Quarkonia Showers in PYTHIA8

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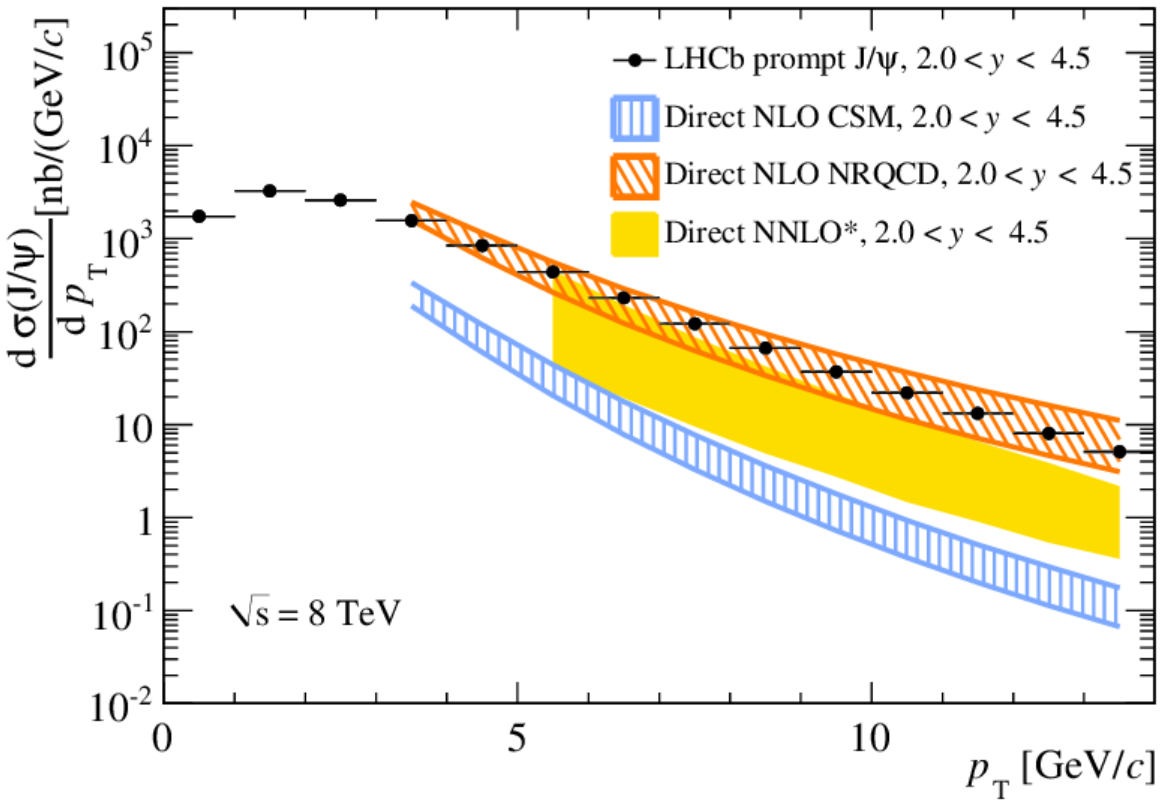
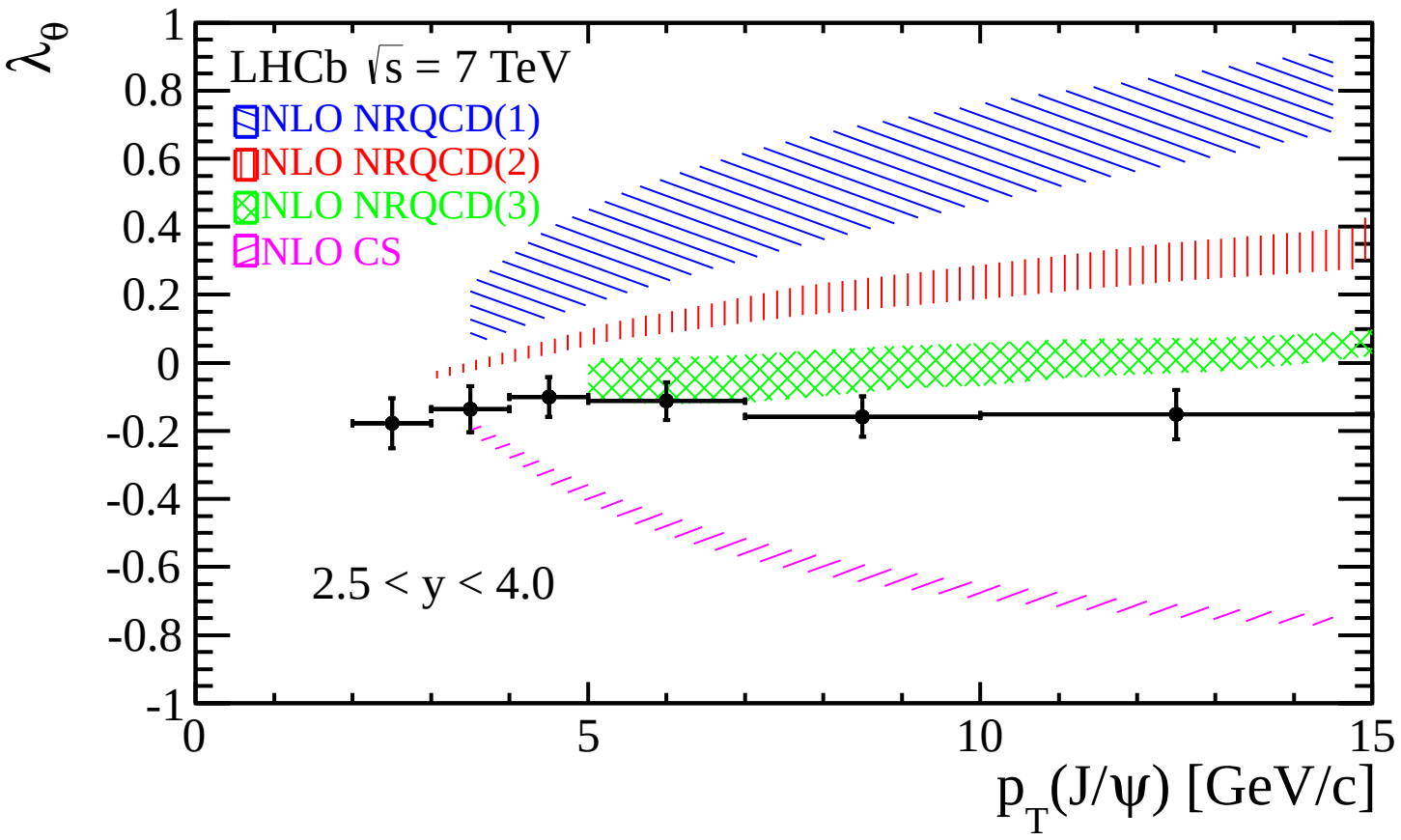
Motivation (i)

