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Measurements of particle production in pp-collisions in the forward region at the LHC with the LHCb detector

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The particle production in proton-proton collisions in the forward region is studied with the LHCb detector. Charged particle multiplicities are measured in different bins of pseudorapidity η at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ and compared with model predictions. In general, the models underestimate the charged particle production significantly. The ratios $\overline{\Lambda}/\Lambda$ and $\overline{\Lambda}/\mathrm{K_S}$ had been measured at centre-of-mass energies of $\sqrt{s} = 0.9\,\text{TeV}$ and $\sqrt{s} = 7\,\text{TeV}$. The ratio $\overline{\Lambda}/\Lambda$, sensitive to baryon number transport is found to be smaller in data than predicted by the models, while the ratio $\overline{\Lambda}/\mathrm{K_S}$, sensitive to baryon-to-meson suppression is found to be significantly larger than predicted. The differential cross-section for inclusive Φ meson production at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ has been measured as a function of the Φ transverse momentum $\mathrm{p_T}$ and rapidity y in the region $0.6 < p_T < 5.0\,\text{GeV}/c$ and $2.44 < y < 4.06$. The cross-section in this kinematic range is $\sigma(\mathrm{p}p \to \Phi X) = 1758 \pm 19(\text{stat})^{+43}_{-14}(\text{syst}) \pm 182(\text{scale})\mu\text{b}$. Predictions based on the Pythia 6.4 generator underestimate the cross-section.

The 2011 Europhysics Conference on High Energy Physics-HEP 2011,
July 21-27, 2011
Grenoble, Rhône-Alpes France

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PoS(EPS-HEP2011)336

1. Introduction

A good understanding of soft QCD processes in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ is required for extracting many important measurements at the LHC. Particle multiplicities and particle production measurements are an important input in the process of tuning of event generators. LHCb's unique forward geometrical acceptance allows it to probe the dynamics of the collision not accessible to the general purpose detectors. In particular the forward region is sensitive to low-x QCD dynamics and multi-parton interactions. The charged hadron multiplicity distribution is sensitive to the underlying QCD dynamics of the proton-proton collision. The measurement of the production ratio of $\overline{\Lambda}/\Lambda$ yields information about the baryon number transport in pp-collisions to the final state hadrons. The ratio $\overline{\Lambda}/\mathrm{K_S}$ is sensitive to the baryon suppression in hadronization process. In addition, the differential cross-section for inclusive Φ meson production has been measured as a function of the Φ transverse momentum $\mathrm{p_T}$ and rapidity y. The results have been compared to a number of phenomenological models implemented in Monte Carlo event generators [2] and significant differences are found.

2. LHCb detector and 2010 low luminosity data sample

The LHCb detector is a single-arm magnetic dipole spectrometer designed for high precision measurements of CP violation and rare decays in the beauty and charm sector. It therefore has excellent tracking and vertexing capabilities. The Vertex Locator (VELO) consists of silicon microstrip modules, distributed in 23 stations arranged along the beam direction, providing an impact parameter resolution for high $\mathrm{P_T}$ particles down to 15 μm. Particles traversing from the interaction region to the downstream tracking stations experience a bending-field integral of around 4 Tm. The other unique feature of the experiment is two Rich detectors which provide hadron identification over a large momentum range. More details about the detector can be found elsewhere [1]. The data used in the analysis presented here are from the low luminosity running period of the LHC in Spring 2010 with very loose trigger thresholds. Monte Carlo event simulation is used to correct for acceptance and resolution effects. More details about the LHCb simulation can be found in [3, 4].

3. Charged Particle Multiplicities

Particles are counted by reconstructing trajectories in the VELO alone. This choice is motivated by the high and uniform reconstruction efficiency. It is the detector closest to the interaction point, and therefore with the minimal amount of material and it provides a partial backward coverage. Since the detector is located outside the magnetic field, no momentum measurement is possible. The loss of very low momentum particles due to bending in the residual magnetic field or because of large multiple scattering is being estimated to be about 1%. In the counting of charged particles we exclude particles from $\mathrm{K^0_S}$ and hyperon decays. On the generator side, this is done by requiring the sum of mean proper lifetimes of all mother particles to be less than 10 ps, while on the reconstruction side, the tracks are required to come from the luminous region. The correction for the remaining non-prompt particle contamination, (5-10)%, which are mainly tracks from converted photons is taken from MC and scaled to the observed charged particle multiplicity. A relative systematic error of 10 % is assigned to this correction. Finally, the distributions need to be corrected for (3.7 ± 0.4) % of the events that have more than one pp-interaction. The event particle multiplicities are obtained by fits to a sum of binomial distributions, which take care of the unfolding of the migrations due to reconstruction inefficiencies in the different bins:

$$f_{\mathrm{obs.}}(k) = \sum_{i=0}^{\infty} a_i \times \begin{pmatrix} i \\ k \end{pmatrix} (1-\varepsilon)^{i-k} \varepsilon^k$$

