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PRELIMINARY

Search for pentaquark states in Z decays

The ALEPH Collaboration

Contact person: Peter Hansen (phansen@nbi.dk)

Abstract

A search for exotic baryons containing five quarks has been carried out in hadronic Z decays using the ALEPH detector at LEP I. No significant signal has been found. At the 95% confidence level, limits can be set on the production rates per hadronic Z decay of exotic states observed in other experiments:

$$\begin{aligned} N_{\Theta(1535)^+} &< 0.0030 \\ N_{\Xi(1862)^{--}} \cdot BR(\Xi^{--}_{1862} \to \Xi^- \pi^-) &< 4 \cdot 10^{-4} \\ N_{\Theta_c(3100)^0} \cdot BR(\Theta^0_c \to D^{*-} p) &< 6 \cdot 10^{-4} \\ N_{\Theta_c(3100)^0} \cdot BR(\Theta^0_c \to D^- p) &< 25 \cdot 10^{-4} \\ N_{\Theta_c(3100)^+} \cdot BR(\Theta^+_c \to \bar{D}^0 p) &< 15 \cdot 10^{-4} \end{aligned}$$

where the charge conjugated states are included in the limits. Also limits on the ratio to non-exotic related particles are obtained:

$$\begin{aligned} \frac{N_{\Theta^+}}{N_{\Lambda(1520)}} &< 0.13 \\ \frac{N_{\Xi(1862)^{--}}}{N_{\Xi(1530)^0}} \cdot BR(\Xi^{--}_{1862} \to \Xi^- \pi^-) &< 0.06 \end{aligned}$$

1 Introduction

Although QCD allows several different stable configurations of quarks and gluons, observations have, until recently, only revealed baryonic states that can be explained as bound states of three quarks. During 2003, however, a large body of experimental evidence was presented for the existence of baryonic states that can not be explained in the three quark picture.

The first observation was a five σ signal for a narrow resonance at 1540 ± 10 MeV/c^2, named Θ^+, in the reaction $\gamma n \to K^-\Theta^+$ followed by $\Theta^+ \to K^+ n$ [1]. The resonance must be a relatively stable baryon with positive strangeness, which is unexplainable in the three quark model, but possible in a five quark interpretation, $(uudd\bar{s})$. This observation was confirmed by many experiments at different laboratories [2, 3, 4, 5, 6, 7], each reporting a narrow peak of about 5σ significance in the nK^+ or pK^0_S channel from the reactions of photon, neutrino or K-meson beams on a nucleon target. The observed masses are consistent and average about 1535 MeV/c^2. From the weak signal of the resonance in K^+n formation reactions, an upper limit of 2 MeV was set on the Θ^+ width [9]. Shortly after, another exotic baryon, doubly charged and doubly strange with a mass of 1860 MeV/c^2, was claimed by the CERN experiment NA49 [8]. More recently, the DESY experiment H1 has observed a possible signal for a relatively stable state at 3100 MeV/c^2 in the pD^{*-} channel [10].

The observed states are in agreement with a prior prediction from the chiral soliton model [11]. Alternative explanations have recently been proposed, invoking "molecules" of tightly coupled quark configurations [12, 13, 14]. The production mechanism could be quite unusual: in the CLAS experiment, a strong contribution seems to come from the decay of a heavy exited nucleon state with a mass around 2400 MeV/c^2 [5]. It is therefore of interest to investigate the formation of these states in e^+e^- reactions [15].

In this study, the exotic baryons are searched for in the fragmentation of quarks from about 4 million hadronic Z decays recorded by the ALEPH experiment during the LEP I operation in the years 1991 to 1995. The (all negative) results from the searches are compared with the positive signals for non-exotic states, such as the $\Lambda(1520)$ and the $\Xi(1530)^0$.

Throughout this paper, any reference to a hadronic state, such as pK^+, implicitely includes also its charge conjugated state, i.e. $\bar{p}K^-$ in this case.

2 Event selection and particle identification

The data used for this analysis consist of the hadronic Z decays recorded by ALEPH during the period 1991 to 1995 in a LEP centre-of-mass energy range within 3 GeV from the Z resonance. Charged tracks are reconstructed in the tracking detectors as described in details elsewhere [17]. In this study, events are selected with at least six charged tracks in the TPC carrying at least 10% of the centre-of-mass energy, ensuring a pure sample of $Z \to q\bar{q}$ events. The thrust axis is required to have an angle to the beam axis exceeding 25° in order to select well measured events. A total of 3.5 million hadronic Z decays are retained, corresponding to 87% of the total hadronic cross-section.

Charged tracks are identified as particles by the ionization loss measurement, dE/dx, using pulse heights from both wires and pads in the TPC. This measurement yields a 2σ π/K separation at momenta exceeding about 2 GeV and excellent particle identification for momenta below about 1 GeV. For intermediate momenta the separation power is poor, and such tracks are ignored in this study. The variable used to identify a particle of type i is the pull:

$$R_i = \frac{\mathrm{dE/dx}(measured) - \mathrm{dE/dx}(expected\ for\ i)}{\sigma(expected\ for\ i)}$$

which is a function of momentum and polar angle.

The identified particles fulfil the following criteria:

$\pi^{\pm}$: $|R_\pi| < 2.5$.

K$^{\pm}$: $|R_K| < 2$ always. $R_\pi < -1.5$ for $p > 1.5$ GeV/c, or $|R_\pi| > 2$ and $|R_e| > 2$ for $p < 0.8$ GeV/c.

p$^{\pm}$: $|R_p| < 2$ always. $R_\pi < -3$ and for $p > 2$ GeV/c, or $R_\pi > 2.5$ and $|R_K| > 2$ and $|R_e| > 2$ for $p < 1.2$ GeV/c.

These criteria select 1.3 million proton candidates with a purity of 52% in the high momentum range and 96% in the low momentum range, according to simulation.

Oppositely charged pairs of tracks are tested for the hypothesis that they are decay products of either a K^0_S or a Λ created at the primary vertex and living for at least 10% of their average lifetime. If the χ^2 of the test (which has 3 degrees of freedom, see Reference [18]) is less than 20, the particular V0 hypothesis is accepted. These criteria select e.g. 1.24 million K^0_S candidates with a purity of 93% .

