~~Heavy flavour in Pythia 8~~
Heavy flavour in showers only

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Heavy Flavour Production at the LHC

IPPP Durham, April 21, 2016

Outline

~~This will be a review of some heavy flavour aspects of Pythia 8:~~

1. Parton shower *initial state / final state*

~~2. Matching & merging~~

~~3. Hadronization and particle decay~~

Sources of mass effects in parton showers

(a) Radiator masses, emission mass (e.g. tabulated in Nucl.Phys. B603 (2001) 297-342)
(b) Recoiler mass, virtuality, dipole mass
(c) Kinematics

General belief: Parton shower should always reduce to DGLAP in the (pseudo)-collinear limit.

But keep in mind: We need to set up kinematics. Not all gluons can split into quarks! DGLAP kernels capture the phase space constraints *only* in particular phase space limits.

Comments:
DGLAP kernels contain divergences in the anti-collinear direction, which has to be removed "by hand" $\Rightarrow$ Angular ordering, dipole showers
Expected differences:
Different z-definitions, evolution-$p_\perp$, phase space factorization all give different mass effects.

Heavy flavour in ISR (I)

For heavy initial quarks, ISR is split into two regions:

Above km_Q^2	Between $m_Q^2 < p_\perp^2 < km_Q^2$

Above km_Q^2

- Massless kernels (possibly with massless ME correction)
- Massive kinematics

For heavy initial quarks, ISR is split into two regions:

Above km_Q^2	Between $m_Q^2 < p_\perp^2 < km_Q^2$

Between $m_Q^2 < p_\perp^2 < km_Q^2$ $(k = 4)$

- Forced evolution of b-quark with only $g \to b\bar{b}$ conversion. No gluon radiation off b-quark.
- Massive kernel
- Conversion forced around threshold.

$\Rightarrow$ **Pythia will always produce a final state b-quark!**

Does this have an effect?

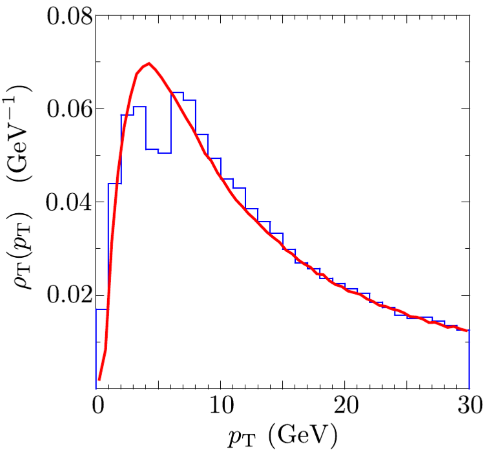
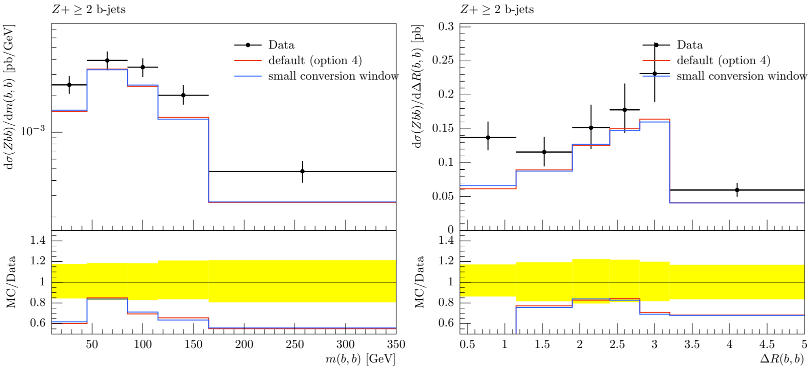


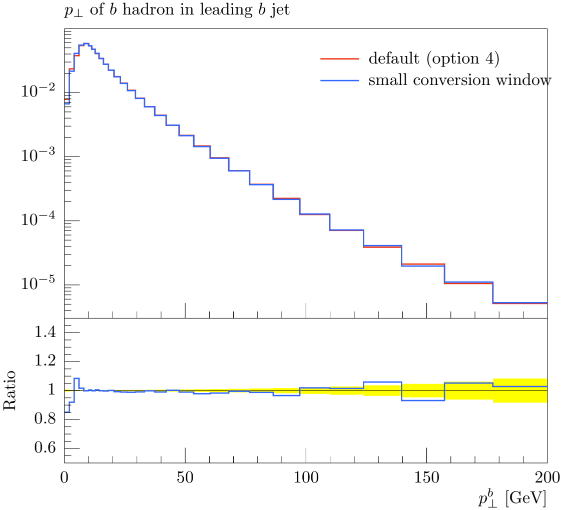
Figure ($p_\perp$ of b-quark in $b\bar{b} \to Z$, boosted Z) taken from arXiv:1401.6364 [hep-ph] by Nagy, Soper

Heavy flavour in ISR: Realistic results



Variation of b-conversion window: Default uses $k = 4$, small window uses $k = 1.01$

Heavy flavour in ISR: Realistic results



Variation of b-conversion window: Default uses $k = (2)^2$, small window uses $k = (1.1)^2$

Heavy flavour in FSR (I)

Mass effects in FSR come from three sources:

(a) Matrix element corrections (mostly V-emission, BSM showers)
Removing ME corrections can mean no mass effects!

