Observation of a baryon resonance with positive strangeness in K^+ collisions with Xe nuclei*

DIANA Collaboration

V.V. Barmin[a], V.S. Borisov[a], G.V. Davidenko[a], A.G. Dolgolenko[a,†], C. Guaraldo[b], I.F. Larin[a], V.A. Matveev[a], C. Petrascu[b], V.A. Shebanov[a], N.N. Shishov[a], L.I. Sokolov[a], and G.K. Tumanov[a]

[a] *Institute of Theoretical and Experimental Physics, Moscow 117259, Russia*

[b] *Laboratori Nazionali di Frascati dell' INFN, C.P. 13-I-00044 Frascati, Italy*

Abstract

The status of our investigation of low-energy K^+Xe collisions in the Xenon bubble chamber DIANA is reported. In the charge-exchange reaction $K^+\text{Xe} \to K^0 p\text{Xe}'$, the spectrum of K^0p effective mass shows a resonant enhancement with $M = 1539 \pm 2$ MeV/c^2 and $\Gamma \leq 9$ MeV/c^2. The statistical significance of the enhancement is near 4.4σ. The mass and width of the observed resonance are consistent with expectations for the lightest member of the anti-decuplet of exotic pentaquark baryons, as predicted in the framework of the chiral soliton model.

*Talk at Session of Nuclear Division of Russian Academy of Sciences, Dec. 3, 2002, to appear in proceedings, Phys. Atom. Nuclei, 2003.

†Corresponding author. E-mail address: dolgolenko@vitep1.itep.ru.

This paper reports an investigation of low-energy K^+–nucleus collisions aimed at testing the hypothesis of an anti-decuplet of exotic pentaquark baryons, as proposed by Diakonov, Petrov, and Polyakov [1] in the framework of the chiral soliton model. Assuming that the known nucleon resonance $P_{11}(1710)$ belongs to the hypothesized anti-decuplet, predictions for the masses and decay widths of its other members have been obtained [1]. Of these, the lightest is the exotic pentaquark state $uudd\bar{s}$ with mass near 1530 MeV/c^2 and decay width $\Gamma < 15$ MeV/c^2. This spin-1/2 isospin-zero state with positive strangeness, referred to as the Z^+ baryon, is expected to decay to K^0p and K^+n.

Two different methods may be employed when searching for formation of the Z^+ baryon in K^+Xe collisions. The first and straightforward approach is to analyze the effective mass of the K^0p system in the reaction $K^+\text{Xe} \to K^0p\text{Xe}'$ for the Z^+ peak near 1530 MeV/c^2. The second approach is to measure the cross sections for formation of the final states K^0p and K^+n as functions of K^+ momentum. Given a target nucleon bound in the Xe nucleus, formation of the Z^+ baryon should manifest itself as an enhancement of partial cross sections of elementary processes $K^+n \to K^+n$ and $K^+n \to K^0p$ at K^+ momentum near 480 MeV/c. Measurements of these partial cross sections in the interval $400 < P_{K^+} < 700$ MeV/c are in progress, and should finally reach a statistical accuracy of (3–6)% with K^+ momentum pitch of 30–40 MeV/c. The latter measurements are also important for clarifying some problems arising in the analysis of low-energy K^+–nucleus collisions [2, 3, 4].

The bubble chamber DIANA filled with liquid Xenon has been exposed to a separated K^+ beam with momentum of 850 MeV/c from the ITEP proton synchrotron. The density and radiation length of the fill are 2.2 g/cm^3 and 3.7 cm, respectively. The chamber has a total volume of $70 \times 70 \times 140$ cm^3 viewed by photographic cameras, and operates without magnetic field [5]. Charged particles are identified by ionization and momentum-analyzed by range in Xenon. On total, some 10^6 tracks of incident K^+ mesons are recorded on film. A half of collected film has been scanned, and nearly 25 000 events with visible K^0 decays, $K^0_S \to \pi^+\pi^-$ and $K^0_S \to \pi^0\pi^0$, have been found.

