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Search for Pentaquarks in the Hadronic Decays of the Z Boson with the DELPHI Detector at LEP

DELPHI Collaboration

Abstract

The quark model does not exclude states composed by more than three quarks, like pentaquark systems. Recent controversial evidence for such states has been published, in particular for a strange pentaquark $\Theta^+(1540)$, for a double-strange state, called the $\Xi(1862)^{--}$ and for a charmed state, the $\Theta_c(3100)^0$; if confirmed, a full pentaquark family might exist. Such pentaquark states should be produced in e^+e^- annihilations near the Z energy. The DELPHI detector at LEP is characterized by powerful particle identification sub-systems, which are crucial in the separation of the signal from the background for these states. In this paper a search for pentaquarks using the DELPHI detector is described. At 95% C.L., upper limits are set on the production rates $< N >$ of such particles and their charge-conjugate state per Z decay:

$$\begin{aligned} < N_{\Theta^+} > &< 4.7 \times 10^{-4} \\ < N_{\Theta^{++}} > &< 1.6 \times 10^{-3} \\ < N_{\Xi(1862)^{--}} > &< 2.8 \times 10^{-4} \\ < N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \to D^{*+}\bar{p}) &< 8.8 \times 10^{-4} . \end{aligned}$$

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1 Introduction

Pentaquark is a name given to describe a bound state of four quarks and one antiquark, e.g. $uudd\bar{s}$. The quark model does not exclude such states. Several models predict the multiplet structure and characteristics of pentaquarks, for example the chiral soliton model, the uncorrelated and correlated quark models, the thermal model, lattice QCD etc. [1]. The current theoretical description of possible pentaquarks is very rich, but it does not provide a unique picture of the pentaquark characteristics. Furthermore, lattice calculations give very different predictions as to whether pentaquarks exist and, if they do, what mass and parity they have.

Pentaquark states were first searched for in the 60's but the few, low statistics, published candidates were never confirmed [2]. Until recently, all the hadronic states observed could be described as bound triplet-quark and quark-antiquark systems. Recent experimental evidence [3], however, may suggest the existence of pentaquark systems. The first possible candidate is[1] the $\Theta^+(1540)$, with mass of 1.54 ± 0.01 GeV/c^2, width smaller than 1 MeV/c^2, and strangeness S=+1, consistent with being made of the quarks ($uudd\bar{s}$). This evidence is still controversial as is that for the other pentaquark states discussed in this letter (see [4] and references therein).

Subsequently, evidence for another exotic baryon, doubly charged and with double strangeness, the $\Xi(1862)^{--}$, has been claimed by the CERN experiment NA49 [5].

More recently, the DESY experiment H1 has reported a signal for a charmed exotic baryon in the pD^{*-} channel [6], the $\Theta_c(3100)^0$. This resonance was reported to have a mass of 3099 ± 3 (stat) ± 5 (syst) MeV/c^2 and a measured width compatible with the experimental resolution. It was interpreted as an anti-charmed baryon with a minimal constituent quark composition of $uudd\bar{c}$. Several experiments tried to verify this finding [4]. The ZEUS collaboration for instance challenged the results of H1; even with a larger sample of D$^{*\pm}$ mesons, such a narrow resonance was not observed [7].

Isospins 0 and 1 are both possible for pentaquarks; isospin 1 would lead to three charge states Θ^0, Θ^+ and Θ^{++}. Thus the search is for a family of pentaquarks.

Pentaquark states could be produced in a significant way in e^+e^- annihilations at the Z energy. In a recent search, ALEPH [8] did not observe significant signals.

Some final states from the decay of pentaquarks could be detected and separated from the background using features of particle identification, like the ones which characterize the DELPHI detector. This paper reports on the results of a search for pentaquark states in hadronic Z decays recorded by DELPHI.

The article is organised as follows. After a short description of the subdetectors used for the analysis (Section 2), Section 3 presents the results of a search for pentaquarks in the pK^0 (the Θ^+) and the pK$^+$ channels. Section 4 presents a search for a doubly-charged, doubly-strange pentaquark (the $\Xi(1862)^{--}$). Section 5 presents a search for a charmed pentaquark (the $\Theta_c(3100)^0$). A summary is given in Section 6.

2 The Detector

The DELPHI detector is described in detail in [9], and its performance is analyzed in [10]. The coordinates can be identified by the z coordinate along the beam axis (with origin at the interaction point), by the polar angle θ measured with respect to the z direction of the e$^-$ beam (assumed as positive), by the azimuth ϕ, and by the radius $R\phi$ in the plane perpendicular to the beam.

