Light, Strange and Charm Hadron Measurements in ep Collisions as a Baseline for Heavy-Ion Physics

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Abstract

An overview of the recent results on hadron spectroscopy from the electron-proton collider experiments H1 and ZEUS at HERA is presented. Production of particles with light and strange quarks is measured and the results are compared to RHIC data and to predictions of Monte Carlo models. The investigation of exotic states in the strangeness sector is reviewed. Measurements in the charm sector cover studies of the radially and orbitally excited charm states.

1 Introduction

High energy particle collisions which give rise to large multiplicities of produced hadrons provide an opportunity to study the hadronisation process, in which quarks and gluons convert to colourless hadrons. Since most hadrons are produced with low transverse momentum, the theory of perturbative quantum chromodynamics (pQCD) is not applicable to describe hadronisation. The production of long-lived hadrons and resonances at high energies was studied in detail in electron-positron (e^-e^+) collisions at LEP using Z^0 decays [1]. The measurements using high energy hadronic interactions were restricted to long-lived and heavy quark hadrons. Recently, the production of the hadronic resonances $\rho(770)^0$, $K^*(892)^0$ and $\phi(1020)$ was measured in heavy-ion and proton-proton (pp) collisions at RHIC [2]. The electron-proton (ep) collider HERA allows the study of particle production in quasi-real photon-proton (γp) collisions, where the nuclear density is much lower than at RHIC. This is particularly interesting, because the γp centre-of-mass energy at HERA is about the same as for colliding nucleons at RHIC.

2 Generic Shape of Hadronic Spectra

Particle production in γp, pp and AuAu collisions has several properties. The transverse momentum (p_T) charged particle spectra [3] are described by a power law distribution

$$\frac{1}{\pi}\frac{d^2\sigma}{dp_T^2dy} = \frac{A}{(E_{T_0} + E_T^{kin})^n}\ , \tag{1}$$

where y is rapidity, $E_T^{kin} = \sqrt{m_0^2 + p_T^2} - m_0$ is the transverse kinetic energy, m_0 is the nominal resonance mass, A is a normalisation factor and E_{T_0} and n are free parameters. At low E_T^{kin} the power law function (1) is behaving like a Boltzmann exponential distribution $\exp(-E_T^{kin}/T)$ with $T = E_{T_0}/n$. This exponential behaviour of the hadronic spectra was interpreted within a thermodynamic picture of hadroproduction [4]. In this framework the parameter T plays the role of the temperature at which hadronisation takes place. At high E_T^{kin} the constant E_{T_0} becomes negligible.

In figure 1, some features for the charged particle spectra are shown. In pp the T increases and n decreases with increasing s. When comparing hadron production in γp, pp and AuAu at fixed s the parameters T and n increase with the complexity of the collisions.

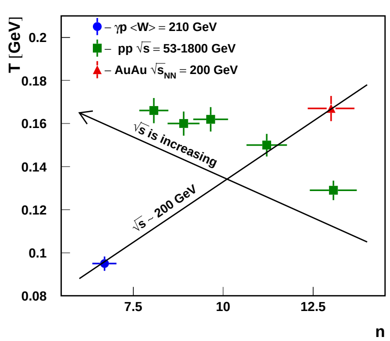

Fig. 1: Fit parameters $T = E_{T_0}/n$ and n from power law distribution of charged particle spectra.

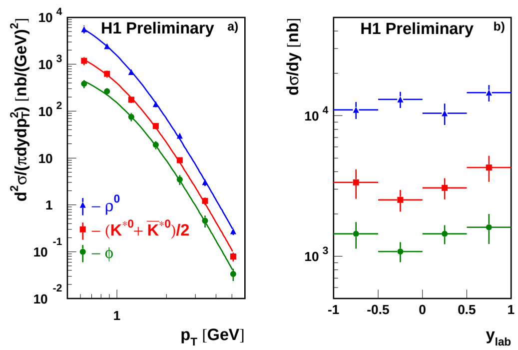

Fig. 2: The measured differential non-diffractive cross-sections for ρ^0, K^{*0} and ϕ mesons.

3 Inclusive Photoproduction of $\rho^0(770)$, $K^*(892)^0$ and $\phi(1020)$ Mesons

First measurements of inclusive non-diffractive photoproduction of ρ^0, K^{*0} and ϕ mesons at HERA are presented by the H1 collaboration. In figure $2a$), the invariant differential cross sections for the production of these resonances as a function of transverse momentum are presented together with a power law fit (1) as for the charged particle spectrum. In figure $2b$), the differential cross sections as a function of rapidity (y_{lab}) are observed to be flat, within errors in the visible range. It is observed that these resonances with their different masses, lifetimes and strangeness content are produced with about the same value of the average transverse kinetic energy. This observation supports a thermodynamic picture of hadronic interactions.

