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Letter of Intent

BARYON SPECTROSCOPY AND A SEARCH FOR PENTAQUARK STATES WITH THE NA49 DETECTOR

Abstract

A sizeable extension of the data sample obtained by the NA49 experiment in elementary p+p collisions is proposed. This would allow decisive progress in the extraction of non-strange and strange baryonic resonances in the mass range up to and beyond 2 GeV. It would also permit a serious and competitive search, at SPS energy, for the recently claimed pentaquark baryonic configurations.

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1 Introduction

The majority of SU(3) baryonic resonances have been discovered and their quantum numbers have been extracted by partial wave analysis in low-energy hadron-nucleon and photon-nucleon ’formation’ experiments. The extension of these studies with ’production’ experiments to higher cms energies suffers from important combinatorial backgrounds which develop rapidly with increasing hadronic multiplicity, a difficulty which is aggravated by the high density of resonant states compared to their widths over the whole known mass scale.

Whereas a vivid activity is continuing in baryon spectroscopy at low energy facilities [1], the efforts in high energy production experiments have been limited to the diffractive area [2] and to the isolated extraction of some of the lowest-lying Δ states [3] in a field that has anyway been practically abandoned decades ago.

On the other hand the production of baryonic resonances has very important consequences for the understanding of the dynamics of the hadronization process. A majority of Δ states for example cannot be produced directly in the SPS energy range because of the absence of charge and flavour exchange: they must be products of heavier N^* cascading processes [2]. If the fact that the majority of final state pions are decay products of mesonic resonances has been recognized since a long time [4], a similar argumentation is absent for final state baryons. This is mostly due to the lack of corresponding measurements of production cross sections for baryonic resonances, especially in the non-diffractive sector of hadronic collisions. The understanding of baryon number transfer processes which have important consequences for non-perturbative QCD [5] and the evolution of energy density in nuclear collisions [6] will not be possible without properly addressing the problematics of baryon resonances.

In recognition of these facts the NA49 collaboration has pursued over the past few years a programme aimed at the study of baryonic resonances [7] in proton+proton interactions. This programme is based on several advantages offered by the NA49 detector:

- wide angle acceptance with high quality tracking via TPC detectors
- good particle identification over most of the acceptance by energy loss measurements in the TPC tracking system
- access to final state neutron production using a hadron calorimeter
- availability of V0 reconstruction yielding strange hyperon detection up to cascade and Omega- baryons

In addition to these features, two more aspects are of importance in this context:

- large statistics event samples are absolutely mandatory for this type of experimentation. The NA49 experiment has by now accumulated about 5 Mevents in proton+proton collisions. This event sample, which constitutes an increase of about one order of magnitude above samples of comparable quality available up to now [3], should be further enhanced.
- building upon a methodology using event mixing techniques developed for ISR energies [8] the extraction of multi-resonance structures in the presence of important combinatorial backgrounds has become feasible.

The above argumentation receives additional topical interest in view of the very recent claims for the discovery of a new class of baryonic objects called penta-quarks. These objects are of the type $(qqq)(q\bar{q})$ where $\bar{q}$ does not have a partner of the same flavour family amongst the other quarks. Their existence would evidently lead to a complete new spectroscopy in the baryonic sector and to an important extension of non-perturbative QCD.

From the theoretical side such states have been contemplated upon since a long time. Recently especially one state, the I=0 $(udd)(u\bar{s})$ baryon, has been predicted to be a narrow resonance of $<$ 20 MeV width at a mass of about 1530 MeV [9].

The discovery of this state has indeed been claimed by (for the time being) four different experiments [10]. Although these claims all come from experiments with cms energies close to production threshold, the search for such states at higher energies is of evident interest. As will be shown below, the NA49 detector offers all the means needed to explore this possibility, under the condition that sufficiently large event samples are obtained.

This necessity may be fulfilled - in complete compatibility with the 'standard' baryon spectroscopy discussed above - by additional runs with the NA49 detector. We therefore propose to perform an extended period of data taking with proton beam in 2004.

