Issues on the top pt distribution in ME+PS and NLO+PS interfaced to Herwig

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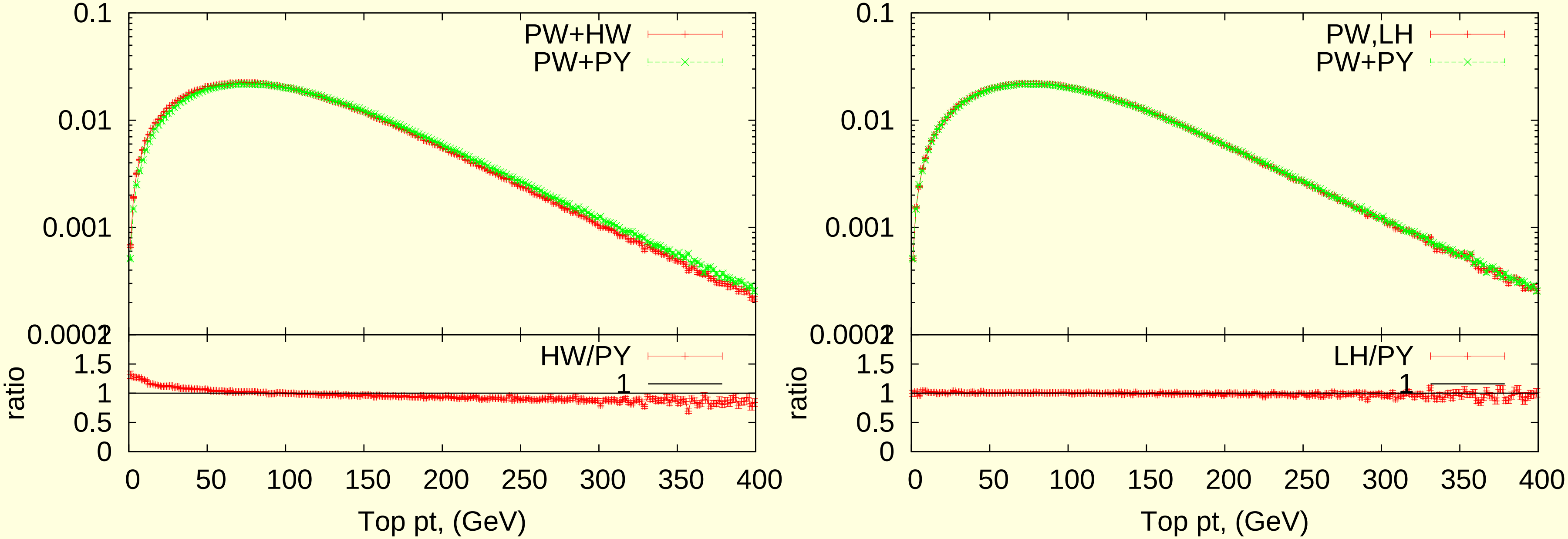
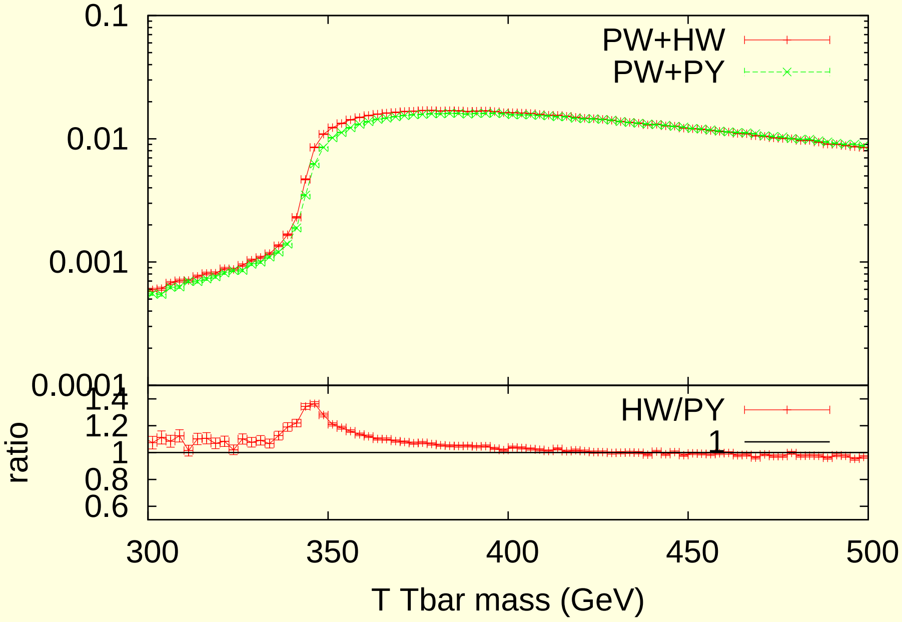
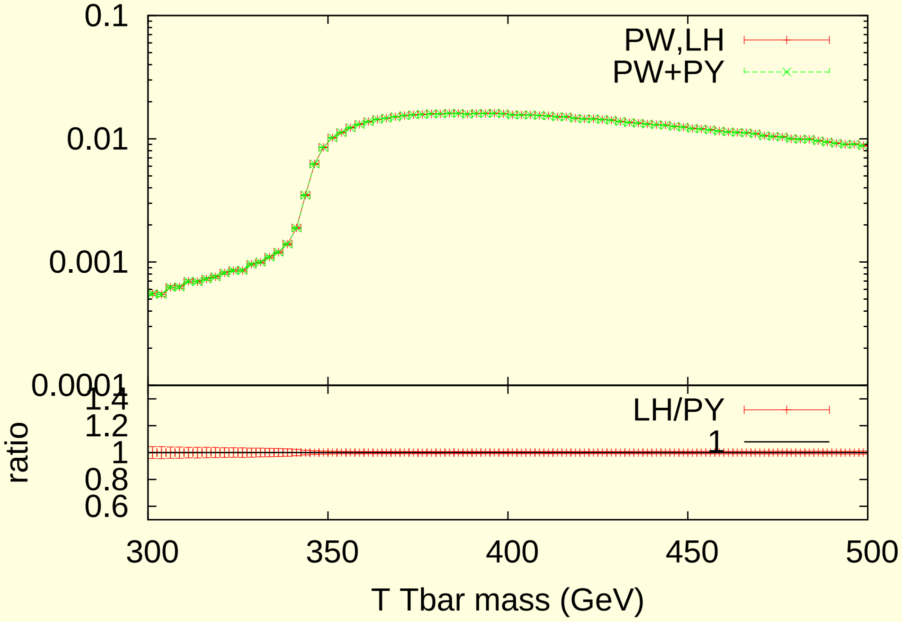
The problem:

Sensible differences observed in the p_t distribution of the top when interfacing POWHEG with PYTHIA versus HERWIG have been reported in several occasions at this workshop. The same problem has been observed in PS+shower matching. We (E. Re, P.N.) have studied this problem while developing a new POWHEG generator for $t\bar{t}$ production. The plots we show in the following are generated with the new generator, but there are essentially no differences with these distributions using the old generator. Top is the last top on the HEP event listing:



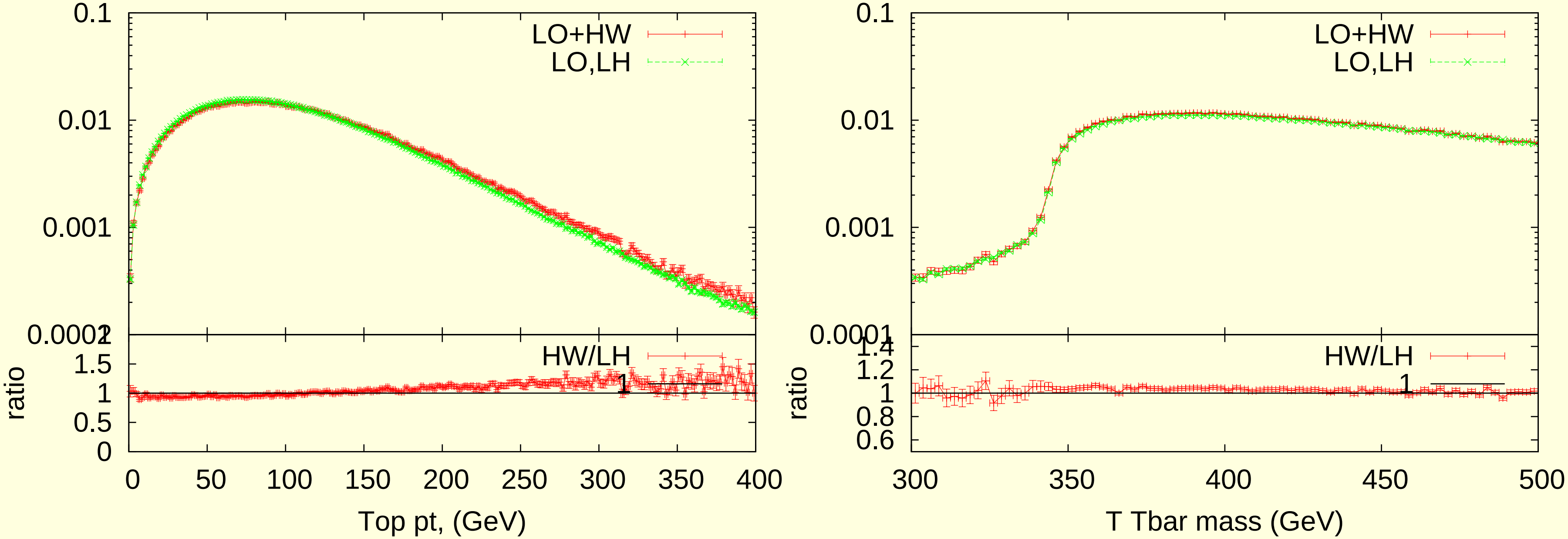
Other related observables? Look at the invariant mass of the $t\bar{t}$ pair:





PYTHIA seems to agree perfectly with the parton (Les Houches) level result; HERWIG yields a softer p_T spectrum.

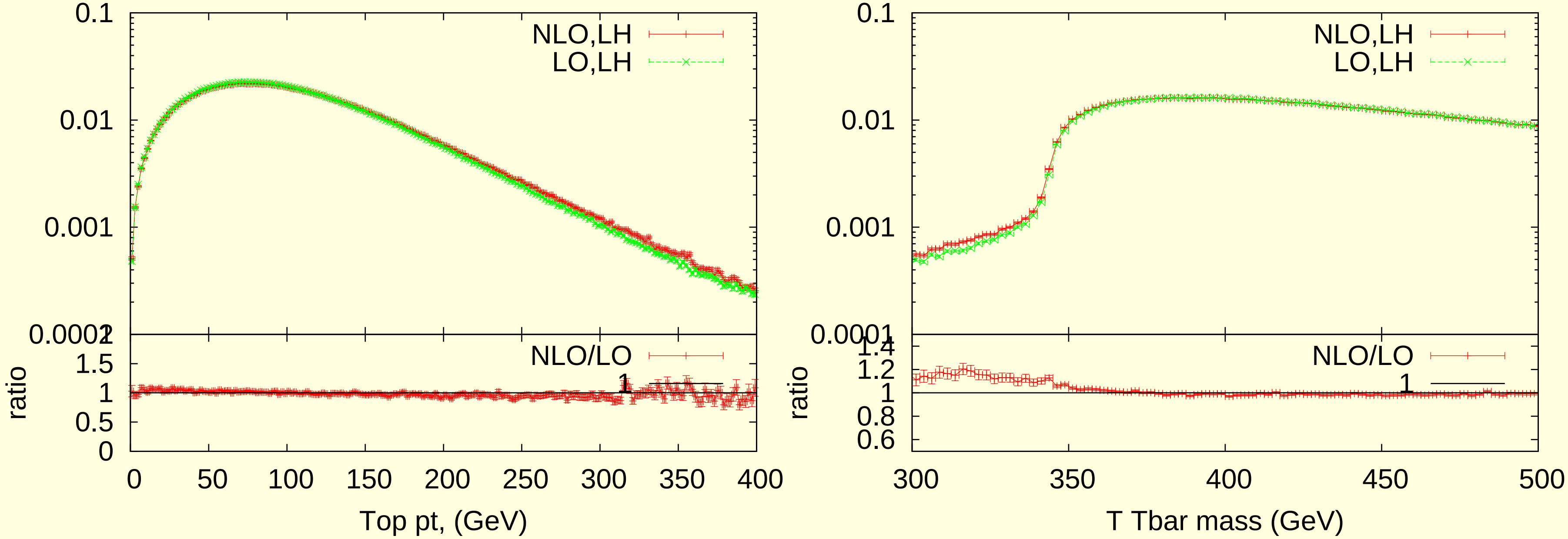
Is this a HERWIG feature? Look at the LO $t\bar{t}$ production with HERWIG, compared to the parton level (Les Houches level)



