PROCEEDINGS OF SCIENCE

Studies of Soft QCD at LHCb

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The LHCb detector at the LHC has a unique pseudorapidity coverage ($2 < \eta < 5$) which allows to perform soft QCD measurements in the kinematic forward region where QCD models have large uncertainties. Selected analyses on soft QCD measurements in pp collisions are summarised in these proceedings. The energy flow has been measured separately for different event classes allowing to probe multi-parton interactions at large η. The measured prompt hadron ratios are important for hadronisation models, while the $\overline{p}/p$ ratio is a good observable to test models of baryon number transport. Charm production has been studied to determine cross-sections and production ratios. All measurements are compared to Monte Carlo simulations or theory predictions.

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1. Introduction

The LHCb experiment at the Large Hadron Collider is a dedicated experiment to study CP-violating processes and rare decays of hadrons containing beauty and charm quarks. The detector is a single-arm forward spectrometer [1] designed to efficiently detect the decay products of B-hadrons in a pseudorapidity range of approximately $2 < \eta < 5$. This allows LHCb to make soft QCD measurements in a kinematic region which is hardly accessible by the general purpose detectors. The analyses presented in these proceedings are selected soft QCD measurements performed with data from proton-proton (pp) collisions at centre-of-mass energies of $\sqrt{s} = 0.9$ and 7 TeV. Events were recorded with minimum bias triggers in the low luminosity running phase in 2010 where the data contain very little contribution from pile-up events. Important for the presented analyses is the tracking system which is composed of a high precision Silicon Vertex Locator (VELO) surrounding the interaction point and the main tracking stations located downstream of a dipole magnet. Particle identification (PID) is performed by two Ring Imaging Cherenkov (RICH) detectors which allow separation of charged particles in a momentum range of $2-100$ GeV/c.

2. Forward Energy Flow

The LHCb collaboration has measured the energy flow (EF) in the kinematic forward region [2]. For a particular pseudorapidity interval $\Delta\eta$ the total energy flow $dE_{tot}/d\eta$ is defined as

$$\frac{1}{N_{int}} \frac{dE_{tot}}{d\eta} = \frac{1}{\Delta\eta} \left(\frac{1}{N_{int}} \sum_{i=1}^{N_{part,\eta}} E_{i,\eta} \right), \tag{2.1}$$

where N_{int} is the number of inelastic pp interactions and $E_{i,\eta}$ the energy of the individual particles. EF at large pseudorapidities directly probes multi-parton interactions (MPI) and parton radiation which contribute to the underlying event in proton-proton collisions. The measurement has been performed in four different event classes, an (1) inclusive minimum bias sample where at least one reconstructed track with a momentum p greater than 2 GeV/c in the forward acceptance ($1.9 < \eta < 4.9$) is required. The second sample is a (2) hard scattering sub-sample which implies at least one high p_T track per event ($p_T > 3$ GeV/c). By exploiting the additional backward coverage of the VELO it was possible to obtain a (3) diffractive enriched and a (4) non-diffractive enriched

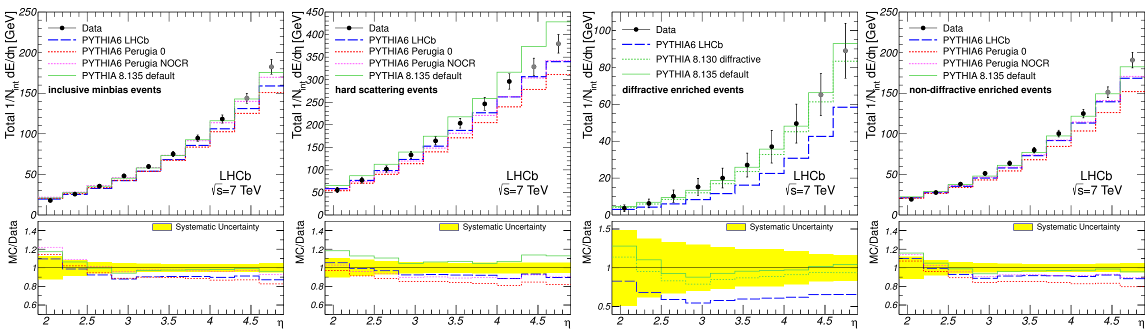

Figure 1: Total energy flow as a function of pseudorapidity presented for four event classes. The LHCb data is compared to different predictions from the PYTHIA event generator.