In figure 3, a modification of the shape of ρ^0 resonance produced in γp collisions at HERA is described by taking into account Bose-Einstein correlations (BEC) in the Monte Carlo model. A similar effect is observed in pp and heavy-ion collisions at RHIC [2] and in e^+e^- annihilation at LEP [5], using Z^0 decays.

The cross section ratios $R(K^{*0}/\rho^0)$, $R(\phi/\rho^0)$ and $R(\phi/K^{*0})$ are estimated. In figure 4, the $R(\phi/K^{*0})$ is compared to results obtained in pp and heavy-ion collisions by the STAR experiment at RHIC [2]. The ratio $R(\phi/K^{*0})$ measured in γp interactions is in agreement with pp results. A tendency of ϕ meson production to be more abundant in AuAu collisions is observed, but an increased accuracy is required to reach firm conclusions.

4 K_S^0, Charged $K^*(892)$ Mesons and Λ Baryon Production in DIS

The H1 collaboration has studied K_S^0 and Λ production in the DIS within the photon virtuality range $2 < Q^2 < 100$ GeV^2 [6] as a function of event variables and final state particle variables.

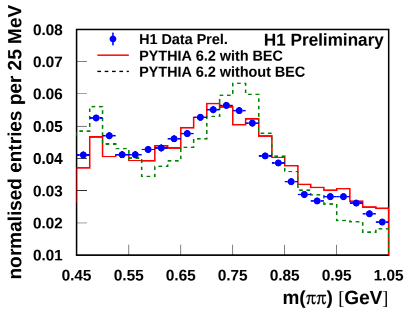

Fig. 3: The unlike-sign mass spectrum with the like-sign spectrum subtracted.

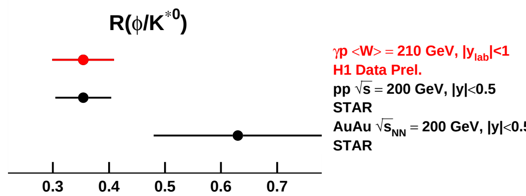

Fig. 4: The ratio $R(\phi/K^{*0})$ of the total cross-sections.

The cross section of K_S^0 and Λ as a function of p_T are presented in figures 5 and 6 correspondingly. The overall features of the data are reproduced by colour dipole model (CDM) based predictions, when using the strangeness suppression factor $\lambda_s = 0.3$ and applying model parameters tuned to LEP e^+e^- data. However, the predictions fail to describe the details of the distributions in various regions of the phase space, in particular at low p_T, low x and large positive rapidity. There was no asymmetry observed between Λ and $\overline{\Lambda}$, which indicates a similar production process for baryons and antibaryons.

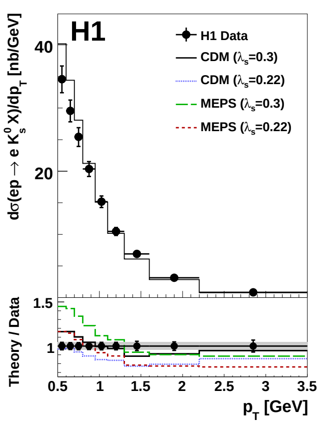

Fig. 5: The differential production cross section for K_S^0 as a function of p_T.

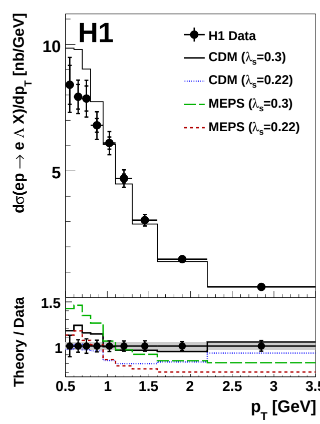

Fig. 6: The differential production cross section for Λ as a function of p_T.

The H1 collaboration has reported the observation of charged $K^*(892)$ mesons in the DIS kinematic region $5 < Q^2 < 100$ GeV^2 [7]. The invariant mass spectrum is shown in figure 7. The cross sections for the $K^{*\pm}$ production are measured as a function of the transverse momentum, pseudorapidity, photon virtuality, Feynman-x and the centre-of-mass energy of the hadronic final state. The measured cross sections are in agreement with DJANGOh1.4 (CDM) and RAPGAP3.1 (MEPS) Monte Carlo model predictions. This is consistent with the results of the K_S^0 and Λ measurements.

