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# Search for pentaquarks decaying to $\Xi\pi$ in deep inelastic scattering at HERA

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**Abstract**

A search for pentaquarks decaying to $\Xi^-\pi^-$ ($\Xi^-\pi^+$) and corresponding antiparticles has been performed with the ZEUS detector at HERA. The data sample consists of deep inelastic *ep* scattering events at centre-of-mass energies of 300 and 318 GeV, and corresponds to 121 pb$^{-1}$ of integrated luminosity. A clear signal for $\Xi^0(1530) \to \Xi^-\pi^+$ was observed. However, no signal for any new baryonic state was observed at higher masses in either the $\Xi^-\pi^-$ or $\Xi^-\pi^+$ channels. The searches in the antiparticle channels were also negative. Upper limits on the ratio of a possible $\Xi^{--}_{3/2}$ ($\Xi^0_{3/2}$) signal to the $\Xi^0(1530)$ signal were set in the mass range 1650–2350 MeV.



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## 1. Introduction

A number of experiments [1] including ZEUS [2] have reported narrow signals in the vicinity of 1530 MeV in the $nK^+$ and $pK_S^0$ invariant-mass spectra. The signals are consistent with the exotic pentaquark baryon state $\Theta^+$ with quark content $uudd\bar{s}$ [3]. Several other experiments have searched for this state with negative results [4–7].

The $\Theta^+$ lies at the apex of a hypothetical antidecuplet of pentaquarks with spin $1/2$ [3]. The baryonic states $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^{+}$ at the bottom of this antidecuplet are also manifestly exotic. According to Diakonov et al. [3], the members of the antidecuplet, which belong to the isospin quartet of $S = -2$ baryons, have a mass of about 2070 MeV and a partial decay width into $\Xi\pi$ of about 40 MeV. On the other hand, Jaffe and Wilczek [8] predicted a mass around 1750 MeV and a width 50% larger for these states than that of the $\Theta^+$. The isospin 3/2 multiplet contains two states with ordinary charge assignments ($\Xi_{3/2}^0$, $\Xi_{3/2}^-$) in addition to the exotic states $\Xi_{3/2}^+(uuss\bar{d})$ and $\Xi_{3/2}^{--}(ddss\bar{u})$. Recently, NA49 [9] at the CERN SPS reported the observation of the $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^0$ members of the $\Xi_{3/2}$ multiplet, with a mass of $1862 \pm 2$ MeV and a width below 18 MeV. The signals were also seen in the corresponding antibaryon spectra. However, searches for such resonances by other experiments [4,5,7,10,11] were negative.

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This Letter describes a search for new baryonic states in the $\Xi^-\pi^\pm$ and $\bar{\Xi}^+\pi^\pm$ invariant-mass spectra in *ep* collisions measured with the ZEUS detector at HERA. The studies were performed in the central pseudorapidity region where hadron production is dominated by fragmentation. The analysis was restricted to the deep inelastic scattering (DIS) regime, and the $\Xi^-$ ($\bar{\Xi}^+$) states were reconstructed via the $\Lambda\pi^-$ ($\bar{\Lambda}\pi^+$) decay channel.

## 2. Experimental setup

ZEUS is a multipurpose detector described in detail elsewhere [12]. The main components used in the present study are the central tracking detector and the uranium-scintillator calorimeter.

The central tracking detector (CTD) [13] is a cylindrical drift chamber with nine superlayers covering the polar-angle[46] region $15° \leqslant \theta \leqslant 164°$ and the radial range 18.2–79.4 cm. The transverse-momentum resolution for charged tracks traversing all CTD layers is

$$\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T,$$

with $p_T$ in GeV. To estimate the energy loss per unit length, $dE/dx$, of particles in the CTD [14], the truncated mean of the anode-wire pulse heights was calculated, which removes the lowest 10% and at least the highest 30% depending on the number of saturated hits. The measured $dE/dx$ values were normalised to the $dE/dx$ peak position for tracks with momenta $0.3 < p < 0.4$ GeV, the region of minimum ionisation for pions. Henceforth, $dE/dx$ is quoted in units of minimum ionising particles (mips). The resolution of the $dE/dx$ measurement for full-length tracks is about 9%. The tracking system was used to establish the primary and secondary vertices.

