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EXPERIMENTAL RESULTS ON THE ANNIHILATIONS $\bar{p}p$ K+K+2π AT REST

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1. The Saclay 81cm hydrogen bubble chamber has been exposed to beams of slow $\bar{p}$'s from the CERN proton synchrotron and the following set of four annihilations of stopped $\bar{p}$'s obtained :

(1)	$\bar{p} + p \longrightarrow K_1^o K_1^o \pi^+ \pi^-$	720 events
(2)	$\bar{p} + p \longrightarrow K_1^o (K^o) \pi^+ \pi^-$	2025 events
(3)	$\bar{p} + p \longrightarrow K_1^o K^{\pm} \pi^{\mp} \pi^o$	2340 events

where (K^o) means a K^o or $\overline{K^o}$ not seen.

An alaysis of reaction (1) has already been published[1]. In this communication we present the results for the other reactions and consider the group as a whole.

2. Experimental Facts

2.1 $\bar{p}p \rightarrow K_1^o K_1^o \pi^+ \pi^-$:

These events are identified by a four-constraint fit with a check of the ionization of the charged particles : the contamination due to annihilations in flight and due to the 5-body annihilation (with an additional π^o) is very small. There is a scanning bias because the K_1^o can decay too near the annihilation apex. A systematic search for such events which would have been classified as 4-charged prongs plus one K_1^o associated, has shown that the loss

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is 8°/o but does not affect the main results. For detailed analysis the loss is corrected by a suitable weighting function.

The various two and three particle effective mass combinations in the final state of reaction (1) have been studied. The $(K_1^o\pi^\pm)$ effective mass spectrum does not exhibit any peak at 888 MeV (K^*) which is pronounced in the other reactions. The $(\pi^+\pi^-)$ effective mass spectrum shows a striking deviation from pure phase space. The $(K_1^o\pi^+\pi^-)$ effective mass spectrum (two combinations per event), Figure 1, shows an enhancement around 1230 MeV. We have explained[1] why we attribute this to a $(K\pi\pi)$ resonant state, called C^o, with the following mass and width :

$$M = 1215 \pm 15 \text{ MeV}/c^2 \qquad = 60 \pm 15 \text{ MeV}/c^2 .$$

A Dalitz plot of the $(K\pi\pi)$ system in the C^o region shows an accumulation of events with large $(\pi^+\pi^-)$ effective mass, Figure 2. Although in the rest system of the C^o there is insufficient energy to produce normal ρ^o (750 MeV) and K^o, the following results are observed :

(a) 60°/o of reaction (1) goes via the channel

$$\bar{p}p \rightarrow C^o K_1^o$$

(b) 80 to 90°/o of the C^o decays via the reaction

$$C^o \rightarrow K_1^o \rho^o .$$

Indeed, a detailed study of the Dalitz plot indicated that we observe

450 C^o's decaying into $K_1^o \rho^o$

80 C^o's decaying into $K^{*\pm}\pi^\mp$.

If the four-body annihilations of protonium (at rest) occur mainly from S-states as has been proved for two-body $(K\bar{K})$ final states[2], reaction (1) cannot occur with $(\pi^+\pi^-)$ system in a relative S-state. Additional evidence that the $(\pi\pi)$ is in a P-state (or higher odd orbital momentum) is provided by the very small number of events attributed to annihilations of the type

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

The lowest angular momentum state for this mode if it comes from the ^1S_o state of protonium (the only (low) initial state allowed) is $\ell_{\pi\pi} = 2$, $\ell_{KK} = 2$, $L_{(\pi\pi),(KK)} = 1$. There would therefore be strong centrifugal suppression for this mode.

If we assume the $(\pi^+\pi^-)$ system is in a P-state, then the charge conjugation of the final state of (1) is C = -1, which implies protonium annihilation in $^3S_1$-state. If we define the charge conjugation of the K_1^o to be -1, then the C^o observed has C = +1.

2.2 $p + \bar{p} \rightarrow K_1^o K_2^o \pi^+\pi^-$

These events are contained in reaction (2) which is identified by a one-constraint fit. To estimate a possible contamination of reaction (2) by events of the type $p\bar{p} \rightarrow K_1^o (K^o)\pi^+\pi^-\pi^o$, we have treated the identified five-body annihilations $(K_1^o K_1^o \pi^+\pi^-\pi^o$ as if only one K_1^o had been seen : there was very small chance of such events being fitted as $K_1^o(K^o)\ \pi^+\pi^-$. Similarly, one of the observed K_1^o of the mode $K_1^o K_1^o \pi^+\pi^-$ was suppressed and although some events were fitted as pseudo-$(K_1^o K^{\pm}\pi^{\mp}\pi^o)$, they could generally be rejected by ionization. We conclude that such ambiguities are very few. We have checked that our scanning efficiency for $K_1^o(K^o)\ \pi^+\pi^-$ is comparable to that of reaction (1) by plotting the flight distance of the K_1^o (normalized by the momentum) : the usual logarithmic distribution of decay lengths was observed with the expected bias corresponding to short lengths.

Reaction (2) contains events of the type $K_1^oK_2^o\pi^+\pi^-$ and $K_1^o(K_1^o)\pi^+\pi^-$ where one K_1^o decay is missed because (a) it decays via the $(\pi^o\pi^o)$ mode or, (b) it escapes from the chamber before decaying $(\pi^+\pi^-)$.

The latter are few and can be corrected for by suitable weighting. To eliminate the $(\pi^o\pi^o)$ mode we subtract from the spectra of reaction (2) one half of the spectra of reaction (1). This assumes that the branching ratio

$$K_1^o \rightarrow \frac{\pi^o\pi^o}{\pi^+\pi^-} \text{ is } \frac{1}{2} \quad .$$

After such subtraction we find that the $(K\pi)$ effective mass spectra is dominated by the $K^*(888)$, Figure 3, but the $(\pi\pi)$ and $(K\bar{K})$ effective mass spectra are compatible with phase space. The $(K_1^o\pi^+\pi^-)$ effective mass spectrum shows almost the same features as the $(K_1^o\pi^+\pi^-)$ system in reaction (1), i.e. an enhancement in the C^o vicinity, but the enhancement for the $(K_1^o\pi^+\pi^-)$ system is not as strong as it is for the $(K_2^o\pi^+\pi^-)$ combination, Figures 4 and 5. We discuss this difference in Section 3. Ignoring for the time being this difficulty, we have analyzed the Dalitz plot for all $(K\pi\pi)$ combinations falling in the region of the C^o, Figure 6, and find about 640 C^o's decaying into $K^{*\pm}\pi^{\mp}$ with the subsequent decay of $K^{*\pm}$ into $K_1^o\pi^{\pm}$ or $K_2^o\pi^{\pm}$. The number of C^o's decaying into $\rho^o K_1^o$ or $\rho^o K_2^o$ is compatible with zero, showing that these events do not come from the ^1S_o protonium state. Assuming annihilations from the $3\ S_1$-state, i.e. 1^- state, the $\pi^+\pi^-$ system must be in an even orbital momentum state.

2.3 $pp \rightarrow K_1^o K^{\pm}\pi^{\mp}\pi^o$

These events are obtained by a one-constraint fit with the additional information about the ionization of the charged tracks. The possible contamination from other reaction channels was studied as above, and it appears that there could be contamination from other channels when the charged particle pertaining to a charged K has a large dip angle and low momentum. A study of the dip angle of such tracks show there is no accumulation towards large dip angles which indicated that the contamination is small.

The study of two and three particle effective mass combinations show :

(a) the strong production of $K^*(888)$ in all possible types of combinations (Fig.7);

(b) a deviation of the $(\pi^{\pm}\pi^o)$ effective mass distribution from phase space with an accumulation towards large values of $(\pi^{\pm}\pi^o)$ mass;

(c) a $(K^{\pm}\pi^{\mp}\pi^o)$ effective mass distribution, Figure 8, similar to that observed in the annihilation into $K_1^o K_1^o \pi^+\pi^-$. The deviation from phase space can be explained by the presence of a C^o resonant state;

(d) the charged three-body system $(K_1^o\pi^{\pm}\pi^o)$ also shows a deviation from phase space, Figure 8, but the enhancement is now centred at 1320 MeV/c^2. This mass difference seems too large to identify this enhancement as the charged counterpart of the C^o. We return to this point in Section 3.

We will only discuss here the characteristics of the neutral system $(K^{\pm}\pi^{\mp}\pi^o)$. The Dalitz plot in the C^o region, Figure 9, shows an accumulation of events both in the $K^*(888)$ bands and in the large $(\pi\pi)$ effective mass region. A detailed study yields :

370 C^o's decaying into $\rho^{\pm}K^{\mp}$

200 C^o's decaying into $K^*\pi$ of which 105 decay into charged K^* and 95 into neutral K^*.

3. Discussion

If we try to summarize the situation we find that in spite of agreement of certain experimental facts we have three difficulties :

3.1 The first difficulty is the difference in reaction (2) of the spectra of $(K_1^o\pi^+\pi^-)$ and $(K_2^o\pi^+\pi^-)$. The purely statistical problem of the similarity of the spectra is difficult. If we ignore the information about the shape of the $(K_1^o\pi^+\pi^-)$ spectrum from reaction (1) and divide the two spectra into 33 bands, we find only 10 bands of the difference $m^2\ (K_1^o\pi^+\pi^-) - m^2\ (K_2^o\pi^+\pi^-)$ which differ from zero by more than one standard deviation, but if we consider only the C^o band, defined by $1.46 < m^2 < 1.62\ (GeV/c^2)^2$, the number of events differ by 2.3 standard deviations. (Figure 10).

