PROCEEDINGS OF SCIENCE

Jet fragmentation and QCD measurements at LHCb

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Jet fragmentation measurements from experiments are important to constrain current transverse-momentum-dependent fragmentation functions and hadronisation models. In these proceedings, results by the LHCb Collaboration are presented which measure the charged hadron content in Z-tagged jets. Firstly, as inclusive hadrons and subsequently separated into π, K, and p. Quarkonia production in jets has also been investigated, where future prospects for this analysis are also presented.

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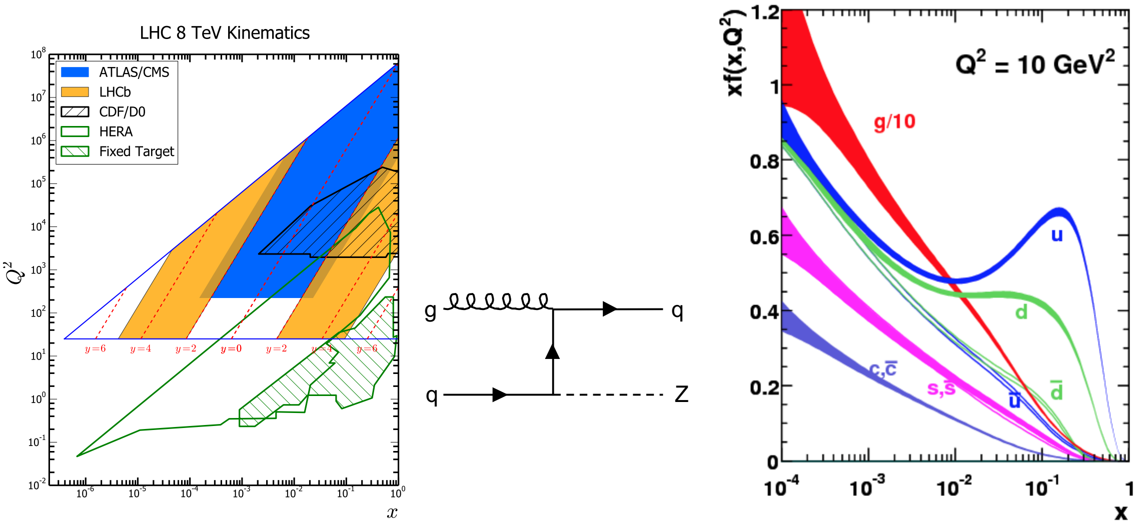


(a) Q^2 vs. x in proton PDF [4]. **(b)** Z+jet diagram. **(c)** PDF distributions [5].

Figure 1: Regions of the $x-Q^2$ plane in the proton PDF that LHCb probes in a), an example Z+jet Feynman diagram in b) and PDF distributions versus x in c).

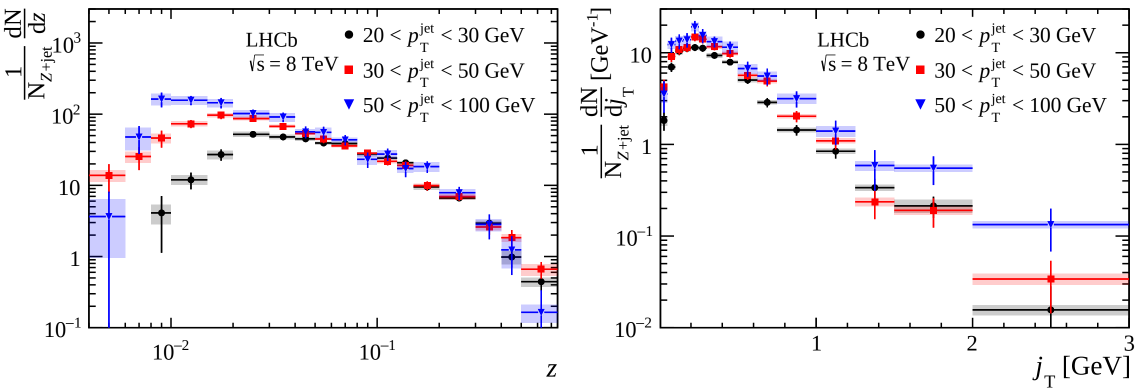
1. Introduction

In these proceedings, three analyses produced by LHCb will be described. Firstly, charged hadron production in Z-tagged jets [1]. Secondly, identified charged hadron production in Z-tagged jets (π,K,p) [2]. Finally, the study of J/ψ production in jets and future prospects for this analysis [3]. LHCb is particularly good at these type of analyses because of the very good hadron particle identification (PID) from the RICH detectors, π^0 PID from the calorimeters, and muon PID from the muon system. Also, due to its layout, it is able to probe a unique phase space in the forward region. This is shown in fig. 1a, where LHCb can probe very low and high x values in the proton PDF, where x is the momentum fraction of the struck parton in the proton. Also, the trigger allows low-momentum particles to be probed.

