A POWHEG generator for $t\bar{t}$ production including radiation in decays

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Geneva, May 2014

Problems with radiating resonances

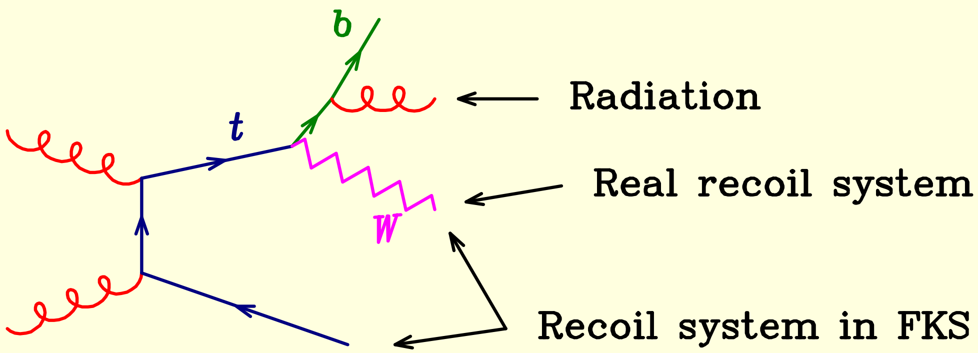
Standard POWHEG generators only distinguish initial state and final state radiation, as if it was all coming from the hard process.

If the process includes the decay of a narrow resonance, and QCD radiation can take place in the decay, this treatment is not adequate.

One needs to adopt a scheme where QCD radiation preserves the resonance mass, both in the NLO calculation and in the shower stage.

As a further problem: do we want multiplicative or additive NLO corrections to dacaying resonances?

NLO calculation with resonances



NLO subtraction counterterm in FKS scheme preserve the CM 4-momentum and the $W\bar{t}$ mass, rather than preserving the t momentum and the W mass. So: t thrown off shell.

As long as the width is finite, the subtraction works. As the width becomes smaller, the subtraction term is cut off because the t goes off shell.

With Catani-Seymour dipoles we would have no problems from a color neutral resonance decay. But in this case, the emitting dipole is $b\bar{t}$, with the $\bar{t}$ absorbing the recoil, and the $b\ \bar{t}g$ 4-momentum being preserved, rather than the t 4-momentum

Shower with resonances

Shower generators (PYTHIA, HERWIG, SHERPA, etc.) preserve the mass of decaying resonances, at least in the shower stage. If we feed a Les Houches User Process event to a shower program, we can specify the groups of partons that arise from a resonance decay. LH compliant shower generators (PYTHIA, HERWIG) will preserve their invariant mass.

However, in a standard POWHEG generated event, if the the hardest radiation comes from a decaying resonance, the resonance mass is not preserved.

The same complication shows up in MC@NLO type NLO+PS approach. In this case, MC subtraction terms from a decaying resonace should be different from the standard MC subtraction terms, if the shower program has treated correctly the radiating resonance.

Radiating resonances in POWHEG-BOX-V2

POWHEG-BOX-V2 is an enhanced version of POWHEG, with several new features that were developed in the first version to deal with particular problems have been merged consistently.

POWHEG-BOX-V2 can deal with radiation in resonance decays in the zero-width limit in a fully general way. In order to implement a process one must:

- Specify the resonance and its decay products in the user provided subprocess list. For example:
  ```
  realfl:[ 0, 0,  6, -6, 24,-24,-11, 12, 13,-14,  5, -5, 0]
  realrs:[ 0, 0,  0,  0,  3,  4,  5,  5,  6,  6,  3,  4, 3]
  ```
  represents a real graph for $gg \to (t \to (W \to \bar{e}\nu)\, b\, g)(\bar{t} \to (W^- \to \mu\bar{\nu}))$.
- Virtual corrections should include virtual corrections to resonance decays.
- Real correction should yield separately the radiation from the hard interaction (if the radiated parton does not belong to a resonance), and the radiation from each decaying resonance, depending upon realrs[n]

Notice:

- As usual in the POWHEG BOX, the phase space (preserving resonance masses, if needed), the real counterterms, the collinear remnants and the soft corrections are generated automatically. Only the Born phase space, the process lists and the matrix elements need to be provided by the authors.

