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

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Abstract

The quark model does not exclude 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. Some of these states could be detected and separated from the background using particle identification systems, like the ones which characterize the DELPHI detector at LEP. In this paper a search for pentaquarks using the DELPHI detector is described. At 95% C.L., preliminary upper limits are set on the production rates $< N >$ of such particles and their charge-conjugate state per Z decay:

$$\begin{aligned} < N_{\Theta^+} > &< 0.005 \\ < N_{\Theta^{++}} > &< 0.006 \\ < N_{\Xi(1862)^{--}} > &< 2.8 \times 10^{-4} \\ < N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \rightarrow D^{*+}\bar{p}) &< 8.8 \times 10^{-4} \,. \end{aligned}$$

1 Introduction

Pentaquark is a name invented 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, correlated quark models, the thermal model, lattice QCD etc. [1]. The current theoretical description of pentaquarks is very rich, but it does not provide a unique picture of the pentaquark existence and characteristics. Furthermore, lattice calculations give very different predictions as to whether pentaquarks exist and, if they do, which 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, only bound triplet-quark and quark-antiquark systems have been found. 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 ($uudd\bar{s}$). Such an evidence is still controversely discussed (see for example [4] and references therein, also for the other pentaquark states discussed in this article).

Subsequently, evidence for another exotic baryon doubly charged and with double strangeness, the $\Xi(1862)^{--}$, has been published 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 [7]; even with a larger sample of $D^{*\pm}$ mesons, such a narrow resonance was not observed.

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 on for a family of pentaquarks.

Pentaquark states might 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 (see Ref. [9, 10]). 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].

[1]The antiparticles are always implicitly included.

The present analysis relies on information provided by the central tracking detectors and the barrel RICH:

- The microVertex Detector (VD) consists of three layers of silicon strip detectors at radii of 6.3, 9.0 and 10.9 cm. $R\phi$ coordinates in the plane perpendicular to the beam are measured in all three layers. The first and third layers also provide z information (from 1994 on). The polar angle (θ) [2] coverage for a particle passing all three layers is from 44°to 136°. The single point resolution 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°(15°-165°from 1995 on) in θ, 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 with additional tracking devices in the forward regions.

To compute efficiencies, 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 Analysis of the pK^0 and the pK$^+$ channels

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

[2] θ is measured with respect to the (z) direction of the e$^-$ beam.

This analysis studies the invariant mass distributions of pK^0, pK^+ pairs in hadronic Z decays. These are compared with the pK^- spectrum, where the $\Lambda(1520)$ is observed.

The data used throughout this analysis were collected in 1994 and 1995. In these data taking periods the DELPHI Time Projection Chamber (TPC) and Ring Imaging Cherenkov (RICH) detectors were optimally set up and functioning in view of the analysis presented.

3.1 Data Selection

An event was selected as a multihadronic event if the following requirements were satisfied:

- There were at least 5 well measured charged particle tracks in the event, each with momentum larger than 300 MeV/c and a polar angle in the barrel region.
- The total reconstructed energy of these charged tracks had to be larger than 11 GeV.
- The total energy of the charged particles in each detector hemisphere (defined by the plane perpendicular to the beam axis) had to exceed 3 GeV.

Beyond the general hadronic cuts it was additionally required that the track impact parameter to the primary vertex was less than 0.5 mm in the $R\phi$-plane and 1 mm in the z direction. This requirement strongly reduces contributions of tracks from particle re-interactions inside the detector material. Furthermore there must be at least two tracks inside the angular acceptance $47° < \theta < 133°$ of the BRICH.

