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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 states composed of more than three quarks, like pentaquark systems. Controversial evidence for such states has been published in the last years, in particular: for a strange pentaquark $\Theta(1540)^+$; for a double-strange state, the $\Xi(1862)^{--}$, subsequently called $\Phi(1860)^{--}$; and for a charmed state, the $\Theta_c(3100)^0$. If confirmed, a full pentaquark family might exist; such pentaquark states could be produced in $e^+e^-$ annihilations near the Z energy. In this Letter a search for pentaquarks is described using the DELPHI detector at LEP, characterized by powerful particle identification sub-systems crucial in the separation of the signal from the background for these states. At 95% CL, upper limits are set on the production rates $\langle N\rangle$ of such particles and their charge-conjugate state per Z decay: $\langle N_{\Theta^+}\rangle \times \mathrm{Br}(\Theta^+ \to pK^0_S) < 5.1\times 10^{-4}$, $\langle N_{\Theta^{++}}\rangle < 1.6\times 10^{-3}$, $\langle N_{\Phi(1860)^{--}}\rangle \times \mathrm{Br}(\Phi(1860)^{--} \to \Xi^-\pi^-) < 2.9\times 10^{-4}$, $\langle N_{\Theta_c(3100)^0}\rangle \times \mathrm{Br}(\Theta_c(3100)^0 \to \mathrm{D}^{*+}\bar{p}) < 8.8\times 10^{-4}$.
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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]. More recent experimental evidence [3], however, may suggest the existence of pentaquark systems. The first possible candidate is[1] the $\Theta(1540)^+$, with mass of $(1.54 \pm 0.01)$ 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 $\Xi(1862)^{--}$ (subsequently called $\Phi(1860)^{--}$, see [5]), has been claimed by the CERN experiment NA49 [6], with mass of $(1862\pm 2)$ MeV$/c^2$.

Later, the DESY experiment H1 has reported a signal for a charmed exotic baryon in the pD$^{*-}$ channel [7], the $\Theta_c(3100)^0$. This resonance was reported to have a mass of $(3099 \pm 3(\mathrm{stat}) \pm 5(\mathrm{syst}))$ 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 [8].

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[1] Charge conjugated states are implied throughout this Letter.

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

This Letter reports on the results of a search for pentaquark states in hadronic Z decays recorded by DELPHI. In a similar analysis, ALEPH [9] did not observe significant signals. The powerful particle identification characterizing the DELPHI detector might facilitate this search, since this feature helps in detecting and separating from the background some decay states of pentaquarks.

The Letter is organized 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 $\mathrm{pK}^0$ (the $\Theta^+$) and the $\mathrm{pK}^+$ (the $\Theta^{++}$) channels. Section 4 presents a search for a doubly-charged, doubly-strange pentaquark (the $\Phi(1860)^{--}$). 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 [10], and its performance is analyzed in [11].

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[2] 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 $\theta$ 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 from 23° to 157° in $\theta$ (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 cm 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 specific 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 provides particle identification in the momentum range from 0.7 to 45 GeV/$c$.

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

To compute the selection efficiency of the various channels studied, $\mathrm{Z} \to q\bar{q}$ events were simulated using the JETSET parton shower generator [12] 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 [11]. The amount of simulated events is more than twice the real data.

For the $\Theta^+$, $\Theta^{++}$ and $\Phi(1860)^{--}$ searches, the data recorded during the LEP1 operation in the years 1991 to 1995 were used. For the $\Theta_c(3100)^0$ search, the analysis was restricted to the years 1994 and 1995, the two highest luminosity years of LEP1, with all DELPHI particle identifiers fully operational.

## 3. Search for strange pentaquarks in the pK system

The state $\Theta^+$ can be detected through its decay into $\mathrm{pK}^0$ pairs; the state $\Theta^{++}$ could be detected through its decay into $\mathrm{pK}^+$. Therefore the invariant mass distributions of $\mathrm{pK}^0$ and $\mathrm{pK}^+$ pairs in hadronic Z decays were studied. These were compared with the $\mathrm{pK}^-$ spectrum, where the $\Lambda(1520)$ is observed.

