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Search for pentaquark baryons in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ channels at HERA

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Abstract

A search for pentaquark baryons in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ channels of decay and their antiparticles has been performed in the central rapidity region of inclusive deep inelastic scattering at an ep centre-of-mass energy of $300 - 318\,\mathrm{GeV}$ for exchanged photon virtuality above $1\,\mathrm{GeV}^2$. A clean signal corresponding to the $\Xi^0(1530)$ state was observed in the $\Xi^-\pi^+$ channel. However, no signal for the pentaquark baryons was observed in either the $\Xi^-\pi^-$ or $\Xi^-\pi^+$ channels. The search in the antiparticle channels shows similar results.

1 Introduction

The recent experimental evidence for an exotic pentaquark baryon state, Θ^+, with strangeness $S = +1$, opened a new chapter in spectroscopy. A number of experiments [1, 2] have reported narrow signals in the vicinity of 1530 MeV in the nK^+ and pK^0_S invariant mass spectra. The signals are consistent with the pentaquark state Θ^+ with quark content $udud\bar{s}$, although its exotic strangeness quantum number cannot be uniquely determined in all cases.

The Θ^+ lies at the apex of a hypothetical anti-decuplet 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 the predictions of Diakonov et al. [3], the members of the anti-decouplet which belong to the isospin quartet of $S = -2$ baryons could have a mass of about 2070 MeV and partial decay width into $\Xi\pi$ of about 40 MeV. On the other hand, a mass around 1750 MeV and a width 50% greater than that of the Θ^+ were predicted by Jaffe and Wilczek [4] for these states. The isospin 3/2 multiplet contains two $\Xi_{3/2}$ with ordinary charge assignments ($\Xi^0_{3/2}, \Xi^-_{3/2}$) in addition to the exotic states $\Xi^+_{3/2}(uuss\bar{d})$ and $\Xi^{--}_{3/2}(ddss\bar{u})$. Recently, NA49 [5] at the CERN SPS reported the observation of the $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ members of the Ξ multiplet, with a mass of 1862 ± 2 MeV and a width below the detector resolution of about 18 MeV. Searches for this resonance were also being performed by the WA49 collaboration and by the CDF collaboration, and negative results have been reported [6, 7].

ZEUS has reported evidence for a narrow baryonic resonance at 1522 MeV decaying to $K^0_S p(\bar{p})$ [2]. This paper discusses recent ZEUS searches for pentaquark baryons in the $\Xi^-\pi^\pm$ and $\bar{\Xi}^+\pi^\pm$ invariant-mass spectra in ep collisions, measured with the ZEUS detector at HERA in the central pseudo-rapidity region. The searches were restricted to the deep inelastic scattering (DIS) regime, and $\Xi^-(\bar{\Xi}^+)$ states were reconstructed via the $\Lambda\pi^-(\bar{\Lambda}\pi^+)$ decay channel.

2 Experimental setup

ZEUS is a multipurpose detector described in detail elsewhere [8]. The main components used in the present study are the central tracking detector and the uranium-scintillator calorimeter. The central tracking detector (CTD) [9] is a cylindrical drift chamber with nine super-layers covering the polar-angle region $15^o < \theta < 164^o$ and the radial range $18.2 - 79.4$ cm. The transverse-momentum resolution for charged tracks traversing all CTD layers is $\sigma(p_T)/p_T = 0.0058p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV.

The CTD is surrounded by the uranium-scintillator calorimeter, CAL [10], 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 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).

3 Data sample

The data sample for this analysis was taken during the 1996-2000 running period in HERA, corresponding to an integrated luminosity of 105 pb^{-1}. The positron beam energy was 27.5 GeV and the proton beam energy was 820 GeV for the 96-97 running period and 920 GeV for the 99-00 running period.

The exchanged photon virtuality, Q^2, was reconstructed by the electron method, which uses measurements of the energy and angle of the scattered positron. The scattered-positron candidate was identified from the pattern of energy deposits in the CAL [11]. The selection of the data sample contains the following DIS requirements:

- $E_{e'} \geq 5\,\text{GeV}$, where $E_{e'}$ is the energy of the scattered positron measured in the CAL;
- $35 \leq \delta \leq 60\,\text{GeV}$, where $\delta = \sum E_i(1 - \cos\theta_i)$, E_i is the energy of the ith calorimeter cell, θ_i is its polar angle with respect to the beam axis and the sum runs over all cells;
- a primary vertex position in the range $\mid Z_{\text{vertex}} \mid < 50$ cm;
- $Q^2 > 1\,\text{GeV}^2$.

