

Are there $S=-2$ pentaquarks?

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Abstract. Recent evidence for pentaquark baryons in the channels $\Xi^- \pi^-$, $\Xi^- \pi^+$ and their anti-particles claimed by the NA49 collaboration is critically confronted with the vast amount of existing data on Ξ spectroscopy which was accumulated over the past decades. It is shown that the claim is inconsistent with these data. In addition two further exotic channels of the pentaquark type available in the NA49 data are investigated. It is argued that this study leads to internal inconsistency with the purported signals.

1 Introduction

Over the past few months a number of observations of an exotic baryonic state in the NK channel, the $\Theta^+(1540)$, have been claimed [1–6]. A common feature of all these claims is a relatively low event statistics with between 20 and 100 entries in the peaks, a signal to background ratio ranging from 1:1 to 1:3, a statistical significance in the region from 3 to 5 standard deviations and, whenever cross section estimations have been made available, a rather large $\Theta^+(1540)/\Lambda(1520)$ ratio of about 1/2 to 3.

This evolution has prompted the search for other members of the corresponding minimal pentaquark anti-decuplet, especially the $S = -2$ isospin-quadruplet. In fact, the NA49 collaboration has claimed the observation of signals in the $\Xi^- \pi^-$ ($I_3 = -3/2$) and $\Xi^- \pi^+$ ($I_3 = +1/2$) combinations and their anti-states [7]. As far as numbers of entries, signal to background ratios and statistical significance are concerned, these claims show surprising similarities to the features mentioned above for the Θ^+ state.

If the claims for the $\Theta^+(1540)$ might benefit, at least for the nK^+ decay, from the absence of preceding high statistics experiments, this is however not true for the $S = -2$ quadruplet. Several decades of experimental work in Ξ spectroscopy have yielded a large thesaurus of data which should be carefully consulted before making any statements about new baryonic states from low statistics data.

In this note we attempt, in Sect. 2, a comparative study of existing data on Ξ spectroscopy. In Sect. 3, we address the minimal internal consistency to be required between the different pentaquark states accessible in the NA49 data. Finally, in Sect. 4 we recall some facts concerning past experience with low statistics spectroscopy.

2 Ξ -Spectroscopy

With the availability of K^- beams at different accelerators a vivid activity concerning the study of Ξ hyperons, their excited states as well as exotic mass combinations containing the Ξ , started in the mid-1960's. When these studies were finally abandoned in the mid-1980's, the available data spanned a wide range of beam momenta from about 2 GeV/c to 16 GeV/c both on proton and deuteron targets. The statistical significance of these data also covered a wide range, from a few hundred measured Ξ^- in the early experiments up to large statistics samples containing about 10^4 Ξ^- .

In the SPS energy range, experiments with hyperon beams, especially using Σ^- and Ξ^- , cover the range from 100 to 350 GeV/c beam momentum. Some results from these experiments which have been terminated more than a decade ago, have been published only recently. These results benefit from an unprecedented event statistics reaching up into the region of more than $2 \cdot 10^5$ detected Ξ^- and $6 \cdot 10^4$ $\Xi^{*0}(1530)$ hyperons.

A straight-forward, non-exhaustive literature search [8–31] shows about 30 different experiments covering the two main classes mentioned above.

After some initial claims of excited Ξ states in different mass ranges, the advent of high statistics data revealed a puzzle that persists even today, namely the difficulty to discern any structure in the $\Xi\pi$ mass spectra above the well-known $\Xi^*(1530)$ resonance. This difficulty concerns exotic as well as non-exotic decay channels in a situation where at least in the non-exotic sector a rich spectroscopy in analogy to the dense coverage of N^* states would be expected.

Given this situation, any experiment attempting the study of Ξ spectroscopy today, especially in p+p interactions with their grave penalty both from initial strangeness and from initial charge content, should carefully confront these rich data samples. In particular it