2. Charged hadron production in Z-tagged jets

Jet fragmentation measurements are useful as the jets produced in an event are correlated to the scattered parton in the initial hard process. This analysis is the first measurement of charged hadrons being produced in jets, recoiling against a Z-boson (Z-tagged jets) in the forward region. Most LHC inclusive jet measurements are dominated by gluon jets. However, this analysis predominantly probes light-quark jets. This is due to the fact that LHCb probes high-x regions of the proton PDF, so as shown in fig. 1c, this is dominated by the light quark PDFs. Hence, the main Z+jet diagram is shown in fig. 1b. This measurement from LHCb can be used to constrain transverse-momentum-dependent fragmentation functions and hadronisation models [1].

The three variables measured in this analysis are z, the longitudinal momentum fraction of the hadron to the jet, j_T, the hadron momentum transverse to the jet axis, and r which is radial



(a) z [1]. **(b)** j_T [1].

Figure 2: z and j_T distributions for different p_T(jet) ranges.

displacement of the hadron in the jet. These are all measured with respect to the jet axis in the laboratory frame [1].

This analysis used the 2012 LHCb data set, with a total integrated luminosity of 2 fb^{-1} at $\sqrt{s}$ =8 TeV. $Z \longrightarrow \mu\mu$ was used as the decay channel, and the main cuts applied were p_T(jet) >20 GeV, $2.5 < \eta(\text{jet}) < 4$, $\Delta\phi_{Z-\text{jet}} \equiv |\phi_Z - \phi_{jet}| > 7\pi/8$. The final results were efficiency corrected and a 2D Bayesian unfolding procedure was applied to correct for the jet energy resolution [1].

Figure 2a shows the measurement of z for different p_T(jet) ranges. The z distribution is roughly constant as a function of p_T(jet) at high z. The visible difference at low z is a consequence of the applied cut p(hadron) > 4 GeV. Therefore, higher p_T(jet) can probe smaller z. Colour coherence effects may also be present here. Ref. [1] shows comparisons of the LHCb results with those from ATLAS. The LHCb results do not fall as steeply at high z as ATLAS. This may be due to differences between light-quark and gluon jet fragmentation [1].

Figure 2b shows the measurement of j_T for different p_T(jet) ranges. j_T peaks at small values, then has a perturbative tail. The results from LHCb are similar to the ATLAS central pseudorapidity results shown in Ref. [1].

3. Identified charged hadron production in Z-tagged jets (π,K,p)

Triple differential distributions in j_T, z and p_T(jet) for unidentified charged hadrons were measured in this analysis, as these were found to be more useful inputs to constrain the transverse-momentum-dependent fragmentation functions. These are shown in fig. 3, which represent double differential jet fragmentation functions of the longitudinal momentum fraction z and the transverse momentum j_T of unidentified charged hadrons in three p_T(jet) intervals. The general trend is that larger z values lead to larger j_T values. The distributions from left to right go to higher p_T(jet) values. This shows that larger p_T(jet) values lead to smaller z (softer particles) and larger j_T. This means fatter jets are produced. This makes sense in a parton shower type of scenario, as the higher the starting parton energy, the more likely the parton is to branch, leading to wider jets [2].

Figure 4 shows measurements of z for different p_T(jet) bins split into three different hadron types, (π,K,p). The z ratio is also shown for K and p with respect to the pion. These show that

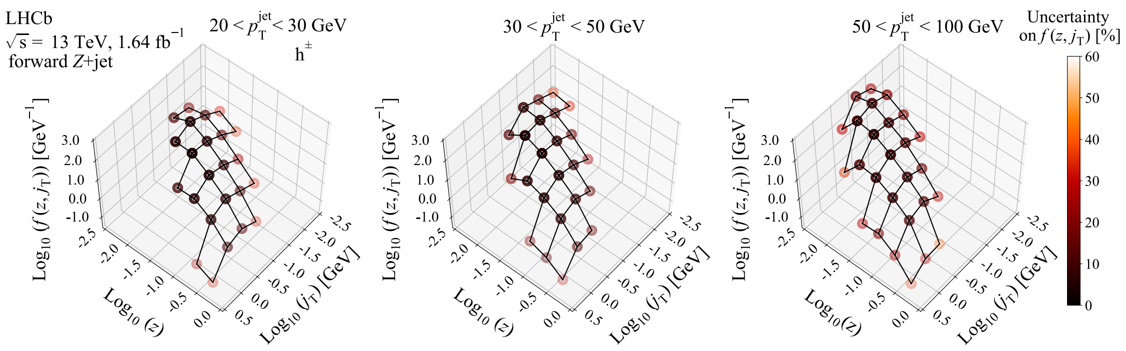


Figure 3: Triple differential distributions in j_T, z and p_T(jet) for unidentified hadrons [2].