3.2 The greatest difficulty is the mass difference between $(K^{\pm}\pi^{\mp}\pi^o)$ and $(K_1^o\pi^{\pm}\pi^o)$ in reaction (3); the difference of 100 MeV/c^2 in energy is too large to be attributed to electromagnetic splitting, so it is impossible to consider them as two states of the same resonance.

If we ignore these difficulties and consider the three similar enhancements centred at 1215 MeV/c^2 with a width of 60 MeV/c^2 in the neutral $(K\pi\pi)$ system in reactions (1), (2) and (3), as a resonant state called C^o, we find it difficult to determine unambiguously the I-spin. As the C^o is observed only in the neutral mode, the only method for determining I-spin comes from decay-branching ratios.

We assume the protonium annihilation is in the $3\ S_1$-state: this has been proved for reactions (1) and (2), and is probably the most important state involved in reaction (3). Table I gives the predicted ratios for I = 1/2 and I = 3/2 for the charge conjugate state +1, i.e. the $3\ S_1$-state. The relative normalization for the $K\rho$ and $K^*\pi$ channels is what we should expect, assuming the validity of SU_3 symmetry correcting for the different phase spaces available (a factor of 2.2 in favour of $K^*\pi$ mode).

Table I

$(\bar{p}p)_{^3S_1} \to C^o K_1^o$	$I = \frac{1}{2}$	$I = \frac{3}{2}$	Experiment
$C^o \to K_1^o\ \rho$	1	1	1
$\to K_2^o\ \rho$	0	0	0
$\to K^{\pm}\ \rho^{\mp}$	2	0.5	0.82
$\pi^o K^{*o} \to K_1^o\ \pi^o$	0	0	-
$\pi^o K^{*o} \to K_2^o\ \pi^o$	0.73	0.73	0.20
$\pi^o K^{*o} \to K^{\pm}\ \pi^{\mp}$	1.46	1.46	0.21
$\pi^{\pm} K^{*\mp} \to K_1^o\ \pi^{\mp}$	1.46	0.36	0.18
$\pi^{\pm} K^{*\mp} \to K_2^o\ \pi^{\mp}$	1.46	0.36	0.71
$\pi^{\pm} K^{*\mp} \to K^{\pm}\ \pi^o$	1.46	0.36	0.23

We have included in the table events corresponding to annihilations

$$\bar{p}p \to K_1^o\ K_2^o\ \pi^o\ \pi^o\ .$$

These events are of course not directly observable but the K_1^o spectrum from the zero-prong sample shows an enhancement corresponding to a two-body process

$$\bar{p}p \to K_1^o\ M$$

with M having a mass 1210 MeV/c^2. If we assume this is evidence for the C^o decaying into $K_2^o\ \pi^o\pi^o$, we can estimate roughly the corresponding branching ratio.

3.3 It is difficult to put estimates of uncertainty to the experimental ratios, but taking these results at their face value we cannot draw any conclusion to favour either I-spin.

4. Conclusion

In spite of these difficulties, it seems to us impossible that the observation of the $(K\pi\pi)$ enhancement with the same mass value in three different final states could be pure chance, and so we will try to study the spin and parity. To do this we have two decay angular distributions to study. As the C^o decays mainly into $K_1^o\rho$ or

$K^{*}\pi$, let θ_1 be the angle between the direction of the ρ (or the K^{*}) in the C^{o} rest system and the line of flight of the C^{o}, and θ_2 be the angle between the direction of the π^{+} (or the K) in the rest system of the ρ (or the K^{*}) and the line of flight of the ρ (or the K^{*}).

Table II gives the expected angular distributions $\omega(\theta_1)$ and $\omega(\theta_2)$ for different assumptions for the spin and parity of the C^{o}. We limit ourselves to S-state annihilations of protonium.

Table II

J^{ρ} of C^{o}	Production State	$\omega(\theta_1)$	$\omega(\theta_2)$
0^{-}	$^{3}S_{1}$ $^{1}S_{o}$	1 X	$\cos^{2}\theta$
1^{-}	$^{3}S_{1}$ $^{1}S_{o}$	$\sin^{2}\theta$ $\cos^{2}\theta$	$\sin^{2}\theta$
1^{+}	$^{3}S_{1}$ $^{1}S_{o}$	1 X	1

Figures 11, 12 and 13 show the decay angular distributions $\omega(\theta_1)$ for reactions (1), (2) and (3). For these figures the C^{o} is defined as

$$1.46 < m^{2}\ (K\pi\pi) < 1.62\ (GeV/c^{2})^{2}.$$

The "ρ" in the (ρK) decay mode of the C^{o} is defined as :

$$m^{2}\ (\pi\pi) > 0.36\ (GeV/c^{2})^{2}$$

and the K^{*} in the ($K^{*}\pi$) mode as :

$$0.72 < m^{2}\ (K\pi) < 0.86\ (GeV/c^{2})^{2}.$$

Figure 11 shows $\omega(\theta_1)$ is strongly peaked forward : this can be interpreted qualitatively as an interference effect of the two possible combinations giving rise to the C^{o} if we consider that the production process is mainly represented by $p\bar{p} \rightarrow K_1^{o}K_1^{o}\rho^{o}$.

Figures 12 and 13 show $\omega(\theta_1)$ compatible with isotropy except for an enhancement between $\cos\theta_1 = +0.1$ and $\cos\theta_1 = 0.6$. This may be an interference effect of the C^o with the K^* which can be formed by the K which is outside the C^o.

For the decay angles θ_2, we present only the distribution for $C^o \rightarrow \rho^o + K^o$, Figure 14, as when the C^o decays into $(K^*\pi)$ it often happens that both combinations of $(k\pi)$ are candidates for K^* and this interference obscures the angular distribution. Figure 14 shows that $\omega(\theta_2)$ is compatible with isotropy, although a $\sin^2\theta$ cannot be completely excluded. Clearly, this study of the angular distributions does not allow a definite determination of the spin and parity of the C^o, but the 1^+ assignment is slightly favoured.

Acknowledgments

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References

1) R. Armenteros et al., Physics Letters 9, 207 (1964).
2) R. Armenteros et al., 1962 International Conference on High Energy Physics at CERN, page 351.

Figure Captions

Figure 1 $(K_1^o\pi^+\pi^-)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^oK_1^o\pi^+\pi^-$.

Figure 2 Dalitz plot of the $(K_1^o\pi^+\pi^-)$ system in :

$$\bar{p}p \rightarrow K_1^oK_1^o\pi^+\pi^-$$

in the limits :

$$1.46 < m^2\ (K\pi\pi) < 1.62\ (GeV/c^2)^2.$$

Figure 3 $(K\pi)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^o K_2^o\pi^+\pi^-$.

Figure 4 $(K_1^o\pi^+\pi^-)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^oK_2^o\pi^+\pi^-$.

Figure 5 $(K_2^o\pi^+\pi^-)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^oK_2^o\pi^+\pi^-$.

Figure 6 Dalitz plot of the $(K_2^o\pi^+\pi^-)$ system in :

$$\bar{p}p \rightarrow K_1^oK_2^o\pi^+\pi^-$$

in the limits :

$$1.46 < m^2\ (K\pi\pi) < 1.62\ (GeV/c^2)^2 .$$

Figure 7 $(K\pi)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^o$.

Figure 8 $(K_1^o\pi^{\pm}\pi^o)$ and $(K^{\pm}\pi^{\mp}\pi^o)$ effective squared mass spectrum in $\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^o$.

Figure 9 Dalitz plot of the $(K^{\pm}\pi^{\mp}\pi^o)$ system in :

$$\bar{p}p \rightarrow K_1^oK^{\pm}\pi^{\mp}\pi^o$$

in the limits :

$$1.46 < m^2\ (K\pi\pi) < 1.62\ (GeV/c^2)^2 .$$

Figure 10 $[m^2(K_1^o\pi^+\pi^-) - m^2(K_2^o\pi^+\pi^-)]$ effective mass squared spectrum in

$$\bar{p}p \rightarrow K_1K_2^o\pi^+\pi^- .$$

Figure 11 Decay angular distributions of $C^o \rightarrow K_1^o\ \rho^o$ in $\bar{p}p \rightarrow K_1^oK_1^o\pi^+\pi^-$

with the following limits :

$$1.46 < m^2\ (K\pi\pi) < 1.62\ (GeV/c^2)^2$$

$$m^2\ (\pi\pi) > 0.36\ (GeV/c^2)^2$$

Figure Captions (cont.)