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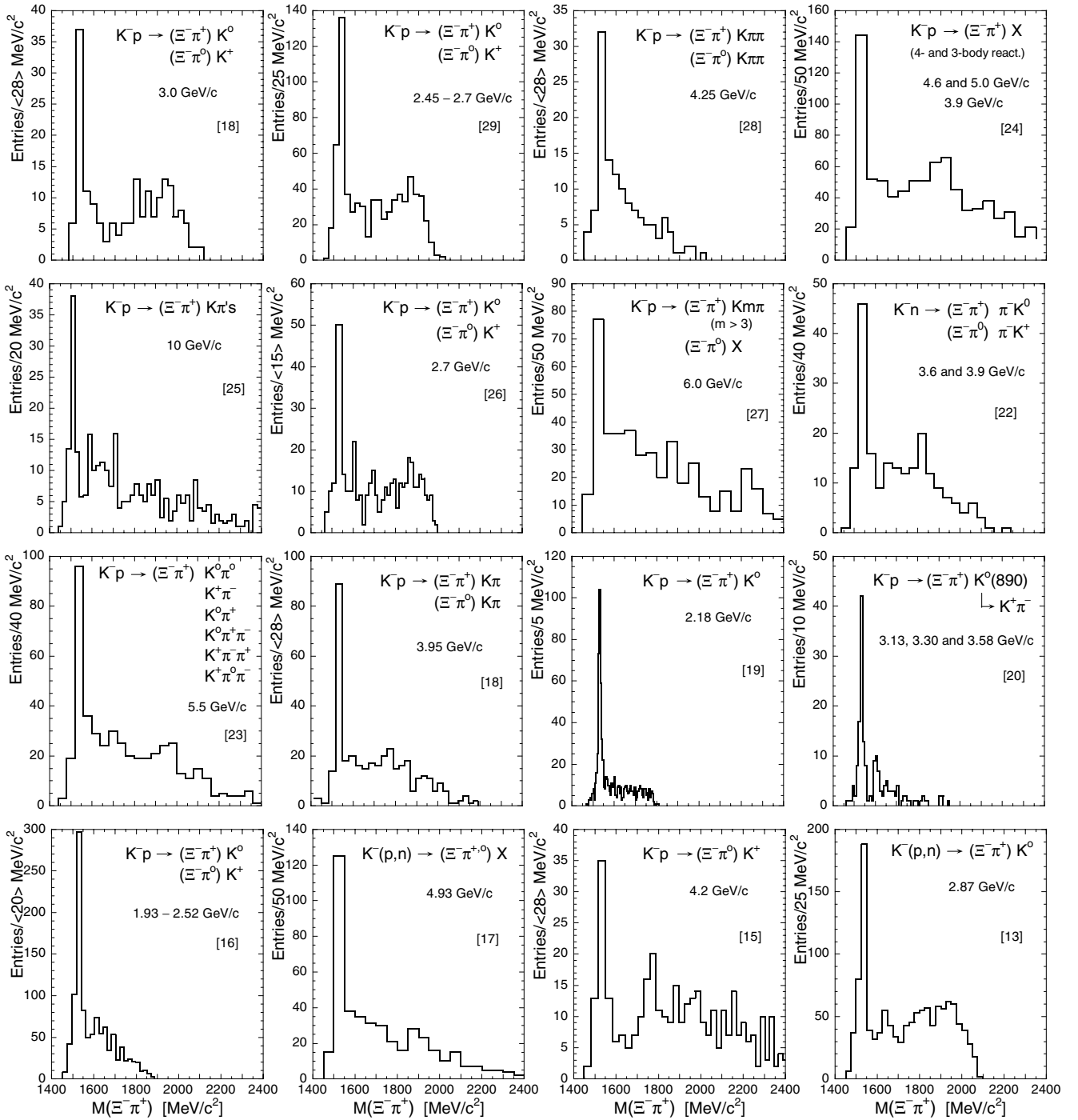


Fig. 1. Compilation of data on $\Xi^- \pi^+$ -spectroscopy

should be made sure that the new data do not fail to come up to the quality of the earlier work.

In the following we attempt to summarize this experimental situation, essentially drawing on published results.

2.1 The $\Xi^- \pi^+$ and $\Xi^- \pi^0$ channels

The combinations $\Xi^- \pi^+$ and $\Xi^- \pi^0$ represent not only the $I_3 = \pm 1/2$ members of the pentaquark quadruplet but also

the non-exotic isospin-doublet of excited Ξ states. A series of mass spectra from different experiments in the lower range of event statistics is shown in Fig. 1 in order to give an overview of the situation without detailed individual discussion which may be found in the original papers. The quadratic mass scale used in some of the publications has been converted into a linear one for ease of comparison, with the average linear bin width in the measured region given on the vertical axis.

Some comments are in place here:

- All experiments see the lowest-lying Ξ^* state at 1530 MeV/c^2 with between about 30 to 300 entries. This resonance can be used as gauge for the comparison of the sensitivity of the different data sets, keeping in mind that the total number of $\Xi^{*0}(1530)$ seen by NA49 is about 150 [34].
- There might be some indications for structure in the higher mass range, but all of them have low statistical significance.
- Cautious claims for definite mass states have been made in the mass ranges 1630, 1820, and 1940 MeV/c^2 . No indication of a structure in the 1860 MeV/c^2 region has been given by author.

In the few cases of identical binning, mass spectra can be added up to improve on statistical significance. These summed mass distributions are shown in Fig. 2. It is evident that in all cases the sensitivity of NA49 is at least reached if not exceeded without showing any evidence for a signal at 1860 MeV/c^2 .