For Λ candidates, the primary vertex constraint is released and the hypothesis that they originate from a Ξ^- decay is tested in a similar way.

Other kinds of secondary interactions, such as photon conversions, nuclear interactions in the detector material and long-lived weak decays of pions, kaons and Σ hyperons are also tagged by a similar algorithm. Tracks from these interactions are ignored in the analysis.

Finally, combinations of a kaon candidate together with two or three pions are tested for a common vertex of origin. If this vertex is separated by more than 2σ from the primary vertex, the combination is tagged as D-meson candidate. For more details, see Reference [19].

3 Search for narrow resonances in the pK system

The Θ^+ signal has been located by other experiments to be in the mass range 1525 MeV/c^2 to 1545 MeV/c^2. In lack of a simulation of such a signal in ALEPH, the mass resolution is deduced from measurements of the widths of various known resonances with Q values between zero and 200 MeV. Using the track selection and particle identification described in the previous section, the mass resolution for $\phi \to K^+K^-$ is found to average 4 MeV/c^2, the resolution for $\Xi^- \to \Lambda\pi^-$ is 2-3 MeV/c^2 and the resolution for $K^* \to \pi K^0_S$ is 6 MeV/c^2. The average resolution for $\Theta^+ \to pK^0_S$ is therefore estimated to be 5 MeV/c^2 with a 1 MeV/c^2 uncertainty.

The mass distribution of pK^0_S combinations is shown in Figure 1 and is found to be in reasonable agreement with the standard ALEPH JETSET simulation [20, 23], incorporating octet and decuplet baryon states but no other baryon resonances, and with parameters, such as heavy flavor hadron properties, tuned to agree with ALEPH measurements. In this and in all the following plots, the simulation is normalized to the total content of data in the plot if nothing else is stated.

An upper limit on the number of $\Theta^+ \to pK^0_S$ decays is obtained from the maximum number of combinations in a sliding window of width 20 MeV/c^2 in excess of a smooth 3rd degree polynomial fit to the data over a long range (1460–1800 MeV/c^2). The fit is made to the data rather than to the MC because the data get contributions from various known, but unsimulated, broad Σ^* resonances in this mass range. The window is slided from 1505 MeV/c^2 to 1570 MeV/c^2 and the maximum excess is found in the interval 1525–1545 MeV/c^2 to be 57 combinations over a background of 2840. The systematic error is estimated to be 50 combinations by varying the resolution and

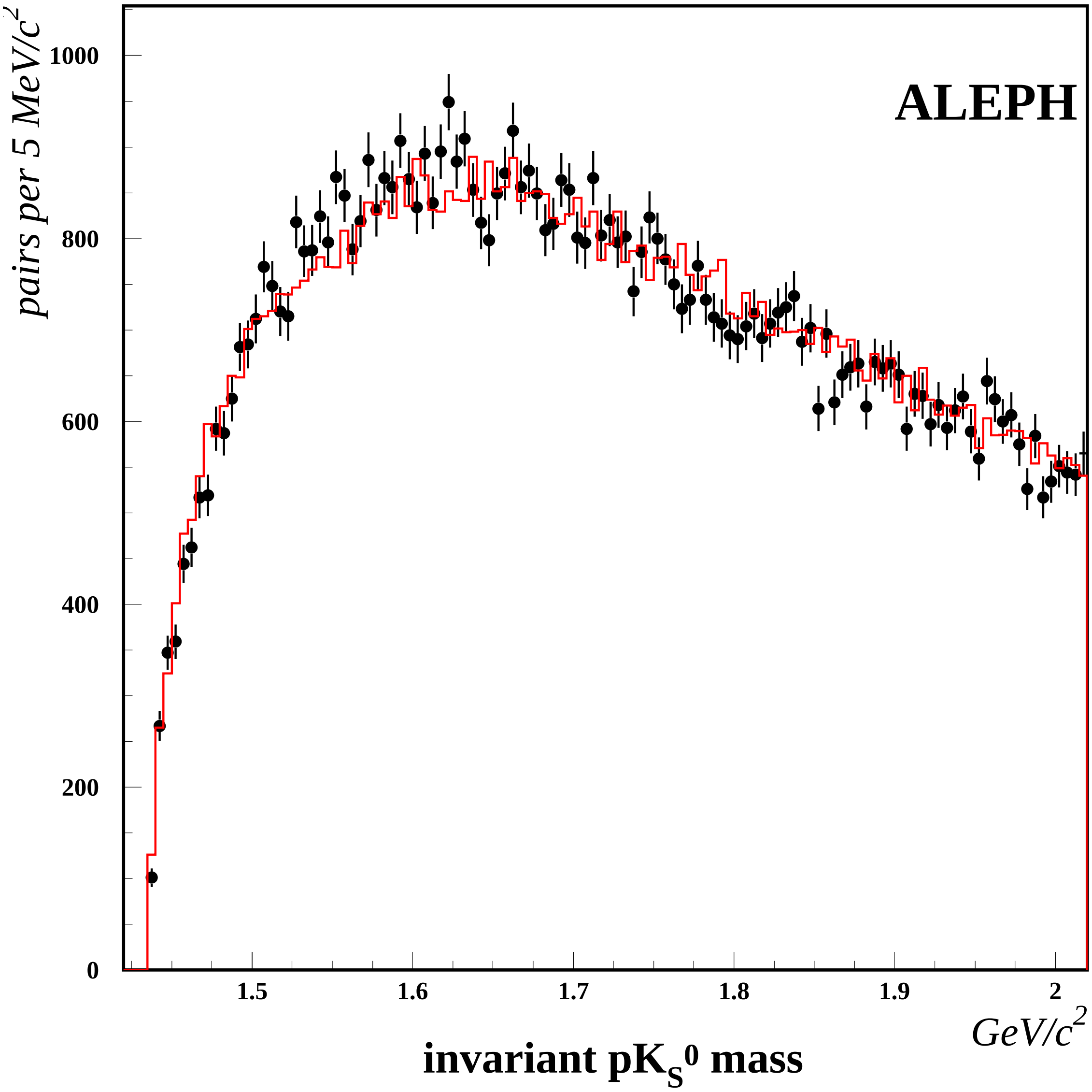

Figure 1: Mass Distribution of pK_S^0 combinations. The dots are data and the histogram is simulation.

the background function. The 95% upper confidence limit on an excess is, conservatively, set to $57 + 1.645 * \sqrt{2840 + 57} + 50 = 195$ combinations.

