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# The Decay $Y_1^*(1660) \rightarrow Y_0^*(1405) + \pi$ †

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Thus far, particles of the same known spin and parity have been successfully assigned into SU3 multiplets by using the Gell-Mann--Okubo mass formula.[1] Attempts to classify particles whose spins and parities are not well established into particular multiplets on the basis of the mass formula may lead to contradictory assignments, as in the case of the $Y_1^*(1660)$.[2,3] Additional information on the multiplet assignment of a particle may be derived from its decay modes. Where the SU3-breaking interaction can be neglected, SU3 gives definite predictions of branching ratios and selection rules for the decay of a member of a given multiplet into a member of other multiplets.[4] We report here experimental evidence for the decay, $Y_1^*(1660) \rightarrow Y_0^*(1405) + \pi$ which can be used as evidence that the $Y_1^*(1660)$ is a member of an octet if $Y_0^*(1405)$ is assumed to be a unitary singlet.

The data on the $Y_1^*(1660)$ or $\Sigma(1660)$[5] decay modes were obtained from an analysis of the following reactions:

$$K^- + p \rightarrow \Sigma^+ + \pi^+ + \pi^- + \pi^- \quad (1)$$

$$K^- + p \rightarrow \Sigma^- + \pi^+ + \pi^+ + \pi^- \quad (2)$$

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^0 + \pi^- . \quad (3)$$

Reactions (1) and (2) give information on the decay $\Sigma(1660) \to \Lambda(1405) + \pi$, and reaction (3) is used to give an upper limit on the amount of $\Sigma(1660) \to \Sigma(1385) + \pi$.

The reactions were studied on film from a recent exposure of the Berkeley 72-inch hydrogen bubble chamber to 2.45-, 2.65- and 2.70-BeV/c $K^-$ beams.[6] The sample of film obtained at each momentum has a $K^-$ path length corresponding to one event expected for a cross section of 0.5 μb, 0.15 μb and 0.3 μb, respectively. The above reactions were analyzed using the Alvarez-group program system.[7] Events that fit more than one hypothesis were designated as ambiguous if the ratio of the $\chi^2$ probabilities for the hypotheses was less than three to one. For these events the higher probability hypothesis was chosen, and these events are included in our data. The location of the ambiguous events has been omitted on Figs. 1 and 2 but is shown in Fig. 3, in order to demonstrate that they are not responsible for the effects which are discussed below. No ambiguous events happen to fall in the sample used in Figs. 4 and 5.

The results reported here are based on an analysis of the distributions which include all events, corresponding to no cutoff in the $\Sigma$ track length. In the analysis of reactions (1) and (2), a minimum length cutoff of 0.5 cm has been considered for the projected length of the sigma track in a plane perpendicular to the optical axes. Events having the projected length greater than 0.5 cm were corrected by an approximate weighting factor to compensate for the effect of the cutoff. The various histograms containing only these weighted events were then compared with the corresponding histograms containing all events (i.e., assuming no cutoff in $\Sigma$ tracklength, and hence all events having a weight of one). The histograms were found to be statistically equivalent, indicating that there is no bias from the scanning efficiency for short $\Sigma$'s. To illustrate, we also show some of the weighted distributions corresponding to the 0.5-cm cutoff (Figs. 3a and b and 5a and b).

It is out of the question that pionic contamination has affected the results presented below. Actually, to understand the effect of the ≈ 20% $\pi^-$ contamination in the beam,[6] we have studied interactions obtained when the bubble chamber was exposed to pure $\pi^-$ beams of about the same momenta. For a number of $\pi^-$ comparable to that present as contamination in our total $K^-$ exposure, we found only 153 events of the same topology as reactions (1) and (2). These events were measured and then analyzed as if they were K-induced events. Of the 153 events, none fitted hypothesis (2) and only two fitted (1). The calculated invariant masses of the $\Sigma^+\pi^+\pi^-$ combinations all fell above 2 BeV in these two cases.