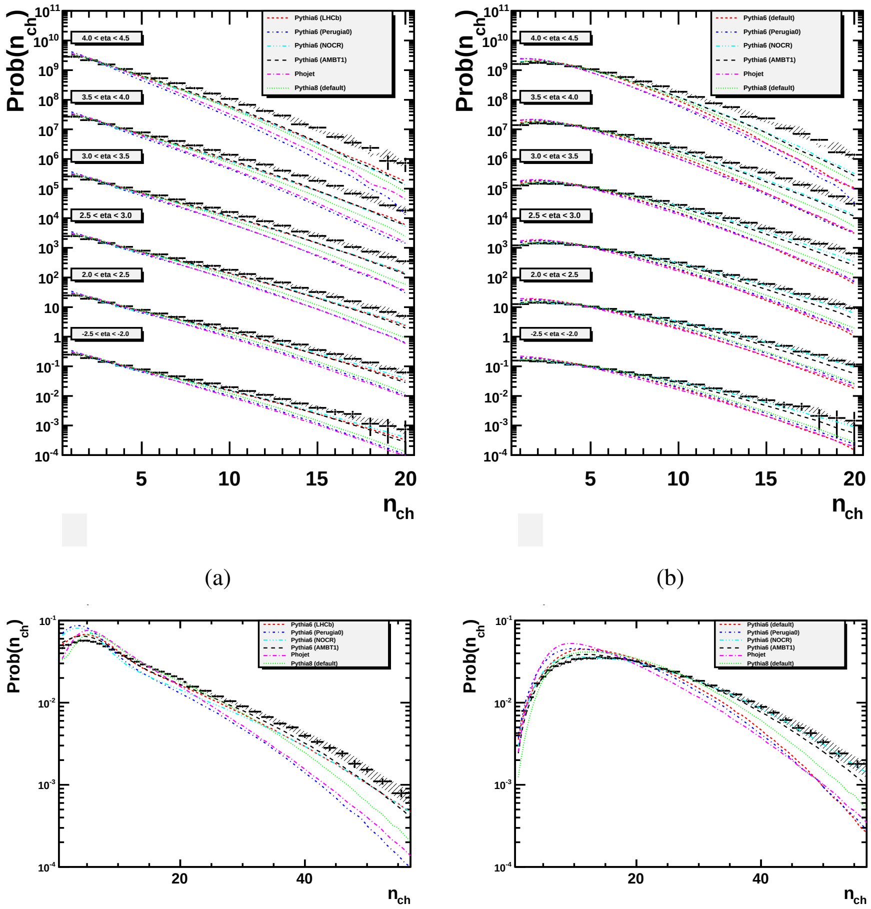
where $f_{\mathrm{obs.}}(k)$ is the observed particle multiplicity distribution corrected for non-prompt particles, ε is the reconstruction efficiency taken from simulations and cross checked with data and a_i are the probabilities for the original particle multiplicity i to occur. Systematics is studied by varying the efficiency by $\pm 4\%$. This accounts for both uncertainties observed by comparing simulation and data, and the uncertainty of missing particles at low $\mathrm{P}_T \lesssim 25\ \mathrm{MeV}/c$. The unfolding procedure had been verified with simulations. The charged particle per event multiplicities are shown in Fig. 1(a) for different intervals of the pseudorapidity and in Fig. 1(c) for one large forward interval. The data points are systematically above the generator predictions, and the differences increase with increasing pseudorapidity. An attempt was made to suppress diffractive events by requiring at least one charged particle to be reconstructed in the forward interval $2.5 < \eta < 4.5$ with a transverse momentum $\mathrm{P}_T > 1\ \mathrm{GeV}/c$. the resulting charged particle per event multiplicities are shown in Fig. 1(b) for different intervals of the pseudorapidity and in Fig. 1(d) for one large forward interval. In general, the differences between data and simulation become smaller, especially for the Pythia tunes LHCb, AMBT1 and NOCR.

Fig. 2(a) shows the mean number of charged particles as function of pseudorapidity in events with at least one charged particle in the η interval of $2.0 < \eta < 4.5$. The data points are systematically above the generator predictions, while the LHCb Pythia tune comes closest to the data.