[1] The antiparticles are always implicitly included.

The present analysis relies mostly on information provided by the central tracking detectors and the Barrel Ring Imaging Cherenkov Counter (BRICH):

- The microVertex Detector (VD) consists of three layers of silicon strip detectors at radii of 6.3, 9.0 and 10.9 cm. $R\phi$ is measured in all three layers. The first and third layers also provide z information (from 1994 on). The θ coverage for a particle passing all three layers is from 44° to 136°. The single point precision has been estimated from real data to be about 8 μm in $R\phi$ and (for charged particles crossing perpendicular to the module) about 9 μm in z.
- The Inner Detector (ID) consists of an inner drift chamber with jet chamber geometry and 5 cylindrical MWPC (straw tube from 1995 on) layers. The jet chamber, between 12 and 23 cm in R and 23° and 157° in θ, (15°-165° from 1995 on) consists of 24 azimuthal sectors, each providing up to 24 $R\phi$ points.
- The Time Projection Chamber (TPC) is the main tracking device. It provides up to 16 space points per particle trajectory for radii between 40 and 110 cm. The precision on the track elements is about 150 μm in $R\phi$ and about 600 μm in z. A measurement of the energy loss dE/dx of a track is provided with a resolution of about 6.5%, providing charged particle identification up to a momentum of about 1 GeV/c.
- The Outer Detector (OD) is a 4.7 m long set of 5 layers of drift tubes situated at 2 m radius to the beam which provides precise spatial information in $R\phi$.
- The Barrel Ring Imaging Cherenkov Counter (BRICH) is the main DELPHI detector devoted to charged particle identification. It is subdivided into two halves ($z > 0$ and $z < 0$) and provides particle identification using Cherenkov radiation produced in a liquid or a gas radiator. This radiation, after appropriate focusing, is transformed into photoelectrons in a TPC-like drift structure and the Cherenkov angles of the track in both media are determined. The BRICH detector provides particle identification in the momentum range 0.7 to 45 GeV/c.

The DELPHI tracking system was completed by two tracking chambers (FCA and FCB) in the forward regions.

To compute the selection efficiency of the various channels studied, $Z \rightarrow q\overline{q}$ events were simulated using the JETSET parton-parton generator [11] and then processed through the DELPHI simulation program, DELSIM, which models the detector response. The simulated events passed through DELSIM were then processed by the same reconstruction program as used for the data, DELANA [10]. The amount of simulated events is more than twice the real data.

3 Search for Strange Pentaquarks in the pK system

The state Θ^+ can be detected through its decay into pK^0 pairs; the state Θ^{++} could be detected through its decay into pK^+.

This analysis studies the invariant mass distributions of pK^0 and pK^+ pairs in hadronic Z decays. These are compared with the pK^- spectrum, where the $\Lambda(1520)$ is observed. The data used were recorded by the DELPHI experiment during the LEP1 operation in the years 1991 to 1995.

3.1 Event selection

Hadronic Z decays for this analysis were selected by requiring at least four reconstructed charged particles and a total energy of these particles (assuming the pion mass) larger than 12% of the centre-of mass (c.m.) energy. The charged-particle tracks had to be longer than 30 cm, with a momentum larger than 400 MeV/c and a polar angle between 20° and 160°. The polar angle of the thrust axis, θ_{thrust}, was computed for each event and events were rejected if $|\cos\theta_{thrust}|$ was greater than 0.95. A total of 3.4 million hadronic events were selected.

The selection efficiency for hadronic events was estimated using the simulation, and found to be larger than 95%.

<table>
<tr><th rowspan="2"></th><th colspan="7">momentum range in GeV/c</th></tr>
<tr><th>0.3 - 0.7</th><th>0.7 - 0.9</th><th>0.9 - 1.3</th><th>1.3 - 2.7</th><th>2.7 - 9.0</th><th>9.0 -16.0</th><th>16.0 - 45.0</th></tr>
<tr><td>π</td><td>TPC</td><td colspan="3">LRICH S</td><td colspan="3">GRICH S</td></tr>
<tr><td>K</td><td>TPC</td><td colspan="3">LRICH S</td><td>GRICH V
+
LRICH S</td><td colspan="2">GRICH S</td></tr>
<tr><td>p</td><td colspan="2">TPC</td><td>TPC
+
LRICH V</td><td>LRICH S</td><td>GRICH V
+
LRICH S</td><td>GRICH V</td><td>GRICH S</td></tr>
</table>

Table 1: Momentum ranges for particle identification: TPC denotes identification using the dE/dx measurement of the TPC, LRICH S (V) denotes identification using a signal (veto) of the liquid RICH, and correspondingly GRICH for the gas RICH.