- In the zero-width limit, the resonances contribution to the radiative corrections can be separated in a gauge invariant way

- When feeding the event to a shower, care must be taken now to veto radiation in resonances, if needed. The LHEF format does not contemplate this possibility. On the other hand, in PYTHIA8 a simple scheme for vetoing resonances is provided. In PYTHIA and HERWIG, one should instead trace radiation in shower events, and discard those that violate the veto.

Implementation in $t\bar{t}$ production

(Campbell,Ellis,Re,P.N.)

Matrix elements from Campbell,Ellis,2012. Resonance decay machinery from `POWHEG BOX V2`.

Further improvements:

- Finite width effects
- Multiplicative vs. additive corrections to resonance decays.

Finite width effects

In certain applications (for example, t mass measurement from end-points) the finite width of the top may have an effect. We implement it in the following way:

- We generate the Born phase space with finite width for the t and $\bar{t}$
- We project the Born finite width phase space onto a zero width phase space with a top mass equal to the average top virtuality. The projection conserves the total CM partonic momentum.
- Matrix elements are computed with the projected phase space.
- Real emission events are projected backward into real emission events initiated by the original (off-shell top) kinematics.
- The final cross section is reweighted either with
  - $\rightarrow$ The exact Born matrix elements for the production of the given final state after decay (from MadGraph), (including interference effects) divided by the projected on-shell matrix element
  - $\rightarrow$ The Breit Wigner shapes of the t and $\bar{t}$

Notice:

- Even far off shell, finite width and interference effects are included accurately at the LO level.
- For typical $t\bar{t}$ observables not requiring that either the t or the $\bar{t}$ are far off shell, the two reweighting schemes yield comparable results.

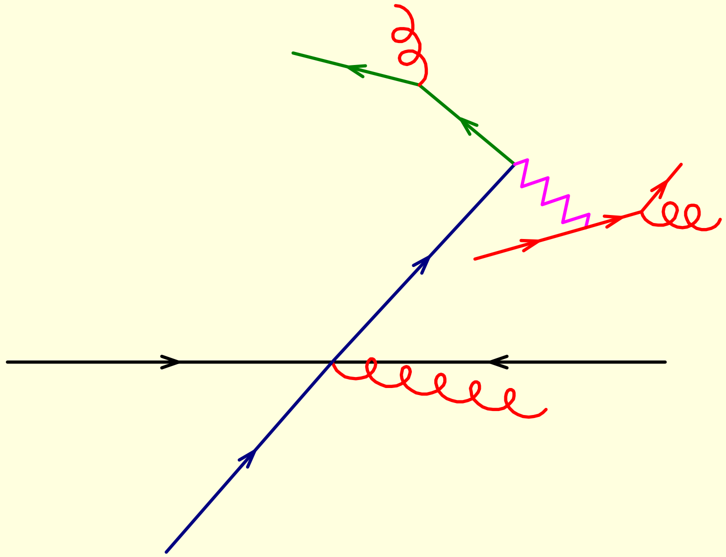
Multiplicative vs. additive corrections

In POWHEG only the hardest emission is generated. All remaining emissions are committed to the Shower generator.

In $t\bar{t}$ production we can have: a production emission, an emission from either t or $\bar{t}$, and an emission for each W decay, if applicable, for a total of 5 emissions. In POWHEG each emission is tried, and only the hardest one is kept. All the remaining one have to be generated by the shower.

Undesirable feature: the emission in hard production is more likely to have large transverse momentum. Emissions from decay become thus rare, and most of the time they will be handled by the shower.
It would of course be more desirable to have an emission from the hard production, plus one for each decaying resonance.

This is in fact implemented: the hard radiation and the emissions from all decaying resonances are kept, and are merged into a single radiation phase space with several radiated partons, up to one for each resonance.