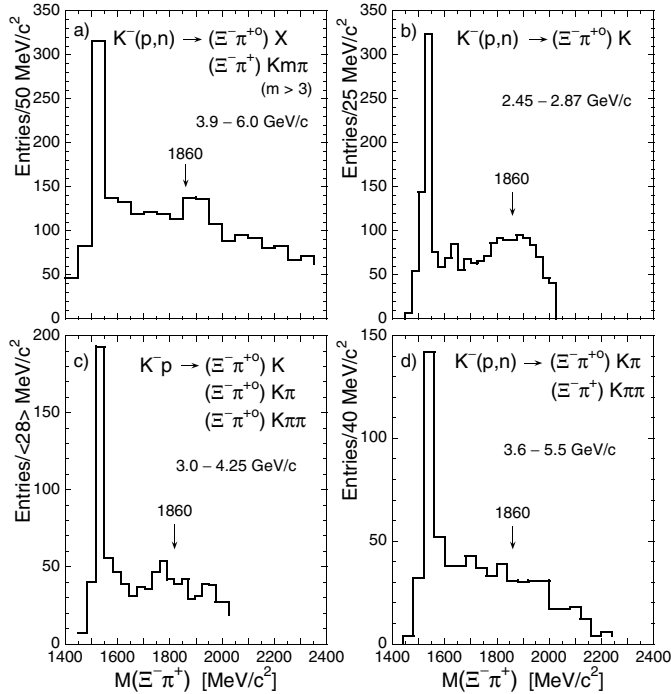


Fig. 2. Summary of data on $\Xi^- \pi^+$ -spectroscopy **a** [24,17,27], **b** [13,29], **c** [28,18,15], **d** [22,23]

A series of mass distributions from experiments with considerably higher statistics is presented in Fig. 3. Here the number of entries in the $\Xi^{*0}(1530)$ peak exceeds the NA49 data by factors of 2 to 15, with bin widths of 20 MeV/c^2 in most cases. No structure in the region 1860 MeV/c^2 is visible in any of the distributions. In fact, the only claim for possible excited states comes from a hyperon beam experiment (Fig. 3f) [10] where a broad structure around 1940 MeV/c^2 is claimed to probably consist

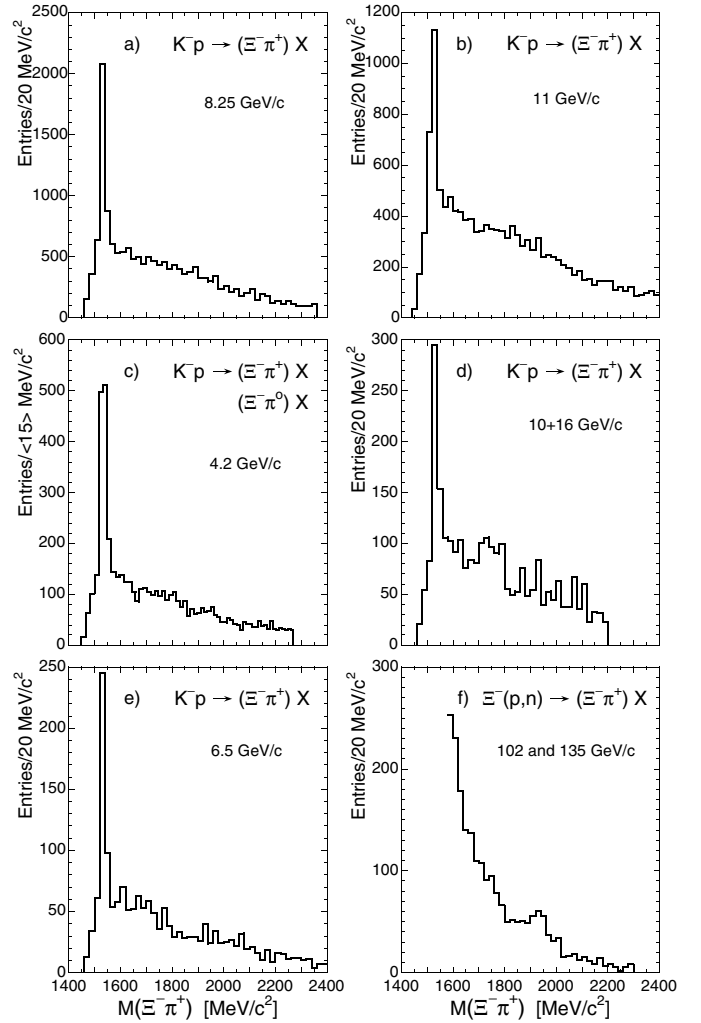


Fig. 3. Compilation of high statistics data on $\Xi^- \pi^+$ -spectroscopy **a** [9], **b** [8], **c** [14], **d** [12], **e** [11], **f** [10]

of several close sub-states. A statistical analysis in this region with respect to a polynomial background fit reveals a significance of order 4σ with no indication for a signal at 1860 MeV/c^2 .

Again, the mass distributions with equal binning can be added up, yielding about 4500 entries in the $\Xi^{*0}(1530)$ peak. This sum distribution is presented in Fig. 4a together with a statistical analysis of the mass region 1550–2200 MeV/c^2 using a polynomial fit (Fig. 4b). There is no evidence for a structure in this whole mass range beyond 2σ , with a projected rms of 1.6.

Calibrating again with the $\Xi^{*0}(1530)$ we conclude that the sensitivity of these combined data exceeds the one of the NA49 experiment by a factor of about 6, also taking into account the lower combinatorial background at the lower energies. This means that a 2σ signal in the NA49 data should appear as a 12σ peak in the combined data, which is clearly not visible in the experimental residual distribution shown in Fig. 4b.