Figure 12 Decay angular distribution of $C^{o} \rightarrow K^{*}\pi$ in $\bar{p}p \rightarrow K_1^{o}K_2^{o}\pi^{+}\pi^{-}$ with the following limits :

$$0.46 < m^2\,(K\pi\pi) < 1.62\ (GeV/c^2)^2$$

$$0.72 < m^2\,(K\pi) < 0.86\ (GeV/c^2)^2.$$

Figure 13 Decay angular distribution of $C^{o} \rightarrow K^{*}\pi$ in $\bar{p}p \rightarrow K_1^{o}K^{\pm}\pi^{\mp}\pi^{o}$ with the following limits :

$$1.46 < m^2\,(K\pi\pi) < 1.62\ (GeV/c^2)^2$$

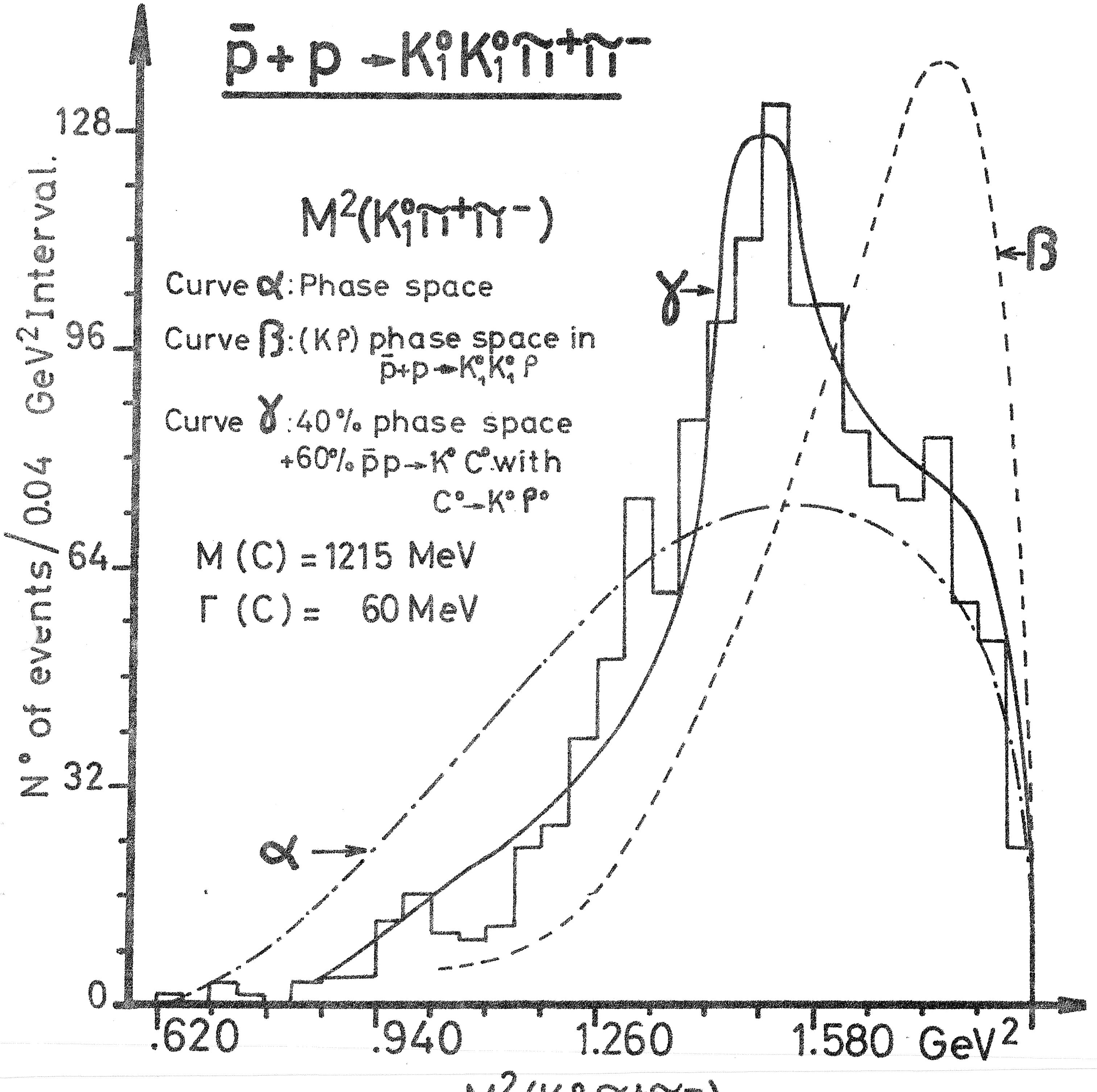
$$0.72 < m^2\,(K\pi) < 0.86\ (GeV/c^2)^2.$$

Figure 14 Decay angular distribution of $\rho \rightarrow \pi^{+}\pi^{-}$ in $\bar{p}p \rightarrow K_1^{o}K_1^{o}\pi^{+}\pi^{-}$ with the following limits :

$$1.46 < m^2\,(K\pi\pi) < 1.62\ (GeV/c^2)^2$$

$$m^2\,(\pi\pi) > 0.36\ (GeV/c^2)^2$$

fig 1


$\bar{p} + p \rightarrow K_1^0 K_1^0 \pi^+ \pi^-$
$M^2(K_1^0 \pi^+ \pi^-)$
Curve α: Phase space
Curve β: (Kρ) phase space in $\bar{p}+p \rightarrow K_1^0 K_1^0 \rho$
Curve γ: 40% phase space +60% $\bar{p}p \rightarrow K^0 C^0$ with $C^0 \rightarrow K^0 \rho^0$
M (C) = 1215 MeV
Γ (C) = 60 MeV
α
β
γ
128
96
64
32
0
N° of events / 0.04 GeV^2 Interval.
.620
.940
1.260
1.580
GeV^2
$M^2(K_1^0 \pi^+ \pi^-)$

