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Decay matrix element corrections in MC@NLO-type simulations with Pythia8

Based on: 2308.06389 (Amoroso, SF, Mrenna)

CERN, 30/11/2023

Bear in mind that:

- I'll talk about tops, but the general arguments apply to any process that features heavy unstable resonances, for which the narrow-width approximation is well defined
- The exercise has been done with Pythia8, but there is no reason why other MCs couldn't do the same (it's mostly an implementation issue)

Top cross sections are affected by large uncertainties

- MC predictivity is increased by means of (N)NLO matching and merging. However, these only go so far
- Fitting "low-energy" parameters (tuning) is a phenomenologically viable procedure. Hard to control (for theorists), with significant differences between different simulations
- Other perturbative effects (chiefly, production spin correlations and MEC) must be included as well, *if relevant*

[

an aside

- I won't say anything about tuning, except for this: we'll have a much more clear picture of what's going on once all simulations will be dealt with consistently. Namely: have tunes specific to each and every (N)NLO-matched or -merged simulation employed

- I won't say anything about production spin correlations – we all agree on how to simulate those

]

From the viewpoint of an NLO-matched simulation, this:

$$pp \longrightarrow b\bar{\ell}_i\nu_i\bar{b}\ell_j\bar{\nu}_j \tag{1}$$

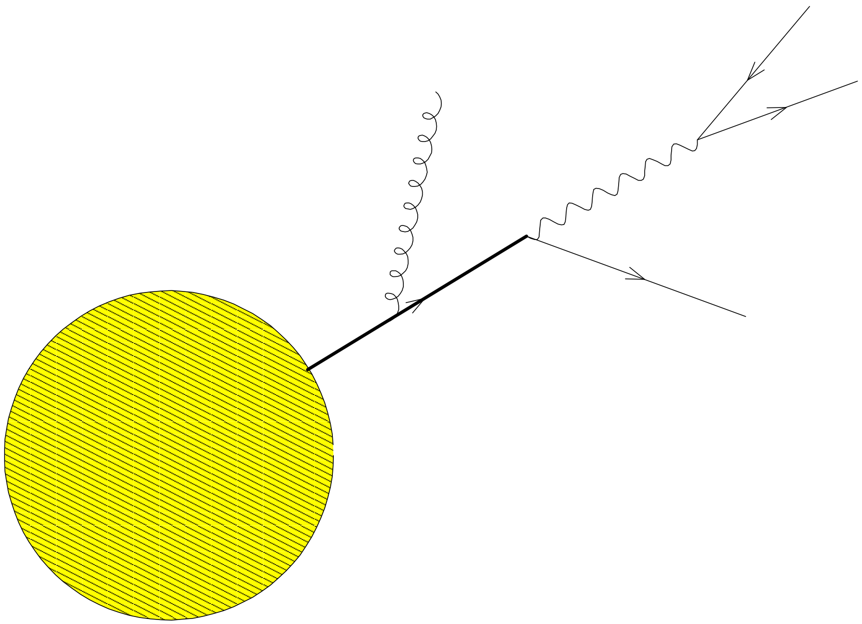
is *not* equivalent to this:

$$pp \longrightarrow t\bar{t} \oplus t \longrightarrow b\bar{\ell}_i\nu_i \oplus \bar{t} \longrightarrow \bar{b}\ell_j\bar{\nu}_j \tag{2}$$

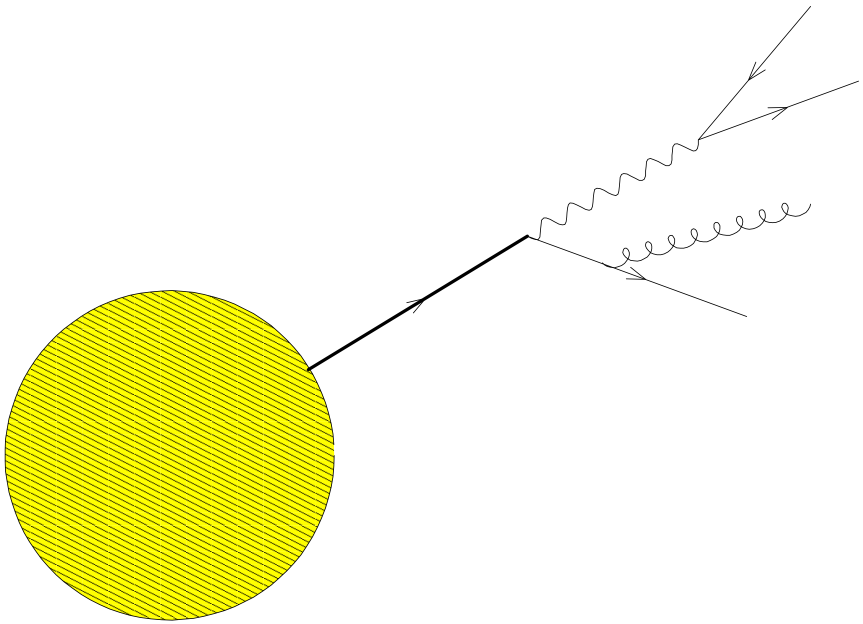
even in the regions dominated by doubly-resonant configurations

Specifically, only (1) automatically includes both production spin correlations and *all* hard recoils

The focus here is (2), which accounts for the vast majority of $t\bar{t}$ LHC simulations. Henceforth, (1) will be ignored



recoil in production



recoil in decay

- Recoil in production is always included in NLO-matched simulations; recoil in decay never is
- (approximated) Recoil in production is included in ISR+FSR MEC by MCs, while (approximated) recoil in decay is included in FSR MEC

Bottom line:

- NLO matching plus MEC generally features double counting

  (of emissions from the hard process)

- This is an issue for MC@NLO (counts powers of α_S), not for POWHEG

  (orders in hardness)

- Decay MEC are phenomenologically important

Since double counting must be avoided, MC@NLO-type simulations switch all MEC off, while POWHEG-type ones do not, thus resulting in potentially large differences *within the same formal accuracy*

Solution for MCs which are MC@NLO-matched:

In FSR, separate production and decay MEC. Turn off ISR MEC *and* FSR production MEC, *and* turn on FSR decay MEC

In the narrow width approximation, this separation typically makes sense. This does not imply that it is implemented by MCs in a streamlined manner...

