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BARYON RESONANCES

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INTRODUCTION:

It is clearly impossible to present in an hour's time a complete survey of all that is known on baryon resonances. Therefore, I have chosen to discuss a selection of new results which, I think, are particularly interesting. My criterium of selection was that these results be obtained by the use of some more or less elaborated considerations. The natural consequence is that I have almost completely neglected new baryon resonances which are at the stage of more or less significant bumps (in a mass distribution, in a curve of cross section, etc.). This does not mean at all that I despise the science of bump hunting. Most of the resonances begin to be first a hump, then a bump, then an enhancement, then a peak. Afterwards they are called a resonant state, and finally a resonance. We would certainly make less interesting discoveries if we were not taking the bumps we find seriously, even if their statistical significance is not quite as satisfactory as it should be, at the date of their birth.

GENERAL CONSIDERATIONS:

Baryon resonances have a definite advantage on meson resonances. If the strangeness is 0 or -1 and the isospin smaller than or equal to 3/2, they can be studied in formation experiments. In such an experiment a primary is shot onto a target particle at an energy which corresponds to the mass of the resonance. The resonance is formed and one studies its decay either in the same channel as the formation channel (elastic process), or in another channel (inelastic process). Since resonances have a finite width, one uses several well-defined energies for the primary, in order to cover the whole region of the resonance plus some control region. In contrast to this method, in a production experiment one uses some catastrophic high-energy process in which one or several new particles are produced. A resonance appears then as a correlation between at least two of the final particles.

Since our target particles are always nucleons, the use of π^+ and π^- as primaries allows us to perform formation experiments on baryon resonances of strangeness 0 and isotopic spin 1/2 or 3/2. K^- primaries will form resonances of strangeness -1 and isotopic spin 0 or 1*.

It is clear that the use of formation experiments allows in many cases studies more systematic than those possible in production experiments. In particular, one can make a real use of the theoretical definition of a resonance. In a production experiment one has to rely on a practical definition : a resonance is represented by an anomaly in some invariant mass spectrum, provided definite quantum numbers (spin, parity, etc.) can be attributed to this anomaly. In formation experiments one can use readily the partial wave theory of interactions. Consider the scattering amplitude Te in a channel of given ℓ and J. Te is given by the following expression:

$$\mathrm{Te} = \frac{\eta e^{2i\delta} - 1}{2i} \qquad (1)$$

where δ is the phase shift and η (a real number) the absorption parameter (for $\eta = 1$ the reaction is purely elastic, for $\eta = 0$ there is no outgoing wave**).

If one plots Te on the complex plane, η and δ have the simple representation of Figure 1. Conservation of probability imposes that the point representing Te should be inside a circle of radius 1/2, whose centre is on the imaginary axis at a distance 1/2 of the origin. This circle is called the unitarity circle. As the energy of the primaries is changed, the point representing Te will move in the plane. In the case of a purely elastic resonance, the representing point will describe the unitarity circle, passing rapidly (as a function of the energy) and in a counter-clockwise direction in the upper part of this circle. The energy at which the point crosses the imaginary axis (Re Te = 0) defines the resonance energy, at this point $\delta = 90^\circ$. Causality limits the velocity at which the circle could be described in a clockwise fashion and one considers having a resonance only if the upper part of the circle is described much faster than the lower part.

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* This does not cover all the possibilities of formation experiments. K^+ primaries could form hypothetical baryon resonances of strangeness +1. Antiprotons could form mesonic resonance of mass larger than 2 GeV/c^2.

** This does not mean that there is no elastic scattering. In the case of $\eta = 0$ the elastic and inelastic cross sections are equal.

If inelastic channels are open, η will be smaller than one, and a resonance will be represented by a trajectory like (a) or (b) in Figure 2. Note that in the case of trajectory (b) the point of crossing the imaginary axis is under the centre of the unitarity circle and at resonant energy one has $\sigma = 0$ and not 90°. The elasticity of the resonance, defined as the ratio of cross section

$$\frac{\sigma \text{ elastic}}{\sigma \text{ total}} = \frac{\left|1 - \eta e^{i2}\right|^{2}}{2-2\eta \cos},$$

is smaller than 1/2. Finally, we can have even more complex situations. Trajectories like (c) and (d) in Figure 2 will indicate the presence of a resonant state added to some non-resonant background in the channel of the same ℓ and J, since they can be represented by the addition of two amplitudes, one varying slowly with energy (the background) and the other describing the characteristic circle of a resonance. In the case of (c) the background is attractive, in the case of (d) it is repulsive.

NUCLEON RESONANCES

Let us now turn our attention specifically to nucleon resonances (baryonic number 1, strangeness 0). Table I presents the list of these resonances as it could have been written at the time of the Dubna Conference. Since this paper does not pretend to be a complete survey of baryon resonance, it is clear that the tables of old or new resonances given in the text should not be taken as the last best word on the actual values of mass and width of resonances. For instance, recent mass determinations have been sacrificed to keep its familiar name to a resonance.

TABLE I

Spin and parities which were then likely but are now sure, have been underlined. In the column marked ℓ , I have marked the partial wave of the πP system which corresponds to the resonance. For the four heaviest resonances the spin and parity are not yet known experimentally. It is interesting to remember that these four resonances have been all discovered by the same technique; measurement of total cross sections as a function of energy. This is in fact the crudest sort of formation experiment. The high statistical accuracy which can be achieved with this technique, makes it possible to discover resonances (or ta least bumps) in spite of a very considerable non-resonant background. This is illustrated in the (π^+P) total cross section in Figure 3 where the last I = 3/2 resonance of the table appears as a small ripple on an otherwise smoothly decreasing curve[1].

Results of phase shift analysis:

The most exciting results, however, have been found in a region of energy that any non-specialist would have thought completely explored since long, the region of mass between 1000 and 1800 MeV/c^2 corresponding to incident π-mesons of less than 1000 MeV kinetic energy. This is essentially due to better and new experiments on differential cross sections and polarizations which, incorporated into phase shift analysis, have yielded surprising results.

It is well known that phase shift analysis has been used since the beginning of π-meson physics and the discovery of the first nucleon resonance. Since then, however, nothing very new has come out of it (at least for non-specialists like me). Very recently two groups, Bareyre et al.[2], Donnachie et al.[3], have published the results of phase shift analysis extending from 300 MeV up to 1000 or 1200 MeV kinetic energy. Another paper on the same subject has been presented at this Conference by Bransden et al.[4]. The salient features of these independent works are the following :

1) All the groups claim that their solution is unique,

2) The solutions are in good qualitative agreement,

3) They imply the existence of many new resonances.

One must remember that the great difficulty of partial wave analysis is to arrive at a unique solution. Therefore, qualitative agreement between two independent* works represents a very good corroboration indeed. The techniques used by the groups were quite different. Bareyre et al. used only experimental results. At each energy different possible solutions could be found, of which all but one could be eliminated by continuity arguments from

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* Independent means that the techniques used to find the solution were different, the input data, i.e. the experimental results, are however the same.

one energy to another. Donnachie et al. used dispersion relations to make predictions from one energy to another. The fitting procedure uses these predictions as well as experimental results as input data. Bransden et al. use the method of "energy-dependent" phase shifts, in which an ad hoc (parametric) dependence of the phase shifts as a function of energy is assumed and fitted to the experimental data.

Figure 4 represents the most striking features of the Bareyre et al. solution in a plot similar to the one of Figures 1 and 2 (the scale is double here). The trajectories of scattering amplitudes corresponding to old resonances (Table I) are shown by dotted lines, full lines correspond to what is new. We see on this graph evidence for three new resonances:

One of isotopic spin 3/2, spin and parity $(1/2)^-$; S_{31}, which appears on top of a strongly repulsive background.

One of isotopic spin 1/2, spin and parity $(1/2)^+$; P_{11}.

One of isotopic spin 1/2, spin and parity $(5/2)^-$; D_{15}.

The last resonance is very inelastic. The phase shift goes to 0.

Not represented on the figure is the behaviour of the S_{11} wave, for which the phase shift passes through 90^o at a kinetic energy corresponding to a mass of 1700 MeV/c^2 for the πP system, η being close to one. This will correspond to a nearly elastic and very broad resonance.

As already emphasized, the results of the other groups are essentially the same. One should however notice that Bransden et al. do not mention the resonance S_{31}. Furthermore, Cence[(5)] has published a phase shift set between 300 - 700 MeV kinetic energy which does not show either the P_{11} resonance nor even the old $D_{13}(1518)$. This shows how difficult it is in this type of work to be sure that one solution and only one solution, corresponding to the true facts of nature, exists. However, the analysis of Cence suffers from two defects:

1) It does not go above 700 MeV, a region which seems essential for the elimination of spurious solutions; 2) Some of his phase shifts, essentially P_{13}, seem to be in gross disagreement with dispersion relation predictions.

We will therefore assume that the surprising unanimity of three groups is a good enough proof for the existence of a resonance and agree that there exist four new resonances whose characteristics are summarized in Table II.

TABLE II

It is only fair to note that the P_{11} resonance at 1400 MeV/c^2 is not entirely new. It was discovered at CERN in a production experiment which I shall discuss later, and a P_{11} resonant behaviour in this mass region has been announced by Roper[6].

It is interesting to see what corresponds to these resonances, if one considers total cross sections only. Figure 5 shows a plot of total cross sections for π^+ and π^- as a function of energy. The "old" resonances, 1518 and 1688, are visible on the $\pi^- P$ curve at energies 600 and 900 MeV, 1920 on the $\pi^+ P$ curve at 1300 MeV kinetic energy. The new S_{31} appears as a shoulder on the $\pi^+ P$ curve at about 850 MeV, but it is almost impossible to find any sign of P_{11}(1400) (energies 450 to 550 MeV) and, of course, nobody could guess that the peak at 900 MeV corresponds to two resonances F_{15} and D_{15}, with the same mass, same width, same spin but different parities, more or less coinciding with a third, broader resonance S_{11}.

The 1688 peak:

Since phase shift analysis is a rather abstract technique, it would be instructive to see on what sort of experimental evidence one can analyse a situation as complicated as the superposition of the F_{15} and D_{15} resonances. Here the most recent work has been performed by a group of the Rutherford Laboratory. Duke et al.[7] measured differential cross sections for π^+ and π^- scattering on protons in the momentum interval 875 - 1579 MeV/c. They also studied polarization effects by use of a polarized target. Angular distributions were expressed in a series of Legendre polynomials:

$$f(\theta) = \sum_n C_n P_n(\cos\theta).$$

Asymmetry parameters, corresponding to polarization effects, were expressed by series of the type: $\sin\theta \sum_n D_n P_n(\cos\theta)$.

Figure 6 shows the behaviour of the coefficients C_5 and D_4 in the momentum region corresponding to the 1688 bump. One sees that C_5 reproduces very accurately a resonant behaviour, whereas D_4 remains close to zero. C_5 and D_4 are interference terms between waves of different parities*. Their complete expression in terms of partial-wave amplitudes is rather complicated but we will somehow oversimplify them by taking into account only $F_{5/2}$ and $D_{5/2}$ waves. Then C_5 is proportional to Re $F^*_{5/2} D_{5/2}$ and D_4 is proportional to Im $F^*_{5/2} D_{5/2}$. The experimental results show us that the product $F^*_{5/2} D_{5/2}$ has a large real part and a negligible imaginary part. Therefore, the complex amplitudes F and D must be connected by a relation F = kD (k real and constant) in this energy region. If one of them follows a resonant trajectory, the other one does too. The argument is rather strong. Indeed, one could reproduce the behaviour of C_5 by supposing that $F_{5/2}$ is resonant and $D_{5/2}$ is purely imaginary but constant with energy; in this case the coefficient D_4 will have the values indicated by the line on the D_4 plot of Figure 6. This is certainly ruled out.

It is important to mention that it is the same experiment, at higher momentum, which firmly established $(7/2)^+$ as the spin and parity of the I = 3/2 1920 resonance.

The problem of the 1400 resonance:

As we have mentioned before, the first evidence for this resonance did not come from a phase shift analysis but from a production experiment. Cocconi et al.[8] at CERN were studying quasi-elastic proton-proton scattering (i.e. inelastic processes at relatively low momentum transfers). Measurements of the angle and momentum of the fast proton (after reaction) give the mass of the recoiling nucleon system. It is a missing mass experiment. The authors found evidence for the excitation of several of the known nucleon resonances. However, at very low momentum transfers, the peak corresponding to the 1518 resonance was replaced by a peak at 1400 which moved towards 1518 at larger and larger momentum transfers.

At the time of the discovery of this effect and of its subsequent confirmation by a Berkeley group[9], it was not clear if the effect was due:

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* In polarization effects one has to consider terms of the type $Y^0_\ell \; Y^1_{\ell'}$; $Y^1_{\ell'}$ has the form: $\sin\theta \dfrac{d}{d\cos\theta} Y^0_{\ell'}$, therefore interference between waves of different parities correspond, for polarization effects, to Legendre polynomials of even parity.

to a genuine new resonance

to a peculiar shift of the 1518 peak by the constraint of low momentum transfer, or

to a special kinematic effect of double N^* 1238 production.

New results by Bellettini et al.[10] seem to rule out all explanations other than the true resonance. Figure 8 shows the results obtained for 19.3 GeV incident protons. The bump in missing mass spectrum, very pronounced for small scattering angles, disappears rapidly at larger angles without being shifted. The kinematic explanation is ruled out because at an energy of 19.2 GeV for incident protons the kinematic effect will produce a bump at a mass very different from 1400. Figure 10 shows a summary of the results for all angles for P-P collisions and P-D collisions. The peaks are very well pronounced. There is a shift between the proton peak and the Deuterium peak. This shift, however, can be explained if one assumes that the Deuterium, with one nucleon excited in the resonance, recoils as a whole; a process which is not unlikely at momentum transfers of the order of 100 MeV/c.

One could ask the question: why is it assumed that this resonance is identical to the P_{11} resonant state of the phase shift analysis, the masses are not even quite the same ? The answer is of course that this identification is only tentative but likely to be correct. Indeed, a general theory of high-energy interactions predicts that excitation processes at very low momentum transfers will produce preferentially states which have the same quantum numbers as the initial non-excited state. A P_{11} resonance has the same quantum numbers as the proton. Therefore, it is indeed likely that it is the state excited in the CERN experiment.