In order to search for the pentaquark states, the pK^0, pK^- and pK^+ invariant mass spectra were constructed using identified particles. Particle identification was performed combining dE/dx and BRICH information. According to the quality of particle identification the tagging categories loose, standard and tight tags are distinguished for each particle species as well as for so called “heavy” tag, reducing the fraction of charged pions. To further improve the quality of particle identification for a track of given momentum and (assumed) particle type it was required that information from the detectors specified in Table 1 was present.

A particle was taken to be a proton if it was tightly tagged or fulfilled the standard tag by identification from ionization loss in the TPC. Kaons were required to be tightly tagged in the momentum ranges $p < 3.5$ GeV/c and $p > 9.5$ GeV/c. In the intermediate momentum range kaons were also identified by a tight heavy particle tag [12] combined with at least a standard kaon tag.

3.1.1 Description of the invariant mass spectra

In the present analysis, the mass spectra were described by a distribution function, $f(M,\vec{a})$, of the invariant mass M. The parameters $\vec{a}$ were determined by a least squares fit of the function to the data. The function $f(M,\vec{a})$ was composed of two parts:

$$f(M,\vec{a}) = f^S(M,\vec{a}) + f^B(M,\vec{a})\,, \tag{1}$$

corresponding to the signal and to the background respectively. The signal function, $f^S(M, \vec{a})$, described the resonance signals in the corresponding invariant mass distributions. It has the form:

$$f^S(M, \vec{a}) = a_1 \cdot R(M, a_2, a_3), \tag{2}$$

where R is either a non-relativistic Breit-Wigner or a normalized Gaussian function accounting for the resonance production; a_2 and a_3 are respectively the fitted peak RMS width and mass m. The background term, $f^B(M, \vec{a})$, was taken to be a third order polynomial in M.

3.2 Analysis of the pK^0 channel

The invariant mass distribution for pK^0 pairs was first studied. K^0 candidates were obtained from the fit of charged particle tracks of opposite charge both consistent with the pion hypothesis, as described in [10]. The K^0 invariant mass is shown in Figure 1 (left).

The pK^0 mass distribution is displayed on Figure 1 (right). No signal is visible in the Θ^+ mass region. In fact the simulation is accounting very well for the data over the whole mass spectrum.

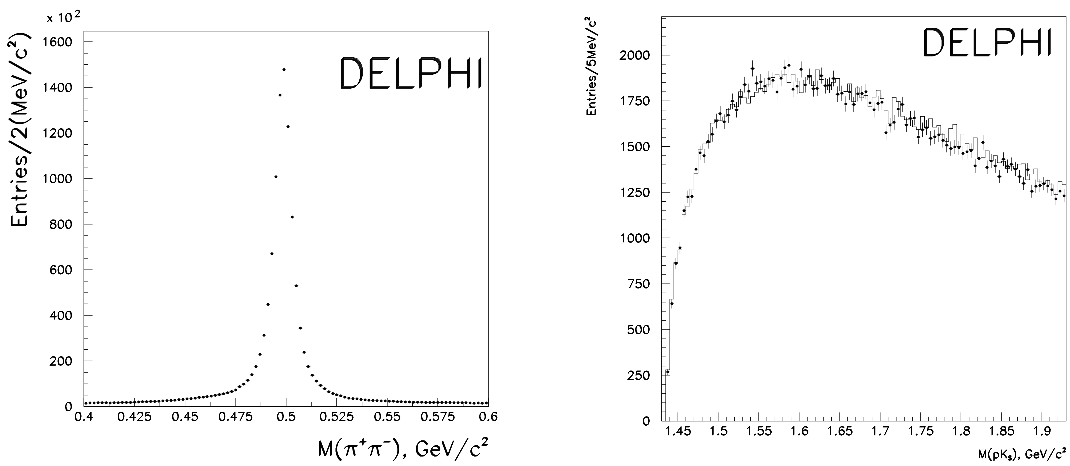

Figure 1: Left: K^0 invariant mass. Right: pK^0 mass spectrum; the histogram represents the MC simulation, while the points represent the data.

To set the limit on the Θ^+ production, we performed the fitting procedure described above, representing a possible signal by a Gaussian function with a central value of 1.54 GeV/c^2 and a RMS width of 10 MeV/c^2, equal to the resolution.