Figure 1(a) shows the invariant mass distribution for the $\Sigma\pi\pi$ particle combinations from reactions (1) and (2), with an overall charge of +1. For the events from reaction (1), two combinations per event are plotted. The curve shown represents the combined effect, averaged over the three incident beam momenta, of phase space plus the effects of the $\Lambda(1405)$ and $\Lambda(1520)$ resonances produced in the $(\Sigma^{\mp}\pi^{\pm})$ system of particles.[8] A definite excess of events is seen about 1660 MeV. The corresponding mass spectrum for the $\Sigma\pi\pi$ system with an overall charge of -1 (Fig. 1b) does not show the same feature. That is, there is some indication of $\Sigma(1660)$ production in the $(\Sigma\pi\pi)^+$ system and none in the $(\Sigma\pi\pi)^-$ system, suggesting that the $\Sigma(1660)$ may be produced peripherially.

The center-of-mass production angular distribution with respect to the incident $K^-$ for the $(\Sigma\pi\pi)^+$ particle combinations lying in the 1620- to 1700-MeV mass range is shown in Fig. 2. The production angle, $\theta^*$, is defined by $\cos\theta^* = -K^- \cdot \pi^-$, where $K^-$ and $\pi^-$ are unit vectors along the direction of the incident $K^-$ and the $\pi^-$ not included in the mass combination, respectively, in the overall c.m. system. From Fig. 2 we conclude that the $\Sigma(1660)$

is produced at very low momentum transfers ($-0.08\ \text{BeV}^2$ to $+0.06\ \text{BeV}^2$).

Figure 3a shows the $(\Sigma\pi\pi)^+$ mass distribution for those events having $\cos\theta^* \leq -0.9$. The presence of the $\Sigma(1660)$ is clearly seen. The $\Sigma^+\pi^+\pi^-$ events are each represented twice on Fig. 1a, but there are only 5 events where both $\Sigma^+\pi^+\pi^-$ combinations have $\cos\theta^* < -0.9$. The lowest mass combination for these events lies above 1860 MeV, so that these events cannot perturb the analysis of the $\Sigma(1660)$.

The solid curve of Fig. 3a represents a best fit to the data for a distribution of the form: a [modified phase space including effects of $\Lambda(1405)$ and $\Lambda(1520)$ resonances in the $(\Sigma\pi)^0$ system] + b [Breit-Wigner form for $\Sigma(1660)$].[9] From this fit we determine the phase-space background in the region $1620 < M(\Sigma\pi\pi) < 1700$ MeV, to be $6 \pm 1\%$. Thus the angular selection $\cos\theta^* < -0.9$ and this mass criterion makes a relatively clean sample of $\Sigma(1660)$. It will be used for the study of $\Sigma(1660)$ decay. The subset of events in Fig. 3a which are produced in reaction (1) are plotted separately in Fig. 3b. These are of particular importance for the decay analysis, since there is only one neutral $\Sigma-\pi$ combination.

The histogram analogous to those in Fig. 3a and b for reaction (3) is presented in Fig. 3c for approximately the same bubble-chamber exposure. In this case the $\cos\theta^* < -0.9$ cutoff does not separate $\Sigma(1660)$ clearly from the background. Those events with mass $\Lambda\pi^+\pi^0$ between 1620 and 1700 MeV represent an upper limit on the production of $\Sigma(1660)$ in our $\cos\theta^*$ interval.

For our sample of $\Sigma(1660)$ events, as defined above, we form Dalitz scatter plots of $\Sigma^+\pi^+\pi^-$ in Fig. 4a, $\Sigma^-\pi^+\pi^+$ in 4b and $\Lambda\pi^+\pi^0$ in 4c. The closed curves represent the boundary defined by the upper and lower mass limits imposed for the $\Sigma\pi\pi$ system. Figure 5a and b show the number of events versus the invariant mass (rather than mass squared) for the $\Sigma^+\pi^+\pi^-$ events of Fig. 4a. If we exclude the 3 events that lie in the $\Lambda(1520)$ region and which could belong to the background, the histogram of the $\Sigma^+\pi^-$ mass (Fig. 5a) shows a pronounced peak near 1405 MeV. A fit to this histogram using a two-parameter distribution of the form [Breit-Wigner $\Sigma(1660)$] × [a + b (Breit-Wigner terms for $\Lambda(1405)$)] gives a branching ratio

$$\frac{\Sigma(1660) \to \Lambda(1405) + \pi}{\Sigma(1660) \to \text{all } \Sigma\pi\pi} = 90^{+10}_{-16}\%.$$

The continuous curve of Fig. 5a represents this best fit; the dashed curve represents the "phase-space" contribution to it. This result is, of course, consistent with the hypothesis that all events belong to the $\Lambda(1405)$ resonance.