Why low momentum transfers processes happen preferentially with no change of quantum numbers for the partners of the reaction, can be understood in the following way: If we observe a process in which a target proton is excited and request at the same time a very low momentum transfer, we favour strongly processes in which the angular distribution of the incident proton after reaction will resemble diffraction scattering. A wave of diffraction scattering at high energy is an "almost plane wave" made out of many partial waves, up to a high ℓ , with definite relationship in amplitude and phases. If the excited state of the target proton has the same spin and parity as a stable proton, all that is transferred from the incident proton to the target proton is energy, but no angular momentum. Therefore, it is likely that all partial waves will receive the same small perturbation, up to angular momenta where they cease to be effective in the interaction, and they are therefore likely to produce a diffraction-like scattering of the incident (non-excited) proton. On the contrary, if the excited state had a high spin, the different partial waves would be affected differently by the production of the resonance and no diffraction-like scattering is to be expected.

This is an interesting feature of these excitation experiments, which might make them very important for the discoveries of new nucleon resonances. Indeed, all these resonances have been found by formation experiments. In this case the cross section for formation of the resonance is proportional to $(2J + 1)$. The consequence is that at higher and higher energies, in the presence of larger and larger background, we will be able to find only such resonances which have high spins. This could lead to premature conclusions of correlation between spin and mass. Excitation experiments for which the situation is reversed, might be a way around that difficulty.

HYPERON RESONANCES

Table III shows the status of our knowledge at the time of the Dubna Conference.

TABLE III

Here again, spin and parity assignments which were tentative and are established by work reported here, are underlined. In fact, most of the new facts on hyperon resonances concern spin and parity. There are, of course, strong indications of new resonances, but they are in the form of bumps in need of some confirmation, and according to the principles described in the introduction, I shall not discuss them here.

The spin and parity of $Y_0^*(1405)$

Dalitz and Tuan[11] have pointed out that the reaction $K^- - P$ at low energy could be represented by use of S-wave scattering length in a zero effective range approximation. There are, of course, two scattering lengths for the I = 0 and I = 1 channels, and both of them are complex, since there are inelastic channels like $K^-P \longrightarrow \Sigma^+ + \pi^-$, etc. If the real part of the I = 0 scattering length is negative and larger (in absolute value) than 1.3 Fermi, this will correspond to a bound state of the K^-P system with a mass sufficiently close to 1405 to allow identification and this will make the spin parity assignment of $Y_o^*(1405)$ $(1/2)^-$. The first analysis along this line was made by Humphrey and Ross[12]. However, as is usual in partial-wave analysis, there were two solutions. The one indicating the existence of the bound state was very much favoured by considerations on the relative phases of the I = 0 and I = 1 states, but the errors on the scattering length remained large and therefore the existence of a bound state, and even more its identification with the resonance 1405, were not firmly established.

In a recent paper in Physical Review Letters, Kim[13] has published the results of the same analysis based on much larger statistics. 13,500 events of the reactions K^-P going into all possible two-body channels (elastic scattering, charge exchange, $Y + \pi$ production) were measured for momenta of K^- ranging from 80 MeV/c to 300 MeV/c. Two solutions were found by least square fits but one is much better than the other. Solution I has a χ^2 of 85 for 98 degrees of freedom, Solution II has a $\chi^2 = 196$.

Figure 9 illustrates how Solutions I and II fit the experimental data, the superiority of Solution I is evident especially in the Σ^-/Σ^+ ratio. Furthermore, in Solution I one has $\varphi_o - \varphi_1 < 0$ (difference of phase, at threshold, between the I = 0 and I = 1 channels) which is the sign required by continuity arguments between K's of 400 MeV/c and 0 momentum, and also by the variation of the Σ^-/Σ^+ ratio between Hydrogen and Deuterium capture (Schulte and Capps[14]). Therefore, Solution I has to be accepted: in this solution the I = 0 scattering length is:

$$a_o + ib_o = [-1.674 \pm 0.038 + i(0.722 \pm 0.040)] \text{ Fermi}$$

and there is a bound state whose mass and width are given by the following formulas:

$$M_B = M_P + M_K - \frac{\hbar^2}{2\mu a_o^2}$$

$$\Gamma = \frac{2 b_o h^2}{\mu |a_o|^3}$$

μ is the reduced mass of the proton-K system.
This gives $M_B = (1410 \pm 1)$ MeV/c^2, $\Gamma = (37 \pm 3)$ MeV/c^2 which are to be compared to the agreed value of 1405 and 35. As pointed out by Kim, the introduction of a non-zero effective range will bring the mass of the bound state closer to the mass, 1405 MeV/c^2, of the $\Sigma\pi$ resonance. We must therefore conclude that the 1405 resonance can be described as a bound s-state of the $\bar{K}N$ system and has therefore spin-parity $(1/2)^-$.*

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* Purist could still find a flaw in the argument. Indeed, in the absence of polarization measurements, angular distributions only do not distinguish between $P_{1/2}$ and $S_{1/2}$ waves (Minami ambiguity). In his short letter Kim does not mention polarization measurements and does not discuss the ambiguity. The resolution of the Minami ambiguity can be seen by the following argument. At very low energy one can have an S 1/2 wave alone, but it is very unlikely to have a P 1/2 wave alone. Even if the P-wave were dominating, the S-P interference would give, in angular distributions, a cos θ term which is not observed. This argument is evidently superior to the single-minded argument that close to threshold there are only S-waves, which is not always correct (see πP scattering). By the way, this argument also eliminates another possible interpretation of the experiment. There might indeed exist two resonances at 1405 - 1410, with about the same mass and same width (a not unlikely situation if we remember what we have learned in nucleon resonances), but in this case interference effects should be observed.

Isotopic spin, spin and parity of the resonance 1765 and 1815

This is a good example of how a complicated situation can be analysed by formation experiments making full use of the properties of bubble chambers to identify and separate different channels.

Total cross section measurements of K^- on nucleons had revealed the presence of a broad bump in the mass region 1815. Comparison between K^-P and K^-N cross sections indicated that this bump corresponded rather to an isotopic spin $I = 0$.

Later on Barbaro-Galtieri et al.[15], studying the reaction $K^- + n \rightarrow K^- + p + \pi^-$ with K^- of 1.5 GeV/c on deuterium, found a peak in the K^-P mass distribution at 1765 MeV/c^2, which they conclude was genuine and not an 1815 resonance distorted by the available phase space. They even proposed quantum number assignments which are confirmed by what follows. Nevertheless, the situation needed clarification.

Two groups attacked the problem almost simultaneously. One in Europe (Armenteros et al.[16]), a CERN-Heidelberg-Saclay collaboration, and one in Berkeley (Birge et al.[17]). Both groups used essentially the same technique: formation experiment in a hydrogen bubble chamber with K^-, at momenta covering the region of the two possible resonances. The Berkeley group took only seven different momenta, the European group 20 different momenta. None of the groups has yet completed its analysis. Nevertheless they were able to arrive at definite and coherent conclusions. Both groups agree that in most of the mixed channels ($I = 0$ and $I = 1$) the 1815 appears much more clearly as a peak than the 1765, which most of the time resembles more a shoulder than a peak. The peak at 1815 appears as rather narrow, $\Gamma = 50$ or 40 MeV/c^2, in contrast to the original total cross-section experiment. Therefore, it is probable that what is seen at 1765 must be one (or several) resonances.

Both groups have studied the angular distribution of the charge exchange process

$$K^- + P \rightarrow K^o + N$$

and analyzed it in terms of Legendre polynomials

$$f(\theta) = \sum_n C_n P_n(\theta)$$

(their notation is A_n instead of C_n; to keep some coherence with the nucleonic part of this talk I have used C).

Both groups agree that terms in C_4 and C_5 are strong in the region of 1765 and 1815, the terms larger than C_5 are compatible with 0. Therefore, both resonances must have spin 5/2 and opposite parities, since the interference term C_5 is strong. Furthermore, while in charge exchange C_5 is negative, in elastic scattering it is positive, which indicates that the two resonances have different isospins*.

In what follows we must consider the two groups separately. The published results of the European group concentrate on the study of the resonance 1765 in the channels

$$
\begin{aligned}
K^- + P \longrightarrow\ & \Sigma^+ + \pi^- + \pi^0 \\
& \Sigma^- + \pi^+ + \pi^0 \\
& \Lambda + \pi^+ + \pi^- + \pi^0 \quad .
\end{aligned}
$$

They first found that these reactions are dominated by the presence of the resonance $Y_0^*(1520)$ in the $\Sigma^+\pi^-$, $\Sigma^-\pi^+$ and $\Lambda\pi^+\pi^-$ mass spectrum. This is shown in Figure 10. Further evidence of the presence of 1520 comes from the fact that the branching ratio of decay of that resonance into $\Sigma\pi$ or $\Lambda\pi\pi$ is as expected. If one selects events for which the $\Sigma\pi$ or the $\Lambda\pi\pi$ mass lies in the region of 1520, one can study the reaction $K^- + P \longrightarrow Y_0^*(1520) + \pi^0$ which is a pure I = 1 channel. Figure 11 shows the variation of cross section for that reaction (results for final decay of $Y_0^*(1520)$ into $\Sigma\pi$ or $\Lambda\pi\pi$ have been separated).

The errors on individual points are rather large but there are many points and the resonance behaviour is evident around the region 1765 ($p_k \approx 940$ MeV/c), whereas there is nothing in the region $p_k = 1040$ MeV/c corresponding to the mass 1815. Therefore, there is a resonance I = 1, the best value for mass and width being $M = (1755 \pm 5)$ MeV/c^2, $\Gamma = (100 \pm 20)$ MeV/c^2.

The fact that the 1765 resonance decays into $Y_0^*(1520) + \pi$ not only determines its isospin as 1, but allows also the determination of its parity. We know already that its spin is 5/2. We know that

* The result on elastic scattering has been obtained by a group from Chicago University which collaborates with the European group.

$Y_0^*(1520)$ is a $(3/2)^-$ particle. Therefore, if we limit ourselves to partial waves of the smallest possible ℓ we will have the following predictions:

if 1765 is:	the wave of the decay system $Y_0^*(1520)+\pi^0$ is a:
$\frac{5}{2}^-$	p wave
$\frac{5}{2}^+$	d wave

The resonance 1765 with spin 5/2 is formed out of a K-meson of spin 0 and a proton of spin 1/2. Therefore, it is formed in an aligned state

$$\mathcal{Y}_{5/2}^{1/2} \quad \text{or} \quad \mathcal{Y}_{5/2}^{-1/2}$$

(the line of the incoming K-meson being the z-axis of quantification).

The subsequent decay in $Y_0^*(1520)+\pi^0$ will have different angular distributions v.s. this axis of quantification if it is on a p or a d-wave. The experimental histogram is shown in Figure 12, and compared to the expected theoretical curves, one sees that a p-wave, corresponding to the assignment $(5/2)^-$, is strongly favoured.

Furthermore, after decay of the 1765, the $Y_0^*(1520)$ is also aligned, this alignment depends also on the parity of the 1765 and will show in the angular distribution of the decay of the 1520 in $\Sigma + \pi$. Here the best axis of reference is the normal to the plane of production $K^- + p \longrightarrow Y_0^*(1520) + \pi^0$. Figure 13 shows the experimental histogram for the decay of 1520 compared to the two theoretical predictions for different parities of the resonance 1765. Here again, $(5/2)^-$ is favoured.

Of course the two angular distributions have been analyzed in terms of Legendre polynomials in order to eliminate what can be subjective in a judgment by eye. The result is decisively for attributing $(5/2)^-$ to the 1765 resonance.

From what was said on the study of charge exchange and elastic scattering, the assignment

$$1765 \quad I = 1 \quad J^P = (5/2)^- \quad \text{has for consequence}$$
$$1815 \quad I = 0 \quad J^P = (5/2)^+ .$$

This result coincides with the one obtained by the American group using a similar but not identical method.

This group studied particularly the reaction $K^- + P \rightarrow \Lambda + \pi^+ + \pi^-$, which is a mixed channel I = 0 and I = 1. Figure 14 shows the cross section for this channel. The 1765 is at best a shoulder but the 1815 is clearly visible (from the fact that the reaction $K^- + P \rightarrow \Lambda + \pi^o$, which is a pure I = 1, has no enhancement in the region of 1815, the assignment I = 0 for 1815 is established). If we consider the $\Lambda\pi^+$ or $\Lambda\pi^-$ mass in the region where the $\Lambda\pi^+\pi^-$ has about the mass 1815, we observe the presence of the $Y_1^*(1385)$ in the majority of the cases. This is exhibited by the Dalitz plot of Figure 15. One therefore observes the reaction

$$K^- + P \rightarrow 1815 \rightarrow Y_1^*(1385) + \pi \ .$$

One can therefore make exactly the same reasoning as previously. 1815 is strongly aligned

$\mathcal{Y}^{+1/2}_{5/2}$ or $\mathcal{Y}^{-1/2}_{5/2}$ to begin with. However, $Y_1^*(1385)$ is a $(3/2)^+$ particle and not a $(3/2)^-$ like $Y_o^*(1520)$. Therefore, we have the following predictions:

if 1815 is:	the wave of the decay system $Y_1^*(1385)+\pi$ is a:
$(5/2)^+$	p wave
$(5/2)^-$	d wave .

Therefore we have to measure the angular distribution of the decay product $Y_1^*(1385)$ vs. the line of the incoming K^-. Since the channel $Y_1^*(1385)+\pi$ is not a pure I = 0 channel, we have to subtract the background of I = 1 which is obtained from a Deuterium experiment:

$$K^- + N \rightarrow Y_1^*(1385)+\pi \ .$$

Figure 16 shows the experimental result. In (a) the shaded histogram shows the I = 1 contribution to be subtracted, in (b) there is the histogram after subtraction, folded around cos $(\theta_{KY_1^*}) = 0$. Here again the p-wave is favoured and therefore 1815 is an I = 0, $J^P = (5/2)^+$ particle from which one infers

1765 is an I = 1, $J^P = (5/2)^-$ particle

in perfect agreement with the previous results.

The parity of the $Y_1^*(1660)$:

In the preceding section we explained how similar but not absolutely identical methods gave the same conclusions for the spin and parity of two resonances. Here we are going to see how identical methods can give contradictory results. The Y_1^*1660 was found[18] in a production experiment as an enhancement in the $\Lambda\pi$ system, amongst others. Bastien and Berge[19] concluded from a formation experiment that the spin of $Y_1^*(1660)$ was most likely 3/2; later on a group at the University of California (Los Angeles) (Tader-Zadeh et al.)[20] made a formation experiment. A study of angular distribution and polarization indicated $(3/2)^+$ as the most likely spin parity assignment. However, statistics were poor and the group remained cautious in its conclusions. At the Dubna Conference the results of a similar experiment ($K^- + P \rightarrow \Lambda^o + \pi^o$), made by a Brookhaven group[21], with ten times as many events, were presented. The conclusion was that the spin parity assignment should be $(3/2)^-$. However, the authors pointed out that they had no clear evidence for the formation of the resonance. All that could be said was that in the momentum region, corresponding to the formation of the resonance the coefficients representing the angular distribution and the polarization of the Λ were characteristic of a $D_{3/2}$ wave and not of a $P_{3/2}$ wave. The absence of a striking resonant effect for the reaction $K^- + P \rightarrow \Lambda + \pi^o$ is not astonishing since now results seem to indicate that the partial width for the decay of the 1660 resonance into $K^- + p$ or $\Lambda + \pi^o$ are both small. Therefore, the result on the parity remained still inconclusive.

