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CONFIRMATION OF THE EXISTENCE OF THE Σ_c^{++} AND Λ_c^+ CHARMED BARYONS

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In a broad-band neutrino exposure of the Fermilab 15-ft. bubble chamber, we observe the production of the $\Sigma_c^{++}(2426)$ charmed baryon followed by its decay to $\Lambda_c^+(2260)$ and π^+. We find the mass of the Λ_c^+ to be (2257 ± 10) MeV and the $m(\Sigma_c^{++}) - m(\Lambda_c^+)$ mass difference to be (168 ± 3) MeV. Previously unseen two body decay modes of the $\Lambda_c^+(2260)$ are observed.

The first evidence for charm was the observation[1)] of the J/ψ at BNL and SLAC. This state is now identified as the spin parity 1^- bound state of charm and anticharm quarks ($c\bar{c}$) and was thus the first case of "hidden charm". Dilepton production[2)] by neutrinos has subsequently been shown to be a manifestation of bare charm. The first observation of a bare charm state was made at BNL in a neutrino interaction in the 7-ft. bubble chamber. This event was identified as the production of the isotriplet charmed baryon state, $\Sigma_c^{++}(2426)$, and its decay to the isosinglet state, $\Lambda_c^+(2260)$.[3)] These states were subsequently observed in photoproduction at FNAL,[4)] and another example of the $\Lambda_c^+(2260)$ has recently been reported by the BNL 7-ft. bubble chamber group.[5)] The bare charmed meson states, the D(1865) and the $D^*(2005)$ were first seen in e^+e^- annihilations at SLAC,[6)] and have since been confirmed in other experiments at SLAC. These states have also been observed in neutrino interactions.[7)]

In this letter, we confirm the existence of the charmed baryons, obtain a measurement of their masses, and report the observation of previously unseen two body decay modes of the Λ_c^+. The $\Sigma_c^{++}(2426)$ is detected through its decay into the $\Lambda_c^+(2260)$ and a π^+. The rate for $\Sigma_c^{++}(2426)$ production for various Λ_c^+ decay modes is also presented.

The experiment was carried out at the Fermi National Accelerator Laboratory using the double horn focused wideband muon neutrino beam and the 15-ft. bubble chamber filled with a heavy neon-hydrogen mixture (64 at. % neon). The results presented here are based on an analysis of the 134,000 photographs taken to date in the experiment.

The interaction length for hadrons in the heavy neon mix is 1.25

[a)] Present address: Rutgers University, New Brunswick, N.J. 08903 meters (the chamber diameter is 3.7 m) so that hadrons produced in the neutrino interactions typically interact, while muons leave the chamber without interacting. Neutral strange particles are detected via their decays such as $K^0_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. The film was scanned, and partially double scanned, for events with a possible neutral strange particle decay (vee). All such events were measured and geometrically reconstructed, and the decays were kinematically fitted using the programs TVGP and SQUAW. Vees that made satisfactory two or three constraint kinematical fits to $K^0_S \to \pi^+\pi^-$ or $\Lambda \to p\pi^-$ decays were retained. Kinematical ambiguities between the decays were resolved using the χ^2 probabilities of the fits and the center of mass decay angular distributions. Events with a leaving negative track with momentum greater than 2 GeV/c, were taken to be charged current interactions. We thus obtained a sample of 3141 $K^0_S \to \pi^+\pi^-$ and 2297 $\Lambda \to p\pi^-$ decays in a total sample of ~ 100,000 charged current neutrino interactions.

In a previous publication[7] (based on part of this data sample) we have reported the observation of the charmed D^0 meson through its decay into $\bar{K}^0\pi^+\pi^-$. We have also searched for the charmed baryon, Λ_c^+, through its decay into $\Lambda\pi^+$, $\Lambda\pi^+\pi^+\pi^-$, $\bar{K}^0p$, and $\bar{K}^0p\pi^+\pi^-$ by examining the distributions in the effective masses of the decay products. No significant structure is visible in the $\bar{K}^0p$ and the $\bar{K}^0p\pi^+\pi^-$ mass distributions. Examination of the $\Lambda\pi^+$ and the $\Lambda\pi^+\pi^+\pi^-$ mass distributions (the $\Lambda\pi^+$ is shown in Fig. 1) shows small enhancements near the expected Λ_c^+ mass. However, the statistical significance of these enhancements is at most two standard deviations each.

