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Search for Pentaquarks in the Hadronic Decays of the Z Boson

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Abstract

The quark model does not exclude pentaquark systems. A possible candidate for a pentaquark system is the Θ^+, with strangeness S=+1 and a mass around 1.54 GeV/c^2, for which there is recent controversial evidence; if confirmed, a full pentaquark family might exist. Such pentaquark states should be produced in a significant way in e^+e^- annihilations near the Z energy. Some of these states could be detected and separated from the background using particle identification, like the ones which characterize the DELPHI detector. In this paper a search for pentaquarks using the DELPHI detector is described.

1 Introduction

The quark model does not exclude pentaquark systems. However, until recently, only bound triplet-quark and quark-antiquark systems have been found. Recent experimental evidence [1] may suggest the existence of a pentaquark system. The possible candidate is 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 evidence is still controversely discussed.

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. Theoretical calculations on the characteristics of the pentaquark family have been published (see e.g. [2]).

Pentaquark states should be produced in a significant way in e^+e^- annihilations at high energy. In recent years thermodynamical [3] and phenomenomenological models [4, 5] 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 multiplicity for the production of the Θ^+ should be [6] of 0.007. According to the model by Chliapnikov and Uvarov [7], the average production rate is expected to be less than 5 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 [1]. 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 multiplicity of 0.0224 ± 0.0027 per hadronic event [8].

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]). In particular, the state Θ^+ could be detected through its decay into pK^0 pairs[1]; the state Θ^{++} could be detected through its decay into pK^+.

This paper 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 paper were collected by the DELPHI detector 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.

This paper is organised as follows. Section 2 gives a brief overview on the detector, experimental procedures used to select tracks and hadronic events as well as on the experimental procedures used for the identification of the decay products of pentaquarks; finally it presents the results of the search for pentaquarks. We conclude in Section 3, where results are compared to the expectation of a phenomenological model for the production of bound states in Z decays.

2 Analysis and Results

The DELPHI detector is described in detail in [10], and its performance is analyzed in [9]. The present analysis relies on information provided by the central tracking detectors and

[1]The antiparticles are always implicitly included.

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 layer 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 (in 1995 straw tube) layers. The jet chamber, between 12 and 23 cm in R and 23°and 157°(15°-165°for 1995) 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%.

- 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.

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

- There were at least 5 well measured charged particles in the event, each with momentum larger than 300 MeV/c and a polar angle in the sensitive angular range of the tracking devices.

- The total reconstructed energy of these charged tracks has to be larger than 11 GeV of the centre-of-mass energy.

- The total energy of the charged particles in each detector hemisphere (defined by the plane perpendicular to the beam axis) has to exceed 3 GeV of the centre-of-mass energy.

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

After these cuts 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.

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 $47^\circ < \theta < 133^\circ$ 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 $\mathrm{pK}^-(\bar{\mathrm{p}}\mathrm{K}^+)$ 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 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 [11] combined with at least a standard kaon tag.

Figure 1 shows the pK^- invariant mass spectrum. A clear $\Lambda(1520)$ signal is observed at about the expected mass. 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.

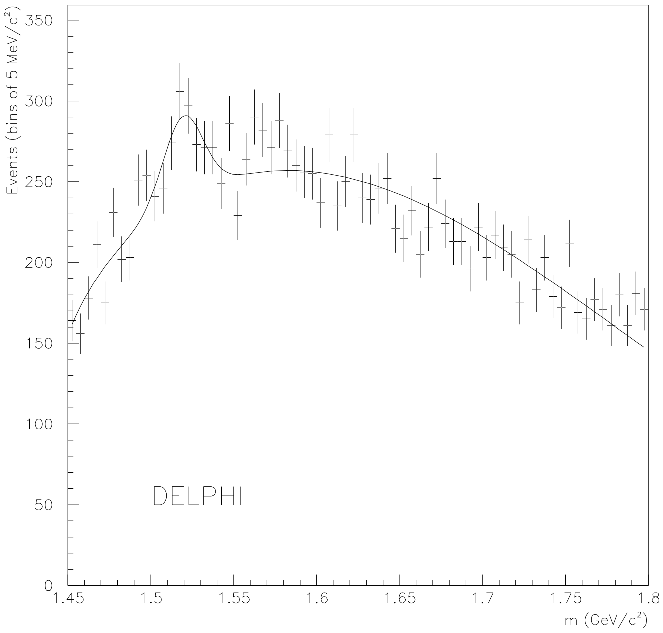

Figure 1: Differential pK$^-$ mass spectra for the overall measured energy range. The line represents the fit described in the text.

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_3 is the fitted peak mass, m.

The background term, $f^B(M, \vec{a})$, was taken [12] to be of the form

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

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

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

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 multiplicity of 0.0224 ± 0.0027 $\Lambda(1520)$ per hadronic event [8].

