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PARTICLE PRODUCTION STUDIES AT LHCb*

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Although optimized for b-physics, LHCb with its unique angular coverage $2 < \eta < 5$ is also able to contribute significantly to the understanding of the hadron production mechanism in high energy collisions. Here, the first data particle production studies at LHCb are reviewed including K^0_{S} and ϕ production cross-section, and measurements of production ratios of $\bar{\mathit{\Lambda}}/\mathit{\Lambda}$, $\bar{\mathit{\Lambda}}/K^0_{\mathrm{S}}$, $\bar{p}/p$.

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1. Introduction

The LHCb experiment at the CERN LHC [1] is dedicated to heavy flavor physics, its primary goal being to look for New Physics through precise measurements of CP violation and rare decays of the b- and c-hadrons. After a long wait, LHC started to collide proton beams at a center of mass energy of 900 GeV in 2009, and at 7 TeV in 2010, about 3.5 times above the highest energies previously reached by accelerators. LHCb took advantage of these new conditions to explore particle production in a kinematic range at high rapidities and low transverse momenta not accessible to the other experiments. Thus, LHCb provides a valuable contribution to the study of the hadrons. The first studies on strangeness production and baryon transport mechanism presented here already provide important information in a kinematic range where theoretical QCD models diverge.

The LHCb detector is a forward spectrometer, covering the angular range of $15 < \theta < 300$ mrad with respect to the beam axis. The detector is fully instrumented over its full acceptance and offers tracking, particle

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identification, calorimetry and muon detection. Momenta of charged particles are determined from the deflection by a dipole magnet with a field integral of 4 Tm. The LHCb tracking system is composed of the silicon Vertex Locator (VELO) around the proton–proton interaction point, a tracking station (TT) in front of the magnet and the main tracking station behind the magnet, consisting of a high granularity Inner Tracker (IT) in the region of large particle densities close to the beam pipe and the Outer Tracker system further away from the beam pipe. While VELO, TT and IT are silicon strip detectors, the OT consists of straw tubes. LHCb is also equipped with a dedicated hadron particle identification (PID) system, based on two Ring Imaging Cherenkov detectors (RICH). One of these is installed in front of the magnet, equipped with two radiators (Aerogel and C_4F_{10}), and a second one is installed behind the magnet, equipped with a CF_4 based radiator. The RICH detectors allow pion, kaon, proton separation in the momentum range between $2 < p < 100$ GeV/c. The tracking and RICH detectors are the main subsystems employed in the measurements included here. The LHCb detector contains also a pre-shower and scintillating pad detector (SPD/PS), electromagnetic calorimeter (ECAL), hadron calorimeter(HCAL) and muon system for the identification of electrons and photons, neutral hadrons and muons, respectively.

LHCb accumulated 6.8 μb^{-1} of data at 900 GeV in 2009. In 2010 a total of 0.3 nb^{-1} and 37.66 pb^{-1} of pp collision data have been recorded at center of mass energies of 0.9 TeV and 7 TeV, respectively. The following studies were performed on the data selected by minimum bias trigger.

2. Measurement of strangeness production

The study of strangeness production is ideal for early measurements due to the larger cross-section, compared to heavy flavors. Since strange quarks are not present as valence quarks in the initial state and have a mass in an intermediate range where QCD predictions have large uncertainties, they directly probe the mechanism of multi-particle production in high energy collisions where the theory is less well understood. Different fragmentation models, tuned on Tevatron data, agree on the total amount of strangeness produced but disagree on its distribution over phase space and on the ratios of the strange hadrons produced. LHCb is particularly interesting for QCD studies since one can measure the production of strange quarks in a range where models are expected to diverge more than for central rapidities. Moreover, V^0-decays (K^0_S, $\mathit{\Lambda}$, $\bar{\mathit{\Lambda}}$) have a very clean experimental signature which allows to identify them unambiguously using only kinematic information[1].

[1] They were actually used for PID calibration.

As for the ϕ-meson, being dominantly an $s\bar{s}$-state it offers a unique way to study primary strangeness production, and via its decay into charged kaon pairs is vital for the calibration of the PID system of LHCb.

