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DISCLAIMER

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ABSTRACT

The A_2 mass spectrum is studied in the reaction $\pi^+p \rightarrow A_2^+p$ at 7 GeV/c in a hydrogen bubble chamber in order to investigate previously reported structure. We report on 1400 A_2 events with mass resolutions of 3.8, 6.7, and 9.2 MeV in the $K^+\overline{K}^0$, 3π, and $\eta\pi^+$ channels.

The first evidence for a dip in the A_2 meson mass distribution was reported in a missing mass spectrometer experiment at CERN[1]. The same group confirmed the A_2 splitting in another experiment using a different apparatus[2]. In both cases the A_2 structure was adequately described either by a double-pole formula[3] or by two interfering resonances. Subsequently, several other experiments[4] have reported indications of structure in the A_2 mass distribution.

We report here on an experiment in which the A_2 is produced in the reaction $\pi^+ p \to A_2^+ p$ and decays via the $K^+\overline{K}^0$, $\pi^+\pi^+\pi^-$, and $\pi^+\eta$ modes[5]. In all cases, whether the modes are considered separately or simultaneously, a Breit-Wigner resonance formula gives an adequate fit to the data, whereas a two-parameter double-pole formula [3] gives poorer fits. The data are also adequately fit by two coherent resonances with masses and widths fixed at the values found by CERN[2], when the amplitudes and relative phase of the two resonances are allowed to vary independently for each decay mode.

Our experiment is a 700 000-picture (~ 45 events/μb) exposure of the SLAC 82-in. hydrogen bubble chamber to an rf-separated π^+ beam[6] of 7.1 GeV/c. The samples of the three decay modes of the A_2 were obtained in the following reactions:

$$\pi^+ p \to K^+ K_1^0 p \qquad (424 \text{ events}) \qquad (1)$$

$$\pi^+ p \to \pi^+\pi^+\pi^- p \qquad (68\,000 \text{ events}) \qquad (2)$$

$$\pi^+ p \to \pi^+\pi^+\pi^-\pi^0 p \qquad (50\,000 \text{ events}) \qquad (3)$$

For reaction (1) we require that the K_1^0 decays visibly in the chamber; these events appear as V-2 prongs. All of the 28 000 events of this topology have been measured and the 15% that failed were remeasured. For reactions (2) and (3) we measured the 245 000 4-prongs for which the scanner recorded the observation of at least one heavily ionizing positive track[7]. This represents 55% of our total sample of 4-prongs but contains most of our A_2 events.

Reactions (1) and (2) are highly constrained kinematically: seven constraints for (1) and four constraints for (2). There is consequently relatively little ambiguity in assigning events to definite reactions[8]. The presence of ambiguities represents a more serious problem for reaction (3); the treatment of these events is discussed under (iii) below.

We now discuss each reaction separately:

(i) $A_2^+ \to K^+\bar{K}^0$. Fig. 1a shows the $K^+K_1^0$ invariant mass distribution for the 424 examples of reaction (1); the A_2 signal is very clear.

(ii) $A_2^+ \to \pi^+\pi^+\pi^-$. For the purpose of studying the A_2^+ in reaction (2), the events with a Δ^{++} in either $p\pi^+$ mass combination were removed[9]. In the three-pion mass distribution of the remaining 25 590 events, the A_2 signal appears on the high-energy side of a large peak at low three-pion mass, the A_1. To suppress the A_1 we have further restricted the sample to events with the invariant four-momentum transfer to the proton, $-t_{pp} > 0.2$ GeV/c (fig. 1b). The A_2 signal is very clear and most of the low-mass peak is absent[10].

(iii) $A_2^+ \to \eta\pi^+$. For reaction (3) we studied those events in which $A_2^+ \to \eta\pi^+$ was followed by $\eta \to \pi^+\pi^-\pi^0$. The $(\pi^+\pi^-\pi^0)$ mass distribution for the one-constraint fit $\pi^+p \to \pi^+\pi^+\pi^-\pi^0 p$ is shown in fig. 2e. The shaded area indicates the events accepted into the sample of two-constraint fits: $\pi^+p \to \pi^+p\eta$ followed by $\eta \to \pi^+\pi^-\pi^0$. These events represent almost all the η events with very little background[11]. The $(\eta\pi)$ mass distribution, after events containing a Δ^{++} have been removed[9], is shown in fig. 1c.

