Heavy quark mass effects for initial state parton showers in Herwig and Herwig++

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Motivation – FOPT vs. VFNS

- heavy quark mass – a new scale in the hard process
- potentially large logarithmic terms $\left[\alpha_S \ln\left(m_b^2 / \mu^2\right)\right]^n$ which should be resummed – really?
- two solutions:

FOPT – Fixed Order Perturbation Theory

- allows for the heavy flavours only in the final state
- doesn't resum logarithms

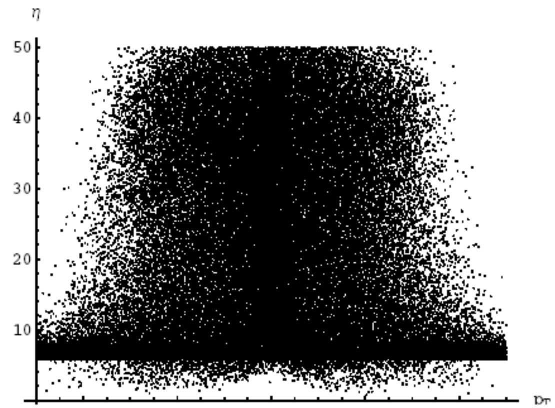
VFNS – Variable Flavour Number Scheme

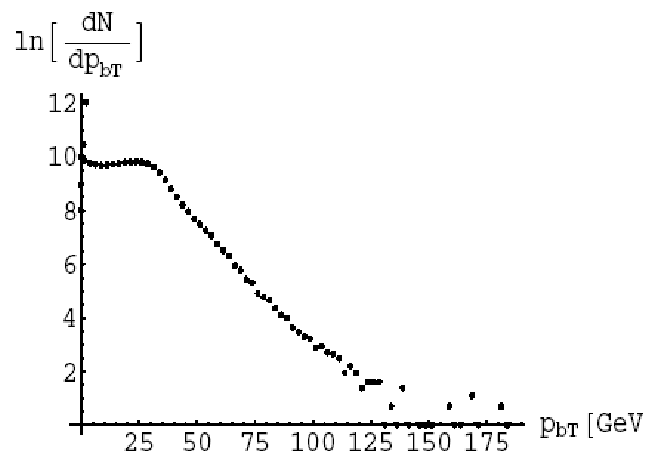
- the flavours appear in the initial state
- treats heavy flavours as massless – unable to describe threshold effects

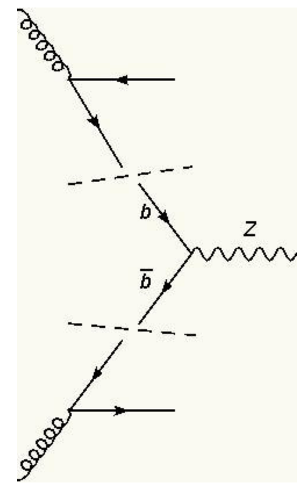
can we have an interpolation in Monte Carlo?

b production in Herwig

- b-quarks naturally appear in initial state parton showers in Drell-Yan production in pp collisions
- strange pt distribution
- massless b-quarks
- cut on radiated parton pt to simulate the dead cone effect
- NO dead cone effect in $g \to b\bar{b}$
- NO coherence effect $g \to b\bar{b}$
- angular ordering inappropriate
- forced non-perturbative splitting







In Herwig++

- situation similar to Herwig:
- mass effects in parton showers – only parton showers from final state – quazi collienar approximation
- no forced b-quarks
- massless heavy quarks in the initial state parton showers
- cut on emitted parton pt
- angular ordering for coherence

Quazi-collinear approximation

- by calculating the splitting functions (SF) not only $q_\perp \to 0$ but also $m \to 0$ by keeping $m \sim q_\perp$
- the SFs factorize and include additional terms

$$P_{Qg}\left(z, m_Q^2 / q_{Q\perp}^2\right) = T_R\left(\frac{2m_Q^2}{m_Q^2 + q_{Q\perp}^2} z(1-z) + z^2 + (1-z)^2\right)$$

$$P_{gQ}\left(z, m_Q^2 / q_{Q\perp}^2\right) = C_F\left(-\frac{2m_Q^2}{z^2 m_Q^2 + p_{Q\perp}^2} z(1-z) + \frac{1+(1-z)^2}{z}\right)$$

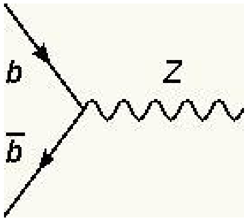
$$P_{QQ}\left(z, m_Q^2 / q_{Q\perp}^2\right) = C_F\left(-\frac{2m_Q^2}{(1-z)^2 m_Q^2 + p_{Q\perp}^2} z(1-z) + \frac{1+z^2}{1-z}\right)$$

