PROCEEDINGS OF SCIENCE

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

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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 $\Xi(1862)^{--}$ and for a charmed state $\Theta_{c}(3100)^{0}$. Such states should be produced in $e^{+}e^{-}$ annihilations in Z decays. In this paper a search for pentaquarks using the DELPHI detector is described. Preliminary upper limits at 95% C.L. are set on the production rates per Z decay of such particles and their charge-conjugate state.

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1. Introduction

The quark model does not exclude pentaquark bound states for four quarks and one antiquark, e.g. $uudd\bar{s}$. Several models predicts the multiplet structure and characteristics of pentaquarks, for example the choral soliton model, the uncorrelated, correlated quark models, the thermal model, lattice QCD, etc. [1].

Recent experimental evidence [2] may suggest the existence of pentaquark systems. The first 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 ($uudd\bar{s}$). Subsequently, evidence for another exotic baryon doubly charged and with doubly strangeness, the $\Xi(1862)^{--}$, has been published by the CERN experiment NA49 [3]. More recently, the DESY experiment H1 has reported a signal for a charmed exotic baryon in the pD^{*-} channel[4], the $\Theta_c(3100)^0$, with a mass of $3099 \pm 3(stat) \pm 5(syst)$ MeV/c^2 and measured width compatible with the resolution. It is interpreted as a constituent quark composition of $uudd\bar{c}$.

Pentaquark states might be produced in a significant way in e^+e^- annihilations in Z boson decays[5]. This paper reports on the results of a search for the $\Theta(1540)^+$, Θ^{++}, $\Xi(1862)^{--}$ and $\Theta_c(3100)^0$ pentaquark states in hadronic Z decays recorded by DELPHI at LEP.

2. Experimental Procedure

The analysis is based on a data sample of over 3 million hadronic Z decays collected from 1991 to 1995 with the DELPHI detector at LEP. The detector is described in detail in [6] and its performance is analyzed in [7].

A charged particle has been accepted in this analysis if, typically, its momentum p is greater than 300-400 MeV/c, its momentum error $\Delta p/p$ is less than 1 and its impact parameter with respect to the nominal crossing point is within 3-4 cm in the transverse (xy) plane and 3-4 cm/$sin\theta$ along the beam direction (z-axis), θ being the polar angle of the track.

Hadronic events are then selected by requiring basically, at least 4 charged particles, 3 GeV as minimum energy of the charged particles in each hemisphere of the event and total energy of the charged particles of at least 11% of the centre-of-mass energy.

Charged particle identification has been provided by the Ring Imaging Cherenkov detector (RICH) for particles with momenta above 700 MeV/c, while the ionization loss measured in the Time Projection Chamber (TPC) as been used for momenta above 100 Mev/c.

The K_s and Λ candidates are detected by their decay in flight into $\pi^+\pi^-$ and $p\pi^-$ respectively. The details of the reconstruction method and the various cuts applied are described in [8].

3. Search for Strange Pentaquarks in the pK^0 and the pK^+ Channels

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

The study was restricted to the 1994 and 1995 data taking periods during which the TPC and RICH detectors were optimally set up and functioning especially for particle identification.

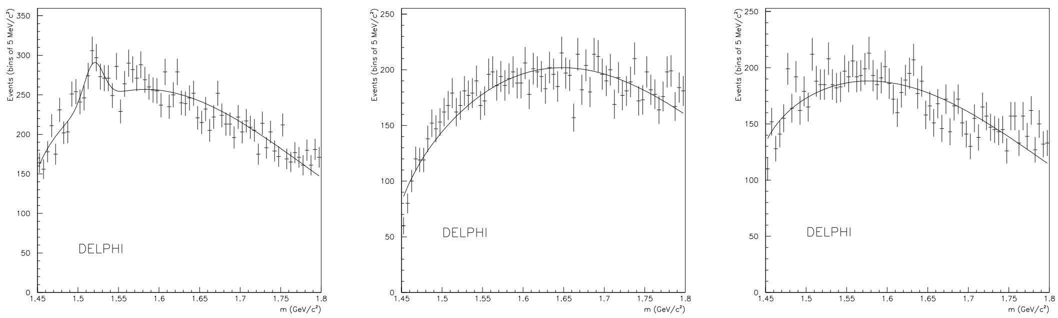

Figure 1: left: (πK^-), middle: (πK^0), right: (πK^+) invariant mass spectra. The curves are the results of the fi ts described in the text.