We have studied our mass resolution in detail since good resolution is critical for the observation of structure in the A_2 peak. Fig. 2a shows the effect of the resolution on the expected valley-to-peak ratio for a double-pole shape.

Knowledge of the beam momentum, in addition to that derived by measuring an individual event[12], is useful in improving mass resolution. We have used highly constrained events to determine the characteristics of the beam momentum distribution in the chamber. The results of these studies, which do not depend on any assumptions about the character of (or aberrations in) the beam optics, show that the beam momentum is known to better than $\pm 0.5\%$[13]. This information (with the $\pm 0.5\%$ uncertainty) was used in all fits. Various examples of the sensitivity of the mass resolution to the assumed uncertainty in the beam momentum are shown in fig. 2b.

We have checked the experimental mass resolution in several cases: for $\eta \to \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$ in 1c fits; for $K^0_1 \to \pi^+\pi^-$ in the reaction $\pi^+p \to K^+p\pi^+\pi^-$ where the K^0 mass and direction were not constrained; and for the proton in the reaction $\pi^+p \to \pi^+p\pi^+\pi^-$ where the proton mass was not constrained. The experimental histograms are shown in fig. 2c-f. For the proton, K^0, and η mass distributions the curves represent the predicted mass resolution calculated when the uncertainties introduced by multiple scattering and measurement errors are propagated by our fitting programs; in the case of the ω the predicted mass resolution was folded with a Breit-Wigner resonance shape of width $\Gamma = 11.9$ MeV[14]. The curves are centered on the known particle masses[14]. In all cases the experimental mass distributions are consistent with or narrower than the predicted curves, and the positions of the peak are consistent with the particle masses within a fraction of an MeV. By fitting the proton, K^0, η, and ω mass distributions with the resolution as an unknown parameter, we find the half width at half maximum (HWHM) of the resolution function to be 2.7 ± 0.1, 3.4 ± 0.2, 5.4 ± 0.4, and 8.0 ± 0.4 MeV, respectively, where 2.8, 3.5, 6.2, and 9.0 MeV were expected. The calculated mass resolutions (HWHM) for the A_2 mass region are 3.8, 6.7, and 9.2 MeV for the $K\overline{K}$, 3π, and $\eta\pi$ decay modes respectively.

The mass distributions in the A_2 region for all three decay modes are presented in fig. 3. No obvious fine structure is observed in any of these distributions.

Previous experiments[1, 2] have shown that a two-parameter double-pole formula[3] is a convenient parametrization of the A_2 structure in their data. Therefore, to quantitatively compare the <u>shape</u> of our A_2 signal with the <u>shape</u> observed in these experiments, we have made fits by using both a Breit-Wigner (BW) and a double-pole (DP) formula over the mass regions shown in fig. 3.

To test how well the BW and DP hypotheses fit the data, least-squares fits were made by using narrow bins (10 MeV for $\eta\pi$ and $K\overline{K}$ and 5 MeV for 3π) in the 1200- to 1400-MeV region and broad bins (10 times the width of the narrow bins) in the outer region (two bins on each side). These uneven bin sizes were chosen so that the confidence level would be determined primarily by the inner resonance region and would be only slightly affected by the outer region. This outer region must be included to determine the background adequately. Maximum likelihood fits were made because the ratio of the likelihoods gives a direct comparison of the DP and BW hypotheses[15].

Fits were made not only to each decay mode separately but to the combination of the $K\bar{K}$ and $\eta\pi$ events and also to all three modes simultaneously [16]. In these combined fits, separate linear backgrounds and resolution functions were used for each mode, but the mass and width of the resonance was required to be the same in all modes. The fits to the combination of $K\bar{K}$ and $\eta\pi$ samples were performed because these two decay modes have a much larger signal-to-background ratio than does the 3π decay mode; therefore, the results of the fits are less sensitive to the shape of the background than are the results from the simultaneous fits to all three decay modes.

The results of these fits are shown in table 1, and curves representing the combined likelihood fit to the data are shown in fig. 3. The tabulated values of the masses, widths, and likelihood ratios come from the likelihood fits, and the confidence levels come from the least-squares fits. In some cases there was more than one solution for the DP hypothesis, and only the one having the largest likelihood is tabulated. Because of the relatively low confidence levels and the ambiguities of these DP fits, we have not quoted errors for the fitted values for this hypothesis.

