Heavy Flavour Production

P. Nason

CERN and INFN, sez. di Milano Bicocca

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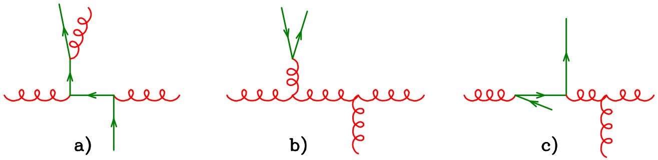
Outline

- Heavy Flavour production simulation
- Enhanced contributions at high p_T
- Analytic resummation for the p_T distribution: FONLL
- NLO+PS simulation
- recent POWHEG studies
- Conclusions

Simulation of heavy Flavour production

- In Shower Monte Carlo: the heavy quark mass acts as a cut-off for collinear singularities. Most modern implementations make use of splitting kernels that are adequate for massive flavours, as for example in the Dipole (Catani,Dittmaier,Seymour,Trocsanyi,2002 and antenna (Gehrmann-De Ridder,Ritzmann, Gehrmann-De Ridder,Ritzmann,Skands 2012, and in Höche,Prestel, 2015 (DIRE shower).
- Among the first NLO+PS generators ever implemented: `MCNLO`, Frixione,Webber,P.N.,2003, `POWHEG`, Frixione,Ridolfi,P.N.,2007

Yet, whenever dealing with transverse momenta much larger than the mass, heavy flavour production poses a difficult QCD two scale problem.



There are three regions of phase space in the production diagrams that are enhanced by one power of $\log p_T^2/m^2$ for each extra power of α_s, up to all orders of perturbation theory. These are

- Radiation from the produced quark (a).
- production via gluon splitting (b).
- production by flavour excitation (c).

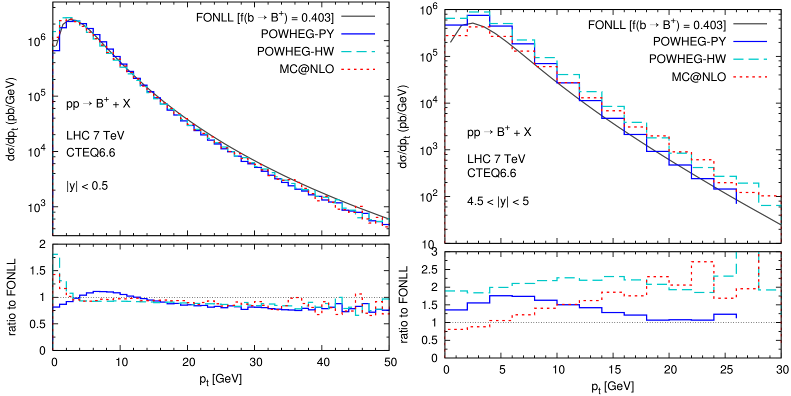
In early heavy-flavour production simulation, a mix of gluon-fusion, gluon splitting and flavour excitation was used to simulate heavy flavour production in Pythia.
This mix is still used: for example in CMS,2011, $B\bar{B}$ angular correlations based on SV reconstruction ...
(no much progress!),

Techniques for all order resummation of the enhanced logarithms are available

- Aivazis,Collins,Olness,Tung,1993 (ACOT), mostly used in DIS context,
- Cacciari,Greco,Nason,1998 (FONLL) for heavy flavour production in hadron-hadron and photon-hadron collisions.

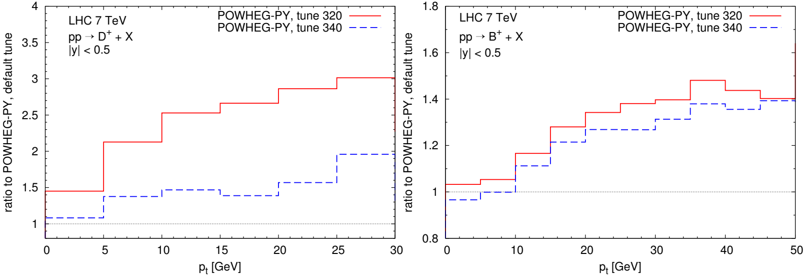
The FONLL method yields cross sections that include all terms of order $\alpha_s^2(\alpha_s \log p_T/m)^n$ and $\alpha_s^3(\alpha_s \log p_T/m)^n$.

