TO BE SUBMITTED
TO NUOVO CIMENTO

CERN/TC/PHYSICS 66-24
10.10.1966.

FURTHER STUDY OF THE E-MESON IN ANTIPROTON-PROTON ANNIHILATIONS AT REST

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1. Several experimental results on the neutral $(K\bar{K}\pi)$ system have shown evidence for an enhancement at M $\sim$ 1420 MeV, called the E-meson when interpreted as a resonance (Ref. 1, 2, 3, 4).

In this paper, we present the results of the analysis of 1.4×10^6 $\bar{p}p$ annihilations at rest (they include the data presented in Ref. 2 which represents roughly half the statistics).

These results correspond to the complete film sample provided by the 81 cm Saclay HBC running at the CERN PS.

Since the rate of $\bar{p}p$ annihilations at rest into 6 bodies : $\bar{p}p \to K\bar{K}\pi\pi\pi\pi$ is negligible, the search for the E $\to$ $K\bar{K}\pi$ is limited, in principle, to the study of the 4 and 5 body annihilations : $\bar{p}p \to K\bar{K}\pi\pi$, $\bar{p}p \to K\bar{K}\pi\pi\pi$. We shall see that quantum number selection rules forbid very likely the 4 body channel for the production of the E-meson : we shall therefore limit our study to the following 5 body reactions :

(1) $\bar{p}p \to K_1^o K^{\pm} \pi^{\mp} \pi^- \pi^+$ 600 ev^{ts}.

(2) $\bar{p}p \to K_1^o K^{\pm} \pi^{\mp} (\pi^o \pi^o)$ 273 ev^{ts}.

(3) $\bar{p}p \to K_1^o K_1^o \pi^+ \pi^- \pi^o$ 657 ev^{ts}.

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PS/5665/rmn

(4) $\bar{p}p \rightarrow K_1^o(K^o\pi^o)\pi^+\pi^-$ 757 ev^{ts}.

(5) $\bar{p}p \rightarrow K^+K^-\pi^+\pi^-\pi^o$ 740 ev^{ts}.

The reactions (2) and (4) do not give rise to a fit since there are two missing particles : they have been selected from the events which do not give a 4 body fit and for which the missing mass is at least as large as $(\pi^o\pi^o)$ and $(K^o\pi^o)$ respectively for reaction (2) and (4). The number of events given for the reaction (5) is obtained from a reduced sample of 0.4×10^6 $\bar{p}$.

In the following, we assume the E is really a $(K\bar{K}\pi)$ resonance and conclude for its properties :

M (E) = (1425 ± 7) MeV Γ (E) = (80 ± 10) MeV

I (E) = 0 C (E) = + 1

$J^P(E) = 0^-$

$E \rightarrow (K\bar{K}^*$ and $\bar{K}K^*) / E \rightarrow K\bar{K}\pi$ 50 o/o

We report at the end a short discussion on the nature of the E.

2. Experimental method

Approximately 1.4×10^6 antiprotons from the CERN PS have been stopped in the Saclay 81 cm hydrogen bubble chamber. The antiprotons, produced in a beryllium target at 700 MeV/c, have been momentum and velocity analysed by means of the beam k4 (Ref. 5) and subsequently degraded by a 10 cm copper absorber down to 400 MeV/c just before entering the bubble chamber. The momentum of 400 MeV/c was chosen so that the antiproton stops would occur near the middle of the bubble chamber. A restricted fiducial volume was chosen so as to reduce to 12 ± 2 o/o the percentage of annihilations in flight before measurements, and to ensure a high detection efficiency for the types of events analysed.

The data have been analysed in the standard manner by means of computer geometry, kinematics and post kinematics programs.

The results of the kinematics programs have been systematically checked against the identification of the secondary particles by means of bubble density : because of the low energy of the secondary particles in the reactions under study, the bubble density is an efficient tool to determine the most likely hypothesis, and we estimate the contamination of the sample of events under study to be less than 5 o/o.

3. Production of the E

Reaction 1 : $\bar{p}p \rightarrow K_1^o K^{\pm} \pi^{\mp} \pi^+ \pi^-$

The mass-squared distributions of all possible combinations between particles in the final state have been studied. Of these, only three show an interesting structure : $(K\pi)_{I=1/2}$, $(K\bar{K})$, $(K\bar{K}\pi)_{Q=0}$. In Fig. 1 we present these distributions, together with the distributions relative to $(K\pi)_{I=3/2}$ and $(K\bar{K}\pi)_{Q=2}$, for comparison.

Whereas $(K\pi)_{I=3/2}$ distribution shows no remarkable structure, the $(K\pi)_{I=1/2}$ spectrum can be interpreted as showing effect of the 890 MeV $K\pi$ resonance.

The $(K\bar{K})$ distribution shows a significant concentration of events with very low $(K\bar{K})$ effective mass (i.e. zero relative energy between the K and the $\bar{K}$).

Finally, whereas the doubly charged $(K\bar{K}\pi)$ spectrum shows no significant peaks, there is a marked concentration of events near M $\sim$ 1400 MeV for the neutral $(K\bar{K}\pi)$ spectrum.

Since only the peak in the $(K\pi)_{I=1/2}$ spectrum can be associated with a known resonance, we have made an effort to see whether a coherent explanation of all the mass spectra could be formulated in terms of the $K^*(890)$; in this spirit, we have investigated the effect that a matrix element would have on the $(K\bar{K}\pi)$ and $K\bar{K}$ mass spectra, taking into account the K^* production, and properly symmetrized with respect to the pion and the K exchange. More specifically, we write down the appropriate matrix element as :

$$M = (A_{13} + A_{14}) \pm (A_{23} + A_{24})$$

with $$A_{ij} = \frac{1}{s_{ij} - s^* + i\, m^* \,\Gamma^*}$$

s_{ij} denotes the effective mass squared of particles i and j, with the labelling :

$K^o K^- \pi^+ \pi^+ \pi^-$ $\quad\quad$ $\bar{K}^o K^+ \pi^- \pi^- \pi^+$

1 2 3 4 5 $\quad\quad$ 1 2 3 4 5

The $K^*(890)$ is inserted in the form of a Breit-Wigner function defined by $m^* = 890$ MeV, $\Gamma^* = 50$ MeV, $s^* = m^{*2}$.

Since $I(K\bar{K}) = 1$, $G(K\bar{K}) = (-1)^{I+L} = \pm 1$, according to the parity of the angular momentum L; therefore, we have investigated the 2 resulting cases, i.e. constructive and destructive interference separately (corresponding to the positive and negative sign left undefined in the above written matrix element).

A superposition of the 2 theoretical curves obtained by an appropriate Monte-Carlo calculation on the mass spectrum of the $K\bar{K}\pi$ system (phase space α, K^* with constructive interference effects : β) shows that no combination of these 2 mechanisms could generate a peak observed in the $(K\bar{K}\pi)_{Q=0}$ spectrum at $M^2 \sim 2.0$ GeV^2. Furthermore, no such combination could generate the sharp peaking observed in the $(K\bar{K})$ spectrum.

Accordingly, we conclude that the K^* production is insufficient to account for the effects observed, and we must introduce, in addition to the K^* effects, a new phenomenon either in the $(K\bar{K})$ system or in the $(K\bar{K}\pi)$, or in both.

1. With a $(K\bar{K})$ effect alone, which a priori should have the same effect on the doubly charged and on the neutral $(K\bar{K}\pi)$ spectrum, we could not explain the two $(K\bar{K}\pi)$ spectra which appear quite different.
2. With both $(K\bar{K})$ and K^* effects (incoherent combination) we are unable to reproduce the $K\bar{K}\pi$ (1400) peak.

We therefore assume in the following that we observe a genuine effect in the neutral $(K\bar{K}\pi)$ system, namely the so called E-meson.

There are two neutral $(K\bar{K}\pi)$ combinations per event : this makes a precise determination of the actual rate of production of the E difficult in this reaction, as well as its mass and width, as long as its spin-parity and decay modes are not completely known. However, the comparison of the neutral $(K\bar{K}\pi)$ spectrum with the double charge one, shows that the non E^o - combinations are distributed like the double charge ones. We are thus allowed, as a first approximation, to fit a Breit-Wigner curve on the spectrum obtained by subtracting the $M^2\ (K\bar{K}\pi)^{\pm\pm}$ spectrum from the $M^2\ (K\bar{K}\pi)^0$ one. (Fig. 1d).

The values of the mass and the width we get this way are :
$M = 1415 \pm 5$ MeV , $\Gamma = 77 \pm 12$ MeV.

Furthermore, taking into account our final results on spin, parity and decay modes of the E-meson, a fit of a $M^2\ (K\bar{K}\pi)^0$ spectrum obtained by Monte-Carlo method to the experimental spectrum gives :

$\bar{p}p \rightarrow E^0\pi^+\pi^-$ $\qquad 600\ ^{+0}_{-60}$ events

$M = (1424 \pm 8)$ MeV $\qquad \Gamma = (80 \pm 15)$ MeV

Reaction 2 : $\bar{p}p \rightarrow K_1^0K^{\pm}\pi^{\mp}(\pi^0\pi^0)$

These events are those which did not give a fit for 0 or 1 π^0 missing, which have a missing mass at least as large as 2 π^0, and for which one charged secondary has been recognized, by bubble density measurement, to be a K meson.

In view of the very low rate of 6-body annihilations, most events satisfying these criteria can safely be interpreted as being representants for the annihilation channel :

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

A fit obtained by the maximum likelihood method on the $(K\bar{K}\pi)$ spectrum gives : (Fig. 2)

$\bar{p}p \rightarrow E^0\pi^0\pi^0$ $\qquad 208 \pm 20$ events (76 o/o of reaction 2)

$M = (1426 \pm 6)$ MeV $\qquad \Gamma = (81 \pm 14)$ MeV .

Reaction 3 : $\bar{p}p \rightarrow K_1^0K_1^0\pi^+\pi^-\pi^0$

This reaction is strongly dominated by the channel :

$$\bar{p}p \rightarrow K_1^0K_1^0\omega^0 .$$

However, the comparison between the $(K_1^0K_1^0\pi^0)$ spectrum and the $(K_1^0K_1^0\pi^{\pm})$ ones show an enhancement at $M^2 \sim 2.0\ GeV^2$ in the first one which corresponds roughly to (64 ± 20) events in the 1.84 - 2.14 GeV^2 region (Fig. 3).

In order to evaluate the production of the E, we have computed by Monte-Carlo method the reflection of the ω^0, taking into account its spin and parity (curve α on Fig. 3b).

Since the Dalitz plot of the reaction $\bar{p}p \to K_1^o K_1^o \omega^o$ shows that the ω^o production occurs mainly in the $^3S_1$ initial state (Ref. 6) the corresponding matrix element used to compute the reflection of the ω^o on the $(KK\pi)$ spectrum is :

$$M^{\mu}(\omega) = \frac{1}{m_{123}} \epsilon^{\mu\nu\rho\sigma} q_{1\nu} q_{2\rho} q_{3\sigma} \frac{1}{m_{123}^2 - m_\omega^2 + i\, m_\omega \Gamma_\omega}$$

where :

$q_{i\mu}$ $(i = 1,2,3;\ \mu = 0,1,2,3)$ are the components of the 4 momenta of the three decaying pions of the ω^o

$m_{123}^2 = (q_1 + q_2 + q_3)^2$ is the invariant mass squared of the three pions

m_ω and Γ_ω are the mass and width of the ω^o

$\epsilon^{\mu\nu\rho\sigma}$ is the completely antisymmetric tensor $(\epsilon^{0123} = +1)$.

The best fit is obtained (curve β on Fig. 3b) when we add 18 o/o background (phase space) and 12 o/o E^o production to the ω^o production (70 o/o) (without taking account of E^o spin-parity assignments) :

$\bar{p}p \to E^o \pi^+ \pi^-$ with $E^o \to K_1^o K_1^o \pi^o$	83 ± 21 events
$\bar{p}p \to K_1^o K_1^o \omega^o$	453 ± 30 events
$\bar{p}p \to K_1^o K_1^o \pi^+ \pi^- \pi^o$ (phase space)	120 ± 34 events

Reaction 4 : $\bar{p}p \to K_1^o (K^o \pi^o)\ \pi^+ \pi^-$

These events are those which did not give a fit for one K^o missing, which have a missing mass at least as large as $(K^o + \pi^o)$, and for which both charged secondaries have been recognized, by bubble density measurement, to be π mesons.

In view of the very low rate of 6-body annihilations, most events satisfying these criteria can safely be interpreted as being representants for the annihilation channel :

$$\bar{p}p \to K_1^o K^o \pi^o \pi^+ \pi^-$$

The reaction $\bar{p}p \to K_1^o K_2^o \pi^+ \pi^- \pi^o$ can be obtained from reaction (4). The reaction (4) is a mixture of $K_1^o K_1^o \pi^+ \pi^- \pi^o$ and $K_1^o K_2^o \pi^+ \pi^- \pi^o$ events; to see the net effect due to the $K_1^oK_2^o\pi^+\pi^-\pi^o$, we subtract from the overall $(K_1^oK^o\pi^o)$ spectrum the $(K_1^oK_1^o\pi^o)$ spectrum observed for reaction (3), since the number of $K_1^oK_1^o\pi^+\pi^-\pi^o$ events in reaction (4) must be equal to the number of events found for reaction (3).