2.1. K^0_S production cross-section

The K^0_S production represented an ideal first measurement for LHCb as a high-purity sample could be obtained without using particle identification information. The 6.8 $\mu\mathrm{b}^{-1}$ of data recorded in the pilot run in 2009 provided the very first K^0_S prompt cross-section measurement at the 0.9 TeV center of mass interaction energy [2]. In figure 1, the LHCb results were presented in bins of y and p_T. The different Monte Carlo predictions agree reasonably well with the data, although they tend to underestimate (overestimate) the measured production in the highest (lowest) p_T bins.

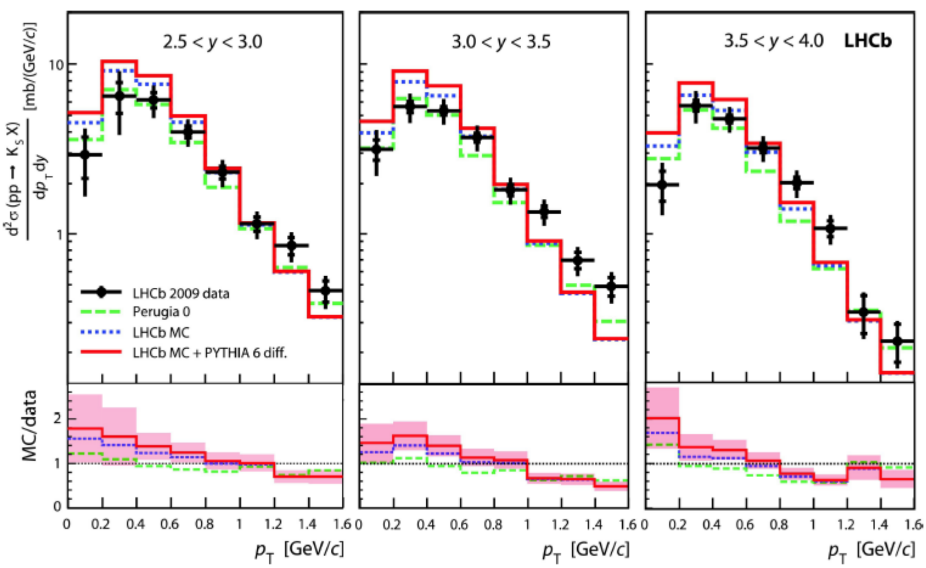

Fig. 1. Differential prompt K^0_S production cross-section in pp collisions at $\sqrt{s} = 900$ GeV as a function of transverse momentum p_T and rapidity y. The points represent LHCb data, with total uncertainties shown as vertical error bars and statistical uncertainties as tick marks on the bars. The histograms are predictions from different settings of the PYTHIA model. The lower plots show the Monte Carlo/data ratios, with the shaded band representing the uncertainty for one of these ratios, dominated by the uncertainty on the measurements (the relative uncertainties for the other ratios are similar).

To determine the absolute luminosity, for this study, a novel method was designed [2,3], employing the high resolution of the LHCb vertex detector to directly measure width and position of the beams using beam–gas and beam–beam interactions. Information about the bunch currents was provided by the LHC machine.

In this analysis the main systematic contributions were given by the bunch intensities 12%, and by the tracking efficiency, 10% in the most challenging bins.

The LHCb measurement is the first one at 900 GeV. As one can see from figure 2, compared to earlier measurements the range in rapidity, y, and transverse momentum, p_{T}, were extended towards larger and smaller values, respectively. In general the agreement with previous measurements is reasonable, given the range of center-of-mass energies and that the results are averaged over different ranges in rapidity or transverse momentum.

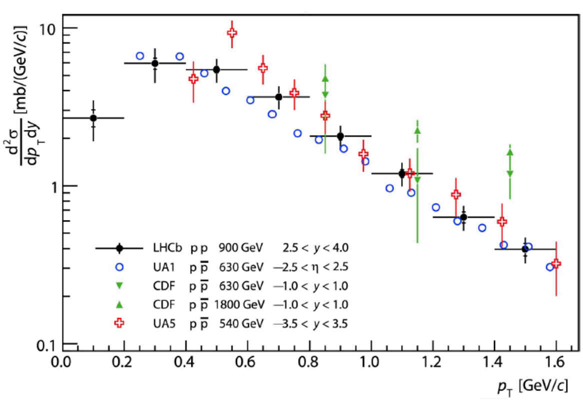

Fig. 2. Absolute measurements of the prompt K^0_{S} production cross-section as a function of transverse momentum p_{T}, performed by the UA1 [4], UA5 [5], CDF [6] and LHCb experiments, at different high-energy hadron colliders and in different rapidity (y) or pseudo-rapidity (η) ranges; for LHCb the tick marks on the error bars represent statistical uncertainties and the black horizontal line represents the width of the p_{T} bin.