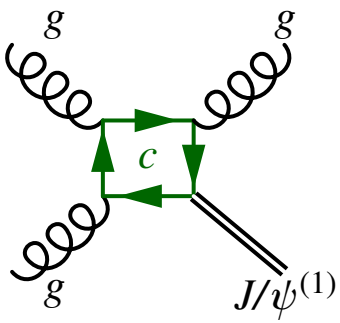


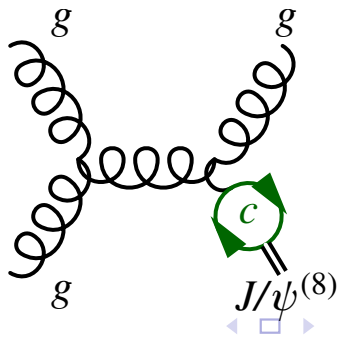
- Hard production Non-Relativistic QCD (NRQCD) predicts:
  - Differential production cross section consistent with measurement.
  - J/ψ produced largely isolated.
  - Large transverse polarisation, minimal observed.

Motivation (ii)



colour singlet
low p_T
longitudinal pol.

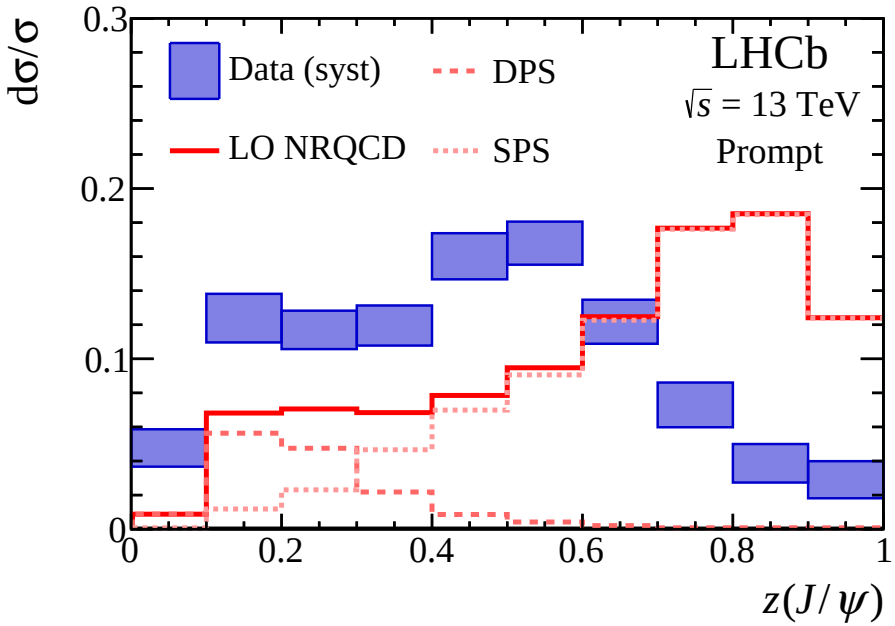


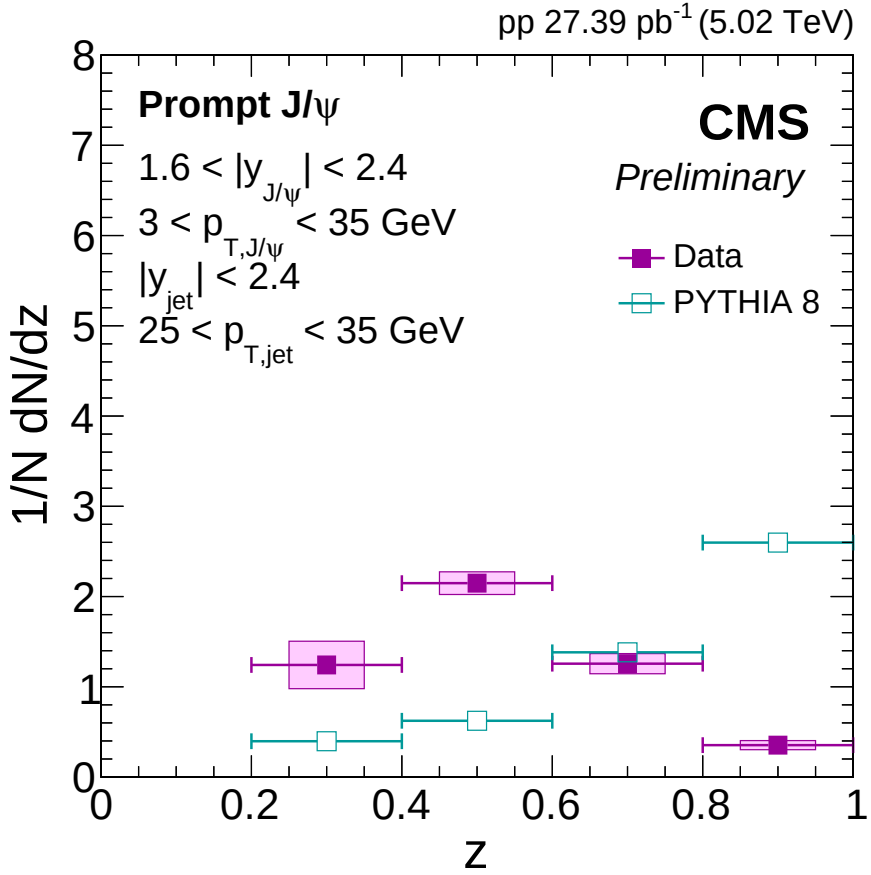


colour octet
high p_T
transverse pol.

