CERN/TC/PHYSICS 65-3
2.2.1965

Study of a (KKπ) enhancement in $K\bar{K}3\pi$ annihilations of antiprotons at rest

R. Armenteros, D.N. Edwards[+], T. Jacobsen, L. Montanet, J. Vandermeulen[++]
CERN, Geneva,

Ch. d'Andlau, A. Astier, P. Baillon, J. Cohen-Ganouna, C. Defoix, J. Siaud, and P. Rivet,
Laboratoire de Physique Nucléaire,
Collège de France, Paris

Introduction

At the Siena Conference, we presented[(1)] evidence for a $(K\bar{K}\pi)$ resonance with a mass $\sim$ 1410 MeV and a width $\sim$ 60 MeV. It was observed in the following channel of $(\bar{p}\, p)$ annihilations at rest:

$$\bar{p}\, p \longrightarrow K_1^o\, K^{\pm}\, \pi^{\mp}\, \pi^+\, \pi^- \quad . \qquad (1)$$

Recently, all the measurements on the available film have been completed and a final sample of 316 events corresponding to channel (1) obtained.

This is to be compared with 144 events presented in the original publication.

In this paper we propose to :

a) show that the complete sample reproduces closely the initial results

b) discuss more thoroughly why we believe the enhancement to be more likely a resonance than a spurious effect

c) present the results of a search for the $(K\bar{K}\pi)$ enhancement in other $K\bar{K}3\pi$ final states, and finally

d) give the available information on the properties of the resonance.

[+] On leave of absence from Liverpool University

[++] Presently at Liège University

Experimental mass-squared distributions

As indicated in reference (1), the mass-squared distributions of all possible combinations between particles in the final state of channel 1 have been studied. Although deviations from phase space are observed everywhere, only the $(K\,\pi)_{I_3} = \pm 1/2$, $(K\,\bar{K})$ and $(K\bar{K}\pi)_{Q=0}$ systems show deviations which could, in principle, represent resonances with not too large widths ($\Gamma < 100$ MeV). These deviations happen, however, to be in close connection. Thus the $(K\,\pi)_{I_3} = \pm 1/2$ enhancement - which corresponds approximatively to the characteristics of the normal $K^*(888)$ - is contained within the $(K\bar{K}\pi)$ enhancement, while the $(K\bar{K})$ enhancement shows up near the $K^* - K^*$ overlapping region.

The first question that arises is the following: is it possible to account for the different observations by considering that the only true resonant effect is the well-established $K^*(888)$? In particular, the $M^2(K\bar{K}\pi)$ distribution should not - as we did at Siena - be compared with the expectation of pure invariant phase space but with a distribution taking into account the strong p-wave $(K\pi)$ interaction possible in the final state of channel 1[2]. We have tried to find this out after the procedure used by Bouchiat and Flamand[3] when considering the final state

$$\bar{p}\,p \longrightarrow K^o\,\overline{K^o}\,\pi^o\,.$$

We have computed the phase space integral

$$F\,(\mu^2) = \int |M|^2 \prod_{i=1}^{5} \frac{d^3\overline{p_i}}{2E_i} \quad \delta^4(\sum_1^5 p_i - P)\;\delta\,(S_{123} - \mu^2) \qquad (2)$$

taking a matrix element, M, of the form

$$M \propto \frac{1}{S_{13} - S^* + im^*\Gamma^*} + \frac{1}{S_{14}\cdots\cdot} + \frac{1}{S_{23}\cdots\cdots\cdot} + \frac{1}{S_{24}\cdots\cdot\cdot} \qquad (3)$$

where S_{ij} denoted the effective mass-squared of particles i and j and where the labelling is as follows :

$$\begin{matrix} K^o & K^- & \pi^+ & \pi^+ & \pi^- \\ 1 & 2 & 3 & 4 & 5 \end{matrix} \qquad\qquad \begin{matrix} \overline{K^o} & K^+ & \pi^- & \pi^- & \pi^+ \\ 1 & 2 & 3 & 4 & 5 \end{matrix}\,.$$

The $(K\pi)$ interaction is inserted in (3) in the form of the K^* (Breit-Wigner function defined by $m^* = 888$ and $\Gamma^* = 50$.)

The coherent addition of the amplitudes involving S_{13} and S_{14}, on the one hand, and S_{23} and S_{24}, on the other, follows from Bose statistics; however, (3) does not represent necessarily the complete amplitude, as we do not know the spin and parity of the system : adding coherently the two resulting amplitudes is not compulsory but gives the largest interference and leads, a priori, to a concentration of $(K^0 K^{\pm})$ masses at low values.

The result of integrating equation (2) is given in Figure 1 together with the experimental M^2 $(K\bar{K}\pi)$ distribution; in Figure 2 the result of a similar integration for the $M^2(K\bar{K})$ distribution is compared with the observed distribution. Clearly, the calculations do not reproduce the experimental results and, on this ground, we propose the existence of a strong $(K\bar{K}\pi)$ interaction or resonance which we call E.

Pais and Nauenberg[(4)], and later Oakes[(5)], have pointed out that the Peierls mechanism[(6)] $\bar{K}^* K \rightarrow \bar{K} K^*$ leads to an enhancement in $(K\bar{K}\pi)$ masses very close to our observed central value of 1415 MeV. Of the two really sensitive tests suggested : angular distribution of the emitted K with reference to the line of flight of the incident $\bar{K}$ and strong assymmetry (rapid rise to the maximum followed by a slow decrease beyond it) of the mass-spectrum, the first is not applicable to our experimental conditions while the second has only been worked out qualitatively[(5)] and does not, in particular, take account of phase space limitations. Thus, although, as we see below, the M^2 $(K\bar{K}\pi)$ distribution does not show any marked deviation from symmetry, we cannot exclude this interpretation.

