ABSTRACT

An analysis of film from the 25" bubble chamber at Lawrence Berkeley Lab taken in 1969 was made. The film observed K^- particles at a momentum of 1.5 GeV/c traversing the chamber. From this analysis, determinations of the lifetime of the charged kaon, the branching ratio for

$K^- \rightarrow \pi^+\pi^-\pi^-$ (tau-mode)

in decays of the kaon, and the total cross section for interaction of kaons at momentum 1.5 GeV/c with protons were made. The values found are:

K^- lifetime	:	$(1.45 \pm .23) \times 10^{-8}$ s
Branching ratio	:	$(7 \pm 2)\%$
Total cross section	:	(32.8 ± 2.4) mb

INTRODUCTION

In the late forties, a new class of particles was discovered. These particles were easily produced, but lived a relatively long time. The ease of production would seem to imply an ease of decay, but that wasn't the case. This was one of the properties of these particles which prompted their description: Strange.

This property also proved extremely useful. Now, particle physicists could make in particle accelerators particles which did not exist in great quantities in nature, and they would last long enough to study in detail. By studying these strange particles, new insights into the nature of fundamental interactions could be gained.

The kaon is one such strange particle. One way to produce it is by this reaction:

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

The incident pions in this case are easily produced in interactions between accelerated protons and atomic nuclei.

In our case, the kaons are produced in the bevatron, a proton accelerator. The protons in the bevatron are allowed to crash into a target after they have been accelerated, and the products are sorted by spectrometers. One type of spectrometer is just a magnetic field. Since nearly all the particles produced have one unit of charge, when the particles pass through a magnetic field, they are deflected in an arc whose radius is proportional to their momentum:

$R = mv/qB$ if B is perp. to v

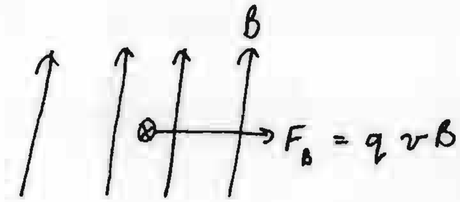
This selects out a small range of momenta to be used. These particles can be further sorted by passing through a magnetic and electric field oriented perpendicularly (see fig. 1.) This type of spectrometer selects out velocities, because while the electric force on the particle is constant (dependent only on charge,) the magnetic field depends on the velocity of the particle. By adjusting the fields properly, the desired particle will pass through undeflected, while others will veer off and be lost. This situation occurs when

$E = vB$ if B is perp. to v

Since particles with identical momenta but different mass have different velocities, this essentially purifies the beam into particles of the mass and charge that is being investigated, which is usually a unique particle. The net result of this is a beam of particles which can be studied at great length.

The particles can then be brought into interaction with matter, and the effects observed. In a uniform medium, the kaon beam will be attenuated in two ways - first, the particles will decay with some mean lifetime τ, and second, the particles will interact with the nuclei in that medium, with a characteristic cross section σ. The cross section is

Particles incident on paper



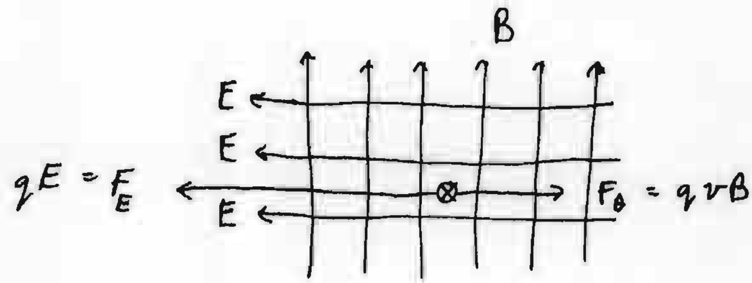


fig. 1

just a measure of how likely it is that the incident particle will interact significantly with a target particle.

A relation for the attenuation of the beam can be derived as follows: Since decay and interaction are the two ways to attenuate the beam, a good place to start is

$$dN/dx = \text{decay rate} + \text{interaction rate}$$

The rate at which the kaons decay is just proportional to the number present, and inversely proportional to their mean life, τ. Thus, $dN/dt' = -N/\tau$ for decays, where t' is the time as measured in the kaon rest frame. Since

$$dN/dx = dN/dt' * dt'/dx$$

the relation for the decay rate in dN/dx is simply obtained. If t is time as measured in the lab frame, and t' is time as measured in a frame in which the kaon is at rest, then

$$dx/dt = v = \beta c \qquad \text{where } \beta = v/c$$

From special relativity, $t = \gamma t'$ where $\gamma = (1-\beta^2)^{1/2}$

$$dx/d\gamma t' = \beta c$$

$$dx/dt' = \gamma\beta c$$

Thus, $dN/dx_{decay} = -N/\gamma\beta c\tau$.

For interactions, we can characterize each particle in the target as having an effective cross-sectional area σ. This means that if a kaon is traveling in a sea of protons, such as in liquid hydrogen, and it passes within an area of size σ centered on a proton, it will interact significantly. In a medium consisting of nuclei of atomic mass A, and density ρ, where N_a is Avogadro's number $= 6.022\times10^{23}$, the number of nuclei per cm^3 = $N_a \rho/A$. Multiplying this by the cross section σ, one obtains the average number of nuclei encountered by a kaon per cm the kaon travels. Multiply by the number of kaons present, and this is just the number of kaons lost through interactions per unit length, or dN/dx for interactions. Thus,

$$dN/dx_{interaction} = -N\ (N_a \rho\sigma/A)$$

So, the total rate at which kaons are lost from the beam is

$$dN/dx = -N(1/\gamma\beta c\tau + N_a \rho\sigma/A)$$

Integrating this is trivial, and yields

$$N = N_0 e^{-x/\gamma\beta c\tau} e^{-xN_a \sigma\rho/A}$$

Kaons have been studied extensively, so much is known about their decay. The charged kaon decays in six major modes, given here in order of decreasing frequency:

$$K^- \to \mu^- \bar{\nu}_\mu$$
$$K^- \to \pi^+ \pi^0$$
$$K^- \to \pi^+ \pi^- \pi^-$$
$$K^- \to \pi^0 e^- \bar{\nu}_e$$
$$K^- \to \pi^0 \mu^- \bar{\nu}_\mu$$
$$K^- \to \pi^+ \pi^0 \pi^0$$

One of our objectives is to determine the fraction of decays that are the third of these.

APPARATUS AND METHODS

The bubble chamber is a particle detector along the lines of a ~~fog~~ cloud chamber, in that charged particles passing through the detector leave visible tracks. In the ~~fog~~ cloud chamber, the track is made up of condensing vapor, whereas in the bubble chamber, the track consists of a stream of bubbles.

Mechanically, the bubble chamber (shown in fig. 2) is just a tank of liquid hydrogen with a window held in a magnetic field to allow determination of charge and momenta of particles. The hydrogen is held at around 27 degrees K, which is warm enough to boil the hydrogen at low pressures, but not at high pressures. Pressure is applied to keep the hydrogen liquid. Very quickly, the pressure is reduced, causing the hydrogen to be superheated. Particles are shot into the chamber, and a picture is taken for later analysis. Then, the pressure is reapplied.