sample of events. These were selected by looking for backward tracks in the pseudorapidity range of $-3.5 < \eta < -1.5$. This selection exploits the fact, that a large rapidity gap is an experimental signature to identify diffractive processes. The measured total EF, which is the sum of charged and neutral EF, is depicted in Fig.1, superimposed with different PYTHIA [3, 4] generator predictions. The EF in the four event samples increases from the diffractive sample to the inclusive minimum bias and non-diffractive sample up to the hard scattering sample. The errors are dominated by systematic uncertainties, e.g. model dependence for correcting detector effects, uncertainties for the track finding and residual pile-up. These uncertainties decrease towards larger η which is the most interesting region for studying MPI phenomena. In all event classes, the PYTHIA 6 tunes underestimate the EF especially at larger pseudorapidities but overestimate it at lower η. The default PYTHIA 8 prediction (8.135) is in better agreement except for the hard scattering sample. The energy flow in diffractive enriched events is well described by PYTHIA 8. The measurement was also compared to predictions of cosmic ray generators as depicted in Fig. 2 which were not tuned to LHC data. The EPOS [5] and SYBILL [6] generators show a good agreement with data in the minimum bias and non-diffractive sample while the QGSJETII-03 [7] prediction is best for hard scattering. The EF in diffractive events seems to be underestimated by all cosmic ray generators.

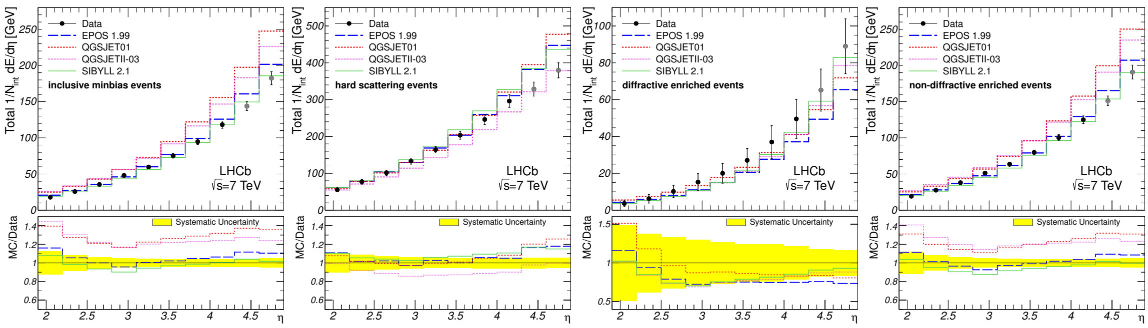

Figure 2: Total energy flow as a function of pseudorapidity presented for four event classes. The LHCb data is compared to predictions from cosmic ray event generators.

3. Prompt Hadron Production Ratios

Prompt hadron production ratios have been measured as a function of pseudorapidity in three different p_T-bins for pp collisions at centre-of-mass energies of $\sqrt{s} = 0.9$ and 7 TeV [8]. The measured anti-particle/particle ratios K^-/K^+, π^-/π^+ and $\overline{p}/p$ as well as the different-particle ratios $(p+\overline{p})/(\pi^+ + \pi^-)$, $(K^+ + K^-)/(\pi^+ + \pi^-)$ and $(p+\overline{p})/(K^+ + K^-)$ are probes for hadronisation models implemented in Monte Carlo event generators. Furthermore, some of these ratios can be used to test models of baryon to meson and strangeness suppression. A crucial ingredient in measuring these ratios is a good particle identification which is provided by the two RICH detectors. The PID efficiencies were directly determined from data using decays of resonances such as $\Lambda \to p\pi^-$, $\phi \to K^+K^-$ and $K^0_S \to \pi^+\pi^-$. The dominant systematic uncertainty remains the PID efficiency because of the limited size of the calibration sample. Comparing the measured hadron ratios to different PYTHIA 6 tunes shows that no tune is able to describe the entire set of measurements. Each individual type of hadron ratio, however, can be described by at least one

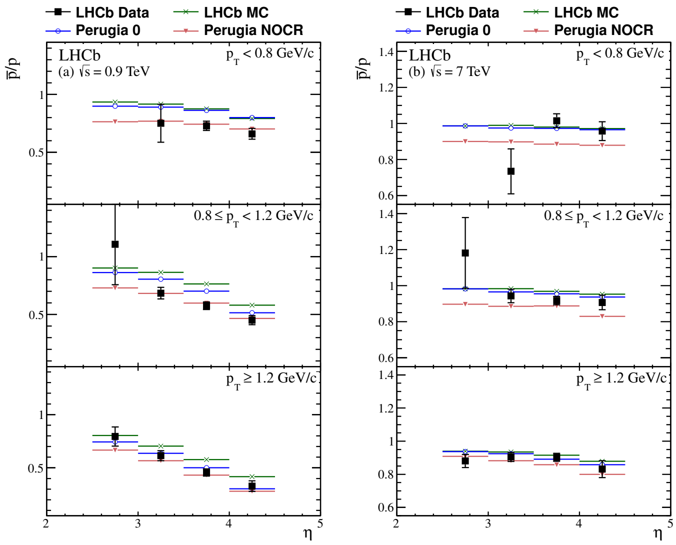

Figure 3: Results for the $\overline{p}/p$ ratio as function of pseudorapidity for $\sqrt{s} = 0.9$ (left) and 7 TeV (right). The LHCb data is compared to three different tunes of the PYTHIA 6 event generator.