- the most important SF is the P_{Qg}
- the changes also affect the Sudakov formfactor

The algorithm

- we neglect the gluon emissions from the heavy quark
- we treat the heavy quark emission separately from the parton shower program

  - starting from the hard subprocess at the scale $\tilde{q}_0 = m_Z$



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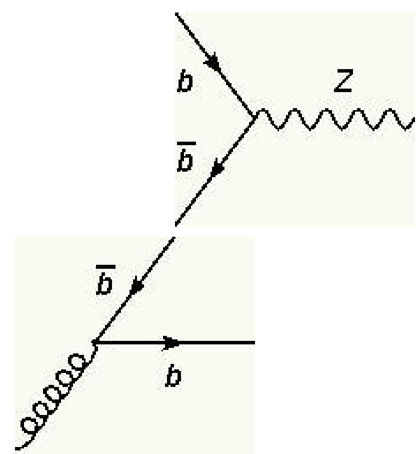

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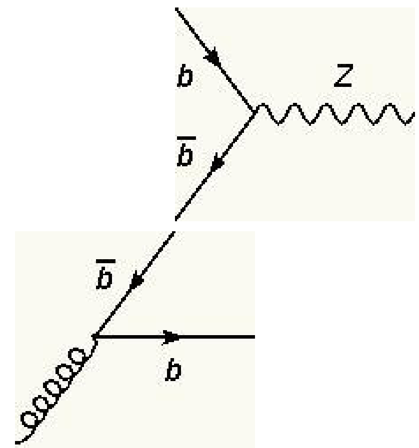
  - evolving to lower scale $\tilde{q}$
  - boost to conserve momentum



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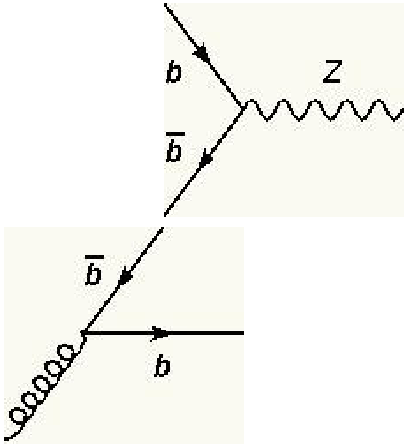
  - starting from the hard subprocess at the scale $\tilde{q}_0 = m_Z$
  - evolving to lower scale $\tilde{q}$
  - boost to conserve momentum
  - shower partons



Emission probability

- the probability for emission of the heavy quark at the scale $\tilde{q}$ is

$$P_{Qg}\left(\tilde{q}, x, m_Q\right) = \frac{\alpha_S\left(z, \tilde{q}\right)}{2\pi} \frac{d\tilde{q}}{\tilde{q}} \Delta\left(\tilde{q}_0, \tilde{q}, x, m_Q\right) \int_x^1 dz P_{Qg}\left(z, m_Q^2 / q_{Q\perp}^2\right) \frac{\frac{x}{z} f_g\left(x/z, \tilde{q}\right)}{x\, f_b\left(x, \tilde{q}\right)}$$

where

$$\Delta\left(\tilde{q}_0, \tilde{q}, x, m_Q\right) = \exp\left(-\int_{\tilde{q}}^{\tilde{q}_0} \frac{d\tilde{q}'}{\tilde{q}'} \frac{\alpha_S\left(\tilde{q}'\right)}{2\pi} \int_x^1 dz P_{Qg}\left(z, m_Q^2 / q_{Q\perp}^2\right) \frac{\frac{x}{z} f_g\left(x/z, \tilde{q}'\right)}{x\, f_b\left(x, \tilde{q}'\right)} \right)$$

- Sudakov formfaktor resumms the logarithmic terms with mass of the heavy quark
- emissions according to the probability distribution are generated using the veto algorithm

Veto algorithm

- one starts with at the starting scale $\tilde{q}_0$
- first one generates the new value scale and z according to an overestimate of the Sudakov formfaktor by introducing

$$P_{Qg}^{\text{over}} = \frac{1}{2}, \qquad PDF^{\text{over}} \geq \frac{\frac{x}{z} f_g\left(\frac{x}{z}, \tilde{q}\right)}{x\, f_b(x, \tilde{q})} \;\forall\, z, \tilde{q}, x\,, \qquad \alpha_S^{\text{over}}$$

