34th International Conference on High Energy Physics, Philadelphia, 2008

Strangeness Production and Hadron Spectroscopy at HERA

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An overview of the recent results on strangeness production and spectroscopy from the electron-proton collider experiments H1 and ZEUS at HERA is presented. Production of particles with light and strange quarks is discussed and compared with both theoretical predictions and with data from e^+e^- experiments. Measurements in the charm sector cover studies of the radially and orbitally excited charm states. Finally, the investigation of exotic states in the strangeness sector at HERA is reviewed.

1. INTRODUCTION

The two experiments H1 and ZEUS measured collisions of electrons[1] with protons at the HERA collider from 1992 to June 2007. The main focus of interest at HERA lies in the study of the structure of the proton, in detailed investigations of the various aspects of perturbative QCD and in searches for new phenomena. Relevant in the context of this conference are the detailed studies of production processes and the differences therein between e.g. mesons, baryons and antiparticles. In addition, details about the non-perturbative aspects of fragmentation are investigated. Search and studies of the production of excited and more "exotic" states in the *ep* environment, such as pentaquarks or glueballs constitute another part of the HERA physics portfolio. Overall, the HERA *ep* results complement the findings of other experiments and help to build phenomenological models with strong predictive power, applicable at other machines.

At HERA two different regimes in the photon momentum transfer squared Q^2 are distinguished: *"photoproduction"* denotes low $Q^2 \approx 0$ GeV^2 , and *"deep inelastic scattering (DIS)"* refers to high Q^2 (in practice $Q^2 \geq 2\text{GeV}^2$). In the case of photoproduction, the additional variable x_γ^{obs} describes the momentum fraction of the photon, that participates in the hard interaction. The total integrated luminosity available for physics at HERA amounts to about 1 fb^{-1}. The results presented below are based on fractions of this.

2. STRANGE PARTICLE PRODUCTION

Production Cross Sections of K-Mesons and Λ-Baryons

The production of strange quarks can proceed perturbatively by the boson-gluon fusion process ($\gamma g \rightarrow s\bar{s}$) and by gluon splitting in parton showers. In addition, the proton parton densities and the non-perturbative string fragmentation can be sources of strange quarks. The strange hadrons are then produced in the hadronisation process, or through decays of higher mass states. A study of K_S and Λ production was reported by the H1 collaboration [1] in DIS for $2 < Q^2 < 100\,\text{GeV}^2$, and by the ZEUS collaboration[2] in DIS with $Q^2 > 25\,\text{GeV}^2$, with $5 < Q^2 < 25\,\text{GeV}^2$, and in photoproduction. The various aspects of the production studied are: single differential cross sections of K_S and Λ, baryon-antibaryon asymmetry, baryon-to-meson ratio, ratio of strange-to-light hadrons, and the Λ and $\bar{\Lambda}$ transverse spin polarization. The spectra include all sources, i.e. direct production and all resonance decays. As an example the K_S^0 spectra are shown in Figure 1 as function of P_T and η in DIS, and of x_γ^{obs} in γp.

A comparison of the various measured single differential spectra with predictions based on LO QCD models shows a good overall agreement, when using a strangeness suppression factor of $\lambda_S = 0.3$. However, a closer look reveals several differences between theory and data. Similar general conclusions can be drawn from the baryon-to-meson ratio distributions. For instance, the shape of the x_γ^{obs} distribution in γp is not properly described

[1] HERA was operated with both electron and positron beams. A reference to electron implies a reference to either electron or positron. Most of the results shown were obtained in e^+p collisions. Also, charge conjugate states are always implicitly included.

