# STUDY OF NARROW BARYONIC PENTAQUARK CANDIDATES WITH THE ZEUS DETECTOR AT HERA*

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The three pentaquark candidates $\Theta^+(1530)$, $\Xi(1862)$ and $\Theta_c^0(3100)$ have been studied in *ep* collisions at a centre-of-mass energy $\sqrt{s} = 300 - 318$ GeV using the full luminosity of the HERA-I data. Searches for narrow baryonic states in the decay channels $K_S^0 p$, $K^+ p$, $\Xi^- \pi^\pm$, $\bar{\Xi}^+ \pi^\pm$ and $D^{*\pm} p^\mp$ are reported. The results support the existence of a narrow resonance decaying into $K_S^0 p$ and $K_S^0 \bar{p}$, consistent with the $\Theta(1530)$ state. No signals are seen in the $K^+ p$, $\Xi^- \pi^\pm$, $\bar{\Xi}^+ \pi^\pm$ and $D^{*\pm} p^\mp$ channels.

## 1. Introduction and Experiment

The HERA e-p collider accelerates electrons (or positrons) and protons to energies of $E_e = 27.5$ GeV and $E_p = 920$ GeV (820 GeV until 1997), respectively. The two collider experiments, H1 and ZEUS, are located at two collision points along the circulating beams. The incoming $e^\pm$ interacts with the proton by first radiating a virtual photon. The photon is either quasi-real with $Q^2 < 1$ GeV$^2$ and $Q^2_{median} \approx 3 \cdot 10^{-4}$ GeV$^2$, where $Q^2$ is the negative squared four-momentum transferred between the electron and proton, or highly virtual ($Q^2 > 1$ GeV$^2$). In the former case no scattered electron is visible and this is the photoproduction (PHP) regime. In the latter case the scattered electron is measured in the main detector and this is the deep inelastic scattering (DIS) regime. The analysis was performed with ZEUS data taken between 1995 - 2000 ("HERA-I"), corresponding to an integrated luminosity of $\approx 120$ pb$^{-1}$. Charged particles are tracked in the Central Tracking Detector (CTD) covering polar angles of $15° < \theta < 164°$.

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The energy loss of particles in the CTD, $dE/dx$, is estimated from the truncated mean of the anode-wire pulse heights, after removing the lowest 10% and at least the highest 30% depending on the number of saturated hits. The $dE/dx$ resolution for full-length tracks is about 9%.

## 2. Evidence for the strange pentaquark $\Theta^+(1530)$

Fixed-target low-energy experiments saw a narrow exotic baryon with strangeness +1 around 1530 MeV decaying into $K^+n$. It was attributed to the $\Theta^+ = uudd\bar{s}$ pentaquark candidate predicted by Diakonov et al. [1] at the top of a $SU(3)$ spin 1/2 anti-decuplet of baryons. Narrow peaks were also seen at a similar mass in the final state $K^0_S p$, which is not necessarily exotic. They were attributed to the $\Theta^+$ as well. It is interesting to search for the $\Theta^+$ baryon in high-energy collider experiments. In particular it can be searched at the central rapidity region, which has little sensitivity to the proton remnant region. This region is dominated by parton fragmentation with no net baryon number, unlike low-energy experiments, where the pentaquark is mainly produced in the nucleon fragmentation region.

The ZEUS search for the $\Theta^+(1530)$ [2] used the 1996 - 2000 HERA data (121 $\text{pb}^{-1}$) and was performed in the DIS regime ($Q^2 > 1$ GeV$^2$). The search in the $K^0p$ mode was complicated due to a few unestablished resonances, such as $\Sigma(1480)$ and $\Sigma(1560)$, called "$\Sigma$ bumps" [3]. There are no such known bumps around the $\Theta^+$ mass range; however, it is difficult to describe the background under a $\Theta$ signal due to these $\Sigma$ bumps.