Finally there are results from the hyperon beam experiment WA89 [30] using the Omega Spectrometer

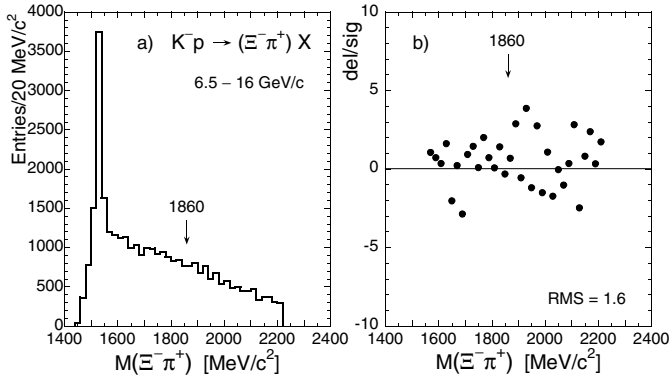


Fig. 4. **a** Summary of high statistics data on $\Xi^-\pi^+$ -spectroscopy [8,9,11,12]; **b** deviation from a straight line fit to the data (excluding the $\Xi^*(1530)$) in units of sigma

at CERN. From a total of 10^8 events this experiment produced more than $2 \cdot 10^5$ Ξ^- and about $6 \cdot 10^4$ $\Xi^{*0}(1530)$ leading to a sensitivity which exceeds the one of the NA49 experiment by a factor of 20. The corresponding $\Xi^-\pi^+$ invariant mass distribution is presented in Fig. 5a, demonstrating the superior statistical accuracy of these data with a bin width of $7 \text{ MeV}/c^2$. The authors claim to observe the $\Xi^*(1690)$ in this channel, with a significance of only about 4σ . This may shed some light on the kind

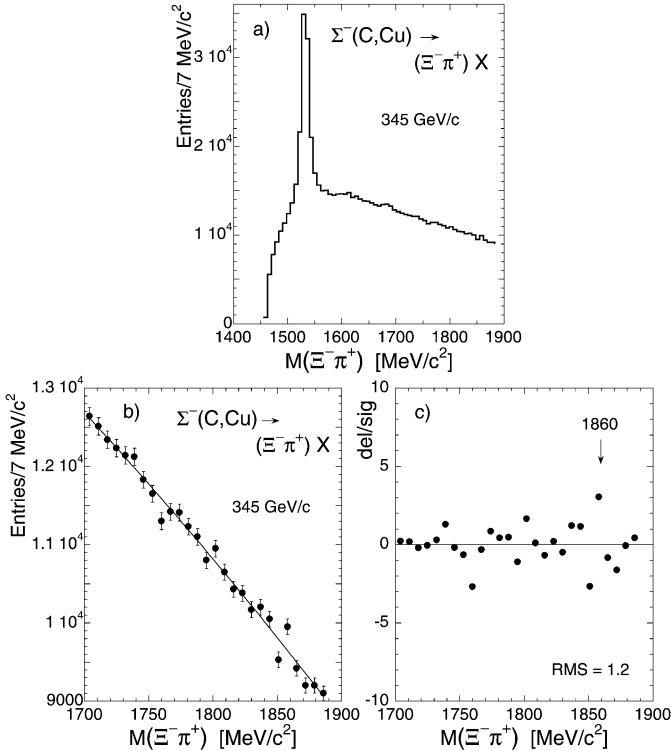


Fig. 5. **a** Very high statistics $\Xi^-\pi^+$ invariant mass distribution [30]; **b** polynomial fit to the data in the mass region $1700\text{--}1900 \text{ MeV}/c^2$; **c** deviation from the polynomial fit in units of sigma

of event sample needed before coming up with evidence for new states in this field. The credibility of the signal is however enhanced in this case by the fact that signals at the same mass have been seen before in different decay particle configurations. The mass region above $1.7 \text{ GeV}/c^2$ is investigated by fitting the data with a polynomial (Fig. 5b) and enumerating the bin-by-bin residuals (Fig. 5c). No structure is visible at $1860 \text{ MeV}/c^2$ beyond $\pm 3\sigma$. The claim of the NA49 collaboration would, on the other hand, correspond to about 10 000 entries at this mass with a significance of more than 40σ .

2.2 The $\Xi^{*0}(1530)\pi^-$ channel

The hyperon beam experiment [31] also allows a look at the $I_3 = -1/2$ channel via the $\Xi^{*0}(1530)\pi^-$ mass combination. Here, two further resonances at $1820 \text{ MeV}/c^2$ and $1950 \text{ MeV}/c^2$ become visible with low statistical significance as shown in Fig. 6. This indicates in the mass range above $1800 \text{ MeV}/c^2$ a preference for a cascade decay via intermediate resonance states rather than a direct decay into two-body ground state combinations. Again, no indication of a structure at $1860 \text{ MeV}/c^2$ is visible and again the high sensitivity needed to claim signals beyond the non-exotic sector is exemplified.

