PENTAQUARK SEARCHES AT ZEUS*

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The current status of pentaquark searches at the ZEUS experiment at HERA is summarised.

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1. Introduction

In the recent past, there have been many reports of observation of pentaquarks [1]. The ZEUS experiment at the HERA *ep* collider has looked for the following states[1], in the following decay channels, in their data sample of approximately 120 pb^{-1} taken through the year 2000:

- $\Theta \to K^0_{\rm s} p$: many fixed target experiments [1] report $\Theta \to K^+ n, K^0_{\rm s} p$ at approximately 1530 MeV.
- $\Xi_{3/2} \to \Xi\pi$: the NA49 experiment reports [2] exotic $\Xi_{3/2}$ at approximately 1860 MeV.
- $\Theta_c \to D^* p$: the H1 collaboration reports [3] $\Theta_c \to D^* p$ at approximately 3100 MeV.

The ZEUS data were taken at $\sqrt{s} = 300$–318 GeV.

2. $\Theta \to K^0_{\rm s} p$

The Θ^+ decaying into $K^+ n$ is a manifestly exotic state ($uudd\bar{s}$). The neutron channel is, however, experimentally inaccessible when searching for the Θ^+ in a non-exclusive production as is the case with the ZEUS detector. A search in the $\Theta \to K^0_{\rm s} p$ channel is possible.

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[1] Unless otherwise noted, the reactions for ZEUS searches are for both particles and anti-particles.

A state decaying to $K_s^0 p$, however, could be an excited Σ. Indeed there are many "Σ bumps" (possible excited Σ states observed by experiments at low significance) in the $K_s^0 p$ spectra around the mass region which would be of interest in a pentaquark search. These include more-or-less established resonances at 1480, 1560, 1580 and 1660 MeV [4]. On the other hand, there is a range 1500 to 1550 MeV where no reported state exists. A narrow state near 1530 MeV in the $K_s^0 p$ spectrum would be consistent with another decay mode of the pentaquark which have been reported in the $K^+ n$ channel.

2.1. Data sample

The search [5] was made in a Deep Inelastic *ep* Scattering (DIS) data sample. The electron beam had an energy of 27.5 GeV and the proton beam 820 or 920 GeV. The component of the ZEUS detector relevant for this analysis is the Central Tracking Detector (CTD), a multi-wire drift chamber which covers the polar angle of $15^\circ < \theta < 164^\circ$ as measured in the proton beam direction from the nominal interaction point. The CTD operates in a magnetic field of 1.43 T. As well as measuring the momenta, the CTD provides information on the ionisation energy loss, dE/dx, of the tracks. Unlike the case of the fixed target experiments operating near the production threshold energy, ZEUS searches are made in, or near, the fragmentation region of the quark "struck" by the beam electron; the initial state baryon number is, most likely, lost down the beam-pipe and not detected.

The events recorded by the ZEUS detector are triggered by the scattered beam electron; thus the sample is not biased in any way by the hadrons produced in the collision.

2.2. Particle identification

The candidates for tracks belonging to the decay $K_s^0 \to \pi^+\pi^-$ were identified by selecting pairs of oppositely charged tracks originating from a secondary vertex. Both tracks were assigned the mass of the charged pion and the invariant mass, $M(\pi^+\pi^-)$, of each pair was calculated. After eliminating e^+e^- pairs from conversions and $p\pi$ pairs from Λ decays using appropriate mass cuts, the spectrum shown in figure 1 was obtained. Approximately 865,000 K_s^0 candidates are identified with very little background.

The protons are identified using the ionisation energy loss in the CTD. Figure 2 shows the dE/dx measured in the CTD as a function of the track momentum. The proton band, as well as the kaon and pion bands are clearly visible. The tracks in the proton band are selected as the proton candidates.

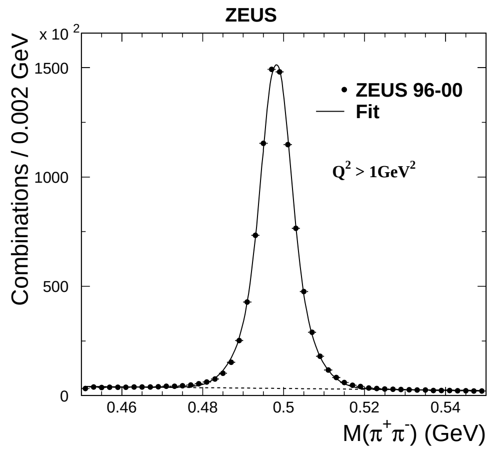

Fig. 1. The $\pi^+\pi^-$ mass distribution for $Q^2 > 1$ GeV^2. The solid line shows the fit result using a double Gaussian plus a linear background, while the dashed line shows the linear background.