The CTD is surrounded by the uranium-scintillator calorimeter, the CAL [15], which is divided into three parts: forward, barrel and rear. The calorimeter is longitudinally segmented into electromagnetic and hadronic sections. The smallest subdivision of the

[46] The ZEUS coordinate system is a right-handed Cartesian system, with the $Z$ axis pointing in the proton beam direction, referred to as the "forward direction", and the $X$ axis pointing left toward the center of HERA. The coordinate origin is at the nominal interaction point.

calorimeter is called a cell. The energy resolution of the calorimeter under test-beam conditions is $\sigma_E/E = 0.18/\sqrt{E}$ for electrons and $\sigma_E/E = 0.35/\sqrt{E}$ for hadrons (with $E$ in GeV). A presampler [16] mounted in front of the calorimeter was used to correct the energy of the scattered electron.[47] The position of electrons scattered with a small angle was measured using the small-angle rear tracking detector (SRTD) [17].

The luminosity was determined from the rate of the bremsstrahlung process $ep \to ep\gamma$, where the photon was measured with a lead-scintillator calorimeter [18] located at $Z = -107$ m.

## 3. Data sample

The data sample for this analysis was taken during the 1996–2000 running period of HERA, and corresponds to an integrated luminosity of 121 $\text{pb}^{-1}$. The electron-beam energy was 27.5 GeV and the proton-beam energy was 820 GeV for the 1996–1997 running period and 920 GeV for the 1998–2000 running period.

The exchanged photon virtuality, $Q^2$, was reconstructed from the energy and angle of the scattered electron. The scattered-electron candidate was identified from the pattern of energy deposits in the CAL [19]. The following requirements were used to select neutral current DIS events:

- $E_{e'} \geqslant 5$ GeV, where $E_{e'}$ is the energy of the scattered electron;
- A primary vertex position in the range $|Z_{\text{vertex}}| \leqslant 50$ cm;
- $35 \leqslant \sum E_i(1-\cos\theta_i) \leqslant 60$ GeV, where $E_i$ is the energy of the $i$th calorimeter cell and $\theta_i$ is its polar angle with respect to the measured primary vertex position, and the sum runs over all cells;
- $Q^2 > 1\ \text{GeV}^2$.

The present analysis was based on tracks measured in the CTD. All tracks were required to pass through at least three CTD superlayers. This requirement corresponds to the pseudorapidity range $|\eta| < 1.75$ in the laboratory frame. Only tracks with transverse momenta $p_T^{\text{lab}} > 150$ MeV were considered. The above cuts restricted this analysis to a region where the track acceptance and resolution of the CTD are high.

The energy-loss measurement in the CTD, $dE/dx$, was used for particle identification. Tracks with $f < dE/dx < F$ were taken as (anti)proton candidates, where $f = 0.3/p^2 + 0.8$ and $F = 1.0/p^2 + 1.2$ ($p$ is the total track momentum in GeV) are functions motivated by the Bethe–Bloch equation. The $dE/dx$ requirements for $\pi^+(\pi^-)$ candidates were $dE/dx < ((0.1/p^2) + 0.8)$ or $dE/dx < 1.8$ mips.

Candidates for long-lived neutral strange hadrons decaying to two charged particles were identified by selecting pairs of oppositely charged tracks fitted to a displaced secondary vertex. Events were required to have at least one such candidate.

