NRQCD in Parton Showers

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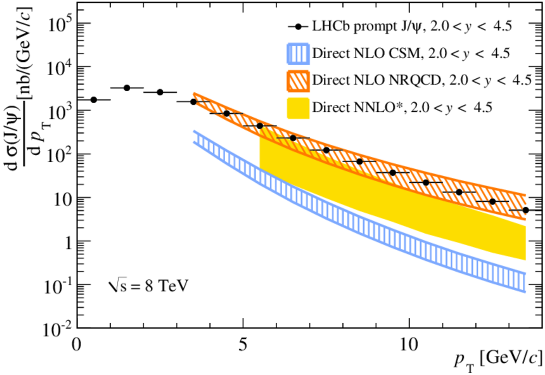
Overview

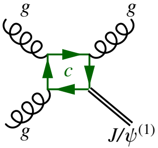
1. What is NRQCD?
2. J/ψ in jets measurements
3. Improving MC predictions with NRQCD fragmentation
4. Implementation into Pythia 8
5. Results
6. Outlook

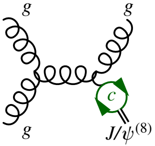
What is NRQCD?

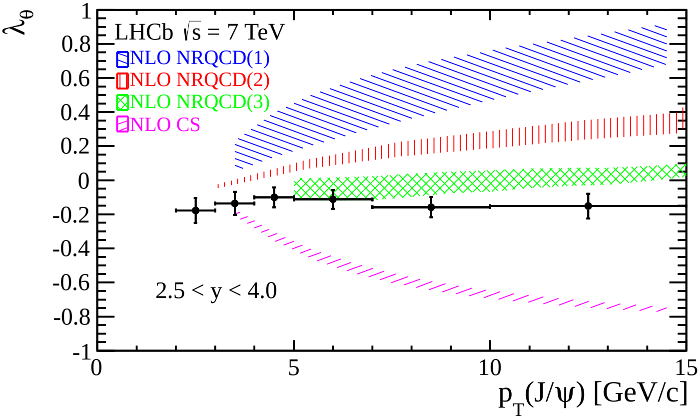
NRQCD (i)

Prompt J/ψ: production from directly from PV, or feed down.

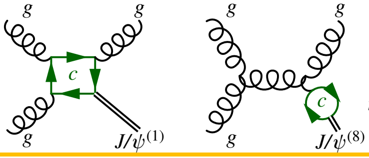








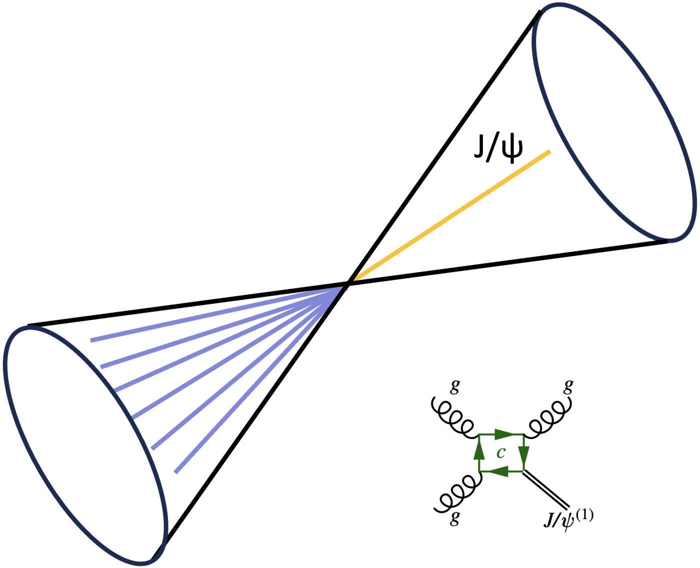
colour singlet
low p_T
longitudinal pol.