Schematic Diagram of
a bubble chamber

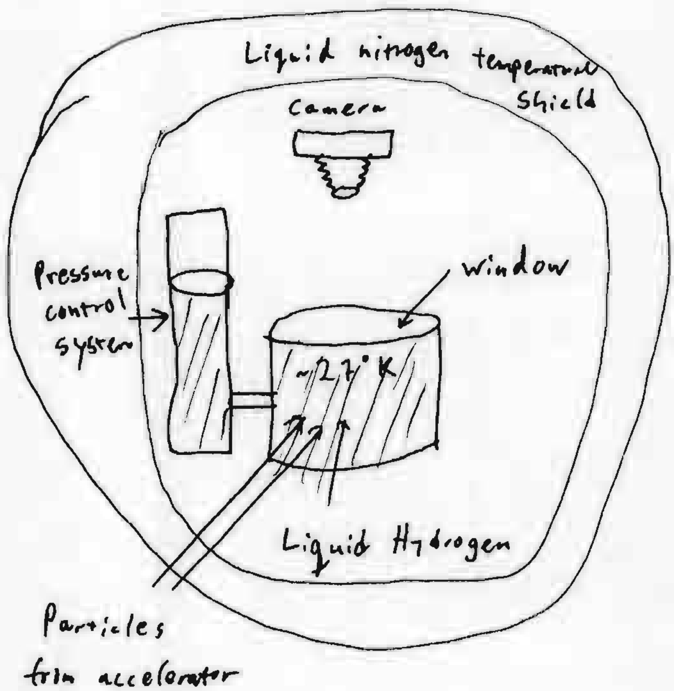


Fig 2

In the short interval that the pressure is reduced, any charged particles moving through the hydrogen will experience loss of energy by ionizing the hydrogen along its path. This ionized hydrogen serves as a nucleation site for the bubbles which are eager to form in the superheated liquid. The bubbles are easily visible to the eye or the camera. When the pressure is reapplied, the bubbles recondense into liquid. This leads to one great advantage of the bubble chamber - it requires little time between recording events. The film can be developed and studied thoroughly later, allowing for large amounts of data to be accumulated.

In this particular experiment, we use negative kaons produced and selected as discussed above to have a momentum of 1.5 GeV/c. The particles are produced in the bevatron, a large synchrotron at LBL (fig. 3.) The kaon beam produced in the bevatron is directed into the 25" bubble chamber, a chamber designed for good visibility. Three cameras are available on the 25" bubble chamber, to allow for three-dimensional trajectories to be measured.

We are analyzing film taken in June of 1969, consisting of some 1500 frames, each with about 10 kaons passing through. The analysis of the film is at first mind-bogglingly easy, in fact, at times tedious (as I am told much of experiment is.) First, a region of the tank is taken as a fiducial region. This is to provide rigid guidelines as to what will be counted and what will be ignored, as well as assuring that a particle that enters the region is a kaon, having the same trajectory and radius of curvature as the others. The procedure is simply to look at as many frames of film as possible, and record all events found inside this region. An event is any instance where a kaon fails to traverse the

Bevatron

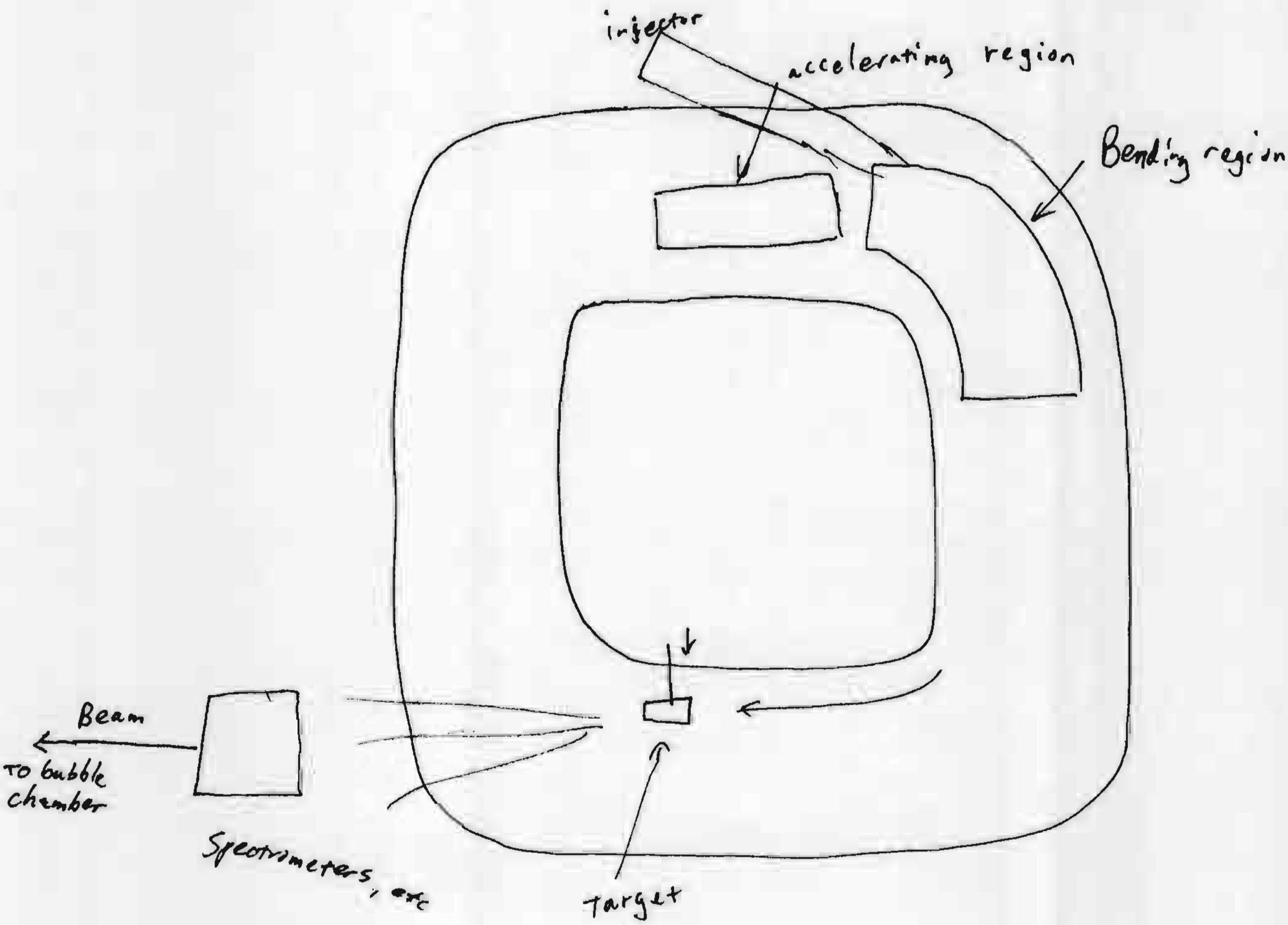


Fig. 3

fiducial region in a smooth arc.

There are many possible forms an event can take, with two main categories. If a K^- decays, charge conservation dictates that the sum of the charges on the charged products will be -1 - this implies an odd number of charged constituents, since none of the charged particles we will see has a charge of other than +/-1. If a K^- interacts with a proton, charge conservation implies an even number of charged products.

So, the two main categories of events are decays with an odd number of charged products, and interactions, with an even number of charged products. No kaon has been observed to decay with more than 3 charged products, and due to the relatively low energy of the incoming kaons, it would be very unlikely to have an interaction with more than 4 charged products. Because an event is manifested by a track in the bubble chamber splitting into 0-4 tracks, the events can be classified by the number of product tracks, or "prongs." Of course, there are complications, for example, a neutral product can decay, giving rise to "vees," tracks that appear to come from nowhere. but in general, the events can be classified by prong number with even numbers being interactions and odd numbers being decays.

