Strangeness production in pp and pPb collisions at LHCb

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Abstract. Strange hadron production provides information about the hadronisation process in high-energy hadron collisions. Strangeness enhancement has been interpreted as a signature of quark-gluon plasma formation in heavy-ion collisions, and recent observations of strangeness enhancement in small collision systems have challenged conventional hadronisation models. With its forward geometry and excellent particle identification capabilities, the LHCb detector is well-suited to study strangeness production in a unique kinematic region. Recent studies of strangeness production with the LHCb detector are presented, including measurements of strangeness enhancement in the charm- and beauty-hadron systems.

1 Introduction

The Quark-Gluon Plasma (QGP) is a phase of the QCD phase diagram where quarks and gluons appear as free particles in thermal equilibrium. The QGP is predicted to have been formed microseconds after the Big Bang and to constitute the inner core of neutron stars. This state of matter can be recreated in a laboratory colliding heavy nuclei at relativistic energies.

Due to the abundance of freely interacting quarks and gluons, the thermalised medium produced in a heavy-ion collision is expected to achieve nearly flavour-chemical equilibrium, yielding an enhanced proportion of strange quarks [1] with respect to *cold* (non-thermalised) hadronic matter. After the collision, the temperature of the system drops, and it undergoes the phase transition, quarks form into hadrons (hadronisation). Shortly after the phase transition, the relative abundance of strange baryons and mesons are fixed at chemical freeze-out according to the Bose-Einstein or Fermi distribution [2].

Therefore, it is expected that the yield of strange hadrons will increase with the size of the QGP formed. This phenomenon, known as *strangeness enhancement* is one of the first probes postulated as a signature of QGP formation. In a heavy-ion collision, the size of the QGP is proportional to the number of nucleons that participate in the collision (participants): higher at lower impact parameter. The number of participants can be related to final-state quantities such as the charged particle multiplicity [3].

Smaller systems, such as pPb and pp collisions, are not expected to achieve enough energy density to form a thermalised medium. However, over recent years there has been an increase in interest in the search for QGP traits in these systems. The ALICE Collaboration has measured a strangeness enhancement in high multiplicity pp collisions [4]. In this paper, we summarise recent LHCb results for heavy flavour strange hadrons in small systems.

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The LHCb detector, at the LHC, is a single-arm forward spectrometer covering the pseudorapidity range $2 \lesssim \eta \lesssim 5$ [5] in the laboratory frame. It is composed of several subdetectors. The tracking system consists of the VErtex LOcator system (VELO) and several planar tracking stations. The VELO is a silicon strip detector whose main purpose is to reconstruct the beams interaction point (primary vertex). Particle identification in LHCb is provided by electromagnetic and hadronic calorimeters, two Cherenkov detectors and muon trackers.

The design of the LHCb detector is optimised to study heavy flavour physics and therefore provides the opportunity to study strangeness enhancement in the relatively unexplored heavy flavour sector. Furthermore, heavy hadrons constitute exceptional probes for hadronisation. The usual model to describe hadronisation in hadronic collisions is fragmentation, where showers of partons produced by outgoing quarks form into hadrons. However, in the case of a very dense medium, readily available quarks with overlapping wave functions could combine into colour singlets, hadronising through coalescence. Coalescence is thought to be the leading mechanism in high-energy heavy-ion collisions where the QGP is formed. In pp and pPb collisions, if coalescence emerges as hadronisation mechanism, the production of strange to non-strange heavy hadrons could increase with particle multiplicity, provided there is strangeness enhancement. This effect would be more pronounced at low transverse momentum (p_{T}) where there is a higher density of light particles in the underlying event.

2 Recent LHCb results of strangeness production in small systems

The following sections constitute a collection of recent LHCb measurements of the ratios of strange to non-strange heavy hadrons in small collision systems: pp and pPb.