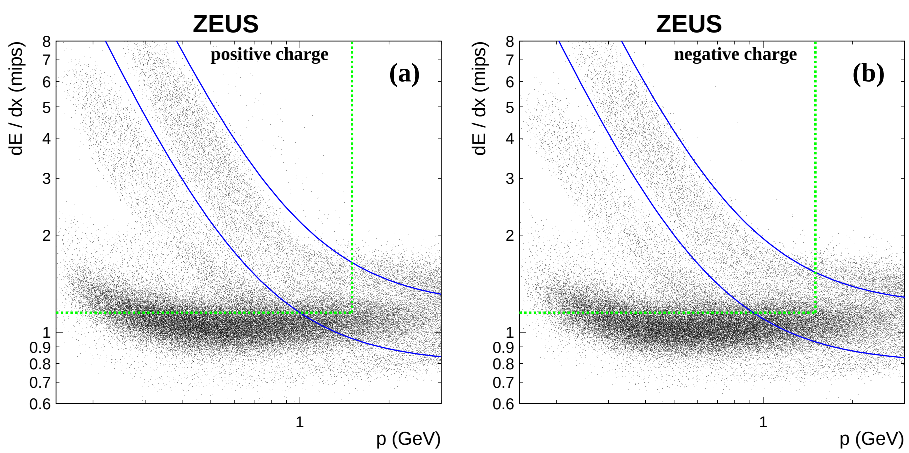

Fig. 2. The dE/dx distribution as a function of the track momentum for: (a) positive and (b) negative tracks. The solid lines indicate the (anti)proton bands used for the $K_{\rm s}p$ analysis.

Particle identification using dE/dx was verified by examining the Kp mass spectra shown in figure 3. The $\Lambda(1520)$ is clearly seen in the K^-p spectrum. On the other hand, no resonance is observed in the K^+p spectrum; a peak of a hypothetical Θ^{++} state would be expected in this spectrum.

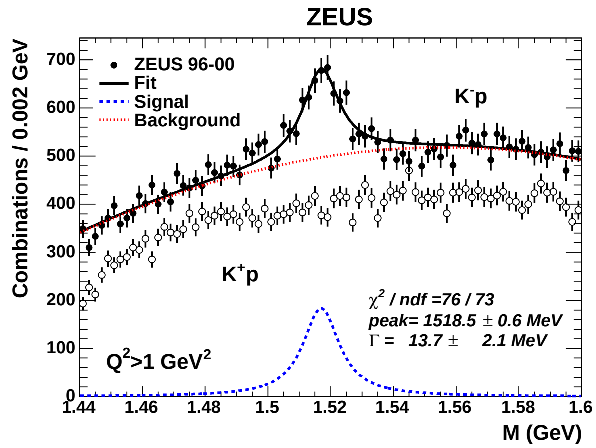

Fig. 3. The K^+p and K^-p mass spectra for $Q^2 > 1$ GeV^2.

2.2.1. $K_{\rm s}p$ mass spectra and Q^2 dependence

Figure 4 shows the $K_{\rm s}p$ spectra for different choices of minimum cuts on the virtuality of the exchanged photon.