To investigate these structures near the Λ_c^+ mass, we consider the possibility that some of the Λ_c^+ events arise from the decays of a Σ_c^{++} into a Λ_c^+ and a π^+. Since the expected Q value for these decays is small, the resolution in the mass difference $\Delta m = m(\Sigma_c^{++}) - m(\Lambda_c^+)$ is very good (~ 5 MeV). In the first BNL charm event,[3] as well as in the Fermilab photoproduction experiment,[4] the Λ_c^+ mass was 2260 MeV and the mass difference was near 166 MeV. Using these values as a guide, we select events with a $\Lambda\pi^+$ effective mass within 2260 ± 25 MeV in which there is at least one additional π^+. (25 MeV is our mass resolution.) The distribution in the mass difference, $\Delta m = m(\Lambda\pi^+\pi^+) - m(\Lambda\pi^+)$, shown in Fig. 2a, shows clustering around 166 MeV. The Δm distributions for the mean of the control regions with $m(\Lambda\pi^+)$ below and above the Λ_c^+ mass (Fig. 2b) shows no clustering. The $\Lambda\pi^+$ mass distribution for events with Δm in the range of 166 ± 6 MeV is shown in Fig. 3a. We observe 8 events at a mass of 2260 MeV, where we expect 1.5 events. The probability that this is a statistical fluctuation is $< 10^{-4}$. The $\Lambda\pi^+$ mass distributions for the mean of the control regions in Δm below and above 166 MeV, Fig. 3b, has no peak at 2260 MeV. We consider this correlation between the $\Lambda\pi^+\pi^+$ and the $\Lambda\pi^+$ masses to be due to the production of the $\Sigma_c^{++}(2426)$, followed by its decay into $\Lambda_c^+(2260)\pi^+$, and subsequently, $\Lambda_c^+(2260) \to \Lambda\pi^+$. The Σ_c^{++} is manifestly exotic and the width of the Λ_c^+ is consistent with zero as would be expected for charmed baryons.

A similar analysis was carried out for three other possible Λ_c^+ decay modes into $\Lambda\pi^+\pi^+\pi^-$, $\bar{K}^0p$, and $\bar{K}^0p\pi^+\pi^-$. To reduce the large combinatorial background in the four body modes, we have selected events where a $\Lambda\pi^+$ mass is in the $Y^*(1385)$ region (1382 ± 25 MeV), or a $\bar{K}^0\pi^-$ mass is in the $K^*(892)$ region (892 ± 32 MeV).[8] The distributions in Δm for the two body Λ_c^+ decays, $\Lambda\pi^+$ and $\bar{K}^0p$ combined, is shown in Fig. 2c, and the combined Δm distribution for all four decay modes is shown in Fig. 2d. The combined $\Lambda\pi^+$ and $\bar{K}^0p$ mass distributions, selecting Δm to be in the range 166 ± 6 MeV, are shown in Fig. 3c while in Fig. 3d we further include the mass distributions for the channels $Y^*(1385)\,\pi^+\pi^-$ and $K^{*-}p\pi^+$. We find a total of 20 events with mass (m) in the range 2260 ± 25 MeV and Δm in the range 166 ± 6, with the breakdown given in Table I. Using the appropriate control regions in m and Δm, we expect a background of 6 events, where we observe 20. The probability of this being a statistical fluctuation is less than 10^{-5}.

In order to estimate the rates for Σ_c^{++} production followed by the decay $\Sigma_c^{++} \to \Lambda_c^+\pi^+$, with the Λ_c^+ decaying as above, we correct the number of these events observed above background by the V^0 branching ratios, the V^0 scan and detection efficiencies (75%), and the efficiency in the measurement and reconstruction of the charged tracks (80% per track). Normalizing this to the total number of charged current interactions, we obtain the rates as given in Table I.