As one can see in table 1, all of the decay modes fit adequately to a single Breit-Wigner hypothesis, and the values of the mass and width of the resonance are in agreement among the three modes. The double-pole fits have lower confidence levels and the values of the mass and width of the double-pole are not in agreement among the three modes. When a simultaneous fit to all three decay modes is made, the likelihood for the Breit-Wigner hypothesis is 10^7 times bigger than the likelihood for the double-pole hypothesis.

Our experiment is not exactly comparable to any of the previous experiments because of differences in one or more of the following: charge of the incident particle, momentum of the incident particle, momentum transfer range studied, and detection and momentum measurement of the charged final state particles. We have therefore considered the case of two coherent resonances, which might reconcile the disagreement in the A_2 mass shapes between experiments. We fitted our data by fixing the masses and widths of the resonances at the values determined by CERN[2] (M_1 = 1298 MeV, Γ_1 = 90 MeV, M_2 = 1297 MeV, Γ_2 = 12 MeV) and varying the relative amplitude and phase of the two resonances independently for each decay mode to achieve the best fit. The fitting was carried out in the same manner as described for the BW and DP hypotheses. The resulting confidence levels were essentially the same as those of the BW fits and were consistent with the narrow resonance having an amplitude comparable to the wide one in all channels.

In conclusion, the particular structure reported in previous experiments for the A_2 has not manifested itself in our data. The double-pole formula, which adequately represents previous A_2 structure, gives poor fits in our case. However, our data can be fitted either by two coherent resonances with the same masses and widths as those found by CERN[2] or by a single Breit-Wigner resonance.

We thank Joseph J. Murray for his work in beam design and construction. We gratefully acknowledge the assistance of the staff of the Stanford Linear Accelerator and the 82-in. bubble chamber in obtaining the data for this experiment. We also thank Lawrence Radiation Laboratory Group A Scanning and Measuring Group for their help in data reduction.

REFERENCES AND FOOTNOTES

*Work done under auspices of the U. S. Atomic Energy Commission.

1. G. E. Chikovani et al., Phys. Letters 25B, (1967) 44. A study of $\pi^- p \rightarrow X^- p$ at 7 GeV/c.

2. H. Benz et al., Phys. Letters 28B, (1968) 233; includes data from the CERN missing mass spectrometer and the CERN boson spectrometer for $\pi^- p$ at 2.6 GeV/c.

3. The formula used is

$$N(M^2) \propto \left[\frac{(M - M_0)}{(M - M_0)^2 + (\frac{\Gamma}{2})^2} \right]^2 .$$

The formula describes the data in refs. 1 and 2 quite well. The data of reference 2 give M = 1298 MeV, Γ = 28 MeV. For references to discussions of the double-pole formalism, see the review talk of D. G. Sutherland, in Proc. 1970 Philadelphia Conference on Experimental Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (Columbia University Press, New York, 1970).

4. D. J. Crennell, U. Karshon, K. W. Lai, J. M. Scarr, and I. O. Skillicorn, Phys. Rev. Letters 20, (1968) 1318. For this $\pi^- p$ experiment at 6 GeV/c, the two-peak fit is better, but not significantly more so than the one-peak fit.

M. Aguilar-Benitez et al., CERN-Paris (C.d. F.)-Liverpool Collaboration, Phys. Letters 29B, (1969) 62. They observe $\bar{p}p \rightarrow A_2 \pi$ at 0, 0.7, and 1.2 GeV/c. With a "signal" (events above background in the 1200- to 1400-MeV region) of 270 events in $A_2 \rightarrow K\bar{K}$, they favor DP (65% probability) over BW (4% probability).

R. Baud et al., Phys. Letters 31B, (1970) 397. They observe $\pi^- p \rightarrow A_2^- p$, $A_2 \rightarrow K^- K^0$ at 7 GeV/c. With a "signal" of 145 events, they have 60% probability for a double pole and 1% for a Breit-Wigner.

K. Böckman et al., Bonn-Durham-Nijmegen-Paris (E. P.) - Torino Collaboration, Nucl. Phys. B16 (1970) 221. They study $\pi^- p \rightarrow p A_2^+$ at 5 GeV/c. With a "signal" of 108 events, they favor the DP hypothesis (63% probability) over the BW hypothesis (20% probability).

5. Preliminary data from this experiment were reported in a review talk by A. Barbaro-Galtieri, in Proc. 1970 Philadelphia Conference on Experimental Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (Columbia University Press, New York, 1970).