The pK^0 selection efficiency was estimated from a Monte Carlo generated sample of Θ^+ events to be $(6.4 \pm 0.3)\%$. The upper limit at 95% C.L. on the average production rate of the Θ^+ is:

$$< N_{\Theta^+} > \; < 4.7 \times 10^{-4} \, .$$

3.3 Analysis of the pK^- and pK^+ channels

The search for a possible Θ^{++} was made in the pK^+ channel, after investigation of the channel pK^-, where the presence of the $\Lambda(1520)$ resonance allows the $pK^-(K^+)$ selection efficiency to be measured in the region of interest. Figure 2 (left) shows the pK^- invariant mass spectrum. A clear $\Lambda(1520)$ signal is observed at the expected mass. It has been checked that there are no prominent reflections from known particle decays in the pK^- mass spectrum. In addition pK^- combinations in which the K^- combined with any identified K^+ had a mass in the ϕ (1020) region were discarded. The total excess in the $\Lambda(1520)$ region, measured from the fit to the mass spectrum of Figure 2 (left), is of:

$$\langle n_{\Lambda(1520)} \rangle = 2130 \pm 450 \text{ events}, \tag{3}$$

with a mass of 1.520 ± 0.002 GeV/c^2 and a width of 0.010 ± 0.004 GeV/c^2, compatible with the experimental resolution. The χ^2 per degree of freedom is 1.4. The $\Lambda(1520)$ selection efficiency determined from the MC simulation is of $(12.8 \pm 0.5)\%$. This corresponds to an average $\Lambda(1520)$ production rate per hadronic event of 0.0217 ± 0.0046 to be compared with the published value [13] of 0.0224 ± 0.0027.

The invariant mass spectrum for pK^+ pairs, obtained using the same cuts, is plotted in Figure 2 (right). No significant peak is visible; the χ^2 per degree of freedom of the fit to the background function only is 2.1.

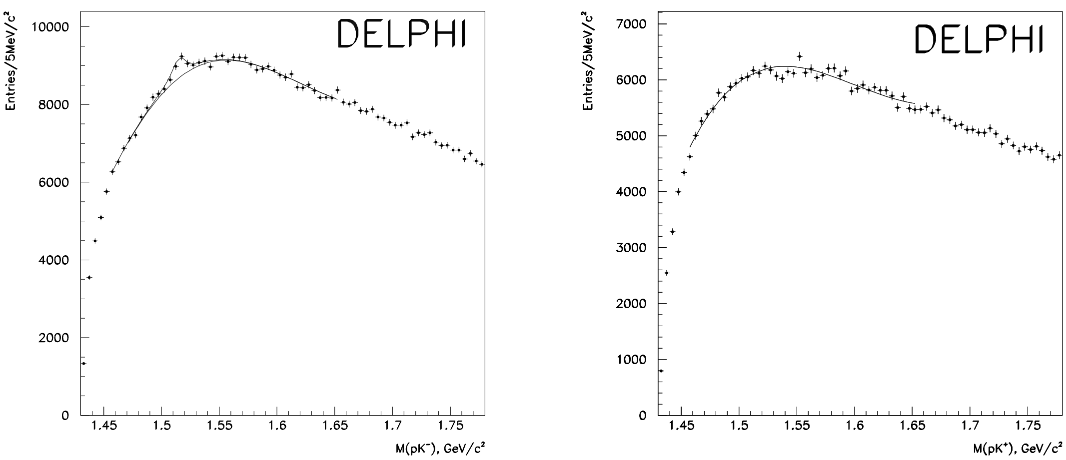

Figure 2: Differential pK^- (left) and pK^+ (right) mass spectra. The lines represent the fits described in the text.

An upper limit for the average production rate of the Θ^{++} can be determined over the range of its mass estimates (1.45 to 1.65 GeV/c^2), assuming the same efficiency as for the $\Lambda(1520)$. It should be taken into account that, while the $\Lambda(1520)$ can decay into a charged pair and into a neutral pair as well, essentially with the same probability, the sensitivity to decay channels of the Θ^{++} is twice that of the $\Lambda(1520)$.

A fit to the form (1) was performed by varying the mass between 1.45 GeV/c^2 and 1.65 GeV/c^2 in steps of 5 MeV/c^2, and by imposing a RMS width of 10 MeV/c^2 (the expected experimental resolution). Limits at 95% C.L. were then calculated as a function of the mass. A general limit

$$< N_{\Theta^{++}} > \ < 1.6 \times 10^{-3}$$

for the mass region between 1.45 GeV/c^2 and 1.65 GeV/c^2 is obtained. This limit is higher than what could be obtained given the sensitivities, due to the about 2σ statistical fluctuations in the mass region between 1.52 GeV/c^2 and 1.58 GeV/c^2.

