ON PENTAQUARKS* **

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(Received November 18, 2005)

The status of the search for an exotic baryonic state, a pentaquark system, is reported on. Evidence from some experiments as well as its lack from other investigations is reviewed; problems and (possible) solutions in searches for a pentaquark are discussed, second generation experiments are described.

PACS numbers: 12.39.Mk, 13.75.Cs, 14.20.–c, 14.80.–j

1. Introduction

The constituent quark model, introduced in 1964 by Gell-Mann [1], explains successfully the particle zoo of mesons and baryons as colourless systems composed of quark–anti-quark or three quarks, respectively. However, the existence of other particles is not ruled by this model and there is possible evidence for exotic objects like hybrids and glueballs [2].

Recently, within their chiral soliton model, Diakonov, Petrov and Polyakov [3] predicted the existence of a new family of particles, an $J = 1/2$ anti-decuplet of baryons, each consisting of four quarks and one anti-quark (see Fig. 1), the so-called pentaquark states. Among these particles are seven non-exotic ones, *i.e.* the anti-quark has the same flavour as one of the other quarks, *e.g.* $uuds\bar{s}$, which are difficult to distinguish from ordinary baryons. The remaining three pentaquark particles, positioned at the corners of the triangle which is upside down in comparison to the $J^P = 3/2^+$ decuplet, are exotic as the anti-quark differs in flavour from the other four quarks,

* Presented at the XXIX Mazurian Lakes Conference on Physics August 30–September 6, 2005, Piaski, Poland.
** Supported by BMBF and Research Center Jülich.

namely $uudd\bar{s}$, which is an isoscalar particle nowadays called, $ddss\bar{u}$ and $uuss\bar{d}$ which are the members of the $I = 3/2$ quadruplet of cascade particles, Ξ^{--} and Ξ^{+}. The Θ^{+} is a manifestly exotic baryon because it has a strangeness of $S = 1$, in contrast to all other baryons known so far which have $S = -1$. The mass of the Θ^{+} is about 1530 MeV/c^2 [3], its width according to Polyakov *et al.* [4] is $\Gamma < 15$ MeV, while Diakonov *et al.* [5] calculate $\Gamma \simeq 2$–4 MeV. Both widths are surprisingly small for a particle decaying by strong interaction.

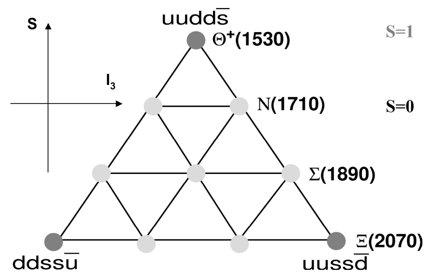

Fig. 1. $J = 1/2$ anti-decuplet of pentaquarks, after [1].

Since strangeness is conserved in hadronic decays, the Θ^{+} might be detectable via its two-body decay into pK^0 or nK^+ pairs where the kaons are a tag for $S = -1$ of the decaying system. When searching for the Θ^{+} one therefore tries to identify it in a given reaction via its invariant mass or by determining the missing mass; in either case the K^0 is identified through its delayed decay as a $K_{\rm S}$ into $\pi^+\pi^-$ pairs. Searches for Ξ^{--} and Ξ^{+} particles have also been performed; they will not be treated in this report.

2. Experimental evidence for Θ^{+}

The first evidence for a narrow $S = +1$ baryon resonance was reported in the photo-production from neutrons at the Laser-Electron Photon Facility at SPring-8 by Nakano *et al.* [6], where a tagged photon beam (back-scattered laser photons off 8 GeV electrons) was used. The actual target was carbon in a scintillator used for time of flight measurements. Fig. 2, left frame, shows the missing mass spectrum obtained with a significant excursion at 1540 ± 10 MeV/c^2 which is missing if photon–proton interactions are selected (dashed histogram in the left frame of Fig. 2). The CLAS Collaboration at JLAB [7] observed in the photoproduction $\gamma D \to K^- p K^+ (n)$ a sharp peak in the invariant nK^+ mass spectrum at 1542 ± 5 MeV/c^2, as reproduced in Fig. 2, right frame. The neutron in this case was reconstructed from kinematics. The dashed histogram shows the spectrum from events associated with the production of $\Lambda(1520)$.