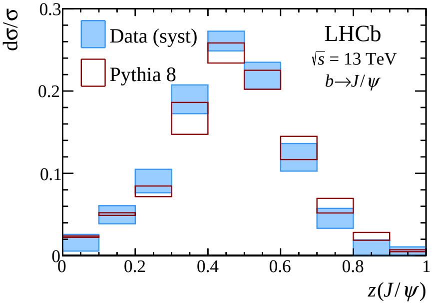
colour octet
high p_T
transverse pol.

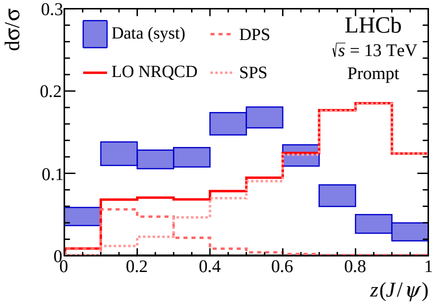
J/ψ *in jets measurements*

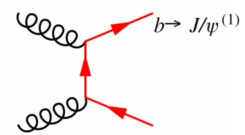
Study of J/ψ production in jets (i)

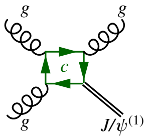


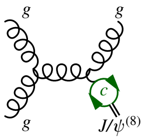
Measure $d\sigma/\sigma$ verses $z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$. Prompt (direct from PV) and displaced (i.e. b decay) distributions, where $p_T(\text{jet}) > 20$ GeV [Phys. Rev. Lett. 118, 192001 (2017)].





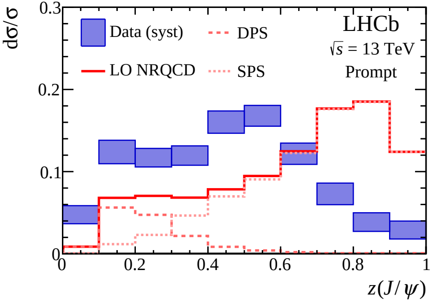




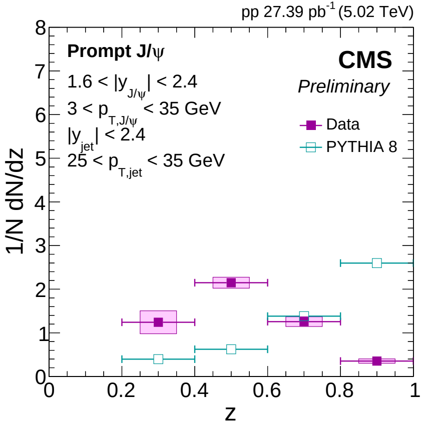


Study of J/ψ production in jets (iii)