single tune. Of special interest is the $\overline{p}/p$ ratio, which is sensitive to baryon number transport. As depicted in Fig. 3, at $\sqrt{s} = 0.9$ TeV the $\overline{p}/p$ ratio shows a significant η dependence which is qualitatively described by all PYTHIA 6 tunes. Only the Perugia NOCR tune, which favours an extreme model of baryon transport, is able to also give a quantitatively good prediction while other generator tunes underestimate baryon transport. However, at $\sqrt{s} = 7$ TeV the Perugia NOCR model tends to now overestimate baryon transport. The same ratio can also be studied as function of rapidity loss $\Delta y = y_{beam} - y_{particle}$, defined as the difference of the rapidity of the beam and the considered particle. This representation allows to compare measurements of experiments at different centre-of-mass energies, as shown in Fig. 4. The LHCb measurement covers a wider range in rapidity loss and improves previous measurements with a better precision. Combining the LHCb data points and the complementary ALICE measurement [9] allows to perform a fit within the Regge model [10]. In this model, baryon production at high energies is driven by Pomeron exchange and

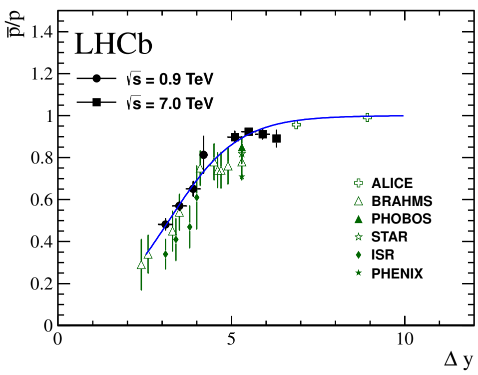

Figure 4: Results for $\overline{p}/p$ ratio as function of rapidity loss. A fit to ALICE and LHCb data is superimposed.

baryon transport by string junction exchange. In this framework, the obtained fit parameters are related to contributions from these two mechanisms. The fit result of a low string junction contribution with low intercept point allows to draw conclusions about the associated standard Reggeon or the Odderon.

4. Prompt Charm Production

Production cross-sections of charmed hadrons have been measured with the LHCb detector in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV [11]. The measured differential cross-sections test predictions of QCD fragmentation and hadronisation models. The results are compared to perturbative calculations at next-to-leading order using the Generalized Mass Variable Flavour Number Scheme (GMVFNS [12]) and at fixed order with next-to-leading-log resummation (FONLL [13]). The accessible phase-space of this measurement reaches from $2 < y < 4.5$ in rapidity and up to 8 GeV/c in transverse momentum. Only promptly produced charm hadrons were considered. They were either directly produced in the primary pp interaction or created due to feed-down from instantaneous decays of excited charm resonances. Five different types of charm hadrons were analysed by using the fully reconstructed decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0(K^-\pi^+)\pi^+$, $D_S^+ \to \phi(K^-K^+)\pi^+$, $\Lambda_C^+ \to pK^-\pi^+$ and their charge conjugates. Also in this analysis, PID efficiencies were determined directly from data. The selection criteria were optimized for each decay mode independently. To disentangle the prompt signal yield from secondary