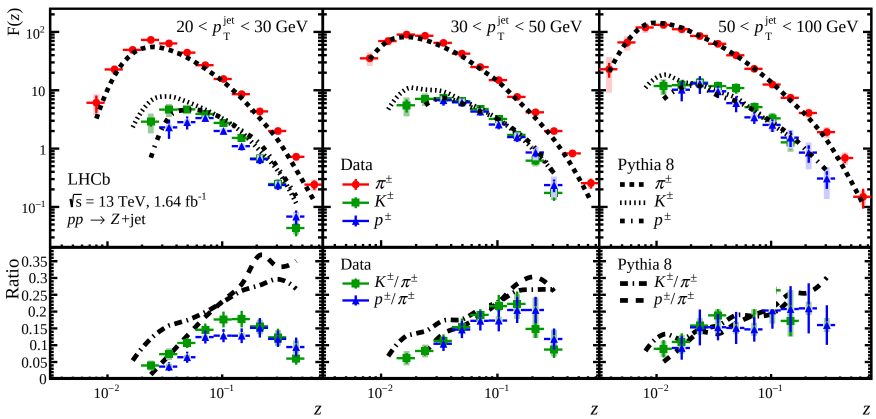


Figure 4: z distributions for different p_T(jet) ranges for π, K and p. Also z ratios for K/π and p/π [2].

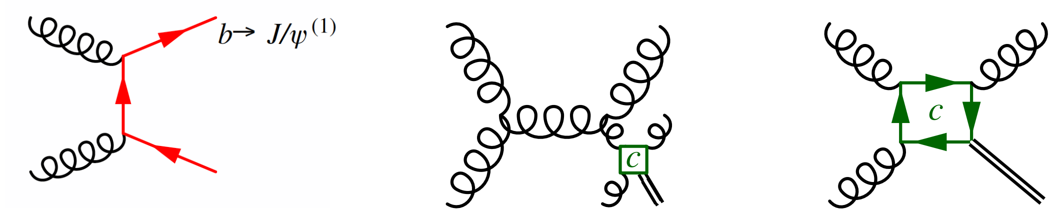
heavier mass hadrons require larger z threshold for formation. The suppression of $K^{\pm}$ production in comparison to π is due to the lack of strangeness content in the proton. The $p^{\pm}$ suppression is because it is harder to form a baryon than a meson. At high p_T(jet) values, the ratios $K^{\pm}/\pi^{\pm}$ and $p^{\pm}/\pi^{\pm}$ are described well by Pythia, in comparison at low p_T(jet) where they are overestimated [2].

4. Study of J/ψ production in jets

Quarkonia production is still not very well understood in particle physics. Hard production non-relativistic QCD (NRQCD) formalism describes quarkonia being produced in colour singlet and colour octet states. Differential production cross sections versus $p_T(J/\psi)$ show that hard production NRQCD models match data distributions by LHCb [6].

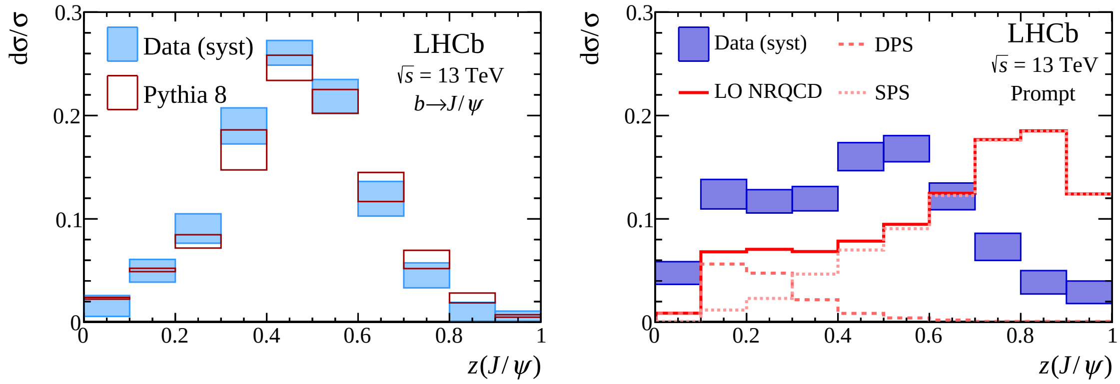
However, polarisation measurements are not consistent with theory predictions. Colour singlet states are typically produced at low $p_T(J/\psi)$ and are longitudinally polarised. In comparison to colour octet states which are produced at high $p_T(J/\psi)$ and are transversely polarised. Hence hard production NRQCD predictions expect J/ψ's to be increasingly more transversely polarised with increasing $p_T(J/\psi)$. However, LHCb data shows minimal polarisation at all $p_T(J/\psi)$ values [7].