$p_T(\text{jet}) > 20$ GeV



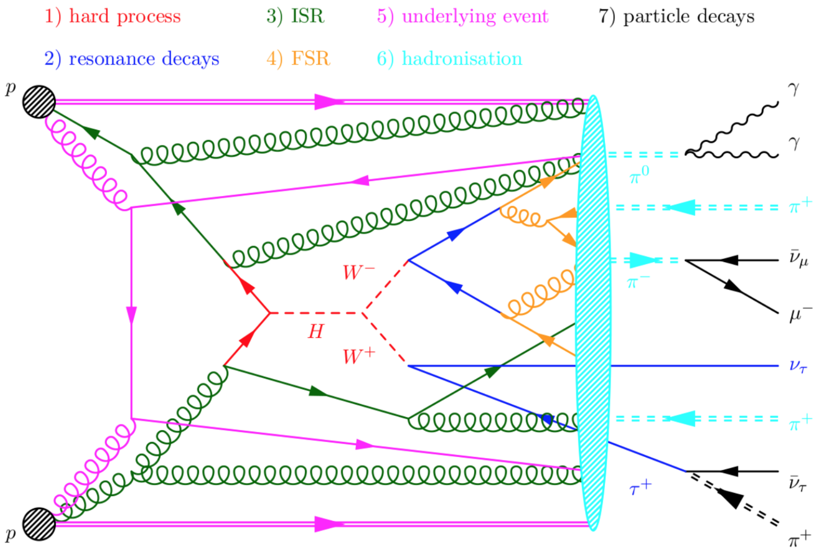
$25 < p_T(\text{jet}) < 35$ GeV



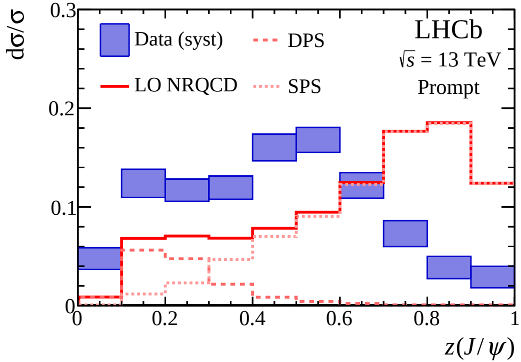
Note: all measurements limited by MC modelling systematic.

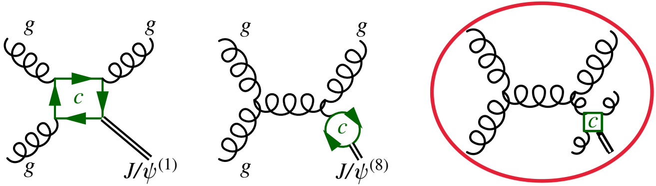
Can we improve MC predictions?

MC Generated Event

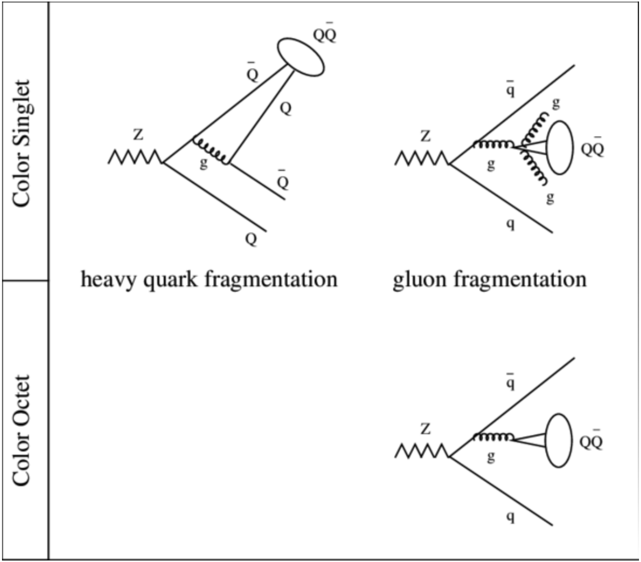


What's missing?





NRQCD Fragmentation



Implementation into PYTHIA *8*

Implementation into PYTHIA 8 (i)

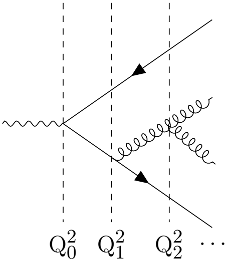
- Implemented the following splittings into PYTHIA 8:
  - $c \to \eta_c^{(1)}\ c$
  - $g \to \eta_c^{(1)}\ g$
  - $c \to \psi(nS)^{(1)}\ c$, $n = 1,2$
  - $g \to \psi(nS)^{(1)}\ gg$, $n = 1,2$
  - $c \to \chi_{ci}^{(1)}\ c$, $i = 0,1,2$
  - $g \to \chi_{ci}^{(1)}\ g$, $i = 0,1,2$
  - $c \to \chi_{ci}^{(8)}\ c$, $i = 0,1,2$
  - $g \to X^{(8)}$, where X is any quarkonia state
- Also the same for bottomonium.
- Validate with analytic expressions, and LHCb/CMS data.