The acceptance is estimated to be 0.063 using the standard JETSET simulation, which does not include any pK^0 resonance. No significant change is expected due to possible resonance behaviour in the pK system. Assuming the Θ^+ to be isoscalar the branching ratio for $\Theta^+ \rightarrow pK_S^0$ is $1/4$, and the 95% confidence limit on the multiplicity of Θ^+ (*plus* its antiparticle) in hadronic Z decays then becomes:

$$N_{\Theta^+} < 0.0030$$

Similarly, no resonance structures are observed in the doubly charged pK combinations, shown

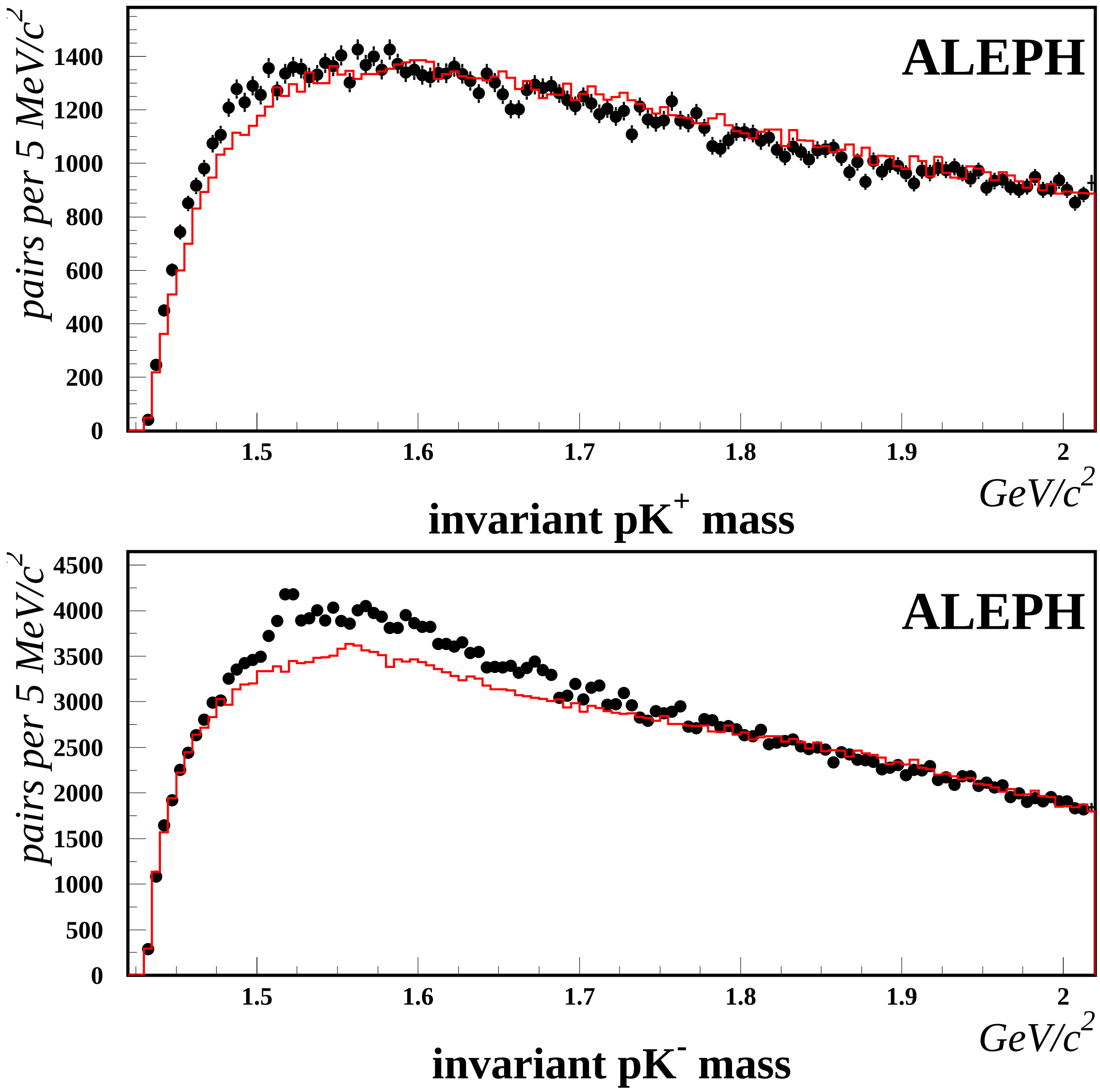

Figure 2: Mass Distribution of $pK^{\pm}$ combinations. The dots are data and the histogram is simulation. In the lower plot, the simulation has been corrected by the ratio of data to simulation in the upper plot.

in Figure 2. However, a smooth deviation from the simulatated mass spectrum is seen at the few percent level. This is caused by imperfect simulation of dE/dx for spacially close track pairs. The ratio of data to simulation in Figure 2 is used to correct the simulation of neutral pK combinations, also shown in Figure 2.

In the neutral pK combinations there is evident resonance activity in the mass range 1460 to 1800 MeV/c^2, with a clear peak due to the $\Lambda(1520)$ and a broad enhancement due to many Σ^* resonances. A simultaneous fit to the strengths of eight more or less established resonances over a background, taken from the simulated mass spectrum and normalised to data around 1.8 GeV/c^2,