<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, first the pK^-($\bar{p}K^+$) invariant mass spectrum was 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" particles combining protons and kaons. To further improve the quality of particle identification for a track of given momentum

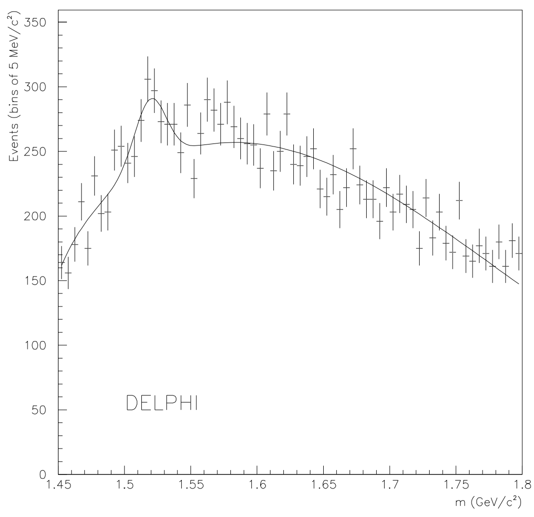

Figure 1: Differential pK^- mass spectra for the overall measured energy range. The line represents the fit described in the text.

and (assumed) particle type it was required that information from the detectors specified in Table 1 was present.

A particle was then taken to be a proton if it was tightly tagged (or fulfilling the standard tag if in the momentum range where the identification is performed by means of the specific ionization loss measured 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.

After the track cuts previously described, about 1.3 million events remained for the 1994 running and 0.6 million events for the 1995 running. This analysis is based on both running periods.

Figure 1 shows the pK^- invariant mass spectrum. A clear $\Lambda(1520)$ signal is observed at the expected mass, consistent with [13]. It has been checked that there are no prominent reflections from known particle decays in the pK^- mass spectrum.

In the present analysis, the mass spectra were described by an anticipated 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. For the pK^- mass distributions it has the form

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

where G is a normalized Gaussian function accounting for the $\Lambda(1520)$ production; a_2 and a_3 are respectively the fitted peak width and the mass m.

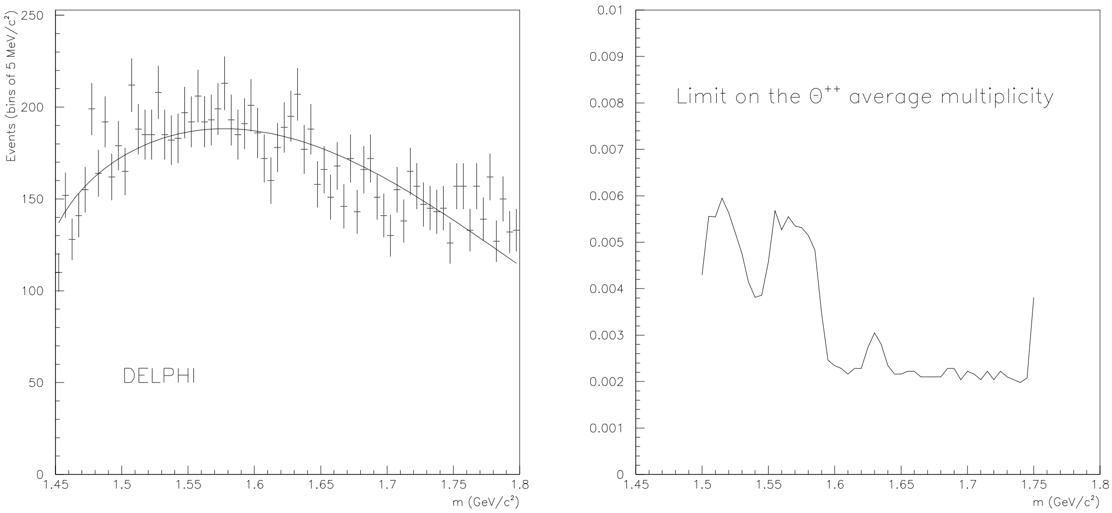

Figure 2: Left: Differential pK^+ mass spectra for the overall measured energy range. The line represents the fit described in the text. Right: 95% limit obtained for the average production rate of the Θ^{++} as a function of the mass.

The background term, $f^B(M, \vec{a})$, was taken [14] to be of the form

$$f^B(M, \vec{a}) = a_4(M - M_{thr})^{a_5} \exp(a_6 M + a_7 M^2 + a_8 M^3)\,, \qquad (3)$$

where M_{thr} is the threshold mass.

The best values for $\vec{a}$ and M were then determined by a least squares fit of the invariant mass distribution.