The invariant mass spectrum for pK$^+$ pairs, obtained using the same cuts, is plotted in Figure 2. 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 multiplicity 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

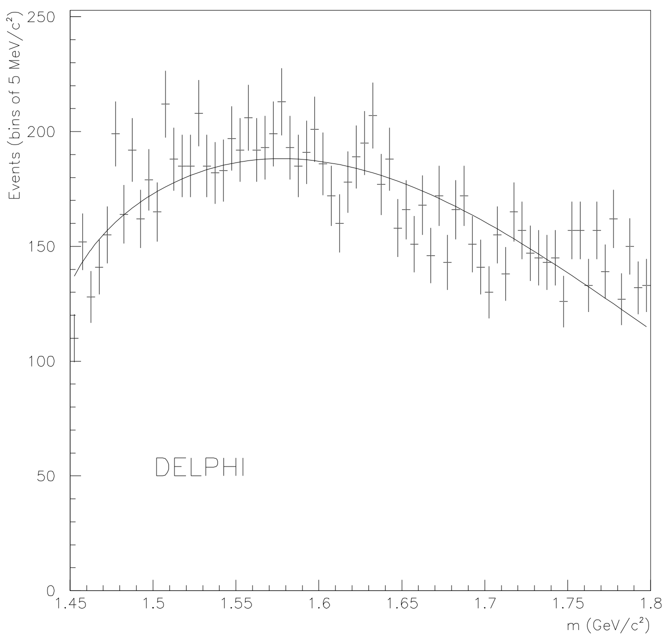

Figure 2: Differential pK^+ mass spectra for the overall measured energy range. The line represents the fit described in the text.

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 3. A general limit

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

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 [9]. The reconstruction efficiency was estimated as the efficiency for the pK^- pairs, divided by the ratio of pK^- to pK^0 pairs in the mass region below 1.8 GeV/c^2. Again no signal was found (Figure 4); 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 multiplicity of the Θ^+ is:

$$< N_{\Theta^+} > \; < 0.015 \, .$$

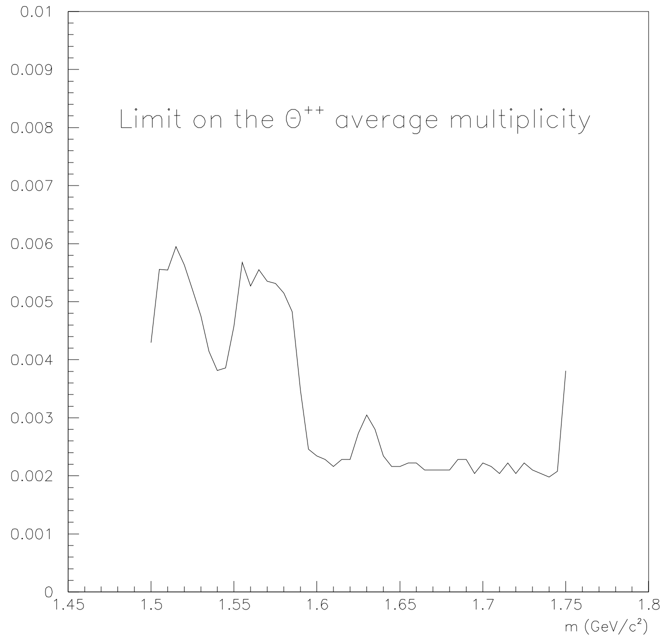

Figure 3: 95% limit obtained for the average multiplicity of the Θ^{++} as a function of the mass.

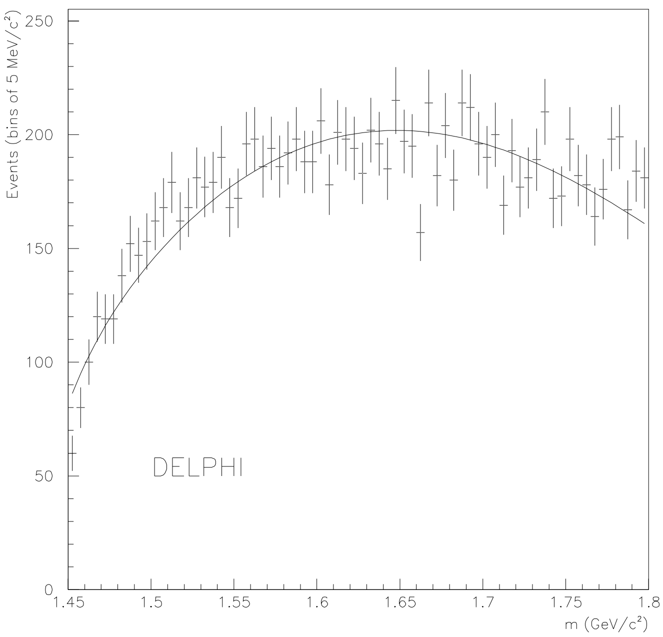

Figure 4: Differential pK^0 mass spectra for the overall measured energy range. The line represents the fit described in the text.

3 Conclusions

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 multiplicity per hadronic event [8] $< N_{\Lambda(1520)} >= 0.0224 \pm 0.0027$.

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

$$< N_{\Theta^{++}} > \quad < \quad 0.006 \tag{5}$$

$$< N_{\Theta^{+}} > \quad < \quad 0.015\,, \tag{6}$$

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

Our upper limits are comparable with the predictions of thermodynamical models accounting for the average multiplicity of identified final states.

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