At least one secondary vertex is required for the event selection.

The first step in the analysis was the search for Λ candidates, which were then combined with the π^- to form the Ξ^- candidates. Next, $\Xi^{--}_{3/2}(\Xi^0_{3/2})$ were reconstructed in the $\Xi^-\pi^-(\Xi^-\pi^+)$ invariant mass spectrum, using all pions associated with the primary vertex. An analogous procedure was used for antiparticles.

Λ-baryons were identified by their charged-decay mode, $\Lambda \to p\pi^-$, using pairs of tracks from secondary vertices. The larger momentum track was assumed to be the proton and assigned the proton mass. Tracks were required to pass through at least three CTD super-layers and have transverse momentum $p_T^{\text{lab}} > 150\,\text{MeV}$ and pseudo-rapidity $|\eta| < 1.75$. The proton and pion tracks were required to have dE/dx values compatible with the corresponding particles [2]. These track quality cuts were applied for all the tracks used later. The resulting $p\pi^-$ invariant mass spectrum is shown in Fig. 1a.

To find Ξ^-, each Λ candidate with a reconstructed invariant mass within $1111-1121\,\text{MeV}$ was combined with all negative charged tracks which passed the track quality cuts described above. A distance of closest approach (DCA) was calculated between the extrapolated Λ candidate momentum vector and each π^- track. A cut on the DCA of 1.0 cm was used to make sure that they came from the same vertex. Further cuts were imposed to increase the significance of the Ξ^- signal:

- the distance between the Ξ^- candidate decay position and the primary vertex was required to be larger than 1.75 cm, since the combinatorial background is concentrated close to the primary vertex;
- the momentum of π^- candidate was required to be less than the momentum of the Λ candidate, since in the Ξ^- decay the Λ takes a bigger fraction of the Ξ^- momentum;
- the distance between the Λ candidate decay position and the primary vertex was required to be greater than the distance between the Ξ^- candidate decay position and the primary vertex, since in the Ξ^- decay the Λ flies nearly in the same direction as the Ξ^-.

The resulting $\Lambda\,\pi^-$ invariant mass spectrum is shown in Fig. 2a. The Ξ^- candidates were selected within the invariant mass range $1317-1327\,\mathrm{MeV}$. Only events with one Ξ^- candidate were retained to decrease combinatorial background.

To search for the exotic $\Xi^{--}_{3/2}$ state, the selected Ξ^- candidates were combined with π^- tracks coming from the primary vertex. In addition to the track quality requirements, only tracks with momenta smaller than those of the Ξ^- were used (92% of the whole sample). Similar studies were done for the $\Xi^0_{3/2}$ and their anti-particles.

4 Results and Conclusions

The resulting invariant mass spectrum of $\Xi\pi$ in all four charge combinations ($\Xi^-\pi^-$, $\Xi^-\pi^+$, $\Xi^+\pi^-$, $\Xi^+\pi^+$) is shown in Fig. 3. The invariant mass spectrum of $\Xi\pi$ in each of these four different charge combinations is shown in Fig. 4. No pentaquark signal is observed near the 1860 MeV mass range in any of the spectra.

A similar analysis was performed for $Q^2 > 20\,\mathrm{GeV}^2$, a kinematic region where the Θ^+ was best seen by ZEUS [2]. The resulting invariant mass spectrum of $\Xi\pi$ in all four charge combinations is shown in Fig. 5. However, again, no pentaquark signal is found.

Despite a clean and significant Ξ^- sample, ZEUS does not observe the NA49 pentaquark signal in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ decay channels. However, in both the $\Xi^-\pi^+$ and $\Xi^+\pi^-$ decay channels, ZEUS clearly observes the $\Xi^0(1530)$ state, which can be used as a gauge for the comparison of the sensitivity to the pentaquark signal. With more than 160 $\Xi^0(1530)$ candidates reconstructed, the statistical sensitivity is almost the same as the one of the NA49 measurement [5].