Analysis of the pK **system:** We first analyzed the $pK^-(\bar{p}K^+)$ invariant mass distribution constructed using identified particles. Fig. 1(left) shows the pK^- invariant mass spectrum. A clear $\Lambda(1540)$ signal is observed at the expected mass, consistent with published results [9]. This invariant mass distribution was fitted to the sum of the a phase space-like term and normalized Gaussian function accounting for the $\Lambda(1540)$ production. The excess of events in the $\Lambda(1540)$ region is of 306 ± 55 events, with a fitted mass and width of 1.520 ± 0.002 GeV/c^2 and 0.010 ± 0.004 GeV/c^2 respectively. The χ^2 per degree of freedom is 1.4. This corresponds to an average $\Lambda(1540)$ production rate per hadronic events of 0.0224 ± 0.0027, compatible with the value reported in [10].

The invariant mass distribution for pK^0 pairs in Fig. 1(middle). No Θ^+ signal is visible around 1.54 Gev/c^2. We performed the same fit as described above. The χ^2 per degree of freedom of the fit is of 1.3. the upper limit at 95% C.L. on the average production rate of the Θ^+, derived from the fit and corrected for inefficiencies is $\langle N_{\Theta(1540)^+} \rangle < 0.005$.

The invariant mass spectrum for pK^+ pairs is shown in Fig. 1(right). No Θ^{++} peak is visible anywhere. The mass fit was repeated over the range of the Θ^{++} mass estimates, i.e. between 1.50 GeV/c^2 and 1.75 GeV/c^2. The χ^2 per degree of freedom of the fit is of 1.7. The corresponding 95% C.L. upper limit on the average Θ^{++} production rate per hadronic Z boson decay, is $\langle N_{\Theta^{++}} \rangle <$ 0.006.

4. Search for Doubly Charged and Doubly Strange Pentaquarks

In this analysis, in addition to the hadronic selection already described. The Ξ^- hyperon was reconstructed through the decay $\Xi^- \to \Lambda\pi^-$. For this, Λ candidates were reconstructed using the standard DELPHI V^0 search algorithm [7] and imposing the invariant mass $M(p\pi^-)$ to be between 1.10 GeV/c^2 and 1.135 GeV/c^2. A multivertex fit was then performed on each Ξ^- candidate decaying into $\Lambda\pi^-$ [10]. The resulting spectrum of the $\Lambda\pi^-$ invariant mass is shown in Fig. 2(left).

Analysis of the $\Xi\pi$ **system:** Fig. 2(middle) shows the invariant mass distribution of reconstructed Ξ^- candidate in the mass range between 1.30 GeV/c^2 combined with a π^+. A clear $\Xi(1540)$ peak of about 820 ± 50 events is observed.

The mass spectrum of $\Xi^-\pi^-$ combinations is shown in Fig. 2(right). No significant excess is observed in the 1.86 GeV/c^2 mass region. The histogram is the JETSET7.3 [11] prediction for the

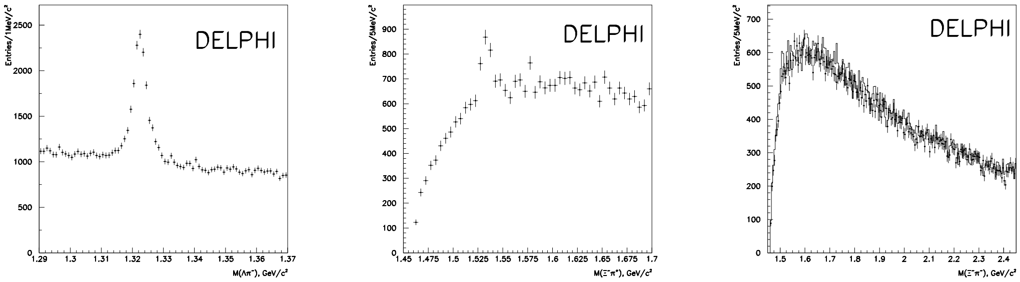

Figure 2: left: $(\Lambda\pi^-)$, middle: $(\Xi^-\pi^+)$, right: $(\Xi^-\pi^-)$ invariant mass spectra. The histogram on the right figure is the MC simulated sample of events.

