NAL PROPOSAL No. 254

Scientific Spokesman:

G. R. Kalbfleisch
Physics Department
Brookhaven National Laboratory
Upton, New York 11973

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Proposal to Search for A Second Muon Neutrino, λ_μ

G. R. Kalbfleisch, BNL, E. C. Fowler, Purdue U., and
NAL - Caltech Expt. 21 Neutrino Group

October 1973

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We request a run of about 3×10^{17} protons in the Cal-Tech apparatus and the NAL narrow-band neutrino beam in order to measure the ratio $R = \sigma(\lambda_\mu N)/\sigma(\nu_\mu N)$ of the interaction cross-sections of Kaon neutrinos λ_μ at about 50-70 GeV and pion neutrinos ν_μ at the same energy (requires running at two different charged particle momenta). For a value of R near unity, R will be measured to about $\pm$ 10% at 3×10^{17} protons. Additional running to about a total of 10^{18} protons (accuracy about $\pm$ 5%, and limited by systematics) may be requested later on. Or another measurement at a substantially higher energy and probably requiring 400-GeV machine operation at a later time may additionally be needed. The accuracy will be assured by monitoring the muon flux in the shielding as well as protons on target and the pions and kaons decaying in the vacuum pipe. The additional muon monitoring outlined in the last section of the proposal will be furnished by BNL-Purdue.

Proposal to Search for a Second Muon Neutrino λ_μ

George R. Kalbfleisch
Brookhaven National Laboratory, Upton, New York 11973

Earle C. Fowler
Purdue University, Lafayette, Indiana 47907

and
NAL - Caltech Expt.21 Neutrino Group.

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Introduction

It is experimentally imperative to check whether or not the neutrino from kaon decay $K^+ \to \mu^+\lambda_\mu$ is different from the neutrino from pion decay $\pi^+ \to \mu^+\nu_\mu$, i.e. $\lambda_\mu = \nu_\mu$? This is experimentally necessary in order to analyze properly the various high energy neutrino experiments currently in progress around the world.

It is also theoretically necessary to check whether $\lambda_\mu = \nu_\mu$, in order to construct correctly lepton and/or lepton-hadron symmetry schemes. Various theoretical conjectures and models regarding this question have been made,[1,2] but no experimental search has been made.

The NAL narrow band neutrino beam provides a unique opportunity to explore this question. If $\lambda_\mu \neq \nu_\mu$ then it is probable that the ratio $R = \sigma(\lambda_\mu N)/\sigma(\nu_\mu N)$ of the interaction cross-sections of the "neutrinos" with nucleons, at the same energy E, differs from unity.

Theoretical Possibilities

The current experimental and theoretical assumption that $\lambda_\mu = \nu_\mu$ requires R = 1. If $\lambda_\mu \neq \nu_\mu$ and if the neutrinos λ_μ and ν_μ respect hypercharge conservation, then $R = \tan^2\theta_{Cabibbo}$ is possible.[1] Any difference between the neutrinos ν_μ and λ_μ presumably is connected with hypercharge (or strangeness).

However, in general other values of R might be expected. This is due to the possibility of mixing[3] (or due to the neutrinos ν_μ and λ_μ being different mixed states of ν_μ^* and λ_μ^*, where ν_μ^* and λ_μ^* have different strangeness).

Even if the production or decay processes yielding neutrinos respect hypercharge conservation, the physical neutrino states observed at some distance (or later time) from their point of origin may be mixed. According to Feinberg,[3] a complete mixture, similar to $(K^o,\bar{K}^o)$ into (K_S,K_L) should occur through the hypercharge violating interaction (nonleptonic weak decay) if the masses of all the neutrinos are identically zero. This depends on whether or not the neutrinos couple to this interaction. If the masses are not equal (say $m_{\nu_\mu} \simeq 0$, $m_{\lambda_\mu} \neq 0$) then the mixing depends on G_{weak} and the mass difference. Let us call λ' and ν' the physical (mixed) states and x a mixing parameter, where $0 \leq x \leq 1$. Then

$$\nu_\mu' = \nu_\mu(1-x^2)^{1/2} + \lambda_\nu x$$

$$\lambda_\mu' = -\nu_\mu x + \lambda_\mu(1-x^2)^{1/2}$$

where $\lambda' = \lambda$, $\nu' = \nu$ for x = 0. Assuming

$$\sigma(\lambda_\mu N) = \sigma_\lambda(E) \text{ and } \sigma(\nu_\mu N) = \sigma_\nu(E)$$

where E is the laboratory neutrino energy, the observable cross sections will be

$$\sigma(\nu'N) = (1-x^2)\sigma_\nu + x^2\sigma_\lambda$$

$$\sigma(\lambda'N) = x^2\sigma_\nu + (1-x^2)\sigma_\lambda$$

For $x = 0$, $R = (\sigma_\lambda/\sigma_\nu)$ and for $x = (1/2)^{1/2}$, $R = 1$ (Feinberg's expectation for massless neutrinos).

For the case in which λ_μ, ν_μ respect hypercharge conservation in production and/or decay processes, we would probably have

$$\sigma(\lambda_\mu N) = \sigma_o \sin^2\theta_C \text{ and } \sigma(\nu_\mu N) = \sigma_o \cos^2\theta_C$$

where $\sigma_o = \sigma_o(E)$ and θ_C = the Cabibbo angle. This gives

$$\sigma(\nu'N) = (1-x^2)\sigma_o\cos^2\theta_C + x^2\sigma_o\sin^2\theta_C$$

$$\sigma(\lambda'N) = x^2\sigma_o\cos^2\theta_C + (1-x^2)\sigma_o\sin^2\theta_C.$$

Now for $x = 0$, $R = \tan^2\theta_C$,[1] while for $x = (1/2)^{1/2}$, $R = 1$ again.

In general, the parameter x, for neutrinos possessing mass, will depend on the time (or distance) difference from emission to absorption. According to Pontecorvo,[4] the "oscillation length" L will be $L \sim E/m\mu$ where m is the mass (or mass difference) of the neutrinos and $1/\mu$ is a length scale ($\mu \lesssim m$ for example). The antineutrino experiments of Reines[5] rule out the possibility of $(m,\mu)_{\nu_e}$ being more than a few electron volts.[4] If all "neutrinos" are stable, then their masses on the average must be less than 4 to 8 ev.[6] Thus $L > E/m^2$ yields $L > 1000$ meters for 100-GeV/c neutrinos with $m < 4$ ev. Therefore $x \sim 0$ for distances $\ell \ll L$ and $x \sim (1/2)^{1/2}$ for $\ell \sim L$.

Since the target-detector distance $\ell_{Expt} < L$ for the experiment proposed here, we expect that $R \neq 1$ unless $\lambda = \nu$ or unless complete mixing à la Feinberg occurs because all neutrinos are massless. We note that similar remarks apply to the electron neutrinos ν_e and λ_e. Also, observation of any energy dependence $R = R(E)$ can be used to infer the value of the mass or mass difference of the neutrinos.

Current Experimental Data and the Value of R.

Under the assumption that $\lambda_\mu \neq \nu_\mu$, we can estimate the value of R from the cross-section measurements of the current CERN Gargamelle neutrino experiment.[7] Under the conditions of that experiment, the flux of neutrinos below 4 GeV/c is due almost entirely to pion decay, i.e. ν_μ. Above 6 GeV/c, λ_μ neutrinos dominate. The region between 4 and 6 GeV/c has comparable numbers of ν_μ and λ_μ. Under the assumption that σ_λ and σ_ν are not different by an order of magnitude or more, we can ascribe the events observed in Gargamelle below 4 GeV/c to $\nu_\mu N$ interactions and those above 6 GeV/c to $\lambda_\mu N$ interactions. Using the additional assumption that the (inelastic) cross-sections are approximately linearly rising with energy

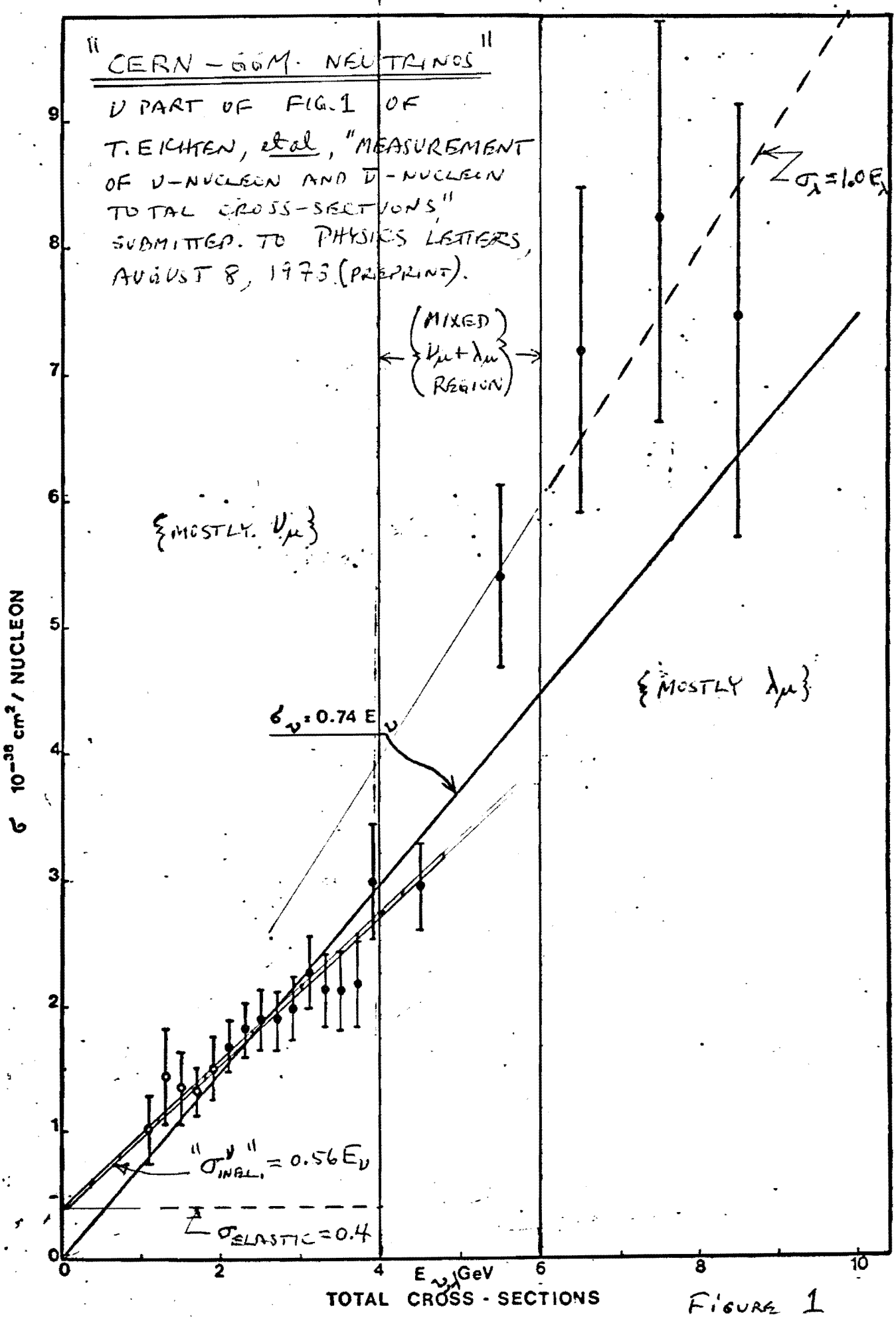
$$\sigma_\nu = \alpha_\nu E_\nu \quad \text{and} \quad \sigma_\lambda = \alpha_\lambda E_\lambda$$

then we can estimate $\alpha_\nu, \alpha_\lambda$ for the CERN neutrino data, shown in Fig. 1.[7] We find

$$\sigma_\nu = (\sigma_{elastic} = 0.4) + (0.56 \pm .05)\ E_\nu$$

$$\text{and} \quad \sigma_\lambda = (1.0 \pm 0.15)\ E_\lambda$$

in units of 10^{-38} cm^2 for E in GeV. Therefore the ratio, R, of the (inelastic)



TOTAL CROSS - SECTIONS

FIGURE 1

cross-sections is

$$R = \alpha_\lambda/\alpha_\nu = 1.7 \pm 0.3.$$

[If one fits a (poor) straight line $\sigma_\nu = \alpha'_\nu E_\nu$ to the data below 4 GeV/c, then $R' = \alpha_\lambda/\alpha'_\nu = 1.4 \pm 0.25$.] The ratio of antineutrino / neutrino cross-sections and the behavior of the average neutrino-to-muon momentum transfer squared versus energy can also be examined for ν_μ and λ_μ. We will not give these here. Obviously the behavior of the ν_μ, λ_μ samples can be very different due to the small statistics of the λ_μ sample, and to systematic errors in the experiment, as well as to the assumptions made above. We see that there is no evidence supporting the usual hypothesis that $\lambda_\mu = \nu_\mu$.