In the fiducial volume of the bubble chamber, K^+ momentum is a function of longitudinal coordinate and varies from 750 MeV/c for entering kaons to zero for those that range out through ionization. (A 150-mm-thick layer of Xenon downstream of the front wall is beyond the selected fiducial volume, and is only used for detecting the secondaries that travel in the backward hemisphere.) Throughout this interval of K^+ momentum, partial cross sections for formation of various final states of K^+Xe collisions can be measured thanks to efficient detection of either the decays and interactions of incident kaons in the Xenon bubble chamber. The momentum of an interacting K^+ is determined from the longitudinal coordinate of interaction vertex with respect to central position of the observed maximum due to decays of stopping K^+ mesons. The uncertainty on K^+ momentum is near 20 MeV/c for P_{K^+} in the range of 500 ± 50 MeV/c.

The methodology of this work is illustrated by Fig. 1 where measured K^+ range before interaction or decay is plotted for different event categories (the upper scale shows corresponding K^+ momentum). These data are based on a throughput measurement of 41 thousand tracks of incident kaons. The distribution of all incident K^+ mesons in track length is shown in Fig. 1a, and of those K^+ mesons that have decayed either in flight or at rest—in Fig. 1b. The enhancement near 945 mm is due to decays of stopping kaons. All K^+ decays have been uniquely identified in the bubble chamber, and observed branching fractions are in agreement with tabulated values. The distribution of selected events of the charge-exchange reaction $K^+\mathrm{Xe} \rightarrow K^0X$ is illustrated in Fig. 1c. This includes the events with either a K^0_S detected by decay to $\pi^0\pi^0$ or $\pi^+\pi^-$, and a K^0_L whose presence is inferred from non-observation of strange particles in the final state[1]. Apart from K^+ decays and the charge-exchange reaction $K^+\mathrm{Xe} \rightarrow K^0X$, the inclusive distribution of Fig. 1a picks contributions from elementary scattering processes $K^+n \rightarrow K^+n$ and $K^+p \rightarrow K^+p$ and from electromagnetic interactions with Coulomb field of the Xe nucleus. The extraction of corresponding partial cross sections is in progress. As indicated above, comparing the partial cross sections of elementary reactions $K^+n \rightarrow K^+n$, $K^+n \rightarrow K^0p$, and $K^+p \rightarrow K^+p$ as functions of K^+ momentum may provide a clue to formation of the hypothesized Z^+ baryon in K^+Xe collisions.

In this paper we adopt an alternative approach that consists in analyzing the K^0p effective mass in the charge-exchange reaction $K^+n \rightarrow K^0p$ on a bound nucleon. The events of this reaction are fully measured and reconstructed in space using specially designed stereo-projectors similar to those proposed in [6]. Of the 25000

[1]Note that of some 6300 events in the latter distribution, 3100 are part of the aforementioned subsample of 25000 events with detected K^0_S decays. Measuring K^+ track length in all such events will significantly increase the statistics of the charge-exchange reaction.

events with visible K^0_S decays, selected for complete reconstruction are those with a single proton and a $K^0_S \to \pi^+\pi^-$ candidate in the final state. The distance between the primary and K^0 vertices is required to exceed 2.5 mm. In a selected event, we measure the K^0_S and proton emission angles with respect to the K^+ direction, π^+ and π^- emission angles with respect to the parent K^0_S direction, and proton and pion paths in Xenon. The momentum is estimated by range for the proton, and by pion ranges and emission angles for the K^0_S. Proton and K^0_S momenta are required to exceed 180 and 170 MeV/c, respectively. Further details on the experimental procedure can be found in [7, 8].

In order to reduce the total volume of measurements, K^+ range before interaction is required to exceed 550 mm. On average, this corresponds to the selection $P_{K^+} < 530$ MeV/c [2]. The distribution of measured events of the reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$ in P_{K^+} is shown in Fig. 2. The mean value of K^+ momentum is close to 470 MeV/c. By now, we have fully measured 1112 events of the charge-exchange reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$; measuring all selected events will nearly double the available statistics of this reaction.