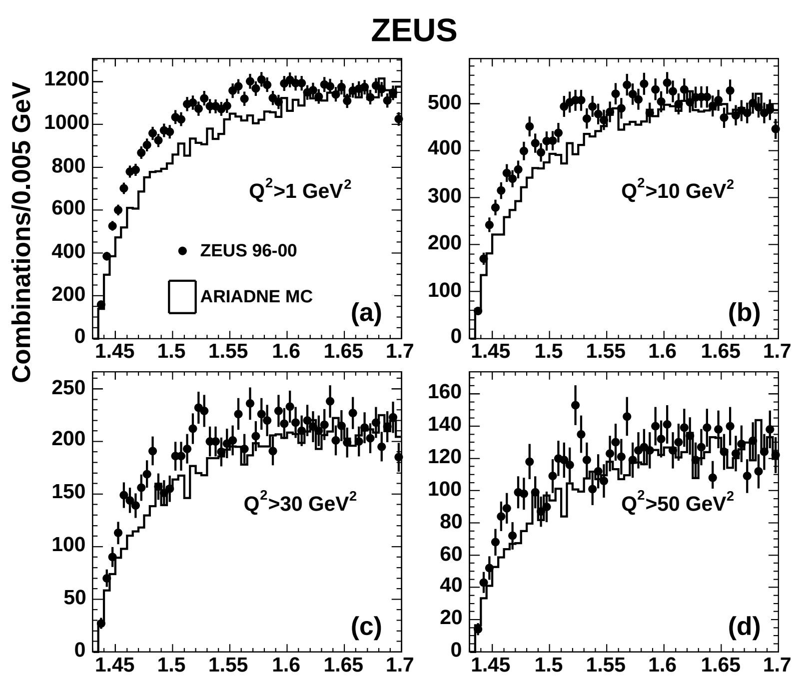

Fig. 4. Mass spectrum for $K_{\rm s}p(\bar{p})$ integrated for (a) $Q^2 > 1$ GeV^2, (b) $Q^2 > 10$ GeV^2, (c) $Q^2 > 30$ GeV^2, and (d) $Q^2 > 50$ GeV^2.

The structure near 1520 MeV is qualitatively discernible at Q^2 values above 10 GeV^2. The Ariadne Monte Carlo program was modified to have Σ^+ particles forced to decay into K_sp at 1530 MeV. This Monte Carlo showed that the "Θ^+" signal/event and signal/background fall as Q^2 falls, but above $Q^2 > 10$ GeV^2 they are constant.

2.2.2. Θ^+ candidate signal

Figure 5 shows the K_sp mass spectrum for $Q^2 > 20$ GeV^2. The Monte Carlo simulation is normalised to the observed spectrum in the mass range 1650–1700 MeV. The simulation does not contain the numerous weakly-established excited Σ states in the range 1450–1700 MeV.

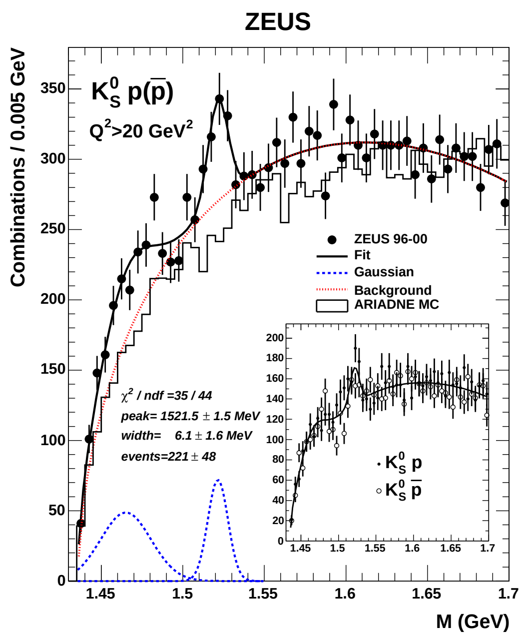

Fig. 5. Mass spectrum for the $K_sp(\bar{p})$ for $Q^2 > 20$ GeV^2. The solid line is the result of a fit to the data using a three-parameter background function plus two Gaussians. The dashed lines show the Gaussian components and the dotted line the background according to this fit. The histogram shows the prediction of the ARIADNE MC simulation normalised to the data in the mass region above 1650 MeV. The inset shows the $K_s\bar{p}$ and K_sp candidates separately, compared to the results of the fit to the combined samples scaled by a factor of 0.5.

The background shape is *a priori* unknown; a fit has been made with a smooth background function and two Gaussians. The Gaussian centred at 1521.5±1.5 MeV has a width compatible with the resolution of the detector.

Convoluting a Breit–Wigner with a Gaussian of the width of the resolution gives a Breit–Wigner width, $\Gamma = 8\pm4$ MeV. This signal is roughly consistent with it being a different decay mode of a pentaquark observed as a narrow signal at 1530–1540 MeV in the K^+n mode in fixed target experiments.

The fit gives the significance of the signal as 3.9–4.6 standard deviations depending on the assumptions of the background. Note that, in the absence of the knowledge of the background shape, the significance should be interpreted as being *as low as 3.9 σ and as high as 4.6 σ*.

The particle and antiparticle combinations are plotted separately in the inset in figure 5. They are consistent with coming from the same parent distributions.