The $\Sigma^+\pi^+$ mass distribution (Fig. 5b) shows an enhancement around 1450 MeV. The solid curve represents the expected distribution if all decays were via $\Lambda(1405) + \pi^+$. This result then constitutes a check of consistency for the hypothesis $\Sigma(1660) \to \Lambda(1405) + \pi$. The fact that such a decay would reflect itself at 1450 MeV in the $\Sigma^+\pi^+$ mass was first noticed by Alston et al.[10]

We can rule out the reciprocal hypothesis that a $\Sigma^+\pi^+$ resonance of mass 1450 MeV exists, and is reflected at 1405 MeV in the $\Sigma^+\pi^-$ distribution, by computing the expected ratio for $\Sigma^-\pi^+\pi^+$ to $\Sigma^+\pi^+\pi^-$ decay modes under the assumption of I = 1 for the $\Sigma^*(1660)$ and I = 2 for the $\Sigma$-$\pi$ system. This ratio would be less than 2/49 for a maximum contribution of interference effects in the $\Sigma\pi\pi$ system. The observed decay branching ratio of 26/45 is totally in disagreement with this number.

The projected $\Sigma^-\pi^+$ mass distributions are shown in Fig. 5c with each event from Fig. 4b plotted twice since there are two $\Sigma\pi$ combinations of zero total charge. The solid curve represents the expected shape of the distribution under the assumption that all events proceed through $\Lambda(1405) + \pi^+$, and that interference effects may be ignored. The curve and histogram appear to be compatible.

It is worthwhile pointing out that decay of $\Sigma(1660)$ into $\Lambda(1405) + \pi^+$ does not necessarily imply a branching ratio of one for the $\Sigma^-$- to $\pi\Sigma^+$ decay modes. We would expect that $\Sigma^-\pi^+$ interference effects of the type discussed by Dalitz and Miller[11] will enhance or suppress that decay channel relative to the $\Sigma^+\pi^-$.

We have investigated the possibility that the 1660-MeV enhancement is merely a result of a reflection caused by strongly peripheral production in the reaction

$$K^- + p \rightarrow \Lambda(1405) + \rho^0,$$

together with the angular selection of the $\pi^-$. We find that only 7 events in the $\Sigma(1660)$ of the sample $\cos\theta^* < -0.9$ have both a $(\Sigma\pi)^0$ combination between 1450 and 1460 MeV, and $(\pi^+\pi^-)^0$ in the ρ-meson mass range (700 to 800 MeV).

There remains the possibility that we are actually observing the $\Sigma\pi$ decay mode of the $\Sigma(1385)$, which is known to be as high as 9% of the total decay.[12] If such a phenomenon were happening, it would mean that our sample 71 events come from 710 $\Sigma(1660)^+$ decays into $\Sigma(1385)^0 + \pi^+$. Isospin conservation would permit us to expect 710 events of the type $\Sigma(1660)^+ \rightarrow \Sigma(1385)^+ + \pi^0$. Taking into account the correction for neutral decay of the $\Lambda$, we should see at least $1420 \times 0.9 \times 2/3 = 850\ \Lambda^0\pi^0\pi^+$ events in our sample selected from Fig. 3c between 1620 and 1700 MeV. The important result to be learned from Fig. 4c -- the Dalitz plot for those events from Fig. 3c that lie in the $\Sigma(1660)$ region -- is that one finds only a comparable number and not 12 times the number of events plotted in Fig. 4a and b. It should be noted in passing that the presence of the simultaneous enhancement is consistent with the hypothesis that constructive interference, of a Dalitz-Miller nature mentioned above, between the modes of decay $\Sigma(1385)^+ + \pi^0$ and $\Sigma(1385)^0 + \pi^+$, is present for high $(\Lambda\pi\pi)^+$ mass, if the $\Sigma(1660)$ has negative parity. If all events of Fig. 4c are considered as the maximum of the examples of $\Sigma(1660)^+ \rightarrow \Sigma(1385) + \pi$, then we may set a lower limit on the $\Lambda(1405)/\Sigma(1385)$ branching ratio of $(71\times3/2)/(3/2\times73) \approx 1$ to take into account the corrections for $\Lambda(1405) \rightarrow \Sigma^0\pi^0$ and $\Lambda^0 \rightarrow n + \pi^0$ decay modes. The uncertainty of this ratio is attributed to (a) the amount of $\Sigma(1660)$ events actually occurring in the $\Lambda\pi\pi$ channel and (b) the difference in rejection efficiency of events in each channel. The latter is not off by more than 25%.