The $(K_1^oK_2^o\pi^o)$ spectrum is shown on Fig. (4). One can see that the number of events for which : $1.84\ GeV^2 < M^2\ (K\bar{K}\pi) < 2.14\ GeV^2$ is 14 ± 20. We therefore cannot attribute more than 20 ± 25 events to the decay $E^o \rightarrow K_1^oK_2^o\pi^o$, in the mass region 1.84 - 2.14 GeV^2; this yields an upper limit of 20 ± 25 events for the reaction :

$$\bar{p}p \rightarrow E^o\pi^+\pi^- \quad \text{with} \quad E^o \rightarrow K_1^oK_2^o\pi^o < 20 \pm 25 \text{ events.}$$

Reaction 5 : $\bar{p}p \rightarrow K^+K^-\pi^+\pi^-\pi^o$

The scanning has been made for a sample of $0.4 \times 10^6\ \bar{p}$ where one $K^\pm$ at least is detected by decay or interaction. This reaction, like reaction (4), is strongly dominated by the ω^o production. The detection of the charged K introduces certainly a bias but it should not affect differently the charged and the neutral $(K\bar{K}\pi)$ spectra : still these two spectra are different, (Fig. 5), the main effect being an excess of neutral $(K\bar{K}\pi)$ combinations in the E^o region.

However, as it is difficult to compare quantitatively the results of this reaction with the others, we did not attempt to estimate the rate of E^o production with the subsequent decay mode $E^o \rightarrow K^+K^-\pi^o$.

4. Mass and width of the E

From the results obtained from reaction (1) and (2), the best estimate for the mass and the width of the E meson are the following :

$$M = (1425 \pm 7)\ MeV \qquad \Gamma = (80 \pm 10)\ MeV$$

The errors due to statistical limitations have been increased to take account of possible systematic alterations of the data.

5. Charge conjugation and isospin of the E

The absence of a double charged $(K\bar{K}\pi)$ enhancement in reaction (1) is taken as an evidence against I(E) = 2, since, assuming I(E) = 2 and non zero transition probability for the process $\bar{p}p \to E^{\pm\pm}\pi^{\mp}\pi^{\mp}$, there is only one amplitude for the decay of the E, therefore no possible cancellation due to interference effects.

We thus limit ourserves, in the following, to the four possible assignments : $C(E) = \pm 1$, $I(E) = 0$ or 1.

If we note A_1 and A_0 the amplitude corresponding to $I(K\bar{K}) = 1$ and $I(K\bar{K}) = 0$ respectively, the decay amplitude for the E into the different observable charge modes are :

<u>C(E) = +1 I(E) = 0</u>

$$(K\bar{K}\pi)^0 = \frac{A_1}{\sqrt{6}} K_1^0K^+\pi^- + \frac{A_1}{\sqrt{6}} K_1^0K^-\pi^+ - \frac{A_1}{2\sqrt{3}} K_1^0K_1^0\pi^0 + \frac{A_1}{\sqrt{6}} K^+K^-\pi^0$$

<u>C(E) = +1 I(E) = 1</u>

$$(K\bar{K}\pi)^0 = \frac{A_1}{2} K_1^0K^+\pi^- - \frac{A_1}{2} K_1^0K^-\pi^+ + \frac{A_0}{2} K_1^0K_1^0\pi^0 + \frac{A_0}{\sqrt{2}} K^+K^-\pi^0$$

$$(K\bar{K}\pi)^\pm = \frac{A_1}{\sqrt{2}} K_1^0K^\pm\pi^0 - \frac{A_1}{\sqrt{2}} K_1^0K_2^0\pi^\pm + \left(\frac{A_1}{\sqrt{2}} + A_0\right) K^+K^-\pi^\pm + \frac{A_0}{\sqrt{2}} K_1^0K_1^0\pi^\pm$$

<u>C(E) = -1 I(E) = 0</u>

$$(K\bar{K}\pi)^0 = \frac{A_1}{\sqrt{6}} K_1^0K^+\pi^- + \frac{A_1}{\sqrt{6}} K_1^0K^-\pi^+ - \frac{A_1}{\sqrt{6}} K_1^0K_2^0\pi^0 + \frac{A_1}{\sqrt{6}} K^+K^-\pi^0$$

<u>C(E) = -1 I(E) = 1</u>

$$(K\bar{K}\pi)^0 = \frac{A_1}{2} K_1^0K^+\pi^- - \frac{A_1}{2} K_1^0K^-\pi^+ + \frac{A_0}{\sqrt{2}} K_1^0K_2^0\pi^0 + \frac{A_0}{\sqrt{2}} K^+K^-\pi^0$$

$$(K\bar{K}\pi)^\pm = \frac{A_1}{\sqrt{2}} K_1^0K^\pm\pi^0 - \frac{A_1}{2} K_1^0K_1^0\pi^\pm + A_0 K_1^0K_2^0\pi^\pm + \left(\frac{A_1}{\sqrt{2}} + A_0\right) K^+K^-\pi^\pm$$

These predictions can be compared to the experimental observations in Table I, in which the production rates take into account the visibility of the K_1^0. M and N are for the square of the transition matrix elements respectively for the production processes :

$\bar{p}p \to E^0\pi^+\pi^-$: M

and $\bar{p}p \to E^\pm\pi^\mp\pi^0$: N

TABLE I

$C(E)$, $I(E)$, $I_3(E)$	Channel	Decay Ampl. per channel	Visibility of K_1^0	Production rate	Prediction	Experiment
+1 , 0 , 0	$K_1^0K^{\pm}\pi^{\mp}$	$\sqrt{2}\,\frac{A_1}{\sqrt{6}}$	.603	$.200\lvert A_1\rvert^2 M$	600*	$600 \begin{smallmatrix}+\ 0\\-\ 60\end{smallmatrix}$
	$K_1^0K_1^0\pi^0$	$-\frac{A_1}{2\sqrt{3}}$	.363	$.030\lvert A_1\rvert^2 M$	90	83 ± 21
	$K_1^0K_2^0\pi^0$	0			0	$<20 \begin{smallmatrix}+\ 25\\-\ 20\end{smallmatrix}$
	$K^+K^-\pi^0$	$\frac{A_1}{\sqrt{6}}$	1	$.166\lvert A_1\rvert^2 M$	497	>150
-1 , 0 , 0	$K_1^0K^{\pm}\pi^{\mp}$	$\sqrt{2}\,\frac{A_1}{\sqrt{6}}$	.603	$.200\lvert A_1\rvert^2 M$	600*	$600 \begin{smallmatrix}+\ 0\\-\ 60\end{smallmatrix}$
	$K_1^0K_1^0\pi^0$	0			0	83 ± 21
	$K_1^0K_2^0\pi^0$	$-\frac{A_1}{\sqrt{6}}$	.603	$.100\lvert A_1\rvert^2 M$	300	$<20 \begin{smallmatrix}+\ 25\\-\ 20\end{smallmatrix}$
	$K^+K^-\pi^0$	$\frac{A_1}{\sqrt{6}}$	1	$.166\lvert A_1\rvert^2 M$	497	> 150
+1 , 1 , 0	$K_1^0K^{\pm}\pi^{\mp}$	$\frac{A_1}{\sqrt{2}}$	.603	$.301\lvert A_1\rvert^2 M$	600*	$600 \begin{smallmatrix}+\ 0\\-\ 60\end{smallmatrix}$
	$K_1^0K_1^0\pi^0$	$\frac{A_0}{2}$	.363	$.091\lvert A_0\rvert^2 M$	83*	83 ± 21
	$K_1^0K_2^0\pi^0$	0			0	$< 20 \begin{smallmatrix}+\ 25\\-\ 20\end{smallmatrix}$
	$K^+K^-\pi^0$	$\frac{A_0}{\sqrt{2}}$	1	$.500\lvert A_0\rvert^2 M$	456	> 150
+1 , 1 , ± 1	$K_1^0K^{\pm}\pi^0$	$\frac{A_1}{\sqrt{2}}$	.603	$.301\lvert A_1\rvert^2 N$	$.603\ \alpha$	?
	$K_1^0K_1^0\pi^{\pm}$	$\frac{A_0}{\sqrt{2}}$	.363	$.181\lvert A_0\rvert^2 N$	0^{x}	$0 \begin{smallmatrix}+\ 7\\-\ 0\end{smallmatrix}$
	$K_1^0K_2^0\pi^{\pm}$	$-\frac{A_1}{\sqrt{2}}$	.603	$.301\lvert A_1\rvert^2 N$	$.603\ \alpha$	?
	$K^+K^-\pi^{\pm}$	$\frac{A_1}{\sqrt{2}} + A_0$	1	$(\frac{A_1}{\sqrt{2}} + A_0)^2 N$	α	≈ 0

TABLE I (contd.)

C(E), I(E), I_3(E)	Channel	Decay Ampl. per channel	Visibility of K_1^0	Production rate	Prediction	Experiment
-1 , 1 , 0	$K_1^0 K^{\pm} \pi^{\mp}$	$\frac{A_1}{\sqrt{2}}$	.603	$.301 \lvert A_1 \rvert^2 M$	600*	$600 {+0 \atop -20}$
	$K_1^0 K_1^0 \pi^0$	0			0	83 ± 21
	$K_1^0 K_2^0 \pi^0$	$\frac{A_0}{\sqrt{2}}$	.603	$.301 \lvert A_0 \rvert^2 M$	20*	$<20 {+25 \atop -20}$
	$K^+ K^- \pi^0$	$\frac{A_0}{\sqrt{2}}$	1	$.500 \lvert A_0 \rvert^2 M$	33	> 150
-1 , 1 , ±1	$K_1^0 K^{\pm} \pi^0$	$\frac{A_1}{\sqrt{2}}$	.603	$.301 \lvert A_1 \rvert^2 N$	0	?
	$K_1^0 K_1^0 \pi^{\pm}$	$-\frac{A_1}{2}$	.363	$.091 \lvert A_1 \rvert^2 N$	0*	$0 {+7 \atop -0}$
	$K_1^0 K_2^0 \pi^{\pm}$	A_0	.603	$.603 \lvert A_0 \rvert^2 N$	.603 β	?
	$K^+ K^- \pi^{\pm}$	$\frac{A_1}{\sqrt{2}} + A_0$	1	$(\frac{A_1}{\sqrt{2}} + A_0)^2 N$	β	≈ 0

Predictions with (*) indicate that the experimental results have been taken as normalization.

For the channel $\bar{p}p \rightarrow K^+K^-\pi^+\pi^-\pi^0$, the loss due to scanning efficiency is important : we can only give a lower limit for $E^0 \rightarrow K^+K^-\pi^0$ and indicate that $E^{\pm} \rightarrow K^+K^-\pi^{\pm}$ is very probably absent.

Let us now compare, in turn, the predictions and the experimental results for different charge conjugation and isospin assignment for the E : For C(E) = +1 and I(E) = 0, one sees that the predictions agree very well with the experiment, in particular the absence of $E^0 \rightarrow K_1^0K_2^0\pi^0$ and the observation of 83 $E^0 \rightarrow K_1^0K_1^0\pi^0$ when 90 are predicted.

The same observations make the assignment C(E) = -1, I(E) = 0 very unlikely.

For $C(E) = +1$ and $I(E) = 1$, we have to consider both $I_3(E) = 0$ and $I_3(E) = \pm 1$: For $I_3(E) = 0$, the predictions agree with the experiment, but they are not as significant as for $C(E) = +1$, $I(E) = 0$ since the two well measured channels $E^o \to K^o K^{\mp} \pi^{\pm}$ and $E^o \to K_1^o K_1^o \pi^o$ have now to be taken as normalization : one can then just say that there is no obvious disagreement. For $I_3(E) = \pm 1$, the only well measured channel is $E^{\pm} \to K_1^o K_1^o \pi^{\pm}$, which seems indeed to be experimentally absent : if one uses this result to assign $A_o = 0$, one is left with a free parameter since the amplitude A_1 takes also part in the disintegration : the experimental information on this amplitude is limited to the channel $E^{\pm} \to K^+ K^- \pi^{\pm}$, which appears to be also absent. The obvious conclusion is then that both A_o and A_1 are equal to zero, i.e. this assignment has to be ruled out. However, another possibility is to assume $N = 0$, i.e. the $E^{\pm}$ is not produced.

To examine the implications of the hypothesis $N = 0$ let us write explicitly the amplitudes for $\bar{p}p \to E\pi\pi$ when $C(E) = +1$, $I(E) = 1$.

We have : $G(E) = -1$

thus : $G(E\pi\pi) = -1$

or : $G(\bar{p}p) = -1$.

This is only satisfied for $C(\bar{p}p) = +1$ when $I(\bar{p}p) = 1$

and for $C(\bar{p}p) = -1$ when $I(\bar{p}p) = 0$.

The possible transition amplitudes are then :

$$\beta_{12}^{+} = \langle \bar{p}p \quad I = 1, \quad C = +1 \mid E\pi\pi \quad I(\pi\pi) = 2 \rangle$$

$$\beta_{11}^{+} = \langle \bar{p}p \quad I = 1, \quad C = +1 \mid E\pi\pi \quad I(\pi\pi) = 1 \rangle$$

$$\beta_{10}^{+} = \langle \bar{p}p \quad I = 1, \quad C = +1 \mid E\pi\pi \quad I(\pi\pi) = 0 \rangle$$

$$\beta_{01}^{-} = \langle \bar{p}p \quad I = 0, \quad C = -1 \mid E\pi\pi \quad I(\pi\pi) = 1 \rangle$$

More explicitly, we have for the wave function :

$$\begin{aligned}
\psi = {} & \beta_{12}^{+} \left[\sqrt{\frac{3}{20}}\, E^{+}(\pi^o\pi^- + \pi^-\pi^o) - \sqrt{\frac{1}{15}}\, (\pi^+\pi^- + 2\pi^o\pi^o + \pi^-\pi^+) + \sqrt{\frac{3}{20}}\, E^{-}(\pi^+\pi^o + \pi^o\pi^+) \right] \\
& + \beta_{11}^{+} \left[\frac{1}{2}\, E^{+}(\pi^o\pi^- - \pi^-\pi^o) - \frac{1}{2}\, E^{-}\, (\pi^+\pi^o - \pi^o\pi^+) \right] \\
& + \beta_{10}^{+} \left[\sqrt{\frac{1}{3}}\, E^{o}(\pi^+\pi^- - \pi^o\pi^o + \pi^-\pi^+) \right] \\
& + \beta_{01}^{-} \left[\sqrt{\frac{1}{6}}\, E^{+}(\pi^o\pi^- - \pi^-\pi^o) - \sqrt{\frac{1}{6}}\, E^{o}(\pi^+\pi^- - \pi^-\pi^+) + \sqrt{\frac{1}{6}}\, E^{-}(\pi^+\pi^o - \pi^o\pi^+) \right]
\end{aligned}$$

Finally, we get for the transition rates :

$\bar{p}p \rightarrow E^{\pm}\pi^{-}\pi^{o}$: $N = \frac{3}{5}\,|\beta^{+}_{12}|^{2} + |\beta^{+}_{11}|^{2} + \frac{2}{3}\,|\beta^{-}_{01}|^{2}$

$\bar{p}p \rightarrow E^{o}\pi^{+}\pi^{-}$: $M_1 = \frac{2}{3}\left[\left|\beta^{+}_{10} - \sqrt{\frac{1}{5}}\,\beta^{+}_{12}\right|^{2} + \frac{1}{2}\,|\beta^{-}_{01}|^{2}\right]$

$\bar{p}p \rightarrow E^{o}\pi^{o}\pi^{o}$: $M_2 = \left|2\sqrt{\frac{1}{15}}\;\beta^{+}_{12} + \sqrt{\frac{1}{3}}\,\beta^{+}_{10}\right|^{2}$

We thus see that to get $N = 0$, we have to have :

$$\beta^{+}_{12} = \beta^{+}_{11} = \beta^{-}_{01} = 0 \;.$$

This condition is certainly not a very natural one, since it implies not only the $^{3}S_{1}$ initial state does not contribute, but also two of the three possible amplitudes related to $^{1}S_{o}$ initial state to be zero. Moreover, it predicts the branching ratio $E^{o}\pi^{+}\pi^{-} / E^{o}\pi^{o}\pi^{o} = 2$ whereas the experimental results is 2.86 ± 0.45.

