NEW RESONANCES IN THE HADRONIC FINAL STATE AT HERA

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HERA-I studies on new resonance searches in the hadronic final state in ep collisions are reviewed. The searches were performed both in meson and baryon resonances. Pentaquark candidates were observed in $K_s^0 p$ system in ZEUS and in D^*p system in H1. The two experiments are compared and the compatibility is discussed.

1. Introduction

HERA provides a unique field for new resonance searches. Thanks to the high centre-of-mass energy of HERA, searches can be performed in various kinematic regions. By tagging the scattered electron, the kinematics of the hadronic system can be well defined, primarily by the standard event variables such as Q^2, x, y and W, and then by a particular phase space in the event, such as the target- or current-fragmentation in the Breit frame. Depending on kinematic regions selected by these variables, quite different mechanisms may take place in particle production.

In my talk, the hadron resonance searches in HERA-I are reviewed in the order of the number of quarks in the system; *i.e.* starting from mesons, continuing to baryons including pentaquarks and finally ending with many quark states.

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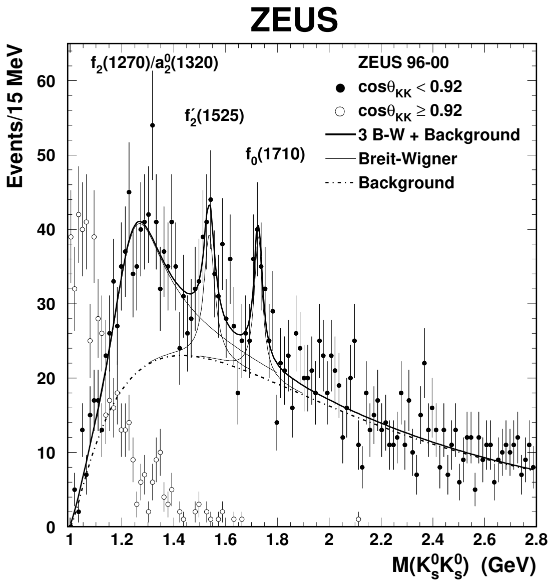

Figure 1. The $K_s^0 K_s^0$ invariant mass spectrum with cuts on the opening angle between the two K_s^0 in the laboratory frame ($\cos\theta_{KK}$). Fitting results using three Breit-Wigners and a background function are also shown.

2. Meson productions at HERA

Meson spectroscopy in the $\pi^+\pi^-$ channel was performed by H1 in photoproduction events[1]. Clear mass peaks from ρ^0, $f_0(980)$ and $f_2(1270)$ were seen. The production cross sections of these resonances and of pions agree well with each other, when they are plotted as a function of its mass plus p_T instead of p_T itself and when the degree of freedom from the spin and isospin is taken into account. Such a thermodynamic behaviour of particle production is often seen in relativistic heavy ion collisions. It is interesting to find a similar behaviour in ep collisions.

Figure 1 shows the mass distribution of $K_s^0 K_s^0$ from the ZEUS collaboration[2]. Three resonance structures are observed. The broad peak at low mass may correspond to the $f_2(1270)$ and/or $a_2^0(1320)$ state. The second peak at 1537^{+9}_{-8} MeV is consistent with the $f_2'(1525)$.

The highest mass state has a mass consistent with the glueball candidate $f_0(1710)$. The measured width is 38^{+20}_{-14} MeV, which is narrower than the value by the Particle Data Group of 125 ± 10 MeV. But it gives an acceptable chi-square when the data are fitted with a mass width fixed to this value.

Most of the $K_s^0 K_s^0$ pairs (93 %) found in the analysis are in the target region of the Breit frame. If the $f_0(1710)$ is a glueball, it is natural for it to be predominantly seen in the target region, where gluons are abundant. Although this analysis is based on the entire data sample of 1996-2000, it is not enough to make separate plots for various kinematics to see if this is the case. It is important to continue the spectroscopy in the HERA-II period.