Implementation into PYTHIA 8 (ii)

Production Type	Flag	Purpose
All Production	`OniaShower:all`	All onia
	`OniaShower:all(1S0)`	All $^1S_0$ onia
	`OniaShower:all(3S1)`	All $^3S_1$ onia
	`OniaShower:all(3PJ)`	All ^3P_J onia
	`OniaShower:all(3DJ)`	All ^3D_J onia
	`CharmoniumShower:all`	All charmonia
	`BottomoniumShower:all`	All bottomonia
Charmonium $^1S_0$ States	`CharmoniumShower:states(1S0)`	η_c
	`CharmoniumShower:O(1S0)[1S0(1)]`	η_c
	`CharmoniumShower:O(1S0)[3S1(8)]`	η_c
	`CharmoniumShower:c2ccbar(1S0)[1S0(1)]c`	η_c
	`CharmoniumShower:g2ccbar(1S0)[1S0(1)]g`	η_c
	`CharmoniumShower:g2ccbar(1S0)[3S1(8)]`	η_c

Implementation into PYTHIA 8 (iii)

Parton shower is an iterative process:



$$d\mathcal{P}_a(z, Q^2) = \frac{dQ^2}{Q^2}\frac{\alpha_s}{2\pi}P_{a\to bc}(z)dz \qquad (1)$$

$$P_{q\to qg}(z) = \frac{4}{3}\frac{1+z^2}{1-z}, \qquad D_{c\to J/\psi(1)c}(z, s) \quad \text{etc.} \qquad (2)$$

Overall, sample a $p^2_{T,\text{evol}}$ and z to evolve the shower.

Implementation into PYTHIA 8 (iv)

Implementation of colour singlet states, e.g. $c \to J/\psi(1)c$ [Phys. Rev. D **48**, 4230]:

$$\begin{aligned}\int_0^1 dz\, D_{c\to J/\psi}(z) &= \frac{8\alpha_s^2|R(0)|^2}{27\pi m_c}\int_0^\infty ds\,\frac{1}{(s-m_c^2)^4}\\ &\int_0^1 dz\,\vartheta\left(s-\frac{4m_c^2}{z}-\frac{m_c^2}{1-z}\right)\Bigg((s^2-2m_c^2 s-47m_c^4)-\\ &z(s-m_c^2)(s-9m_c^2) + 4\frac{z(1-z)}{2-z}s(s-m_c^2)\\ &-4\frac{8-7z-5z^2}{2-z}m_c^2(s-m_c^2) + 12\frac{z^2(1-z)}{(2-z)^2}(s-m_c^2)^2\Bigg) \end{aligned} \tag{3}$$

Translate $\{s, z\} \to \{p^2_{T,\mathrm{evol}}, z\}$ and find overestimate.

Implementation into PYTHIA 8 (v)

Implementation of g → J/ψ(1)gg [Phys. Rev. D **52**, 6627]:

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

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

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

$$\begin{aligned} f_0(r,y) &= r^2(1+r)(3+12r+13r^2) - 16r^2(1+r)(1+3r)y \\ &- 2r(3-9r-21r^2+7r^3)y^2 + 8r(4+3r+3r^2)y^3 - 4r(9-3r-4r^2)y^4 \\ &- 16(1+3r+3r^2)y^5 + 8(6+7r)y^6 - 32y^7 , \qquad (4) \\ f_1(r,y) &= -2r(1+5r+19r^2+7r^3)y + 96r^2(1+r)y^2 + 8(1-5r-22r^2-2r^3)y^3 \\ &+ 16r(7+3r)y^4 - 8(5+7r)y^5 + 32y^6 , \qquad (5) \end{aligned}$$

Translate $\{r, y, z\} \rightarrow \{p^2_{T,evol}, z, m^2_{gg}\}$ and find overestimate.

