Title
A REVIEW OF RECENT BOSON RESONANCES

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Sulamith Goldhaber

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A Review of Recent Boson Resonances

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In the review of multipion resonances I will focus my attention mainly on new developments that have occurred within the last five months and those that have not been fully treated in the review given by Gerson Goldhaber at the Conference on Symmetry Principles at High Energy in Coral Gables, Florida.[1] My review will include the following topics:

1. Spin Determination of Boson Resonances
2. The A_1 and A_2 Meson
3. Observations on the B Meson
4. The $K\pi\pi$ Resonances
5. General Comments on the $K\bar{K}\pi$ System
6. The D Meson, a $K\bar{K}\pi$ Enhancement at 1285 MeV
7. The E Meson
8. Evidence for $K\bar{K}\pi$ (1510)
9. Evidence for a New 2π Resonance at 700 MeV
10. The M_1 Meson, a KK Enhancement at 1280 MeV with S = +2
11. Decay Modes of the ω Meson
12. The Reactions $K^+d \longrightarrow K^*d$ and $K^+d \longrightarrow K^*d\pi$

In the last year we have become more and more aware of the fact that the complexity of multi-boson resonances make the identification of their quantum numbers difficult. A multi-boson state can only be accepted as a resonance particle if we can associate with it specific quantum numbers. The main problem that an experimentalist has to face in determining those quantum numbers is to obtain the observed mass peak as free from background as possible. Before I start my discussion of specific resonances I would like to summarize some of the experimental methods employed in spin and parity determinations.

1. Spin Determination of Boson Resonances

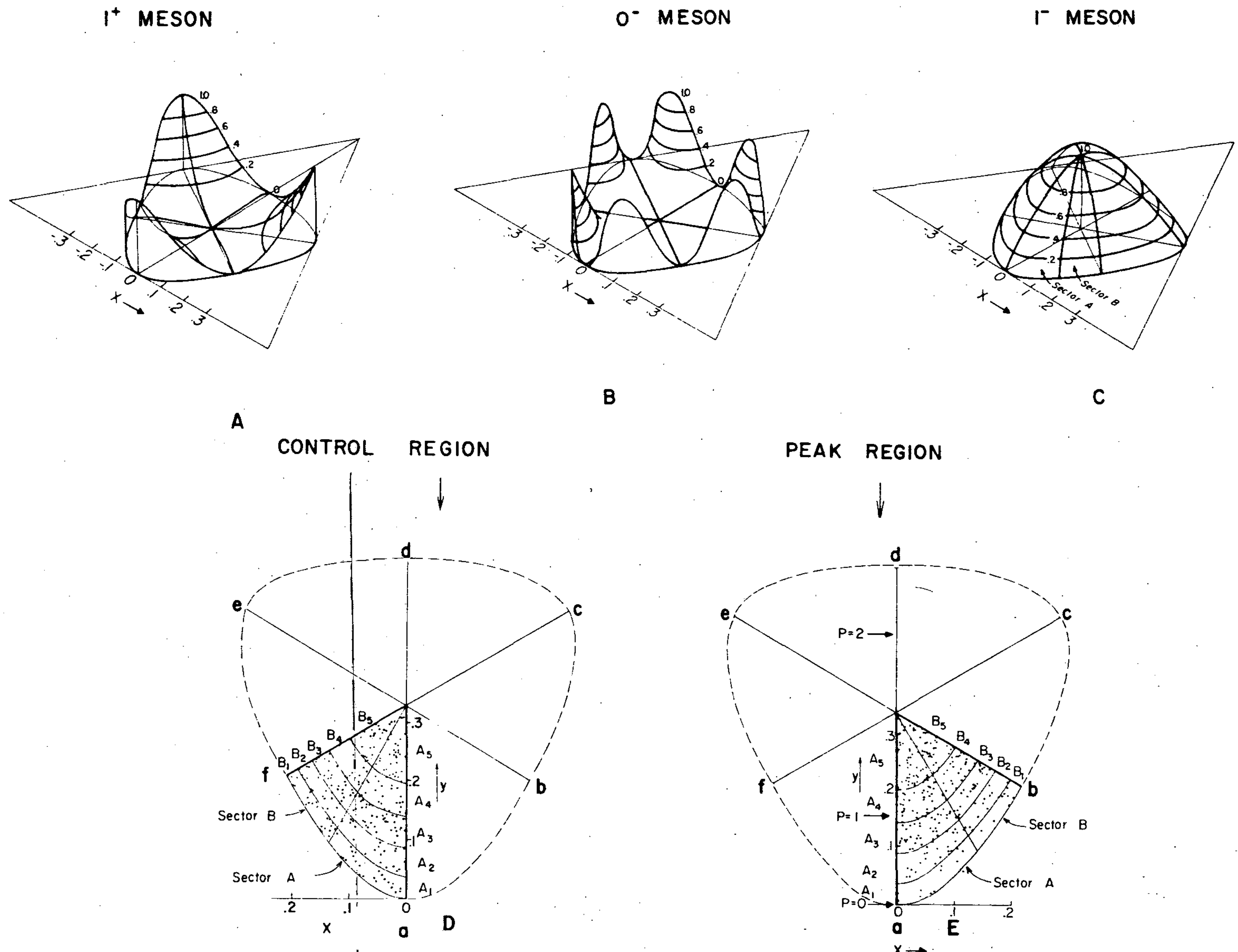
There are three basic methods that have been successfully employed in determining spins of resonances:

(a) A study of the angular distribution of the resonance decay in its rest frame, using the incident direction as quantization axis. This method is only useful if the resonance is produced with an aligned spin. Classical examples are the small momentum transfer reactions

$$K^+ + p \longrightarrow K^{*o} + N^*$$
$$\pi^+ + p \longrightarrow \rho^o + N^*$$

in which the 0^- quantum number exchange results in the respective K^* and ρ^o spin alignment. The decay distribution in the above examples corresponds to $\left|Y_1^o(\theta)\right|^2 \sim \cos^2\theta$.

(b) For three particle decays of resonances a study of the density distribution in a Dalitz plot may reveal the characteristic symmetry pattern of the decay matrix. The classic examples are the ω and η decays. Fig. 1-1 shows a density distribution of the Dalitz plot (in three dimensions) for the matrix elements corresponding to $J^P = 1^+, 0^- + 1$ mesons as well as the observed data of Stevenson et al.[(1)] for the ω meson. Fig. 1-2 shows the pattern in the Dalitz plot for matrix elements corresponding to various I, J^P values according to Zemach.[2] The regions of the Dalitz plot where the density must vanish because of symmetry requirements are shown in black.



STEVENSON et. al.

MUB-783

FIGURE 1-1

ZEMACH

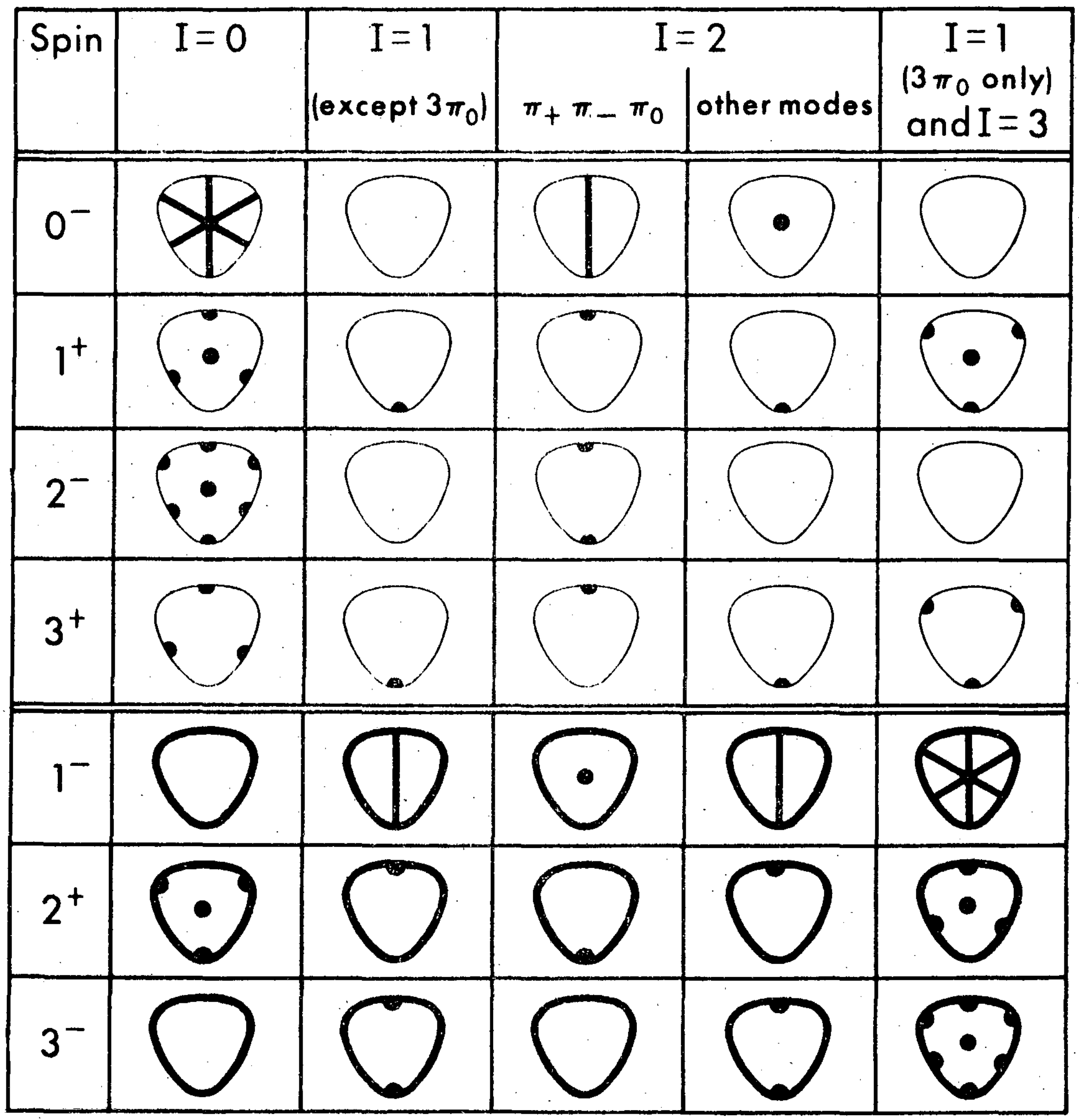


FIGURE 1-2

(c) If more than one decay mode of a resonance is observed this can lead to a spin and parity determination. For example in the case of the A_2 meson the presence of both the $\pi\rho$ and $K\bar{K}$ decay mode led to the suggestion[3] of the spin assignment $J^{PG} = 2^{+-}$. For such a case it is however necessary to show that the two decay modes represent the decay of a single resonance. This implies that the branching ratios must be independent of the production process.

2. <u>The A_1 and A_2 Mesons</u>

(a) The π–ρ decay mode

Although there have been consistent theoretical arguments to rule out the Peierls mechanism as a possible explanation for the A_1 meson, a number of other arguments have been given which attempt to relate the A_1 to a kinematical enhancement. In particular I want to mention the calculation of Maor and O'Halloran[1]. Stimulated by the work of Deck,[2] who considers the effect as being due to diffraction scattering of the virtual π on the proton, these authors consider the asymmetry in π^+p scattering as the cause for the A_1 enhancement. It is well known that the π^+p scattering cross section is forward peaked above the $N^*(1238)$ resonance (s– and p–wave interference). In the reaction $\pi^+ + p \rightarrow \pi^+ + \pi^- + \pi^+ + p$ the π^+p mass region above the resonance is the one involved in the A_1 peak. Maor and O'Halloran thus suggest that the A_1 peak is a consequence of this π^+p asymmetry when the π^+ is combined with the ρ meson. (see Fig. 2–1a) Recently N. P. Chang[3] has published a calculation in which he shows that Bose symmetrization can lead to a mass enhancement in the A_1 region of the πρ system. We have also carried out a calculation to see whether $\rho + N^*$ formation, considering only the tail of the Breit–Wigner formula for the N^* resonance, can reproduce the A_1 peak when proper account is taken of Bose symmetrization. These calculations do not lead to a sharp peak in the A_1 region. They do, however, lead to a broad enhancement in the three pion mass distribution between 1–1.3 BeV. In Fig. 2–2 we show a compilation of the available data on the πρ enhancement in the 3–4 BeV/c region.

It appears as if the A_1 and A_2 are sitting on a broad pedestal. Such an effect is particularly evident in the 8 GeV/c[(4)] data as was also pointed out by the Aachen–Berlin–CERN collaboration (see Fig. 2–3a). If this broad enhancement indeed represents a background effect to the A_1 and A_2, direct spin measurements in the π–ρ system are subject to uncertainties. In Fig. 2–4 we show the Dalitz plots for the A_1 and A_2 as well as the density distribution in the ρ band. The curves correspond to various spin assignments calculated according to Zemach.

(b) Other decay modes

The SOBB collaboration[5] have compiled data on the π–η decay mode of the A_2 meson. These authors suggest the possibility of a π–η decay mode for the A_1 as well. More data will be needed, however, to establish this decay mode (see Fig. 2–5). New data presented by Morrison at the 1965 Washington Meeting suggest the possibility that in the 8 GeV/c $\pi^+ + p$ data the $\pi\eta$ and $K\bar{K}$ decay modes are not present. Depending on how one estimates the number of the A_2 mesons above background in the π–ρ decay mode (See Fig. 2–3) the observed number of $\pi\eta$ and $K\bar{K}$ events in the A_2 mass band are lower by a factor of 2 to 4 than the branching ratios quoted from the 3 to 4 BeV/c experiments (See Table I and Fig. 2–6). Here it must be stressed, however, that in view of the uncertainty in the large background in the region of the A_2 meson, the data may actually be consistent with the 3–4 BeV/c data despite the apparent discrepancy. If the observation by Morrison et al. is confirmed, it would imply of course that the phenomena ascribed to the A_2 meson correspond to two distinct resonances, i.e., $A_2 \longrightarrow \pi\rho$; $A_2' \longrightarrow \pi\eta$, and $A_2' \longrightarrow K\bar{K}$. This situation would of course remove the discrepancy with the Brozan-Low[3] quantum number. Table II summarizes the allowed spin and parity values for the A_1 and A_2 mesons. (<u>Note Added in Proof:</u>) Bettini et al.[7] on a further analysis of the A_2 mesons formed in the reaction $p\bar{p} \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ at rest, present arguments favoring $J^P = 2^+$ from direct measurements on the $\pi\rho$ decay mode. Here we must note that due to the absence of the nucleon in the final state of the $p\bar{p}$ annihilation the background problems are quite different from those in the π^+p reactions.

TABLE 2-I

Branching Ratio for $A_2^{\pm}$ Decay from Data at 3-4 BeV/c in the Reaction $\pi^{\pm}p \longrightarrow A_2^{\pm} + p$.

$A_2^{\pm}$	$\longrightarrow$	$\rho^{o}\pi^{\pm}$	~35%	
	$\longrightarrow$	$\rho^{\pm}\pi^{o}$	~35%	(Assumed on charge independence)
	$\longrightarrow$	$K^{\pm}K^{o}$	~10%	Chung et al.
	$\longrightarrow$	$\eta^{o}\pi^{\pm}$	~20%	Trilling et al.

TABLE 2-II

Allowed Spin and Parity Values for Various A Decay Modes for T=1, G=Odd

$J^P(\pi\eta)$	$J^P(K\bar{K})$	$J^P(\pi\rho)$
—	—	0^-
0^+	0^+	—
1^-	—	1^-
—	—	1^+
—	—	2^-
2^+	2^+	2^+

Possible values for A_1 from absence of $\pi\eta$ and $K\bar{K}$ modes, 1^+, 2^- preferred from density distribution in ρ band for $\pi\rho$ decay mode

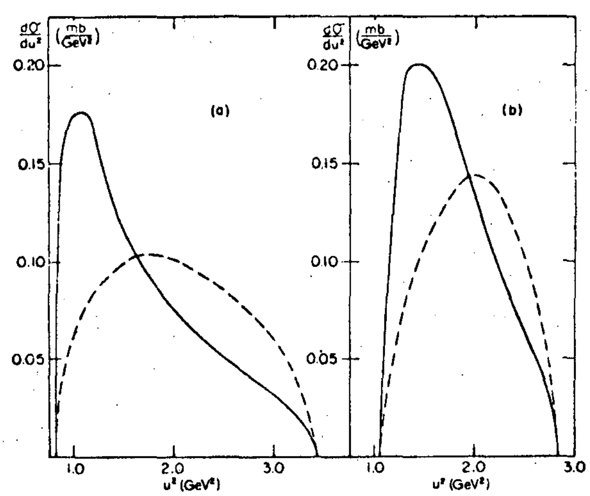
Assigned to A_2 from decay mode comparisons

MAOR and O'HALLORAN

Calculations based on asymmetry of $\pi^+ p$ scattering above N^{*++} resonance.

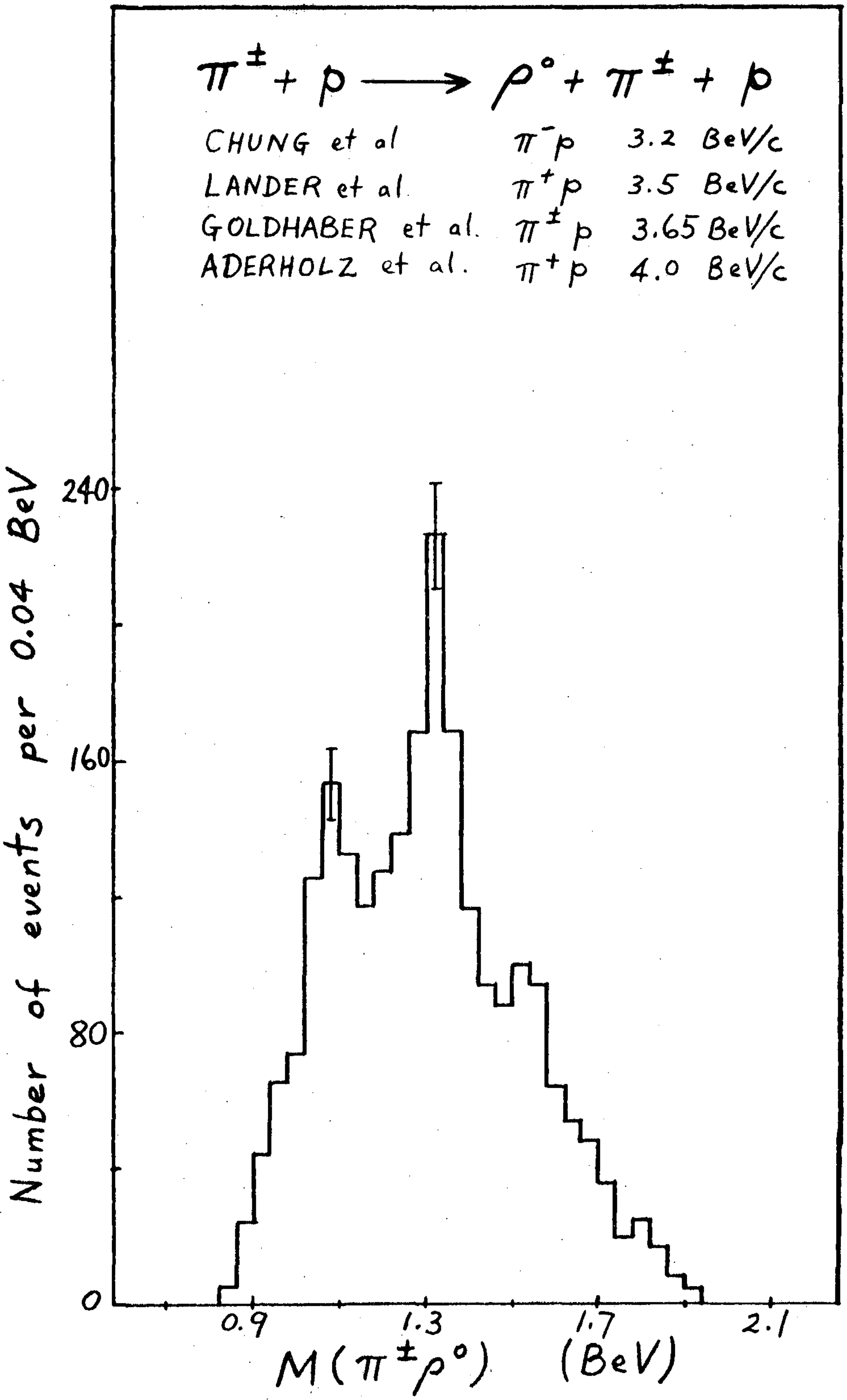
$\pi^+ \rho^o$
E=1050 MeV
$\Gamma \sim 50$ MeV

$\pi^+ K^{*o}$
E=1180 MeV



a) π^+-ρ^0 calculated mass distribution for reaction (1) at 3.65 GeV/c incident momentum. b) π^+-K^{*0} calculated mass distribution for reaction (6) at 3.0 GeV/c. Both distributions are compared with the appropriate normalized phase-space distributions (dashed line).