2.2. Inclusive ϕ cross-section

The ϕ meson candidates are reconstructed in $\phi \to K^+K^-$ decay mode, the cross-section measurement covering the kinematic range $p_{\mathrm{T}} \in [0.8, 5.0]$ GeV$/c$ and $y \in [2.44, 4.06]$. In this study [7], two data samples are used, one in which at least one kaon is required to pass a RICH based selection, the tag sample, and one in which both kaons have to pass this selection, the probe sample. To minimize the dependence on Monte Carlo (MC) simulations the PID efficiency in p_{T}, y bins is estimated with this tag and probe technique.

The LHCb luminosity used in this cross-section estimation is based on a continuous analysis of hits in the Scintillator Pad Detector [1], which has been normalized to the absolute luminosity scale. The absolute scale was determined with the beam-gas method mentioned before.

In figure 3 there are shown projections on the y and p_{T} axis within the same kinematic region. Also plotted are the results from the PERUGIA0 [8] tuning of PYTHIA6.4 [9] and the standard LHCb MC [10, 2] based also on the same version of PYTHIA. In general, both Monte Carlo samples underestimate the measured ϕ meson production in the phase space region of the measurement. There is a tendency to better agreement for lower transverse momenta.

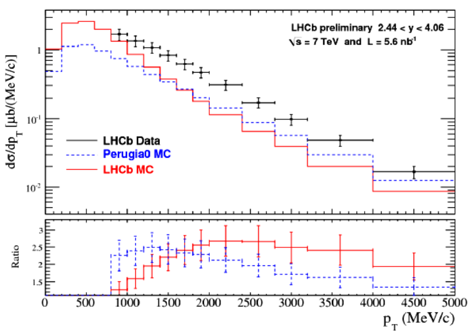

Fig. 3. Inclusive differential ϕ production cross-section as a function of p_{T} (left) and y (right), measured with data (black), and compared to the LHCb MC (solid, red) and PERUGIA0 (dashed, blue). The inner error bars represent the statistical uncertainty, the outer show the quadratic sum of statistical and systematic errors. Error bars shown in the ratio plots are statistical only.

The analysis results from the two samples with opposite magnet polarity are compared in figure 4. They agree well within their statistical uncertainty.

The inclusive ϕ meson production cross-section for all available kinematic region, measured on the magnet up sample of 5.6 nb^{-1} integrated luminosity, is found to be

$$\sigma(pp \to \phi X) = (1493 \pm 12(\text{stat.}) \pm 12(\text{uncorr. syst.}) \pm 209(\text{corr. syst.}))\,\mu\text{b}\,.$$

3. Baryon number transport and baryon suppression

Other observables probing the dynamics of particle production in high energy hadron collisions are cross-section ratios, where luminosity and many systematic uncertainties cancel. In baryon–antibaryon ratios like $\bar{\Lambda}/\Lambda$ or $\bar{p}/p$, the baryon contains valence quarks in common with the proton, while all three antiquarks of the antibaryon have to be produced in the collision.