$K^0_S$ particles were reconstructed from secondary-vertex CTD tracks with transverse momenta $p_T > 0.15$ GeV and pseudo-rapidities $|\eta| < 1.75$. The $K^0$ transverse momenta and pseudorapidities were required to have $p_T(K^0) > 0.3$ GeV and $|\eta(K^0)| < 1.5$. A very clean $K^0 \to \pi^+\pi^-$ signal was obtained [2]. After requiring $0.483 < M(\pi^+\pi^-) < 0.513$ GeV, the number of $K^0_S$ candidates was $\approx 867,000$ with only $\approx 6\%$ background.

Protons and antiprotons were selected from a wide $dE/dx$ proton band, motivated by the Bethe-Bloch equation, defined for primary-vertex tracks [2]. Pion and kaon contamination was reduced by requiring the proton momentum to be less than 1.5 GeV and $dE/dx$ to be above 1.15 minimum ionising particles (mips). The purity of the proton sample obtained was $\approx 60\%$.

The $K^0_S p(\bar{p})$ mass spectrum is shown in Fig. 1(a-f) with a minimum $Q^2$ ranging from 1 to 50 GeV$^2$, as well as with $Q^2 > 1$ GeV$^2$ for two separate bins of the photon-proton centre-of-mass energy, $W$. For $Q^2 > 10$ GeV$^2$ or $Q^2 > 1$ GeV$^2$ and $W < 125$ GeV, a peak is seen near 1.52 GeV. The histograms are the ARIADNE Monte Carlo (MC) simulation, normalised to the data above 1.65 GeV. The shape of the data distributions is not well described by the MC which does not simulate the $\Sigma$ bumps.

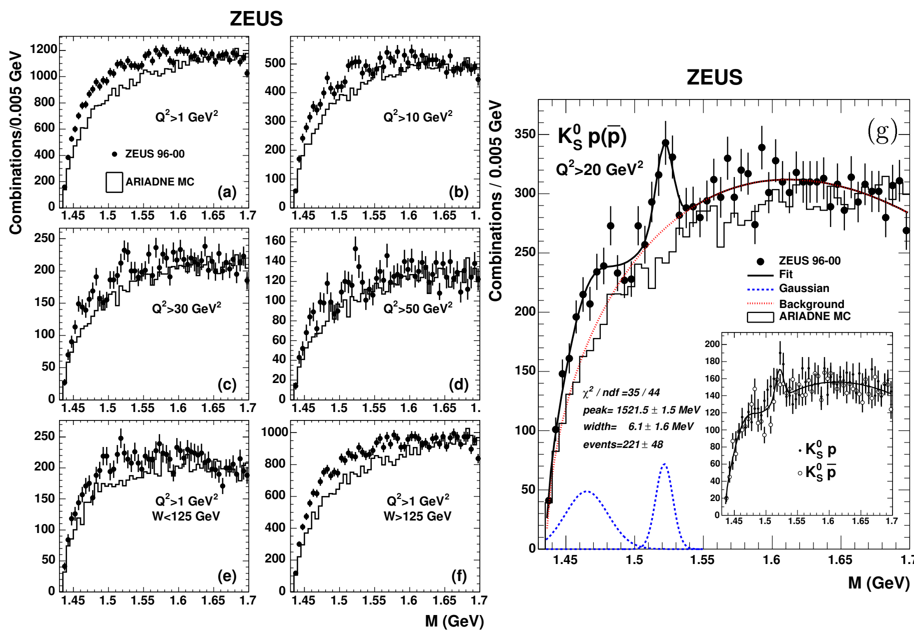


Figure 1. $M(K^0_S p(\bar{p}))$ for (a-d) $Q^2 > 1, 10, 30, 50$ GeV$^2$; (e-f) $W < 125$ and $> 125$ GeV; (g) $Q^2 > 20$ GeV$^2$. The histograms are MC predictions normalised to the data above 1.65 GeV. The solid line in (g) is a fit to the data using a background function (dotted line) plus two Gaussians (dashed lines). The inset shows the $K^0_S\bar{p}$ (open circles) and $K^0_S p$ (black dots) combinations, compared to the combined sample fit scaled by 0.5.