That being sorted out, examining the film is simple and requires little knowledge of physics. One simply needs to determine whether a track is legitimate, i.e. enters the fiducial region at the proper angle and has the proper curvature, then see that it exits the fiducial region with no deflection of its path or spurs of other particles. If it fails to traverse the region, the number of prongs is recorded. It is necessary to know, in addition to how many and what kind of events there are, how many kaons enter the fiducial region. Counting the kaons in every frame would be time consuming, and if many frames are examined, or scanned, unnecessary. In our particular case, we scanned about 750 frames, and counted the number of legitimate kaons in 2 out of every 10 frames. This provided us a good statistical sample of frames, and allowed us to calculate to within 3% how many kaons entered the fiducial region in all of the frames scanned.

Some of the more interesting events are sketched after the text of this report.

ANALYSIS OF DATA

Here are the raw data that were collected:

Total frames scanned:			752		
Prongs:	0	1	2	3	4
Events:	46	146	200	11	13

Average # kaons/frame: 9.26+/-.24

Assume standard poisson errors of $\sqrt{N}$ for # of events

The length of our fiducial region on the scanning table was 28.8+/-.1 cm. Along the path of a kaon, the length was 29.5+/- .1 cm. From a schematic of the windows in the bubble chamber, a certain pattern visible in each frame was arranged in a 12" square. On the [redacted] projection surface, this pattern was not quite square, with sides that ranged from 11-7/16" to 11-9/16". Using this information, the distance a kaon travelled in the fiducial region was 30.78+/-.21 cm

The kaon's mass is 493.6 MeV, so at a momentum of 1.5 GeV/c, the relation $E^2 = p^2c^2 + m^2c^4$ gives the energy of the kaons to be (in the lab frame of reference) 1.579 GeV. Using the relation $E = \gamma mc^2$, this gives a value for γ of 3.199. β is easily found to be .9499 from this value of γ. I've neglected errors in this paragraph because the statistical errors in number of events will outweigh a small distribution of momentum.

From the average number of kaons/frame, the total number

6964 ± 180

of kaons that entered the fiducial region is 6970+/-185. Those kaons that interact or decay will do so, on average, in the middle of the region, and will only be valid kaons for, on average, 1/2 the length of the region. So, the number of available kaons is the number that entered the region minus half of the total number of events, or 6760+/-180 kaons.

?

From the discussion of beam attenuation,

$$dN/dx_{\text{interaction}} = -N(N_a \sigma\rho/A)$$

$\Delta N/\Delta x \cong dN/dx$ for small values of Δx. With ΔN = -(total number of interactions), N = number of available kaons, Δx = distance travelled by a kaon in the fiducial region, A = 1 (hydrogen) and ρ = .063+/-.0019 g/cm^3, the cross-section is given by:

what is your ΔN

$$\sigma = \Delta N/(N\Delta x) * A/(N_a\rho)$$

This works out to be 3.3×10^{-26} cm^2, or 32.8+/-2.4 mb, which would correspond to an "effective radius" of 1×10^{-13} cm. This value for the cross section agrees quite well with those quoted in CERN/HERA 70-6 for beam momenta in the neighborhood of 1.5 GeV/c, the cross section is very close to 33.5 mb. This is very good agreement considering the low statistics of the data.

Again, from the discussion of beam attenuation above,

$$dN/dx = -N/\gamma\beta c\tau$$

Thus, $\tau = -N\Delta x/(\Delta N \gamma\beta c)$, where N = -(total # of decays) and the other values are as before. This yields a value for the mean lifetime of the K^- of

again, what is it?

$$\tau = (1.45 +/- .12)\times10^{-8} \text{ s}$$

The value in the 1990 Particle Data Booklet (PDB) is 1.237 $\times10^{-8}$ s, which is a bit low to be accounted for by the error bars on the above result from our experiment. [redacted].

↑ your measurement is within two standard deviations from the current value which is not bad.

The data on decays is reproduced here for convenience:

Prongs:	1	3
Events:	146	11

Assuming that all the 3-prong decays are to the tau-mode ($K^- \to \pi^+\pi^-\pi^-$) is valid, since other 3-prong decays are nearly non-existent, according to the PDB. Taking the ratio of 3-prong decays to total decays gives the branching ratio for

$$K^- \to \text{tau mode}/\ K^- \to \text{all} = 7 +/- 2\ \%$$

According to the PDB, this ratio is 5.6%, so our value is perhaps a little high, though the error is large enough to account for it.

There are several factors that can cause the overestimation of the branching ratio and the K^- lifetime. One of these is that in a 1-prong decay to a muon, the decay may escape attention if the 'kink' at the decay point is small enough. Since the kaon has no spin, the distribution of decay product momenta will be isotropic. If the z-axis is oriented along the path of the kaon, θ is the angle the muon's momentum makes with the z-axis in the lab frame, and θ' is the same angle in the rest frame of the kaon, the two will be related by

$$\tan\theta = (\sin\theta')/\gamma(1 + (\beta/\beta_\mu)\cos\theta')$$

where β_μ is the velocity of the muon in the lab frame. For small angles, this reduces approximately to

$$\theta = \theta'/2$$

If we assume a limit of 3 degrees sensitivity in the lab frame, this corresponds to an angle of 6 degrees in the rest frame. The fraction of muons that will go into that angle is the ratio of the solid angle formed by that to 4π, the full spherical angle:

$$2\pi\left(\int_0^6 d\theta' \sin\theta'\right)/4\pi$$

Evaluating the integral gives this to be about .3%, not nearly enough to help with the excess lifetime.

A much bigger factor is scanning inefficiency. It is nighly impossible for one person to see all of the events on the film. If we assume that the film contains a fixed number D of a particular type of event, then a given observer will have some efficiency at finding those events, defined by

$$e_1 = D_1/D$$

If two independent observers with unique e's scan the film, the number of events that both observers find is, on average,

$$D_{12} = e_1 e_2 D$$

So, the efficiency of scanner #1 may be estimated to be

$$e_1 = D_{12} / D_2$$

Their combined efficiency is obtained as follows. The likelihood that either of two scanners find an event is one minus the probability that neither do, $(1 - e_1)(1 - e_2)$. This works out to be

$$e_{12} = e_1 + e_2 - e_1 e_2$$

Since it is difficult to be in the same room using the same equipment and still make completely independent scans, my lab partner and I split up for the last bit of the lab, and made independent scans of 251 frames of film while the other was not present. From this run, the following data are taken (I am scanner 1, my partner is scanner 2.)

	D_{12}	D_1	D_2
Decays:	71	77	75
Inter.:	91	98	92

(insufficient statistics for effs. for particular prongs)

This leads to efficiencies for detecting decays of 92% ±? for my partner and 94.7% ±? for myself, and a combined efficiency of 99.6%.

±?

