Measurements of $K^\pm$, $K^0_S$, $\Lambda$ and $\bar{\Lambda}$ and Bose-Einstein Correlations between Kaons at ZEUS

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Abstract

Measurements of production of the neutral and charged strange hadrons in $e^\pm p$ collisions with the ZEUS detector are presented. The data on differential cross sections, baryon-to-meson ratios, baryon-antibaryon asymmetry and Bose-Einstein correlations in deep inelastic scattering and photoproduction are summarized [1].

1 Introduction

After pions, strange hadrons are the most copiously produced particles in $e^\pm p$ collisions with a centre-of-mass energy of 318 GeV at HERA. In phenomenological models based on the Lund string scheme [2], an intensity of strange quark production is regulated by a free parameter $\lambda_s$, which has a value in the range from 0.2 to 0.4 for different processes.

The experimental results on $K^\pm$, $K^0_S$, $\Lambda$, and $\bar{\Lambda}$ production [3, 4] presented in this note are based on a data sample of 121 pb$^{-1}$ collected by the ZEUS experiment at HERA. This is about 100 times larger data sample than used in previous HERA publications [5, 6] and extend the kinematical region of the measurements, thereby providing a tighter constraint on models.

2 Measurements of $K^0_S$, $\Lambda$ and $\bar{\Lambda}$

Weak decaying neutral $K^0_S$ and $\Lambda$ are well reconstructed in the modes $K^0_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ via displaced secondary vertices. The measurements have been performed in three different regions of $Q^2$: deep inelastic scattering (DIS) with $Q^2 > 25$ GeV$^2$; DIS with $5 < Q^2 < 25$ GeV$^2$; and photoproduction (PHP), $Q^2 \approx 0$ GeV$^2$. In the PHP sample, two jets, each of at least 5 GeV transverse energy, were required.

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2.1 Spectra of $K^0_S$ and $\Lambda + \bar{\Lambda}$ in DIS

Measured differential cross sections are shown in Fig. 1. The cross sections are compared to the absolute predictions of ARIADNE 4.12 [7] and LEPTO 6.5 [8] MC calculations. The ARIADNE program with $\lambda_s = 0.3$ describes the $\Lambda + \bar{\Lambda}$ data reasonably well in both $Q^2$ samples. The description of the $K^0_S$ data by ARIADNE is less satisfactory. The slope of the $P_{LAB}^T$ dependence is incorrect and in the high-$Q^2$ domain the data requires $\lambda_s < 0.3$. The cross section at low $x_{Bj}$ (not shown) is underestimated for both the low- and the high-$Q^2$ samples [3]. The LEPTO MC does not describe the data well and predicts a too fast growth of the cross sections with $Q^2$. We conclude that for the production of baryons the data requires $\lambda_s$ to be approximately constant, but in case of $K^0_S$ production $\lambda_s$ has to decrease with $Q^2$.

2.2 Baryon-antibaryon asymmetry in DIS and PHP

A positive asymmetry of 3.5% is predicted in DIS [9], due to the so-called gluon-junction mechanism that makes it possible for the baryon number to travel several units of rapidity, in this case from the proton beam direction to the rapidity around 0 in the laboratory frame.

The baryon-antibaryon asymmetry

$$A = \frac{N(\Lambda) - N(\bar{\Lambda})}{N(\Lambda) + N(\bar{\Lambda})}$$

has been measured and compared to MC predictions from ARIADNE, LEPTO and PYTHIA [10]. The following value was obtained at high $Q^2$: $A = 0.3 \pm 1.3^{+0.5\%}_{-0.8\%}$ which has to be compared to the ARIADNE ($\lambda_s = 0.3$) prediction of $0.4 \pm 0.2\%$. In PHP, $A = -0.07 \pm 0.6^{+1.0\%}_{-1.0\%}$, compared to the PYTHIA prediction of $0.6 \pm 0.1\%$.

Figure 2 shows $A$ at high-$Q^2$ and in PHP. In all cases, $<A>$ is consistent both with no asymmetry and with a very small asymmetry predicted by the Monte Carlo. However, as shown in Figs 2 in DIS the baryon-antibaryon asymmetry becomes positive and increases in the incoming proton hemisphere ($\eta_{LAB} > 0$), as well as at $P_{LAB}^T$ below 1 GeV.

2.3 Baryon-to-meson ratio in photoproduction

The relative yield of strange baryons and mesons was studied with the ratio

$$R = \frac{N(\Lambda) + N(\bar{\Lambda})}{N(K^0_S)}.$$ 

Figure 3 shows $R$ for the PHP sample. For the direct-enriched sample, where $x_{\gamma}^{OBS} > 0.75$, $R$ is about 0.4, the same value as in DIS at low $x_{Bj}$ and low $Q^2$ [3]. However, $R$ rises to a value of about 0.7 towards low $x_{\gamma}^{OBS}$ (resolved-enriched sample), while it stays flat in the PYTHIA prediction.