2 Baryon Spectroscopy

The spectroscopy of N^* and Δ resonances in their two body decay channels

(1) $\Delta^{++} \rightarrow p + \pi^+$
(2) $\Delta^+/N^{*+} \rightarrow n + \pi^+$
(3) $\Delta^0/N^{*0} \rightarrow p + \pi^-$
(4) $\Delta^- \rightarrow n + \pi^-$

presents a real challenge to data extraction due to the large number of contributing states and their small mass spacing. This is exemplified in Fig. 1 a-d where the corresponding mass plots after subtraction of their combinatorial backgrounds are presented. This background subtraction is based on an event mixing technique combined with a Monte Carlo generation of the contributing states as shown at the right hand sides of Fig. 1 a-d. Several features of these distributions are noteworthy:

- the pure Δ states (1) and (4) are governed by the lowest lying $\Delta(1232)$. This is due to the 100% branching fraction of $\Delta^{++}(1232)$ and $\Delta^-(1232)$, to the scarcity of higher states in the mass range below 1.9 GeV and to their relatively small two-body branching fractions.
- in channels (2) and (3) where N^* resonances contribute, the Δ states are much less prevalent. Their branching fractions are comparable or inferior to the ones of N^* which clearly govern the production spectrum especially in the 1440, 1520 and 1680 mass ranges.
- channels (2) and (4) involving neutrons detected in the NA49 hadronic calorimeter deliver spectra which are similar in resolution to the ones based on charged particles alone (Notice that in (2) a fraction of $\Sigma^+(1190)$ are reconstructed at vertex and form a shoulder on the $\Delta^+(1232)$ peak in contrast to the $\Lambda(1115)$ in Fig. 1c).

This spectroscopy has been extended to three body decay channels (not shown here), as e.g.

(5) $\Delta^+/N^{*+} \rightarrow p + \pi^+ + \pi^-$
(6) $\Delta^0/N^{*0} \rightarrow n + \pi^+ + \pi^-$

This extension allows an internal cross check of the extraction method as long as the ratio of branching fractions is sufficiently well known, of course with the exclusion of $\Delta(1232)$.

In view of the discussion of pentaquark states which are exotic in the nucleon+kaon system, the non-exotic channels

$$(7) \qquad \Sigma^{*-} \rightarrow n + K^-$$
$$(8) \qquad \Sigma^{*0}/\Lambda^{*0} \rightarrow p + K^-$$

are of particular interest as they may be used as 'gauge' reference for pentaquark spectroscopy, in particular as the states are relatively narrow at least in reference to the Δ and N^* resonances. The corresponding mass plots, again after subtraction of the combinatorial backgrounds, are shown in Fig. 2 a-b. Several remarks are in place:

- also in these channels the importance of heavy resonances up to and beyond 2 GeV in central hadronic production is evident.
- again the decays involving neutrons give encouraging results
- compared to the nucleon+pion channels the statistical accuracy becomes limiting even in a 5 Mevent sample, since the K^-/π^- ratio is only about 0.05 at SPS energies
- this is aggravated in $n + K^-$ decay due to the lower n yields and necessary additional fiducial cuts e.g. for photon/hadron separation in the calorimeter.
- the Λ^*/Σ^* spectroscopy is of considerable importance for the understanding of $\overline{K}$ production, in particular concerning isospin effects in p+p and n+p collisions as they were uncovered by NA49 [11].

Two further decay channels available to NA49 should be mentioned in this context:

$$(9) \qquad \Sigma^{*+} \rightarrow p + K_S^0$$
$$(10) \qquad \Sigma^{*0}/\Lambda^{*0} \rightarrow n + K_S^0$$

The V0- analysis necessary for the detection of K_S^0 has been developed by the collaboration mainly for the study of Λ^0, cascade and Ω^- baryons, where the first observation of Ω^- and $\bar{\Omega}^+$ in p + p collisions was reported [12]. The use of K_S^0 for spectroscopy has to rely on very large data samples as decay vertex distance cuts for background-free extraction of K_S^0 have to be imposed. Work concerning these channels is in progress.