The total excess in the $\Lambda(1520)$ region, measured from a fit to the mass spectrum given in Figure 1, is of

$$\langle n_{\Lambda(1520)} \rangle = 306 \pm 55 \text{ events}, \qquad (4)$$

corresponding to a mass of 1.520 ± 0.002 GeV/c^2 and to a width of 0.010 ± 0.004 GeV/c^2. The χ^2 per degree of freedom was 1.4. This excess must be compared with an average production rate of 0.0224 ± 0.0027 $\Lambda(1520)$ per hadronic event [15].

The invariant mass spectrum for pK^+ pairs, obtained using the same cuts, is plotted in Figure 2 (left). No peak is visible; the χ^2 per degree of freedom of the fit to the background function is of 1.7.

An upper limit for the average production rate of the Θ^{++} in the mass region studied can be determined 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 1.5 GeV/c^2 and 1.75 GeV/c^2 in bins of 5 MeV/c^2, and by imposing the width of 0.010 MeV (the expected experimental resolution). Limits at 95% C.L. were then calculated as a function of the mass; the result is plotted in Figure 2 (right). A general limit

$$< N_{\Theta^{++}} > \; < 0.006$$

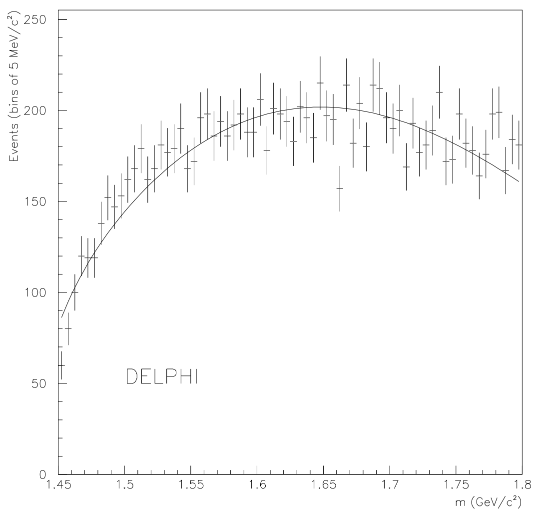

Figure 3: Differential pK^0 mass spectra for the overall measured energy range. The line represents the fit described in the text.

for the mass region between 1.5 GeV/c^2 and 1.75 GeV/c^2 is obtained.

Finally, the invariant mass distribution for pK^0 pairs was studied. K^0 candidates were obtained from the fit of charged tracks of opposite charge both consistent with the pion hypothesis, as described in [10]. The reconstruction efficiency was estimated from the efficiency for π^+K^- pairs. Again no signal was found (Figure 3); the χ^2 per degree of freedom of the fit of the background function is of 1.3.

We performed the same procedure used for setting the limit on the Θ^{++}, restricting the mass scan to the mass region between 1.52 GeV/c^2 and 1.56 GeV/c^2, corresponding to the Θ^+ mass. The upper limit at 95% C.L. on the average production rate of the Θ^+ is:

$$< N_{\Theta^+} > \; < 0.005 \,.$$

3.2 Summary and Interpretation

A 5σ 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. This is consistent with the production of the $\Lambda(1520)$, which has an average production rate per hadronic event [15] $< N_{\Lambda(1520)} >= 0.0224 \pm 0.0027$.

No excess has been found in the distribution of invariant mass for pK^+ and pK^0 pairs in the mass region below 1.8 GeV/c^2; this allows to set an upper limit for the production of the strange pentaquarks Θ^{++} and Θ^+. Such a limit at 95% C.L. is

$$< N_{\Theta^{++}} > \;\; < \;\; 0.006 \qquad (5)$$

$$< N_{\Theta^{+}} > \;\; < \;\; 0.005 \,, \qquad (6)$$

where the limit on the Θ^{++} production rate corresponds to a mass between 1.5 GeV/c^2 and 1.75 GeV/c^2.