In summary, we conclude that the $\Sigma\pi\pi$ decay of the $\Sigma(1660)$ is dominated by the intermediate state $\Lambda(1405) + \pi^+$, and that it is at least comparable to the decay $\Sigma(1385) + \pi$.

Under the assumption that the $\Lambda(1405)$ is the member of a unitary singlet,[13] the decay mode $\Sigma(1660) \rightarrow \Lambda(1405) + \pi$ is forbidden by SU3 interactions if the $\Sigma(1660)$ belongs to any multiplet other than an octet. Certainly if that decay mode proceeds via SU3-breaking interactions, it is difficult to understand why a forbidden process would have a rate higher than or comparable to $\Sigma(1660) \rightarrow \Sigma(1385) + \pi$, which is allowed by SU3 interactions up to a high order of multiplet assignment for the $\Sigma(1660)$.

Therefore, unless we invoke some mixing,[14] we conclude that either the $\Sigma(1660)$ is a member of an octet, or that the $\Lambda(1405)$ is not a unitary singlet.

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## FOOTNOTES AND REFERENCES

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13. See, for example, S. L. Glashow and A. H. Rosenfeld (Ref. 2) and I. P. Gyuk and S. F. Tuan, Phys. Rev. Letters 14, 121 (1965).

14. We mean some particle mixing of the type considered between the ω and the φ. See M. Gell-Mann, Phys. Rev. 125, 1067 (1962) and J. J. Sakurai, Phys. Rev. Letters 9, 472 (1962). Of course we have no candidate as a "mixing mate" for the Σ(1660) or for the Λ(1405).

## FIGURE LEGENDS

Fig. 1. Distribution of $\Sigma\pi\pi$ invariant mass with an estimate of non-$\Sigma(1660)$ events. (a) Net charge positive; (b) net charge negative.

Fig. 2. $\cos\theta^*$ distribution [$\theta^*$ is the production angle for the $(\Sigma\pi\pi)^+$ system in overall center-of-mass system].

Fig. 3. Distribution of $Y\pi\pi$ invariant mass for $\cos\theta^* < -0.9$. On (a) and (b) the dashed histogram represents the weighted events with a projected length greater than 0.5 cm for the $\Sigma$. The shaded events are ambiguous. The continuous curve represents our fit; the dashed curve is the contribution of background estimated from the fit. (a) All $(\Sigma\pi\pi)^+$ events; (b) $\Sigma^+\pi^+\pi^-$ events only; (c) $\Lambda^0\pi^+\pi^0$ events.

Fig. 4. Dalitz plot for the sample of events selected for the study of $\Sigma(1660)$ decay. (a) $\Sigma^+\pi^+\pi^-$ events; (b) $\Sigma^-\pi^+\pi^+$ events; (c) $\Lambda^0\pi^+\pi^0$ events.

Fig. 5. Distribution of $\Sigma\pi$ invariant mass of the events appearing in Fig. 4. (a) $\Sigma^+\pi^-$ invariant mass; (b) $\Sigma^+\pi^+$ invariant mass; (c) $\Sigma^-\pi^+$ invariant mass. On (a), the continuous curve represents our best fit, described in the text; the dashed curve is the estimated contribution of non-$\Lambda(1405)$ events. On (b) and (c), the curves represent the expected distribution if all events are due to the $\Lambda(1405)$ resonance.

