

CALTECH USERS GROUP

PROPOSAL TO STUDY PHOTOPRODUCTION OF NEUTRAL BOSONS AT LOW  
FOUR MOMENTUM TRANSFER

A. Scope:

This proposal is a request for 175 hours of beam time to study the processes

(1)	$\gamma + p \rightarrow p + \pi^0$	100 hours
(2)	$\gamma + p \rightarrow p + \rho^0$	50 hours
(3)	$\gamma + p \rightarrow p + B^0$ (mass search)	25 hours

in the region of photon energies between 3 BeV and 15 BeV and with "four momentum transfer" limited by  $0.2 \leq t \leq 1.0$  (BeV/c)<sup>2</sup>. The experiment will use the 8 BeV/c spectrometer to detect the recoil protons which have a momentum greater than 450 MeV/c and come out at angles between 60° and 75° in the laboratory. The 8 BeV/c spectrometer, with its large flight path, is ideally suited to identify the proton by means of a crude time of flight criterion. For instance, at the highest  $t$  of 1 (BeV/c)<sup>2</sup> the recoil proton takes 20 nanoseconds longer to traverse the spectrometer than do relativistic particles. Hence we propose to pulse the machine with 25 nanosecond pulses or longer depending upon the value of  $t$  being measured. Of course, if the chopped beam system is operating at the time of this running, that scheme could also be used. However, we feel that a single short pulse is probably the simpler of the two methods.

The kinematics that is being explored here is similar to the "Jacobian region" used in the missing mass spectrometers. It has the important feature that the mass resolution remains good even though a large  $\delta k/k$  is used. As a result relatively high counting rates are anticipated in this experiment.

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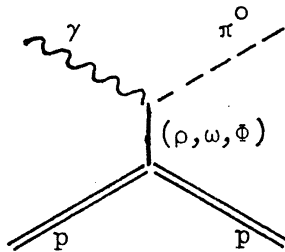
B. Physics Background:

1.  $\gamma + p \rightarrow p + \pi^0$

It is believed that in the region of  $t$  that we are exploring for this reaction the data can be fit with a Regge pole. The measurements made at Caltech<sup>1)</sup> and at Hamburg<sup>2)</sup> show a strong peaking in the forward direction for photon energies between 900 MeV and 3 BeV. At the higher energies the cross section takes the simple form

$$\frac{d\sigma}{dt} = \beta(t) \left(\frac{s}{s_0}\right)^{2\{\alpha(t)-1\}} .$$

The diagram for the Regge pole contribution is the following:



The analysis at Caltech has given approximately the correct coupling constants expected in the diagram, and the higher energy data from Hamburg seem to lie along a trajectory very close to that found for the  $\rho$  in the pion scattering experiments. We wish to test this hypothesis at energies up to 15 BeV.

We propose to measure this cross section at  $k = 3, 5, 10, 15$  BeV for 5 momentum transfers between  $0.2$  and  $1.0$   $(\text{BeV}/c)^2$  with 8.5% statistical accuracy.

2.  $\gamma + p \rightarrow p + \rho^0$

In interesting contrast to the above case,  $\rho^0$  production at lower energies as measured at Hamburg seems to have a cross section that levels off as a function of photon energy to about 15  $\mu\text{barns}$  above

3 BeV and an angular distribution that is exponentially falling in  $t$ , and the mechanism is thought to be diffraction production. Again, an extension of the data from the low energy region of Hamburg to 15 BeV would help to establish the basic mechanism in this reaction. For some values of  $t$  the mass resolution can be high enough to also observe  $\omega$ 's and  $\phi$ 's. Therefore, we propose to measure the cross section for photoproduction of  $\rho^0$  at  $k = 5, 10, 15$  BeV for three different momentum transfers,  $|t| = 0.3, 0.5, 0.7$  (BeV/c)<sup>2</sup>, with a statistical accuracy of 5%.

### 3. $\gamma + p \rightarrow p + B^0$ (mass search)

We propose to spend 25 hours looking for the photoproduction of Bosons heavier than the  $\rho$ ,  $\omega$ , or  $\phi$ . Mesons of mass  $M_x$ ,  $1.6 \leq M_x \leq 2.4$  GeV have been observed from the reaction  $\pi^- + p \rightarrow x^- + p$  at CERN with differential cross sections in the range of  $30-130 \mu\text{b}/(\text{BeV}/c)^2$  for momentum transfers  $t$  given by  $0.2 \leq -t \leq 0.4$  (GeV/c)<sup>2</sup>. If the particles are produced at high  $t$  by photons and the cross section is of the order of  $1.0 \mu\text{b}/(\text{GeV}/c)^2$ , then we could expect to find them by observing the recoil proton. The details of this mass search are discussed below.

## C. Pion Photoproduction:

### 1. Requirements

(1) 8 BeV/c spectrometer in experimental area A, with peripheral equipment (SDS, etc.). Removal of timing counters is necessary for counting on slow protons. However, the  $p, \theta$  hodoscope counters will be untouched.

(2) Mylar (.005") enclosed target cell of 2 cm diameter and 20 cm long with fill and temperature ports. Dummy cell for empty target runs. Scattering chamber with .005" mylar windows.

(3) Primary radiator .01 radiation lengths. Additional collimation so that beam is 1 cm vertically and 1.8 cm horizontally at the hydrogen target.

(4) Photon beam monitor.

(5) One hundred hours running time with electron beam intensities up to 10  $\mu$ amp. and pulse length as short as 15 nsec.

## 2. Timing

The proton laboratory momenta of interest in this experiment are  $P_p \lesssim 1$  GeV. The time difference between these and relativistic charged particles traversing the 22 meter spectrometer is  $\Delta t \geq 20$  nanoseconds, and this difference as a function of  $t$  is shown in figure 1. It is not known if  $K^+$  will present a problem.