3 Detector Improvements

The NA49 detector layout has been recently improved by the addition of a TPC which covers the acceptance gap in far forward direction imposed by the presence of the ion beam which cannot be accommodated in the active volumes of the standard NA49 tracking chambers. This opens the way for resonance studies in the region of low mass diffraction. Up to now only half of the statistics has been obtained with the improved layout.

A further addition is actually being implemented by the installation of two walls of lead glass blocks which come from the forward electromagnetic calorimeter of the OPAL detector. This will improve the hermeticity of the NA49 detector in the forward hemisphere and open up new channels for spectroscopy involving final state π^0. This calorimeter will be brought into operation in a pilot run during October 2003.

4 Mass Resolution in Decay Channels Involving Neutrons

The determination of the influence of calorimeter energy and angle resolution on the mass resolution in decay channels involving neutrons is a clear pre-requisite for the study of narrow resonances. The neutron calorimeter used in the NA49 experiment [13] is a venerable instrument constructed in the 1970's [14] and employed since in a whole range of experiments. It is of the sampling type containing a Pb/scintillator section for electromagnetic deposits and a Fe/scintillator part for hadron detection. Its hadronic energy resolution can be characterized by

$$\sigma(E)/E = \sqrt{c1/E + c2}$$

where the constants c1=0.9 GeV and c2=0.02 were obtained from measurements with beam particles in the range between 20 and 160 GeV.

The calorimeter has a cellular structure with a granularity of between 10×10 and 20×20 cm^2 at 20 m distance from vertex. This yields by center-of-gravity determination an angular resolution which is of order 1 mrad at neutron energies around 30 GeV. As with increasing energy the wider charge clusters provide a more precise position determination, the resulting transverse momentum smearing is roughly energy independent.

In Figure 3 the mass smearing due to calorimeter effects in the mass region close to threshold in $n{+}K^+$ decays is shown for energy and angular resolution separately and combined. The calorimeter response creates a non-Gaussian mass smearing sharply peaked on particle mass and corresponding to a FWHM resolution of order 40 MeV for $n + K$ decay in the mass range of 1.5 GeV. This value is only mildly depending on resonance mass up to masses of 2 GeV.

This result is clearly compatible with the $n + \pi$ and $n + K$ mass spectra shown in Figs.1 and 2. Concerning the detection of narrow structures with predicted widths of about 20 MeV we consider this response as limiting but - especially due to its non-Gaussian shape - as still allowing a senseful pentaquark search also in neutron decay modes.

Improvements on the mass resolution are possible if fiducial cuts favouring energy deposition in several adjacent cells are introduced off line. The results shown in this letter have been obtained without such additional cuts.

5 Search for Pentaquarks

At present the experimental evidence for pentaquark baryons comes from one $S = +1$ state, the $\Theta^+(1540)$ close to $N + K$ threshold. This state is claimed to be seen in the $n + K^+$ or $p + K^0$ decay configurations. The experimental mass spectra from four different experiments [10] - all published in 2003 - are confronted in Fig.4. Several remarks should be made:

- in all experiments the resonance is found close to the top of a sharply peaking background. As usual in such situations, the exact shape of the background is very difficult to estimate.
- the experiments extract a signal of between 20 and 60 entries over estimated backgrounds of 15 to 110 entries. From this they claim a statistical significance of between 4 and 5 standard deviations.
- strong cuts have been applied to the event samples in all cases.

This situation is reminiscent of the non-exotic partner of this state, the $\Sigma^*(1550)$ which has been seen by several experiments as a narrow peak in the $\Lambda^0 + \pi$ channel. One of the experimental mass plots [15] is shown in Fig.5 where a significance of five standard deviations is claimed. This state is up to now not recognized as an established resonance in the PDG tables.

The fact that all signals are in the same ballpark of low statistics and in the range of 4-5 standard deviations is also reminiscent of the host of charmed meson and baryon and even beauty baryon states claimed at the ISR in the late 70ies, once their masses were known. The majority of these claims has been shown to violate the tight upper limits on cross sections imposed by lepton pair production [16].