3.4 Summary

No excess has been found in the distribution of invariant mass for pK^0 and pK^+ pairs in the mass region below 1.8 GeV/c^2. On the other hand a 4.7σ excess has been found in the distribution of the invariant mass for pK^- pairs for a mass of 1.520 ± 0.002 GeV/c^2, consistent with the published average $\Lambda(1520)$ production rate per hadronic event [13]. This allows upper limits to be set for the production of the strange pentaquarks Θ^+ and Θ^{++}. The limits at 95% C.L. is:

$$< N_{\Theta^{+}} > \ < 4.7 \times 10^{-4} \quad (4)$$

$$< N_{\Theta^{++}} > \ < 1.6 \times 10^{-3}, \quad (5)$$

where the limit on the Θ^{++} production rate corresponds to a mass between 1.45 GeV/c^2 and 1.65 GeV/c^2.

4 Search for Doubly Charged and Doubly Strange Pentaquarks in the $\Xi^-\pi^-$ system

4.1 Event selection

The hadronic Z decays sample for this analysis is the same as described in section 3.1, corresponding to data recorded by the DELPHI experiment during the LEP1 operation in the years 1991 to 1995. Similarly the exotic baryons with double charge and double strangeness, decaying into $\Xi^-\pi^-$, were searched for in the fragmentation of quarks from hadronic Z decays.

4.2 Ξ^- Reconstruction

The Ξ^- hyperon was reconstructed through the decay $\Xi^- \to \Lambda\pi^-$. For this, all V^0 candidates, i.e., all pairs of oppositely charged particles, were considered as Λ candidates. For each pair, the highest momentum particle was assumed to be a proton and the other a pion, and a vertex fit performed using the standard DELPHI V^0 search algorithm [10].

The $\mathrm{p}\pi^-$ invariant mass is shown in Figure 3 (left, top).

The Λ candidates were selected by requiring an invariant mass $M(\mathrm{p}\pi^-)$ between 1.100 GeV/c^2 and 1.135 GeV/c^2, a χ^2 probability of the V^0 vertex larger than 10^{-5} and a decay length greater than 0.2 cm in the plane transverse to the beam.

A constrained multivertex fit was performed on each Ξ^- candidate decaying into $\Lambda\pi^-$ [14]. The 16 measured variables in the fit were the five parameters of the helix parameterization of each of the three charged particle tracks and the z coordinate of the beam interaction point (the x and y coordinates were so precisely measured that they could be taken as fixed). The fitted variables were the decay coordinates of the Ξ^- and Λ.

The fit constrained the sum of the Λ and π momenta to be equal to the Ξ^- momentum. The constraint on the Λ decay products to give the nominal Λ mass value 1115.683 ± 0.006 MeV/c^2 [13] was also applied.

The resulting spectrum of the $\Lambda\pi^-$ invariant mass after the fit is shown in Figure 3 (top, right).