6. For a description of the beam see S. Flatté, Lawrence Radiation Laboratory-Berkeley Group A Physics Note No. 646, 1968 (unpublished).

7. All events were measured on a Spiral Reader and the measured pulse heights were used to obtain track ionization information. Remeasurements of the V-2 prongs that failed were made on a Franckenstein. In addition we remeasured all the $A_2^+ \to K^+K_1^0$ candidates and about half the $A_2^+ \to \pi^+\eta$ candidates on a Franckenstein and compared the first and second measurements; we observed no systematic shifts in the mass spectrum between the two measurements.

8. In case of ambiguity, the hypothesis with the smallest total χ^2 (sum of kinematic and ionization chi square) was chosen. The kinematic confidence level was required to be greater than 10^{-5}.

9. We eliminated the Δ^{++} by removing events with $M(\pi^+p) < 1.38$ GeV.

10. We find that selecting a ρ makes a negligible change in the A_2 signal, but it distorts the background because of the well-known crossing bands effect. See for example A. H. Rosenfeld et al., Rev. Mod. Phys. 40, (1968) 77; S.-Y. Fung et al., Phys. Rev. Letters 21, (1968) 47, and A. Barbaro-Galtieri and P. Söding in Meson Spectroscopy, edited by C. Baltay and A. H. Rosenfeld (W. A. Benjamin, Inc., New York, 1968), p. 137.

11. The acceptance criteria were: (1) no 4-constraint fit to reaction (2) with confidence level greater than 10^{-5}; (2) a 2-constraint fit with confidence level $> 2 \times 10^{-3}$ and track ionization densities consistent with the track mass interpretations; (3) the 1-constraint fit with the same track identities as the 2c fit having the smallest sum of kinematic and ionization χ^2 of all 1c fits; (4) $M(\pi^+\pi^-\pi^0)$

from the 1-constraint fit within ± 25 MeV of the accepted η mass; (5) proton lab momentum < 2.0 GeV/c (a few percent effect). Examination of events with fitted proton momentum > 2 GeV/c on a scanning table showed that these events often had their tracks misidentified. We also found that events with confidence level for a 2c fit $< 2\times10^{-3}$ increased the background but not the A_2 signal.

12. For a description of the treatment of beam momentum correlations and the beam averaging technique we used (applied to another experiment), see S. Flatté, Lawrence Radiation Laboratory-Berkeley Group A Physics Note No. 664, 1968 (unpublished). We have compared the A_2 mass distributions obtained with and without external knowledge of the beam and find no discrepancies.

13. The full spread of the beam momentum is ± 1.5%. However, for a given position in the chamber the < ± 0.5% result holds.

14. Particle Data Group, Review of Particle Properties, Phys. Letters 33B (1970) 1.

15. For the 3π data the maximum likelihood analysis was performed on the data in 5-MeV bins in order to avoid long computer runs.

16. For all fits a mass-dependent width was used and the background was assumed to have a linear dependence on the mass. We use the same parametrization as that of P. J. Davis, S. E. Derenzo, S. M. Flatté, M. A. Garnjost, G. R. Lynch, and F. T. Solmitz, Phys. Rev. Letters 23, (1969) 1071. The resolution function for each distribution was folded in with the resonance shape.

Table 1
Results of the fits

Decay mode	Events fitted	HWHM Resolution (MeV)	σ	Events in resonance	Breit-Wigner Mass (MeV)	Breit-Wigner Width (MeV)	Breit-Wigner Confidence level (%)	Double pole Mass (MeV)	Double pole Width (MeV)	Double pole Confidence level (%)	Likelihood ratio DP/BW
$K\bar{K}$	208	3.8	3.2	132	1301±7	90±24	4	1285[a]	24	0.6[b]	0.016
3π	3398	6.7	5.7	941	1306±4	79±12	42	1316[a]	29	9	0.004
$\eta\pi$	311	9.3	7.9	189	1312±7	103±20	33	1302[a]	36	21	0.29
$\eta\pi + K\bar{K}$	519	—		—	1307±5	102±15	8	1302	29	0.5	8×10^{-5}
All modes	3917	—		—	1307±3	90±10	16	1315	29	0.2	$\sim10^{-7}$

a) Note that the masses obtained from the separate double-pole fits to the three decay modes are in disagreement.

b) This is the best of the three double-pole fits obtained for the $K\bar{K}$ channel.