We then conclude the assignment $C(E) = +1$, $I(E) = 1$ is much less probable than $C(E) = +1$, $I(E) = 0$.

The last possible assignment : $C(E) = -1$, $I(E) = +1$ is clearly excluded by the presence of 83 $E^{o} \rightarrow K^{o}_{1}K^{o}_{1}\pi^{o}$ when the prediction is 0, the abundance of $E^{o} \rightarrow K^{+}K^{-}\pi^{o}$, and the experimental situation for the $E^{\pm}$ which seems again to indicate $A_1 = A_o = 0$.

Of the four possible assignments considered for the E, we thus conclude that $C(E) = +1$, $I(E) = 0$ is the only one which reproduces the experimental facts in a satisfactory way.

With this assignment, the only possible initial state for $\bar{p}p \rightarrow E^{o}\pi^{o}\pi^{o}$ is $^{1}S_{o}$ ($C = +1$, $J^{P} = 0^{-}$) since $C(\pi^{o}\pi^{o}) = +1$. We have also $I(\pi^{o}\pi^{o}) = 0$; then, from the number of $E^{o}\pi^{o}\pi^{o}$ observed in reaction (2), we deduce that $(208 \times 2) \pm 20$ events in reaction (1) : $\bar{p}p \rightarrow E^{o}\pi^{+}\pi^{-}$ come from $^{1}S_{o}$ (since $\pi^{+}\pi^{-} / \pi^{o}\pi^{o} = 2$ for $I(\pi\pi) = 0$). We then conclude that less than 30 o/o of the E^{o} production in reaction (1) comes from $^{3}S_{1}$ $\bar{p}p$ annihilation state.

6. Spin and Parity of the E

Assuming I(E) = 0 and C(E) = +1, we have G(E) = +1, then $G(K\bar{K}) = -1$, but since $I(K\bar{K}) = 1$, we have $L(K\bar{K})$ even and $J^P(K\bar{K}) = 0^+, 2^+ \ldots$

Both the production and the decay of the E^0 can be considered for the study of its spin and parity.

E^0 decay :

Fig. 6 shows the main features of the E^0 decay. Fig. 6a indicates a possible presence of $K^*(890)$ in the decay. Fig. 6b shows the strong accumulation of the $K\bar{K}$ masses in the low value region : this strongly favours the assignment $J^P\ (K\bar{K}) = 0^+$ rather than $2^+ \ldots$ Fig. 6c shows that the decay angular distribution $W_1\ (\cos\theta)$ of the $K\bar{K}$ system, which is not compatible with uniformity, cannot be explained in the case of $L(K\bar{K}) = 0$ without the introduction of K^* interference effects.

The assignment $J^P(K\bar{K}) = 0^+$ leads to the following possible spin-parity for the E^0 meson :

$$J^P\ (E) = 0^-,\ 1^+,\ 2^- \ldots$$

We have tried to explain the three distributions of Fig. 6 by the following decay modes : $E^0 \to K^*\bar{K}\ (\bar{K}^*K)$, $E^0 \to (K\bar{K})\pi$ where $(K\bar{K})$ stands for a possibly resonating $K\bar{K}$ system near threshold (Ref. 7). Using the technique of cartesian tensors (Ref. 8) we performed a fit of these distributions with the following decay matrix elements :

$$J^P(E) = 0^- \qquad |M^0|^2 = a\ |M^0(K^*)|^2 + (1-a)|M^0(K\bar{K})|^2$$

$$J^P(E) = 1^+ \qquad |M^1|^2 = a\left[M^i(K^*)\ M_i^*(K^*)\right] + (1-a)\left[M^i(K\bar{K})\ M_i^*(K\bar{K})\right]$$

$$J^P(E) = 2^- \qquad |M^2|^2 = a\left[\sum_{ij} M^{ij}(K^*)M_{ij}^*(K^*)\right] + (1-a)\left[\sum_{ij} M^{ij}(K\bar{K})M_{ij}^*(K\bar{K})\right]$$

where the explicit expressions (not normalized) of $M^0(K^*)$, $\vec{M}(K^*)$, $M^{ij}(K^*)$, $M^0(K\bar{K})$, $\vec{M}(K\bar{K})$, $M^{ij}(K\bar{K})$ are given in Table II.

TABLE II

E^o decay matrix elements for $K^*\bar{K}$ and $(K\bar{K})\pi$ modes

0^-	$M^o(K^*) = \vec{P}_{K_1\pi} \cdot \vec{P}_{K_2}\, B\,W\,(K_1^*) + \vec{P}_{K_2\pi} \cdot \vec{P}_{K_1}\, B\,W\,(K_2^*)$
	$M^o(K\bar{K}) = B\,W\,(K\bar{K})$
1^+	$M^1(K^*) = \vec{P}_{K_1\pi}\, B\,W\,(K_1^*) + \vec{P}_{K_2\pi}\, B\,W\,(K_2^*)$
	$M^1(K\bar{K}) = \vec{P}_\pi\, B\,W\,(K\bar{K})$
2^-	$M^{ij}(K^*) = [P^i_{K_1\pi} P^j_{K_2} + P^j_{K_1\pi} P^i_{K_2} - \frac{2}{3}\, \delta^{ij}\, (\vec{P}_{K_1\pi} \cdot \vec{P}_{K_2})]\, B\,W\,(K_1^*) + [P^i_{K_2\pi} P^j_{K_1} + P^j_{K_2\pi} P^i_{K_1} - \frac{2}{3}\, \delta^{ij}\, (\vec{P}_{K_2\pi} \cdot \vec{P}_{K_1})]\, B\,W\,(K_2^*)$
	$M^{ij}(K\bar{K}) = (P^i_\pi P^j_\pi - \frac{1}{3}\, \delta^{ij}\, \vec{P}^2_\pi)\, B\,W\,(K\bar{K})$

$$B\,W\,(K^*) = \frac{1}{m^2_{K\pi} - m^{*2} + i m^* \Gamma}$$

$m^* = 890$ MeV
$\Gamma = 50$ MeV

$$B\,W\,(K\bar{K}) = \frac{1}{m^2_{K\bar{K}} - m^{o2} + i m^o \Gamma^o}$$

$m^o = 2\, m_K$
Γ^o = given by the fit (70 MeV)

$\vec{P}_{K_1}$, $\vec{P}_{K_2}$, $\vec{P}_\pi$ vector parts of the three decaying particle 4-momenta in E^o - CM

$P_{K_{1,2\pi}}$ vector part of the 4-vector $P^\mu_\pi - P^\mu_{K_{1,2}} - \frac{m^2_\pi - m^2_K}{m^2_{K_{1,2\pi}}} (P^\mu_\pi + P^\mu_{K_{1,2}})$ in E^o - CM

The best fit corresponds to the hypothesis :

$J^P(E) = 0^-$

$E^o \rightarrow K^*\bar{K}\ (\bar{K}^*K)$ ≈ 50 o/o

$E^o \rightarrow (K\bar{K})\pi$ ≈ 50 o/o

as can be seen in Table III.

TABLE III

Reaction	$J^P_{(E)}$	o/o K^*	o/o $K\bar{K}$	o/o Background (*)	$\Gamma_{K\bar{K}}$ MeV	$\chi^2/\langle\chi^2\rangle$	Probability o/o
$\bar{p}p \to E^o\pi^+\pi^-$	0^-	46 ± 3	42 ± 3	12 ± 6	70	52/34	2.0
	1^+	43 ± 3	33 ± 3	24 ± 6	30	63/34	0.2
	2^-	57 ± 3	25 ± 3	18 ± 6	50	76/34	0.0
$\bar{p}p \to E^o\pi^o\pi^o$	0^-	48 ± 4	52 ± 4		70	34/30	30.0
	1^+	64 ± 4	36 ± 4		50	44/30	5.0
	2^-	68 ± 4	32 ± 4		50	46/30	3.0

(*) For the reaction $\bar{p}p \to E^o\pi^+\pi^-$ the presence of the background is due to the fact that we did not take into account interference effects between the two possible E^o's. This may explain the poor fit obtained in this case.

E^o production :

Let us consider the process

$$\bar{p}p \to (K_1K_2\pi_1)\pi_2\pi_3 \qquad (K_1K_2\pi_1) \to (K_1K_2)\pi_1$$

(we call the three π's: π_1, π_2, π_3 and the two K's: K_1, K_2) where $(K_1K_2\pi_1)$ and (K_1K_2) represent systems with fixed mass.

The geometry of such a process (Fig. 7) is defined by three vectors which we call $\vec{k}$, $\vec{K}$, $\vec{P}$: They are the vector parts in the total centre of mass of the following 4-vector :

$$k^\mu = p^\mu_{\pi_3} - p^\mu_{\pi_2} \qquad \text{In } (\pi_2\pi_3) \text{ rest frame, } k = (0, \vec{p}_{\pi_3} - \vec{p}_{\pi_2})$$

$$K^\mu = (p^\mu_{\pi_2} + p^\mu_{\pi_3}) - \frac{(p_{\pi_2} + p_{\pi_3}).\,Q}{Q^2}\,Q^\mu$$

where $Q = p_{k_1} + p_{k_2} + p_{\pi_1} + p_{\pi_2} + p_{\pi_3}$

In total C.M. $(Q = 0)$ $\quad K = (0, \vec{p}_{\pi_2} + \vec{p}_{\pi_3})$

$$p^\mu = p^\mu_{\pi_1} - \frac{p_{\pi_1} \cdot (p_{K_1} + p_{K_2} + p_{\pi_1})}{(p_{K_1} + p_{K_2} + p_{\pi_1})^2} (p_{K_1} + p_{K_2} + p_{\pi_1})^\mu$$

in $(K_1 K_2 \pi_1)$ rest frame $P = (0, \vec{p}_{\pi_1})$

We define three angles φ, ψ, χ by

$$\cos\varphi = \frac{\vec{P}.\vec{K}}{|\vec{P}|.|\vec{K}|} \qquad \cos\psi = \frac{\vec{P}.\vec{k}}{|\vec{P}|.|\vec{k}|} \qquad \cos\chi = \frac{\vec{K}.\vec{k}}{|\vec{K}|\ |\vec{k}|}$$

the square of the matrix element is a covariant function of the three 4-vectors k^μ, K^μ, P^μ

$$|M|^2 = f(k^\mu, K^\mu, P^\mu)$$

which we can evaluate in the total centre of mass

$$|M|^2 = F(\vec{k}, \vec{K}, \vec{P})$$

We call $d\Omega_k$, $d\Omega_K$, $d\Omega_P$ the differential solid angles defined by the directions $\vec{k}$, $\vec{K}$, $\vec{P}$.

We get the angular distribution $W_2(\cos\varphi)$, $W_3(\cos\psi)$, $W_4(\cos\chi)$ by integration of $F(\vec{k}, \vec{K}, \vec{P})$ over $d\Omega_k$, $d\Omega_K$, $d\Omega_P$.

The experimental angular distributions (Fig. 7) are obtained by selecting events which satisfy :

$$1.84 < M^2(K\bar{K}\pi) < 2.24 \text{ GeV}^2$$
$$M^2(K\bar{K}) < 1.08 \text{ GeV}^2 .$$

Since the mass of the (K_1K_2) system will be fixed at threshold in the following calculations, the E^o decay matrix element depends only on the vector $\vec{P}$ characterizing the momentum of π_1 in the centre of mass of the when the two K's are colinear. The calculations presented below are therefore independant of the particular decay mode of the E^o ($E^o \rightarrow K^* K$, $E^o \rightarrow (K\bar{K})\pi$).

In fact, we have verified, by Monte-Carlo techniques, that with a cut on the mass of the (K_1K_2) system : $M^2(K\bar{K}) < 1.08$ GeV^2, we get the same theoretical angular distributions, for a given spin-parity assignment, both for $E^o \rightarrow K^* K$ and $E^o \rightarrow (K\bar{K})\pi$ decay.

We give in appendix the explicit expression of the matrix elements and the details on the integration in the following cases :

initial state = ^1S_o , $^3S_1$; $J^P(E) = 0^-, 1^+, 2^-$

The theoretical normalized angular distributions are shown in Table IV where α, β, and ω represent the amplitudes for $\ell\ (\pi\pi) = 0$, $\ell\ (\pi\pi) = 2$ and relative phase of the production $\bar{p}p \rightarrow E\pi\pi$ (when it occurs in ^1S_o state).