The current NAL neutrino experiments can also be examined. We will not discuss these here, except to note that the small statistics so far presented from experiment 21 and the preliminary nature of the total cross-section data of experiment 1 also do not give any significant evidence regarding this question.

Other Possible Experiments to Determine Whether $\lambda_\mu \neq \nu_\mu$.

It is probable that the reactions $\lambda_\mu N$ and $\nu_\mu N$ "conserve" hypercharge to differing degrees, from complete conservation to maximal violation. For complete conservation, $\lambda_\mu N$ interactions will yield muons in association with a strange hadron-baryon system only.[1]

The ratio of "strange" to nonstrange final states, as a function of energy, which will be done in the near future with the CERN Gargamelle data, will tell us a little about this situation. For E > 6 GeV, the neutrino

spectrum arises mostly from kaon decay. The statistics will be limited ($\sim$ 300 events). These events are reasonably complicated due to their high energy, so that the "strangeness" may be indeterminate.

The Columbia spark chamber neutrino experiment[8] can only say, if $\sigma(\lambda_\mu N) = \sigma(\nu_\mu N)$, that (mixed) $\lambda_\mu' N$ does not always produce strange final states.

Also data on the elastic cross-sections for $\lambda_\mu' N$ might yield useful information.

Outline of the Method of this Proposal

The method of this proposal is to produce a beam of ν_μ at some appropriate energy E_1 from a momentum analyzed pion beam and observe their interactions. Then a beam of λ_μ at the same energy E_1 from a kaon beam of lower momentum is used. Then the ratio R can be determined from the following three ingredients.

(1) The event yields from $\nu_\mu N$ and $\lambda_\mu N$ interactions,

(2) the relative π and K yields measured relative to protons on target and monitored by various counters looking at the charged particle beams,

and (3) the relative acceptance of the neutrinos in the apparatus due to the different decay kinematics of pions and kaons (to be calculated via a "Monte Carlo" of the setup).

This gives a "zero-constraint" calculation to determine R. The <u>observation</u> of

(4) the muon flux in the shielding

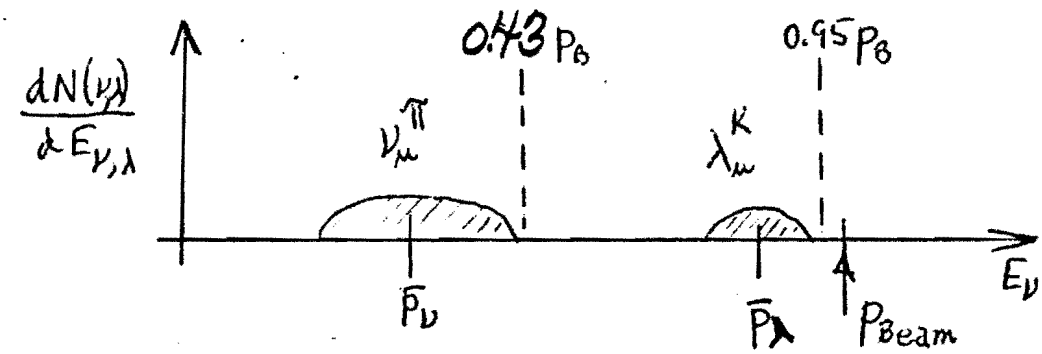
will allow a "constrained" calculation, since the muon fluxes can also be predicted from (2) and (3) above. Muon monitoring using counters in the enclosures in the shielding will ensure correct results. We anticipate some early low intensity running in order to check this "constrained-relationships" between items (2) and (4) above.

The use of the narrow-band "dichromatic" beam will result in several accurate total cross-section measurements in addition. The run for ν_μ at energy E_1 will yield λ_μ at a higher energy E_2, and the run for λ_μ at E_1 will yield ν_μ at a lower energy E_o.

The Experiment

The "neutrino" spectrum from a narrow-band "dichromatic" beam is schematically (e.g. experiment ν21)

Fig. 2 - "NARROW BAND BEAM"



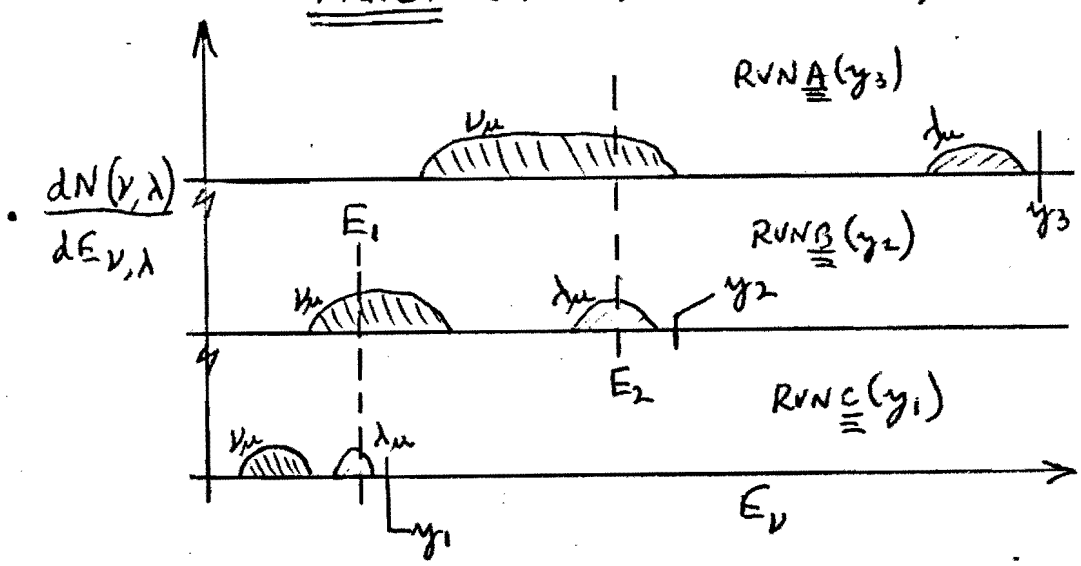
where the widths of the peaks $\Delta p_{\nu,\lambda}$ depend on the forward angular acceptance $\delta\theta$, on the $\Delta p/p$ bite of the beam and on the value of p_{Beam}. The $\Delta p/p$ of the beam is about $\pm 11\%$. The angular acceptance $\delta\theta$ is $\pm$ 0.6 mr on the average; it is fixed by the sizes of the detector and the hadron beam. The angular acceptance increases with the momentum p_B of the beam. About half of the pion decay's solid angle is accepted; the acceptance changes slowly with p_B (like $p_B^{1/2}$ approximately). Thus for the ν_μ^π flux, a large momentum bite Δp_ν is accepted. For the λ_μ^K flux, the decay solid angle covered corresponds to a Δp width $\propto p^2\theta^2$ which is narrow compared to the momentum spread Δp_B. Thus Δp_ν is mainly determined by the decay kinematics and Δp_λ by the charged

particle beam momentum spread. Δp_ν can be made smaller by imposing a smaller forward angle cut on the events accepted by the detector (i.e. using those ν_μ events occurring near the axis of the beam through the detector).

In order to measure the ratio R, we need to run at at least two beam momenta, overlapping the λ_μ spectrum from one run with the ν_μ spectrum of the other. Since the ratio R may in general be energy-dependent, we would prefer to measure R at two energies. Initially, however, we propose to make the measurement at only one energy, probably at 50-70 GeV.

In order to measure R at two energies, runs at at least three charged particle beam momenta must be made. For experiment ν21, $\bar{p}_\nu \sim 50$ GeV/c and $\bar{p}_\lambda \sim 145$ GeV/c for $p_B = 160$ GeV/c. At lower momenta, $\bar{p}_\nu$ will be a larger fraction of $\bar{p}_\lambda$, say 0.4. We define $y = p_B/E_p$, where E_p = energy at which the NAL accelerator is operating. Let us consider running at three momenta $y_1 = 0.4y_2$, $y_2 = 0.5y_3$, and $y_3 \leq 0.7$, where $y_3E_p < 300$ GeV/c, i.e.

FIG. 3 (E_1, E_2) OVERLAP OF λ, ν



We will measure $R(E_1)$ and $R(E_2)$. This will be accomplished by measuring the pion yield per proton at y_3 and y_2 and the kaon yield/proton at y_2 and y_1 respectively (counters, Cerenkov, etc.). The acceptance due to decay kinematics averaged over the angle and momentum spectra at the apparatus will be calculated. Several hundred hours of running will give the event rates for one measurement of R at energy E_1. In addition, muon monitoring measurements in some enclosure(s) in the shielding will be made (see below) in order to check the correctness of the result.

Estimate of Data Rate and Running Time Required

Figure 4 gives data from which relative event rates can be estimated until the actual π,K fluxes are measured. We note that Barish, et al.,[9] obtained 112 analyzable events at p_B = 160 GeV/c in a run of $\sim 3 \times 10^{16}$ protons. The new trainload for this beam (June 1973) gives a factor of three larger event rate. Thus some 3000 events can be obtained at a momentum $y \simeq 0.5$ for about 3×10^{17} protons. Choosing p_B = 280 GeV/c ($y = 0.7$ at E_p = 400 GeV) and 130 and 150 GeV/c ($y = 0.4$ and 0.17 respectively at E_p = 300 GeV), we obtain the following table (Table I) of relative yields.

For the initial measurement of R at energy E_1, the 0.4 π^+ and 0.17 K^+ entries in Table I are relevant. Also in order to reduce systematic effects due to the variation of the νN (and λN) cross-sections with energy over the rather wide energy bands of the experiment, a smaller angular cut (as indicated above) will be made on the ν_μ data (from 0.4 π^+). This will reduce the ν_μ events by about a factor of two relative to the λ_μ events, but will more closely match the widths of the λ_μ and ν_μ energy bands.

Fig. 4 Possible π^+ and K^+ spectra vs. y. These figures are from F.A. Nezrick, "Empirical Pion and Kaon Fluxes from 200-GeV Proton Interactions," NAL 1969 Summer Study, Vol. I, p. 403. (N.B. $y = E_i/E_{machine}$; see text.)