3. Baryon productions at HERA

The search for new baryons is a very hot topic since the LEPS experiment found a strange pentaquark candidate Θ^+ in the missing mass distribution in low-energy photon-nucleus interactions[3]. Soon after the observation, many other experiments reported the presence or absence of a signal. The recent high statistic measurements by the CLAS experiment in γp and γd reactions show negative results, while the new measurements from the LEPS experiment indicate an associate production of Θ^+ and $\Lambda(1520)$[4].

As already mentioned, HERA offers a wide range of kinematic region where different hadronisation processes may take place. It is very important to understand how ordinary baryons are produced in various phase spaces, to compare with the pentaquark candidates.

There are still only a few results on stable baryon production at HERA. H1 measured the proton production cross sections in photoproduction. The proton yield is about half of the prediction from the PYTHIA Monte Carlo generator[5]. Lambda production in DIS shown by ZEUS shows a good agreement except for small deviations in the Λ/K^0 ratio at low-x and low-p_T regions[6]. Such a difference may indicate that baryon production in ep collisions is different from e^+e^- collisions. Here again, it is important to study further by specifying the phase space more carefully.

Related to the Θ^+ pentaquark searches shown in the next section, ZEUS studied several strange and charmed baryons which decay to a kaon and a nucleon, such as Λ_c and $\Lambda(1520)$. These baryons are observed in a wide pseudorapidity (η) region, both in photoproduction and in DIS. The behaviour of baryons and anti-baryons is similar; *i.e.* there is no visible baryon/anti-baryon asymmetry[7].

3.1. *Strange pentaquarks*

ZEUS already reported the observation[8] of a peak in the invariant mass distribution of the $K_s^0 p$ system, as shown in figure 2. The peak position is $1521.5 \pm 1.5(stat.)^{+2.8}_{-1.7}(syst.)$ MeV and is consistent with the $\Theta^+(1530)$. The measured Gaussian width is $6.1 \pm 1.6(stat.)^{+2.0}_{-1.4}(syst.)$ MeV, which is above, but consistent with, the experimental resolution of 2.0 ± 0.5 MeV.

On the other hand, the H1 collaboration found negative results[9]. The upper limit on new resonance are shown in figure 3. This can be compared with the visible cross section $\sigma_{vis} = 125 \pm 27^{+36}_{-28}$ pb, reported by ZEUS[10], and corresponding to a slightly larger phase space. In the mass region around 1530 MeV, the H1 upper limit and the ZEUS measurement overlap each other, so that the two measurement are still compatible, with the current statistics.

ZEUS tried to enhance the Θ^+ peak by refining the kinematic cuts[7]. The signal is best seen when the Kp system is going in the proton direction in the laboratory frame and in the high-Q^2 ($Q^2 > 20$ GeV^2) event sample. The $K^0_s p$ peak is more visible than the $K^0_s \bar{p}$ one. This behaviour is contrasted with the case for the normal baryons mentioned in the previous section.

The ratio of the production cross section of Θ^+ to Λ is measured[10] to

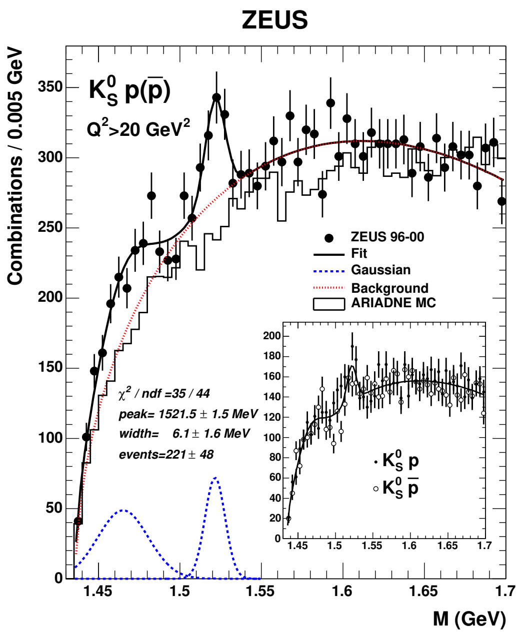

Figure 2. Invariant mass spectrum for the $K^0_s p(\bar{p})$ for $Q^2 > 20$ GeV measured by the ZEUS experiment. Results of a fit with the Gaussians and a background function are also shown. The inset shows the $K^0_s p$ and $K^0_s \bar{p}$ candidates separately.