## 3. Resolution

Consider the reaction  $\gamma + p \rightarrow p + B^0$  for given spectrometer setting on the recoil proton ( $P_p, \theta_p$ ) there is a one-to-one correspondence between meson mass ( $M_x$ ) and photon energy ( $k$ ):

$$k(M_x) = \frac{1}{2} \frac{2M_p T_p + M_x^2}{P_p \cos \theta_p - T_p} \quad (1)$$

where  $T_p$  = proton kinetic energy. If we assume that all events are due to single pion production ( $M_x = M_\pi$ ), then the distribution

in  $k_s = k(M_\pi)$  for accepted events follows directly. This assumption is valid down to the threshold for  $2\pi$  production to the extent that final states containing photons are relatively small. The bremsstrahlung end point on such a distribution occurs at

$$k_0 = \frac{1}{2} \frac{2M_p T_p + M_\pi^2}{P_p \cos \theta_p - T_p} , \quad (2)$$

while multi-pion events will occur with  $k < k'$

$$k' = \frac{1}{2} \frac{2M_p T_p + (2M_\pi)^2}{P_p \cos \theta_p - T_p} . \quad (3)$$

Therefore this "bridge"

$$\frac{\delta k}{k_0} = \frac{k_0 - k'}{k_0} = \frac{3M_\pi^2}{2M_p T_p + M_\pi^2} = 3 \frac{M_\pi^2}{t + M_\pi^2} \approx 3 \frac{M_\pi^2}{t} \quad (4)$$

adjacent to the bremsstrahlung end point will contain only single  $\pi$  events (see figure 2). The distribution in  $k_s$  provides an unambiguous check on the experiment. This distribution should be empty of events for  $k_s \gtrsim k_0$ . Its shape for  $k_s < k_0$  should be essentially that of the bremsstrahlung spectrum modified by the differential cross section for  $\pi$  production. For  $k < k'$ , events with more than a single  $\pi$  in the final state may be present.

We have therefore required that the resolution in reconstructing  $k_s$  be better than  $\frac{\delta k}{k_0}$  in order that bremsstrahlung subtractions at the end point be meaningful. In calculating this

resolution, we have taken into account the following:

- (a) Error in measurement of  $\theta_p$  due to multiple scattering in the target;
- (b) Error in measurement of  $P_p$  due to
  - 1) Dispersion from vertical beam dimension ( $\pm 0.5$  cm)
  - 2) Ionization loss in 2 cm wide target
  - 3) Multiple scattering in  $\theta$  measuring counters, which are 0.5 meters upstream of the  $\Delta p/p$  hodoscope.

Figure 3 shows this resultant measurement errors in  $\Delta p/p$  and  $\Delta\theta$ . Shown also is the overall measurement error in  $\Delta k/k$  to be compared with the  $\delta k/k_0$  region of interest. We conclude that the resolution allows rather clean measurements for  $0.2 < t < 1.0$   $(\text{GeV}/c)^2$ .

Figures 4 and 5 show the spectrometers ( $p-\theta$ ) window at  $t = 0.3$  and  $1.0$   $(\text{GeV}/c)^2$ . The small shaded square represents the ultimate hodoscope resolution, while the open square indicates the experimental resolution as derived from figure 3.

#### 4. Rate

The total rate for counting single  $\pi$  events in the "bridge" adjacent to the bremsstrahlung end point is approximately

$$\text{Rate} = (N_e \ell) \frac{\delta k}{k} \frac{\frac{d\sigma}{dt}}{\frac{d\Omega}{dt}} \Delta\Omega \left( \frac{\rho N_0 \ell_H}{A} \right) \quad (5)$$

where  $(N_e \ell)$  = equivalent quanta in bremsstrahlung beam

$N_e$  = electron current

$\ell$  = thickness in radiation lengths of the radiator

$$\begin{aligned} \frac{d\Omega}{dt} &= \text{rate of change of laboratory solid angle with} \\ &\quad \text{respect to the square of momentum transfer} \\ &\approx \frac{\pi \cos \theta}{t} p \quad \text{with } \theta_p = \text{lab angle of recoil proton} \\ l_H &= \text{length of the H}_2 \text{ target} \\ \frac{\rho N_O l_H}{A} &= \text{number of protons per cm}^2 \text{ in H}_2 \text{ target} \\ \Delta\Omega &= \text{solid angle subtended by spectrometer} \\ &= 10^{-3} \text{ steradians for } \theta_p < 68.5^\circ \\ &= \frac{2.5}{\tan \theta_p} \times 10^{-3} \text{ steradians for } \theta_p > 68.5^\circ \end{aligned}$$

Hence

$$\text{Rate} = (N_e l) \frac{3M^2}{t} \frac{\pi}{\pi \cos \theta} \frac{t}{\pi \cos \theta} \frac{d\sigma}{dt} \Delta\Omega' \frac{\rho N_O l_H}{A} .$$

For

$$\begin{aligned} N_e &= 3.3 \text{ } \mu\text{amps} = 2.08 \times 10^{13} \text{ e}l/\text{sec} \\ l &= 0.01 \\ l_H &= 20 \text{ cm} \\ \frac{\rho N_O l_H}{A} &= \frac{(.07)(6 \times 10^{23})(20)}{1} = 8.4 \times 10^{23} \text{ cm}^{-2} \\ \cos \theta &\approx 0.25 \\ \Delta\Omega' &\approx 10^{-3} \text{ ster. ,} \end{aligned}$$

we find

$$\begin{aligned} \text{Rate} &= (2.08 \times 10^{11}) \times \frac{(.06)}{\frac{1}{4}(3.14)} \times 10^{-3} \times 8.4 \times 10^{23} \\ &\quad \times 10^{-30} \frac{d\sigma}{dt} \\ &= 13 \frac{d\sigma}{dt} \text{ sec}^{-1} \\ \frac{d\sigma}{dt} &\text{ is in } \mu\text{b}/(\text{BeV}/c)^2 \end{aligned}$$

Figure 6 shows the approximate cross section expected in this experiment. They were obtained using the Regge pole approximation:

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{k=2} \left(\frac{k}{2}\right)^{2\alpha(t)-2} \quad (6)$$

where  $\left(\frac{d\sigma}{dt}\right)_{k=2}$  and  $\alpha(t)$  were obtained from the fits to the above equation made in reference 1) using data at 2.0 and 3.0 BeV.