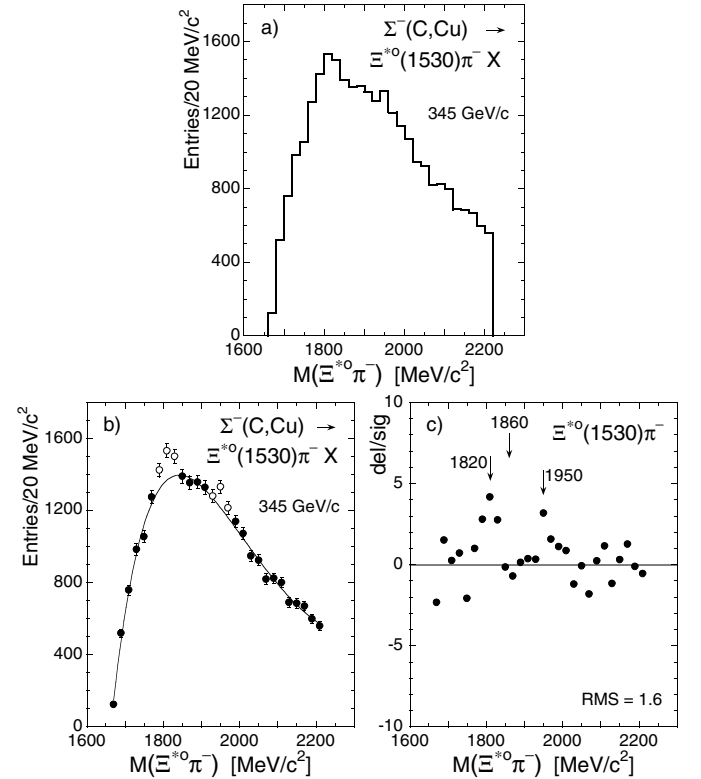


Fig. 6. **a** $\Xi^{*0}(1530)\pi^-$ invariant mass distribution [31]; **b** polynomial fit to the data excluding the mass regions around 1820 and $1950 \text{ MeV}/c^2$ (open symbols); **c** deviation from the polynomial fit in units of sigma

2.3 The $\Xi^{*0}(1530)\pi^+$ channel

The exotic combination $\Xi^{*0}(1530)\pi^+$ corresponds to the $I_3 = +3/2$ member of the pentaquark quadruplet. The respective invariant mass distribution is also available in [31] and is reproduced in Fig. 7. A statistical analysis of this distribution over the full mass range from 1700 to 2200 MeV/c^2 reveals no structure beyond 2σ . It should be noted that also here the experimental sensitivity is more than one order of magnitude above the one of the NA49 experiment.

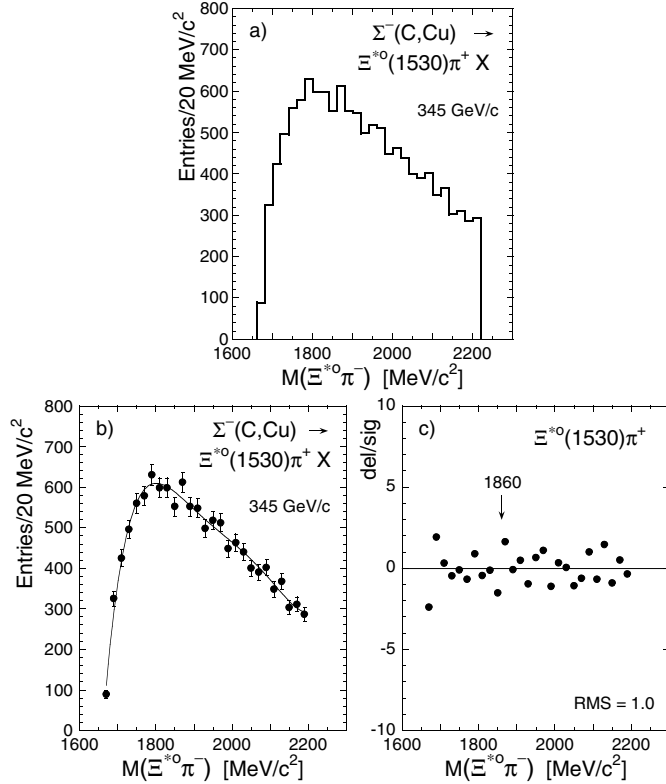


Fig. 7. **a** $\Xi^{*0}(1530)\pi^+$ invariant mass distribution [31]; **b** polynomial fit to the data; **c** deviation from the polynomial fit in units of sigma

2.4 The $\Xi^-\pi^-$ channel

The interest in this exotic state was vivid mostly in the early days of Ξ spectroscopy. The later, high statistics experiments generally do not show the corresponding mass distributions, although in some publications [17] [24] [29] the absence of structure in this channel is explicitly mentioned.