### 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, $\theta_{\mathrm{thrust}}$, was computed for each event and events were rejected if $|\cos\theta_{\mathrm{thrust}}|$ 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% within the angular acceptance.

In order to search for the pentaquark states, the $\mathrm{pK}^0$, $\mathrm{pK}^-$ and $\mathrm{pK}^+$ 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 are distinguished for each particle species as well as for so-called "heavy" tag, which severely reduces the fraction of charged pions. To further improve the quality of particle identi-

[2] In the standard DELPHI coordinate system, the $z$-axis is along the electron beam direction, the $x$-axis points towards the center of LEP, and the $y$-axis points upwards. The polar angle to the $z$-axis is called $\theta$ and the azimuthal angle around the $z$ axis is called $\phi$; the radial coordinate is $R = \sqrt{x^2 + y^2}$.

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

| | Momentum range in GeV/$c$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0.3–0.7 | 0.7–0.9 | 0.9–1.3 | 1.3–2.7 | 2.7–9.0 | 9.0–16.0 | 16.0–45.0 |
| $\pi$ | TPC | LRICH S | | | GRICH S | | |
| K | TPC | LRICH S | | | GRICH V + LRICH S | GRICH S | |
| p | TPC | | TPC + LRICH V | LRICH S | GRICH V + LRICH S | GRICH V | GRICH S |

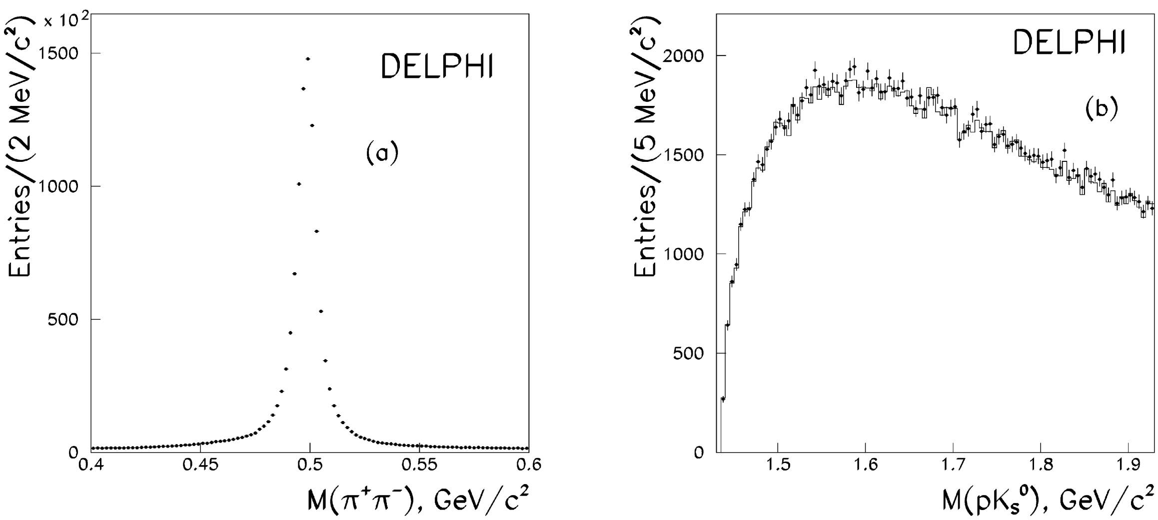


Fig. 1. (a) $\pi^+\pi^-$ invariant mass (b) $\mathrm{pK}^0_S$ mass spectrum. The histogram represents the simulation, while the points represent the data.

fication for a track of given momentum and (assumed) particle type it was required that information from the detectors specified in Table 1 was present. Only in the years 1994 and 1995 all particle identification detectors were fully operational; the identification was essentially only based on TPC during the years 1991 to 1993.

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 $p < 3.5$ and $p > 9.5$ GeV/$c$. In the intermediate momentum range kaons were also identified by a tight heavy particle tag [13] 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:

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

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 $\mathrm{pK}^0$ pairs was first studied. $\mathrm{K}^0$ candidates were obtained from the fit of charged particle tracks of opposite charge consistent with the pion hypothesis, as described in [11]. The $\pi^+\pi^-$ invariant mass is shown in Fig. 1(a).