Comparison with NLO+PS generators



(from Cacciari,Frixione,Houdeau,Mangano,Ridolfi,P.N. 2011)

Reasonably good comparison of NLO+PS with FONLL, some problems at high rapidity, and ...



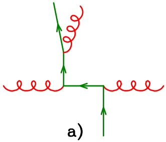
strong sensitivity to MC tuning of fragmentation parameters.

NLO+PS simulation

- OK at transverse momenta of the order of the quark mass
- For $p_t \gg m$, they don't resum properly the enhanced regions.
- Comparison with FONLL at large transverse momenta seems OK. Is this just an accident?

POWHEG studies

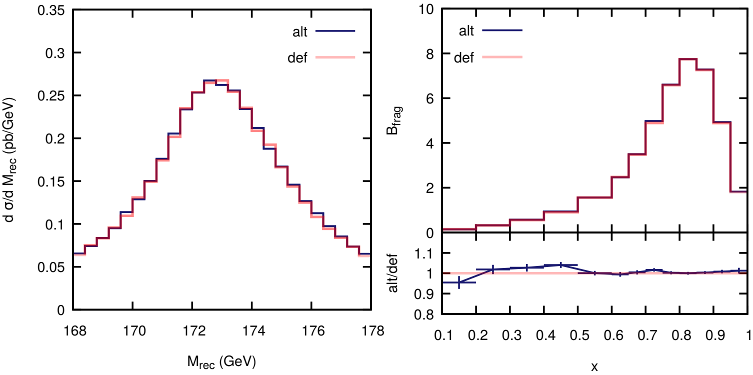
Radiation from heavy quarks:



- Framework for handling radiation from heavy quark available since Barzé,Montagna,Nicrosini,Piccinini,P.N. 2012, developed in the framework of EW corrections to W decays.
  Applied later to
  - $t\bar{t}$ prod. and decay Campbell,Ellis,Re,P.N. 2012
  - $pp \to b\bar{l}\nu_l \bar{b}\ell\bar{\nu}_\ell$, Ježo,Lindert,Oleari,Pozzorini,P.N. 2016

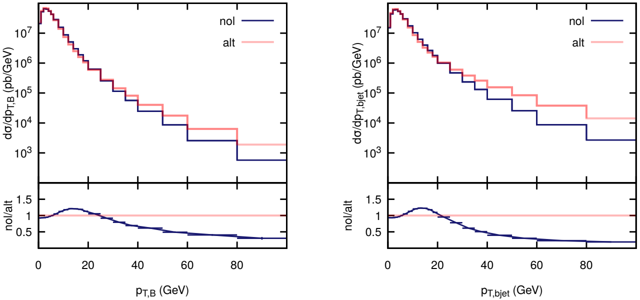
  Never applied to heavy flavour production
- Buonocore, Tramontano, P.N. 2017:
  - developed new (simpler and faster) method for the generation of radiation from heavy quarks in POWHEG.
  - Studied in b production.

Comparison of new and old method for top decays



The new and old method yield equivalent results for radiation from *b* quarks in top decays.

Comparison of old hvq generator (with no POWHEG treatment of radiation from heavy quark) and the same generator including the correct treatment of heavy quark radiation yields unacceptable results:



This behaviour is due to the fact that POWHEG separates the real contributions to the cross section into singular regions.

- Traditional hvq: only one singular region, i.e. ISR.
- New implementation: ISR plus radiation from heavy quark.

However, there are other singular regions: gluon splitting and flavour excitation.
The associated large contributions are split among the singular ones, and treated in an improper way.

Reminder

In POWHEG the real cross section (Born+radiation) is separated into singular regions:

$$R = \sum_{\alpha} R_{\alpha}, \qquad R_{\alpha} = \frac{d_{\alpha}^{-1}}{\sum_{\alpha'} d_{\alpha'}^{-1}}$$

The d_{α}: distance from the singular region.
(For example, for ISR d_{α} could be the p_T of radiation).

Each region α is treated with the appropriate kinematics, and the corresponding radiation is generated with the appropriate Sudakov form factor and couplings.