In recent years thermodynamical [16] and phenomenological models [17, 18] have appeared, which successfully describe the overall particle production rates in high energy interactions with very few parameters. According to the model by Becattini, the average production rate for the production of the Θ^+ at the Z energy should be [19] of 0.007. According to the model by Chliapnikov and Uvarov [20], 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 the prodution rate of a known resonance, the $\Lambda(1520)$, which is observed with an average production rate of 0.0224 ± 0.0027 per hadronic event [15].

4 Search for Doubly Charged and Doubly Strange Pentaquarks

In this study, the exotic baryons with double charge and double strangeness, decaying in to $\Xi^-\pi^-$, are searched for in the fragmentation of quarks from hadronic Z decays recorded by the DELPHI experiment during the LEP1 operation in the years 1991 to 1995.

4.1 Event selection and simulation

Hadronic Z decays for this analysis were selected by requiring at least four reconstructed charged particles and a total energy of these particles (assumed to be pions) larger than 12% of the center-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 trust axis, θ_{thrust}, was computed for each event and events were rejected if $|\cos\theta_{thrust}|$ was greater than 0.95. A total of 3.5 million hadronic events were selected.

Applying the selection criteria on simulated events as on data shows that the hadronic selection efficiency is larger than 95%.

4.2 Ξ^- Reconstruction

The Ξ^- hyperon was reconstructed through the decay $\Xi^- \rightarrow \Lambda\pi^-$. 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 Λ candidates were selected by requiring an invariant mass $M(\mathrm{p}\pi^-)$ between 1.10 GeV/c^2 and 1.135 GeV/c^2, a χ^2 probability of the V^0 vertex larger than 10^{-5} and an $R\phi$ decay length greater than 0.2 cm.

A constrained multivertex fit was performed on each Ξ^- candidate decaying into $\Lambda\pi^-$. 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 [15] was also applied.

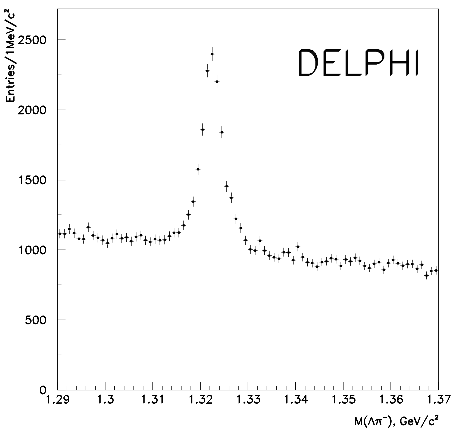

Figure 4: Invariant $\Lambda\pi^-$ mass distribution.

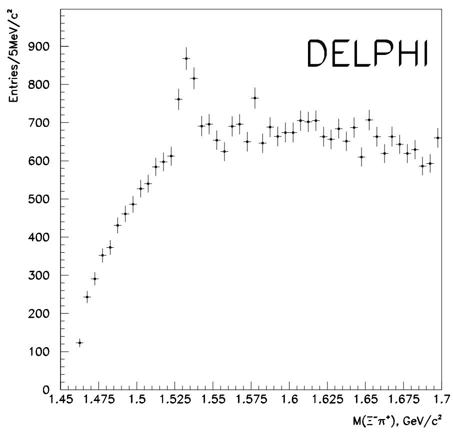

Figure 5: Invariant $\Xi^-\pi^+$ mass distribution.

The resulting spectrum of the $\Lambda\pi^-$ invariant mass after the fit is shown in Figure 4.

4.3 Search for narrow resonances in 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 5; a clear $\Xi(1530)$ peak of about 820 ± 50 events is observed.

The mass spectrum of combinations $\Xi^-\pi^-$ is shown in Figure 6. No significant excess is observed. The continuous line gives the prediction of JETSET7.3 for the $\Xi^-\pi^-$ spectrum without pentaquarks. To estimate the number of pentaquarks we performed a fit of the $\Xi^-\pi^-$ spectrum to a polynomial background and a Gaussian with a 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 best 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

No evidence for an exotic narrow baryon, with double charge and double strangeness has been found in the $e^+e^- \to$ Z $\to q\overline{q}$ 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

