MC tools for top production

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Plan of the talk

- Available tools for Top production
- Treatment of spin correlations, off-shell effects, and NLO corrections to decays.
- Areas of improvement
- New developments in spin correlations and NLO corrections to decays.

Available generators

MC@NLO and POWHEG: $t\bar{t}$ and single top production available since some time.

All generators include NLO correction in production, and an approximate spin correlation mechanism in decay.

If the matching Shower Monte Carlo supports MEC (Matrix-Element corrections) to top and W decays, also an approximate form of NLO corrections to the decays is included.

Treatment of spin correlations and off shell effects

Both `MC@NLO` and `POWHEG` generate undecayed $t\bar{t}$ pairs according to their respective recipes.

Decays and off shell effects are added in an approximate way:

$$\frac{d\sigma(\bar{e},\nu,b;e,\bar{\nu},\bar{b},[p])}{d\Phi_{\rm dec}d\Phi_{t\bar{t}[p]}}=\frac{d\sigma^{\rm NLO+PS}(t;\bar{t},[p])}{d\Phi_{t\bar{t}[p]}}\times\underbrace{\frac{\frac{d\sigma^{\rm Tree}(\bar{e},\nu,b;e,\bar{\nu},\bar{b},[p])}{d\Phi_{\rm dec}d\Phi_{t\bar{t}[p]}}}{\frac{\sigma^{\rm Tree}(t,\bar{t},[p])}{d\Phi_{t\bar{t}[p]}}}}_{\text{Integrates to 1 in } d\Phi_{\rm dec}}$$

(Frixione,Laenen,Motylinskyi,Webber 2007)

$t\bar{t}$ off shell effects are also approximately introduced in the factor on the right, and incorporated into $d\Phi_{\rm dec}$.

This recipe can be applied to any MC generator, with different effects.

For example:

`MC@NLO` applies a Born corrections to S events, real correction to H events

`POWHEG` applies a Real emission correction to (essentially) all events.

Some shower generators are capable to include approximate NLO effects in t and W decays (for example, `Pythia8`).

Given (for example) a W decayed into a $q\bar{q}$ pair on the Les Houches interface, they shower them including `MEC` (i.e. such that the rotational averaged $q\bar{q}g$ matrix element is correct; some reasonable rotational correlation with the initial $q\bar{q}$. are also maintained.)

Virtual corrections divide out in a branching ratio, so that they cancel upon rotational average. In this sense, they are partially included.

MC@NLO and POWHEG comparison

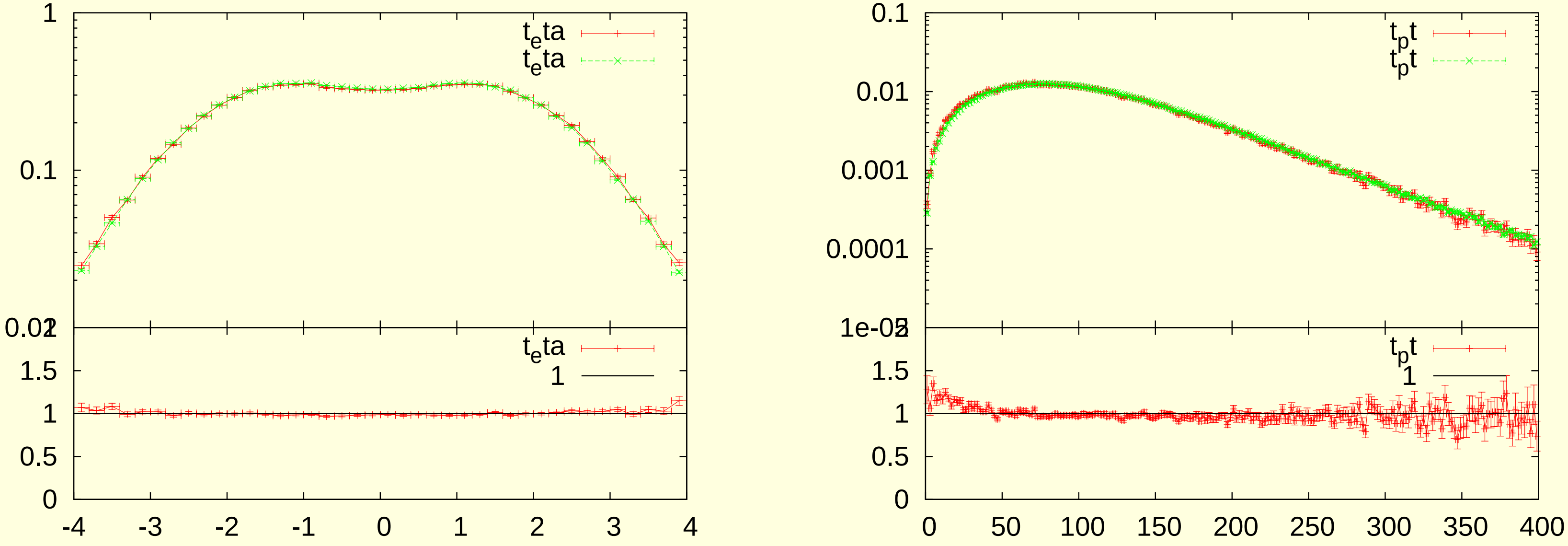
Traditionally known to compare well. Largest discrepancy found in the rapidity distribution of radiation (Mangano,Moretti,Piccinini,Treccani, 2006).