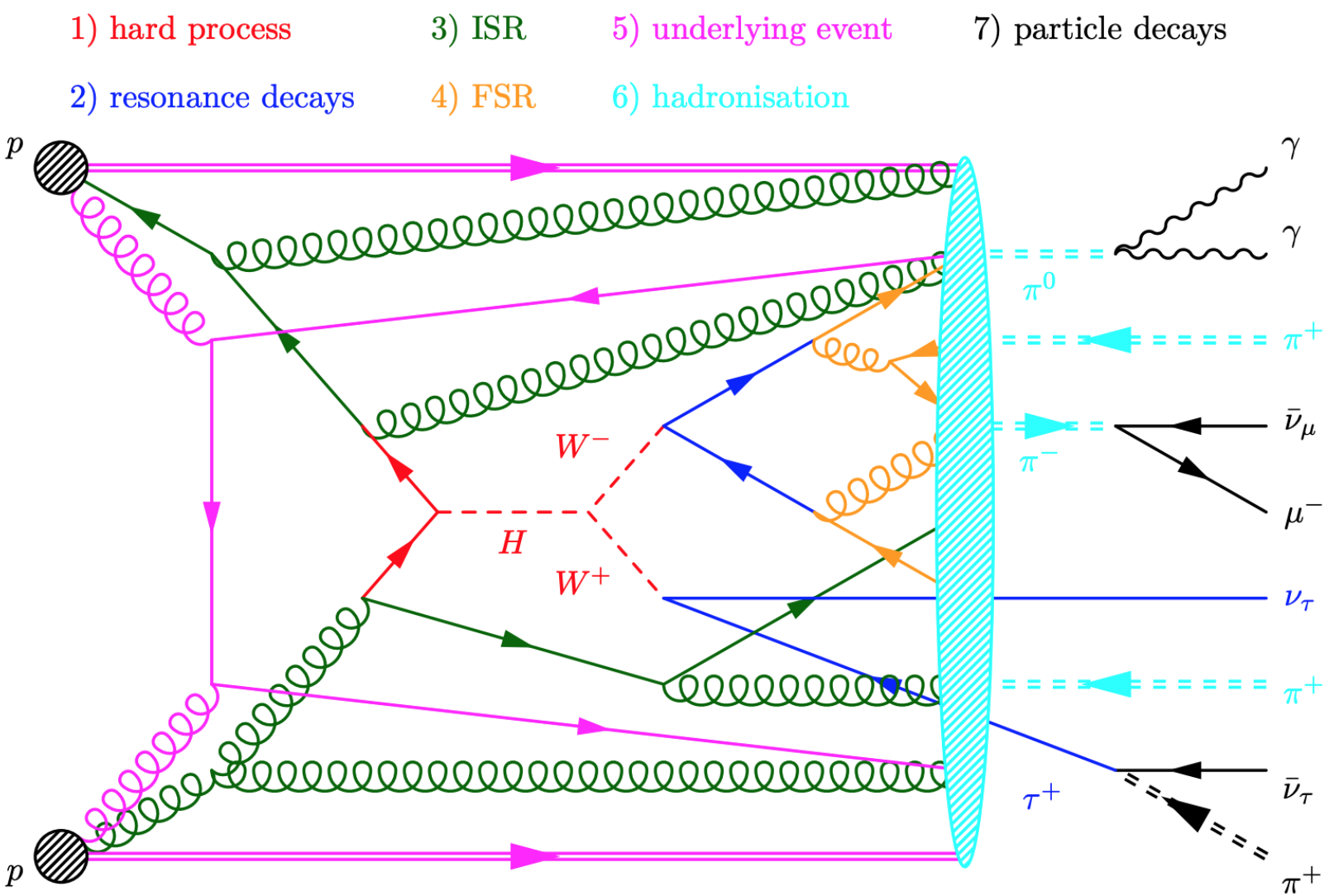
Recent experimental measurements

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





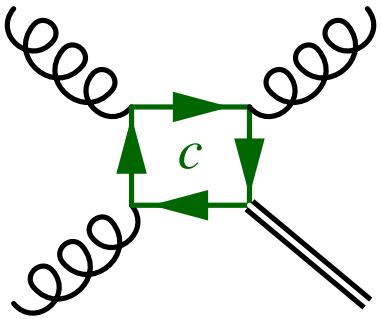
How does an MC generator work?



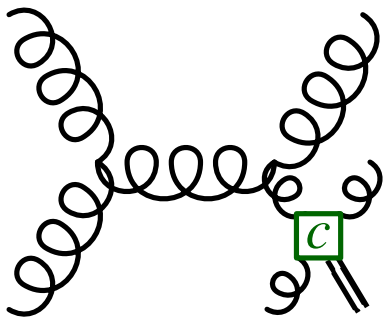
Courtesy of P. Ilten.

Current status of Pythia8

- At the moment, J/ψ's are only produced directly in the hard process, or in particle decays.



- Shower production analytic resummation NRQCD predicts:
  - Lack of polarisation.
  - J/ψ rarely produced in isolation.
- Hence can incorporate quarkonia production within the parton shower!



