PHOTO- AND ELECTROPRODUCTION OF SINGLE HADRONS AND RESONANCES

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Production of single hadrons and resonances emerges as a promising field for the study of Quantum Chromodynamics at HERA. Four recent studies are presented here to illustrate the scope and reach of the technique: light mesons and resonances test the universality of hadroproduction, strange particles challenge the hadronisation models or directly probe the quark content of the proton sea while the first observation of $K-K$ resonant states offers a glueball candidate.

1. Introduction

The process by which quarks and gluons convert into colorless hadrons is not well described by Quantum Chromodynamics (QCD) processes. This is particularly true for light quarks, where perturbative QCD does not apply. As a consequence, phenomenological hadronisation models such as the Lund String Model or the Cluster Fragmentation Model are widely used to represent the processes.

Production studies of particles such as some of the light mesons or baryons containing a strange quark, or light resonances, should therefore contribute to the understanding of the hadronisation mechanisms. In many ways, HERA lags behind LEP in several of such measurements, but its different kinematical reach and the presence of quarks in the initial state strongly enhances its potential.

This paper will cover four examples of photo- and electroproduction processes: neutral hadronic resonances, strange particles, the use of strange mesons to probe the proton sea content and the study of $K^0_s K^0_s$ resonances in the search for special states of matter.

2. Neutral Hadronic Resonances at HERA

This first extensive set of measurements done by the H1 experiment at HERA on light hadronic mesons and resonances used the 39 pb^{-1} of the 2000 data, covering the laboratory rapidity region of $|y_{lab}|<1$ with an average energy of 210 GeV in the photon-proton system. The production rates of η, ρ^0, $f_0(980)$ and $f_2(1270)$ were investigated[1].

A large fraction of the η's decay in a pair of photons which can be identified by clusters in the liquid argon detector, as illustrated in figure 1. The other states are predominantly decaying in $\pi^+\pi^-$ pairs, easily detected as charged tracks in the jet chambers. However, as shown in figure 2, the low-mass background is considerable and special care had to be taken in its combinatorial representation and in the assumptions regarding reflections from ω and K^* states. The ρ^0 peak is shifted to low values from the expectations, but this is also partly due to the acceptance limitations in that range and introduces but a negligible bias on the f_0 and f_2 resonant peaks.

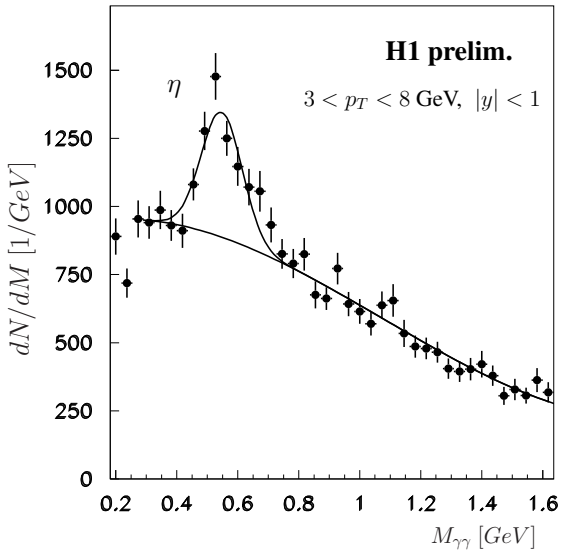

Figure 1. The two-photon mass spectrum. The curves were obtained from a fit to a Gaussian distribution and a polynomial background function.

When the single isospin data is corrected for spin and plotted as function of the sum of the meson mass and its transverse momentum (figure 3), one observes a striking scaling as the same behaviour of light, long-lived hadrons is reproduced, thus testing the universality of hadroproduction.