In Fig. 1(g) the $K^0_S$ $p$ $(\bar{p})$ mass spectrum is shown for $Q^2 > 20$ GeV$^2$ together with a fit to two Gaussians and a background of the form $P_1(M - m_p - m_{K^0})^{P_2} \cdot (1 + P_3(M - m_p - m_{K^0}))$, where $M$ is the $K^0_S p$ mass, $m_p$ $(m_{K^0})$ is the proton $(K^0)$ mass and $P_{1,2,3}$ are free parameters. The fit $\chi^2/ndf$ (35/44) is significantly better than a one-Gaussian fit for the $\Theta$ only. The improvement is mainly in the low mass region, where the second resonance may correspond to the $\Sigma(1480)$. The $\Theta$ peak position is $M = 1521.5 \pm 1.5(stat.)^{+2.8}_{-1.7}(syst.)$ MeV, with a Gaussian width $\sigma = 6.1 \pm 1.6(stat.)^{+2.0}_{-1.4}(syst.)$ MeV, which is above, but consistent with the resolution ($\approx 2$ MeV). The fit gives $221 \pm 48$ events above background, corresponding to $4.6\sigma$. The probability of a fluctuation leading to the observed signal in the mass range $1.5 - 1.56$ GeV is below $6 \cdot 10^{-5}$. Fitting the $\Theta$ with a Breit-Wigner convoluted with a Gaussian fixed to the experimental resolution, the intrinsic full width of the signal is estimated to be $\Gamma = 8 \pm 4(stat.)$ MeV.

The signal is seen for both proton charges (inset in Fig. 1g). The fitted number of events in the $K_S^0\bar{p}$ channel is $96 \pm 34$. If the signal originates from the $\Theta$, this is a first evidence for the anti-pentaquark $\Theta^-$.

The $\Theta$ production cross section was measured [4] in the kinematic region $Q^2 > 20$ GeV$^2$, $0.04 < y < 0.95$, $p_T(\Theta) > 0.5$ GeV and $|\eta(\Theta)| < 1.5$ to be $\sigma(ep \to e\Theta^\pm X \to eK^0p^\pm X) = 125 \pm 27(stat.)^{+36}_{-28}(syst.)pb$, where $y$ is the lepton inelasticity. The acceptance was calculated using the RAPGAP MC, where $\Sigma^+$ baryons were treated as $\Theta^+$ with $M = 1.522$ GeV, forced to decay 100% to $K_S^0p(\bar{p})$. The $\Theta$ visible acceptance was $\approx 4\%$. Fig. 2(a) shows the cross section integrated above several $Q^2_{min}$ values. The cross-section ratio to that of $\Lambda(1116)$, $R = \sigma(\Theta^+ \to K^0p)/\sigma(\Lambda)$ (antiparticles are included), was measured in the same kinematic region. $\Lambda$ baryons were measured in the decay mode $\Lambda \to p\pi^-$ and protons were selected by $dE/dx$ with identical cuts as for the $\Theta^+$. The $\Lambda$ acceptance ($\approx 10\%$) was calculated using the ARIADNE MC. The result for $Q^2 > 20$ GeV$^2$ is $R = (4.2 \pm 0.9^{+1.2}_{-0.9})\%$. Fig. 2(b) shows $R$ for these $Q^2_{min}$ values. It is not compatible with upper limits from HERA-B and ALEPH, where $R < 0.5\%$.

