Quarkonia Showers in PYTHIA8

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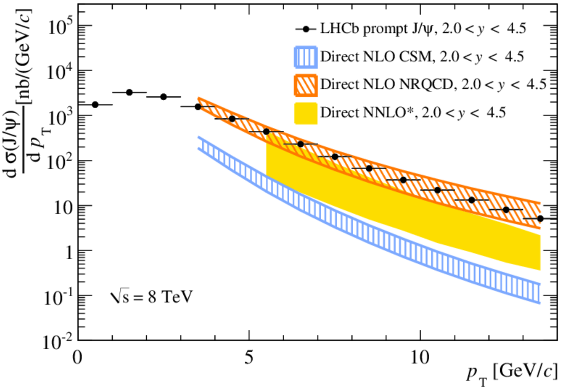
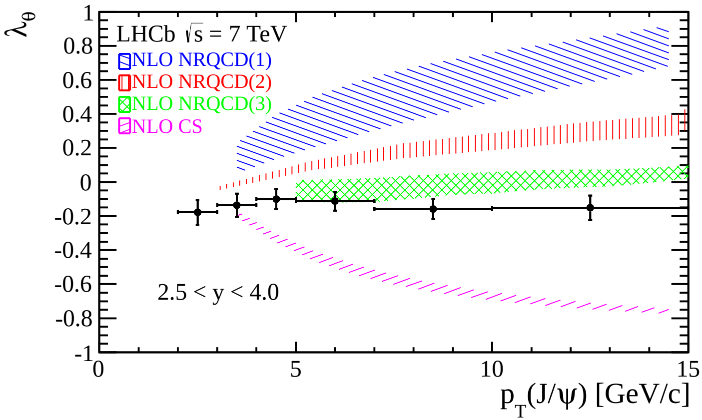
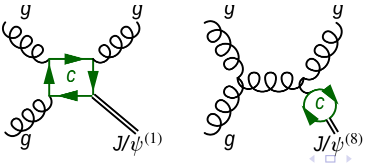
Motivation (i)



- Hard production Non-Relativistic QCD (NRQCD) predicts:
  - Di□erential production cross section consistent with measurement.
  - J/ψ produced largely isolated.
  - Large transverse polarisation, minimal observed.

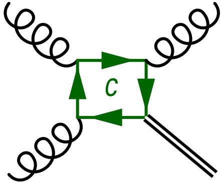


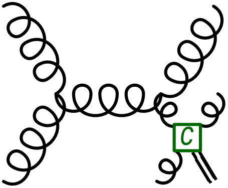
colour singlet
low p_T
longitudinal pol.



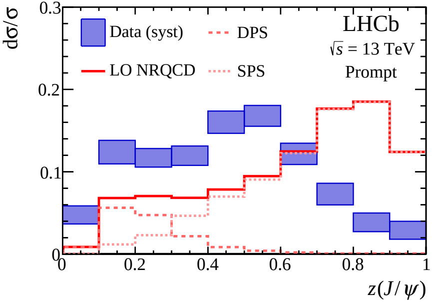
colour octet
high p_T
transverse pol.

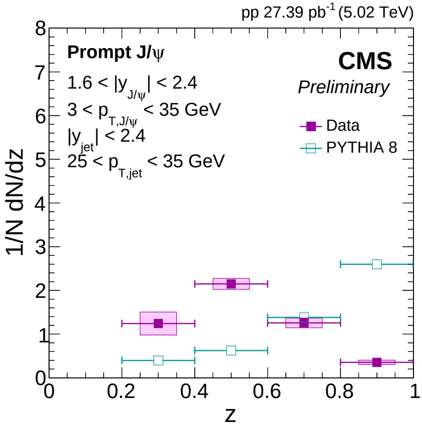
- Shower production analytic resummation NRQCD predicts:
  - Lack of polarisation.
  - J/ψ rarely produced in isolation.
- Two pictures of quarkonia production distinguished by studying radiation associated with them → JETS.





Instead of measuring the differential production cross section wrt $p_T(J/\psi)$, take into account surrounding radiation with $z \equiv p_T(J/\psi)/p_T(\text{jet})$.