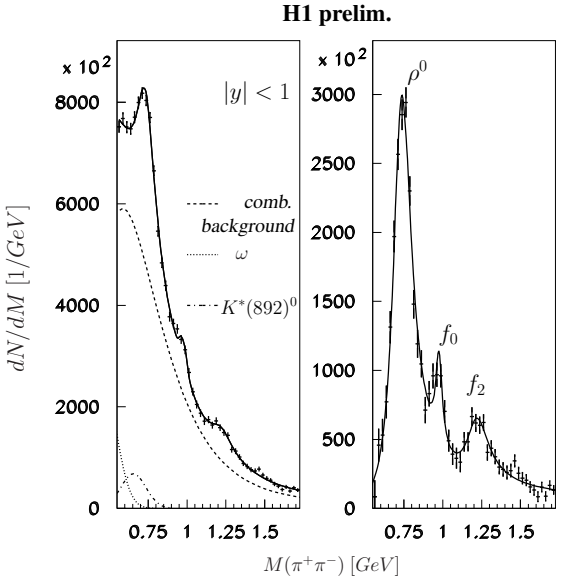

Figure 2. The $\pi^+\pi^-$ invariant mass spectrum before and after subtraction of the background and of the estimated low-energy contributions from reflections. The curves contain relativistic Breit-Wigner shapes from the fit.

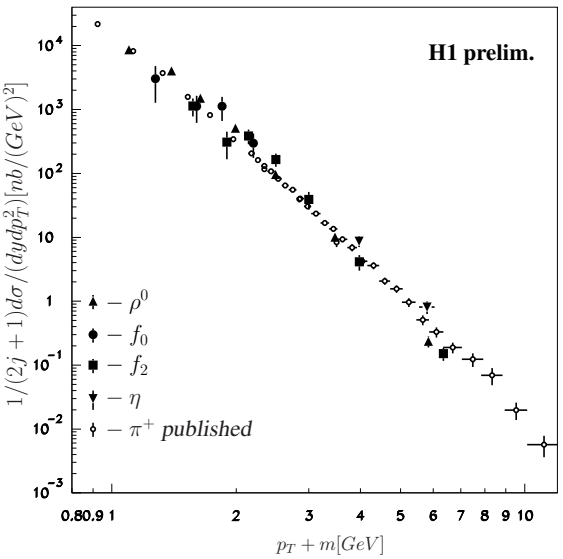

Figure 3. The differential photoproduction cross sections of light mesons as function of the sum of the meson mass and its transverse momentum p_T.

3. Strangeness Production

Strange quarks may be produced by flavour excitation, QCD Compton, gluon-splitting, boson-gluon fusion, various hadronisation processes, decay from higher mass states or diffractive processes, most of which are not always readily differentiated. Strange particle production becomes very useful because of the associated low masses, copious rates and unambiguous signals. K_s^0's and Λ's have been studied previously at HERA in deep inelastic scattering (DIS) and photoproduction, but only from very early data sets[2,3,4,5], and no cross-section had as yet been determined.

Using the 60 pb^{-1} of the ZEUS 1999-2000 data[6,7] in the DIS regime ($50<Q^2<500$ GeV^2), and restricting the particle p_T range to the 0.5–5 GeV interval, figure 4 shows the quality of the particle identification for the main decays of the particles. Table 1 compares the results to HERWIG and the Lund Color Dipole Model (under ARIADNE) for two configurations of the strangeness suppression factor $\lambda_s = P(s)/P(d)$, whereby $P(d) = P(u)$. The measurements fall between the values of 0.2 and 0.3 in Lund model while HERWIG fails to predict the total cross sections. The ratio between Λ and $\overline{\Lambda}$ remains however unity.