We show in Fig. 8a–d the available invariant mass distributions from 4 publications. Although there are some uncertainties concerning the normalization of the respective final states, we estimate from similar distributions of the non-exotic state (see Fig. 1) that their event statistics corresponds to between 50 and 100 $\Xi^{*0}(1530)$, i.e. only a

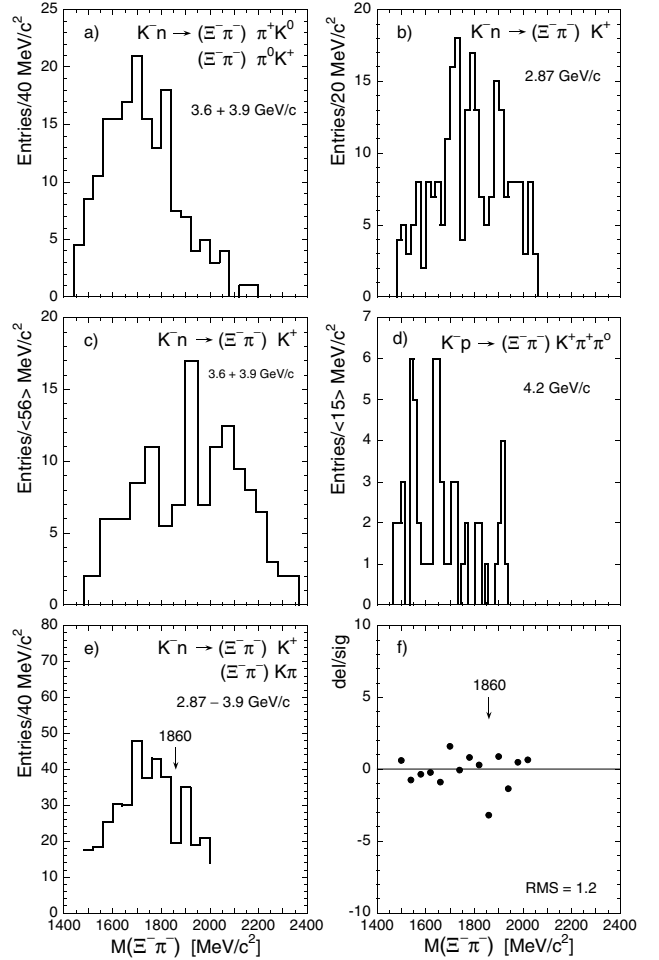


Fig. 8. Compilation of data on $\Xi^-\pi^-$ -spectroscopy **a** [22] **b** [13] **c** [22] **d** [18]; **e** sum of **a** and **b**; **f** deviation from a polynomial fit to **e** in units of sigma

factor of about 1.5 to 3 below the NA49 sample. The first two distributions may be added up by doubling the bin size in the second one. This sum distribution is shown in Fig. 8e and the deviation from a polynomial fit in units of σ in Fig. 8f. Again no structure is seen around 1860 MeV/c^2 with a sensitivity close to the one of NA49, but of course the bigger bin size has here to be considered.

Serious upper limits could be expected from the high statistics data [9] [8] [14] [10] [30] had they shown the spectra. The absence of this information does of course not imply that the according mass distributions have not been looked at. Nothing should therefore prevent the claimants of a new state to enquire about this with eventually still active members of the corresponding collaborations. Such a quest could be most successful with the hyperon beam experiment where data are still being published [32]. In this case, the expected signal of 20 000 entries in the peak with a significance in excess of 60σ (scaled from the NA49 claim) should indeed be rather difficult to miss.¹

¹ For recent results from high statistics experiments see note added at the end of the paper.

3 Internal consistency

The NA49 experiment offers additional possibilities to study exotic spectroscopy due to its wide acceptance including charged particle identification and due to the detection of neutrons in its hadronic calorimeter. The channels to be discussed here are pK^+ and nK^+ . They have recently been presented in a Letter of Intent submitted to the SPS-Committee [35]. We will concentrate on an estimate of yields in relation to the $\Lambda(1520)$ resonance and in relation to the claimed double-strange pentaquarks.

3.1 The $\Lambda(1520)$ resonance as gauge channel

Figure 9 presents the pK^- invariant mass distribution from NA49 using the available event statistics in p+p interactions. About 4000 $\Lambda(1520)$ hyperons are contained in the prominent peak of this distribution. A more detailed analysis of this mass distribution would have to take account of the higher resonances above 1600 MeV/c^2 [35] but for the present discussion a rough estimate of the $\Lambda(1520)$ yield is sufficient. Including branching ratio, acceptance and fiducial cuts this corresponds to about $4 \cdot 10^4$ produced $\Lambda(1520)$ hyperons.