In order to study this effect further, the PHP events were divided into two samples. In the first, called fireball-enriched, the jet with the highest transverse energy was required to contribute at most 30% to the total hadronic transverse energy. The other sample, containing all the other events, was called fireball-depleted. The measured $R$ (see Fig. 3 Bottom) is larger for the fireball-enriched sample, most significantly at high $P_{LAB}^T$, than it is for the fireball-depleted sample. This feature is not reproduced by PYTHIA, which predicts almost the same $R$ for both samples. The PYTHIA prediction reasonably describes the measured values of $R$ for the fireball-depleted sample. This is not surprising
as Pythia generates jets in events according to the multiple interaction mechanism, which makes several independent jets, like those in DIS or $e^+e^-$ where baryons and mesons are created locally.

We note that the increase of the ratio $R$ toward the proton hemisphere, reflects a rapid growth of the $\Lambda + \bar{\Lambda}$ cross section as $\eta^{LAB}$ increases, as compared to the $K_s^0$ cross section grow [3].

3 Bose-Einstein correlations of charged and neutral kaons in DIS

Primordial quantum correlations between identical bosons, so-called Bose-Einstein correlations (BEC), so far is the only method to estimate the space-time geometry of an elementary particle emission source. The measurements of the radius of the emission source have been mostly performed with pure quantum states $\pi^\pm$, $K^\pm$, $p/\bar{p}$. For mixed quantum states, like $K_s^0$, the information is scare.

The results presented below were obtained with charged kaons selected using the energy-loss measurements, $dE/dx$. The identification of $K^\pm$ is possible for $p < 0.9$ GeV. The resulting data sample contained 55522 $K^\pm K^\pm$ pairs. The $K_s^0$ mesons were identified via displaced secondary vertices. After all cuts, the selected data sample contained 18405 $K_s^0 K_s^0$ pairs and 364 triples [4].

Figure 4 shows the two-particle correlation function $R(Q_{12})$ for identical kaons calculated using the double ratio method

$$R(Q_{12}) = \frac{R_{data}(Q_{12})}{R_{MC}(Q_{12})},$$

where $R_{data}(Q_{12})$ is the ratio of the two-particle densities constructed from pairs of kaons coming from the same and different events. $R_{MC}(Q_{12})$ is obtained in a similar way for Ariadne MC events without BEC. $Q_{12}$ is given by $Q_{12} = \sqrt{-(p_1 - p_2)^2}$. Assuming a Gaussian shape of emission source, $R(Q_{12})$ were fitted by the standard Goldhaber-like function

$$R(Q_{12}) = \alpha(1 + \lambda e^{-Q_{12}^2 r^2})$$

to extract the degree of the source coherence $\lambda$ and the source radius $r$. The measured radii for $K^\pm K^\pm$ and $K_s^0 K_s^0$ are close to each other [4]. In case of $K_s^0 K_s^0$, the fit (see Fig. 4) does not take into account a possible contamination from the scalar $f_0(980)$ decaying below the threshold. The most probable fraction of $f_0(980)$ which allows to describe the excess of data over MC was estimated to be 4%. The results corrected for the $f_0$ contamination are $\lambda = 0.70^{+0.19+0.53}_{-0.53}$ and $r = 0.63^{+0.09+0.11}_{-0.08}$ fm. Thus, the $f_0(980) \rightarrow K_s^0 K_s^0$ decay can significantly affect the $\lambda$ parameter for $K_s^0 K_s^0$ correlations. The radius-values obtained in DIS agree with $e^+e^-$ annihilation results at LEP [3].

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Figure 1: Differential $K^0_S$ and $\Lambda + \bar{\Lambda}$ production cross-sections. The model predictions are at values of a strangeness suppression factor $\lambda_s$ shown in parenthesis.
Figure 2: The baryon-antibaryon asymmetry $A$ as a function of $P_T^{\text{LAB}}, \eta^{\text{LAB}}, x_{\text{Bj}}$ and $Q^2$ for the DIS sample (top), and as a function of $P_T^{\text{LAB}}, \eta^{\text{LAB}}$ and $x_{\text{OBS}}^\gamma$ for the photoproduction sample (bottom). The different lines are the predictions of the different MC generators, as indicated in the plots.
Figure 3: The ratio $R$ as a function of $P_T^{LAB}$, $\eta^{LAB}$, and $x^{OBS}_\gamma$ for the PHP events. Top: the ratio from the whole PHP sample. Bottom: the ratio from the fireball-enriched (squares) and the fireball-depleted (triangles) samples. The predictions from PYTHIA for $\lambda_s = 0.3$. 

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Figure 4: The two-particle correlation functions at $<Q^2> = 35$ GeV$^2$ for neutral kaons with fits to the Goldhaber function. Arrows indicate $Q_{12}$ regions with contributions from resonances in the $K^0_S K^0_S$ system.