(b) $g \to b\bar{b}$ splitting

(c) Massive recoilers in $g \to gg$ splittings[1]

The construction of $g \to b\bar{b}$ allows choices:

Evolution variable can be different from g-emission case

Energy sharing variable can be different from g-emission case

Effect of finite dipole mass (phase space boundaries)?

Argument of running coupling?

[1] *Recent suggestion by Thaler, Maltoni and Selvaggi. Less realistic dead cone without this. Thanks!*

Options by Sjöstrand,
see online manual

Choices for $g \to b\bar{b}$ $\Rightarrow$ Pythia allows to assess effect by offering various kernels.

Basic observations:

Quark masses for $e^+e^- \to \gamma^* \to Q\bar{Q}$ mean

$$\frac{d\sigma(e^+e^- \to \gamma^* \to Q\bar{Q})}{d\cos\theta} \propto \beta\left(1+\cos^2\theta + \frac{4m_Q^2}{m_{\gamma^*}^2}\sin^2\theta\right)$$
$$\propto \beta\left(z^2+(1-z)^2+\frac{8m_Q^2}{m_{\gamma^*}^2}z(1-z)\right)$$

Last part is ony true if $z_\theta = \frac{1+\cos\theta}{2}$, not for $z = \frac{(E+p_z)_Q}{(E+p_z)_\gamma}$.
Using angle directly very complicated: Depends on virtuality (only known after z is chosen) and "dipole mass" $m_{\gamma^*}^2$.

Heavy flavour in FSR: $g \to b\bar{b}$ (II)

Options by Sjöstrand, see online manual

$e^+e^- \to \gamma^* \to Q\bar{Q}$ does not address going from 2 to 3 on-shell particles.
$\Rightarrow$ Rederive kernel from $h \to gg \to b\bar{b}g$, use (z, Q^2, m_D^2) to calculate z_θ
$\Rightarrow$ New kernel option:

$$W_4(z_\theta) \quad = \quad \beta\left[z_\theta^2 + (1-z_\theta)^2 + 8rz_\theta(1-z_\theta)\right]\frac{(1+\delta)}{(1-\delta)}(1-\delta)^3 \quad \text{"full ME"}$$

with $r = m_Q^2/Q^2$, $\beta = \sqrt{1-4r}$ and $\delta = Q^2/m_D^2$.

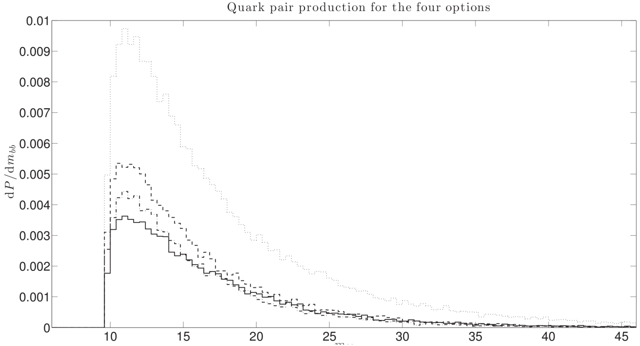
Integrated rate agrees with DGLAP if the factor $(1-\delta)^3$ is removed:
$\Rightarrow$ New kernel option:

$$W_3(z_\theta) \quad = \quad \beta\left[z_\theta^2 + (1-z_\theta)^2 + 8rz_\theta(1-z_\theta)\right]\frac{(1+\delta)}{(1-\delta)} \quad \text{"simple } m_D \text{ correction"}$$

These options differ by their virtuality and dipole mass dependence.

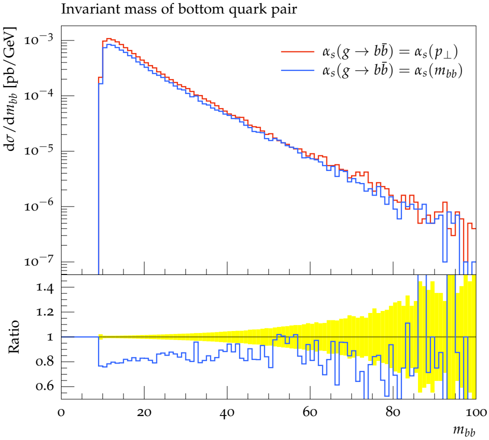
Heavy flavour in FSR: Theory results

Figure 8: Bottom-antibottom pair production as a function of the invariant mass. Pythia options: default (solid), 2 (dashed), 3 (dotted) and 4 (dashed-dotted).