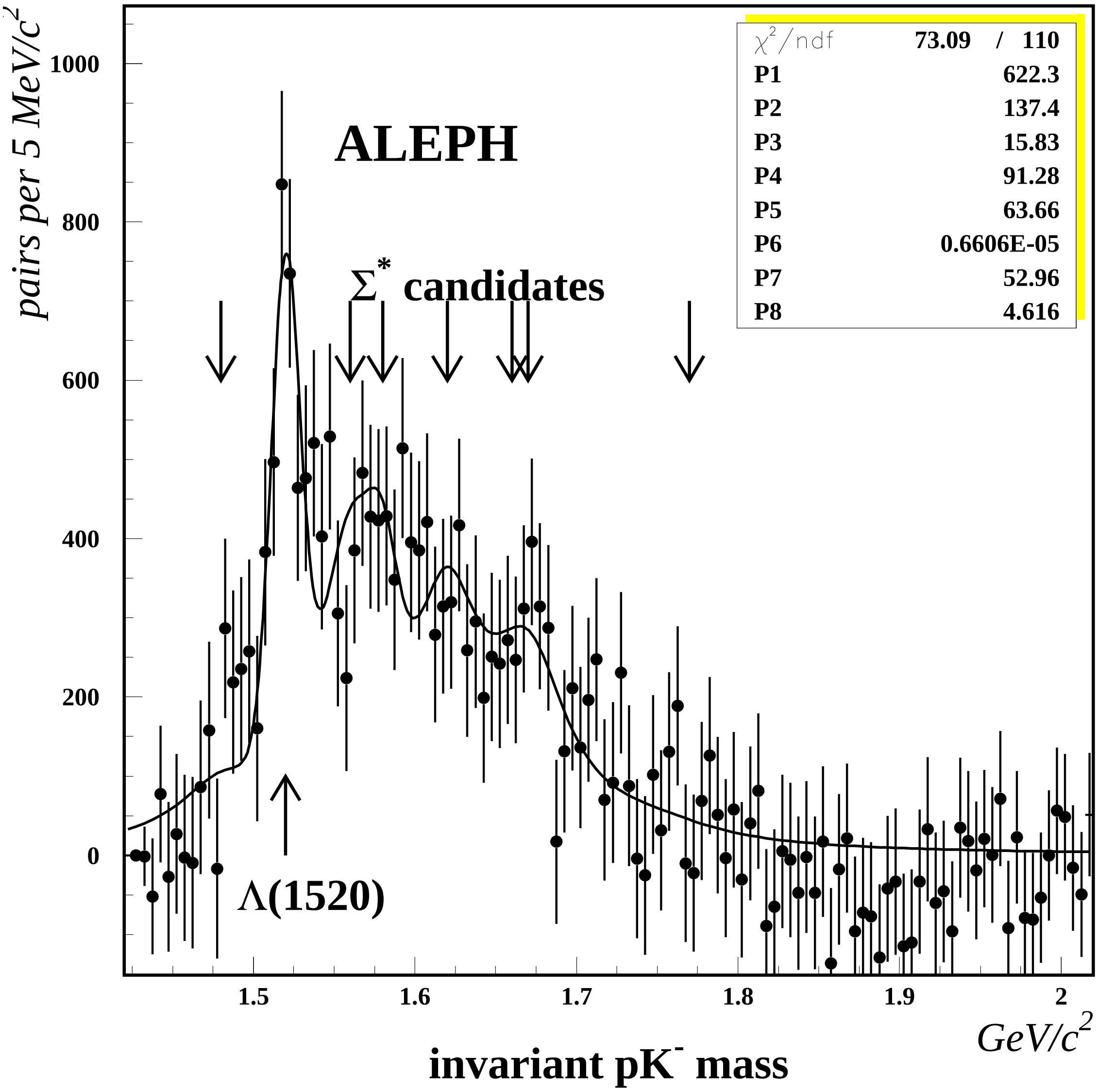

Figure 3: Mass Distribution of $pK^{\pm}$ combinations with the simulated spectrum subtracted. A fit to eight more or less established resonances in the NK system is performed.

is presented in Figure 3. The result is a $\Lambda(1520)$ excess of 2814 ± 293 combinations. If instead the $\Lambda(1520)$ excess is just counted in a 30 MeV/c^2 interval centered at 1520 Mev/c^2, the result is 400 combinations lower than the 2814, but it is also possible to obtain higher counts by changing the normalization point of the MC or the parameters of the resonances. The 400 counts are taken as the systematic error.

Taking the average acceptance of 0.10 into account, again obtained from simulating JETSET generated kaons and protons in the invariant mass range around the resonance, as well as the branching ratio of 22.5% for $\Lambda(1520) \rightarrow pK^-$, the average multiplicity becomes:

$$N_{\Lambda(1520)} = 0.029 \pm 0.003 \pm 0.004$$

This result agrees within errors with a measurement from DELPHI ($0.029 \pm 0.005 \pm 0.005$ [21]) and from OPAL ($0.021 \pm 0.002 \pm 0.002$ [22]).

For the ratio of Θ^+ to $\Lambda(1520)$ production in Z decays, we get the 95% confidence upper limit:

$$N_{\Theta^+}/N_{\Lambda(1520)} < 0.13$$

using the 1σ lower limit of the present measurement in the denominator.