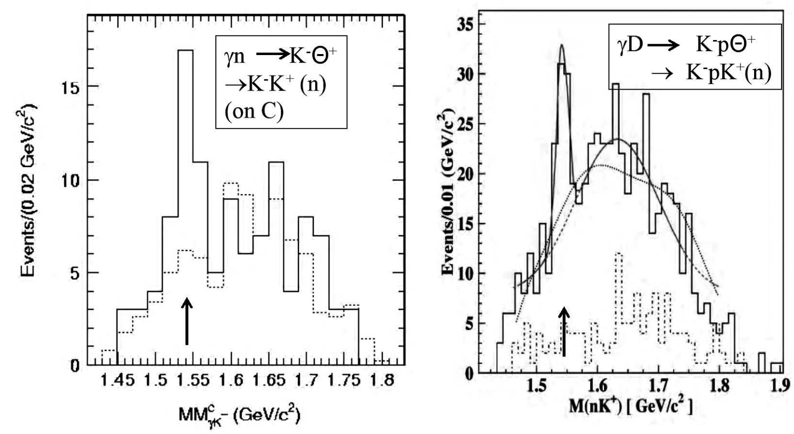

Fig. 2. Left frame: K^- missing mass spectrum of the $\gamma n \rightarrow K^+K^-n$ reaction on carbon [6]; right frame: nK^+ invariant mass spectrum from the $\gamma D \rightarrow K^-p\Theta^+$ reaction [7].

Only a short time later, the SAPHIR Collaboration at ELSA, Bonn, published their results from the $\gamma p \rightarrow K_{\rm S}K^+(n)$ reaction, [8] again — with the neutron reconstructed from kinematics — a sharp peak at 1540 ± 6 MeV/c^2 appears in the invariant nK^+ mass spectrum (Fig. 3, left frame). Similarly, CLAS [9] showed for the same entrance channel data on $\gamma p \rightarrow K^-\pi^+K^+(n)$ with a resonance at 1555 ± 10 MeV/c^2, also with the neutron reconstructed from kinematics (Fig. 3, right frame).

Further evidence for the existence of a Θ^+ stems from experiments carried out at DESY. The HERMES Collaboration [10] scanned their data on positron–deuteron interactions searching for events of the type $e^+d \rightarrow p\pi^+\pi^-X$ and the ZEUS Collaboration [11] theirs on deep inelastic e^+p — scattering at large photon virtuality ($Q^2 > 20$ GeV^2) looking for $e^+p \rightarrow e^+K_{\rm S}pX$ events. In either case resonances were observed at 1528 ± 3 and 1522 ± 3 MeV/c^2, respectively. The results are reproduced in Fig. 4. These authors determine the non-resonant background below the supposed Θ^+ resonance in their spectra by applying model calculations with the codes PYTHIA6 and ARIADNE, respectively. The HERMES data (sub-frame (a)) are reproduced by superimposing to the non-resonant background known resonances with arbitrary weight and a supposed resonance at 1527 MeV/c^2. Sub-frame (b) shows the same data together with a polynomial fit. In contrast, the resonant excursion in yield in Fig. 2 and 3 is determine above a smooth curve adjusted to fit the background which, however, lacks physical explanation.

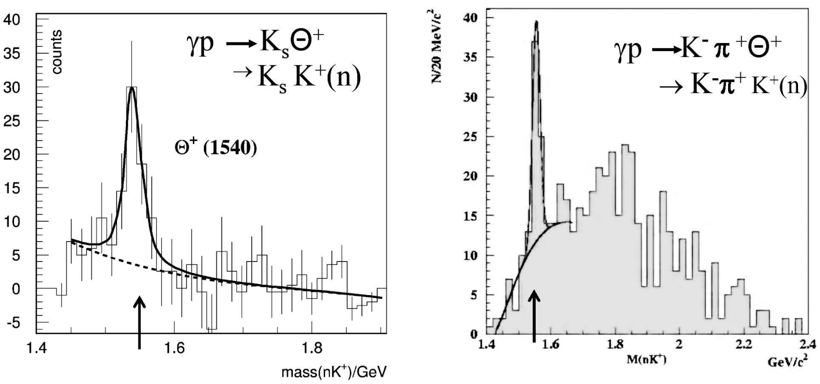

Fig. 3. Left frame: nK^+ invariant mass spectrum of the $\gamma p \to K_{\rm S} K^+(n)$ reaction from the SAPHIR Collaboration [8]; right frame: nK^+ invariant mass spectrum from the $\gamma p \to K^-\pi^+K^+(n)$ reaction from the CLAS Collaboration [9].