On the other hand, when the production occurs in the $^3S_1$ state, we limit ourselves to the lowest angular momentum assumption, that is $\ell\ (\pi\pi) = 1$. For $J^P(E) = 2^-$, there are two production amplitudes, written A and B, with a relative phase δ, which correspond to the two different ways of combining the angular momenta.

TABLE IV

$J^P(E) = 0^-$

^1S_o

$$W_2^o(\cos\varphi) = 1$$
$$W_3^o(\cos\psi) = 1$$
$$W_4^o(\cos\chi) = \alpha^2 + \frac{5\beta^2}{4}(3\cos^2\chi - 1)^2 + \sqrt{5}\,\alpha B\cos\omega\,(3\cos^2\chi - 1)$$

$^3S_1$

$$W_2^1(\cos\varphi) = 1$$
$$W_3^1(\cos\psi) = 1$$
$$W_4^1(\cos\chi) = \frac{3}{2}\sin^2\chi$$

$J^P(E) = 1^+$

^1S_o

$$W_2^o(\cos\varphi) = 3\alpha^2\cos^2\varphi + \frac{3\beta^2}{10}(3 + \cos^2\varphi)$$
$$W_3^o(\cos\psi) = \alpha^2 + \frac{\beta^2}{2}(3\cos^2\psi + 1) + \sqrt{2}\,\alpha\beta\cos\omega\,(3\cos^2\psi - 1)$$
$$W_4^o(\cos\chi) = \alpha^2 + \frac{\beta^2}{2}(3\cos^2\chi + 1) + \sqrt{2}\,\alpha\beta\cos\omega\,(3\cos^2\chi - 1)$$

TABLE IV (contd.)

$^3S_1$

$$W_2^1(\cos\varphi) = 1$$
$$W_3^1(\cos\psi) = \frac{3}{2}\sin^2\psi$$
$$W_4^1(\cos\chi) = 1$$

$J^P(E) = 2^-$

^1S_o

$$W_2^o(\cos\varphi) = \frac{5}{4}\alpha^2(3\cos^2\varphi - 1)^2 + \beta^2$$
$$W_3^o(\cos\psi) = \alpha^2 + \frac{5}{4}\beta^2(3\cos^2\psi - 1)^2$$
$$W_4^o(\cos\chi) = \alpha^2 + \beta^2 + \alpha\beta\cos\omega(3\cos^2\chi - 1)$$

$^3S_1$

$$W_2^1(\cos\varphi) = \frac{A^2}{4}(-3\cos^2\varphi+5) + \frac{3B^2}{4}(1+\cos^2\varphi) + \frac{\sqrt{3}}{2}AB\cos\delta(1-3\cos^2\varphi)$$
$$W_3^1(\cos\psi) = \frac{A^2}{4}(-3\cos^2\psi+5) + \frac{3B^2}{4}(1+\cos^2\psi) - \frac{\sqrt{3}}{2}AB\cos\delta(1-3\cos^2\psi)$$
$$W_4^1(\cos\chi) = \frac{3A^2}{2}\sin^2\chi + \frac{3}{10}B^2(3+\cos^2\chi)$$

We have fitted to the experimental angular distributions $W_i (i = 2,3,4)$ a theoretical distribution $bW_i^o + (1-b)W_i^1$ $(i = 2,3,4)$, b being the percentage of ^1S_o initial state in the reaction (1). The results are given in Table V.

TABLE V

$J^P(E)$	$\chi^2/<\chi^2>$	Probability o/o	o/o ^1S_o	o/o $\ell_{\pi\pi}=0$ in ^1S_o	ω (degrees)
0^-	44/37	20	83 ± 6	99^{+1}_{-6}	
1^+	40/37	30	96 ± 6	10 ± 5	165 ± 15
2^-	52/37	5	5 ± 5	20 ± 5	52 ± 15

Conclusion :

The study of the decay and production of the E favours the 0^- assignment, excludes 2^- and indicates the 1^+ assignment is unlikely for the following reasons :

$J^P(E) = 2^-$: this assignment gives a poor fit, both for decay and production of the E, when compared to the other possible assignments :

E^o decay in reaction (1) :
Probability = 0.0 o/o against 2 o/o (0^-)

E^o decay in reaction (2) :
Probability = 3 o/o against 30 o/o (0^-)

E^o production :
Probability = 5 o/o against 20 o/o (0^-)

Moreover, it requires a large percentage of $^3S_1$ initial state for reaction (1), in complete disagreement with the data (95 ± 5 o/o against < 30 o/o).

For the two remaining possible assignments, 0^- and 1^+, the comparison of the probability of the fits for both decay and production does not lead to a clear cut decision :

E^o decay in reaction (2) : 2 o/o (0^-) against 0.2 o/o (1^+)
E^o decay in reaction (2) = 30 o/o (0^-) against 5 o/o (1^+)
E^o production : 20 o/o (0^-) against 30 o/o (1^+) .

Moreover both assignments give a proportion of $^3S_1$ initial state in agreement with the data.

However, the goodness of the fit obtained for the production of the E for 1^+ assignment is spoiled by the fact that it requires a large percentage of $\ell(\pi\pi) = 2$ (90 o/o); this is indeed very unsatisfactory since the relative momentum of the two pions which is less than 170 MeV/c should imply a very low contribution of the d-wave. Clearly, if we impose an important contribution of the dipion s-wave, which is a more likely physical situation, the predicted angular distributions for 1^+ assignment are in complete disagreement with the data. In particular, the angular distribution predicted for W_2^o ($\cos\varphi$) is then $\cos^2\varphi$ (see Table IV, $J^P(E) = 1^+$, when $\beta=0$) whereas the W_2 ($\cos\varphi$) experimental distribution is uniform (see Fig. 7a).

The quantum numbers of the E are thus very likely :

$I^G J^P = 0^+ 0^-$

7. Mass distribution of the $\pi\pi$ system produced with the E-meson

Fig. 8 gives the effective mass squared spectrum of the $\pi\pi$ system produced with the E meson ; Fig. 8a refers to $\bar{p}p \rightarrow E^o\pi^+\pi^-$, Fig. 8b to $\bar{p}p \rightarrow E^o\pi^o\pi^o$.

Two curves have been drawn on each of these spectra. The curves α correspond to a simplified calculation of the reflection of the E-meson, using the percentages of ℓ $(\pi\pi) = 0,1,2$ obtained for the fit of the production of the E for the $I^GJ^P = 0^+,0^-$ assignment. Clearly, these curves do not reproduce the experimental distributions in a very satisfactory way.

More precisely, the χ^2 obtained are :

1) $\bar{p}p \rightarrow E^o\pi^+\pi^-$ $\quad \chi^2 = 56$ when $\langle\chi^2\rangle = 9$
2) $\bar{p}p \rightarrow E^o\pi^o\pi^o$ $\quad \chi^2 = 35$ when $\langle\chi^2\rangle = 8$.

In view of these results, we have computed again the overall fit of the production of the E, according to the description given in the above chapter, but including the $\pi\pi$ mass spectrum in the data to be fitted.

Although the results of these new fit give a better interpretation of the $\pi\pi$ mass spectrum, they correspond to a proportion of $^3S_1$ initial state for reaction (1) in poor agreement with the proportion deduced from the conservation of isospin (chapter 5) :

$^3S_1$: 70 ± 10 o/o when the observed ratio $\frac{E^o\pi^+\pi^-}{E^o\pi^o\pi^o}$ leads to an upper limit of 30 o/o .

1) $\bar{p}p \rightarrow E^o\pi^+\pi^-$ $\quad \chi^2 = 35$ when $\langle\chi^2\rangle = 22$
(75 ± 10) o/o ℓ $(\pi\pi) = 0$
2) $\bar{p}p \rightarrow E^o\pi^o\pi^o$ $\quad \chi^2 = 7$ when $\langle\chi^2\rangle = 12$

However, to get these fits, we have been lead to introduce some simplifications in the calculation of the theoretical ℓ $(\pi\pi) = 0,1,2$ curves : it could explain, at least partially, the difficulties encountered to reproduce the $(\pi\pi)$ mass spectrum.

Moreover, it is interesting to remark that several experiments have already shown similar anomalies for the $\pi\pi$ mass spectrum in the same energy region, namely, for the decay of the $\tau^\pm$, $\tau^{\pm\prime}$ and K_2^o (Ref. 9), for the decay of the η (Ref. 10) and of the η' (Ref. 11 and Fig. 9c). There is also a striking analogy between our $\pi\pi$ mass spectra and the results obtained by J. Kirtz et al. (Ref. 12 and Fig. 9d) for the $\pi^+\pi^-$ mass spectrum in the reaction $\pi^- p \rightarrow \pi^+\pi^- n$ at 360 MeV.

Several hypothesis have been proposed to interpret these anomalies. One of them assumes the existence of a scalar $\pi\pi$ resonance ($I^G J^P = 0^+0^-$) at M $\sim$ 400 MeV (Ref. 13), the so-called σ meson.

To get a better interpretation of the overall data, we have therefore been lead to introduce tentatively an additional physical phenomenon under the form of a Breit-Wigner form factor in the ($\pi\pi$) spectrum. Conserving the assignment $I^G J^P(E) = 0^+0^-$, we obtain (curves β) :

1) $\bar{p}p \rightarrow E^o\pi^+\pi^-$ $\chi^2 = 22.5$ when $\langle\chi^2\rangle = 19$
(74$\pm$5) o/o of ^1S_o initial state
(99$\pm$1) o/o of $\ell(\pi\pi) = 0$
(50$\pm$10) o/o of the dipion exterior to the E-meson are attributed to a resonance described by the Breit-Wigner formula with :
$M = 445 \pm 10$ MeV
$\Gamma = 65 \pm 10$ MeV

2) $\bar{p}p \rightarrow E^o\pi^o\pi^o$ $\chi^2 = 4.5$ when $\langle\chi^2\rangle = 11$
(60$\pm$10) o/o of the dipion in the σ^o resonance
$M = 460 \pm 20$ MeV
$\Gamma = 80 \pm 20$ MeV

These last results indicate that the σ meson might be present in the final state $\bar{p}p \rightarrow E^o\pi\pi$.

8. Conclusion

The analysis we have presented in this paper on the 5 body annihilations $\bar{p}p \rightarrow K\bar{K}3\pi$ is consistent with the assumption that the ($K\bar{K}\pi$) enhancement is really a resonance : Table VI gives a summary of its properties :

TABLE VI

Properties of the E meson

Mass : 1425 ± 7 MeV

$I^G J^P$: $0^+ 0^-$

Width : 80 ± 10 MeV

Observed decay modes :

$E^o \rightarrow K^* \bar{K}$ (and $\bar{K}^* K$) : (50 ± 10) o/o

$E^o \rightarrow (K\bar{K})\pi$: (50 ± 10) o/o

$(K\bar{K})$ means here a $(K\bar{K})$ resonance with

$M(K\bar{K}) = 1000$ MeV

$\Gamma(K\bar{K}) = 70$ MeV

Observed production modes :

$\bar{p}p \rightarrow E^o \pi\pi$ with $E^o \rightarrow K\bar{K}\pi$:

^1S_o initial state : 2810 ± 200 events, rate $= 2. \pm .2 \times 10^{-3}$

$^3S_1$ initial state : 824 ± 80 events, rate $= .6 \pm .06 \times 10^{-3}$

The fact that the ^1S_o initial state gives a larger contribution to the production of the E than $^3S_1$ initial state can be explained by the presence of centrifugal barriers in the latter case (the orbital angular momentum of the E with respect to the recoil dipion must be at least 1 for $^3S_1$ initial state whereas it is 0 for ^1S_o).

Another consequence of the quantum numbers proposed for the E meson is to forbid the production mode :

$\bar{p}p \rightarrow E^o \pi^o$.

The final state being in this case purely C = +1, the only possible initial state would be ^1S_o but the reaction is then forbidden by parity conservation since ^1S_o is 0^- whereas the spin-parity of the final state are related by : $P = (-1)^L$ (L being the orbital angular momentum of the E with respect to the recoil dipion). These observations may explain why the E meson is only produced in 5 body annihilations.

Of course, to reinforce the hypothesis of a resonance, it would be interesting to observe other decay modes of the E-meson : the simplest ones seem to be 4π and $\eta\pi\pi$ if our determination of its quantum numbers is correct.

It may be worthwhile to compare these predictions with an experimental result obtained by A. Bettini et al. (Ref. 14) which suggests the existence of a neutral (4π) enhancement at $M \sim 1400$ MeV with $\Gamma \sim 80$ MeV in $\bar{p}n \rightarrow 5\pi$ annihilations.

In principle, one cannot exclude, a priori, the triangular singularity mechanism as studied in particular by M. Month (Ref. 15) to explain such a $(K\bar{K}\pi)$ enhancement : however, our experimental results do not completely agree with such a mechanism since, in particular, the decay $E^0 \rightarrow K^*\bar{K}$ is observed even outside the interference region of the two $K^*\bar{K}$ and $\bar{K}^*K$ amplitudes. Moreover, C. Schmid (Ref. 16) has shown that this mechanism cannot lead to such a large enhancement : it may, on the other hand, strengthen the production of the resonance. One should also notice that such a triangular singularity affects the charged $(K\bar{K}\pi)$ system as well as the neutral one, while our experimental results do not show any effect in the charged $(K\bar{K}\pi)$ system.

One may object that the E meson, with the quantum numbers proposed above, does not fill any hole in the usual classification of the mesons; while this objection is not really valid in terms of SU_3, for which it is always possible to add a new representation, in particular a representation 1 (which is sufficient for an $I = 0$ particle), it is perhaps more difficult to reconcile the existence of a tenth pseudoscalar particle (3π, 2K, $2\bar{K}$, η, η', E) with the quark-antiquark model proposed by R.H. Dalitz for the mesons.