FIGURE 2-1



$\pi^{\pm} + p \longrightarrow \rho^{\circ} + \pi^{\pm} + p$
CHUNG et al $\pi^{-}p$ 3.2 BeV/c
LANDER et al $\pi^{+}p$ 3.5 BeV/c
GOLDHABER et al. $\pi^{\pm}p$ 3.65 BeV/c
ADERHOLZ et al. $\pi^{+}p$ 4.0 BeV/c
Number of events per 0.04 BeV
240
160
80
0
0.9
1.3
1.7
2.1
$M(\pi^{\pm}\rho^{\circ})$ (BeV)

FIGURE 2-2

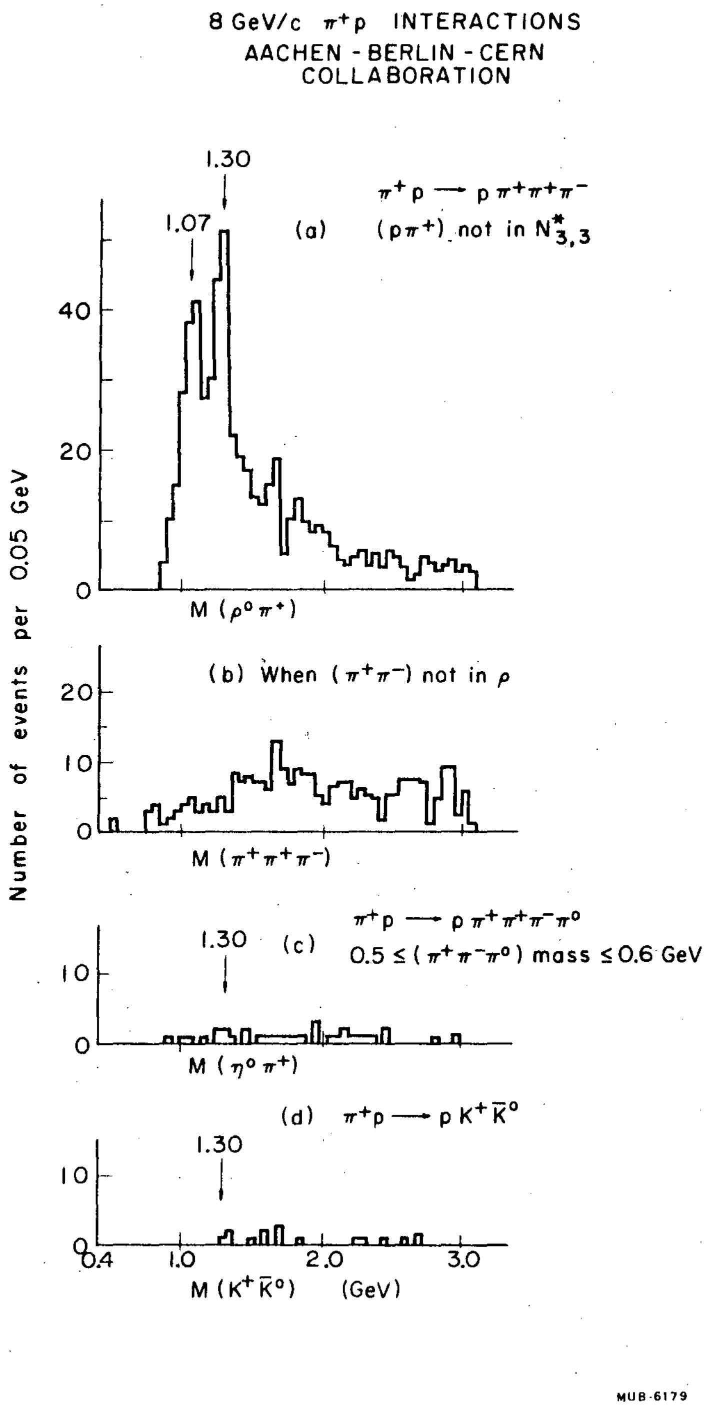

8 GeV/c π+p INTERACTIONS
AACHEN - BERLIN - CERN
COLLABORATION
1.30
1.07
(a)
π+p → p π+π+π−
(pπ+) not in N*3,3
40
20
0
M (ρ° π+)
(b) When (π+π−) not in ρ
20
10
0
M (π+π+π−)
Number of events per 0.05 GeV
1.30
(c)
π+p → p π+π+π−π°
0.5 ≤ (π+π−π°) mass ≤ 0.6 GeV
10
0
M (η° π+)
(d) π+p → p K+K̄°
1.30
10
0
0.4
1.0
2.0
3.0
M (K+K̄°) (GeV)
MUB-6179

FIGURE 2-3

$\pi^+ p \rightarrow p\,\pi^+\pi^+\pi^-$ AT 8 GeV/c. AACHEN-BERLIN-CERN COLLABORATION

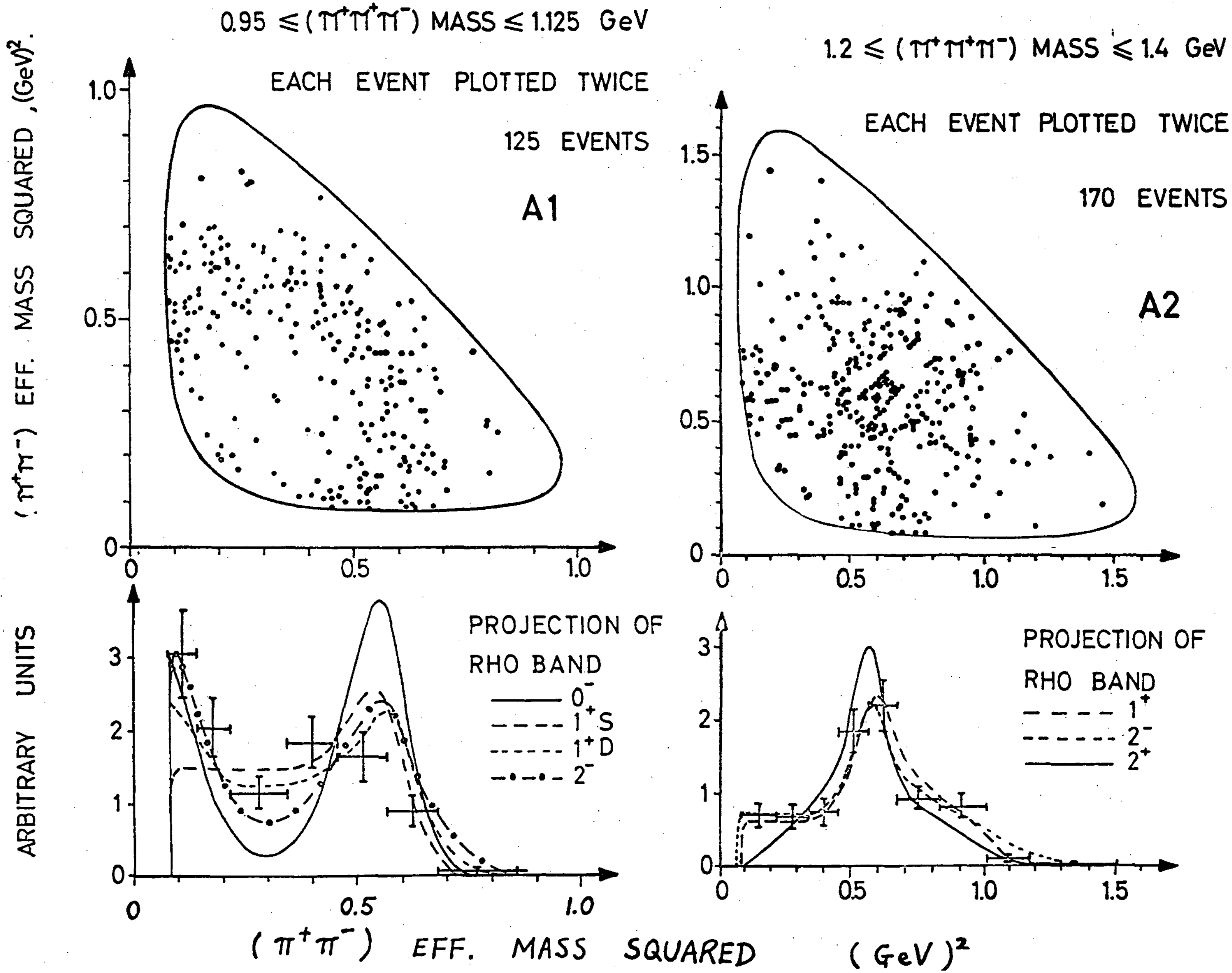


FIGURE 2-4

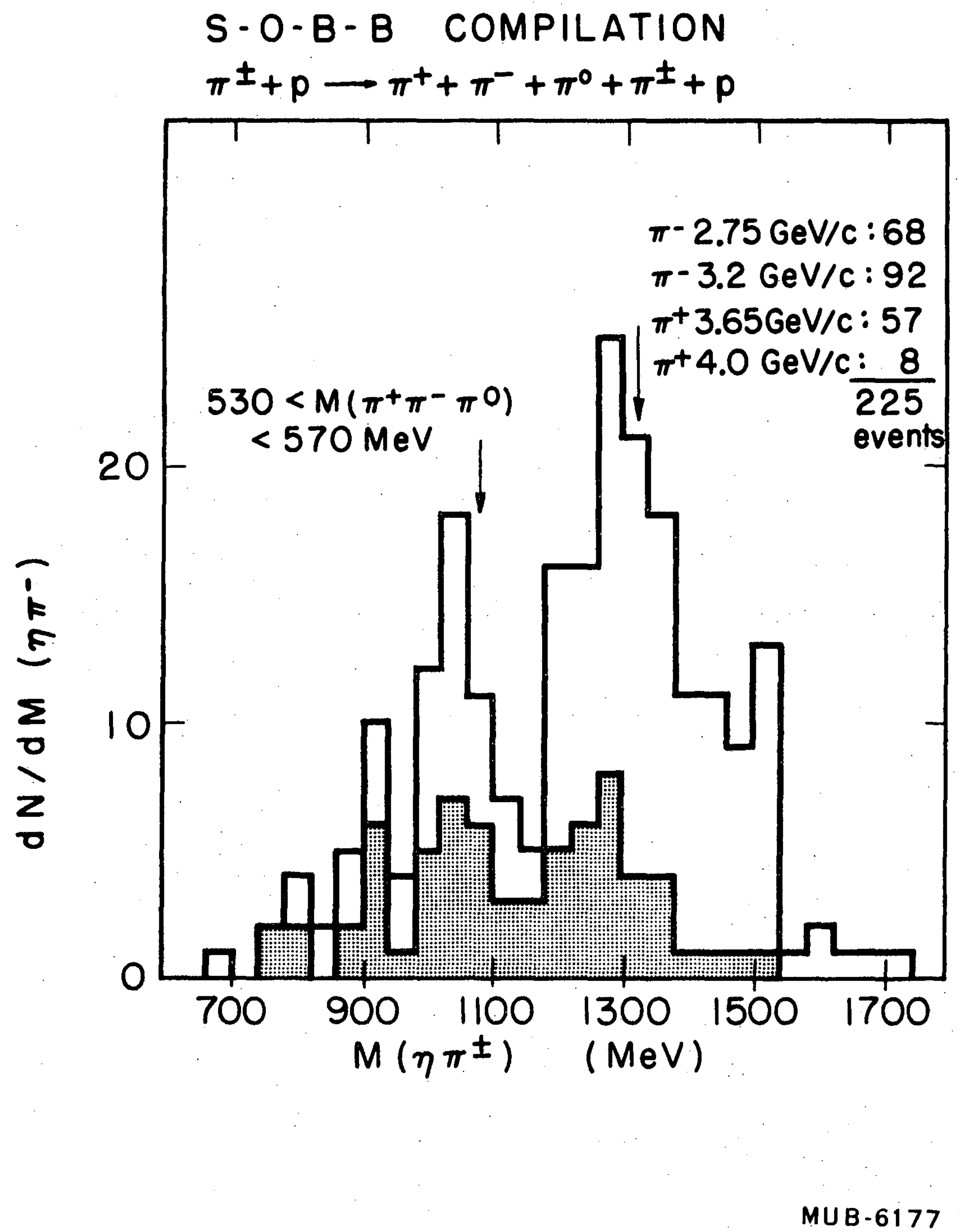
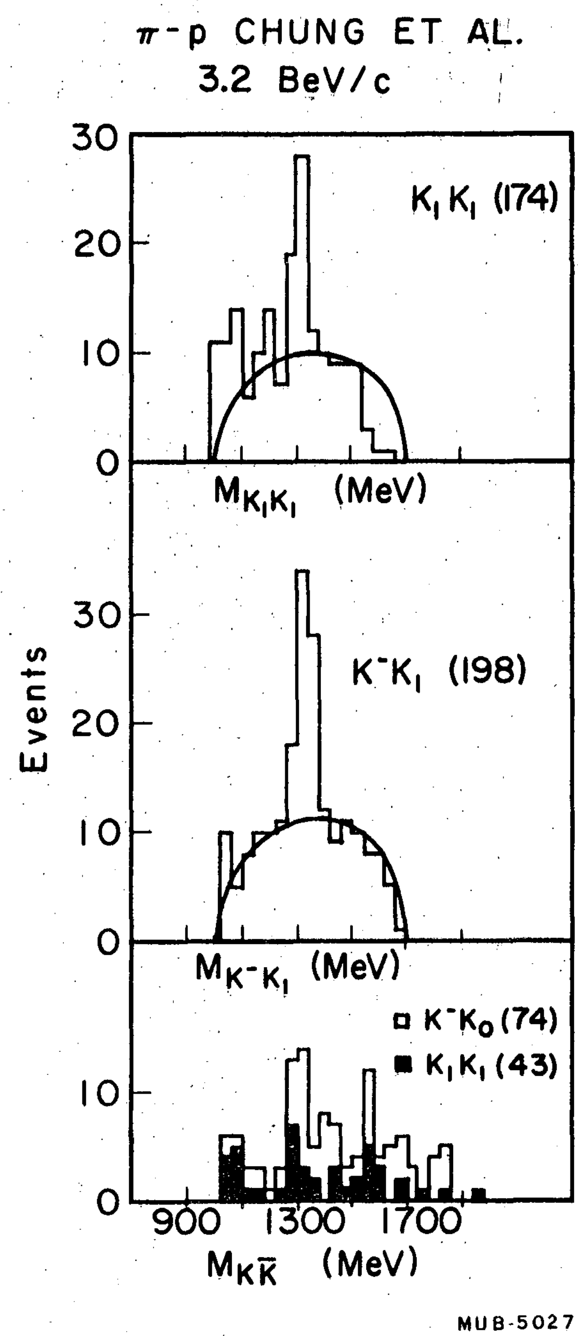

S-O-B-B COMPILATION
$\pi^{\pm} + p \longrightarrow \pi^{+} + \pi^{-} + \pi^{0} + \pi^{\pm} + p$
π^- 2.75 GeV/c : 68
π^- 3.2 GeV/c : 92
π^+ 3.65GeV/c : 57
π^+ 4.0 GeV/c : 8
225 events
$530 < M(\pi^+\pi^-\pi^0)$
< 570 MeV
$dN/dM\ (\eta\pi^-)$
0
10
20
700
900
1100
1300
1500
1700
$M(\eta\pi^{\pm})$ (MeV)
MUB-6177

FIGURE 2-5



π-p CHUNG ET AL.
3.2 BeV/c
K₁K₁ (174)
M K₁K₁ (MeV)
K⁻K₁ (198)
Events
M K⁻K₁ (MeV)
K⁻K₀ (74)
K₁K₁ (43)
900 1300 1700
M KK̄ (MeV)
MUB-5027

FIGURE 2-6

3. Observations on the B Meson

We have observed a new and suprising effect in our study of the $B^{\pm}$ meson in the reaction [1]

$$\pi^{\pm} p \longrightarrow B^{\pm} + p \quad \text{at } 3.65 \text{ BeV/c} \qquad (1)$$

The spin determination of the B mesons has been always difficult because of background problems. In an attempt to reduce background we have made use of the fact that the $B \longrightarrow \pi + \omega$. By further making use of the properties of the ω decay matrix element it is possible to purify the ω sample. The ω decay matrix element is proportional to $(\overline{p}_i \times \overline{p}_j)$ which leads to a density distribution in the ω Dalitz plot peaked in the center (see Fig. 1–1). By choosing the ω mesons in the center we improve the ω/background ratio considerably. Here we assume that background is uniformly distributed. The peripheral ω events, however, will now be much more diluted by background events. The surprising results we have observed are that the purified ω sample does not lead to a significant ωπ enhancement in the B meson band whereas the "diluted" ω sample shows a significant B peak. In Fig. 3–1a we show the normalized Dalitz plot for pion triplets defined by:

$$760 \leq M_{\pi_1^+ \pi^- \pi^0} \leq 820 \text{ MeV} \qquad (2)$$

The radial density distribution is shown in Fig. 3–1b. The solid curve corresponding to the expected radial density distribution for the total ω sample agrees well with the predicted one.

The curve in the Dalitz plot has been drawn so that for a pure 1^{--} decay matrix the number of ω mesons should be equal in the two regions. If we now choose a 4π mass region corresponding to the B meson, i.e.,

$$1160 \leq M_{4\pi} \leq 1300 \text{ MeV} \qquad (3)$$

and look at the Dalitz plot of the $\pi^+\pi^-\pi^0$ mass triplet corresponding to the ω mass we obtain a radial density distribution of points in the plot shown in Fig. 3-1d. The probability that this experimental distribution corresponds to a pure 1^{--} matrix element is $\leq$ 1/2 %.

Next I would like to show the reduction of background in the ω mass region that is obtained by choosing the central region of the Dalitz plot. For this purpose we include all $\pi^+\pi^-\pi^0$ triplets irrespective of their mass in a normalized Dalitz plot. The curve separating the Dalitz plot into two regions we leave the same as for the ω mass sample. The resulting $\pi^+\pi^-\pi^0$ mass plots are shown in Fig. 3-2. It is clear that the ω mesons in the periphery have a much larger background contribution.