As a first step in the $\Xi^-\pi^-$ ($\Xi^-\pi^+$) invariant-mass reconstruction, $\Lambda$ baryons were identified. Then, the $\Lambda$ baryons were combined with a $\pi^-$ to form $\Xi^-$ candidates. Finally, the $\Xi^-\pi^-$ ($\Xi^-\pi^+$) invariant mass was reconstructed using pions associated with the primary vertex. The same procedure was used for the antiparticles.

The $\Lambda$ baryons were identified by their charged decay mode, $\Lambda \to p\pi^-$, using pairs of tracks from secondary vertices. In order to reduce background further, the track with the higher momentum was required to have a $dE/dx$ consistent with that of a proton and was assigned the proton mass. The resulting invariant-mass spectra for $p\pi^-$ and $\bar{p}\pi^+$ are shown in Fig. 1. The measured number of $\Lambda$ baryons, as well as the background under the peak, are higher for the $p\pi^-$ than for the $\bar{p}\pi^+$ spectrum. This is because of tracks produced in secondary interactions in the beampipe.

To reconstruct $\Xi^-$ candidates, $\Lambda$ candidates with invariant masses in the range 1111–1121 MeV were combined with negatively charged tracks. The distance of closest approach (DCA) in three dimensions between the trajectories of the $\Lambda$ and the $\pi^-$ was calculated and a cut on the DCA of 1.0 cm was used to select preferentially those coming from the same vertex. In addition, the following cuts were applied to increase the significance of the $\Xi^-$ signal:

- The distance between the decay of the $\Xi^-$ and the primary vertex was required to be larger than 1.75 cm, since most of the combinatorial back-

[47] From now on, the word "electron" is used as a generic term for either electrons or positrons.

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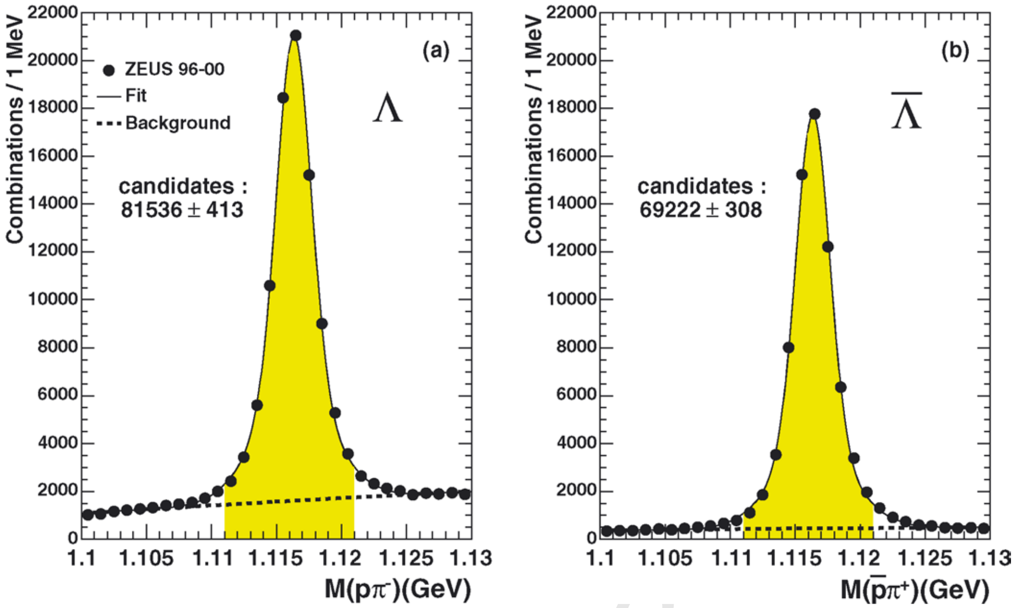


Fig. 1. The (a) $p\pi^-$ and (b) $\bar{p}\pi^+$ invariant-mass spectra for $Q^2 > 1$ GeV$^2$. The solid line shows the result of a fit using a double Gaussian plus a first-order polynomial background function, while the dashed line shows the background. The shaded areas indicate the mass range of the selected candidates.

ground comes from tracks originating from the primary vertex [20];

- The momentum of the $\pi^-$ candidate was required to be less than the momentum of the $\Lambda$ candidate, since in the $\Xi^-$ decay, the $\Lambda$ takes the largest fraction of the $\Xi^-$ momentum;
- The $\Lambda$ decay was required to be further from the primary vertex than the $\Xi^-$ decay.