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DIA 21320

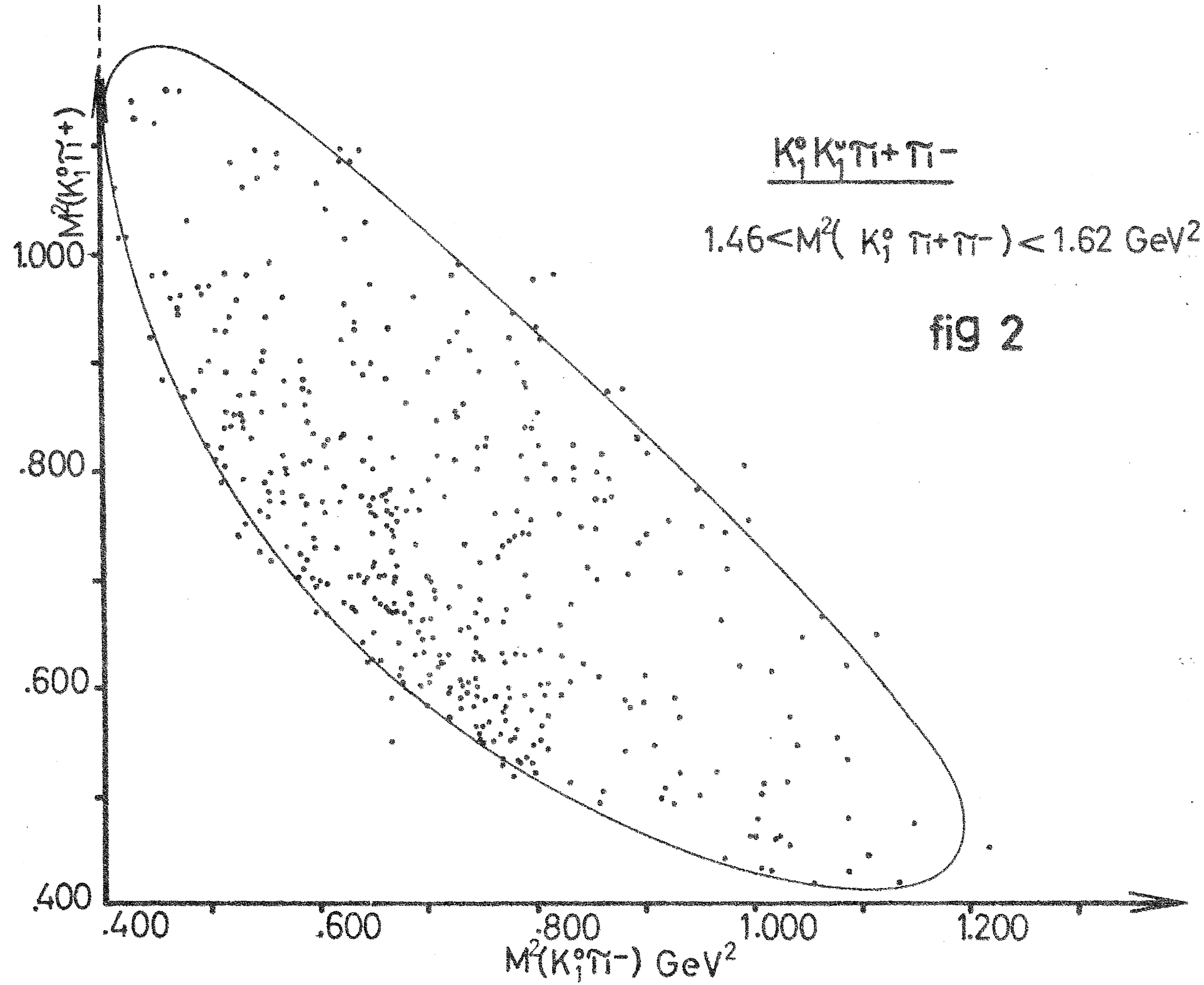
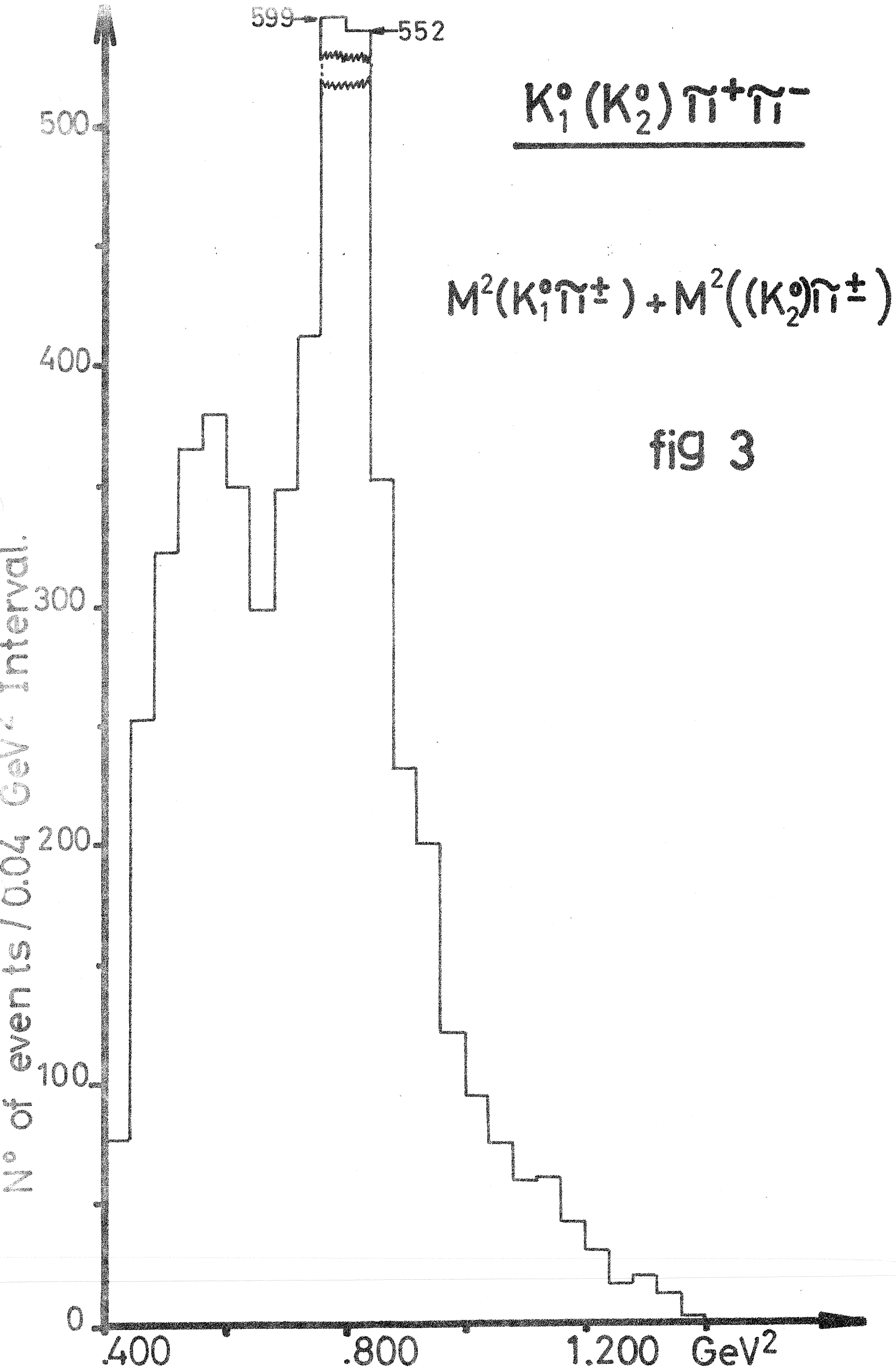
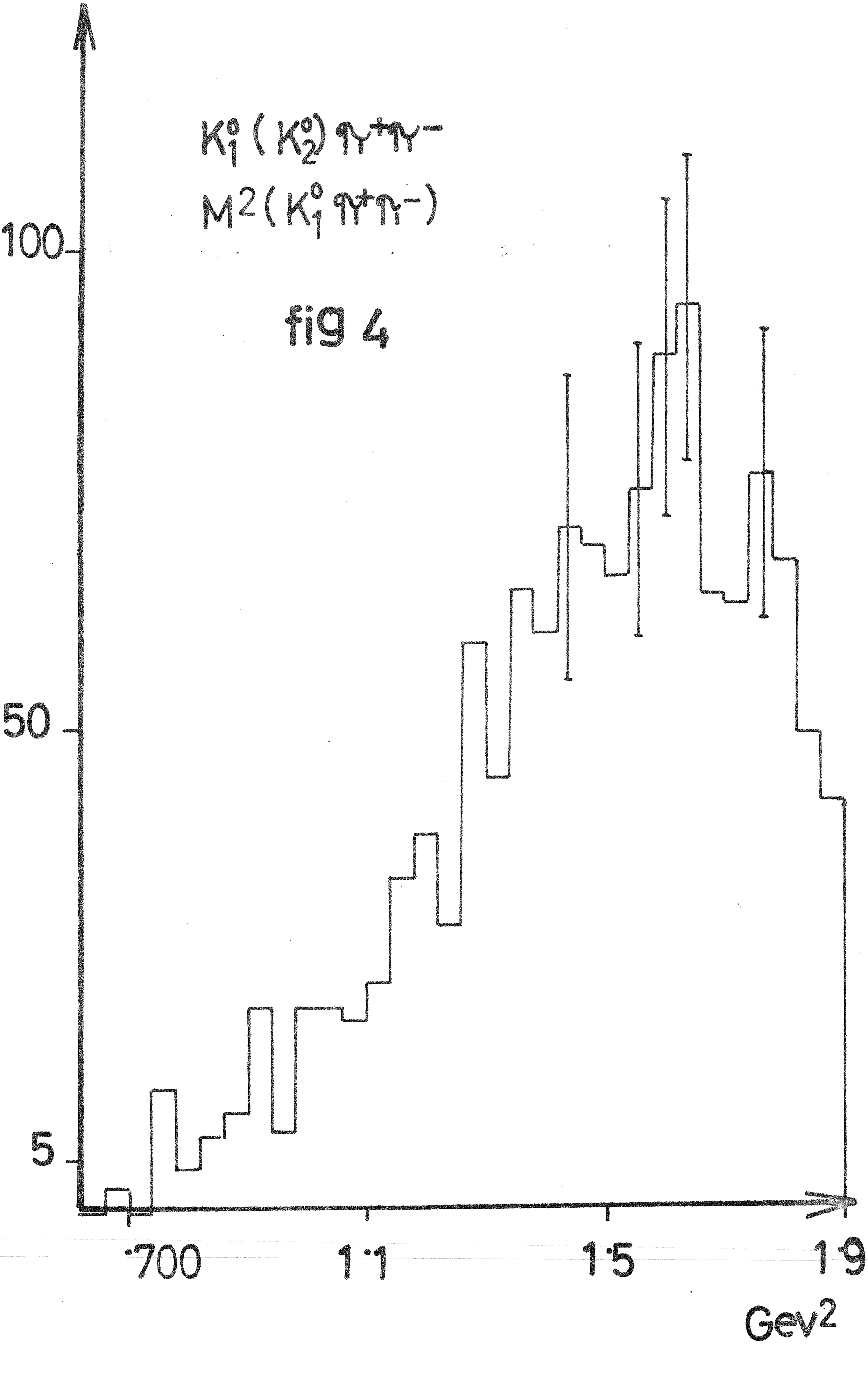


fig 2



$K_1^0 (K_2^0) \pi^+\pi^-$
$M^2(K_1^0\pi^\pm) + M^2((K_2^0)\pi^\pm)$
599
552
N° of events / 0.04 GeV^2 Interval.
500
400
300
200
100
0
.400
.800
1.200
GeV^2

fig 3



$K_1^0\,(K_2^0)\,\pi^+\pi^-$
$M^2(K_1^0\,\pi^+\pi^-)$
fig 4
100
50
5
·700
1·1
1·5
1·9
Gev^2