The $\mathrm{pK}^0_S$ mass distribution is displayed in Fig. 1(b), for an invariant $\mathrm{K}^0_S$ mass between 0.45 and 0.55 GeV/$c^2$. No signal is visible in the $\Theta^+$ mass region; the simulation accounts very well for the data over the whole mass spectrum.

To set the limit on the $\Theta^+$ production, the fitting procedure as described above was applied, modeling a possible signal by a Gaussian function with a central value of 1.54 GeV/$c^2$ and a RMS width[3] of 10 MeV/$c^2$, equal to the resolution.

The $\mathrm{pK}^0_S$ selection efficiency was estimated from a Monte Carlo generated sample of $\Theta^+$ events to be $(6.4 \pm 0.3)\%$. The error is dominated by the systematic uncertainties coming from $\mathrm{K}^0_S$ reconstruction and proton identification.

The estimated number of events in the signal region was $-20 \pm 64$(stat). The corresponding upper limit, at 95% CL, on

[3] Throughout the Letter, if the fit is done by a Breit–Wigner function the width indicates the value of the $\Gamma$ parameter, while in the case of a Gaussian function it indicates the RMS error $\sigma$.

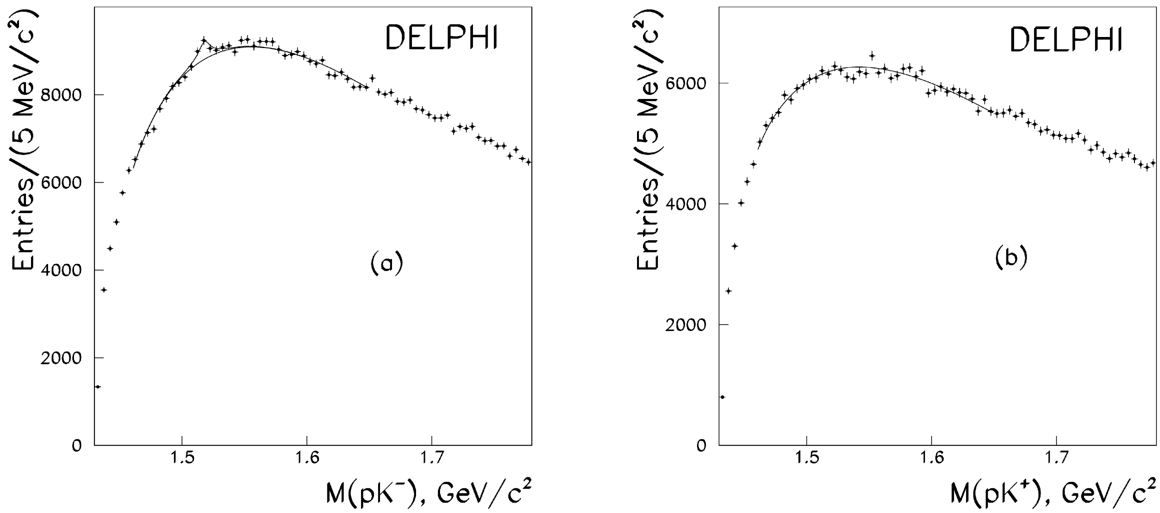


Fig. 2. (a) Differential $pK^-$ and (b) $pK^+$ mass spectra. The lines represent the fits described in the text.

the average production rate per hadronic event of the $\Theta^+$ is:

$$\langle N_{\Theta^+}\rangle \times \mathrm{Br}\big(\Theta^+ \to \mathrm{pK}^0_S\big) < 5.1 \times 10^{-4},$$

where the systematic uncertainty was added in quadrature to the statistical error. The result has been corrected for the branching fraction $\mathrm{Br}(\mathrm{K}^0_S \to \pi^+\pi^-)$.

### 3.3. Analysis of the $pK^-$ and $pK^+$ channels

The search for a possible $\Theta^{++}$ 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. Fig. 2(a) 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 $\phi(1020)$ region were discarded. The total excess in the $\Lambda(1520)$ region, measured from the fit to the mass spectrum of Fig. 2(a) is of:

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

with a mass of $1.520 \pm 0.002$ GeV/$c^2$ and a width of $0.010 \pm 0.004$ GeV/$c^2$, compatible with the experimental resolution. The $\chi^2$ per degree of freedom is 1.4. The $\Lambda(1520)$ selection efficiency determined from the simulation is $(12.8 \pm 0.5)\%$. This corresponds to an average $\Lambda(1520)$ production rate per hadronic event of $0.0217 \pm 0.0046$(stat) to be compared with the published value [5] of $0.0224 \pm 0.0027$.