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

Example splitting kernel

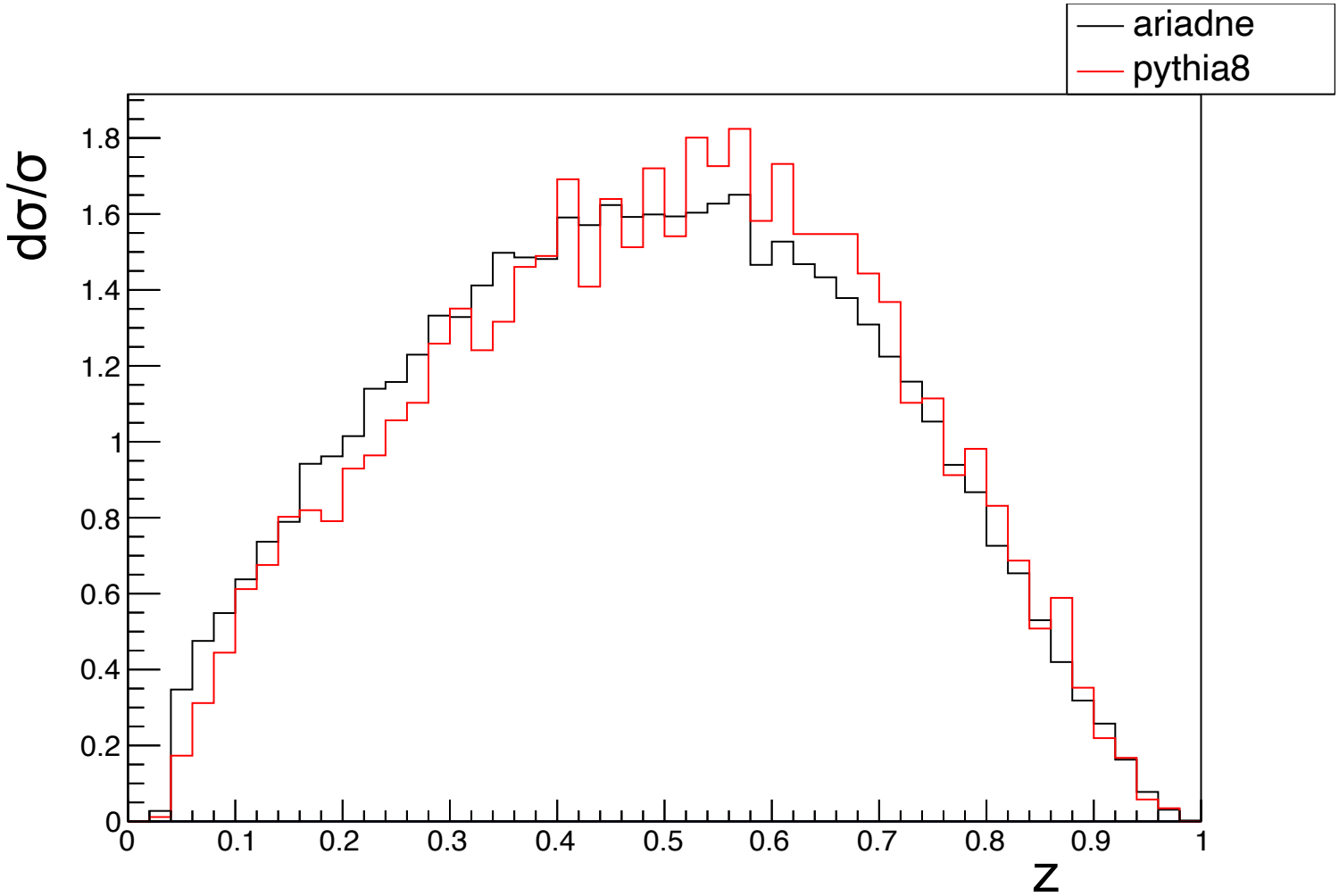
For example $c \to J/\psi^{(1)}\ c$:

$$\frac{8\alpha_s{}^2|R(0)|^2}{27\pi m_Q}\int_0^\infty ds\frac{1}{(s-m_Q^2)^4}\int_0^1 dz\theta\left(s-\frac{4m_Q^2}{z}-\frac{m_Q^2}{1-z}\right)$$

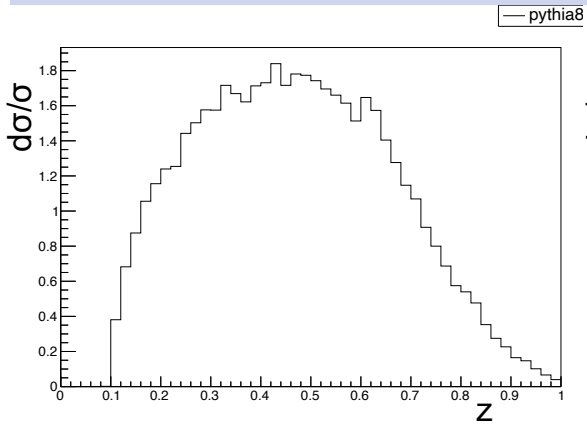
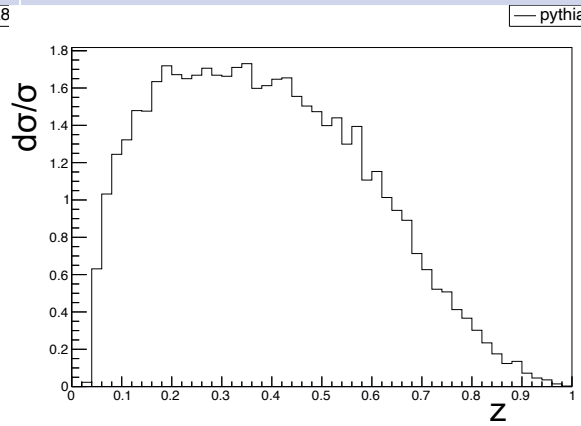
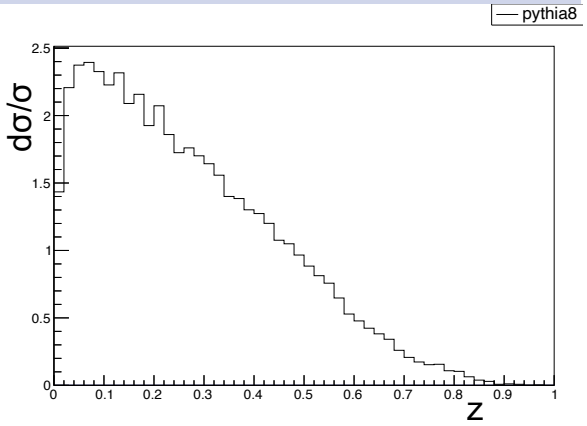
$$(s^2-2m_Q^2s-47m_Q^4)-z(s-m_Q^2)(s-9m_Q^2)+4\frac{z(1-z)}{2-z}s(s-m_Q^2)-$$
$$4\frac{8-7z-5z^2}{2-z}m_Q^2(s-m_Q^2)+12\frac{z^2(1-z)}{(2-z)^2}(s-m_Q^2)^2$$

Need to translate to Pythia8 shower evolution variables, i.e. $\{s,z\} \to \{p^2_{T,evol},z\}$, where $s = \frac{p^2_{T,evol}}{z(1-z)}$. Also, choose an overestimate to estimate the integral.