To obtain our best estimate of the Λ_c^+ mass and the $\Sigma_c^{++} - \Lambda_c^+$ mass difference, we use the 3 events with $\Lambda_c^+ \to \Lambda\pi^+$ since this sample has the smallest background. The values obtained are

$$m(\Lambda_c^+) = 2257 \pm 10 \text{ MeV}$$
$$m(\Sigma_c^{++}) - m(\Lambda_c^+) = 168 \pm 3 \text{ MeV}.$$

It is interesting to note that one of the 20 events is probably an example of quasielastic charm baryon production. Kinematics and track identification suggest that the reaction is $\nu\,\text{Ne} \to \mu^-\Lambda\pi^+\pi^+\pi^+\pi^-$ with no missing particles. The event thus has the $\Delta S = -\Delta Q$ signature of charm production. Examination of the masses then indicates that the event is another example of the reaction:

$$\nu p \to \mu^-\Sigma_c^{++};\ \Sigma_c^{++} \to \Lambda_c^+\pi^+;\ \Lambda_c^+ \to Y^{*+}\pi^+\pi^-;\ Y^{*+} \to \Lambda\pi^+.$$

Two of the three π^+'s in this event are overstopped as K^+ and the interpretation of the third positive track heavily favors π^+ over K^+ by geometrical reconstruction, ionization and longitudinal momentum balance. Transverse momentum is balanced to within [illegible] MeV/c. There is no visible evidence for stubs at the primary vertex or additional neutrals in the downstream 7 radiation lengths and 2.5 interaction lengths. The probability that this event is associated strange particle production with a missing K_L^0 has been calculated to be less than 3%. The two relevant masses are $m(\Lambda_c^+) = (2276 \pm 25)$ MeV and $\Delta m = (163 \pm 5)$ MeV.

In summary we have presented evidence for the existence of both the Σ_c^{++} and Λ_c^+ baryons, a measurement of their masses, as well as the first observations of two body decay modes of the Λ_c^+: $\Lambda_c^+ \to \Lambda\pi^+$ and with less significance, $\Lambda_c^+ \to \bar{K}^0p$.

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TABLE I. Observed Events of the Type $\nu Ne \rightarrow \mu^- \Sigma_c^{++} + \ldots$, $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ with 2.235 GeV < $M_{\Lambda_c^+}$ < 2.285 GeV and 160 MeV < Δm < 172 MeV

Λ_c^+ Decay Mode	Events	Background	Signal*	$\sigma \cdot B/\sigma$(charge current)
$\Lambda\pi^+$	8	1.5	17.6	$(1.8 \pm 0.8) \times 10^{-4}$
$\bar{K}^0 p$	7	2.0	25.5	$(2.7 \pm 1.6) \times 10^{-4}$
$\Lambda\pi^+\pi^+\pi^-$ $(Y^*\pi^+\pi^-)$	4	1.5	12.4	$(1.5 \pm 1.4) \times 10^{-4}$
$\bar{K}^0 p\pi^+\pi^-$ $(K^* p\pi)$	1	1.0	-	-
	20	6.0	55.5	$(6 \pm 2.3) \times 10^{-4}$

*Signal is events[9] above background corrected for detection efficiencies and unseen neutral decays of the $\bar{K}^0$ and the Λ.

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8. The two BNL charm baryon events (Refs. 3,5) have a $Y^*(1385)$ and $K^*(892)$, respectively, in their Λ_c^+ decay products.
9. Figures show all mass combinations. In Table I we have made corrections for multiple combinations within an event for both the signal and the background.