To reduce background, NA49 used a cut on the opening angle between the Ξ and the π and a momentum cut. The combination of these cuts changes the background shape by reducing events near the $\Xi\pi$ mass threshold. Similar cuts were tried in this analysis and the cuts were varied over a wide range. A signal did not emerge.

It should be noted that NA49 is a fixed target experiment, which has good acceptance in the forward region. The absence of the signal in the ZEUS data may indicate that this state is predominantly produced in the forward region. Clearly, this will need to be resolved using future high-luminosity HERA data and results from other experiments.

In conclusion, a search for pentaquark baryons in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ channels of decay was done in ZEUS using a data sample corresponding to an integrated luminosity of 105 pb^{-1}. No pentaquark signal is found.

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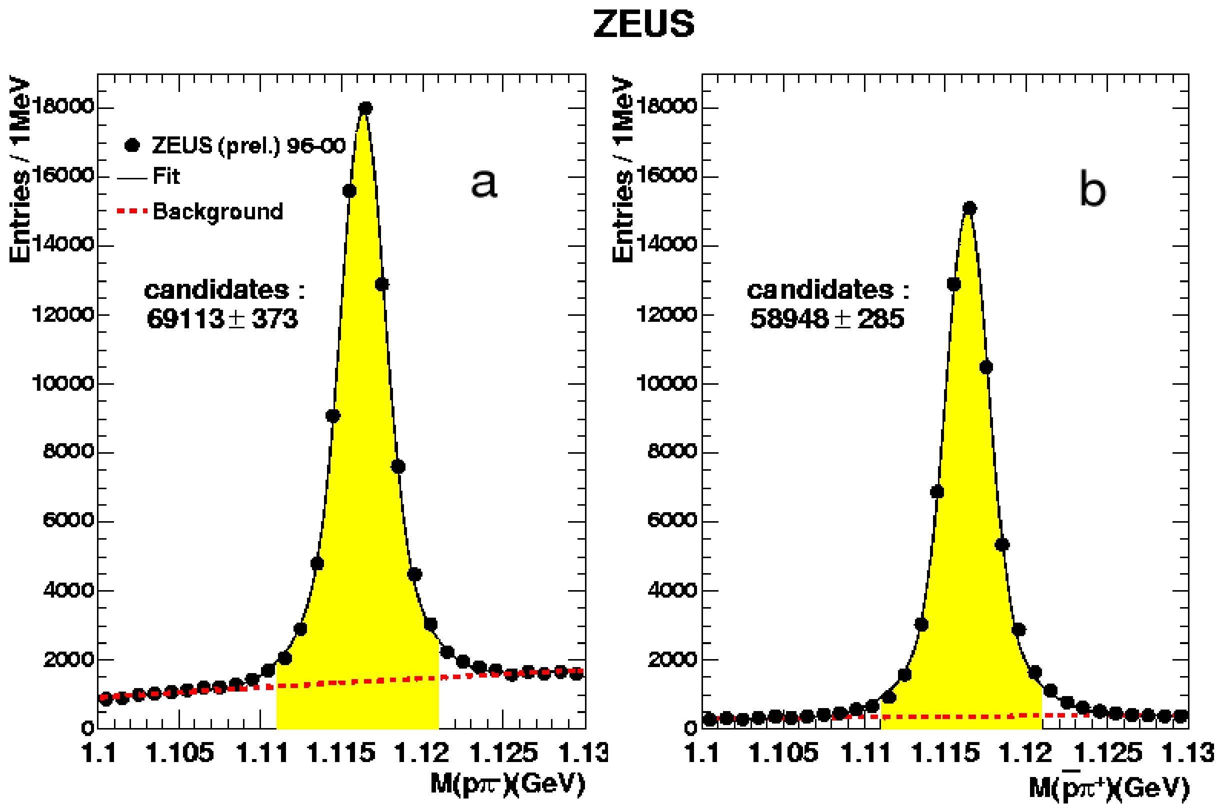

Figure 1: *The (a) $p\pi^-$ and (b) $\bar{p}\pi^+$ invariant-mass spectra for $Q^2 > 1$ GeV^2.*