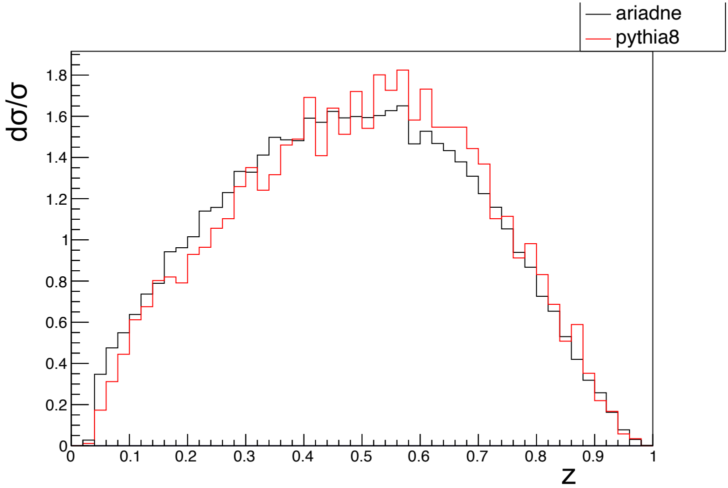


Procedure

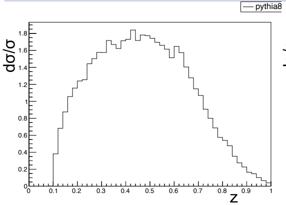
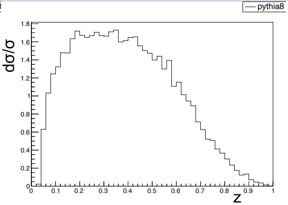
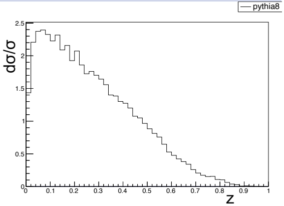
- Aim to implement the following splittings into Pythia8:
  - $c \to \eta_c^{(1)}\ c$ (A)
  - $g \to \eta_c^{(1)}\ g$
  - $c \to \psi(nS)^{(1)}\ c$, $n = 1,2$ (A)
  - $c \to \chi_{ci}^{(1)}\ c$, $i = 0,1,2$
  - $g \to \chi_{ci}^{(1)}\ g$, $i = 0,1,2$
  - $g \to \psi(nS)^{(1)}\ gg$, $n = 1,2$ (A)
  - $g \to \psi(nS)^{(8)}$, $n = 1,2$ (A)
- Compare output with Ariadne (A) where possible. (Note: change in evolution variable etc.)
- Validate with LHCb and CMS data.

$c \rightarrow \eta_c^{(1)}\, c$

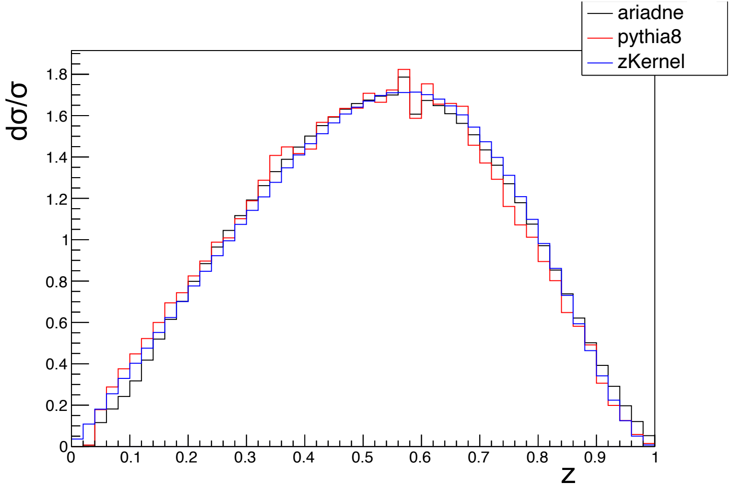
Tests produced without ISR and MPI initially. Define $z \equiv p_T(Q)/(s/2)$.