Pythia8

- For FSR MEC and for a given radiating dipole, one distinguishes between exactly-matching- and equivalent-matrix-elements, the latter defined according to table 1 of hep-ph/0010012 (Norrbin & Sjöstrand)
  - Example of exactly-matching MEs: $t \to Wbg$ and $W \to q\bar{q}g$ (FSR, relevant to top decay MEC)
  - Example of equivalent MEs: $\gamma^* \to t\bar{t}g$ (FSR, relevant to $t\bar{t}$ production MEC)

- Exactly-matching and equivalent matrix elements are controlled in different manners. This allows one to turn decay MEC on and production MEC off (there are exceptions)

Pythia8 – in practice

Starting from Pythia8.219 up to the current version, one can use:

`X::MEcorrections` : If `=on`, use MEC whenever available, regardless of whether they entail the use of equivalent or exactly-matching matrix elements.

`X::MEextended` : If `=on`, use equivalent matrix elements for MEC; ignored if `X::MEcorrections=off`.

`X::MEafterFirst` : If `=on`, apply MEC also to all emissions after the first; ignored if `X::MEcorrections=off`.

where `X=SpaceShower` (ISR) or `X=TimeShower` (FSR)

Pythia8 – in practice

Old settings (all MEC are off)

```
SpaceShower:MEcorrections = off
TimeShower:MEcorrections = off
```

New settings (all MEC are off bar for decay MEC which are on)

```
SpaceShower:MEcorrections = off
TimeShower:MEcorrections = on
TimeShower:MEextended = off
```

Either value of `TimeShower::MEafterFirst` is acceptable

Results

Consider:

1. MG5_aMC+PY8 NLO with decay MEC (blue) – new default
2. MG5_aMC+PY8 NLO without decay MEC (green) – old default
3. POWHEG-BOX+PY8, with MEC (orange)
4. PY8, with MEC (red)

and show them as distribution (main frames), or as $2/1$, $3/1$, and $4/1$ ratios (lower insets)

- The parameters that control hard radiation in the various codes are *not* consistent with each other. To assess the impact of these, as alternatives to 3 and 4 also consider:

Results

Consider:

1. MG5_aMC+PY8 NLO with decay MEC (blue) – new default
2. MG5_aMC+PY8 NLO without decay MEC (green) – old default
3. MG5_aMC+PY8 LO with decay MEC (orange)
4. MG5_aMC+PY8 LO without decay MEC (red)

and show them as distribution (main frames), or as $2/1$, $3/1$, and $4/1$ ratios (lower insets)

- In all the MG5_aMC simulations, all of the parameters that control hard radiation are mutually consistent

Results

On the left panels:

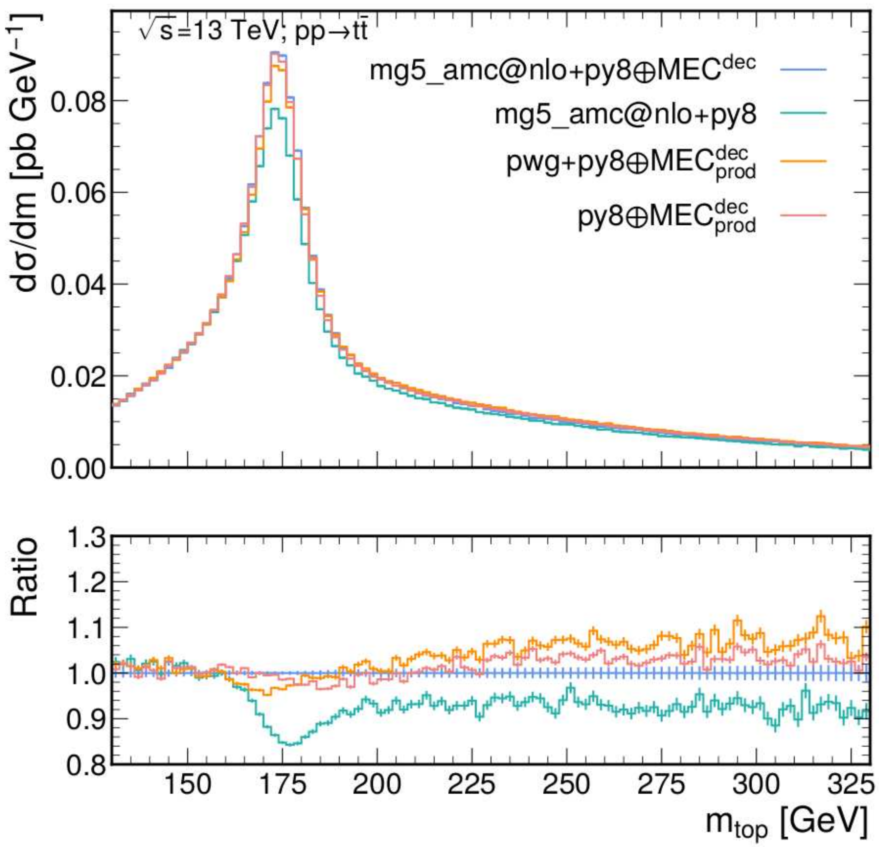
- Blue vs orange: MC@NLO- vs POWHEG-matching, new settings
- Green vs orange: MC@NLO- vs POWHEG-matching, old settings

