TO BE SUBMITTED TO
PHYSICS LETTERS

CERN/TC/PHYSICS 65-9
12.4.1965

# EXPERIMENTAL RESULTS ON THE ANNIHILATION $\bar{p}p \dashrightarrow \bar{K}K\pi$ AT REST

R. Armenteros, D.N. Edwards+), T. Jacobsen, L. Montanet and
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,
College de France, PARIS.

1. In an exposure of the Saclay 81 cm H.B.C. to beams of slow $\bar{p}$'s from the CERN P.S., we have obtained 1,145 events, corresponding to the annihilation $(\bar{p}p)$ at rest,

$$\bar{p} + p \dashrightarrow K_1^o + K^{\pm} + \pi^{\mp} \qquad (1)$$

and 199 events of the type :

$$\bar{p} + p \dashrightarrow K_1^o + K_1^o + \pi^o. \qquad (2)$$

Taking into account the number of $\bar{p}$'s annihilating in flight, the scanning efficiency, and the probability of observing the charged decay of a $K_1^o$ in the useful volume of the chamber, the number of events observed for channels (1) and (2) corresponds, respectively, to a rate of annihilation of :

$$R_{(1)} = (28.2 \pm 1.1) \times 10^{-4}$$
$$R_{(2)} = (\ 7.8 \pm 0.6) \times 10^{-4}.$$

Figures (1) and (2) show the production Dalitz-plots for channels (1) and (2), respectively. The 1,145 events plotted in Fig. (1) correspond to 585 $\bar{p}p \dashrightarrow K_1^o K^+ \pi^-$ and 560 $\bar{p}p \dashrightarrow K_1^o K^- \pi^+$.

The asymmetry of Fig. (1), with respect to the first diagonal, is evidence of the presence of interference effects between the two amplitudes $A_1$ and $A_o$, relative to the two isospin states I = 1 and I = 0 of the $(\bar{p}p)$ system. The asymmetry disappears if we build the Dalitz-plot (Fig. (3)), taking the energies

---

+) On leave of absence from the University of Liverpool.

of the K's ($K^+$ and $K^o$) as the abscissae and the energies of the $\bar{K}$'s ($K^-$ and $\bar{K}^o$) as the ordinates.

## 2. Production of $K^*$

Fig. (1) and, to some extent Fig. (2), shows an appreciable fraction of annihilations (1) and (3) via the two-body channels :

$$\bar{p}p \dashrightarrow K_1^o \; K^{*o} \hookrightarrow K_1^o \; \pi^o \tag{3}$$

$$\bar{p}p \dashrightarrow K_1^o \; K^{*o} \hookrightarrow K^{\pm} \; \pi^{\mp} \tag{4}$$

$$\bar{p}p \dashrightarrow K^{\pm} \; K^{*\mp} \hookrightarrow K_1^o \; \pi^{\mp} \; . \tag{5}$$

The $K^*$ production for reaction (1) has been studied by fitting the population of the Dalitz-plot by a density function of the form :

$$k\left(A_N \frac{1}{(s_N - s_N^*)^2 + s_N^* \Gamma^2} + A_C \frac{1}{(s_C - s_C^*)^2 + s_C^* \Gamma^2} + 1\right) \tag{A}$$

where $s_N$ is the squared mass of the neutral ($K\pi$) system,
$s_C$ is the squared mass of the charged ($K\pi$) system,
$\Gamma$ is the total width of the $K^*$
$A_N$, $A_C$, $s_N^*$, $s_C^*$ and $\Gamma$ are the parameters to be fitted,
k is a normalisation constant, function of the parameters, determined by equating the integral of (A) to the total number of events in the plot.

The optimal values found for $s_N^*$ and $s_C^*$ are, within the errors, compatible and equal to $(890.5 \text{ Mev})^2$; for the width, we find $\Gamma = 31$ Mev. The rates of $K^{*o}$ and $K^{*\pm}$ productions are 0.20 ± 0.04 and 0.14 ± 0.04, respectively. For reaction (2), one finds a rate of two-body annihilations (3) of 0.15 ± 0.07.

These results are summarized in Table I, where we have added the information obtained by the study of the 0-prong events with one or two associated $K_1^o$ from which one deduces (Ref. 1) the rate of the channel :

$$\bar{p}p \dashrightarrow K_1^o \; K^{*o} \hookrightarrow K_2^o \; \pi^o \; . \tag{6}$$

## Table I

| Channel | No. of observed events | No. of produced events | Rate x $10^4$ |
|---|---|---|---|
| $\bar{p}p \to K_1^0 K^{*0}$<br>$\hookrightarrow K_1^0 \pi^0$ | 30 | 82 ± 40 | 1.2 ± 0.6 |
| $\bar{p}p \to K_1^0 K^{*0}$<br>$\hookrightarrow K^\pm \pi^\mp$ | 235 | 390 ± 80 | 5.7 ± 1.2 |
| $\bar{p}p \to K^\pm K^{*\mp}$<br>$\hookrightarrow K_1^0 \pi^\mp$ | 158 | 273 ± 80 | 4.0 ± 1.2 |
| $\bar{p}p \to K_1^0 K^{*0}$<br>$\hookrightarrow K_2^0 \pi^0$ | 88 | 150 ± 35 | 2.2 ± 0.5 |

The quoted errors are predominantly due to the uncertainty of determining the number of $K^*$ events from the Dalitz plots.

Assuming that the annihilation at rest goes essentially via S-states (as it has been experimentally found for the two-body annihilations $K_1^0K_1^0$, $K_1^0K_2^0$ (Ref. 2)), the rates obtained for reactions (3), (4) and (6) are related in the following way. The final state of reaction (3) being a pure C = +1 state, allows us to estimate the contribution of the singlet $^1S_0$ state of the protonium, while the reaction (6), being a pure C = -1, is related to the triplet $^3S_1$ state of the protonium. Taking for the branching ratio of the decay modes of the $K^{*0}$ :

$$\frac{K^{*0} \to K^+\pi^-}{K^{*0} \to K^0\pi^0} = 2$$

we have the relation $R_{(3)} + R_{(6)} = \frac{1}{2} R_{(4)}$ .

This relation is well satisfied by our results; it shows that the singlet state contributes about 35°/o to the total annihilation rate for reaction (4). This ratio is compatible with the observed population of the plot within the $K^*$ bands.

## 3. Study of the non-$K^*$ resonating events

The distribution of the events outside the $K^*$ bands has been studied. More precisely, if we concentrate our attention on the events for which both K's have an energy smaller than 760 Mev, we find for reactions (1) and (2) the ($\bar{K}K$) effective mass squared distributions of Fig. (4) and Fig. (5).