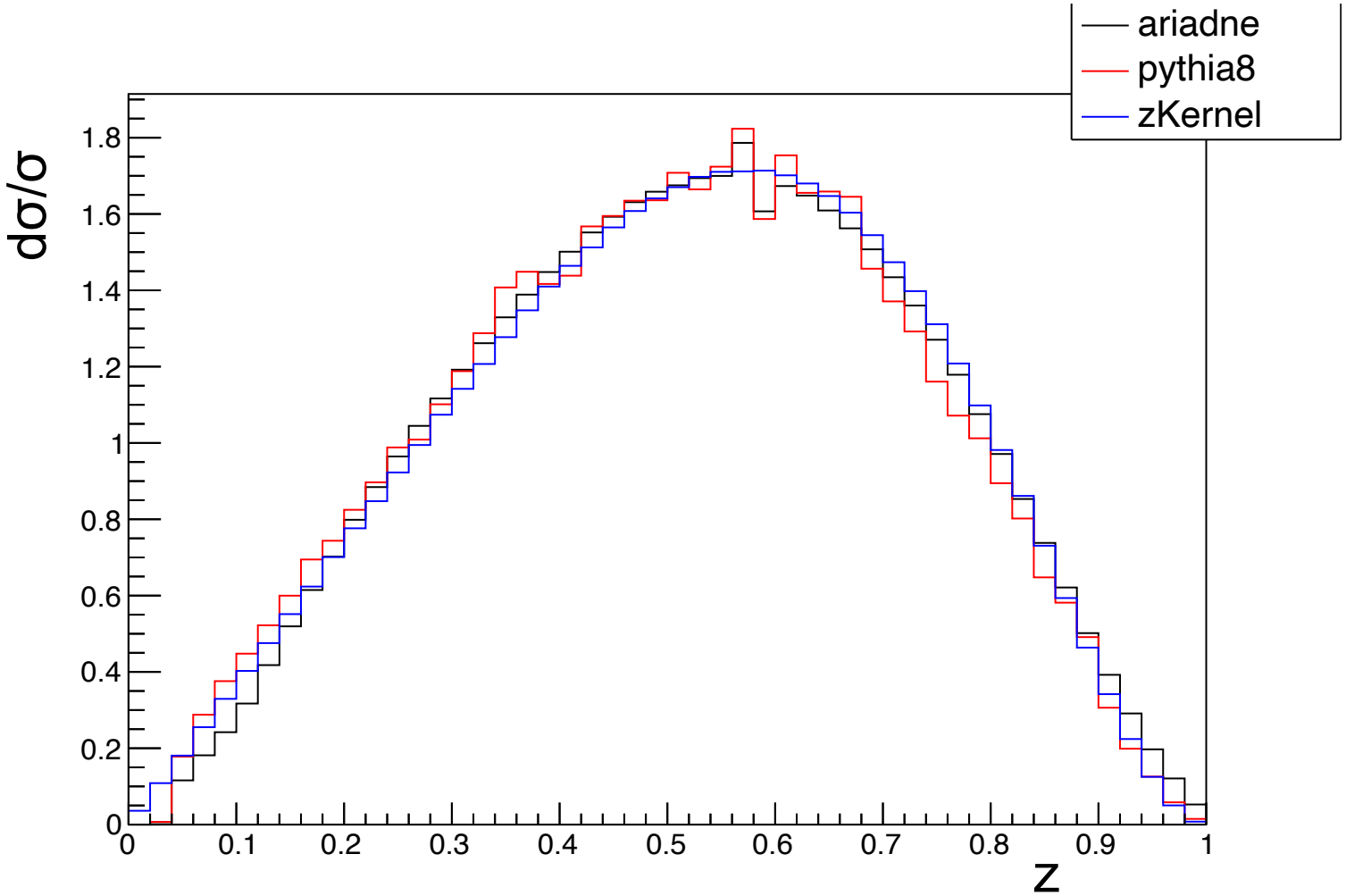
Tests produced without ISR and MPI initially. Define $z \equiv p_T(Q)/(s/2)$.



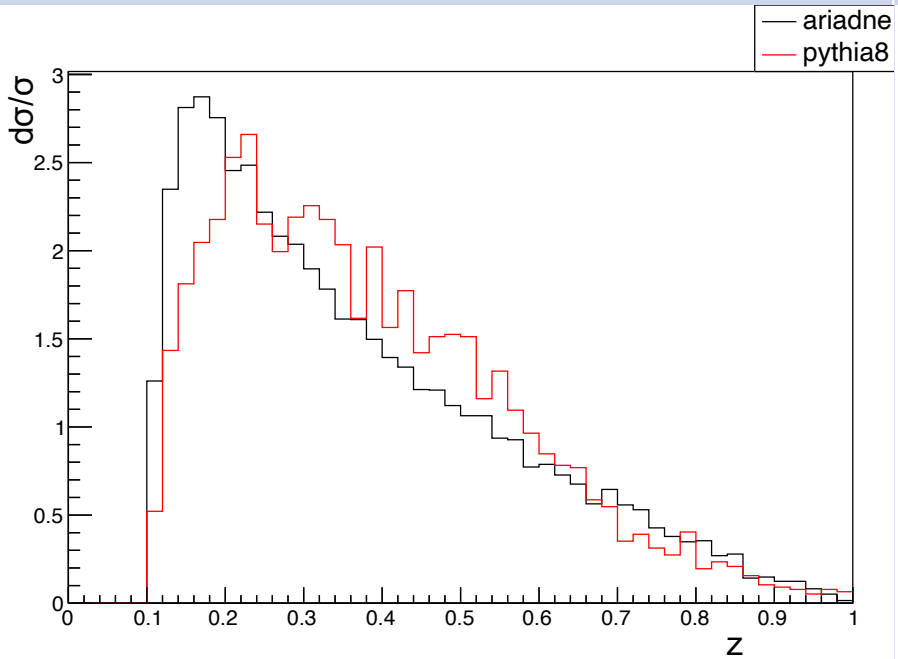
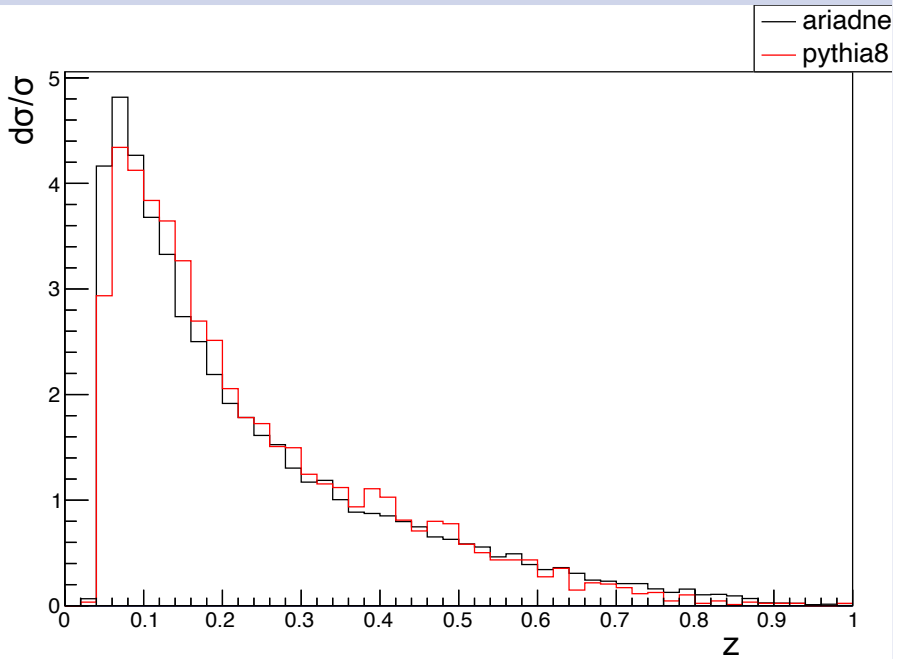
$g \to \eta_c^{(1)}\ g$