Table I gives the total time required in minutes to acquire enough events within 5% of the bremsstrahlung end point to quote 8.5% statistical error at each photon energy and momentum transfer desired for this run. The differential cross section of figure 6 are assumed.

k \ t	3	5	10	15
0.2	0.5	1.5	6	12
0.4	1.1	3.3	13.3	27.7
0.6	3.7	11.1	44.5	89.0
0.8	17.2	52.0	207	414
1.0	36	107	430	860
total hours	1	3.4	11.7	23.4

39.5 hours  
total

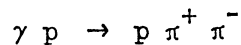
Including empty target runs and synchrotron subtraction runs when necessary, we require a total of 100 hours to complete this experiment.



D.  $\rho^0$  Photoproduction:

1. Expected Cross Sections

From the Hamburg<sup>2)</sup> and CEA<sup>3)</sup> bubble chamber experiments, there is strong evidence that  $\rho^0$  photoproduction proceeds by a diffraction mechanism. Furthermore, the reaction



seems to be dominated by  $\rho^0$  meson production for photon energies greater than 3 BeV. Accordingly, we have estimated our  $\rho^0$  yields on the basis of the observed angular distribution at 5 BeV,

$$\frac{d\sigma}{dt} (\gamma p \rightarrow p \rho^0) = 110 e^{-7.7|t|} \quad . \quad (7)$$

From the same experiments, it appears that of all recoil protons coming from photoproduction reactions with  $|t| \lesssim 1(\text{BeV})^2$ , about half are from  $\rho^0$  production. If this condition persists to higher energies, it means that the  $\rho^0$  production process can be readily studied by using a bremsstrahlung subtraction to define the photon energy. Anticipating this result, we have assumed that the proton yield from bremsstrahlung photons with insufficient energy to make a  $\rho^0$  is double the  $\gamma p \rightarrow p \rho^0$  yield. We feel that this is a conservative estimate.

2. Experimental Method

The experimental method we propose is the classic one of observing proton yield as a function of bremsstrahlung end point,  $E_0$ , for a fixed spectrometer setting. However, a more intuitively appealing method is possible for some of the points if the background yield is actually as small as we anticipate. In much of our

kinematical region, the photon energy bite defined by the full spectrometer ( $p-\theta$ ) window is very large (20% to 40%). It may then be desirable to define the photon energy with a subtraction to a value considerably smaller than this. The yield after such a subtraction can then be projected out of the spectrometer hodoscope matrix along lines of constant  $B^0$  invariant mass. Observation of the  $\rho^0$  mass distribution would be compelling evidence that we are detecting the reaction of interest. The running time estimates calculated below, however, are based upon using the spectrometer aperture to define the photon energy bite contributing to  $\rho^0$  production. The subtraction of yields from  $E_0$  runs above and below the photon energies contributing to  $E_0$  production is used to eliminate background; it is not a "bremsstrahlung subtraction" in the sense of defining the photon energy.

Figure 7 shows the full  $(k,p)$  kinematics plane for a constant proton angle. Also shown is the 4% spectrometer momentum aperture for the  $k = 10$  BeV,  $t = 0.5$  (BeV/c)<sup>2</sup> point. Figure 8 shows a blown up view of the kinematics around this point. The kinematics is displayed in this manner to call attention to the sources of observed protons in the unsubtracted yields. In a small band of angles around  $65^\circ$  ( $\pm 2$  mr is adequately small. See figure 7.) and with the bremsstrahlung end point at 8.5BeV, one observes protons coming from  $\pi^0$ 's and  $\eta$ 's photoproduced by 4.5 BeV and 7.3 BeV photons respectively as well as from a mass continuum starting with dipions at  $k = 5.2$  BeV. The yields from single  $\pi^0$  and  $\eta$  production are negligible and have been ignored. An estimate of the contribution from dipions distributed according to phase space gives less than 20% of the anticipated  $\rho^0$

yield. The phase space integral was normalized by assuming its total cross section was the same as the  $\rho^0$  total cross section. On the basis of this result and the bubble chamber data, we feel that our assumption that the proton yield when the end point is at 8.5 BeV is twice the expected  $\rho^0$  yield is quite conservative.

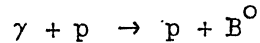
When the bremsstrahlung end point is 10 BeV, the 4% momentum window covers the entire  $\rho$  mass region and the momentum hodoscope counters should show a yield distribution increasing from the background level at the high momentum end to the full  $\rho^0$  yield at the low momentum end.

Finally, at an end point of 11 BeV, the full momentum aperture counts protons from  $\rho^0$ 's.

We plan to take six to ten runs with different linac energies,  $E_0$ , at one spectrometer setting in order to measure the  $E_0$  dependence of the background yield. With these data we can test the assumption that the behavior of the background can be found by using the counting rate in parts of the hodoscope to which  $\rho^0$  mesons do not contribute. Thus, for example, in the 4 mr angular aperture under consideration,  $\rho^0$ 's do not contribute to the high half of the momentum aperture when  $E_0 = 8.5$  BeV and  $E_0 = 9.1$  BeV and they contribute fully to the low half at  $E_0 = 10.5$  and 11.0 BeV. If the  $E_0$  dependence of the background is observed to be  $t$  independent, only these four  $E_0$ 's need have been measured to obtain the background. Assuming that we gain confidence in this background subtraction procedure, we plan to run at only four  $E_0$ 's at the other eight points.

### 3. Expected Counting Rates and Running Times

The number of proton counts in a momentum-solid angle window  $(\Delta\Omega \frac{\Delta p}{p})$  from the two body reaction



is

$$N_p = \left( \frac{p^2}{\mu^2 + t} \right) \left( \frac{M}{E} \right) \left( \frac{2}{\pi} p k \right) \frac{d\sigma}{dt} (\Delta\Omega \frac{\Delta p}{p}) (N_e \ell) \left( \frac{\rho N_O^H}{A} \right) \quad (8)$$

where  $B^0$  has mass  $\mu$  and the other symbols have been defined. The bremsstrahlung spectrum is taken as  $dk/k$ .