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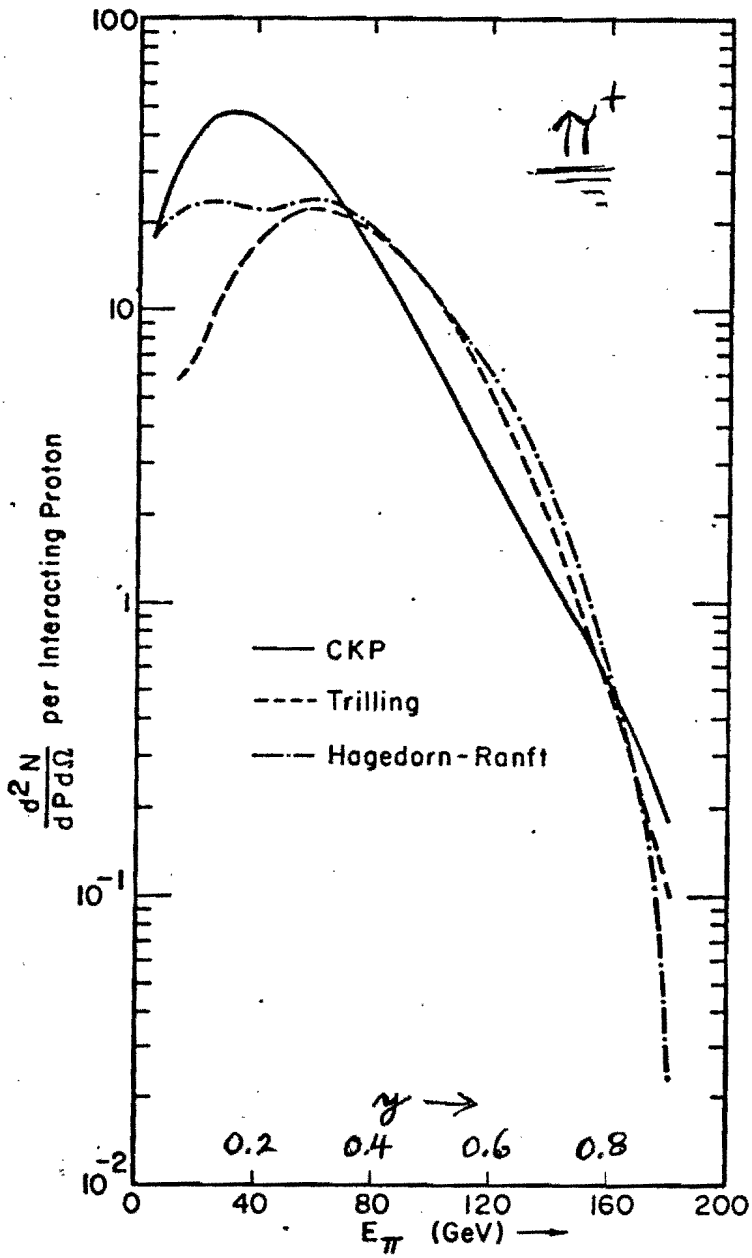
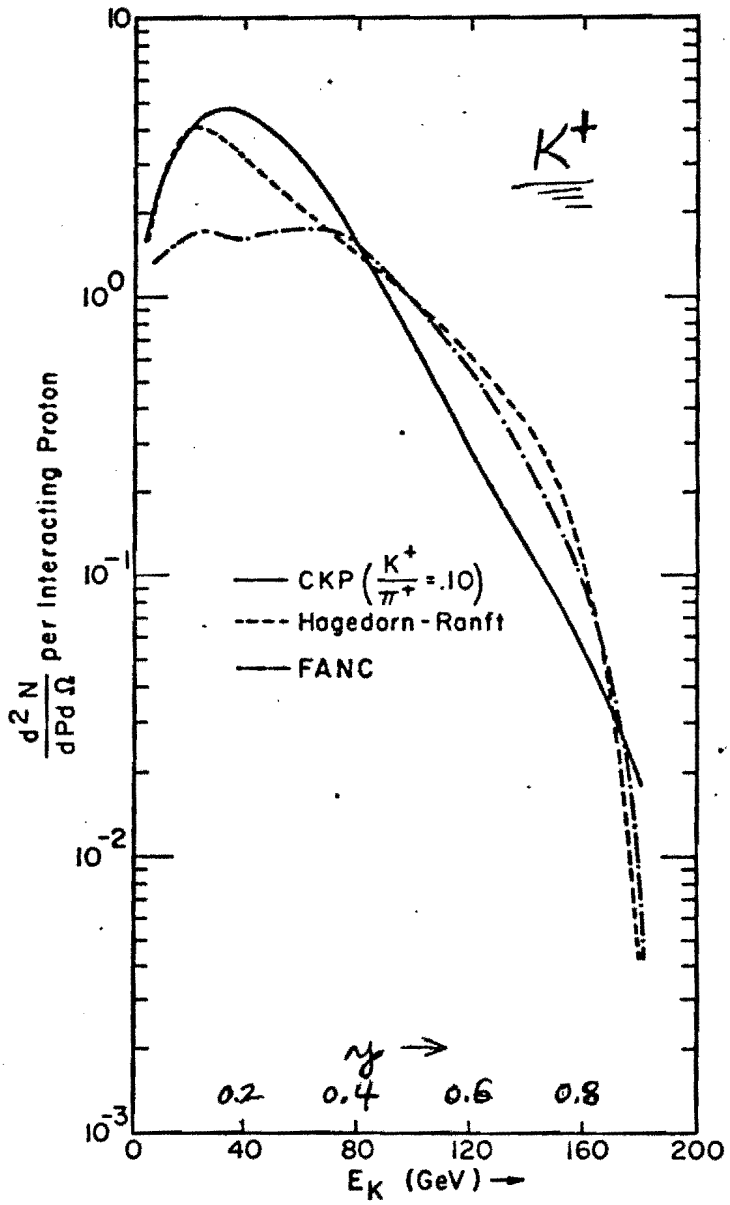


Forward π^+ spectra for 200-GeV proton interactions.

SS-1



Forward K^+ spectra for 200-GeV proton interactions.

Table 1

Relative Event Rates Assuming R = 1 (or $\lambda_\mu = \nu_\mu$) for Current Beam

				Event Rates[a]		
y	π^+ flux	K^+ flux	$\Delta\Omega\Delta p$	σ=const.	$\sigma \propto E$	$\sigma \propto E^2$
0.7 π^+ (400-GeV protons)	1-2	-	3.	1-4	3-8	6-16
0.4 K^+ (300 GeV)	-	1.4	1[b]	1[b]	1[b]	1[b]
0.4 π^+ (300 GeV)	15-20	-	1[b]	5 ± 2[c]	5 ± 2[c]	5 ± 2[c]
0.17 K^+ (300 GeV)	-	2-5	0.1	.3-.7	.2-.4[d]	.1-.2

a. For $\sigma \propto E$, the increase of the cross section with energy approximately cancels the lower decay rate of the π,K beam.

b. Reference point.

c. The observed event ratio ($94\ \nu_\mu^{\pi}/18\ \lambda_\mu^{K}$ - Barish 1973); an estimate of (1-10) to 1 can be made for this ratio in absence of actual flux measurements.

d. Figure 8 of expt. ν21's proposal predicts $\sim$ 0.3.

A measurement of the ratio R to a precision of $\sim \pm 5\%$ (including systematics) for a value of R of the order of one (i.e. $\delta R = \pm .05$) requires $\geq 600\ \lambda_\mu N$ events. From Table I, for the probable situation $\sigma \propto E$, the λ_μ event rate at $y_{K+} = 0.17$ (300 GeV) is about 1/20th of the ν_μ event rate of 3000 events per 3×10^{17} protons at $y_{\pi+} = 0.4$, where experiment ν21 has generally run. A run of $\sim 10^{18}$ protons would be required to achieve this accuracy. This would take about 2 months of accelerator time at 10^{12} protons per pulse; operation at 2×10^{12} protons per pulse would be desirable. Since this number of protons is large compared to current runs, we request initially $\sim 3 \times 10^{17}$ protons for a $\leq 10\%$ measurement.

Estimate of Error δR on R

Assuming R = 1 and $\sigma \propto E$, we can estimate δR as follows. The statistical error on R is a straightforward propagation of $(N)^{1/2}$ errors. The systematic errors on the π/proton monitor and K/proton monitor will be determined from the flux measurements and will be assumed to be $\lesssim 5\%$. In addition, the variation with energy $E_{\nu,\lambda}$ of the cross-section, averaged over the energy bands of the data, will lead to a systematic uncertainty. Assuming the average energy over the energy band of each data sample can be estimated to about one-tenth of the energy bite, an uncertainty of about 3% will result.

For a sample of $\sim 600\ \lambda_\mu$ events and a somewhat larger ν_μ sample, the statistical accuracy will be about $\lesssim 4\%$. For a value of R near unity, the error δR will be $\sim \pm .05$ [i.e. $((<.05)^2 + (.03)^2 + (.04)^2)^{1/2}$]. A value of R of, say, 1.06 ± 0.05 would not prove the identity of λ_μ and ν_μ. However, such a value would allow the use of the assumption $\lambda_\mu = \nu_\mu$ as a practical one in the analysis of neutrino data. Obviously, values of R = 1.7 or 1.4 illustrated by the CERN Gargamelle data above would be clearly distinguished from unity.

Muon Monitoring

It should be possible to monitor the muons from the decay region immediately after the hadron beam stops in enclosure 100. The current hadron absorber of five feet of steel is adequate to attenuate the narrow-band hadron feedthrough below the muon level since the proton beam is dumped on the train 400 meters upstream. (For wide-band operation, the protons are dumped in or near this hadron plug and the "hadron feedthrough" exceeds the muon flux by a large factor.) However, backscattering, etc., of hadrons leaking around the hadron plug (and through the beam holes in it) and the muons produced in the plug will be troublesome. The hadron plug is to be increased soon to ten feet of steel (about October 1973). This will reduce the leakage problem and the plug produced muons considerably.

By using small size counters, probably telescoped pairwise and in coincidence, and shielded from low energy neutrons and gammas, we should be able to monitor the muons at this point. This position at the end of the hadron shield is ideal, since the effects of the muon beam and of inhomogeneities in the subsequent shielding are avoided and because at this position the kaonic muons extend radially beyond the pionic muons (negligible multiple scattering due to the shielding).

The hadron beam size (FWHM) at the plug is about one foot horizontally by one-half foot vertically ($\Delta p/p \simeq \pm 15\%$). The pionic muons will be confined largely inside this area, whereas a large fraction of the kaonic muons will be outside it. No "Monte Carlo" has been performed yet of this situation, but the distribution of muons radially should roughly be as shown in Fig. 5 for 70-GeV/c π^+ and K^+ decays (about the momentum for the λ_μ running).

Thus, up to four pairs of approximately 3 cm x 3 cm counters, numbered 1-4 in Fig. 6, near the corners of the 38" x 38" hadron plug, and four pairs of

FIG 5 μ RADIAL INTENSITY AFTER HADRON PLUG, (10^1 Fe)
(ENCLOSURE 100)

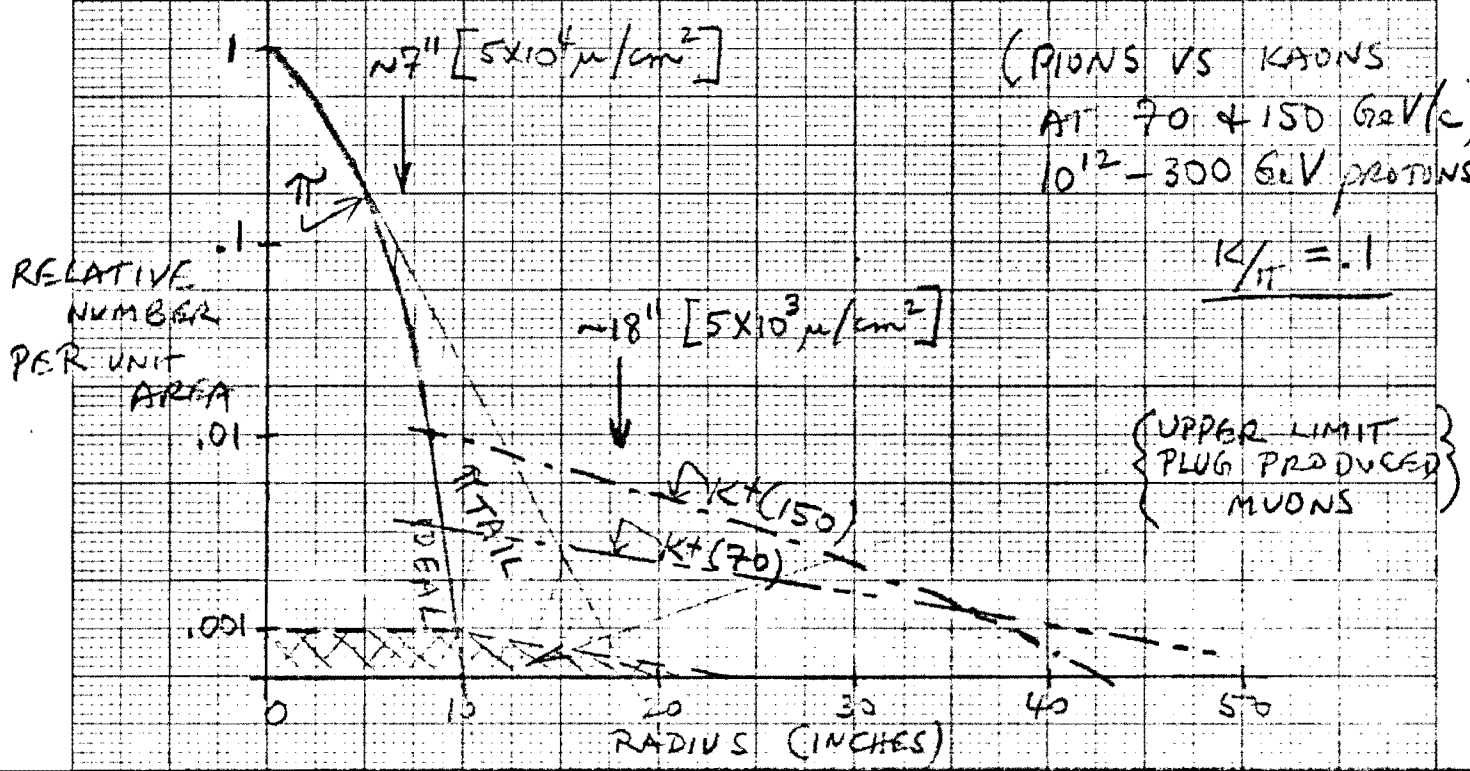
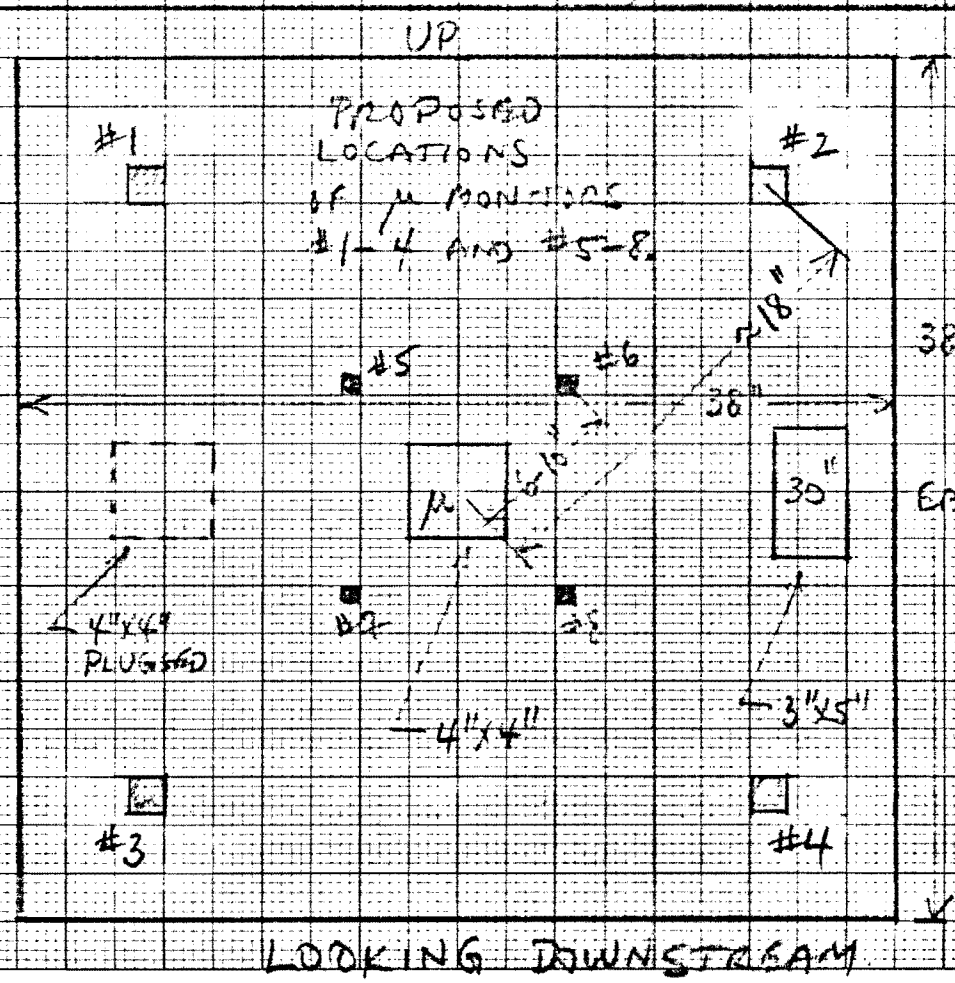