Notwithstanding these possible criticisms we feel that the fundamental interest of pentaquark states, should they exist, is so high that it requires a serious search effort also at SPS energies. This is the more so as this search can be at least started with a very small effort in funding and manpower by an extended run of the NA49 experiment in its present configuration.

5.1 Decay channels

Up to now a quantum number assignment of the $\Theta(1540)$ is of course absent. If it would be an isospin singlet state, only the decay channels

(11) $\Theta(1540) \rightarrow n + K^+$
(12) $\Theta(1540) \rightarrow p + K^0$

would be present. An assignment as isospin triplet is in principle also possible, in which case the isospin partners would allow the additional channels

(13) $(I_3 = +1) \rightarrow p + K^+$
(14) $(I_3 = -1) \rightarrow n + K^0.$

All four channels are in fact accessible to NA49. The sharpest signals are to be expected from channels (12) and (13) where the intrinsic mass resolution of the detector has been shown to be on a level of a few MeV. As discussed above, the channels involving neutron detection are more limiting due to calorimeter resolution. An additional complication arises in (12) and (14) from the admixture of $\bar{K}^0$ in the K^0_S. This could mix-in ”normal” Σ^* and Λ^* states of the type $\Sigma^*(1550)$ mentioned above. In the low energy experiments this can be solved by detecting - in the quasi-exclusive mode available at low multiplicity - an additional K^- to fix the s quark, or by operating with incoming K^+. Even at SPS energy however, requesting an additional K^- in the same hemisphere should strongly suppress wrong assignments at the sole expense of reduced event statistics.

5.2 Mass Spectra

From the presently available data, a first impression of the mass spectra in decay channels (11) and (13) may be obtained. These mass distributions are shown in Fig.6. They extend at SPS energies of course to a much higher mass range as compared to the low energy experiments shown in Fig.4 and they are characterized by a sizeable combinatorial background. However the direct comparison with the non-exotic charge combination $p + K^-$ in the region of the $\Lambda^*(1520)$ resonance also shown in Fig.6 demonstrates that sensible upper limits may be extracted for these channels provided that sufficiently large data samples are obtained.

We reiterate here that in order to approach an unambiguous situation concerning this new type of baryon spectroscopy, very serious efforts should also be spent in the SPS energy range.

Here the NA49 detector offers a unique possibility to contribute rapidly and with minimum expense to this exciting field.

5.3 Further States Accessible to NA49

As emphasized by R. Jaffe and F. Wilczek [17] complete sets of new multiplets have to be expected in a possible pentaquark spectroscopy, amongst others a new quadruplet of cascades. Here, e.g. the states

$$(dss)(d\bar{u}) \rightarrow \Xi^- + \pi^- \qquad (15)$$

$$(uds)(s\bar{d}) \rightarrow \Lambda^0 + \overline{K}^0 \qquad (16)$$

would be accessible to NA49. As first example of a preliminary study of states including V0 reconstruction we show in Fig.7 the mass distribution corresponding to combination (12). Again it is clear that the establishment of sensible upper limits for such new states depends essentially on our possibilities to improve on event statistics.

6 Beam Request

We request a sizeable period of datataking in 2004 with proton beam in the H2 beam line. For instance, 3 months of running would yield about a factor of 4 increase in number of events compared to our present data sample and would allow us to fully exploit the detector upgrades described above. We consider the corresponding gain in data volume and quality as crucial both for our programme in baryon spectroscopy and for a serious search for pentaquark states.