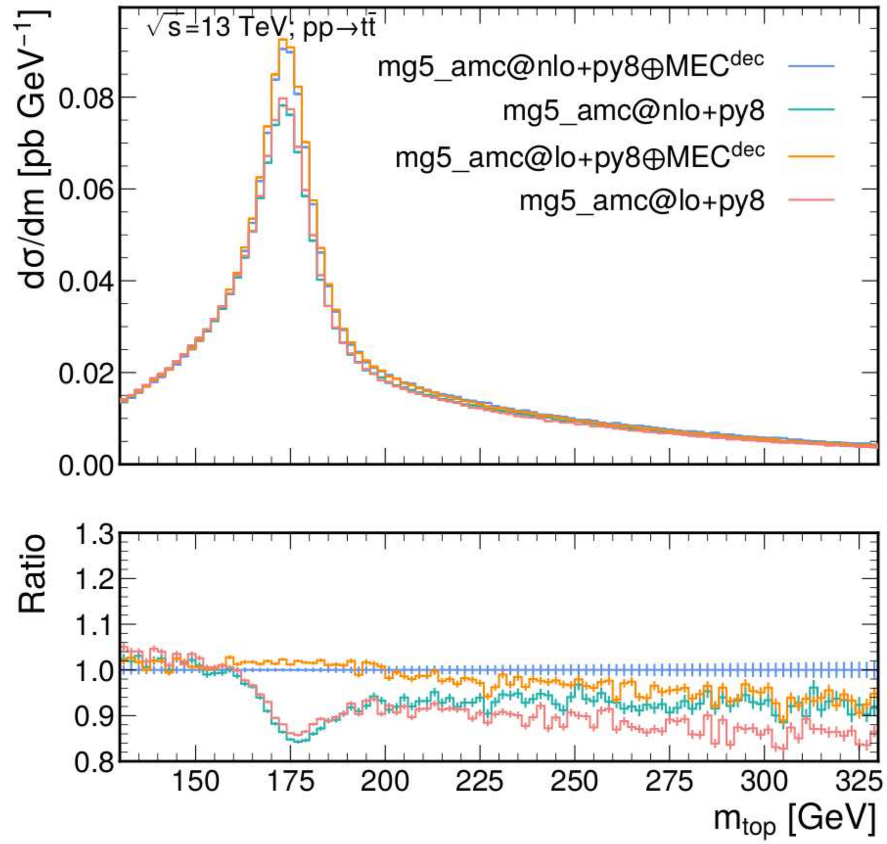
On the right panels:

- Blue vs orange and green vs red: effect of hard radiation
- Blue vs green (NLO) and orange vs red (LO): effect of decay MEC

- Compare left and right panels to *estimate* the impact of inconsistent hard-radiation parameter settings in MG5_aMC, POWHEG-BOX, and PY8 (matching and tuning effects are also present)