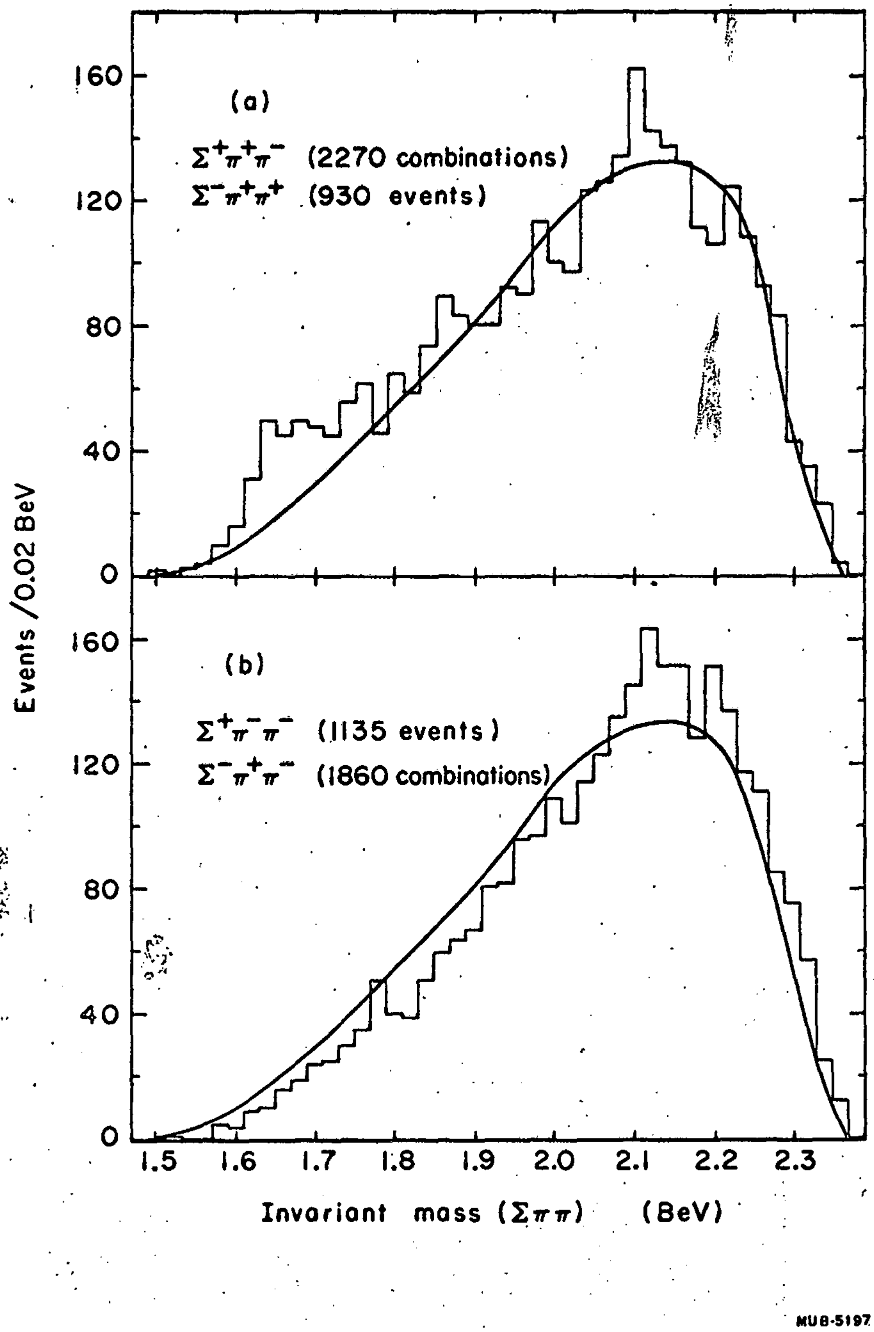