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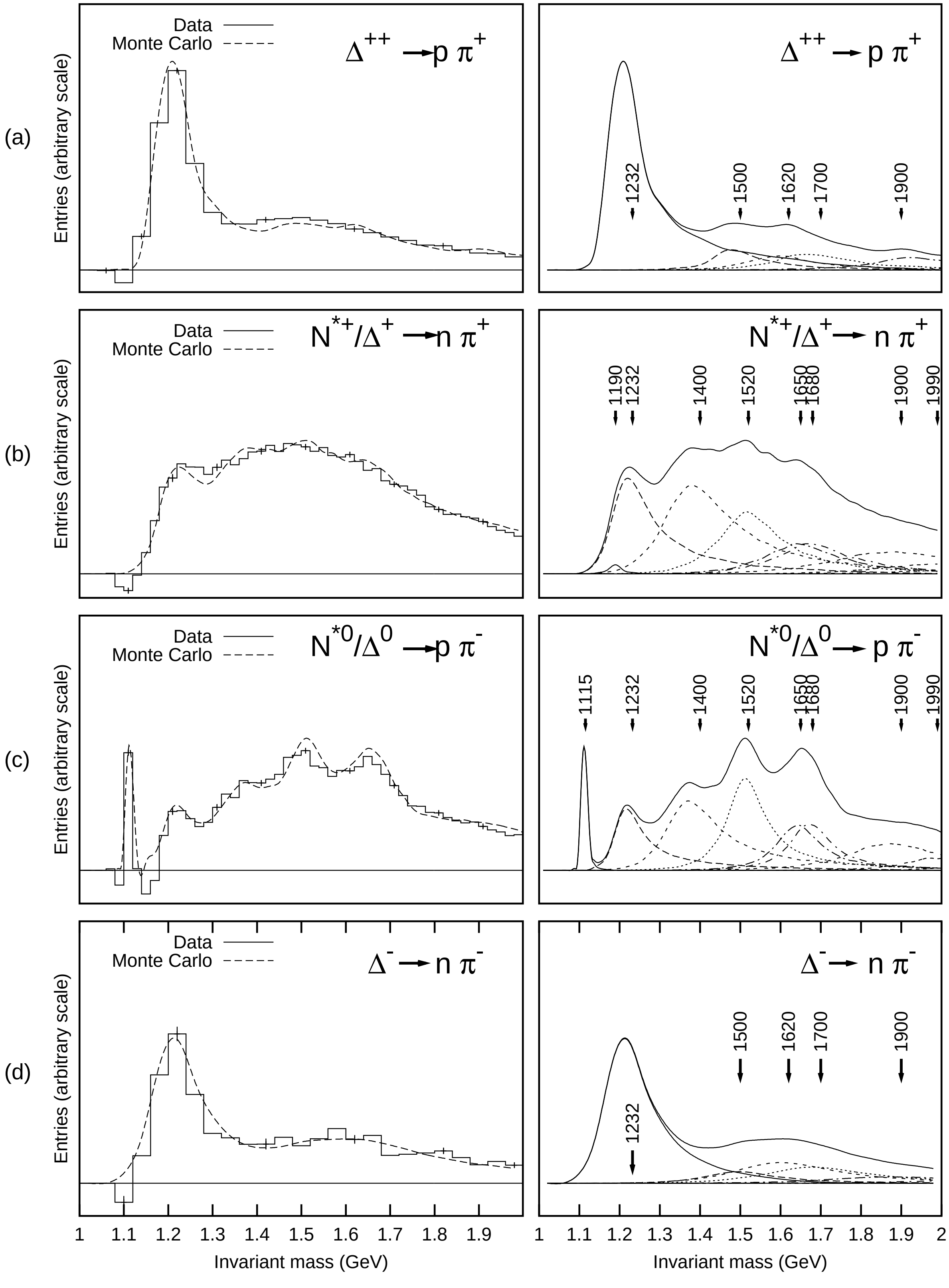

Figure 1: Background subtracted pion nucleon effective mass distributions for (a) $p + \pi^+$ (b) $n + \pi^+$ (c) $p + \pi^-$ (d) $n + \pi^-$ (preliminary NA49)