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

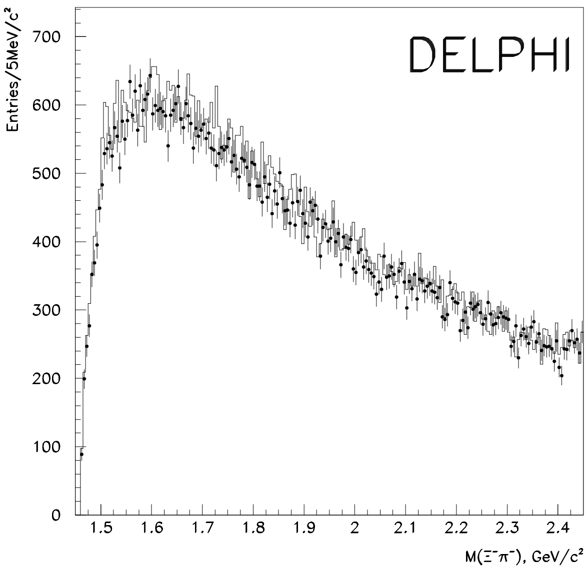

Figure 6: Invariant $\Xi^-\pi^-$ mass distribution. The data are shown as points with error bars. The histogram is for the simulated sample of events.

5 Search for Charmed Pentaquarks

The data used throughout this analysis were collected in 1994 and 1995. As stated before, during these data taking periods the DELPHI Time Projection Chamber (TPC) and Ring Imaging Cherenkov (RICH) detectors were optimally set up and functioning in view of the analysis presented.

5.1 Data Selection and Event Reconstruction

After the standard event selection and quality cuts were applied, events corresponding to the decay chain $D^{*+} \to D^0 \to K^-\pi^+$ 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 c.m. 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 c.m. system;
- the decay length of the D^0 had to be larger than 0 and smaller than 2.5 cm, and different from 0 by at least three standard deviations;

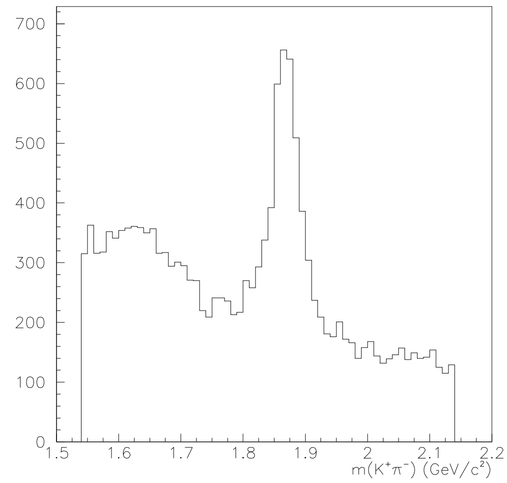

Figure 7: Invariant $K^+\pi^-$ mass.

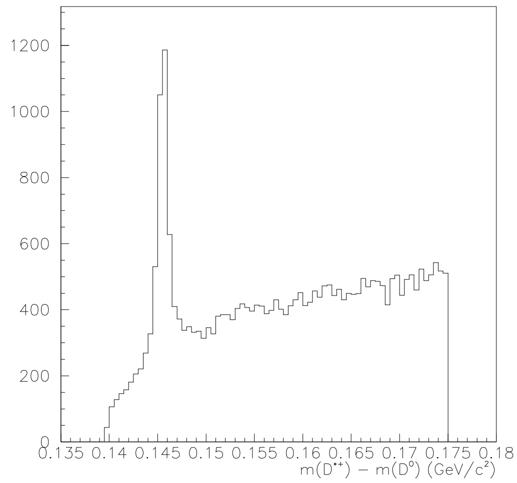

Figure 8: $m(D^{*+}) - m(D^0)$.

- $\cos\theta_K > -0.9$, where $\cos\theta_K$ is the angle between the D^0 flight direction and the K direction in the D^0 rest frame;
- $1.79\text{GeV}/c^2 < m_{K\pi} < 1.91\text{GeV}/c^2$ and $0.1425\text{GeV}/c^2 < \Delta M < 0.1485\text{GeV}/c^2$, where $\Delta M = m_{K\pi\pi} - m_{K\pi}$;
- the K and π candidates were requested to have at least one hit in the VD;
- the K candidates should not have a positive identification as a pion. This cut suppresses about 50% of the combinatorial background surviving all other cuts.