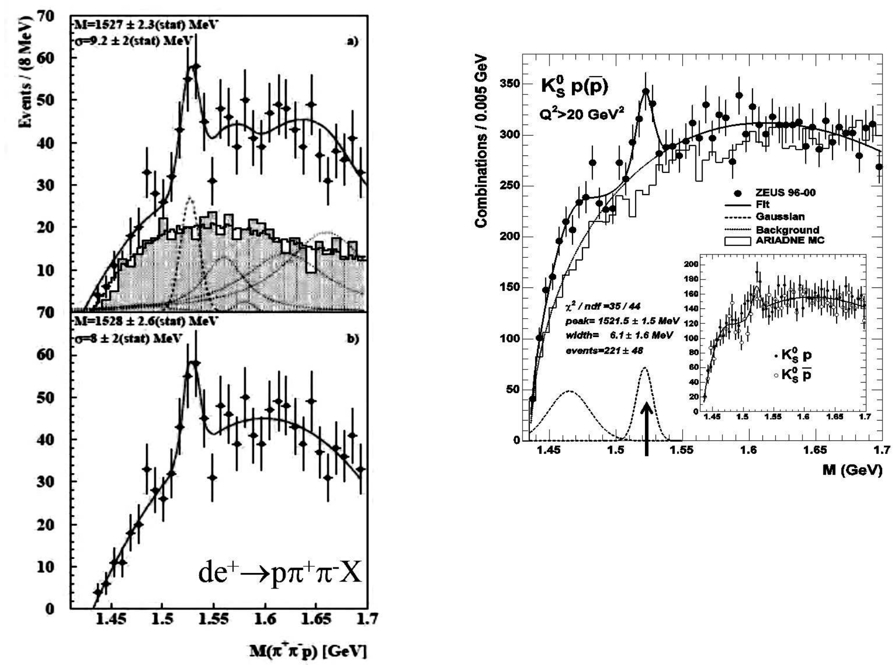

Fig. 4. Left frame: $\pi^+\pi^-p$ invariant mass spectrum from the $e^+d \to \pi^+\pi^-pX$ reaction (taken from [10]), right frame: $K_{\rm S}p$ invariant mass spectrum from the $e^+p \to e^+K_{\rm S}pX$ reaction (taken from [11]).

Not only experiments carried out with electromagnetic probes show evidence for the Θ^+, but also experiments on nuclei induced by either neutrinos and anti-neutrinos or by kaons. The ITEP group, Asratyan *et al.* [12], analysed data from past experiments with the bubble chambers at FNL and CERN. Results combined from D_2 and Ne data are shown in the left frame of Fig. 5, where the pK_S invariant mass spectrum shows a prominent resonance at 1533 ± 5 MeV/c^2. The right hand frame shows results from low energy K^+Xe collisions in the Xe filled bubble chamber DIANA at ITEP (DIANA Collaboration, Barmin *et al.* [13]). The K^0p invariant mass spectrum shows a significant excursion at 1539 ± 2 MeV/c^2. The reaction which is likely to have taken place is $K^+n \to \Theta^+ \to K_Sp$.

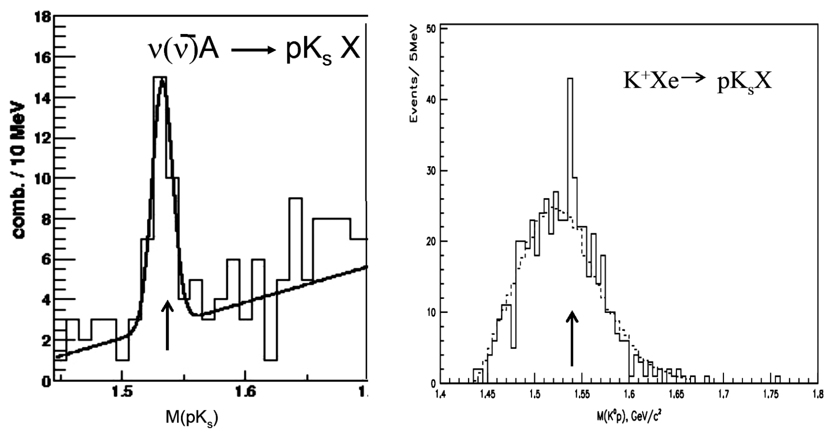

Fig. 5. Left frame: pK_S invariant mass spectrum obtained from neutrino–nucleus (D, Ne) interactions in bubble chambers (taken from [12]); right frame: K^0p invariant mass spectrum from K^+ interactions in a Xe filled bubble chamber (taken from [13]).

