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# PENTAQUARKS SEARCH AT HERMES*

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An experimental search for quasi-real photoproduction of possible $\Theta^+$ and $\Theta^{++}$ resonances was performed using the decay modes $pK_{\rm S}$ and $pK^+$ with the HERMES experiment at DESY. We report evidence for the existence of a $\Theta^+$ peak with a statistical significance of $4\sigma$. The absence of a peak in the $pK^+$ spectrum in the vicinity of the $\Theta^+$ mass yields an estimate of the upper limit for the quasi-real photoproduction cross-section of the $\Theta^{++}$ resonance. In addition, a search for exotic baryon resonances with $S=-2, Q=-2$ or 0 has been performed in quasi-real photoproduction on a deuterium target by isolating the decay channel $\Xi^-\pi^- \to \Lambda\pi^-\pi^- \to p\pi^-\pi^-\pi^-$ and $\Xi^-\pi^+ \to \Lambda\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$. No evidence for the previously reported $\Xi^{--}(1860)$ and $\Xi^0(1860)$ resonances is found in the $\Xi^-\pi^-$ and $\Xi^-\pi^+$ invariant mass spectra, respectively. Upper limits for their photoproduction cross sections of 2.1 nb and 2.5 nb are found at the 90% confidence level. The photoproduction cross section for the $\Xi^0(1530)$ resonance, which has the same decay mode as the hypothetical $\Xi^0(1860)$ peak, is found to be between 9 and 24 nb.

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## 1. Introduction

As QCD does not prohibit the existence of baryons consisting of five quarks, such a configuration was already discussed [1] in the early days of QCD inspired models. However, experimental searches [2] performed in the 1970's did not produce any convincing evidence for the existence of such a state. In the early 1980's it was noted [3,4] that the Skyrme model predicts

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new exotic states belonging to higher SU(3) representations. Using this model, Praszalowicz [5] provided the first estimate of the mass of the lightest exotic pentaquark state at $M \approx 1530\,\mathrm{MeV}$. The more recent prediction of the existence of narrow exotic baryon resonances [6], based on the Chiral Soliton Model, has triggered an intensive search for the exotic members of an anti-decuplet with spin $1/2$. In this anti-decuplet [6] all three vertices are manifestly exotic. The lightest exotic member of this anti-decuplet lying at its apex, named the $\Theta^+$ [7], was predicted to have a mass of 1530 MeV and a narrow width. It corresponds to a $uudd\bar{s}$ configuration, and decays through the channels $\Theta^+ \to pK^0$ or $\Theta^+ \to nK^+$. In the model of Ref. [6] the $\Theta^+$ is an isosinglet. Other approaches, based on the constituent quark model [8], or on the Chiral Soliton model [9], predict that rather than an isosinglet $\Theta^+$, an isotriplet or an isovector $\Theta$ particle should exist.

Several experimental groups have reported evidence for a new, manifestly exotic $(B = 1, S = 1)$ baryon resonance. The first experimental evidence for the $\Theta^+$ came from the LEPS experiment [10] in Japan, which reported the observation of a narrow resonance at $1540 \pm 10(\mathrm{sys})\,\mathrm{MeV}$ by analyzing the $K^-$ missing mass spectrum in the reaction $\gamma n \to K^- K^+ n$ on $^{12}\mathrm{C}$. The decay mode corresponds to an $S = +1$ resonance, containing an $\overline{s}$ quark with baryon number $+1$, signaling a manifestly exotic pentaquark state with minimum quark content $(uudd\bar{s})$. Confirmation came quickly from a series of experiments, with the observation of narrow peaks [11–21] in $pK^0$ or $nK^+$ mass spectra near 1530 MeV, in each case with a width consistent with the experimental resolution. Some doubts have been raised recently, concerning the validity of these observations, because of the failure to observe a signal in other experiments [22–28].