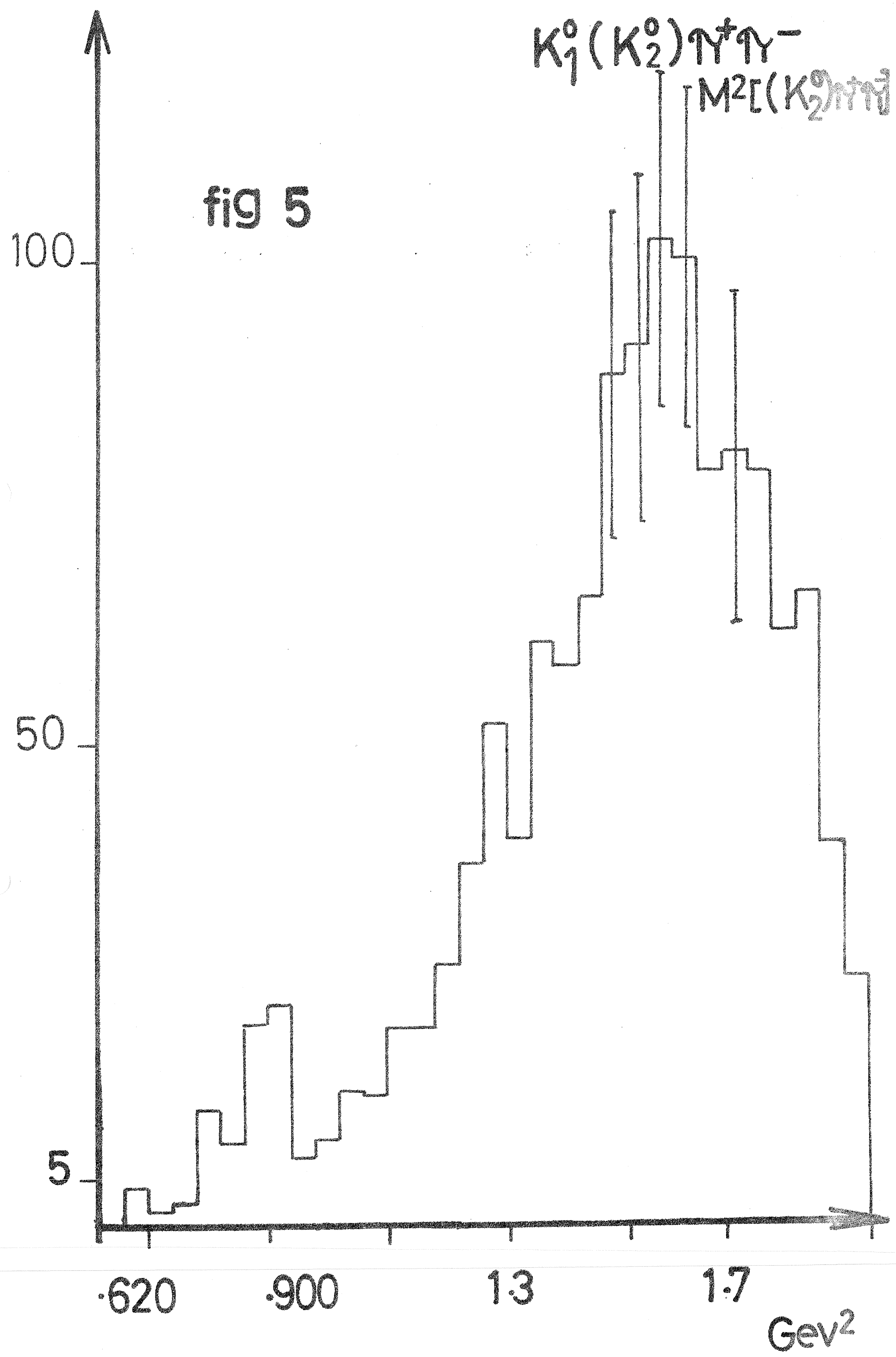


fig 5

PS/4984
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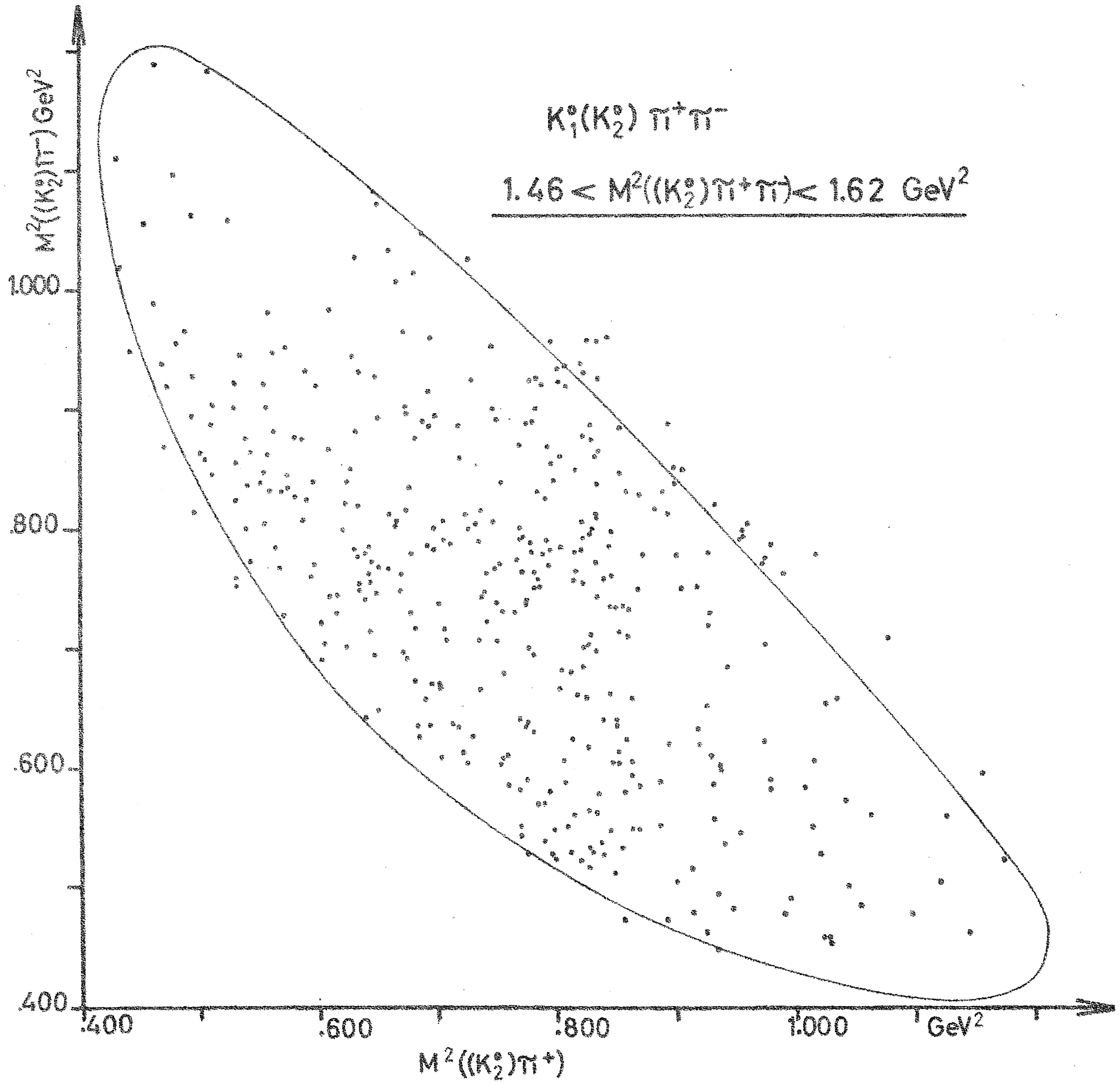