Implementation into PYTHIA 8 (vi)

Implementation of colour octet states, e.g. $g \to J/\psi(8)$ [Phys. Rev. D **52**, 6627]:

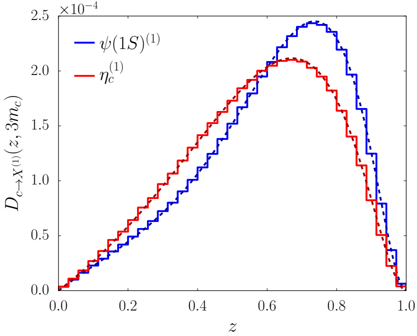
$$\frac{\pi \langle 0|\mathcal{O}_8^{\psi}(^3S_1)|0\rangle}{24 m_Q^3}\delta(1-z)\delta(1-\frac{s}{M_\psi^2})$$

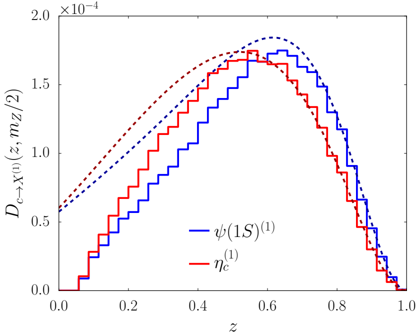
Handle delta functions, by only allowing generation of splitting to occur just above onium mass.

Results

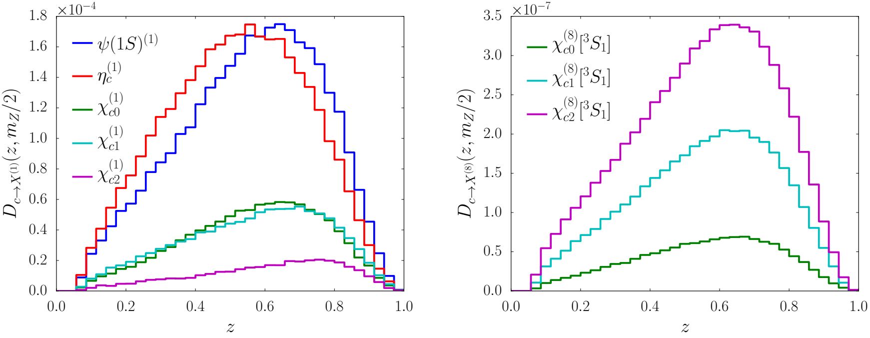
Results: charm splittings to colour singlet J/ψ and η_c

Production of colour-singlet S-wave states from charm splittings compared between (solid) PYTHIA 8 and (dashes) analytic expressions at the energy scales of (left) $3m_c$ and (right) $m_Z/2$.



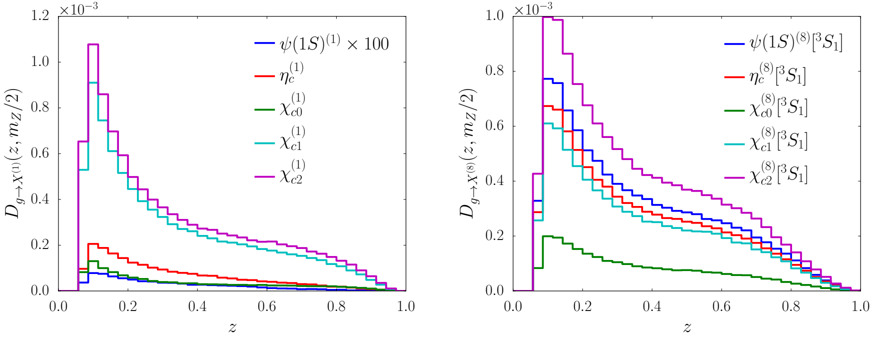


Production of (left) colour-singlet and (right) colour-octet states from charm splittings with PYTHIA 8 at the energy scale of $m_Z/2$.