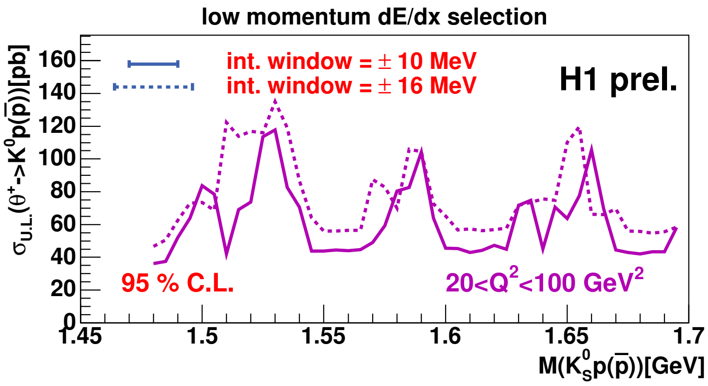

Figure 3. Upper limits set by the H1 experiment on the Θ production cross sections ($\sigma_{U.L.}(e+p \longrightarrow e\Theta^+X \longrightarrow eK^0p(\bar{p})X)$) at 95% confidence level for $20 < Q^2 < 100$ GeV^2.

be about 0.05. This would be large enough for the LEP experiments to see the Θ^+, if the same ratio can be applied to e^+e^- collisions.

All these observations indicate that the production mechanism of the pentaquark is different from ordinary baryons. However, it should be pointed out that these results are from the same event sample and hence the results are highly correlated. It is, therefore, too early to draw any positive/negative conclusions about the strange pentaquark. We need to wait for analyses with the new HERA-II data.

A search of pentaquarks which decay to $\Xi\pi$ was also performed[11]. The narrow peak found by the NA49 experiment[12] at 1862 MeV was not seen in a DIS data sample.

3.2. *Charmed pentaquarks*

The H1 experiment reported a narrow peak in the $D^{*-}p$ mass distribution[13]. Since the D^{*-} contains an anti-c quark, the resonance has an anti-valence quark with a positive baryon number, so that this is another pentaquark candidate. The peak position is $3099 \pm 3 \pm 5$ MeV and its width is very narrow; 12 ± 3 MeV. As seen in figure 4, the signal is clearly seen both in DIS and in photoproduction, although the background is larger in the photoproduction sample.

The production cross section is estimated based on the events in the peak[14]. Since it is unknown how the $D^{*-}p$ resonance (called $D^*p(3100)$, hereafter) is produced and decays, a model is developed with the RAP-

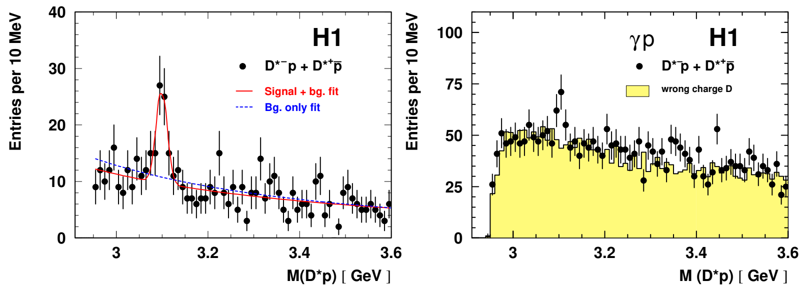

Figure 4. Invariant mass distribution of opposite-charge D^*p combination in DIS and in photoproduction measured by H1.

GAP Monte Carlo, assuming that it is produced in a similar manner to the D mesons such as $D_1(2420)$ and $D_2^*(2460)$. Isotropic decay is also assumed. Cross sections as a function of η and p_T are shown in figure 5. The Monte Carlo predictions with the above assumptions are also shown after the overall visible cross section is normalised to the data. In the model, the η distribution of the resonance is flat but the data have a suppression in the central region. The transverse momentum distribution is slightly softer in the data. These might indicate a different production mechanism of the resonance, but, as already mentioned in the case of the ZEUS studies of Θ^+, the studies done so far are based on a single sample taken in the HERA-I period.