No sign of problems in the invariant mass. Slight hardening of the top p_T spectrum after shower. What's going on?

A reminder

The invariant mass of the pair and the top transverse momentum display little sentitivity to NLO radiative corrections.



This is due to the fact that most radiation is ISR. The top being so massive does not have collinear singularities, and does not radiate much.

Follow HERWIG shower

Follow the hint:

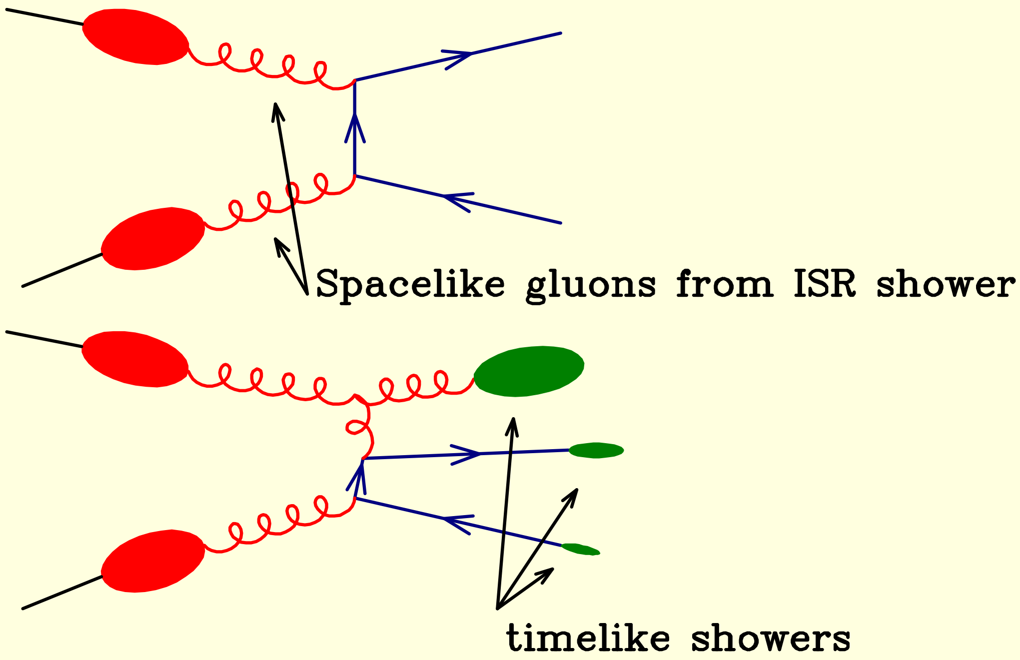
- LO+HW: radiation generated mostly by ISR.

  Does not affect the invariant mass distribution

- NLO+HW: hardest radiation appears to HERWIG as FSR:

  marked effect on $m_{t\bar{t}}$

The cause: MOMENTUM RESHUFFLING



ISR shower throws off shell the incoming gluon. In order to conserve 4-momentum, the final state is boosted. The mass $m_{t\bar{t}}$ is preserved

FSR shower changes the mass of final state partons. In order to conserve 4-momentum, the final state momenta are rescaled.