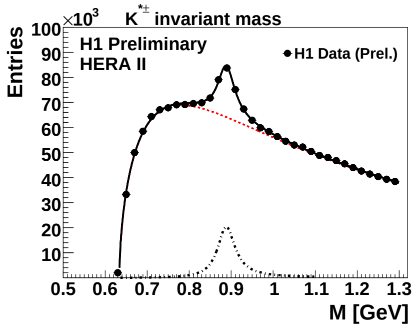

Fig. 7: The measured $K_S^0\pi^\pm$ invariant mass spectrum.

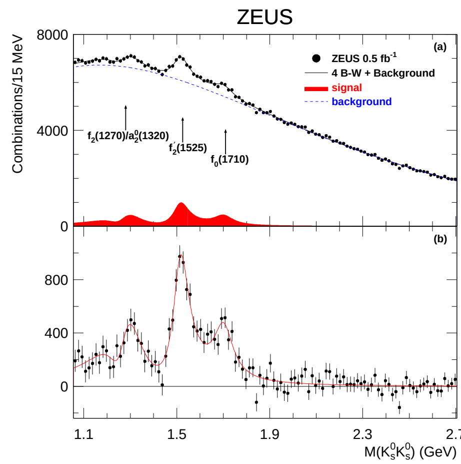

Fig. 8: (a) The measured $K_S^0K_S^0$ invariant mass spectrum. (b) The background-subtracted $K_S^0K_S^0$ invariant mass spectrum.

5 Exotic States in the Strangeness Sector

The $K_S^0K_S^0$ final state was studied with the ZEUS detector [8]. In figure 8, the measured invariant mass distribution is shown. Three enhancements which correspond to $f_2(1270)/a_2^0(1320)$, $f_2'(1525)$ and $f_0(1710)$ were observed. No state heavier than the $f_0(1710)$ is seen. The invariant distribution was fitted taking into account the interference pattern predicted by SU(3) symmetry arguments. The measured masses of the $f_2'(1525)$ and $f_0(1710)$ states are slightly below the PDG values [9], while the widths are consistent with the PDG values [9]. The $f_0(1710)$ state, which has a mass consistent with the lower lying $J^{PC} = 0^{++}$ glueball candidate, is observed with a five standard deviation statistical significance. However, if this state is the same as that seen in $\gamma\gamma \to K_S^0K_S^0$ [10], it is unlikely to be a pure glueball state, since photons can couple in partonic level only to charged objects.

6 Charmed Particle Production

ZEUS studied excited charm and charm-strange mesons. The signals are reported [11] of $D_1(2420)^0$, $D_2^*(2460)^0$ and $D_{s1}(2536)$ mesons in the decay chains D_1^0, $D_2^{*0} \to D^{*\pm}\pi^\mp$, $D^\pm\pi^\mp$ and $D_{s1}^\pm \to D^{*\pm}K_S^0$, $D^0K^\pm$. The measured masses are in reasonable agreement with the world average values [9] while the measured D_1^0 width is above the world average value.

The measured D_1^0 helicity parameter is $h(D_1^0) = 5.9^{+3.0}_{-1.7}(\text{stat.})^{+2.4}_{-1.0}(\text{syst.})$, which is inconsistent with the prediction of $h = 0$ for a pure S-wave decay of the 1^+ state, and is consistent with the prediction of $h = 3$ for a pure D-wave decay. The measured D_{s1}^+ helicity parameter is $h(D_{s1}^+) = -0.74^{+0.23}_{-0.17}(\text{stat.})^{+0.06}_{-0.05}(\text{syst.})$, which is inconsistent with the prediction of $h = 3$ for a pure D-wave decay of the 1^+ state, and is barely consistent with the prediction of $h = 0$ for a pure S-wave decay. Both D- and S-wave seem to contribute to the $D_{s1}^+ \to D^{*+}K_S^0$ decay. These measurements are consistent with e^+e^- results.

No radially excited $D^{*\prime+}(2640)$ meson was observed. The best upper limit on the charm branching fraction is estimated to $f(c \to D^{*\prime +}) \cdot \mathcal{B}_{D^{*\prime +} \to D^{*+}\pi^+\pi^-} < 0.4\%$ (95% C.L.).

7 Summary

Production of particles consisting of light and strange quarks was measured and compared to the RHIC data and to the predictions of Monte Carlo models. The ratio $R(\phi/K^{*0})$ measured in γp interactions is in agreement with pp results. A tendency of ϕ meson production to be more abundant in AuAu collisions is observed, but an increased accuracy is required to reach firm conclusions. 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-pertubative effects. The $K^0_S K^0_S$ final state spectrum shows clear evidence for the $f_0(1710)$ state, consistent with the lowest lying $J^{PC} = 0^{++}$ glueball candidate. Excited charm and charm-strange mesons were observed and their helicity structure were studied.

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