One can notice that with the E^0, we have now three mesons which have the same angular quantum numbers : $I^G J^P = 0^+0^-$: $\eta(550)$, $\eta'(960)$, E(1425). They are perhaps the three first terms of a series of excited 0^- levels differing by their "radial" quantum numbers. When discussing the possibility of the presence of the σ-meson in our data (see Chapter 7), we have already mentioned the analogies between the two processes : $\bar{p}p \rightarrow E\pi\pi$ and $\eta' \rightarrow \eta\pi\pi$.

Acknowledgements

We should like to express our thanks to Profs. B. Gregory, L. Leprince-Ringuet and J. Teillac for their interest and support, and to Profs. R. Armenteros, Ch. Peyrou and J. Prentki for many stimulating discussions.

PS/5665/rmn

Appendix

ℓ, L, J are the angular momenta corresponding to the decomposition k, K, P.

A. Initial state ^1S_o

$J^P(E) = 0^-$

$\ell = 0,\quad L = 0,\ J = 0,\ M_o = 1$

$\ell = 2,\quad L = 2,\ J = 0,\ M_2 = (k^ik^j - \frac{1}{3}\,\delta^{ij}k^2)(K^iK^j - \frac{1}{3}\delta^{ij}K^2) = (\vec{k}.\vec{K})^2 - \frac{1}{3}\,k^2K^2 .$

$$|M(^1S_o)|^2 = \alpha^2M_o^2 + \beta^2M_2^2 + 2\alpha\beta\cos\omega\, M_oM_2$$

integrate over

$$d\Omega_k \qquad W_2^o(\cos\varphi) = 1$$

$$d\Omega_K \qquad W_3^o(\cos\psi) = 1$$

$$d\Omega_P \qquad W_4^o(\cos\chi) = \alpha^2+\beta^2\,(3\cos^2\chi - 1)^2 + 2\alpha\beta\cos\omega\,(3\cos^2\chi - 1)$$

$J^P(E) = 1^+$

$\ell = 0,\ L = 1,\ J = 1,\ M_o = \vec{P}.\vec{P}$

$\ell = 2,\ L = 1,\ J = 1,\ M_2 = P^i(k^ik^j - \frac{1}{3}\,\delta^{ij}k^2)K^j = (\vec{P}.\vec{k})(\vec{k}.\vec{K}) - \frac{1}{3}\,k^2\,(\vec{P}.\vec{K})$

$$|M(^1S_o)|^2 = \alpha^2M_o^2 + \beta^2M_2^2 + 2\alpha\beta\cos\omega\, M_oM_2$$

integrate over

$$d\Omega_k \qquad W_2^o(\cos\varphi) = \alpha^2\cos^2\varphi + \frac{\beta^2}{45}\,(3 + \cos^2\varphi)$$

$$d\Omega_K \qquad W_3^o(\cos\psi) = \frac{\alpha^2}{3} + \frac{\beta^2}{27}\,(3\cos^2\psi + 1) + \frac{2}{9}\,\alpha\beta\cos\omega\,(3\cos^2\psi - 1)$$

$$d\Omega_P \qquad W_4^o(\cos\chi) = \frac{\alpha^2}{3} + \frac{\beta^2}{27}\,(3\cos^2\chi + 1) + \frac{2}{9}\,\alpha\beta\cos\omega\,(3\cos^2\chi - 1)$$

$J^P(E) = 2^-$

$\ell = 0,\ L = 2,\ J = 2,\ M_o = (K^iK^j - \frac{1}{3}\,\delta^{ij}K^2)(P^iP^j - \frac{1}{3}\,\delta^{ij}P^2) = (\vec{K}.\vec{P})^2 - \frac{1}{3}\,K^2P^2$

$\ell = 2,\ L = 0,\ J = 2,\ M_2 = (k^ik^j - \frac{1}{3}\,\delta^{ij}k^2)(P^iP^j - \frac{1}{3}\,\delta^{ij}P^2) = (\vec{K}.\vec{P}) - \frac{1}{3}\,k^2P^2$

$$|M(^1S_o)|^2 = \alpha^2M_o^2 + \beta^2M_2^2 + 2\alpha\beta\cos\omega\, M_oM_2$$

integrate over

$$d\Omega_k \qquad W_2^o(\cos\varphi) = \alpha^2\,(\cos^2\varphi - \tfrac{1}{3})^2 + \frac{4\beta^2}{45}$$

$d\Omega_K \qquad W_3^o(\cos\psi) = \frac{4\alpha^2}{45} + \beta^2 (\cos^2\psi - \frac{1}{3})^2$

$d\Omega_P \qquad W_4^o(\cos\chi) = \frac{4\alpha^2}{45} + \frac{4\beta^2}{45} + \frac{4\alpha\beta}{45} \cos\omega\,(3\cos^2\chi - 1)$

B. <u>Initial state $^3S_1$</u>

We limit ourselves to the lowest angular momentum decomposition.

<u>$J^P(E) = 0^-$</u>

$\ell = 1$, $L = 1$, $J = 0$, $\vec{M} = \vec{k} \times \vec{K}$

$$|\overrightarrow{M(^3S_1)}|^2 = k^2K^2 - (\vec{k}.\vec{K})^2$$

integrate over

$d\Omega_k \qquad W_2^1(\cos\varphi) = 1$

$d\Omega_K \qquad W_3^1(\cos\psi) = 1$

$d\Omega_P \qquad W_4^1(\cos\chi) = \sin^2\chi$

<u>$J^P(E) = 1^+$</u>

$\ell = 1$, $L = 0$, $J = 1$, $\vec{M} = \vec{k} \times \vec{P}$

$$|\overrightarrow{M(^3S_1)}|^2 = k^2P^2 - (\vec{k}.\vec{P})^2$$

integrate over

$d\Omega_k \qquad W_2^1(\cos\varphi) = 1$

$d\Omega_K \qquad W_3^1(\cos\psi) = \sin^2\psi$

$d\Omega_P \qquad W_4^1(\cos\chi) = 1$

<u>$J^P(E) = 2^-$</u>

There are two amplitudes $\vec{M}_1$ and $\vec{M}_2$ corresponding respectively to $\ell + L = 1$ and $\ell + L = 2$.

$\ell = 1$, $L = 1$, $J = 2$,

$$M_1^m = (\epsilon^{ij\ell} k^j K^\ell)(P^i P^m - \frac{1}{3}\delta^{im} P^2)$$

$$M_2^m = \epsilon^{mi\ell}(k^i K^j + K^i k^j - \frac{2}{3}\delta^{ij}(\vec{k}.\vec{K})(P^j P^\ell - \frac{1}{3}\delta^j P^2)$$

or

$$\vec{M}_1 = \vec{P}\,(\vec{P}.(\vec{k} \times \vec{K})) - \frac{1}{3}\,(\vec{k} \times \vec{K})\;.\;P^2$$

$$\vec{M}_2 = (\vec{P} \times \vec{K})(\vec{P}.\vec{k}) + (\vec{P} \times \vec{k})(\vec{P}.\vec{K})$$

$$|\vec{M}(^3S_1)\,|^2 = A^2M_1^2 + B^2M_2^2 + 2AB\cos\delta\,\vec{M}_1.\vec{M}_2$$

$$\vec{M}_1^2 = \frac{1}{3}\,P^2(\vec{P}.(\vec{k} \times \vec{K}))^2 + \frac{1}{9}\,P^4\,(\vec{k} \times \vec{K})^2$$

$$\vec{M}_2^2 = P^2K^2(\vec{P}.\vec{k})^2 + P^2k^2(\vec{P}.\vec{K})^2 + 2P^2(\vec{k}.\vec{K})(\vec{P}.\vec{k})(\vec{P}.\vec{K}) - 4(\vec{P}.\vec{K})^2\,(\vec{P}.\vec{k})^2$$

$$\vec{M}_1.\vec{M}_2 = -\frac{1}{3}\,P^2k^2\,(\vec{P}.\vec{K})^2 + \frac{1}{3}\,P^2K^2\,(\vec{P}.\vec{k})^2$$

$d\Omega_k$ $$W_2^1\,(\cos\varphi) = \frac{A^2}{27}\,(-3\cos^2\varphi + 5) + \frac{B^2}{3}\,(1 + \cos^2\varphi\,) + \frac{2AB}{9}\,\cos\delta\,(1 - 3\cos^2\;\;)$$

$d\Omega_K$ $$W_3^1\,(\cos\psi) = \frac{A^2}{27}\,(-3\cos^2\psi + 5) + \frac{B^2}{3}\,(1 + \cos^2\psi) - \frac{2AB}{9}\,\cos\delta\,(1 - 3\cos^2\psi)$$

$d\Omega_P$ $$W_4^1\,(\cos\chi) = \frac{2A^2}{9}\,\sin^2\chi + \frac{2B^2}{15}\,(3 + \cos^2\chi)$$

<u>Remark</u> - To integrate, we used the following formulae, $\vec{V} = (V_1, V_2, V_3)$ being a three vector :

$$<V_i^2>_v = \frac{\int V_i^2\,d\Omega_v}{\int d\Omega_v} = \frac{V^2}{3}$$

$$<V_iV_j>_v = \frac{\int V_iV_j\,d\Omega_v}{\int d\Omega_v} = 0$$

$$<V_i^4>_v = \frac{\int V_i^4\,d\Omega_v}{\int d\Omega_v} = \frac{V^4}{5}$$

$$<V_i^3V_j>_v = 0$$

$$<V_i^2V_j^2>_v = \frac{V^4}{15}$$

$$<(\vec{V}.\vec{A})(\vec{V}.\vec{B})>_v = \frac{1}{3}\,(\vec{A}.\vec{B})\,V^2$$

$$<(\vec{V}.\vec{A})^2(\vec{V}.\vec{B})^2>_v = \left[\frac{3}{15}\,(\vec{A}.\vec{B})^2 + \frac{1}{15}\,(\vec{A} \times \vec{B})^2\right]\,V^4$$

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Figure Captions

Fig. 1 $\bar{p}p \rightarrow K_1^o K^{\pm} \pi^{\mp} \pi^+ \pi^-$

(1a) $(K\pi)$ effective mass spectra. The dark line gives the distribution of $(K\pi)_{I=1/2}$ (4 combinations per event) whereas the grey line gives the distribution of $(K\pi)_{I=3/2}$ (2 combinations per event)

(1b) $(K\bar{K})$ effective mass spectrum.

(1c) $(K\bar{K}\pi)$ effective mass spectra. The dark line gives the distribution of $(K\bar{K}\pi)_{Q=0}$ (2 combinations per event) whereas the grey line gives the distribution of $(K\bar{K}\pi)_{Q=2}$ (1 combination per event). Curves α and β correspond respectively to phase-space and 100 o/o of K^* production with constructive interferences effects.

(1d) $(K\bar{K}\pi)$ effective mass spectrum obtained when subtracting the $(K\bar{K}\pi)_{Q=2}$ distribution from the $(K\bar{K}\pi)_{Q=0}$ one.
The curve represents the fit obtained for a Breit-Wigner distribution with : $M = 1415$ MeV, $\Gamma = 77$ MeV.

Fig. 2 $\bar{p}p \rightarrow K_1^o K^{\pm} \pi^{\mp} \pi^o \pi^o$

$(K\bar{K}\pi)$ effective mass spectrum.
The curve represents the fit obtained for a Breit-Wigner distribution with : $M = 1426$ MeV, $\Gamma = 81$ MeV.

Fig. 3 $\bar{p}p \rightarrow K_1^o K_1^o \pi^+ \pi^- \pi^o$

(3a) $3\pi^+\pi^-\pi^o)$ effective mass spectrum.

(3b) $(K\bar{K}\pi)$ effective mass spectra. The dark line gives the distribution of $(K\bar{K}\pi)_{Q=0}$ (1 combination per event), whereas the grey line gives the distribution of $(K\bar{K}\pi)_{Q=\pm 1}$ (2 combinations per event).
The curve α represents the effect of the ω^o production on the $(K\bar{K}\pi)$ spectrum.
The curve β is obtained when adding to the ω^o production (70 o/o) 18 o/o of background (phase-space) and 12 o/o of E^o production : it corresponds to the best fit.

Fig. 4 $\bar{p}p \rightarrow K_1^o\pi^+\pi^-$ $(K^o\pi^o)$

(4a) $(K\bar{K}\pi)^o$ effective mass spectrum.

(4b) $(K\bar{K}\pi)^o$ effective mass spectrum obtained when subtracting the $(K_1^oK_1^o\pi^o)$ distribution of reaction (3) from the $(K\bar{K}\pi)^o$ distribution of reaction (4) : it corresponds to the $(K_1^oK_2^o\pi^o)$ distribution of the reaction $\bar{p}p \rightarrow K_1^oK_2^o\pi^+\pi^-\pi^o$.

Fig. 5 $\bar{p}p \rightarrow K^+K^-\pi^+\pi^-\pi^o$

$(K\bar{K}\pi)$ effective mass spectra. The solid line gives the distribution of $(K\bar{K}\pi)_{Q=0}$ (1 combination per event), whereas the dotted line gives the distribution of $(K\bar{K}\pi)_{Q=\pm 1}$ (2 combinations per event).

Fig. 6 Decay of the E meson :

a_1, b_1, c_1 refer to reaction (1) : $\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^+\pi^-$ when the $(K\bar{K}\pi)^o$ effective mass squared satisfy the conditions : 1.84 GeV^2 < $M^2(K_1^oK^{\pm}K^{\mp})$ < 2.14 GeV^2. This selection is made in order to get distributions corresponding as close as possible to the E-decay.

a_2, b_2, c_2 refer to reaction (2) : $\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^o\pi^o$. The same conditions as for reaction (1) are requested.

(a) : $(K\pi)$ effective mass spectra (2 combinations per event).

(b) : $(K\bar{K})$ effective mass spectra.