Experimental evidence for a second exotic member of the anti-decuplet came from the reported observation of a $S = -2$, $Q = -2$ baryon resonance in proton–proton collisions at $\sqrt{s} = 17.2\,\mathrm{GeV}$ at the CERN SPS [29]. A narrow peak at a mass of about 1862 MeV in the $\Xi^- \pi^-$ invariant mass spectrum is proposed as a candidate for the predicted exotic $\Xi^{--}_{3/2}$ baryon with $S = -2$, $I = 3/2$ and a quark content of $(ddss\bar{u})$. At the same mass, a peak is observed that is a candidate for the $\Xi^0_{3/2}$ member of this isospin quartet. The corresponding anti-baryon spectra show enhancements at the same invariant mass. The observed mass of 1862 MeV falls below the prediction of Ref. [6] and above a prediction of Ref. [1, 30], although it is closer to the latter. However, the result of Ref. [29] has been disputed [31]. In addition, this resonance has not been confirmed by other experimental searches [27, 32, 33]. Many further searches for the $\Xi^{--}$ are presently underway [34] for which no final results are available yet.

## 2. Experiment

The HERMES [35] collaboration has performed an experimental search for the $\Theta^+, \Theta^{++}, \Xi^{--}$ and $\Xi^0$ particles in quasi-real photoproduction on a deuterium target. The data were obtained with the 27.6 GeV positron beam of the HERA storage ring at DESY. An integrated luminosity of $296\,\mathrm{pb}^{-1}$ was collected on a deuterium gas target.

The trigger was formed by requiring a coincidence between either a set of scintillating hodoscopes, a preshower detector and a lead-glass calorimeter, or between three scintillating hodoscopes and two tracking planes, requiring that at least one charged track appears in each of the detector halves of the spectrometer [35]. The analysis searched for inclusive photo-production of the $\Theta^+$ followed by the decay $\Theta^+ \to pK^0_{\mathrm{S}} \to p\pi^+\pi^-$. The search for the $\Theta^{++}$ was pursued via the possible decay mode $\Theta^{++} \to pK^+$. Events selected contained at least three tracks for the $\Theta^+$ with two oppositely charged pions in coincidence with one proton, and two tracks for the $\Theta^{++}$ with one proton and one kaon. Since no constraint was placed on the sign of the kaon, the well known $\Lambda(1520) \to pK^-$ is also contained in this event sample. The search for inclusive photo-production of $\Xi(1860)$ pentaquarks was performed assuming the decay modes: $\Xi^{--} \to \Xi^-\pi^- \to \Lambda\pi^-\pi^- \to p\pi^-\pi^-\pi^-$ or $\Xi^0 \to \Xi^-\pi^+ \to \Lambda\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$. Events selected contained at least four tracks: three charged pions in coincidence with one proton.

Identification of charged pions and protons was accomplished with a Ring-Imaging Čerenkov (RICH) detector [36] which provides separation of pions, kaons and protons over most of the kinematic acceptance of the spectrometer. The RICH identification efficiencies and cross contaminations were determined in a limited kinematic domain using known particle species from identified resonance decays. This was accomplished by means of a Monte Carlo simulation based on the PYTHIA6 event generator. The data from the simulation indicated that cross contaminations in the search of the $\Theta^+$ and $\Theta^{++}$ resonances is negligible if protons are restricted to a momentum range of 4–9 GeV/$c$, kaons to 2–15 GeV/$c$ and pions to 1–15 GeV/$c$. In the search of the $\Xi(1860)$ baryons, the requirements on the proton and pion momenta were restricted to a momentum range of 2–15 GeV/$c$ and 0.25–15 GeV/$c$ respectively, because the intermediate $\Lambda$ and $\Xi^-(1321)$ particles were clearly identified in the particle reconstruction.

The event selection included constraints on the event topology to maximize the yield of the $K^0_{\mathrm{S}}$, $\Lambda$ or $\Xi^-(1321)$ peaks in the $M_{\pi^+\pi^-}$, $M_{p\pi^-}$ and $M_{\Lambda\pi^-}$ spectra, respectively, while minimizing their background. The constraints used included a minimum distance of approach between two tracks, a minimum radial distance of the production vertex from the positron beam axis, a production vertex inside the target cell and a $K^0_{\mathrm{S}}$, $\Lambda$ or $\Xi^-(1321)$

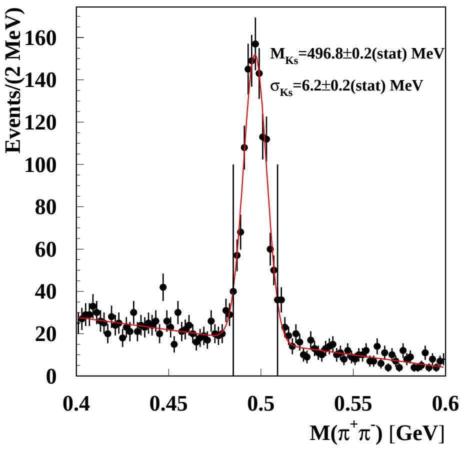


Fig. 1. Invariant $M_{\pi^+\pi^-}$ distribution. A window corresponding to $\pm 2\,\sigma$ is shown by the vertical lines.