In order to estimate the uncertainty on effective mass of the $K^0 p$ system, we invoke our earlier measurements [9] of two-prong secondary vertices (or Vees) formed by a proton and a charged pion, that relied on same techniques. The distribution of effective mass of such Vees, illustrated in Fig. 3, shows a prominent Λ^0 peak at the expected mass of $M(p\pi^-) = 1116 \pm 1$ MeV/c^2 with instrumental width of $\sigma = 3.3 \pm 1.0$ MeV/c^2. Note that distributions of either the total momentum and proton momentum are very similar for the $p\pi^-$ system from Λ^0 decay and for the $K^0 p$ system formed in the reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$. At the same time, the K^0 and π^- momenta are measured with very similar precision. We may conclude that effective mass of the $K^0 p$ system, like that of the $p\pi^-$ system, is measured to a precision of a few MeV/c^2.

Effective mass of the $K^0 p$ system formed in the charge-exchange reaction is plotted in Fig. 4a for all measured events. Qualitatively, a narrow enhancement is seen at the expected mass of the Z^+ baryon ($M \simeq 1530$ MeV/c^2). To estimate the level of background, the mass spectrum of Fig. 4a has been fitted to a linear combination of two regular distributions:

[2]Mean momentum of incident K^+ beam varied by some ± 15 MeV/c in different exposures.

- the K^0p mass spectrum expected for the nonresonant charge-exchange reaction $K^+n \to K^0p$, obtained through a simulation that takes into account the momentum distribution of interacting K^+ mesons, the Fermi motion and binding energy of the target nucleon, the differential cross section for K^0 emission in the charge-exchange reaction [10], and actual conditions of the discussed experiment; and

- a distribution obtained by the method of random stars.

The results of the fit are illustrated by the dashed line in Fig. 4a. In the mass interval of 1535–1545 MeV/c^2 populated by 107 events, thus estimated background amounts to 83 events resulting in a statistical significance of 2.6σ.

It is interesting to see if the observed enhancement is affected by rescattering of reaction products in nuclear matter. In order to remove the events worst affected by rescatterings, additional topological selections[3] are applied:

- $\theta_p < 100^o$ and $\theta_K < 100^o$ for the proton and K^0 emission angles with respect to K^+ direction in the laboratory frame;

- $\cos\Phi_{pK} < 0$ for the azimuthal angle between the proton and K^0 directions (that is, the proton and K^0 are required to be back-to-back in the plane transverse to beam direction).

According to a simulation that accounts for Fermi motion of the target neutron, these selections keep the bulk of events of the charge-exchange reaction that are not affected by proton and K^0 rescattering in nuclear matter. Of the 1112 measured events of the reaction $K^+\mathrm{Xe} \to K^0p\mathrm{Xe}'$, nearly a half (541 events) survive the additional selections. In the K^0p mass spectrum for these events, that is shown in Fig. 4b, the enhancement near 1540 MeV/c^2 becomes more prominent. In the mass interval of 1535–1545 MeV/c^2, the total number of events is 73 with an estimated background of 44 events, resulting in a statistical significance of 4.4σ. In order to estimate the mass and width of the observed resonance, a Gaussian with floating position and r.m.s. is added to the fitting function. The latter fit yields the values $M = 1539 \pm 2$ MeV/c^2 and $\sigma = 3$ MeV/c^2.

[3] At this stage of the analysis, no kinematic selections based on constraining measured events to $K^+n \to K^0p$ are used.

To summarize, a baryon resonance with mass $M = 1539 \pm 2$ MeV/c^2 and width $\Gamma \leq 9$ MeV/c^2 has been observed in the K^0p effective-mass spectrum for the reaction $K^+\text{Xe} \to K^0p\text{Xe}'$. The statistical significance of the signal is estimated as 4.4σ. The resonance is a strong indication for formation of the exotic pentaquark Z^+ baryon[4]. Our work is still in progress.