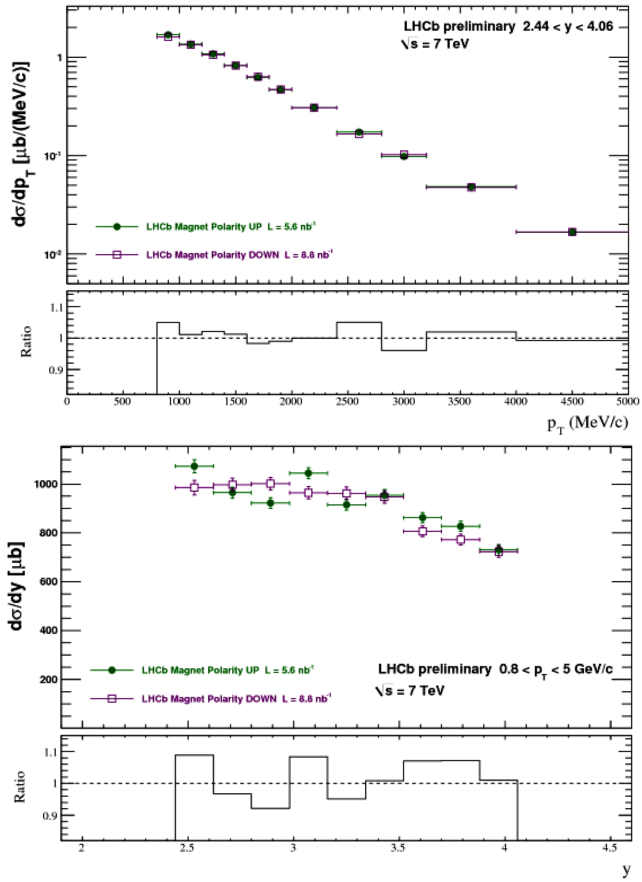

Fig. 4. Inclusive differential ϕ production cross-section as a function of p_{T} (top) and y (bottom), as measured in the magnet up (filled circles, green) and the magnet down (unfilled boxes, magenta) subsamples. Uncertainties on the ratios are statistical only.

The ratio of the production cross-sections thus measures the baryon-number transport from the beam particles to the final state. Several models exist to describe this transport, but the mechanisms is not well understood. Also the strange meson-to-baryon ratio is a good test for different fragmentation models, which do not agree between them in this phase space region [11] and where there were no experimental data available before.

For the V^0 studies, high-purity, prompt K^0_{S}, Λ and $\bar{\Lambda}$ samples were selected based on a Fisher discriminant constructed using the logarithms of the impact parameters of the V^0 particles and of their daughters [12]. The selection requirement of a primary vertex ensured that mainly the candidates coming from non-diffractive events are kept. For the two available energies the analyzed data correspond to 0.31 nb^{-1} at $\sqrt{s} = 900$ GeV and 0.2 nb^{-1} at $\sqrt{s} = 7$ TeV.

Results from the study of the $\bar{\Lambda}/\Lambda$, cross-section ratio are shown in figure 5. In general one observes that the measured ratio is lower, *i.e.* indicating larger baryon number transport, than the expectation from the Monte Carlo models. The effect becomes stronger in the forward region and when going to lower center-of-mass energies.

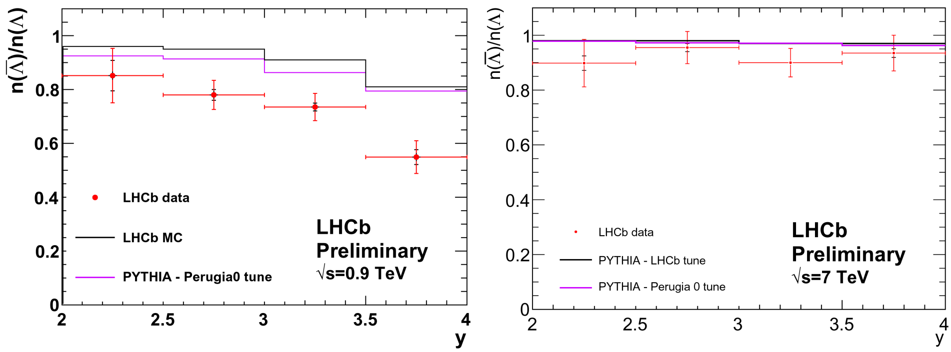

Fig. 5. The $\bar{\Lambda}/\Lambda$ ratio as a function of rapidity is shown (left) at $\sqrt{s} = 900$ GeV and (right) at $\sqrt{s} = 7$ TeV. For the data points the error bars are the quadratic sum of statistical and systematic uncertainties. Data are compared to LHCb Monte Carlo and Pythia6 Monte Carlo generator with Perugia0 tuning.