Mass and width of the $E \rightarrow K\bar{K}\pi$

Inspection of the histogram M^2 $(K\bar{K}\pi)$ for total charge Q = 0 (two combinations per event) and Q = 2 (only one combination per event) suggests strongly the following simple model: one of the two M^2 $(K\bar{K}\pi)$ combinations with Q = 0 gives almost invariably a contribution to the enhancement centered at 2.0 GeV^2, the other Q = 0 and the Q = 2 combinations behave quite similarly and contribute only to the broad shoulder in the low mass region, which can then be considered to be the reflection of the resonant combination. Subtraction of the Q = 2 distribution from the Q = 0 should result then in a M^2 $(K\bar{K}\pi)$ distribution containing just the resonant effect. That this is compatible with the experimental results has been verified in a scatter diagram of the two $(K\bar{K}\pi)$ combinations with Q = 0; the number of double combinations falling within the peak agrees well with the model.

In Figure 3 the subtracted histogram is shown; it can be seen to fit reasonably well with the assumption of 100 o/o E-production in channel (1). The superimposed curve is the result of multiplying the expression (2) by a $(K\bar{K}\pi)$ Breit-Wigner function with $M = 1415$ MeV/c^2 and $\Gamma = 70$ MeV. A best fit has not been attempted but the errors in M and Γ are not expected to exceed $\pm$ 15 MeV^2.

Search for E in other channels

Besides channel (1), there exist the following five-body channels containing at least one $K_1^o \longrightarrow \pi^+ \pi^-$ decay in the final state:

$$\begin{array}{ll} K_1^o\, K_1^o\, \pi^+\, \pi^-\, \pi^o & (a) \\ K_1^o\, K^{\pm}\, \pi^{\mp}\, \pi^o\, \pi^o & (b) \\ K_1^o\, K_2^o\, \pi^+\, \pi^-\, \pi^o & (c)\ . \end{array} \qquad (4)$$

Channel (4a) is readily detected from the kinematical analysis of events corresponding topologically to a two-pronged annihilation with two visible K_1^o - decays associated to it. Channel (4b) is observed as $K_1^o\, K^{\pm}\, \pi^{\mp}$ M and (4c) as $K_1^o\, \pi^+\, \pi^-$ M ; in both cases, M stands for a mass larger than that of one π^o after taking account of measurement errors. The identification of M with $\pi^o + \pi^o$ in (4b) and to $K^o\, \pi^o$ in (4c) follows from the fact that we have very seldom found in our sample annihilations into a $K\bar{K}$ pair plus four pions. From the number of events in channel (4a) and the branching ratio $\dfrac{K_1^o \longrightarrow \pi^+ \pi^-}{K_1^o \longrightarrow \pi^o \pi^o} = 2$, one can deduce the number of $K_1^o\, K_2^o\, \pi^+\, \pi^-\, \pi^o$ events in $K_1^o\, [K^o]\, \pi^+\, \pi^-\, \pi^o$ ($[K^o]$ represents a not seen decay) and, by subtraction, different mass-distribution in (4c) can be established statistically. The relevant results obtained from the analysis of channels (4) are :

(4a) is strongly dominated by ω^o $(\pi^+\, \pi^-\, \pi^o)$-production, but in about 100 events not corresponding to $K_1^o\, K_1^o\, \omega^o$ we find no evidence for an enhancement $(K_1^o\, K_1^o\, \pi^o)$ or $(K_1^o\, K_1^o\, \pi^{\pm})$ anywhere - in particular in the E mass region.

In (4b) only the M^2 $(K_1^o\, K^{\pm}\, \pi^{\mp})$ can be studied directly, this distribution is shown by the dotted line in histogram of Figure 3. It is noticed that the distribution follows closely the resonant Q = 0 distribution in the system $(K_1^o\, K^{\pm}\, \pi^{\mp})$ of channel $K_1^o\, K^{\pm}\, \pi^{\mp}\, \pi^+\, \pi^-$; there are no indications of a reflection coming from a possible - but not directly observable - enhancement in $(K_1^o\, K^{\pm}\, \pi^o)$.

Channel (4c) is weakly - if at all - present, as can be seen from Figure 4, where the M^2 $(K_1^o\, K_1^o\, \pi^o)$ in channel (4a) and M^2 $(K_1^o$ M) - which is most likely M^2 $(K_1^o\, K^o\, \pi^o)$ - in channel (4c), are displayed.

<u>Possible quantum numbers of the E-resonance</u>

<u>I-spin</u>:

The isospin of the ($K_1^o K^{\pm} \pi^{\mp}$)-system can be 0, 1 or 2. The absence of the E in the Q = 2 charge state eliminates the I = 2 probability.

As it was said in the previous section, no direct or indirect evidence in favour of $E^{\pm}$ has been obtained and thus it is very likely that the isospin of the E is zero. In the following considerations $I_E = 0$ will be taken for granted.

<u>Spin and parity</u>:

To speculate about the spin and parity of the E we have two sources of information. The first one is the population of the Dalitz plot (<u>Figure 5</u>). Unfortunately, because of the fairly large width of the E, the contours corresponding to the lower and higher values of the mass are very distant from each other. This makes difficult a study of the population of the plot - even if we split the plot into two ($K\bar{K}\pi$) mass-bounds as has been done in <u>Figures 6a and 6b</u>. Nevertheless, a concentration of events in the K^* overlap region is clearly seen; the explanation of the concentration of events in the top-right region of the Dalitz plot is not unique : we could as well say that the Dalitz plot shows a concentration of events for low ($K\bar{K}$) masses; however, we shall limit ourselves in the following to the hypothesis that the K^* production plays a dominant role for the interaction; then, one sees from the Dalitz plot that the decay angular distribution of the K^* does not follow a $\cos^2\theta$ rule.