HWHM = 1.18 σ For Gaussian

FIGURE LEGENDS

Fig. 1. Mass plots showing the A_2 signal in the three decay channels studied in this paper.

Fig. 2. (a) The effect of folding a Gaussian resolution shape with standard deviation σ_r into the double-pole formula. The valley-to-peak ratio is plotted. The upper scale is σ_r/Γ_{DP} and the lower assumes Γ_{DP} = 28 MeV. [The resolution (HWHM) $=(2\ln 2)^{1/2}\sigma_r$]. (b) Mass resolutions as a function of the assumed accuracy, $\Delta p/p$. Δp is the error in the incident beam momentum (p) from sources other than the measurement of an individual event. The arrow indicates $\Delta p/p$ = 0.5%, the value used by our fitting programs. (c) Mass of the proton in three-constraint fits to reaction (2), where the proton mass is allowed to vary. The curve is the predicted resolution (2.8 MeV HWHM) centered on the known proton mass. (d) The events of reaction (1) fitted to $\pi^+ p \rightarrow K^+ p \pi^+ \pi$ to determine the accuracy of the resolution function in the K^0 mass region. The curve represents the predicted resolution (3.5 MeV HWHM) centered on the known K^0 mass. (e) $M(\pi^+\pi^-\pi^0)$ from the 1c fits of reaction (3) in the η region. Shaded events chosen to fit the reaction $\pi^+ p \rightarrow p\pi^+\eta$. The curve represents the predicted resolution (6.2 MeV HWHM) centered on the known η mass. (f) $M(\pi^+\pi^-\pi^0)$ from reaction 3 in the ω region. The curve represents a BW fit to the data with Γ= 11.9 MeV and the predicted resolution (9.0 MeV HWHM) folded in, and centered on the known ω mass.

Fig. 3. Mass plots in the A_2 region. The curves are from the likelihood fit to the three decay modes simultaneously; BW (solid line) and DP (dashed line).