4 Search for narrow resonances in the $\Xi\pi$ system

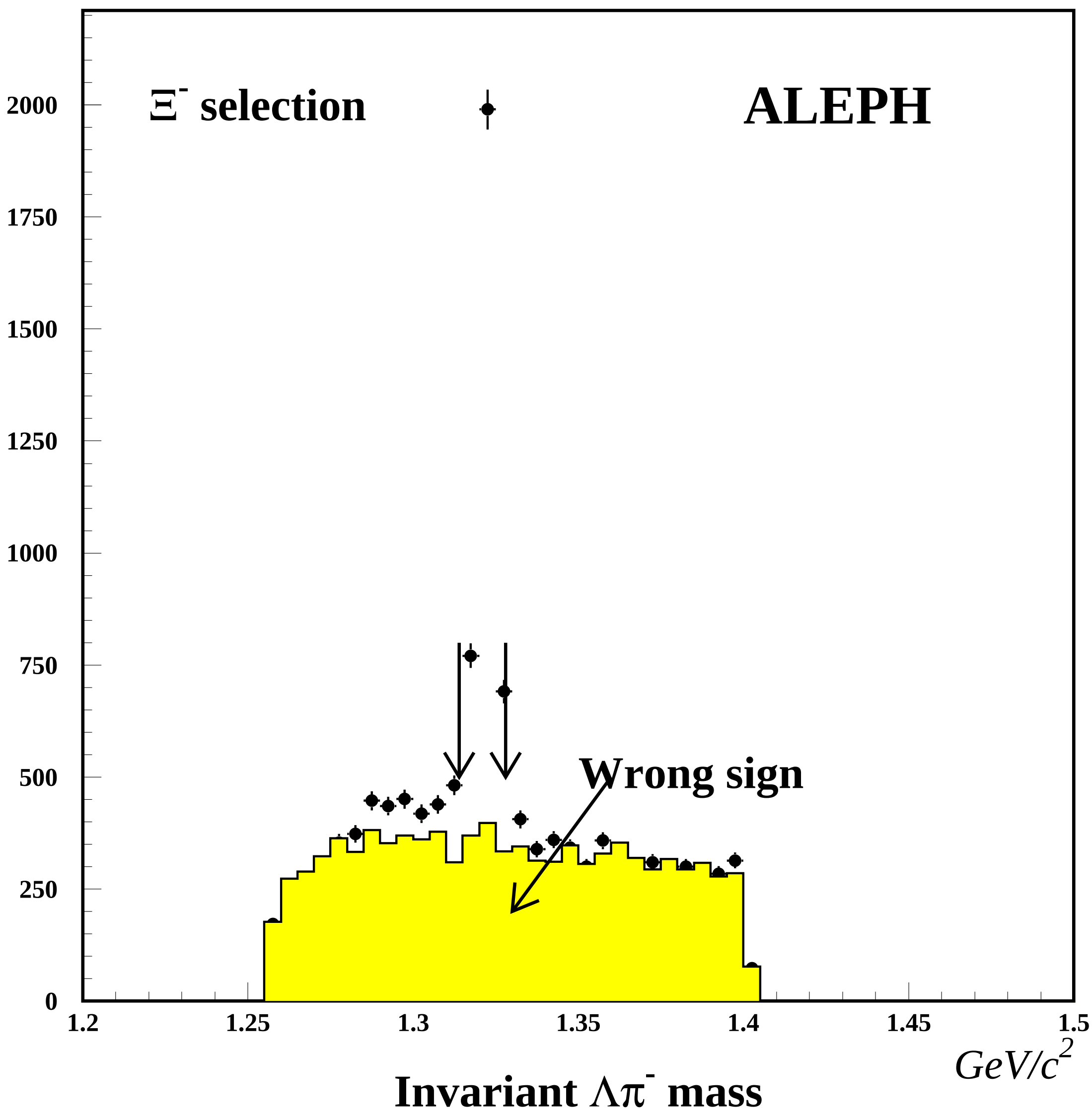

Figure 4: Mass Distribution of $\Lambda\pi^{\pm}$ combinations. A sample of combinations is selected within 7 MeV from the Ξ mass, as indicated by the arrows.

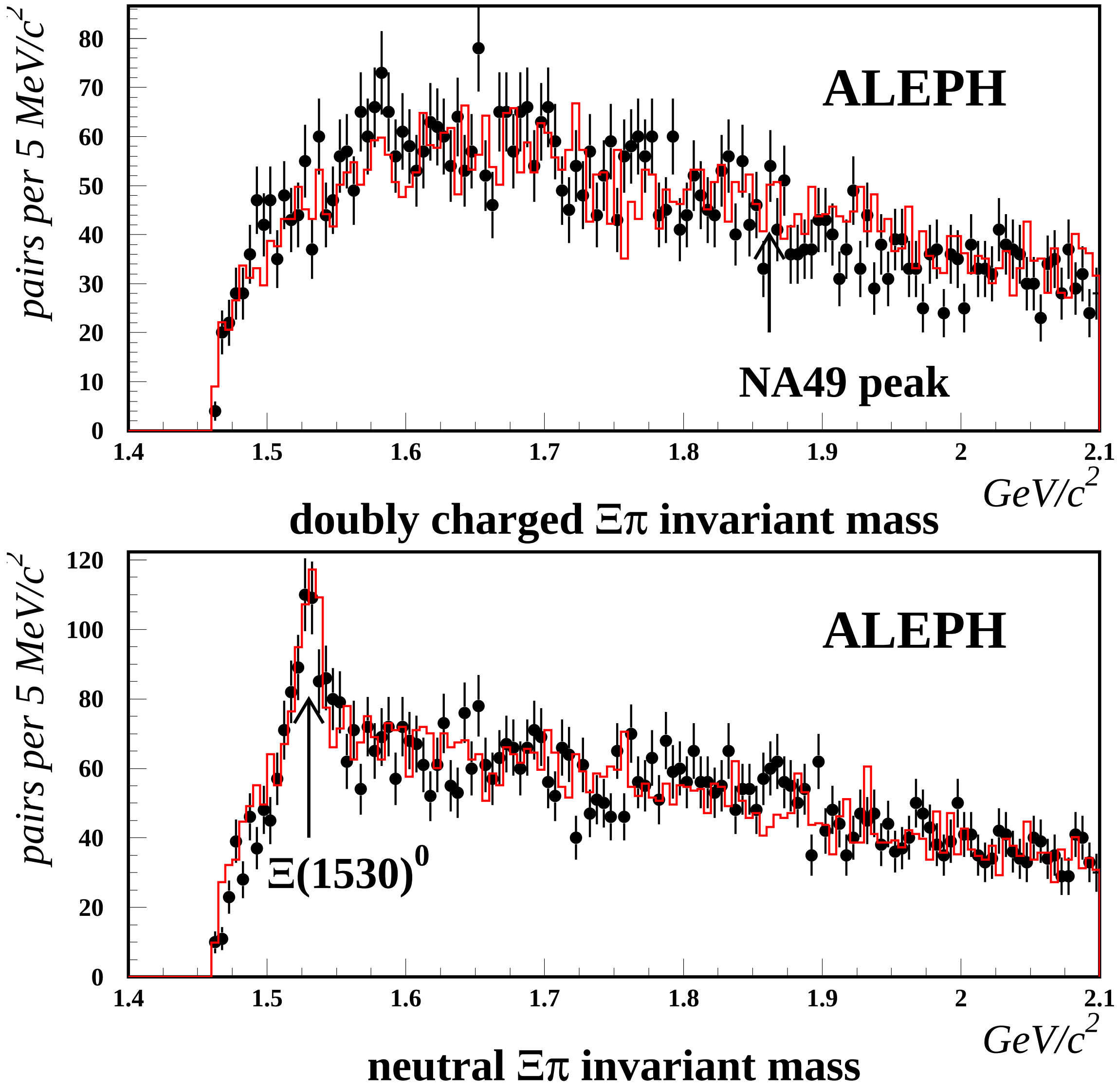

Figure 5: Mass Distribution of $\Xi\pi^{\pm}$ combinations. The dots are data and the histogram is simulation. The arrow in the upper plot indicates the location of the exotic narrow resonance observed by NA49.