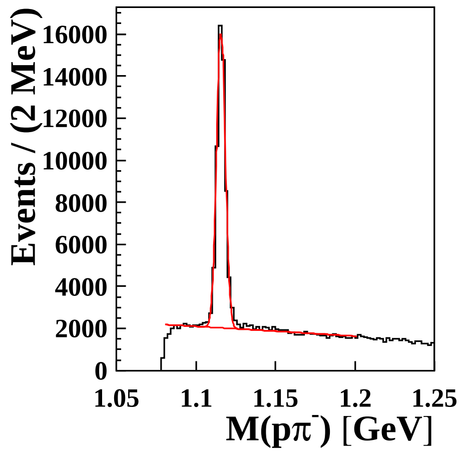


Fig. 2. Invariant mass distribution of the $p\pi^-$ and charge conjugate (c.c.) system.

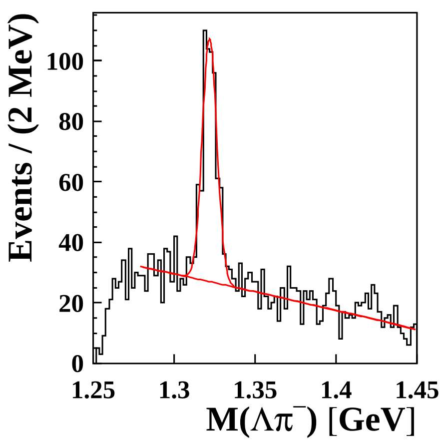


Fig. 3. Invariant mass distribution of the $p\pi^-\pi^-$ plus (c.c.) system. The peak near 1.32 GeV corresponds to the excitation of the $\Xi^-(1321)$ resonance.

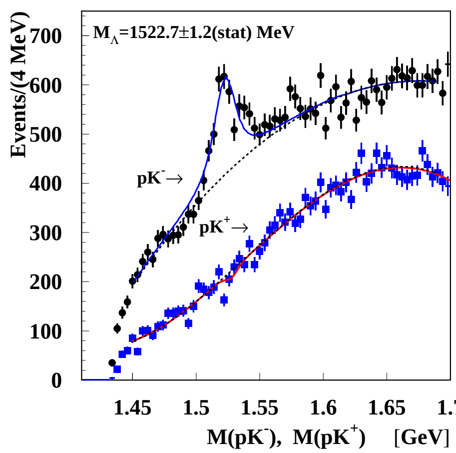


Fig. 4. Spectra of the invariant mass distributions $M_{pK^-}$ (top) and $M_{pK^+}$ (bottom). A clear peak is seen for the $\Lambda(1520)$ in the $M_{pK^-}$ invariant mass distribution, but none for the hypothetical $\Theta^{++}$ peak near 1530 MeV.

decay length of greater than 7 cm, 7 cm and 10 cm, respectively. The resulting $M_{\pi^+\pi^-}$, $M_{p\pi^-}$, $M_{\Lambda\pi^-}$ and $M_{pK^-}$ spectra are shown in Figs. 1–4. The position of the $K^0_{\rm S}$ and other reconstructed known particles in the HERMES experiment ($\Lambda(1115)$, $\Phi(1020)$, $\Xi^-(1321)$, $\Sigma^\pm(1385)$, $\Lambda(1520)$) were used as a measure of the systematic uncertainty in the mass reconstruction.