- second step consists from accepting or rejecting the new values according to a veto

$$\frac{\alpha_S(z,\tilde{q})}{\alpha_S^{\text{over}}} \frac{P_{Qg}\left(z, m_Q^2 / q_{Q\perp}^2\right)}{P_{Qg}^{\text{over}}} \frac{\frac{x}{z} f_g\left(\frac{x}{z}, \tilde{q}\right)}{x\, f_b\left(x, \tilde{q}\right)} < \mathcal{R}$$

where $\mathcal{R}$ is a random number from (0,1). If rejected the new scale is chosen as the starting scale and the procedure is repeated

The choice of the scale

- the angular ordering – the evolution scale $E_i\theta_i$ – is not appropriate
- the choice of the evolution scale is not obviously clear
- we tried these choices:
  - transversal momentum of the emitted heavy Q
  - virtuality of the evolved heavy Q
  - the angular scale from Herwig++
- we have applied presented algorithm to Z boson production in $b\bar{b}$ annihilation
- we compared the pt distributions of the emitted bottom with the pt distribution of b from MCFMs $gg \to b\bar{b}Z$

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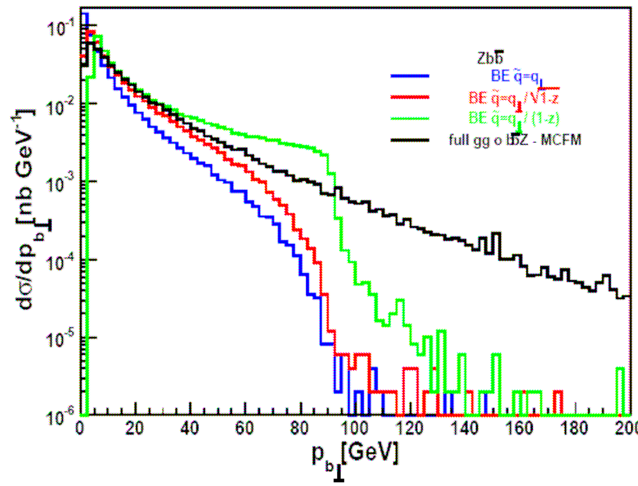

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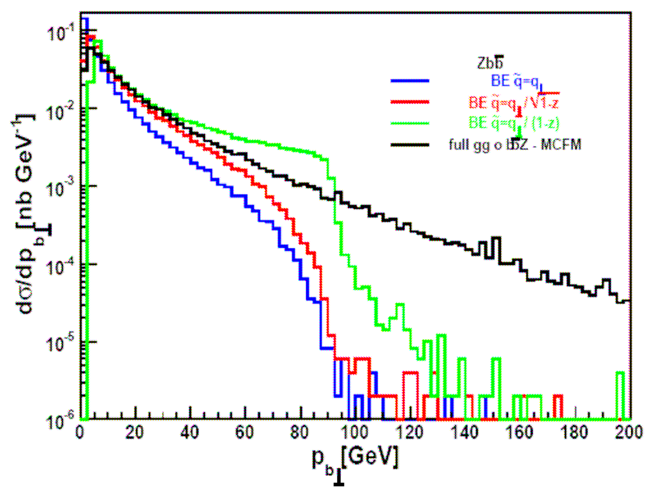

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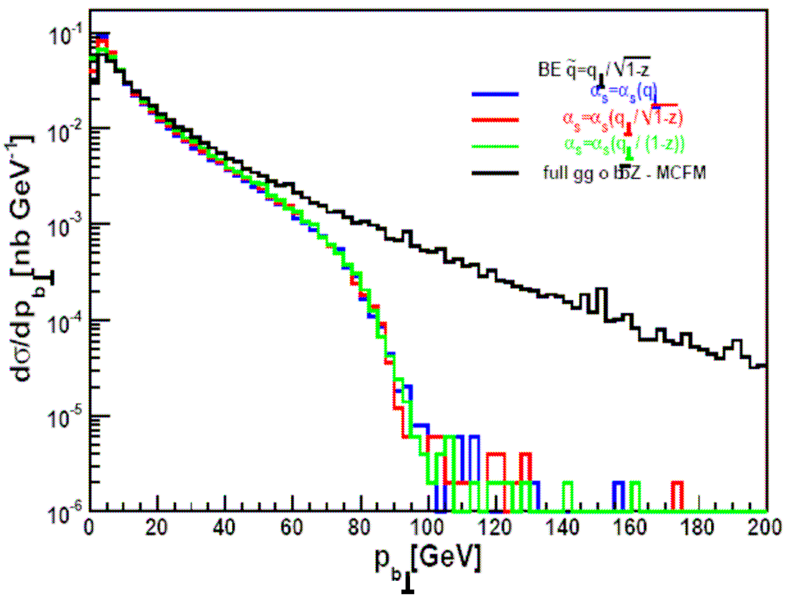
Scale in α_S