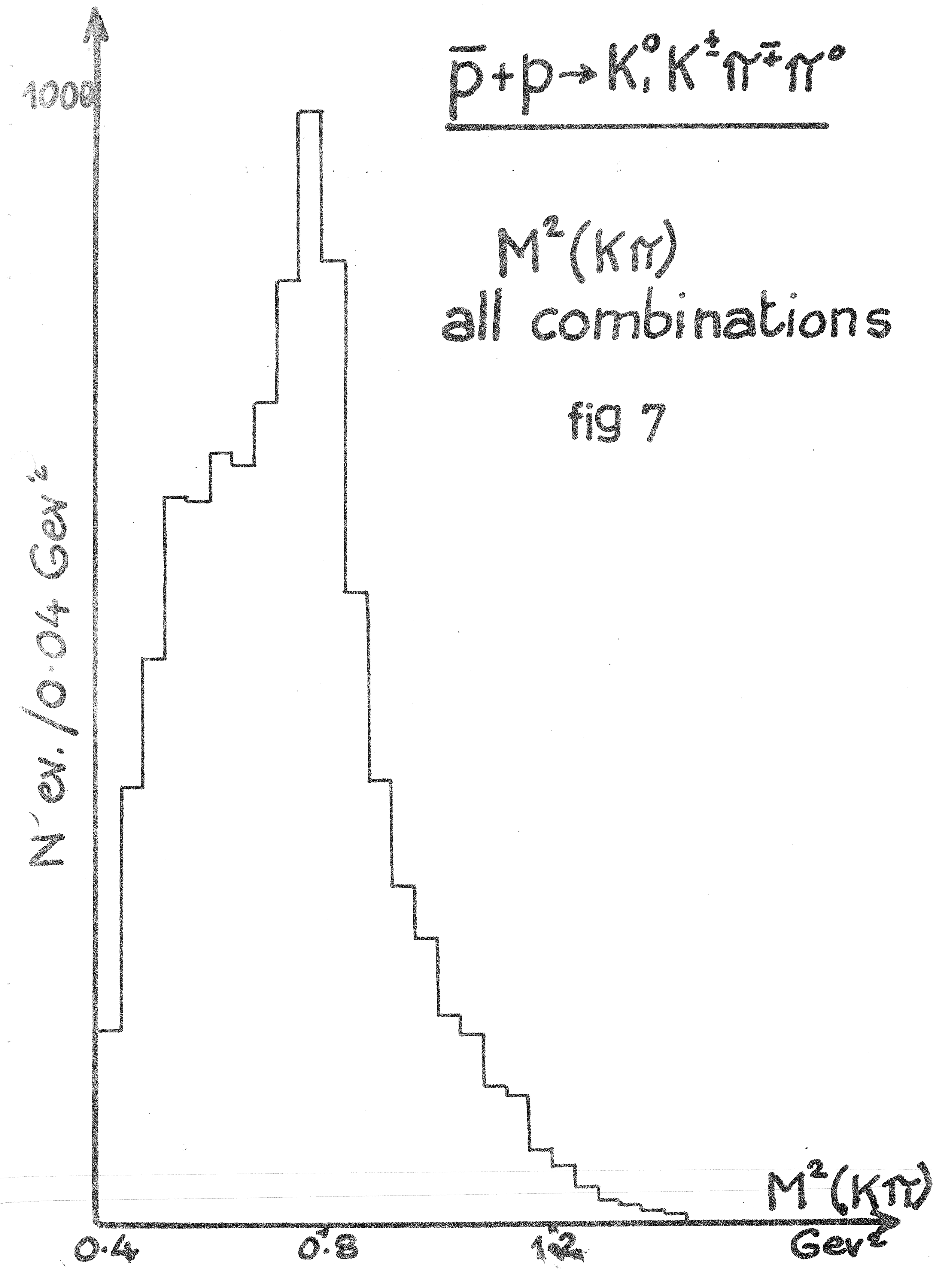
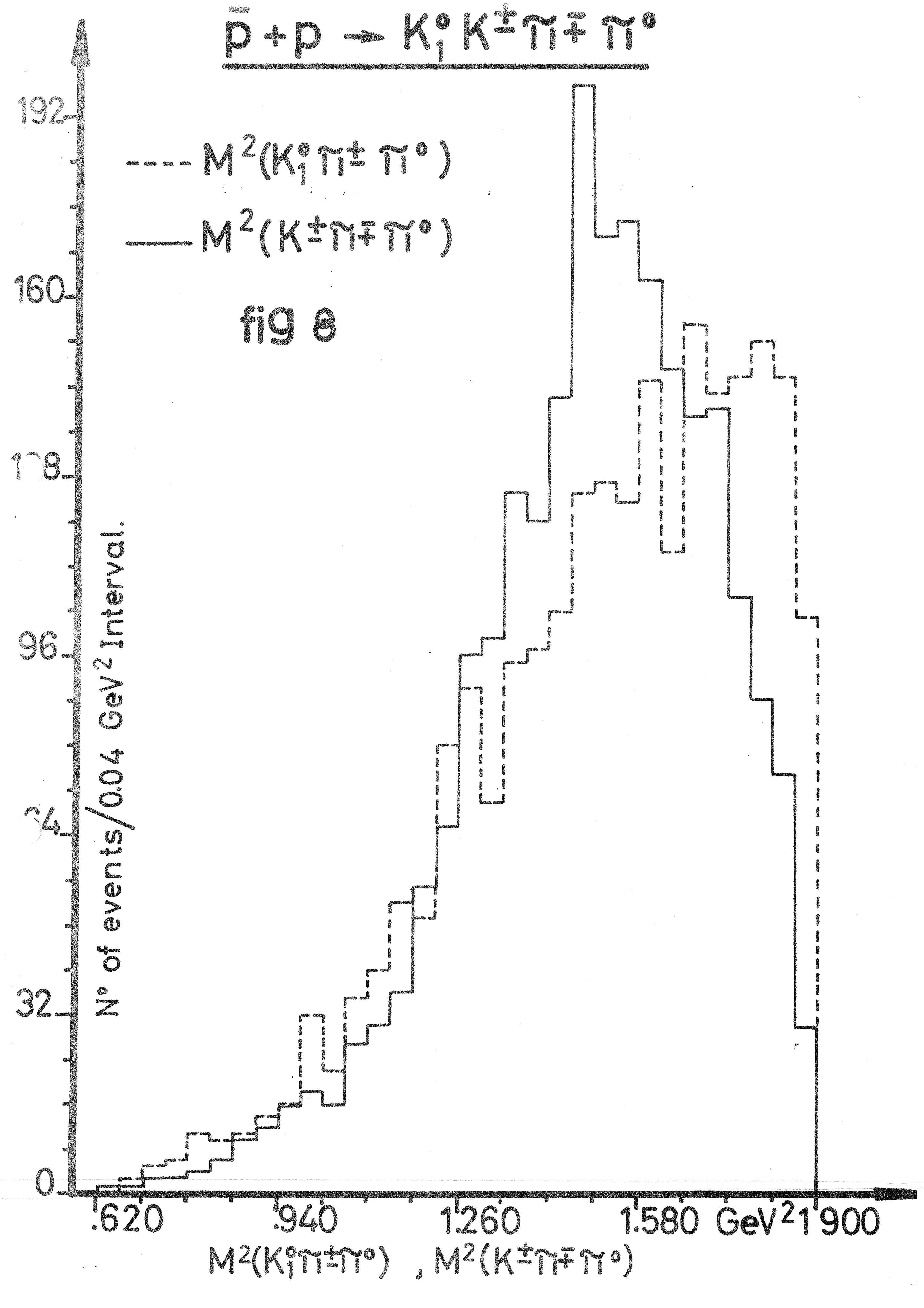
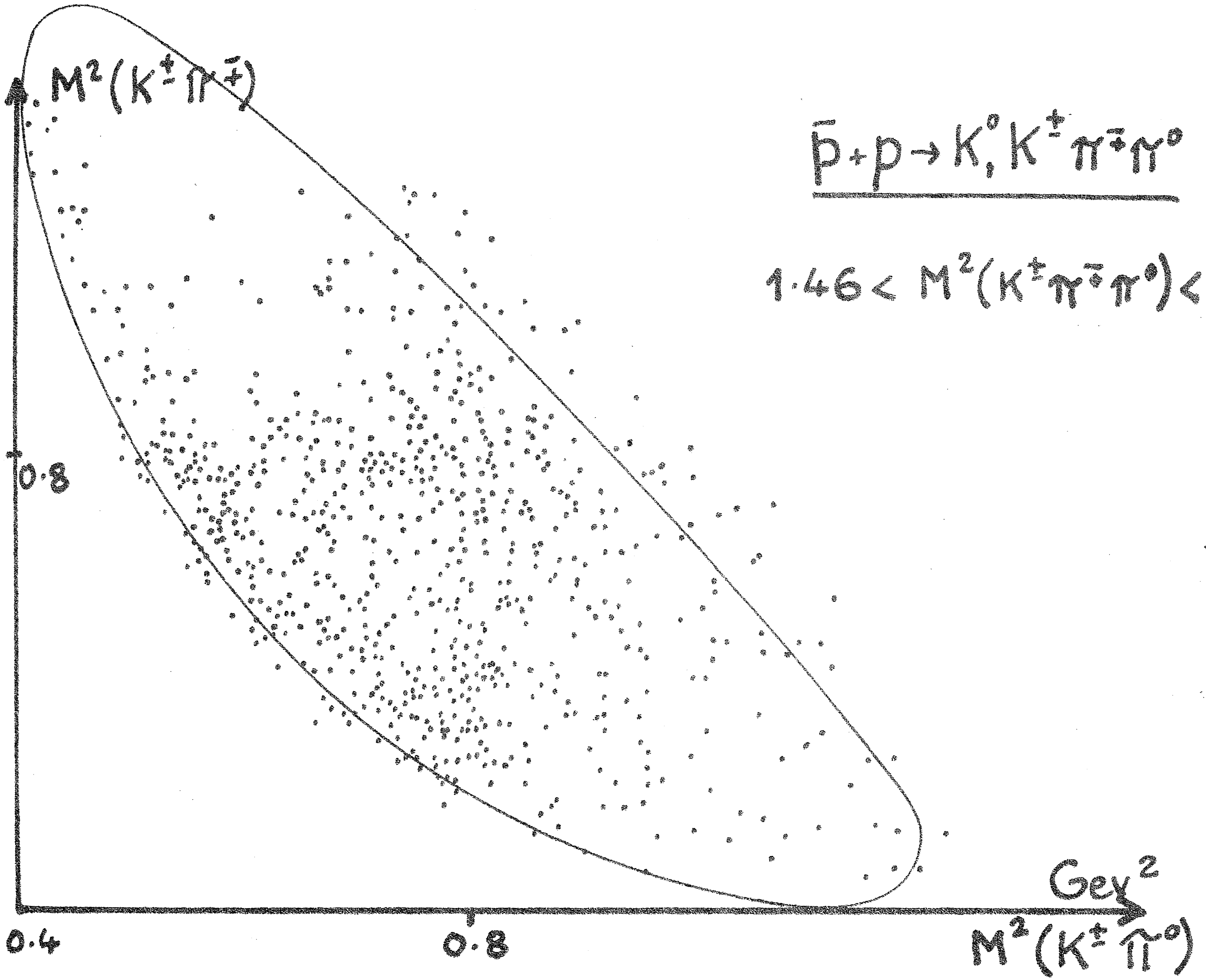


