Heavy quark radiation in NLO+PS

Francesco Tramontano
francesco.tramontano@unina.it

Università “Federico II” & INFN sezione di Napoli

in collaboration with:
Luca Buonocore and Paolo Nason

Higgs Couplings 2018 - KFC center - Tokyo 26-30 November 2018
The LHC is an heavy quark factory

- radiation accompanying top and bottom production have to be known accurately to make tests of the Standard Model and discoveries at the LHC
  - about 60% of the Higgs bosons decay into bottom quarks
  - background processes for Higgs boson production and its decay into bottom quarks are important sources of background also for a large number of BSM searches at the LHC
  - good knowledge of radiation from top quarks at large transverse momentum mandatory to disentangle genuine BSM signal from SM physics
Higgs boson decay

- Radiation from bottom quarks

- Although there is not a real collinear divergence, the emission of a quasi collinear gluon provides an enhancement of the cross section for this phase space region
Higgs boson decay

- The enhancement could be “resummed” including it in the POWHEG Sudakov and matching the full NLO corrections to the Higgs boson decay to the Parton Shower

- more and more important when the emitter is lighter and lighter wrt the scale of the process (here of the order of the Higgs mass)
  - Electroweak corrections
Higgs boson decay

- The enhancement could be “resummed” including it in the POWHEG Sudakov and matching the full NLO corrections to the Higgs boson decay to the Parton Shower.

- NLO corrections to Higgs boson decay into bottom quarks recently matched to PS for VH(bb) production under POWHEG-BOX-RES [Astill, Bizoń, Re, Zanderighi 2018]
  - also doable of course for VBFH(bb), ttH(bb) and ggH(bb)
Higgs boson decay

- good modelling of heavy quark radiation is also relevant to quantify $V_{bb}$ background to the associated production $VH(bb)$ (ongoing study in the HXSWG)

\[ \bar{b} \rightarrow b \]
\[ u \rightarrow d/\bar{d} \]
\[ W^+/Z \]

- and also for a precise knowledge of the signal

\[ \bar{b} \rightarrow b \]
\[ Z \rightarrow b \]
for heavy flavour production in QCD the situation is more involved

- many experimental data (and rivet analyses available)
- plan to measure cross section at very high pt (~1 TeV) at HL-LHC

at large transverse momentum of the heavy quark each of these diagrams provide an enhancement of $\alpha_s \log p_T^2/m^2$ up to all orders in perturbation theory
General case

- **FONLL**: in this approach the resummation of these large logarithms is matched to the fixed order prediction that is valid at small transverse momentum of the heavy quark

  \[\text{[Cacciari, Greco, Nason, 1998]}\]

- however this approach predicts “only” doubly differential (pt and rapidity) single inclusive distributions. 
  Not an event generator
General case

- In Shower Monte Carlo programs the heavy quark mass acts as a regulator for the collinear singularities.

  ‣ Modern implementations make use of splitting kernels specific for massive flavours.

    Dipole [Catani, Dittmaier, Seymour, Trocsanyi 2002]
    Antenna [Gehrmann-De Ridder, Ritzmann, Skands 2012]
    DIRE shower [Höche, Prestel 2015]

  ‣ Correct at leading logarithmic level and fully exclusive. Not enough to claim control over normalisation and the additional jet activity
General case

• NLO+PS generator for heavy quark production available since long

  MC@NLO [Frixione, Nason, Webber 2003]
  POWHEG [Frixione, Nason, Ridolfi 2007]

  ‣ no special treatment of radiation from heavy quarks
FONLL vs NLO+PS
[Cacciari, Frixione, Houdeau, Mangano, Nason, Rodolfi 2011]

- Reasonably good agreement at low rapidity
- some differences at large rapidity
Strong sensitivity to Monte Carlo tuning of fragmentation parameters
NLO+PS

- NLO+PS OK at transverse momentum of the order of the heavy quark mass
- for \( p_T \gg m \) they do not resum properly the enhanced regions
  - comparison with FONLL at large \( p_T \) seems ok.
    Just an accident?
Let’s consider radiation from the heavy quark contrary to the other two real radiation configurations there exist and underlying Born configuration among the Born subprocesses. It is possible to include this kind of collinear enhancement consistently in the POWHEG framework.
POWHEG studies

\[d\sigma_{NLO} = \bar{B} \, d\Phi_n \left[ \Delta(\Phi_n, t_{min}) + \sum_\alpha \frac{[d\Phi_{rad} \Delta(\Phi_n, K_\perp(\Phi_{n+1}) R(\Phi_{n+1})]}{B(\Phi_n)} \right] \]

\[\Delta(\Phi_n, p_T) = \Theta(p_T - t_{min}) \exp \left( -\sum_\alpha \frac{[d\Phi_{rad} \Theta(K_\perp(\Phi_{n+1}) - p_T) R(\Phi_{n+1})]}{B(\Phi_n)} \right) \]

- in the early version of POWHEG for heavy quark production, just a single radiation region was considered correspond to the true divergence all captured by ISR