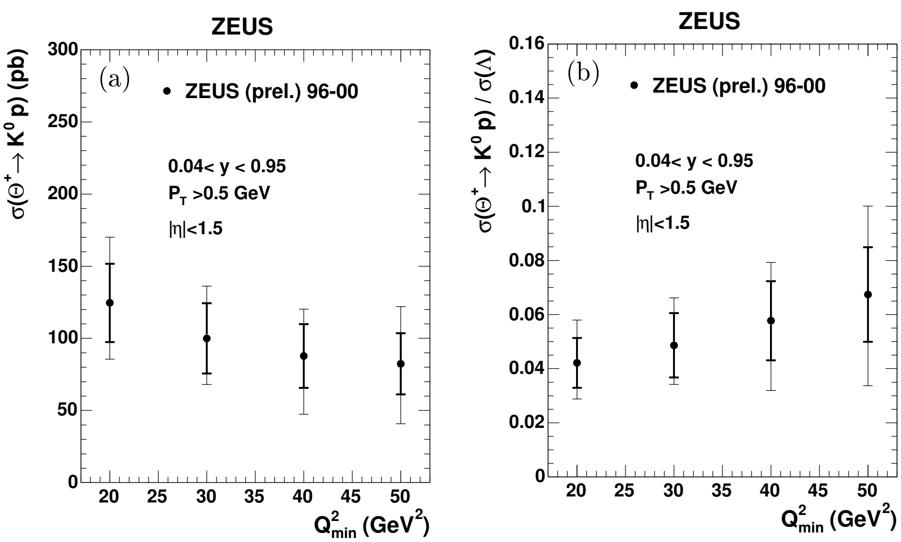


Figure 2. (a) Visible cross sections for the $\Theta^\pm$ baryon decaying to $K^0p(\bar{p})$ as a function of $Q^2_{min}$. (b) Cross section ratio $R = \sigma(\Theta^+ \to K^0p)/\sigma(\Lambda)$ as a function of $Q^2_{min}$.

If the observed 1.52 GeV peak is due to a $I = 1$ state, a $\Theta^{++}$ signal is expected in the $K^+p$ and $K^-\bar{p}$ spectrum. Selecting protons and charged kaons using $dE/dx$, no peak was seen in the above distribution. A clean $10\sigma$

$\Lambda(1520) \to K^-p$ or $K^+\bar{p}$ signal was seen with mass and width consistent with the PDG values [3]. The number of $\Lambda(1520)$ and $\bar{\Lambda}(1520)$ are similar.

## 3. Search for pentaquarks in the $\Xi\pi$ channels

The $pp$ fixed-target NA49 Collaboration ($\sqrt{s} =$ 17.2 GeV) reported [5] observation of the $\Xi$ multiplet pentaquark candidates $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ predicted [1] at the bottom of the anti-decuplet of baryons. They found narrow peaks in these $\Xi\pi$ combinations at $M \approx 1862$ MeV with a width $< 18$ MeV. The significance of the signal for the sum of all 4 $\Xi\pi$ channels is $5.8\sigma$.

ZEUS searched for such states in its DIS HERA-I data [6]. $\Xi^-(\bar{\Xi}^+)$ states were reconstructed via the $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ decay channel, with $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$). Very clean $\Lambda$ and $\Xi$ signals were obtained with $\approx 130000$ $\Lambda + \bar{\Lambda}$ and $\approx 2600$ $\Xi + \bar{\Xi}$ candidates. In Fig. 3 the $\Xi\pi$ invariant mass spectrum for $Q^2 > 1$ GeV$^2$ is shown. The left histograms show each charge combination separately. The right histogram is the sum of all $\Xi\pi$ combinations. A clean $\Xi^0(1530) \to \Xi\pi$ signal of $\approx 4.8\sigma$ is seen in the combined plot. No evidence is seen for the NA49 signal around 1862 MeV in any of the $\Xi\pi$ mass plots. No signal is visible also with $Q^2 > 20$ GeV$^2$. The discrepancy may be due to the fact that the ZEUS results come from the central rapidity region, while NA49 also covers the forward region.