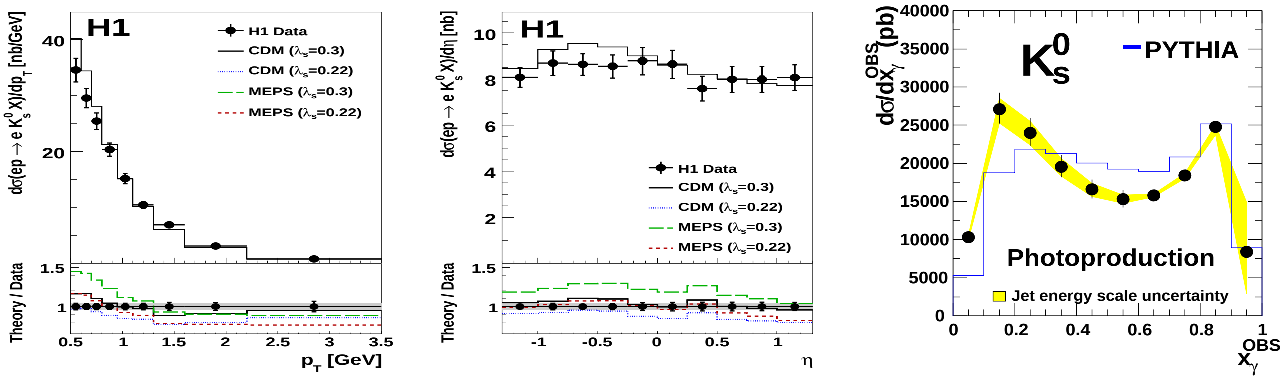

Figure 1: *Distribution of the K^0_S production cross section as a function of a) P_T, b) η in the laboratory frame for the DIS Q^2 region by H1 [1], and c) x^{obs}_γ in γp by ZEUS [2].*

by the PYTHIA simulation in both cases. The general features of the strange-to-light hadron ratio measurements (see Figure 2) are pretty well described by the simulations, provided a lower λ_S value such as 0.22 is chosen. There was no asymmetry observed between Λ and $\bar{\Lambda}$, which indicates a similar production process for baryons and antibaryons. Studies of angular distributions in the Λ decays did not reveal any non-zero transverse polarization in the Λ or $\bar{\Lambda}$ production. A first measurement of the production cross section of the excited $K^*(892)$ kaon state,

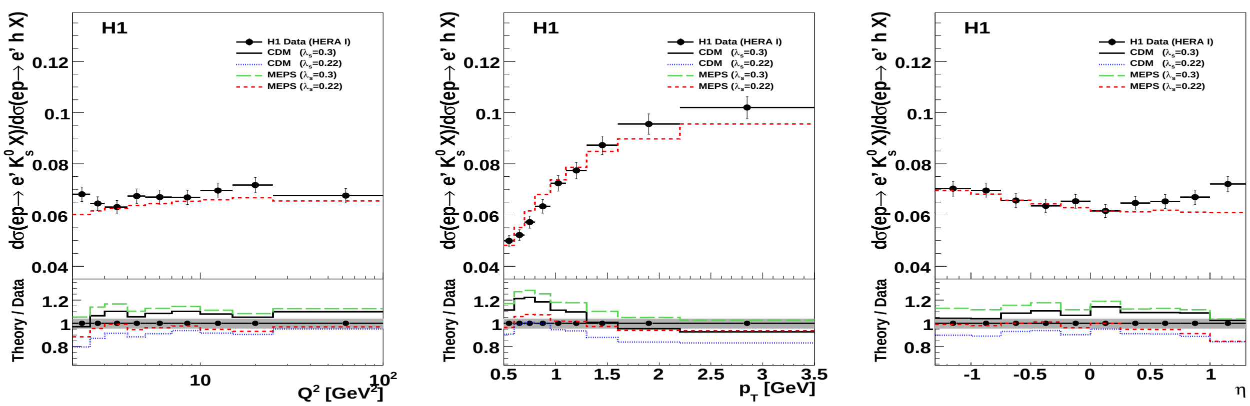

Figure 2: *Distribution of the K^0_S to charged particles ratio $N(K^0_S)/N_{\rm ch}$ as a function of a) Q^2 b) P_T and c) η for the DIS region (H1 [1]).*

detected through the decay $K^*(892) \to K^0_S\pi$ in the DIS region $5 < Q^2 < 100$ GeV^2 and $0.1 < y < 0.6$ was presented by the H1 collaboration [3]. Comparisons of the results with predictions of leading order Monte Carlo models matched to parton showers exhibit a picture, which is well consistent with the conclusions drawn from the K_S, Λ production measurements. In summary, a single strangeness suppression factor λ_S is not sufficient for a consistent description of all distributions in detail. This is partly due to the fact, that in various regions of phase space, the relative contributions of direct production of strange to other quarks differ; in particular at larger scales (e.g. Q^2 , p_T) the charm contributions become substantial and need to be properly included into the description.