The charged particle multiplicity distributions fit well with single negative binomial functions, with k-values starting from 1.1 for the lowest η interval increasing to 1.4 for the last η interval, while the mean values decrease at the same time. Experimentally, it is found that the product of k-value and mean stays about constant. When plotting the charged particle multiplicities as function of the KNO-variable [5], it is found that all η intervals overlap with each other 2(b).

4. V0 Ratio Measurements

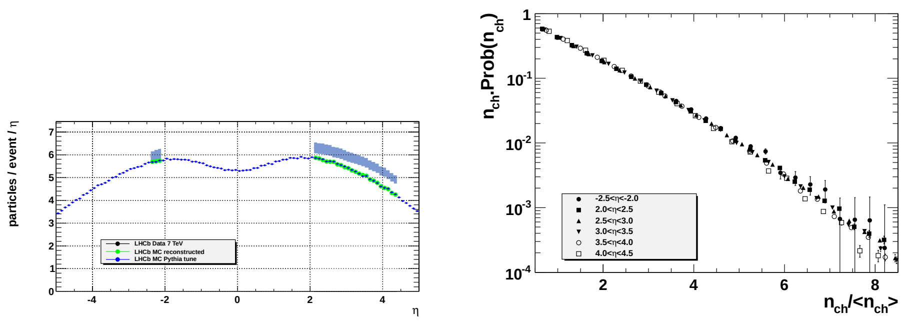
Measurements of the ratios of $\overline{\Lambda}/\Lambda$ and $\overline{\Lambda}/\mathrm{K}^0_\mathrm{S}$ were performed at two different centre-of-mass energies, $\sqrt{s} = 0.9\,\mathrm{TeV}$ and $\sqrt{s} = 7\,\mathrm{TeV}$ [3]. The first ratio is sensitive to the baryon number transport to final state hadrons and the second is sensitive to baryon suppression. By plotting the ratios as function of the rapidity difference between beam and particle, see Fig.3 it is seen that the data at the two energies are in good agreement. There is also good agreement to measurements of the Star collaboration [6]. Comparisons to the event generators are shown in Fig.4; significant differences are seen. The NOCR tune of Pythia6 can describe the $\overline{\Lambda}/\Lambda$ ratio at large rapidity, but fails at low rapidity. It is also found that baryon suppression is overestimated, there are more baryons compared to mesons in data than predicted by the models in all measured bins of rapidity.



(a) (b)

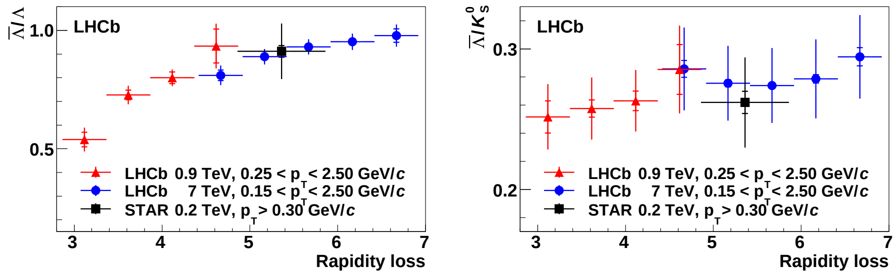
(c) (d)

Figure 1: Comparison of the LHCb data with predictions of different event generators for nobias events (a) & (c) and hard interaction events (b) & (d).The different η-distributions are scaled by factors of 10 to fit in one plot.



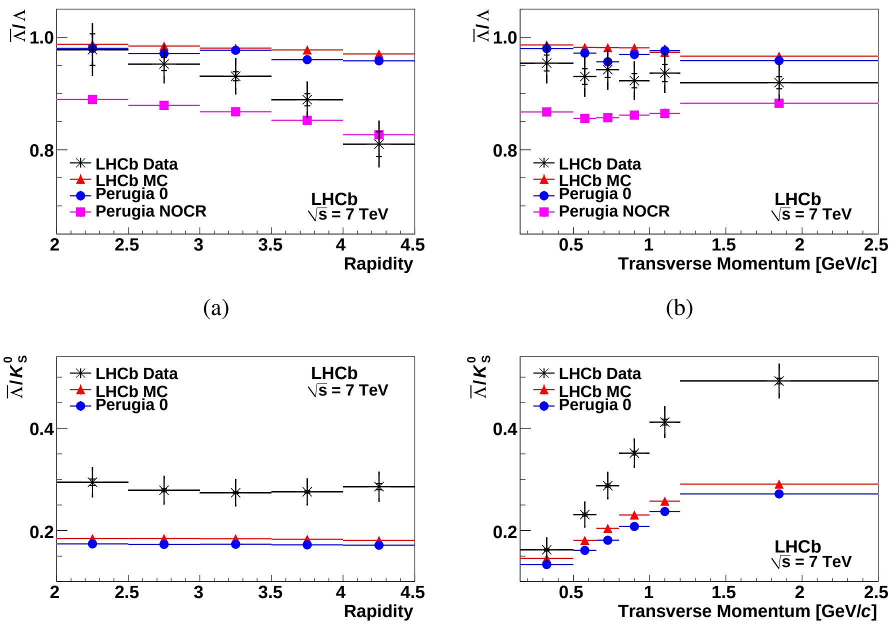
(a) (b)