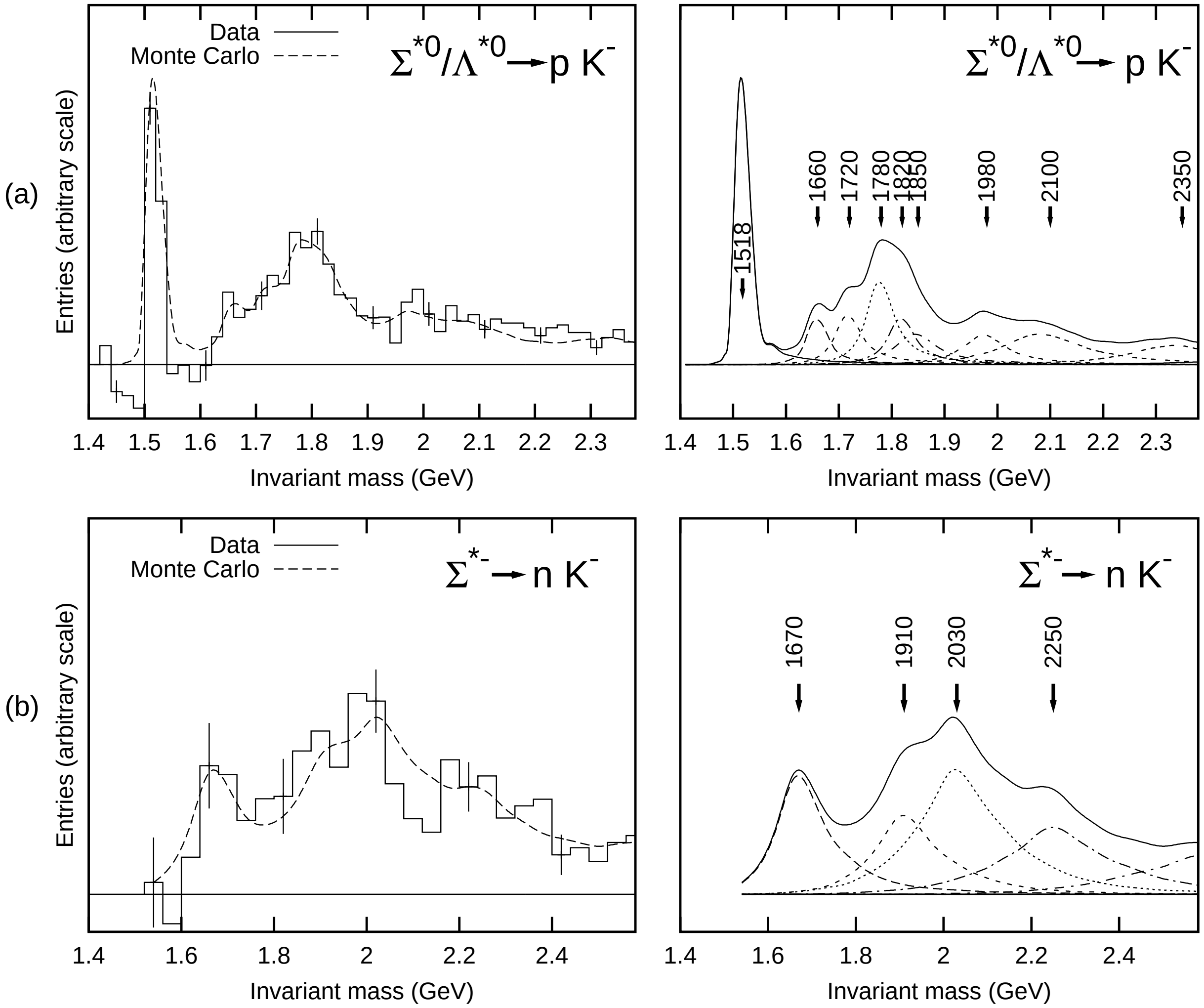

Figure 2: Background subtracted kaon nucleon effective mass distributions for (a) $p + K^-$ (b) $n + K^-$ (preliminary NA49)