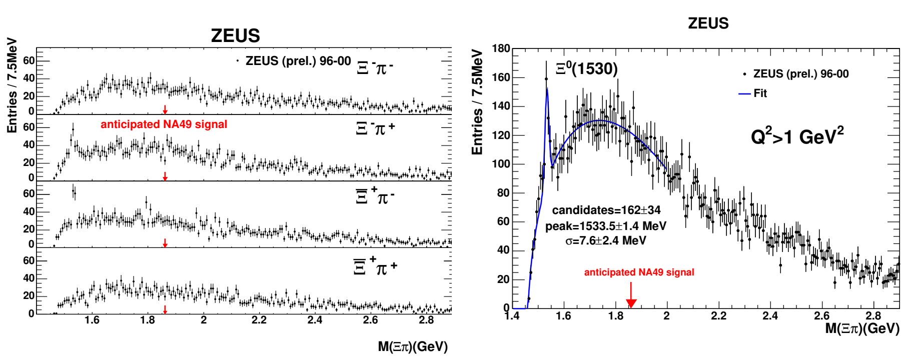


Figure 3. $M(\Xi\pi)$ for $Q^2 > 1$ GeV$^2$ for each charge combination (left) and for all charge combinations combined (right).

## 4. Search for a charmed pentaquark decaying to $D^{*\pm}p^{\mp}$

The existence of the strange pentaquark $\Theta^+$ implies that charmed pentaquarks, $\Theta^0_c = uudd\bar{c}$, should also exist. One type of model [7] predicts $M(\Theta^0_c) \approx 2710$ MeV, which is below the threshold to decay strongly to $D$ mesons. Another model [8] predicts a $\Theta_c^0$ which decays mainly to $D^-p$ or $D^0n$ (charge conjugate included) with $M(\Theta_c^0) = 2985$ MeV and $\Gamma(\Theta_c^0) \approx$ 21 MeV. If $M(\Theta_c^0)$ is above the sum of the $D^*$ and $p$ masses (2948 MeV), it can decay also to $D^{*\pm}p^{\mp}$.

The H1 Collaboration found [9] a narrow signal in the $D^{*\pm}p^{\mp}$ invariant mass at 3.1 GeV with a width consistent with the detector resolution. The signal was seen in a DIS sample of $\approx 3400$ $D^{*\pm} \to D^0\pi^{\pm} \to (K^{\mp}\pi^{\pm})\pi^{\pm}$ with a rate of $\approx 1\%$ of the visible $D^*$ production. A less clean signal of a comparable rate was seen also in the H1 PHP sample.

The $\Theta_c^0$ search of ZEUS in the $D^{*\pm}p^{\mp}$ mode was performed with the full HERA-I data [10]. Clean $D^{*\pm}$ signals were seen in the $\Delta M = M(D^{*\pm}) - M(D^0)$ plots (Fig. 4 left). Two $D^{*\pm} \to D^0\pi^{\pm}$ decay channels were used with $D^0 \to K^{\mp}\pi^{\pm}$ and $D^0 \to K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$. The $\Theta_c^0$ search was performed in the kinematic range $|\eta(D^*)| < 1.6$ and $p_T$ $(D^*)$ $>$ 1.35 (2.8) GeV and with $\Delta M$ values between $0.144 - 0.147(0.1445 - 0.1465)$ GeV for the $K\pi\pi$ $(K\pi\pi\pi\pi)$ channel. In these shaded bands a total of $\approx 62000$ $D^*$'s was obtained (Fig. 4a-b left) after subtracting wrong-charge combinations with charge $\pm 2$ for the $D^0$ candidate. Selecting DIS events with $Q^2 > 1$ GeV$^2$ yielded smaller, but cleaner $D^*$ signals with a total of $\approx 13500$ $D^*$'s (Fig. 4c-d left).