One sees on Fig. (4) two enhancements centred at $m^2 = 1.05$ ($m = 1025$ Mev/$c^2$) and $m^2 = 1.56$ ($m = 1250$ Mev/$c^2$), with widths of about 40 and 50 Mev, respectively. They depart from phase space by 4.4 and 3.8 standard deviations, respectively. When we divide our data into two parts corresponding to $K_1^oK^+\pi^-$ and $K_1^oK^-\pi^+$ (146 events and 145 events, respectively), we find the results shown in Fig. (6). The two distributions appear different. If this effect is non-statistical, it would imply a breakdown of charge conjugation conservation in strong interactions. That such an effect might happen is discussed by Prentki and Veltman (Ref. 3). In view of the importance of this we made a contingency test of the distributions.

The answers obtained depend critically on the size and position of the intervals chosen in the histograms or on the way the Dalitz-plots are divided into cells. Although we cannot estimate precisely and uniquely the significance of the difference between the two distributions, the answers fluctuate around a 10°/o compatibility level when the data is split into intervals (or cells) ranging from 10 to 30.

The stopped antiproton experiment at Columbia (Ref. 4), with similar statistical accuracy, supports the two enhancements qualitatively, but does not show the same difference between the $K^+$ and $K^-$ distributions (Figs. (7) and (8)).

For the rest of our discussion we will ignore any possible difference between the $K^+$ and $K^-$ behaviour.

The enhancements were looked for in other annihilation channels. Fig. (5) shows the $K\bar{K}$ effective mass squared in the mode $K_1^oK_1^o\pi^o$ : it does not show an enhancement at $m^2 = 1.05$, but a broad enhancement centred at about $m^2 = 1.65$ ($m = 1285$ Mev/$c^2$) ; its width is about 120 Mev. These enhancements were also sought in the annihilations into four and five bodies. Unfortunately, these channels are dominated by other known resonances in such a way that any $K\bar{K}$ structure is masked; in particular, the accumulation of ($K^oK^\pm$) effective masses at low energy values observed in the $K_1^oK^\pm\pi^\mp\pi^+\pi^-$ annihilations could be interpreted as an interference effect of $K^*$ production (Ref. 5).

## $(K_1^0K^{\pm})$ enhancements :

In an attempt to discuss the possible quantum numbers of these two enhancements, considered as resonances, we have listed in Table II the predicted decay angular distributions for the different lowest spin parity assignments and for the possible initial states of the protonium, assuming as before only S-state annihilations. One should notice that the I-spin of the charged $K\bar{K}$ system is one.

### Table II

| Initial state | $J^{PG}$ assignment of the $(K\bar{K})$ system | Orbital angular momentum of the $\pi$ with respect to the $(K\bar{K})$ system | Decay angular distribution of the $(K\bar{K})$ system |
|---|---|---|---|
| $^1S_0\ (0^-)$ | $0^{+-}$ | 0 | 1 |
| | $1^{-+}$ | 1 | $\cos^2\theta$ |
| | $2^{+-}$ | 2 | $(1 - 3\cos^2\theta)^2$ |
| $^3S_1\ (1^-)$ | $0^{+-}$ | forbidden by parity conservation | |
| | $1^{-+}$ | 1 | $\sin^2\theta$ |
| | $2^{+-}$ | 2 | $\sin^2\theta\ \cos^2\theta$ |

a) The 1025 Mev $(K\bar{K})^{\pm}$ enhancement

$0^{+-}$ assignment : then the only possible initial state is $^1S_0$ ; the enhancement should show up in the $K_1^0K_1^0\pi^0$, which is uniquely related to $^1S_0$. If the non-observation of this enhancement in $(K_1^0K_1^0)$ is significant, $0^{+-}$ must be excluded.

$1^{-+}$ assignment : this assignment excludes the $(K_1^0K_1^0)$ channel, in agreement with the observation. Moreover, if $^1S_0$ and $^3S_1$ contribute to the production of the enhancement in a comparable way, one expects an almost isotropic decay angular distribution for the $(K\bar{K})^{\pm}$ system : this is not excluded by the experimental results (Fig. 9a).

$2^{+-}$ assignment : to explain the absence of the enhancement in the $K_1^0K_1^0\pi^0$ events, one has to assume that ${}^1S_0$ does not contribute to the production of the enhancement : then one expects a $\sin^2\theta\cos^2\theta$ angular distribution for the decay of the $(K\bar{K})^{\pm}$ events, in poor agreement with the experimental results.

b) The 1250 Mev $(K\bar{K})^{\pm}$ enhancement

If, in spite of the different masses and widths, we consider the enhancement seen in the $K_1^0K_1^0\pi^0$ final state as the neutral counterpart of the same phenomenon, then only $0^{+-}$ and $2^{+-}$ assignments are allowed; if not, $1^{-+}$ is possible.

The angular distribution does not allow us to decide between these three possible assignments (Fig. (9b)).

c) The 1285 Mev $(K_1^0K_1^0)$ enhancement

If we assume that the $(K_1^0K_1^0)$ enhancement is a specific phenomenon (it can have isotopic spin $I = 0$), the simplest assignments will then be $0^{++}$ and $2^{++}$. In that case, it could be identified with the well-known $f^0$ resonance, although the experimental angular distribution differs from the expected one ($\sin^2\theta\cos^2\theta$).

<u>Remark</u>

Finally, we can try to identify the 1250 Mev $(K^0K^{\pm})$ enhancement to the well-known resonances B or $A_2$. Bettini et al. (Ref. 6) have reported, at the 1964 Dubna Conference, a large production of $A_2^{\pm}$ with antiproton at rest; according to these authors, $\bar{p}p \dashrightarrow A_2^{\pm}\pi^{\mp}$ represents a rate of about 0.02. If we assume that the 100 events $(K^0K^{\pm})$ we observe in the region of the 1250 Mev enhancement represent the $K\bar{K}$ decay mode of the $A_2$ resonance, we can assign an upper limit for the branching ratio :

$$\frac{A_2 \dashrightarrow K^0K^{\pm}}{A_2 \dashrightarrow \rho^0\pi^{\pm}} = \frac{0.0004}{0.02} = 0.02 \qquad (7)$$

This result is in disagreement with the results of R.I. Hess et al. (Ref. 7), but agree with the results obtained by the Aachen-Berlin-CERN $\pi^+p$ 8 GeV Collaboration (Ref. 8). Of course, the 1250 Mev $(K\bar{K})^{\pm}$ enhancement we observe may be different from the $A_2$ : in this case the branching ratio (7) is even lower.