2.1 B_s^0 over B^0 production ratio in pp collisions at $\sqrt{s}$ = 13 TeV

The pp collisions data used for this measurement [6] were collected at a centre-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to a total integrated luminosity of $5.4\,\mathrm{fb}^{-1}$. The B_s^0/B^0 ratio was studied for several normalised multiplicity intervals. The chosen multiplicity proxies are the number of tracks reconstructed by the VELO ($\mathrm{N}_{\mathrm{tracks}}^{\mathrm{VELO}}$), and a subset of these that point backwards with respect to LHCb ($\mathrm{N}_{\mathrm{tracks}}^{\mathrm{back}}$), in the pseudorapidity interval $-3.5 < \eta < -1.5$. The B_s^0/B^0 ratio consistently increases with $\mathrm{N}_{\mathrm{tracks}}^{\mathrm{VELO}}$, which is not the case for $\mathrm{N}_{\mathrm{tracks}}^{\mathrm{back}}$. The lack of dependence on $\mathrm{N}_{\mathrm{tracks}}^{\mathrm{back}}$ could indicate that the mechanism responsible for the increase in the ratio is related to the local particle density. The ratio as a function of multiplicity is studied for several p_{T} intervals. Figure 1 shows that there is only a significant increase of the ratio at the lowest p_{T} interval, where the B mesons have p_{T} smaller or similar to their mass.

2.2 Strange over non-strange charm hadron production ratios in pPb collisions

In pPb collisions, the kinematic reach of LHCb is extended by reversing the direction of the proton and the lead beams, accessing forward ($1.5 \lesssim y^* \lesssim 4$) and backward ($-5 \lesssim y^* \lesssim -2.5$) rapidities[1]. The pPb collision data were acquired during two LHC runs, the first in 2013, at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, with an integrated luminosity of $1.1\,\mathrm{nb}^{-1}$ ($0.4\,\mathrm{nb}^{-1}$) for forward (backward) collisions, and the second in 2016 at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, with $12.5\,\mathrm{nb}^{-1}$ ($19.3\,\mathrm{nb}^{-1}$).

In the charm sector, we first look at the results of prompt D-meson production ratios D_s^+/D^+ and D_s^+/D^0 measured in pPb collisions at 5 TeV [7]. The ratios do not show significant dependence with p_{T} or rapidity.

[1] y^* is the nucleon-nucleon centre-of-mass rapidity. Since the proton beam had a higher energy per nucleon than the Pb beam, the nucleon-nucleon centre-of-mass was moving in the laboratory frame with a rapidity of -0.465 in the direction of the proton beam, causing the pPb and Pbp configurations to have different $|y^*|$ acceptances.

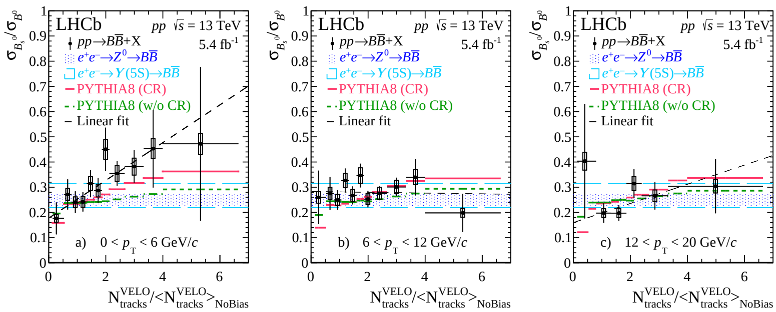

Figure 1. Ratio of cross sections $\sigma_{B^0_s}/\sigma_{B^0}$ measured against normalised $\mathrm{N}^{\mathrm{VELO}}_{\mathrm{tracks}}$, for three p_{T} ranges. The normalisation factor, $\langle \mathrm{N}^{\mathrm{VELO}}_{\mathrm{tracks}} \rangle_{\mathrm{NoBias}}$, is the average number of VELO tracks for unbiased events, which are selected based on the Large Hadron Collider beam clock, without any other trigger requirements. The vertical error bars (boxes) represent point-to-point uncorrelated (fully correlated) uncertainties. The horizontal bands show the values measured in e^+e^- collisions. From Ref. [6].