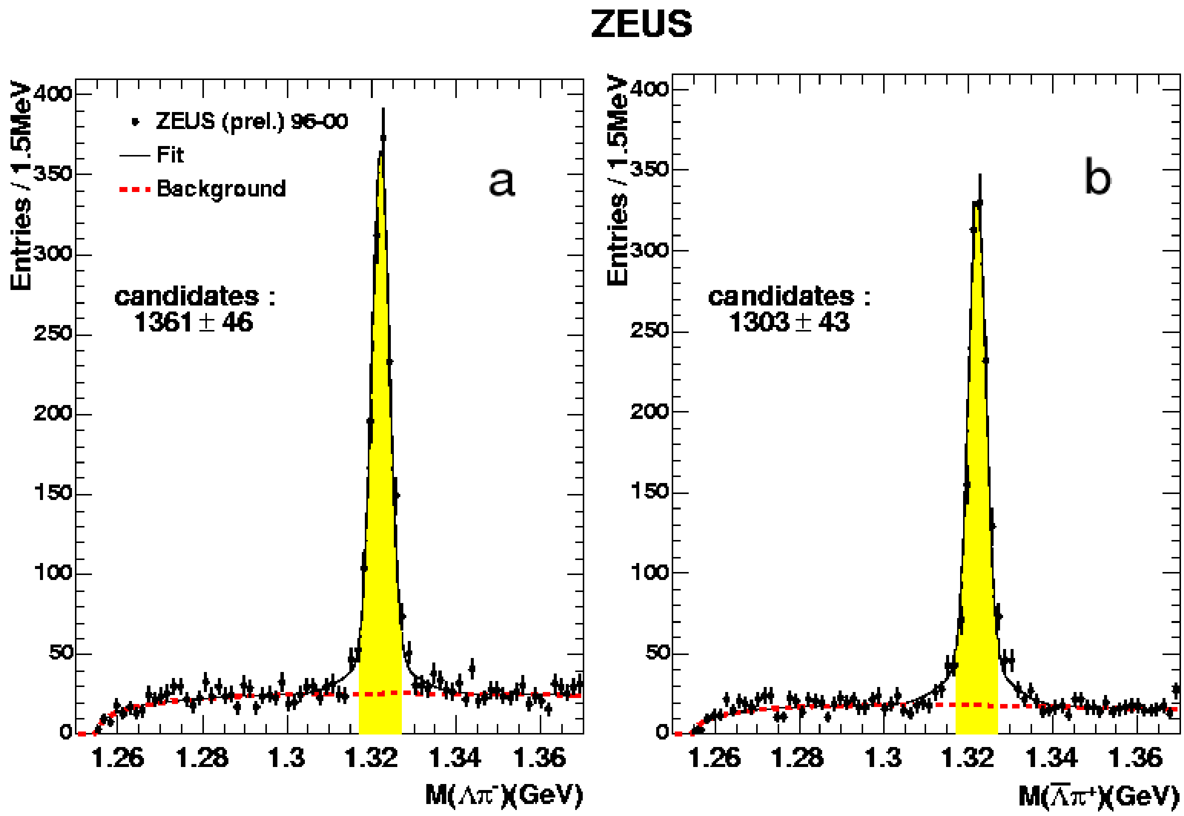

Figure 2: *The (a)* $\Lambda\pi^-$ *and (b)* $\bar{\Lambda}\pi^+$ *invariant-mass spectra for* $Q^2 > 1$ GeV^2.