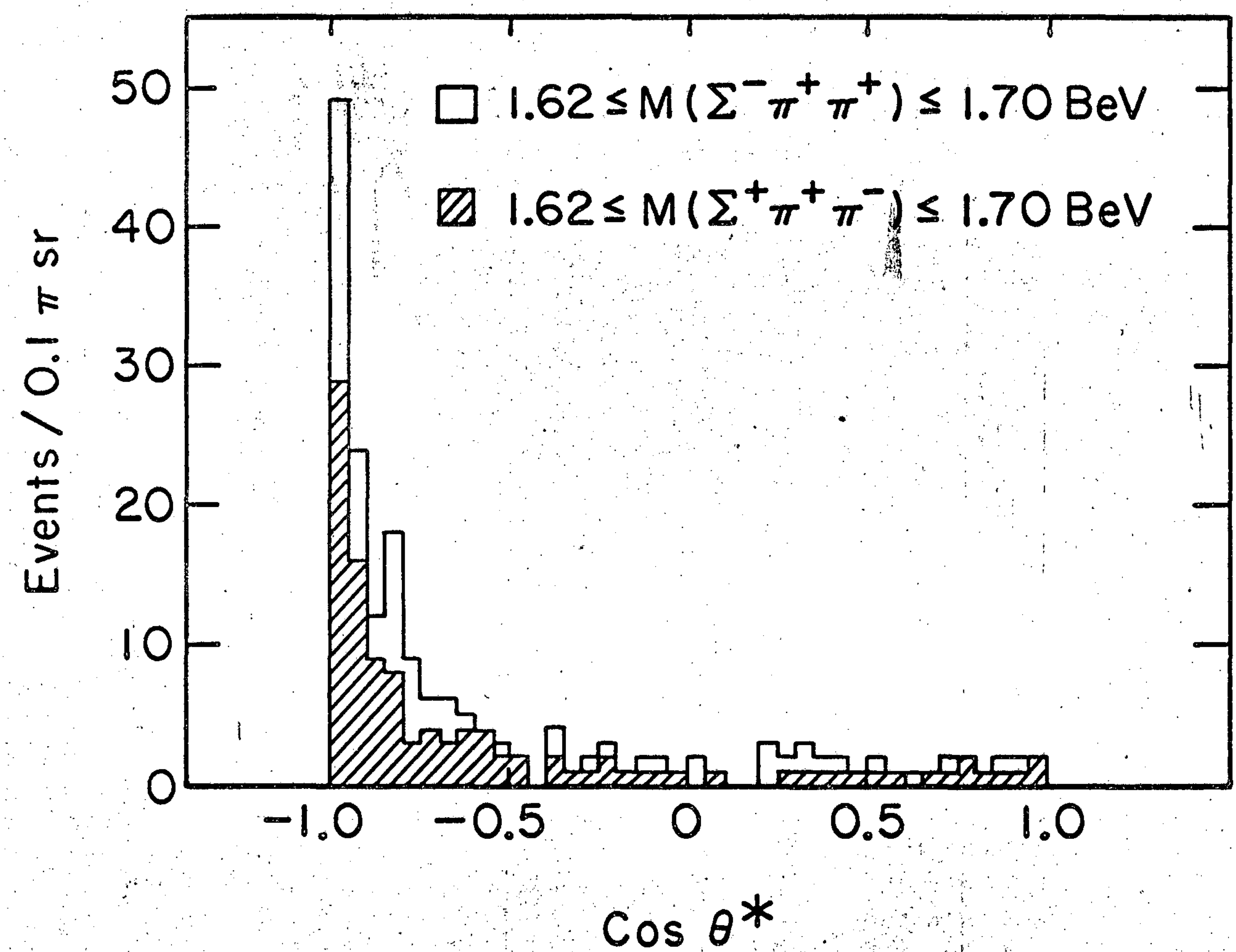