We now are ready to look at the 4π mass distribution. First let me show you the 4π mass distribution for the entire sample having selected the $\pi^+\pi^-\pi^0$ mass triplet to lie between 760 – 820 MeV. (See Fig. 3-3) The shaded region represents the events outside the N^{*++} (1238) resonance. The black insert represents events in which the four pions can form two ω mesons in the same reaction. For the π^+p interaction for instance

$$\pi^+ + p \longrightarrow \pi_1^+ \pi^0 \pi^- \pi_2^+ p$$

both $\pi_1^+ \pi^0 \pi^-$ and $\pi_2^+ \pi^0 \pi^-$ lie in the ω mass band for the events in the black insert. As will be noted these four pions give a mass enhancement peaked below the "B meson" mass band. The curves shown correspond to phase space calculation by a Monte Carlo method which takes into account reflection due to resonance formation viz. ωN^*, $\omega p\pi$, $\pi\pi\pi N^*$ and non-resonating $\pi\pi\pi\pi p$ in the experimentally observed ratios. For comparison Fig. 3-4 shows a new compilation of data on the B meson available to us.[2,3,4]

Next I would like to show you the 4π mass distribution with pion triplets from the central and peripheral region of the Dalitz plot. This is shown in Fig. 3-5a and Fig. 3-5b respectively. Here we note the surprising result that the B enhancement seems to be mainly associated with the pion triplets from the peripheral region, i.e., with the "diluted" ω mesons. We can now summarize what we have learned about the B meson.

(a) By considering all available data [1,2,3,4] there is good evidence for an enhancement in the four pion mass distribution if the neutral pion triplet is restricted by conditon (2). This enhancement with E_B = 1220 MeV and Γ_B = 120 MeV has been called the B meson.

(b) From our present work it appears however that the B meson is not primarily associated with the $J^{PG} = 1^{--}$ ω meson. Furthermore, the observed peak appears to be somewhat narrower than indicated in earlier experiments.

(c) There does not appear to be any 2π or $K\bar{K}$ decay mode for B meson.[5,6] This rules out the spin $J^P = 1^-$ and 3^- assignments for the B meson (see Table 3-I).

It is not clear to us at present what the correct interpretation of the B peak is. Some possibilities we have considered are:

(a) Distortion of the matrix element due to final-state interactions. Here we consider the possibliity that the effect we observed is due to $B \rightarrow \pi\omega$ but that the ω matrix element is distorted because of the B decay process. The effects of Bose statistics will be most pronounced for the "double ω" events. As was pointed out above, however, these occur primarily outside the B peak. Furthermore, the ratio of $\Gamma\omega/\Gamma_B$ is such as to make distortion effects unlikely.

(b) A kinematical enhancement.

Here we have to assume that the background events which are constrained by condition (2) can lead to an enhancement in conjunction with another two or three particle resonance other than the ω. While there is no convincing evidence for the existence of such a resonance in our data, we note that if $M(\pi_2^+ \pi^- \pi^0)$ constrained to a mass 950–1000 MeV an enhancement in the 4π mass distribution would result at the "B" meson mass region.

(c) Decay into four pions.

We can make the assumption that the B meson is indeed a resonance and that the $\omega\pi$ decay mode is rigorously forbidden. This would occur in the case of a $J^{PG} = 0^{++}$ assignment for the B meson, for example. Such a meson could decay into four pions. The problem, however, is to explain why three of these pions appear to be bunched in the vicinity of the ω meson mass, since on simple phase space considerations only 12% of the three-pion-mass triplets would fall into the mass band given by condition (2).

(d) Decay into a π and a definite three-pion state with $J^P \neq 1^-$.

If the B meson, considered again as a 0^{++} particle, decays into a pion and a definite three-pion state with mass similar to that of the ω meson, the quantum numbers of such a three-pion state would be $I = 0$ and $J^{PG} = 0^{--}, 1^{+-}, 2^{--}$, etc. We note here that for the above J^{PG} assignments to the three-pion system the density distribution goes to zero at the center of the Dalitz plot. Our data alone do not have the statistical accuracy, however, nor do we have any direct evidence to ascertain the existence of such a three-pion state.

TABLE 3-1

Allowed Spin and Parity Values

For Various B Decay Modes

For T=1, G=even

$J^P(\pi\pi\pi\pi)$	$J^P(\pi\omega)$	$J^P(\pi\pi)$	$J^P(K\bar{K})$
0^-	0^-	———	———
0^+	———	———	———
1^-	1^-	1^-	1^-
1^+	1^+	———	———
2^-	2^-	———	———
2^+	2^+	———	———
3^-	3^-	3^-	3^-
3^+	3^+	———	———

Possible value if $\pi\omega$ mode forbidden (arrow to the 0^+ row)

Ruled out, $\pi\pi$ and $K\bar{K}$ decay mode not seen (arrows to 1^- and 3^- in the $J^P(K\bar{K})$ column)

$\pi^{\pm} p$ 3.65 BeV/c

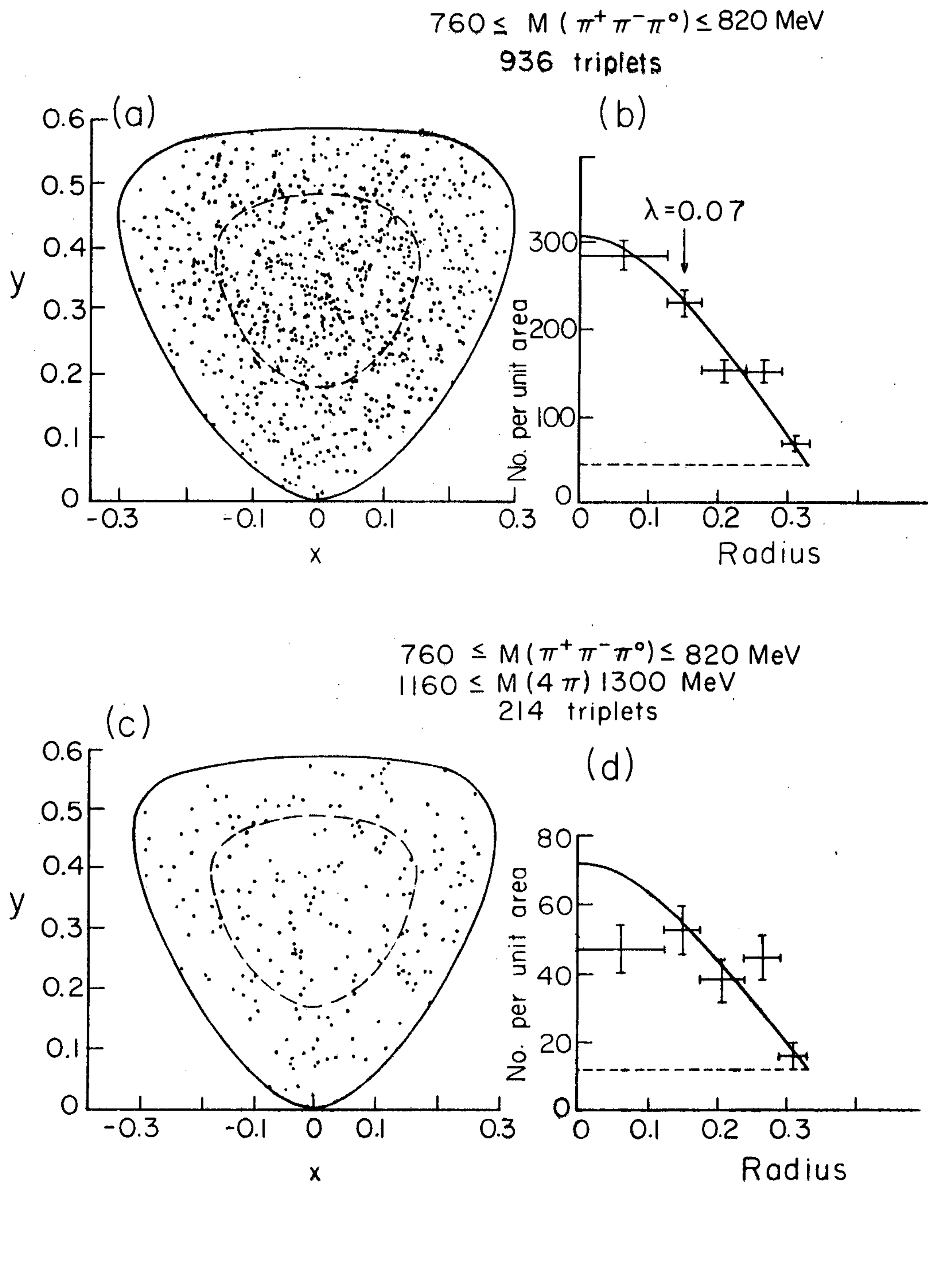


FIGURE 3-1

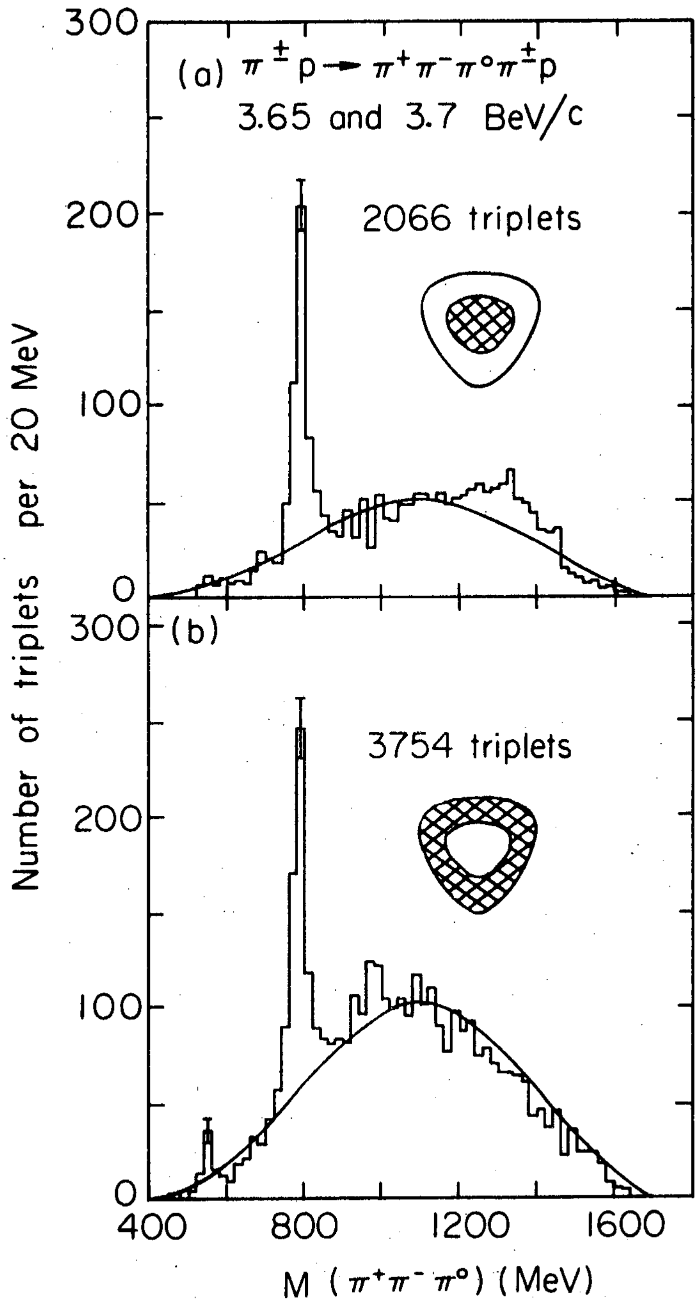

(a) $\pi^{\pm}p \rightarrow \pi^{+}\pi^{-}\pi^{0}\pi^{\pm}p$
3.65 and 3.7 BeV/c
2066 triplets
(b)
3754 triplets
Number of triplets per 20 MeV
M $(\pi^{+}\pi^{-}\pi^{0})$ (MeV)
300
200
100
0
400
800
1200
1600
MUB-6020

FIGURE 3-2

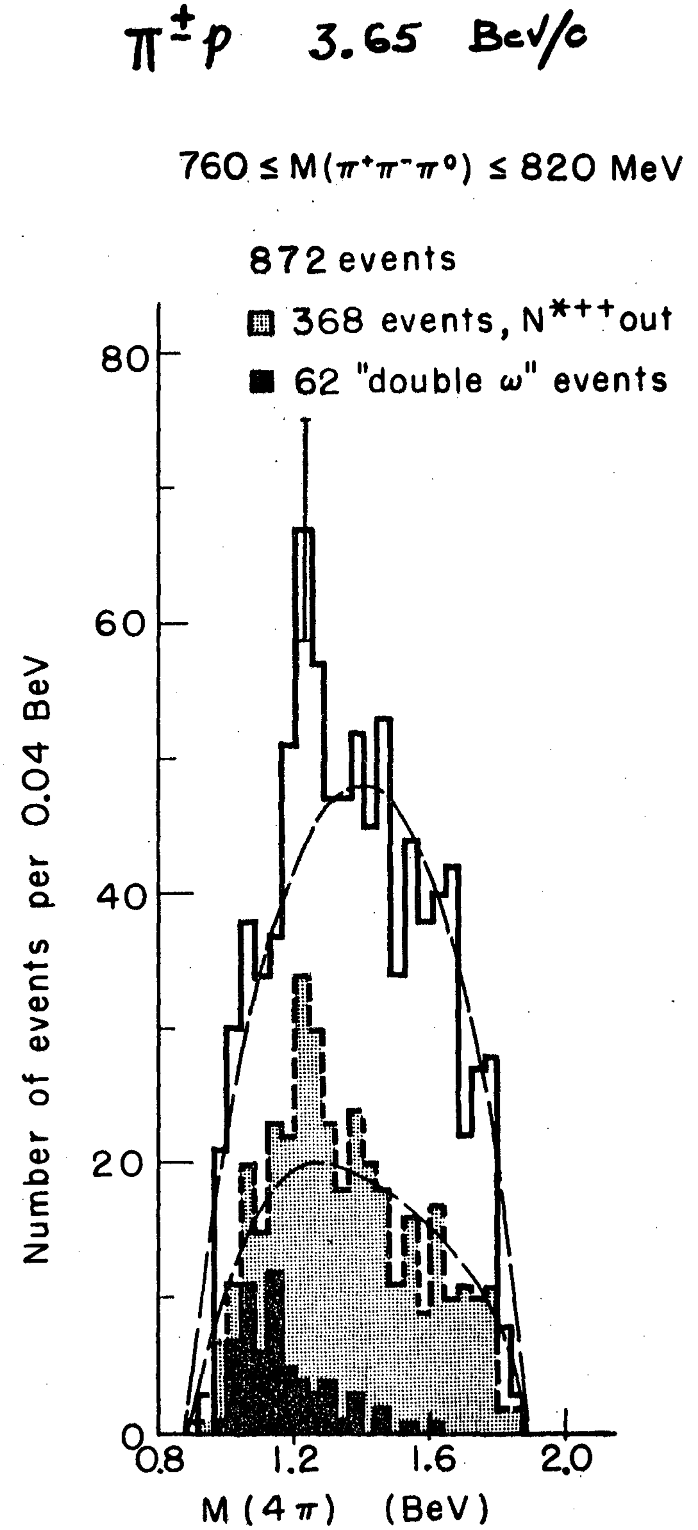
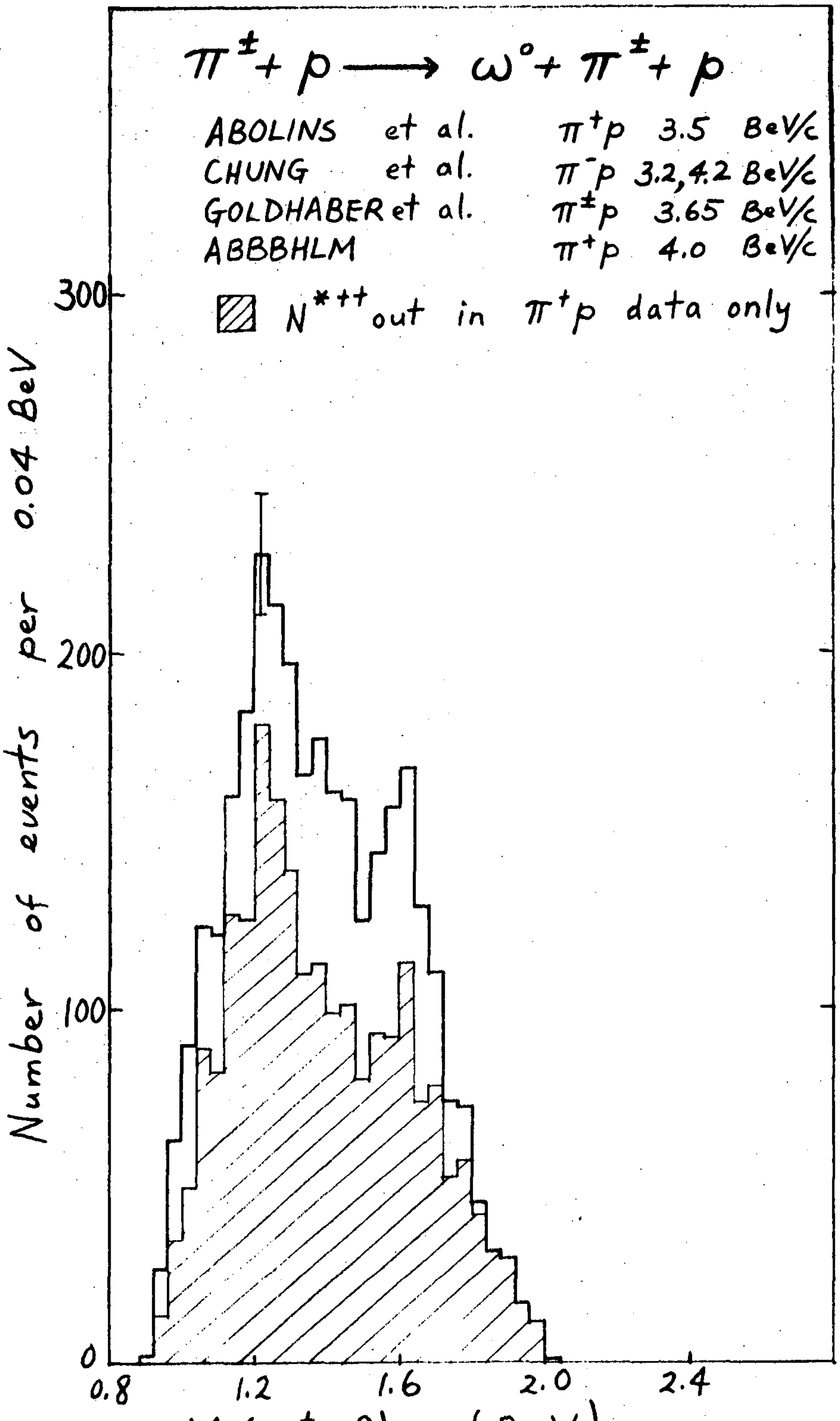