Also experiments with protons were carried out in order to search for the Θ^+. The first data published stem from at IHEP where the SDV-2 experiment was used to search for indications of a Θ^+ resonance in reactions induced in a silicon microstrip vertex detector (Aleev *et al.* [14]). Above a background, which is described by the Fritjof model, a clear excursion is seen at 1526 ± 3 MeV/c^2, if events of low multiplicity were selected.

3. The COSY-TOF experiment

The only proton–proton experiment which has been performed so far in search of the Θ^+ is the COSY-TOF experiment [15] at the Research Centre of Jülich. A sketch of this Time of Flight spectrometer, located at an external beam line of the Cooler Synchrotron is shown in Fig. 7.

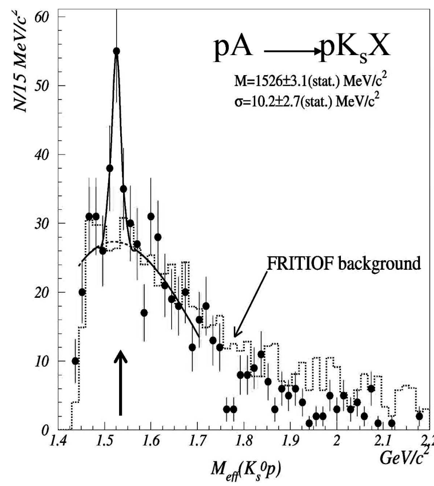

Fig. 6. $K_{\rm S}p$ invariant mass spectrum obtained from pA reactions with a 70 GeV proton beam (taken from [14]).

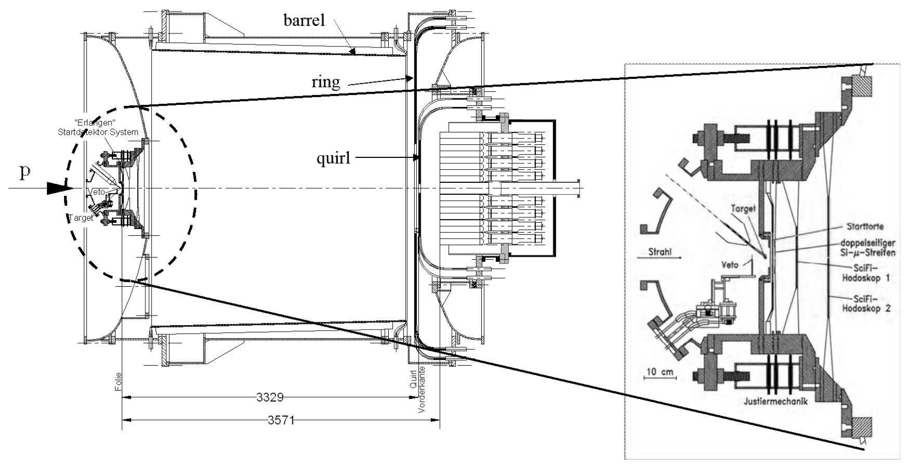

Fig. 7. Sketch of the COSY-TOF spectrometer.

The proton beam hits a liquid hydrogen target [16], the ejectiles are followed through a tracking device consisting of the start detector ("Starttorte") of 2×12 overlapping scintillator sectors, a double layer Si-micro-strip detector of 128 sectors (front side) and 100 concentric annuli (back side) [17] and two hodoscopes of crossed scintillating fibres; the time of flight stop signal is derived from scintillation detector which covers the inside of the cylindrical vacuum vessel: 96 scintillator bars cover the cylinder barrel and are read out at both sides, yielding time and position information [18]; the endcap ("quirl" and ring) consist of three layers of scintillators, one layer has sectors, the other two consist of archimedian spirals being closewise or counter clockwise wound [19]. The spatial overlap of these three layers define pixels; the photomultipliers attached, if they have fired, uniquely specify the pixel location in space.