Recent results on the 1660 resonance come mostly from the following reactions:

$$K^- + p \rightarrow \Sigma^+ + \pi^- + \pi^- + \pi^+$$

$$K^- + p \rightarrow \Sigma^- + \pi^+ + \pi^+ + \pi^- \quad .$$

They have been presented by a French-English group (Lévèque et al.)[22], who used K^- of 3 GeV/c and 3.5 GeV/c moments, a Berkeley-Illinois group (Eberhard et al.)[23], momenta of the K^- 2.45, 2.65, 2.7 GeV/c, and a Brookhaven group (London et al.)[24], K^- momentum 2.2 GeV/c.

The groups agree to say that there is a clear formation of 1660 in the reactions mentioned. It appears in the two systems of positive charge $\Sigma^- + \pi^+ + \pi^+$ and $\Sigma^+ + \pi^+ + \pi^-$, but not in the system of negative charge. The production of the 1660 is strongly peripheral and a cut in momentum transfer gives quite a pure sample of the resonance with small background contamination. Both Brookhaven and Berkeley-Illinois agree that 1660 does not decay frequently into a $\Sigma\pi\pi$ three-body channel, but that this decay goes most of the time in two steps

$$Y_1^*(1660) \longrightarrow Y_0^*(1405) + \pi^+$$
$$\quad\quad\quad\quad \hookrightarrow \Sigma^+ + \pi^-$$
$$\quad\quad\quad\quad \hookrightarrow \Sigma^- + \pi^+ \ .$$

Figure 17 shows the evidence of Eberhard et al. (a) represents the histogram of the invariant mass of the $\Sigma^+\pi^-$ system in the decay 1660 $\longrightarrow$ $\Sigma^+ + \pi^- + \pi^+$. The concentration around 1405 is clear. (b) is the histogram for the $\Sigma^+\pi^+$ system. The distribution agrees with what is expected if $\Sigma^+\pi^-$ is in the 1405 resonance. Clearly, if the decay of 1660 was a pure three-body process ruled by phase space, the two distributions would have been identical.

The evidence is not so conclusive for the $\Sigma^-\pi^+\pi^+$ system (histogram (c)), since both π^+'s can be in the resonance. Nevertheless, the experimental distribution is in agreement with a superposition of (a) and (b).

The fact that I have not quoted here the European group does not mean that they disagree with the others, but only that they have published nothing on this particular topic. There is, however, a point to worry about already. Both American groups find in the decay of 1660 a ratio Σ^+/Σ^- of the order of 2, whereas 1 would be expected if the decay went always via the $Y_0^*(1405)$. Therefore, there must be a background which interferes strongly with this mode of decay. Furthermore, for the data of the European group, the situation is reversed (Mulvey's discussion at this Meeting). Therefore: either somebody is wrong or the background changes rapidly with incident K momentum.

We now come to the question of parity, assuming that the spin is 3/2. The system $\Sigma^+ + \pi^+ + \pi^-$ is not of very great interest for that study. Theoretical predictions for relevant distributions are very similar for parity + or - and an experiment will require great precision to decide between the two hypothesis.

The situation is (or should be) very much better for the $\Sigma^- \pi^+ \pi^+$ decay. Here the two identical π-mesons must obey Bose statistics, a constraint which enhances the difference between what is expected if $Y_1^*(1660)$ is a $(3/2)^+$ or a $(3/2)^-$ particle.

One can see, at least qualitatively, how this happens. Bose statistics requires that the (2π) system has parity + . Therefore, if $Y_1^*(1660)$ has parity - , the Σ must be on a p or f wave relative to the (2π) system. If the $Y_1^*(1660)$ has parity + , then the Σ can be on an s wave.

Therefore, configurations of the type: "Energy of the Σ small, the two π's go in opposite directions", will be suppressed, if $Y_1^*(1660)$ is a $(3/2)^-$ particle, by the effect of the p wave centrifugal barrier. This will not be the case if spin and parity are $(3/2)^+$.

The fact that most of the decays go via the intermediate step $Y_0^*(1405) + \pi$ will tend to wash out the effect. This is simple to understand. If the $Y_0^*(1405)$ were a very long-lived particle, the spectrum of the Σ would depend solely on the angular distribution of the decay of 1405 in its own centre of mass and on the width of 1660. This statement does not imply, of course, that the π's will not obey Bose statistics any more. It means simply that if two identical particles are emitted very far away one from the other, the fact that their wave function is symmetric or antisymmetric has no observable consequence.

Since $Y_0^*(1405)$ has a sizeable width, the parity of 1660 still had an influence on the final state $\Sigma^- \pi^+ \pi^+$, but it is less strong than expected for a direct three-body decay.

The European group disposed of 25 events of decay $Y_1^*(1660) \longrightarrow \Sigma^- + \pi^+ + \pi^+$. From a likelihood method and from comparison with Monte Carlo generated events, they concluded that the odds are 100 to 1, that $Y_1^*(1660)$ is a $(3/2)^+$ particle.

The Berkeley-Illinois group has 49 events. From a likelihood method and from comparison with Monte Carlo generated events, they concluded that the odds are 100 to 1, that $Y_1^*(1660)$ is a $(3/2)^-$ particle !!! This group however has not yet published this result because they think that the question of interference effect, apparent in the Σ^+/Σ^- ratio must be clarified.

The results of the two groups are shown in Figures 17 and 18. It must be emphasized that these histograms are put here for illustration of the problem. The conclusions are based on the likelihood method.

In Figure 18 one sees the histogram of the distribution in energy of the Σ for the data of the European group. The same histogram is reproduced twice in comparison with the theoretical curves for $Y_1^*(1660)$ being $(3/2)^-$ (top) and $(3/2)^+$ (bottom). The dotted lines represent the theoretical expectations for the direct three-body decay. The solid lines are for the decay via $Y_0^*(1405)$. The difference between the two types of decay is clearly visible.

Figure 19 (top) shows the result of the Berkeley-Illinois group. Here the parameter is the angle between the two π's. The theoretical curves are for decay of 1660 via 1405. Only 25 events (out of 49), for which the π's have almost equal energies, were used for that histogram. These are the events which are most sensitive to the parity assignment and the effects of Bose statistics.

To summarize this section we must conclude that the parity of $Y_1^*(1660)$ is still unknown. The method of analysis via the $\Sigma^-+\pi^++\pi^+$ seemed very good. But either one of the groups has been the victim of a large statistical fluctuation or the method is hampered by strong interference effects with an energy dependent background. In which case another method has to be found.

CONCLUSIONS

From all I have said in this talk many points should be evident to everybody. Formation experiments culminating in phase shift analysis are a very powerful tool for the study of baryon resonances. They are not a universal tool, they will dissimulate resonances of small elasticity, or of high mass and small spin. Production experiments will have to be performed, either in bubble chambers or in missing mass experiments.

Another fact appears as very striking. Bubble chambers have made significant contributions only for hyperon resonances. There have been bubble chamber works (not reported here) on nucleon resonances, but they were mostly concerned with mechanisms of production. Clearly, this comes from the fact that hyperons are much more suitable for bubble chamber work than nucleons. Nevertheless, the situation should change. Bubble chambers should contribute to the study of inelastic channels of nucleon resonances. They should help in the study of the highest resonances. This will be difficult by any technique since the background is 10 times as large as the effect. Nevertheless it is to be hoped that this background is mostly peripheral, then formation experiments and study of non-peripheral decay channels might help in the determination of spin of these higher mass resonances.

Therefore, the final conclusion is the usual one: there are many interesting experiments to be done and to be reported at future conferences.

Table I

Nucleon Resonances (Old)

$S = 0 \quad I = \frac{1}{2}$

ℓ	J^P	M	Γ
D_{13}	$\frac{3}{2}^-$	1518	{100, 60
F_{15}	$\frac{5}{2}^+$	1688	100
		2190	200
		2640	360

$S = 0 \quad I = \frac{3}{2}$

ℓ	J^P	M	Γ
P_{33}	$\frac{3}{2}^+$	1238	125
F_{37}	$\frac{7}{2}^+$	1920	170
		2360	200
		2840	400

Table II(*)

Nucleon Resonances (New)

$S = 0$	$I = \frac{1}{2}$			$S = 0$	$I = \frac{3}{2}$		
ℓ	$\mathcal{J}^P$	M	Γ	ℓ	$\mathcal{J}^P$	M	Γ
P_{11}	$\frac{1}{2}^+$	1400	200	S_{31}	$\frac{1}{2}^-$	1690	230
S_{11}	$\frac{1}{2}^-$	1700	300				
D_{15}	$\frac{5}{2}^-$	1688	100				

(*) It is difficult to find the parameters of a resonance from the circle-like trajectory of Te. This has been attempted only by Donnachie et al. for S_{31} and their numbers figure in the table. For 1400 I have put the numbers given by Bellettini et al. in the work discussed later, phase shift analysis seems to give systematically a higher mass, 1450 or even 1480. For D_{15} and S_{11} the numbers on the table are rather my guesses.

Not included is the resonance postulated by Hendry and Moorhouse (25) for S_{11} at 1510 MeV/c^2 close to the η threshold. There seems to be unanimity about the behaviour of the S_{11} wave in that region, but I was unable to make sure that all authors would agree to interpret it as a resonance.

Table III

Hyperon Resonances

$S = -1$	$I = 0$		$S = -1$	$I = 1$		$S = -2$	$I = \frac{1}{2}$	
J^P	M	Γ	J^P	M	Γ	J^P	M	Γ
$\frac{1}{2}^-$	1405	35	$\frac{3}{2}^+$	1385	35	$\frac{3}{2}^+$	1530	7
$\frac{3}{2}^-$	1520	16	$\frac{3}{2}$	1660	45		1820	12 30
$\frac{5}{2}^+$	1815	50	$\frac{5}{2}^-$	1765	100			

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FIGURE CAPTIONS

Fig. 1 Graphical representation of the scattering amplitude Te, the absorption parameter η and the phase shift .

Fig. 2 Typical resonant trajectories of Te:

(a) resonance with elasticity greater than 0,5

(b) resonance with elasticity smaller than 0,5

(c) resonance with an attractive non resonant background of same spin and parity

(d) resonance with a repulsive non resonant background of same spin and parity.

Fig. 3 The π^+p total cross sections in the region of the 2840 resonance.

Fig. 4 Trajectories of certain $\bar{\Lambda}P$ scattering amplitudes.

Fig. 5 Total cross sections of π^+p and π^-p.

Fig. 6 The behaviour of C_5 and D_4 in the region of the resonances at 1688.

Fig. 7 Missing mass plot of the quasi-elastic scattering P + P for different angles of scattering.

Fig. 8 Missing mass plot for P-P and P-D quasi-elastic scattering experiments.

Fig. 9 Comparison of cross sections for K^-P interactions at low energies with the solution I and II of Kim's analysis.

Fig. 10 Evidence for $Y_0^*(1520)$ in the reactions

$$K^- + P \longrightarrow \Sigma + \pi + \pi$$

$$K^- + P \longrightarrow \Lambda + \pi + \pi + \pi$$

for K^- of 850 to 1100 MeV/c momentum.

Fig. 11 Cross section for the reaction

$$K^- + P \longrightarrow Y_0^*(1520) + \pi^0$$

Evidence for the resonance 1765.

Fig. 12 Angular distribution of the decay of the resonance 1765 into $Y_0^*(1520)+\pi_0$. Compared to the predictions for $Y_1^*(1765)$ $(5/2)^-$ and $(5/2)^+$.

Fig. 13 Angular distribution of the decay of $Y^*(1520)$ referred to the normal to the plane of production $K^- + P \longrightarrow Y_0^*(1520)^0 + \pi_0$.

Fig. 14 Cross section of the reaction

$$K^- + P \longrightarrow \Lambda + \pi^+ + \pi^-$$

Evidence for the resonance 1815.

Fig. 15 Dalitz plot of the decay of $Y_0^*(1815)$ into $\pi\pi$.

Evidence for the presence of $Y_1^*(1385)$.

PS/5124/rmn

Figure Captions (cont'd)

Fig. 16 Angular distribution of the decay of $Y_0^*(1815)$ into $Y_1^*(1385) + \pi$.

(a) The shaded histogram is the background in the channel I = 1.
(b) Comparison to theoretical predictions after substraction of background.

Fig. 17 Evidence for the decay of $Y_1^*(1660)$ into $Y_0^*(1405) + \pi$.

(a) Mass of $\Sigma^+\pi^-$

(b) Mass of $\Sigma^+\pi^+$

(c) Mass of $\Sigma^-\pi^+$

Fig. 18 Distribution of the energy of Σ^- in the decay of $Y_1^*(1660)$ into $\Sigma^- + \pi^+ + \pi^+$ (Lévèque et al.).

Fig. 19 Distribution of the angle φ between the two π^+'s in the decay of $Y_1^*(1660)$ into $\Sigma^- + \pi^+ + \pi^+$ (Eberhard et al.).
The bottom histogram is for the angle $\pi^+\pi^-$ in the decay $\Sigma^+ + \pi^+ + \pi^-$.