m_{top}



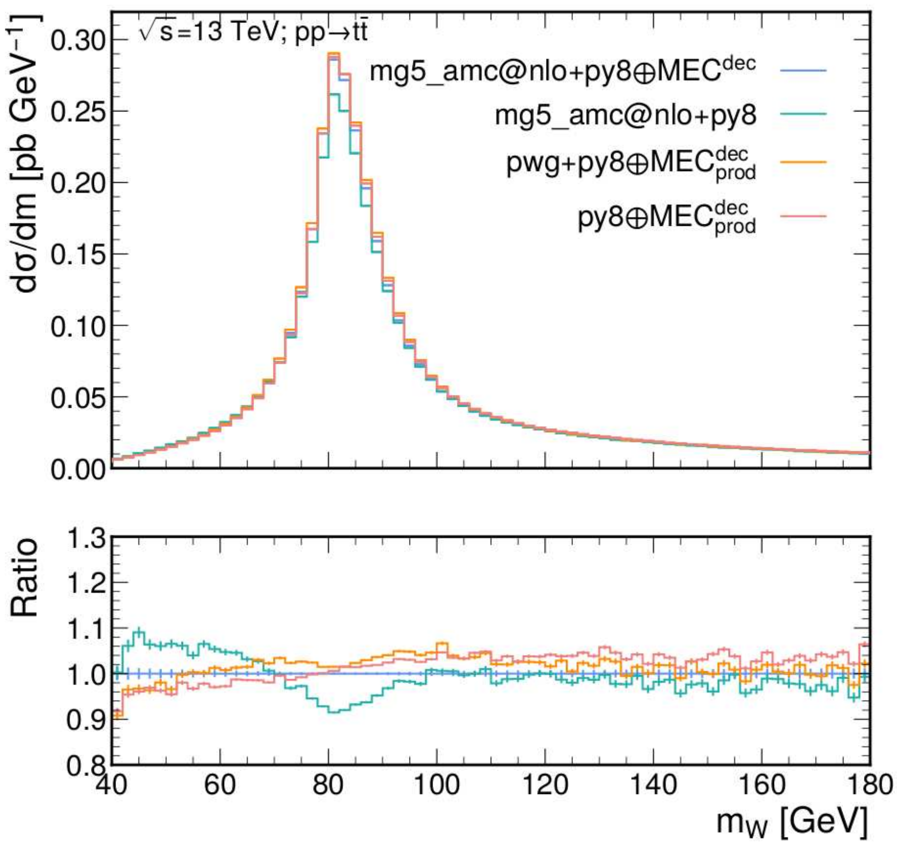


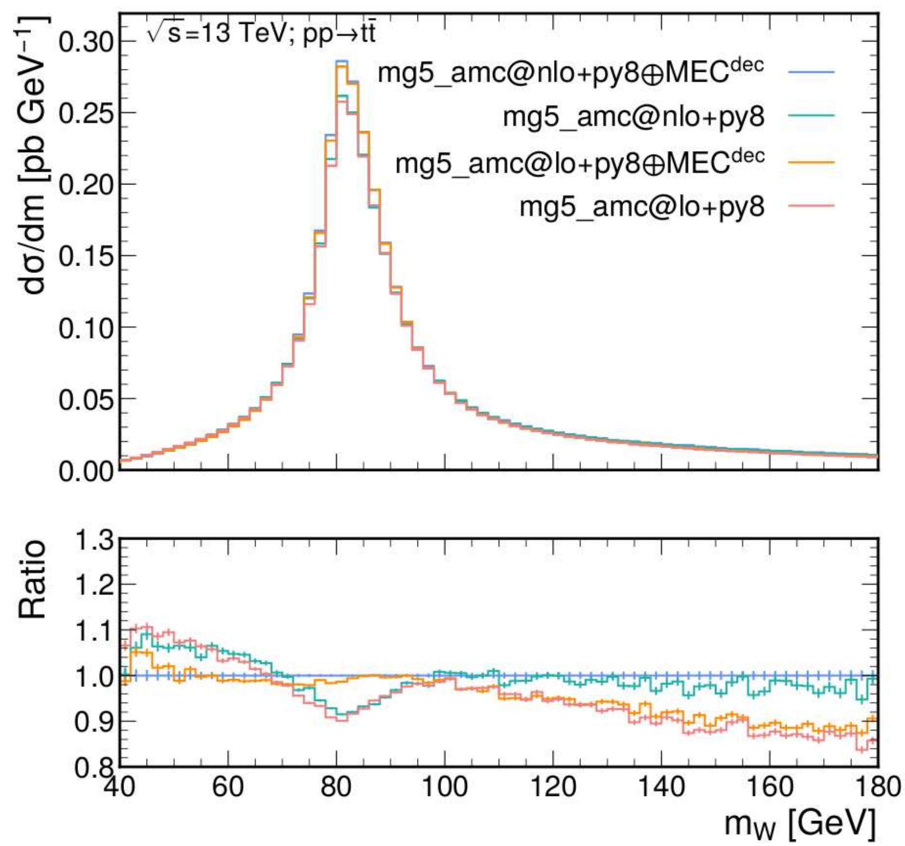
MG5_aMC vs PWG vs PY8

MG5_aMC, NLO vs LO

Hard radiation settings impact $m_{top} \gtrsim 200$ GeV

m_W



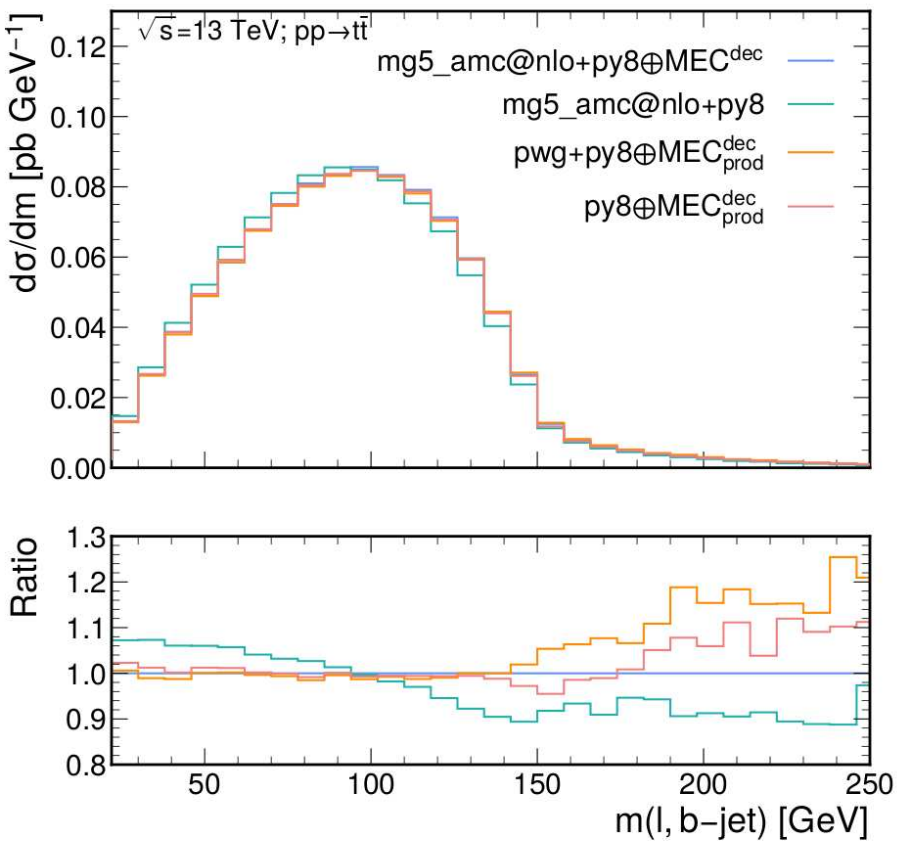


MG5_aMC vs PWG vs PY8

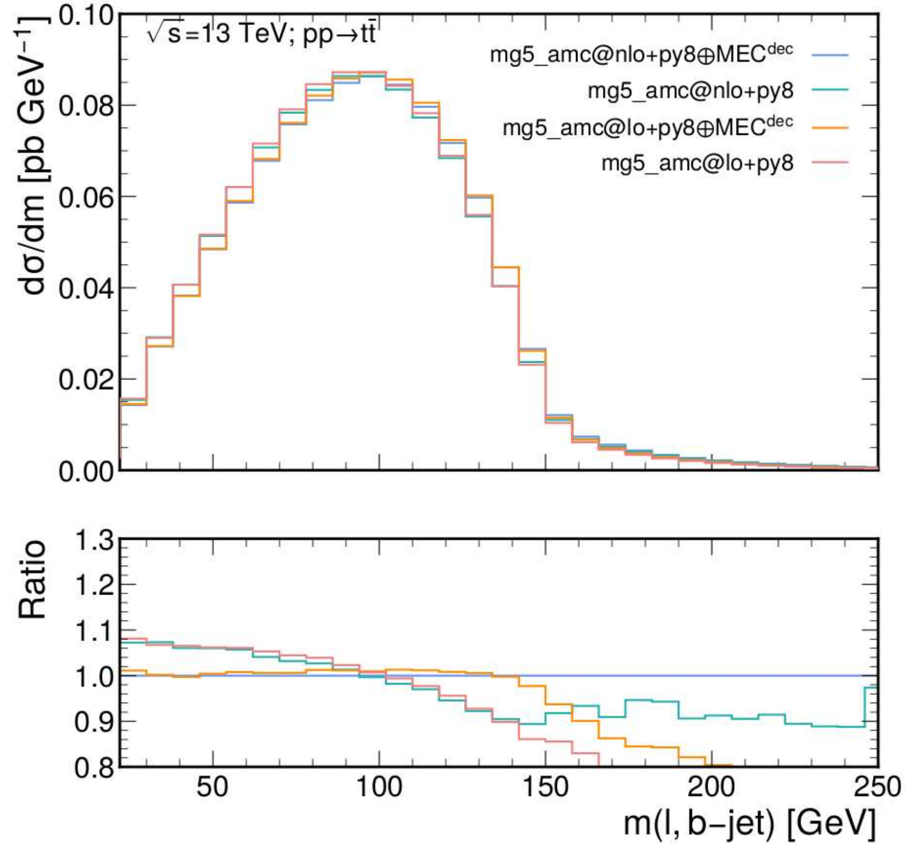
MG5_aMC, NLO vs LO

Hard radiation settings impact $m_W \gtrsim 100$ GeV

m_{ℓ,j^b}



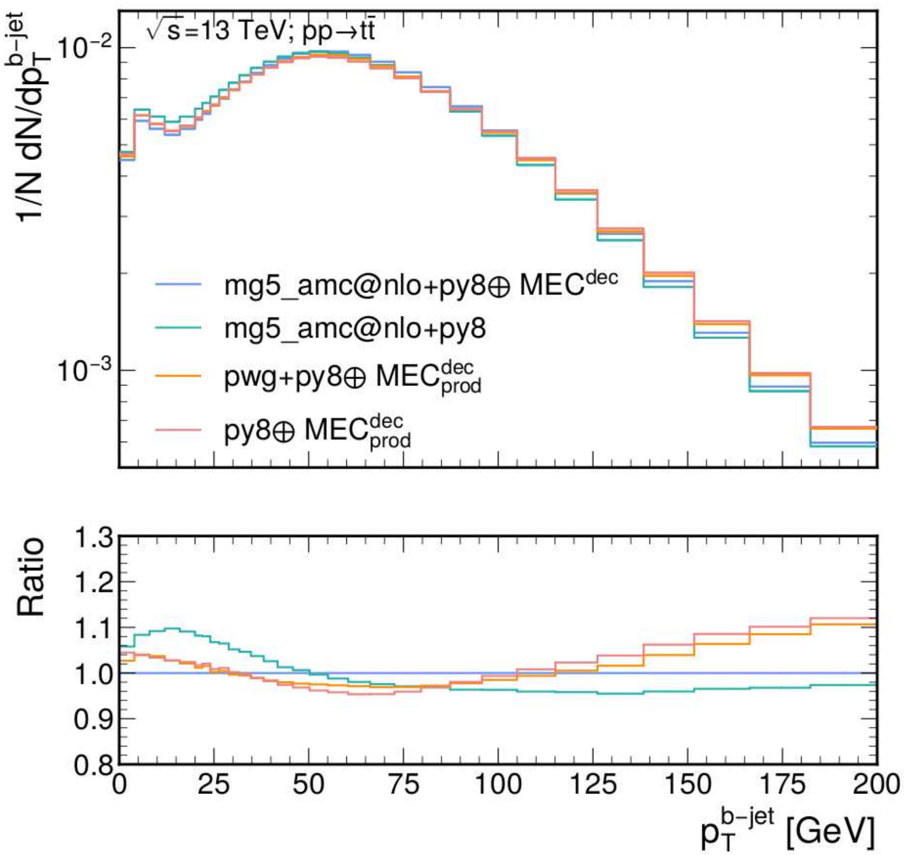