In the same hypothesis, the second source of information is the angular distribution of the K^* in the centre of mass of the E-resonance. Due to the fairly abundant number of E decays in which both the ($K\ \pi$) and ($\bar{K}\ \pi$) combinations give masses compatible with the K^*- mass, it is not possible to give clearly this angular distribution. Whenever there is ambiguity, both values of the angle have been used in the distribution of <u>Figure 7</u>. If we use only those decays of the E for which only 1 K^* occurs, the distribution still looks isotropic but, of course, the statistical accuracy is greatly diminished.

We assume that the annihilation $\bar{p}\ p$ proceeds from S-states. The experimental branching ratio:

$\bar{p}p \longrightarrow E^o \pi^o \pi^o / \bar{p}p \longrightarrow E^o \pi^+ \pi^- = 196/316 = 0.62 \pm 0.06$ strongly supports the hypothesis that the reactions occur in a I = 0 state; indeed, the experimental ratio is just compatible with the expectation for this case, namely 0.5; any contribution of I = 1 state would decrease this number.

The final state $E^o \pi^o \pi^o$ being a pure C state imposes severe constraints on the possible quantum numbers of the E resonance:

a) If the charge conjugation of E is + 1, that means, ${}^1S_o$ initial state for $E^o \pi^o \pi^o$ production and if I(E) = 0, then $G_E = + 1$ and G $(K\bar{K}) = - 1$. Since I $(K^o K^{\pm}) = + 1$, the angular momentum state of the $K\bar{K}$ system must be even. The spin-parity of the E is then given by $P = (-1)^J$ i.e. 0^-, 1^+, 2^-, ---.

For 0^- assignment the $K^* \bar{K}$ relative angular momentum is 1, that implies a $\cos^2\theta$ K^* decay angular distribution with respect to its line of flight in the Ecm since this is not consistent with observation we exclude 0^-.

Now 1^+ is also improbable for the E. The argument is the following : the predicted angular momentum for E production is :

initial stat	final state	
${}^1S_o$ c = + 1, P = - 1	1^+ E, 0^+ $\pi^+ \pi^-$, L = 1	0^+ for $\pi^+ \pi^-$, since its c is + 1 like E
${}^3S_1$ c = - 1, P = - 1	1^+ E, 1^- $\pi^+ \pi^-$, L = 0	1^- for $\pi^+ \pi^-$, since its c is - 1 to have a global c = - 1

Therefore we have no selection rule to forbid I-spin 1 for $\pi^+ \pi^-$, in contradiction with what has been said above.

b) If $c_E = - 1$, the initial state for $E^o \pi^o \pi^o$ production being now ${}^3S_1$, then $G_E = - 1$ and the lowest angular momentum of the $K\bar{K}$ - system is 1.

The possible quantum numbers are then 0^-, 1^-, 1^+, 2^-, ---.

0^- is excluded for the same reason as for $c_E = + 1$

1^+ is also improbable for the same reason as for $c_E = + 1$

${}^1S_o$ — 1^+ E, 1^- $\pi^+ \pi^-$, L = 0

${}^3S_1$ — 1^+ E, 0^+ $\pi^+ \pi$, L = 1

although the argument is weaker, because the smaller statistical weight of the ${}^1S_o$ state.

1^- seems to be favoured by the fact that the lowest angular momentum configurations are

$$^1S_0 \qquad \underbrace{\underset{E}{1^-} \qquad \underset{\pi^+\pi^-}{1^-}}_{L\,=\,1}$$

$$^3S_1 \qquad \underbrace{\underset{E}{1^-} \qquad \underset{\pi^+\pi^-}{0^+}}_{L\,=\,0}$$

and here centrifugal barrier considerations can exclude $^1S_0$.

In conclusion one can say that of the simple J^P possibilities, we have just examined, the 1^- seems to be the best one. It has to be noted, however, that we have not strongly excluded 1^+. Furthermore, the effects of the overlapping K^* within the E - resonance have not been taken into account and consequently only quantitative arguments are possible. The resulting charge conjugation quantum number assignment $c_E = -1$ meets with the difficulty that no $E \rightarrow K_1^o K_2^o \pi^o$ decay has been seen. The fact that no $E \rightarrow K_1^o K_1^o \pi^o$ (this would imply $c_E = +1$) has been seen does not help, therefore, in the determination of c_E.