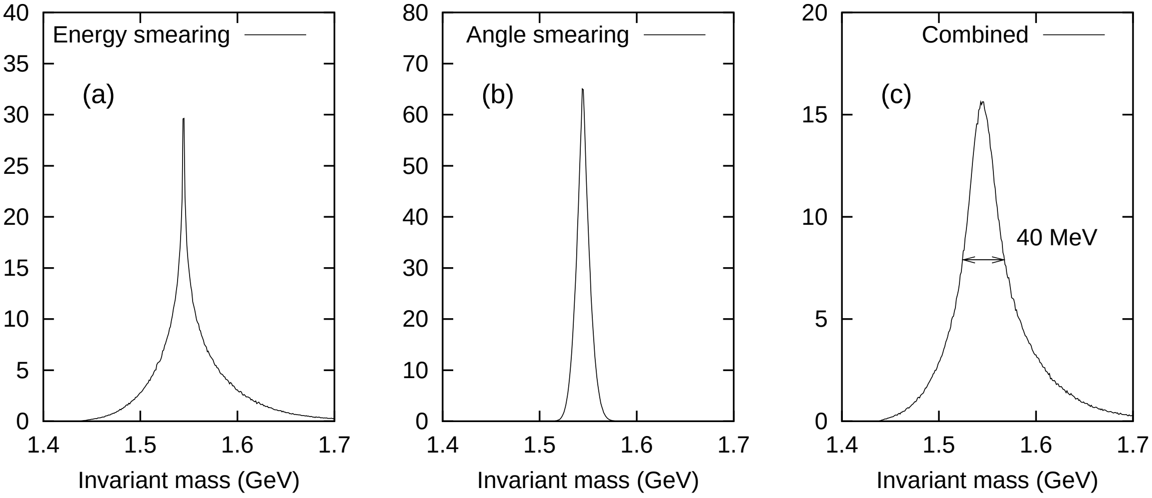

Figure 3: Influence of calorimeter energy and angular response on mass resolution in the $n + K$ channel (a) energy smearing alone, (b) angle smearing alone, (c) combined effect

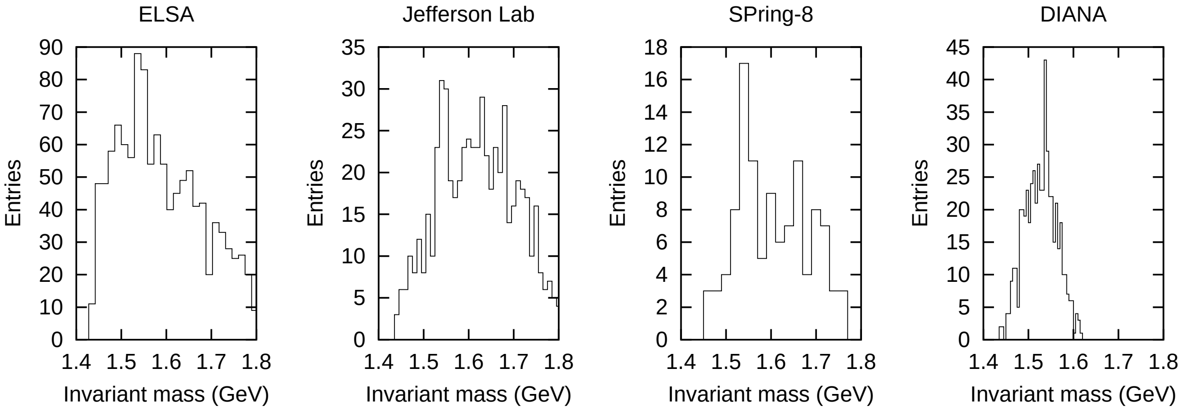

Figure 4: Published mass distributions in the exotic channels $n + K^+$ and $p + K^0$ (ref.10)

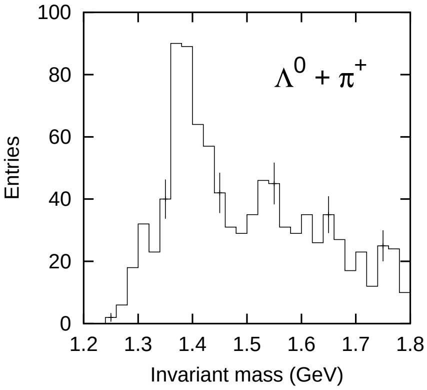

Figure 5: Mass distribution in the channel $\Lambda^0 + \pi^+$ showing the $\Sigma^{*+}(1375)$ and the $\Sigma^{*+}(1550)$ signals [15]