It seems unlikely that our (1250) Mev $(K\bar{K})^{\pm}$ enhancement could be a manifestation of the B-meson (1215), since this resonance has not been observed to decay into $(K\bar{K})$ (Ref. 7), and taking into account the mass difference between the B-meson and our results.

## Acknowledgments

We should like to express our thanks to Professors Ch. Peyrou, L. Leprince-Ringuet, B.P. Grégory, J. Sakurai, C. Bouchiat, B. d'Espagnat, Ph. Meyer, J. Prentki, M. Veltmas and S. Wojcicki for stimulating discussions.

We would also like to express our gratitude to our colleagues L. Dobrzynski and M. Della Negra for their efficient help.

## References

(1) R. Armenteros et al., 1962 International Conference on High Energy Physics, CERN, Geneva, p. 295. For further explanations, see P. Rivet's thesis, Fac. des Scien.,Paris 1964 (unpublished).

(2) R. Armenteros et al., 1962 International Conference on High Energy Physics, CERN, Geneva, p. 351.

(3) J. Prentki and M. Veltman, "Possibility of C.P. violation in semi-strong interactions" (CERN - TH 519).

(4) Private communication from Prof. J. Steinberger.

(5) R. Armenteros et al., "Study of a $(K\bar{K}\pi)$ enhancement in $K\bar{K}3\pi$ annihilations of $\bar{p}$ at rest", 1964 Dubna Conference.

(6) A. Bettini et al., "Annihilation of $\bar{p}$ at rest into pions", 1964 Dubna Conference.

(7) R.I. Hess et al., "Production and decay of boson resonant states in $\pi^- + p$ interactions at 3.2 GeV/c", U.C.R.L. 11443.

(8) Private communication from Dr. D.R.O. Morrison.

## Figure Captions

Fig. 1 Production Dalitz-plot for $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$ (1145 events).

Fig. 2 Production Dalitz-plot for $\bar{p}p \dashrightarrow K_1^0 K_1^0 \pi^0$ ( 199 events).

Fig. 3 Symmetrized production Dalitz-plot for $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$.

Fig. 4 Squared effective mass spectrum $(K\bar{K})^{\pm}$ for $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$, with the restriction : $E(K) < .760$ GeV/$c^2$ (291 events). The curve represents the normalised phase space.

Fig. 5 Squared effective mass spectrum $(K\bar{K})^0$ for $\bar{p}p \dashrightarrow K_1^0 K_1^0 \pi^0$, with the restriction $E(K) < .760$ GeV/$c^2$ (67 events). The curve represents the normalised phase space.

Fig. 6 Squared effective mass spectra for $(K\bar{K})^+$ and $(K\bar{K})^-$ in $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$, with the restriction $E(K) < .760$ GeV/$c^2$ (146 and 145 events).

Fig. 7 Squared effective mass spectra of $(K\bar{K})^+$ and $(K\bar{K})^-$ in $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$, with the restriction $E(K) < .760$ GeV/$c^2$ (Columbia experiment).

Fig. 8 Squared effective mass spectra for $(K\bar{K})^{\pm}$ in $\bar{p}p \dashrightarrow K_1^0 K^{\pm} \pi^{\mp}$, with the restriction $E(K) < .760$ GeV/$c^2$ (Columbia experiment). The curve represents the normalised phase space.

Fig. 9 a) Decay angular distribution of the 1025 Mev $(K\bar{K})^{\pm}$ system.

b) Decay angular distribution of the 1250 Mev $(K\bar{K})^{\pm}$ system, after elimination of the $K^*$ bands.

c) Decay angular distribution of the 1285 Mev $(K_1^0 K_1^0)$ system.