FIG.6


$\bar{p}+p \to K^0_1 K^{\pm} \pi^{\mp} \pi^0$
$M^2(K\pi)$
all combinations
1000
N° ev. /0.04 GeV²
0.4
0.8
1.2
$M^2(K\pi)$
GeV²
fig 7


$\bar{p} + p \rightarrow K_1^0 K^{\pm} \pi^{\mp} \pi^0$
$M^2(K_1^0 \pi^{\pm} \pi^0)$
$M^2(K^{\pm} \pi^{\mp} \pi^0)$
fig 8
192
160
128
96
64
32
0
N° of events/0.04 GeV^2 Interval.
.620
.940
1.260
1.580
GeV^2
1.900
$M^2(K_1^0 \pi^{\pm} \pi^0)$, $M^2(K^{\pm} \pi^{\mp} \pi^0)$

DIR 21792



$\bar{p} + p \rightarrow K^0_1 K^{\pm} \pi^{\mp} \pi^0$

$1{\cdot}46 < M^2(K^{\pm}\pi^{\mp}\pi^0) < 1{\cdot}62$

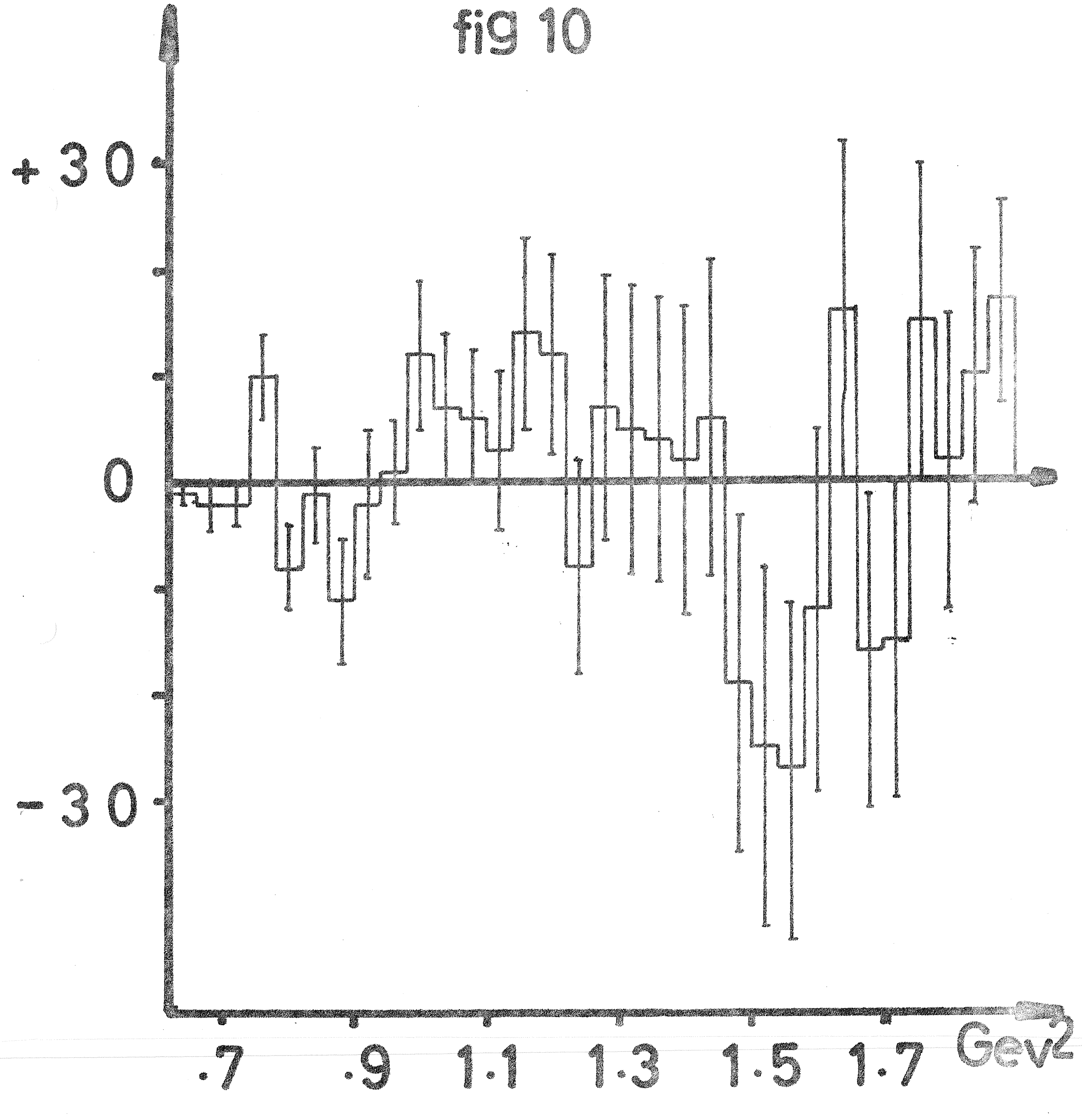
FIG. 9

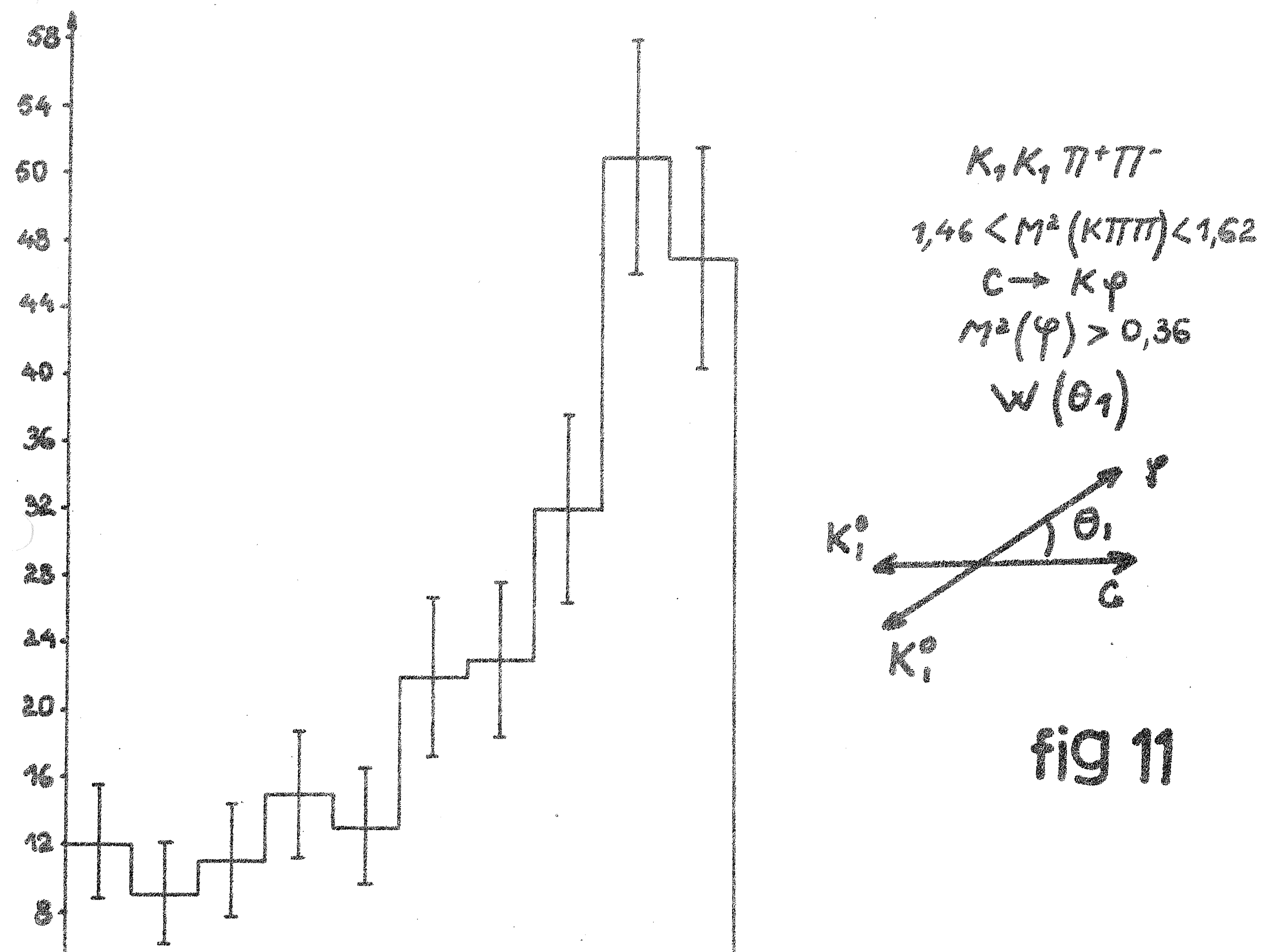
PS/4484

$$p\bar{p} \rightarrow K_1^0 K_2^0 \pi^+ \pi^-$$

$$M^2(K_1^0\pi^+\pi^-) - M^2(K_2^0\pi^+\pi^-)$$

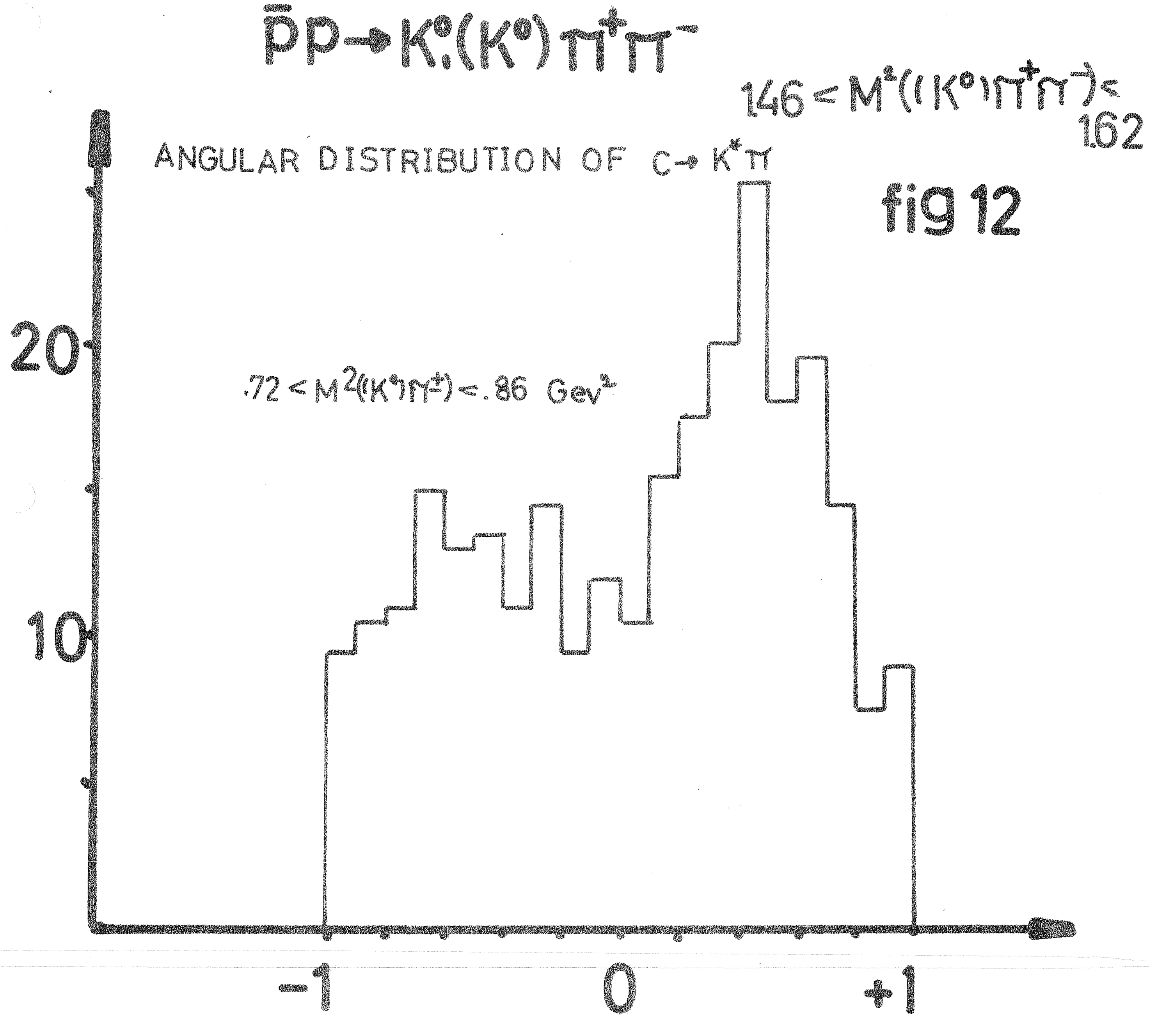
fig 10





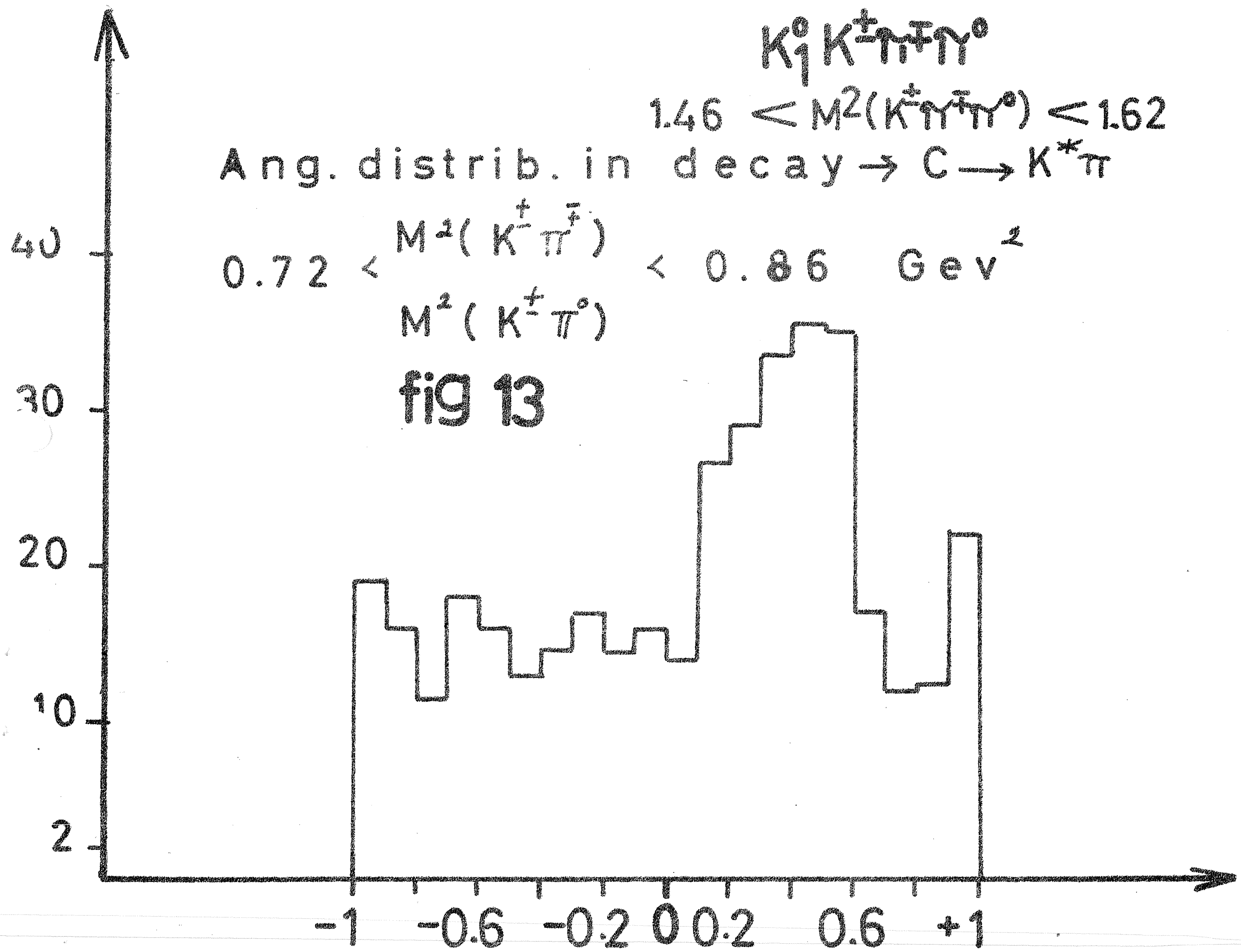
58
54
50
48
44
40
36