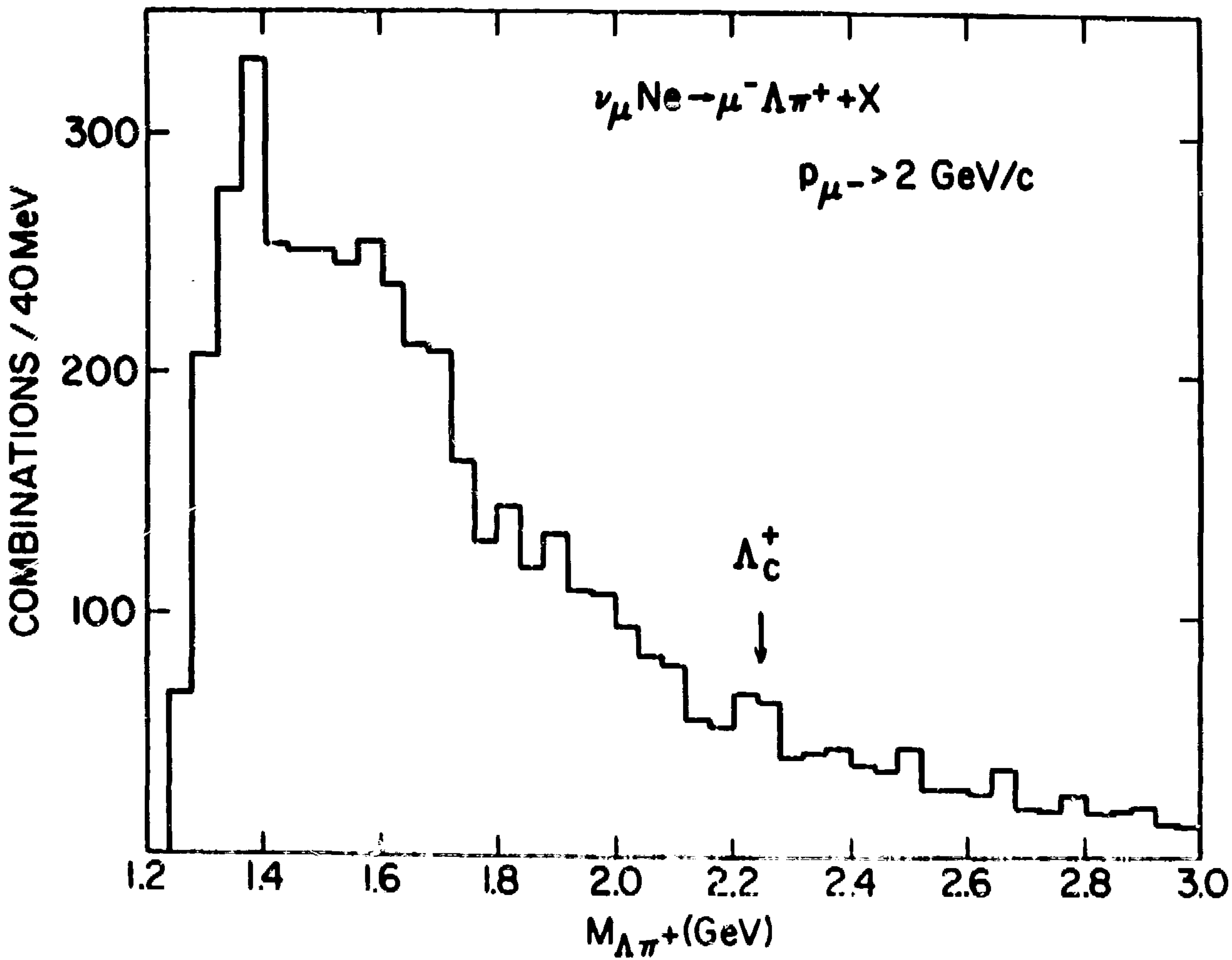

Fig. 1 Distributions in the $\Lambda\pi^+$ effective mass.