30 GeV	80 GeV	1000 GeV
		

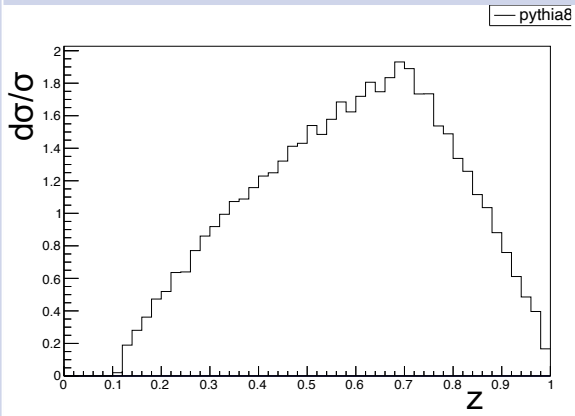
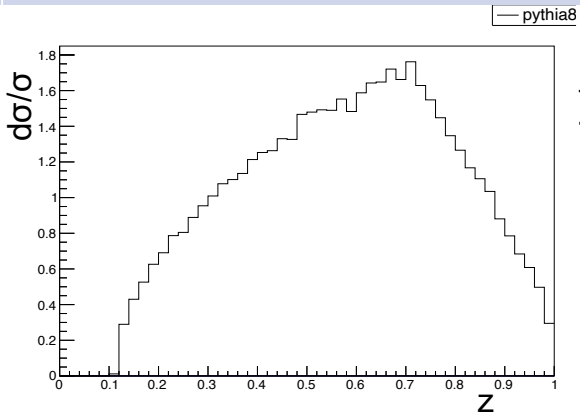
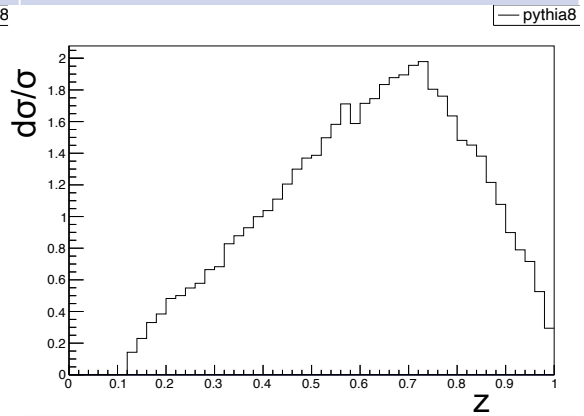
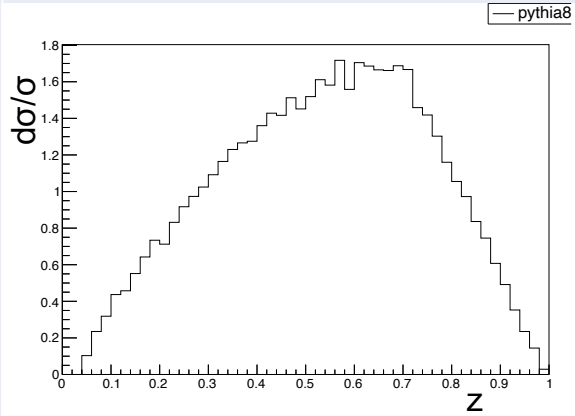
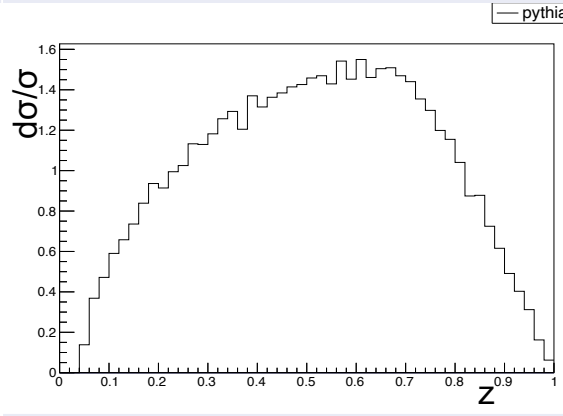
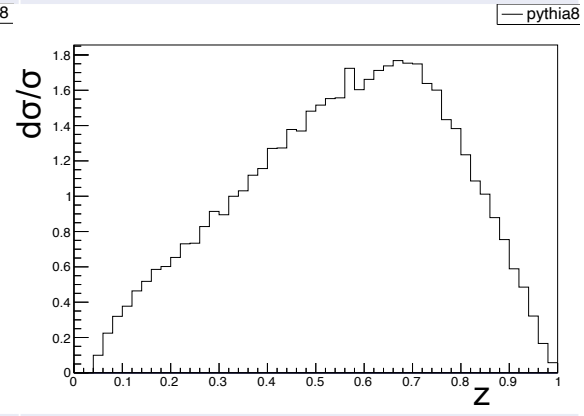
$c \rightarrow J/\psi^{(1)}\ c$



Due to di-gluon mass, translate variables from $\{r,y,z\} \to \{p^2_{T,evol}, m^2_{gg}, z\}$.