Mass spectra of $m_{K\pi}$ and ΔM, with all the cuts listed above except for the quantity plotted, are shown in Figure 7 and Figure 8 respectively. One can see that the background under the very clear D^0 and ΔM peaks (corresponding to the decay $D^* \to D^0\pi$) is quite small.

5.2 Results

Figure 9 shows the effective mass distributions of D*p, for total charge zero and for absolute total charge 2 respectively. Figure 9 (left) shows the D*p effective masses with right charge (for a possible pentaquark). No narrow resonance peak around 3.1 GeV/c^2 was detected.

The wrong charge mass combinations are given in Figure 9 (right).

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

For this purpose, pentaquark signals were generated using the simulation, and the 95% C.L. 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}.

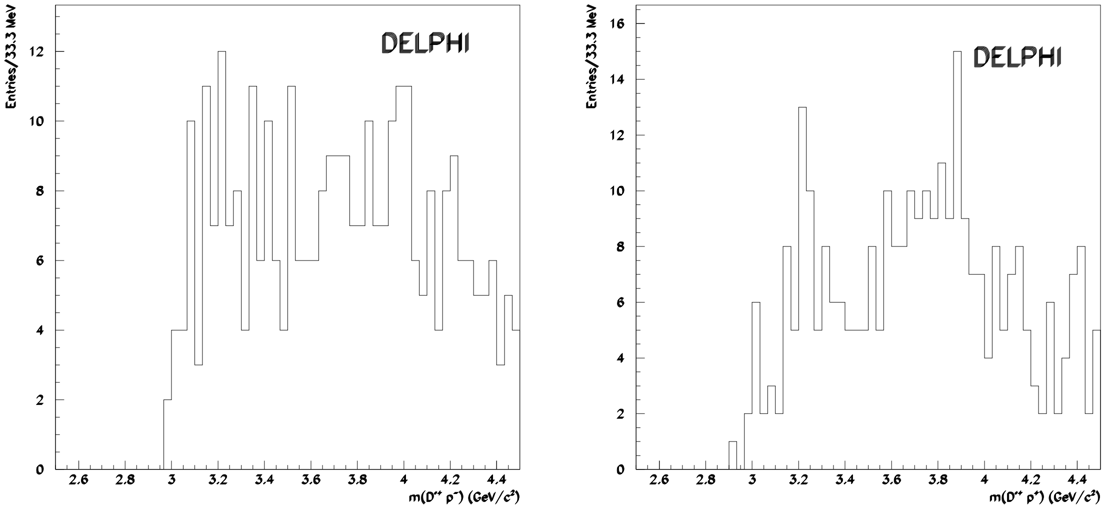

Figure 9: $m(\mathrm{D}^{*+}\bar{p})$, left, and $m(\mathrm{D}^{*+}p)$, right.

5.3 Summary

No evidence of a charmed pentaquark state $\Theta_c(3100)^0$ decaying into $\mathrm{D}^{*+}\bar{p}$ has been found in $e^+e^- \to \mathrm{Z} \to hadrons$ events collected by the DELPHI collaboration at LEP. The estimated upper limit of the production rate per Z decay of such an exotic resonance at 95% confidence level is

$$< N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \to D^{*+}\bar{p}) \; < 8.8 \times 10^{-4} \, . \tag{7}$$

6 Conclusions

A search for pentaquarks in hadronic Z decays was performed. At 95% C.L., preliminary upper limits were established on the average production rates $< N >$ of such particles and their charge-conjugate state per Z decay:

$$\begin{aligned} < N_{\Theta^+} > &< 0.005 \\ < N_{\Theta^{++}} > &< 0.006 \\ < N_{\Xi(1862)^{--}} > &< 2.8 \times 10^{-4} \\ < N_{\Theta_c(3100)^0} > \cdot Br(\Theta_c(3100)^0 \to D^{*+}\bar{p}) &< 8.8 \times 10^{-4} \, . \end{aligned}$$

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