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

An upper limit for the average production rate of the $\Theta^{++}$ can be determined over the range of its mass estimates (1.45–1.65 GeV/$c^2$), assuming the same efficiency as for the $\Lambda(1520)$. It should be taken into account that, since 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 $\Theta^{++}$ is twice that of the $\Lambda(1520)$.

A fit to the form (1) was performed by varying the mass between 1.45 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% CL were then calculated as a function of the mass, yielding a maximum signal of $350 \pm 187$ events. The systematic uncertainties on the production rate of a $\Theta^{++}$ with a mass close to the $\Lambda(1520)$ mass, can be expected to be of the same order as those of the $\Lambda(1520)$ production rate, which were estimated to be of 16% [14]. Such systematics are therefore negligible with respect to the error from the fit. A general limit

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

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

## 4. Search for doubly charged and doubly strange pentaquarks in the $\Xi^-\pi^-$ system

The exotic baryons with double charge and double strangeness were searched through the decay into $\Xi^-\pi^-$. The hadronic Z decays sample for this analysis is the same as described in Section 3.1; it corresponds to a total of 3.4 million hadronic events after the cuts, recorded in the years 1991 to 1995.

### 4.1. $\Xi^-$ reconstruction

The $\Xi^-$ 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 $\Lambda$ candidates. For each pair, the higher 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 [11].