More specifically (HERWIG manual and private communication by B. Webber), one goes to the CM of the system of timelike showers and rescales all their 3-momenta by a common factor, so that the energy of the system matches the hard process energy.

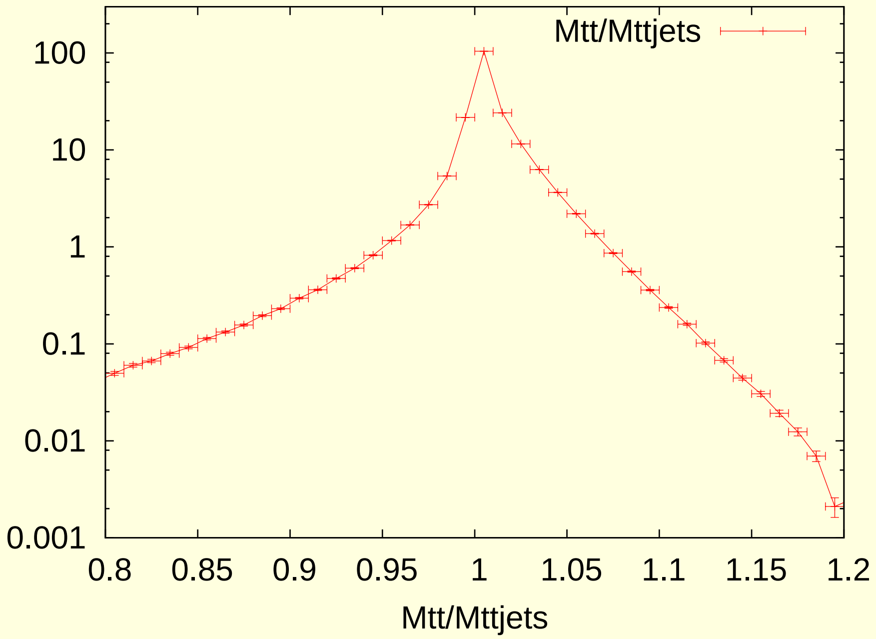
This mechanism can be checked in detail in HERWIG, where one can access

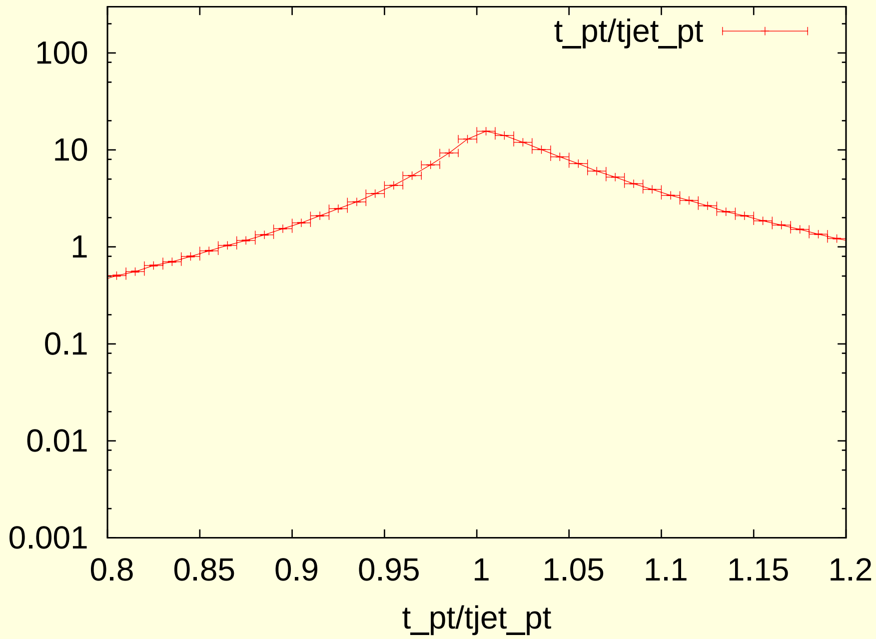
- The t, $\bar{t}$ and light parton at the hard process level (`isthep=123,124`)
- The correspondings jets (`isthep=143,144`, traced back using `jmohep`)
- The t, $\bar{t}$ after shower