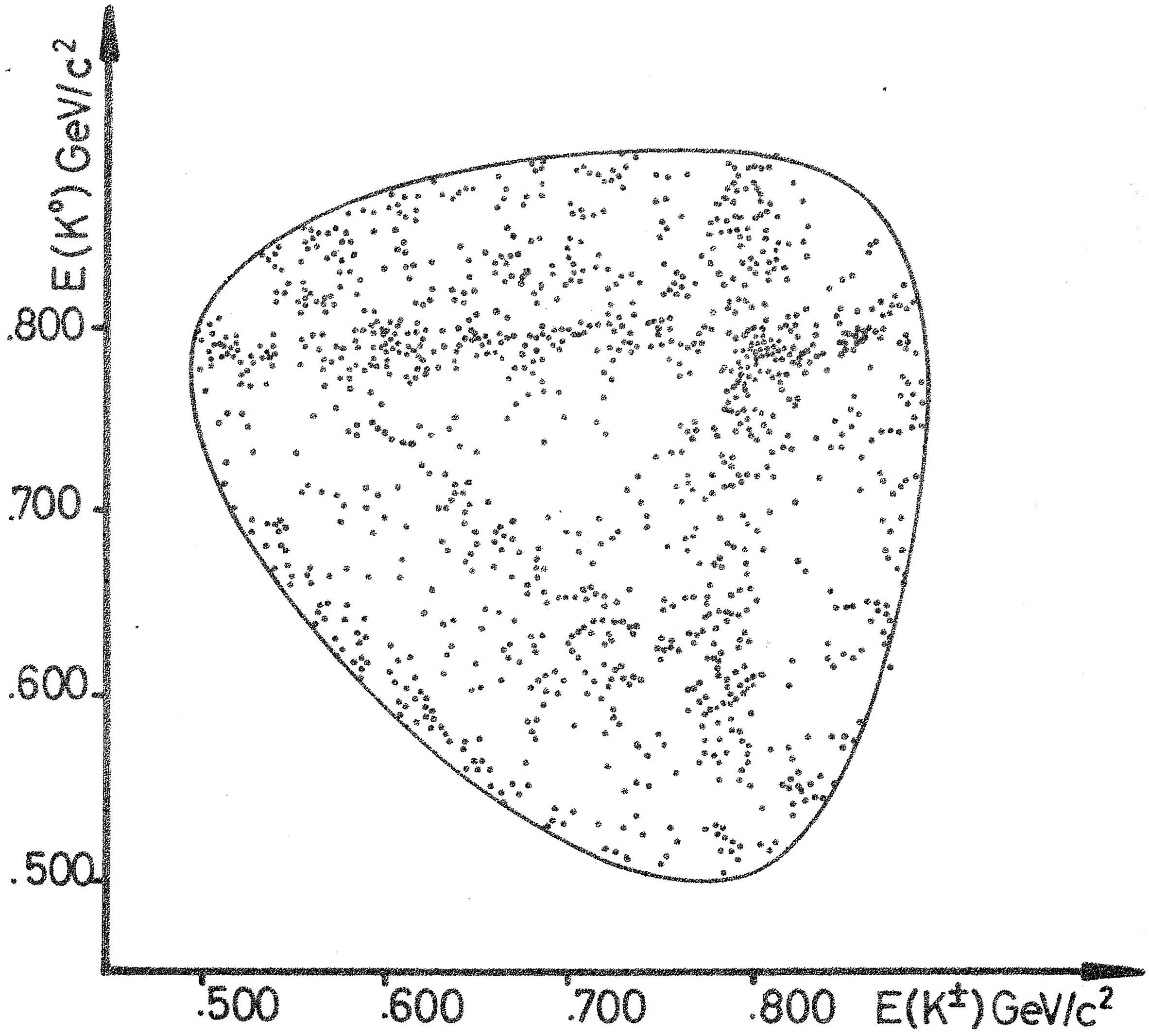

FIG. 1

DIA 22967
PS/4860

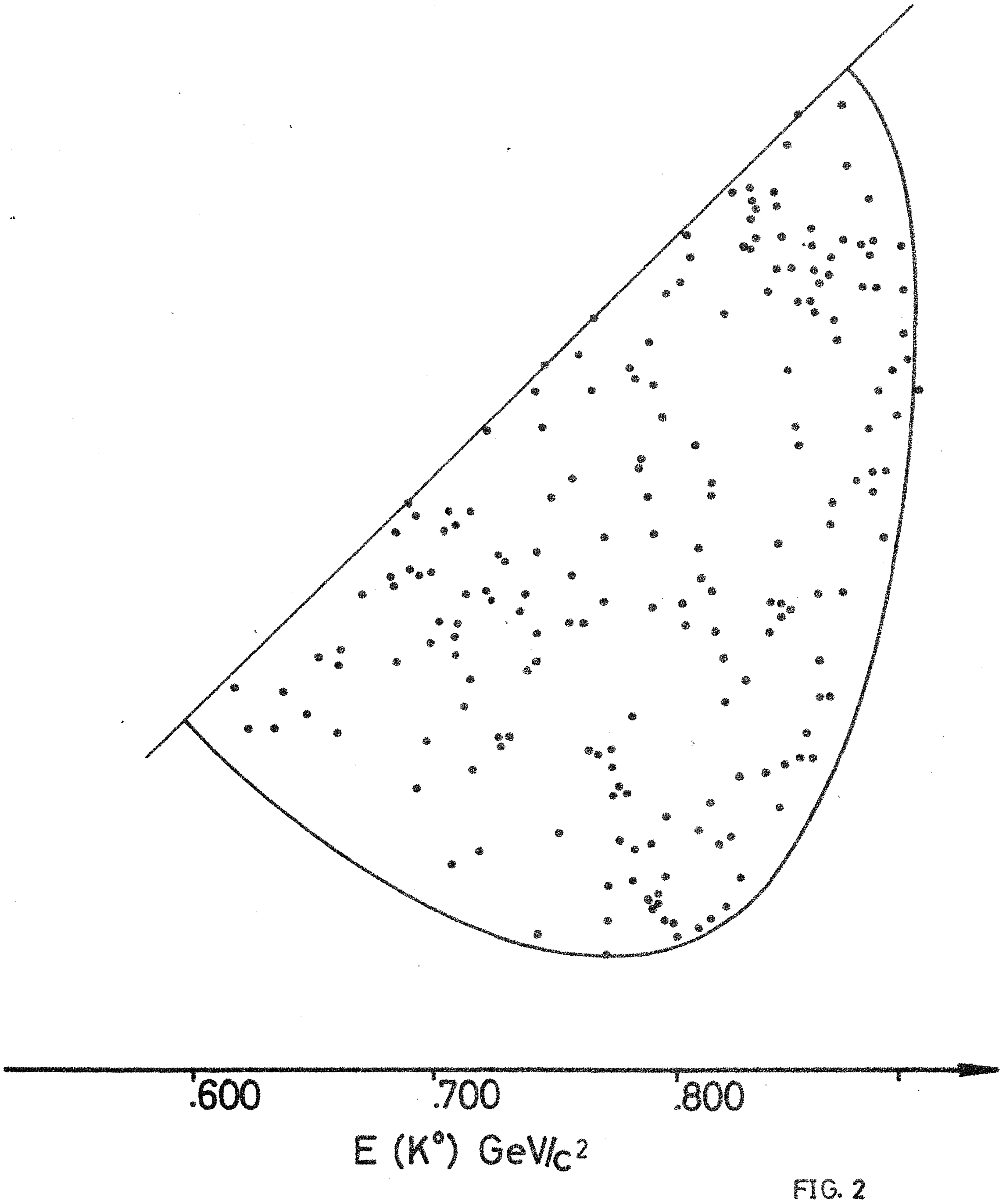

FIG. 2

DIA 22972