Another ratio to look at is the $\bar{\Lambda}/K^0_{\rm S}$ cross-section ratio. Since the $\bar{\Lambda}$ has no valence quarks in common with the initial state protons, this ratio measures the suppression of baryon- relative to meson-production. Experimental results compared to Monte Carlo predictions are shown in figure 6. Both data and Monte Carlo show a slight increase in the ratio when going from $\sqrt{s} = 900$ GeV to $\sqrt{s} = 7$ TeV [12].

This is plausible, since particle masses and kinematic factors in general should become less important at higher energies. It is, however, striking that in both cases the ratio is significantly underestimated by the Monte Carlo models. Since both the Λ and the $K^0_{\rm S}$ contain a single strange valence quark, the discrepancy cannot be explained by a mismatch in strangeness suppression between data and Monte Carlo. Instead it probes directly the understanding of baryon production in the fragmentation process.

For the measurement of $\bar{p}/p$ ratio a data sample similar to the previous study was used and the two polarities of the magnetic field were employed [13]. RICH information allows to isolate almost pure samples of pions, kaons and protons using delta log-likelihood cuts on particle type hypotheses. The hadron particle identification was calibrated using secon-

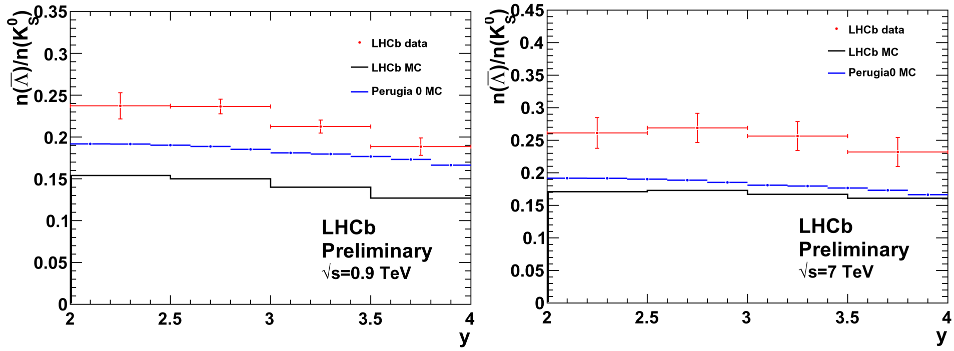

Fig. 6. The $\Lambda/K^0_{\rm S}$ ratio as a function of rapidity is shown (left) at $\sqrt{s} = 900$ GeV and (right) at $\sqrt{s} = 7$ TeV. For the data points the error bars are the quadratic sum of statistical and systematic uncertainties. Data are compared to LHCb Monte Carlo and Pythia6 Monte Carlo generator with Perugia0 tuning.

daries from the decays $K^0_{\rm S} \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ with pions and protons identified using kinematic cuts only. Charged kaons were selected from the decay $\phi \to K^+K^-$, using a tag and probe approach where only one of the kaons was required to be identified by RICH. Similar to the baryon transport pattern for $\bar{\Lambda}/\Lambda$ the $\bar{p}/p$-ratio shows a big deviation in ratio from unity at low energy (except of the highest $p_{\rm T}$ bin), figure 7. At 7 TeV, there is reasonable agreement observed with both tunings of the Pythia Monte Carlo event generator.