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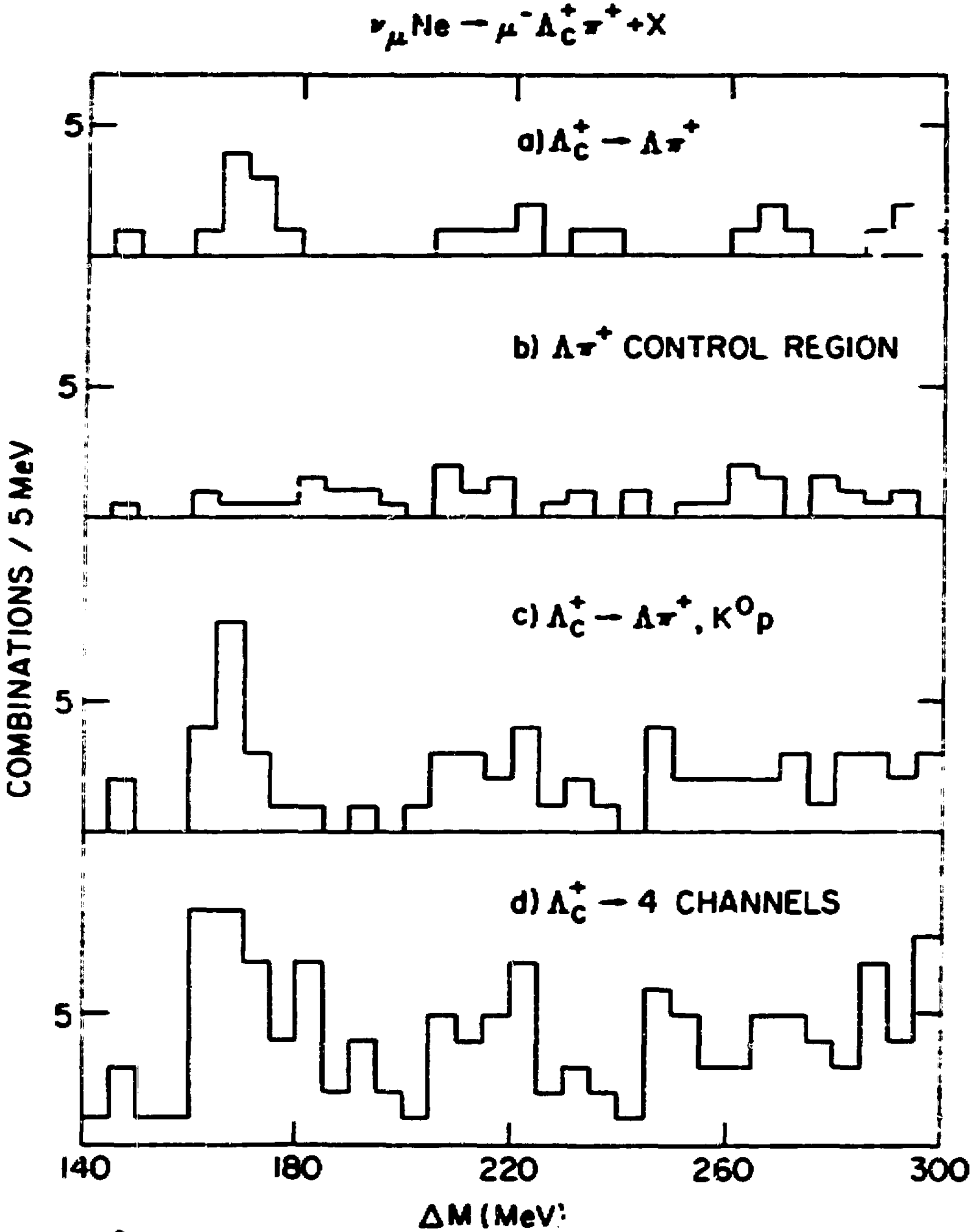

Fig. 2 Distribution[9] in the mass difference ΔM for a) events in the Λ_c^+ region, $m(\Lambda\pi^+) = 2260 \pm 25$ MeV; b) average of the control regions above and below the Λ_c^+ mass, $m(\Lambda\pi^+) = 2210 \pm 25$ MeV, and $m(\Lambda\pi^+) = 2310 \pm 25$ MeV, respectively; c) events in the Λ_c^+ mass region, $m = 2260 \pm 25$ MeV, combined for $\Lambda\pi^+$ and $\bar{K}^0 p$; d) events in the Λ_c^+ mass region, $m = 2260 \pm 25$ MeV, combined for $\Lambda\pi^+$, $\bar{K}^0 p$, $Y^{*+}\pi^+\pi^-$, and $K^{*-}p\pi^+$.