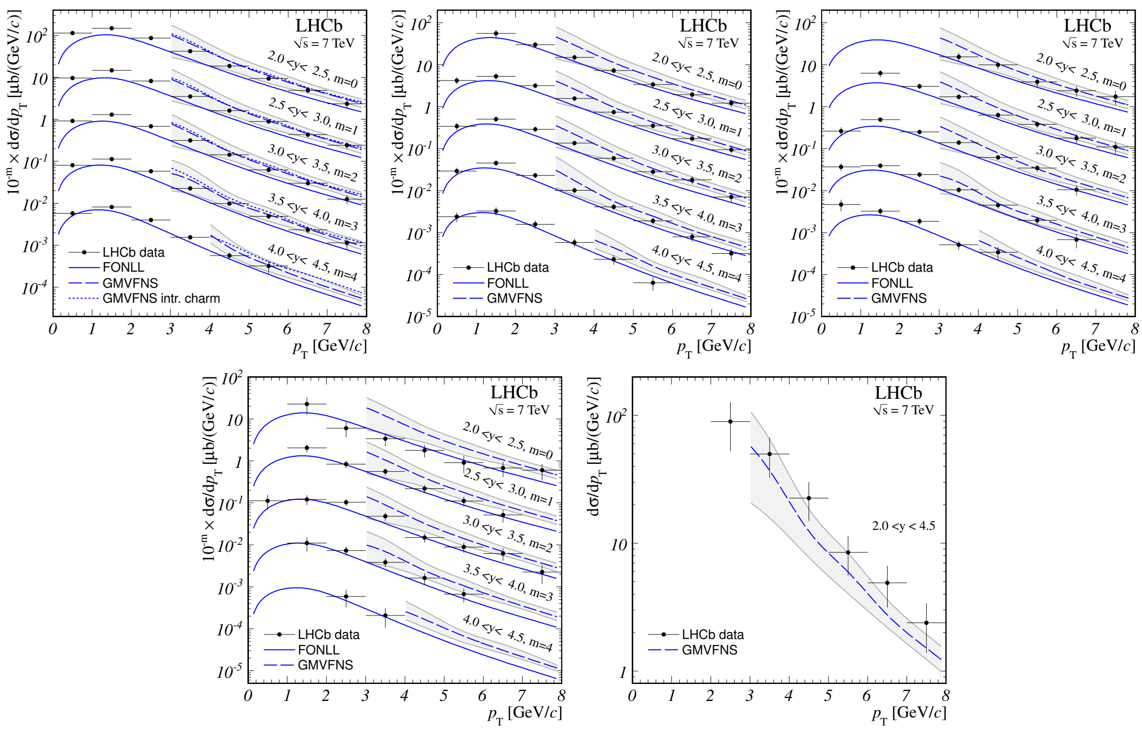

Figure 5: Differential cross-section for D^0 (top left), D^+ (top centre), D^{*+} (top right) and D_S^+ (bottom left), Λ_c^+ (bottom right). Cross-sections in different rapidity bins are shown as function of transverse momentum.

charm contributions and combinatorial background, a multidimensional extended maximum likelihood fit has been performed to the mass and to impact parameters distributions. In case of the D^{*+} decay mode the additional background due to a mismatch of the slow pion is identified by considering also the mass difference of the reconstructed D^{*+} and D^0. The systematic uncertainties include globally correlated sources such as luminosity and track finding but also correlated and uncorrelated uncertainties between bins or decay modes. These are e.g. PID efficiencies, branching fractions, reconstruction and selection efficiencies and uncertainties due to the fit models which were used.

The measured differential cross-sections for the charmed mesons and the Λ_C^+ baryon are shown in Fig. 5. The measurement is performed as a function of transverse momentum in different bins of rapidity. Both theoretical predictions (GMVFNS & FONLL) which are compared to in the plots showed good performance in describing data from the Tevatron [14] and measurements from the ALICE experiment [15, 16, 17] in the central rapidity region. The FONLL calculations include estimates of theoretical uncertainties due to the charm quark mass and the renormalisation and factorisation scale. In this plots only the central values are displayed. Transition probabilities describing the primary charm quark to exclusive hadron state transition are based on measurements from e^+e^- colliders. The GMVFNS framework includes the convolution with fragmentation functions describing $c \rightarrow H_C$ transitions, normalised to the respective total transition probabilities. The fragmentation functions were also obtained from e^+e^- colliders. Uncertainties from scale variations were determined only for D^0 production and assumed to have the same relative sizes for the other hadron species. Predictions were provided only for $p_T > 3$ GeV/c as displayed in Fig. 5. The theory calculations are in good agreement with the LHCb measurement. To calculate charm hadron production ratios and total cross-sections for the kinematic range of $0 < p_T < 8$ GeV/c and $2.0 < y < 4.5$ only bins with an uncertainty on the yield of better than 50% were used. Contributions from remaining bins were accounted by extrapolations using PYTHIA 6.4 simulations. Combining the five individual cross-sections results in the total charm cross-section of

$$\sigma(c\bar{c})_{p_T>8\,\mathrm{GeV/c},\,2.0<\mathrm{y}<4.5} = 1419 \pm 12(\mathrm{stat}) \pm 116(\mathrm{syst}) \pm 64(\mathrm{frag})\mu\mathrm{b},$$

where the final uncertainty is due to the fragmentation functions.

5. Summary

The LHCb detector offers an excellent environment to study soft QCD in the forward kinematic region. The presented results give insights in the understanding of multi parton interactions contributing to the underlying event and allow to test fragmentation and hadronisation models implemented in Monte Carlo simulations. The given results will be references for future generator optimizations, not only for the LHC but also for cosmic ray event generators. The measured charm cross-sections and production ratios offer the possibility for further improvements, but also confirm theoretical calculations which were so far only tested in the central rapidity region.

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