The method of extracting events with the signature of the reaction $pp \to pK^0\Sigma^+$ relies on the delayed decay of both K^0 (decaying as $K_S \to \pi^+\pi^-$) and $\Sigma^+ \to \pi^+ n$ and is visualised in Fig. 8. Hits in the tracking device forming a straight line are associated with a proton, hits in the fibre hodoscopes which can be combined to form a secondary vertex with its origin behind the Si-strip detector are assumed to stem from the K_S decay in two pions. Hits in the "starttorte" and in the Si-strip detector define a track which is assumed to be due to a Σ^+, if no hits are found in the fibre hodoscopes along its flight direction. The direction of flight of the three particles can be used to determine their momenta as they must add up to the beam momentum. The mass of the decaying kaon then follows from the opening angle of the secondary pions. Together with the proton mass the missing mass of the third particle, the Σ^+, can be calculated. The left frame of Fig. 9 shows

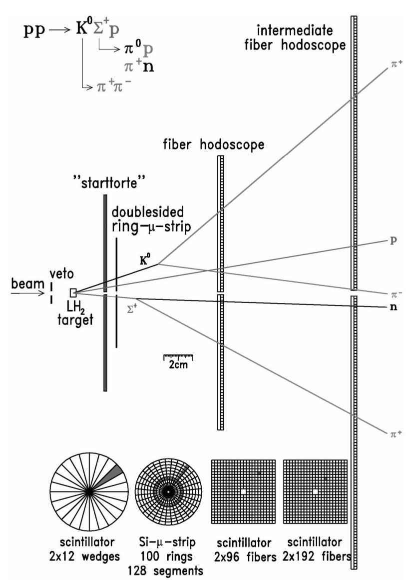

Fig. 8. Sketch of the tracking device with $pp \to pK^0\Sigma^+$ reaction included.

the yield of events as function of the mass of the particle decaying into pion pairs *vs.* the missing mass of the third particle. This yield peaks at the kaon and sigma mass, which is taken as evidence for a correct identification of the reaction channel under consideration. An addition, the time of flight of the proton and the time of flight differences of the two pions can be used to further constrain the missing mass of the third particle. The result of this procedure is shown in the right frame of Fig. 9. It should be mentioned that events outside the phase space, allowed for the $pp \to pK^0\Sigma^+$ reaction, were rejected and that geometrical cuts on tracks and vertices were used to suppress background.

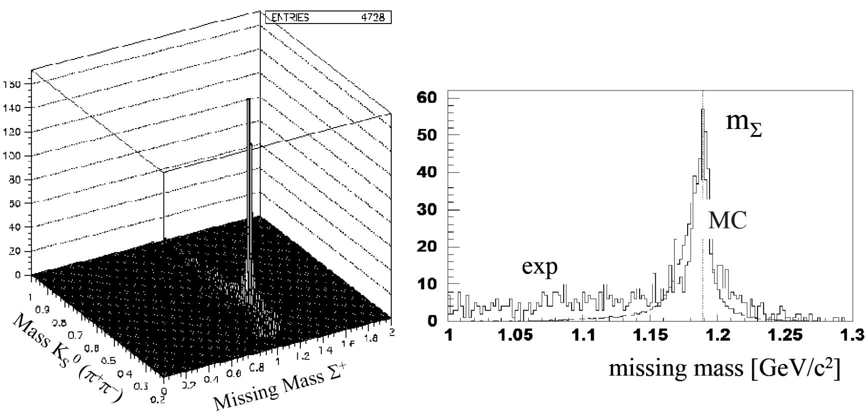

Fig. 9. Left frame: yield of events as function of the mass of the particle decaying into pion pairs *vs.* the missing mass of the third particle; right frame: missing mass of the third particle if the time of flight information is used in addition.

The invariant mass of the K^0p system is shown in Fig. 10 together with two Dalitz plots. The latter show that the phase space of the reaction is fully covered. The excursion at 1530 ± 5 MeV$/c^2$ on top of a smooth background, fitted with a third order polynomial, is taken as evidence for the Θ^+. The width at FWHM is 18 ± 4 MeV$/c^2$ is, according to the Monte Carlo analysis, compatible with the experimental resolution of the TOF spectrometer.