However, looking at details, other differences are found. As the needed precision increases, we should also understand these differences.

In this study: t, $\bar{t}$, W^+, W^-, b and $\bar{b}$ are identified by MC truth (last particle in hep common block with right features)

All results presented in the following are highly PRELIMINARY

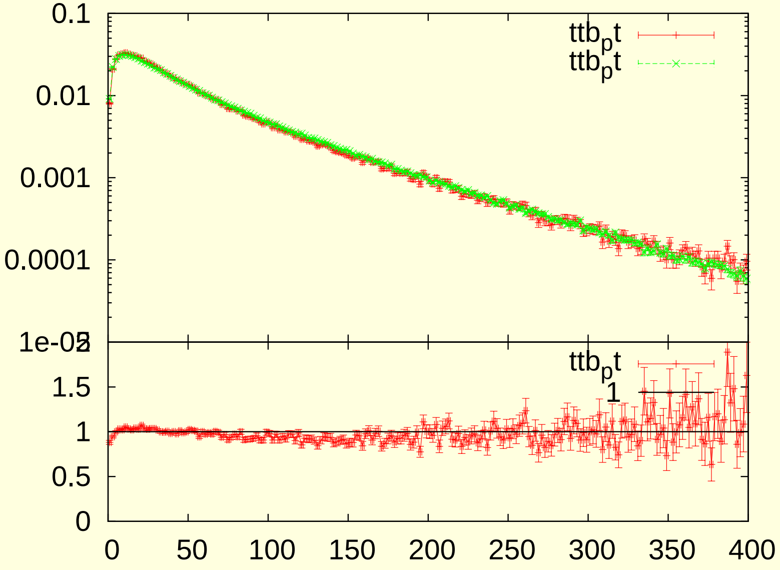
POWHEG (red) and MC@NLO (green)



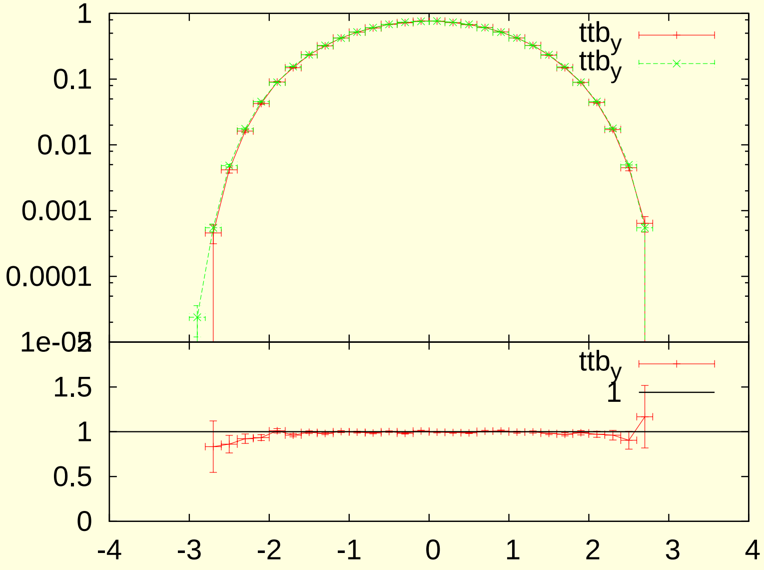
$$\frac{d\sigma}{d\eta_{\rm top}}\,(\mathrm{pb}) \qquad \frac{d\sigma}{dp_t^{(\rm top)}}\,(\mathrm{pb/GeV})$$

We see a slight eccess of POWHEG over MC@NLO at small top p_t.