30 GeV	80 GeV
	

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

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

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

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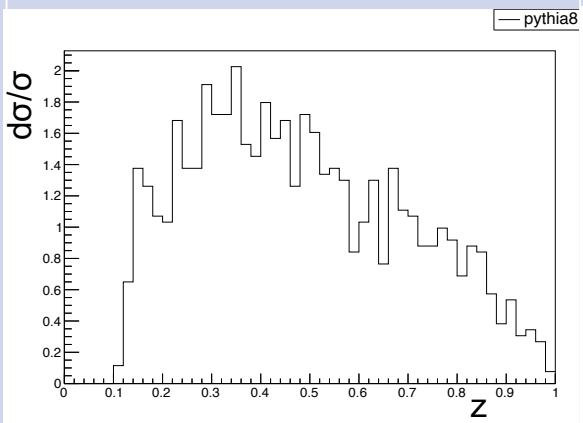
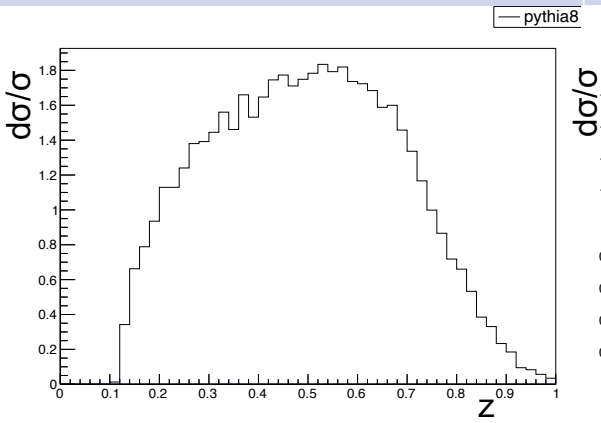
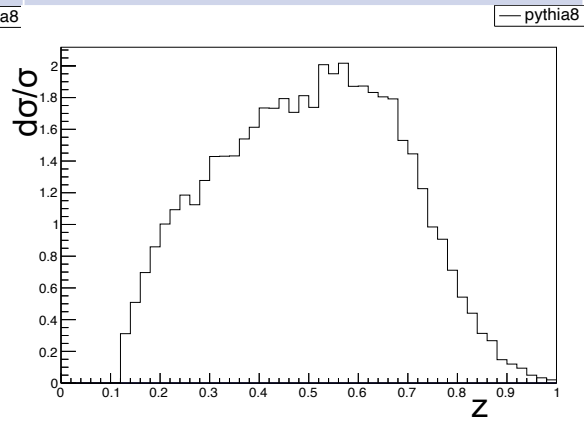
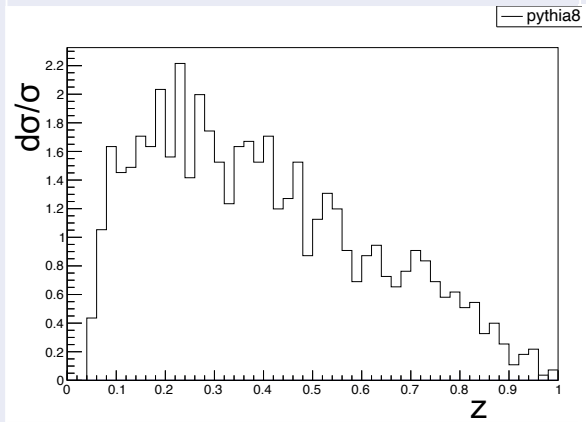
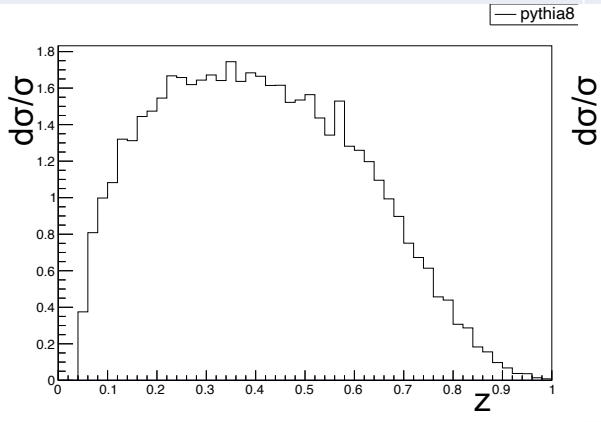
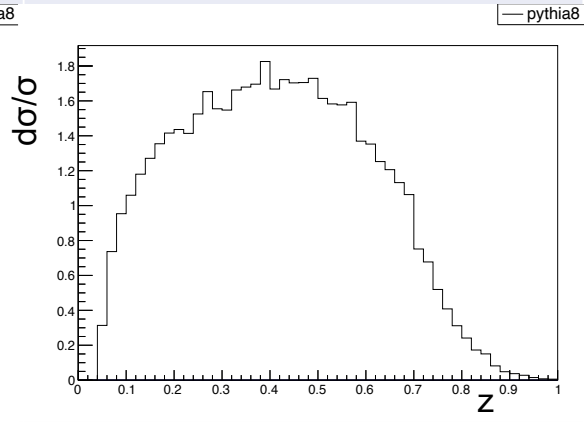
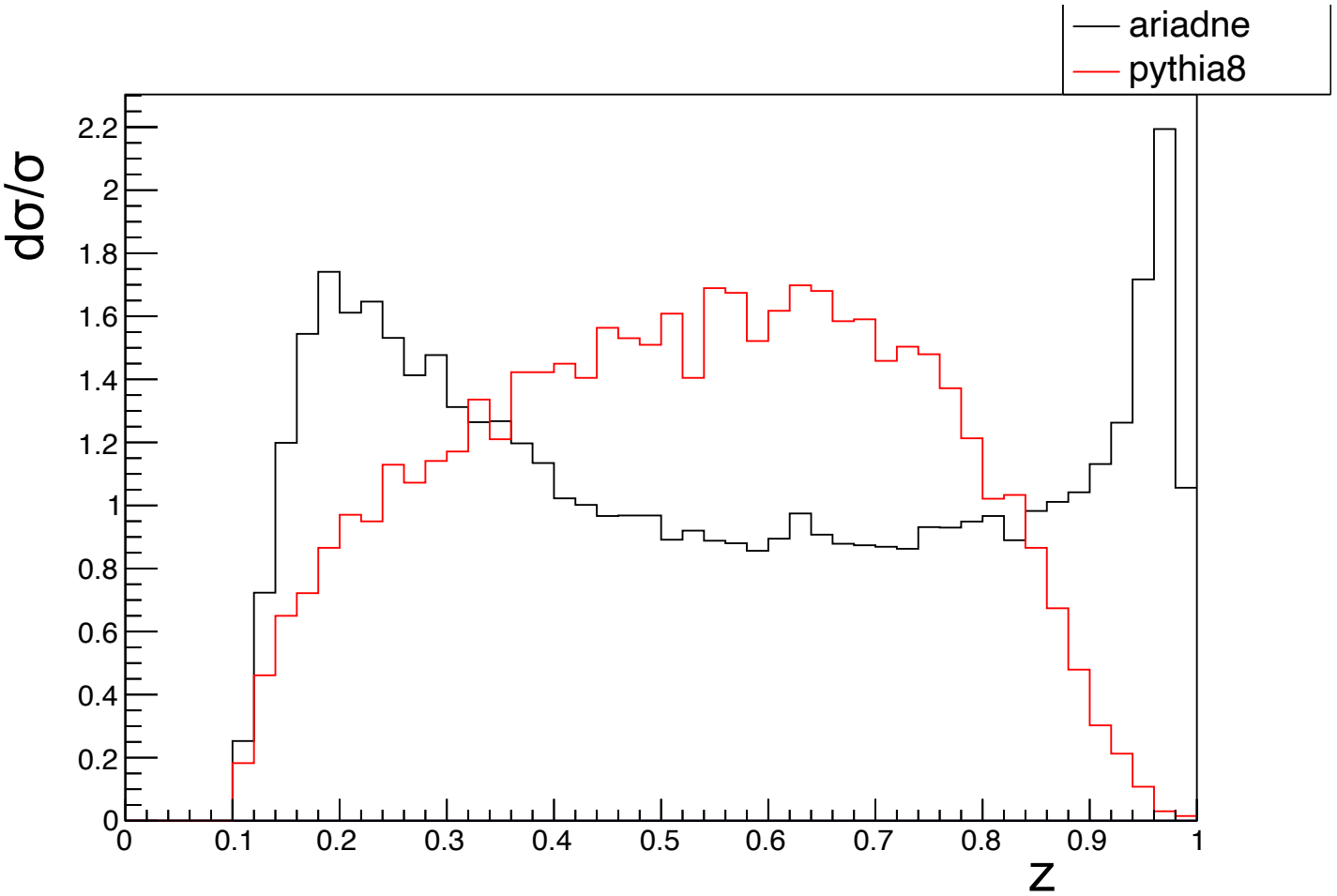
30 GeV			
80 GeV			

