The Dead Cone in Pythia8

& ALICE substructure analyses

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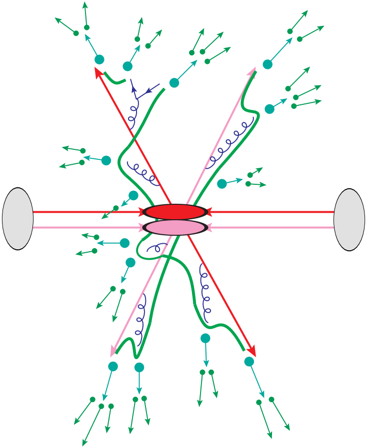
What is Pythia8?

A machine that generates realistic, high-energy particle collision event records using all the Standard Model physics we know and inspired models to fill in the rest.



MANY DIVERSE PHENOMENOM

Short-distance cross section:
μ_r^H, μ_f^H, PDF^H, α_s^H
Parton shower:
μ_q^{PS}, μ_r^{PS}, μ_f^{PS}, μ_{cut}^{PS}, PDF^{PS}, α_s^{PS}
Multiple interactions:
μ_q^{MPI}, PDF^{MPI}, α_s^{MPI}...
String fragmentation:
$f(z)$, string p_T, tension
Beams:
Primordial k_T, remnants
Particle Decays:
BRs, MEs, BE correlations
...

QCD Radiation off Heavy Particles

Norrbin & Sjöstrand

Eikonal Limit

$$\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{q\bar{q}g}}}{\sigma_{\mathrm{q\bar{q}}}} &\propto (-1)\left(\frac{p_1}{p_1 p_3} - \frac{p_2}{p_2 p_3}\right)^2 \frac{\mathrm{d}^3 p_3}{E_3} \\
&= \left(\frac{2 p_1 p_2}{(p_1 p_3)(p_2 p_3)} - \frac{m_1^2}{(p_1 p_3)^2} - \frac{m_2^2}{(p_2 p_3)^2}\right) E_3 \mathrm{d}E_3 \, \mathrm{d}\cos\theta_{13} \; .
\end{aligned}$$

In the limit of small angles θ_{13} this gives a mass suppression factor

$$\frac{\mathrm{d}\sigma(x_3, \theta_{13}, r)}{\mathrm{d}\sigma(x_3, \theta_{13}, 0)} \approx \left(\frac{\theta_{13}^2}{\theta_{13}^2 + 4r^2}\right)^2 ,$$

i.e. the characteristic dead cone of opening angle approximately $2r = m_{\mathrm{q}} / E_{\mathrm{q}}$.

Same effect, different view

$$\text{Propagator} = \frac{1}{p_{Q^*}^2 - m_Q^2}$$

$$p_{Q^*} = p_Q + p_g, p_Q^2 = m_Q^2, p_g^2 = 0$$

$$\begin{aligned} \text{Propagator} &= \frac{1}{2E_g E_Q(1 - \beta\cos\theta_{gQ})} \\ &\simeq \frac{1}{E_g E_Q(m_Q^2/E_Q^2 + \theta_{gQ}^2)} \end{aligned}$$

Soft singularity as $E_g \to 0$
No collinear singularity as $\theta_{gQ} \to 0$

Ingredients to N-Sj paper

Choose parton shower (PS) evolution variable (inverse propagator) to include mass

Rewrite PS formula with massive kinematics

Rewrite matrix element (ME) formula where appropriate and available in terms of PS variables

Reweight PS by ME where possible

Use good guesses for reweighting where you must

The result is “The Table”

colour	spin	γ_5	example	codes
$1 \to 3 + \overline{3}$	—	—	(eikonal)	6 – 9
$1 \to 3 + \overline{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{Z}^0 \to \mathrm{q}\overline{\mathrm{q}}$	11 – 14
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \mathrm{bW}^+$	16 – 19
$1 \to 3 + \overline{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{H}^0 \to \mathrm{q}\overline{\mathrm{q}}$	21 – 24
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \mathrm{bH}^+$	26 – 29
$1 \to 3 + \overline{3}$	$1 \to 0 + 0$	1	$\mathrm{Z}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$	31 – 34
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{W}^+$	36 – 39
$1 \to 3 + \overline{3}$	$0 \to 0 + 0$	1	$\mathrm{H}^0 \to \tilde{\mathrm{q}}\overline{\tilde{\mathrm{q}}}$	41 – 44
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{\mathrm{q}} \to \tilde{\mathrm{q}}'\mathrm{H}^+$	46 – 49
$1 \to 3 + \overline{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{\chi} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$	51 – 54
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\chi}$	56 – 59
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\chi}$	61 – 64
$8 \to 3 + \overline{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{\mathrm{g}} \to \mathrm{q}\overline{\tilde{\mathrm{q}}}$	66 – 69
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}}$	71 – 74
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\mathrm{t} \to \tilde{\mathrm{t}}\tilde{\mathrm{g}}$	76 – 79
$1 \to 8 + 8$	—	—	(eikonal)	81 – 84