FIG. 6 38" x 38" HADRON PLUG.



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approximately 1 cm x 1 cm counters, 5-8, around the muon beam hole makes a reasonable arrangement. The outer pairs monitor kaonic muons and the inner ones monitor all muons. The sizes of the counters will be chosen such that the intensity will be $\lesssim 10^5$ muons each; for a useful spill as short as 0.1 second, the rate will not exceed 1 Megahertz, keeping accidentals, etc., to a low level ($\leq$ few percent). The counters will monitor the muons as well as the steering and targeting of the"neutrino" beam. These counters will be furnished by BNL-Purdue.

REFERENCES AND FOOTNOTES

1. G.R. Kalbfleisch and E.C. Fowler, "Color the Quark 'Muon'," BNL Preprint 17914 (NG-259), June 11, 1973, and S.P. Rosen, "Weak Interactions and the Kalbfleisch-Fowler Model of Hadrons and Leptons," Purdue preprint, June 1973 (both submitted for publication).

2. See, e.g., S.L. Glashow, Journal de Physique (Paris) 32, Colloq C-3, p. 109 (1971); V. Gupta, Phys. Rev. 135, B783 (1964); R.M. Weiner, Phys. Rev. Lett. 20, 296 (1968).

3. G. Feinberg (Columbia U.), private communication.

4. B. Pontecorvo, Soviet Physics JETP 26, 984 (1968); V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969).

5. F.A. Nezrick and F. Reines, Phys. Rev. 142, 852 (1966), measured the cross-section for the reaction $\bar{\nu}_e p \rightarrow e^+ n$. They obtain for fission $\bar{\nu}_e$'s, $\sigma(\text{expt})/\sigma(\text{theory}) = 0.88 \pm 0.13$. See also F. Reines and C.L. Cowan Jr., Phys. Rev. 113, 273 (1959).

6. R. Cowsik and J. McClelland, Phys. Rev. Lett. 29, 669 (1972).

7. T. Eichten, et al., "Measurement of ν-nucleon and $\bar{\nu}$-nucleon Total Cross-Sections," Phys. Lett. B46, 274 (73) (preprint dated 8 August 1973).

8. W.Y. Lee (Columbia), private communication. About 100 of their total 1000 events can be used to look at the strangeness of the final state. About 30% of their muon neutrinos arise from kaon decay ($\approx$ 3% are ν_e from kaon x(65% $K_{\mu 2}$/5% K_{e3})), but the strange particle detection efficiency is poor and also poorly determined. They observed, for example, no $\bar{\lambda}_\mu N \rightarrow \mu^+ \Lambda$ events (out of a sample of 100), whereas CERN Gargamelle collaboration has observed $\sim$ 12 such events in $\approx$ 1000 antineutrino events (T. Eichten, et al., Phys. Lett. 40B, 593 (1972)).

9. B.C. Barish, et al., Phys. Rev. Lett. 31, 565 (1973); Phys. Rev. Lett. 31, 180 (1973); Ibid., p. 410.

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ADDENDUM TO FNAL PROPOSAL #254

G.R. Kalbfleisch, J. Alspector, BNL
and
E.C. Fowler, N. Baggett, Purdue

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Physics Motivation

Purely hadronic weak decays such as $\Lambda \to p\pi^-$, $K^+ \to \pi^+\pi^o$ completely violate strangeness conservation. The question as to whether semi-leptonic decays, $n \to pe^-$"ν" and $\Lambda \to pe^-$"ν", violate strangeness conservation at all, partially or totally, depends on whether the "ν" knows anything about the strangeness quantum number. We know neutrinos "know" about "electron" and "muon" number. The rates for $n \to pe^-$"ν" and $\Lambda \to pe^-$"ν" are not governed by the same decay constant; Cabibbo theory succeeded in redefining "universality" so that μ, n, and Λ beta decay rates are related as G^2, $G^2\cos^2\theta_C$ and $G^2\sin^2\theta_C$, where θ_C is the Cabibbo angle ($\sin^2\theta_C \sim 0.2$). This idea applied also to purely hadronic decays like $\Lambda \to p\pi^-$ predicts that rate to be like $G^2\sin^2\theta_C\cos^2\theta_C$. However, experimentally $\Lambda \to p\pi^-$ proceeds like $\approx G^2 \cdot 1$ even after accounting for the strong final-state interactions as well (or as poorly) as is possible.[1] A distinction between the neutrinos "ν" in n and Λ beta decay, i.e. $n \to pe^-\nu$ and $\Lambda \to pe^-\lambda$ might account for these facts. This implies another doubling of the number of neutrino states: original Pauli ν, doubled to $\nu,\bar{\nu}$, doubled to ν_e,ν_μ and possibly now to $(\nu,\lambda)_{e,\mu}$ due to their knowledge of the strangeness quantum number. Possible additional relationships between ν and λ are given in the original proposal #254.

The relationship of baryon and lepton numbers, strangeness, isospin and possible new speculated quantum numbers (charm, fancy, etc.) are not

really known. The question of the distinguishability of ν and λ is crucial to such an understanding. Various leptonic symmetries are possible:

(1) just the two doublets (e,ν_e), (μ,ν_μ);

(2) additional doublets;

(3) triplets $(\mu^+,"\nu_4",e^-)$ where "ν_4" is a pair of two component neutrinos, one $\bar{\nu}_\mu$ and one ν_e;

(4) heavy lepton triplets or quadruplets (M^+,ν_μ,μ^-) or (M^+M^o,ν_μ,μ^-) and electronic counterparts; or

(5) distinguishable ν and λ giving triplets $(e^-\nu_e\lambda_e)$, $(\mu^-,\nu_\mu,\lambda_\mu)$.

We note that the experiment proposed here is definitive in that we will find ν and λ indistinguishable (to $\sim$ 8% level, see below) or (surprisingly perhaps) that they are distinguishable. The Cabibbo angle and the $\Lambda \rightarrow p\pi^-$ problems mentioned above indicate that there is nothing speculative about performing this experiment.

The Experiment

The experiment has been outlined in proposal #254 itself and in the Appendix of June 10, 1974. In the following pages of this addendum, we show that a measurement of the cross-section ratio R of ν_μ and λ_μ at 70 GeV to $\pm$8% appears attainable by utilizing the proposed sampling muon monitors as outlined previously and discussed further herein. We are convinced of this from our detailed calculations and the test measurements made recently. The value of δR from current experiments is $\pm$30 to $\pm$40%. The test data in Enclosure 100 were obtained with the cooperation of Fermilab and Cal-Tech (E-320) very recently, September 27-October 1, 1974.

The calculations are described first. Then a description of the test runs is given and comparison with the calculations is made. A discussion of actual running conditions for the real experiment follows, including the estimation of number of protons required and the accuracy expected. A summary of the impact of our studies of muon monitoring on slow spill neutrino experiments is given.

We request approval to perform this experiment to the 8% level. This requires a run of 1.5×10^{18} protons, about 10^{17} of which will be test and calibration runs of the finally chosen parameters for the data-taking runs.

We urge consideration, approval and execution of this proposal at an early date, prior to the proposed relocation of the CalTech apparatus to the new laboratory. Details of additional requirements of Fermilab for the support of this experiment are not given here. The possibility of studying the differences of the neutral current interactions of ν_μ and λ_μ in this experiment has not yet been considered.

Monte Carlo Calculations

We have attempted to understand the muon flux in Enclosure 100 downstream of the 15-ft. plug by means of a Monte Carlo calculation. These muons come from five major sources: (1) Pion decays in the 345-m-long decay pipe; (2) Two- and three-body kaon decays in the pipe; (3) Muons produced in the 15-ft. plug at Enclosure 100 due to undecayed hadrons initiating a hadronic cascade; (4) Muons produced in the 12-ft. aluminum

dumps on the train after the production target due to uninteracted protons initiating a hadronic cascade; (5) Pion and kaon decays on the train between the production target and the start of the decay pipe. We have modeled all but the last source.

Our model starts with the production target and creates hadrons according to a semi-empirical formula.[2] The point-to-parallel optics of the beam train are then treated using a thin-lens approximation with appropriately placed aperture stops. Two-body pion and two- and three-body kaon decays then produce muons in the 345 m decay pipe and reach Enclosure 100 after being multiple scattered and degraded in energy by the 15-ft. plug. Counting rates are based on the geometrical angular acceptance of our four-counter telescope. This calculates sources (1) and (2), the major sources of interest of muons and, of course, neutrinos.

Sources (3) and (4) are background and are calculated according to a simple cascade model. The number of particles in the cascade as a function of depth are obtained from an analytic formula based on shielding studies in steel.[3] This is combined with an assumed energy distribution of secondaries subjected to conservation of energy. It is further assumed that 2/3 of the secondaries are charged pions and kaons, the rest being neutral and therefore not muon producing. Muon producing decays are then generated in small segments throughout the cascade. The muons again reach Enclosure 100 degraded in energy and multiple scattered. This simple cascade model predicts $\sim$ 0.12% μ/p through 17' of steel, which is corroborated by a measurement in another FNAL beam line.[4]

General Features of Muon Distribution

Generally, muons from sources (1) and (2) are high energy (about 2/3 the secondary beam energy) with kaon decays having a larger energy width. Muons from sources (3) and (4) are low energy (exponentially falling distribution of

about 3 and 15 GeV respectively). Similarly sources (1) and (2) give muons with small angular divergence (about 4 milliradians full width) while (3) and (4) have large divergence (40 mr and 20 mr).

The lateral distribution of muons in Enclosure 100 from pions (source 1) is confined to little more than beam size while that of kaons (source 2) is more spread out. Source 3 muons are slightly larger than beam size while source 4 muons have a flat lateral distribution over the whole plug because they are produced so far away.

The expected counting rates on axis for sources 1, 2, 3, and 4 are roughly down by an order of magnitude from one to the next. At a radius of greater than about 30 cm, source (2) kaons dominate.