(Pointed out by Mark Ohlfeld, ATLAS SUSY group)

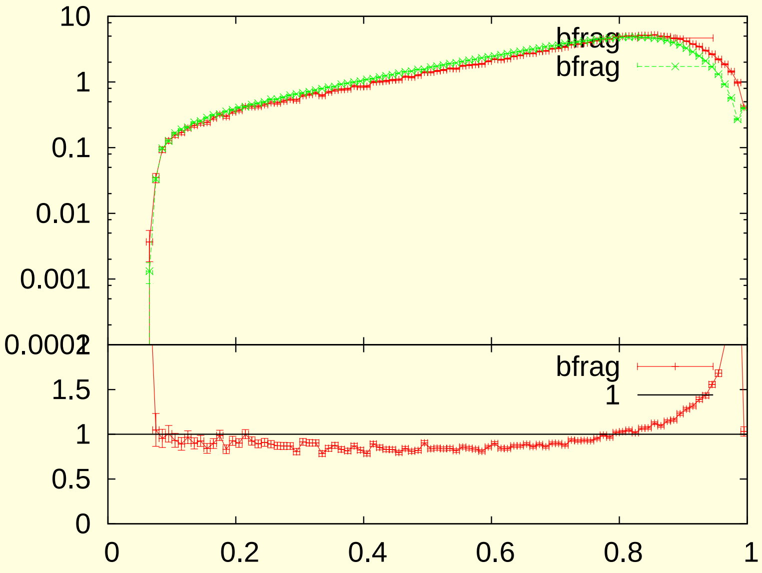


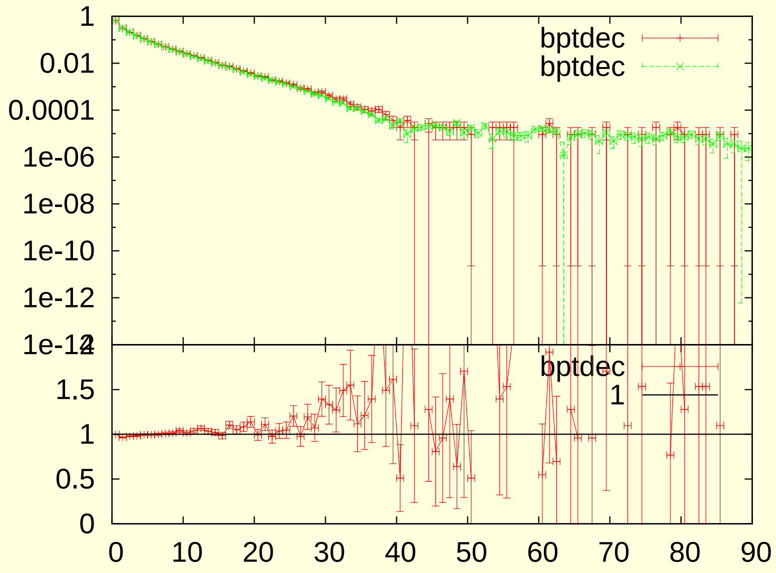
$$\frac{d\sigma}{dp_t^{(t\bar{t})}}\,(\mathrm{pb/GeV})$$



$$\frac{d\sigma}{d\eta_{(t\bar{t})}}\,(\mathrm{pb/GeV})$$

$t\bar{t}$ distribution sensitive to NLO radiation; very good agreement.





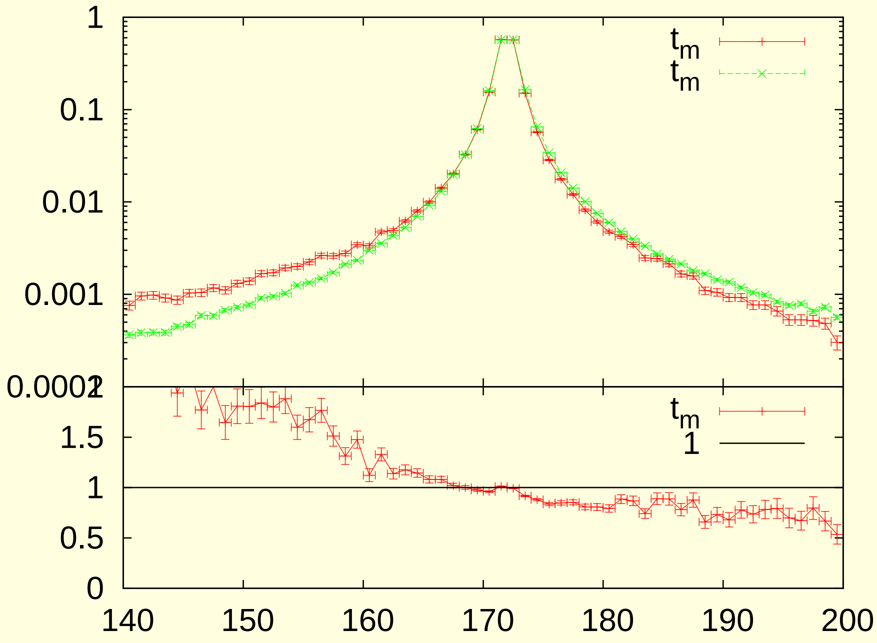
$$\frac{d\sigma}{dx_b}\,(\mathrm{pb/GeV})$$

$$\frac{d\sigma}{dp_t^b}\,(\mathrm{pb/GeV})$$

b energy fraction in t CM.