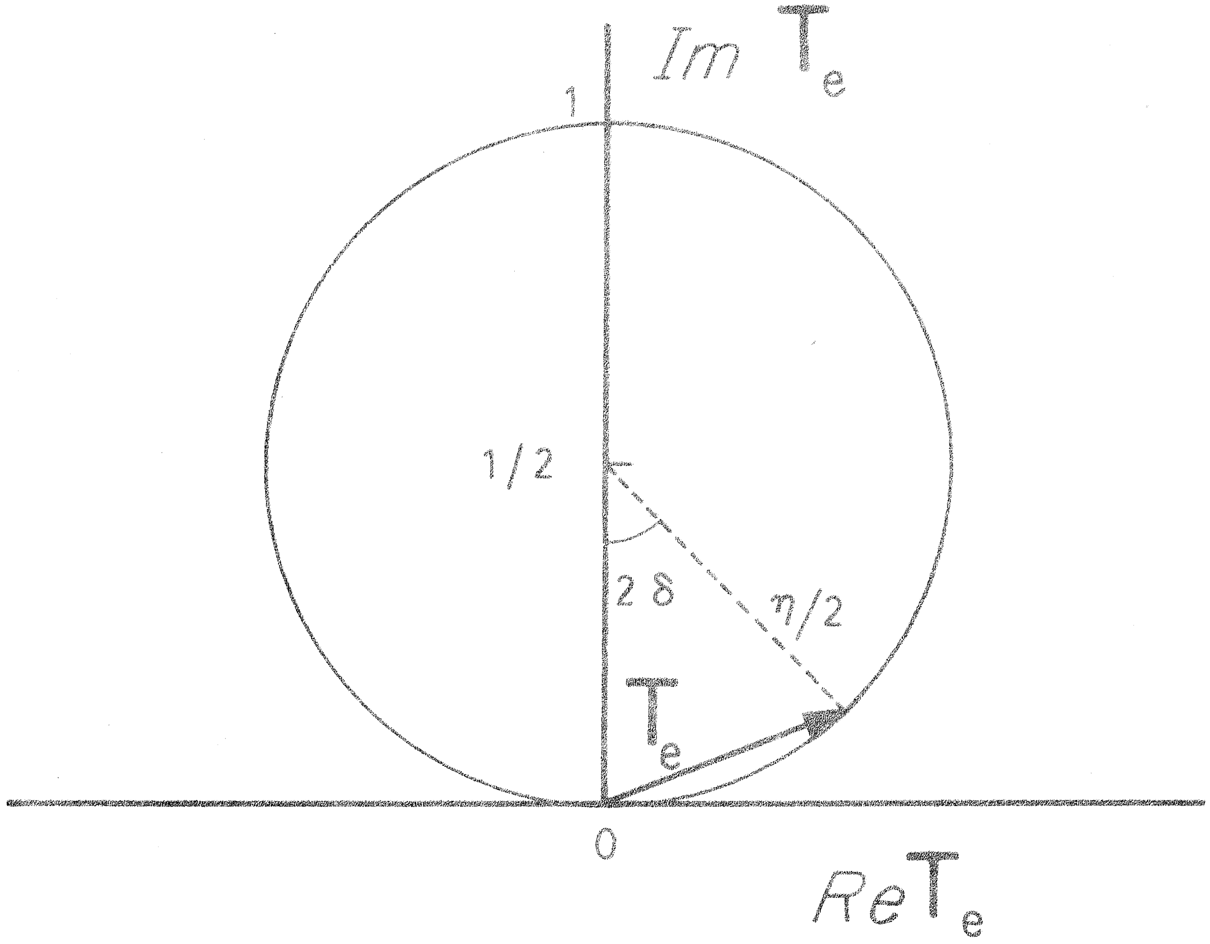


FIG. 1

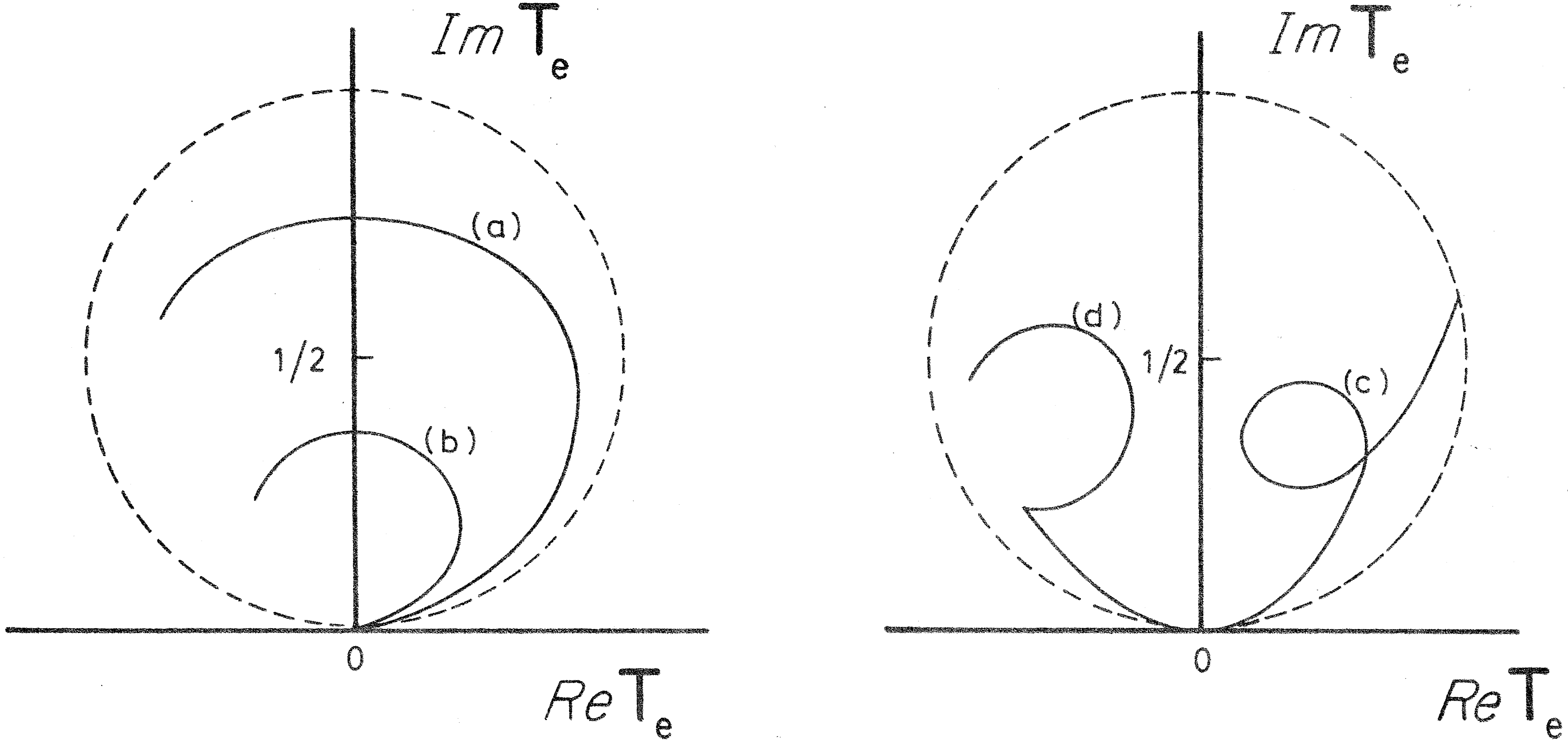
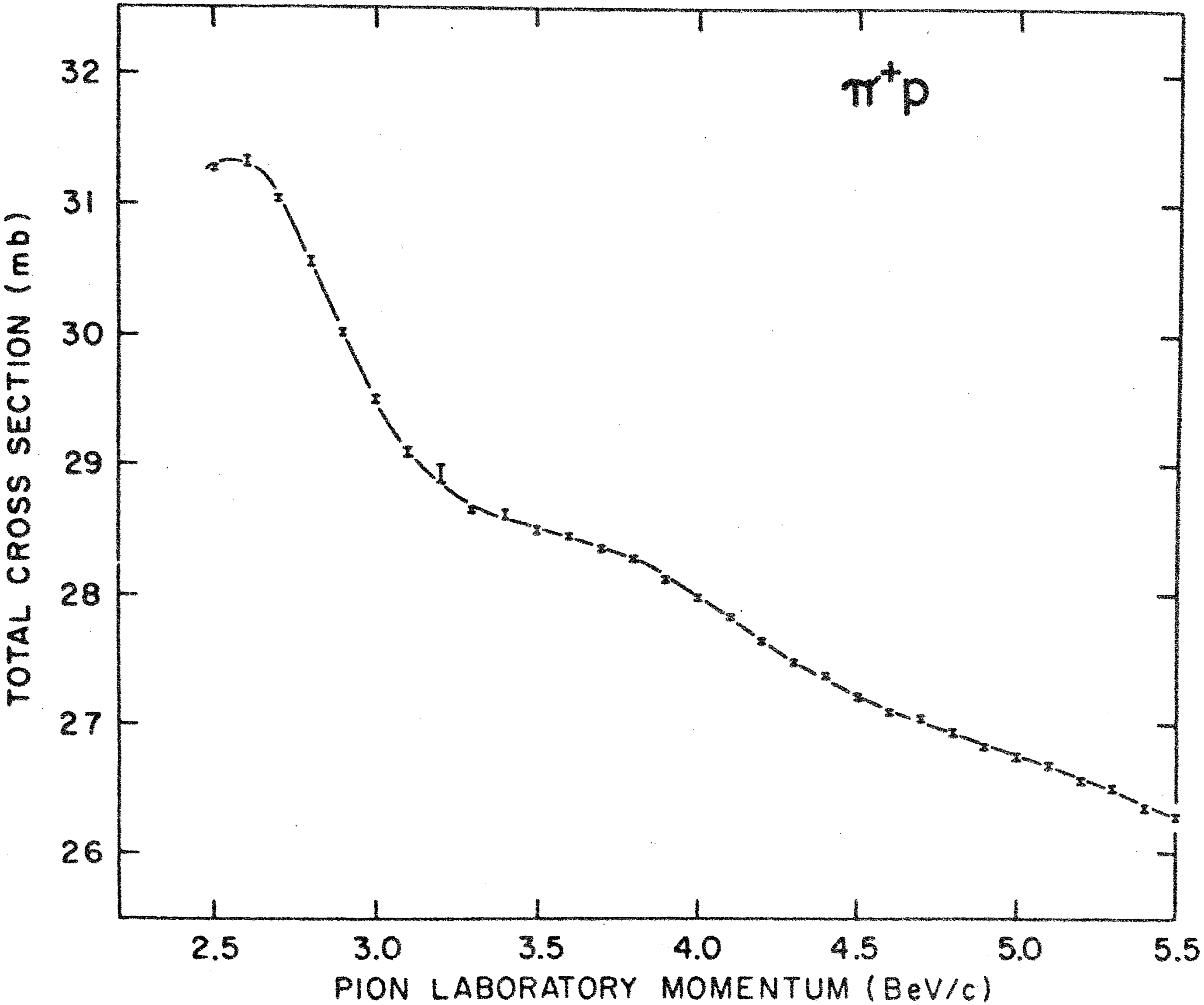


FIG. 2



$\pi^+ p$
TOTAL CROSS SECTION (mb)
26
27
28
29
30
31
32
2.5
3.0
3.5
4.0
4.5
5.0
5.5
PION LABORATORY MOMENTUM (BeV/c)

FIG. 3

FIG: 4

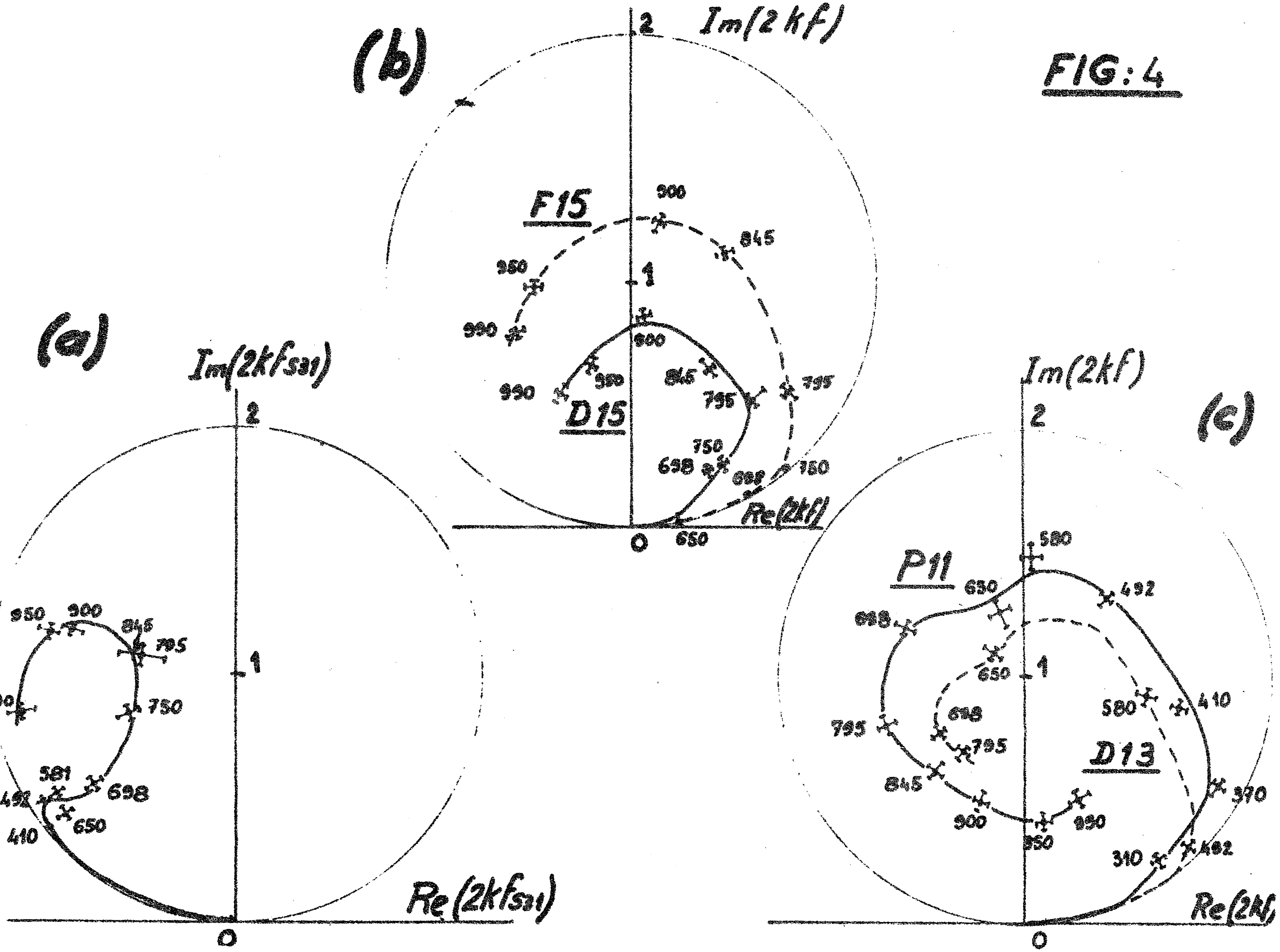
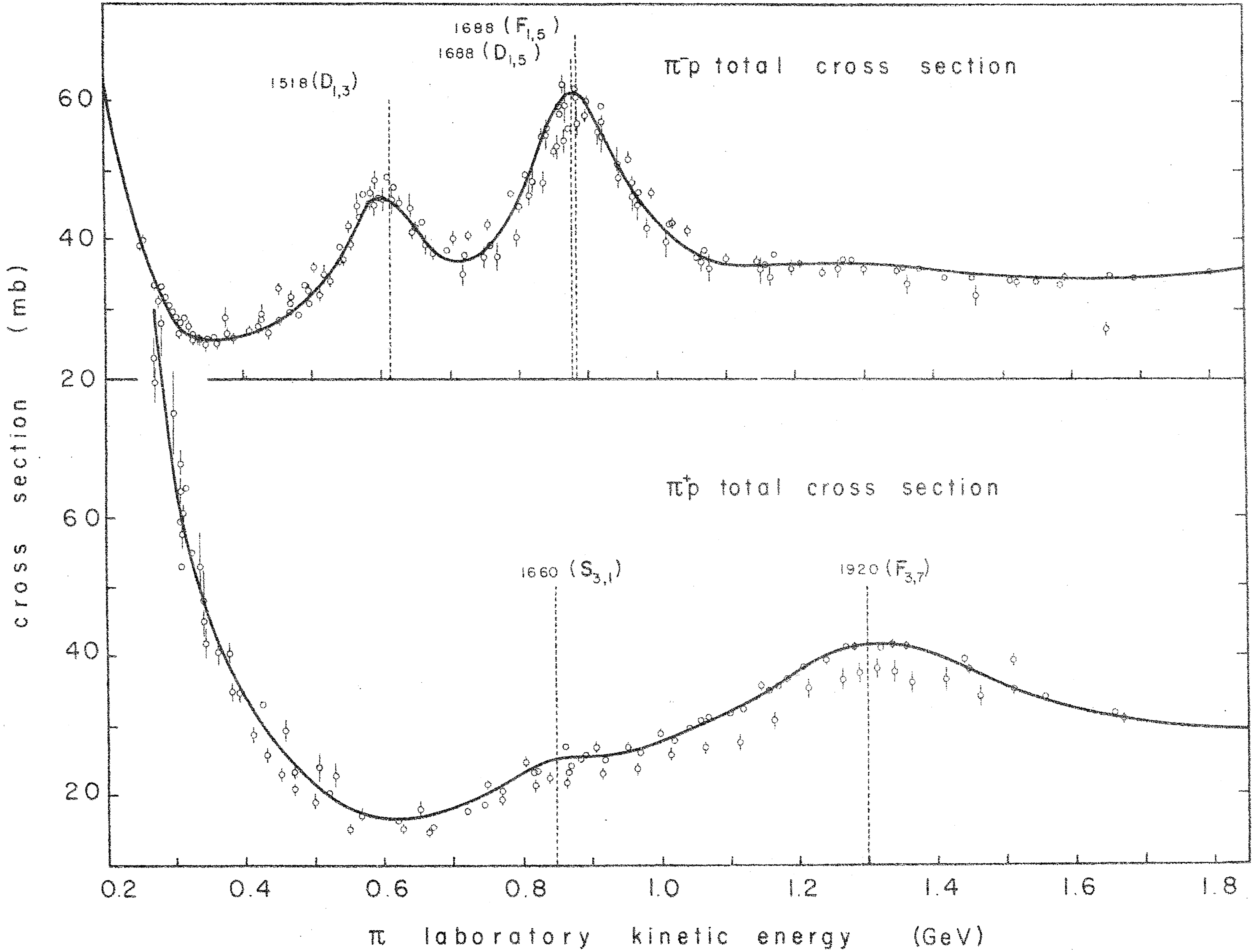