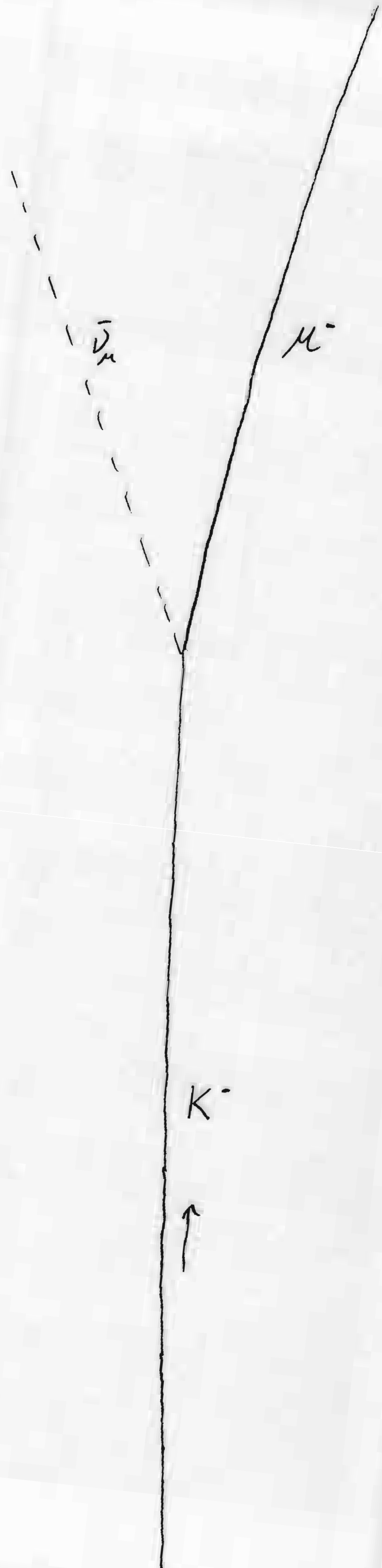
So, between the efficiency and the small-angle missed decays, our decay total should be about .9% higher, reducing the lifetime by a factor of 1.009, to

$$\tau = \left(1.44 +/- .12\right) \times 10^{-8} \text{ s}$$

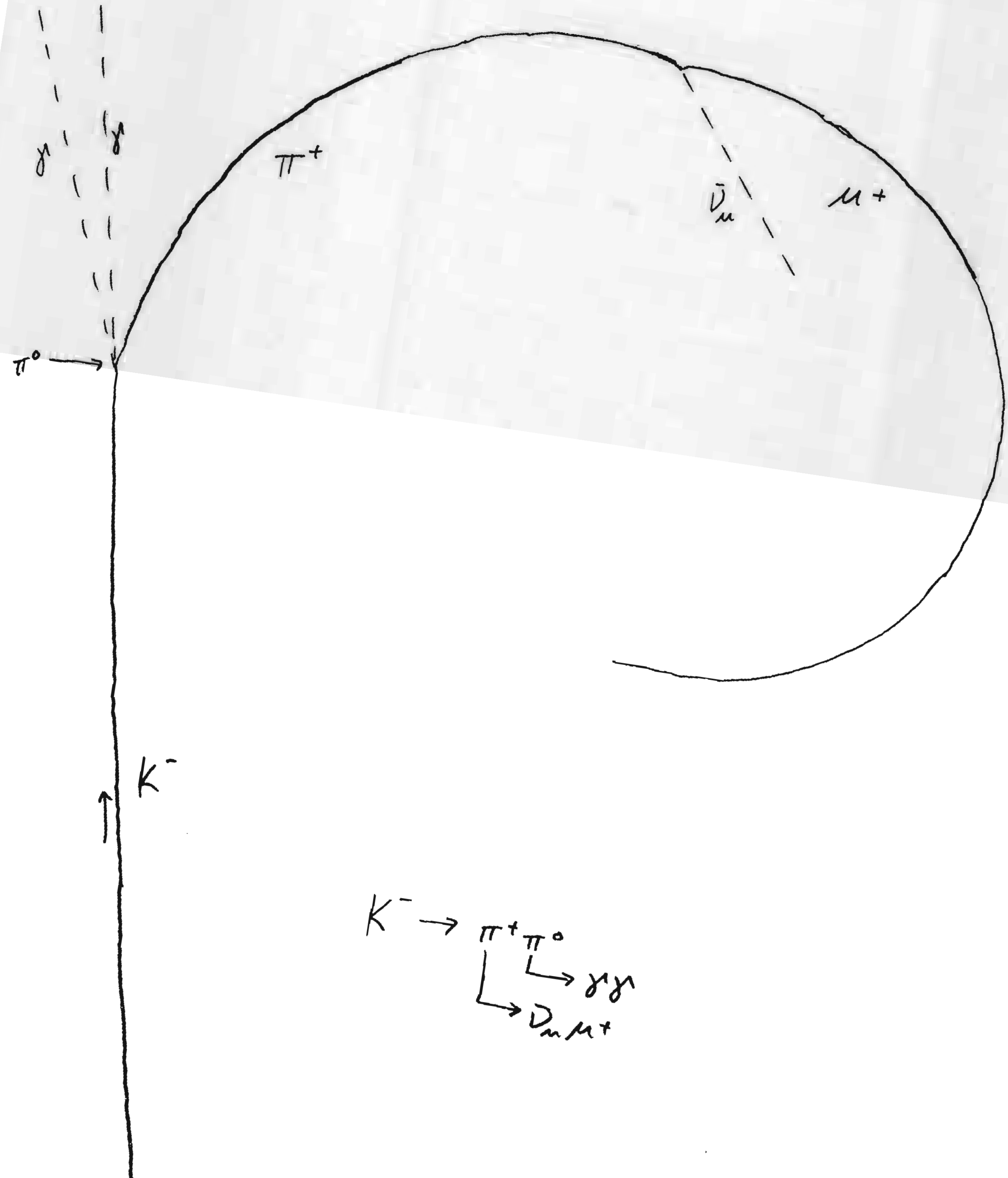
This is still far too high. Perhaps the beam momentum was slightly higher than 1.5 GeV/c, but more likely than that is that our efficiencies were actually lower than we found them to be. This might be because by the time we did the efficiency check, we had practice, and probably adjusted our sensitivity to match the other scanner.

CONCLUSION

It is amazing to me how much good science was done before the age of computerized data acquisition. It is incredible to think of the time and effort that must have gone into getting large enough samples for decent results in those days. Of course, the complexity of experiments seems to rise to the technology's capacity to handle them, and rather than having better data, more work is put in to achieve the same quality data as in days of old. Now, however, a computer has replaced the scanner paid to sit and listen to a rather large film projector 8 hours a day.