b transverse momentum in t CM

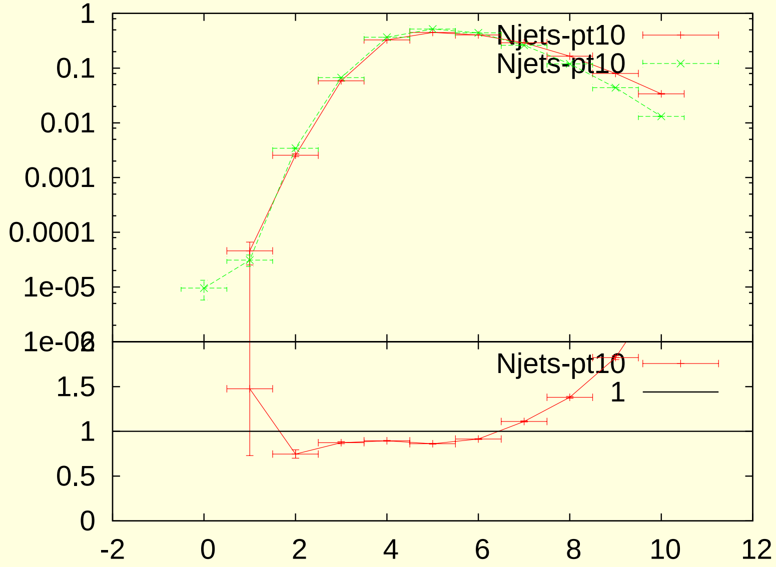
The difference in the b fragmentation (only due to HERWIG) is likely due to the fact that the b is not given a mass by default in POWHEG. A generic routine to give masses to quarks and reshuffle momenta is available. It probably should be applied by default.



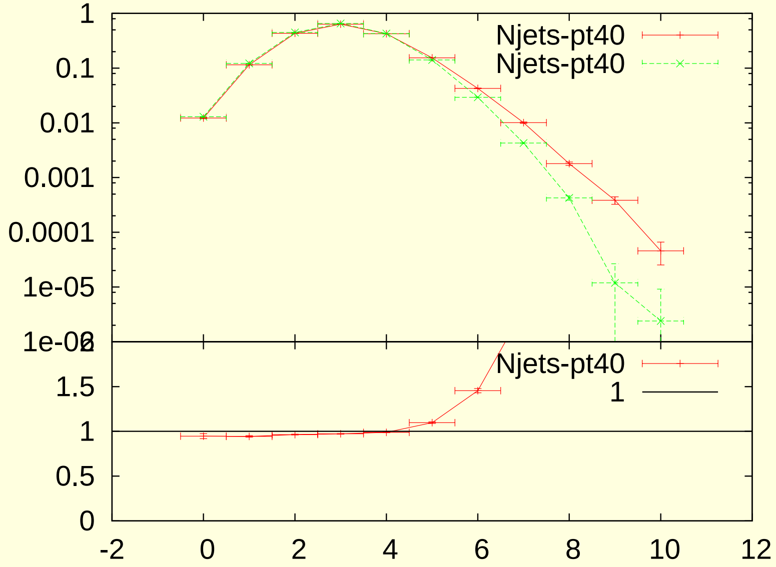
$$\frac{d\sigma}{dm_t}(\mathrm{pb/GeV})$$

Difference in (approximate) t width implementation!

Study of finite width effects with `MadGraph` could help resolving this, although we don't expect either implementation to be so good far off shell.