Unfortunately, the resonance structure is not seen in the ZEUS measurements[15]. The observation of H1 implies that the $D^*p(3100)$ contributes roughly 1% of the D^* production rate in DIS with $Q^2 > 1$ GeV^2 although the analysis cuts are different. Figure 6 shows the ZEUS results with such an estimated pentaquark signal. In contrast to the Θ^+ case, the H1 and ZEUS results are already not compatible.

In summary, the pentaquark searches at HERA do not show clear results and it is hard to draw any conclusions at this stage. It is very important for both collaborations to repeat the analyses with the HERA-II data to confirm/reject the candidates.

4. Instantons

To end my talk, I would like to mention searches for the many-quark states induced by QCD instantons[16]. QCD is a non-Abelian gauge theory and

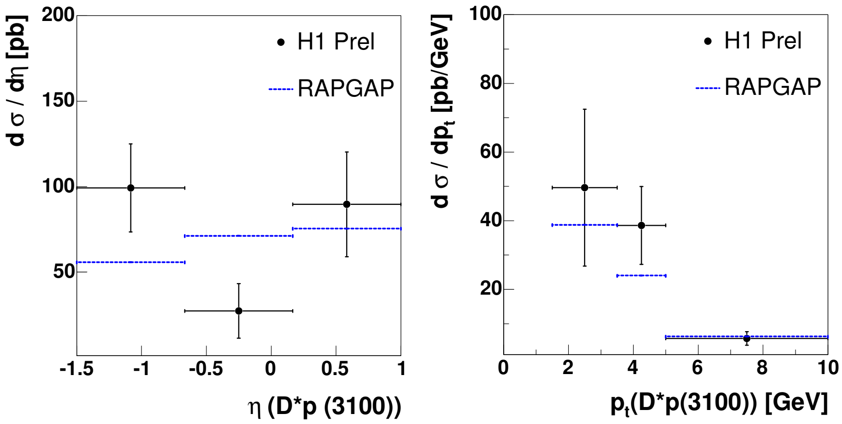

Figure 5. Differential $D^*p(3100)$ cross section as a function of pseudorapidity (η) and transverse momentum (p_T) of the $D^*p(3100)$ system. Data (closed symbols) are compared with the expectation of a model (RAPGAP) assuming a production and decay mechanism as described in the text. Only statistical errors are shown.

has a complicated vacuum structure. Tunnelling processes between topologically different types of vacuum states can occur. These are mediated by instantons.

The cross section for instanton induced processes in DIS is predicted[17] to be $O(10^{-3})$ of the total DIS cross section. This is still small, but by using sophisticated final state selection procedures, it is possible to enhance this fraction.

In (anti-)instanton processes, light quarks and anti-quarks are produced "democratically" and with the same chirality:

$$\gamma^* + g \stackrel{I}{\Longrightarrow} \sum_{flavours} (\overline{q}_R + q_R) + n_g g, \quad (I \to \overline{I}, R \to L), \tag{1}$$

with $n_g \sim 3$. It is very difficult to measure the handedness in the final state, so the signature used in searches is based on the emission of a large number of partons in a limited rapidity range.

An example[18] of the difference in the final state is shown in Figure 7. The variable used in the plots is the sphericity of particles in the reconstructed instanton rest frame. The left plot is made before enhancement cuts. Instanton events are more circular than "normal" DIS events, but the fraction is very small so that in the plot it is rescaled by a factor of 500.