PS/4860

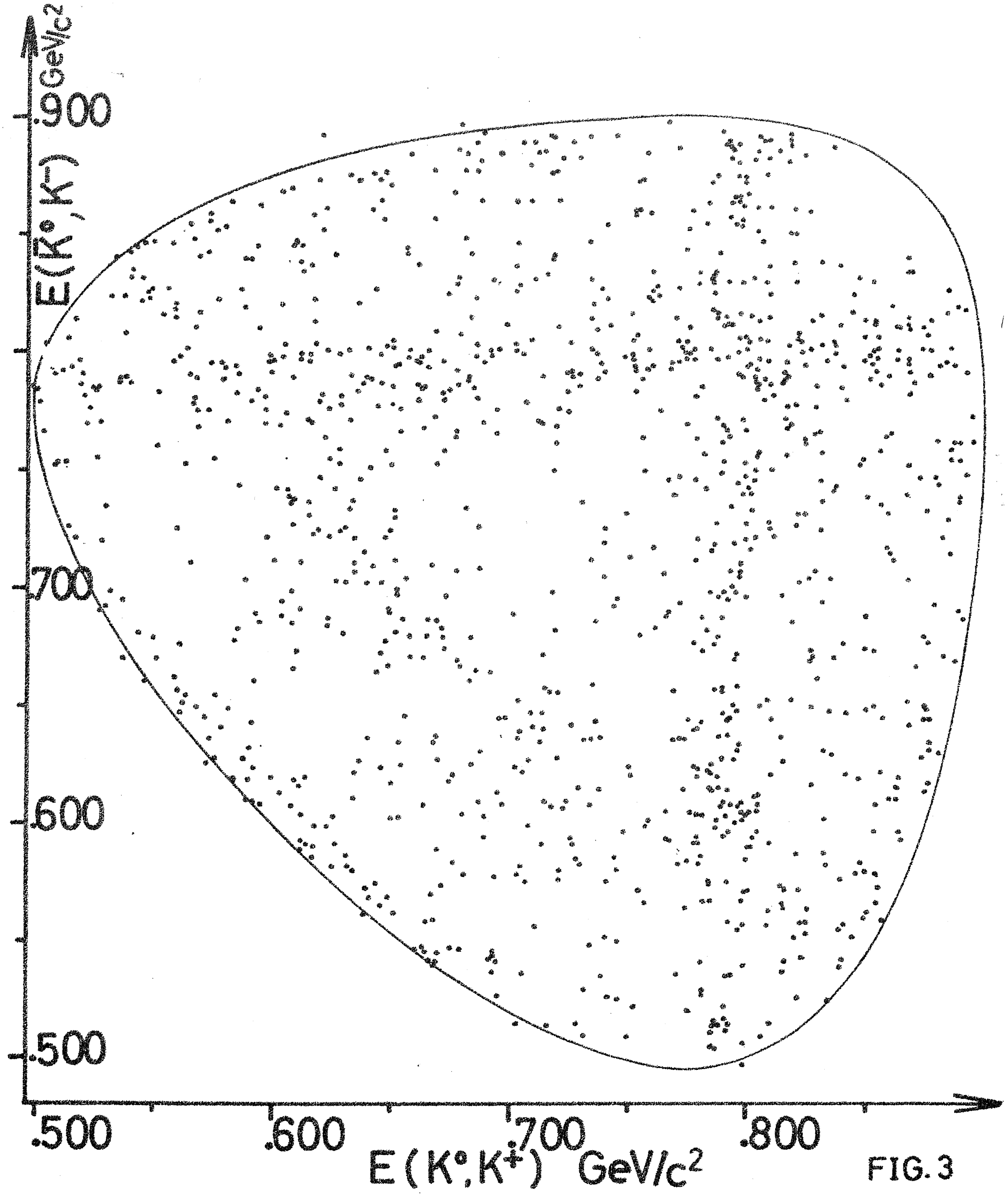

FIG. 3

DIA 22968
PS / 4860

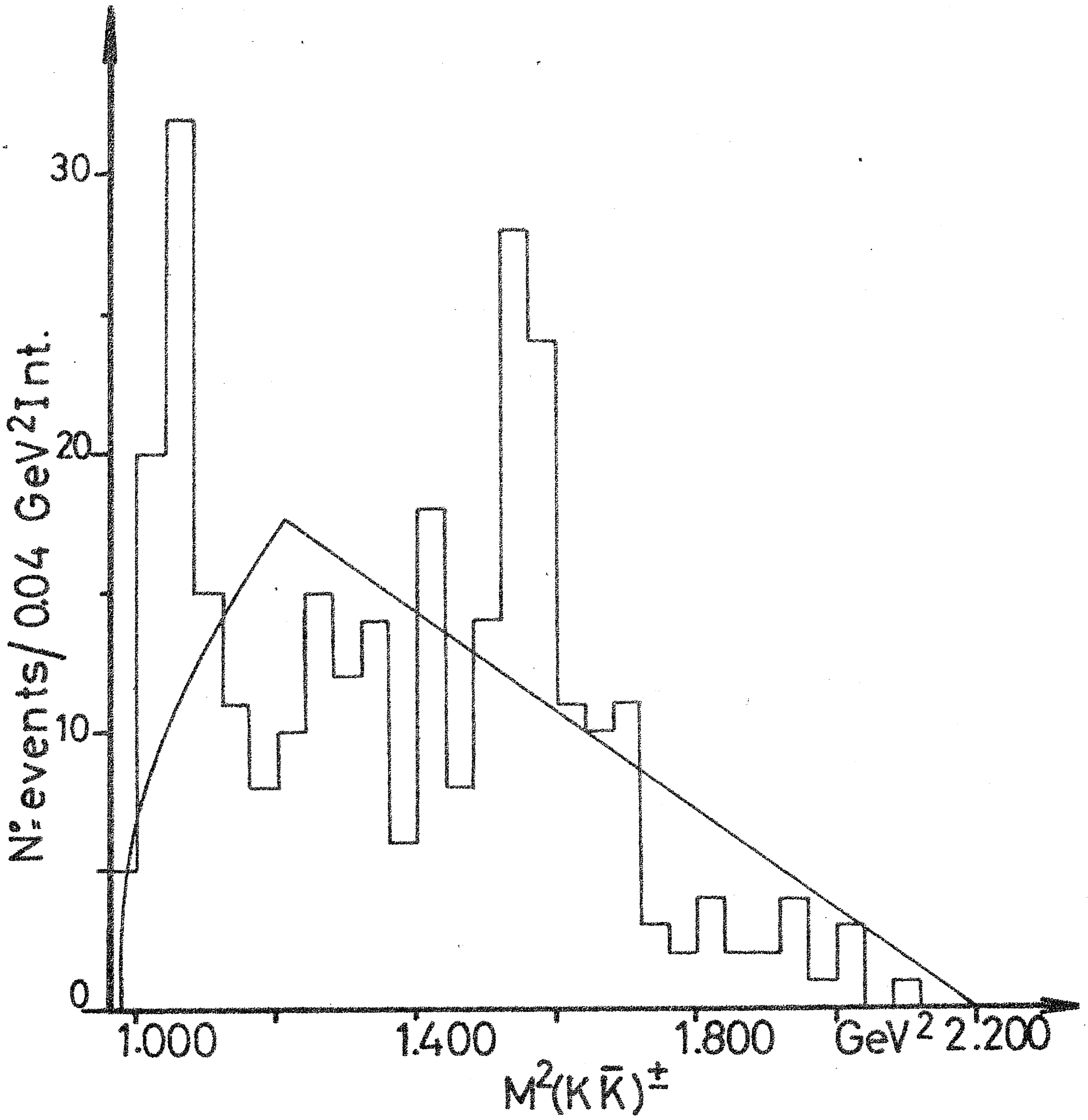

FIG 4

DIA 22969