(a)
Im(2kfs31)
Re(2kfs31)
(b)
Im(2kf)
Re(2kf)
F15
D15
(c)
Im(2kf)
Re(2kf)
P11
D13
0
1
2
990
950
900
845
795
750
698
650
581
580
492
410
370
310

FIG. 5


π⁻p total cross section
π⁺p total cross section
1518 (D1,3)
1688 (F1,5)
1688 (D1,5)
1660 (S3,1)
1920 (F3,7)
cross section (mb)
π laboratory kinetic energy (GeV)
60
40
20
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

24988 VIA

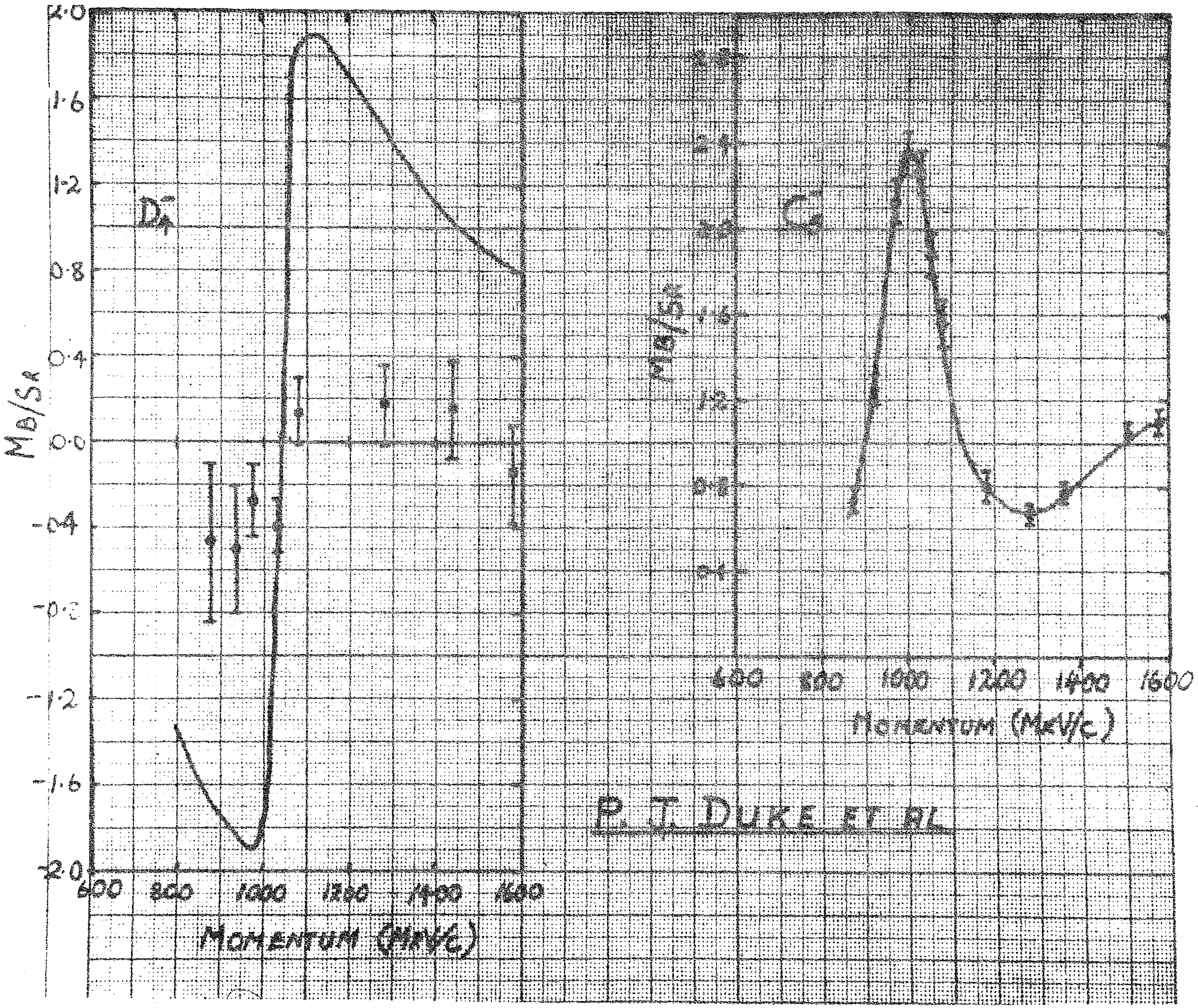


FIG: 6

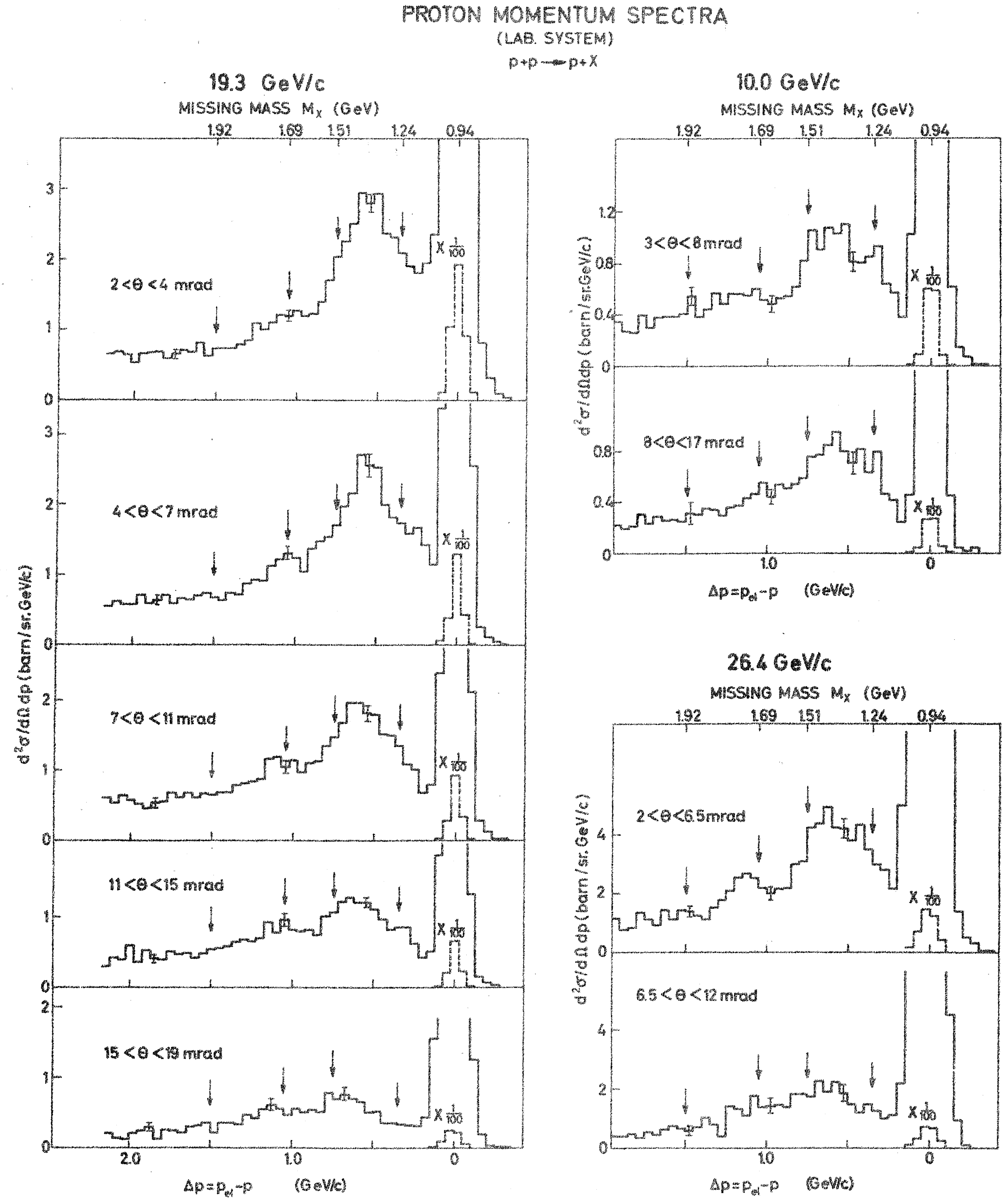


FIG: 7

Dia. 24031