References

1. R. Armenteros et al., Proceedings of the Siena International Conference on Elementary Particles (1963).

2. Different persons - in particular, N. Cabibbo - have pointed this out to us.

3. C. Bouchiat and G. Flamand, Nuovo Cimento, Vol. XXIII, pg. 13 (1962).

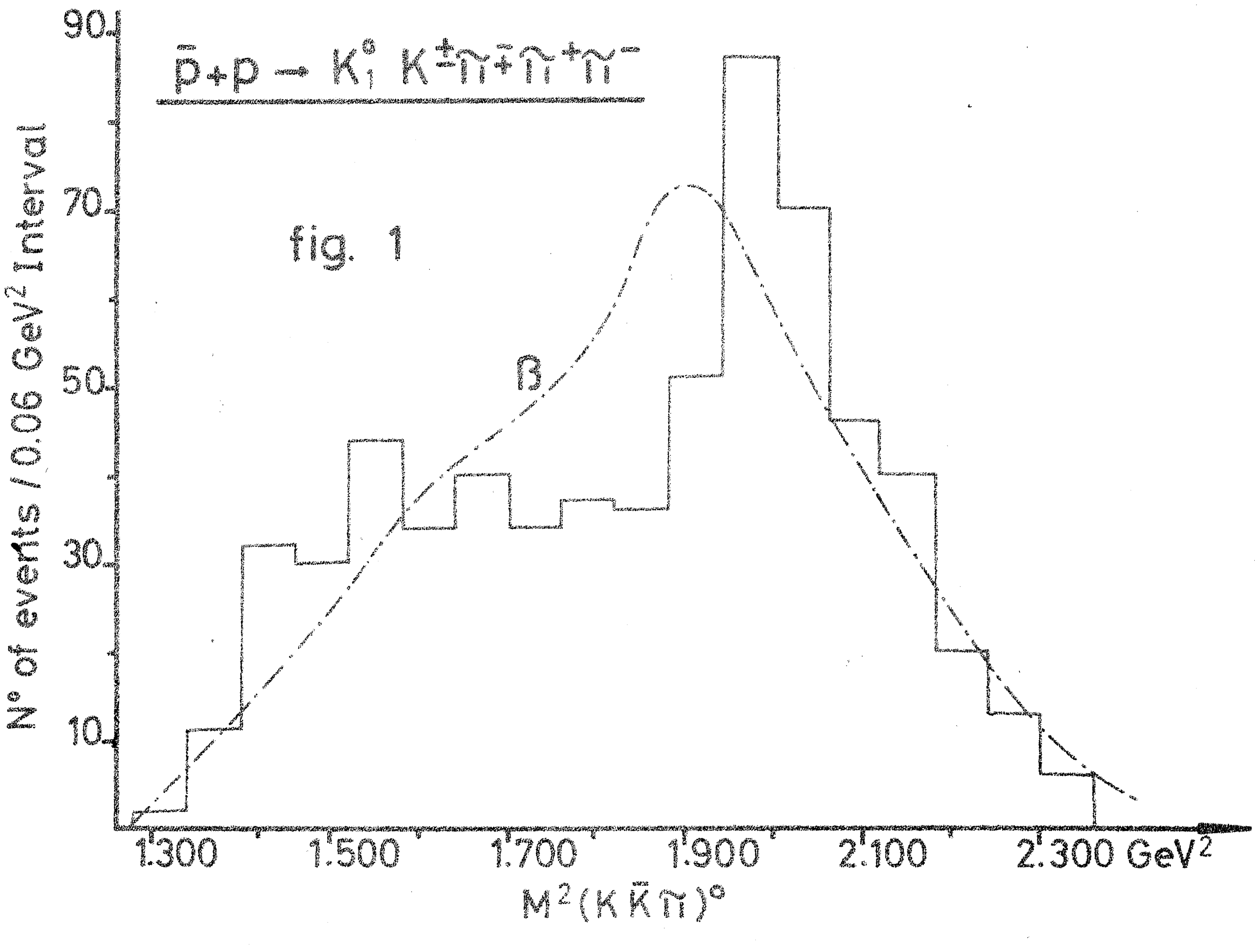
4. M. Nauenberg and A. Pais, Phys. Rev. Letters 8, 82 (1962).

5. R.J. Oakes, Phys. Rev. Letters.

6. R.F. Peierls, Phys. Rev. Letters 6, 641 (1961).

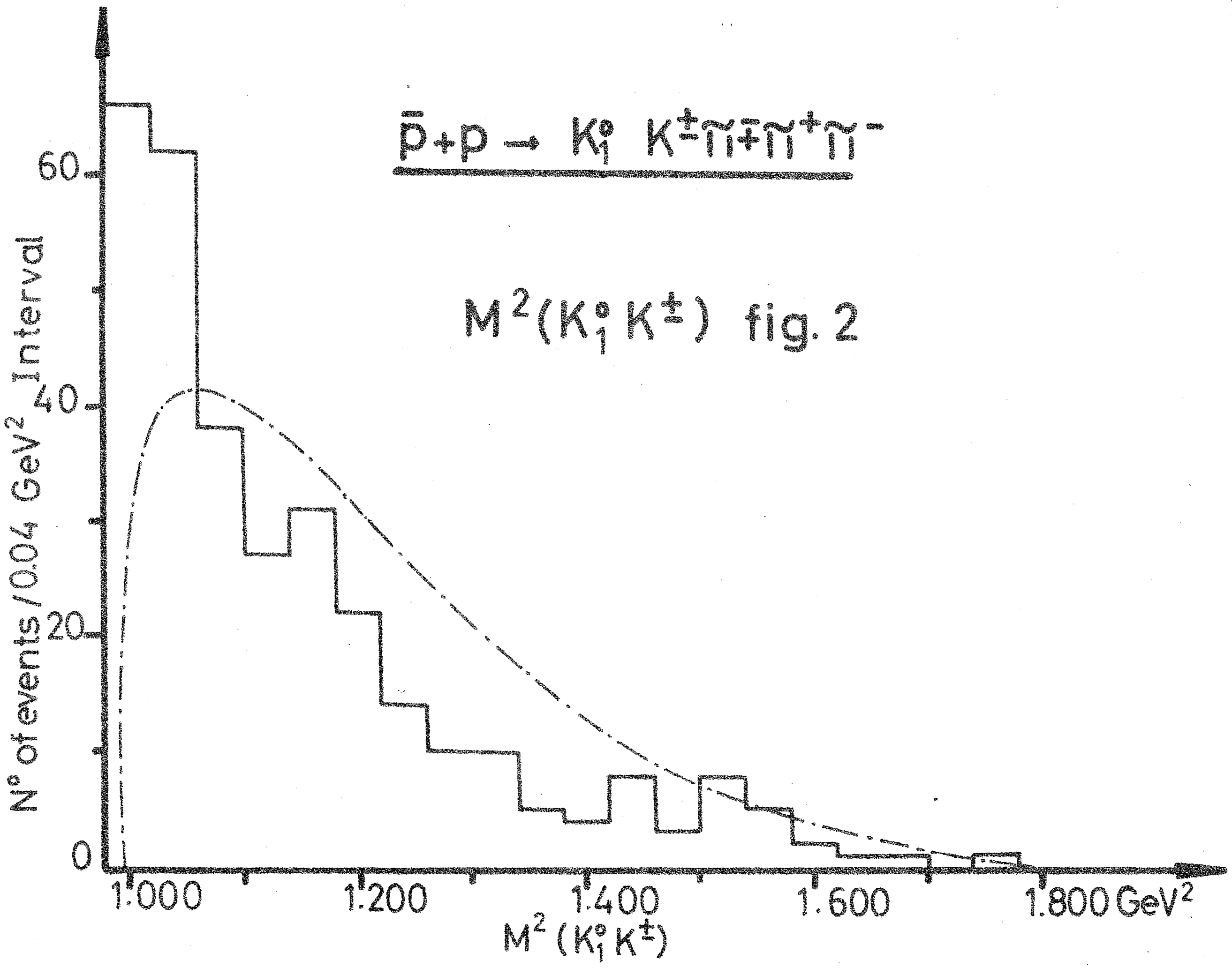
7. R.H. Dalitz, Proceedings of the Siena International Conference on Elementary Particles (1963).