As beam energy increases, source (1) lateral distribution narrows while source (2) is unaffected. Source (3) becomes relatively more important because the p/π ratio in the beam increases strongly and protons initiate cascades as well as pions. The $\pi/K/p$ ratios we use are based on a measurement at another beam at FNAL.[4]

The Test Run

The calculations above indicated the need to measure the muon flux over an x,y grid perpendicular to the beam, the angular distributions of these muons, and to obtain some information about the five muon sources and of the low-momentum character of the DUMP and PLUG backgrounds. A four-fold coincidence telescope, placed on a turret, was mounted on a lathe bed which provided 28" of horizontal motion (East-West). The turret was able to be rotated about a vertical axis over a 90 mr total angular interval. In addition, vertical profiles were possible using the double ramping capability of the last dipole on the narrow band train (OPT3), which could run

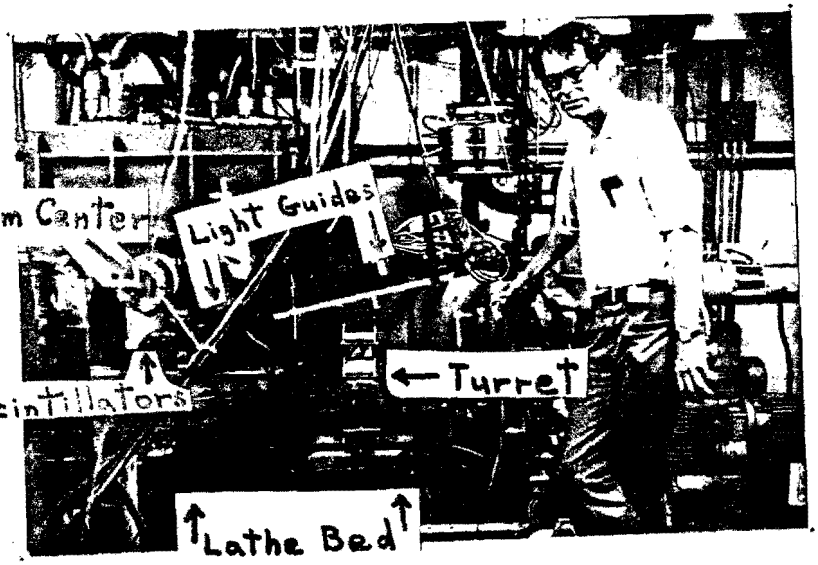
at two different DC levels during the course of the spill. Finally, a magnet with an $\int B \cdot d\ell$ of 3 Kg-meters was installed at one position, about 8" radially (West and below) from the beam centerline. The background muon sources were expected to be of low momentum; this magnet was to be able to affect such muons (< 5-10 GeV/c).

Figure 1 shows some views of the apparatus. Looking upstream, 1(a) shows the lathe bed and turret on which the scintillation counters are mounted. Looking across the beam, 1(b) shows the position of the magnet and an end view of the counters. Figures 1(c) and 1(d) are views of the experimental Porta-kamp and the High Rise Central Laboratory respectively.

The telescope consisted of four scintillators, 0.1" horizontally x 1.0 cm vertically by 1.0" long (in beam direction), spaced out over a 9" length. The scintillators were glued onto 5-mil Al covering a plastic "hexcell" frame for precise alignment on a nearly massless base. The scintillation light was piped to 56 AVP photomultipliers via air light guides made from "rolled up" aluminized mylar and taped light tight. The angular acceptance of the telescope in the horizontal plane is 12 mr (FWHM) and 48 mr in the vertical plane. The acceptance function is of course triangular. The efficiency of the telescope was found to be $\geq$ 98% at the peak.

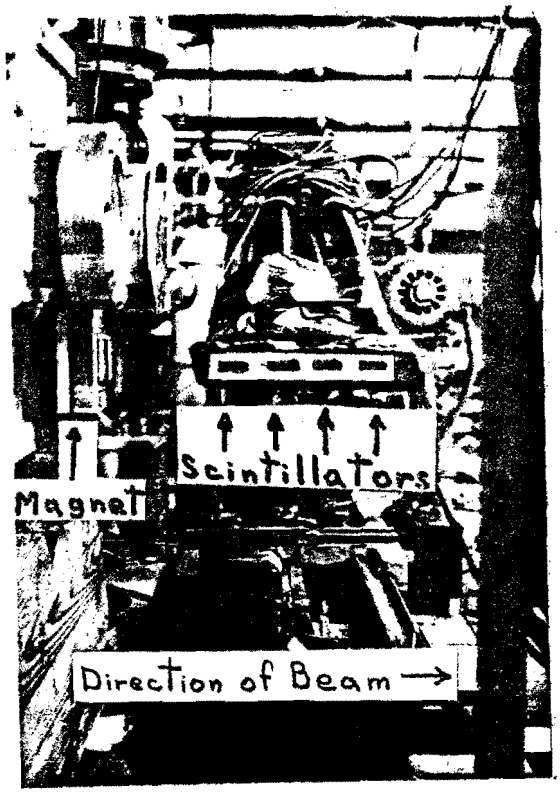
Electronics and Controls

The telescope was viewed via a closed circuit TV. The turret and lathe were remotely controlled, with rotation and horizontal position determined by the resistance of the calibrated potentiometers geared to the drive motors. The calibrations were linear and the motions were essentially free of backlash. A four-fold in time coincidence and a four-fold



(a)

Looking South (Upstream) in Enclosure 100



(b)

Looking West

(c)

Looking East in Porta-Kamp

(d)

Looking North from High Rise

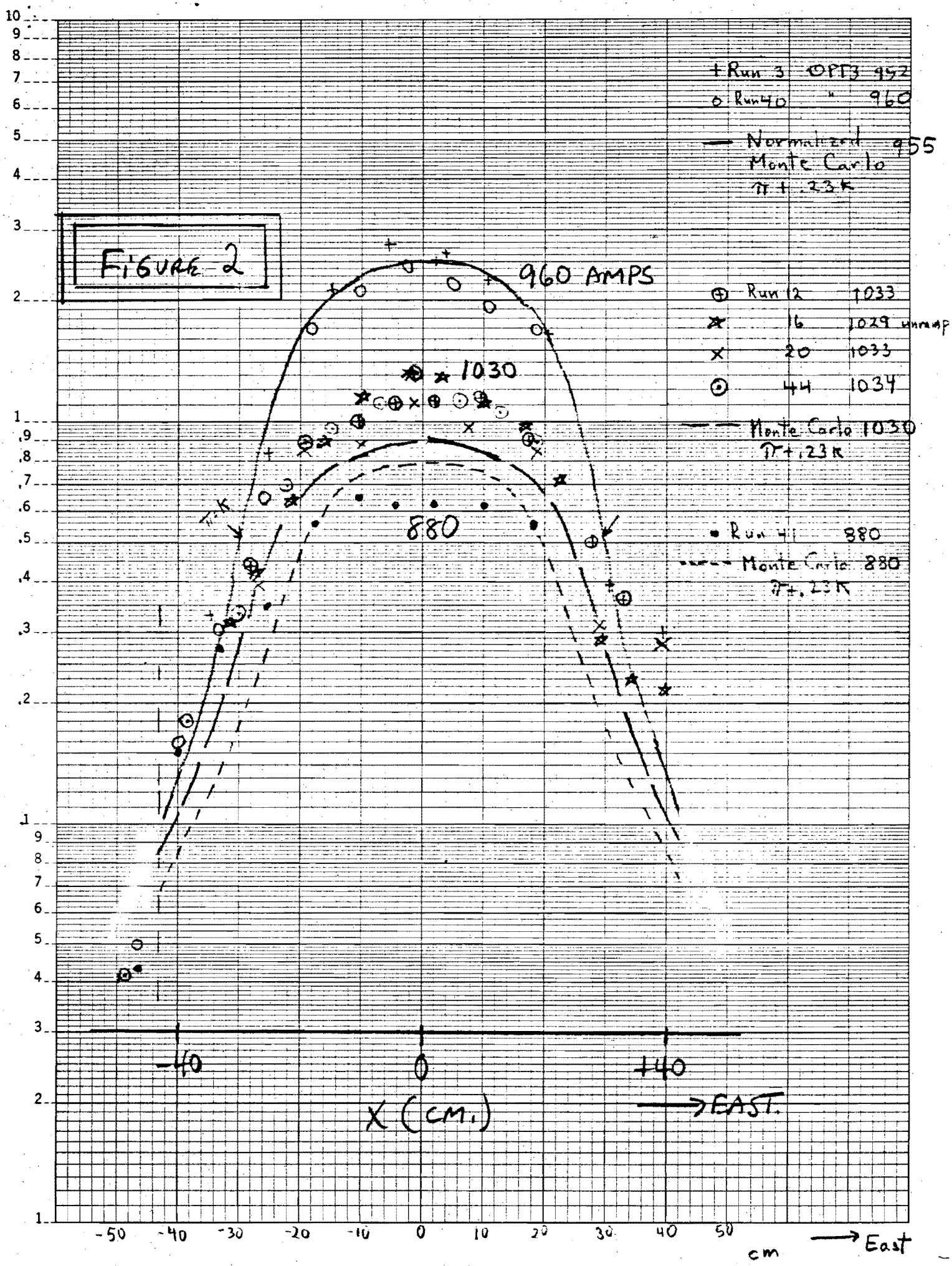
Fig. 1

accidentals coincidence (each counter delayed by one or more RF bucket, $\sim$ 18.5 ns, than the preceding one), and the 90° monitor were scaled during a gate set to exclude the three 30" bubble chamber enhanced portions of the slow spill. The gate was restricted also to that portion of the spill appropriate to the desired OPT3 ramp (usually the 0.3 sec. interval between the first two bubble chamber spikes). The slow spill contained about 2×10^{11} protons/pulse before gating. The 90° monitor was calibrated against the slow spill gated SEM reading the proton flux on target. The OPT3 magnet ramp was not completely stable ($\sim$ 5-10 ampere variation). The beam spot on target was somewhat unstable also; it was hard to monitor (low intensity on the SWIC's T1 and T2) and no attempt was made to obtain better control. We estimate an average effective spot size of 3 mm radius during the slow spill.

Test Run Data

Some 54 runs were made scanning x, the horizontal lathe motion, θ, the turret rotation, OPT3 vertical sweeps with the ramped train dipole, and with the magnet energized at $\pm$13 Kg ($\pm$9 amps) and with it off. Most data were at +170 GeV.

Some of these data, representative of these runs, are shown in Figs. 2-6 along with some Monte Carlo curves normalized to the data. The semilog graphs of counting rate, four-fold coincidence 1 2 3 4, over 90° monitor vs. x, OPT3 or θ are displayed. Figure 2 shows three x scans at three different OPT3 values, corresponding to the peak vertically and off on either side (960, 1033 and 880 amps). A 3mm proton spot (HWHM) on target gives the higher curve which fits the data very well. The two lower curves average the two lower data sets: sweeping the vertical profile with OPT3 is not the



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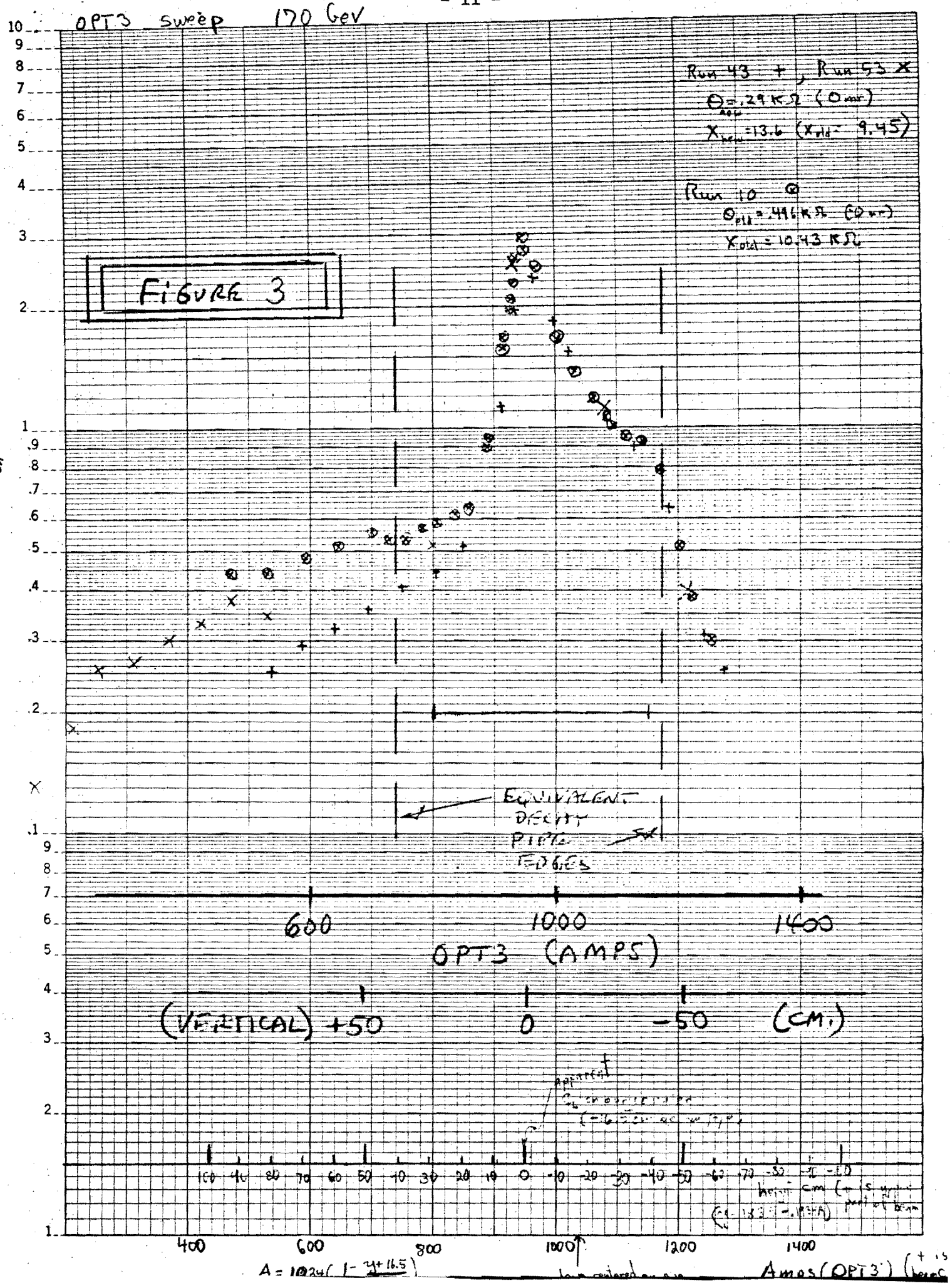
46 5490
1234/70 • MON