PROTON MOMENTUM SPECTRA
(LAB-SYSTEM)
$P_o = 19.3$ GeV/c

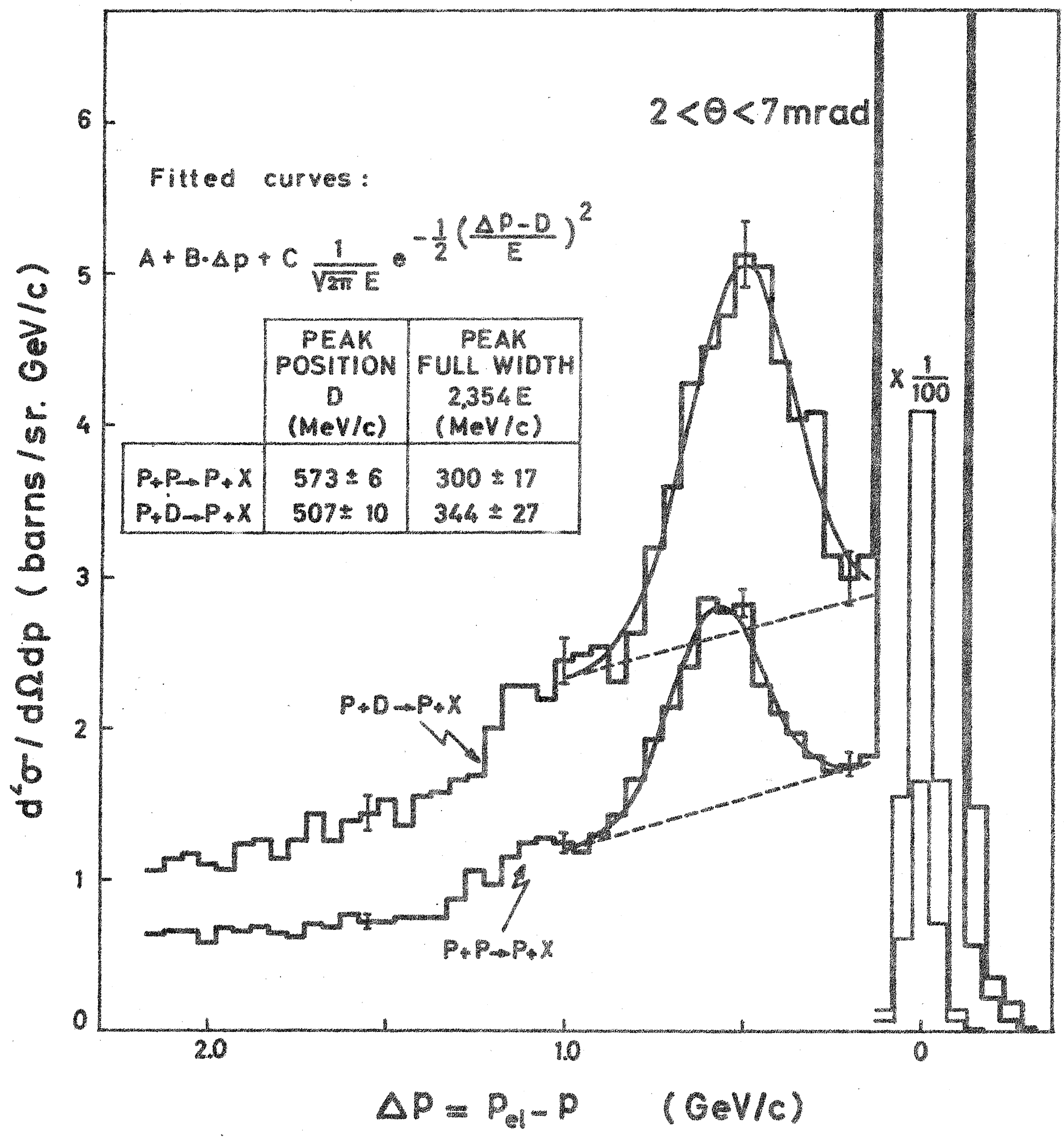


FIG: 8

Dia. 24030

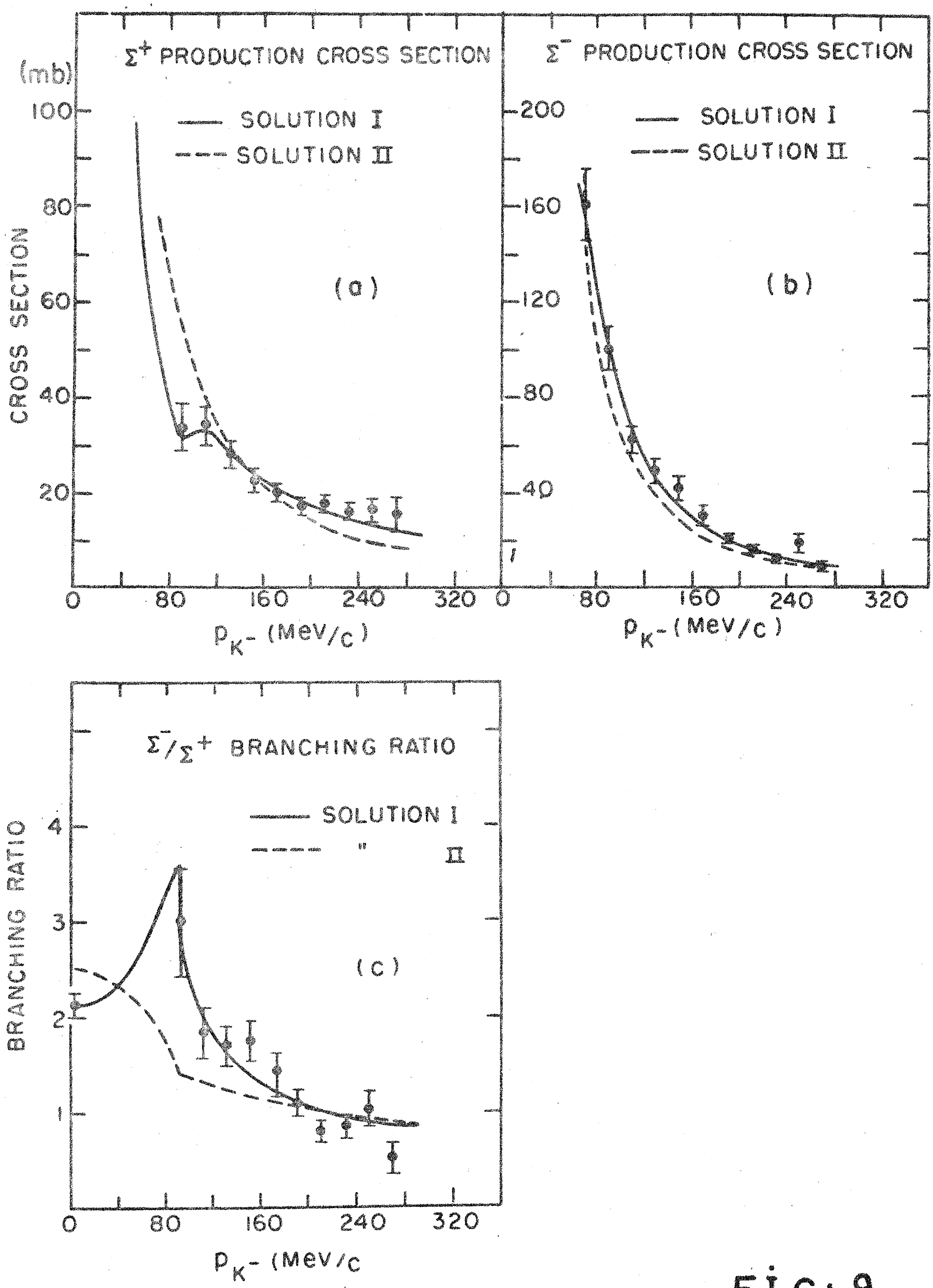
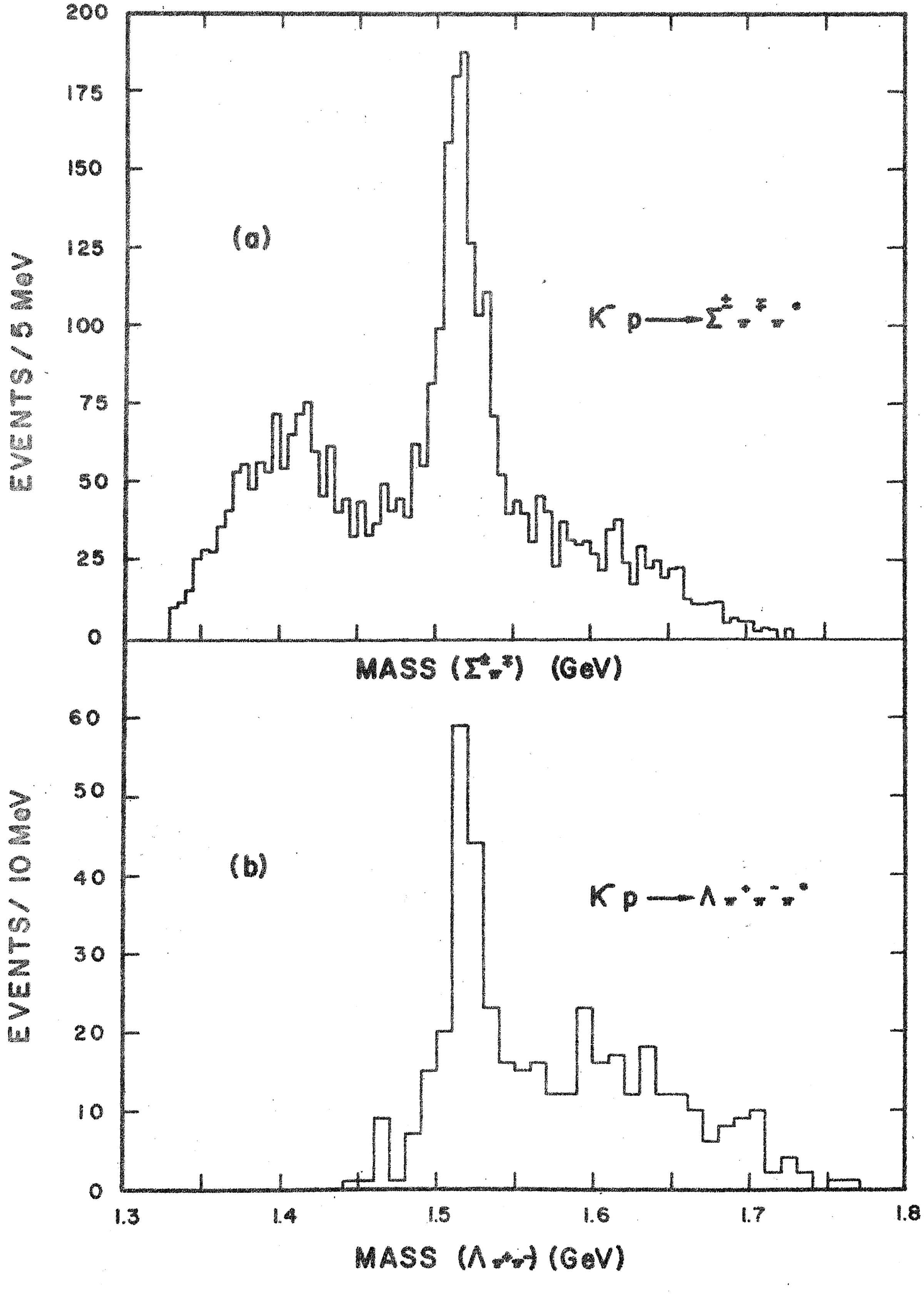


FIG: 9

Dia. 24307



EVENTS / 5 MeV
200
175
150
125
100
75
50
25
0
(a)
$K^- p \longrightarrow \Sigma^{\pm} \pi^{\mp} \pi^{0}$
MASS ($\Sigma^{\pm}\pi^{\mp}$) (GeV)
EVENTS/ 10 MeV
60
50
40
30
20
10
0
(b)
$K^- p \longrightarrow \Lambda \pi^{+} \pi^{-} \pi^{0}$
1.3
1.4
1.5
1.6
1.7
1.8
MASS ($\Lambda \pi^{+}\pi^{-}$) (GeV)

