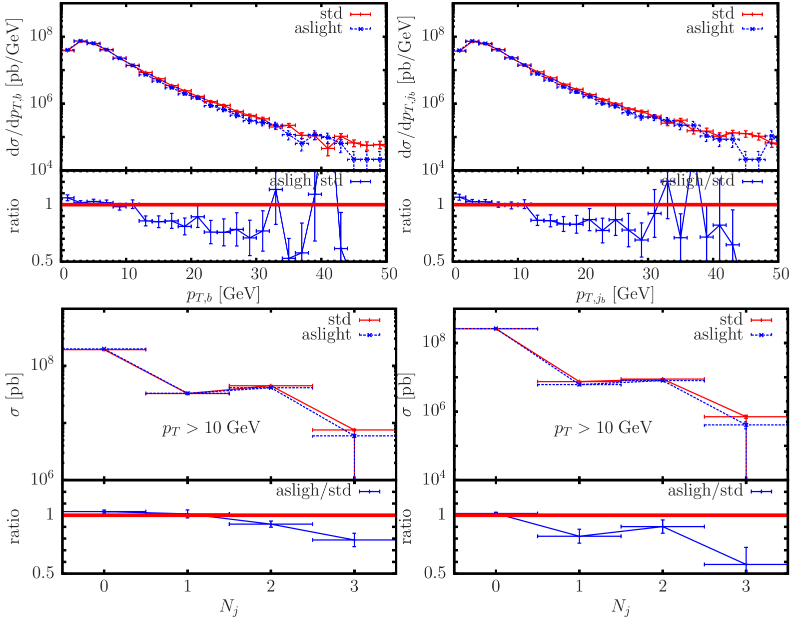
# Study of impact in hvq generator (unpublished)



# Heavy quarks in massless approximation

Interpretation of the result:

- When generating radiation in the "std" approach, the coupling scale is set to the transverse momentum relative to the beam.
- When generating radiation in the `hvqaslight` approach, for radiation near the heavy flavours, the coupling scale is set to the transverse momentum relative to the heavy flavour.
- More degradation of momentum, due to enhanced near collinear radiation, in the `hvqaslight` approach.
- Less hard non-$b$ jets in the `hvqaslight` approach.

In comparison with the large uncertainties present at NLO in bottom production these differences are minor. However, further studies and tuning may be useful.

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# Top, and bottom in top decays

POWHEG $t\bar{t}$ generators with strong corrections in top decay have been available for some time:

- ttb_NLO_dec, Campbell,Ellis,Re,P.N. 2014. Uses the NLO corrections computed in the on-shell approximation (production and decay do not interfere) from MCFM. The $b$ is massive.
- RES, Ježo,Lindert,Oleari,Pozzorini,P.N., current. Uses the full matrix elements for $W^+W^-b\bar{b}$ production (including $W$ decay) from OpenLoops. Interference is fully included. The $b$ is massive.

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# Top, and bottom in top decays

- Both `ttb_NLO_dec` and `RES` treat the radiating resonances (the top, and eventually the $W$'s if they decay hadronically) in a proper way, preserving the resonance mass when near the mass shell.
- In `ttb_NLO_dec` radiation from production and from resonance decays are distinct at the matrix element level. It is straightforward to preserve the resonance masses in decay.
- In `RES`: no unambiguous separation of radiation from resonance and from decay, since interference is also present. A method for separating the real cross section into components with different resonance histories has been put forward in Ježo,P.N. 2015, and is used in `RES`. In essence, each component is associated with a specific resonance history of the production process, and becomes dominant when the kinematics is such that the corresponding resonances are near the mass shell.

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- Both `ttb_NLO_dec` and `RES` can optionally (`allrad` option) generate Les Houches events with more than one radiation: one radiation for the production process, and one for each resonance decaying into coloured particles.
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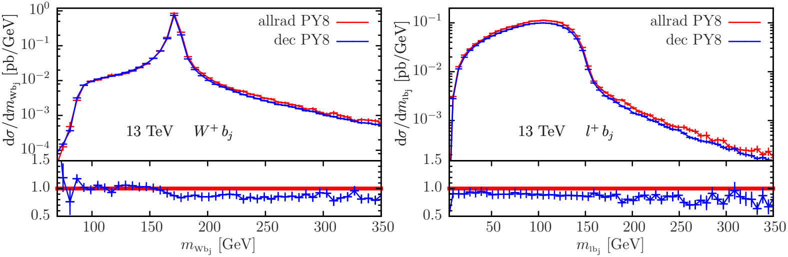
# Top, and bottom in top decays

`ttb_NLO_dec` (blue) versus `RES` (red); shower by `Pythia8`.