best way to measure it. Also, this is the optical plane in which the chromatic aberrations are present, and we have more work to do to understand it. Figure 3 shows a OPT3 sweep at the horizontal beam center. The slowly falling tails are not explained by our calculations yet. However, the equivalent decay pipe radius, shown as the vertical dotted lines define the region of the main beam, which concerns us here. Figure 4 shows the central region indicated by the horizontal bar in Fig. 2 on an enlarged OPT3 scale with the Monte Carlo curve. Substantial agreement at the peak is seen.

Figure 5 shows two θ scans, the higher one under "open slit" conditions, the other "closed slit." E320 was running with the momentum slit fully open for neutral current data and fully closed for background measurements (decays on the narrow-band train itself). The open slit data corresponds to looking at all 5 sources of muons and the closed slit data only to sources 4 and 5, as labeled. The solid curve is the Monte Carlo convoluted with the angular resolution function of the telescope; the dotted lines connect the closed slit data only to guide the eye (no calculation; source 5 not yet modeled).

Figure 6 shows an x scan across the local region where the magnet was situated for current in the magnet of +9, 0 and -9 amps (13, 0, -13 Kg over 22 cm length), with the telescope looking at an angle of 45 mr to the West (corresponds to <u>arrow</u> labeled "magnet" on Fig. 5). We have not modeled a quantitative calculation of these data; the various lines connect the data points for clarity only. Qualitatively, the magnetic field changes the effective direction in which the telescope looks as its x position is changed. The increase in counting rate is proof that low momentum source 3 (plug) muons are present <u>and</u> have an angular distribution peaked forward (that


OPT3 sweep 170 GeV
Run 43 +, Run 53 X
Θ_{new} = .29 KΩ (0 mr)
X_{new} = 13.6 (X_{old} = 9.45)
Run 10 ⊗
Θ_{old} = .496 KΩ (0 mr)
X_{old} = 10.43 KΩ
FIGURE 3
EQUIVALENT DECAY PIPE EDGES
600
1000
1400
OPT3 (AMPS)
(VERTICAL) +50
0
-50
(CM.)
apparent
height cm
400
600
800
1000
1200
1400
Amps (OPT3)
1234/90° mon
46 5490
K+E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
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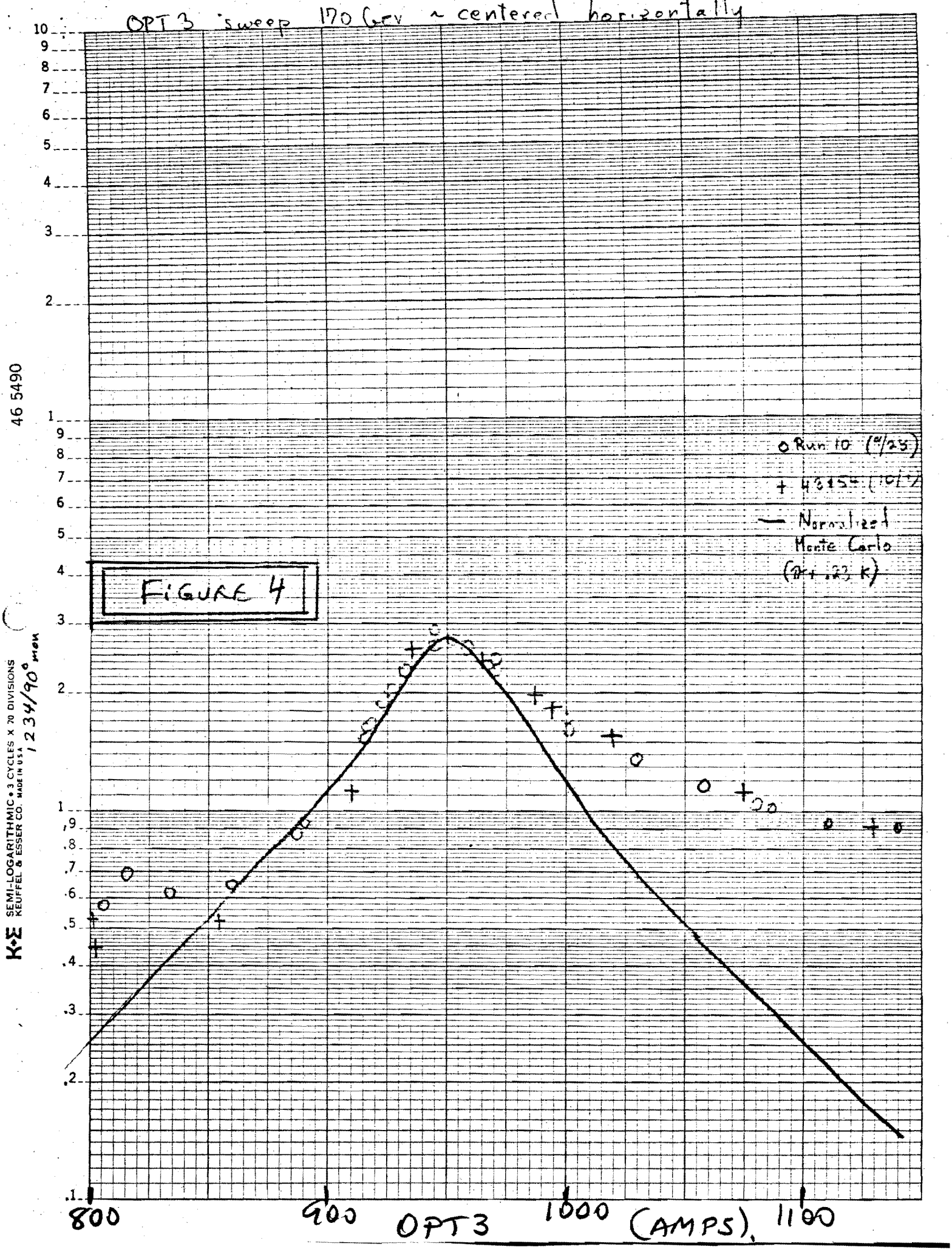
OPT 3 sweep 170 Gev ~ centered horizontally
FIGURE 4
o Run 10 (9/25)
+ 43&54 (10/1)
— Normalized Monte Carlo
(Dr + .23 K)
1234/90° mon
800
900
1000
1100
OPT3 (AMPS)
46 5490
K+E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.

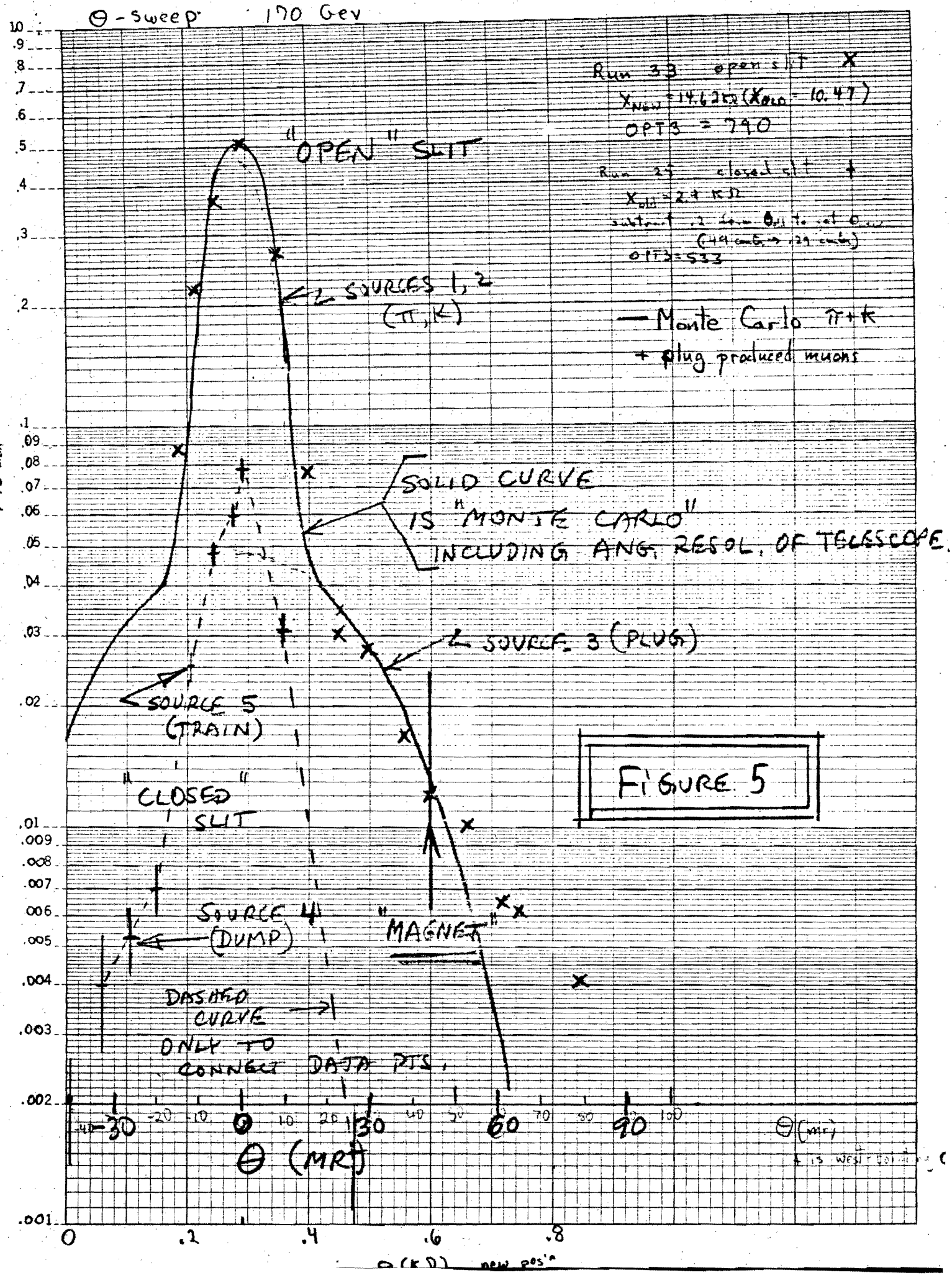
Θ - Sweep 170 Gev
Run 33 open slit X
X_{NEW} = 14.62 kΩ (X_{OLD} = 10.47)
OPT3 = 790
Run 25 closed slit +
X_{old} = 2.9 kΩ
OPT3 = 533
"OPEN" SLIT
SOURCES 1, 2 (π, K)
— Monte Carlo π+K
+ plug produced muons
SOLID CURVE IS "MONTE CARLO" INCLUDING ANG. RESOL. OF TELESCOPE.
SOURCE 3 (PLUG)
SOURCE 5 (TRAIN)
"CLOSED" SLIT
SOURCE 4 (DUMP)
"MAGNET"
DASHED CURVE ONLY TO CONNECT DATA PTS.
Θ (MR)
Θ (mr)
+ is west
1234/90° mon 46 5490
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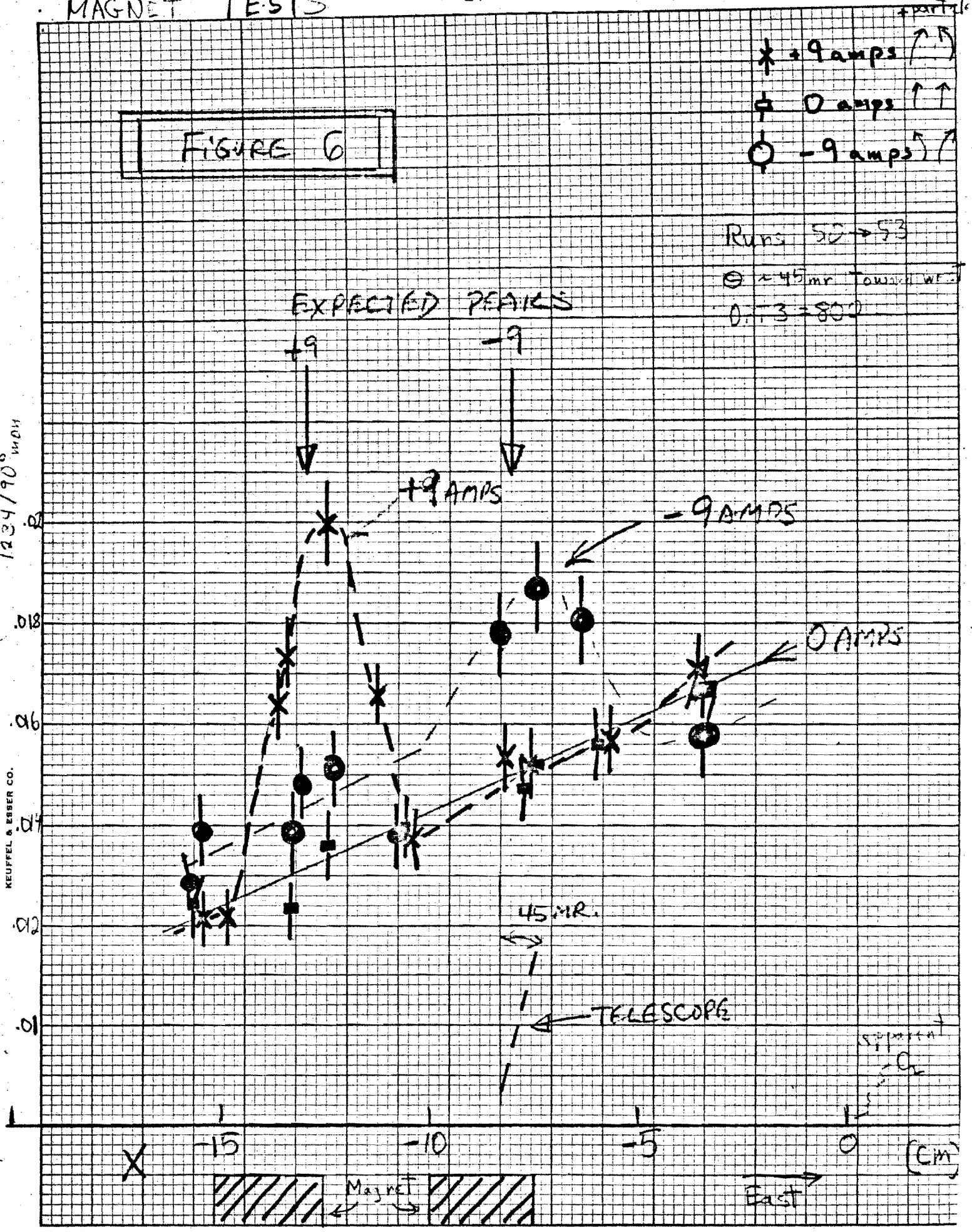
FIGURE 5