Number of jets (pb), $p_t^{\mathrm{jet}} > 10\,\mathrm{GeV}$

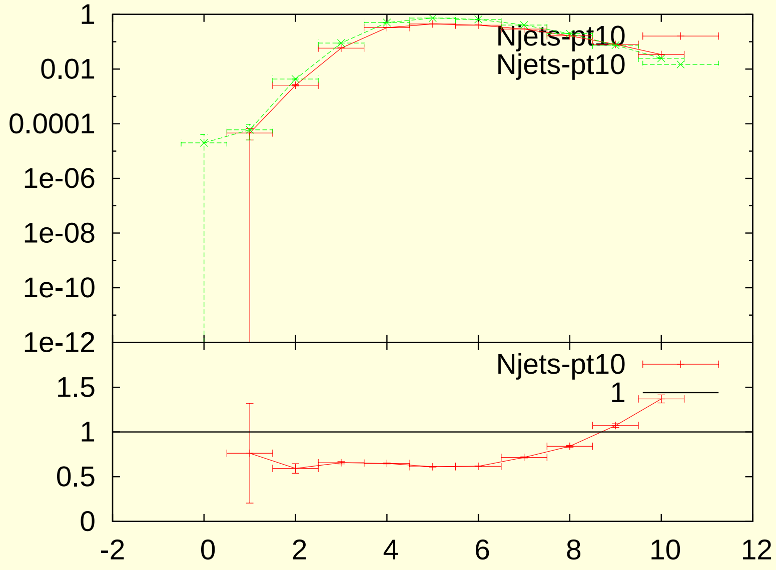


Number of jets (pb), $p_t^{\mathrm{jet}} > 40\,\mathrm{GeV}$

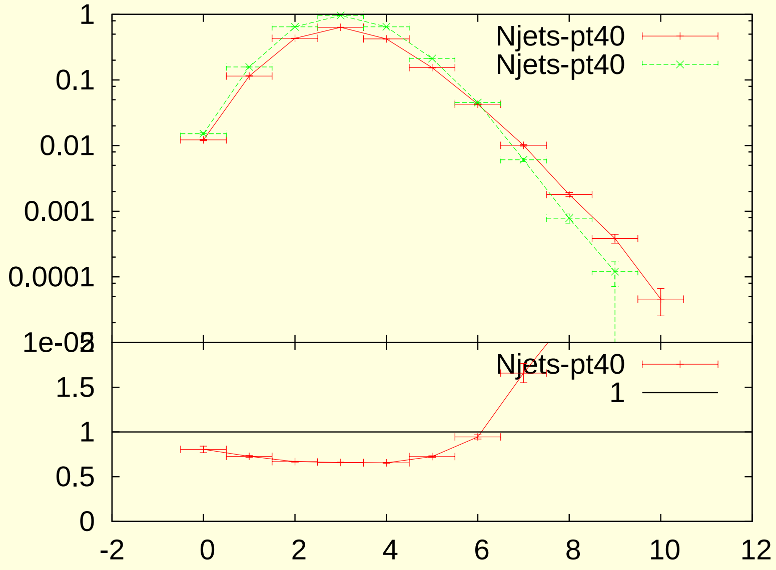
(Pointed out by Mark Ohlfeld, ATLAS SUSY group)

We are inclined to think that njet>4 is HERWIG responsability ...
Apparently, this is not the case!

POWHEG (red) and HERWIG (green)



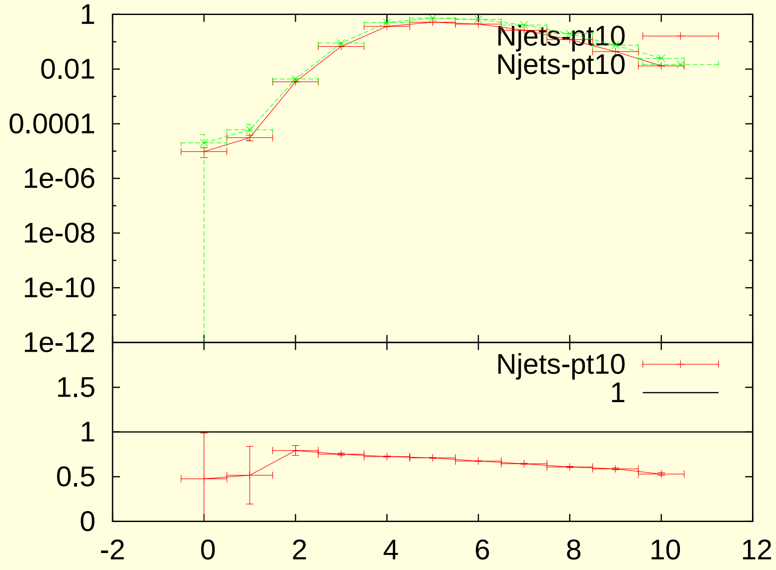
$\text{Number of jets (pb)}, p_t^{\text{jet}} > 10\,\text{GeV}$

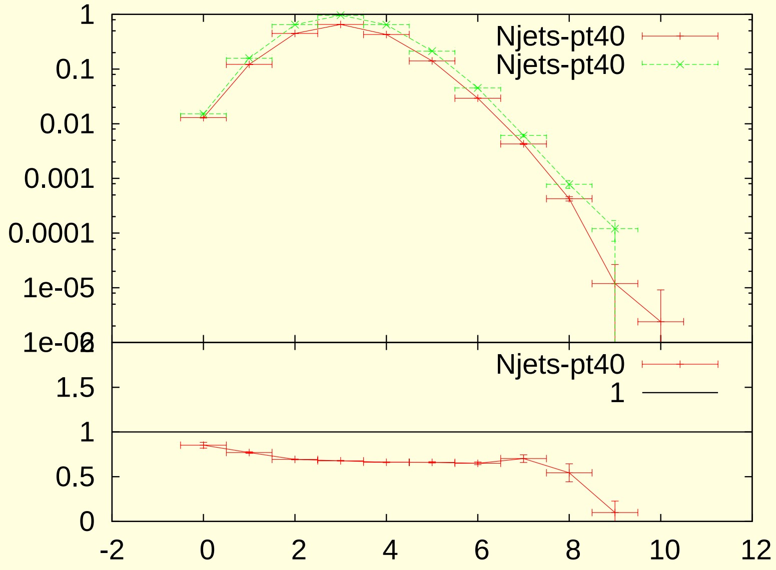


$\text{Number of jets (pb)}, p_t^{\text{jet}} > 40\,\text{GeV}$

Still an effect, less marked;

POWHEG (red) and HERWIG (green)





Number of jets (pb), $p_t^{\mathrm{jet}} > 10\,\mathrm{GeV}$ Number of jets (pb), $p_t^{\mathrm{jet}} > 40\,\mathrm{GeV}$

Opposite trend of MC@NLO w.r.t. HERWIG!

