PROCEEDINGS OF SCIENCE

Jet fragmentation measurements at LHCb

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In these proceedings, the first measurements of $\psi(2S)$ and $\chi_{c1}(3872)$ production in jets at any experiment is presented, which are produced by the LHCb experiment. These jet fragmentation measurements are important to constrain current theoretical models, in particular Non-Relativistic Quantum Chromodynmaics (NRQCD).

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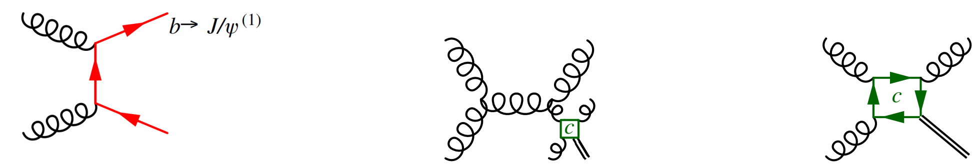


(a) Displaced. **(b)** Fragmentation. **(c)** Hard production.

Figure 1: Feynman diagrams of displaced J/ψ production in a) and prompt J/ψ production in b) and c).

1. Study of J/ψ production in jets

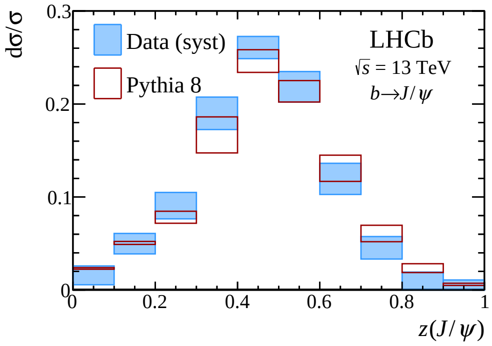
In particle physics, the production of quarkonia is still not very well understood. One of the main theories to describe their production is the effective field theory, non-relativistic QCD (NRQCD). The consequence of these NRQCD fixed-order calculations, also called hard production calculations, show that quarkonia are produced in colour singlet and colour octet states. These hard production NRQCD predictions are able to match data distributions of differential production cross sections versus $p_T(J/\psi)$ at multiple experiments, including LHCb [1]. However, polarisation measurements are not consistent with these theoretical predictions. Hard production NRQCD predicts that J/ψ's are produced transversely polarised at high $p_T(J/\psi)$, in comparison to experimental measurements which show they are minimally polarised at all $p_T(J/\psi)$ values [2].

Subsequently, NRQCD was reformulated to not only include quarkonia produced through hard production, as shown in fig. 1c, but also through fragmentation as shown in fig. 1b. More gluons are associated with quarkonia produced through fragmentation rather than hard production, hence these production mechanisms can be distinguished experimentally by studying the radiation associated with them by clustering them into jets. Hence, cross sections can be measured with respect to $z(J/\psi) \equiv p_T(J/\psi)/p_T(\text{jet})$, to take into account the surrounding radiation, rather than $p_T(J/\psi)$.

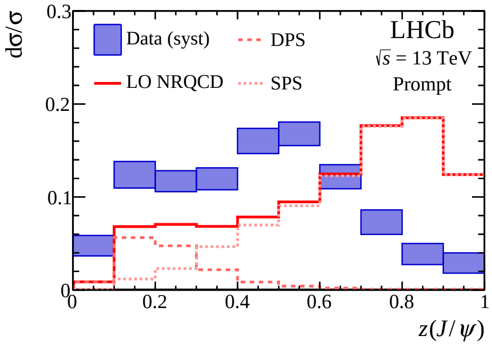
In 2017, normalised cross sections were measured versus $z(J/\psi)$ for J/ψ's at LHCb for jets with $p_T(\text{jet}) > 20$ GeV/c [3]. These were separated into prompt (produced directly at the primary vertex (PV)) and displaced (produced from B decays) production as shown in fig. 2. Prompt production here also includes J/ψ's produced from feed down of χ_c decays, as the decay times are too short to produce a distinguishable secondary vertex by the LHCb detector. The displaced distribution matches Pythia 8 [4] predictions within uncertainty. However, prompt J/ψ mesons in data are observed to be less isolated than predicted by Pythia 8. The Pythia 8 predictions shown here only include quarkonia production through NRQCD hard production and not through NRQCD fragmentation [3].