- Amazingly consistent for distributions involving $b$-jets.
- Top peak shape described consistently by the two generators.

Bottom radiation dynamics is similar, but:

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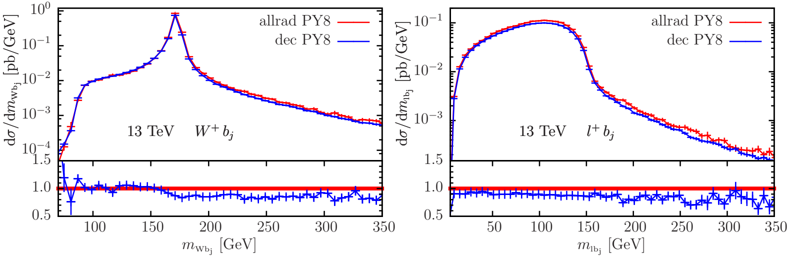


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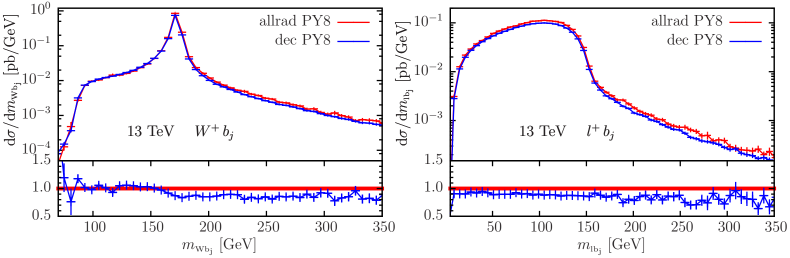


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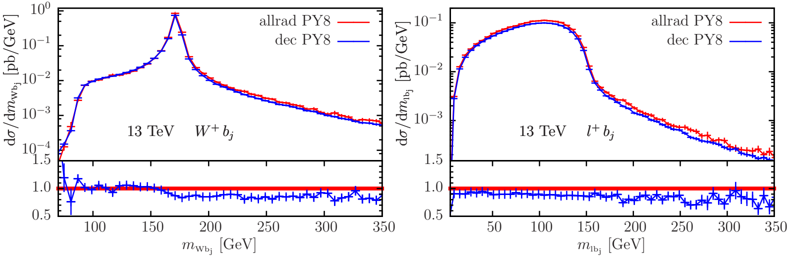


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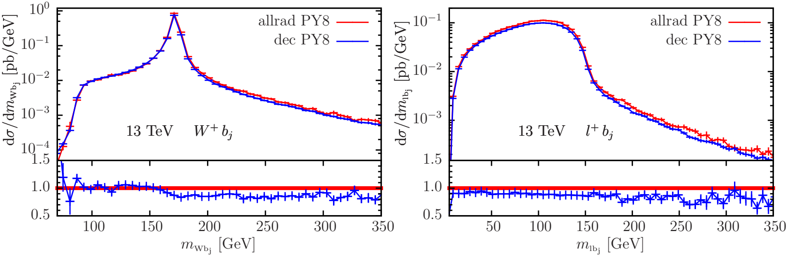


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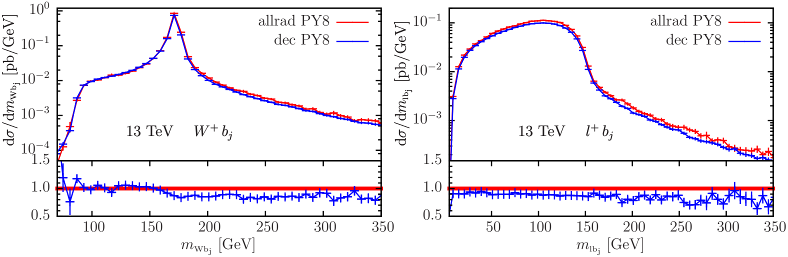