MG5_aMC vs PWG vs PY8



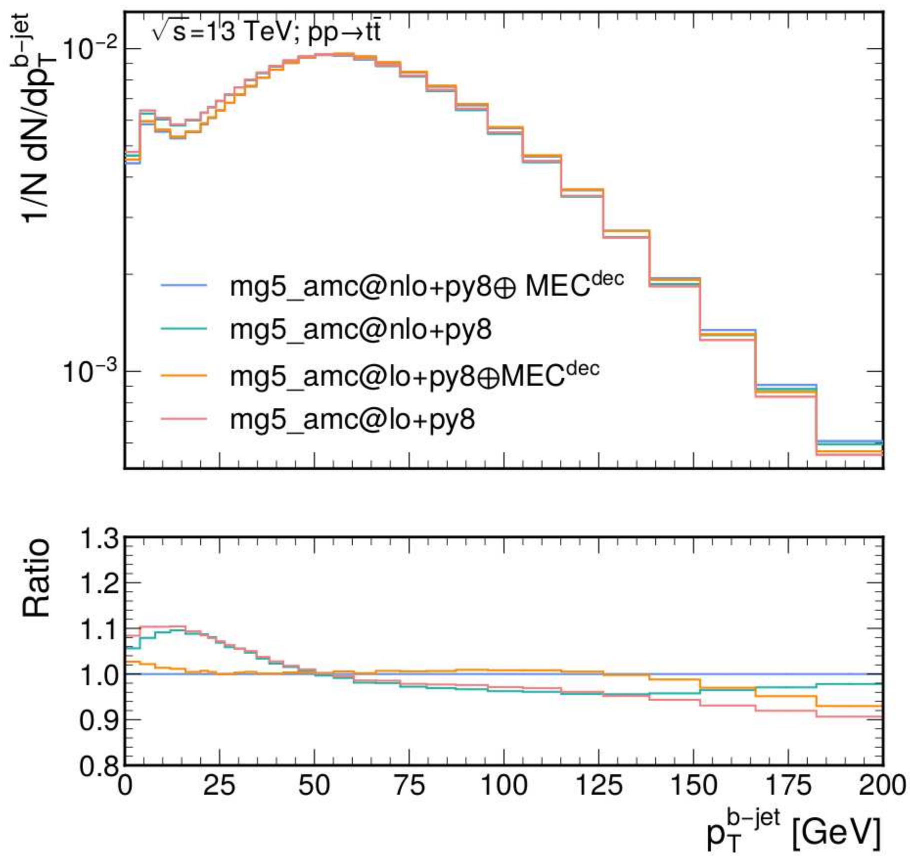
MG5_aMC, NLO vs LO

Hard radiation settings impact $m_{\ell,j^b} \gtrsim 150$ GeV

$p_T^{j^b}$



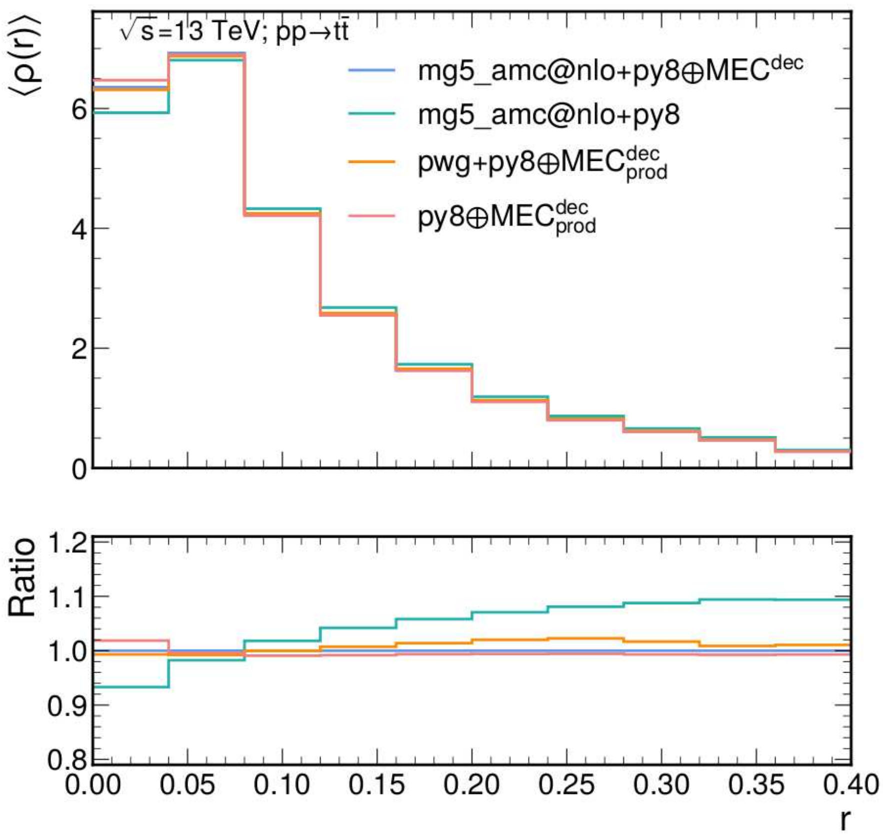
MG5_aMC vs PWG vs PY8



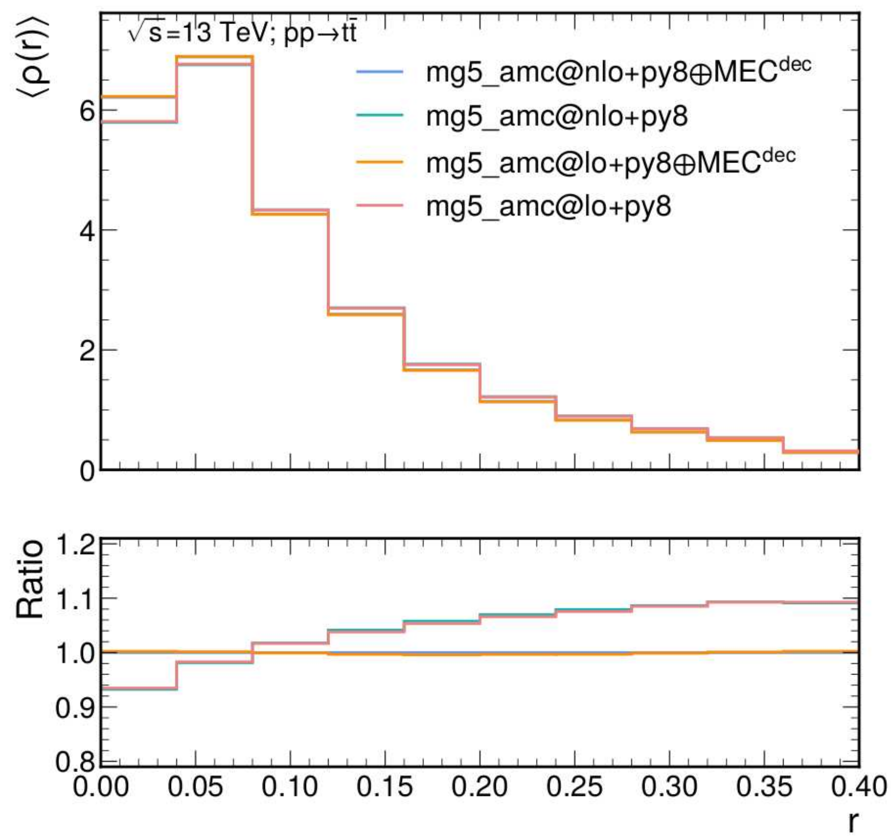
MG5_aMC, NLO vs LO

Hard radiation settings impact $p_T^{j^b} \gtrsim 130$ GeV

b-jet shape



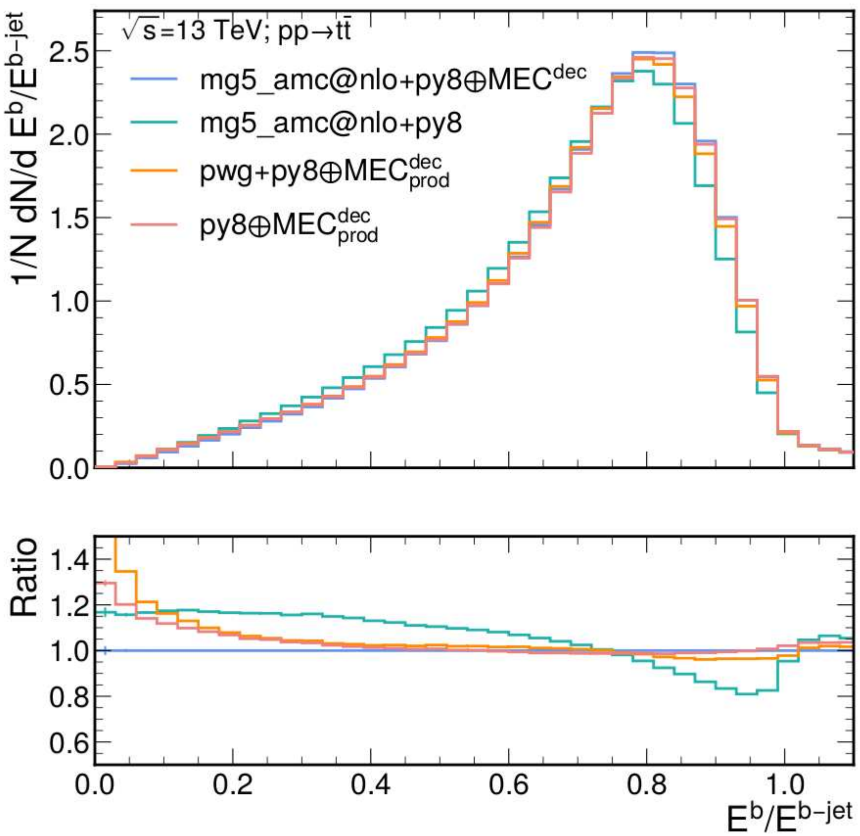