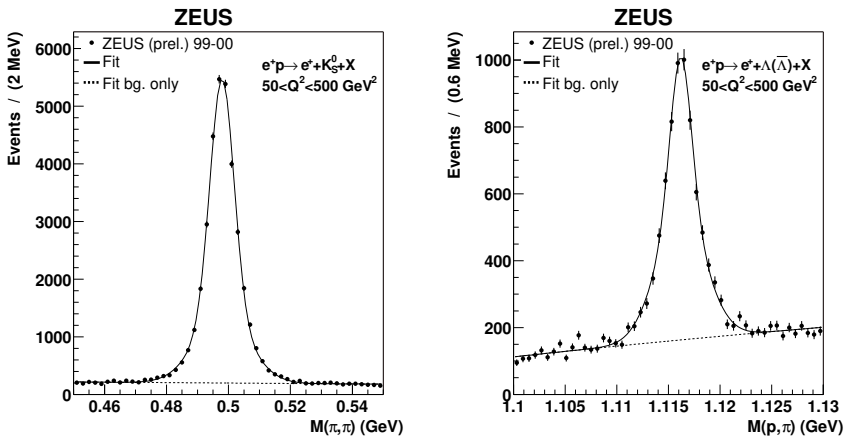

Figure 4. The K_s^0 (left) and Λ (right) invariant mass spectra.

In figure 5, drawn in the laboratory frame, even a renormalized HERWIG simulation does not reproduce the shapes of the distributions. Moreover, the effect of changing the value of λ_s is shown to be non-uniform according to the type of particle or its transverse momentum. From the pseudorapidity (η) plot, there is an indication of increased baryon to meson production in the forward region.

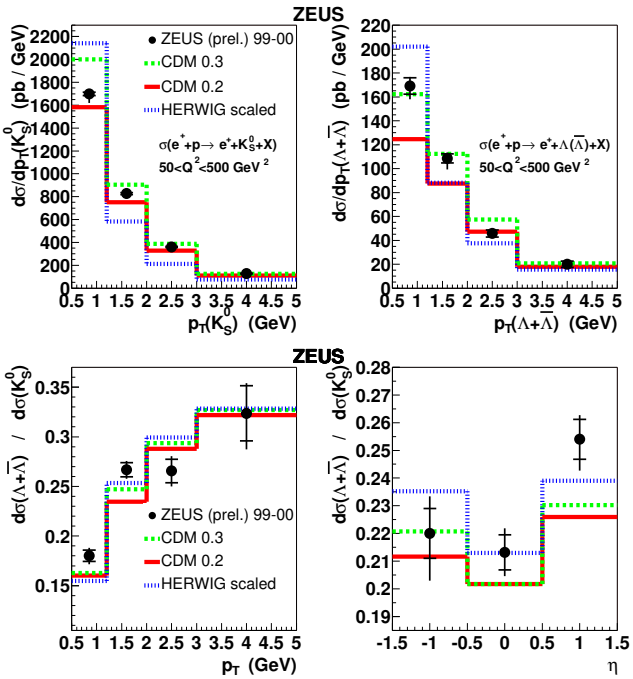

Figure 5. Differential cross sections for K^0_s and Λ as function of the transverse momentum p_T and the pseudorapidity η in the laboratory frame.

Table 1. Preliminary cross-sections and ratios thereof for K^0_s and Λ.

	$\sigma(K^0_s)$ $[pb]$	$\sigma(\Lambda+\overline{\Lambda})$ $[pb]$	$\sigma(\Lambda+\overline{\Lambda})/\sigma(K^0_s)$
ZEUS (prelim.)	$2454\pm 18^{+32}_{-102}$	$567\pm 12^{+13}_{-34}$	$0.231\pm0.005^{+0.005}_{-0.006}$
CDM ($\lambda_s = 0.3$)	2762	603	0.218
CDM ($\lambda_s = 0.2$)	2257	483	0.214
HERWIG	1854	1329	0.717

	$\sigma(\Lambda)$ $[pb]$	$\sigma(\overline{\Lambda})$ $[pb]$	$\sigma(\Lambda)/\sigma(\overline{\Lambda})$
ZEUS (prelim.)	$292\pm 9^{+7}_{-18}$	$279\pm 9^{+12}_{-18}$	$1.05\pm 0.05^{+0.05}_{-0.05}$
CDM ($\lambda_s = 0.3$)	302	301	1.00
CDM ($\lambda_s = 0.2$)	240	243	0.99
HERWIG	661	668	0.99