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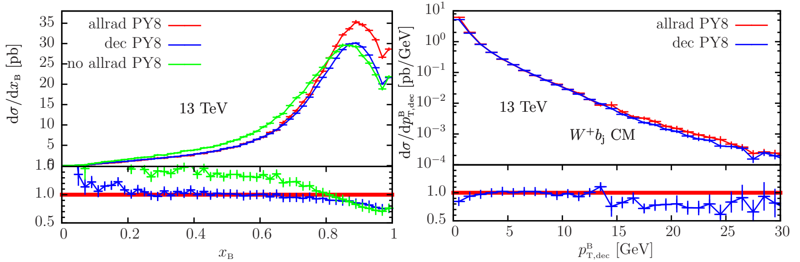
Look at bottom distributions:

- $B$ fragmentation: go to the reconstructed top rest frame, define $x_B = E_B / E_B^{\max}$
- $p_{T,\mathrm{dec}}^B$: in the reconstructed top rest frame, take $B$ momentum component orthogonal to $W$ direction.




Difference in fragmentation function seem to arise from radiation with $p_{T,\mathrm{dec}}^B$ of the order of $\Gamma_t$: interference effects?

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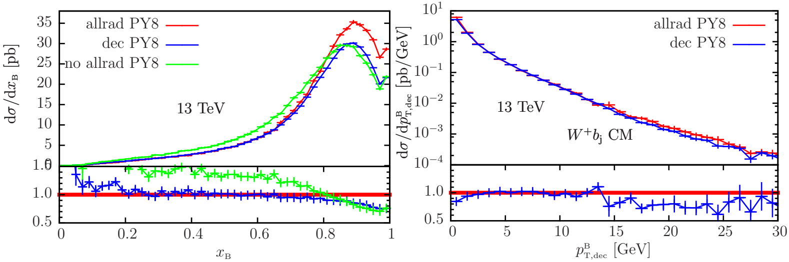


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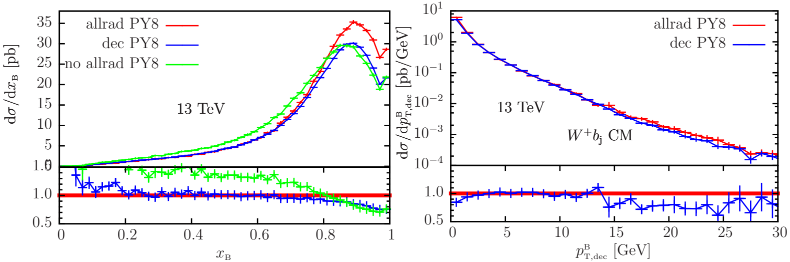


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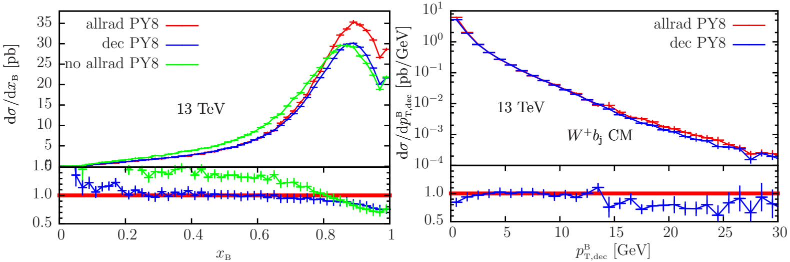


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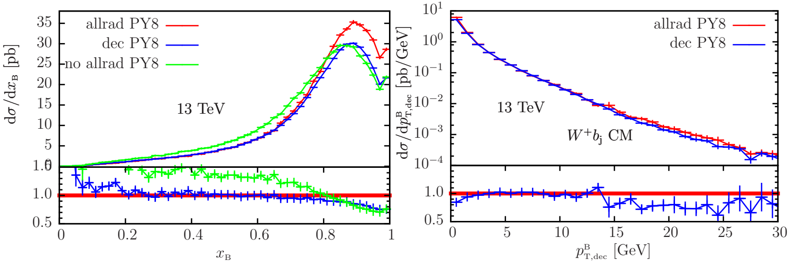


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# Conclusions

- Minimal heavy flavour treatment in standard `POWHEG` for heavy flavours in massless limit. Much room for improvement, but low priority. The Shower is more important for finite mass effects.
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