Bose Einstein Correlations of Charged and Neutral Kaons

Bose-Einstein correlations (BEC) have been used in particle physics as a method of determining the size and the shape of a particle emitting source. BEC originate from the symmetrization of the two-particle wave function of identical bosons and lead to an enhancement of boson pairs emitted with small relative momenta. The ZEUS collaboration reported [4] on studies of BEC for pairs of identical kaons, both neutral and charged, in DIS. ZEUS studied the two-particle correlation function $R(Q_{12})$ as a function of the four-momentum difference of the kaon pairs,

$Q_{12} = \sqrt{-(\mathrm{p}_1 - \mathrm{p}_2)^2}$, assuming a Gaussian shape for the particle source. The actual correlation function $R(Q_{12})$ was calculated by means of a double ratio, comparing with a reference sample free from the BOSE-Einstein effect. The measured distributions are shown in Figure 3.

The values of the radius of the production volume, r, and of the correlation strength, λ, were determined from these distributions. While the charged kaon data sample yields quite precise results, the neutral kaon data suffer from larger systematic errors due to background contributions from the $f_0(980) \to K_S^0 K_S^0$ decays.

The radii for charged and neutral kaons are found to be in agreement within errors, similar to the ones measured in DIS and are also seen to be consistent with those obtained at LEP. A comparison of these results with other published values is shown in Figure 3c.

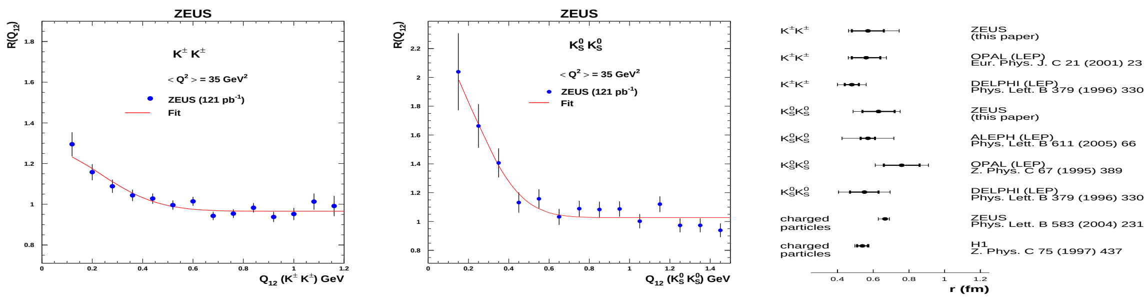

Figure 3: *The two-particle correlation function as measured by ZEUS [4] for a) charged kaons and b) neutral kaons. In c) the measured source radii are compared to published values from LEP and HERA.*

3. CHARMED PARTICLE PRODUCTION

The ZEUS collaboration has reported[5] the observation of excited D and D_s mesons in the decay chains $D_1(2420)^0,\ D_2^*(2460)^0 \to D^{*\pm}\pi^\mp, D^\pm\pi^\mp$ and $D_{s1}^\pm(2536) \to D^{*\pm}K_S^0,\ D^0K^\pm$. Based on a sample of $\approx$ 57000 D^* and $\approx$ 20400 $D^\pm$ and $\approx$ 22000 D^0 mesons, the decays are studied in detail. From a total of 3110 $D_1(2420)^0$, 1560 $D_2^*(2460)^0$ and 236 $D_{s1}^\pm(2536)$ states, properties like mass, widths and decay fractions are determined. In general, the measured properties agree well with the PDG values [6], except the width of the $D_1(2420)^0$ state, which is found to be larger than the world average. The measured fragmentation fractions for these states f_c in ep are found to be compatible with the ones observed in e^+e^-, supporting the universality of fragmentation.

In addition, an helicity analysis of the angular distributions between the K_S and the π_s in the D^* restframe for the $D_{s1}^\pm(2536)$ yielded a helicity parameter of $h(D_{s1}^\pm) = -0.74^{+0.23}_{-0.17}(stat)^{+0.06}_{-0.05}(syst)$. This non-zero value of the helicity parameter h suggests the state to be rather a mixture of two 1^+ states, e.g. to contain contributions from both S- and D-waves, as $h = 0(3)$ is expected for a pure $S(D)$-state.

A search for the radially excited state $D^{*'+}(2640)$ does not show a significant signal, and thus leads to the presently best upper limit on the charm branching fraction $f(c \to D^{*'+}(2640))$.