MAGNET TESTS



causes the increase). Both of these conditions are expected for PLUG muons since they are low-momentum, produced forward generally and multiply scattered to larger angles with a falling distribution. Some magnet scans were done for closed slit DUMP (source 4) muons but were incomplete and statistically limited due to the order of magnitude lower rates. The meager data collected (not shown) are consistent with a picture like Fig. 6, however.

We feel that the results shown in Figs. 2-6 show a good understanding of the total situation regarding muon sources. The five sources are all found at the expected level and with the correct properties. In addition, each source, as expected, can be measured in some region or other utilizing x, y, θ and magnet scans. Understanding of the OPT3 sweeps far from the center may not be possible without the ability to be in control of the proton beam on target (i.e. nonparasitic running) and without restricting the apertures of the narrow-band train, in particular, a smaller momentum bite. We plan to run with a restricted bite in order to improve various systematics, better separation of π and K neutrino events, ability to see the muons from K decay clearly, etc. Also, improved calculations will be implemented to better understand the train's vertical chromatic optics.

We conclude that all 5 muon sources can be calculated to the required level and also be actually measured. We turn to consideration of the calculations closer to the real conditions expected for the execution of this experiment.

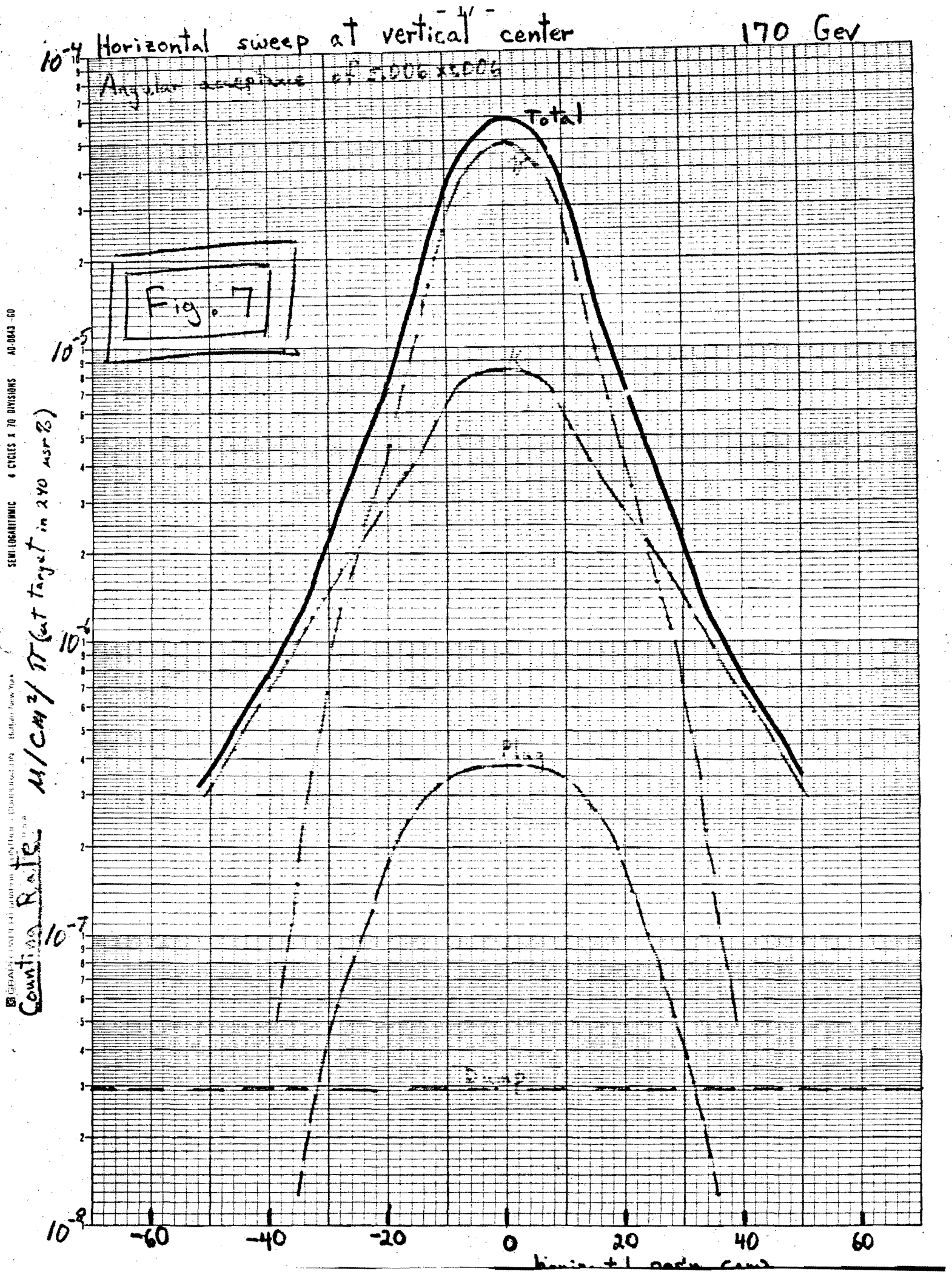
The Actual Experiment

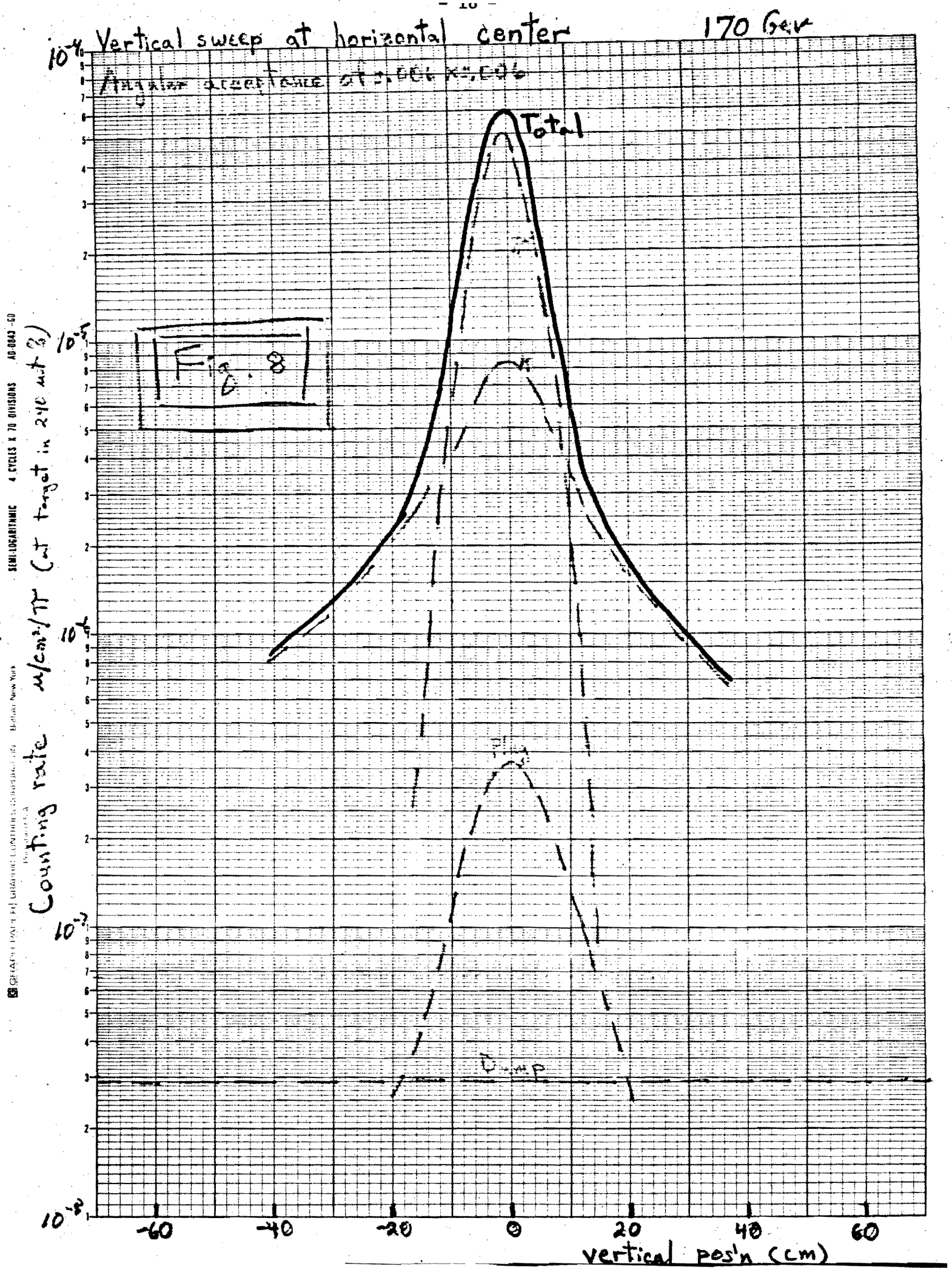
We present in Figs. 7-10 some representative Monte Carlo curves for the expected conditions of the experiment. In particular, a 1 mm radius