Protons were selected with $p_T(p) > 0.15$ GeV. To reduce the pion and kaon background, a parameterisation of the expected $dE/dx$ as a function of $P/m$ was obtained using tagged protons from $\Lambda$ decays and tagged pions from $K_S^0$ decays. The $\chi^2$ probability of the proton hypothesis was required to be above 0.15. Fig. 5 shows the $M(D^*p) = M(K\pi\pi p) - M(K\pi\pi) + M(D^*)_{PDG}$ distributions for the $K\pi\pi$ channel for the full (left) and the DIS (right) samples, where $M(D^*)_{PDG}$ is the $D^{*\pm}$ mass [3]. In the low-$P$ selection (Fig. 5b), a clean proton sample separated from the $\pi$ and $K$ $dE/dx$ bands was obtained by taking only tracks with $P < 1.35$ GeV and $dE/dx > 1.3$ mips. In the high-$P$ selection (Fig. 5c) only tracks with $P(p) > 2$ GeV were used. The latter selection was prompted by the H1 observation [9] of a better $\Theta_c^0$ signal-to-background ratio for high proton momenta. No narrow signal is seen in the $K\pi\pi$ (Fig. 5) as well as in the $K\pi\pi\pi\pi$ (Fig. 4b,d right) channel. The $K\pi\pi$ analysis was repeated using very similar selection criteria as in the H1 analysis [9]. No indication of a narrow resonance was found in either the DIS or the PHP event sample [10].

95% C.L. upper limits on the fraction of $D^*$ mesons originating from $\Theta_c^0$ decays, $R(\Theta_c^0 \to D^*p/D^*)$, were calculated in a signal window $3.07 < M(D^*p) < 3.13$ GeV for the $K\pi\pi$ and $K\pi\pi\pi\pi$ channels. A visible

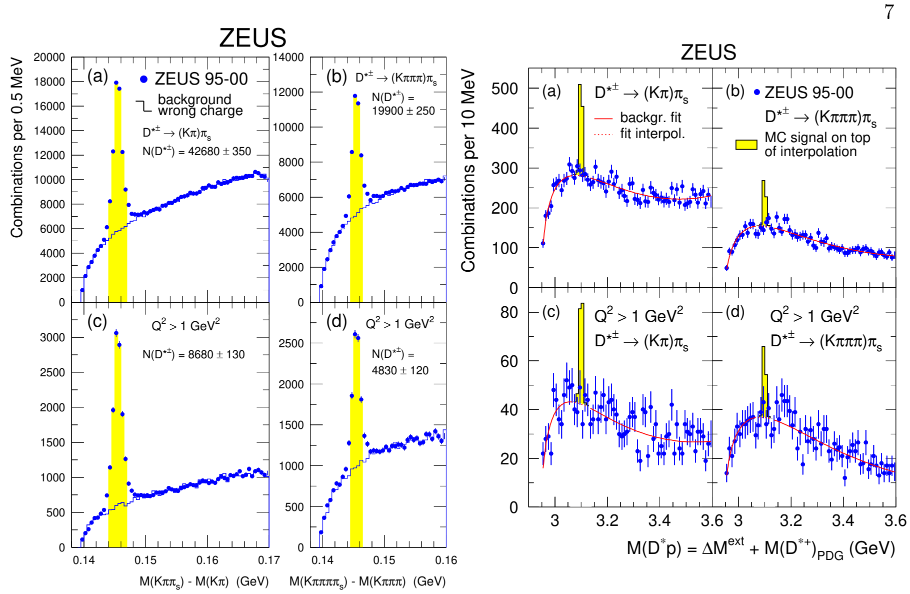


Figure 4. Left: $\Delta M$ distributions (dots) for (a) $D^* \to K\pi\pi$ and (b) $D^* \to K\pi\pi\pi\pi$ candidates. Events with $Q^2 > 1$ GeV$^2$ for the two channels, respectively, are shown in (c) and (d). The histograms are for wrong charge combinations. Right: $M(D^{*\pm}p^{\mp})$ distributions (dots) for the same samples. Solid curves are fits to a background function (see text). Shaded historgams are MC $\Theta_c^0$ signals, normalised to $\Theta_c^0/D^* = 1\%$, on top of the background fit.