160
120
80
40
0
(a)
Σ⁺π⁺π⁻ (2270 combinations)
Σ⁻π⁺π⁺ (930 events)
(b)
Σ⁺π⁻π⁻ (1135 events)
Σ⁻π⁺π⁻ (1860 combinations)
Events /0.02 BeV
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
Invariant mass (Σππ) (BeV)
MUB-5197

Fig. 1




MUB-5198

Fig. 2

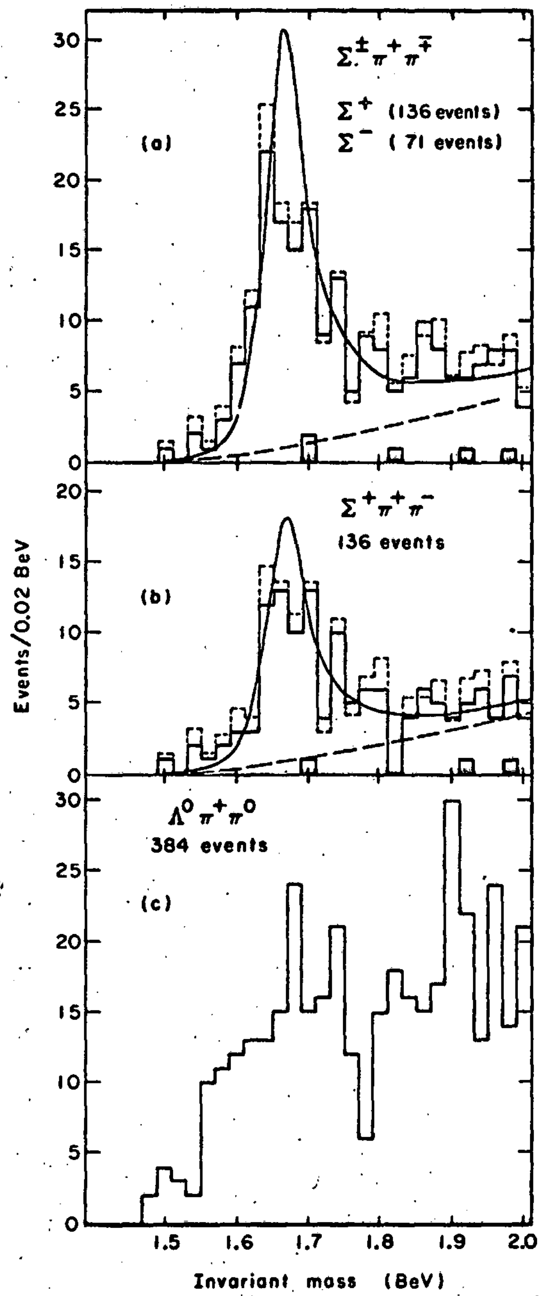

$\Sigma^{\pm}\pi^{+}\pi^{\mp}$
$\Sigma^{+}$ (136 events)
$\Sigma^{-}$ (71 events)
(a)
$\Sigma^{+}\pi^{+}\pi^{-}$
136 events
(b)
$\Lambda^{0}\pi^{+}\pi^{0}$
384 events
(c)
Events/0.02 BeV
Invariant mass (BeV)
1.5
1.6
1.7
1.8
1.9
2.0
MUB-5199