32
28
24
20
16
12
8
4
0
-1
0
+1
$K_1 K_1 \pi^+ \pi^-$
$1{,}46 < M^2 (K\pi\pi) < 1{,}62$
$C \rightarrow K\varphi$
$M^2(\varphi) > 0{,}36$
$W(\theta_1)$
φ
θ_1
K_1^0
C
K_1^0

fig 11



$\bar{p}p \to K^0_1(K^0)\pi^+\pi^-$
$1.46 < M^2((K^0)\pi^+\pi^-) < 1.62$
ANGULAR DISTRIBUTION OF $C \to K^*\pi$
$.72 < M^2((K^0)\pi^\pm) < .86$ Gev^2
20
10
-1
0
+1

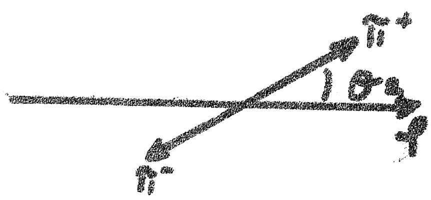
fig 12

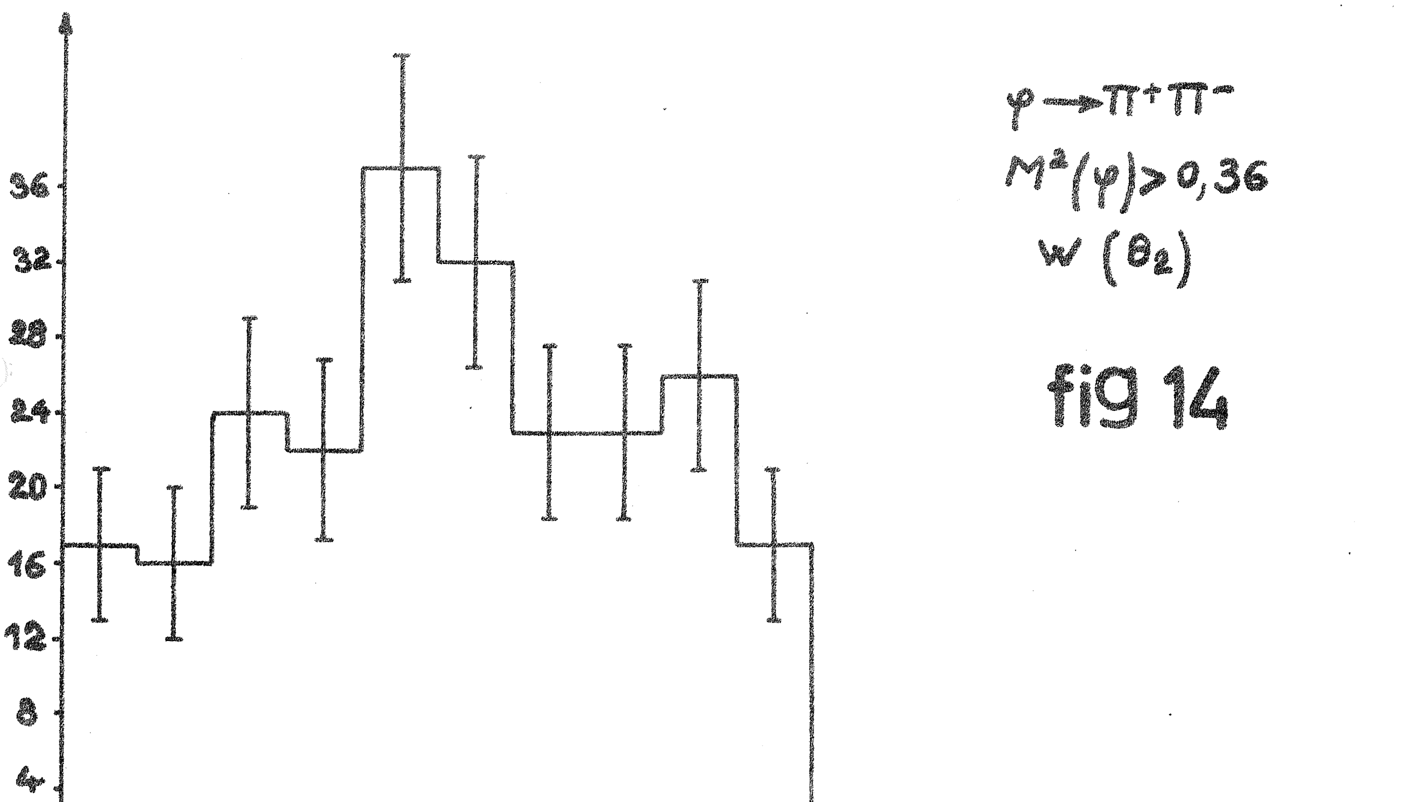

$K_1^0 K^{\pm} \pi^{\mp} \pi^0$
$1.46 < M^2(K^{\pm}\pi^{\mp}\pi^0) < 1.62$
Ang. distrib. in decay → C → $K^*\pi$
$0.72 < \frac{M^2(K^{\pm}\pi^{\mp})}{M^2(K^{\pm}\pi^0)} < 0.86$ Gev^2
fig 13
40
30
20
10
2
-1
-0.6
-0.2
0
0.2
0.6
+1

$\bar{p} + p - K_1^0 K_1^0 \pi^+ \pi^-$

$1.46 < M^2(K_1^0 \pi^+ \pi^-) < 1.62$

$M^2(\pi^+ \pi^-) > 0.36$





$\varphi \rightarrow \pi^+ \pi^-$

$M^2(\varphi) > 0,36$

$w(\theta_2)$

fig 14