Then:

- boost t, $\bar{t}$ and the light parton to their CM;
- do the same for the corresponding jet
- Check that the energy of the two systems are the same
- Check that the momenta are proportional by a common factor

It is now clear what happens: the light parton shower can build up a sizeable mass; the t and $\bar{t}$ do not radiate much in the shower. Assuming that they don't radiate at all, in order to conserve energy the momenta of the t, $\bar{t}$ and parton jet are reduced by a common factor, to compensate for the energy increase due to the mass of the parton jet. Thus, the $t\bar{t}$ mass is decreased by this momentum reshuffling.

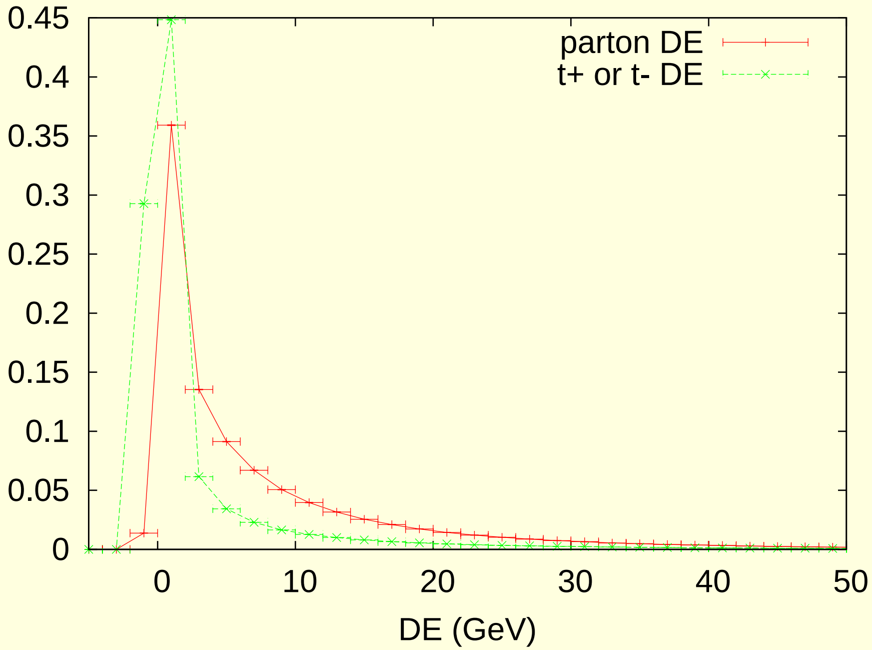




Compute the ratio of $m_{t\bar{t}}$ (or $p_T^{(\mathrm{top})}$) computed at the hard parton level over the same quantity computed at the jet level.

Large fraction of events with jet level observable smaller than hard parton one.

Now compute the increase DE in CM energy of the $t\bar{t} + \mathrm{parton}$ system due to the `HERWIG` shower acting on t or $\bar{t}$ (together) and on the parton:



We see that the shower of the light parton has a dominant effect in increasing the CM energy, and thus in determining the required momentum rescaling factor.