In Table II, columns 3 and 4 give the spectrometer settings for the selected points. Column 5 gives the cross section calculated using formula 7 above. This is reduced to a cross section differential in the spectrometer aperture in column 6. The yields given in column 7 are based upon a 3.3  $\mu$ m electron beam, a .01 r.l. radiator, a 20 cm liquid hydrogen target, the full 4% momentum aperture, and a quarter of the solid angle aperture. Column 8 gives the time required to measure 2000 counts from  $\rho^0$ 's. This is the number required to achieve 5% statistical accuracy if the background yield is twice the desired yield. To allow for the several runs at different  $E_0$ 's, the time in column 8 is multiplied by 5. to get the actual running time. The total time does not include the runs necessary to measure the detailed yield vs.  $E_0$ , nor empty target runs. However, if these estimates and the method prove reliable, it is clear that we will be able to make measurements at perhaps 3 times as many points as the minimum set of nine in the requested 50 hours.

Table II

1	2	3	4	5	6	7	8	9
k (BeV)	t (BeV) <sup>2</sup>	p (BeV/c)	θ (deg)	$\frac{d\sigma}{dt}$ ( $\mu\text{b}/\text{BeV}^2$ )( $\mu\text{b}/\text{sr}-100\%$ )	$\frac{d\sigma}{dp/p d\Omega}$ ( $\mu\text{b}/\text{sr}-100\%$ )	Yield (cnt) (sec)	Time (2000 p's) (min)	Running Time (min)
	.3	.57	64.5	11	6.5	11.0	3	15
5	.5	.76	60.4	2.3	2.4	4.1	8	40
	.7	.91	57.0	0.5	.7	1.2	28	140
	.3	.57	68.8	11	12	22.0	1.4	7
10	.5	.76	65.0	2.3	4.7	8.0	4.1	21
	.7	.91	61.6	0.5	1.3	2.2	15.0	75
	.3	.57	70.6	11	19.5	33	1.0	5
15	.5	.76	66.4	2.3	7.1	12	2.8	14
	.7	.91	63.0	0.5	2.0	3.4	10.0	50

Total Time 6 hours

#### 4. Other Reactions

In addition, we plan to try to detect  $\omega^0$  and  $\phi^0$  with the recoil proton method to find out if it is feasible. The method will be to define the photon energy with a bremsstrahlung subtraction with sufficient precision that it contributes less than about 15 MeV to the mass resolution. Subtracted yields projected out of the (p- $\theta$ ) hodoscope along constant mass lines could then show an  $\omega$  or  $\phi$  bump over the background. The details of this feasibility test have not yet been worked out.

#### E. Mass Search:

For  $M_x = 2$  GeV,  $\frac{d\sigma}{dt} = 1.0 \mu\text{b}/(\text{GeV}/c)^2$  at  $k = 12.4$  GeV, and  $t = 1.0 (\text{GeV}/c)^2$ , we estimate a counting rate of 20 per second into the spectrometer acceptance. Further, assuming that the major source of background to be subtracted at high  $t$  occurs with an effective cross section (integrated over  $k$ )  $\frac{d\sigma}{dt} \lesssim 15 \mu\text{b}/(\text{GeV}/c)^2$ , then a bremsstrahlung subtraction of less than 15/1 is required.

Ten runs, each one hour in length with  $\Delta k/k$  differences of 5% give 10% statistical error on each of the subtracted 9 points. The mass resolution under these circumstances is 50 MeV.

#### F. Personnel:

The C.I.T. Users Group consists of the following people:  
B. Barish, R. Gomez, G. Jones, C. Peck, J. Pine, F. Sciulli, B. Sherwood,  
A. Tollestrup, J. van Putten. Experience on the 8 BeV Spectrometer is now being acquired by Pine and Barish. C. Peck aided in the initial design.

References

- 1) R.M. Talman, C.R. Clinesmith, R. Gomez, A.V. Tollestrup, Phys. Rev. Lett. 9, 177, 1962. See also later measurements up to 1500 MeV reported in a CalTech Thesis on  $\pi^0$  Photoproduction by L. Hatch 1966.
- 2) Paper reported at 1966 Berkeley meeting. By Hamburg Bubble Chamber Group.
- 3) C.E.A. Bubble Chamber Group, Phys. Rev. 146, 994 (1966).