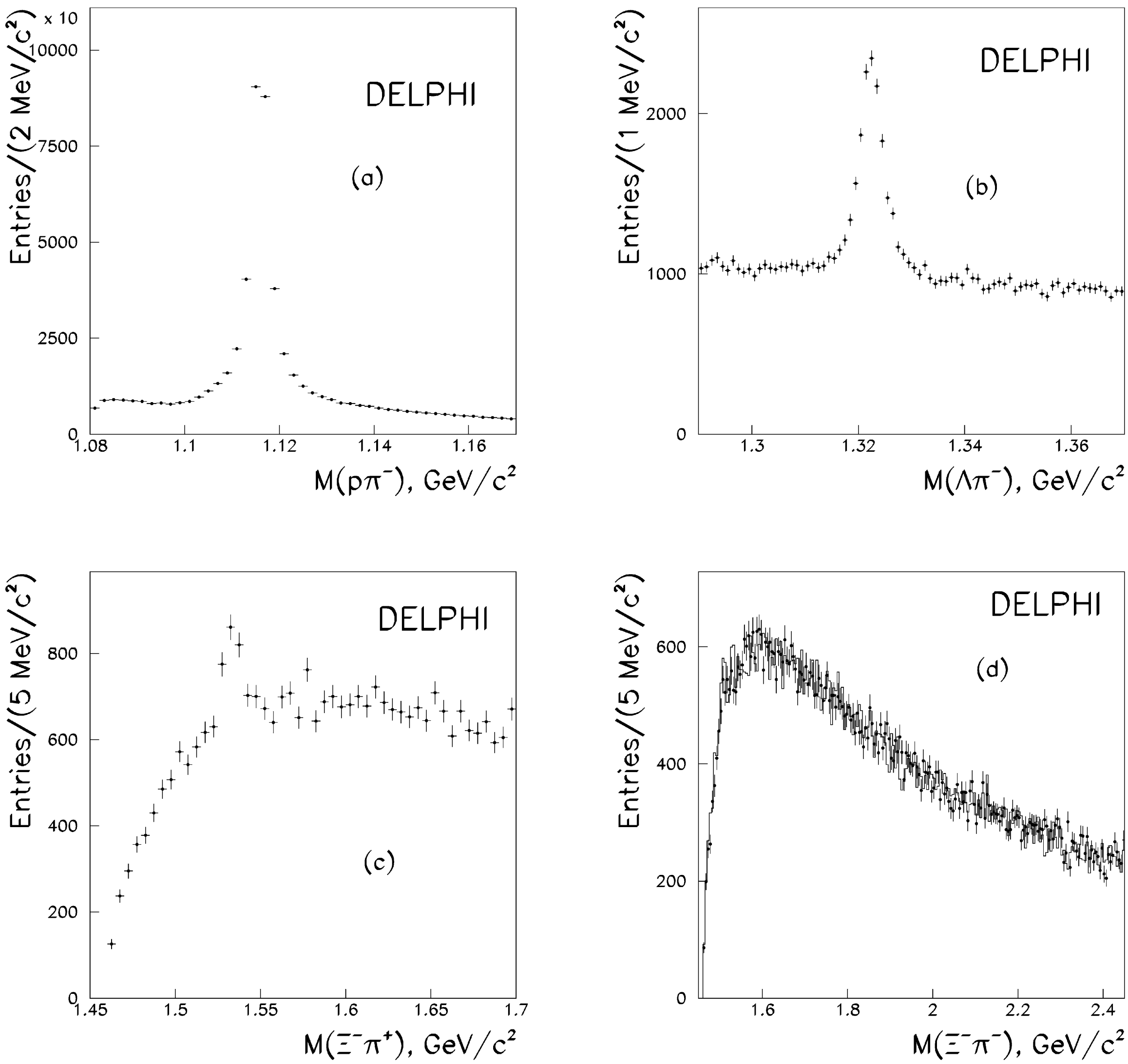


Fig. 3. (a) Invariant $p\pi^-$ mass spectrum. (b) Invariant $\Lambda\pi^-$ mass distribution. (c) Invariant $\Xi^-\pi^+$ mass distribution. (d) Invariant $\Xi^-\pi^-$ mass distribution. The histogram represents the simulation.

The $p\pi^-$ invariant mass is shown in Fig. 3(a). The $\Lambda$ candidates were selected by requiring an invariant mass $M(p\pi^-)$ between 1.100 and 1.135 GeV/$c^2$, a $\chi^2$ probability of the $V^0$ vertex fit larger than $10^{-5}$ and a decay length from the interaction point greater than 0.2 cm in the plane transverse to the beam.

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

The fit constrained the sum of the $\Lambda$ and $\pi$ momenta to be equal to the $\Xi^-$ momentum. The constraint on the $\Lambda$ decay products to give the nominal $\Lambda$ mass value $1115.683 \pm 0.006$ MeV/$c^2$ [5] was also applied.

The resulting $\Lambda\pi^-$ invariant mass spectrum after the fit is shown in Fig. 3(b).

### 4.2. Analysis of the $\Xi\pi$ system

Each reconstructed $\Xi^-$ candidate in the mass range 1.30–1.34 GeV/$c^2$ was combined with a pion.

The mass spectrum of neutral combinations $\Xi^-\pi^+$ is shown in Fig. 3(c); a clear $\Xi(1530)$ peak of $820 \pm 50$ events is observed. The production properties of $\Xi(1530)$ have already been measured by DELPHI in [16].

The mass spectrum of combinations $\Xi^-\pi^-$ is shown in Fig. 3(d). No significant excess is observed. The histogram shows the prediction of the simulation 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 $-50 \pm 75$, dominated by the error from the fit itself. The reconstruction efficiency of a possible $\Phi(1860)^{--}$ object decaying into $\Xi^-\pi^-$ has been computed from a Monte Carlo generated