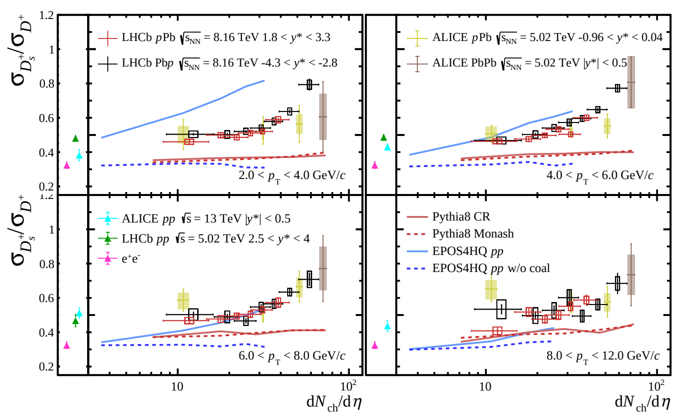

Figure 2. Cross-section ratio of D_s^+ over D^+ in different p_{T} intervals. The red (black) points show the results measured by LHCb for forward (backward) pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$. The measurements from the ALICE Collaboration for pPb and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ are included as well as the results from e^+e^- collisions and pp collisions. The vertical error bars show the statistical uncertainties and the boxes show the systematic uncertainties. Calculations from Pythia 8 and EPOS4HQ with and without coalescence mechanism are also shown. From Ref. [8].

The higher luminosity 8.16 TeV data sample allows for the study of the D_s^+ over D^+ production ratio with more precision [8]. The charged particle multiplicity in the forward region ($dN_{ch}/d\eta$) is obtained from a subset of $\mathrm{N}^{\mathrm{VELO}}_{\mathrm{tracks}}$ that is used to reconstruct the primary vertex, applying corrections based on simulation. Figure 2 shows the dependence of the ratio with $dN_{ch}/d\eta$ for different p_{T} intervals. At low multiplicity, the results resemble those of pp collisions, while at high multiplicities the ratio increases and is compatible with measurements from PbPb collisions. This trend is observed both in forward and backward rapidities. The data is compared to predictions from Pythia8 and EPOS4HQ. All models show some discrepancies with data, although EPOS4HQ depicts the increasing trend when accounting for coalescence as hadronisation mechanism.

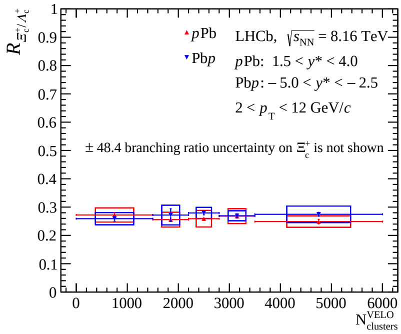

Figure 3. The LHCb measurements of the Ξ_c^+ over Λ_c^+ multiplicity ratio as a function of $\mathrm{N}_{\mathrm{clusters}}^{\mathrm{VELO}}$ for forward (backward) pPb collisions are shown as red (upside down blue) triangles. The error bars represent the statistical uncertainties, while the squares indicate the systematic uncertainty. The 48.4% branching ratio uncertainty of the Ξ_c^+ is not accounted for. From Ref. [9].

The baryon ratio of Ξ_c^+ over Λ_c^+ production is measured in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ [9]. The sample was divided into multiplicity classes using the number of energy clusters deposited in the VELO stations ($\mathrm{N}_{\mathrm{clusters}}^{\mathrm{VELO}}$). As shown in Figure 3, the ratio does not show a significant dependence on multiplicity.

3 Summary

The relative production of several strange to non-strange hadrons was studied in small collision systems at LHCb. In pp collisions at $\sqrt{s} = 13$ TeV, there is an observed enhancement of the B_s^0/B^0 ratio at high multiplicity and low p_{T}, which is qualitatively compatible with a coalescence hadronisation mechanism. This enhancement is not observed when using backward tracks as multiplicity estimator. In pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ the D_s^+/D^+ and D_s^+/D^0 ratios do not show a clear trend with p_{T} or η. In pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$, a significant enhancement of the D_s^+/D^+ ratio is observed in events with high multiplicity. However, the baryon ratio Ξ_c^+/Λ_c^+ appears to be constant when studied as a function of $\mathrm{N}_{\mathrm{clusters}}^{\mathrm{VELO}}$.

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