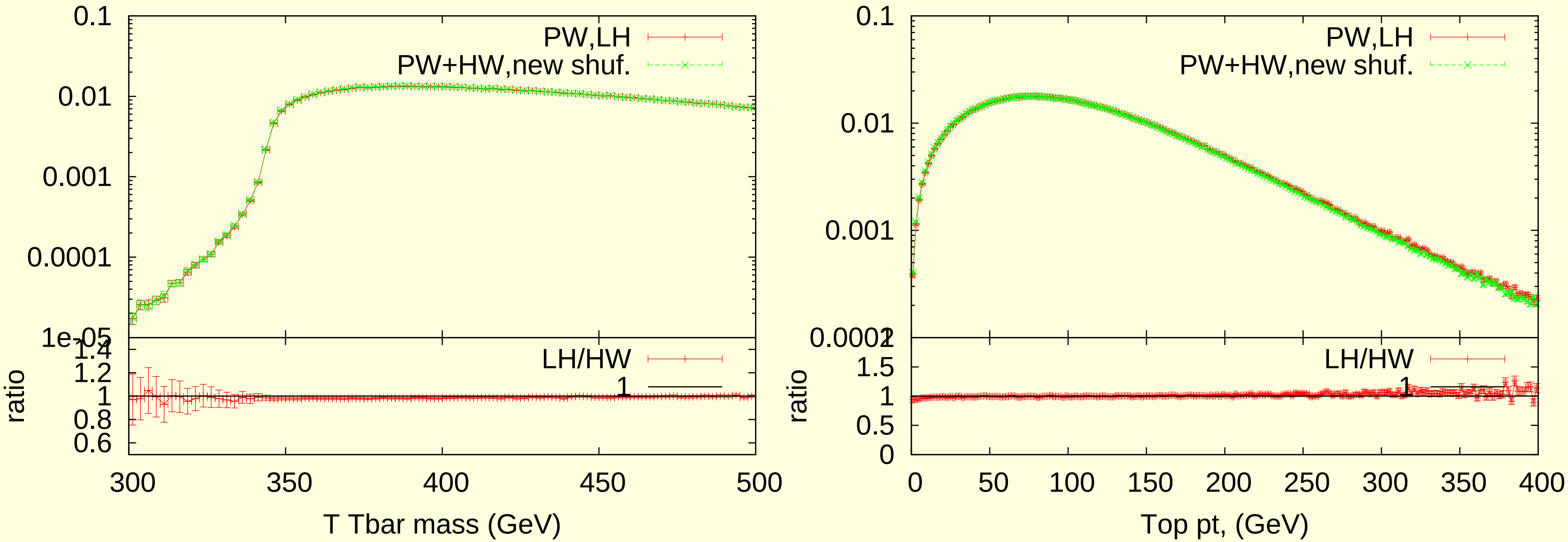
Further developments

In e-mail interaction with Bryan Webber, we discussed possible variants of the `HERWIG` reshuffling procedure that may not display this feature.

Bryan has implemented the following scheme in fortran `HERWIG`:

Let us call p_i the momenta of the final state particles in their CM, and P_i the momenta of the corresponding parton shower (if i is coloured.). We have $\vec{p_i} = \vec{P}_i$, $P_i^5 \geqslant p_i^5$. Pick the $i = k$ with the largest $P_i^5 - p_i^5$, and reshuffle the P_i using two opposite boosts B_1 and B_2, such that B_1 is applied to P_k, and B_2 to all remaining P_i, and such that the total 3-momentum remains zero, and the total energy matches the initial energy.

New reshuffling scheme: full agreement of showered and LH results!



This fully confirms that reshuffling is at the heart of the problem. Summarizing:

- Original reshuffling: $\vec{p}_g, \vec{p}_t, \vec{p}_{\bar{t}}$ rescaled by same factor by 3 boosts
- New reshuffling: $\vec{p}_g, \vec{p}_t + \vec{p}_{\bar{t}}$ rescaled by same factor by 2 boost (t and $\bar{t}$ undergo the same boost, $m_{t\bar{t}}$ preserved)

Notice that other reshuffling alternatives are possible. For example:

Let us call p_i the momenta of the final state particles in their CM, and P_i the momenta of the corresponding parton shower (if i is coloured.). We have $\vec{p_i} = \vec{P}_i$, $P_i^0 \geqslant p_i^0$. Pick the $i = k$ with the largest $P_i^0 - p_i^0$, and reshuffle the set of momenta $p_i, i \neq k$, P_k, boosting the $p_i, i \neq k$ system as a whole.

Continue recursively with the next largest $P_i^0 - p_i^0$.

Other schemes may take into consideration colour correlated partons, and perform rescaling in a similar way to dipole shower generators.