- in the newer version the collinear emission from heavy quark is added as another radiation region

  \[ K_\perp \text{ has to be a smooth function of the radiation variables that has to reduce to the transverse momentum in approaching the soft and collinear limits} \]

  \[ K_\perp^2 = 2 \frac{k^0}{p^0} p \cdot k \]

  \( p \) massive quark

  \( k \) emitted gluon

[Barzé, Montagna, Nason, Nicrosini, Piccinini 2012]
POWHEG studies

\[ d\sigma_{NLO} = \bar{B} \, d\Phi_n \left[ \Delta(\Phi_n, t_{min}) + \sum_{\alpha} \frac{[d\Phi_{rad}\Delta(\Phi_n, K_{\perp}(\Phi_{n+1})R(\Phi_{n+1})]_{\alpha}}{B(\Phi_n)} \right] \]

\[ \Delta(\Phi_n, p_T) = \Theta(p_T - t_{min}) \exp \left( -\sum_{\alpha} \frac{[d\Phi_{rad}\Theta(K_{\perp}(\Phi_{n+1}) - p_T)R(\Phi_{n+1})]_{\alpha}}{B(\Phi_n)} \right) \]

- On a more technical ground an efficient integration and event generation a là POWHEG is based on the construction of:
  - a mapping of the real phase space configurations into a born configuration plus radiation variables (and its inverse)
    \[ \Phi_{n+1} \leftrightarrow \Phi_n, \quad \Phi_{rad}(\xi, y, \phi) \]
  - an appropriate upper bound function for the ration R/B in the heavy quark radiation region

- First done in [Barzé, Montagna, Nason, Nicrosini, Piccinini 2012] called def in the following

- More recently an alternative method proposed in [Buonocore, Nason, FT 2018] (simpler and faster) called alt in the following
Validation of the methods

• Setup

  ‣ HVQ generator: 200GeV pp collisions and 1.96TeV ppbar;  
b_bbar_4l generator: 13TeV pp collisions

  ‣ NNPDF3.0

  ‣ Pythia 8.2.23

  ‣ mb=4.75GeV, mt=173.2GeV
Validation of the methods

- NLO plots: HVQ generator for 200GeV pp collisions

- non trivial check: mapping construction with an independent formulation
- perfect agreement is found
Validation of the methods

- NLO+PS plots: b_bbar_4l @ 13TeV + Pythia

- check: Monte Carlo implementation of upper bound function
- new and old methods yield equivalent results for radiation from b quarks in top decay
hvq generator for b quarks

- Comparison of old hvq generator (no POWHEG treatment of radiation from heavy quark) and the same generator including the correct treatment of heavy quark radiation yields unacceptable differences:
hvq generator for b quarks

• This behaviour is not totally unexpected

• POWHEG separates the real cross section into singular regions.
  ‣ Traditional hvq (nol): only one singular region, i.e. ISR.
  ‣ New implementation (alt): ISR plus radiation from heavy quark.

• However, there are the other logarithmically enhanced regions:

  ![Diagram](image)

  a) b) c)

• The large contributions associated to gluon splitting and flavour excitation are split among the singular ones, and treated in an improper way in both generators
POWHEG (reminder)

• The real cross section (Born+radiation) is separated into singular regions:

\[ R_\alpha = \frac{d^{-1}_\alpha}{\sum_{\alpha'} d^{-1}_{\alpha'}} R \]

\[ R = \sum_{\alpha} R_\alpha \]

• \( d_\alpha \) quantify the distance from the singular region, for example for ISR one can use \( d_{iSR} = k_T \) of the radiation

• the contribution to the cross section from each region is computed using the appropriate kinematics and stored

• radiation is then attached to Born configurations that embody the whole NLO cross section, on the base of the relative contribution from each radiation region and distributed according to the corresponding Sudakov form factor
hvq generator for b quarks

- In order to remedy to this problem, we have separated out the real contributions due to the flavour excitation and gluon splitting regions

- We define the distances

\[
\begin{align*}
d_{\text{ISR}} &= k_t^2 \\
d_q &= 2k_q \cdot k_{\frac{k_0}{k_q}} + m_q^2 \\
d_{q,\text{flex}} &= k_{\frac{k_0}{q},\bot}^2 + m_q^2 \\
d_{\bar{q},\text{flex}} &= k_{\frac{k_0}{\bar{q}},\bot}^2 + m_q^2 \\
d_{\text{GLSP}} &= 2k_q \cdot \frac{k_0}{k_q} \cdot \frac{k_q \cdot k_\bar{q}}{(k_0 + k_\bar{q})^2} \\
d_{\bar{q}} &= 2k_\bar{q} \cdot k_{\frac{k_0}{k_\bar{q}}} + m_q^2 \\
R_{\alpha} &= \frac{d_{\alpha}^{-1}}{\sum_{\alpha'} d_{\alpha'}^{-1}} R \\
R &= \sum_{\alpha} R_{\alpha}
\end{align*}
\]
We then define for the traditional generator:

\[ D = \frac{d_{\text{isr}}^{-1}}{d_{\text{isr}}^{-1} + d_{\text{glsp}}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1} + d_{q,\text{flex}}^{-1} + d_{\bar{q},\text{flex}}^{-1}} \]

\[ R^{(s)} = RD \quad R^{(r)} = R(1 - D) \]

and for the new one:

\[ D = \frac{d_{\text{isr}}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1}}{d_{\text{isr}}^{-1} + d_{\text{glsp}}^{-1} + d_{q}^{-1} + d_{\bar{q}}^{-1} + d_{q,\text{flex}}^{-1} + d_{\bar{q},\text{flex}}^{-1}} \]

\[ R^{(s)}_{i} = R_{i}D \quad R^{(r)}_{i} = R_{i}(1 - D) \]