## 3. Results

To search for $\Xi^{--}_{3/2}$ ($\Xi^{0}_{3/2}$) candidates, first events were selected with an invariant mass $M_{p\pi^-}$ within $\pm 3\,\sigma$ of the centroid of the $\Lambda$ peak. These events were combined with a $\pi^-$ to form the $\Xi^-$. In the next step, events were selected with a $M_{\Lambda\pi^-}$ invariant mass within $\pm 3\,\sigma$ of the centroid of the $\Xi^-$ peak. The resulting spectrum of the invariant mass of the $p\pi^-\pi^-\pi^-$ system is displayed in Fig. 5. No peak structure is observed near 1862 MeV. Fig. 6 shows the resulting spectrum of the invariant mass of the $p\pi^-\pi^-\pi^+$ system subject to the same set of kinematic requirements. While no peak structure is observed near 1862 MeV, one appears at the mass of the known $\Xi^0(1530)$ resonance.

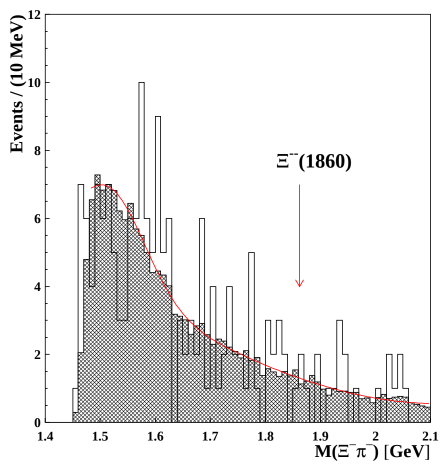


Fig. 5. Invariant mass distribution of the $p\pi^-\pi^-\pi^-$ (plus c.c.) system, subject to the constraints on the event topology discussed in the text. The mixed-event background is represented by the gray shaded histogram, which is normalized to the background component of the fitted curve. The arrow shows the hypothetical $\Xi^{--}_{3/2}$ mass.

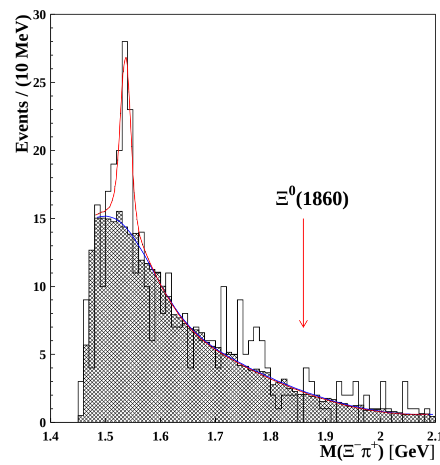


Fig. 6. Invariant mass distribution of the $p\pi^-\pi^-\pi^+$ (plus c.c.) system, subject to the constraints on the event topology discussed in the text. The arrow shows the hypothetical $\Xi^{0}_{3/2}$ mass. The excess near 1770 MeV has a statistical significance of only $1.8\,\sigma$. The peak near 1530 MeV represents the $\Xi^0(1530)$ resonance.

To search for the $\Theta^+$ candidates, events were selected with a $M_{\pi^+\pi^-}$ invariant mass within $\pm 2\sigma$ of the centroid of the $K^0_{\mathrm{S}}$ peak. The resulting $p\pi^+\pi^-$ invariant mass spectrum is shown in Fig. 7. A narrow peak is observed at $1528.0 \pm 2.6 \pm 2.1$ MeV with a Gaussian width of $\sigma = 8 \pm 2$ MeV and a statistical significance of $N_{\mathrm{s}}/\delta N_{\mathrm{s}} = 3.7\,\sigma$. There is no identified $\Sigma^{*+}$ state with $S = -1$ in the invariant mass region between 1500 and 1550 MeV.

Therefore, the state observed here may be interpreted as the predicted exotic $\Theta^+$ pentaquark $S = +1$ baryon.

In an attempt to better understand the origin of the background, the PYTHIA6 Monte Carlo code (shaded histogram in Fig. 8), tuned for HERMES kinematics, was taken to represent the non-resonant background, and the remaining strength in the spectrum was attributed to a combination of six known broad resonances and a new structure near 1530 MeV. Using this background model, a peak is obtained at 1527.0$\pm$2.3$\pm$2.1 MeV with a statistical significance of 4.3 $\sigma$. Also shown in Fig. 8 is the mixed-event background (fine binned histogram), which was obtained by combining a kaon from one and a proton from another event, while keeping all other constraints fixed.