rate of 1% for this fraction (Fig. 4 right), as claimed by H1 [9], is excluded by $9\sigma$ ($5\sigma$) for the full (DIS) combined sample. The $M(D^*p)$ distributions were fitted to the form $x^a e^{-bx+cx^2}$, where $x = M(D^*p) - M(D^*) - m_p$ (Fig. 4 right). The number of reconstructed $\Theta_c^0$ baryons was estimated by subtracting in the signal window the background function from the observed number of events, yielding $R(\Theta_c^0 \to D^*p/D^*) < 0.23\%$ and $< 0.35\%$ for the full and DIS combined two channels. The acceptance-corrected rates are, respectively, 0.37% and 0.51%. The 95% C.L. upper limit on the fraction of charm quarks fragmenting to $\Theta_c^0$ times the branching ratio $\Theta_c^0 \to D^*p$ for the combined two channels is $f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to\ D^*p} < 0.16\%$ ($< 0.19\%$) for the full (DIS) sample.

## 5. Summary

The ZEUS HERA-I data sample was used to search for narrow baryonic pentaquark candidates. For the inclusive DIS sample a $4.6\sigma$ narrow signal was seen in the fragmentation region in the combined $M(K_S^0 p)$ and $M(K_S^0 \bar{p})$ plot at the $\Theta^\pm$ mass range. If due to the $\Theta$ baryon, this is the first evidence

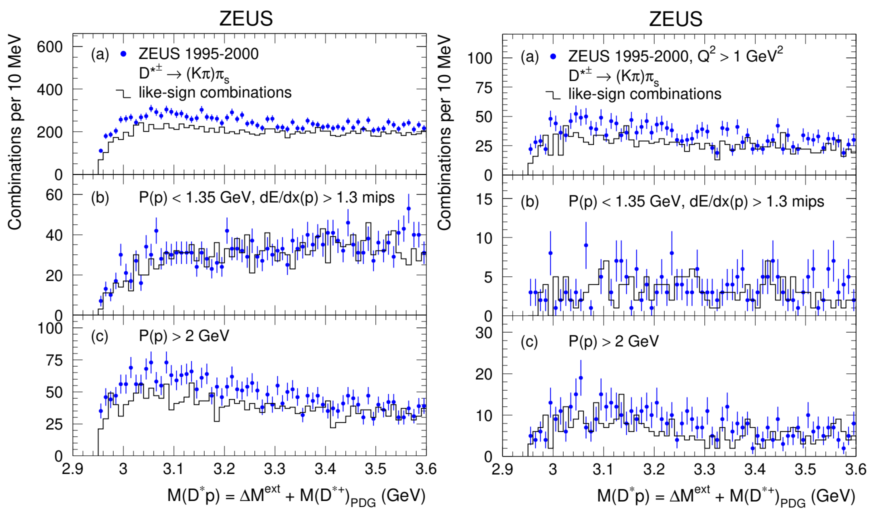


Figure 5. Left: $M(D^{*\pm}p^{\mp})$ distributions for the $K\pi\pi$ channel (dots) with (a) all proton candidates, (b) candidates with $P(p) < 1.35$ GeV and $dE/dx > 1.3$, and (c) candidates with $P(p) > 2$ GeV. Histograms show the $M(D^{*\pm}p^{\pm})$ like-sign combinations. Right: Same for DIS events with $Q^2 > 1$ GeV$^2$.

for the anti-pentaquark $\Theta^-$. The cross-section ratio $\sigma(\Theta^+ \to K^0 p)/\sigma(\Lambda)$ for $Q^2 > 20$ GeV$^2$ is $(4.2 \pm 0.9^{+1.2}_{-0.9})\%$. No evidence is found for the NA49 $\Xi\pi$ signal at 1862 MeV in the inclusive DIS sample. No resonance structure is seen in $M(D^{*\pm}p^{\mp})$ around 3.1 GeV. The 95% C.L. upper limit on the visible rate $R(\Theta_c^0 \to D^*p/D^*)$ is 0.23% (0.35% for DIS). The ZEUS data are not compatible with the H1 result of $\approx 1\%$ of the above rate. Such a rate is excluded by $9\sigma$ for the full data and by $5\sigma$ for the ZEUS DIS data.

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