8. R.H. Dalitz in Reference 7 has remarked that a real concentration of E-decays in the N-E region of the plot would imply a contribution of an S-wave ($K\bar{K}$)-system and hence a G = +1 assignment for the E-resonance. The large width of the resonance, however, does not permit a clear definition as the boundary plot and hence the concentration at the boundary may only be an apparent effect.



DIA 21663
PS/4763

DIA 21668



PS/4763

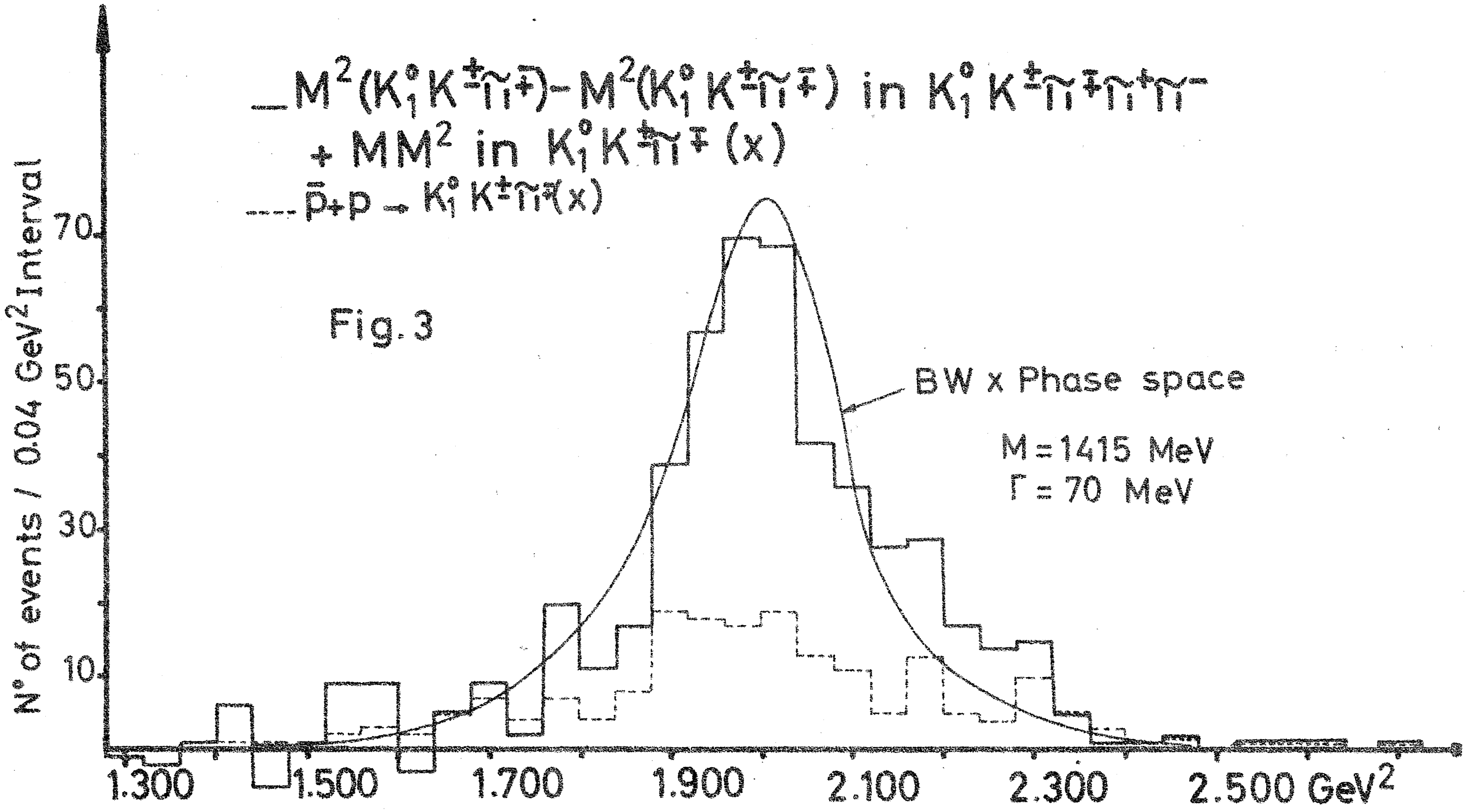

— $M^2(K_1^0 K^{\pm}\pi^{\mp}) - M^2(K_1^0 K^{\pm}\pi^{\mp})$ in $K_1^0 K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$
+ MM^2 in $K_1^0 K^{\pm}\pi^{\mp}(x)$
---- $\bar{p}+p \to K_1^0 K^{\pm}\pi^{\mp}(x)$
N° of events / 0.04 GeV^2 interval
70
50
30
10
BW x Phase space
M = 1415 MeV
Γ = 70 MeV
1.300
1.500
1.700
1.900
2.100
2.300
2.500 GeV^2