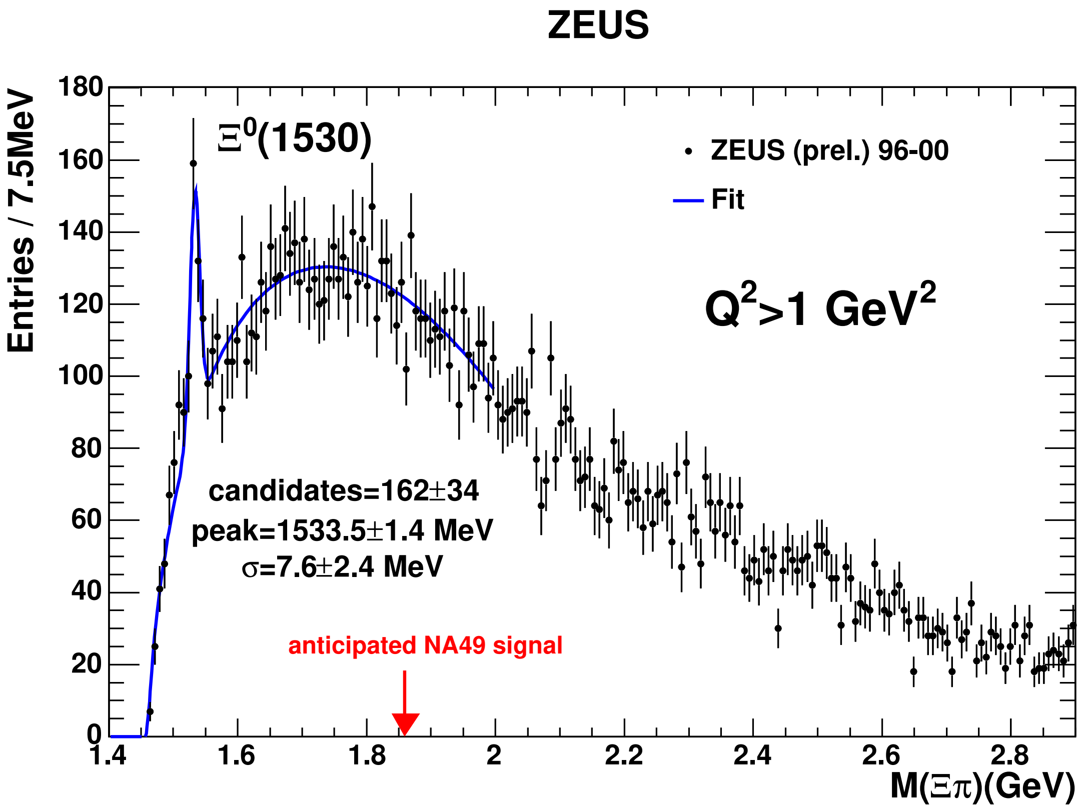

Figure 3: *The $\Xi\pi$ invariant-mass spectrum for $Q^2 > 1\ GeV^2$ (all four charge combinations).*