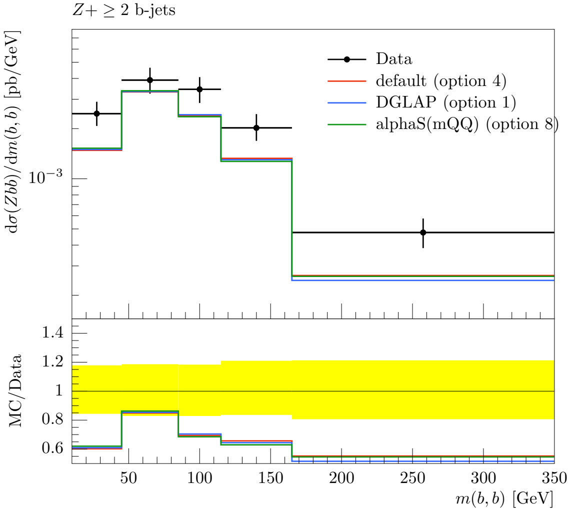
Invariant mass of b pairs at LEP, from LU TP 14-15 master thesis.

We can also investigate the effect of $\alpha_s(p_\perp^2) \to \alpha_s(m_{qq}^2)$



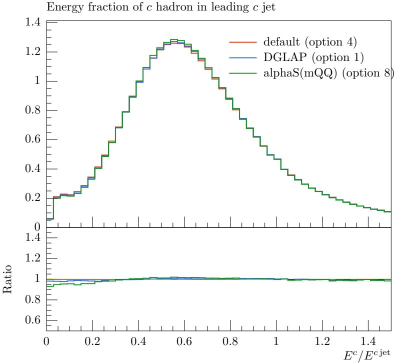
Invariant mass of b's at *ee*@200 GeV. Moderate overall shift. (Rivet analysis by Frank Krauss)

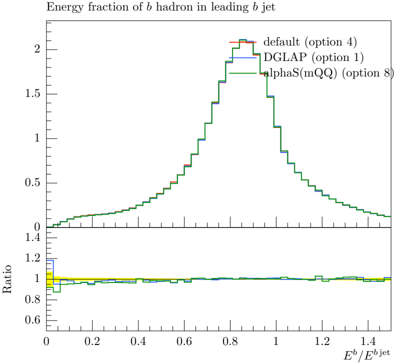
Heavy flavour in FSR: Realistic results



Invariant mass of b-jet pairs, from JHEP 1410 (2014) 141

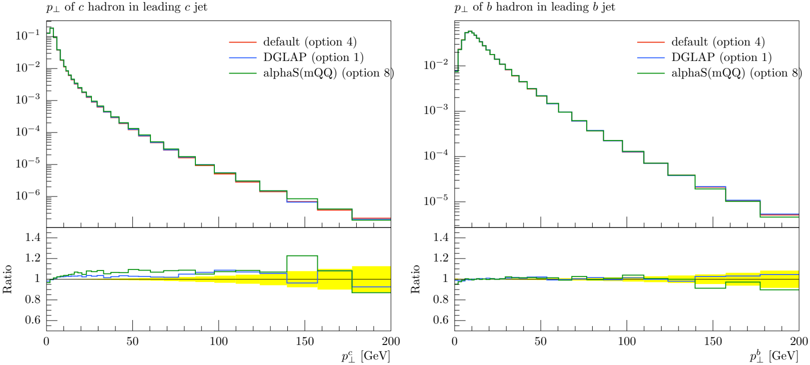
Heavy flavour in FSR: Realistic results





Rivet analyis by Andy Buckley.

Heavy flavour in FSR: Realistic results



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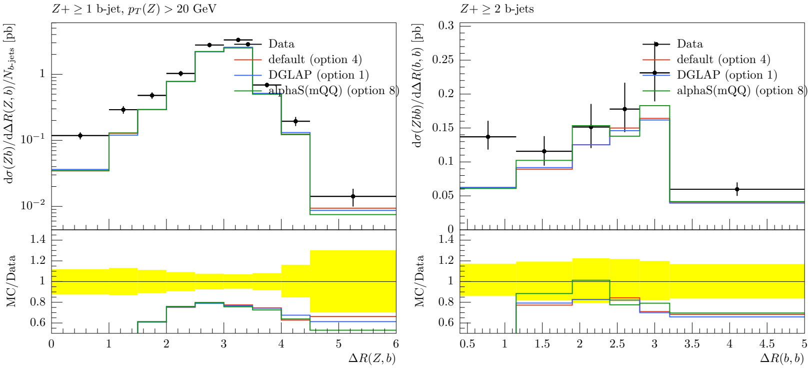
Heavy flavour in FSR: Realistic results

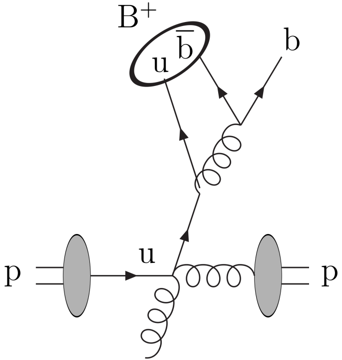


ΔR distributions from JHEP 1410 (2014) 141

Notes:

No heavy flavour produced though hadronization.

Heavy hadrons can have larger momenta than parent quarks.



In string model, heavy (and light) hadrons feel colour drag:

Hadrons from string end connected to jet "core" will be dragged towards jet core.

Hadrons from string end connected to beam will be dragged to beam.

Drag can lead to asymmetries because of proton composition:
@ pp, more high-$p_\perp$ B^+ than B^-
Mostly permille-level effect.