PS/4860

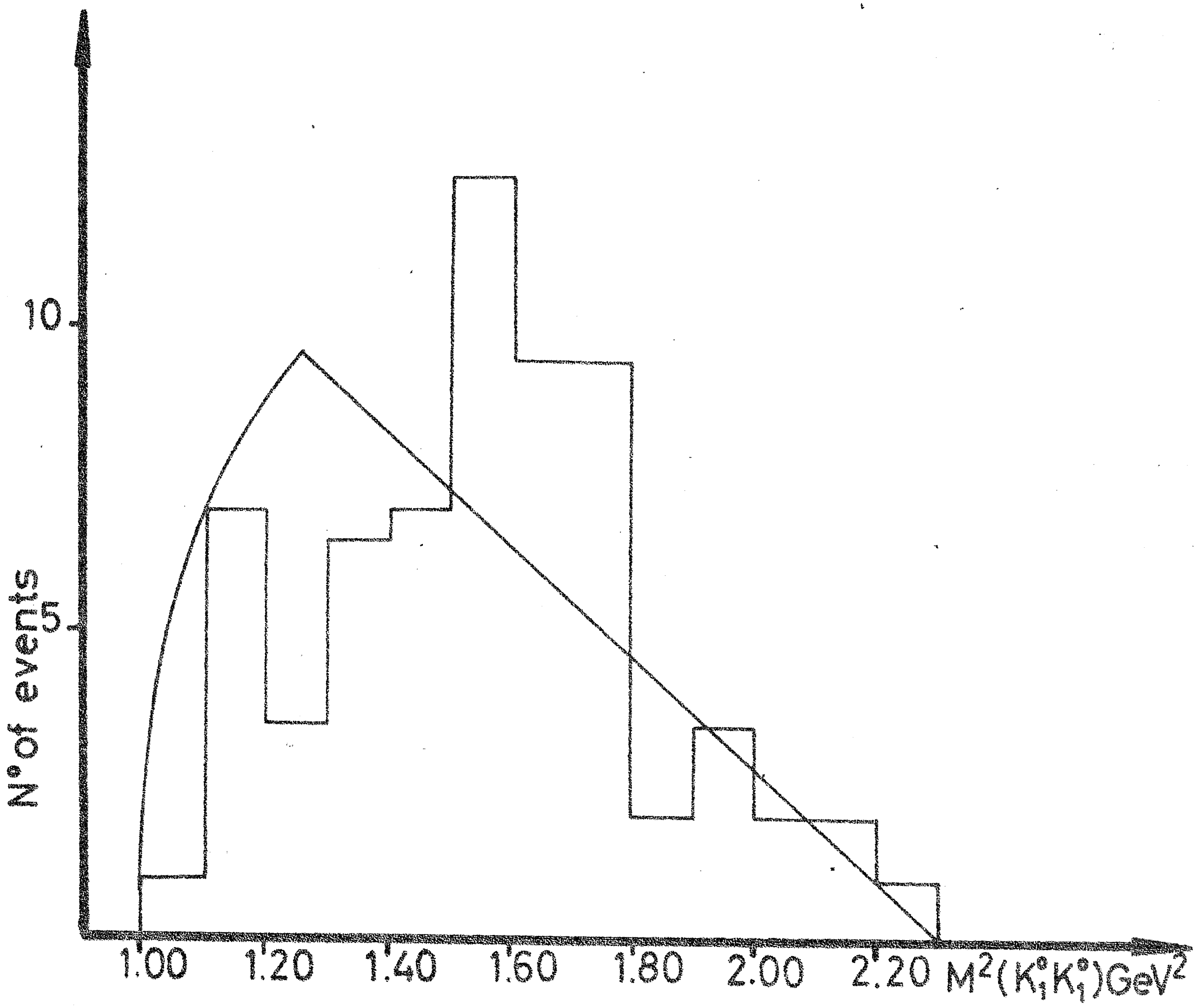

FIG. 5

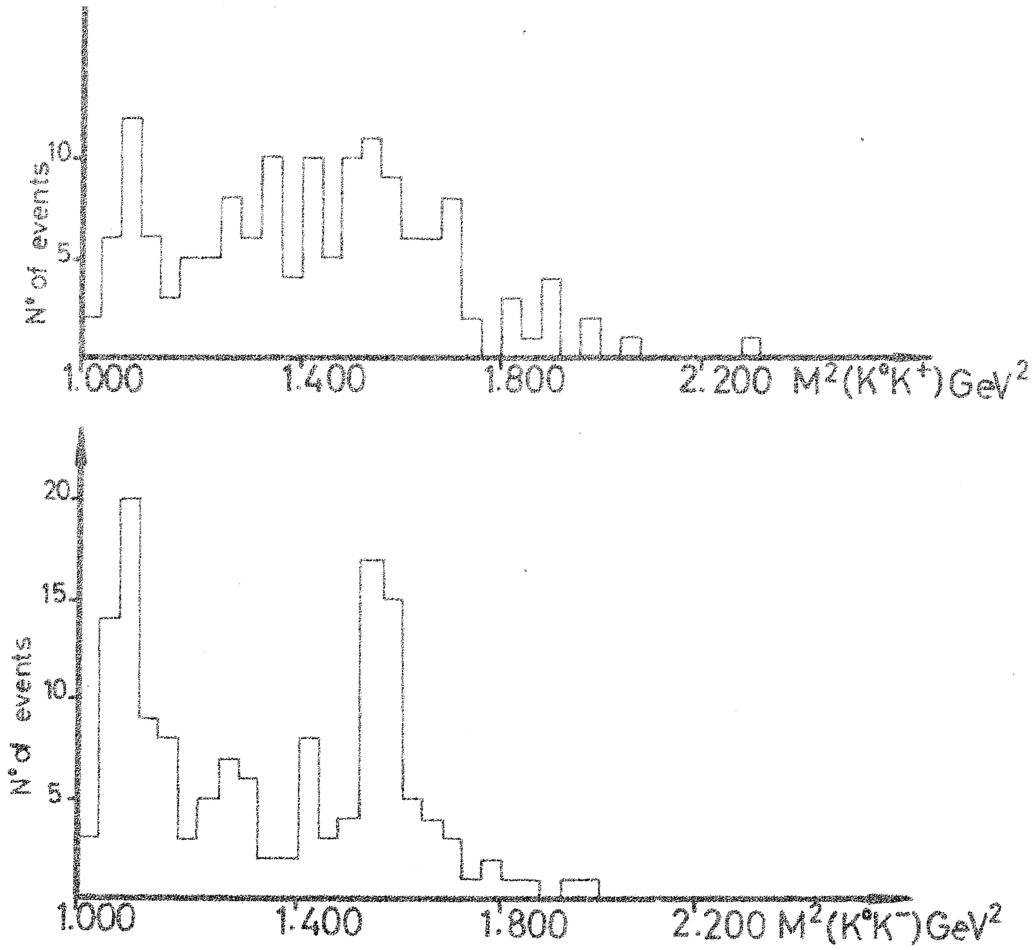

FIG.6

DIA 22970
PS/4860