We wish to thank A.E. Asratyan for useful comments and discussions. This work is supported by the Russian Foundation for Basic Research (grant 01-02-16465).

References

[1] D. Diakonov, V. Petrov, and M. Polyakov, Z. Phys. A359, 305 (1997).

[2] C.B. Dover and G.E. Walker, Phys. Rep. 89, 1 (1982).

[3] R. Weiss et al., Phys. Rev. C49, 2569 (1994).

[4] N. Kaiser et al., Nucl. Phys. A594, 325 (1995).

[5] V.V. Barmin et al., Prib. Tekhn. Eksp. 4, 61 (1984).

[6] J.W. Cronin et al., Phys. Rev. Lett. 18, 25 (1967).

[7] V.V. Barmin et al., Nucl. Phys. A566, 409 (1993).

[8] V.V. Barmin et al., Phys. At. Nucl. 57, 1655 (1994).

[9] V.V. Barmin et al., Nucl. Phys. A683, 305 (2001).

[10] U. Casadei et al., CERN–HERA 75-1.

[4]The existence of a baryon resonance with positive strangeness looks even more reliable in connection with the recent paper by Y. Nakano et al. (arXiv:hep-ex/0301020) which reports the observation of a baryon resonance in the K^+n system with $M = 1.54 \pm 0.01$GeV/c^2, $\Gamma < 25$ MeV/c^2, and significance of 4.6σ in the reaction $\gamma n \to K^+K^-n$ on ^{12}C.