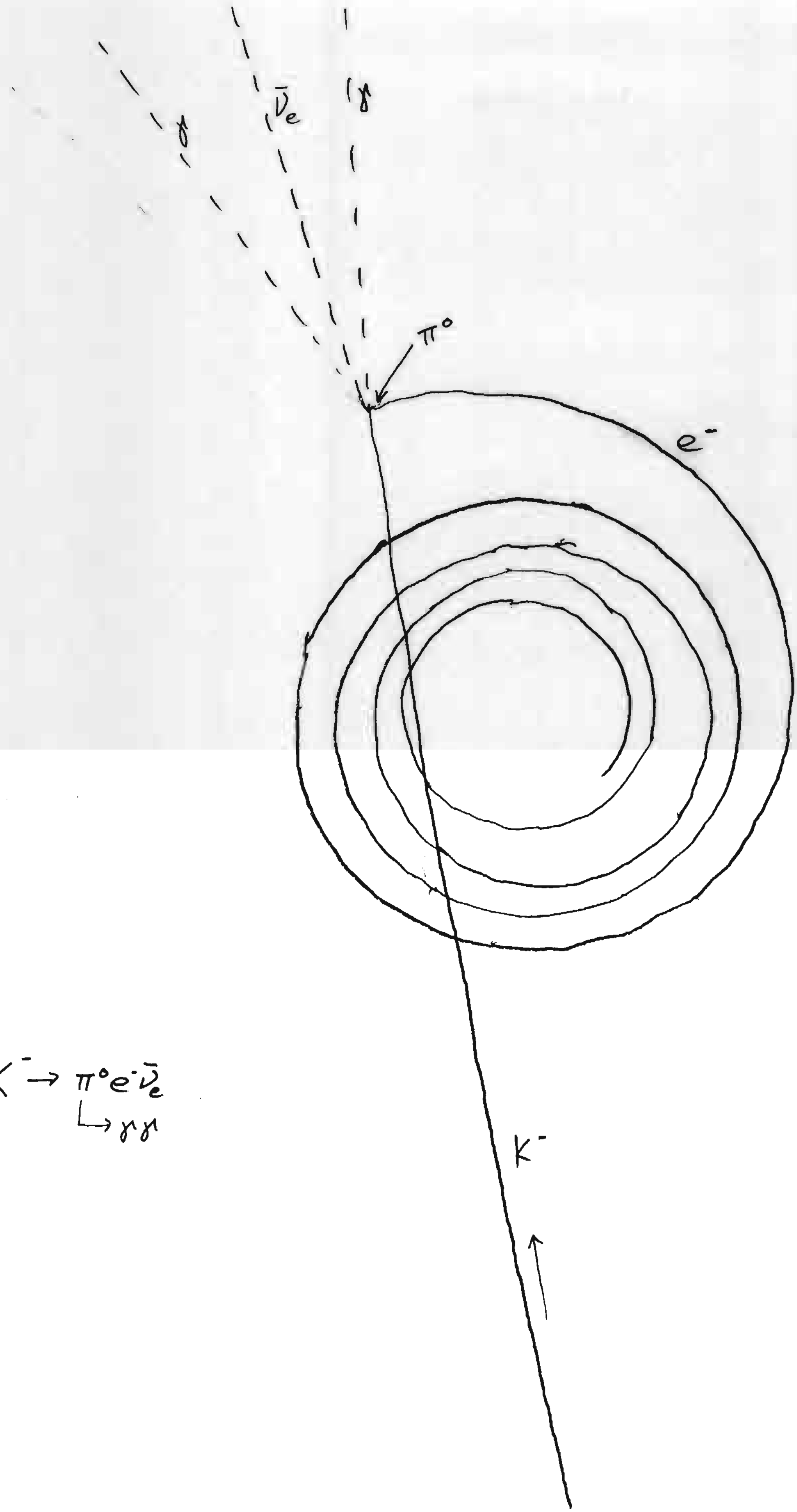
$K^- \rightarrow \mu^- \bar{\nu}_\mu$ or $\pi^- \pi^0$



$$K^- \to \pi^+ \pi^0$$

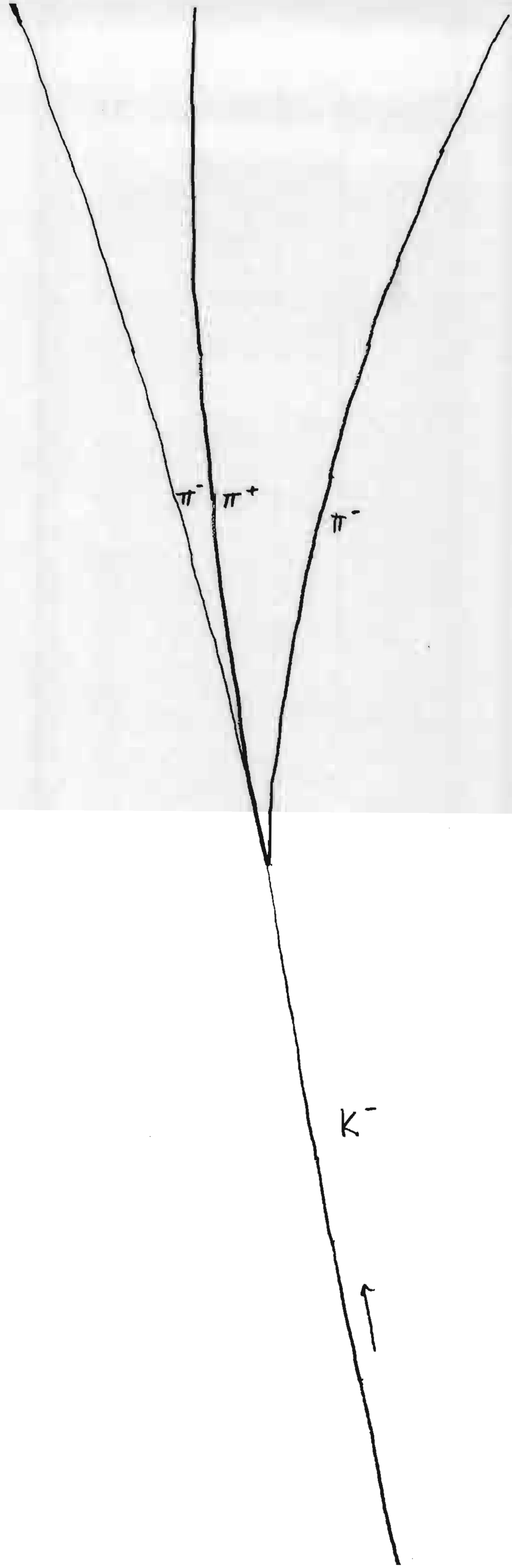
$$\pi^0 \to \gamma\gamma$$

$$\pi^+ \to \nu_\mu \mu^+$$



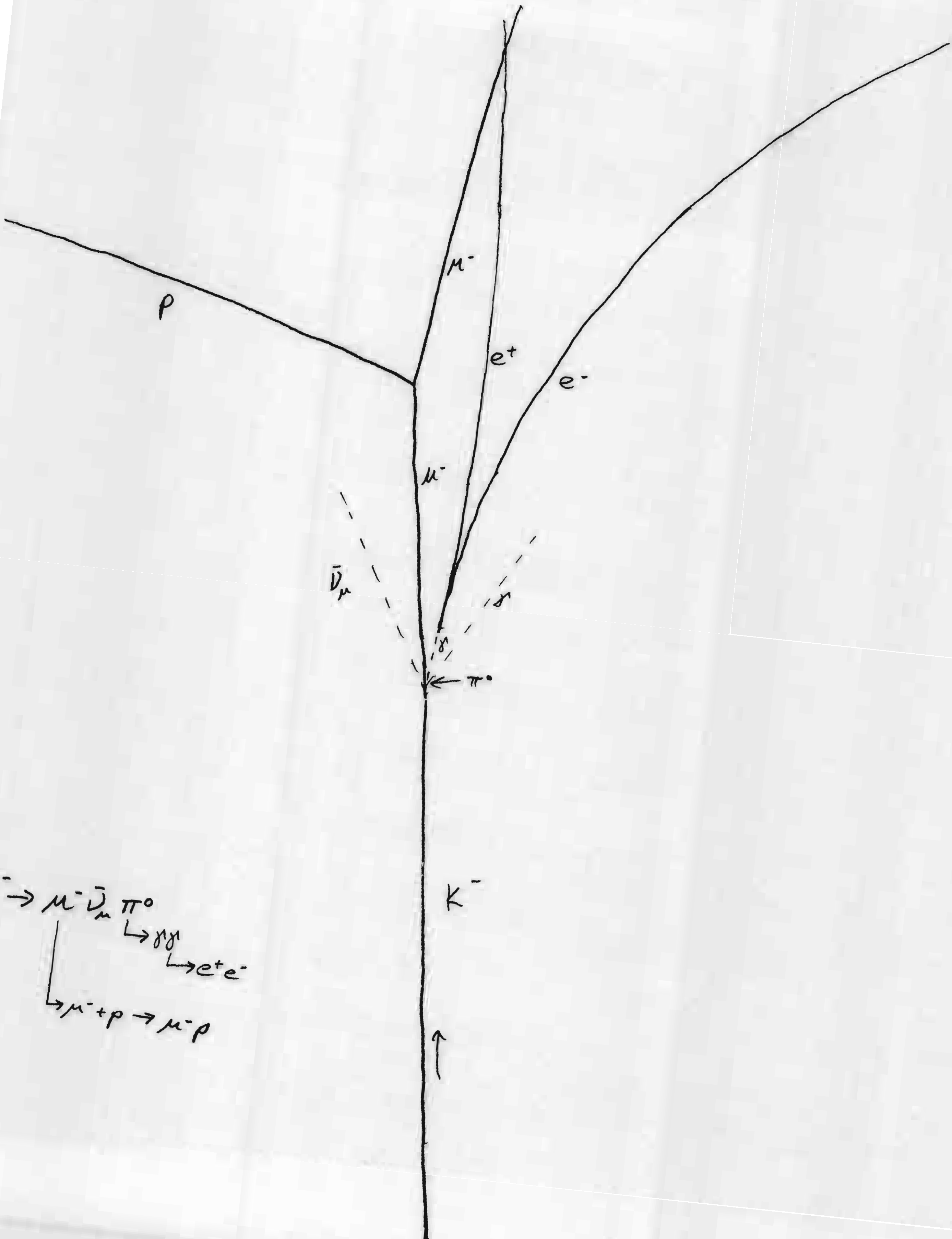
$K^- \to \pi^0 e^- \bar{\nu}_e$
$\quad \hookrightarrow \gamma\gamma$