Figure Captions

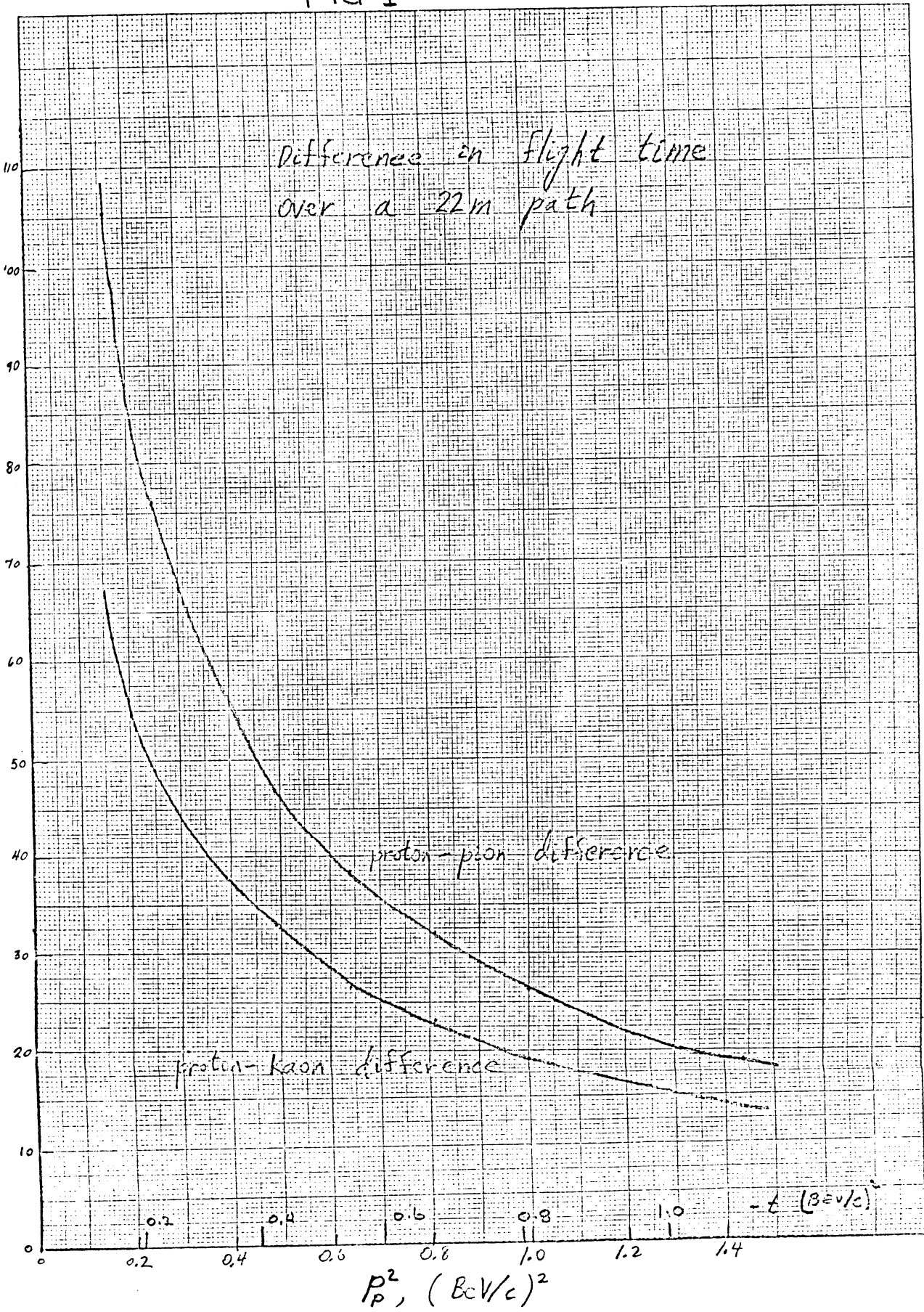
- Fig. 1. Difference of flight time between relativistic particles and protons as a function of  $t$ , the four-momentum transfer.
- Fig. 2. Kinematics for 10 BeV photoproduction in the region of low  $t$ . The insert shows an expanded view of the spectrometer  $p, \theta$  plane.
- Fig. 3. Comparison of experimental resolution with the  $\delta k/k$  "bridge" which separates the single  $\pi$  from multiple  $\pi$  production.
- Fig. 4. Spectrometer plane at  $t = 0.3 \text{ (BeV/c)}^2$ .
- Fig. 5. Spectrometer plane at  $t = 1.0 \text{ (BeV/c)}^2$ .
- Fig. 4,5, show a comparison of the spectrometer hodoscope bins (shaded), experimental resolution (unshaded) and the  $\pi^0$  photoproduction kinematics.
- Fig. 6. Predicted  $\pi^0$  cross-section using a Regge Pole extrapolation from 2 BeV.
- Fig. 7. Kinematics at Fixed  $\theta_p$  for various different mass Bosons.
- Fig. 8. Expanded kinematics for a typical  $\rho^0$  Measurement.



FIG 1

K<sub>10</sub> 10 X 10 TO THE CENTIMETER 46 1510  
16 X 25 CM. MADE IN U.S.A.  
KEUFFEL & ESSER CO.