Later, NRQCD was reformulated to not only include hard production, as shown in fig. 5c, but analytically resummed in shower production. An example diagram is shown in fig. 5b. Comparing



(a) B decays. **(b)** Shower production. **(c)** Hard production.

Figure 5: Feynman diagrams of displaced J/ψ production in a) and prompt J/ψ production in b) and c).



(a) Displaced [3]. **(b)** Prompt [3].

Figure 6: Normalised cross sections versus $z(J/\psi)$.

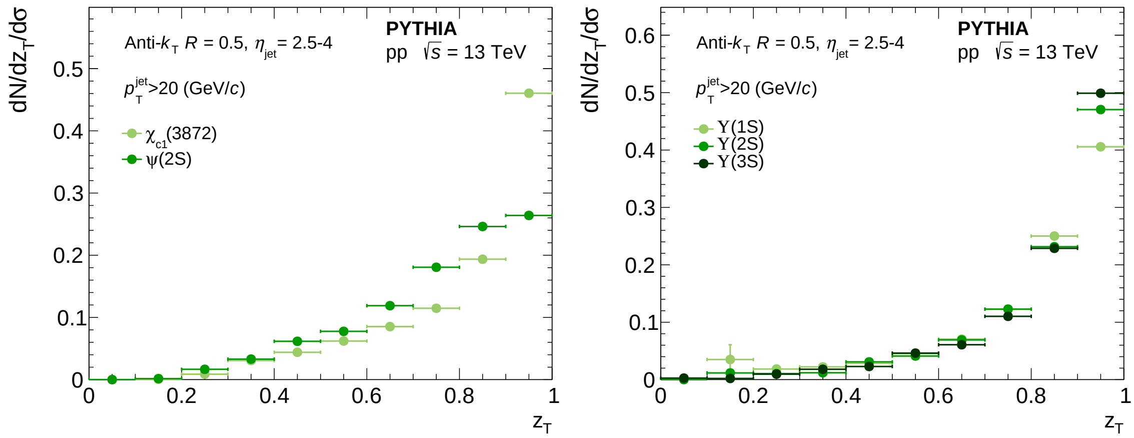
fig. 5c with fig. 5b, there are more gluons associated with the J/ψ in shower production than hard production. Hence, these two types of quarkonia production can be distinguishable experimentally by studying the radiation associated with them by clustering them into jets. Instead of measuring the cross section with respect to the $p_T(J/\psi)$, the surrounding radiation is taken into account with $z(J/\psi) \equiv p_T(J/\psi)/p_T(jet)$. This can also be thought of as a fragmentation variable.

Hence, normalised cross sections are measured versus $z(J/\psi)$. The J/ψ are either produced directly at the primary vertex (PV), prompt, or from B decays, displaced, so these are separated in fig. 6. The displaced distribution matches Pythia 8 [8] predictions within uncertainty. However, prompt J/ψ mesons in data are observed to be much less isolated than predicted by Pythia 8. There also seems to be a large contribution from double parton scattering at low $z(J/\psi)$. At the moment, quarkonia production through NRQCD fragmentation is not included in Pythia 8 [3].

Analyses to measure this variable for $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $X(3872)$ are in progress. Predictions for the z distributions are shown in fig. 7, where the Υ's are predicted to be more isolated than $\psi(2S)$ and $X(3872)$.

5. Conclusions

In conclusion, measurements by LHCb have provided more information on jet fragmentation, in particular to be able to further constrain transverse-momentum dependent fragmentation functions. Discrepancies between measured LHCb data and Pythia 8 predictions have also been observed,



(a) $\psi(2S)$ and X(3872). **(b)** $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$.

Figure 7: Pythia predictions for normalised cross sections versus z.

for the prompt production of J/ψ mesons. Extending this to other quarkonia is the next step to understanding jet fragmentation and QCD in more detail.

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