MG5_aMC vs PWG vs PY8



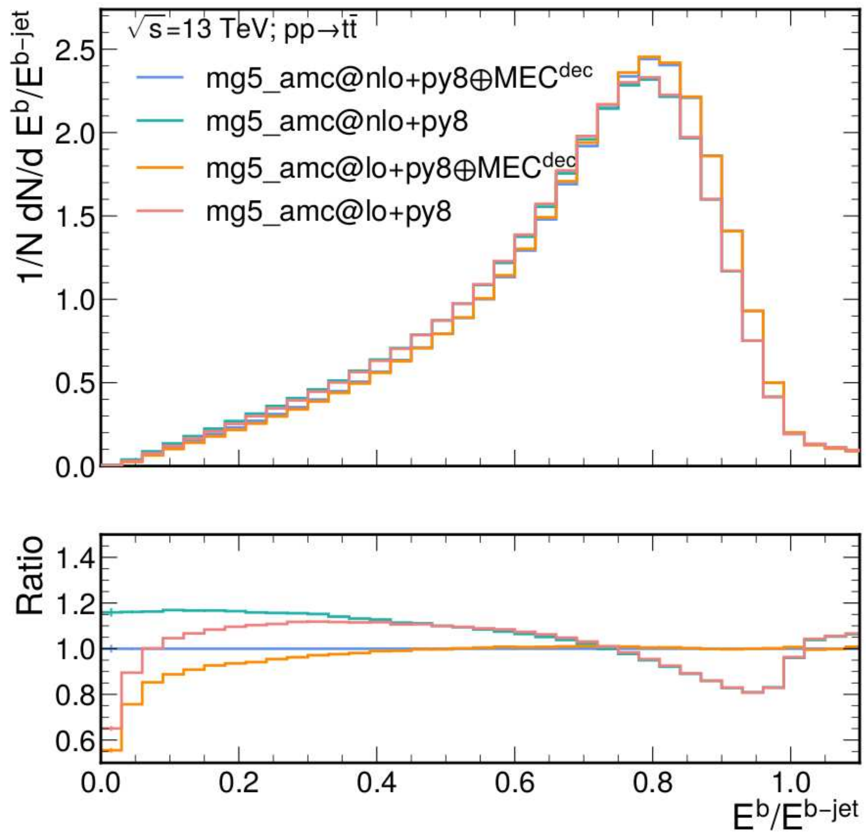
MG5_aMC, NLO vs LO

Hard radiation settings impact: no effect

B-hadron scaled energy



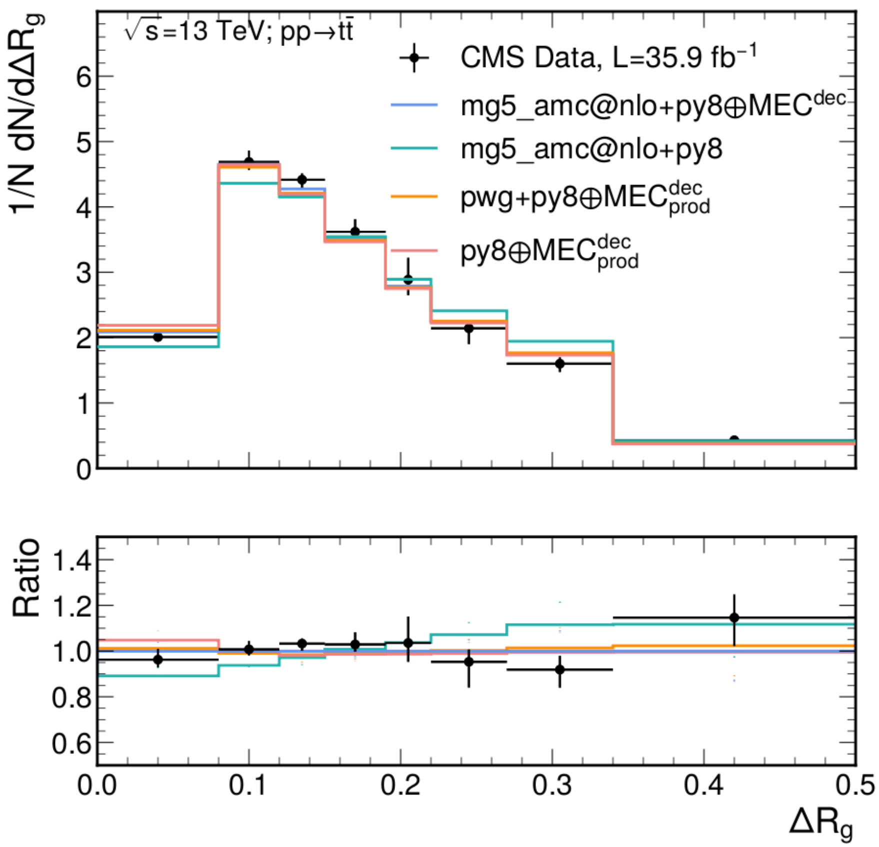
MG5_aMC vs PWG vs PY8



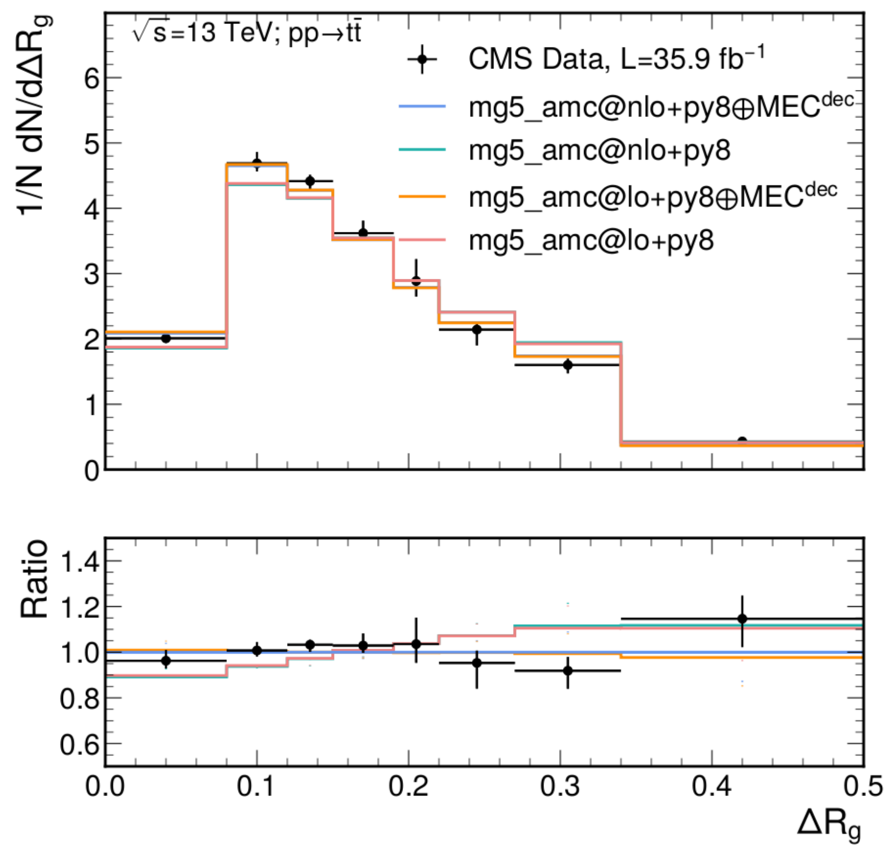
MG5_aMC, NLO vs LO

Hard radiation settings impact $E^b/E^{j^b} \lesssim 0.4$

Groomed subjet distance



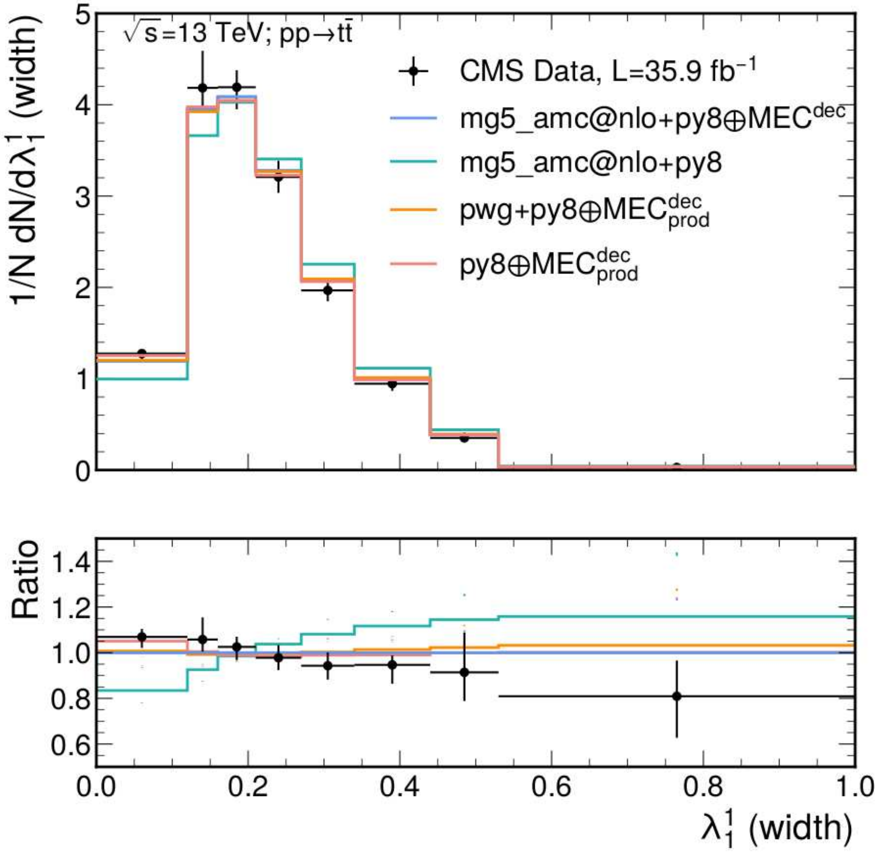