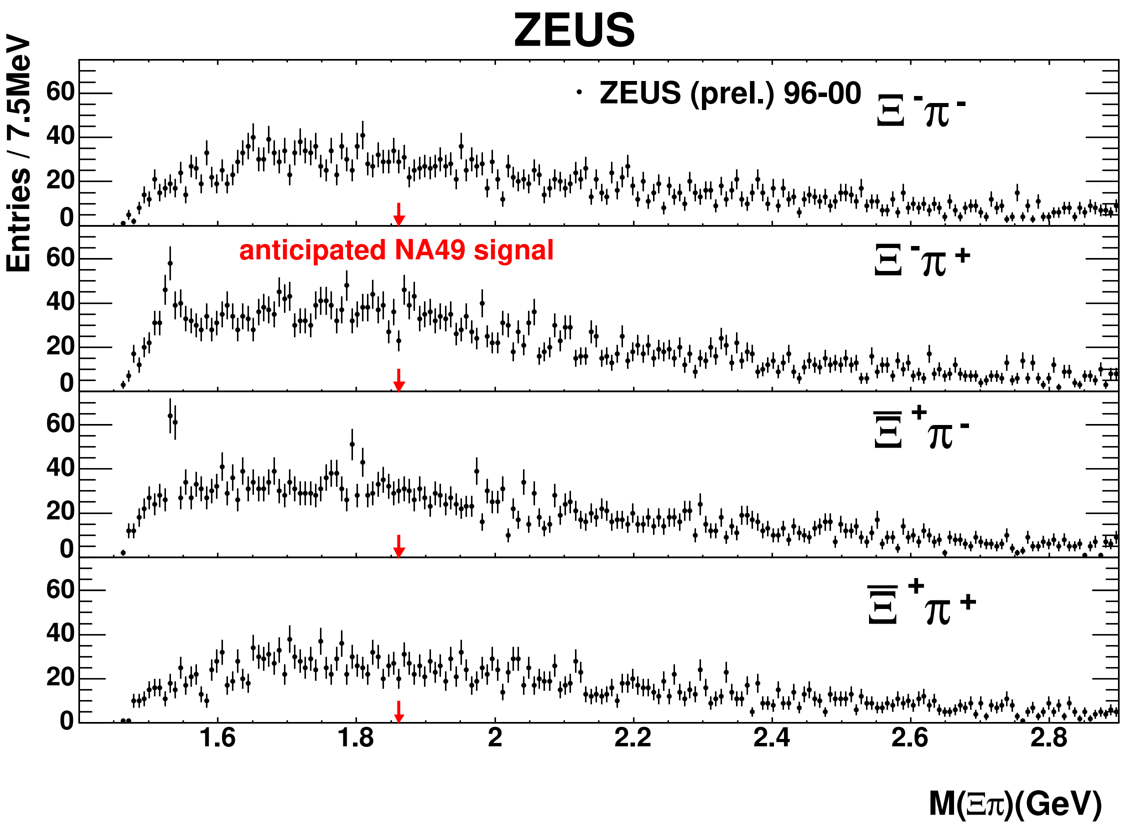

Figure 4: *The $\Xi\pi$ invariant-mass spectra for $Q^2 > 1$ GeV^2 (each different charge combination).*

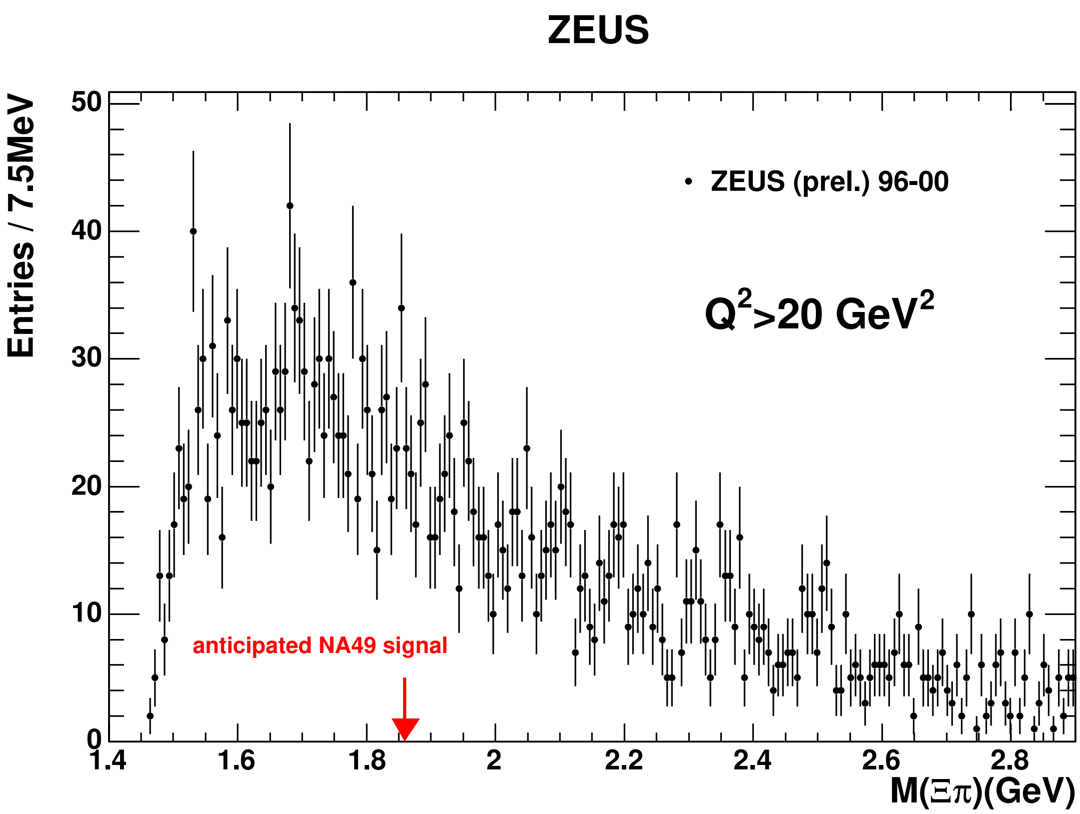

Figure 5: *The $\Xi\pi$ invariant-mass spectrum for $Q^2 > 20\ GeV^2$ (all four charge combinations).*