In Fig. 11 the mass and width of the Θ^+ from various experiments, as composed by Zhao and Close [20], is depicted. It is worth noting that data where the Θ^+ is inferred from its decay into pK^0 group at somewhat smaller masses than those where the nK^+ decay is observed.

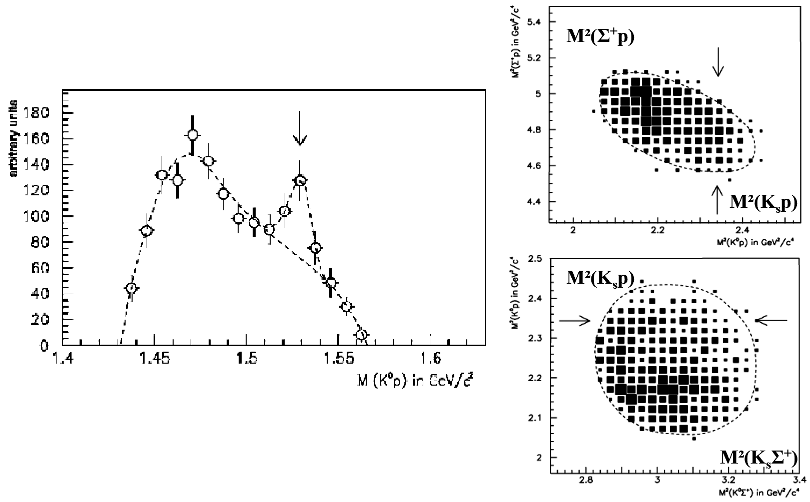

Fig. 10. K^0p invariant mass spectrum together with Dalitz plots obtained in the reaction $pp \to pK^0\Sigma^+$ (from [15]).

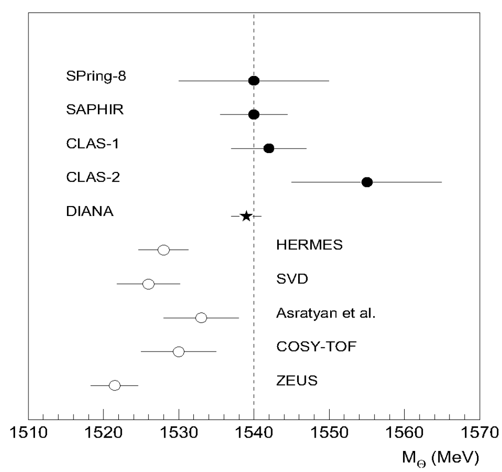

Fig. 11. Experimental data on masses and widths of the Θ^+. The $K_{\rm S}p$ data are shown by open circles, the K^+n data by full dots. The $K^+n \to \Theta^+ \to K_{\rm S}p$ data of DIANA, denoted by a star, connects the two sets of data, from [20].

4. Lack of evidence

Data from various experiments using e^+e^- interactions or hadronic probes at high energy lack evidence for the existence of the Θ^+, *e.g.* BaBar [21], BELLE [22], BES [23], Phenix [24] and HyperCP [25].

As an example the result from the BaBar experiment at SLAC is reproduced in Fig. 12, where the pK_S invariant mass was determined from a large data sample of e^+e^- annihilations. No excursion of statistical significance is observed in the mass region of interest. The BaBar Collaboration went a step further and deduced an upper limit of the production rate and compared it with other rates for reactions of the type $e^+e^- \to$ hadrons. Fig. 12 shows their results. The production rate of the ordinary octet and decuplet of baryons in the same mass range is much larger than the upper limits given for the pentaquark systems.

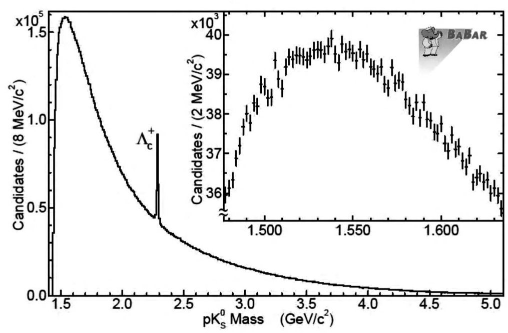

Fig. 12. Spectrum of the pK_S invariant mass from e^+e^- annihilations, from [21].