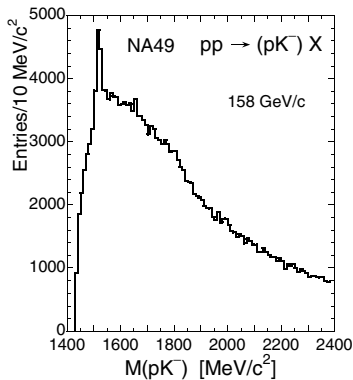


Fig. 9. pK^- invariant mass distribution measured by NA49

3.2 The pK^+ channel

Figure 10a shows the pK^+ invariant mass distribution for the same event sample, again already presented in [35]. The statistical analysis of this mass distribution with respect to a multi-polynomial fit reveals no fluctuations beyond 2σ , with a projected rms of 1.05, over the full mass range (Fig. 10b). The corresponding pentaquark state ($uudu\bar{s}$) would be an $I = 1$ partner of the $\Theta^+(1540)$. Assuming its mass to be 1650 MeV/c^2 [36], a width of 10 MeV/c^2 , and a yield of 10% with respect to the $\Lambda(1520)$, a signal as shown in Fig. 10c would result, corresponding to a statistical significance of 7σ (Fig. 10d). We conclude that such candidates can be excluded over the full mass range on a level of 5% with respect to the $\Lambda(1520)$ yield.

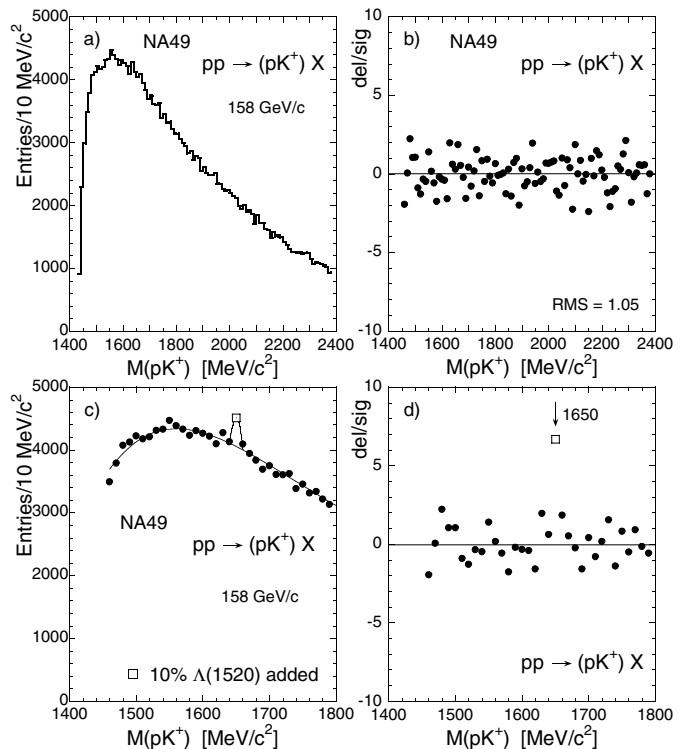


Fig. 10. **a** pK^+ invariant mass distribution measured by NA49; **b** deviation from a multi-polynomial fit to the data in units of sigma; **c** Isovector Pentaquark added to the pK^+ distribution at $M = 1650 \text{ MeV}/c^2$ (see text) assuming a yield of 10% of the $\Lambda(1520)$; **d** statistical significance of the added Isovector Pentaquark

3.3 The nK^+ channel

The nK^+ invariant mass distribution is shown in Fig. 11a. Again with respect to a multi-polynomial fit, no deviation above the 3σ level is observed in the range around 1540 MeV/c^2 (Fig. 11b). As argued in [35] this channel suffers in mass resolution due to the performance of the NA49 hadron calorimeter. The expected resolution in the 1540 MeV/c^2 range has been studied and evaluated to a FWHM of 40 MeV/c^2 (see [35] for details). Assuming the yield of a possible Θ^+ resonance to be 30% of the $\Lambda(1520)$, and convoluting the experimentally claimed width of the Θ^+ with the (dominant) experimental mass resolution, a predicted “signal” as shown in Fig. 11c is produced. This would correspond to a 3–4 σ deviation with respect to a smooth background over several bins (Fig. 11d) forming a shoulder which should be readily visible experimentally. We therefore conclude on a Θ^+ yield of less than 30% of the $\Lambda(1520)$ yield.

3.4 Consistency arguments

Even allowing for a rather wide margin of liberty in predicting the relative yields of pentaquark states in the anti-decuplet for a given energy and type of interaction, there are some basic considerations that allow at least a very