From a given underlying Born configuration (take away the radiated gluons), in the longitudinal rest frame of the $t\bar{t}$ system:
ISR: transverse boost of the whole $t\bar{t}$ system
t radiation in decay: W boosted along its momentum in t rest frame
W radiation in decay: either q or $\bar{q}$ direction preserved. In order to combine all of them:

- Start from Born phase space, including W radiation in decay if present.
- If t radiation in decay is present, add the corresponding gluon, and replace the b and W momentum (boosting the W system along its momentum in the t rest frame)
- If ISR is present, perform transverse boost of $t\bar{t}$ system and add the gluon

This prescription guarantees that

- The hardest radiation is generated with full NLO accuracy, and the subsequent ones are at least accurate in the collinear limit
- Rotationally invariant shape observables for the resonance decays are all NLO accurate.

Some plots

We have generated LH events for leptonic top decays (e^+, μ^-), with radiation in decays not included (LO Dec) and included (NLO Dec).

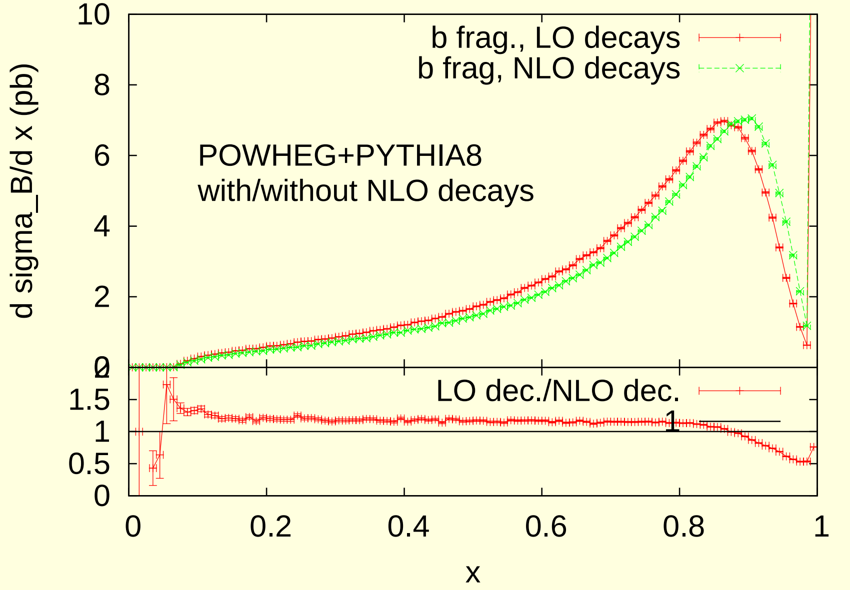
The events of the LO Dec sample were fed to `Pythia8`, with no further action. Pythia8 takes care of adding radiation in top decays.
The events of the NLO Dec sample were fed to `Pythia8`. Care was taken to compute the transverse momentum of radiation in top decays (in the top rest frame) and instruct `Pythia8` to veto radiation in resonance decays (using `canSetResonanceScale` and `scaleResonance` in `UserHooks` class)

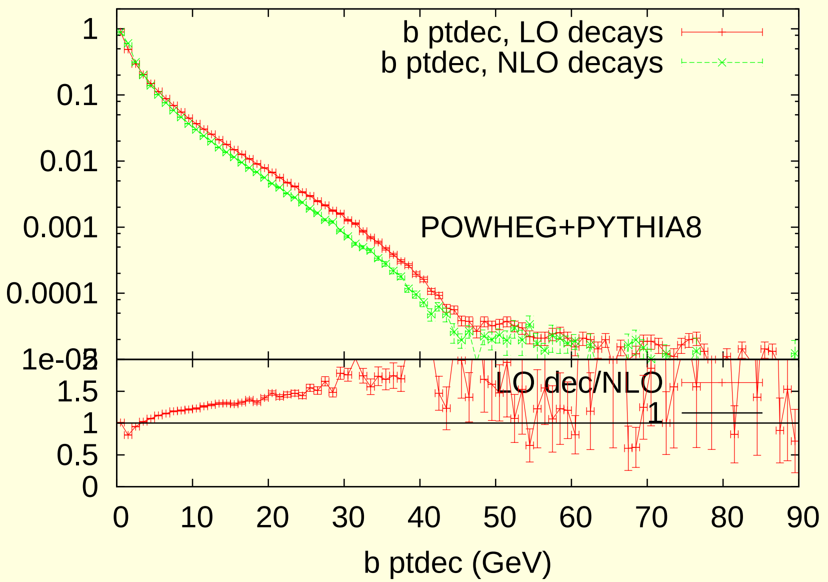
In the following plots:

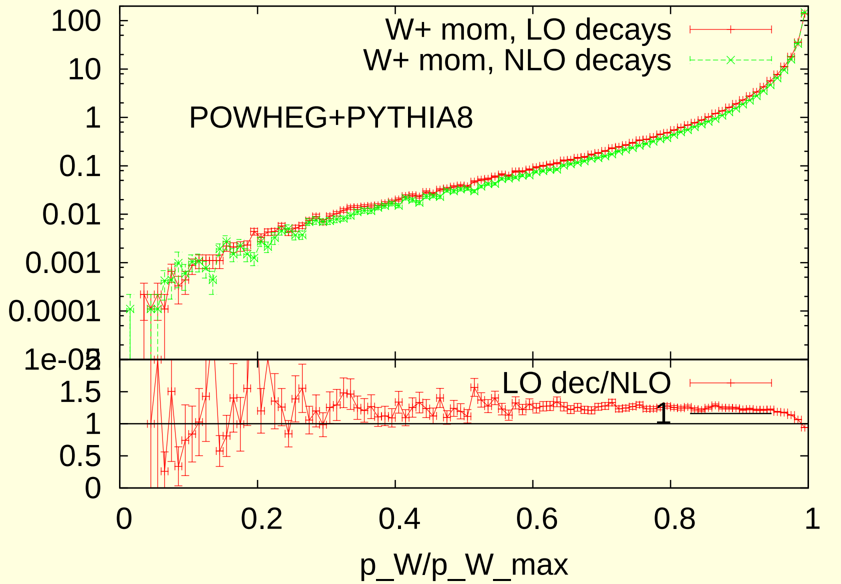
- b stands for the hardest b flavoured hadron (not $\bar{b}$!)
- W^+ stands for the MC truth (last in hep block) W^+
- l^+ stands for fermion coming from $t \to W^+ \to l^+$ (MC truth)
- $b\,\mathrm{jet}$ stands for anti-kt $b\,\mathrm{jet}$ $(R = 0.5)$

b fragmentation properties in t decays

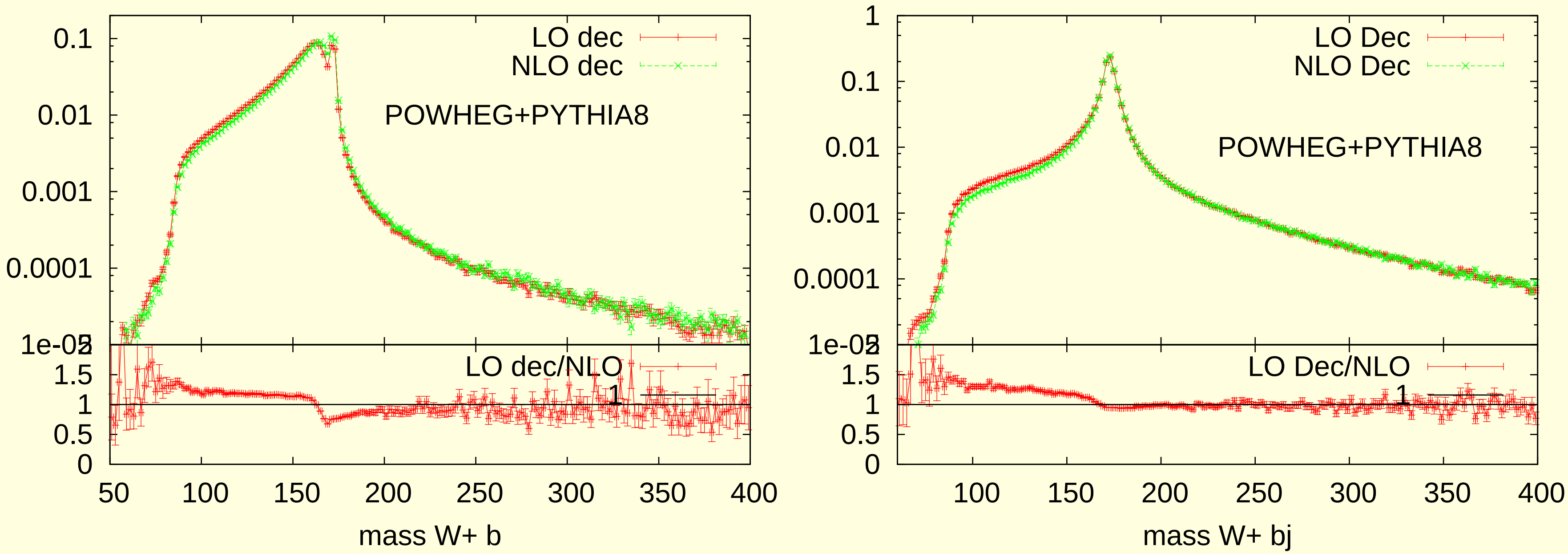
Observables computed in t rest frame.
b stands for hardest b flavoured hadron