Roll 5450
Fram 406

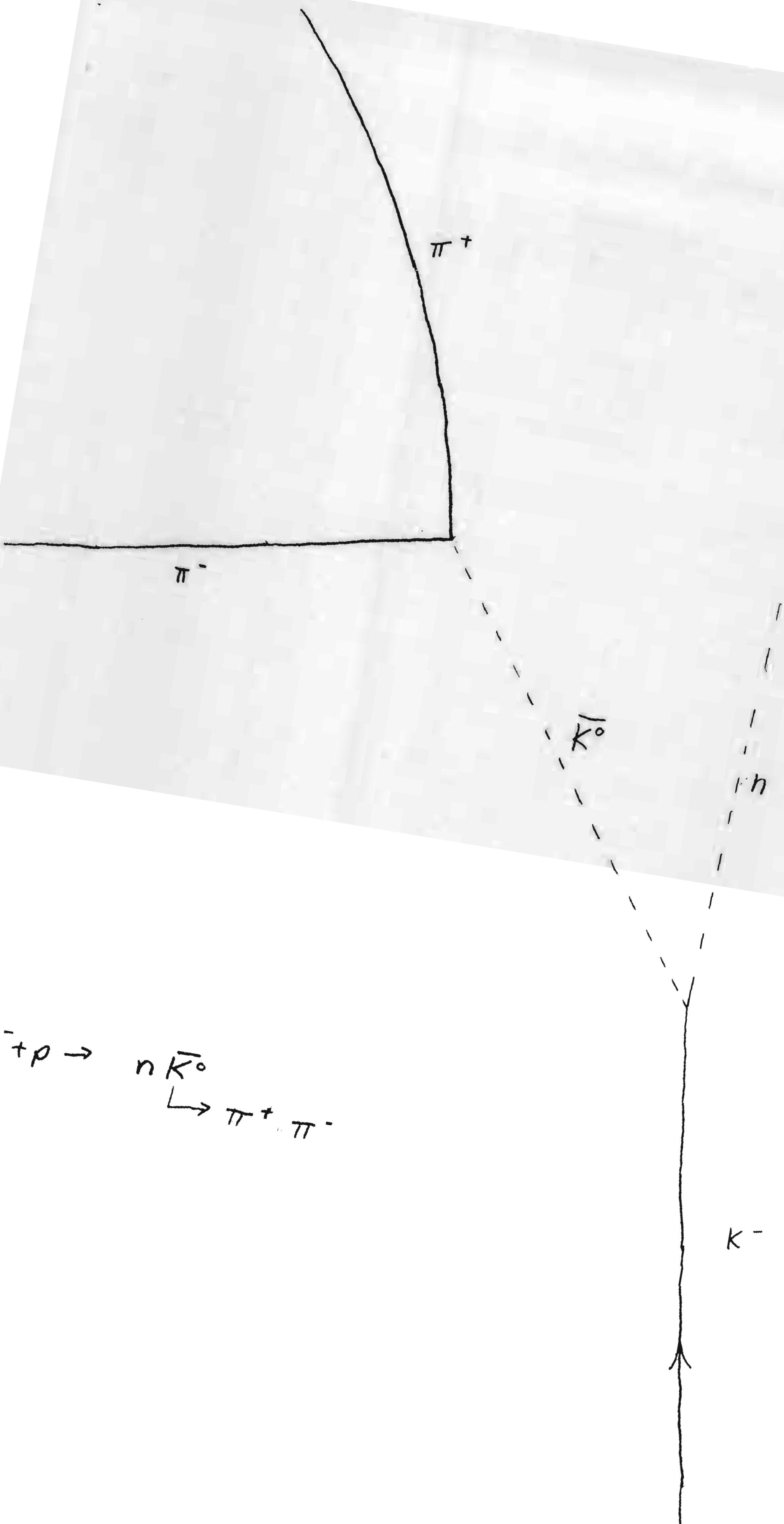


$K^- \to \pi^+\pi^-\pi^-$

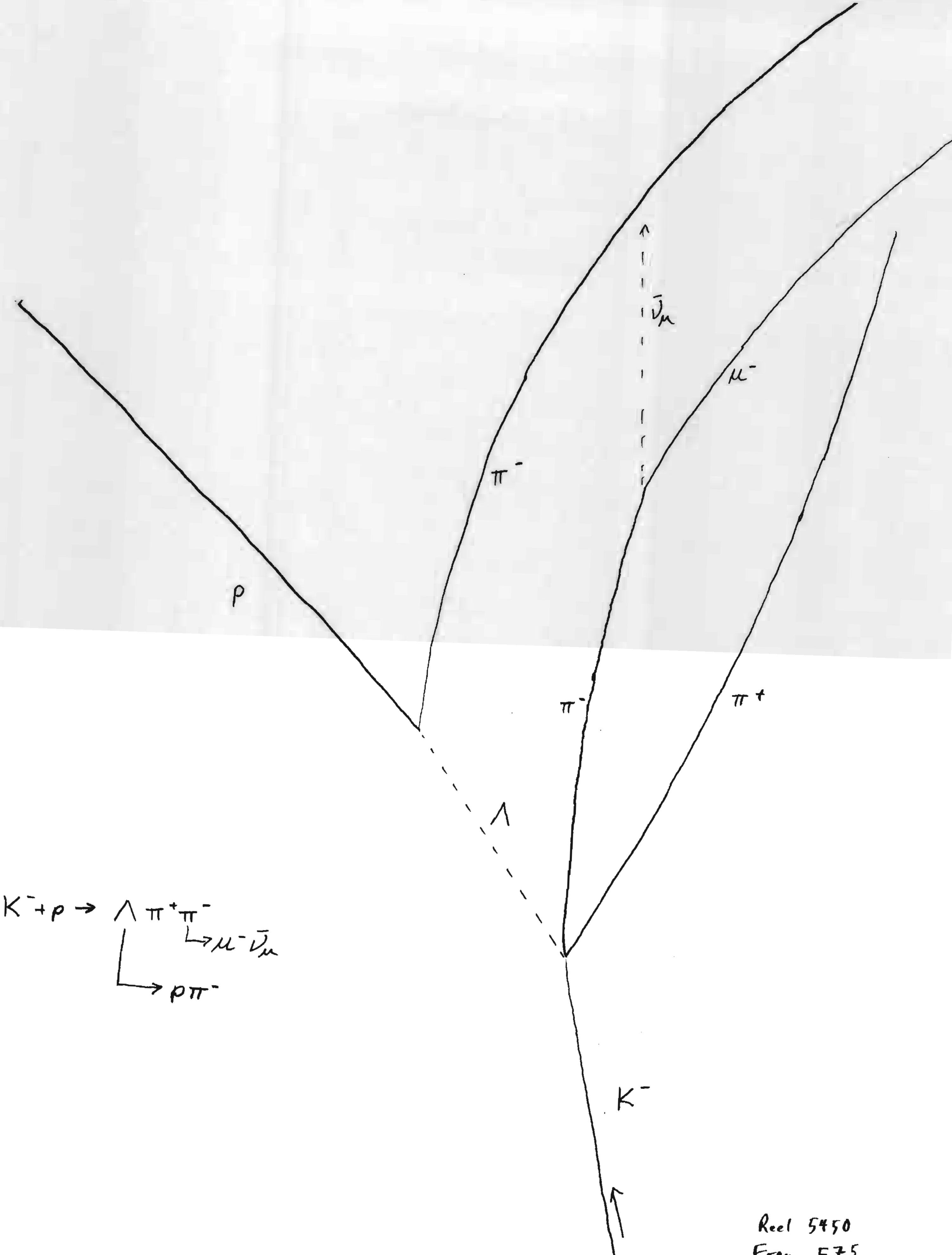
Roll 5450
Fr. 1040



$$K^- \to \mu^- \bar{\nu}_\mu \pi^0$$
$$\pi^0 \to \gamma\gamma$$
$$\gamma \to e^+ e^-$$
$$\mu^- + p \to \mu^- p$$