Fig. 3

PS/4763

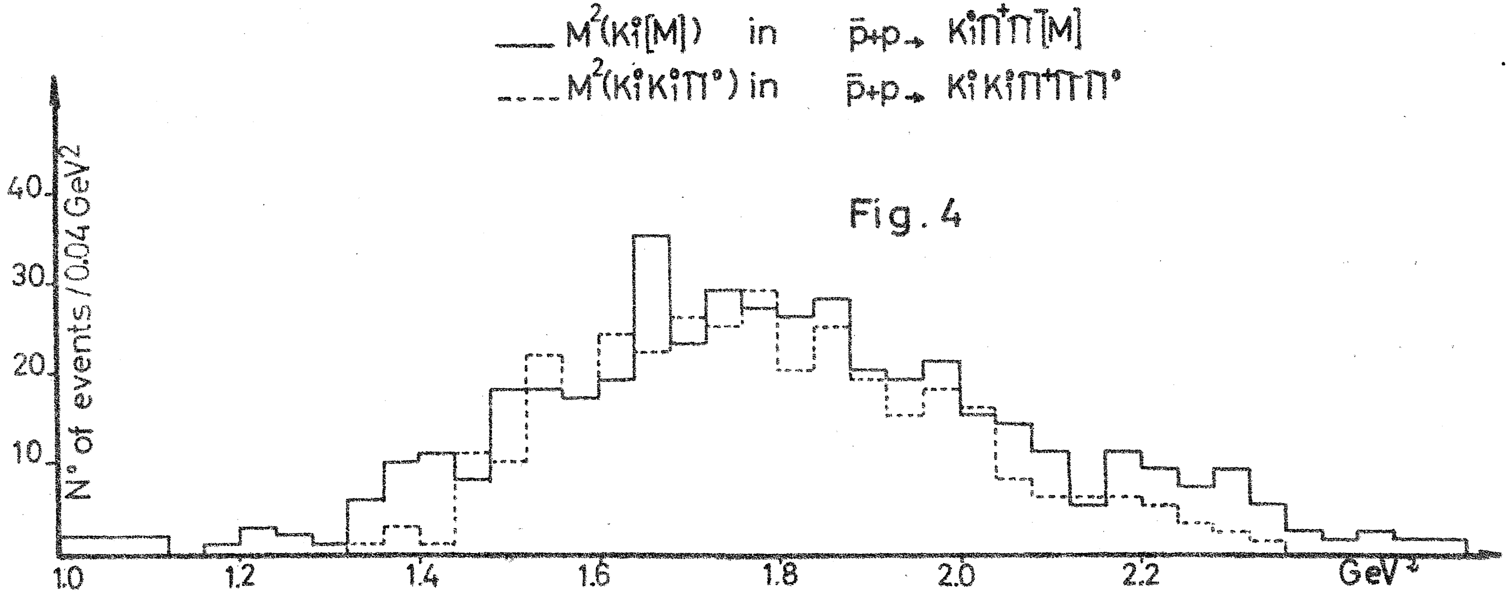


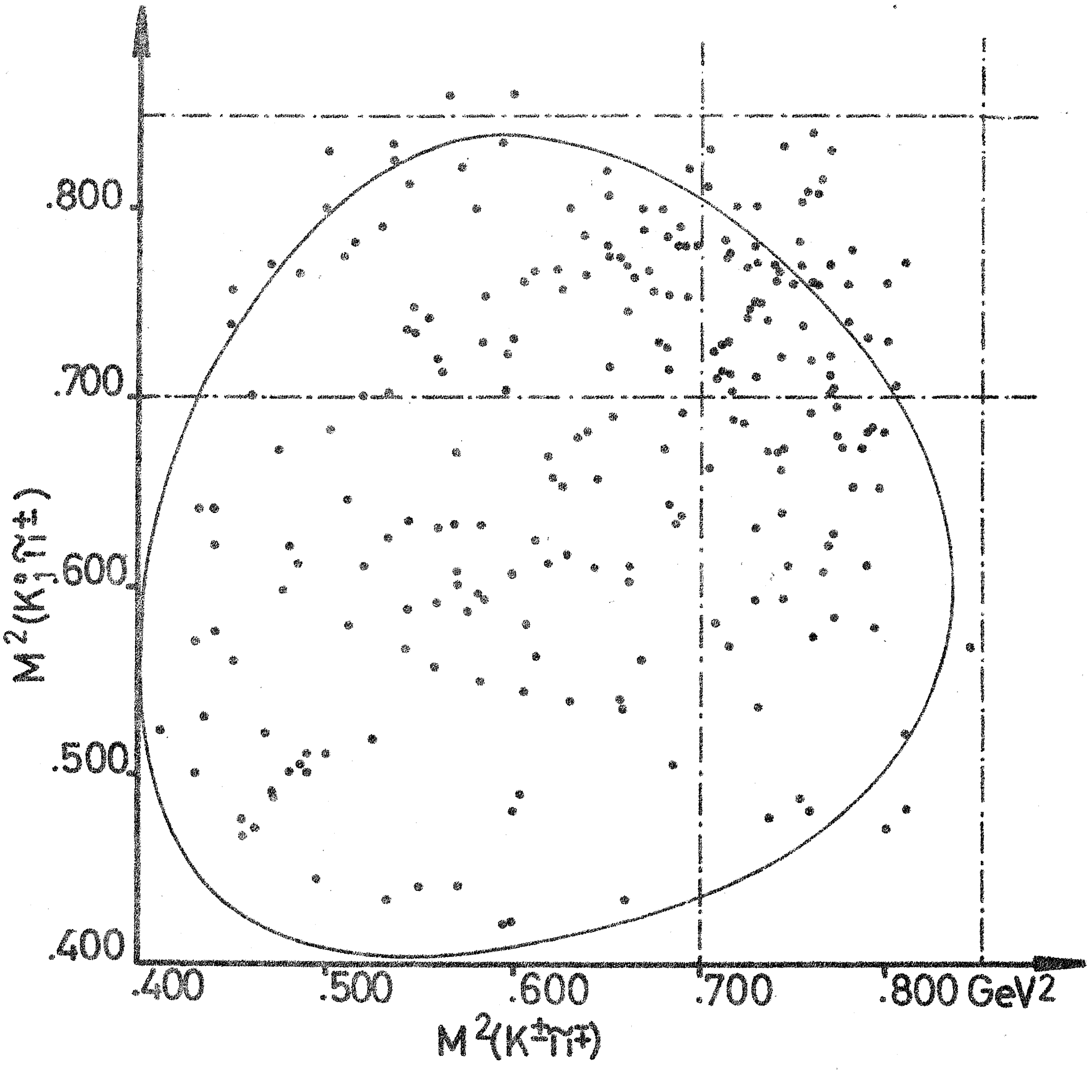
Fig. 4

PS/4763