Not a big issue: neither POWHEG nor MC@NLO can do well in this region;
Yet: where do these differences come from?

Room for improvement

Are present, approximate spin correlation and NLO corrections to decays sufficiently accurate? We should recall that:

- LHC is a top factory
- top processes are important background to new physics searches
- LHC will do precision physics with top

It makes sense to try to improve over the present generator, to fully include spin correlations and NLO effects in decay.

POWHEG+MCFM

Campbell, Ellis, 2012 have computed several top production processes including spin correlations and decays, and inserted them in the MCFM package: $t\bar{t}$, s- and t- channel single top, tW and $t\bar{t}W$.
This kind of NLO computations have been illustrated by K.Melnikov yesterday.

Include them in the POWHEG BOX! (Campbell,Ellis,P.N., current work).

Need to modify several aspects of the `POWHEG BOX`:

- Now processes are represented by a string of flavours:
  3 -3 11 -12 -11 12 5 -5 is $q\bar{q} \to e\,\bar{\nu}\,\bar{e}\,\nu\,b\,\bar{b}$. Now we need to add resonance information: $q\bar{q} \to (t \to b\,(W^+ \to \bar{e}\,\nu))(\bar{t} \to b(W^- \to e\,\bar{\nu}))$ is
  3 -3 6 -6 24 -24 11 -12 -11 12 5 -5
  0 0 0 0 3 4 6 6 5 5 3 4
- Real processes are different, dipending upon the origin of the radiated parton, whether it is from production or resonances. So:
  3 -3 6 -6 24 -24 11 -12 -11 12 5 -5 0
  0 0 0 0 3 4 6 6 5 5 3 4 0,3,4, 3 independent contributions!
  For hadronic W's, the radiated parton may also come from the W's.

When requesting a real matrix element to `MCFM`, we invoke the appropriate routine (production or decay), depending upon the value of the pointer to a resonance of the radiated parton.

- POWHEG defines and underlying Born for each real emission kinematics. Now the underlying Born is different if the radiation comes from a resonance. In FSR, the underlying Born is such that the whole final state system recoiling from the splitting pair of partons is boosted to conserve total energy and momentum.
  Now, if a resonance is radiating, the recoil system is formed only by the partons belonging to the resonance, and this subset of parton is boosted to conserve the resonance 4-momentum.
- The soft terms, to be added to the virtual term, must be computed in the resonance rest frame, if they arise from real graphs where the radiation comes from a resonance.

The POWHEG BOX also implements an automatic subtraction scheme for NLO calculations. All these aspects must be update for resonance treatment.

These extensions have all been completed. They are designed to be fully general, and they have been applied to the $t\bar{t}$ and single top processes.
We are now at the level that we have high confidence that the Les Houches events are generated correctly.

Interface to Shower

- With no NLO corrections to decays (but exact NLO spin correlations): can be interfaced to shower as before.
- With NLO corrections to decays: `POWHEG` generates the hardest radiation, whether it comes from production or decay. The shower should not generate anything harder, neither in production nor in decays.

Les Houches user process allows to veto radiation in production, by setting the variable `scalup`. The shower treats resonance decays independently.
Must go beyond Les Houches: Pythia 8 has methods for vetoing the shower off a resonance, allowing for a great deal of flexibility.

We implemented a (fortran) Pythia8 interface such that:

- Pythia 8 can be called from fortran, and the analysis can be performed in fortran.
- Radiation off resonances is vetoed using `scalup`