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



Conclusion

Completed:

- Implemented the splittings: $x \to \eta_c^{(1)}\, x$, $x \to J/\psi^{(1)}\, x$, $g \to J/\psi^{(8)}$, $x \to \chi_{ci}^{(1)}\, x$.
- Interleaved the above splittings with ISR and MPI.
- Included all above in available splittings such as $g \to q\bar{q}/q \to qg/g \to gg$.

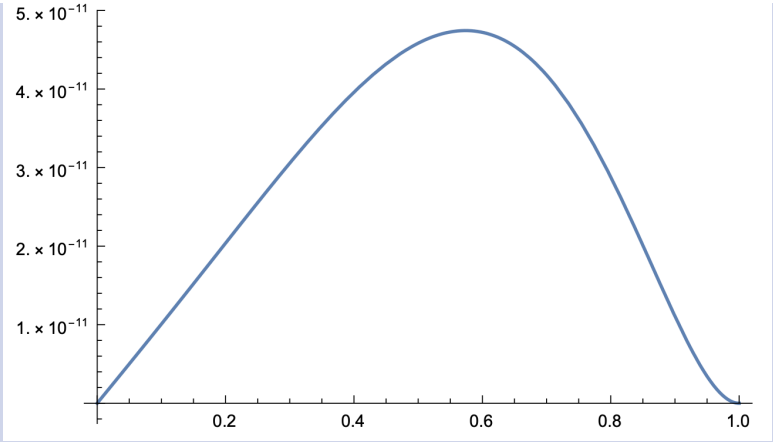
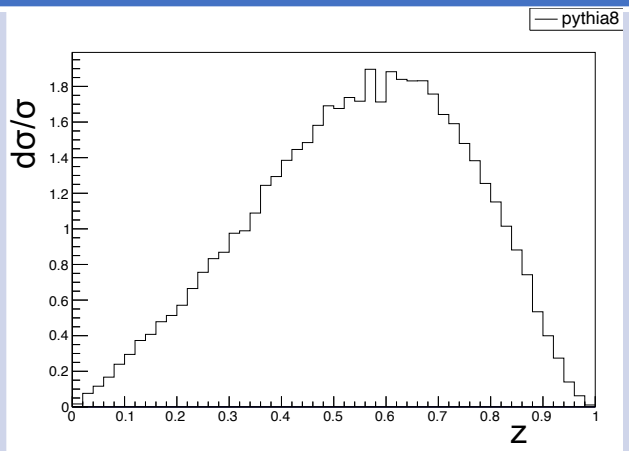
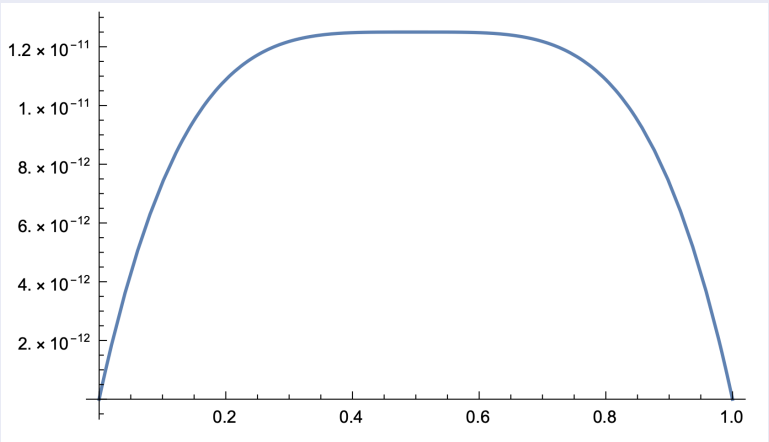
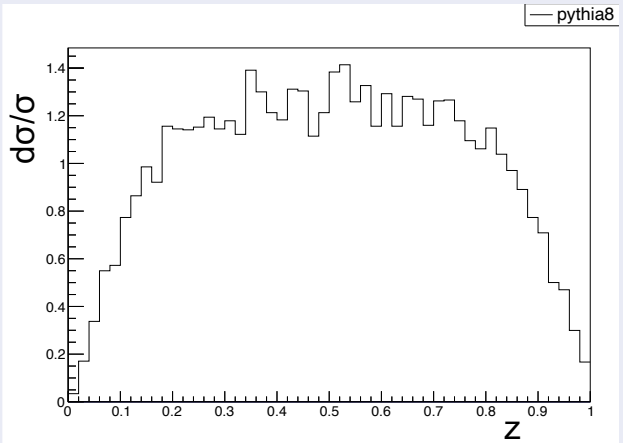
Work in progress:

- Include higher resonances + competition between them.
- Comparisons with data.

Future work:

- Matrix element correction.
- Matching + merging.

Analytical comparison

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