This last observation motivated further investigation in the Breit Frame, where the radiation from the struck quark is naturally separated from the proton remnant (figure 6). The variable x_p represents the particle scaled momentum. The current region is equivalent to one hemisphere of a e^+e^- collider system and the results confirm the low sensitivity to the λ_s param-

eter. In the target region, associated to the proton remnant, the data tend towards the higher value $\lambda_s = 0.3$, which may suggest that this parameter could be related to the gluon density. A single parameter might not be adequate to estimate the production rates of strange particle over such kinematical ranges. Studies of the heavier strange particles Σ and Ξ are currently being done in ZEUS to further extend the scope of this study.

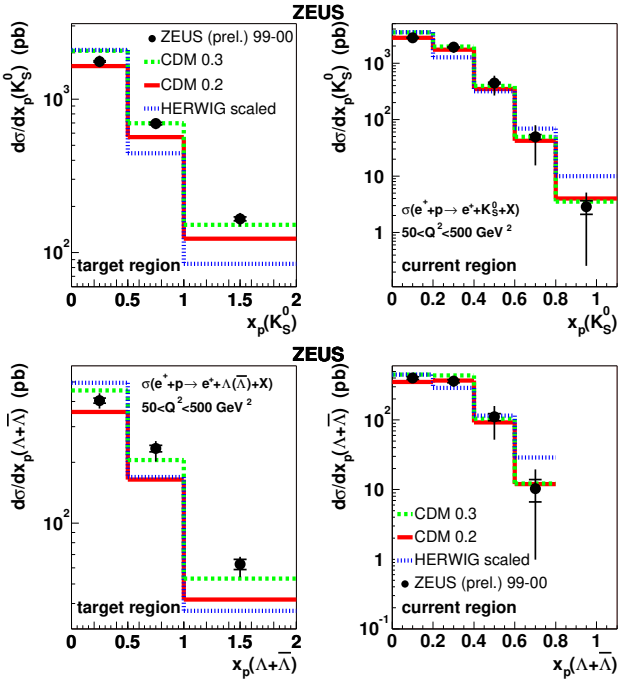

Figure 6. Differential cross sections for K_s^0 and Λ as function of the scaled momentum x_p in the Breit Frame.

4. Strange Content of the Sea

The ϕ-meson is another strange particle with a clean decay mode of a pair of kaons at the vertex which can be used to study not only hadron production in yet another channel, but also to probe directly the content of the proton sea. Detection of ϕ's in the 1995-1997 ZEUS data sample[8] reveals a high background but exhibits a clear signal in the laboratory frame, which becomes even more enhanced in spite of low statistics in the current region of the Breit Frame (figure 7).

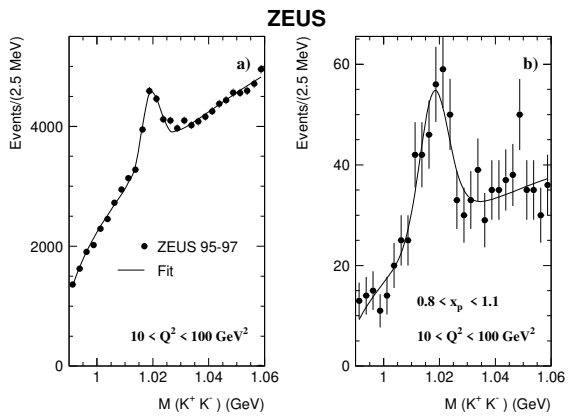

Figure 7. Invariant mass plot of K^+K^- pairs in the laboratory and in the Breit Frame.