FIG: 10

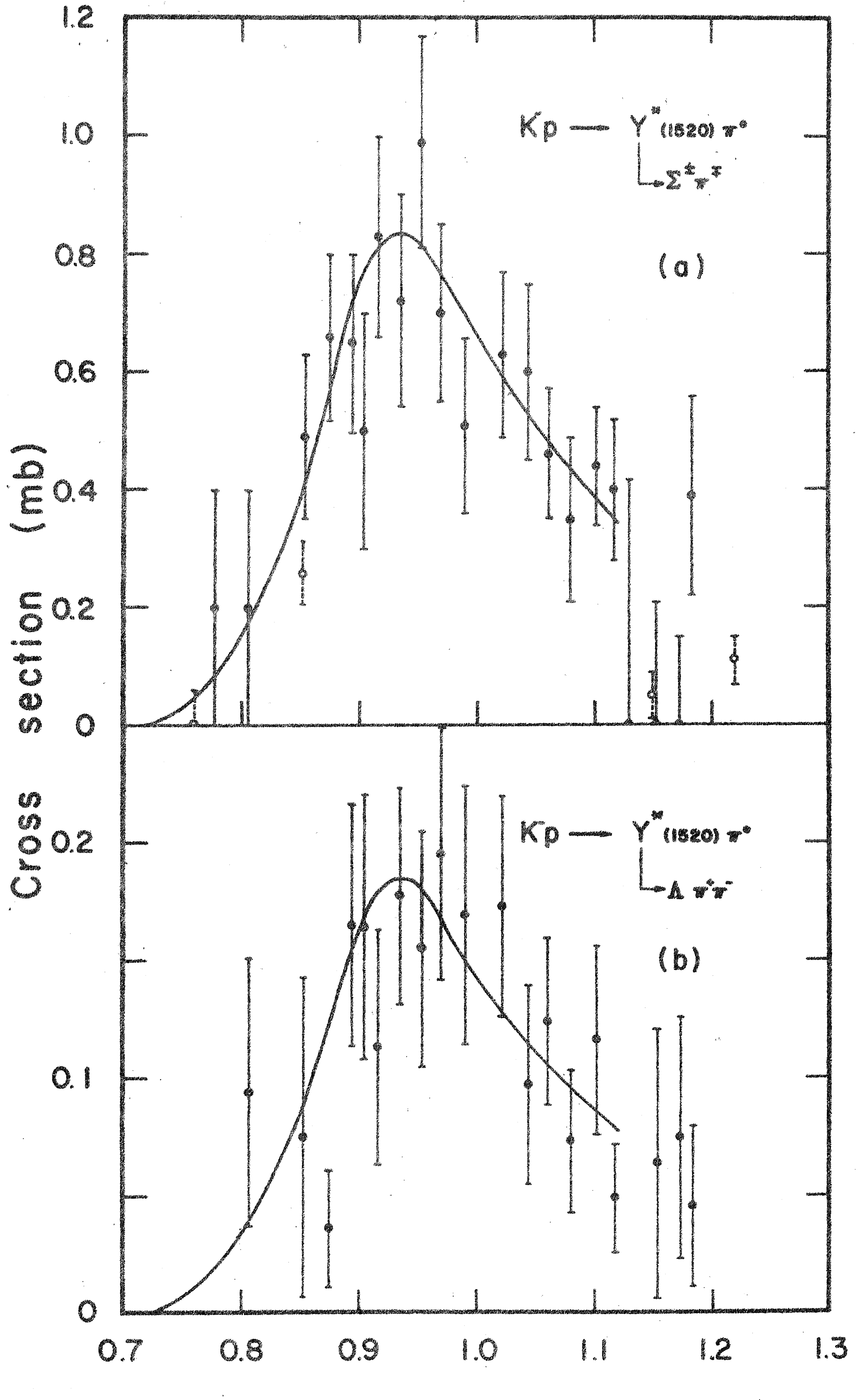


FIG: 11

Dia 24550

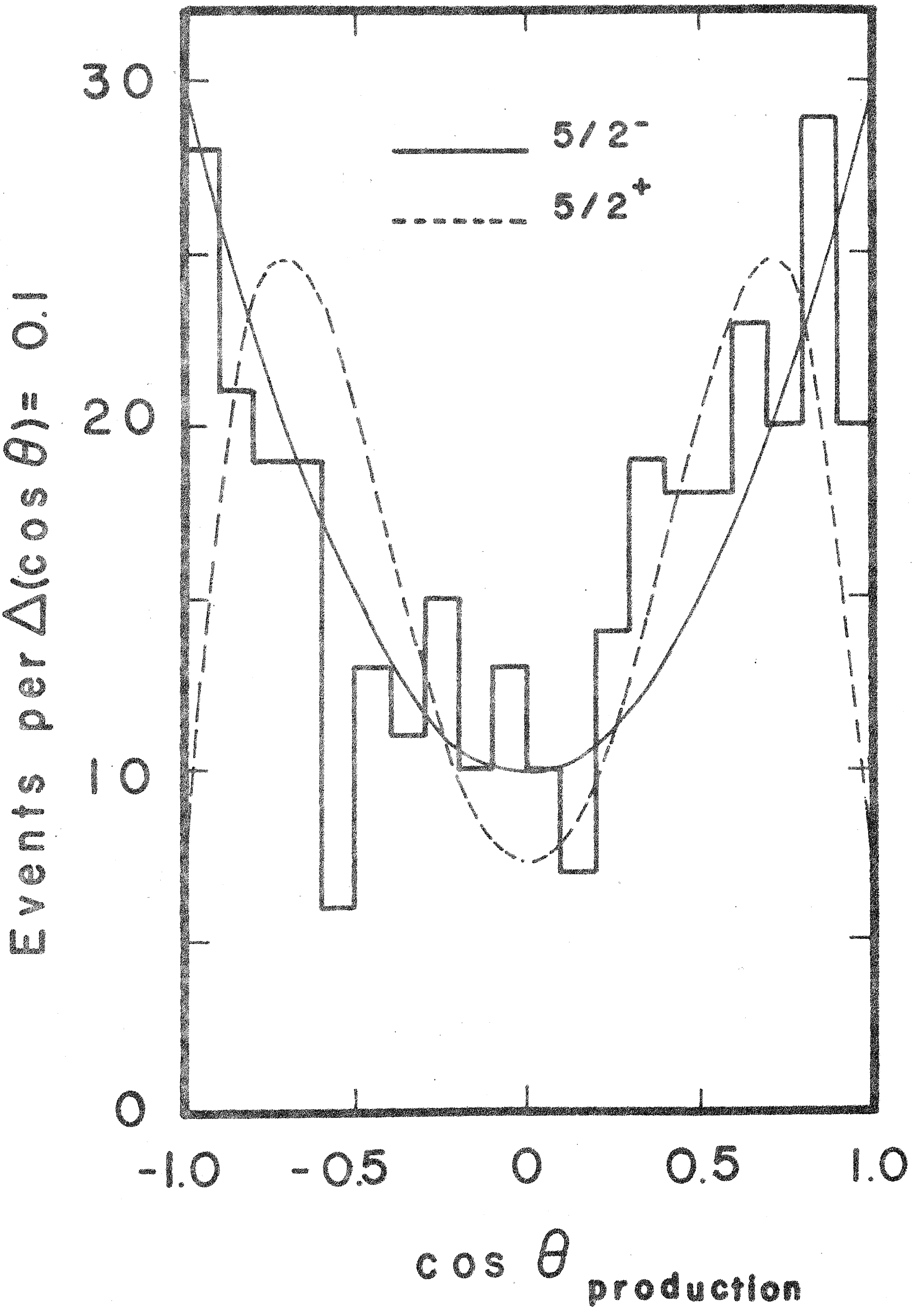


FIG: 12

Dia 24548

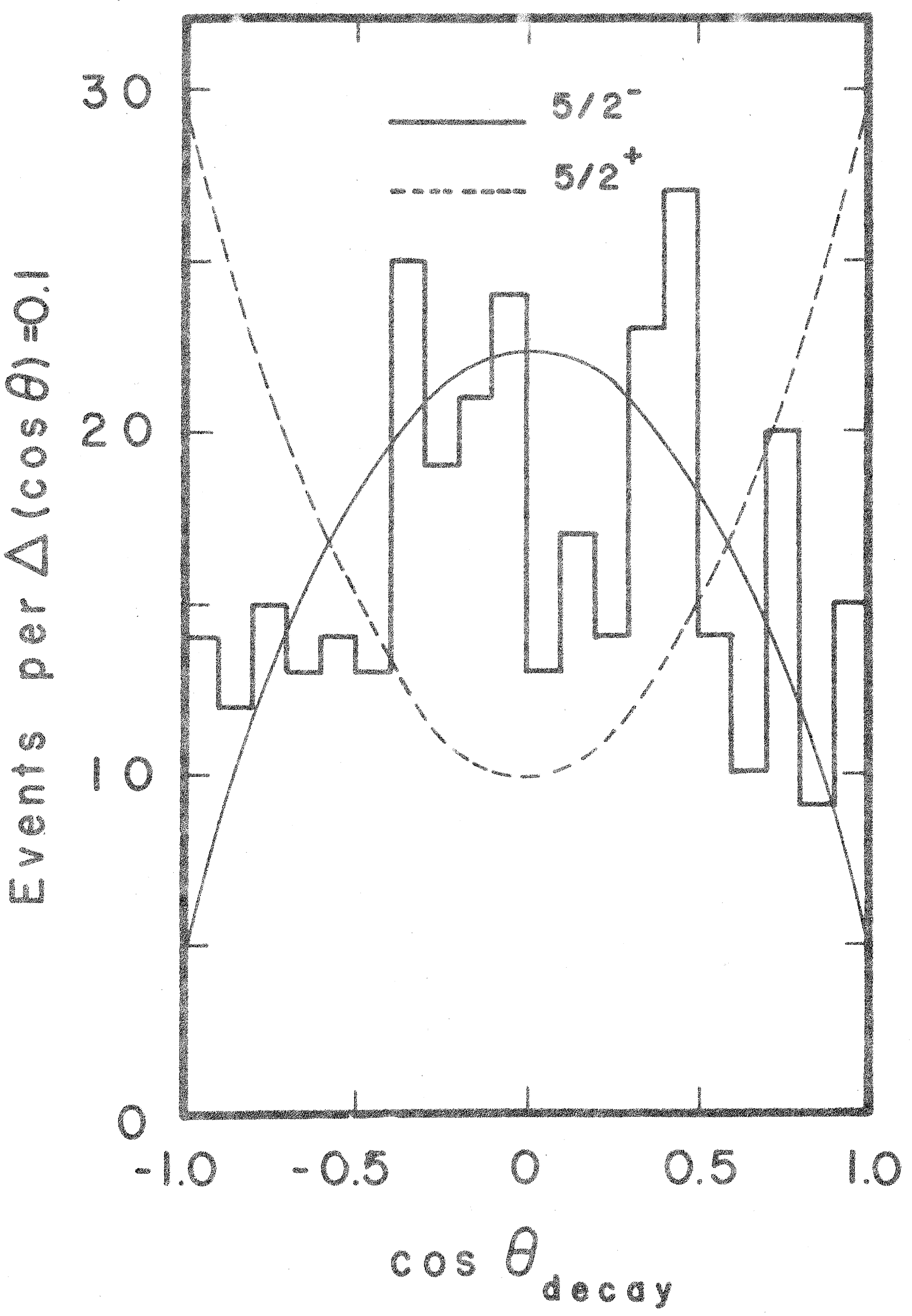
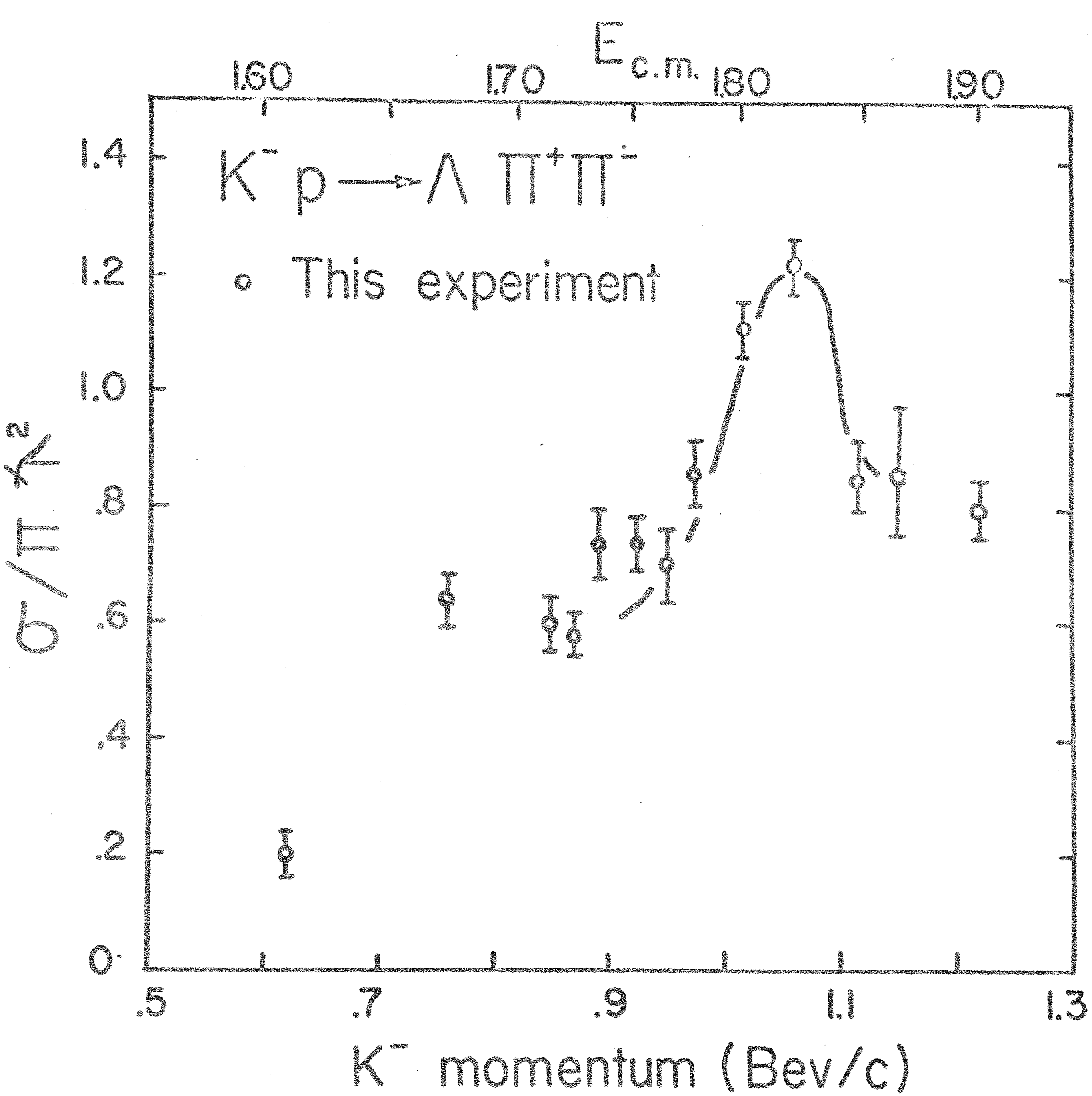


FIG:13

Dia 24549



$E_{c.m.}$
1.60
1.70
1.80
1.90
$K^- p \longrightarrow \Lambda\, \pi^+ \pi^-$
○ This experiment
$\sigma / \pi \lambda\!\!\!^{-2}$
1.4
1.2
1.0
.8
.6
.4
.2
0
.5
.7
.9
1.1
1.3
K^- momentum (Bev/c)