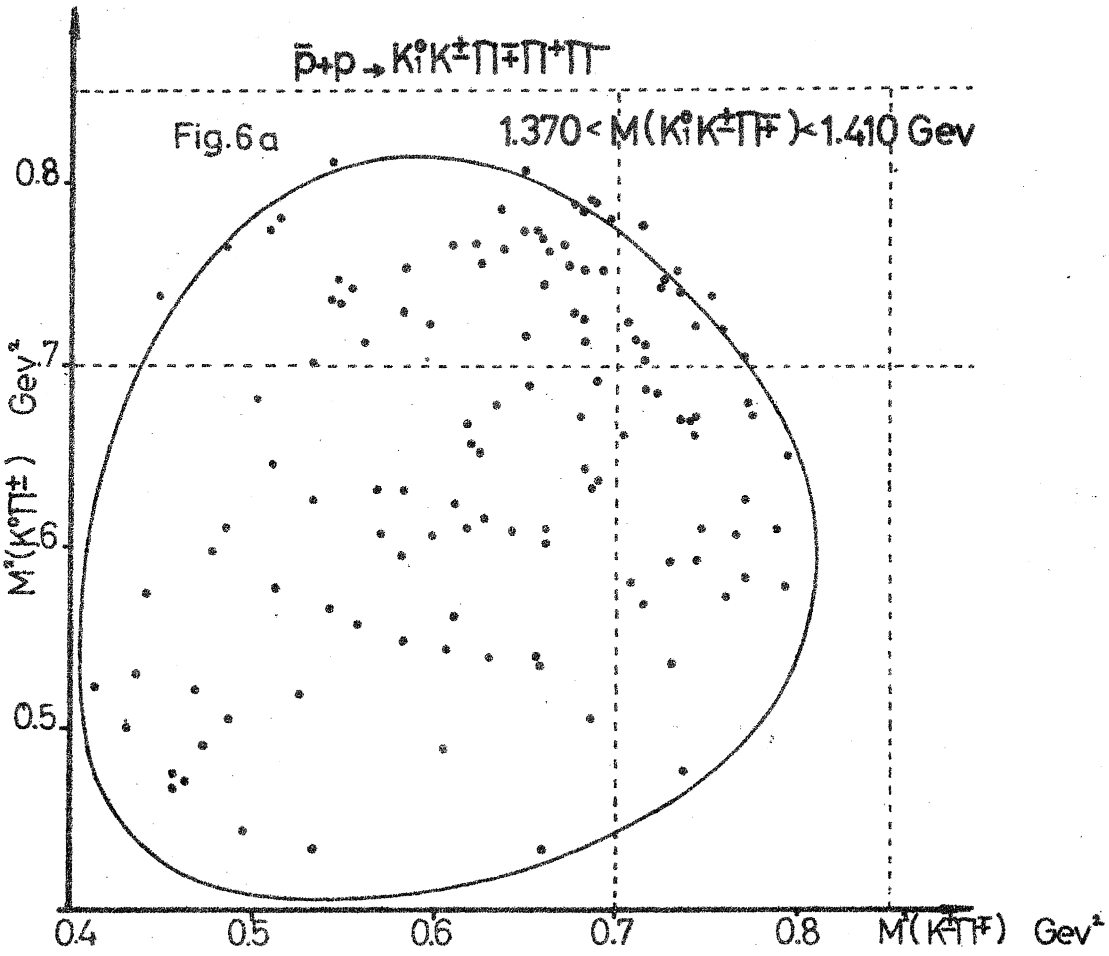
DIA 21665

$\bar{p}+p \rightarrow K_1^0 K^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$ Fig. 5