Figure 2: (a) Particle multiplicity as function of η comparing data with LHCb Monte Carlo for events with at least one charged particle in the forward acceptance, $2.0 < \eta < 4.5$. (b) The KNO distributions in different bins of η.



(a) (b)

Figure 3: The ratios (a) $\overline{\Lambda}/\Lambda$ and (b) $\overline{\Lambda}/\mathrm{K}^0_\mathrm{S}$ from LHCb are compared at two energies $\sqrt{s} = 0.9\,\mathrm{TeV}$ (triangles) and $\sqrt{s} = 7\,\mathrm{TeV}$ (circles) with the published results from STAR [6] (squares) as a function of rapidity loss, $\Delta y = y_{\mathrm{beam}} - y$. Vertical lines show the combined statistical and systematic uncertainties and the short horizontal bars (where visible) show the statistical component.

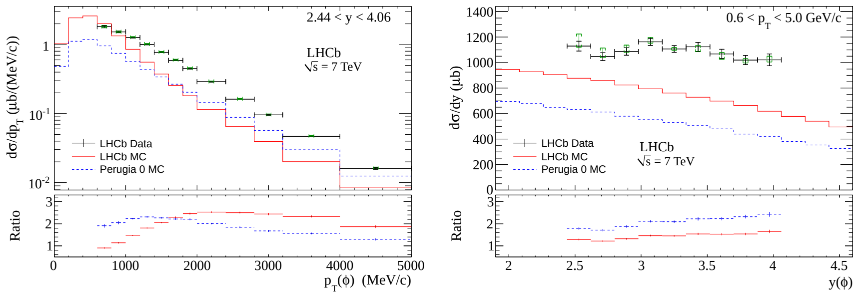


(a) (b) (c) (d)

Figure 4: The ratios $\overline{\Lambda}/\Lambda$ and $\overline{\Lambda}/\mathrm{K}^0_\mathrm{S}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ compared with the predictions of the LHCb MC, Perugia 0 and Perugia NOCR as a function of (a) & (c) rapidity and (b) & (d) transverse momentum. Vertical lines show the combined statistical and systematic uncertainties and the short horizontal bars (where visible) show the statistical component.

5. Inclusive Φ Production

In Fig. 5, significant differences between event generator predictions and data are seen for the inclusive Φ production. The integrated cross-section in the region $0.6 < p_T < 5.0\,\mathrm{GeV}/c$ and $2.44 < y < 4.06$ is $\sigma(pp \to \phi X) = 1758 \pm 19(\mathrm{stat})\,^{+43}_{-14}(\mathrm{syst}) \pm 182(\mathrm{scale})\,\mu\mathrm{b}$[4], where the first systematic uncertainty arises from the bin-dependent contribution, while the second one is the common systematic uncertainty. The simulations underestimate the measured ϕ production in the



(a) (b)

Figure 5: Inclusive differential ϕ production cross-section as a function of p_T (a) and y (b), measured with data (points), and compared to the LHCb default MC tuning (solid line) and Perugia 0 tuning (dashed line). The error bars represent the statistical uncertainty, the braces show the bin dependent systematic errors. The lower parts of the plots show the ratio data cross-section over Monte Carlo cross-section. Error bars in the ratio plots show statistical uncertainties only.

considered kinematic region by a factor 1.43 ± 0.15 (LHCb MC) and 2.06 ± 0.22 (Perugia 0).

6. Conclusions

The particle production in proton-proton collisions in the forward region had been studied with the LHCb detector. Charged particle multiplicities at $\sqrt{s} = 7\,\text{TeV}$ are in general underestimated by Monte Carlo models. Measurements of the ratios of $\overline{\Lambda}/\Lambda$ and $\overline{\Lambda}/K^0_S$ at the two different beam energies are in good agreement when plotting as function of the rapidity difference between beam and particle, and also agree with low energy data . Monte Carlo models overestimate significantly the baryon suppression. The measured differential cross-section for inclusive Φ meson production at $\sqrt{s} = 7\,\text{TeV}$ are largely underestimated by the Pythia 6.4 generator.

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