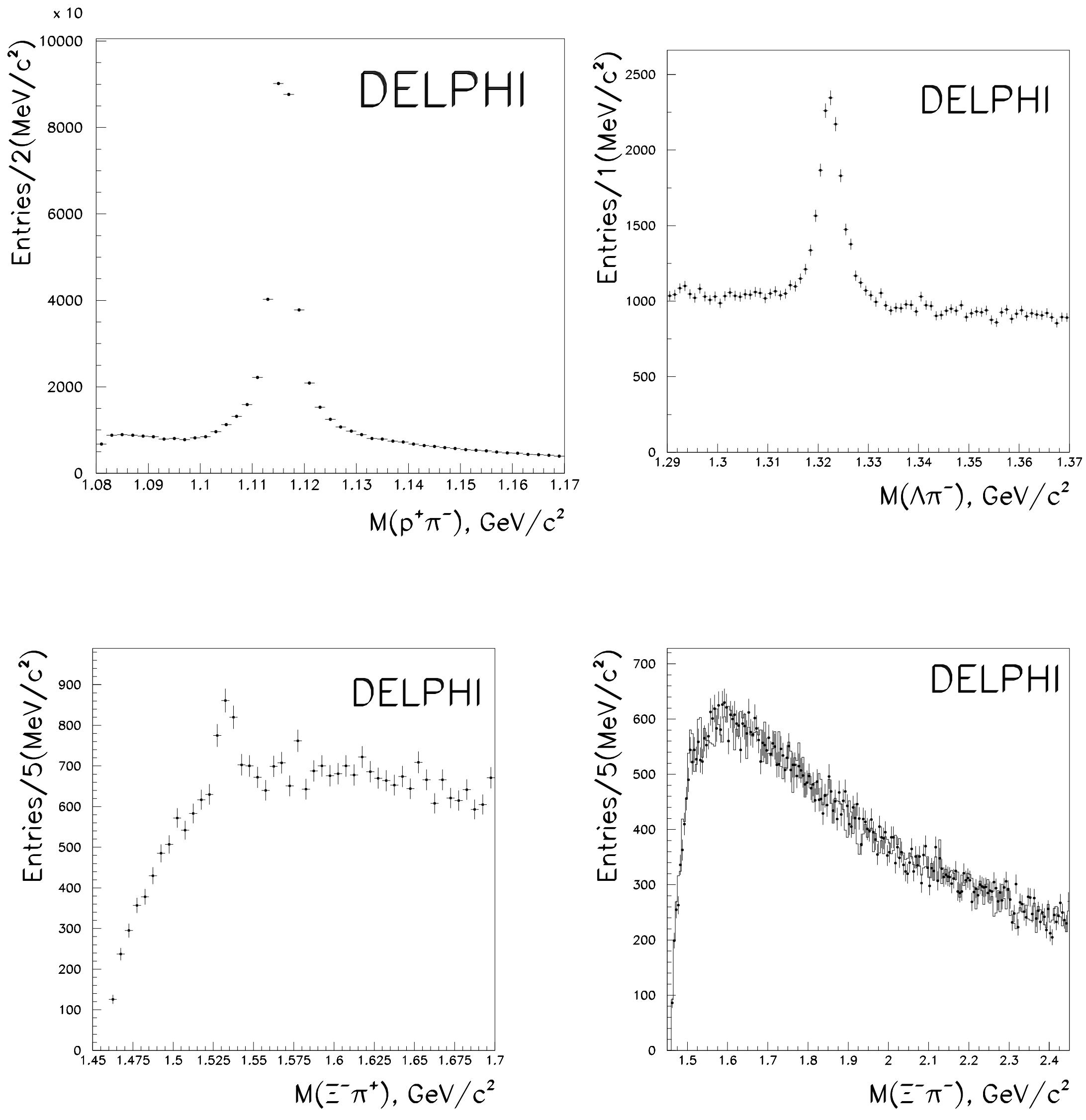

Figure 3: Top, left: Invariant $p\pi^-$ mass spectrum. Top, right: Invariant $\Lambda\pi^-$ mass distribution. Bottom, left: Invariant $\Xi^-\pi^+$ mass distribution. Bottom, right: Invariant $\Xi^-\pi^-$ mass distribution; the histogram represents the MC simulation.

4.3 Analysis of the $\Xi\pi$ system

Each reconstructed Ξ^- candidate in the mass range between 1.30 GeV/c^2 to 1.34 GeV/c^2 was combined with a pion.

The mass spectrum of neutral combinations $\Xi^-\pi^+$ is shown in Figure 3 (bottom, left); a clear $\Xi(1530)$ peak of about 820 ± 50 events is observed, corresponding to the average multiplicity [13] of 0.0053 ± 0.0013 per Z decay.

The mass spectrum of combinations $\Xi^-\pi^-$ is shown in Figure 3 (bottom, right). No significant excess is observed. The continuous line gives the prediction of JETSET for the $\Xi^-\pi^-$ spectrum without pentaquarks. To estimate the number of pentaquarks we performed a fit of the form (1) to the $\Xi^-\pi^-$ mass spectrum, with a Gaussian central value of 1.862 GeV/c^2 and a width of 0.015 GeV/c^2 equal to the resolution in this mass region. The number of events resulting from the fit is equal to -50 ± 75. The reconstruction efficiency of a possible $\Xi(1862)^{--}$ object decaying into $\Xi^-\pi^-$ has been computed from a Monte Carlo generated sample of $\Xi(1862)^{--}$ events, to be $(10.0 \pm 0.5)\%$. This leads to an estimate of the upper limit of the production rate of a $\Xi(1862)^{--}$ object, per hadronic Z boson decay, of 2.8×10^{-4}, at the 95% confidence level.