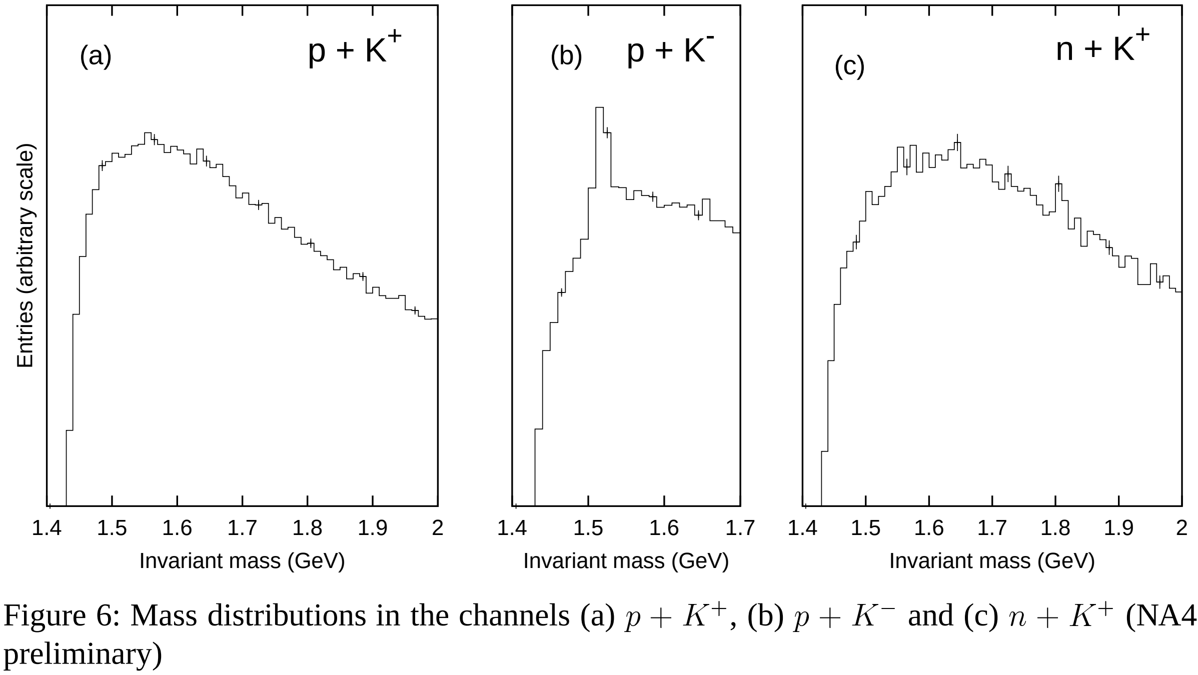

Figure 6: Mass distributions in the channels (a) $p + K^+$, (b) $p + K^-$ and (c) $n + K^+$ (NA49 preliminary)

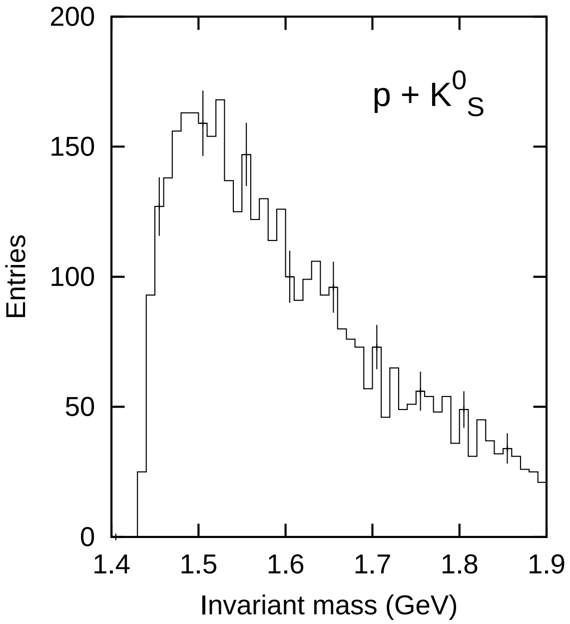

Figure 7: Mass distribution in the channel $p + K^0_S$ (NA49 preliminary)