The resulting $\Lambda\pi^-$ and $\bar{\Lambda}\pi^+$ invariant-mass spectra are shown in Fig. 2. Because of the short decay length of the $\Xi$, the cuts eliminate the contributions from secondary interactions in the beampipe; the number of $\Xi^-$ and $\bar{\Xi}^+$ are the same within their uncertainties. The measured width of the $\bar{\Xi}^+$ is somewhat larger than that of the $\Xi^-$ as expected from the different momentum resolution for positive and negative particles. The $\Xi^-$ candidates were selected within the invariant-mass range 1317–1327 MeV, shown as the shaded areas. In order to decrease the combinatorial background, only events with one $\Xi^-$ candidate, which comprises 92% of the whole sample, were retained.

To search for the exotic $\Xi_{3/2}^{--}$ state, the selected $\Xi^-$ candidates were combined with $\pi^-$ tracks from the primary vertex. To reduce background, only tracks with momenta smaller than those of the $\Xi^-$ were used. Analogous searches were performed for the $\bar{\Xi}_{3/2}^{++}$, $\Xi_{3/2}^{0}$ and $\bar{\Xi}_{3/2}^{0}$.

A number of checks were carried out to verify the robustness of the above reconstruction procedure: (a) the $dE/dx$ requirements for pions and protons were removed; (b) events with multiple $\Xi^-$ candidates were retained; (c) the cut on the DCA was varied between 0.5 and 3.0 cm; (d) the cut on the distance between the decay position of the $\Xi^-$ and the primary vertex was varied between 1.0 and 3.0 cm. In all these cases, the variations had a small impact on the reconstruction efficiency of the $\Xi^- \to \Lambda\pi^-$ and $\Xi^0(1530) \to \Xi^-\pi^+$ decay channels, or led to a reduction of the signal-to-background ratio at the level of 10–30%.

## 4. Results and conclusions

The resulting $\Xi\pi$ invariant-mass spectrum for the sum of all four charge combinations, $\Xi^-\pi^-$, $\Xi^-\pi^+$, $\bar{\Xi}^+\pi^-$, $\bar{\Xi}^+\pi^+$ is shown in Fig. 3(a) for $Q^2 > 1$ GeV$^2$. The invariant-mass spectra for each