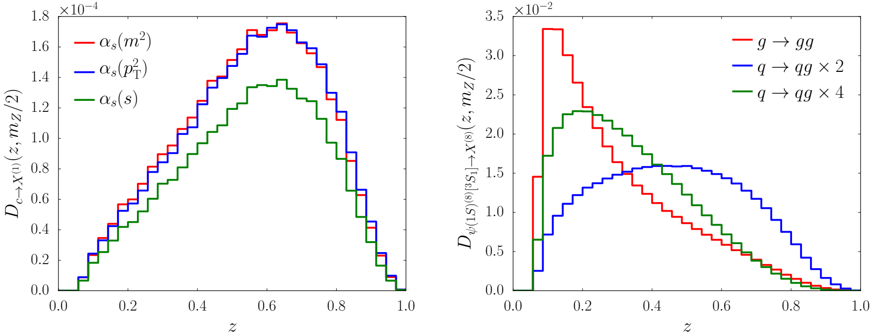
Results: compare gluon splittings to all onia

Production of (left) colour-singlet and (right) colour-octet states from gluon splittings with PYTHIA 8 at the energy scale of $m_Z/2$.



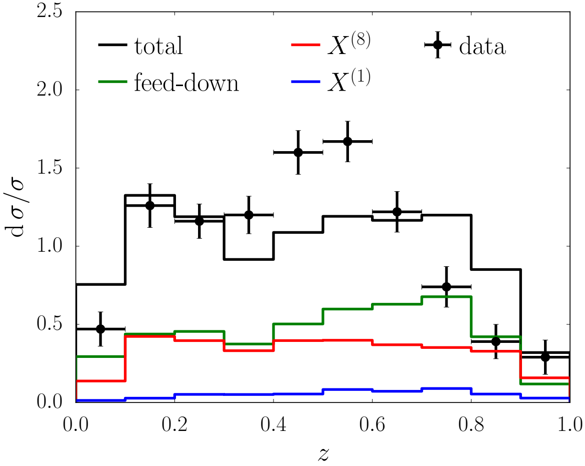
Technical Implementations

Comparison of (left) scale choices for the colour-singlet ${}^3S_1$ splitting and (right) splitting kernel choices for the colour-octet ${}^3S_1$ splitting with PYTHIA 8 at the energy scale of $m_Z/2$.



Comparison to LHCb data

Comparison of the current Pythia 8 implementation with all splittings to onia with LHCb data.



Outlook

Future prospects with Pythia 8

- Incorporated into Pythia version 8.310.
- Initial paper out on arXiv: 2312.05203. Submitted to EPJC.
- I'm a Pythia author. Feel free to test the shower, and tag me on the Pythia issue desk!
- Compare with experimental results: e.g. LHCb/CMS J/ψ in jets.
- Explore LDME values.

	$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$ $\times$ GeV^3	$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$ $\times 10^{-2}$ GeV^3	$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$ $\times 10^{-2}$GeV^3	$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle/m_c^2$ $\times 10^{-2}$GeV^3
B & K [5, 6]	1.32 ± 0.20	0.224 ± 0.59	4.97 ± 0.44	-0.72 ± 0.88
Chao, et al. [12]	1.16 ± 0.20	0.30 ± 0.12	8.9 ± 0.98	0.56 ± 0.21
Bodwin et al. [13]	1.32 ± 0.20	1.1 ± 1.0	9.9 ± 2.2	0.49 ± 0.44

- Expand to heavy ion collisions, and other areas.
- (Polarisation).

Conclusion

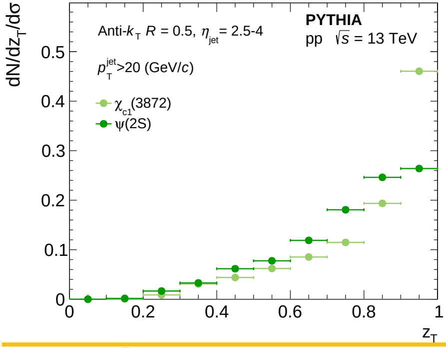
- Implemented splittings of colour singlet + colour octet quarkonia into the parton shower.
- Interleaving the above splittings with ISR and MPI, and in all the available splittings: $g \to q\bar{q}$/$q \to qg$/$g \to gg$.
- Initial predictions with LHCb data and Higgs measurements are promising!
- Paper out on arXiv: 2312.05203. Submitted to EPJC.
- Improve with NLO calculations, matching and merging, tune with data etc.
- Explore heavy ion prospects and other mesons.