FIGURE 3-3

MUB-6160



$\pi^{\pm} + p \longrightarrow \omega^{\circ} + \pi^{\pm} + p$
ABOLINS et al. $\pi^{+}p$ 3.5 BeV/c
CHUNG et al. $\pi^{-}p$ 3.2, 4.2 BeV/c
GOLDHABER et al. $\pi^{\pm}p$ 3.65 BeV/c
ABBBHLM $\pi^{+}p$ 4.0 BeV/c
N^{*++} out in $\pi^{+}p$ data only
Number of events per 0.04 BeV
300
200
100
0
0.8
1.2
1.6
2.0
2.4
$M(\pi^{\pm}\omega^{\circ})$ (BeV)

FIGURE 3-4

π± p 3.65 BeV/c

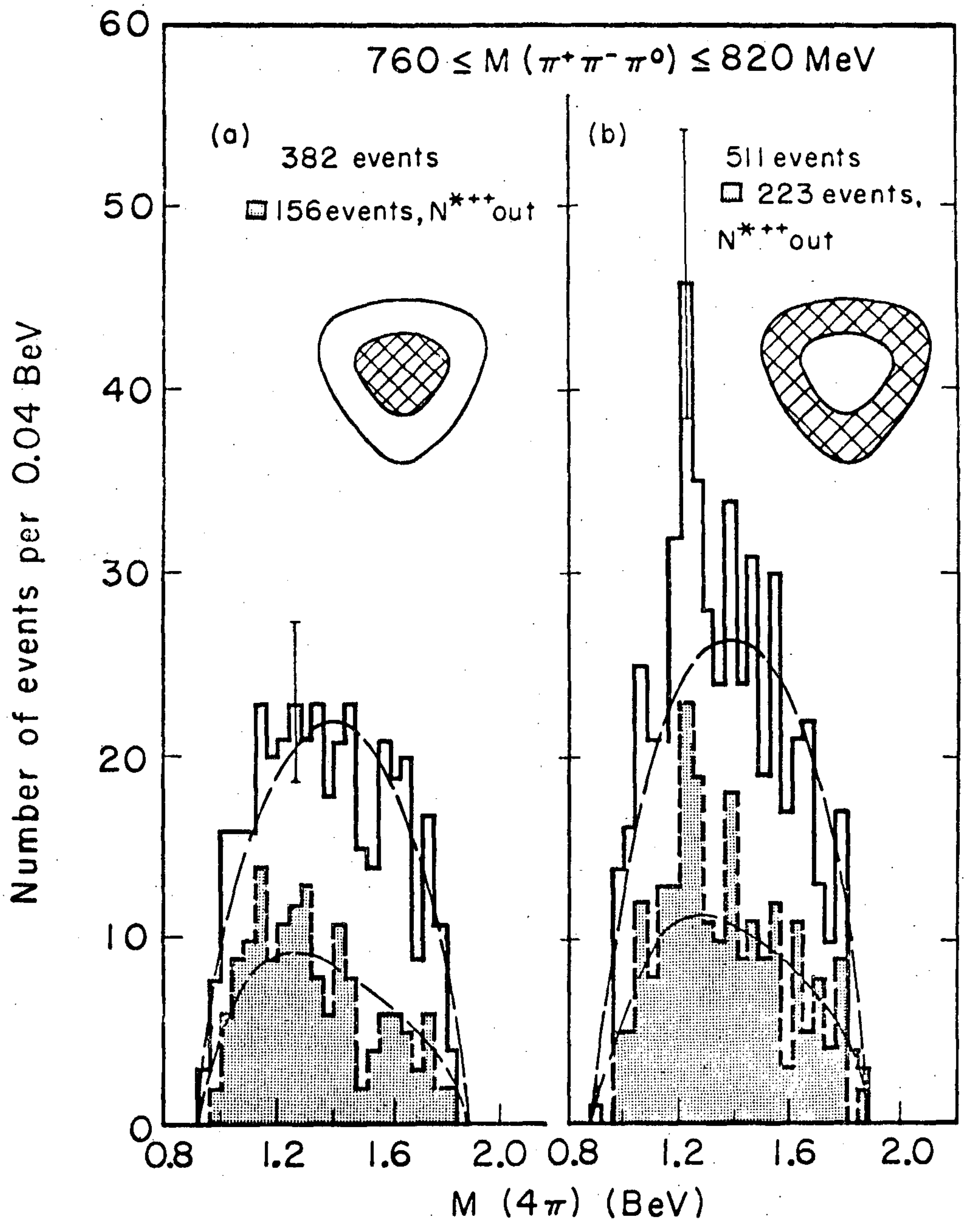


Fig. 3-5

4. <u>The Kππ Resonances</u>

The resonances that have been claimed in the literature[1,2,3,4] all involving the Kππ system are summarized in Table 4–I.

(a) <u>The C Meson</u>

The C meson has been observed in annihilations at rest by the groups at CERN–College de France[2] and Columbia–Rutgers–Brookhaven[3] (see Fig. 4–1 and Fig. 4–2). The puzzling problem is that this Kππ state at 1215 MeV has only been seen in the neutral mode, while for I = 1/2 one expects to see also the $|Q| = 1$ mode. Some evidence has been presented by the CERN collaboration for a charged ($K_1^o \pi^\pm \pi^o$) state at 1320 MeV.

(b) <u>The Kππ State at 1270 MeV.</u>

This state has only been observed in a $\bar{p}p$ annihilation at 3 BeV/c by the CERN–Paris–London group. It has however not been observed by the Yale Group[5] in an experiment of $\bar{p}p$ annihilation at 3.7 BeV/c. The results are shown in Fig. 4–3.

(c) <u>The Kππ Q = 1 System, K^{**}(1320).</u>

A new preprint has reached us two days before I left reporting on a Kππ singly charged enhancement at 1320 MeV. Almeda et al.[6] from theCavendish Laboratory in Cambridge carried out a study of the reaction:

$$K^+ + p \longrightarrow K^+ \pi^- \pi^+ p$$

at 5 GeV/c. They observe an enhancement in the $K^+ \pi^- \pi^+$ system at 1320 MeV in particular for events outside the N^{*++} (1238) band. (see Fig. 4–4) The dominant decay mode of the proposed resonance is via K^{**+} (1320) $\longrightarrow K^{*o} + \pi^+$. The mass quoted is

TABLE 4-I. The $K\pi\pi$ Resonances

Name	I	Mass	Γ	Reaction	P_{inc}	Comments
	1/2 or 3/2	1175	40 ± 15	$\pi^- + p \to \Lambda + K\pi\pi$	~3 GeV/c	discrepancy between similar experiments
C^0	1/2 (3/2)	1215 ± 15	60 ± 15	$\bar{p} + p \to K\bar{K}\pi^+\pi^-$	at rest	only seen in $\bar{p}p$ at rest
	3/2	1270 ± 20	60 ± 20	$\bar{p} + p \to K^0 K^{\pm} \pi^+ \pi^- \pi^{\mp} \pi^0$	3 GeV/c	not observed at $\bar{p}p$ 3.7 GeV/c
K^{**}	1/2 (?)	1320	60	$K^+p \to K^+\pi^-\pi^+p$	5 GeV/c	preprint

$$E_{K^{**}} = 1320 \pm 25 \text{ MeV}$$

$$\Gamma_{T_{K^{**}}} = 60 \pm 20 \text{ MeV}$$

It is perhaps relevant to note here that this proposed charged $K\pi\pi$ state may be the same Q=1 object observed by Armenteros et al.[2] in the $\bar{p}p$ annihilation at rest.

$\bar{p}p$ ANNIHILATIONS AT REST — (CERN)

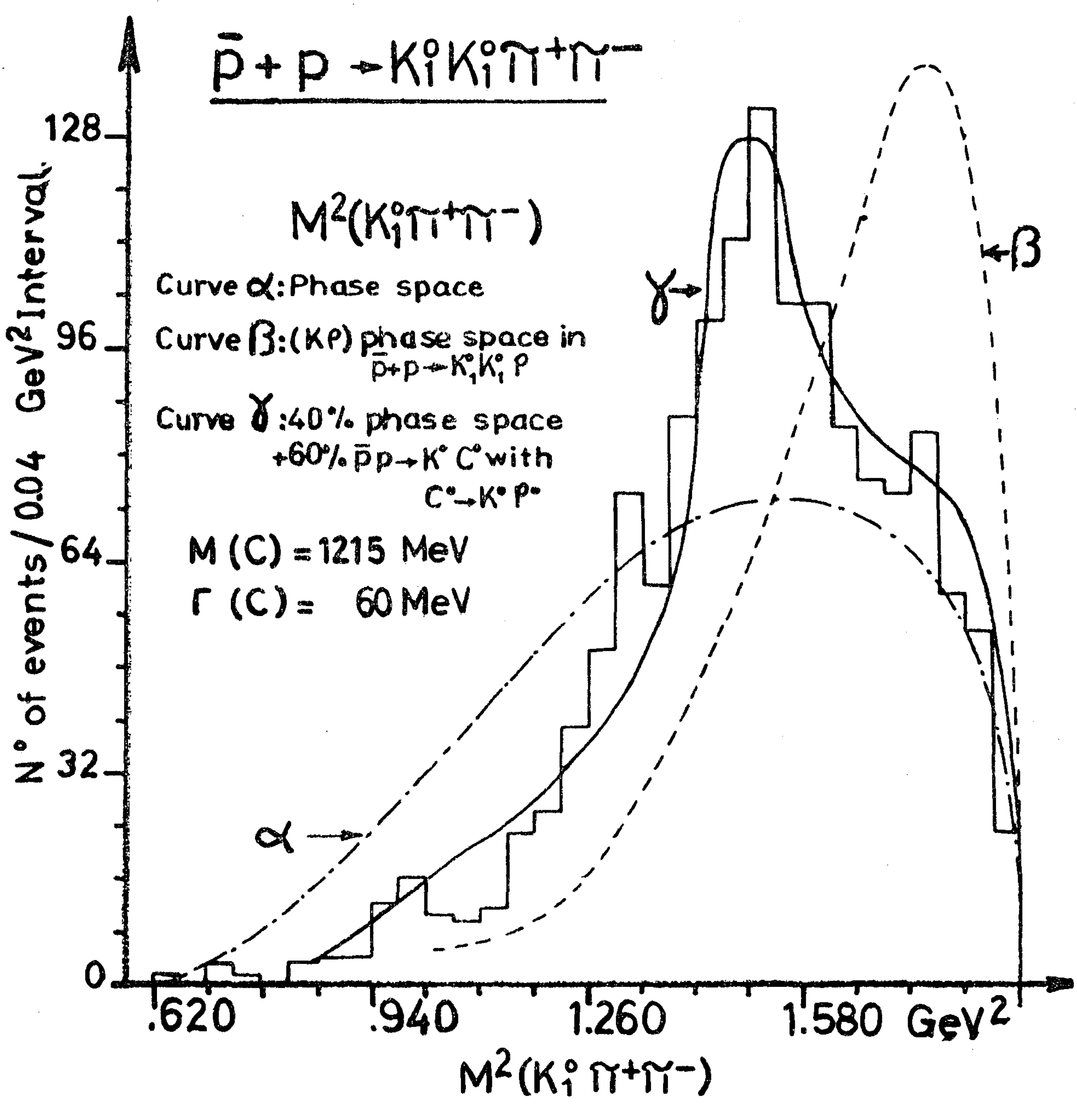
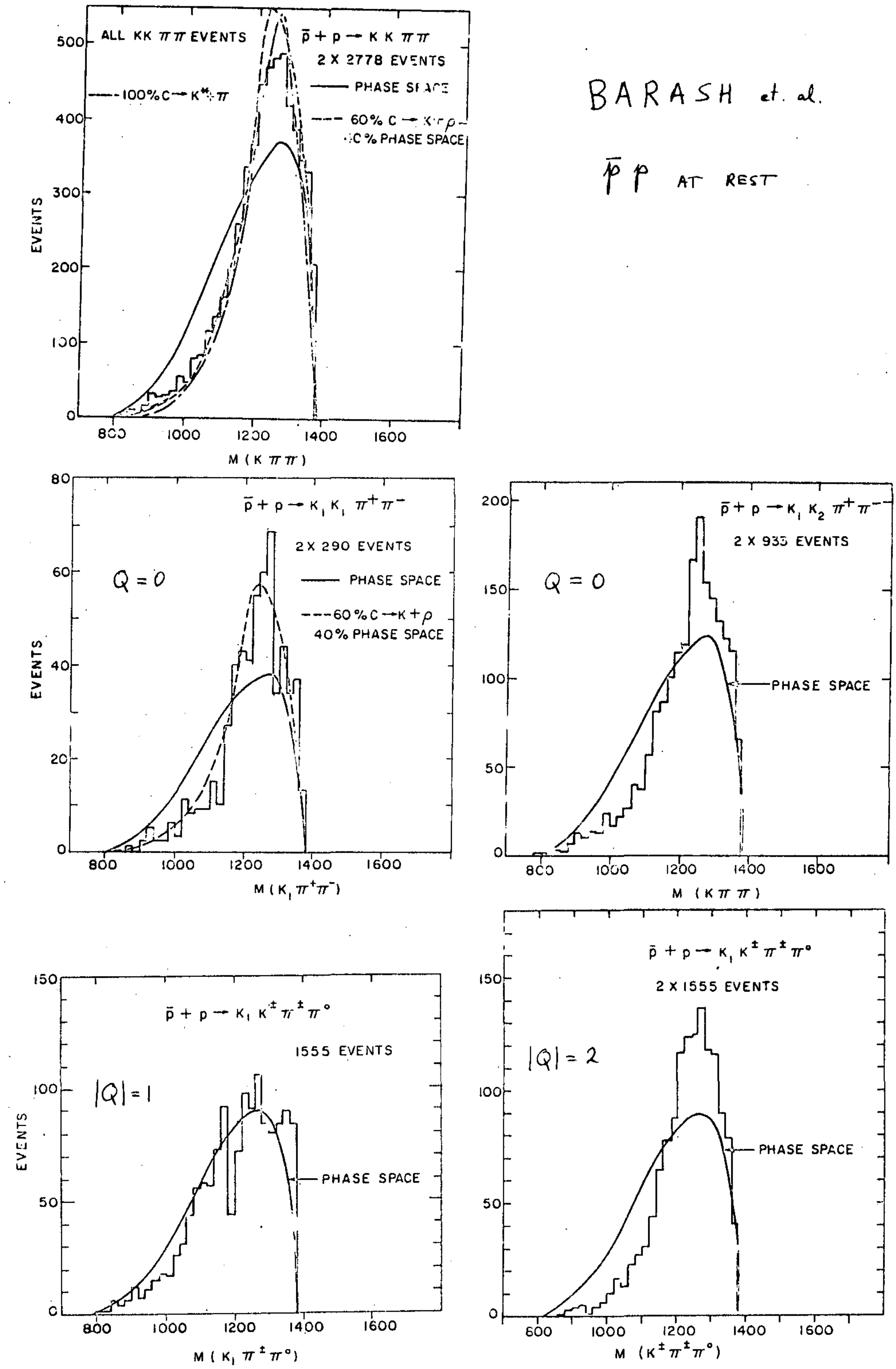


FIGURE 4-1



ALL KK ππ EVENTS
p̄ + p → K K π π
2 X 2778 EVENTS
PHASE SPACE
100% C → K* + π
60% C → K + ρ
40% PHASE SPACE
EVENTS
M (K π π)
BARASH et. al.
p̄ p AT REST
p̄ + p → K₁ K₁ π⁺ π⁻
2 X 290 EVENTS
Q = 0
PHASE SPACE
60% C → K + ρ
40% PHASE SPACE
M (K₁ π⁺ π⁻)
p̄ + p → K₁ K₂ π⁺ π⁻
2 X 935 EVENTS
Q = 0
PHASE SPACE
M (K π π)
p̄ + p → K₁ K± π± π°
1555 EVENTS
|Q| = 1
PHASE SPACE
M (K₁ π± π°)
p̄ + p → K₁ K± π± π°
2 X 1555 EVENTS
|Q| = 2
PHASE SPACE
M (K± π± π°)

FIGURE 4-2

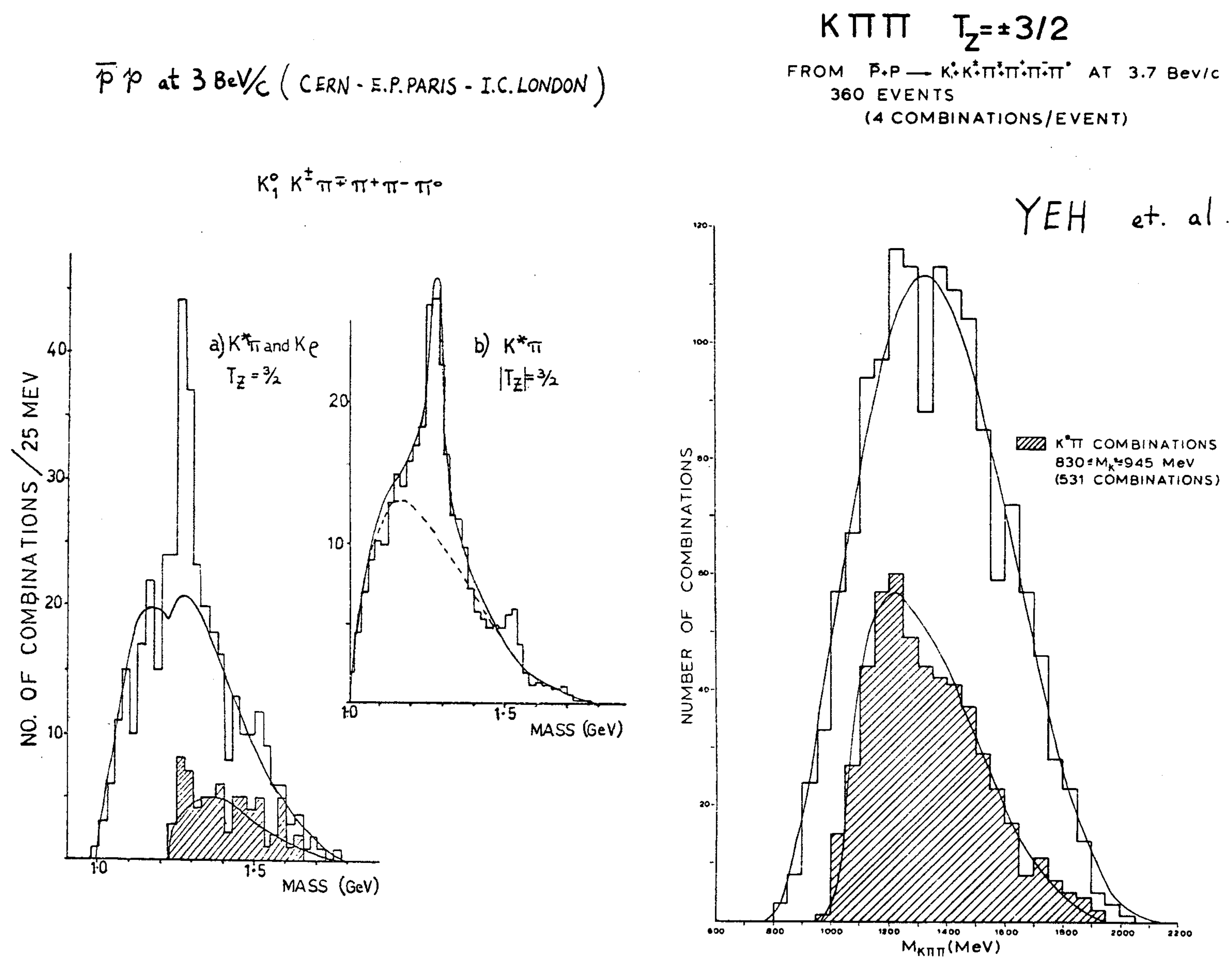
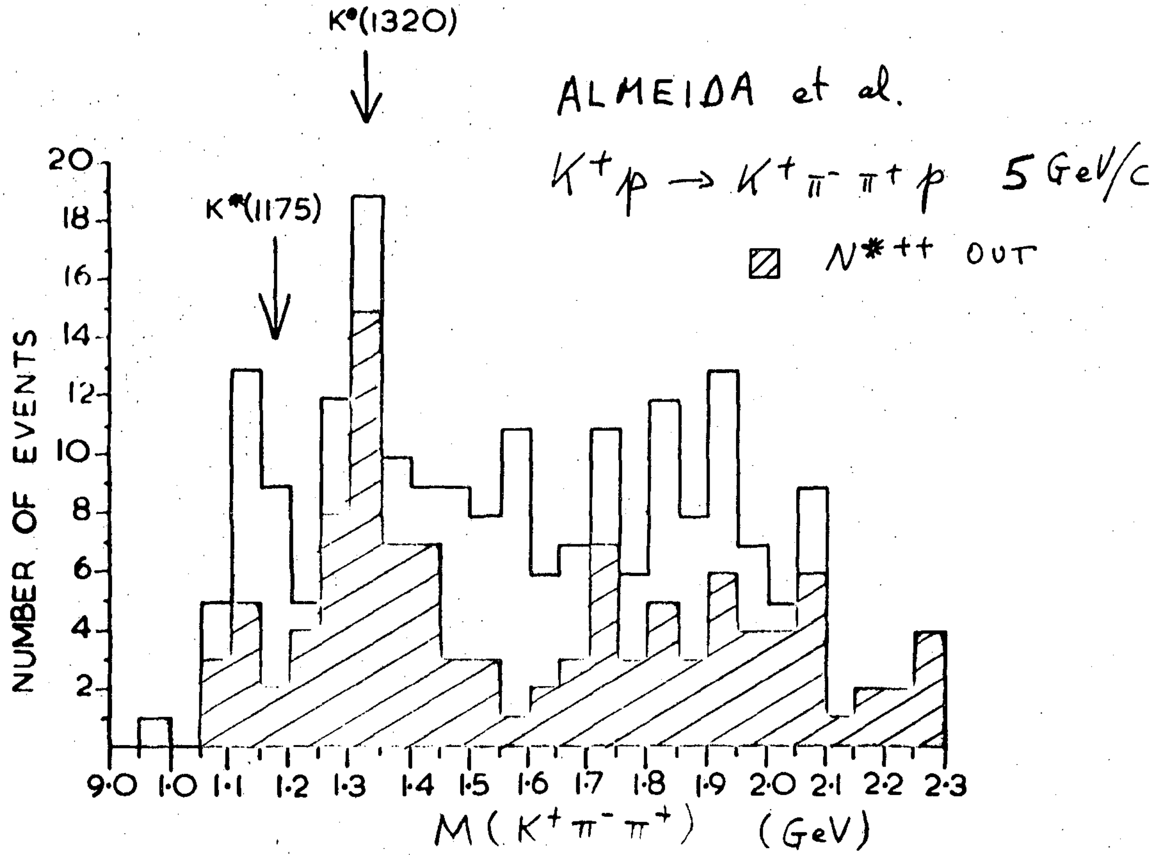