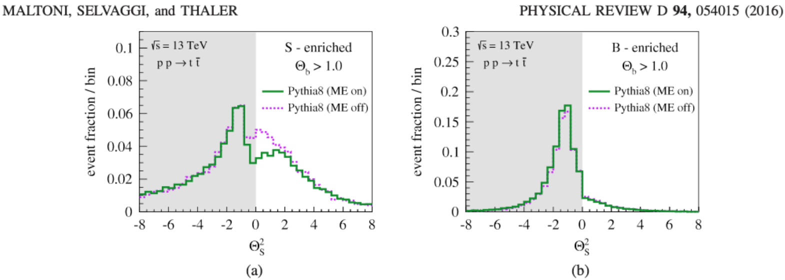
Developments since that paper

- New shower variable $p_\perp$, but $m^2 \sim \dfrac{p_\perp^2}{z(1-z)}$
- All of the massive effects and ME corrections are retained
- New gluon splitting options

```
mode  TimeShower:weightGluonToQuark   (default = 4; minimum = 1; maximum = 8)
Different options to assign kinematics distributions and weights for g-> q qbar branchings,
notably for charm and bottom quarks. These options also have the corresponding effect on
gamma -> f fbar branchings. Notation: r_q = m_q^2/m_qq^2, beta = sqrt(1 - 4r_q), with m_q the
quark mass and m_qq the q qbar pair invariant mass. The scale factor k
is described below, TimeShower:scaleGluonToQuark.

option 1 : same splitting kernel (1/2) (z^2 + (1-z)^2) for massive as massless quarks,
 only with an extra beta phase space factor.
option 2 : a splitting kernel (beta/2) (z^2 + (1-z)^2 + 8r_q z(1-z)).
option 3 : a splitting kernel z^2 + (1-z)^2 + 8r_q z(1-z), normalized so that the z-integrated
 rate is (beta/3) (1 + r/2).
option 4 : same as 3, but additionally a suppression factor (1 -m_qq^2/m_dipole^2)^3, which reduces
 the rate of high-mass q qbar pairs.
option 5 : same as 1, but reweighted to an alpha_s(k m_qq^2) rather than the normal alpha_s(pT^2).
option 6 : same as 2, but reweighted to an alpha_s(k m_qq^2) rather than the normal alpha_s(pT^2).
option 7 : same as 3, but reweighted to an alpha_s(k m_qq^2) rather than the normal alpha_s(pT^2).
option 8 : same as 4, but reweighted to an alpha_s(k m_qq^2) rather than the normal alpha_s(pT^2).
```

Does the implementation of the dead cone matter?




```
// z weight for g -> g g; optional suppression for massive recoiler.
} else if (dip.flavour == 21) {
  wt = (1. + pow3(dip.z)) / wtPSglue;
  if (recoilDeadCone && dip.mRec > 0.) {
    double r2G = dip.m2Rec / dip.m2Dip;
    double x1G = (1. - r2G + dip.m2 / dip.m2Dip) * dip.z;
    double x2G =  1. + r2G - dip.m2 / dip.m2Dip;
    wt *= 1. - (r2G / max(XMARGIN, x1G + x2G - 1. - r2G))
      * (max(XMARGIN, 1. + r2G - x2G) / max(XMARGIN,1. - r2G - x1G));
  }
```

Gluon effectively radiates in the direction of the heavy quark, violating the dead cone constraint (artifact of how the dipole is partitioned)

Does it matter for ALICE?