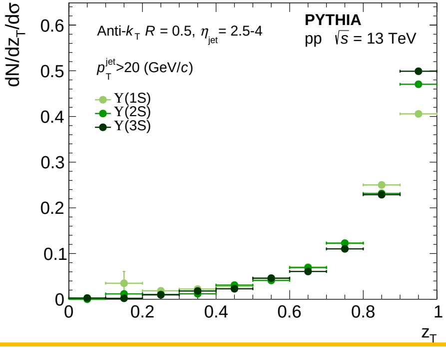
Back up slides

Future experimental prospects

Quarkonia in jets measurements:

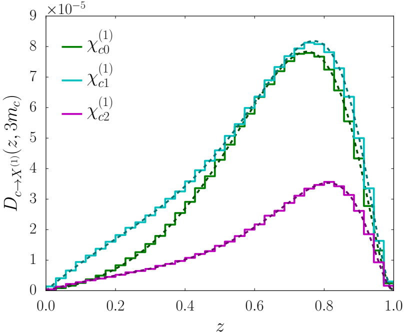
- Analyses for $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and X(3872) are in progress at LHCb.
- Predictions for the z distributions are shown below, with current version of PYTHIA 8 where Υ's are predicted to be more isolated than $\psi(2S)$ and X(3872).

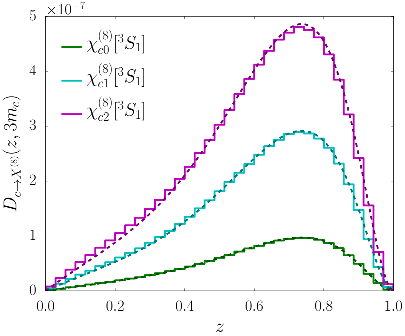




Results - charm splittings to χ_{cJ} (1,8)

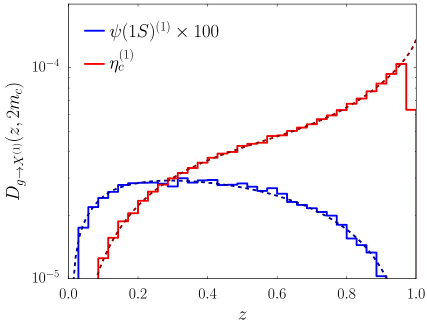
Production of (left) colour-singlet and (right) colour-octet P-wave states from charm splittings compared between (solid) PYTHIA 8 and (dashes) analytic expressions at the energy scale of $3m_c$.

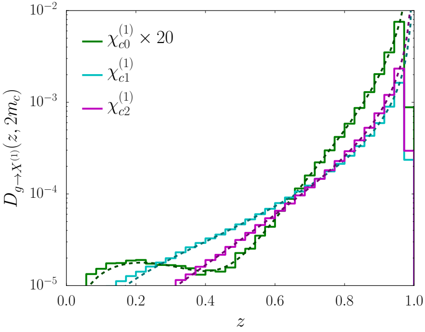




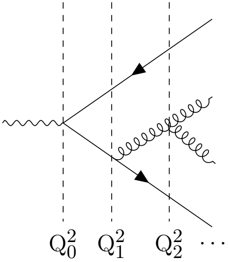
Results - gluon splittings to colour singlet onia

Production of colour-singlet (left) S-wave and (right) P-wave states from gluon splittings compared between (solid) Pythia 8 and (dashes) analytic expressions at the energy scale of $2\mathrm{m_c}$.





Parton shower



$$\mathcal{P}_a^{no}(Q^2_{max}, Q^2) = \exp\left(-\int_{Q^2}^{Q^2_{max}} \int_{z_{min}}^{z_{max}} d\mathcal{P}_a(z', Q'^2)\right) = \Delta_a(Q^2, q^2) \quad (4)$$

$$\text{FSR} : Q^2 = s - m_a^2 = \frac{p^2_{T,evol}}{z(1-z)} \quad (5)$$

Overall, sample a $p^2_{T,evol}$ and z to evolve the shower.