$$K^- + p \to n\,\bar{K}^0$$
$$\hookrightarrow \pi^+\,\pi^-$$

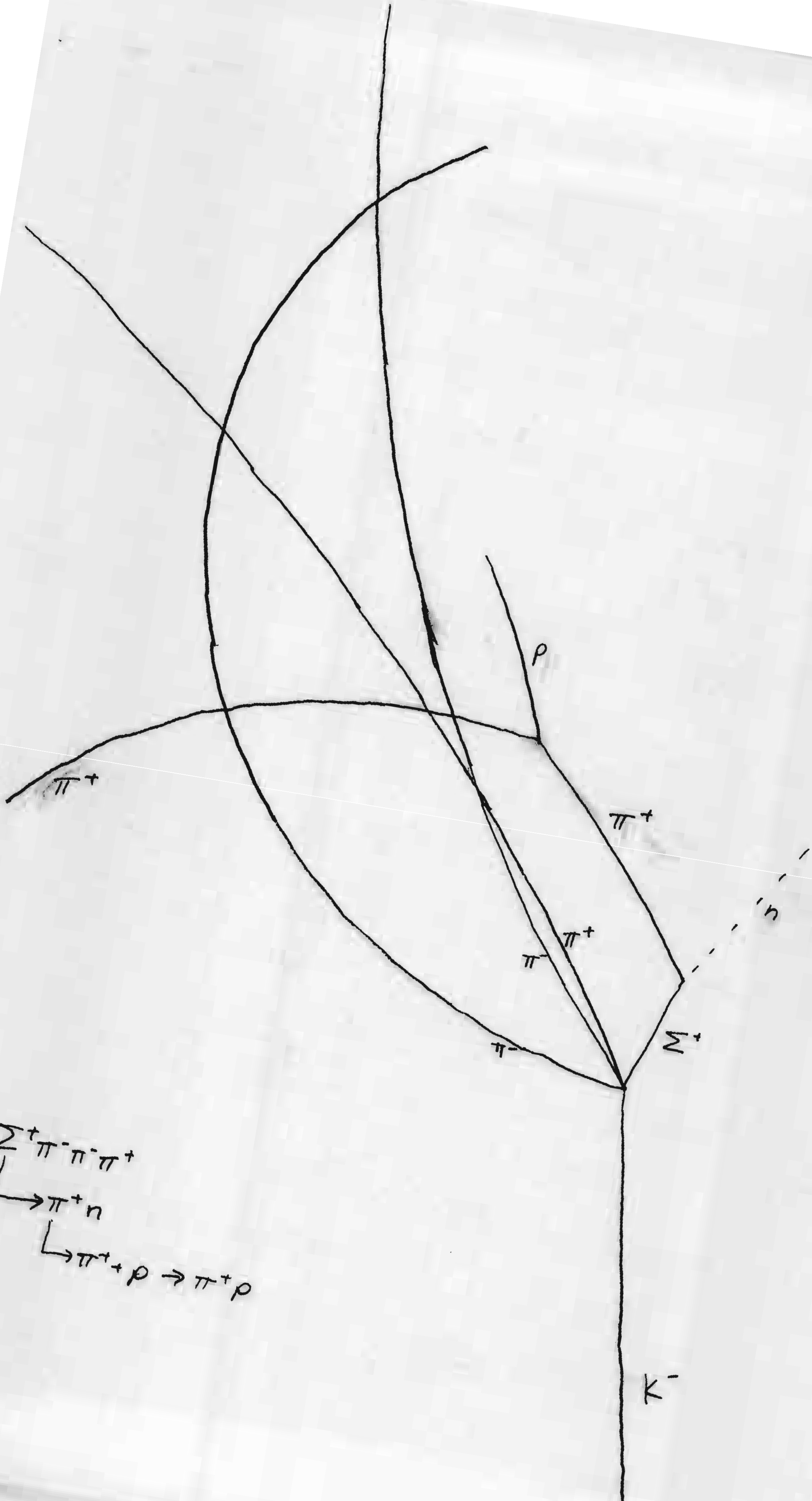


$K^- + p \rightarrow \Lambda \pi^+ \pi^-$

$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

$\Lambda \rightarrow p \pi^-$

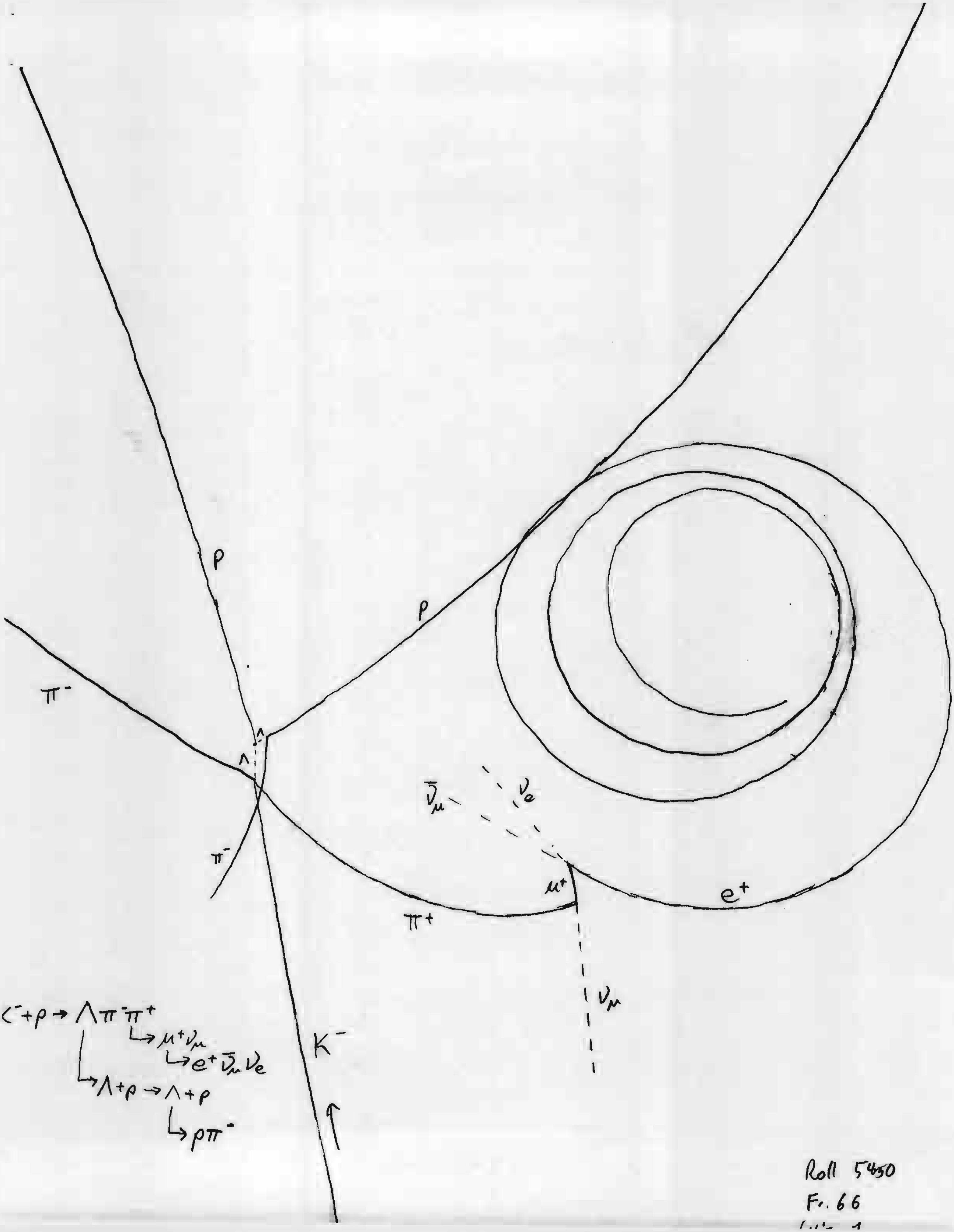
Reel 5450



$K^- \to \Sigma^+\pi^-\pi^-\pi^+$

$\hookrightarrow \pi^+ n$