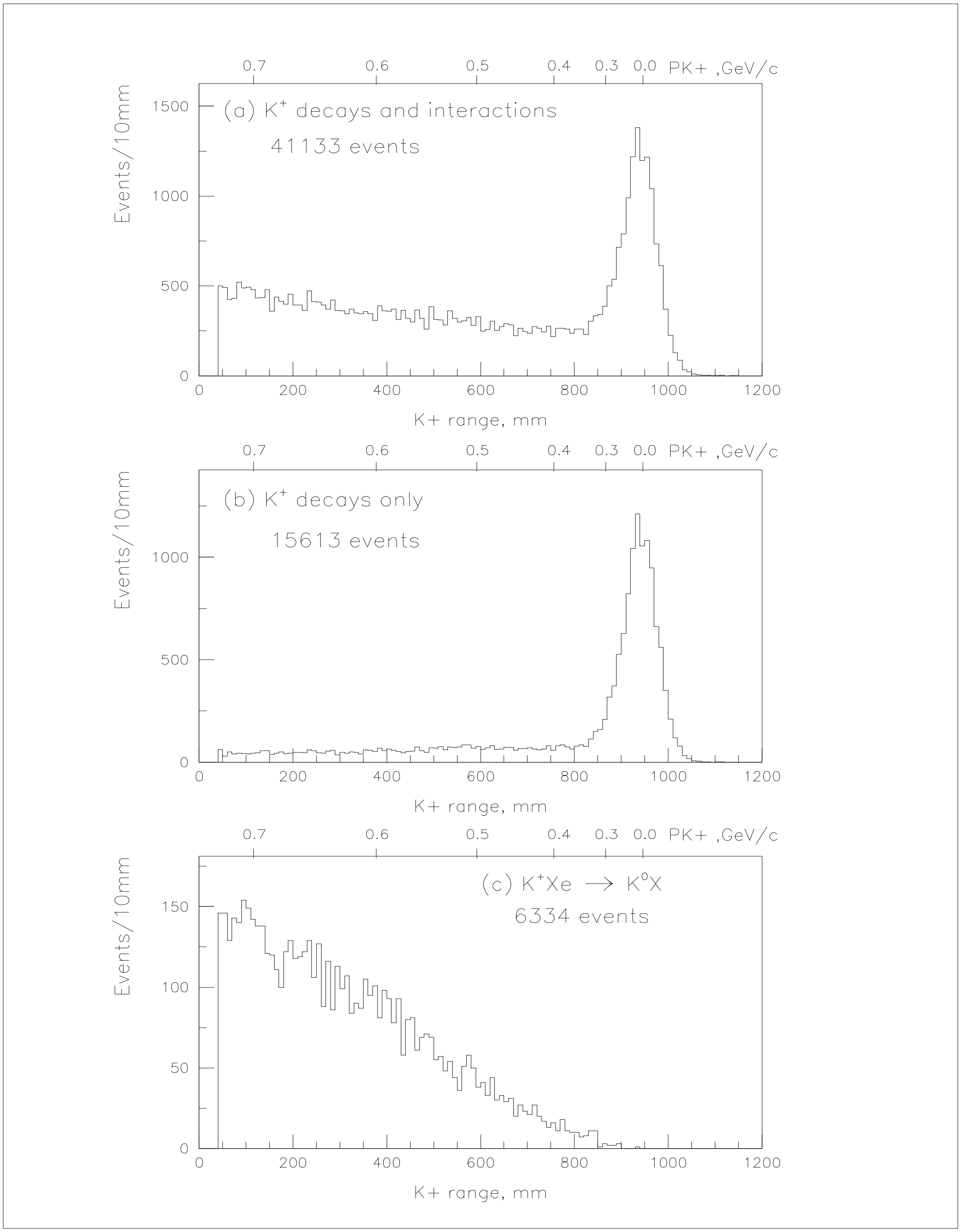

Figure 1: Range and equivalent momentum (top scale) of the incident K^+ for different event categories: (a) for all K^+ decays and interactions; (b) only for K^+ decays; (c) only for the charge-exchange reaction $K^+\mathrm{Xe} \rightarrow K^0 X$.