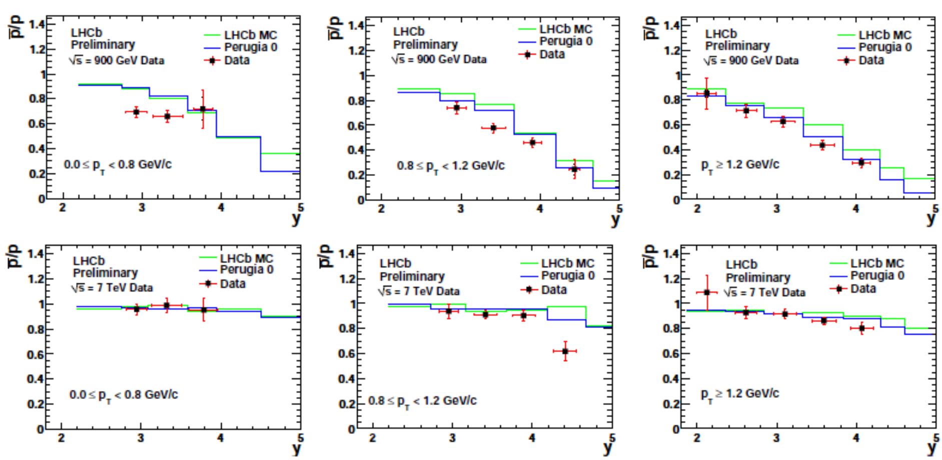

Fig. 7. Distribution of the ratio $\bar{p}/p$ against y after corrections for reconstruction biases: up at $\sqrt{s} = 900$ GeV, down at $\sqrt{s} = 7$ TeV.

Ratios benefit from reduced systematic uncertainties since an absolute luminosity measurement is not required and many systematic effects cancel. Residual effects come from kinematical differences between data and Monte Carlo or finite statistics in the RICH calibration sample. The final results are still systematics limited, with a 2% error for $\bar{\Lambda}/\Lambda$, 2–12% for $\bar{\Lambda}/K^0_{\rm S}$ and 3–14% for $\bar{p}/p$.

A natural variable to study baryon number transport is the rapidity difference to the beam, *rapidity loss*, $\Delta y = y_{\rm beam} - y$, where $y_{\rm beam}$ is the rapidity of the incoming beam. The measurements span an interval in Δy of almost 4 units, reaching up to a highest value of close to $\Delta y = 7$. In a given $p_{\rm T}$ bin the measurements appear consistent with a monotonic distribution. There is an indication that the results have some $p_{\rm T}$ dependence. Figure 8 shows the LHCb results, together with measurement of the same quantity performed by other experiments [15, 16, 17, 18, 19, 20, 21]. Reasonable consistency is observed.

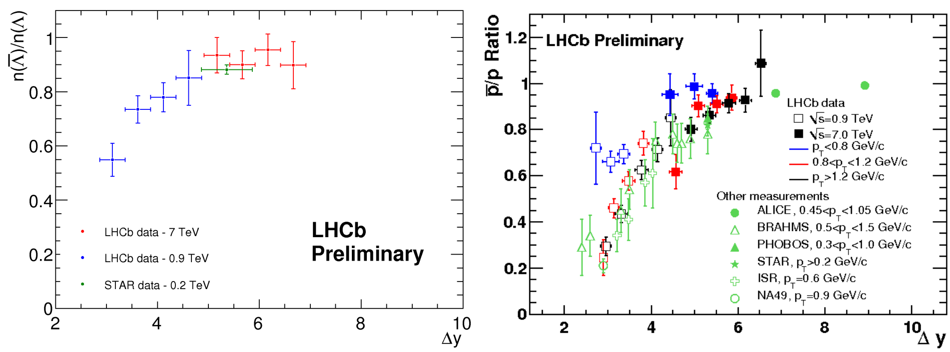

Fig. 8. Left: The LHCb $\bar{\Lambda}/\Lambda$ ratio *versus* Δy is compared to a single data point at $\Delta y = 5$ from the STAR Collaboration [14]; Right: Measurements of the p/p ratio performed by LHCb and other experiments [15, 16, 17, 18, 19, 20, 21], plotted *versus* Δy. The error bar in all cases represents the total uncertainty, apart from the points marked ISR, where it signifies the statistical uncertainty alone. The region in Δy between 2 and 4.5 corresponds to the LHCb measurements at 900 GeV, while the region between 5 and 7.0 corresponds to the LHCb measurements at 7 TeV.

4. Conclusions

The first studies with data from the 2009 and 2010 runs showed that the LHCb experiment is ready for its core physics program. Early data were used to perform and to check the calibration of the different subdetectors, as well as to perform new measurements in a unique range of rapidity and transverse momentum. A first $K^0_{\rm S}$ cross-section measurement at 900 GeV was produced at larger rapidities and smaller transverse momenta than previous measurements. Preliminary results for ϕ inclusive cross-section were shown. Preliminary measurements for ratios of V^0 and protons suggest lower baryon suppression and higher baryon transport in data than in the Monte Carlo models investigated. The LHCb data are consistent with data from lower energy experiments.

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