4.4 Summary

Although a clear production of $\Xi(1530)$ is observed in the $\Xi^-\pi^+$ system, no evidence for an exotic $\Xi^-\pi^-$ narrow baryon, with double charge and double strangeness has been found in the $e^+e^- \to$ Z $\to q\bar{q}$ decays collected by the DELPHI detector during the LEP1 running period. The estimated upper limit of the production rate of such resonance, at the 95% confidence level, is

$$< N_{\Xi(1862)^{--}} > \; < 2.8 \times 10^{-4} \, .$$

5 Search for Charmed Pentaquarks in the D*p system

The data used throughout this analysis were restricted to 1994 and 1995, the two highest integrated luminosity years of LEP 1. This sample corresponds to a total of about 2.1 million hadronic events after the selection.

5.1 Event Selection

After the standard hadronic event selection criteria listed in section 3.1 were applied, events containing the decay chain $D^{*+} \to D^0X \to K^-\pi^+X$ were selected as a first step of the analysis.

Additional cuts were performed to suppress the background:

- $x_E(D^0) \geq 0.15$, where x_E is the energy fraction with respect to the beam energy;
- in the reconstructed D^0 decay, it was required that both the kaon and pion momenta were larger than 1 GeV/c, and that the angles between the K and π momenta were smaller than 90° in the centre-of-mass system;
- the momentum of the bachelor pion had to be between 0.3 GeV/c and 2.5 GeV/c, and the angle between the D^0 candidate and the bachelor π momenta had to be smaller than 90° in the centre-of-mass system;
- the decay length of the D^0 had to be smaller than 2.5 cm, but positive by at least three standard deviations;
- $\cos\theta_K > -0.9$, where $\cos\theta_K$ is the angle between the D^0 flight direction and the K direction in the D^0 rest frame;

- the invariant mass of the Kπ system had to be between 1.79 GeV/c^2 and 1.91 GeV/c^2, and the mass difference $\Delta M = m_{K\pi\pi} - m_{K\pi}$ was required to be between 0.1425 GeV/c^2 and 0.1485 GeV/c^2;
- the K and π candidates were required to have at least one hit in the VD;
- the K candidates should not have a positive pion tag. This requirement suppresses about 50% of the combinatorial background surviving all other cuts.

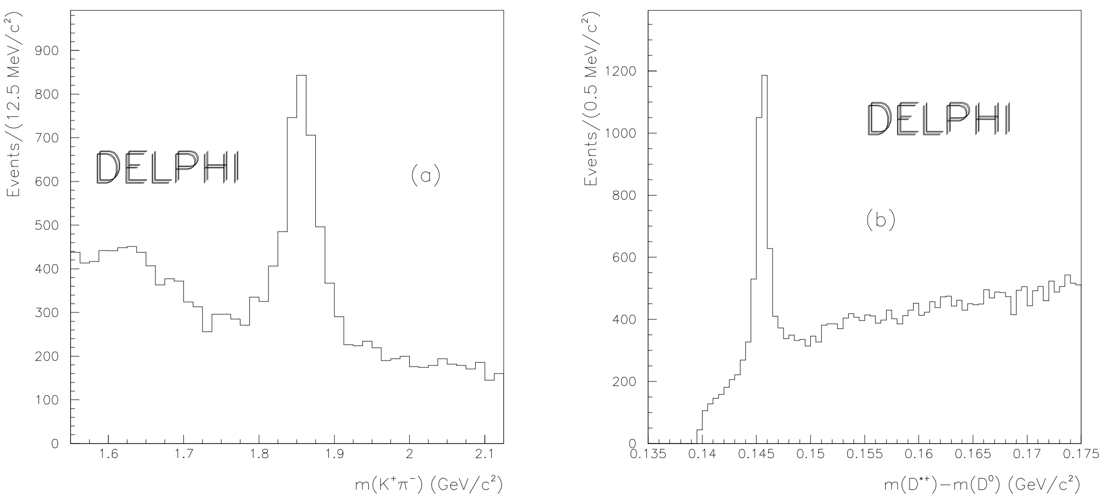

Figure 4: Invariant $K^+\pi^-$ mass (a). Distribution of $\Delta M = m_{K\pi\pi} - m_{K\pi}$ (b).

5.2 Analysis of the D*p system

Mass spectra of $m_{K\pi}$ and ΔM, with all the cuts listed above except for the quantity plotted, are shown in Figure 4. One can see that the background around the very clear D^0 and ΔM peaks (corresponding to the decay $D^* \to D^0\pi$) is quite small.