Fig. 3

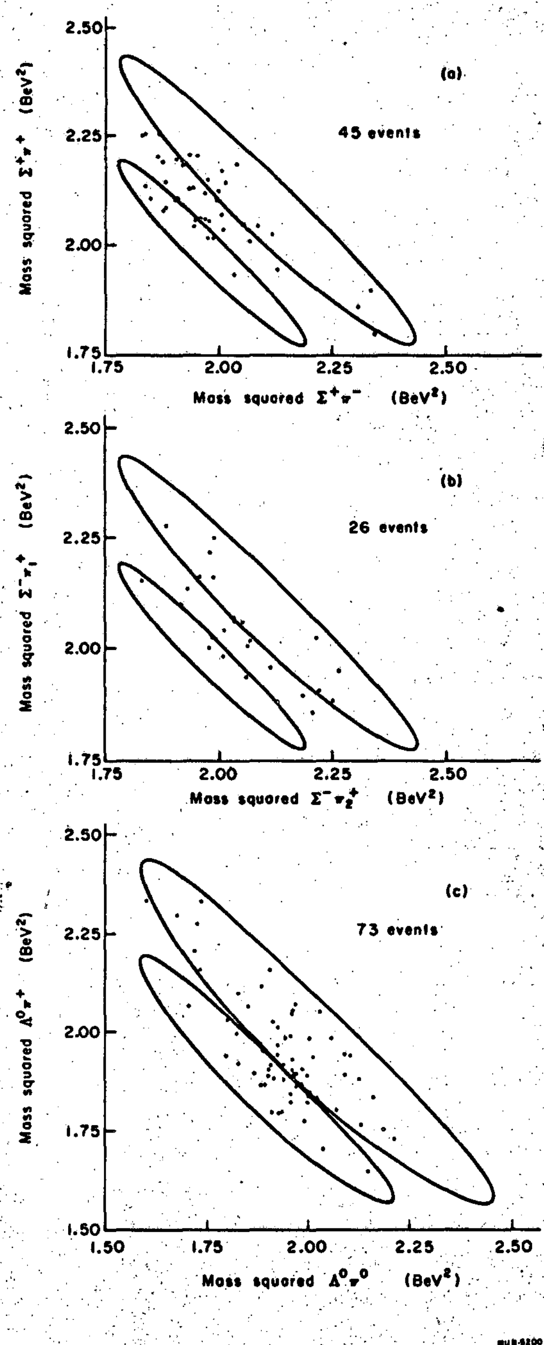

(a)
45 events
2.50
2.25
2.00
1.75
1.75
2.00
2.25
2.50
Mass squared Σ+π1+ (BeV2)
Mass squared Σ+π− (BeV2)
(b)
26 events
Mass squared Σ−π1+ (BeV2)
Mass squared Σ−π2+ (BeV2)
(c)
73 events
1.50
Mass squared Λ0π+ (BeV2)
Mass squared Λ0π0 (BeV2)

Fig. 4

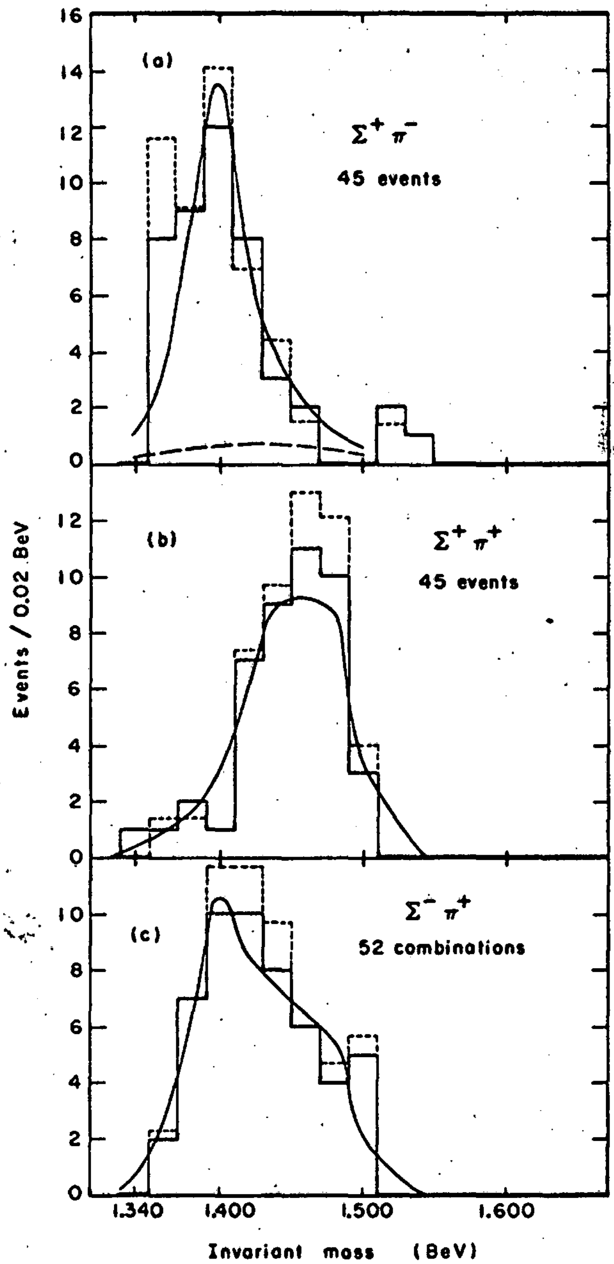

(a)
Σ⁺ π⁻
45 events
(b)
Σ⁺ π⁺
45 events
(c)
Σ⁻ π⁺
52 combinations
Events / 0.02 BeV
Invariant mass (BeV)
1.340
1.400
1.500
1.600
MUB-5201

Fig. 5