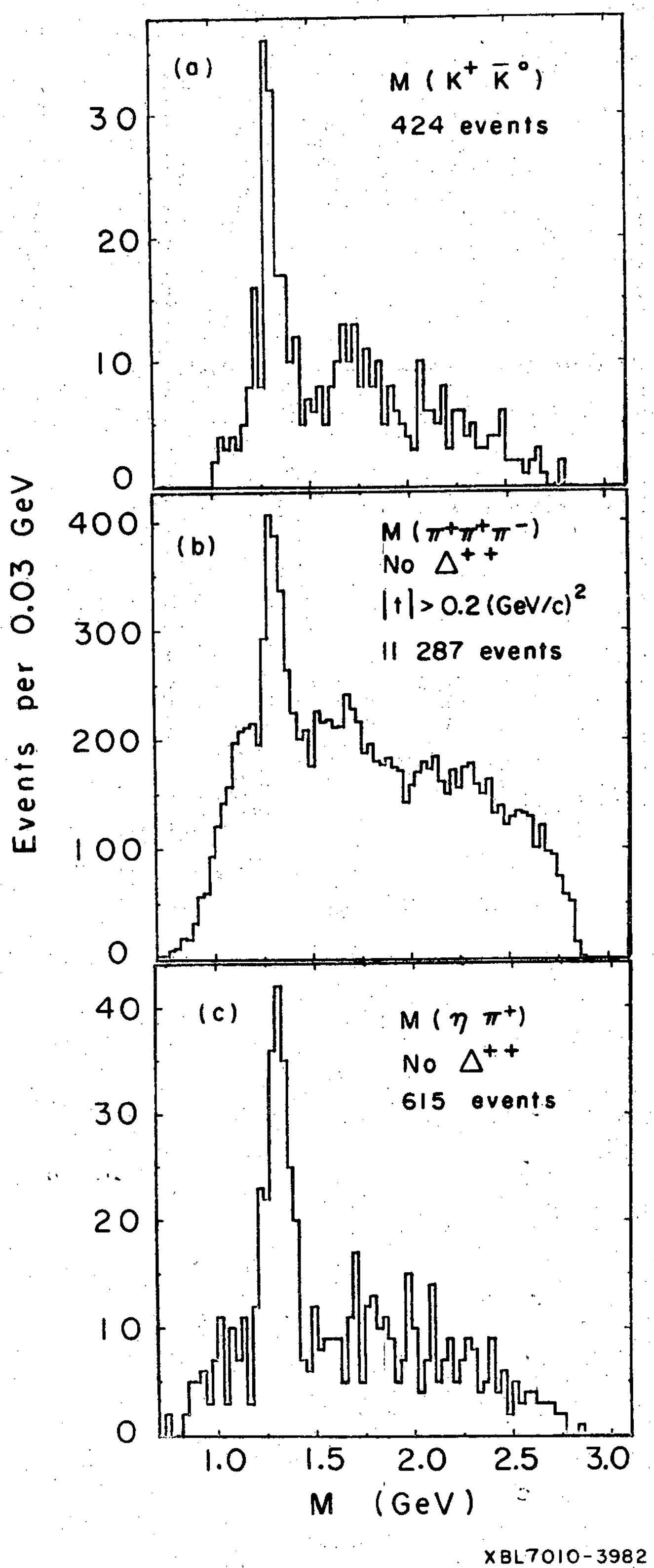
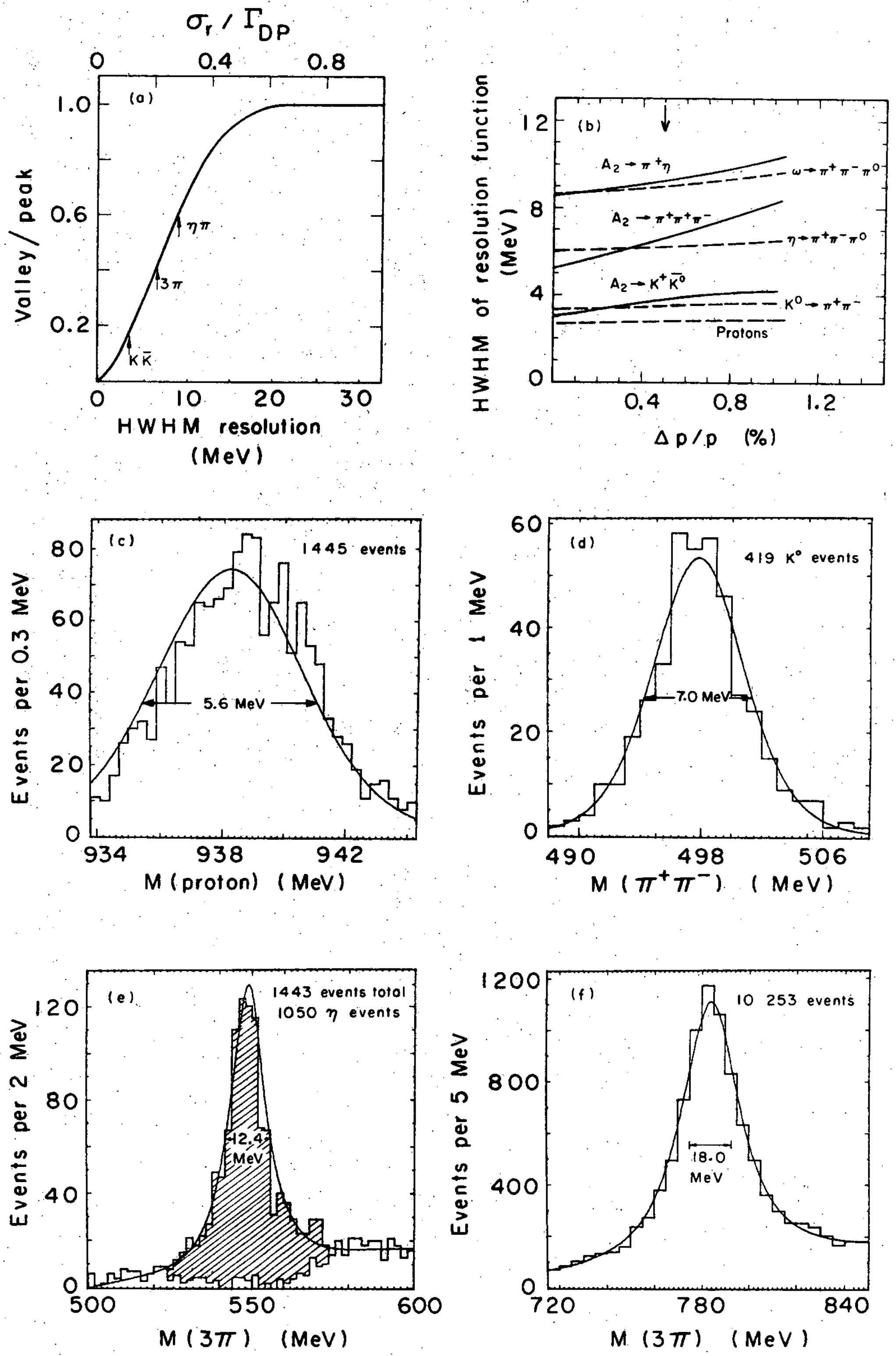