2. Study of $\psi(2S)$ and $\chi_{c1}(3872)$ production in jets

The first measurements of $\psi(2S)$ and $\chi_{c1}(3872)$ production in jets are presented here. $\psi(2S)$ is interesting to measure as it is an excited state of the J/ψ. For their prompt production, $\psi(2S)$'s have negligible feed down contributions from higher excited states, such as χ_c states, in comparison to J/ψ's. Hence, it is intriguing to explore if the different feed down contributions will effect the prompt jet fragmentation results between the two quarkonia states. $\chi_{c1}(3872)$ is measured also to add further information to if it is inherently a tetraquark or a molecular state.



(a) Displaced [3].



(b) Prompt [3].

Figure 2: Normalised cross sections versus $z(J/\psi)$.

Normalised cross sections vs. z are measured for the $\psi(2S)$ and $\chi_{c1}(3872)$ and separated into their displaced and prompt components. The decay channel $J/\psi\pi\pi$ is used to reconstruct both particles. In comparison to the J/ψ in jets measurement, jets with $p_T(\text{jet}) > 5$ GeV/c are probed, and the normalised cross section distributions are measured in different $p_T(\text{jet})$ ranges, as well as z. Figures 3 and 5 show the displaced distributions of $\psi(2S)$ and $\chi_{c1}(3872)$ production respectively, with some selected $p_T(\text{jet})$ ranges from low to high $p_T(\text{jet})$ values. As $p_T(\text{jet})$ increases, the z distribution shape becomes invariant with $p_T(\text{jet})$. This is because at low $p_T(\text{jet})$, most of the energy of the jet is taken up by the rest mass of the quarkonia state. At high $p_T(\text{jet})$, Pythia 8 [4] matches both the $\psi(2S)$ and $\chi_{c1}(3872)$ displaced distributions. Figures 4 and 6 show the prompt distributions of $\psi(2S)$ and $\chi_{c1}(3872)$, both of which show fairly isolated distributions at low $p_T(\text{jet})$ again due to the fact most of the energy of the jet is taken up by the rest mass of the quarkonia state. However, in fig. 4 as $p_T(\text{jet})$ increases, a two-prong structure starts to appear in the $\psi(2S)$ prompt distributions, an isolated peak at $z \approx 1$ and a non-isolated peak at $z \approx 0.7$. In the NRQCD picture, the isolated peak could be $\psi(2S)$'s produced through hard production and the non-isolated peak due to fragmentation. This isolated peak then disappears at high $p_T(\text{jet})$ values. The Pythia 8 [4] predictions, which only include quarkonia production through NRQCD hard production and not through NRQCD fragmentation, do not match the $\psi(2S)$ data distributions. The prompt $\chi_{c1}(3872)$ distributions in fig. 6 at high $p_T(\text{jet})$ differ from the prompt $\psi(2S)$ distributions, which do not exhibit the two-prong structure and are fairly isolated at all $p_T(\text{jet})$ ranges. This is interesting given the fact that the $\psi(2S)$ and $\chi_{c1}(3872)$ have similar masses. This is exaggerated more in fig. 7, which compares prompt J/ψ, $\psi(2S)$ and $\chi_{c1}(3872)$ in similar $p_T(\text{jet})$ ranges. All exhibit different behaviour to one another, with J/ψ's showing non-isolated behaviour, $\chi_{c1}(3872)$'s showing isolated behaviour and $\psi(2S)$'s exhibiting both. All particles do not match the NRQCD hard production predictions produced by Pythia 8 [4].

As well as measuring prompt distributions in different $p_T(\text{jet})$ ranges, they are also measured in different $p_T(\text{tag})$ ranges, where tag is another name for the $\psi(2S)$ or $\chi_{c1}(3872)$. This explores different kinematics in comparison to the $p_T(\text{jet})$ distributions. Example distributions are shown in fig. 8 for the $\psi(2S)$ and $\chi_{c1}(3872)$ in similar $p_T(\text{tag})$ ranges to one another. The $\chi_{c1}(3872)$ also shows isolated behaviour like in $p_T(\text{jet})$ plots, and the $\psi(2S)$ shows again a more exaggerated two-prong structure in the distribution than in the $p_T(\text{jet})$ case.