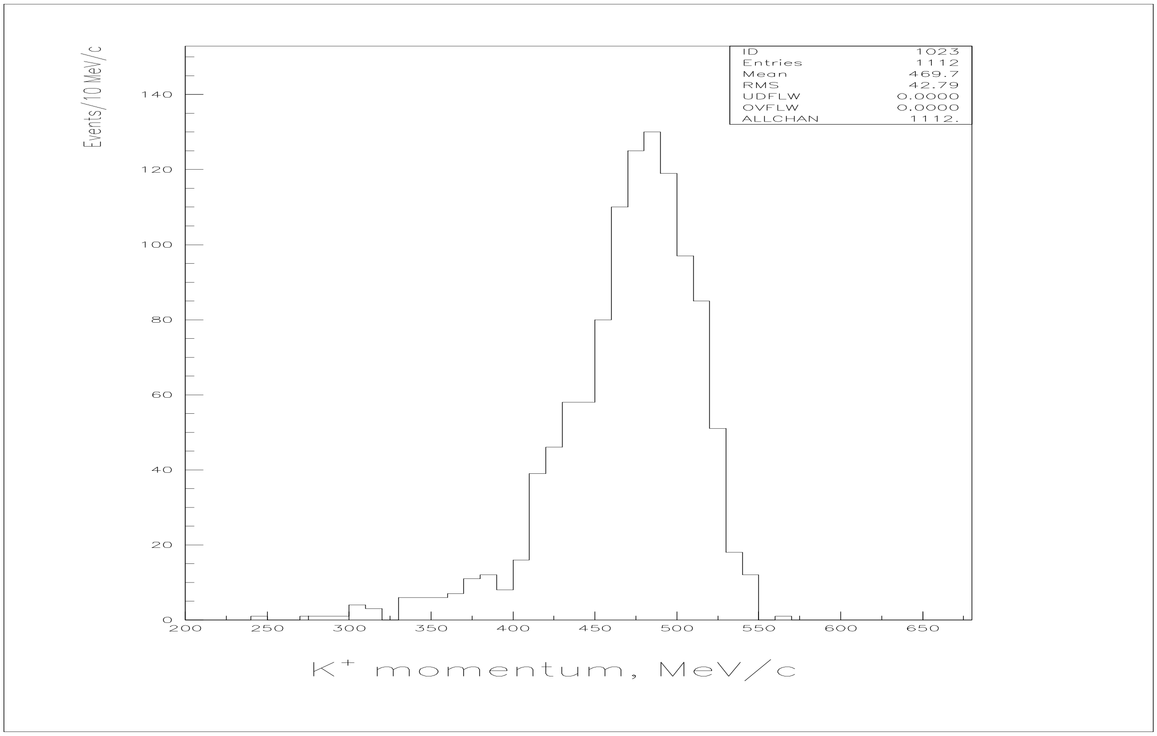

Figure 2: Incident K^+ momentum for measured events of the reaction $K^+\mathrm{Xe} \to K^0 p\mathrm{Xe}'$.

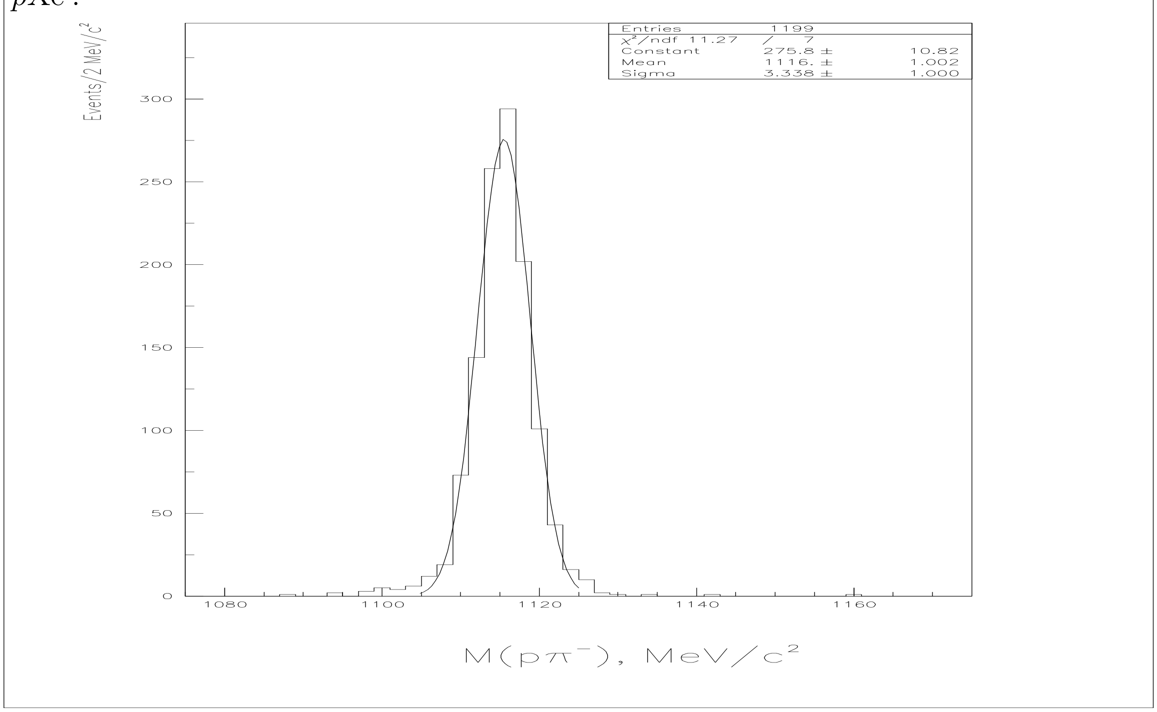

Figure 3: Effective mass of the $p\pi^-$ system for secondary vertices of the type $V \to p\pi^-$.