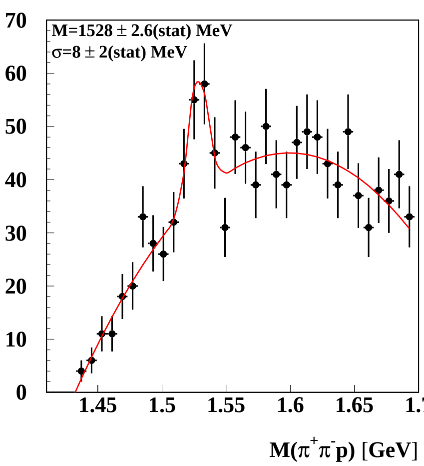


Fig. 7. Distribution in invariant mass of the $p\pi^+\pi^-$ system. The smooth curve results from a fit to the data of a Gaussian plus a third-order polynomial.

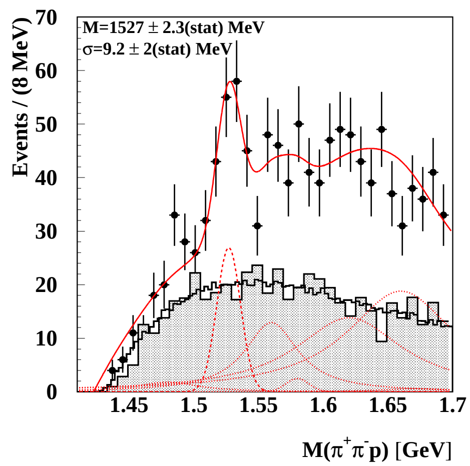


Fig. 8. The same as in Fig. 7, but with a different description of the background (see description in text).

In view of the speculation that the observed resonance is isotensor [8, 9], the possibility that the $\Theta^{++}$ partner is present in the $M_{pK^+}$ spectrum was explored. Although Fig. 4 shows a clear peak for the $\Lambda(1520)$ in the $M_{pK^-}$ spectrum, there is no peak structure observed in the $M_{pK^+}$ mass distribution at that mass. This suggests that the $\Theta^+$ is likely to be isoscalar.

Independent of the background model, the observed 19–24 MeV (FWHM) width of the peak in Fig. 7 is larger than the experimental resolution. As a result, a Breit–Wigner form convoluted with a Gaussian representing the simulated instrumental resolution was used to estimate the intrinsic width of the observed resonance. The resulting average value is [16]

$$\Gamma = 17 \pm 9\,(\mathrm{stat}) \pm 3\,(\mathrm{sys})\,\mathrm{MeV}\,.$$

Estimates of the total spectrometer acceptance from detector simulations have been used to extract the inclusive cross section in the reaction $\gamma^* D \to \Theta^+ X$. The result varies between 100 and 220 nb $\pm$ 25%(stat) depending on the model for the background and the functional form fitted to the peak. An additional factor of two uncertainty is due to the unknown initial kinematic distributions which are assumed to be close to the distributions observed for the $\Lambda(1115)$ at HERMES. The cross section for photo-production of the $\Lambda(1520)$ is found to be $62 \pm 11$(stat) nb. If the branching ratio for the $\Xi^0(1530) \to \Xi^- \pi^+$ decay is taken to be 2/3 [38], its photoproduction cross section is found to be between 8.8 and 24 nb [39].

## 4. Discussion

Because the present experiment cannot determine the strangeness of the $\Theta^+$, the question arises whether the observed resonance near 1530 MeV in the $pK^0$ spectrum can be attributed to previously unobserved $\Sigma^{*+}$ resonance [41]. If the peak were a $\Sigma^{*+}$ resonance, a peak should also appear [42] in the $M_{\Lambda\pi^+}$ spectrum, as shown in Fig. 9. However, no peak appears near 1530 MeV, even though other, well established baryon resonances are clearly seen in the $M_{\Lambda\pi^+}$ and $M_{\Lambda\pi^-}$ spectra. This indicates that the observed peak in the $M_{pK_S}$ invariant mass spectrum cannot be due to a previously unobserved $\Sigma^{*+}$ resonance.