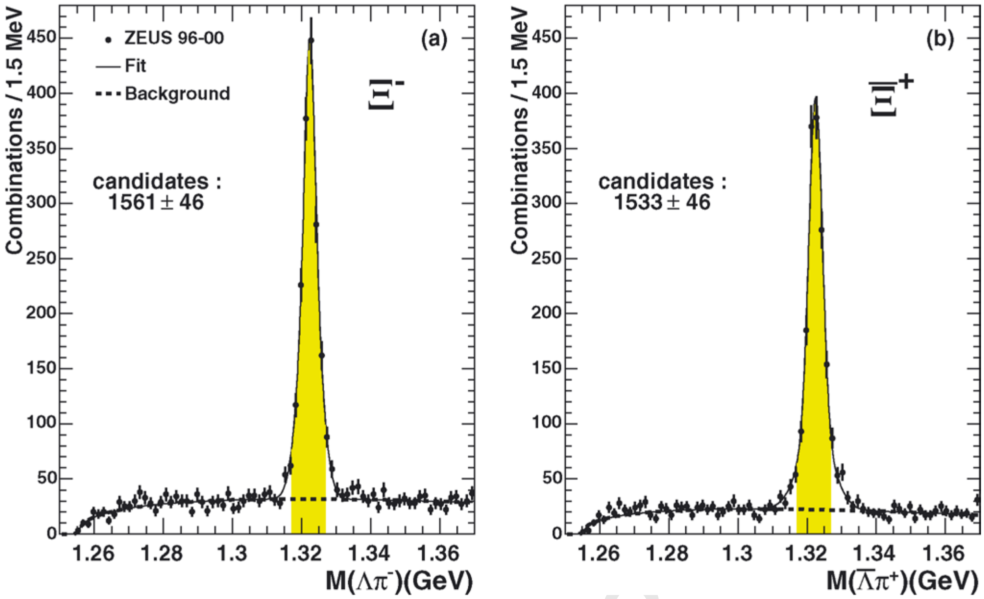


Fig. 2. The (a) $\Lambda\pi^-$ and (b) $\bar{\Lambda}\pi^+$ invariant-mass spectra for $Q^2 > 1\ \text{GeV}^2$. The solid line shows the result of a fit using a double Gaussian plus a second-order polynomial background function, while the dashed line shows the background. The shaded areas show the mass range of the selected candidates.

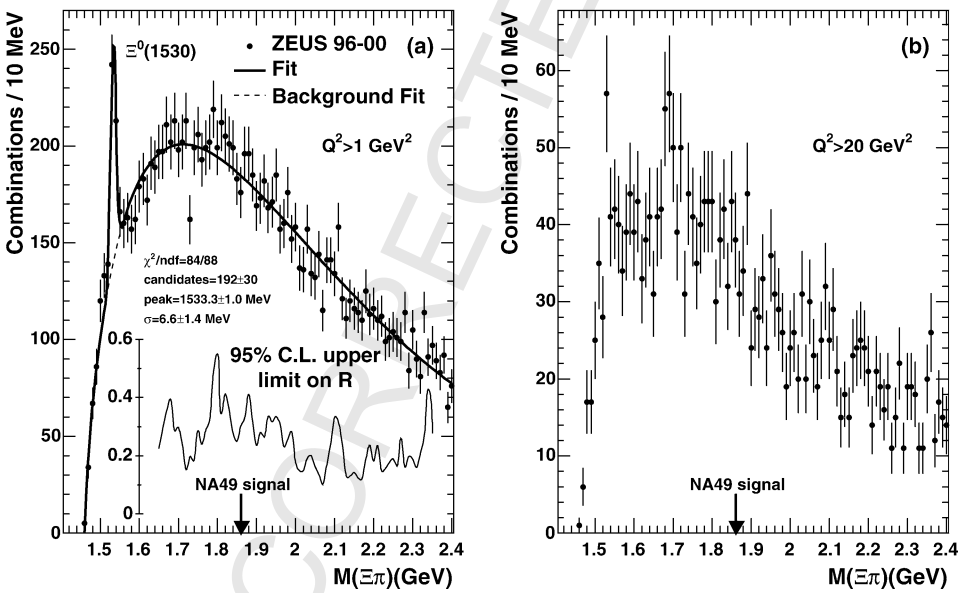


Fig. 3. The $\Xi\pi$ invariant-mass spectrum for: (a) $Q^2 > 1\ \text{GeV}^2$, and (b) $Q^2 > 20\ \text{GeV}^2$ (all four charge combinations summed). The solid line in (a) is the result of a fit to the data using a Gaussian plus a three-parameter background defined by Eq. (1). The dashed line shows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