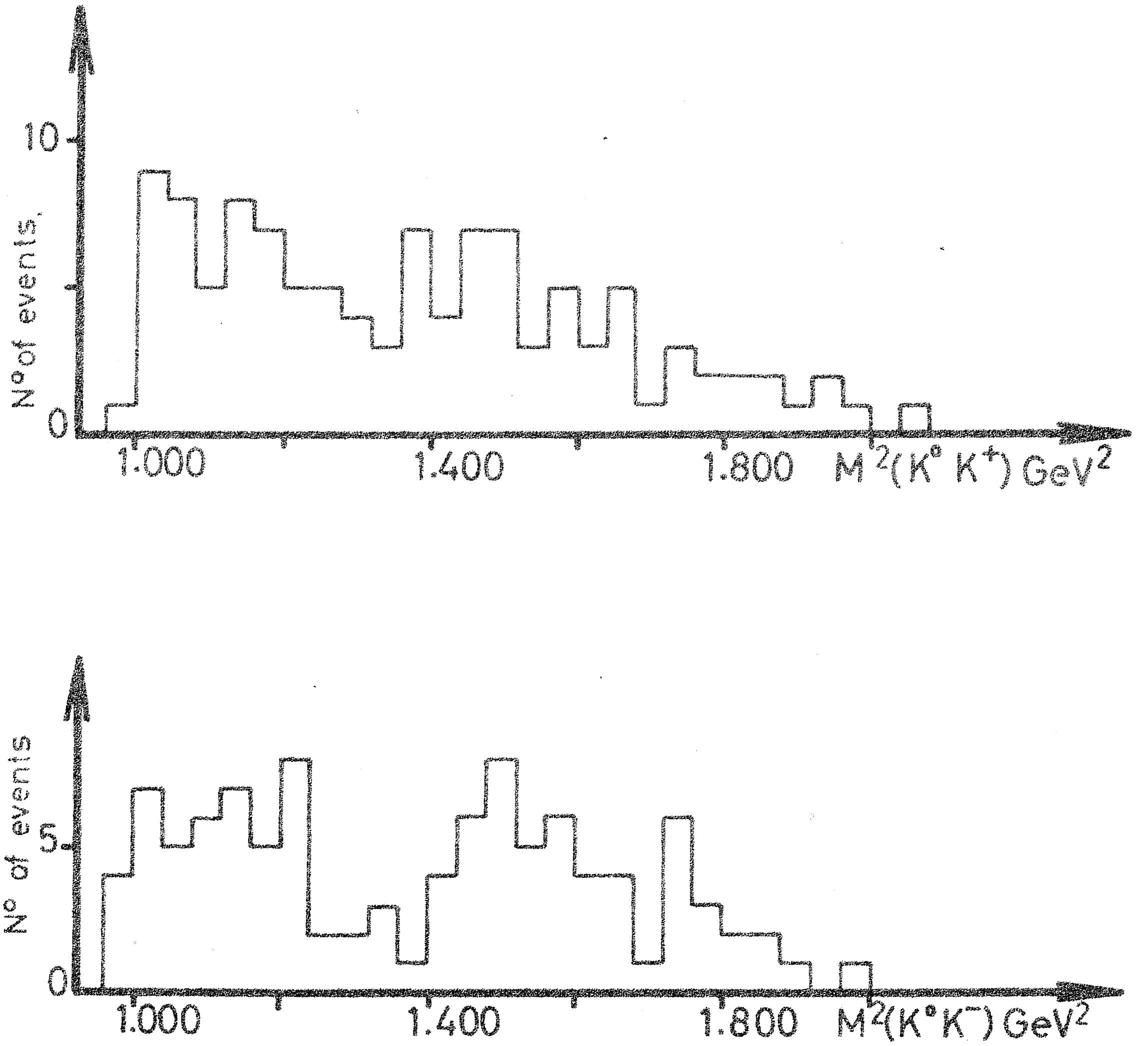

FIG. 7

DIR 23178

PS/4860

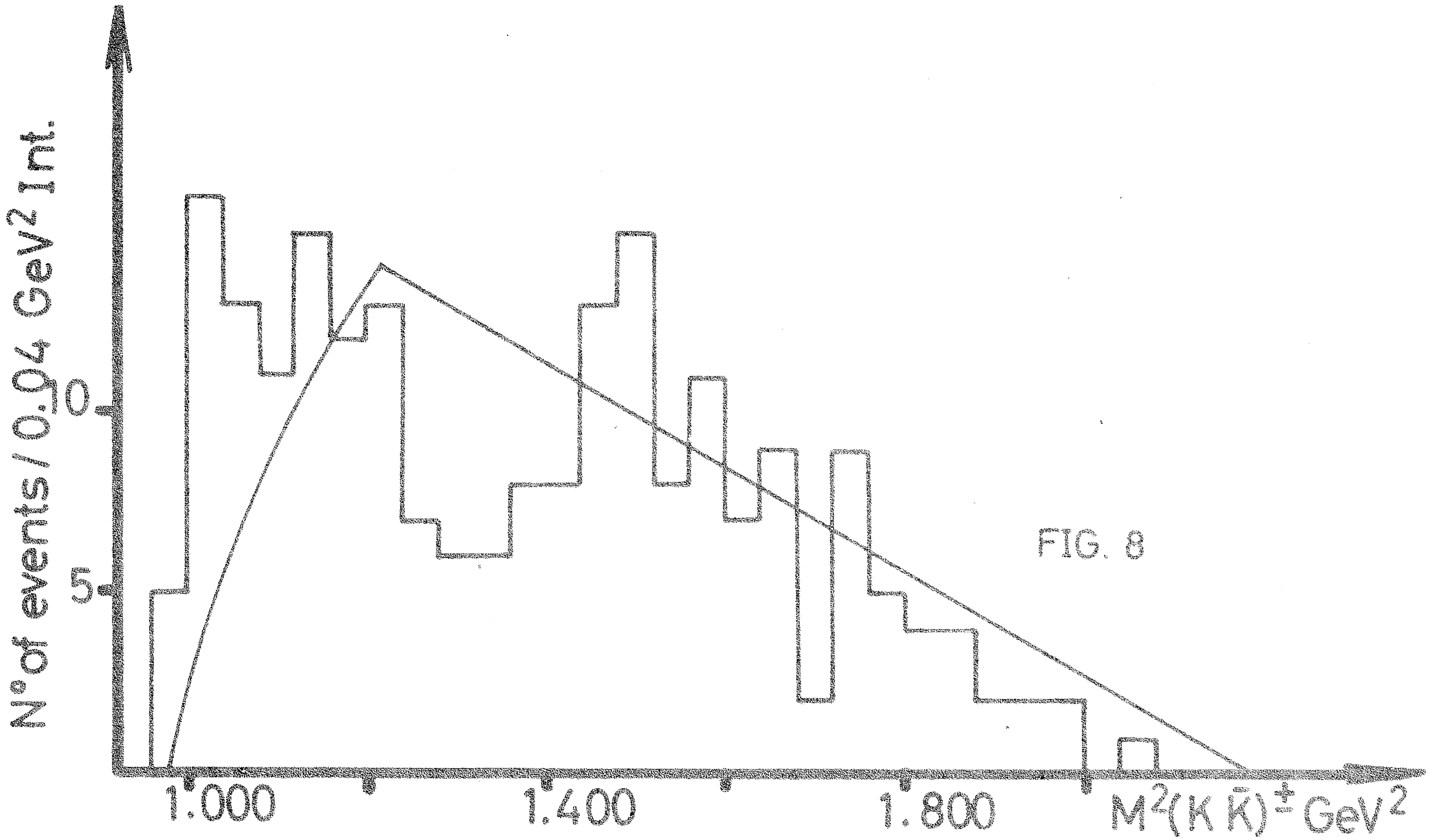

FIG. 8