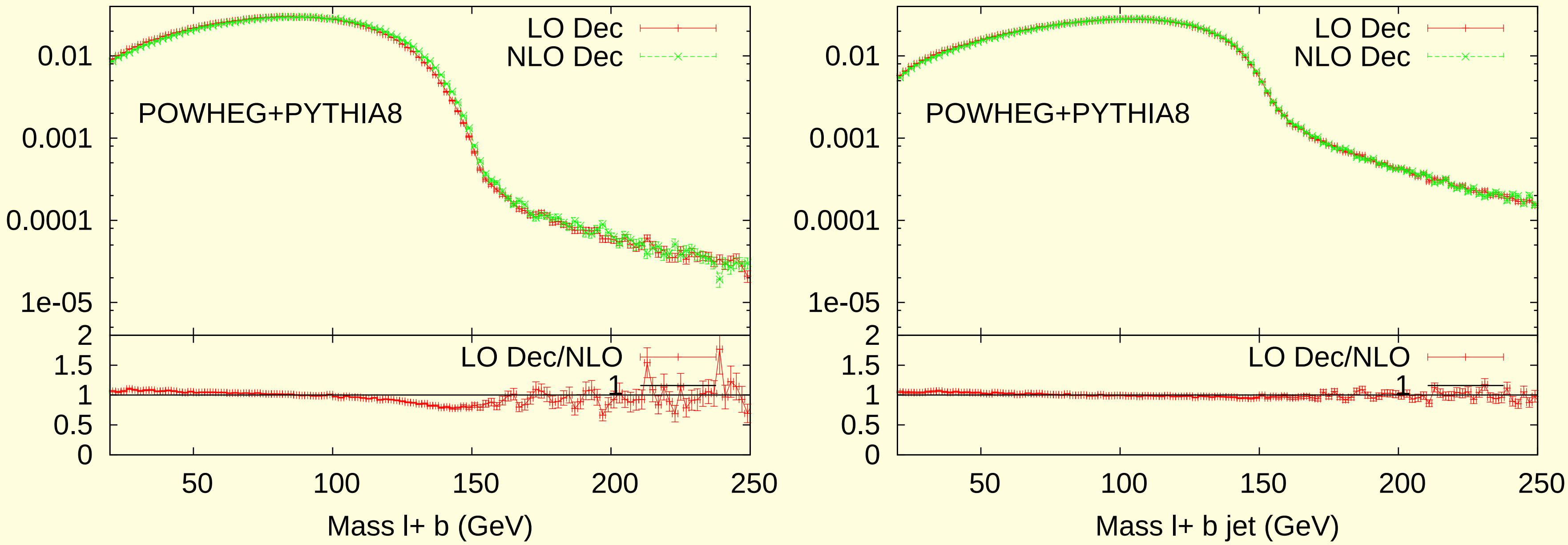




t mass pseudo observables



Notice small peak in W^+b plot, due to $x=1$ peak in b fragmentation function.



Effect of different fragmentation behaviour shows up in M_{l+b}, but not in $M_{l+b\,\mathrm{jet}}$.