The production cross-section of the state has been evaluated using the Monte Carlo in which the Σ^+ particle has been forced to decay isotropically to $K_{\rm s}p$ at the mass of 1522 MeV. The cross-section of the production of Θ_c which decay subsequently to $K_{\rm s}p$ for $Q^2 > 20$ GeV, $|\eta| < 1.5$, $0.04 < y < 0.95$ and $P_{\rm T} > 0.5$ GeV is roughly 100 pb [6].

3. $\Xi_{3/2} \to \Xi\pi$

The NA49 experiment has reported [2] the observation of doubly charged decuplet partner of the Θ the $\Xi^{--}_{3/2}$ as well as the $\Xi^0_{3/2}$. ZEUS has searched for this state [7] in the same 121 pb^{-1} DIS sample as for the Θ search.

The Λ candidates were identified in the $p\pi$ spectra where the particles are identified via dE/dx. The Λs are further combined with a π in order to reconstruct Ξ, as shown in figure 6. The Ξ candidates are reconstructed with a very good signal to noise ratio.

The Ξ candidates are further combined with pions in order to search for the $\Xi_{3/2}$. The result is shown in figure 7(a); a prominent signal for the known resonance $\Xi^0(1530)$ can be seen. The number of $\Xi^0(1530)$s are about the same as that in the NA49 analysis. There is no signal around 1860 MeV. The limit for the ratio of the number of $\Xi_{3/2}$ to $\Xi^0(1530)$ around 1860 MeV is 0.29.

It should be noted that, since this result is for a search in the fragmentation region in DIS, it does not necessarily contradict the NA49 result.

Figure 7(b) shows the same spectrum as 7(a) except at $Q^2 > 20$ GeV^2 where the Θ candidate was observed in ZEUS. There is no evidence for a state around 1860 MeV. The weak enhancement of events, corresponding to about 2 σ, around 1700 MeV may be the poorly-established $\Xi(1690)$.

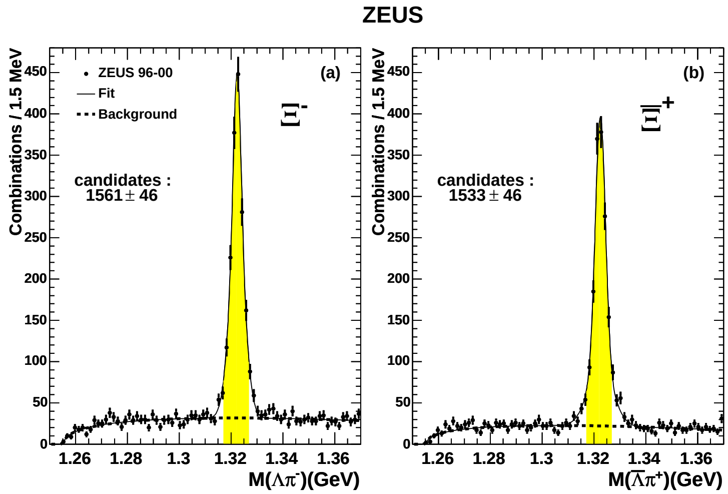

Fig. 6. (a)The $\Lambda\pi^-$ and (b) $\Lambda\pi^+$ mass spectra for $Q^2 > 1$ GeV^2.