Figure 5 shows the invariant mass distributions of D*p, for total charge zero and for absolute total charge 2 respectively. Figure 5 (a) shows the D*p effective masses with right charge (for a possible pentaquark). No narrow resonance peak around 3.1 GeV/c^2 is seen. The wrong charge mass combinations are shown in Figure 5 (b).

Since no hint has been found for a pentaquark signal, an upper limit for the production of a possible $\Theta_c(3100)^0$ state can be given.

For this purpose, pentaquark signals were simulated; the detection efficiency was estimated, and the 95% confidence level limit on the average production rate per hadronic decay of the Z corresponding to the observed invariant mass distribution, with subsequent decay into D^*p, was computed to be 8.8×10^{-4}.

5.3 Summary

No evidence of a charmed pentaquark state $\Theta_c(3100)^0$ decaying into $D^{*+}\bar{p}$ has been found in $e^+e^- \to Z \to$ *hadrons* events collected by the DELPHI experiment at LEP. The estimated upper limit of the production rate per Z decay of such an exotic resonance at

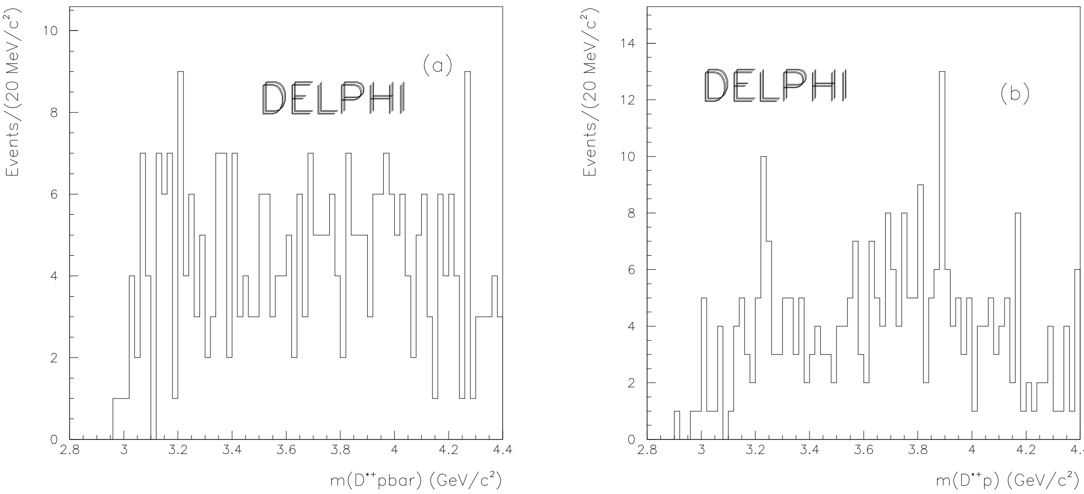

Figure 5: Invariant masses $m(\mathrm{D}^{*+}\bar{p})$ (a) and $m(\mathrm{D}^{*+}p)$ (b).

95% confidence level is

$$< N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \to D^{*+}\bar{p}) \ < 8.8 \times 10^{-4} \,. \qquad (6)$$

6 Conclusions

A search for pentaquarks in hadronic Z decays was performed, and none of the states searched for was found. Upper limits were established at 95% C.L. on the average production rates $< N >$ of such particles and their charge-conjugate state per Z decay:

$$\begin{aligned} < N_{\Theta^+} > \ &< \ 4.7 \times 10^{-4} \\ < N_{\Theta^{++}} > \ &< \ 1.6 \times 10^{-3} \\ < N_{\Xi(1862)^{--}} > \ &< \ 2.8 \times 10^{-4} \\ < N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \to D^{*+}\bar{p}) \ &< \ 8.8 \times 10^{-4} \,. \end{aligned}$$

These limits improve previously published results [8].

In recent years thermodynamical [15] and phenomenological models [16,17] have appeared, which successfully describe the overall particle production rates in high energy interactions with very few parameters. According to the model by Becattini [15], the average production rate for the production of the Θ^+ at the Z energy should be of 0.007 [18]. According to the model by Chliapnikov and Uvarov, the average production rate is expected to be less than 5 $\times 10^{-6}$, if the Θ^+ is dominantly produced from the intermediate N^*/Δ^* baryon state with the mass of 2.4 GeV/c^2 as indicated by the CLAS experiment [3]. On the other hand, if the Θ^+ production mechanism is similar to the one for ordinary baryons produced at LEP, its average production rate should be comparable with that of a known resonance, the $\Lambda(1520)$, which is observed with an average production rate of 0.0224 ± 0.0027 per hadronic event [13].

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