4. EXOTIC STATES IN THE STRANGENESS SECTOR

Strange Pentaquark States

Both experiments, H1 and ZEUS, have searched for the doubly strange pentaquark candidate states $\Xi^{++/00}$ in both charge combinations (doubly charged or neutral) decaying in $\Xi^{++/00} \to \Xi^+\pi^+$ and $\to \Xi^\pm\pi^\mp$. Such states could be interpreted as the Ξ_{5q}^{--} $(S = -2,\ I_3 = -3/2)$ and the Ξ_{5q}^0 $(S = -2,\ I_3 = +1/2)$ members of the isospin 3/2 quartet $\Xi_{3/2}$ in the anti-decuplet [7]. The invariant $\Xi\pi$ mass spectra measured by the H1[8] and ZEUS[9] collaborations do not show any indication of a signal, apart from the well known $\Xi(1530)^0$ baryon resonance. Therefore the non-observation of any resonance state in the mass range $1600 - 2300$ MeV in neither of the charge combinations limits the production rate of a hypothetical $\Xi^{++/00}$ pentaquark to values of order 20% on average at the 95% C.L. relative to the well known $\Xi(1530)^0$ baryon production rate, depending on the $(\Xi\pi)$-mass.

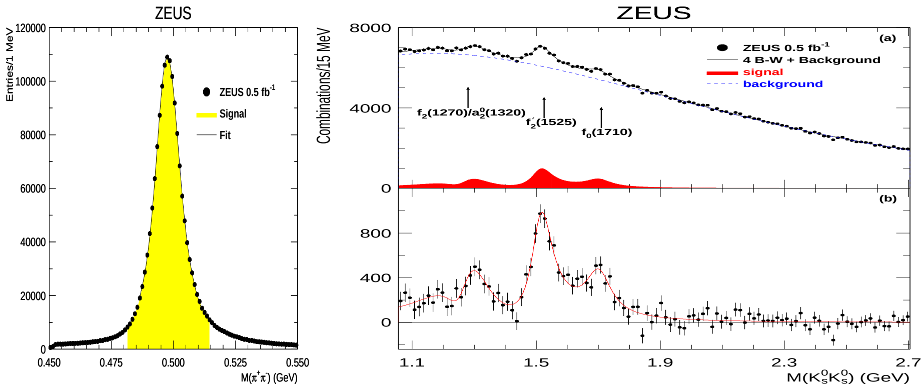

Figure 4: The invariant mass spectrum for a) $K^0_S \rightarrow \pi^+\pi^-$ and b) for $K^0_S K^0_S$ combinations in the final states (ZEUS [10]).

Glueball Candidates in the $K^0_S K^0_S$ Final State

The ZEUS collaboration performed a detailed analysis of the $K^0_S K^0_S$ final state [10], based on a total sample of about 1.2 million reconstructed K^0_S (see Figure 4a). The measured $K^0_S K^0_S$ invariant mass distribution is shown in Figure 4b) and clearly exhibits three prominent structures. The structures are elaborately analysed, employing multiple relativistic Breit-Wigner functions and allowing for interferences between the various components. The background subtracted result of the fit is depicted in the lower part of Figure 4b). Clear evidence for the $f_2'(1525)$ and the $f_2(1710)$ are observed at the 5 sigma level. The masses and the widths of the different contributions are measured. The widths are found to be consistent with the PDG values [6], whereas the masses of the $f_2'(1525)$ and the $f_2(1710)$ are found to be slightly below the PDG values [6]. The $f_2(1710)$ state is found to be consistent with the lowest lying $J^{PC} = 0^{++}$ glueball candidate.

5. SUMMARY

The overall features of the strange particle production are well described by theoretical models. However, there are still many details that need improvements, in particular concerning the treatment of the non-perturbative effects. The effect of Bose-Einstein correlation has been measured in charged and neutral kaon final states, and the resulting source radii are found to be in agreement with values determined in e^+e^- collisions at LEP. Measurements in the charm sector cover the excited charmed states, in agreement with the PDG values, and they have confirmed the hypothesis of fragmentation universality. The searches for pentaquarks in the doubly strange states at HERA have not turned up any signals, leading to limits in the production relative to the well known baryon state $\Xi(1530)^0$. The prominent structures in the $K^0_S K^0_S$ final states show clear evidence for the $f_0(1710)$ state, consistent with it being the lowest lying $J^{PC} = 0^{++}$ glueball candidate.

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