p̄p at 3 BeV/c (CERN - E.P. PARIS - I.C. LONDON)
$K_1^0 K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}\pi^{0}$
a) $K^*\pi$ and $K\rho$
$T_Z = 3/2$
b) $K^*\pi$
$|T_Z| = 3/2$
NO. OF COMBINATIONS / 25 MEV
MASS (GeV)
MASS (GeV)
$K\pi\pi$ $T_Z = \pm 3/2$
FROM $\bar{p}+p \to K^0_1+K^{\pm}+\pi^{\mp}+\pi^{+}+\pi^{-}+\pi^{0}$ AT 3.7 Bev/c
360 EVENTS
(4 COMBINATIONS/EVENT)
YEH et. al.
$K^*\pi$ COMBINATIONS
$830 \le M_{K^*} \le 945$ MeV
(531 COMBINATIONS)
NUMBER OF COMBINATIONS
$M_{K\pi\pi}$ (MeV)

FIGURE 4-3


K*(1320)
ALMEIDA et al.
$K^+p \to K^+\pi^-\pi^+p$ 5 GeV/c
N^{*++} OUT
K*(1175)
NUMBER OF EVENTS
20
18
16
14
12
10
8
6
4
2
9·0 1·0 1·1 1·2 1·3 1·4 1·5 1·6 1·7 1·8 1·9 2·0 2·1 2·2 2·3
$M(K^+\pi^-\pi^+)$ (GeV)

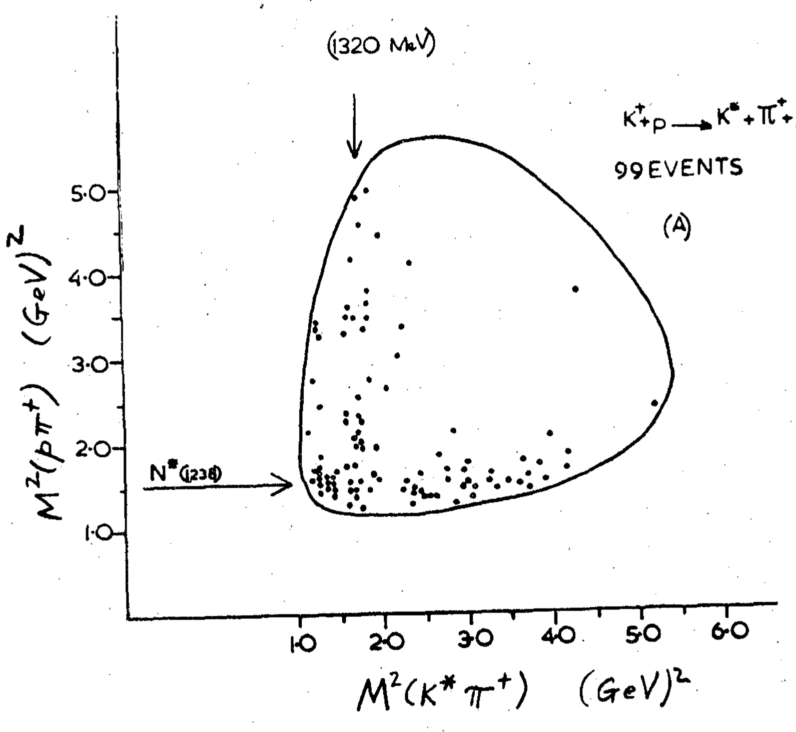

(1320 MeV)
$K^+ + p \to K^* + \pi^+ + p$
99 EVENTS
(A)
$N^*(1238)$
$M^2(p\pi^+)$ $(GeV)^2$
5·0
4·0
3·0
2·0
1·0
1·0 2·0 3·0 4·0 5·0 6·0
$M^2(K^*\pi^+)$ $(GeV)^2$

FIGURE 4-4

5. General Comments on the $K\bar{K}\pi$ System

A number of resonances and enhancements have been observed in the $K\bar{K}\pi$ system. We will first make some general observations on the possible quantum numbers. For I = 0 the $K\bar{K}\pi$ system is best considered in the $K\bar{K}$ center of mass. Here the $K\bar{K}$ system is I = 1, thus since $G(K\bar{K}) = (-1)^{I+\ell}$ we have $G(K\bar{K}) = -(-1)^{\ell}$. Furthermore since $G(\pi) = -1$ we have the result that $G(K\bar{K}\pi) = (-1)^{\ell}$ and thus depends only on the angular momentum in the $K\bar{K}$ system.

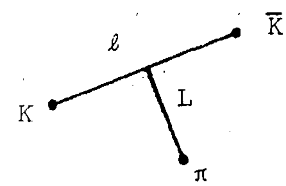
We can summarize and extend these comments in Table 5-1 where ℓ is the angular momentum in the $K\bar{K}$ system and L the angular momentum between π and the $K\bar{K}$ system. Table 5-II gives the possible quantum numbers J^{PG} for various low values of ℓ and L.

TABLE 5-I

Relations between the Quantum Numbers for $K\bar{K}\pi$ with I=0

	π	$K\bar{K}$	$K\bar{K}\pi$
I	1	1	0
G	-1	$-1(-1)^{\ell}$	$(-1)^{\ell}$
P	-1	$(-1)^{\ell}$	$-(-1)^{\ell+L}$
J	0	ℓ	$\lvert\ell-L\rvert \leq J \leq \ell+L$

TABLE 5–II. Possible quantum numbers for resonances in the $(K\bar{K}\pi)^{0}$ system with I=0. Also shown are possible alternate decay modes. The system is analyzed in terms of the $K\bar{K}$ and π breakdown in the $K\bar{K}$ center of mass. Here G = C since I = 0. Only decay via strong interactions is considered here.



$K\bar{K}\pi$ System in $K\bar{K}$ Center of Mass			Some Other Possible Decay Modes			
ℓ^{P}	L^{P}	$J^{PG}(K\bar{K}\pi)$	$J^{PG}(K\bar{K}_{I=0})$	$J^{PG}(\pi\pi)$	$J^{PG}(\pi\pi\pi)$	$J^{PG}(\pi\pi\eta)$
0^{+}	0^{+}	0^{-+}	——	——	——	0^{-+}
0^{+}	1^{-}	1^{++}	——	——	——	1^{++}
1^{-}	0^{+}	1^{+-}	——	——	1^{+-}	——
1^{-}	1^{-}	0^{--}	——	——	0^{--}	——
		1^{--}	$K_1^{0}K_2^{0}$; 1^{--}	——	1^{--}	——
		2^{--}	——	——	2^{--}	——
0^{+}	2^{+}	2^{-+}	——	——	——	2^{-+}
2^{+}	0^{+}	2^{-+}	——	——	——	2^{-+}
1^{-}	2^{+}	1^{+-}	——	——	1^{+-}	——
		2^{+-}	——	——	2^{+-}	——
2^{+}	1^{-}	1^{++}	——	——	——	1^{++}
		2^{++}	$K_1^{0}K_1^{0}$ or $K_2^{0}K_2^{0}$ 2^{++}	2^{++}	——	2^{++}

6. The D Meson, A $K\bar{K}\pi$ Enhancement at 1285 MeV

Miller et al.[1] have observed an enhancement in the $K\bar{K}\pi$ system in the reactions

$$\pi^- + p \longrightarrow K^+ + \bar{K}^0 + \pi^- + n$$

$$\pi^- + p \longrightarrow K^0 + K^- + \pi^+ + n$$

at incident momenta 2.7 – 4.2 BeV/c. They call the new state D meson. The properties observed are:

$$E_D = 1280 \pm 10 \text{ MeV}$$

$$\Gamma_D = 40 \pm 10 \text{ MeV}$$

The observed peak occurs only in the neutral $K\bar{K}\pi$ system from which they deduce the isotopic spin to be $I_D = 0$. In Fig. 6–1 the $(K\bar{K}\pi)^0$ mass distribution is shown. A peak at 1280 corresponding to the D meson as well as a peak at 1420 corresponding to the E meson can be seen. Also shown is the singly charged $(K\bar{K}\pi)^-$ which is produced in the same experiment in the reactions

$$\pi^- + p \longrightarrow K^0 + \bar{K}^0 + \pi^- + p$$

$$\pi^- + p \longrightarrow K^0 + K^- + \pi^0 + p$$

As may be noted neither the D nor the E meson appear in the singly charged mode. In Fig. 6–2 are shown the distributions in $\cos\theta$ where θ is defined in the $K\bar{K}$ rest frame as shown in the figure. Also shown is the $K\bar{K}$ mass distribution. The angular distribution is nearly isotropic except for possible distortions due to the tail of the K^* resonance. One may thus conclude that either ℓ or L are zero giving the possible J^{PG} values 0^{-+}, 1^{++}, or 2^{-+}. From the $K\bar{K}$ mass distribution Miller et al. conclude that the quantum numbers of the D meson can be either $IJ^{PG} = 01^{++}$ or 02^{-+}. (Note Added in Proof) A similar observation has recently been reported by C. D'Andlau et al.[6-2] confirming the existence of the D meson.

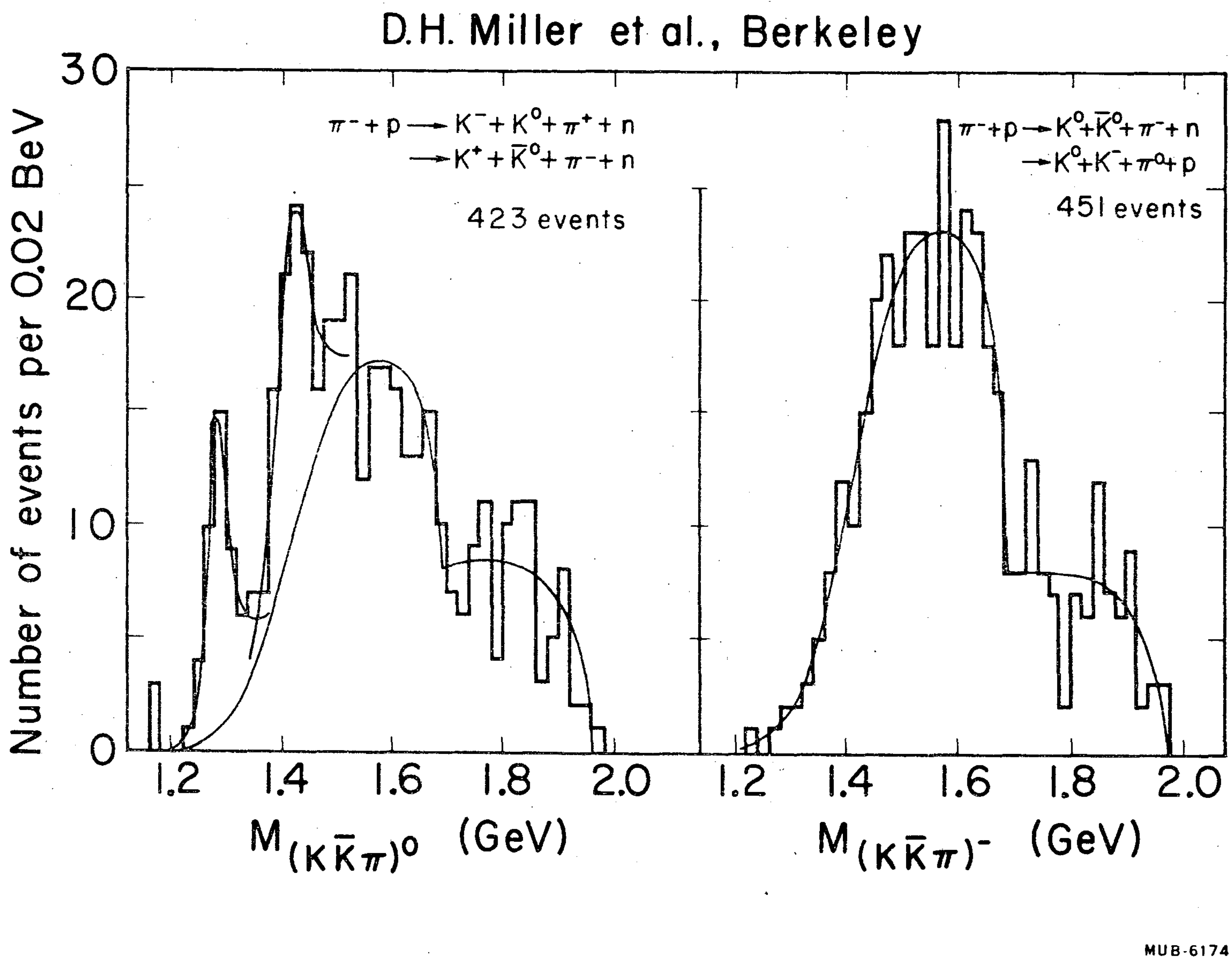
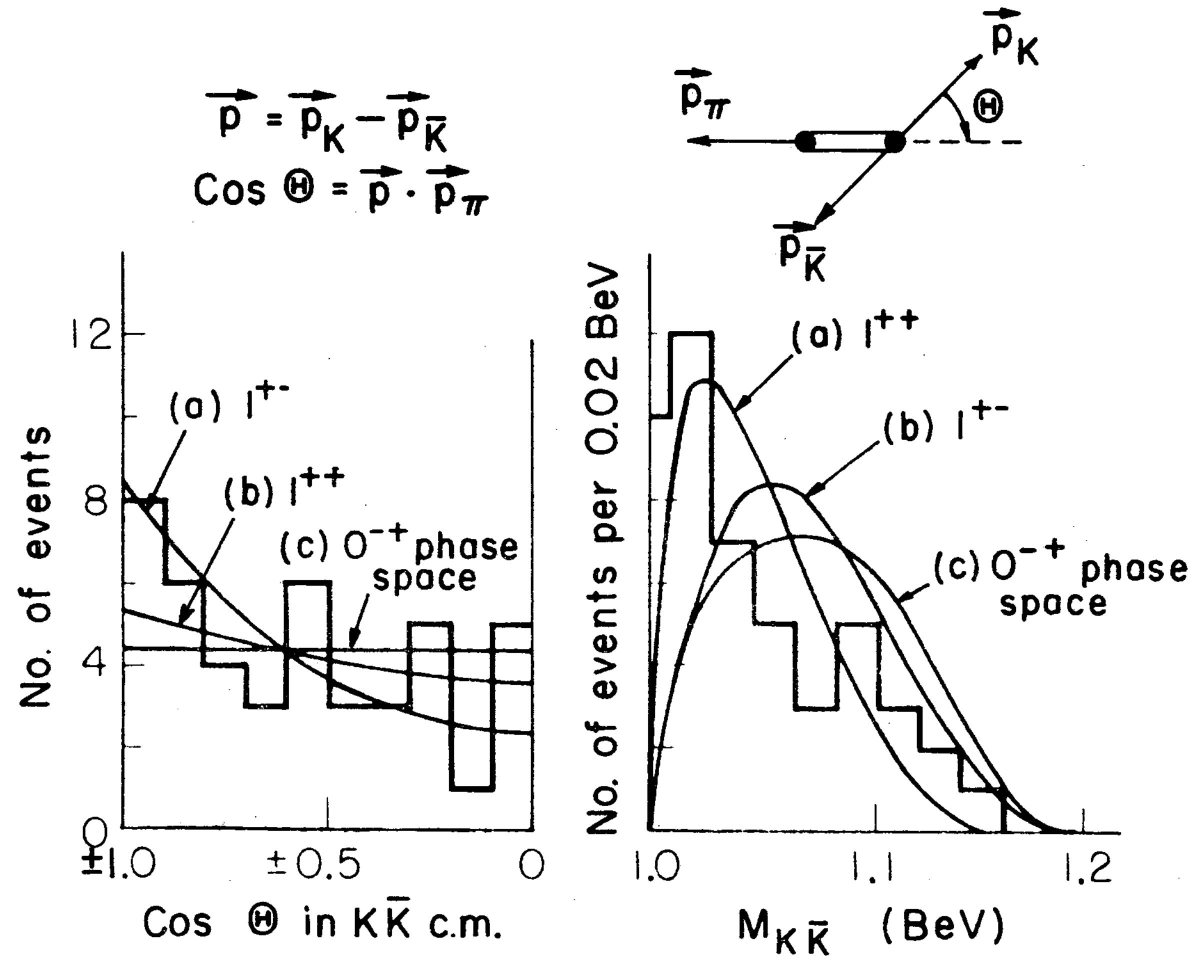

D.H. Miller et al., Berkeley
Number of events per 0.02 BeV
$\pi^- + p \rightarrow K^- + K^0 + \pi^+ + n$
$\rightarrow K^+ + \bar{K}^0 + \pi^- + n$
423 events
$\pi^- + p \rightarrow K^0 + \bar{K}^0 + \pi^- + n$
$\rightarrow K^0 + K^- + \pi^0 + p$
451 events
$M_{(K\bar{K}\pi)^0}$ (GeV)
$M_{(K\bar{K}\pi)^-}$ (GeV)
MUB-6174

FIGURE 6-1

D.H. Miller et al.