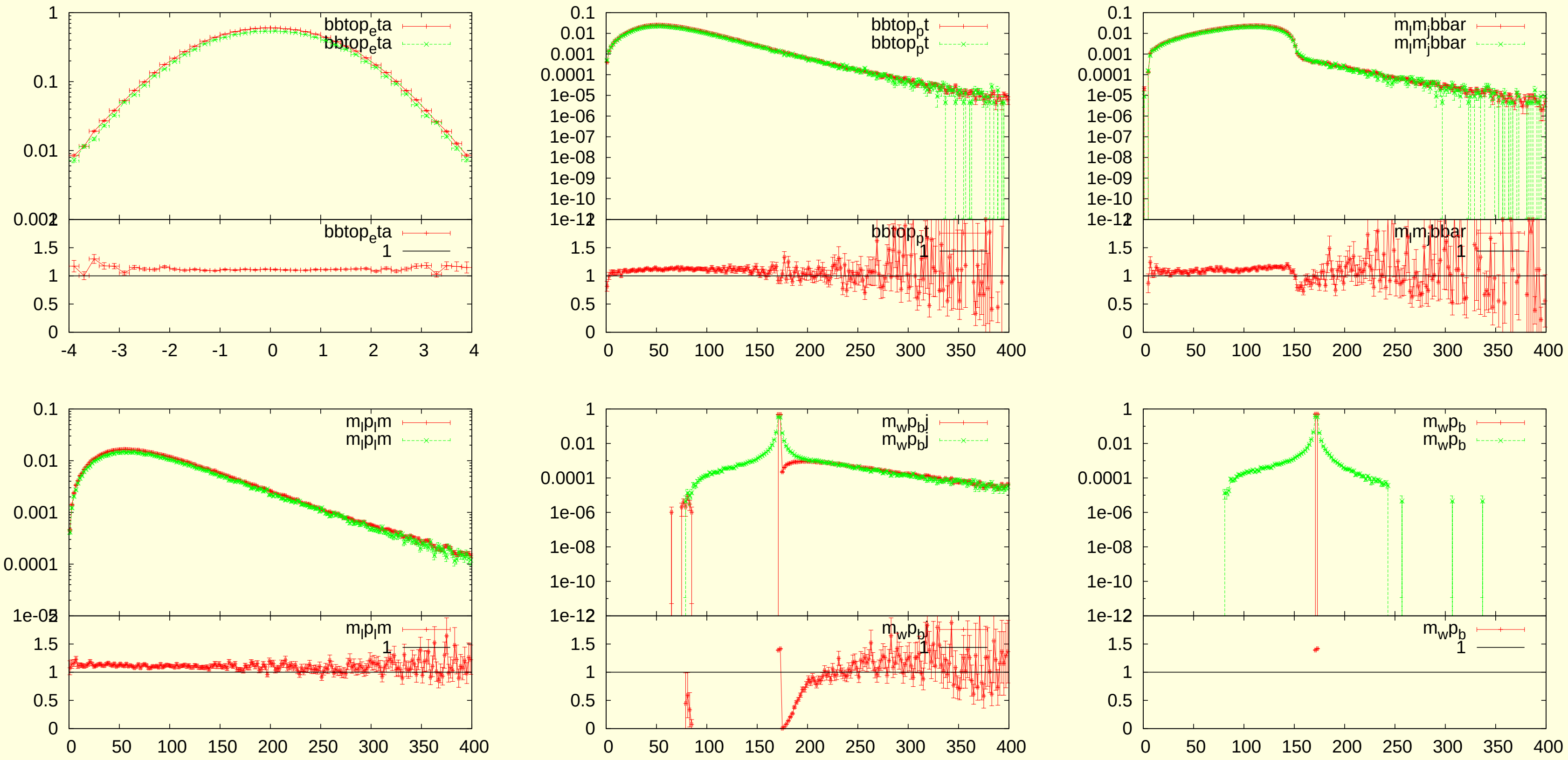
Plans for testing:

- Compare approximate spin correlation with exact NLO spin correlation (with NLO corrections to decay switched off). Enough to do fully leptonic decays, only at the LHE level (before shower).
- Compare full showered result including NLO corrections to decays with result without NLO corrections to decays (they are provided by the PS).
- Consider first fully leptonic (no corrections to W decays), then include hadronic W decays.

Lot of Work! Here some very preliminary plots for the first two points ...

Approximate (green) with exact (red) spin correlations

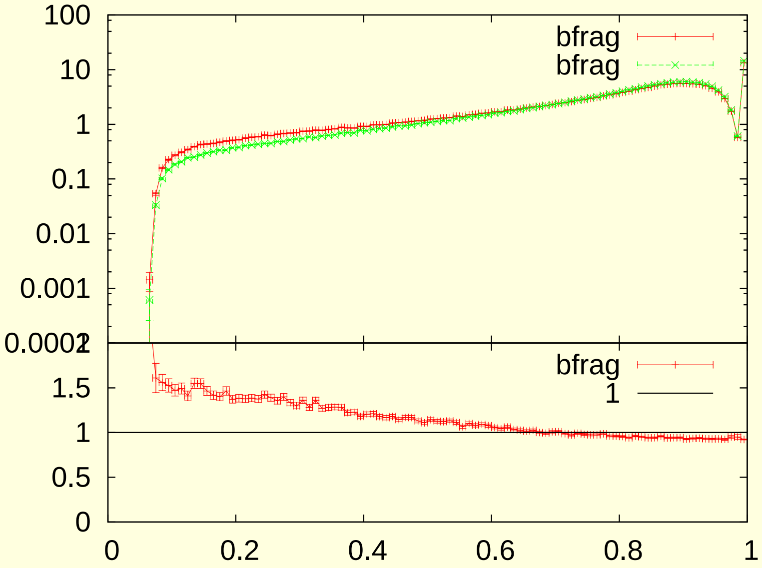
No sign of differences up to now:



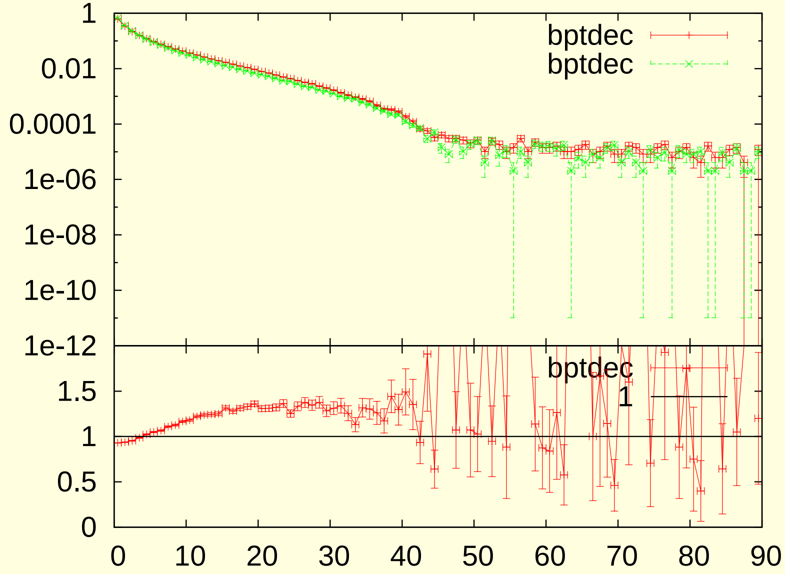
Difference due to slightly different branching, and to top width effects.

Look for more specialized observables?

Approximate (green) with exact (red) spin correlations



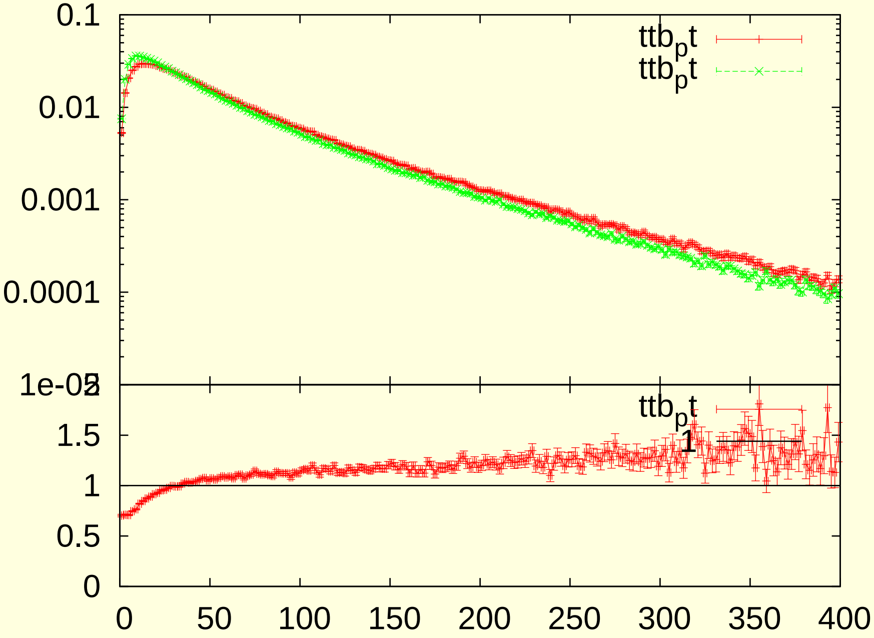
$$\frac{d\sigma}{dx_b}\,(\mathrm{pb/GeV})$$



$$\frac{d\sigma}{dp_t^b}\,(\mathrm{pb/GeV})$$

b radiation makes a difference. These quantities may also be validated by computing with similar methods the same quantities in Z decays.

However, more work on the interface of `POWHEG` and `PYTHIA8` is needed:



$$\frac{d\sigma}{dp_T^{(t\bar{t})}}\,(\mathrm{pb/GeV})$$

This is a clear problem in the matching. The further Sudakov suppression due to forbidden radiation in decays in not suitably compensated by the `PYTHIA8` shower.

Conclusions and prospects

- Need to revisit available tools for heavy flavour production, and better understand the differences.
- New tools using the full computation of NLO corrections for production and decays are being implemented in a shower context.
- The interface between shower and `POWHEG` needs to be refined to account for resonances.
- Automatic tools like `MadGraph`/`MadLoop` don't handle resonance decays at the moment (as far as I know the `POWHEG BOX` is now the only automatic tool that is resonance aware) ... room for extensions!