(c) : W_1 $(\cos\theta)$: angular distribution of the K mesons in the $(K\bar{K})$ centre of mass. For these angular distributions, an additional condition is required, namely : $M^2(K_1^oK^{\pm})$ < 1.08 GeV^2.

a_3, b_3, c_3 : theoretical curves for $M^2(K\pi)$, $M^2(K\bar{K})$, $W_1(\cos\theta)$ distributions corresponding to the decay : $E \rightarrow K^*\bar{K}$ (and $\bar{K}^*K$) for $J^P(E)$ = 0^-, 1^+, 2^- (solid curves : 0^-, dotted curves : 1^+, mixed curves : 2^-). The curves drawn on a_1, b_1, c_1, a_2, b_2 and c_2 distributions correspond to the hypothesis $J^P(E) = 0^-$, with : $E \rightarrow K^*\bar{K}$ (and $\bar{K}^*K$) : 50 o/o

$E \rightarrow (K\bar{K})\pi$: 50 o/o

where $(K\bar{K})$ stands for a resonance with M = 1000 MeV and Γ = 70 MeV.

Fig. 7 E^o production.

Angular distributions for the two step process : $\bar{p}p \rightarrow E^o\pi\pi$, $E^o \rightarrow (K\bar{K})\pi$, where E^o is defined by 1.84 GeV^2 < $M^2(K_1^oK^{\pm}\pi^{\mp})$ < 2.14 GeV^2

and $(K\bar{K})$ by $M^2(K\bar{K}) < 1.08\ GeV^2$.

$7a_1$, $7a_2$: W_2 $(\cos\varphi)$ angular distributions respectively for reaction (1) $\bar{p}p$ $E^0\pi^+\pi^-$ and reaction (2) : $\bar{p}p \rightarrow E^0\pi^0\pi^0$. φ is the decay angle of the E^0 into $(K\bar{K})$ and π, in the centre of mass of the E^0. (see Fig. 7d).

$7b_1$: $W_3(\cos\psi)$ angular distribution for reaction (1) : $\bar{p}p \rightarrow E^0\pi^+\pi^-$. ψ is the angle between the vector $\vec{p}$ characterizing the decay of the E into $(K\bar{K})$ and π, and the vector $\vec{k}$ characterizing the decay of the $(\pi_2\pi_3)$ dipion exterior to the E : ψ is measured in the total centre of mass.

$7c_1$: $W_4(\cos\chi)$ angular distribution for reaction (1) : $\bar{p}p \rightarrow E^0\pi^+\pi^-$. χ is the decay angle of the $(\pi_2\pi_3)$ dipion into π_2 and π_3, in the centre of mass of $(\pi_2\pi_3)$.

7d : summarizes the definitions used for angles, momenta and angular momenta in the study of the E production.

Fig. 8 Effective mass spectra of the dipion produced with the E.

8a refers to reaction (1) : $\bar{p}p \rightarrow E^0\pi^+\pi^-$

8b refers to reaction (2) : $\bar{p}p \rightarrow E^0\pi^0\pi^0$

Since for reaction (1) there are two $(K_1^0K^{\pm}\pi^{\mp})$ neutral combinations, we have selected for the distribution (8a) the combination which corresponds to the $M^2(K\bar{K}\pi)^0$ the closest to the central value of the $E(M^2 = 2.0\ GeV^2)$. We also introduce the conditions : $1.84\ GeV^2 < M^2(K\bar{K}\pi) < 2.14\ GeV^2$ both for distribution (8a) and (8b).

Curves α, and β, are explained in the text.

Fig. 9 Effective mass spectra of the dipion

(9a) : for reaction $\bar{p}p \rightarrow E^0\pi^+\pi^-$

(9b) : for reaction $\bar{p}p \rightarrow E^0\pi^0\pi^0$

(9c) : for the decay $\eta' \rightarrow \eta\pi\pi$ (Ref. 11)

(9d) : for reaction $\pi^-p \rightarrow \pi^+\pi^-n$ at 360 MeV (Ref. 12)