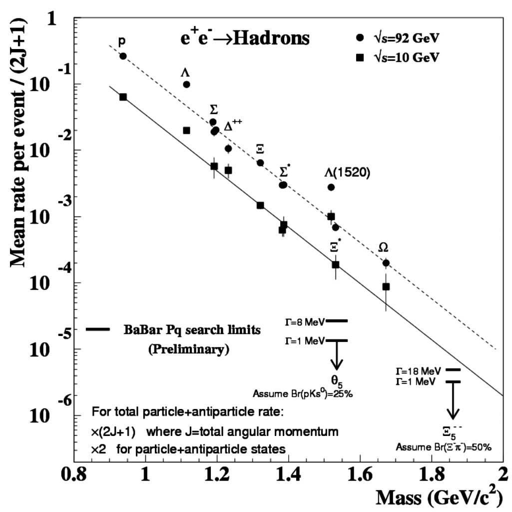

Fig. 13. Production rates for reactions of the type $e^+e^- \to$ hadrons, from [21].

5. Conclusions

The existence of the pentaquark state Θ^+ has not been proven beyond doubt. Most of the experiments performed so far suffer from small data samples and have therefore limited statistical significance. Some of the data were taken with spectrometers which have a limited acceptance and may, hence, probe only certain regions of phase space. In most cases the physical background stemming from competing reactions is not fully understood and cuts are tailored to enhance the signal to background ratio. Such cuts may produce artificial structures if signal and background deviate from pure phase space in different ways. It is not at all clear why most of the data taken at high energies lack evidence. It should also be noted that all results, positive or negative ones, are not obtained from dedicated experiments performed to search for pentaquark states, but stem from the analysis of data being taken already, and their analysis was triggered by the theoretical work of [3].

In order to solve the intriguing puzzle of pentaquark states, second generation experiments are needed which provide data which are not only of statistical significance due to large data samples but are also exclusive and cover the whole phase space available to the reaction. With large data samples at hand, Dalitz plots can be produced which reveal the full dynamics of the reaction, *i.e.* angular distributions; partial wave analyses should be performed to pin down contributions from so far unknown states. Of equal importance is to understand the physical background originating from known baryon resonances and its simulation with Monte Carlo codes and, in turn, its analysis with the same programme used for the analysis of the experimental data.

First results from an experiment with high statistical significance are available from the CLAS-Collaboration at JLAB [26]. The nK^+ invariant mass spectrum from the reaction $\gamma p \to K_S K^+ n$ is reproduced in Fig. 14. Obviously, there is no excursion of statistical significance in the mass region of the supposed Θ^+.

Dedicated experiments which aim at large data samples have also been performed by the LEPS Collaboration, by CB@ELSA, the follow-up experiment of SAPHIR, and with COSY-TOF. The results are expected by the community with great eagerness.

If the pentaquark state Θ^+ will still be alive after these experiments, important questions still remain to be answered:

1. What is the spin and the parity of this state? Only if it is $J^P = 1/2^+$ it can be a member of the antidecuplet.

2. Why this strongly decaying resonance has such an unusual small width?

3. Why is it produced only in certain reactions and not in others?

However, if the existence of this manifestly exotic particle can be proven it will have serious impact on our understanding of the structure of baryons.

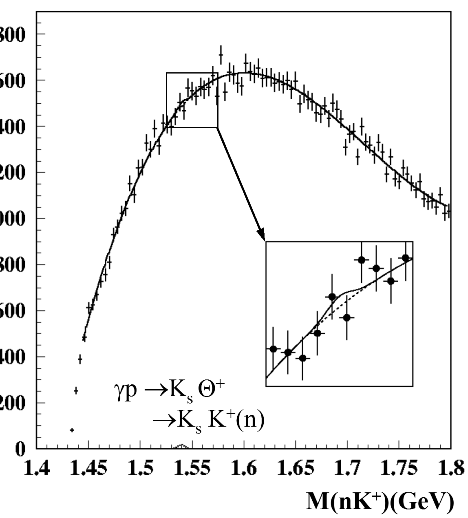

Fig. 14. nK^+ invariant mass spectrum from the reaction $\gamma p \to K_S K^+ n$ measured by the CLAS-Collaboration at JLAB, from [26].

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