$g \to \eta_c^{(1)}\ g$

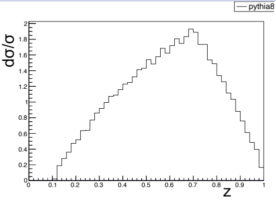
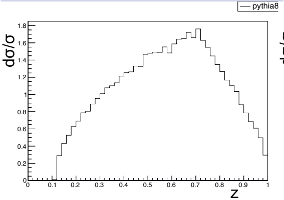
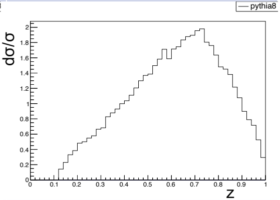
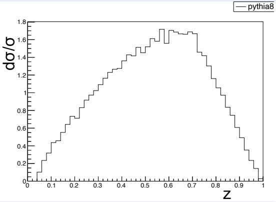
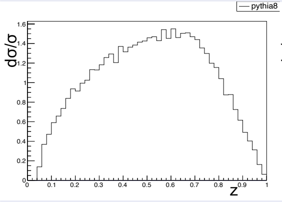
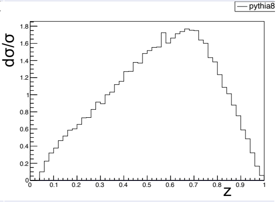
30 GeV	80 GeV	1000 GeV
		

$c \to J/\psi^{(1)}\ c$

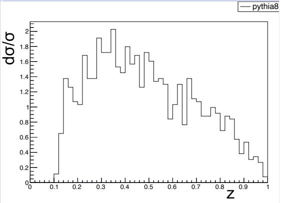
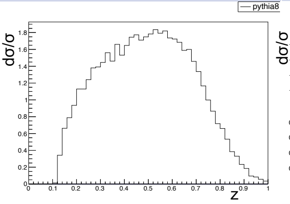
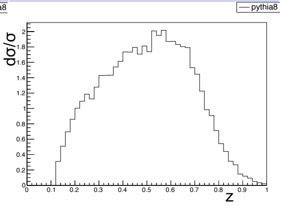
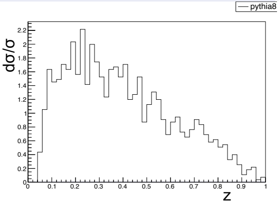
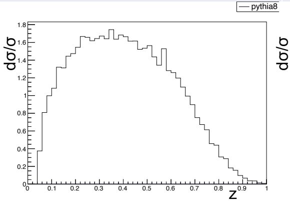
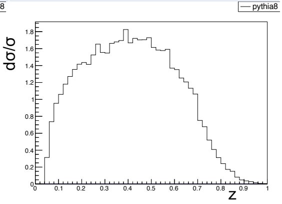


ariadne
pythia8
zKernel
dσ/σ
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z

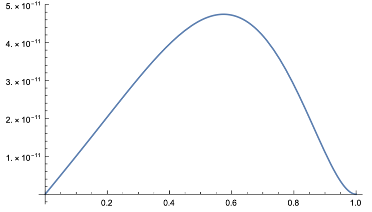
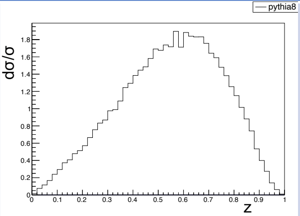
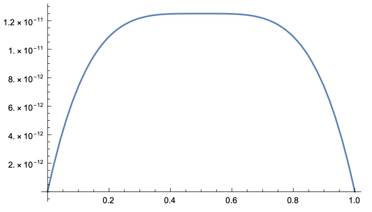
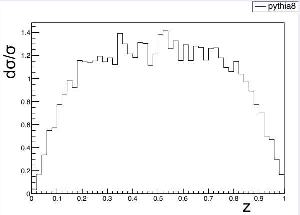
$c \to \chi_{ci}^{(1)}\ c$

	$c \to \chi_{c0}^{(1)}\ c$	$c \to \chi_{c1}^{(1)}\ c$	$c \to \chi_{c2}^{(1)}\ c$
30 GeV			
80 GeV			