FIG: 14

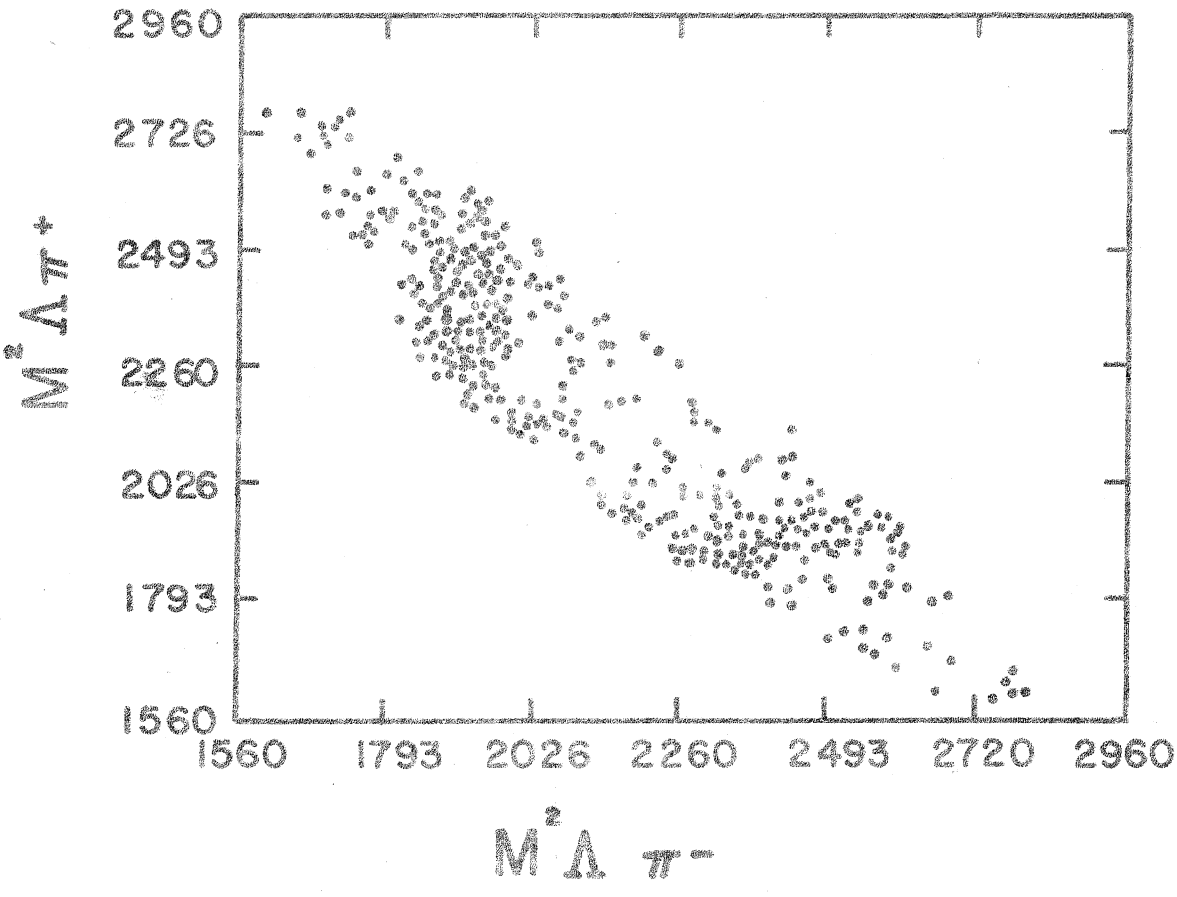
FIG. 15

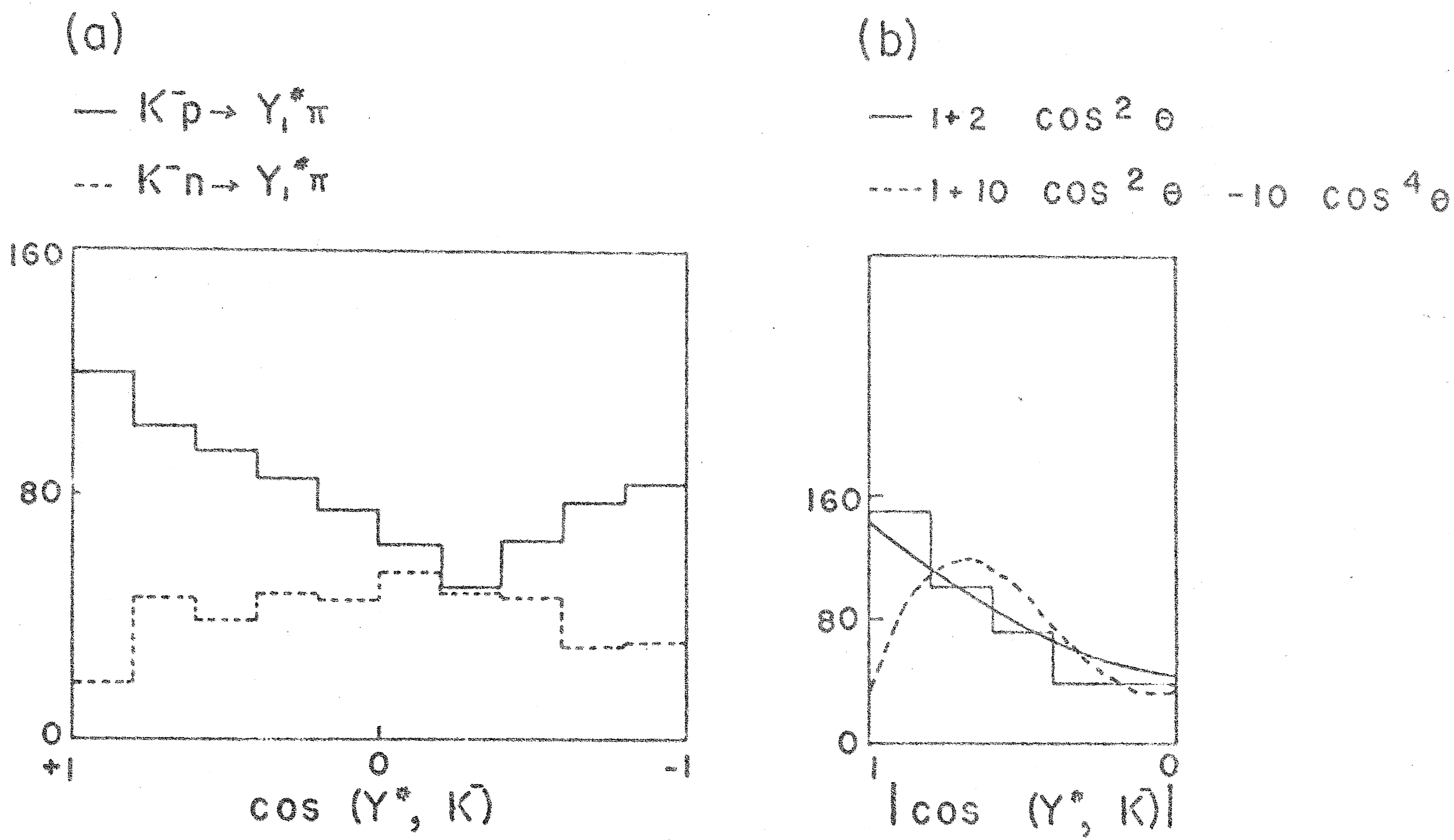
25 INCH HYDROGEN CHAMBER FAIR

OUTPUT RUN 015674 DATE 650608

ASN GP RE80 LEVEL Z1Q364

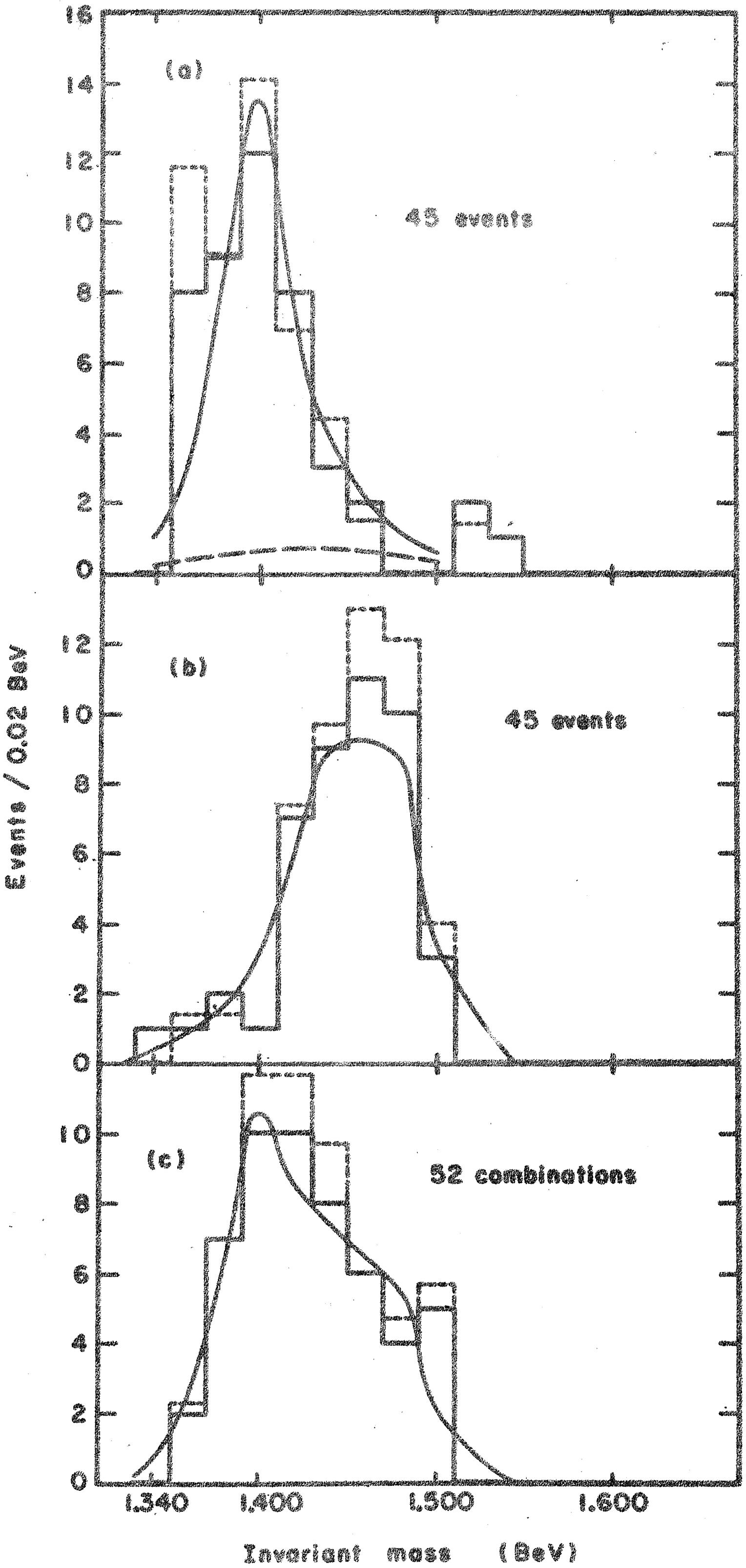
PLOT N.13 NUMB. OF POINTS PLOTTED 450





(a)
— K⁻p → Y₁*π
--- K⁻n → Y₁*π
160
80
0
+1
0
-1
cos (Y*, K⁻)
(b)
— 1+2 cos² θ
---- 1+10 cos² θ -10 cos⁴ θ
160
80
0
1
0
|cos (Y*, K⁻)|

FIG. 16



Distribution of $\Sigma\pi$ invariant mass of the events appearing in Fig. 3. (a) $\Sigma^+\pi^-$ invariant mass; (b) $\Sigma^+\pi^+$ invariant mass; (c) $\Sigma^-\pi^+$ invariant mass. On (a), the continuous curve represents our best fit, described in the text; the dashed curve is the estimated contribution of non-Λ(1405) events. On (b) and (c), the curves represent the expected distribution if all events are due to the Λ(1405) resonance.

FIG:17

DPa 24380

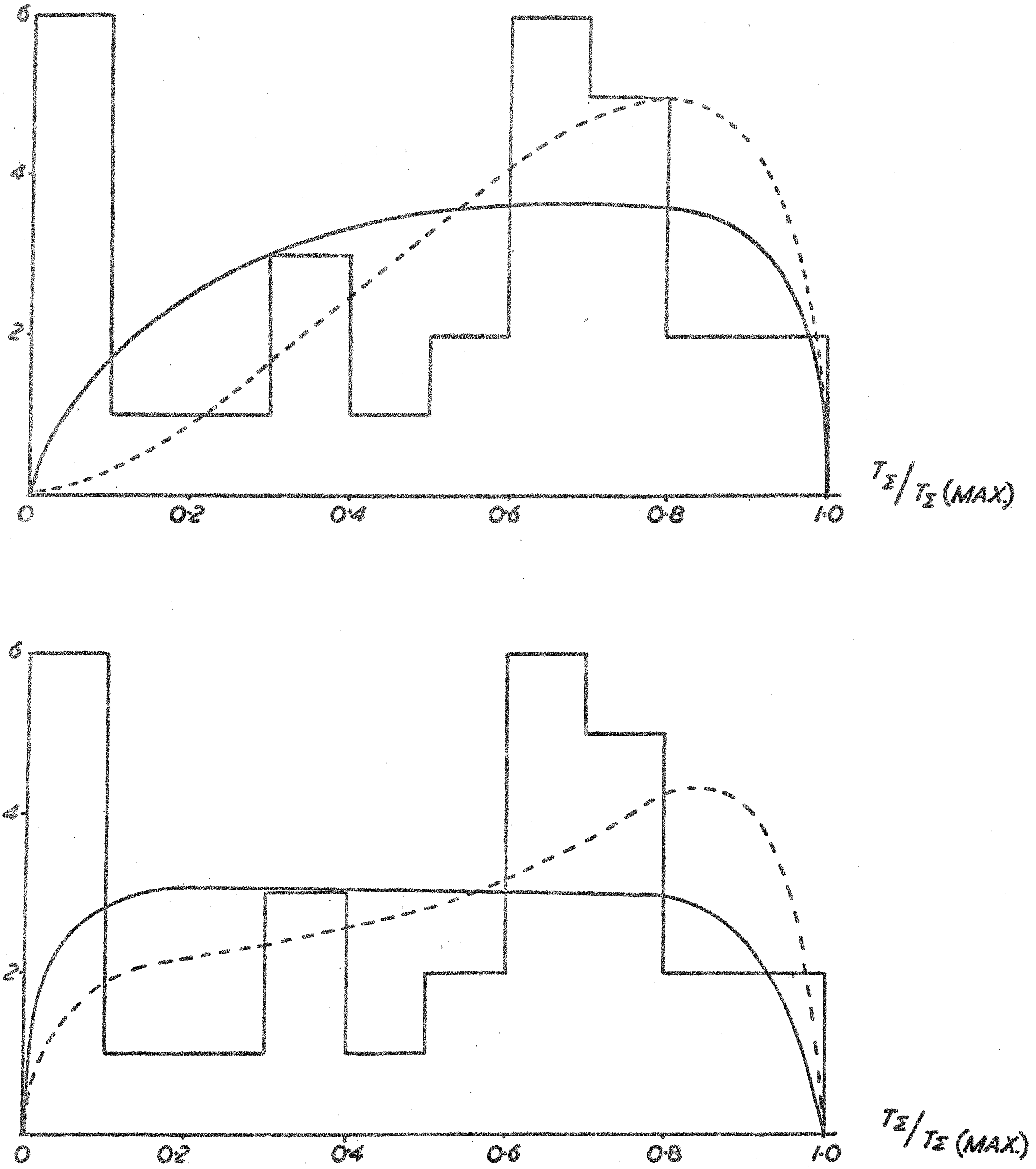

6
4
2
0
0·2
0·4
0·6
0·8
1·0
T_Σ / T_Σ (MAX.)
6
4
2
0
0·2
0·4
0·6
0·8
1·0
T_Σ / T_Σ (MAX.)

FIG: 18

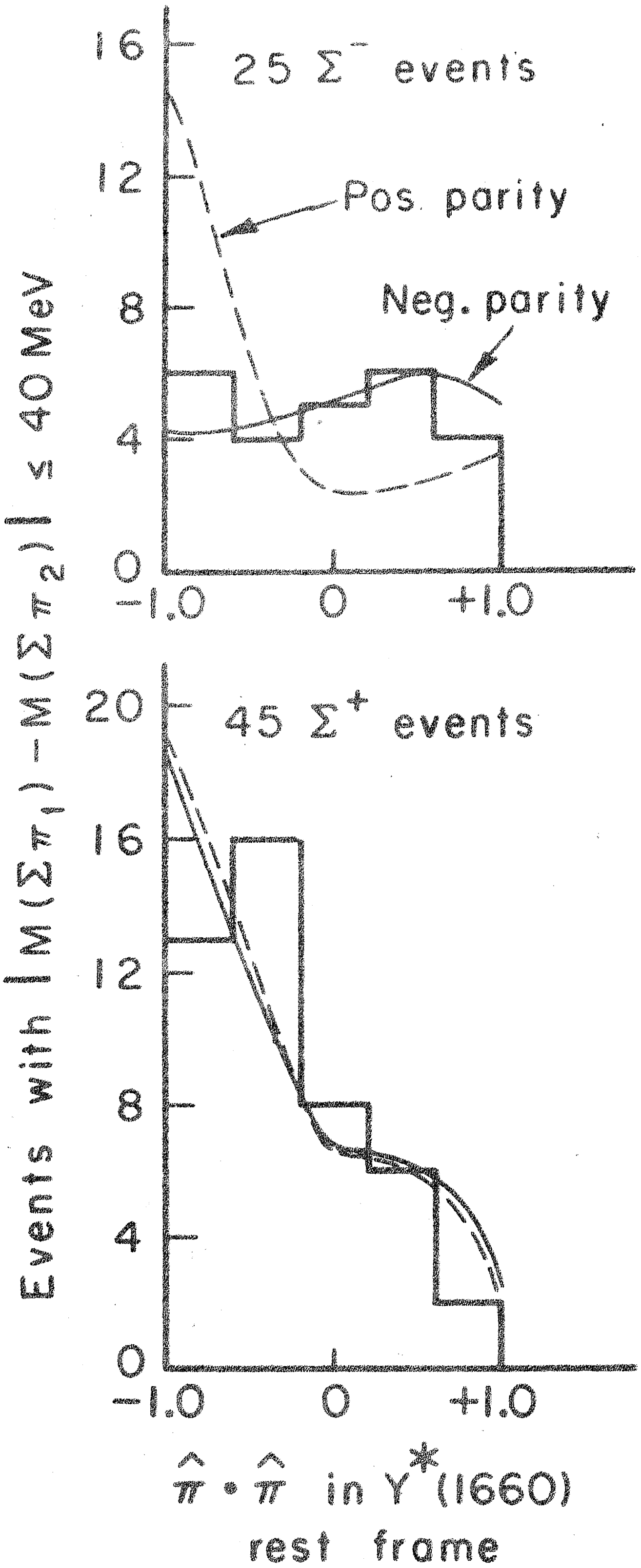


FIG: 19

DIA 24989