For curves (a) and (b) the effect of the tail of the $K\pi$ (890) resonance has been included

MUB-6178

FIGURE 6-2

7. The E Meson

In the annihilation of $\bar{p}p$ at rest Armentéros et al.[1] investigated the reaction

$$\bar{p}p \longrightarrow K + \bar{K} + \pi + \pi + \pi$$

They observe a distinct enhancement in the neutral $(K\bar{K}\pi)^0$ system which they call the E meson with the characteristics

$$E_E = 1415 \pm 15 \text{ MeV}$$

$$\Gamma_E = 70 \pm 15 \text{ MeV}$$

the channels studied are

$$\text{(a)} \quad \bar{p}p \longrightarrow (K_1^0 K^{\pm} \pi^{\mp})\, \pi^+ \pi^-$$

$$\text{(b)} \quad \bar{p}p \longrightarrow (K_1^0 K^{\pm} \pi^{\mp})\, \pi^0 \pi^0$$

$$\text{(c)} \quad \bar{p}p \longrightarrow K_1^0 K_1^0 \pi^0 \pi^+ \pi^-$$

$$\text{(d)} \quad \bar{p}p \longrightarrow K_1^0 K_2^0 \pi^0 \pi^+ \pi^-$$

The effect is observed strongly in reaction (a) (see Fig. 7-1) and is also evident, though weaker, in reaction (b). Reaction (c) proceeds predominantly via ω production and there is no evidence for an enhancement in $K_1 K_1 \pi^0$ mass distribution. Little evidence is available for the production of channel (d). There is no evidence for an enhancement of $K\bar{K}\pi$ in the charge states Q = 1 or Q = 2. The authors conclude that $I_E = 0$. Miller et al.[6-1] (see Fig. 6-1) confirm the observation of the E meson and this conclusion. The principal decay mode of the E meson is

$$E \longrightarrow \bar{K}^* + K$$

$$\longrightarrow K^* + \bar{K}$$

which can be noted in the Dalitz plot in Fig. 7-2. Frequently both the $\bar{K}\pi$ and $K\pi$ lie in the K^* band. This phenomenon constitutes either the cause or the effect of an enhancement in the $K\bar{K}$ system at a mass band 1000-1050

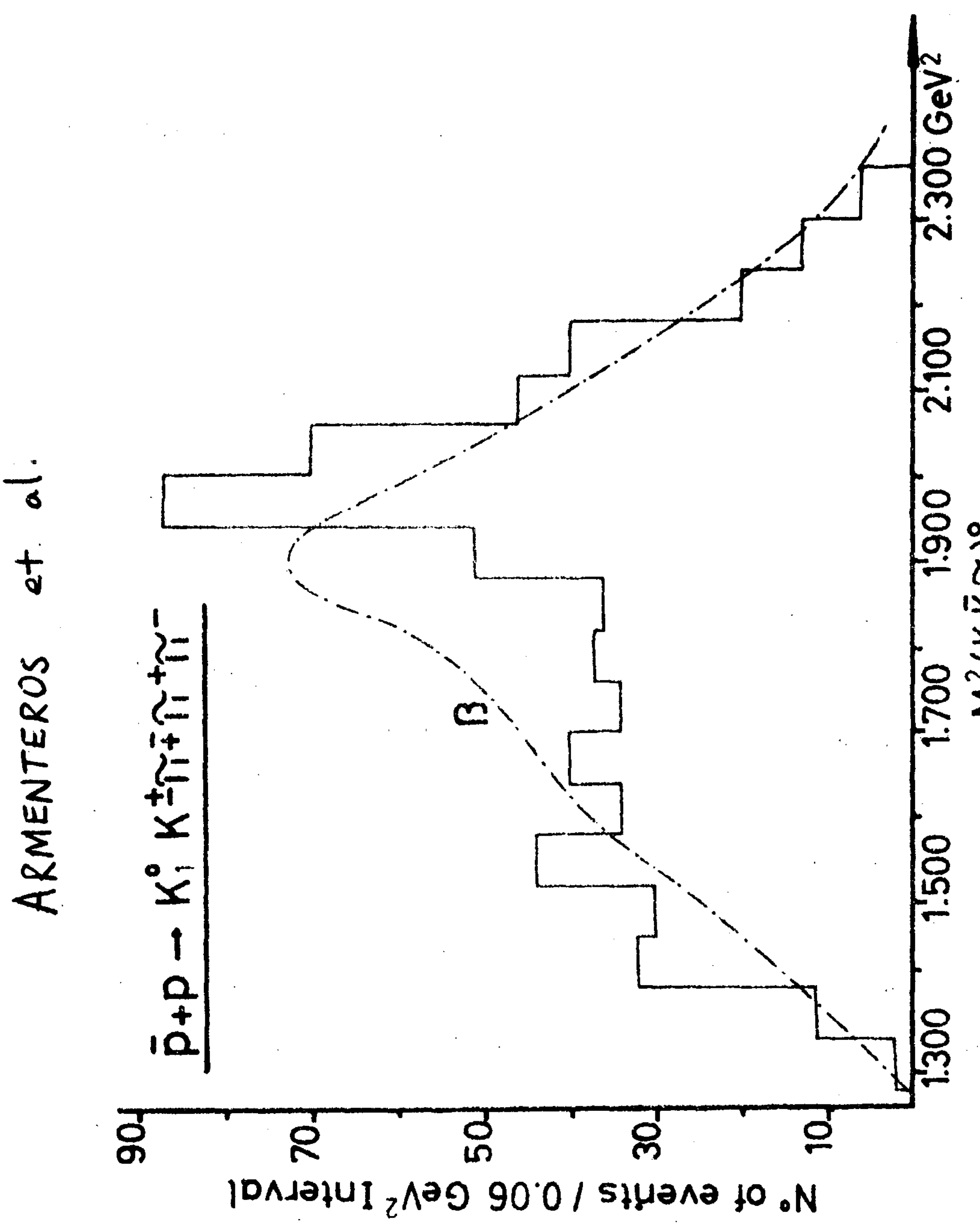

ARMENTEROS et al.
$\bar{p}+p \rightarrow K^{\circ}_{1}\ K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
B
N° of events / 0.06 GeV² Interval
90
70
50
30
10
1.300
1.500
1.700
1.900
2.100
2.300 GeV²
M²(K K̄ π)°

FIGURE 7-1

ARMENTEROS et. al.

$\bar{p}+p \rightarrow K_1^0 K^\pm \pi^\mp \pi^+ \pi^-$

$1.370 < M(K_1^0 K^\pm \pi^\mp) < 1.450$ GeV

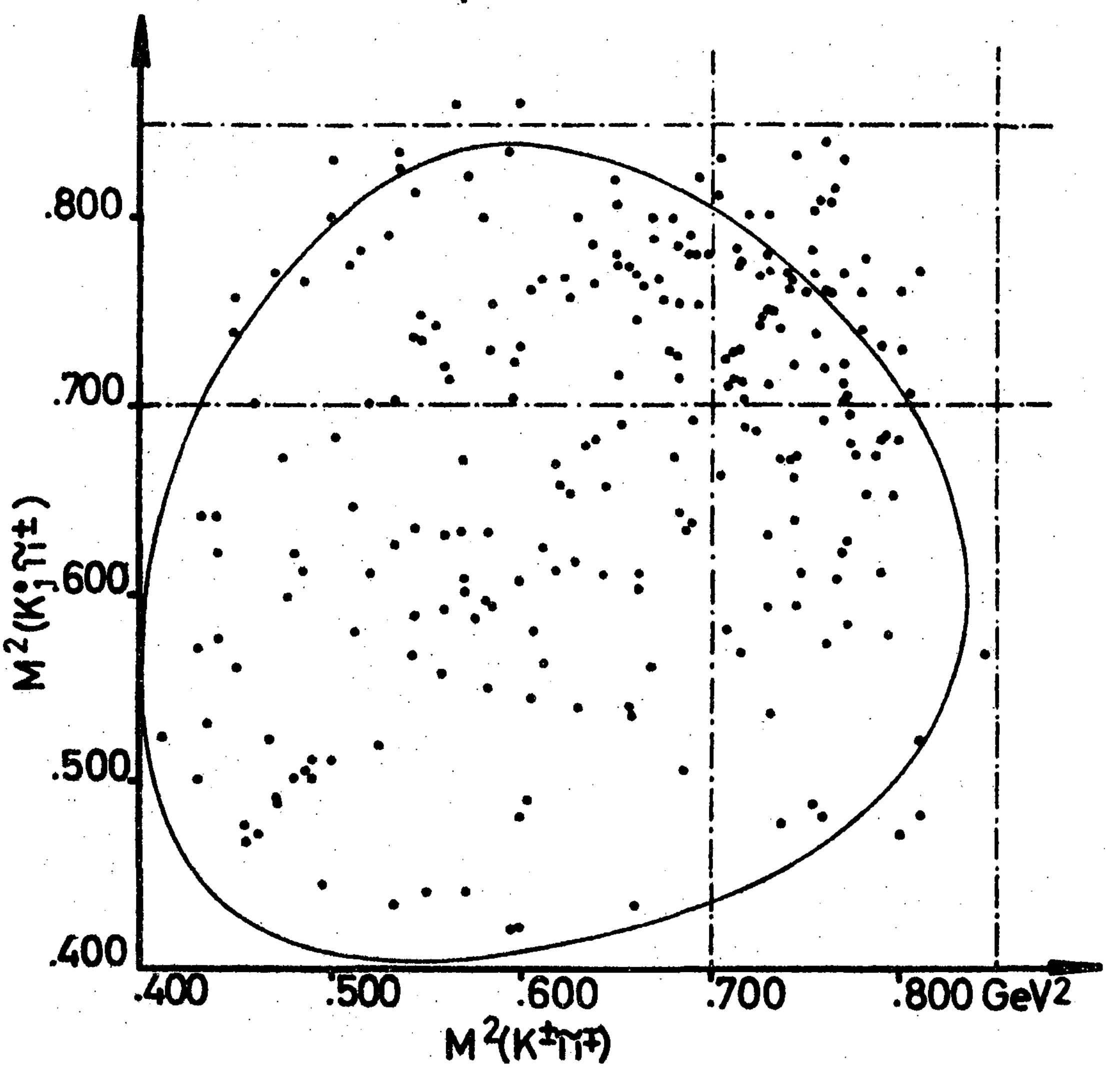


FIGURE 7-2

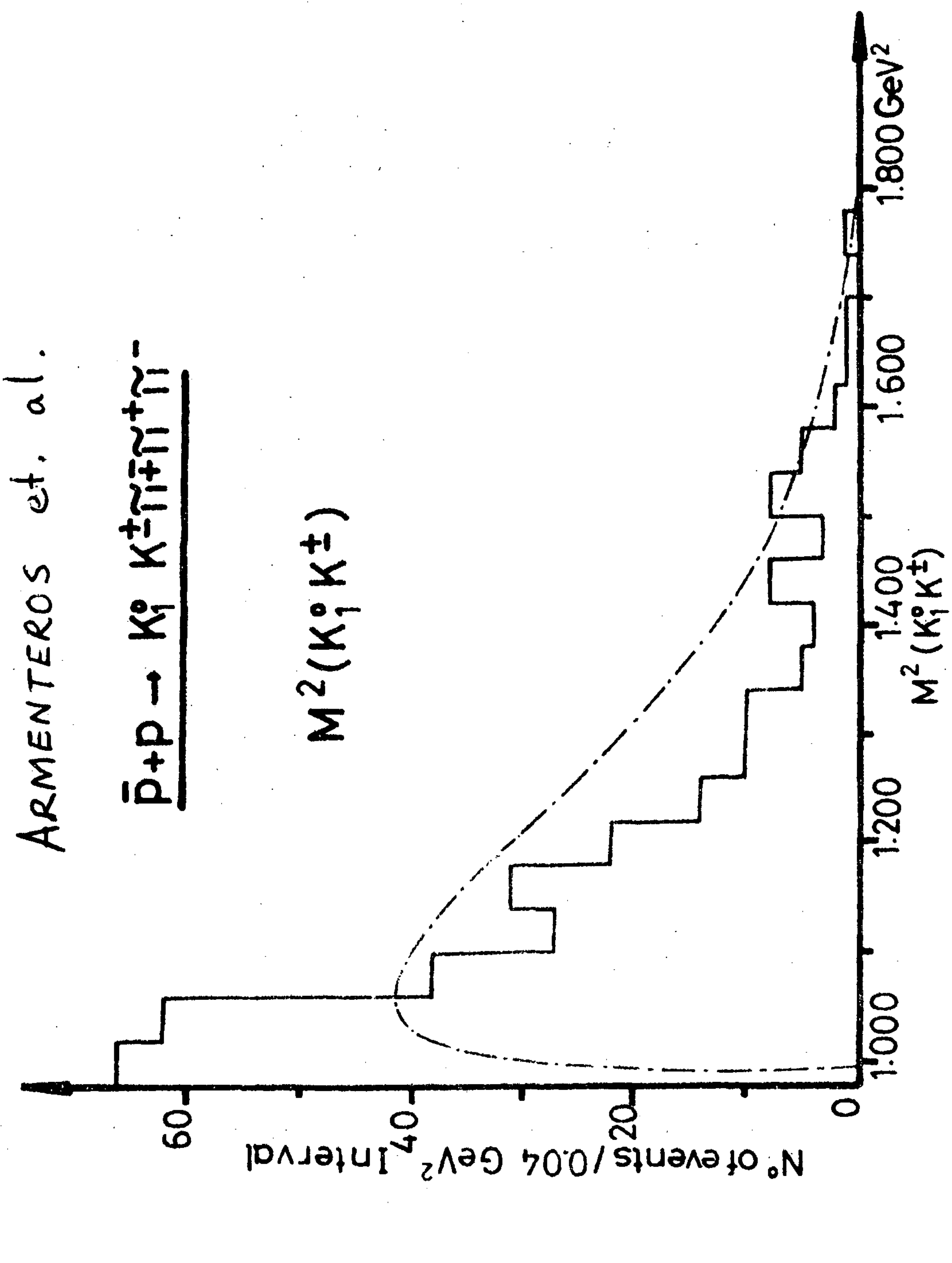
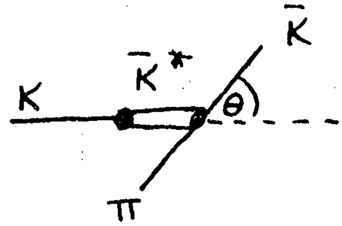

ARMENTEROS et. al.
$\bar{p}+p \rightarrow K_1^0 K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
$M^2(K_1^0K^{\pm})$
N° of events / 0.04 GeV² Interval
0
20
40
60
1.000
1.200
1.400
1.600
1.800 GeV²
$M^2(K_1^0K^{\pm})$

FIGURE 7-3

MeV (see Fig. 7-3). Considering E as a $K^* K$ system the authors have examined the angular distribution of the K^* in its rest system with respect to its line of flight in the E center of mass.



They find this distribution to be consistent with isotropy. This eliminates 0^- assignment for the E since the latter would require spin alignment for the K^*. From the observed branching ratio

$$\frac{E^0 \pi^0 \pi^0}{E^0 \pi^+ \pi^-} \sim 0.6$$

they conclude that the reaction proceeds most likely in an I = 0 state. On the assumption that $\bar{p}p$ annihilation proceeds from $^1S_0$ (J = 0, P = -1, C = +1) or $^3S_1$ (J = 1, P = -1, C = -1) they favor the spin and parity 1^- for E meson although they cannot rule out 1^+ or 2^-.

8. Evidence for a $K\bar{K}\pi$ (1510)

London et al.,[1] have presented preliminary data at the 1965 Washington meeting. They reported that in the reactions

$$K^- + p \longrightarrow \Lambda K\bar{K}\pi$$
$$K^- + p \longrightarrow \Lambda K^o \bar{K}^o$$

at 4.6–5 BeV/c they observed an enhancement in the $K\bar{K}\pi$ as well as $K\bar{K}$ systems at ~ 1500 MeV. Fig. 8–1 shows the enhancement in the $K\bar{K}\pi$ system. Fig. 8–1a shows that the $K\bar{K}\pi$ system is produced peripherally. The mass projection is shown in Fig. 8–1b. The mass distribution for events produced with backward Λ hyperons is shown in Fig. 8–1c.

The results of the study of the $K^o \bar{K}^o$ system is illustrated in Fig. 8–2. In part (a) the Dalitz plot shows the ϕ meson very clearly for the events consistent with the $K_1^o K_2^o$ system while events for the $K_1^o K_1^o$ system show a small peak at ~ 1500 MeV as may be seen in the mass projection. (Fig. 8–2b)

If these two phenomema indeed represent decay modes of the same state the J^{PG} value is uniquely determined and must be 2^{++} as may be seen from Table 5–2.