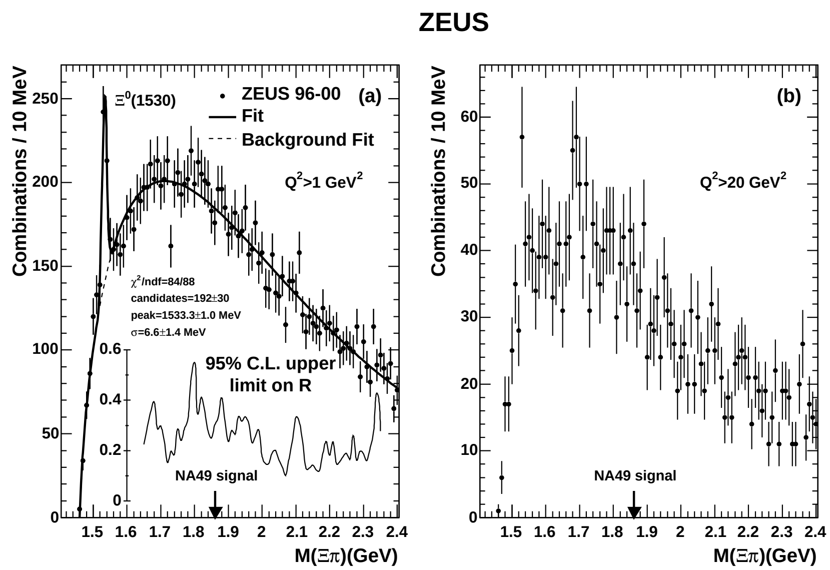

Fig. 7. The $\Xi\pi$ mass spectrum for: (a) $Q^2 > 1$ GeV^2 and (b) $Q^2 > 20$ GeV^2 (all charge combinations summed). The solid line in (a) is the result of a fit to the data using a Gaussian plus a three-parameter background. The dashed line shows the background according to this fit. The 95% confidence upper limit on R (the ratio of the $\Xi^{--}_{3/2}(\Xi^0_{3/2})$ signal to $\Xi^0(1530)$) is also shown as a function of mass for $Q^2 > 1$ GeV^2. The arrows show the location of the signal observed by NA49.

4. $\Theta_c \to D^*p$

The H1 collaboration has reported an observation [3] of a narrow state Θ_c decaying to D^*p at 3099 MeV in DIS. The signal of 51±11 events corresponds to about 1% of the observed number of D^*s. H1 also reports a compatible signal observed in photoproduction.

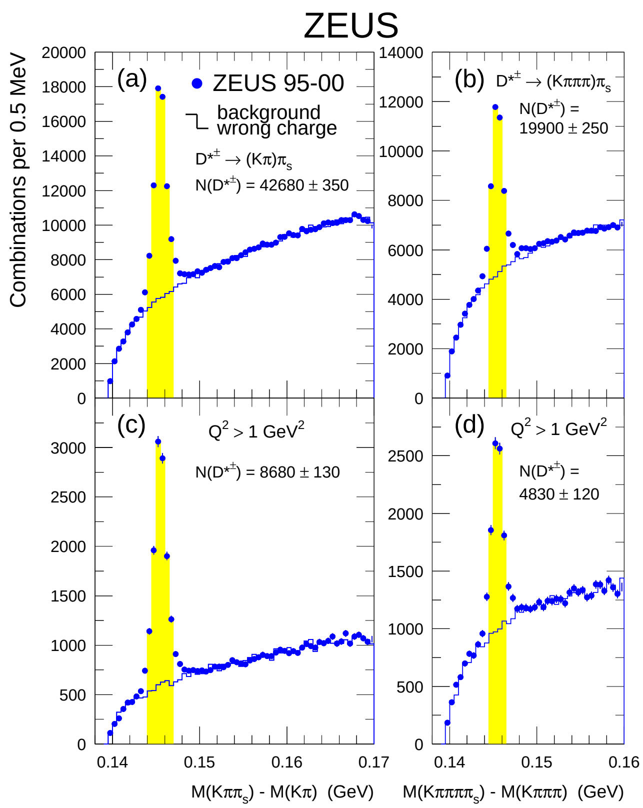

Fig. 8. The distribution of the mass difference ΔM for (a) $D^* \to (K\pi)\pi_s$ candidates in the full data sample (both DIS and photoproduction), (b) $D^* \to (K\pi\pi\pi)\pi_s$ candidates in the full data sample, (c) $D^* \to (K\pi)\pi_s$ candidates in DIS with $Q^2 > 1$ GeV^2 and (d) $D^* \to (K\pi\pi\pi)\pi_s$ candidates in DIS with $Q^2 > 1$ GeV^2. The histograms show the ΔM distributions for wrong charge combinations. Only D^* candidates from the shaded bands were used for the charmed pentaquark search.

The ZEUS collaboration has searched for the Θ_c in 126 pb^{-1} of DIS and photoproduction sample [8]. In order to increase the sample as much as possible, both the $K2\pi$ and $K4\pi$ decay modes of the D^* were used. Altogether, the number of D^*s in the analysis was 62600. This corresponds to more than an order of magnitude larger number of D^*s as that in the H1 observation in DIS. If 1% of these D^*s come from a Θ_c decay, more than 600 Θ_cs are expected to be observed. In DIS alone there are 13500 D^*s, so that more than 130 Θ_cs are expected. Figure 8 shows the ΔM spectra for the D^*s.