$\Delta T$ , nsec



Kinematics: proton momentum vs angle (in lab) for

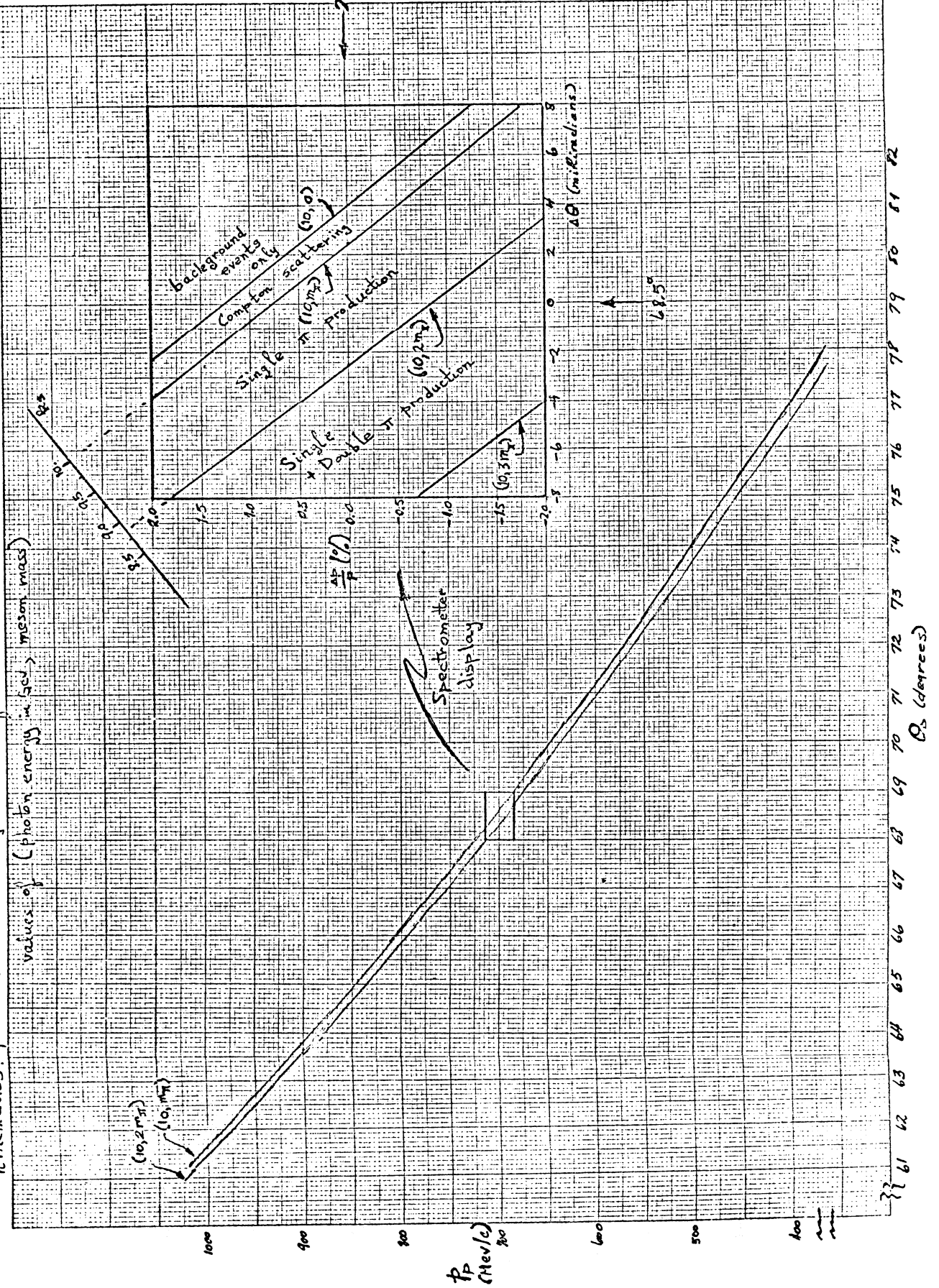
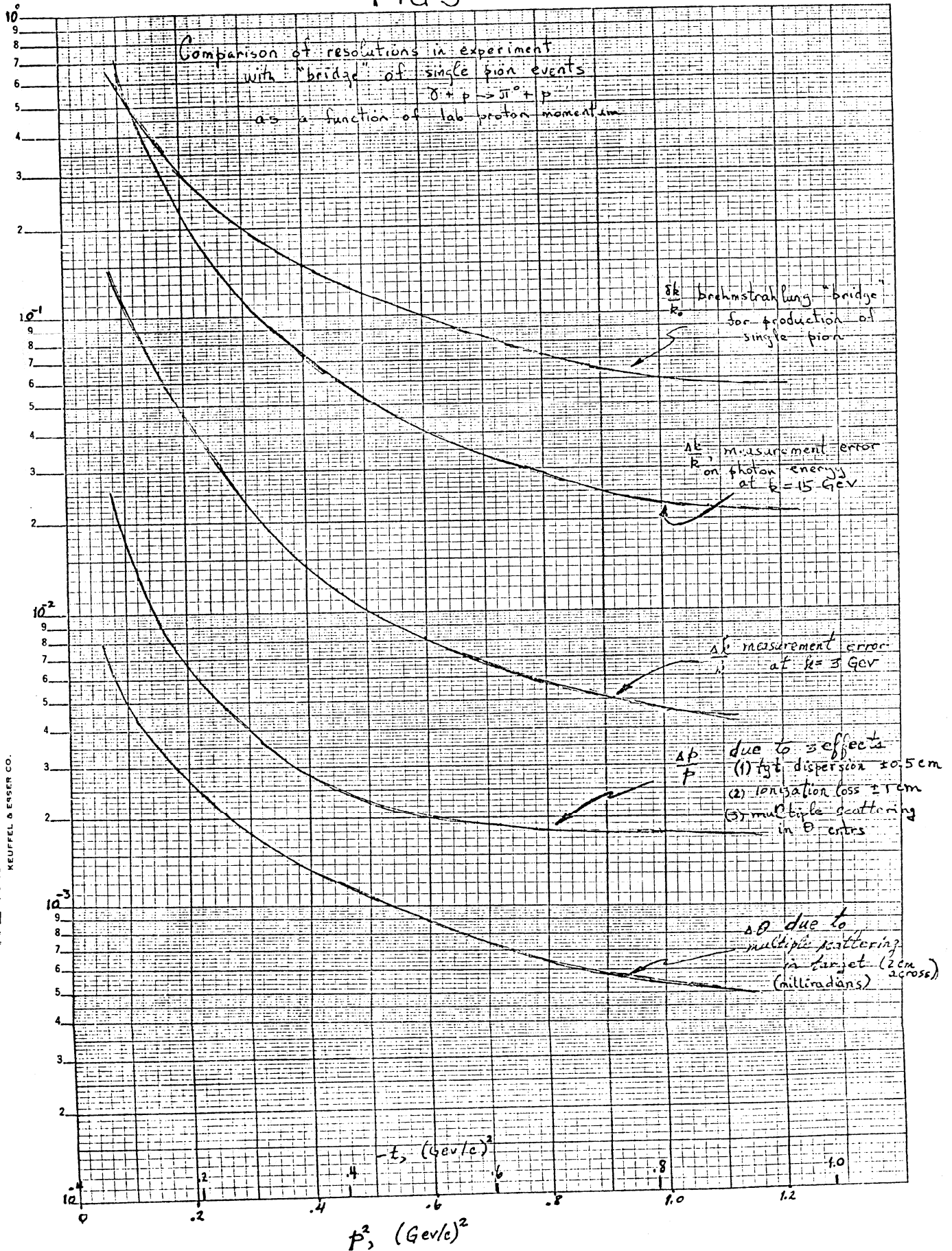


FIG 2

# FIG 3

Comparison of resolutions in experiment  
with "bridge" of single pion events  
 $\pi^0 + p \rightarrow \pi^+ + p$   
as a function of lab proton momentum



KEE SEMI-LOGARITHMIC 46 6010  
4 CYCLES X 70 DIVISIONS MADE IN U.S.A.  
KEUFFEL & ESSER CO.