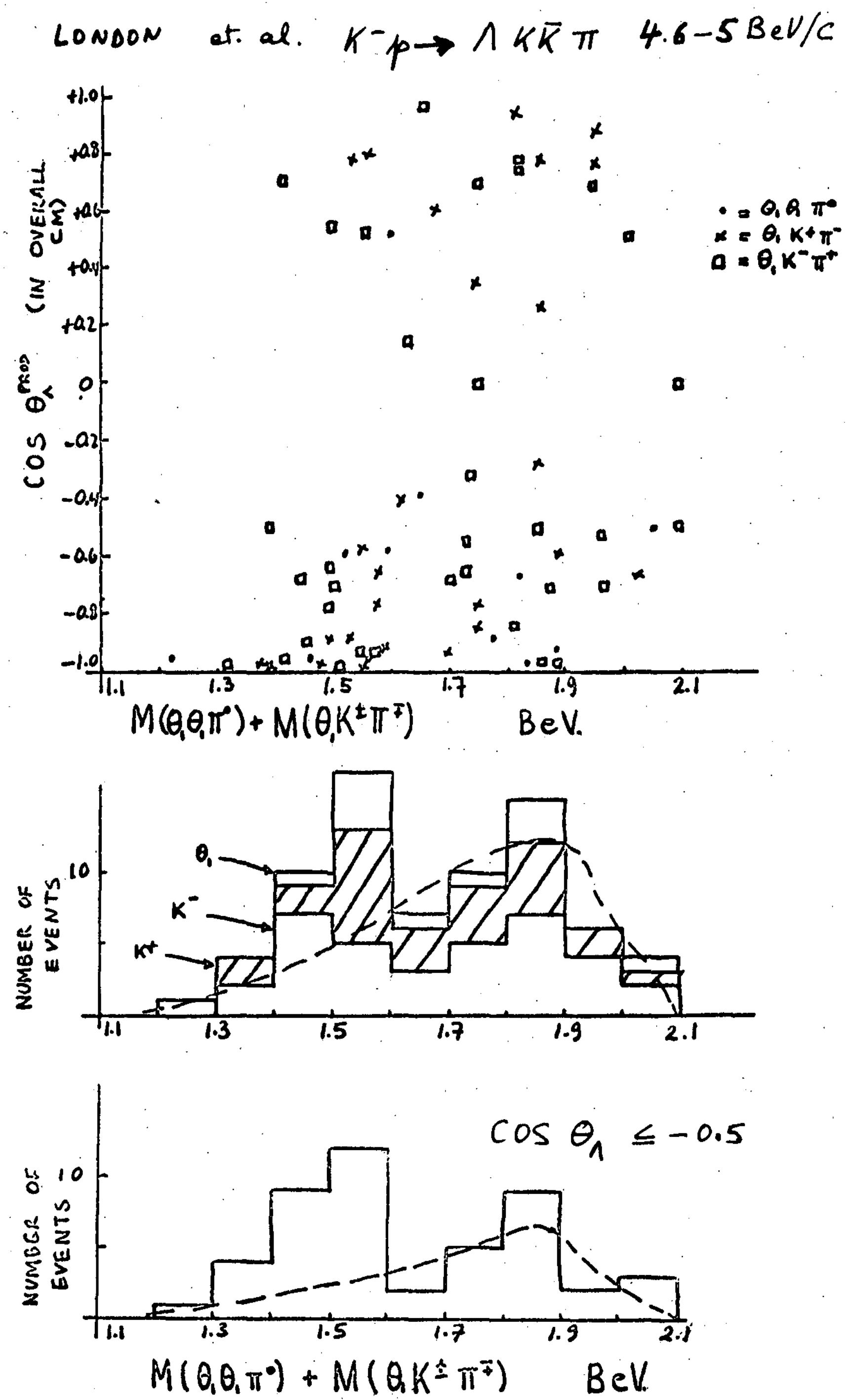
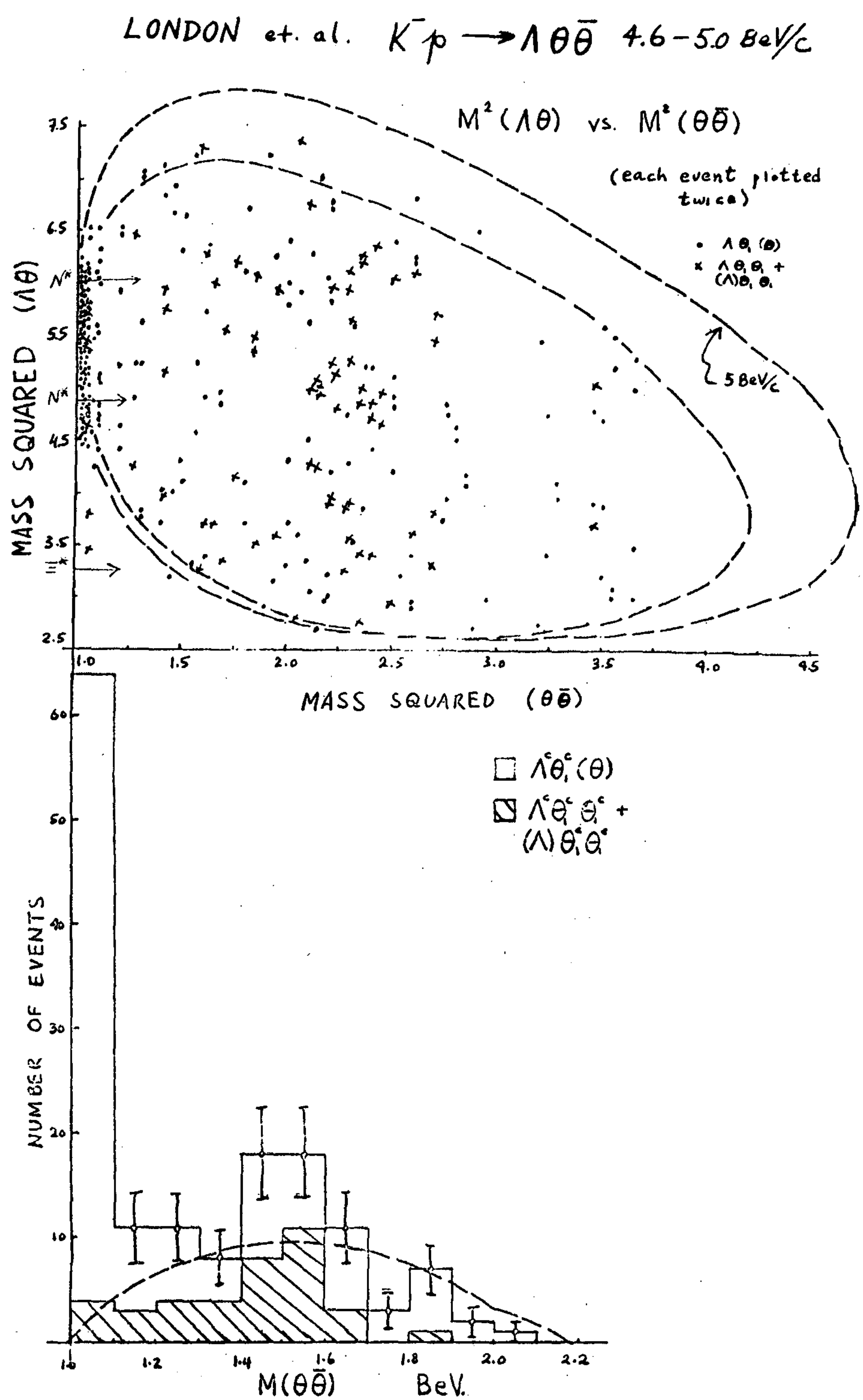

LONDON et. al. K⁻p → Λ K K̄ π 4.6-5 BeV/c
COS θ_Λ^PROD (IN OVERALL CM)
• = θ, θ, π°
× = θ, K⁺π⁻
□ = θ, K⁻π⁺
M(θ,θ,π°) + M(θ,K±π∓) BeV.
NUMBER OF EVENTS
θ,
K⁻
K⁺
COS θ_Λ ≤ -0.5
M(θ,θ,π°) + M(θ,K±π∓) BeV

FIGURE 8-1



LONDON et. al. K⁻p ⟶ Λθθ̄ 4.6–5.0 BeV/c
M²(Λθ) vs. M²(θθ̄)
(each event plotted twice)
5 BeV/c
MASS SQUARED (Λθ)
MASS SQUARED (θθ̄)
N*
N*
Ξ*
NUMBER OF EVENTS
M(θθ̄) BeV.

FIGURE 8-2

9. Evidence for a new 2π Resonance at 700 MeV

Feldman et al.,[1] in a collaborative experiment between the University of Pennsylvania and Columbia University at the A. G. S. in Brookhaven report evidence for a resonance $S^o \longrightarrow \pi^o \pi^o$ with

$$E_{S^o} \approx 700 \text{ MeV}.$$

The experiment was carried out with a 1.52 BeV/c π^- beam incident on a hydrogen target, partially surrounded by anti-coincidence counters.

The reaction investigated was

$$\pi^- p \longrightarrow n + \text{neutrals}.$$

The method used consisted of a neutron time of flight measurement at a fixed angle in the laboratory. This determined the neutron recoil momentum vector and allows a unique mass determination of the neutral meson system produced in the reaction.

In Fig. 9-1a the neutron time of flight distribution is presented. This shows a peak at 780 MeV presumably corresponding to the neutral decay of the ω^o as well as a pronounced peak corresponding to a mass at 700 MeV. The experiment furthermore utilized a series of spark chambers to observe the decay products associated with the peak in the neutron time of flight. The experimentors find a significant peak in 4γ production at a neutron time of flight corresponding to the 700 MeV peak. These presumably come from the decay of two π^o mesons. They conclude that they have found a new two pion resonance and suggest as the simplest quantum numbers

$$S^o \; (I, J^{PG}) = (0, 0^{++}).$$

Such a resonance could of course be the culprit responsible for the mysterious behavior of the asymmetry in the ρ^o decay.

FELDMAN et. al. $\pi^- + p \rightarrow n + neutrals$

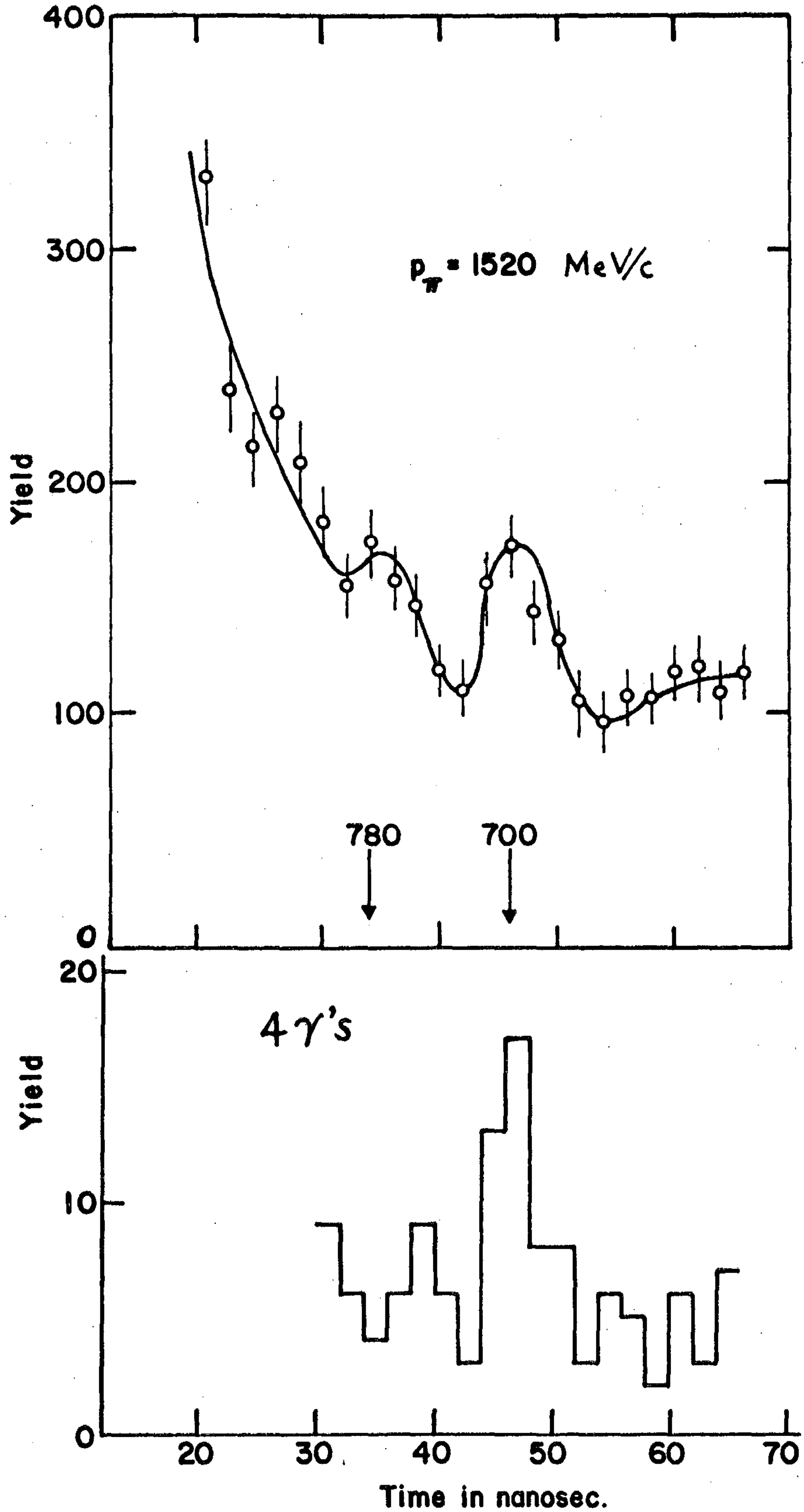


FIGURE 9-1

10. The M_1 Meson or KK Enhancement at 1280 MeV with S = +2

Ferro Luzzi et al.[1] have presented further evidence on a strangeness +2 Meson. By combining their data on K^+p interactions at 3, 3.5 and 5 GeV/c respectively, they observe a definite mass enhancement in the mass spectrum of the positive strangeness KK mesons, which they call the M_1 meson.

The reactions investigated are

$$K^+p \longrightarrow K^+ K^+ \Lambda$$
$$K^+ K^+ \Sigma^o$$
$$K^+ K^o \Sigma^+$$
$$K^+p \longrightarrow K^+ K^+ \Lambda\pi^o$$

The central mass and width of the resonance is

$$M_{M_1} = (1280 \pm 20) \text{ MeV}$$
$$\Gamma_{M_1} = (110 \pm 40) \text{ MeV.}$$

From the observation of the decay of the resonance

$$M_1 \longrightarrow K^+ K^+$$
$$\longrightarrow K^+ K^o$$

the isotopic spin and parity can be deduced as well as the permitted spin choices, i.e.,

$$IJ^P (M_1) = 1,0^+ \text{ or } 1,2^+$$

The limited statistics does not permit the authors to give a definite spin assignment for the M_1 meson although at present J = 0 seems to be preferred. The resonance is produced peripherally, i.e., with momentum transfers $\Delta^2_{KK} < 1(\text{GeV/c})^2$ indicating that single particle exchange plays a dominant role in the production mechanism. Fig. 10-1 gives the results for the three body final state. The shaded area represent the events with $\Delta^2_{KK} < 1(\text{GeV/c})^2$. We should note here that in the framework of SU_3 a strangeness S = + 2 meson has to be a member of a 27 multiplet.

FERRO-LUZZI ET AL CERN
K^+P INTERACTIONS 3-5 GeV/c

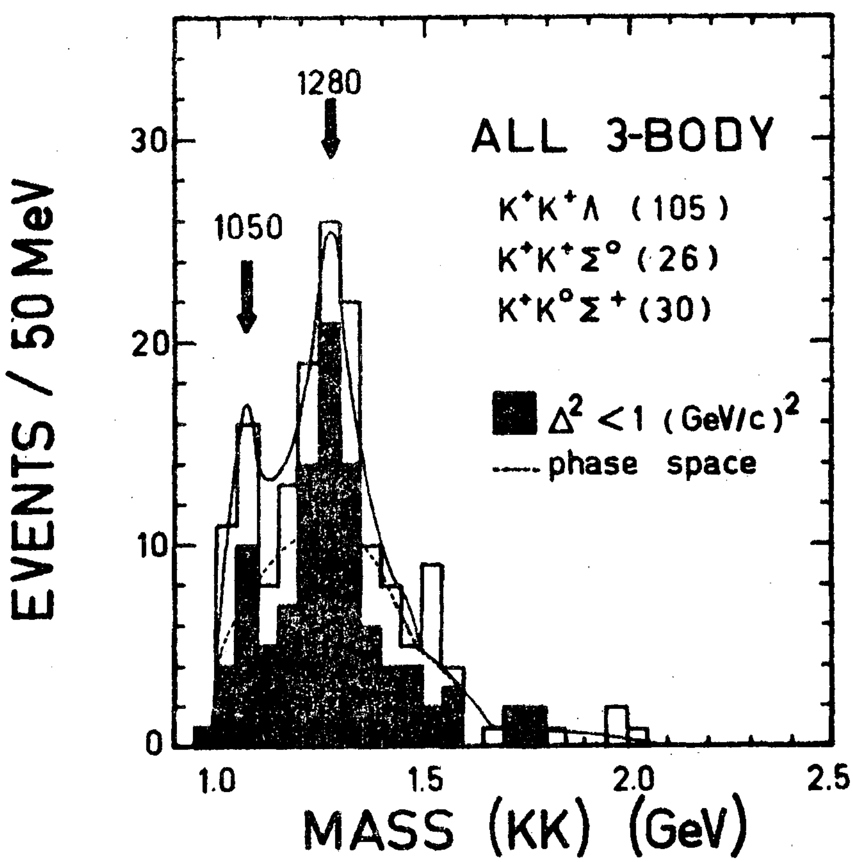


Fig. 10-1

11. Decay Modes of the ω Meson

Flatté et al.[1] at the Lawrence Radiation Laboratory have studied 4600 ω decays in the reaction

$$K^- p \longrightarrow \Lambda + \pi^+ + \pi^- + \pi^0 \quad (1)$$

$$\longrightarrow \Lambda + \pi^+ + \pi^- \quad (2)$$

$$\longrightarrow \Lambda + \text{neutrals} \quad (3)$$

They have found the branching ratios shown in Table 10-1.

Table 10-1. Decay Modes of the ω

(a)	$\Gamma(\omega \longrightarrow \text{neutral})/\Gamma(\omega \longrightarrow \pi^+\pi^-\pi^0)$	=	$(9.7 \pm 1.6) \times 10^{-2}$
(b)	$\Gamma(\omega \longrightarrow \eta + \text{neut})/\Gamma(\omega \longrightarrow \pi^+\pi^-\pi^0)$	≤	1.7×10^{-2}
(c)	$\Gamma(\omega \longrightarrow \pi^+\pi^-\gamma)/\Gamma(\omega \longrightarrow \pi^+\pi^-\pi^0)$	≤	0.1
(d)	$\Gamma(\omega \longrightarrow \pi^+\pi^-)/\Gamma(\omega \longrightarrow \pi^+\pi^-\pi^0)$	=	$(0.17 \pm 0.03)^2 = 2.9 \times 10^{-2}$

Of particular interest is the radial density distribution in the Dalitz plot (see Fig. 10-1). Here the experimental distribution is compared with curves calculated for 1^- and 3^- matrix elements. We note that $J^P = 3^-$ can be ruled out for the ω.

Furthermore, in the study of events corresponding to reaction (2), from which the Y^* events have been eliminated, they observe evidence which may represent the two pion decay of the ω (see Fig. 10-2). The exact branching ratio depends the analysis of the ρ-$\omega(\longrightarrow 2\pi)$ interference. This in turn depends on the magnitude and phase of the two superimposed amplitudes for $\rho \longrightarrow \pi^+ + \pi^-$ and $\omega \longrightarrow \pi^+ + \pi^-$.

The authors point out that one cannot rule out the possibility that the observed two pion peak could be an effect independent of the ω located at E = 775 MeV with a width of 30 MeV.

Flatté et. al.