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.
First comparisons with data (preliminary)

- Comparison with B hadron pair production measured by ATLAS @ LHC8
  - 3 muon signal: $b\, b \rightarrow B(J/\psi(\mu\mu)) \, B(\mu)$
  - selection: (dressed) muon pt > 6, $|\eta| < 2.5$ (2.3 for J/Ψ muons)

  [Aaboud et al, ATLAS collaboration 1705.03374]
  [rivet analysis 11598613]

- in the following the case with special treatment of the radiation from heavy quark will be called asl (for as light)

- we compare data with:
  - nol: traditional hvq generator
  - nol-remn: hvq generator with remnant separation of the 3 enhanced regions
  - asl-remn: hvq generator with radiation from heavy quark in the POWHEG Sudakov and the gluon splitting and flavour excitation in the remnants
First comparisons with data (preliminary)

- Only normalised distributions available
- Treatment of radiation from heavy quark and separation of the enhanced regions improve shape comparisons

[Aaboud et al, ATLAS collaboration 1705.03374]
First comparisons with data (preliminary)

[Aaboud et al, ATLAS collaboration 1705.03374]

- Only normalised distributions
- Treatment of radiation from heavy quark and separation of the enhanced regions improve shape comparisons
Region specific remnant separation

- We define also separations that are specific for each radiation region:

\[
D_{\text{isr}} = \frac{d_{\text{isr}}^{-1}}{d_{\text{isr}}^{-1} + d^{-1}_{\text{glsp}} + d_{q,\text{flex}}^{-1} + d_{\bar{q},\text{flex}}^{-1}}
\]

\[
D_q = \frac{d_q^{-1}}{d_{\text{glsp}}^{-1} + d_q^{-1} + d_{q,\text{flex}}^{-1} + d_{\bar{q},\text{flex}}^{-1}}
\]

\[
D_{\bar{q}} = \frac{d_{\bar{q}}^{-1}}{d_{\text{glsp}}^{-1} + d_{\bar{q}}^{-1} + d_{q,\text{flex}}^{-1} + d_{\bar{q},\text{flex}}^{-1}}
\]

\[R_i^{(s)} = R_i D_i, \quad R_i^{(r)} = R_i (1 - D_i)\] with no summation on repeated \(i\) index.

Note: now there is no need to regularise the soft divergence with the quark mass.

\[
d_q = 2k_q \cdot k \frac{k_0^0}{k_q^0}
\]

\[
d_{\bar{q}} = 2k_{\bar{q}} \cdot k \frac{k_0^0}{k_{\bar{q}}^0}
\]
First comparisons with data (preliminary)

• Comparison with B hadron pair production measured by CMS @ LHC7
  ‣ selection: $p_t(B) > 15$, $|\eta(B)| < 2$

[Khachatryan et al, CMS collaboration 1102.3194]  
[rivet analysis S8973270]
First comparisons with data (preliminary)

• Reasonable level of agreement, for both normalisation and shapes, for all pt cuts
• Slight improvement wrt the previous remnant separation criterium
Conclusions

• Large transverse momentum production of heavy quark pairs (b and t) can be measured at the LHC, and even more so at the high-luminosity phase. An accurate modelling of both is mandatory, also because this process constitute an important source of background to several new-physics searches.

• Such studies are relevant also to the aim of improving the event generation for the production and decay of resonances into heavy quarks and the associated production of heavy quarks and gauge bosons.

• We have reconsidered heavy flavour production in POWHEG, introducing new options in the treatment of the enhanced regions.

• Next step is the systematic comparison with all available data, using double differential cross sections, both in B hadrons and in b-jets.

• The exploration is just started and there is quite some room for variants.
Conclusions

• Large transverse momentum production of heavy quark pairs (b and t) can be measured at the LHC, and even more so at the high-luminosity phase. An accurate modelling of both is mandatory, also because this process constitute an important source of background to several new-physics searches

• Such studies are relevant also to the aim of improving the event generation for the production and decay of resonances into heavy quarks and the associated production of heavy quarks and gauge bosons

• We have reconsidered heavy flavour production in POWHEG, introducing new options in the treatment of the enhanced regions

• next step is the systematic comparison with all available data, using double differential cross sections, both in B hadrons and in b-jets

• The exploration is just started and there is quite some room for variants

Stay tuned!