$\Xi^-\pi^-$ spectrum without pentaquark. We performed a fit of the $\Xi^-\pi^-$ spectrum to a polynomial background and a Gaussian a central value of 1.862 GeV/c^2 and a width of 0.015 GeV/c^2 equal in this mass region. The fitted number of events is equal to -50 ± 75. The reconstruction efficiency, estimated from a Monte Carlo generated sample of $\Xi(1862)^{--}$ events decaying into $\Xi^-\pi^-$ is $(10.0 \pm 0.5)\%$. This leads to a 95% C.L. estimate of the upper limit of the production rate of a $\Xi(1862)^{--}$ object, of $\langle N_{\Xi}(1862)^{--}\rangle < 2.8 \times 10^{-4}$.

5. Search for Charmed Pentaquarks

This study was also restricted to the 1994 and 1995 data taking periods. After the standard hadronic event selection applied, events corresponding to the decay chain $D^{*+} \to D^0 \to K^-\pi^+$ were selected as a first step of the analysis.

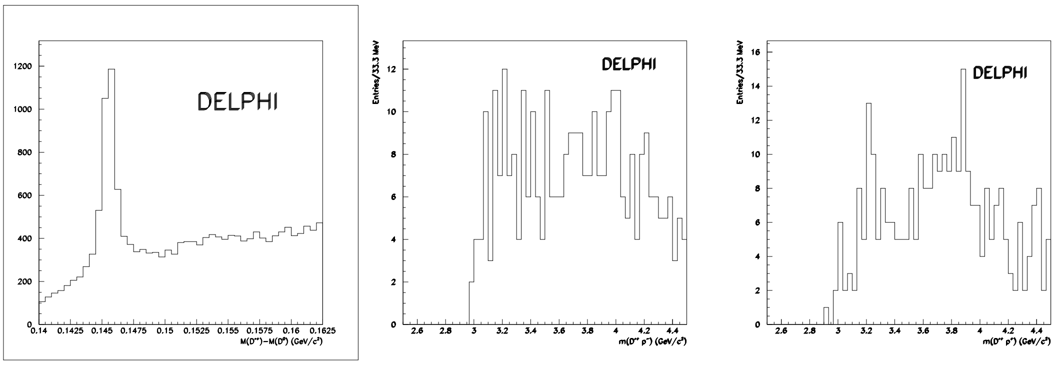

Figure 3: left: $(M(D^{*+}) - M(D^0))$, middle: $(D^* + \overline{p})$, right: $(D{*}{+}p)$ invariant mass spectra.

Additional cuts were performed to suppress the background: $x_E(D^0) > 0.15$, where x_E is the energy fraction with respect to the beam energy; the momentum of the bachelor pion had to be between 0.3 GeV/c and 2.5 GeV/c; the decay length of the D^0 had to be larger than 0 and smaller than 2.5 cm; 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; $cos\theta_K > -0.9$, where $cos\theta_K$ is the angle between the D^0 flight direction and the K direction in the D^0 rest frame; the K candidates should not have a positive identification as a pion.

The distribution of $\Delta M = M_{K\pi\pi} - M_{K\pi}$ with 1.79 GeV/c^2 $< M_{K\pi} <$1.91 GeV/c^2 is shown in Fig. 3(left). One can see a very clear D^* peak over a quite small background.

Analysis of the D^*p system: Fig. 3(middle and right) shows the effective mass distributions of $D^* p$ for total charge zero and for absolute total charge 2 respectively. No narrow resonance peak around 3.1 GeV/c^2 shows up. A 95% C.L. estimate of the upper limit for the production rate, per Z hadronic decay, of a possible $\Theta_c(3100)^0$ state has been worked out, correcting for inefficiencies estimated from a Monte Carlo generated sample of $\Theta_c(3100)^0$ events decaying into $D^* p$. It is: $\langle N_{\theta_c(3100)^0}\rangle < 8.8 \times 10^4$.

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 $\langle N\rangle$ of such particles and their charge-conjugate state per Z decay:

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

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