A sample of 3350 Ξ candidates with a purity of 76% is selected as shown in Figure 4. Each candidate is combined with each charged pion in the same hemisphere, resulting in the two mass spectra of the doubly charged and neutral combinations shown in Figure 5. The mass resolution is estimated to 6 MeV/c^2 from simulation of the $\Xi(1530)^0$.

The mass spectrum of the doubly charged combinations is well fitted by a linear background in the range 1620 MeV/c^2 to 2100 MeV/c^2. In a mass interval around the NA49 signal [8], conservatively taken as 1835 MeV/c^2 to 1885 MeV/c^2, the observed excess is -2 combinations over a background of 436. The acceptance for simulated $\Xi^-\pi^-$ combinations from fragmentation is 0.021.

The systematic uncertainty of 8% includes uncertainties in the Λ and Ξ reconstruction efficiency and Monte Carlo statistics. This leads to a 95% upper limit on the number of $\Xi^{--} \rightarrow \Xi^-\pi^-$ decays per Z:

$$N_{\Xi(1862)^{--}} \cdot BR(\Xi^{--}_{1862} \rightarrow \Xi^-\pi^-) < 4\ 10^{-4}$$

In the mass spectrum of neutral combinations, a clear $\Xi(1530)$ peak is observed. A signal of 296 ± 32 combinations is counted in excess of the simulated background in the interval 1500 MeV/c^2 to 1565 MeV/c^2. From signal simulation, the acceptance is 0.0157. The Clebsch-Gordan coefficient for the decay channel is $\sqrt{\frac{2}{3}}$. This leads to a $\Xi(1530)^0$ multiplicity of:

$$N_{\Xi(1530)^0} + N_{\bar{\Xi}(1530)^0} = (70 \pm 8 \pm 6)\ 10^{-4},$$

compatible with the published ALEPH result, optimized for this particular channel, which gave $(72 \pm 4 \pm 6)\ 10^{-4}$ [23], and with the OPAL result $(68 \pm 5 \pm 4)\ 10^{-4}$ [22].

Using the 1σ lower limit on the rate of $\Xi(1530)^0$ from the published measurements in the denominator, a 95% upper limit is obtained on the ratio:

$$N(\Xi(1862)^{--} \rightarrow \Xi^-\pi^-)/N_{\Xi(1530)^0} < 0.06$$

5 Search for narrow resonances in the proton D-meson system

High purity samples of D^0 and D^{*+} and a roughly 50% pure sample of $D^\pm$ is selected as shown in Figure 6. Details of the selection are described elsewhere [19]. Each particle in this sample is paired with all the protons in the same hemisphere.

The mass distributions of the proton D^* combinations are shown in Figure 7 and those of proton D-meson combinations in Figure 8. The mass range up to 4 GeV/c^2 has been scanned for resonances, but only the range up to 3.3 GeV/c^2 is shown for clarity. The MC is normalised to the total number of $pD^{\pm0}$ combinations with masses below 4 GeV/c^2. The mass resolution is improved by calculating the mass as $M(Dp) = M_{\mathrm{meas}}(Dp) - M_{\mathrm{meas}}(D) + M_{\mathrm{PDG}}(D)$. It is known from a previous ALEPH measurement of D_s^{**} [24] that the mass resolution is 3 MeV/c^2. The exotic resonance signal observed by H1, Θ_c^0 [10], is located at 3100 MeV/c^2 $\pm$ 3 MeV/c^2 with a width of less than 12 MeV/c^2. Therefore, a window of width 20 MeV/c^2 should be adequate to cover such an enhancement.

In the $D^{*-}p$ channel, where the H1 signal appears, 2 combinations are observed with an invariant mass between 3090 Mev/c^2 and 3110 Mev/c^2, with 3.5 combinations expected from Monte Carlo simulation of standard physics. In the D^-p channel, not covered by H1, 13 combinations are observed with 8.5 expected. A possible charged partner to the H1 signal is searched for in the $\bar{D}^0p$ channel using a wider window of 40 MeV. Here, 21 combinations are observed with 14 expected. Since Monte Carlo statistics is only twice that of the data, there can be significant fluctuations also in the expected number of combinations.

Taking into account the reconstruction efficiencies of 0.0014 for the $D^{*-}p$ channel, 0.00125 for the D^-p channel and 0.0029 for the $\bar{D}^0p$ channel, the 95% upper confidence limits on the number of Θ_c decays per Z are:

$$\begin{aligned} N_{\Theta_c(3100)^0} \cdot BR(\Theta_c^0 \rightarrow D^{*-}p) &< 6 \cdot 10^{-4} \\ N_{\Theta_c(3100)^0} \cdot BR(\Theta_c^0 \rightarrow D^-p) &< 25 \cdot 10^{-4} \\ N_{\Theta_c(3100)^+} \cdot BR(\Theta_c^+ \rightarrow \bar{D}^0p) &< 15 \cdot 10^{-4} \end{aligned}$$