(a)
M (K⁺ K̄°)
424 events
(b)
M (π⁺π⁺π⁻)
No Δ⁺⁺
|t| > 0.2 (GeV/c)²
11 287 events
(c)
M (η π⁺)
No Δ⁺⁺
615 events
Events per 0.03 GeV
M (GeV)
XBL7010-3982

Fig. 1



XBL7010-3980

Fig. 2

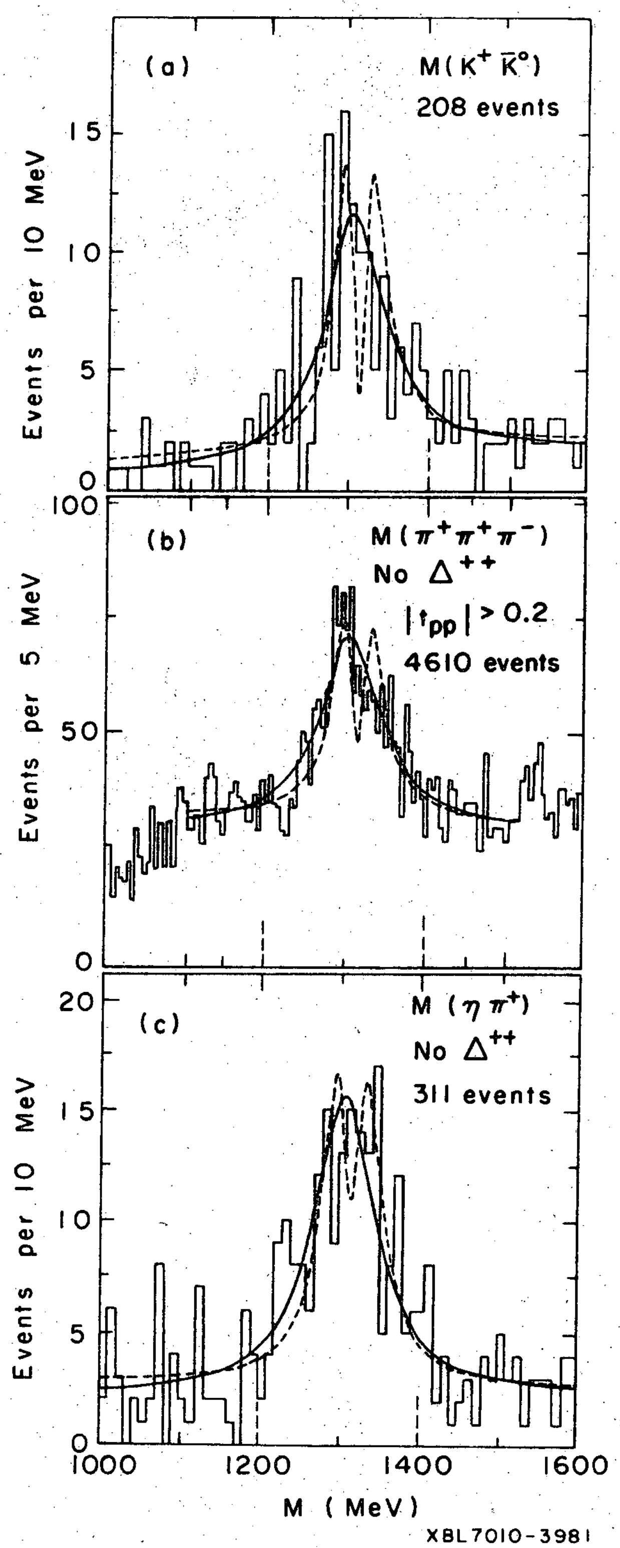

(a)
M(K+ K̄°)
208 events
Events per 10 MeV
(b)
M(π+π+π−)
No Δ++
|tpp| > 0.2
4610 events
Events per 5 MeV
(c)
M (η π+)
No Δ++
311 events
Events per 10 MeV
M (MeV)
XBL7010-3981

Fig. 3

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