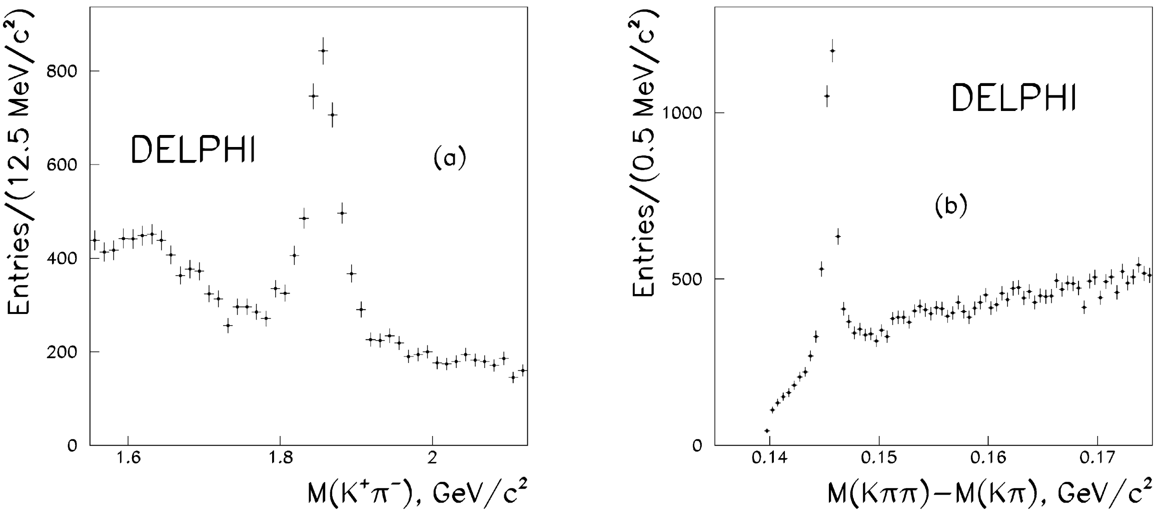


Fig. 4. (a) Invariant $K^+\pi^-$ mass. (b) Distribution of $\Delta M = M_{K\pi\pi} - M_{K\pi}$.

sample of $\Phi(1860)^{--}$ events, to be $(10.0 \pm 0.5)\%$; the error is dominated by the uncertainties on particle reconstruction and identification. This leads to an estimate of the upper limit of the production rate of a $\Phi(1860)^{--}$ object decaying into $\Xi^-\pi^-$ per hadronic Z decay, at 95% CL:

$$\langle N_{\Phi(1860)^{--}}\rangle \times \mathrm{Br}\big(\Phi(1860)^{--} \to \Xi^-\pi^-\big) < 2.9 \times 10^{-4}.$$

## 5. Search for charmed pentaquarks in the D*p system

### 5.1. Event selection

After the standard hadronic event selection criteria listed in Section 3.1 were applied to the data collected in 1994 and 1995, about 2.1 million hadronic events remained.

Events containing the decay chain $D^{*+} \to D^0X \to K^-\pi^+X$ were selected as a first step of the analysis. The following selection criteria were required to suppress the background:

- $x_E(K\pi) \geqslant 0.15$, 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 angle between the K and $\pi$ momenta were smaller than 90° in the $D^*$ system;
- the momentum of the bachelor pion (the soft pion coming from the $D^* \to D\pi$ decay) had to be between 0.3 and 2.5 GeV/$c$, and the angle between the bachelor $\pi$ momentum in the rest frame of the reconstructed $D^0$ and the momentum of the $D^0$ candidate had to be smaller than 90°;
- 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 $K\pi$ system had to be between 1.79 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 and 0.1485 GeV/$c^2$;
- the K and $\pi$ 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.

### 5.2. Analysis of the D*p system

The $M_{K\pi}$ and $\Delta M$ spectra obtained after the cuts listed above are shown in Fig. 4. The backgrounds around the very clear $D^0$ and $D^*$ (corresponding to the decay $D^* \to D^0\pi$) peaks are quite small.

Fig. 5 shows the invariant mass distributions of $D^*p$, for total charge zero (right charge for a possible pentaquark) and total charge 2 (wrong charge) respectively. No narrow resonance peak around 3.1 GeV/$c^2$ is seen in Fig. 5(a), which corresponds to the right charge.

To obtain an upper limit for the production of a possible $\Theta_c(3100)^0$ state, a pentaquark signal was simulated; the detection efficiency for a $\Theta_c(3100)^0$ state decaying into $D^{*+}\bar{p}$ was estimated to be about 0.8%, taking into account the relevant branching fractions of the $D^*$ and of the $D^0$.