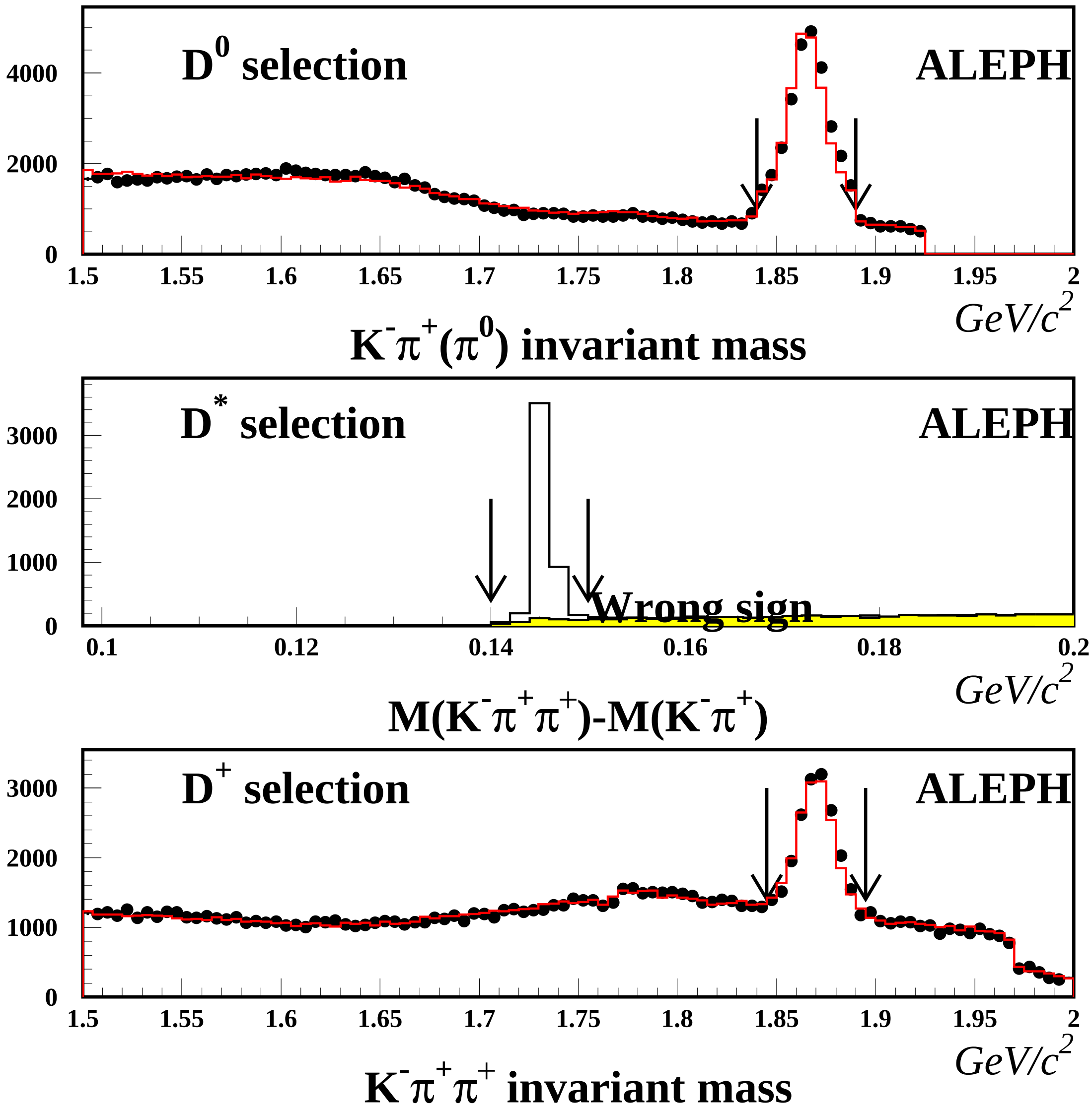

Figure 6: Selection of D^0, D^* and D^+ candidates. The dots are data and the histogram is simulation. The arrows indicate the selection cuts.

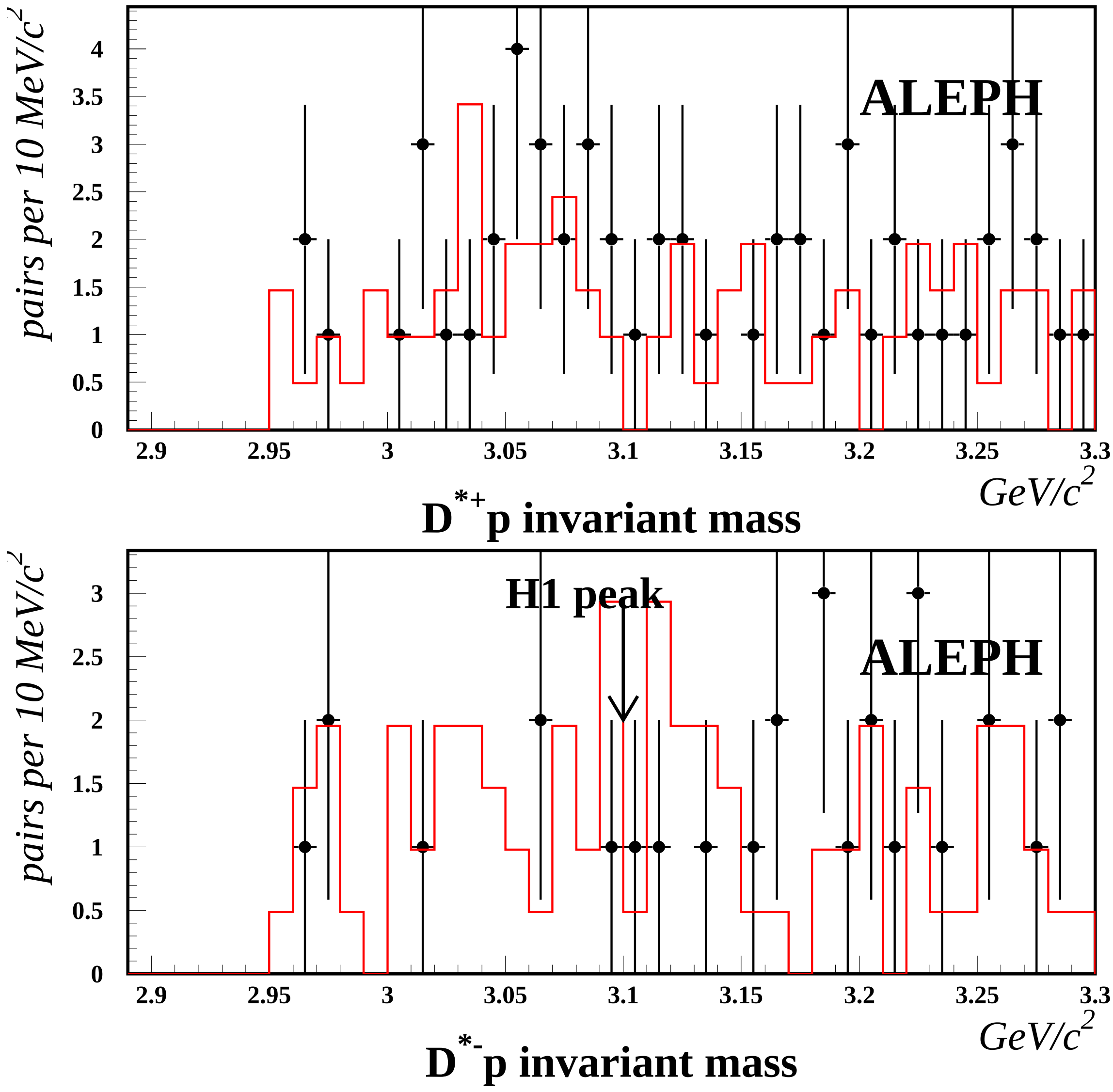

Figure 7: Invariant mass distribution of D^*p combinations. The dots are data and the histogram is simulation.