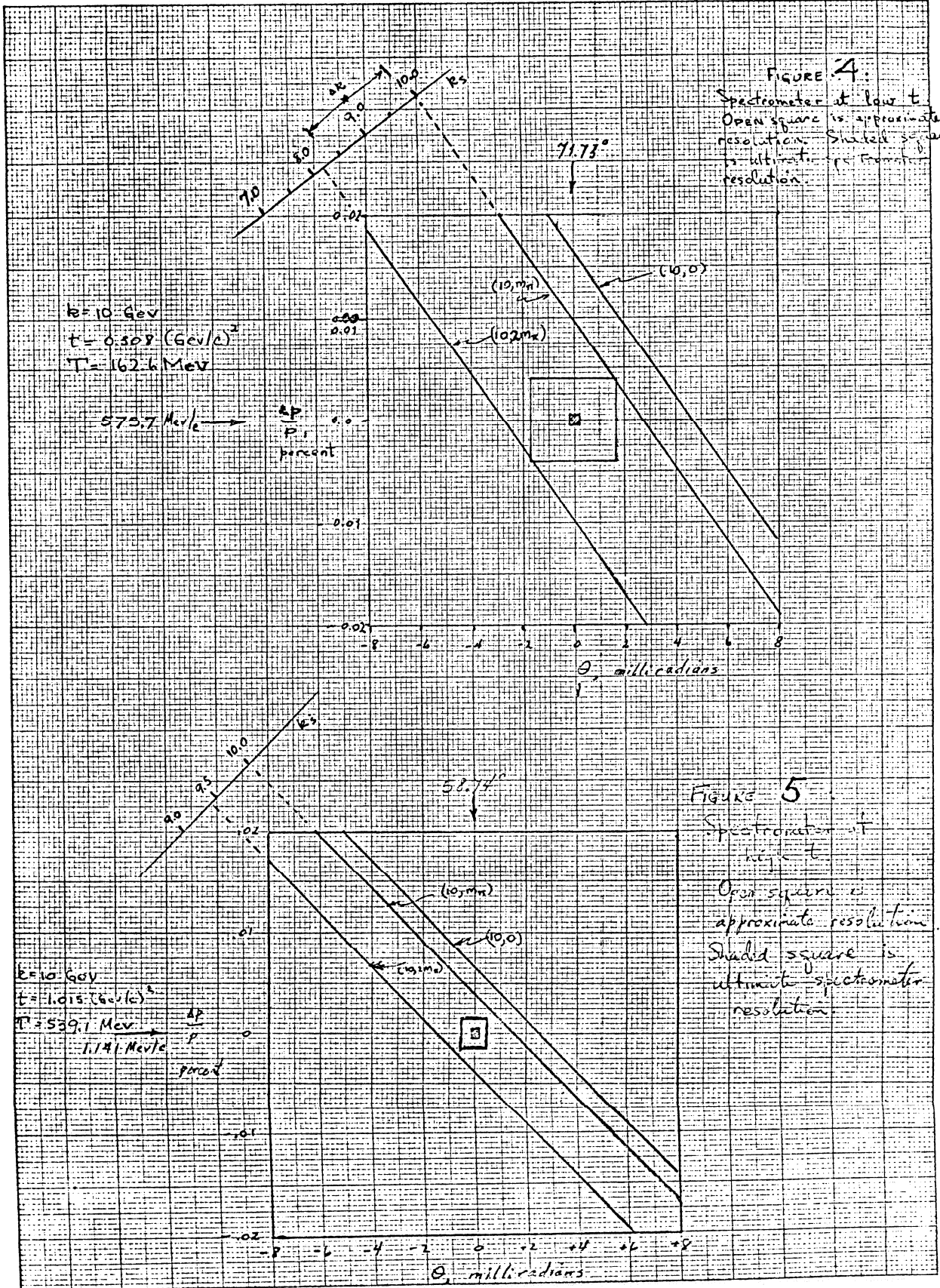
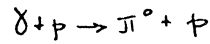


FIG 6



Calculated cross-sections from

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_0 \left(\frac{k}{k_0}\right)^{2\alpha-2}$$

where  $\left(\frac{d\sigma}{dt}\right)_0, k_0$  taken from Bonn data at 2 Gev

$\alpha$  taken from Bonn data fits at 2 and 3 Gev.

This formulation good for  $k \gg m_p$

$\frac{d\sigma}{dt}$   
in  $\mu\text{barn}/(\text{GeV}/c)^2$

Semi-Logarithmic  
4 Cycles X 10 to the inch  
width in inch.