Almost none of “The Table” is used in generic b-quark production and radiation

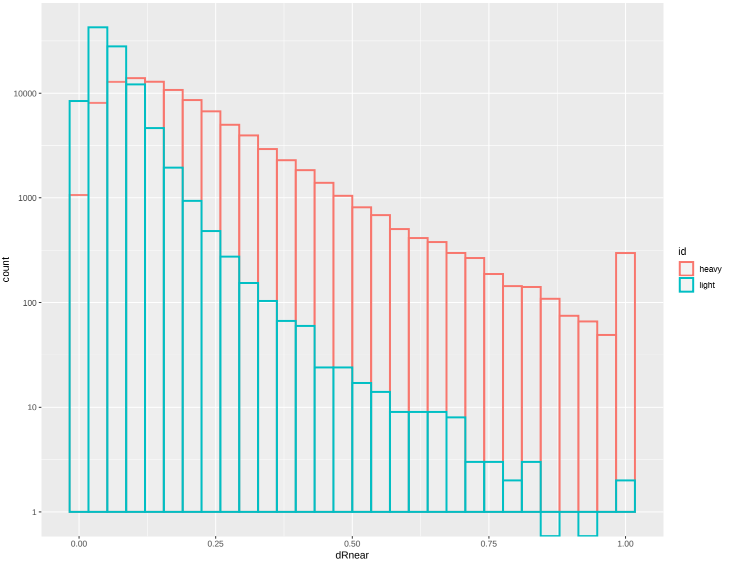
The fix introduced for the top study is called – but not very relevant

Some quick comparisons: based on direct $b\bar{b}$ ($q\bar{q}$) production in `Pythia8.3` with $25 < p_{\perp} < 30$ GeV

- heavy vs light
- different heavy types
- string effect

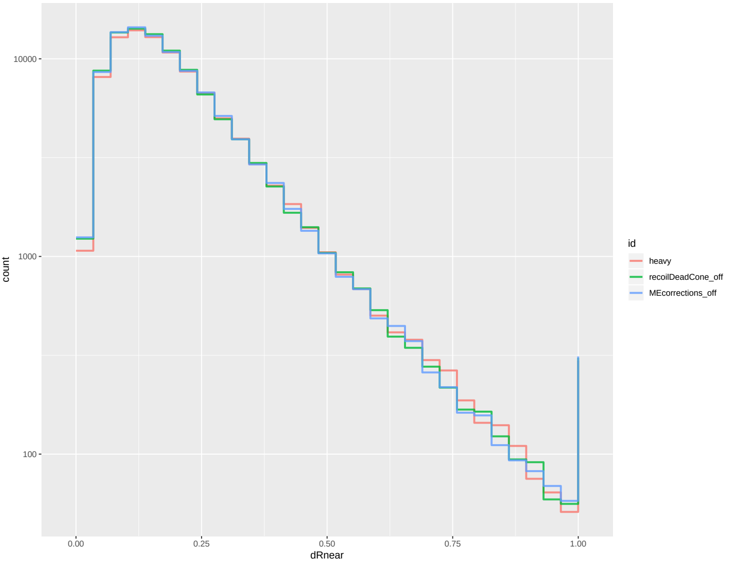
Heavy vs Light

As expected, suppression for $\Delta R \to 0$.



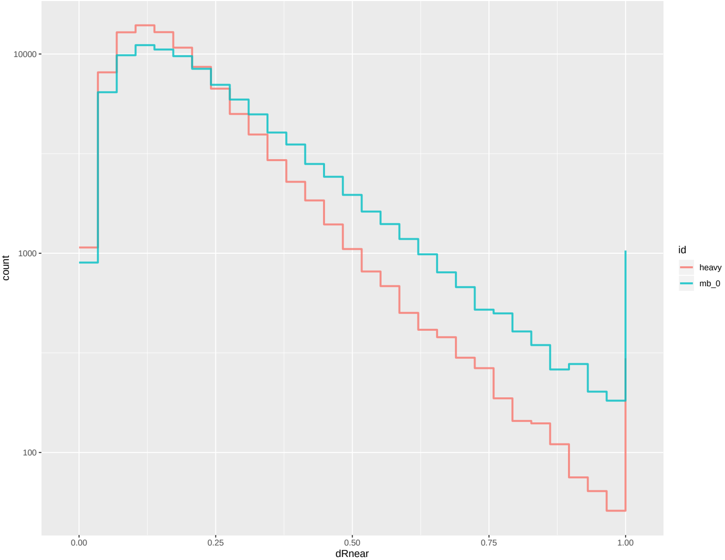
Different Heavy Options

The current spin implementations are irrelevant. Effect is kinematic.



Fragmentation Effect

A “light” b-quark at string end absorbs collinear gluons to form heavy hadron.



Reflections

Prediction is driven by kinematics – dead cone effect is universal as $\theta \to 0$

Behavior away from this limit is not accounting for any ME corrections

A case for more phenomenological work, or an argument for using merged samples

Unclear on how to quantify overlap with string fragmentation

Depending upon the event selection, gluon splitting should be relevant, and the new options should be studies

`DIRE` treatment is now integrated directly in `Pythia 8.3`