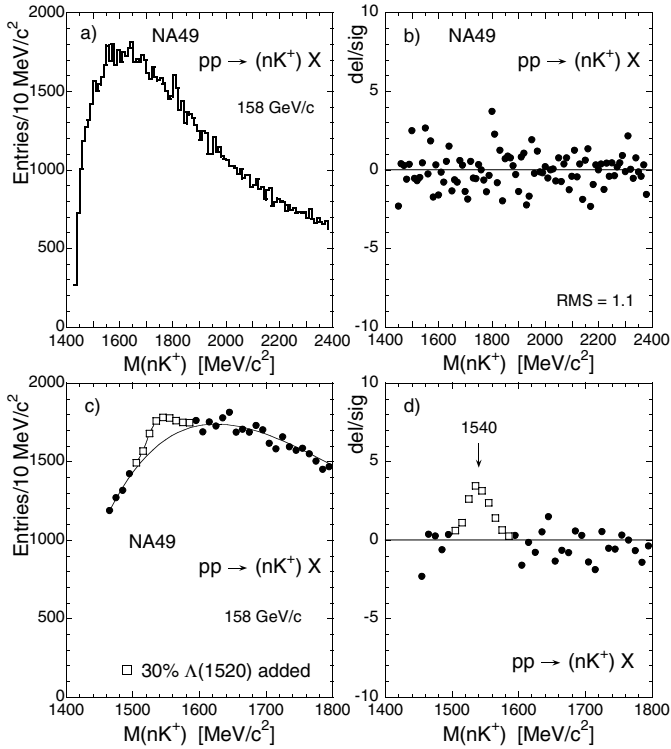


Fig. 11. **a** nK^+ invariant mass distribution measured by NA49; **b** deviation from a multi-polynomial fit to the data in units of sigma; **c** $\Theta^+(1540)$ added to the nK^+ distribution at $M=1540$ MeV/ c^2 assuming a yield of 30% of the $\Lambda(1520)$; **d** statistical significance of the added $\Theta^+(1540)$

rough estimation of the relation between the $S = +1$ singlet and the $S = -2$, $I_3 = -3/2$ baryons.

- Reconstruction efficiency:
The mean reconstruction efficiency for Ξ hyperons in NA49 is known to be 25% [37].
- Additional cuts:
The acceptance for π and the additional cuts introduced result in an effective loss of at least a factor of 2 for the $\Xi^-\pi^-$ combination.
- Branching fraction:
In addition to the $\Xi^-\pi^-$ decay also the channels $Y\bar{K}$, $\Xi^*(1530)\pi$ and other multi-pion final states are open. We therefore estimate the two-body $\Xi^-\pi^-$ branching fraction to less than 20%.
- Charge conservation:
In hadronic collisions there is in general a charge penalty to be paid if produced particles deviate far from the initial charge configuration. For pp interactions, this factor should be at least 4 between a positive and a double-negative state.
- Strangeness conservation:
Similar penalty factors exist for each step in strangeness content of a produced particle with respect to the initial state. Very conservatively this factor can be estimated to about 10 – 20 between the two states concerned.

Contracting these factors and starting from the number of entries in the $\Xi^-\pi^-$ peak, we arrive at more than 80 000 Θ^+ baryons to be produced in the NA49 experiment. This yield, which has to be regarded as a lower limit, exceeds by far the known production rate of $\Lambda(1520)$ hyperons. This is inconsistent with the upper limit of 30% of $\Lambda(1520)$ established in Sect. 3.3 above.

This consistency argument stresses the necessity of keeping track of relative yields and production cross sections in all stages of the experimental studies.

4 Past claims concerning exotic or rare hadron spectroscopy

In the present context it might be useful to look back on two historic examples of claims which suffered from insufficient statistical accuracy.

35 years ago, a spectrometer experiment announced the discovery of the deviation of the $a_2(1320)$ resonance from the standard Breit-Wigner form to a dipole-type shape with a significance of 6σ . No less than five further, different experiments found similar deviations over the following two years, with significances in the range of 3σ . It took more than four years of work and the results of a superior BNL experiment to disclaim the split with a more than 20σ significance in 1971. See the review of R.H.Dalitz [38] for an excellent description of the facts and the statistical problems involved.

25 years ago, and after the masses of heavy flavour hadrons had become known from work at e^+e^- storage rings, there was a host of claims for hadronic heavy flavour production by different experiments and collaborations at the CERN-ISR. These claims started with the D^+ production [39] in 1979 and culminated with experimental evidence for beauty baryon production [40] in 1981. A common feature of all these claims was a statistical significance of typically 4-6 σ with a low number of some dozen entries in the corresponding peaks. This is very reminiscent of the present situation around the different pentaquark claims.

When finally serious cross sections were elaborated [41] and compared to strict upper limits from lepton pair production [42], the majority of the claims turned out to be above those limits by typically 1 to several orders of magnitude.

5 Conclusion

Following the claim of $S = -2$ pentaquark states by the NA49 collaboration, published mass distributions in the $\Xi\pi$ and $\Xi^*(1530)\pi$ channels have been re-investigated. As a result, for all four $S = -2$ states in the minimal pentaquark anti-decuplet, signals at the quoted mass of 1860 MeV/ c^2 can be excluded with a sensitivity which is at least one order of magnitude above the one of the NA49 data.

In addition it is argued that the claimed number of entries in this channel is inconsistent with the absence of

any signal in the nK^+ decay of the $\Theta^+(1540)$ state studied with the same NA49 data set.

In this context, some of the negative experiences accumulated in the past with low-statistics, low-significance hadron spectroscopy, are recalled.

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Note added: High statistics $\Xi^-\pi^-$ invariant mass distributions are indeed available now in different input channels [33], especially also in p+p interactions. None of these distributions shows any indication of a signal at 1860 MeV/c². The upper limits given for the ratio $\Xi(1860)/\Xi^*(1530)$ are in the range 0.3–7% to be compared to 24% claimed by NA49.