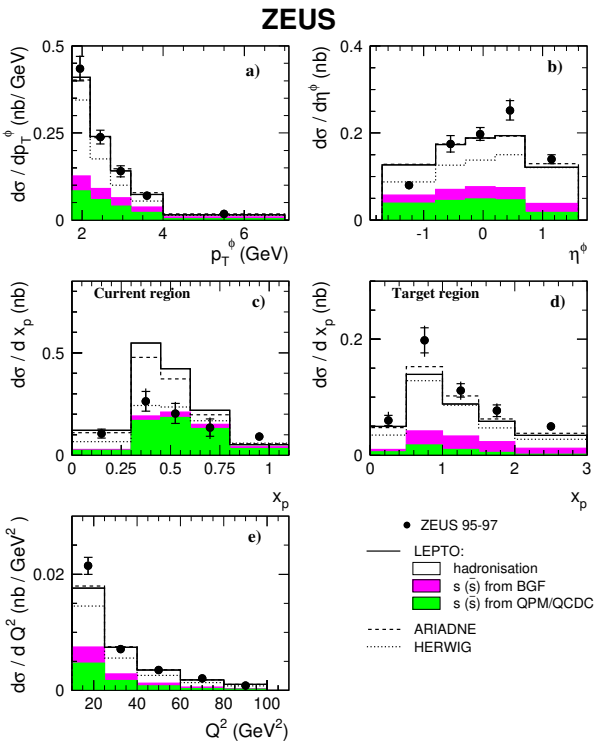

Figure 8. Differential ϕ-meson cross-sections as function of the kinematic variables p_T, η, x_p (current and target regions) and Q^2. Contributions of subprocesses of Boson-Gluon Fusion, Quark Parton Model or QCD Compton are also indicated.

The cross-section measured in the selected kinematical range, $\sigma(e^+p \rightarrow e^+\phi X) = 0.57 \pm 0.022^{+0.010}_{-0.008}\, nb$ agrees very well with the LEPTO ($0.0501\, nb$) and ARIADNE ($0.509\ nb$) simulations while establishing a preliminary value of 0.22 ± 0.02 for λ_s in that range. The plots of figure 8, whereby the Monte-Carlo inputs can be controlled, illustrate some of the observations: the hard QCD processes give very significant relative contributions in the current region of the Breit Frame while vanishing in the target region. This, coupled to the fact that their fraction increases as function of p_T or x_p, points to important involvement of the sea s-quarks.

By concentrating on the leading ϕ-mesons (x_p>0.8), one realizes that uncertainties in the QCD processes and hadronisation are very small at high p_T, that gluon emissions become negligible and that the photon scattering on s-quarks is a QED process, i.e. well described. The main uncertainties left arise from the modellisations themselves and the allowed λ_s range, which is taken to be 0.2–0.3. Under such conditions, the leading ϕ-mesons in figure 9 unambiguously require s-quark scattering, thus showing direct evidence of the proton strange sea contribution to hadron production at low values of the scaled momentum x.

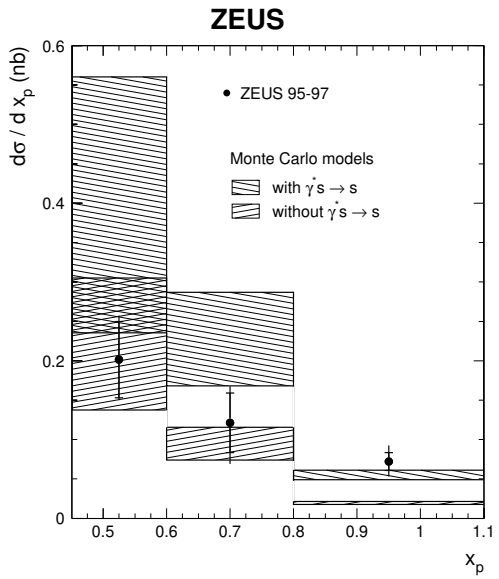

Figure 9. Cross sections for leading ϕ-mesons as function of x_p in the current region of the Breit Frame. The hatched bands represent the full range of uncertainties in the simulations.