The D^* candidates are combined with protons identified using dE/dx. The resulting mass spectra are shown in figure 9. No signals are found. The shaded histograms are Monte Carlo simulations of Θ_c of mass 3099 MeV decaying into D^*p isotropically. They are plotted on top of the fit to the data. The $P_{\rm T}$ and η distributions of the simulated Θ_c were taken to the same as that for D^*s. The magnitude of the simulated signal shown is set to be 1% of the observed number of D^*s. Such a signal is ruled out at 9 σ for all events and 5 σ for DIS only. The 95% upper limit on the fraction D^* originating from Θ_c decay is 0.23%; for DIS with $Q^2 > 1$ GeV^2 is 0.35%.

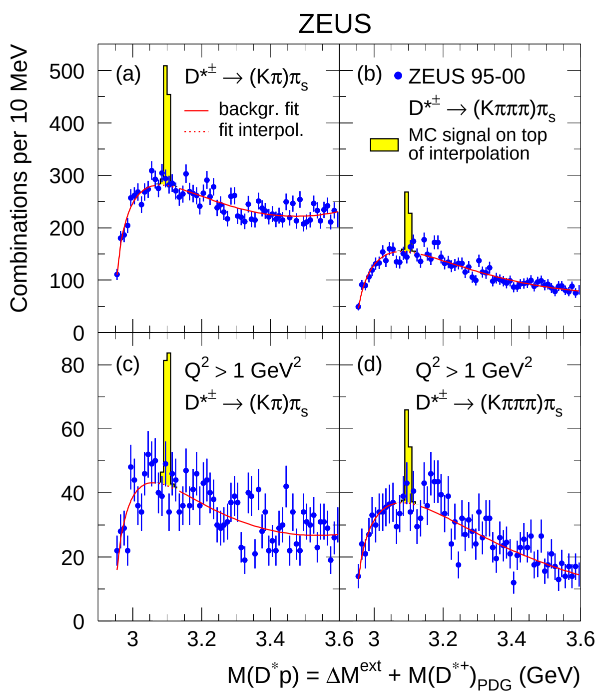

Fig. 9. The distribution of $M(D^*p)$ for charmed pentaquark candidate (dots) selected in (a) the full data sample using $D^* \to (K\pi)\pi_{\rm s}$, (b) the full sample using $D^* \to (K\pi\pi\pi)\pi_{\rm s}$, (c) in DIS with $Q^2 > 1$ GeV^2 using $D^* \to (K\pi)\pi_{\rm s}$ and (d) in DIS with $Q^2 > 1$ GeV^2 using $D^* \to (K\pi\pi\pi)\pi_{\rm s}$. The solid curves are fits to the background function outside the signal window 3.07–3.13 GeV. The shaded histograms show the Monte Carlo Θ_c signals normalised to 1% of the number of reconstructed D^* mesons, and shown on top of the fit interpolations (dashed curves) in the signal window.

The ZEUS search is in a wider kinematic region than is the case for the H1 results. Also, ZEUS considered two decay modes rather than only the $K2\pi$ mode. As a check, the ZEUS search was modified so that the selection criteria was very similar to that used by the H1 collaboration. In this case, the number of D^*s in the analysis was 17600 (5900 for DIS alone). No indication of a signal was found.

5. Conclusions

The current status of pentaquark searches at ZEUS is the following.

- $\Theta \to K^0_{\rm s}p$
  - A state at 1521.5±1.5 MeV and Breit–Wigner width $\Gamma = 8 \pm 4$ MeV was observed in 121 pb^{-1} of DIS sample in the $K_{\rm s}p$ spectrum at $Q^2 > 20$ GeV^2.
  - The significance is 3.9–4.6 σ. The exact number cannot be determined due to the unknown background shape.
  - The state can be interpreted as:
    - The same state as the Θ^+ pentaquark observed elsewhere. If this is the case, then it is the first observation of the pentaquark in fragmentation as well as the first observation of the anti-pentaquark.
    - A so-far unobserved excited Σ, or a structure due to some unknown interference.
    - A statistical fluctuation.
- $\Xi_{3/2} \to \Xi\pi$
  - No $\Xi_{3/2}$ state was observed.
  - The number of $\Xi(1530)$ observed in the ZEUS search is about the same as that for the NA49 result.
  - The ratio N($\Xi_{3/2}$)/N($\Xi(1530)$) at about 1860 MeV is < 0.29 at 95% confidence level.
  - Since the ZEUS search is in the fragmentation region, these results do not necessarily contradict the NA49 result.
- $\Theta_c \to D^*p$
  - No resonance structure was observed in a sample of > 60000 D^*s.
  - The upper limit of observed D^*s originating from Θ_c is 0.23% at 95% confidence level.
  - These results are not compatible with the observations of the H1 collaboration.

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