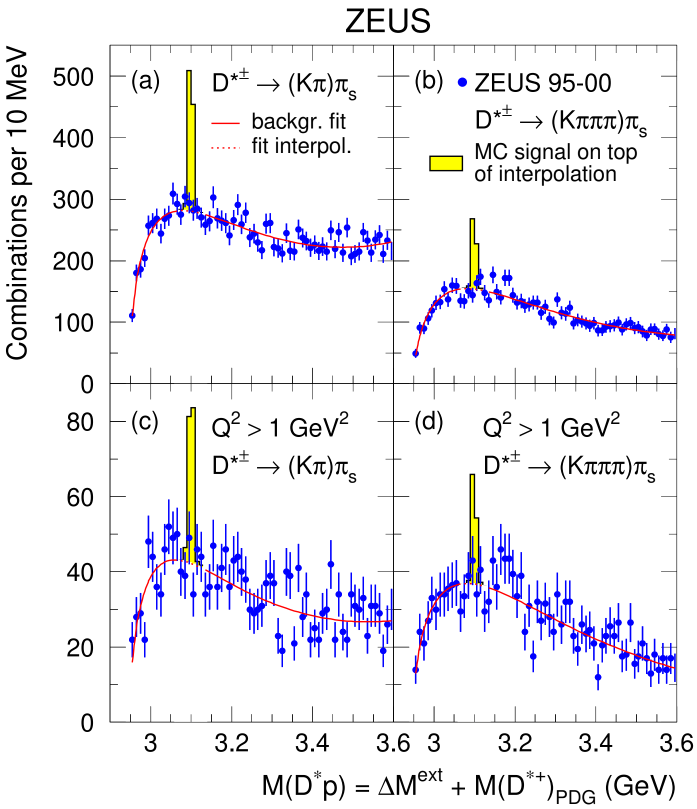

Figure 6. ZEUS measurements on the D^*p mass distributions in two different D^0 decay modes and Q^2 ranges. The shaded histograms show the Monte Carlo $D^*p(3100)$ signal, assuming 1% of D^*'s are the decay product of $D^*p(3100)$.

After enhancement cuts using various kinematic variables[18], the instanton contribution becomes of comparable size to the DIS background (the right plot). The shape of the distributions of the "normal" DIS Monte Carlo predictions is, however, similar to that arising from the instanton process. Moreover, the difference between the two DIS MCs is comparable to the expected instanton contribution. Given these systematic uncertainties, the 95% confidence limit of the cross section for instanton induced events is set to 221 pb, which is about a factor of five above the prediction.

ZEUS made a similar search[19] in a higher Q^2 range ($Q^2 > 120$ GeV^2)

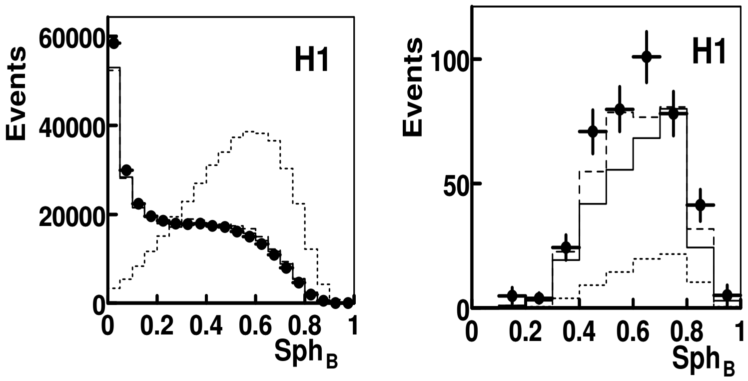

Figure 7. Distributions of the sphericity (Sph_B) in the reconstructed instanton centre-of-mass frame before and after instanton enrichment cuts. Data (filled circles), two QCD model background MCs (solid and dashed line) and the instanton MC (dotted line) are shown. In the left plot, the instanton prediction is scaled up by a factor of 500.

where the theory prediction is expected to be more reliable. The difference of the two DIS MCs again limits making a strong conclusion. Conservatively assuming that all remaining data after the selections belong to an instanton signal, the upper limit on the instanton cross section is set to 26 pb at a 95% confidence level, to be compared with the theoretically predicted cross section of 8.9 pb.

5. Conclusions

Many measurements of meson and baryon production have been performed at HERA. Trying to enhance (exotic) signals, various selections were tried. This capability to control the kinematic region in the search is one of the advantages at HERA.

Pentaquark results from H1 and ZEUS do not allow us to make a definite conclusion at this stage. We need new results from HERA-II data to answer if a five-quark system exists.

The search for genuine QCD effects such as instanton-induced processes was performed in HERA-I. We need to understand normal DIS better. At the same time we need to find better observables.

All results shown in this talk are from HERA-I data. We expect further progress by using high-statistics HERA-II data, since many results shown are, after various selection cuts, still statistics limited.

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