- there is freedom in choosing the scale for the running of α_S
- one can look at how the distributions vary with the scale for α_S



for evolution scale – virtuality of heavy quark

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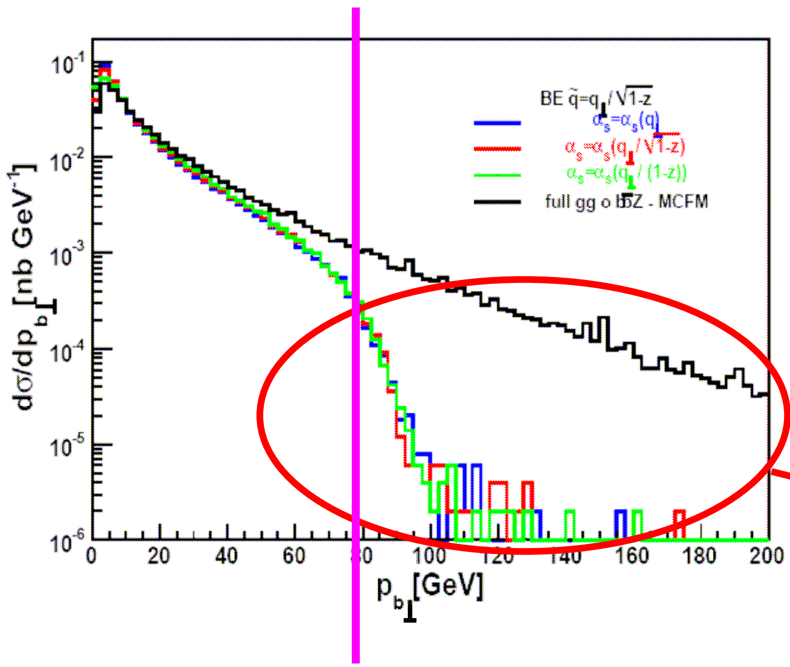


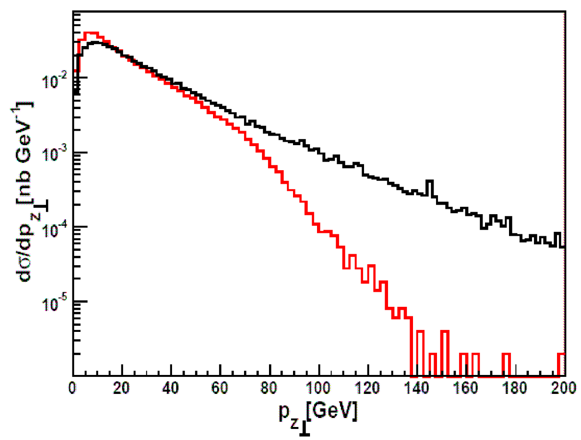
for evolution scale –
virtuality of heavy quark

missing pt tail
matrix element
corrections needed

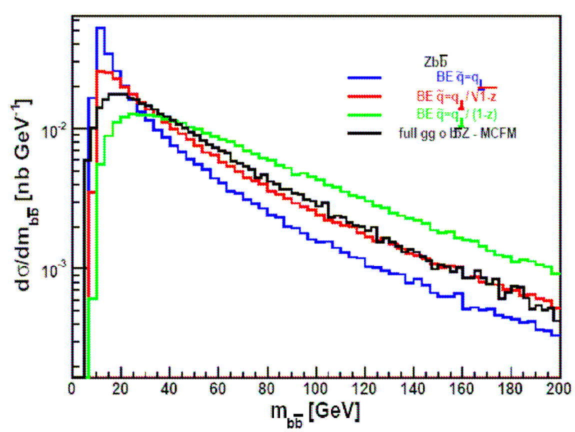
- there are small variations in very small pt region

Other distributions

- the transversal momentum of the *Z* boson generated mainly by the pts of the quarks is also of interest



- in the distribution of invariant mass $m_{b\bar{b}}$ of the quark-antiquark pair



Summary and outlook

- motivation why to be interested in treating heavy quarks differently in Monte Carlo generators – especially in parton shower programs
- one step forward in this direction was done
- splitting functions for initial state massive partons were obtained in quasi-collinear limit
- subroutine for generating heavy quark emission based on veto algorithm was written
- results for various distributions were presented
- next step will be matrix element correction of the heavy quark pt tail