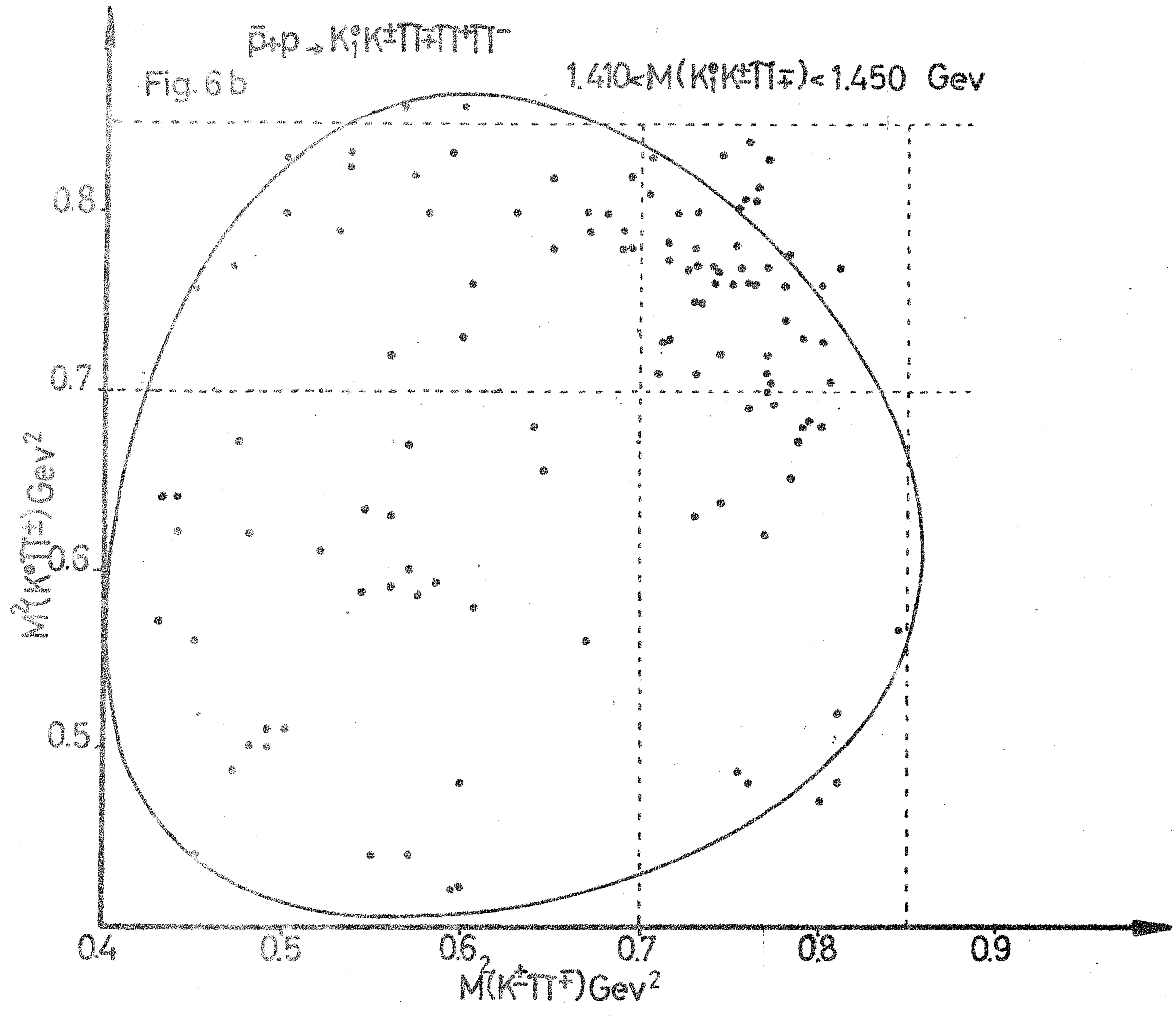
$1.370 < M(K_1^0 K^{\pm} \pi^{\mp}) < 1.450$ GeV



DIA 21666
PS/4763



DIA 21662
PS/4763

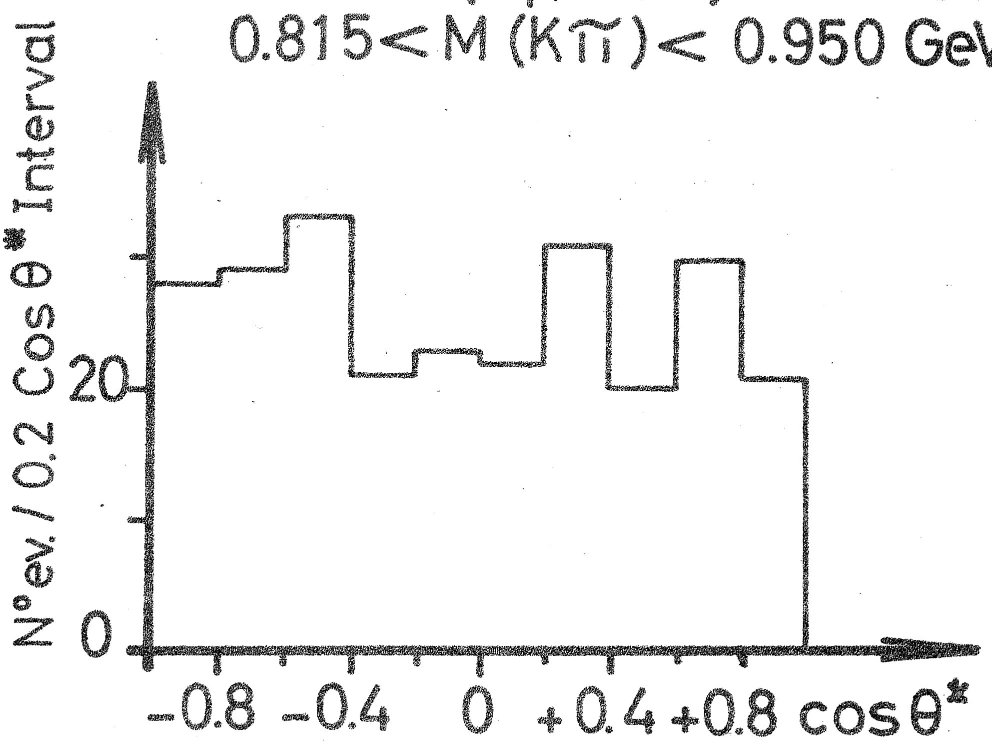


$\bar{p}+p \rightarrow K_1^0 K^{\pm} \pi^{\mp} \pi^{+} \pi^{-}$
Fig. 6 b
$1.410 < M(K_1^0 K^{\pm} \pi^{\mp}) < 1.450$ Gev
0.8
0.7
0.6
0.5
$M^2(K^0 \pi^{\pm})$ Gev^2
0.4
0.5
0.6
0.7
0.8
0.9
$M^2(K^{\pm} \pi^{\mp})$ Gev^2

$\bar{p} + p \to K_1^0 K^{\pm} \pi^{\mp} \pi^+ \pi^-$ Fig.7

angular distribution of K^* in E c.m

$1.370 < M(K_1^0 K^{\pm} \pi^{\mp}) < 1.450$ GeV
$0.815 < M(K\pi) < 0.950$ GeV



DIA 21669
PS/4763