Early Warnings (2007)

First POWHEG $t\bar{t}$ paper
Frixione, Ridolfi, P.N.
JHEP 0709 (2007) 126

Discrepancy in p_t of top between POWHEG and MC@NLO, both with HERWIG.

Contrary to expectations, HERWIG is responsible for the discrepancy.

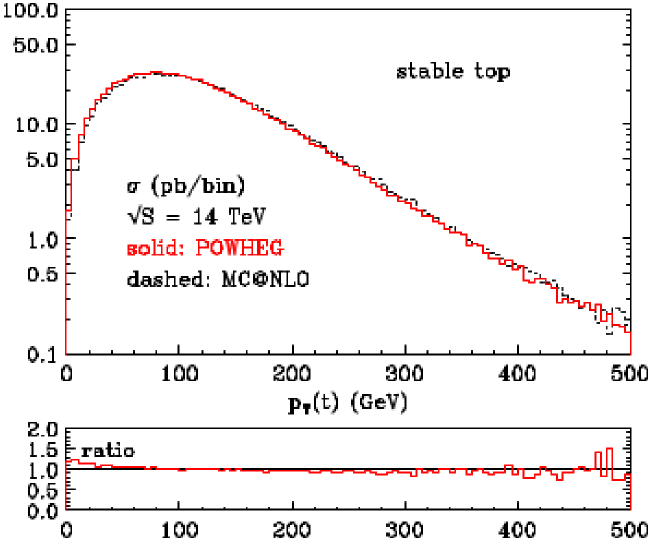


Figure 4: Transverse momentum distribution of a top quark at the LHC.

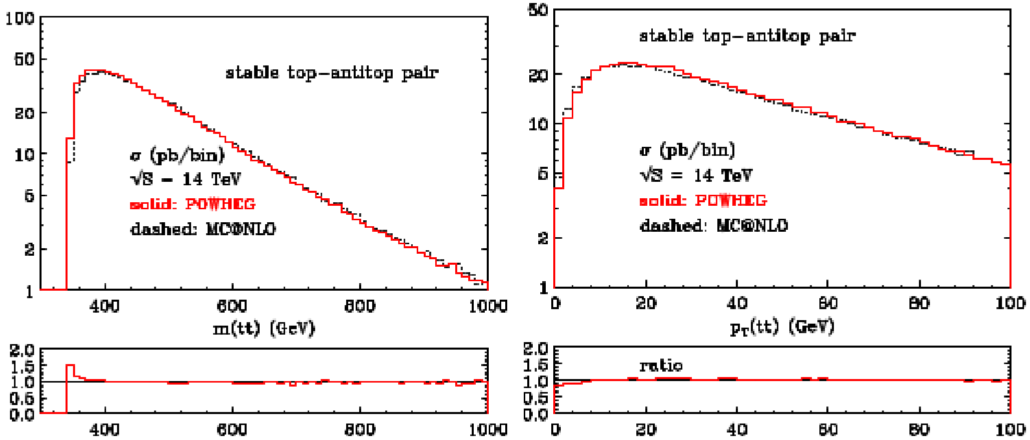


Figure 5: Invariant mass and transverse momentum distributions of $t\bar{t}$ pairs at the LHC.

Summary

- FSR momentum reshuffling of light radiated parton identified as the cause of the difference.
- The Jet mass is of order $E_j\alpha_s$; the change in energy is of order

$$\sqrt{\vec{p}^{\,2}+\alpha^2 E_j^2}-\sqrt{\vec{p}^{\,2}}\approx E_j\,\alpha_s^2 \quad \left(E_j\approx\sqrt{\vec{p}^{\,2}}\right)$$

that induces a momentum rescaling of order $p \to p \times (1-\alpha_s^2)$. This can be seen as a change in cross section of order α_s^4 (NNLO effect).
Can we exclude this option looking at NNLO results (Czakon and Mitov)?
Not so easy ... Detailed study show that for 20 GeV partons, the acquired energy is around 10 GeV. This suggests that multiple emissions may have an important role in this, not only NNLO.
Very conservative attitude: consider this difference as an uncertainty, wait for the community to reach consensus on admissible reshuffling procedures