$g \to \chi_{ci}^{(1)}\, g$

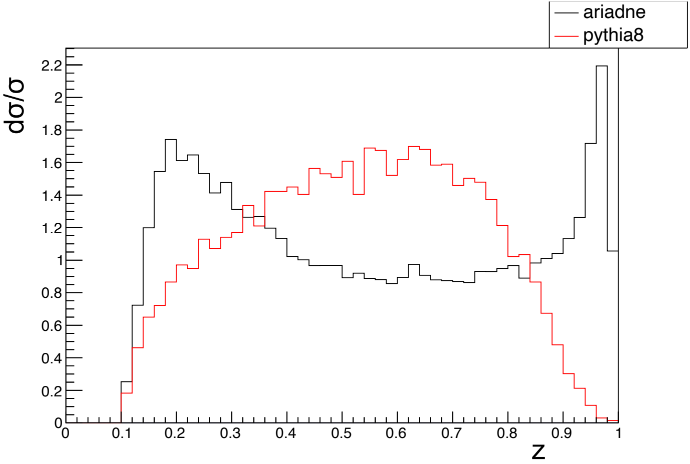
	$g \to \chi_{c0}^{(1)}\, g$	$g \to \chi_{c1}^{(1)}\, g$	$g \to \chi_{c2}^{(1)}\, g$
30 GeV			
80 GeV			

Analytical comparison

	Analytical	Pythia8
$c \to J/\psi^{(1)} c$		
$g \to \eta_c^{(1)} g$		

$g \rightarrow J/\psi^{(8)}$

$$\frac{\pi \langle 0|\mathcal{O}_8^{\psi}(^3S_1)|0\rangle}{24m_Q^3}\delta(1-z)\delta(1-\frac{s}{M_\psi^2})$$



$g \to J/\psi^{(1)}\, gg$

It's complicated...

calculated by the same method used for the $^1S_0$ state in Ref. [1]. The calculation is rather involved and we present only the final result:

$$d_1^{(^3S_1)}(z, 2m_Q) \;=\; \frac{5}{5184\pi m_Q^3}\alpha_s(2m_Q)^3 \int_0^z dr \int_{(r+z^2)/2z}^{(1+r)/2} dy \, \frac{1}{(1-y)^2(y-r)^2(y^2-r)^2}$$

$$\times \sum_{i=0}^{2} z^i \left(f_i(r,y) \; + \; g_i(r,y) \frac{1+r-2y}{2(y-r)\sqrt{y^2-r}} \log \frac{y-r+\sqrt{y^2-r}}{y-r-\sqrt{y^2-r}} \right) . \qquad (3)$$

The integration variables are $r = 4m_Q^2/s$ and $y = p \cdot q/s$, where p and q are the 4-momenta of the quarkonium and the fragmenting gluon and $s = q^2$. The functions f_i and g_i are

$$\begin{aligned} f_0(r,y) \;&=\; r^2(1+r)(3+12r+13r^2) \; - \; 16r^2(1+r)(1+3r)y \\ &- \; 2r(3-9r-21r^2+7r^3)y^2 \; + \; 8r(4+3r+3r^2)y^3 \; - \; 4r(9-3r-4r^2)y^4 \\ &- \; 16(1+3r+3r^2)y^5 \; + \; 8(6+7r)y^6 \; - \; 32y^7 \, , \end{aligned} \qquad (4)$$

$$\begin{aligned} f_1(r,y) \;&=\; -2r(1+5r+19r^2+7r^3)y \; + \; 96r^2(1+r)y^2 \; + \; 8(1-5r-22r^2-2r^3)y^3 \\ &+ \; 16r(7+3r)y^4 \; - \; 8(5+7r)y^5 \; + \; 32y^6 \, , \end{aligned} \qquad (5)$$

Conclusion

Completed:

- Implement the splittings: $x \to \chi_{ci}^{(1)}\, x$, $x \to \eta_c^{(1)}\, x$, $c \to J/\psi^{(1)}\, c$
- Interleaving the above splittings with ISR and MPI.
- Including all above in available splittings such as $g \to q\bar{q}$/$q \to qg$/$g \to gg$

Work in progress:

- ISR dipoles when octet is involved.
- $g \to J/\psi^{(1)}\, gg$
- Include higher resonances + competition between them
- Comparisons with data

Future work:

- Matrix element correction
- Matching + merging