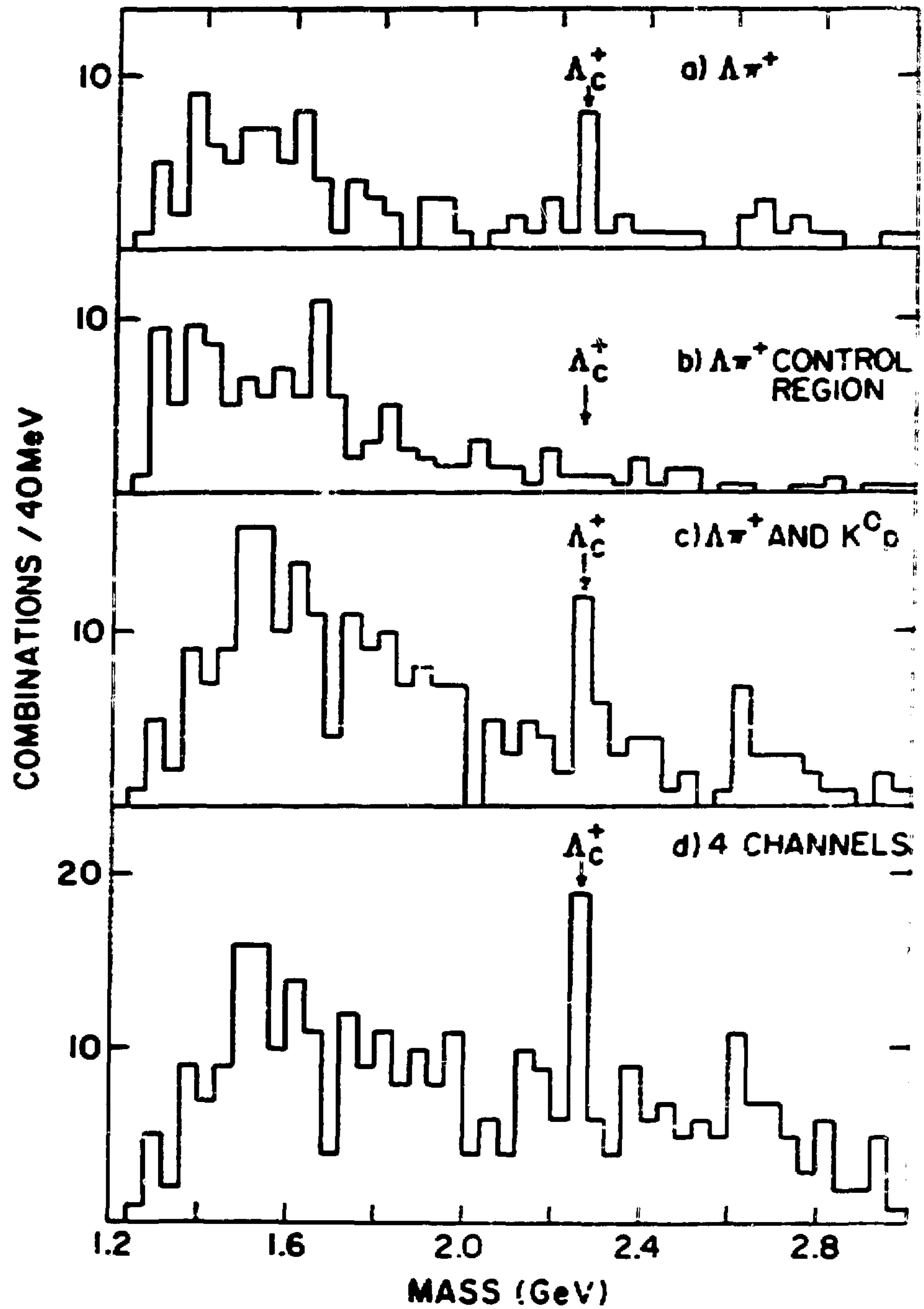

Fig. 3 a) $\Lambda\pi^+$ invariant mass distribution[9] for Δm = 166 ± 6 MeV; b) $\Lambda\pi^+$ invariant mass distribution for the average of the control regions at Δm = 154 ± 6 MeV and Δm = 178 ± 6 MeV; c) combined $\Lambda\pi^+$ and $\bar{K}^0p$ mass distribution for Δm = 166 ± 6 MeV; d) combined $\Lambda\pi^+$, $\bar{K}^0p$, $Y^{*+}\pi^+\pi^-$, and $K^{*-}p\pi^+$ mass distributions for Δm = 166 ± 6 MeV.