DIA 33425
PS/5665

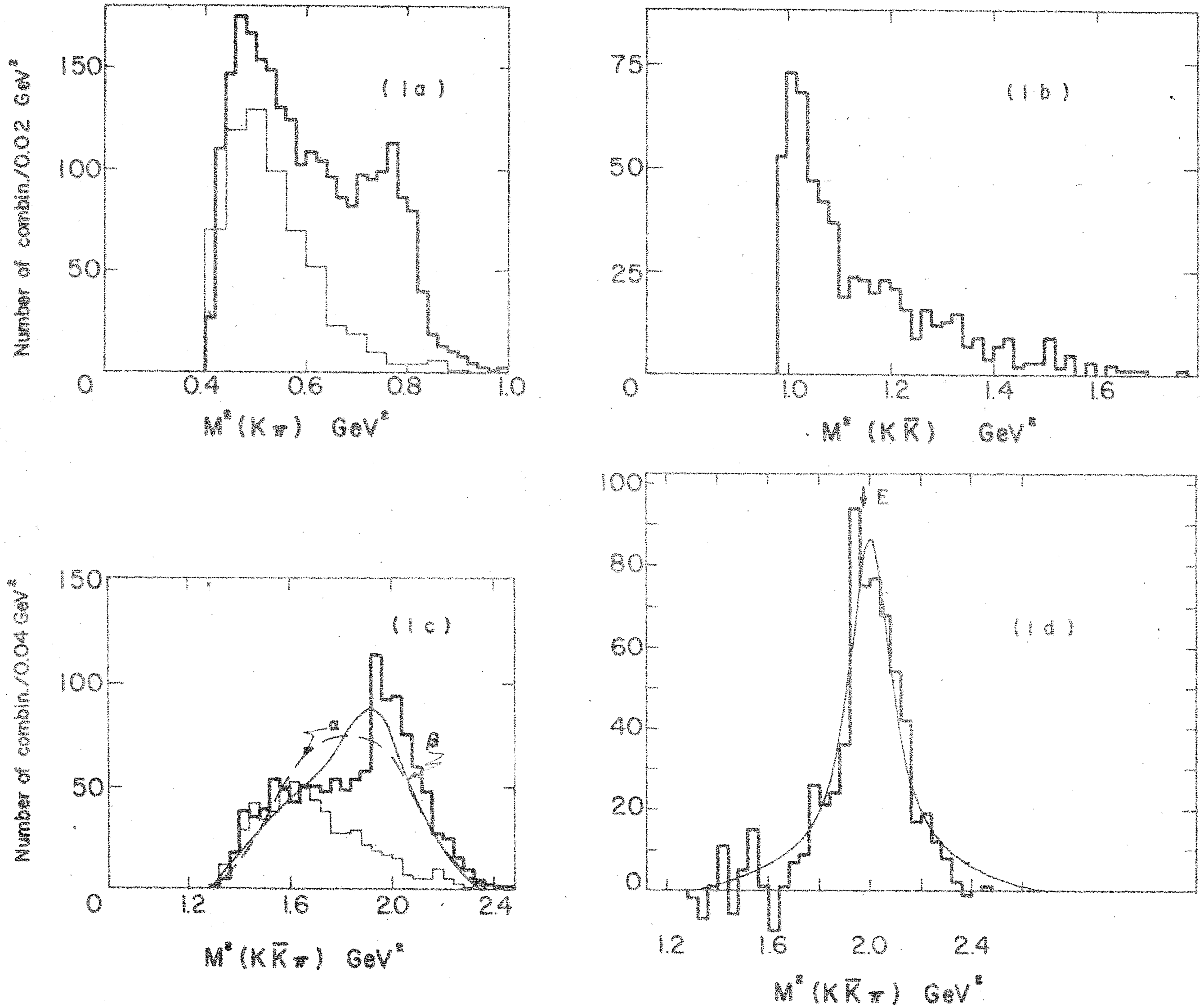

Fig 1

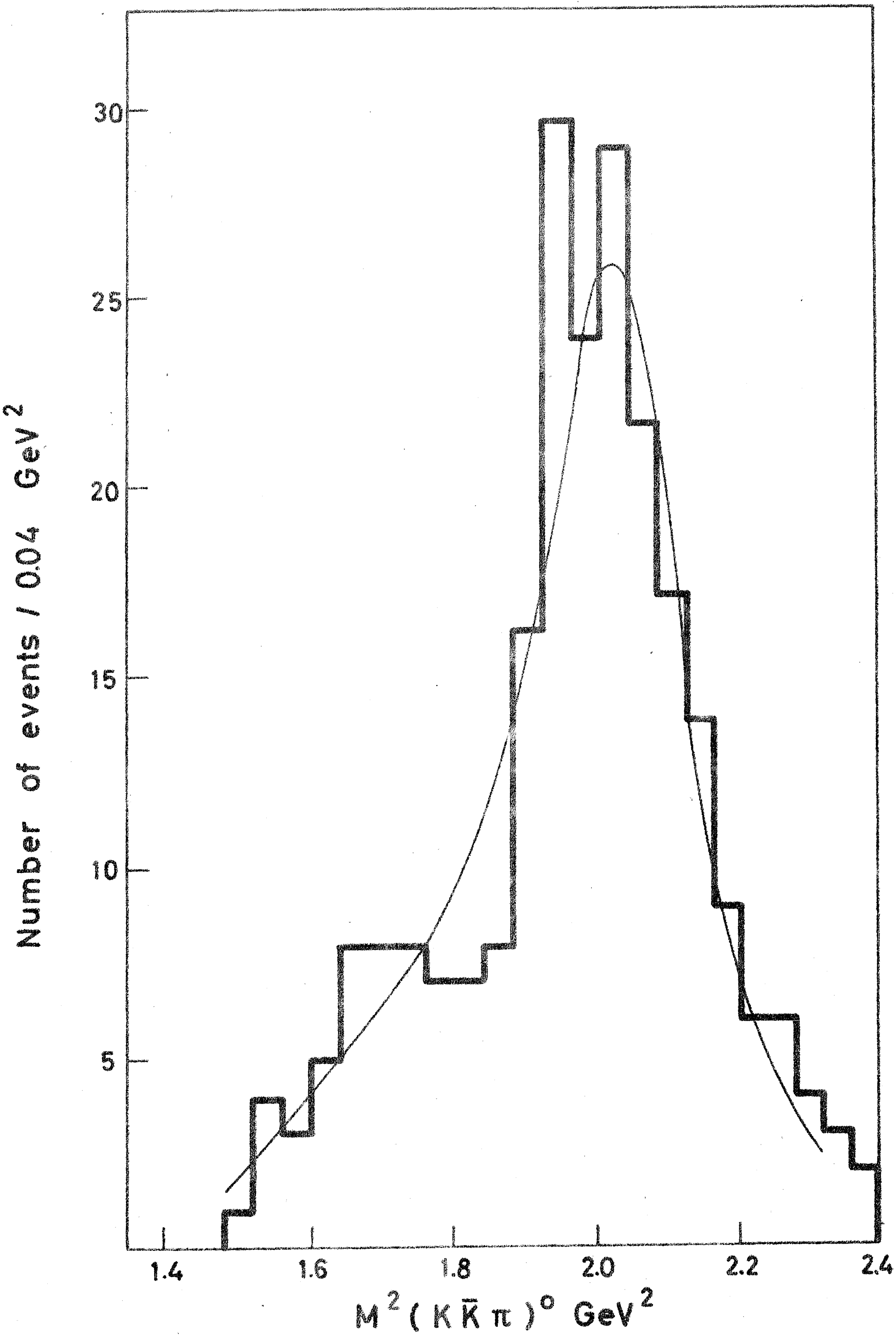

Fig 2

DIA 28419 PS/5665

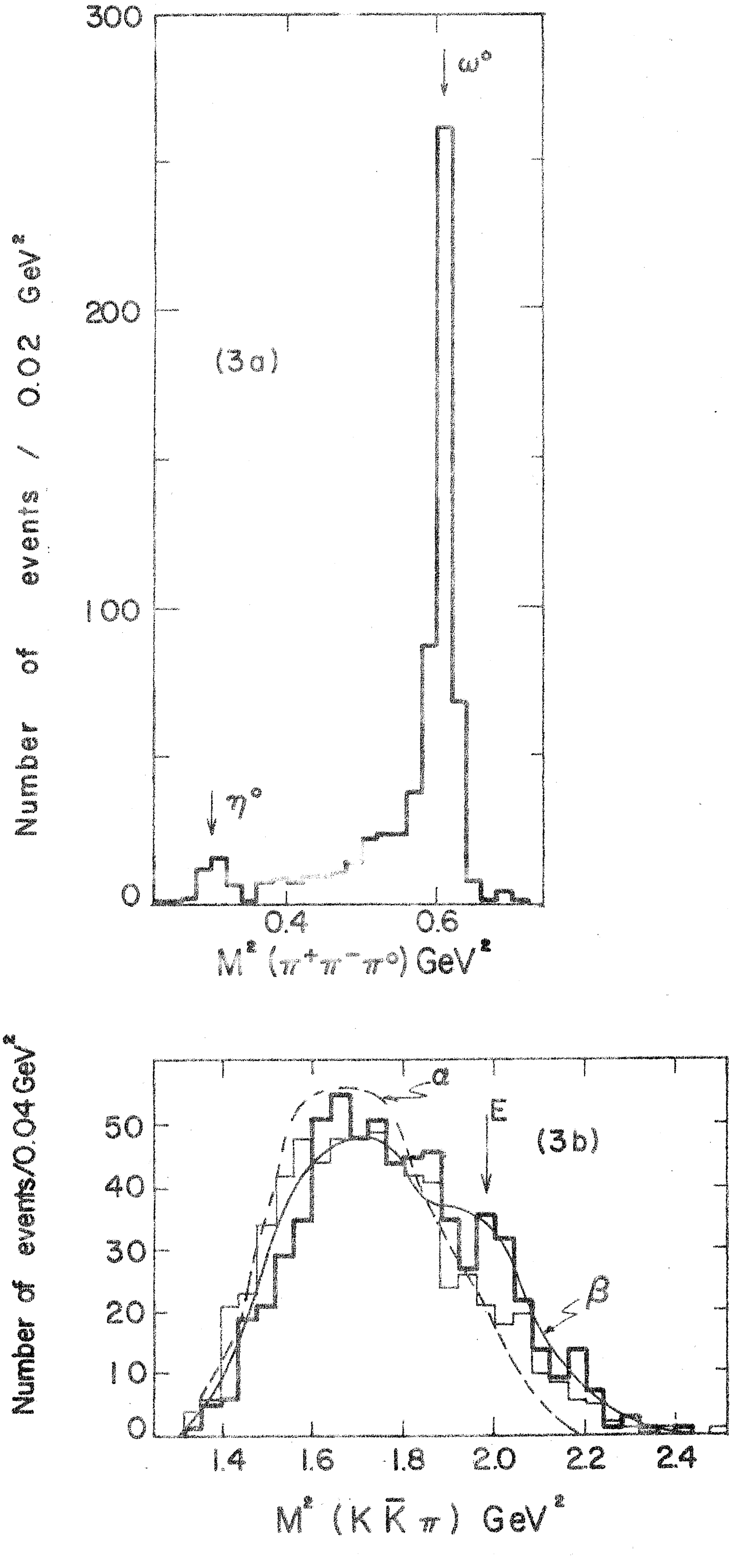

Fig 3

DIA 28423 PS/5665

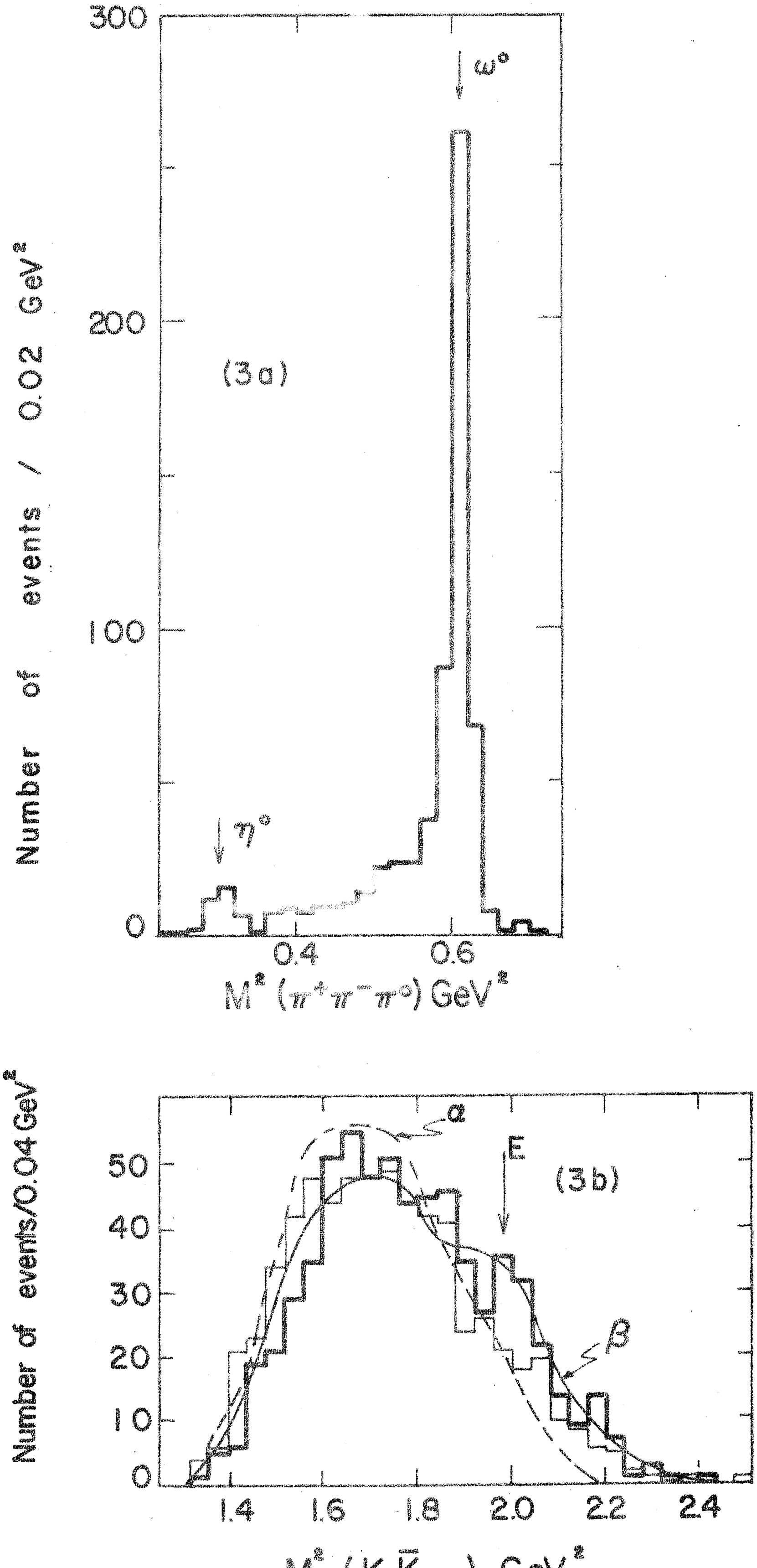

Fig 3

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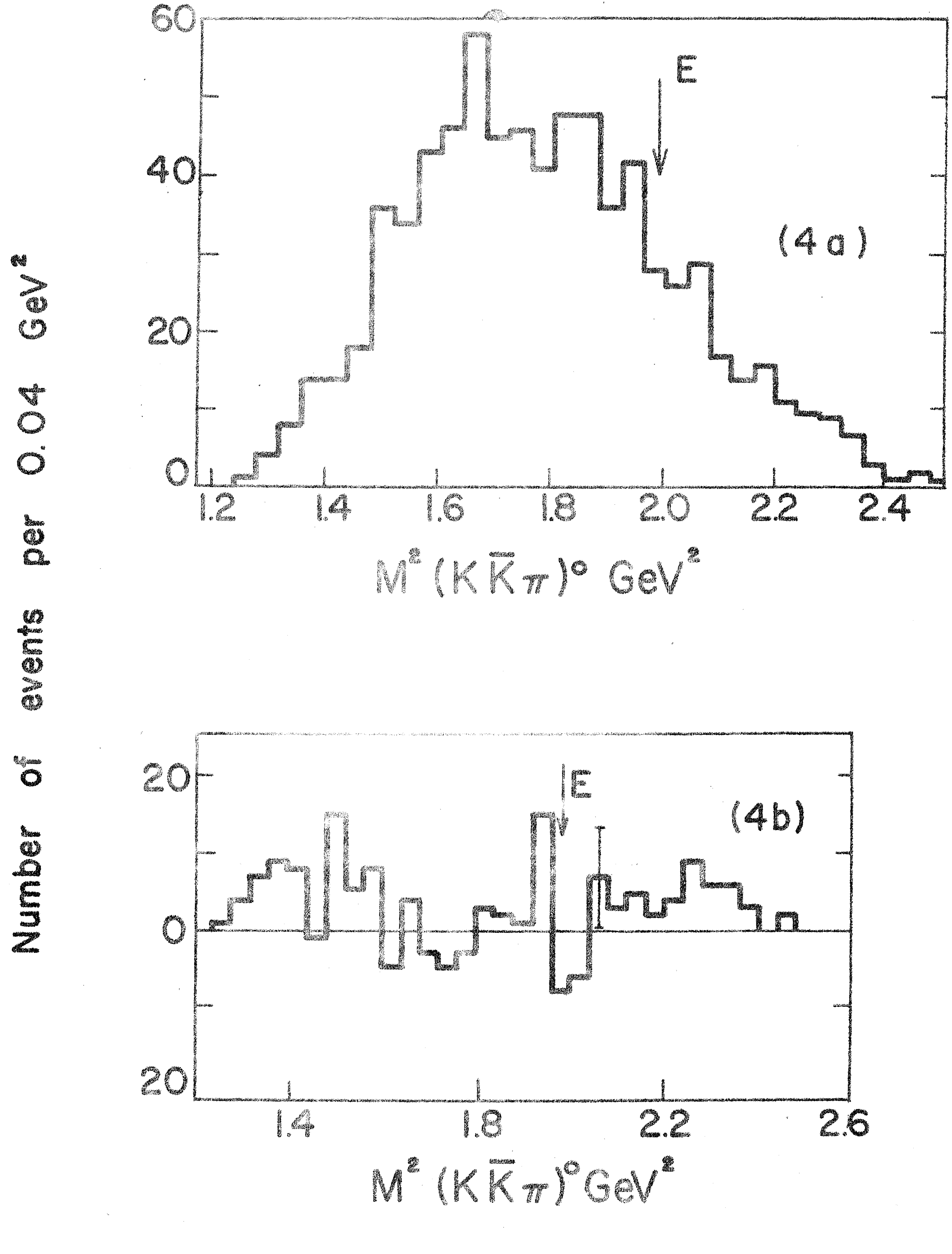
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40
20
0
E
(4a)
1.2
1.4
1.6
1.8
2.0
2.2
2.4
M² (KK̄π)° GeV²
20
0
20
E
(4b)
1.4
1.8
2.2
2.6
M² (KK̄π)° GeV²

Fig 4

PS/5665

PS/5665

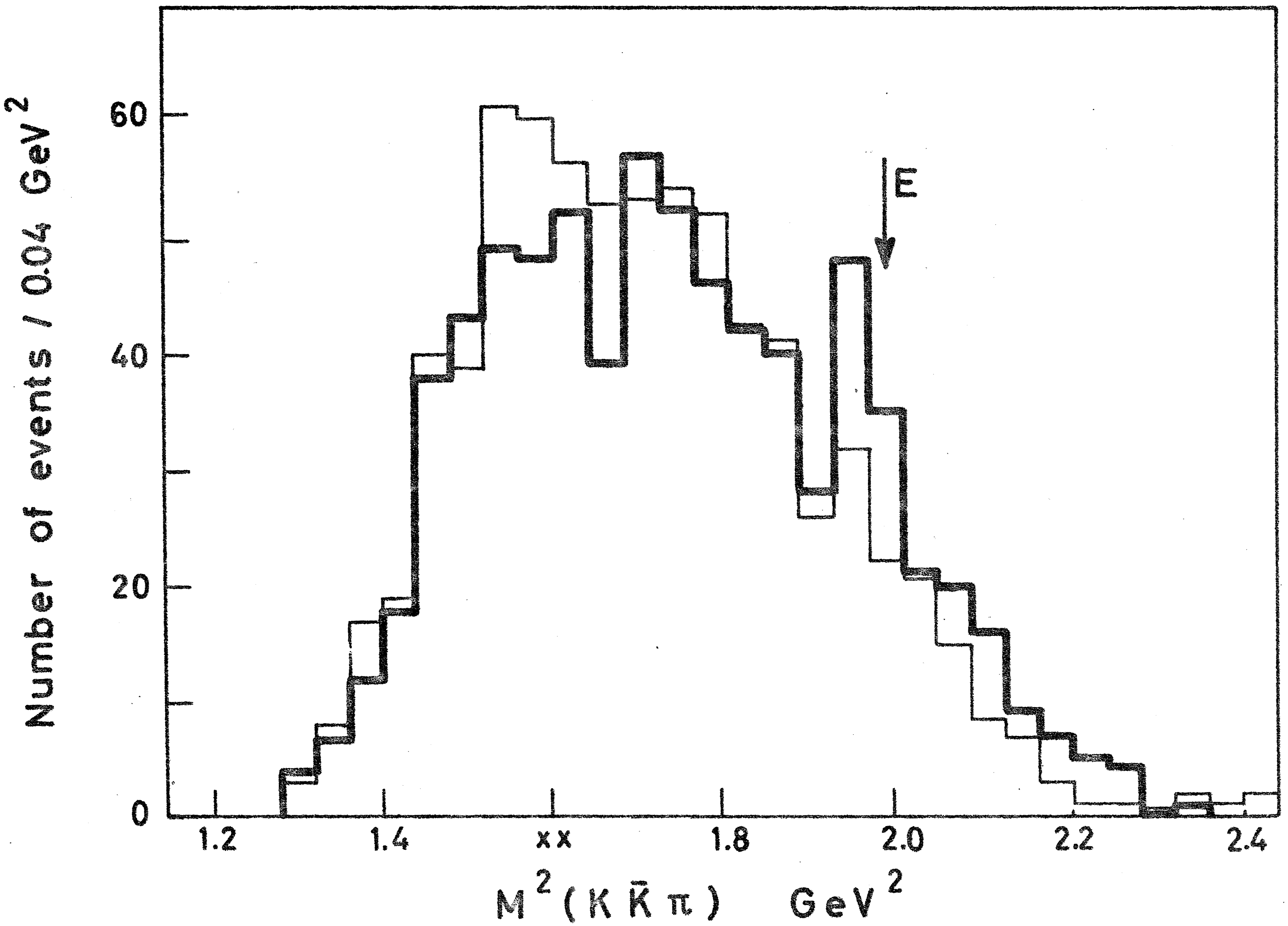
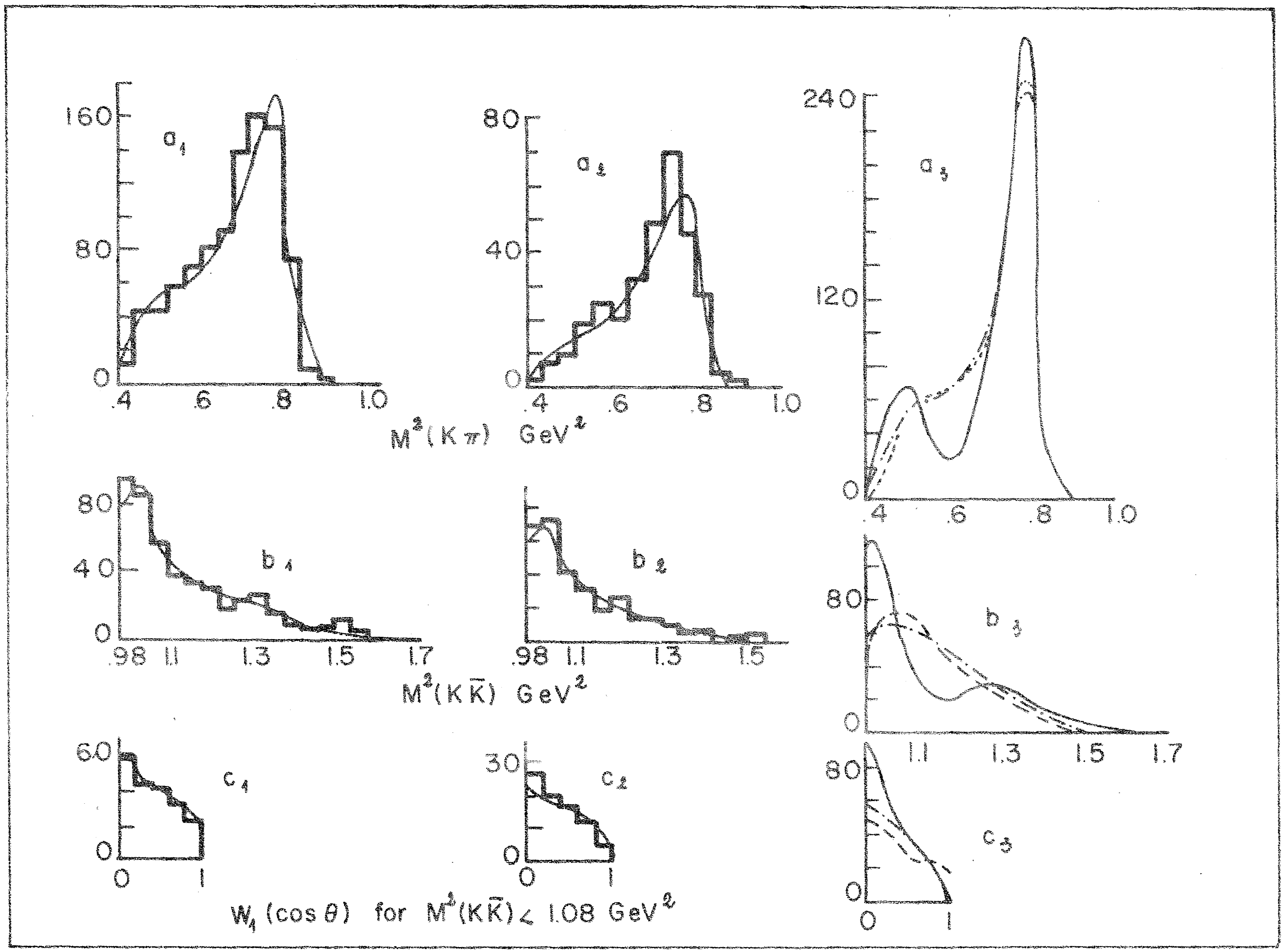