12-184  
5784

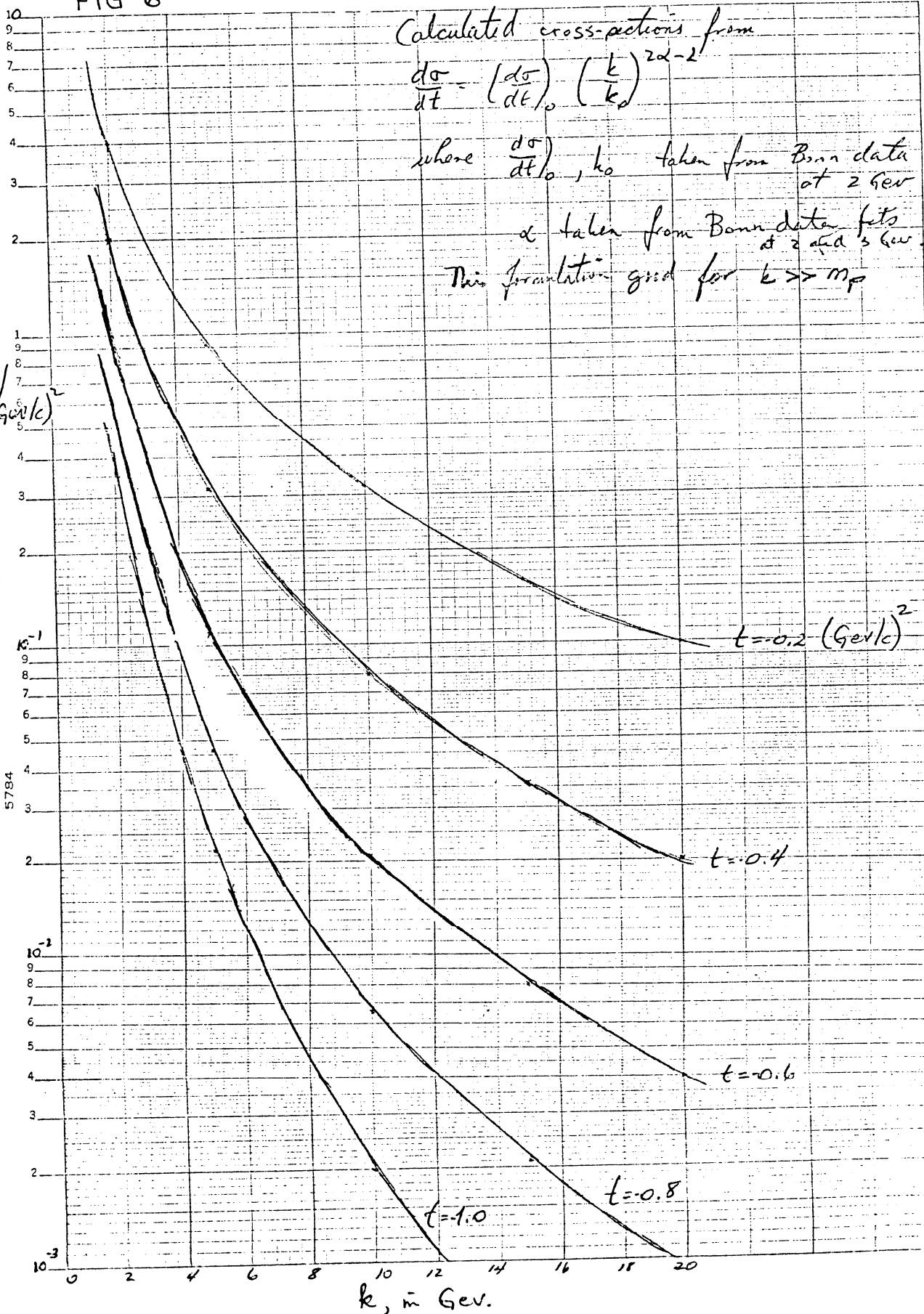


FIG 7

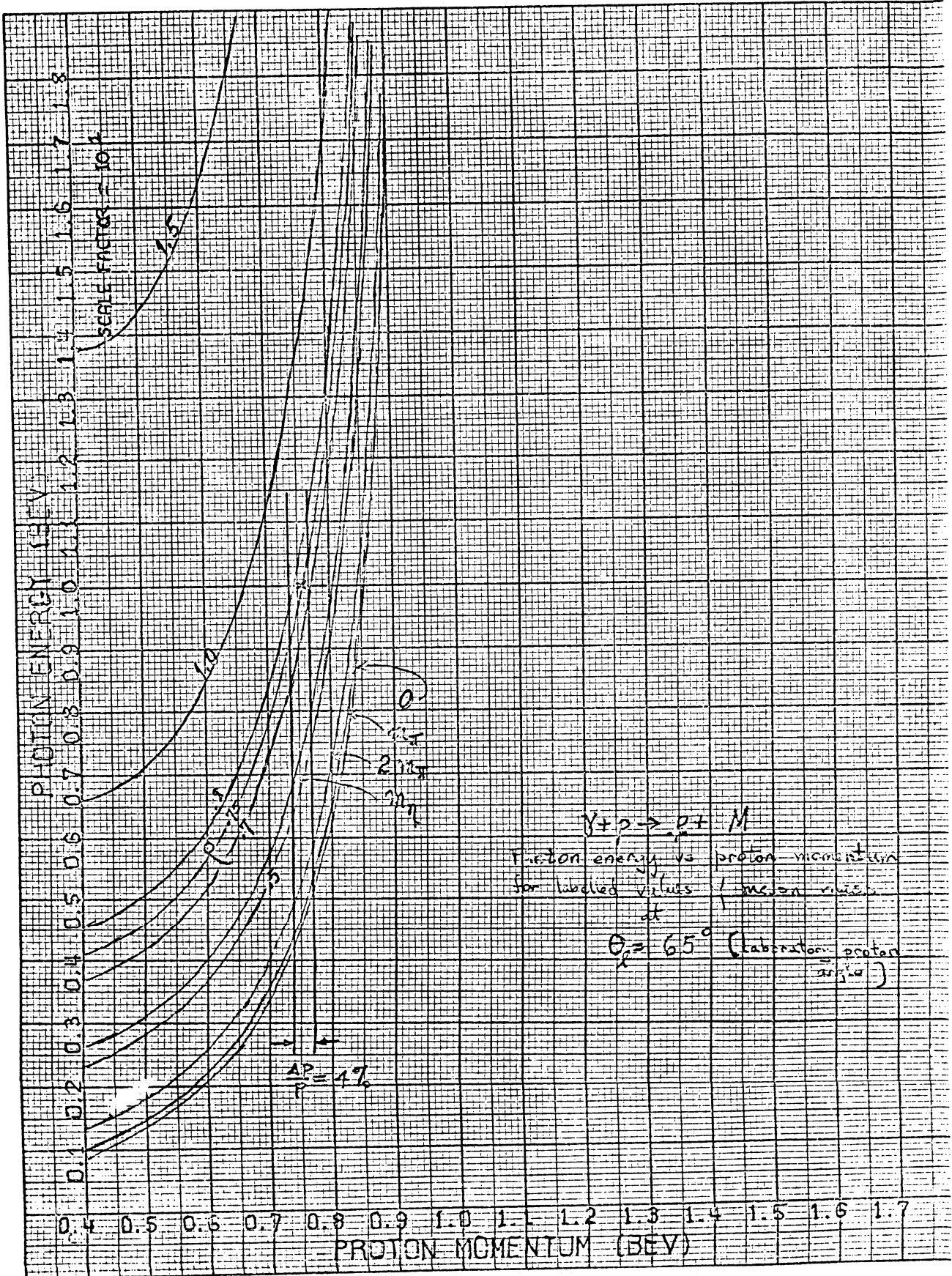


FIG 8

Kinematics for  $\rho^0$  Measurement at  
 $k = 10 \text{ BeV}$ ,  $t = -0.5 (\text{BeV})^2$