5. $K_s^0 K_s^0$ Resonances

With the maturity of the experiments and the recent developments in the field, there is now considerable interest in "meson spectroscopy" at HERA. The striking example of the $K_s^0 K_s^0$ resonant states in DIS with the ZEUS experiment[9,10] illustrates the potential for discoveries.

Kaons are again chosen in this search because of their high detection efficiency, good acceptance and low background in the central rapidity region. The K_s^0 momentum threshold is chosen to be 200 MeV. A special cut on the opening angle θ_{KK} between the 2 kaons is applied to reject the $f_0/a_0(980)$ state. 2553 candidates are found. Their invariant mass plot of the system is displayed in figure 10 and fitted with three relativistic modified Breit-Wigner distributions and one background function.

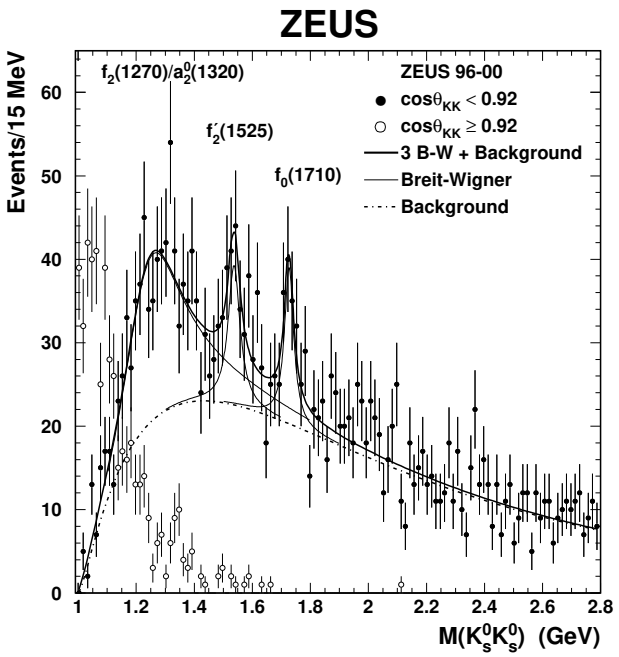

Figure 10. Invariant mass plot of the $K_s - K_s$ pairs. The lines identify the residual combinatorial background and the peaks used in the overall fit to the data (full dots). The open dots describe the already rejected f_0/a_0 background.

Three regions are identified. Below 1500 MeV, the contributions from the $f_2(1270)$ and $a_2^0(1320)$ merge over the acceptance threshold. The θ_{KK}

cut is shown to leave negligible possible contributions under the remaining two peaks. The first of these, at 1537±9 MeV and with a width of ∼50 MeV, is consistent with the known $f_2'(1525)$ state. The second peak, at 1726±7 MeV, contains 79^{+29}_{-23} events and has a measured width of 38^{+20}_{-14} MeV. This width is in open contradiction from the observations from BES, Belle and L3, which published 167, 323 and 200 MeV respectively. A large number of permutations and assumptions has been tested in the fits to the data, the other state widths, the background shapes, etc.. but results in this high mass range were proven to be rather insensitive to them. A further check in the Breit Frame revealed that 93% of the candidates are found in the target region, i.e. associated with the proton remnant. The expected sizeable initial state gluon radiation thus strengthens the hypothesis that the state could be a glueball candidate.

6. Summary

First measurements of inclusive photoproduction cross-sections of the light resonances η, ρ^0, $f_0(980)$ and $f_2(1270)$ have been reported. Strangeness production studies in deep inelastic scattering reveal details of hadronisation processes and inconsistencies in some of the currently available simulation packages. ϕ-mesons were further used to provide direct evidence of the strangeness content of the proton sea. Finally, in a first case of complex resonant system of K^0_s pairs, two high mass states have been clearly identified, offering one glueball candidate.

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