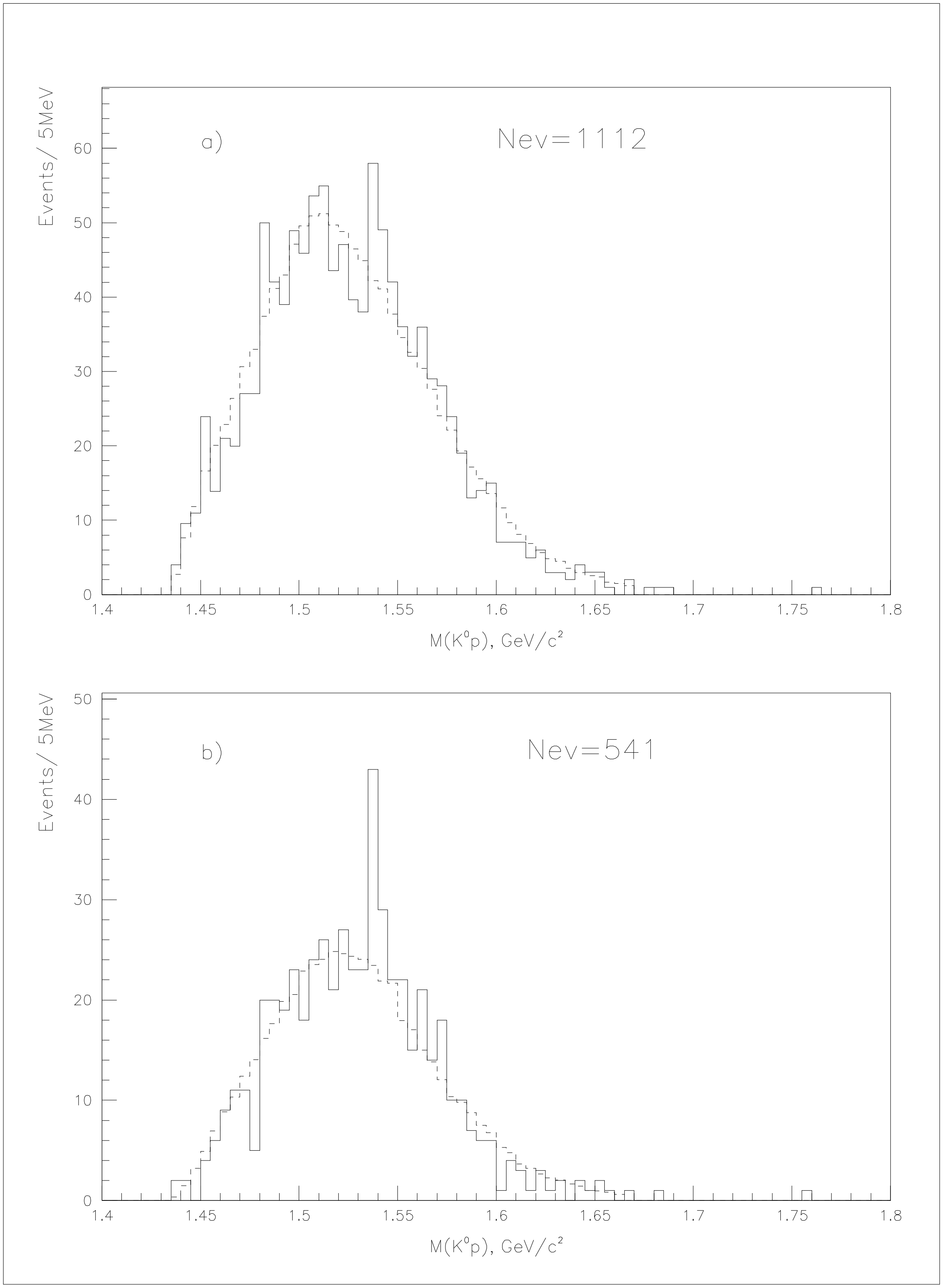

Figure 4: Effective mass of the K^0p system formed in the reaction $K^+\mathrm{Xe} \rightarrow K^0p\mathrm{Xe}'$: (a) for all measured events, (b) for events that pass additional selections aimed at suppressing proton and K^0 reinteractions in nuclear matter (see text). The fit to the expected functional form is depicted by the dashed line.