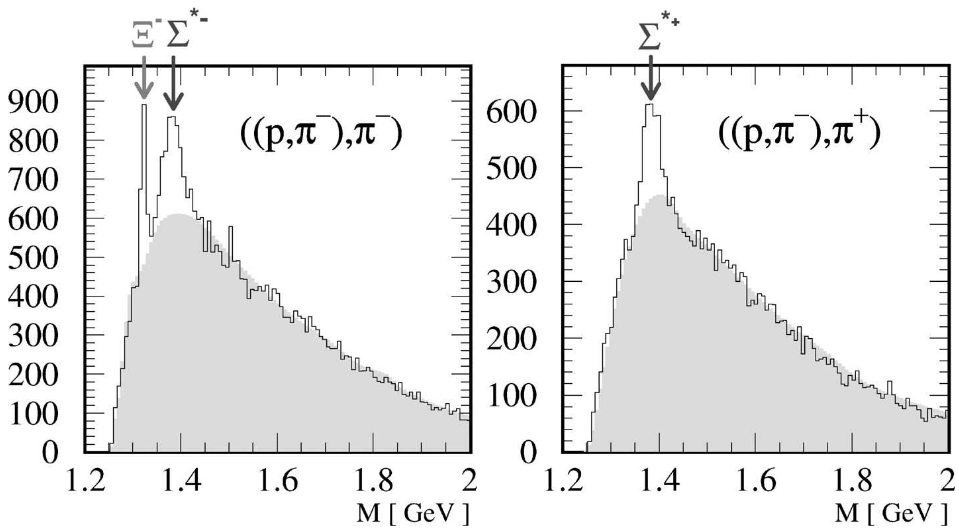


Fig. 9. Distribution in invariant mass of the $(p\pi^-)\pi^-$ (left panel) and $(p\pi^-)\pi^+$ (right panel) system. The mixed event spectrum is shown as a shaded histogram [40].

It is important to note, though, that the existence of pentaquark baryons is still unsettled. The experiments reporting evidence for the $\Theta^+$, listed in Fig. 10 as of January 2005, are confronted with a large number of experiments that fail to see a signal [22–28]. In addition, as shown in Fig. 10, there are large variations in the reported mass values for the $\Theta^+$ state. While this is not entirely uncommon for new decaying particles, it has lead to speculations that the $nK^+$ and $pK_S$ decays result from different states, pointing to the existence of another $\Sigma_5^+$ pentaquark [30, 41]. A number of experiments have performed careful systematic studies to check their reported results, as reported for example in Ref. [43] for the HERMES experiment, without finding any indication of possible errors in the analysis that could lead to fake signals. Given the present ambiguous experimental situation opposing views can be found in the recent literature on this subject [44, 45], in efforts to resolve the apparent experimental inconsistencies.

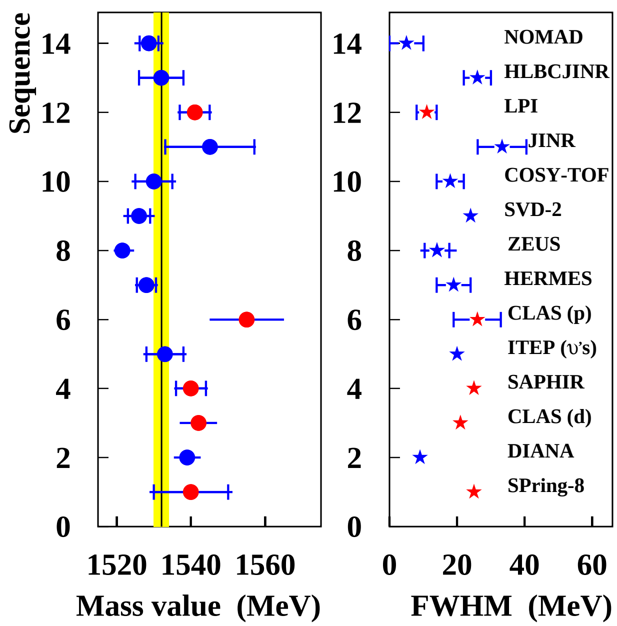


Fig. 10. Mass values and experimental FWHM widths observed in various experiments search for the hypothetical $\Theta^+$ state, as of January 2005. The hatched area corresponds to the weighted average(1532.1 $\pm$ 2.1) of all data $\pm$1 standard deviation. The uncertainty of the average was scaled by the usual factor of square root of the reduced $\chi^2$.

All this brings us to the conclusion that only dedicated, high statistics and high resolution measurements can settle the question whether or not exotic baryons such as the hypothetical $\Theta^+$ pentaquark state do exist.

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