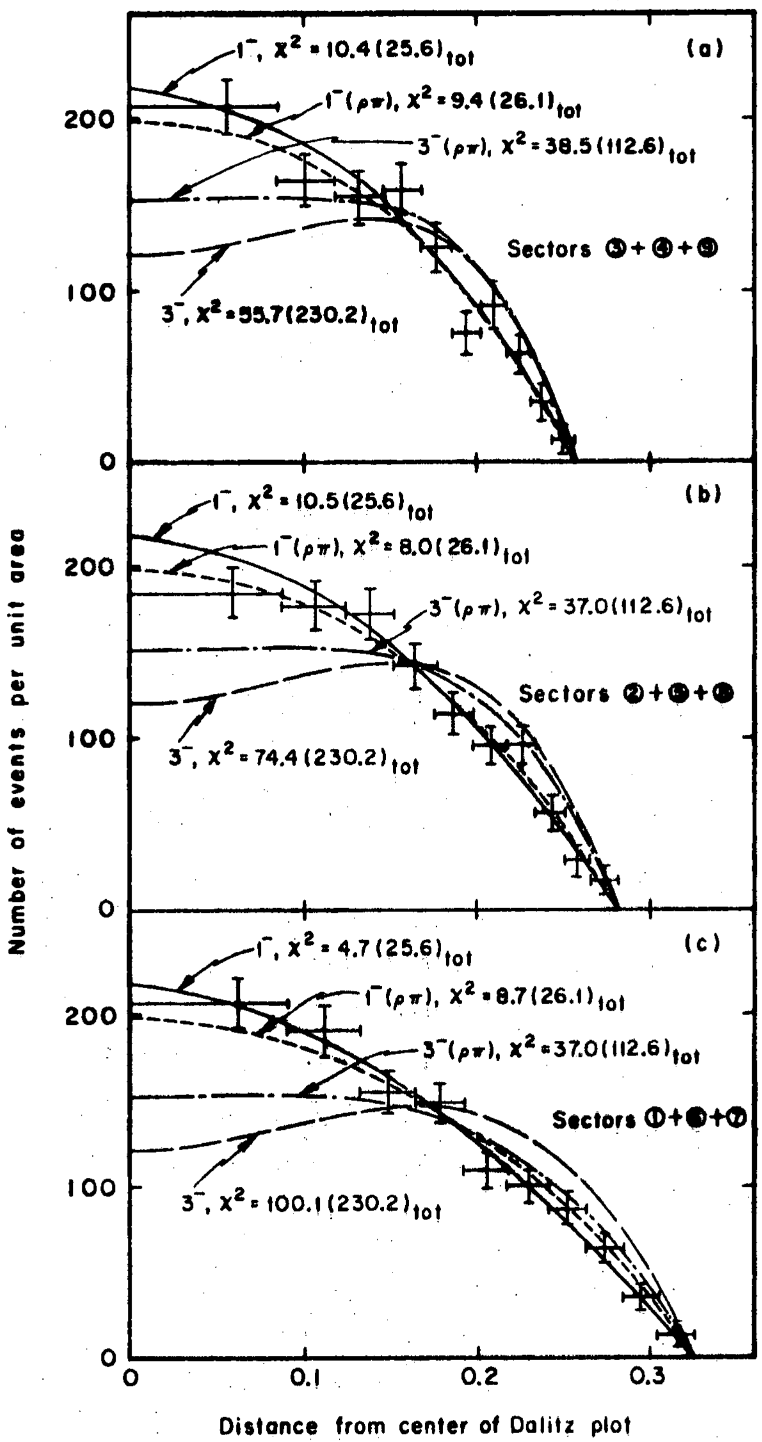


FIGURE 11-1

Flatté et. al.

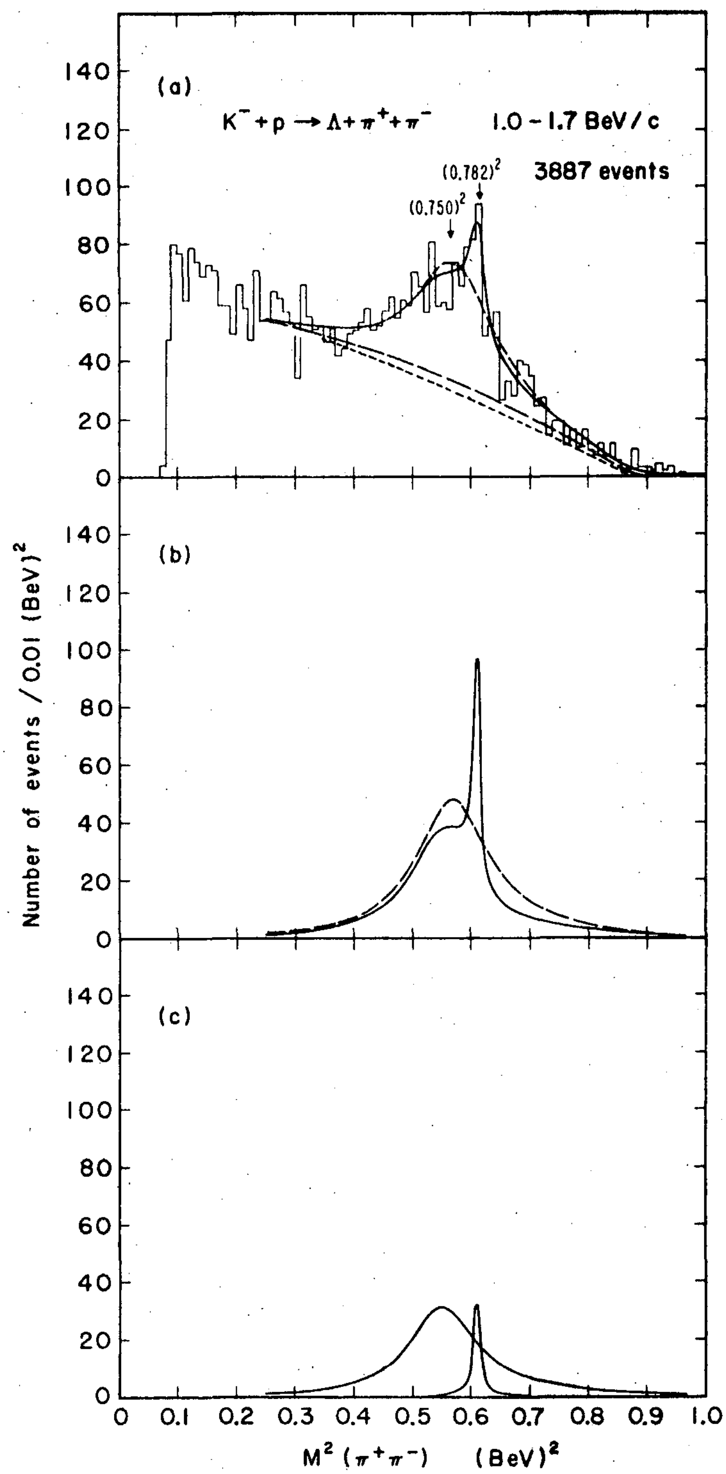


FIGURE II-2

MUB-5822

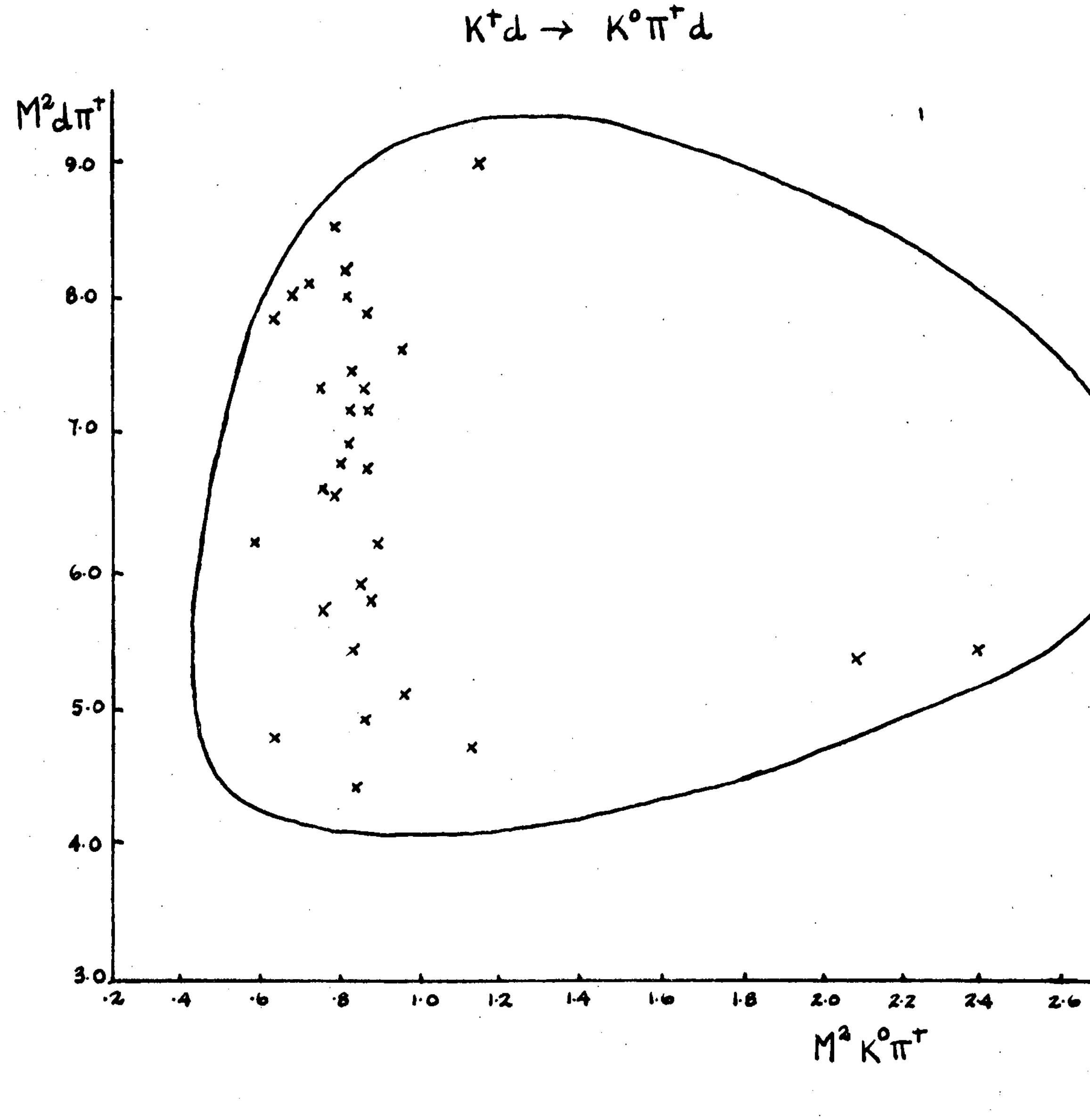
12. The Reactions $K^+d \longrightarrow K^*d$ and $K^+d \longrightarrow K^*\pi d$

In the analysis of the K^+d experiment at 2.3 BeV/c, which I discussed at the Dubna Meeting[1], we have found a new and interesting phenomenon. We find that in about 3% of the events leading to three or four particles in the final state the K^+ meson interacts with the deuteron as a whole.

i.e., (1) $K^+ + d \longrightarrow K^o + \pi^+ + d$

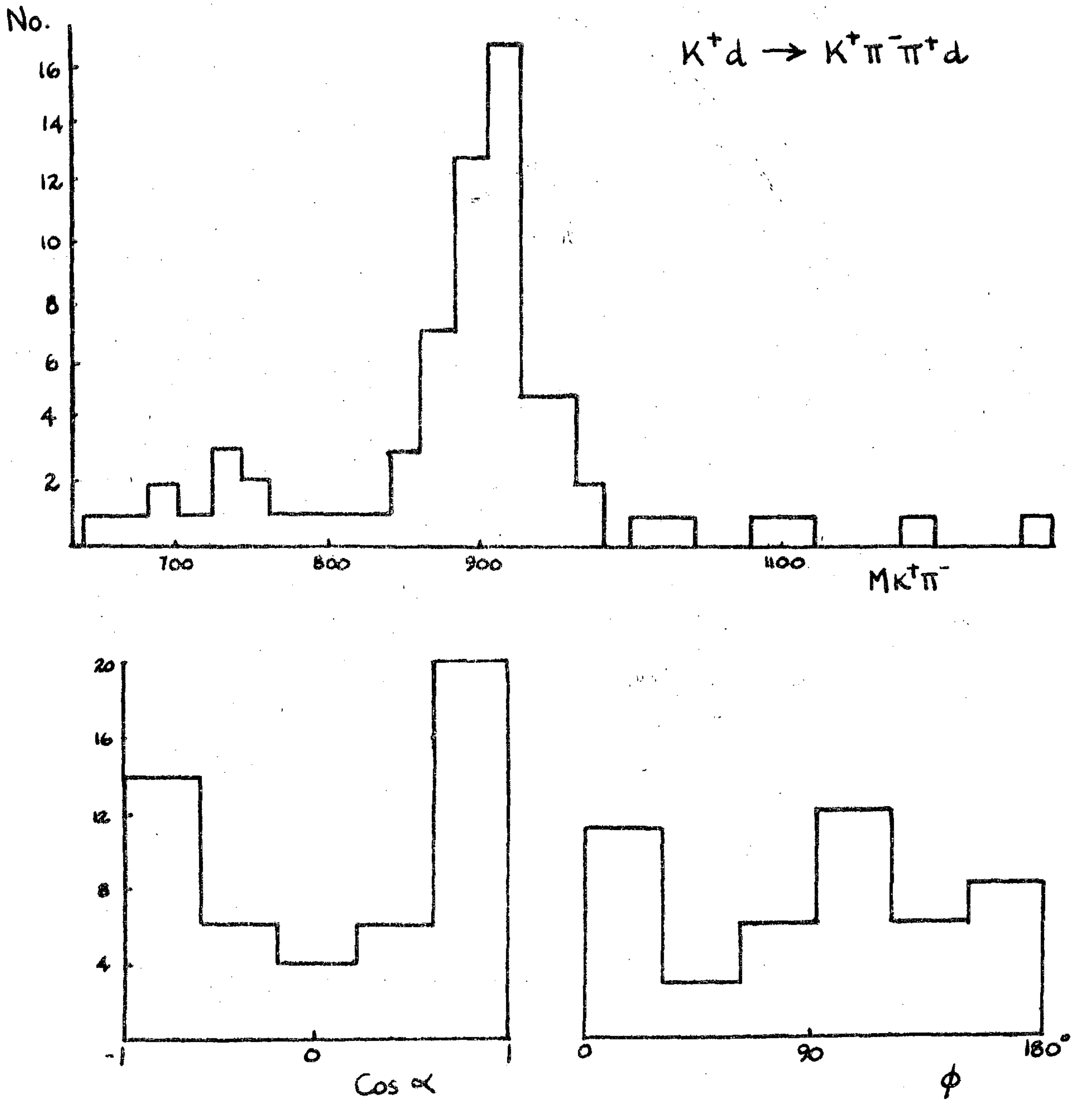
(2) $K^+ + d \longrightarrow K^+ + \pi^- + \pi^+ + d$

It is clear that such interactions can only occur for small momentum transfer to the deuteron. For large momentum transfer the deuteron would break-up. The interesting feature is that reactions (1) and (2) proceed actually via K^* production leading to final states $K^{*+}d$ and $K^{*o}\,\pi^+\,d$ respectively. Fig. 12-1 shows the Dalitz plot for reaction (1) where we plot the square of the $(K^o\,\pi^+)$ mass on the x axis and that of the $(d\pi^+)$ mass on the y axis. As can be noted almost all events lie within the K^* mass band. The $K^+\,\pi^-$ mass distribution for reaction (2) is shown in Fig. 12-2. Again we note that the majority of events lie in the K^* mass band. If we now examine the Dalitz plot for reaction (2) where the three participating particles are $K^{*o}\,\pi^+\,d$ we note a strong enhancement in the $K^*\pi$ system in the mass region centered around 1180 MeV. (See Fig. 12-3). We maintain however, that this mass enhancement is most likely due to a kinematical constraint imposed on the reaction (a) by the small momentum transfer to the deuteron and (b) by the presence of the K^* resonance. By examining the Chew Low plot of this reaction, where we plot the square of the $K^*\pi$ mass versus the square of the momentum transfer $(\Delta^2_{K^*\pi})$ we note that all events are bunched at low $K^*\pi$ masses. This phenomenom has a simple explanation. The deuteron acts as a momentum transfer filter by virtue of its weak binding which in turn restricts the $K^*\pi$ system to low masses. We deduce from these observations that we are here most probably dealing with a kinematic bump.



MUB-6036

FIGURE 12-1



MUB-6037

FIGURE 12-2

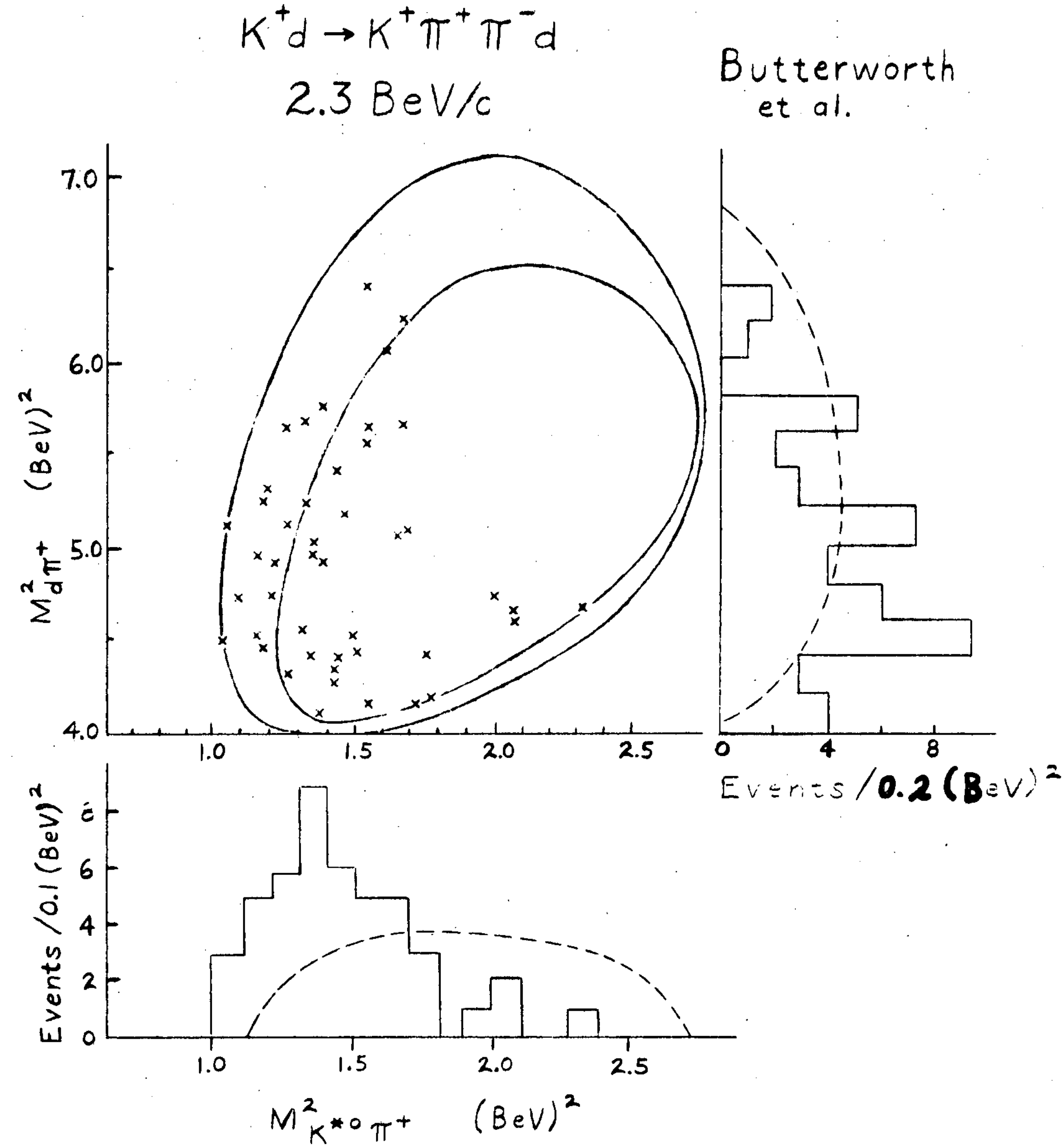

K⁺d → K⁺π⁺π⁻d
2.3 BeV/c
Butterworth et al.
7.0
6.0
5.0
4.0
M²dπ⁺ (BeV)²
1.0
1.5
2.0
2.5
0
4
8
Events /0.2 (BeV)²
Events /0.1 (BeV)²
6
4
2
0
M²K*⁰π⁺ (BeV)²

Fig. 12-3

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