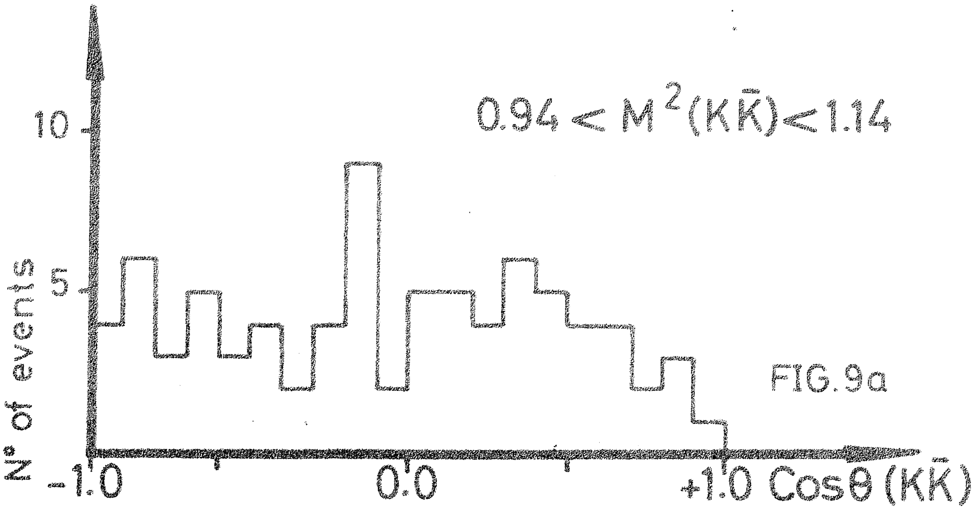

FIG. 9a

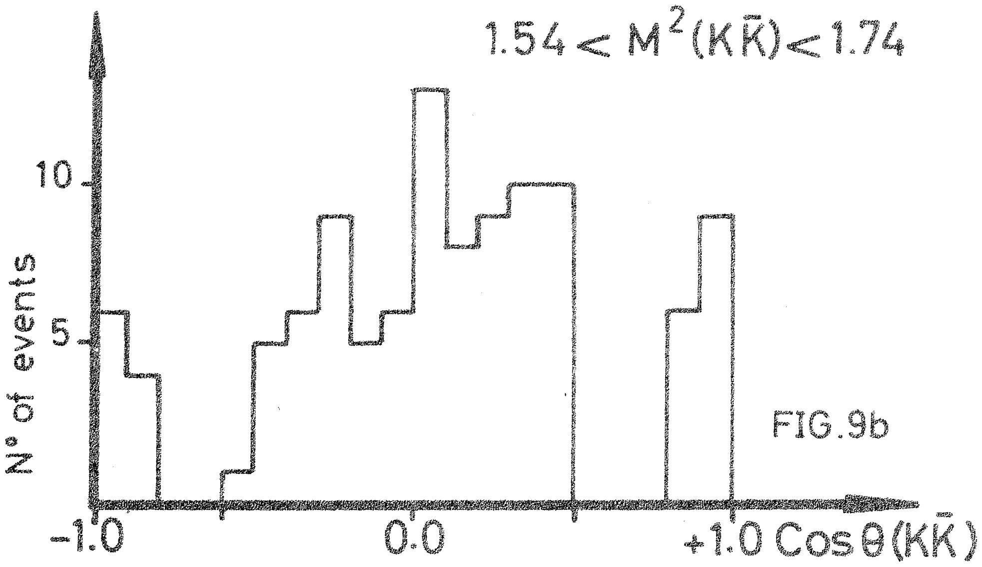

FIG. 9b

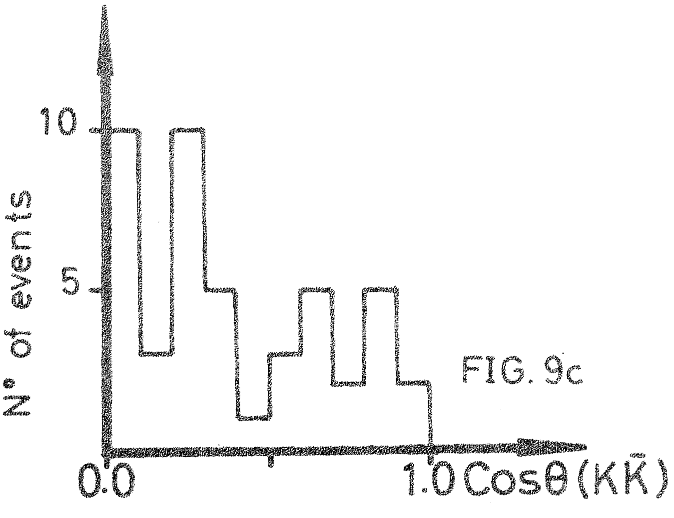

FIG. 9c