The best fit to the mass distribution of right charge pairs for a mass of 3100 MeV/$c^2$ and a width corresponding to the experimental resolution, with the same procedure as described in the previous sections, gives an excess of $7 \pm 4$ events. The systematic uncertainties, dominated by the uncertainties on particle identification efficiencies, are negligible with respect to the error from the fit. The 95% CL upper limit on the average production rate, per hadronic Z decay, of a $\Theta_c(3100)^0$ object decaying into $D^{*+}\bar{p}$, is

$$\langle N_{\Theta_c(3100)^0}\rangle \times \mathrm{Br}\big(\Theta_c(3100)^0 \to D^{*+}\bar{p}\big) < 8.8 \times 10^{-4}. \quad (3)$$

## 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% CL on the average production rates $\langle N\rangle$ of such particles and their charge-conjugate state per

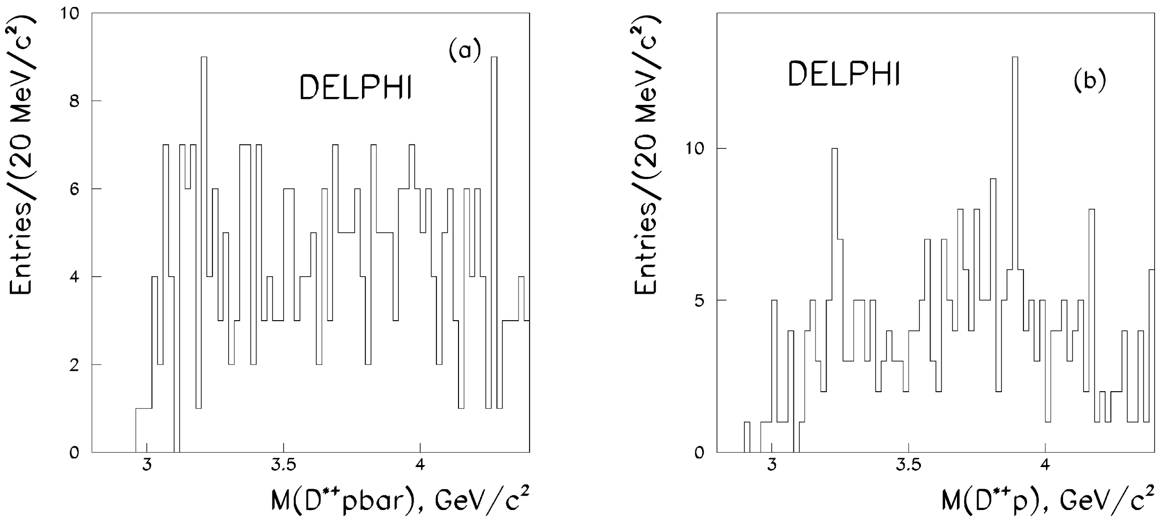


Fig. 5. Invariant masses (a) $M(\mathrm{D}^{*+}\bar{\mathrm{p}})$ and (b) $M(\mathrm{D}^{*+}\mathrm{p})$.

hadronic Z decay:

$\langle N_{\Theta^+}\rangle \times \mathrm{Br}(\Theta^+ \to \mathrm{pK}^0_S) < 5.1 \times 10^{-4}$,

$\langle N_{\Theta^{++}}\rangle < 1.6 \times 10^{-3}$,

$\langle N_{\Phi(1860)^{--}}\rangle \times \mathrm{Br}(\Phi(1860)^{--} \to \Xi^-\pi^-) < 2.9 \times 10^{-4}$,

$\langle N_{\Theta_c(3100)^0}\rangle \times \mathrm{Br}(\Theta_c(3100)^0 \to \mathrm{D}^{*+}\bar{\mathrm{p}}) < 8.8 \times 10^{-4}$.

These limits improve previously published results [9].

In recent years thermodynamical [17] and phenomenological models [18,19] have appeared, which successfully describe the overall particle production rates in high energy interactions with very few parameters. According to the model by Becattini [17], the average production rate for the production of the $\Theta^+$ at the Z energy should be of 0.007. According to the model by Chliapnikov and Uvarov [18], the average production rate is expected to be less than $5 \times 10^{-6}$, if the $\Theta^+$ is dominantly produced from the intermediate $N^*/\Delta^*$ baryon state with the mass of 2.4 GeV$/c^2$ as indicated by the CLAS experiment [3]. On the other hand, if the $\Theta^+$ 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 $0.0224 \pm 0.0027$ per hadronic event [5].

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