Thus:

- Traditional hvq: radiation from heavy quark, flavour exitation and gluon splitting are all treated as if they where ISR radiation effects.
- New implementation: flavour exitation and gluon splitting are all treated as if they where ISR radiation effects.

In order to remedy to this problem, we have separated out of the real contributions due to the flavour excitation and gluon splitting regions. We define the distances

$$\begin{aligned}
d_{\mathrm{isr}} &= k_t^2, & d_{\mathrm{glsp}} &= 2k_q \cdot k_{\bar{q}} \tfrac{k_q^0 k_{\bar{q}}^0}{(k_q^0 + k_{\bar{q}}^0)^2}, \\
d_q &= 2k_q \cdot k \tfrac{k^0}{k_q^0} + m_q^2, & d_{\bar{q}} &= 2k_{\bar{q}} \cdot k \tfrac{k^0}{k_{\bar{q}}^0} + m_q^2, \\
d_{q,\mathrm{flex}} &= k_{\bar{q},\perp}^2 + m_q^2, & d_{\bar{q},\mathrm{flex}} &= k_{q,\perp}^2 + m_q^2
\end{aligned}$$

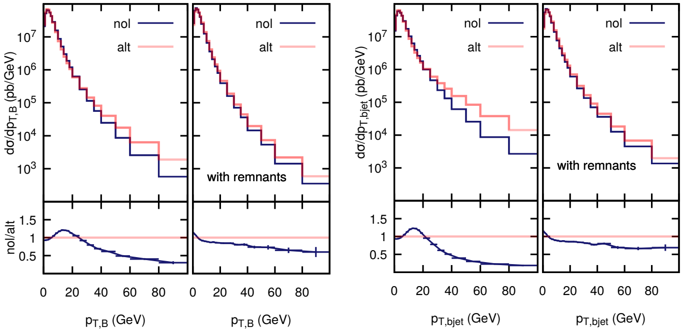
We then define for the traditional generator:

$$
\begin{aligned}
D &= \frac{d_{\rm isr}^{-1}}{d_{\rm isr}^{-1} + d_{\rm glsp}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1} + d_{q,\rm flex}^{-1} + d_{\bar{q},\rm flex}^{-1}}, \\
R^{(s)} &= RD, \qquad R^{(r)} = R(1-D)\,.
\end{aligned}
$$

and for the new one:

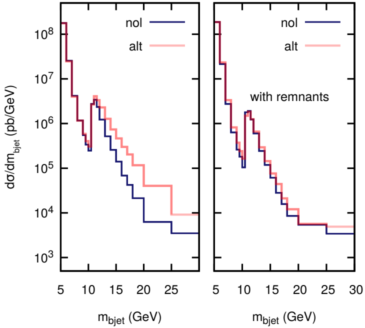
$$
\begin{aligned}
D &= \frac{d_{\rm isr}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1}}{d_{\rm isr}^{-1} + d_{\rm glsp}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1} + d_{q,\rm flex}^{-1} + d_{\bar{q},\rm flex}^{-1}} \\
R_i^{(s)} &= R_i D, \qquad R_i^{(r)} = R_i(1-D)\,,
\end{aligned}
$$

where i labels the three singular regions: ISR and radiation from the quark and the antiquark.
The $R^{(r)}$ terms are treated as remnants in POWHEG.



- Both nol (traditional) and alt (new) yield softer distributions when the remnant separation is performed.
- nol and alt are much closer with the remnant separation
- alt yields transverse momentum spectra that are closer to the traditional hvq generator (nol with no remnants).

It is interesting to look at the *b*-jet mass:



The peak at 10 GeV is when both *B*'s are in the same jet, i.e. can be thought as due to gluon splitting. Here we see that the treatment with remnants is considerably different from the traditional one.

Conclusions

- We have reconsidered heavy flavour production in POWHEG, introducing new options in the treatment of the enhanced regions.
- There is quite some room for variants, and it would be important to test these new options by comparing with data, using double differential cross sections, both in B hadrons and in b-jets.
- Large transverse momentum production of $t\bar{t}$ pair can be measured at the LHC, and even more so at the high-luminosity phase. An accurate modeling of $t\bar{t}$ production is mandatory, also because this process constitute an important background to several new-physics searches. The study of b production can certainly contribute important information for an accurate top modeling.