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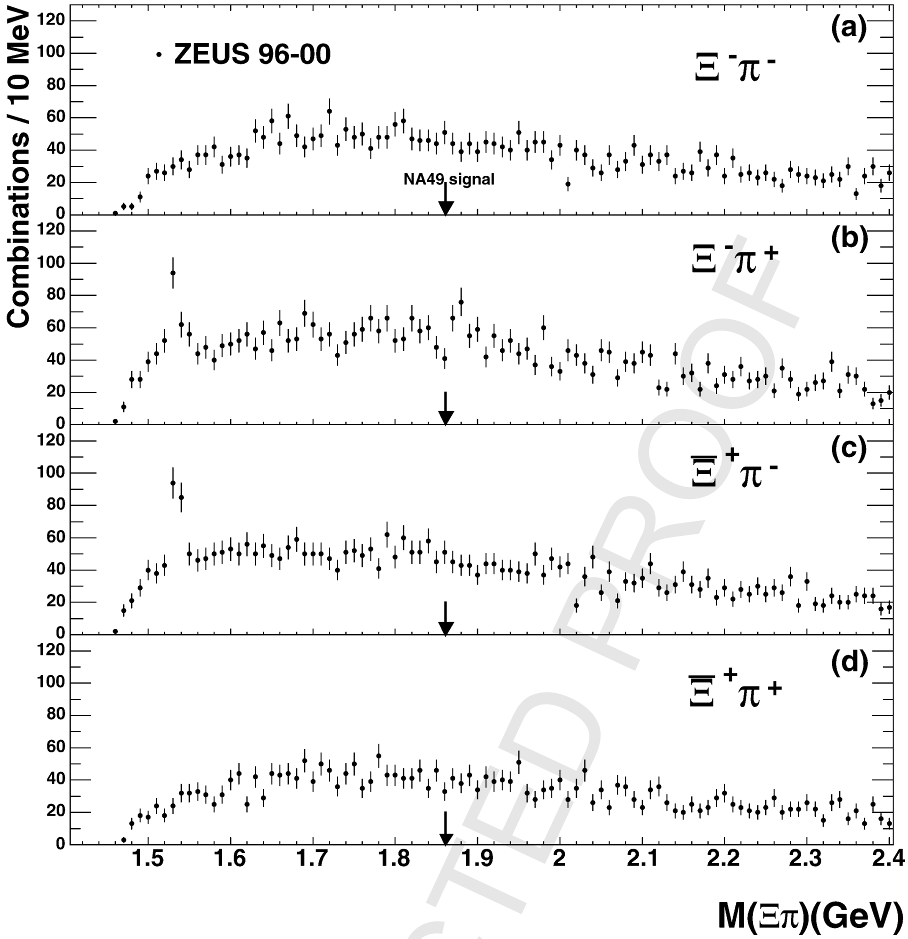


Fig. 4. The $\Xi\pi$ invariant-mass spectra for each charge combination reconstructed at $Q^2 > 1\ \text{GeV}^2$. The arrows show the location of the signal observed by NA49.

$\Xi\pi$ combination separately are shown in Fig. 4. In both the $\Xi^-\pi^+$ and $\bar{\Xi}^+\pi^-$ spectra, the well established $\Xi^0(1530)$ state [21] is observed. The $\Xi^0(1530)$ peak was fitted by a Gaussian, and the background was parametrised by the function:

$$B(M) = P_1(M - m_\Xi - m_\pi)^{P_2} e^{-P_3(M - m_\Xi - m_\pi)}, \quad (1)$$

where $M$ is the $\Xi\pi$ invariant mass, $m_\Xi$ and $m_\pi$ are the masses of the $\Xi$ and the $\pi$, respectively, and $P_1$, $P_2$ and $P_3$ are free parameters. The extracted number of signal events was $192 \pm 30$. The measured peak position of $1533.3 \pm 1.0(\text{stat.})$ MeV is consistent with the PDG value [21], taking into account a systematic uncertainty of 1–2 MeV on the mass measurement. The measured width of $6.6 \pm 1.4(\text{stat.})$ MeV is consistent with the detector resolution. No signal is observed near 1860 MeV in any of the spectra.

A similar analysis was performed for $Q^2 > 20\ \text{GeV}^2$, a kinematic region of DIS where the $\Theta^+$ state was most clearly observed by ZEUS [2]. The resulting invariant-mass spectrum of $\Xi\pi$ for the sum of all four charge combinations is shown in Fig. 3(b). Again, no signal is observed near 1862 MeV.