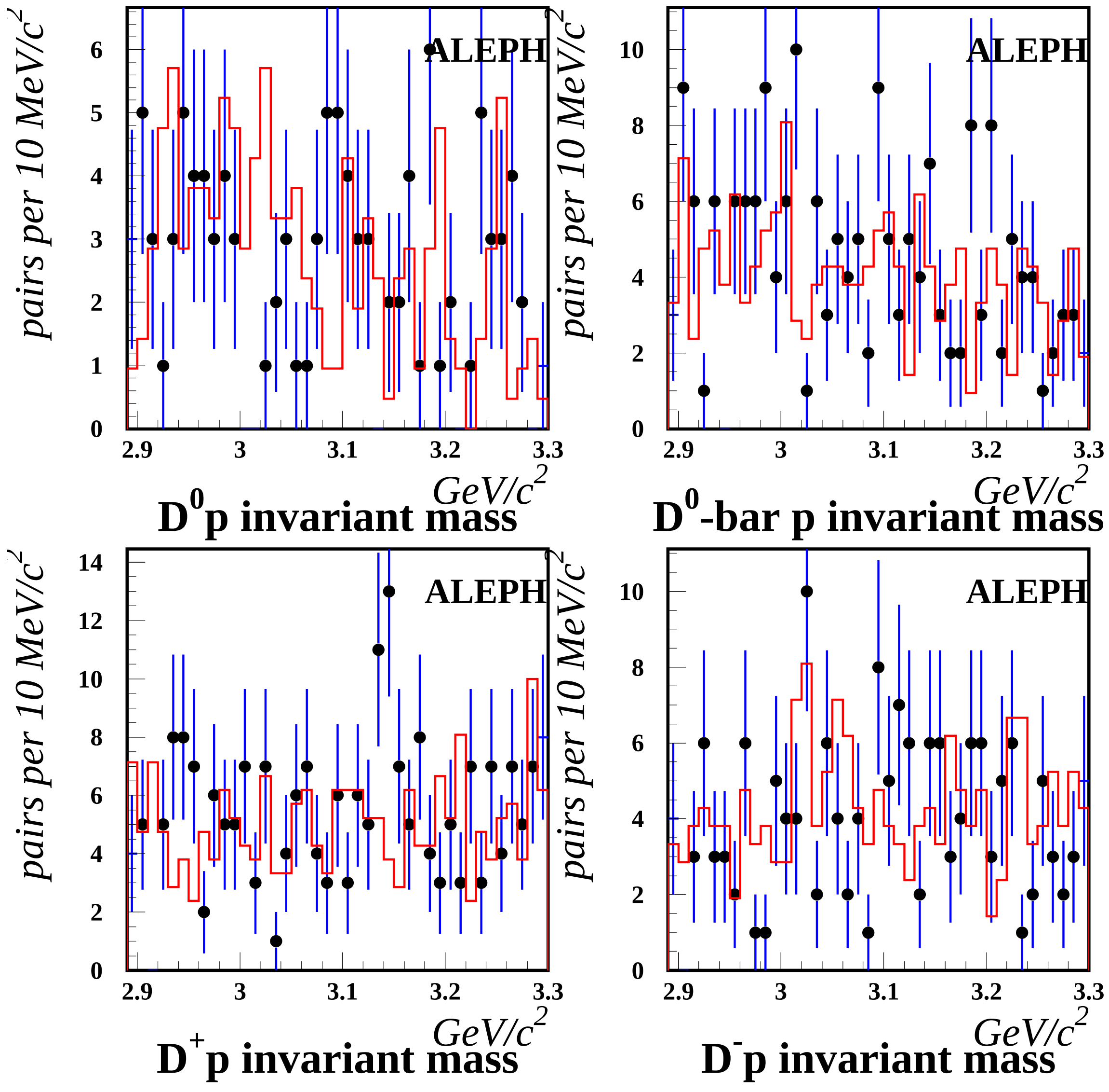

Figure 8: Invariant mass distributions of Dp and $\bar{D}p$ combinations. The histogram is simulation.

6 Conclusions

No evidence for exotic narrow baryon resonces have been found in the $e^+e^- \to Z \to q\bar{q}$ reactions collected by ALEPH during the LEP I running period. Upper limits at the 95% confidence level have been set on the multiplicity of such resonances, observed by other experiments, per hadronic Z decay:

$$\begin{aligned}
N_{\Theta(1535)^+} &< 0.0030 \\
N_{\Xi(1862)^{--}} \cdot BR(\Xi^{--}_{1862} \to \Xi^-\pi^-) &< 4 \cdot 10^{-4} \\
N_{\Theta_c(3100)^0} \cdot BR(\Theta^0_c \to D^{*-}p) &< 6 \cdot 10^{-4} \\
N_{\Theta_c(3100)^0} \cdot BR(\Theta^0_c \to D^-p) &< 25 \cdot 10^{-4} \\
N_{\Theta_c(3100)^+} \cdot BR(\Theta^+_c \to \bar{D}^0p) &< 15 \cdot 10^{-4}
\end{aligned}$$

where the charge conjugated states are included in the limits.

Comparing with related non-exotic baryon states, 95% confidence level upper limits are set on the following ratios:

$$\begin{aligned}
\frac{N_{\Theta^+}}{N_{\Lambda(1520)}} &< 0.13 \\
\frac{N_{\Xi(1862)^{--}}}{N_{\Xi(1530)^0}} \cdot BR(\Xi^{--}_{1862} \to \Xi^-\pi^-) &< 0.06
\end{aligned}$$

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