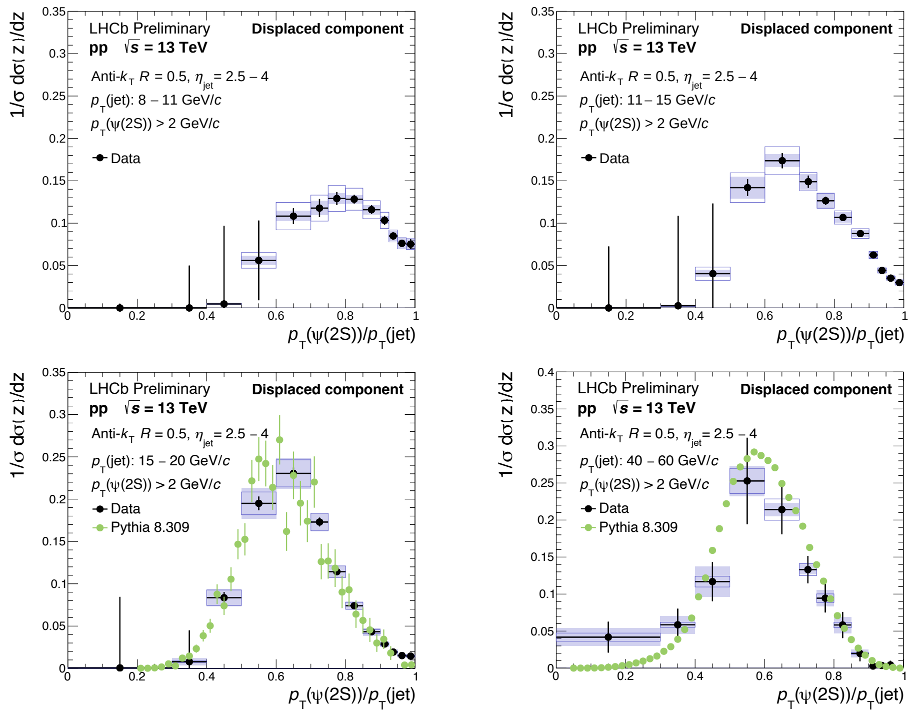


Figure 3: Normalised displaced cross sections versus $z(\psi(2S))$ in different p_T(jet) ranges.

3. Conclusions

In conclusion, measurements by LHCb have provided more information on jet fragmentation for various quarkonia states. For the $\psi(2S)$ and $\chi_{c1}(3872)$, displaced z distributions are described well by Pythia 8. The prompt z distributions are less isolated than Pythia 8 predictions, with $\psi(2S)$ being even more so. The two-prong structure in $z(\psi(2S))$ could be explained by an NRQCD hard production and fragmentation mixture. New Pythia 8 developments which now include NRQCD fragmentation in the parton shower should improve MC predictions for quarkonia production in jets, and significantly improve jet unfolding procedures [5].

References

[1] LHCb collaboration, *Measurement of forward J/ψ production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP 10 (2015) 172.

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[4] Torbjörn Sjöstrand, et al. *An introduction to PYTHIA 8.2*, Comp. Phys. Comm. 191 (2015).

[5] Naomi Cooke, et al. *Non-relativistic quantum chromodynamics in parton showers*, Eur. Phys. J. C 84:432 (2024).