$\hookrightarrow \pi^+ + p \to \pi^+ p$



$K^- + p \to \Lambda \pi^- \pi^+$

$\quad \hookrightarrow \mu^+ \nu_\mu$

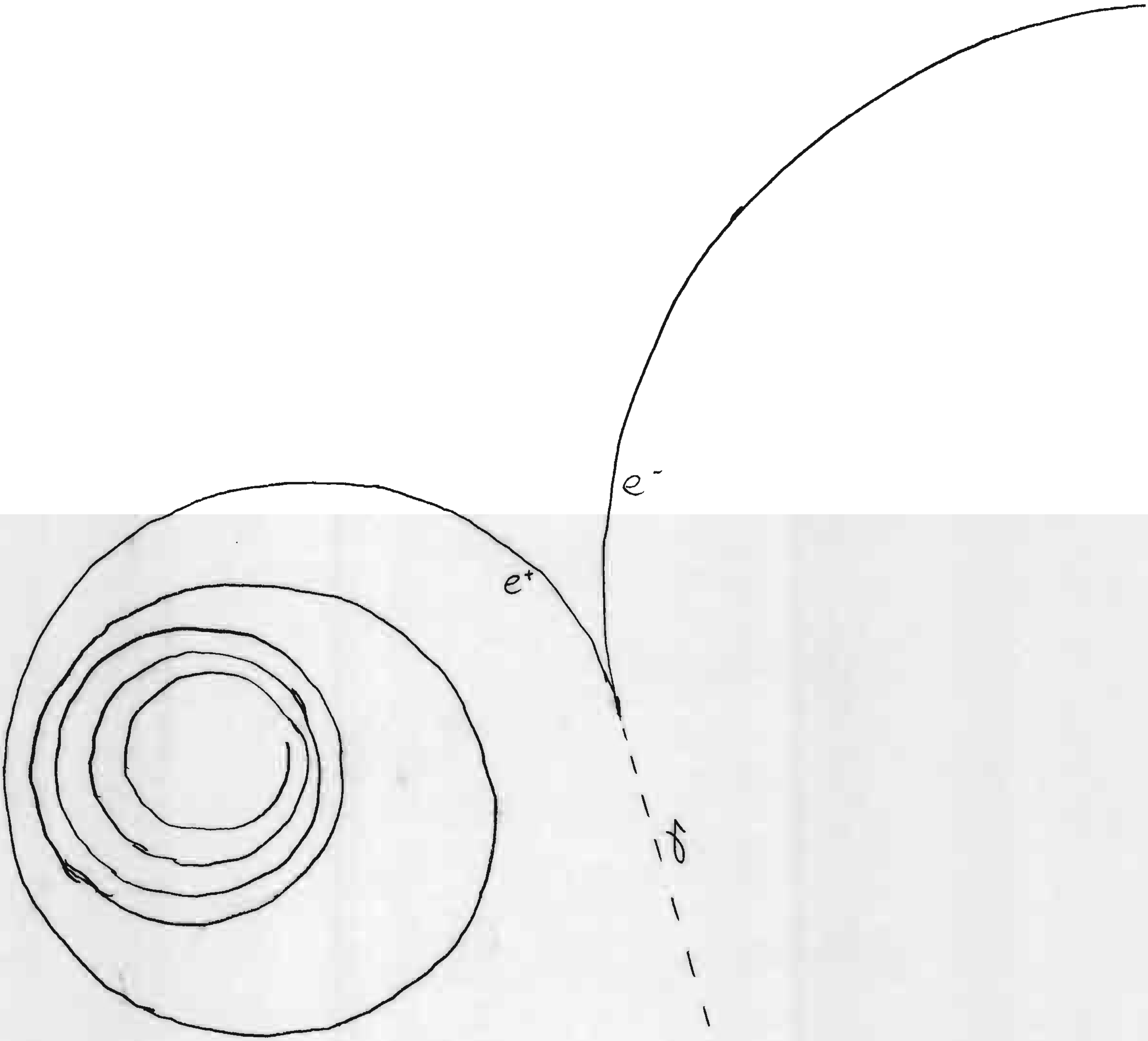
$\quad\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

$\hookrightarrow \Lambda + p \to \Lambda + p$

$\quad \hookrightarrow p \pi^-$

Roll 5450

Fr. 66



$\gamma \rightarrow e^+e^-$

Reel 5450

Frame 528