MG5_aMC vs PWG vs PY8



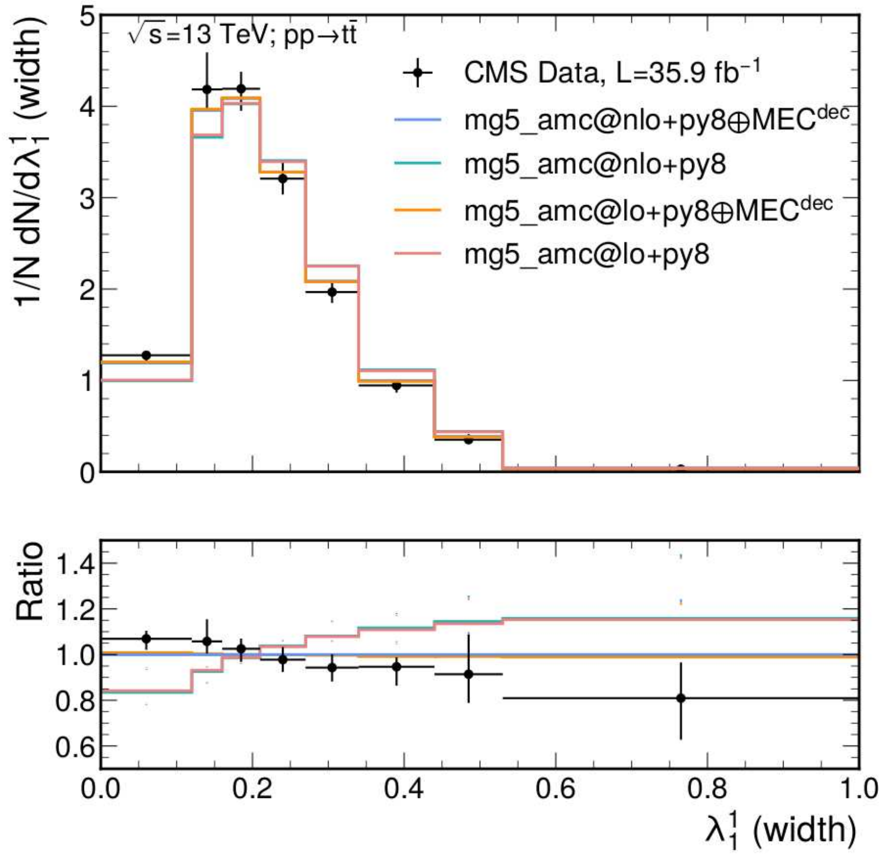
MG5_aMC, NLO vs LO

Hard radiation settings impact: no effect

Jet width



MG5_aMC vs PWG vs PY8



MG5_aMC, NLO vs LO

Hard radiation settings impact: no effect

Conclusions

- Decay MEC can now be consistently included in MC@NLO-type simulations (at least with Pythia8) without spoiling the NLO accuracy

- In the decay-sensitive observables we have considered, we observe effects up to $\mathcal{O}(20\%)$ wrt the old settings that did not include decay MEC

- In all cases there is a reduction of the differences with POWHEG predictions, thus resulting in a reduction of the theoretical systematics

- New versions of Pythia8 will have an easier and more flexible way to control MEC

ATLAS is currently producing $t\bar{t}+\leq 2j$ FxFx samples with the new MEC settings