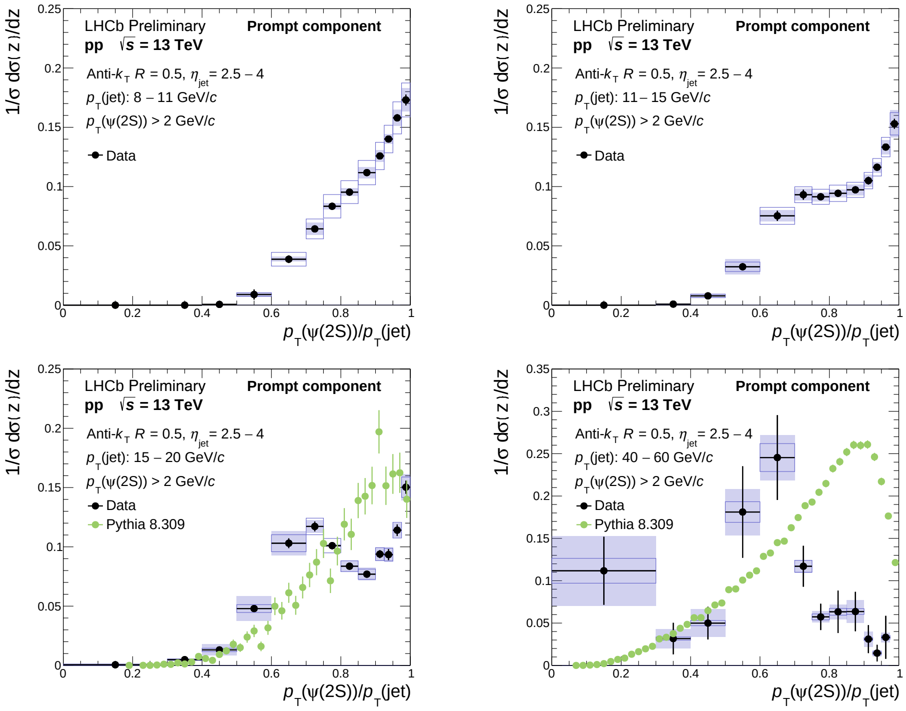


Figure 4: Normalised prompt cross sections versus $z(\psi(2S))$ in different p_T(jet) ranges.

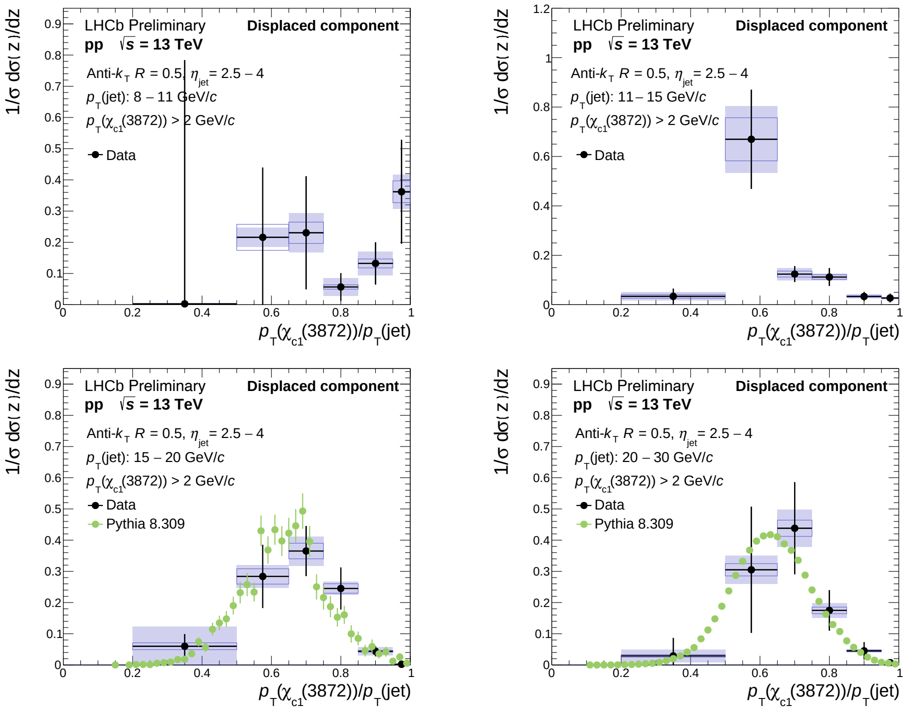


Figure 5: Normalised displaced cross sections versus $z(\chi_{c1}(3872))$ in different p_T(jet) ranges.