Fig 5

DIA 28421



a_1
a_2
a_3
$M^2(K\pi)$ GeV^2
b_1
b_2
b_3
$M^2(K\bar{K})$ GeV^2
c_1
c_2
c_3
$W_1(\cos\theta)$ for $M^2(K\bar{K}) < 1.08$ GeV^2

Fig 6

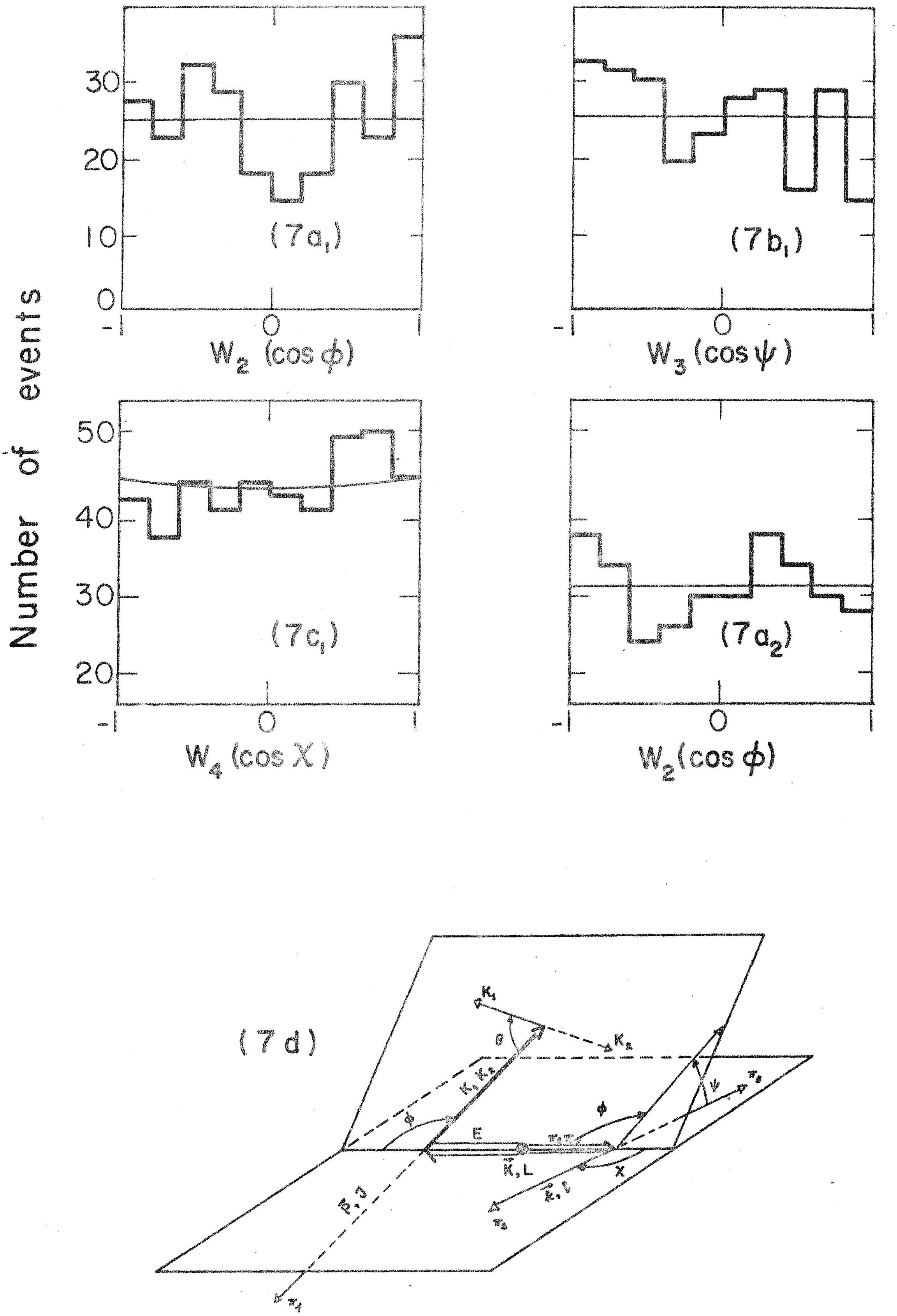


Fig 7

DIA 28427 PS/5665

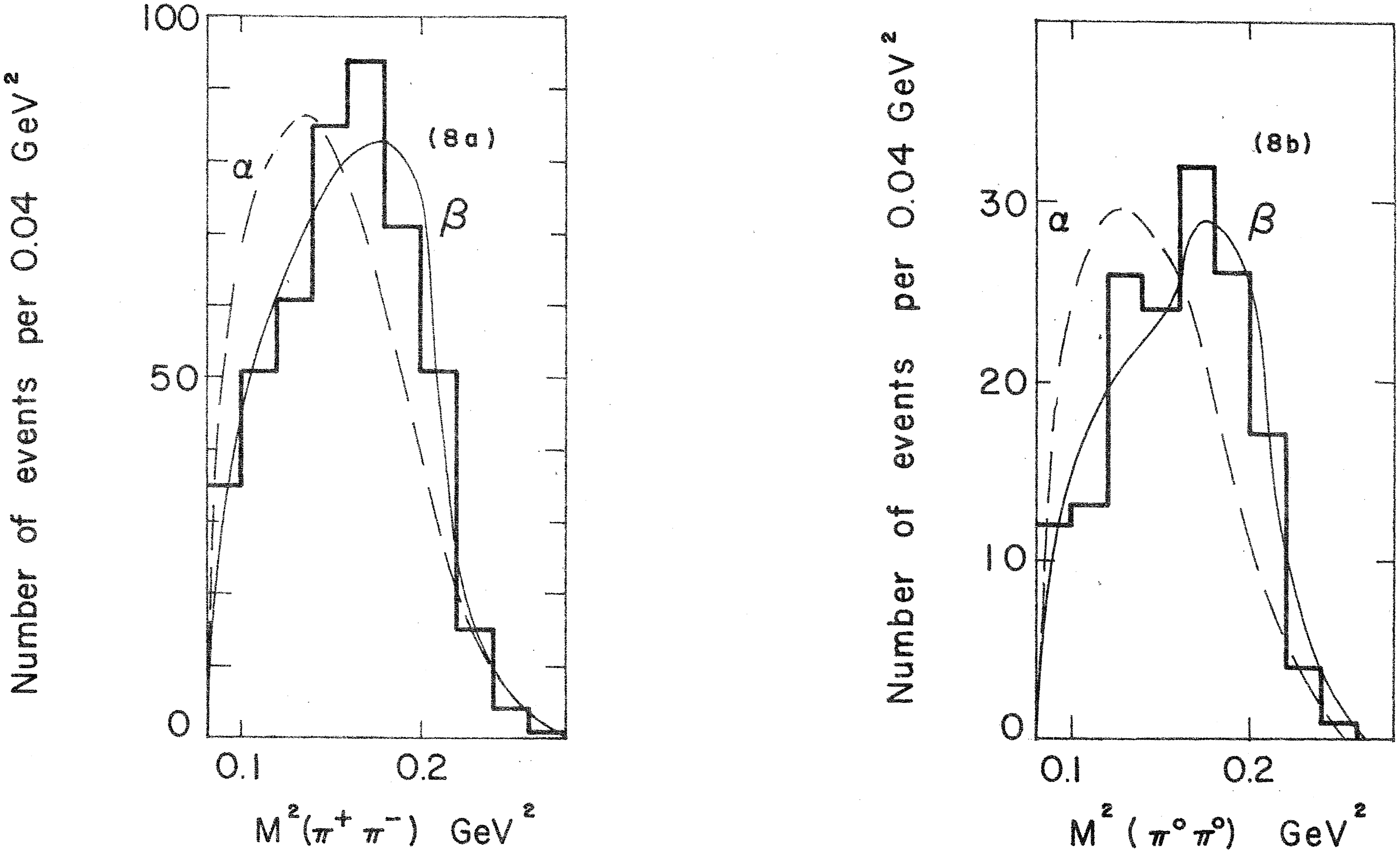

100
50
0
Number of events per 0.04 GeV²
(8a)
α
β
0.1
0.2
M²(π⁺ π⁻) GeV²
30
20
10
0
Number of events per 0.04 GeV²
(8b)
α
β
0.1
0.2
M² (π° π°) GeV²

Fig 8

PS/5665

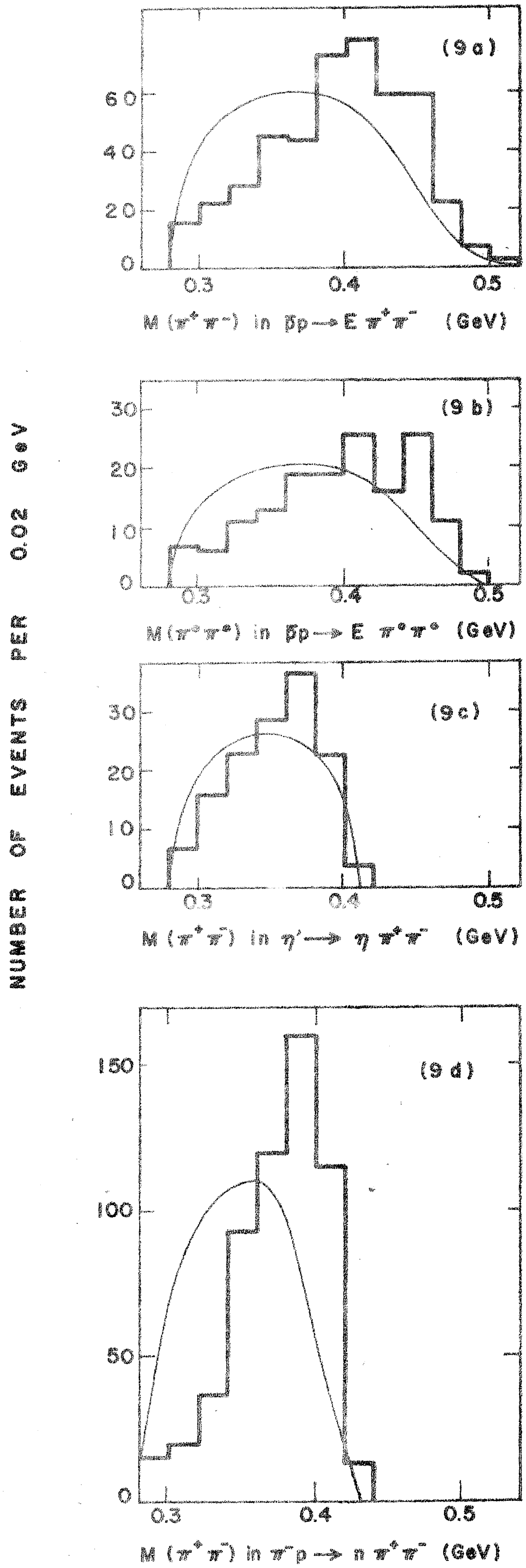


Fig 9

DIA 28426 PS/5665