In addition to the peak near 1530 MeV due to the established $\Xi^0(1530)$ state, a possible peak near 1690 MeV for $Q^2 > 20\ \text{GeV}^2$ is observed (Fig. 3(b)). This enhancement could be due to the $\Xi(1690)$ baryon, the properties of which are not well determined [21]. Using the fit described in Eq. (1), the mass of this peak was found to be at $1687.5 \pm$

4.0(stat.) MeV, and the Gaussian width was 9.5 ± 3.7(stat.) MeV. The statistical significance of this signal is $2.5\sigma$.

According to the NA49 study [9], two additional cuts were used to reduce the background for the pentaquark searches: a cut on the opening angle between the $\Xi$ and the $\pi$, and a cut on the momentum of the pion used in the reconstruction of the $\Xi\pi$ invariant mass. These two cuts were also tried in this analysis, with the opening-angle cut varied from 0.1 to 0.5 radians, and the $\pi$ momentum cut varied from 0.5 GeV to 1.5 GeV. In no case was a pentaquark signal seen. However, these two cuts changed the background shape by rejecting events near the $\Xi\pi$ mass threshold, reducing or completely suppressing the $\Xi^0(1530)$ signal.

Given the absence of a signal in our data, 95% C.L. limits were set on the production of new states decaying to $\Xi^-\pi^-$ or $\Xi^-\pi^+$ in the mass range 1650–2350 MeV in DIS for $Q^2 > 1\ \text{GeV}^2$. The upper limits on the ratio, $R$, of the number of events in a (sliding) mass window to the reconstructed number of $\Xi^0(1530)$ events are presented. This ratio is a good indicator of the sensitivity to a new state, given the robust signal observed for the established $\Xi^0(1530)$ state. Most of the acceptances and reconstruction efficiencies largely cancelled in the ratio; some residual effects are present since the acceptance has a dependence on the mass of the state. For example, the rapidity distribution of the $\Xi\pi$ combinations in the centre-of-mass system changes markedly over the mass range.

The limits were set using Bayesian statistics assuming flat prior distributions for $R$. The width of the search window was set equal to 26.4 MeV, which is $\pm 2\sigma$ of the measured width of the $\Xi^0(1530)$. The background was modelled using Eq. (1). The 95% C.L. limits on $R$ varied between 0.1 to 0.5 as a function of the central value of the mass window, as shown in Fig. 3(a). In the NA49 signal region, $R$ is less than 0.29 at the 95% C.L.

In addition to the above method, the 95% C.L. limits on the ratio $R$ were calculated assuming a Gaussian probability function in the unified approach [22] and fixing the reconstruction width of the expected pentaquark state to 10 MeV, which is close to expectations. Similar values for the limits were obtained.

The number of $\Xi^0(1530)$ signal events reconstructed in this analysis is about the same as for the NA49 data analysed without the opening-angle and momentum cuts [23]. Therefore, the statistical sensitivity should be about the same for the two analyses in this mass region. However, it should be noted that NA49 is a fixed target experiment, which has good acceptance in the forward region. The non-observation of this signal in the central-fragmentation region in the ZEUS data does not necessarily contradict the observation of a signal predominantly produced in the forward region.

In conclusion, a search for new baryons that decay to $\Xi^-\pi^-$ and $\Xi^-\pi^+$ was performed with the ZEUS detector using a DIS data sample with $Q^2 > 1\ \text{GeV}^2$ corresponding to an integrated luminosity of 121 $\text{pb}^{-1}$. No pentaquark signal was found. Upper limits at 95% C.L. on the ratio of the $\Xi^{--}_{3/2}$ ($\Xi^0_{3/2}$) signal to the $\Xi^0(1530)$ are set in the mass range 1650–2350 MeV.

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