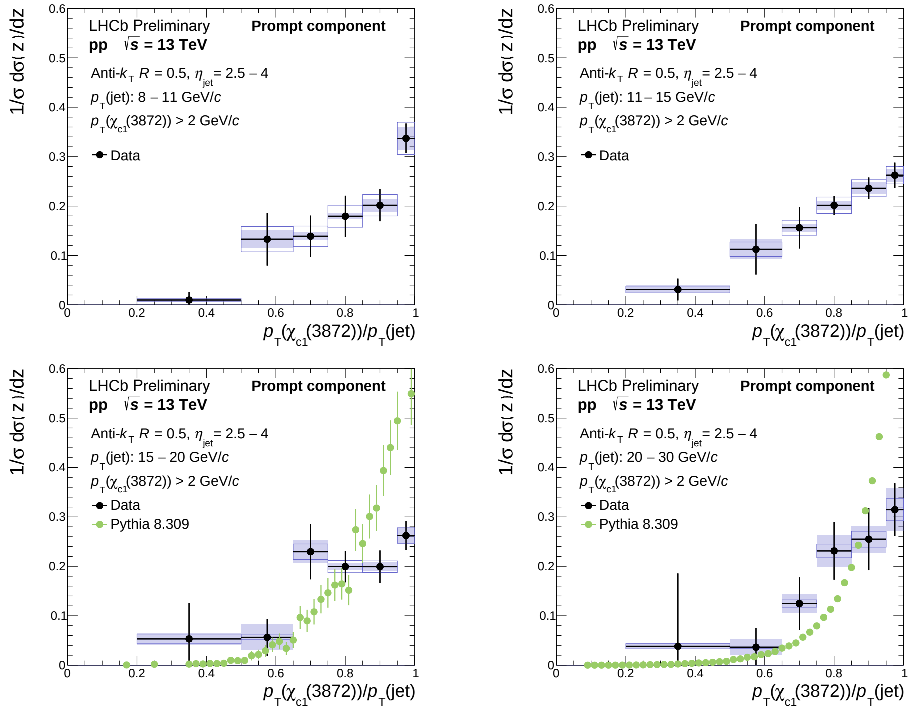
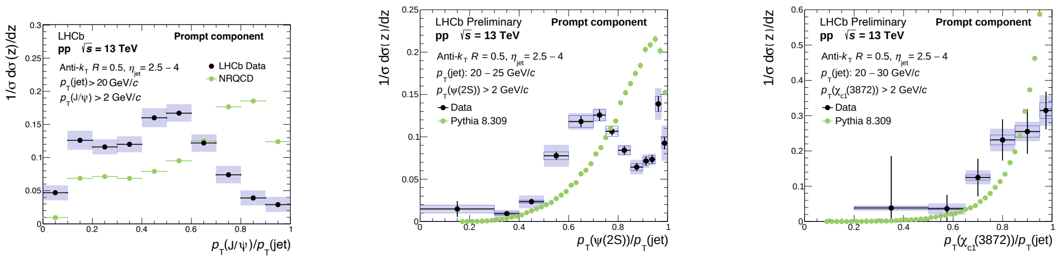
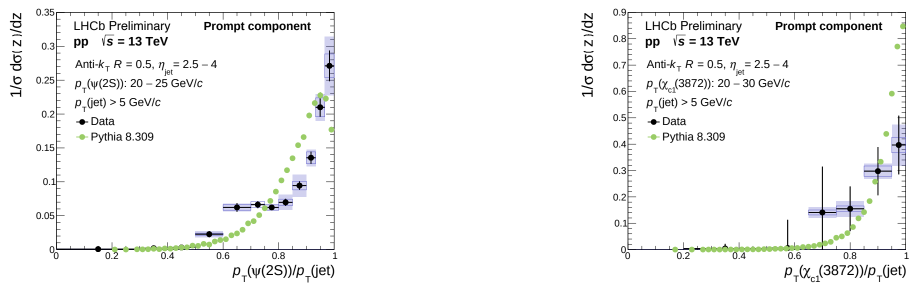


Figure 6: Normalised prompt cross sections versus $z(\chi_{c1}(3872))$ in different p_T(jet) ranges.



(a) J/ψ: p_T(jet) > 20 GeV/c. **(b)** ψ(2S): 20 < p_T(jet) < 25 GeV/c. **(c)** χ_{c1}(3872): 20 < p_T(jet) < 30 GeV/c.

Figure 7: Comparison of a) J/ψ, b) ψ(2S) and c) χ_{c1}(3872) prompt normalised cross sections versus z in similar p_T(jet) ranges.



(a) ψ(2S): 20 < p_T(tag) < 25 GeV/c. **(b)** χ_{c1}(3872): 20 < p_T(tag) < 30 GeV/c.

Figure 8: Comparison of a) ψ(2S) and b) χ_{c1}(3872) prompt normalised cross sections versus z in similar p_T(tag) ranges.