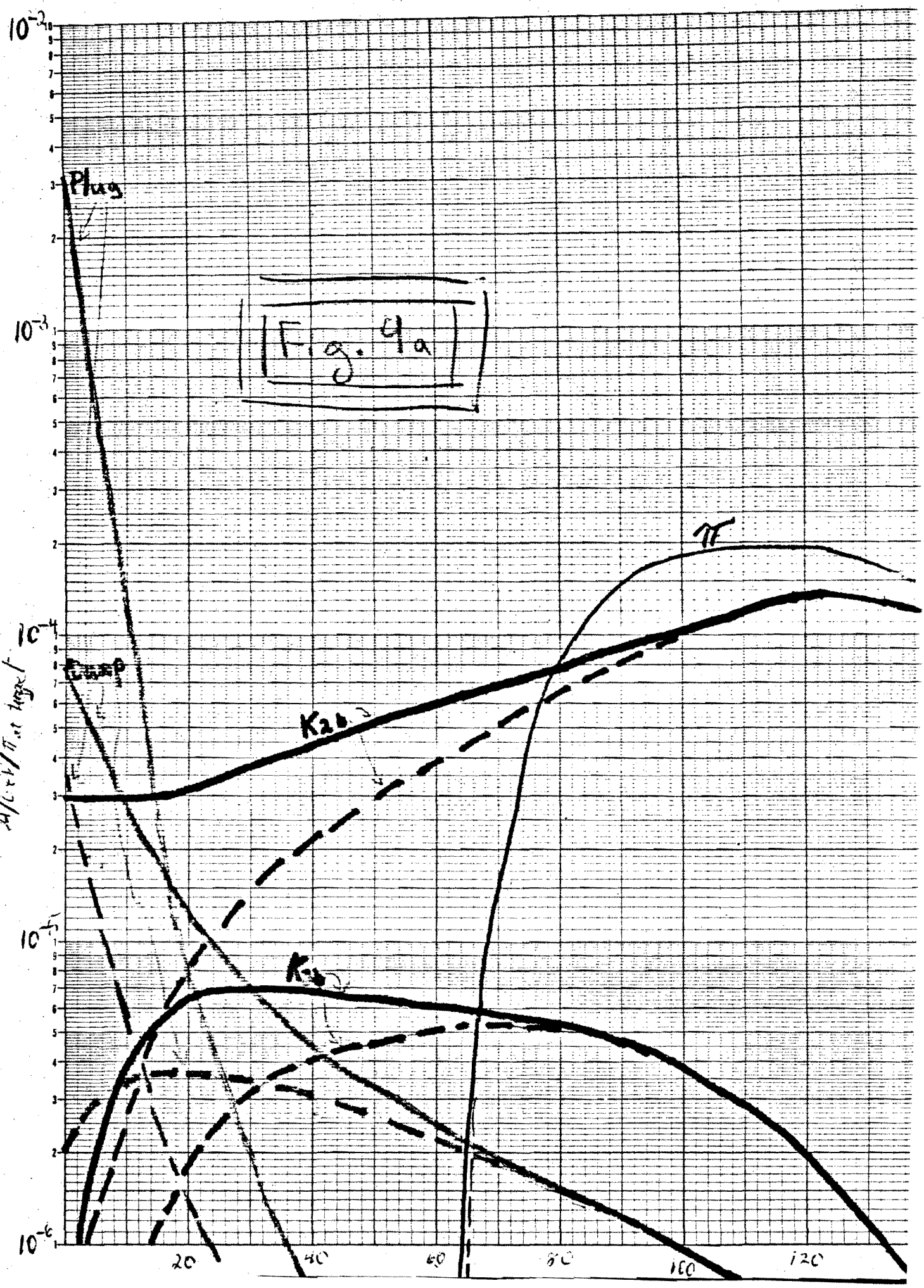
proton spot is assumed and about one-half of the aperture of the narrow-band train (i.e. we will close the momentum slit, half way). If the proton spot size during extended operation cannot be controlled to a 1mm radius, we will require SWIC readouts to the data stream for pulse-by-pulse tracking of its position or require a special small cross-section target which will insure "good optics." The curves shown are for +170 GeV/c secondary momenta although the experiment will require running at +70 GeV for λ_μ and +190 GeV for ν_μ.

Figure 7 shows the horizontal distribution of muons at the vertical center with contributions from the four calculated sources. Figure 8 shows the vertical distribution at the horizontal center. Note that, because the beam is much narrower in the vertical dimension, the separation of π's and K's is much easier than in the horizontal distribution. We assume that our telescope has an angular acceptance of ± 6 milliradians in both x and y for these calculations. We expect to measure the K/π ratios from the muon distributions during one or two special tuning sessions in which all conditions are carefully controlled. During data taking, the telescopes will not be required to detect K vs. π muons. The 8-telescope array envisaged and described in the proposal proper (and the June 10, 1974, Appendix) is now envisaged also to be remotely x,y scanned over the face of the dump during data taking to continuously monitor the muons. It may be necessary to run with the center muon hole plugged.

Figure 9 shows the momentum distribution of muons from the various sources. The solid lines are integrated over all angles and the whole plug area. The dotted lines are restricted to the previously mentioned ± 6 mr by ± 6 mr angular acceptance. Note that the narrow angular acceptance gives very good low-momentum discrimination. This is because low-momentum


Horizontal sweep at vertical center
170 Gev
Angular acceptance of .006 x .006
Total
Fig. 7
Counting Rate μ/cm²/π (at target in 240 μsr-B)
-60
-40
-20
0
20
40
60


Vertical sweep at horizontal center
170 GeV
Angular acceptance of ±.006 x ±.006
Total
Fig. 8
Counting rate μ/cm²/π (at target in 240 μs %)
vertical pos'n (cm)
-60
-40
-20
0
20
40
60
SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS AD-0843-GD



GRAPH PAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
SEMI-LOGARITHMIC 4 CYCLES X 70 DIVISIONS AD-0843-CD

$P_{beam} = 170$ GeV

	Source	μ/π [illegible]	[illegible]
1	π	1.314×10^{-2}	1.302×10^{-7}
2	K_{2a}	[illegible]	1.07×10^{-2}
	K_{2b}	[illegible]	4.35×10^{-4}
3	Plug	$9.[illegible] \times 10^{-3}$	3.65×10^{-7}
4	Dump	9.87×10^{-4}	2.29×10^{-4}

Fig. 9b

particles are scattered at wider angles and do not count in the narrow acceptance of the telescope. Thus sources 1 and 2, the major sources of interest, are enhanced relative to the background sources 3 and 4.

Figure 10 shows the momentum distribution of neutrinos from sources 1 and 2 in the 1.27 m square fiducial volume of the neutrino detector. Note that with the narrower momentum bite of this beam the π and K peaks are well separated.

Estimate of Accuracy Expected

At this time the systematics will still be dominated by the error on the K/π ratio averaged over the large acceptance of this beam. However, a greater accuracy may actually obtain after the coming work with the improved Cerenkov counter, the muon measurements under stringently controlled conditions and with the utilization of other measurements that become available. We desire to anticipate some improvement in the 7% systematics from this source and aim for $\sim$ 5% statistics. Table I summarizes the various estimated sources of error on R for λ_μ assumed identical to ν_μ (i.e. R=1). An error δR of $\pm 8\%$ directly measured is anticipated.

Current experiments (Gargamelle and CalTech-Fermilab) have δR (indirect) of ± 30 to $\pm 40\%$. The estimate of $\leq$ 2% for item 1 in Table I comes from the agreement of two different OPT3 runs (3 days apart) to 2% (integrated counting rate) shown in Fig. 11 with smooth, hand-drawn interpolating curves drawn thereon.

Event Rates

The relative event rates are given in Table II. Using event yields observed by CalTech-Fermilab at 120 GeV[5] we can estimate the number of

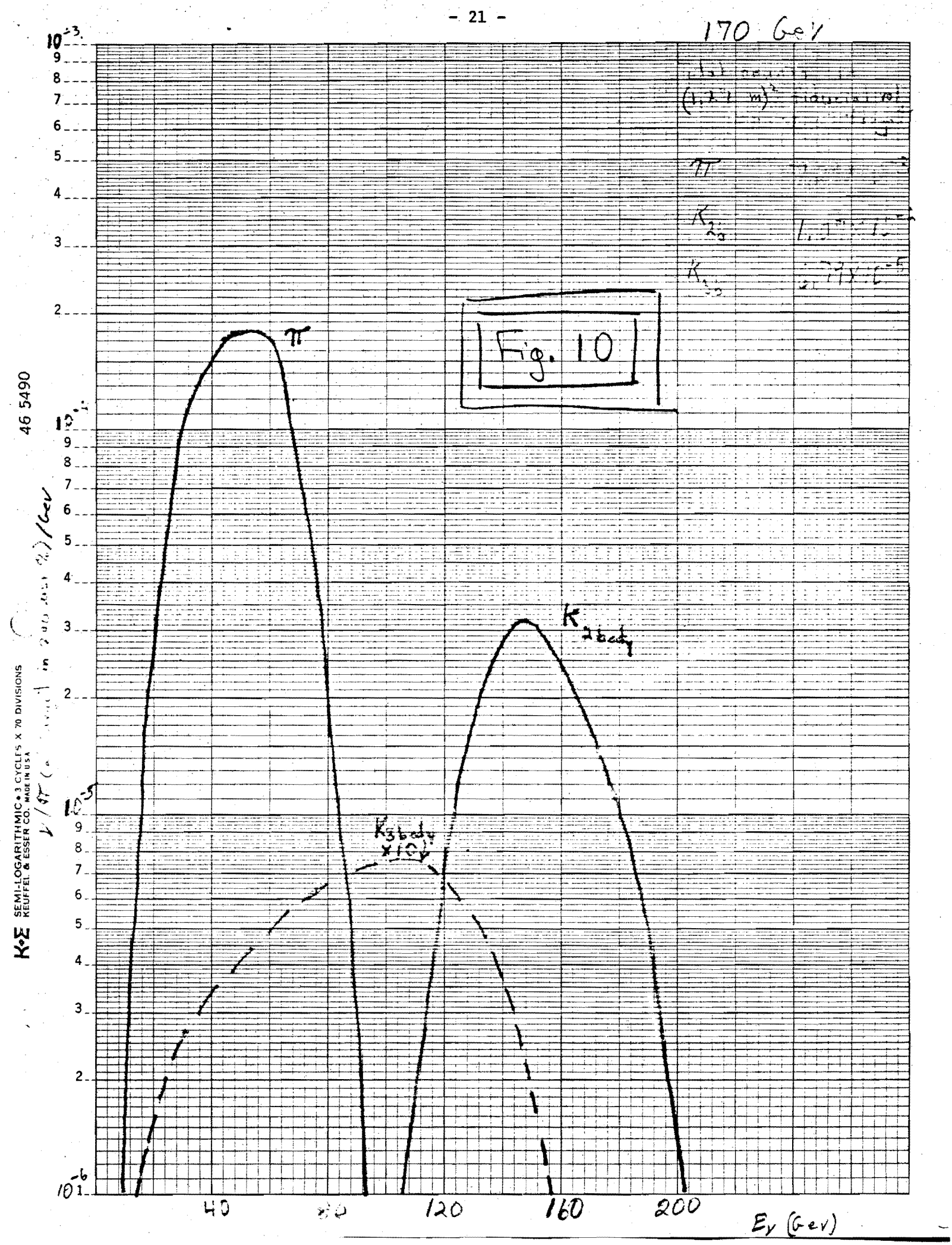

170 GeV
Fig. 10
π
K2bdy
K3bdy x10
40
80
120
160
200
Eν (GeV)
46 5490
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TABLE I

Estimate of Overall Error on Ratio of Cross Sections if $\nu_\pi \equiv \lambda_K$ (i.e. R=1)

Beam Systematics		
1.	Instability due to proton spot on target	$\leq$ 2%*
2.	Relative π^+, K^+ yields (combined result of Cerenkov and muon results)	$\lesssim$ 5%+
3.	Inefficiency and calibration of muon telescopes	$\leq$ 1%
4.	Subtraction of background muon sources	$\leq$ 1%**
5.	Subtraction of accidental counts	$\leq$ 1%***
Detector Systematics		
6.	Relative efficiency for ν_π and λ_K events	$\sim$ 3%
7.	Event separation due to energy resolution (calorimetry and muon momentum)	$\sim$ 3%
	Total Systematics	6-7%
Statistics - π^+(190): .4x10^{18} protons; K^+(70): 1.0x10^{18} protons		
8.	Approx. $\gtrsim$ 600 ν_π and $\gtrsim$ 600 λ_K events if R=1	$\sim$ 4% each
	Combined Statistics	$\sim$ 5-6%
	Estimated Total Error	$\sim$ 8%
Current Values of δR++		
	Gargamelle (CERN)	$\pm$30% (Statistics of λ_K)
	E21 (CalTech-Fermilab)	$\pm$40% (Systematics)

* See text and Fig. 11.

\+ Much effort will be devoted to reduction of this error.

** Error of $\leq$ 10% of a 5-10% subtraction.

*** See June 10, 1974 Appendix regarding accidentals, rates, etc.

++ Indirect value, comparing ν_π and λ_K events at different energies, under assumption that the cross sections rise linearly with energy; proposal #254 will be making a direct measurement.

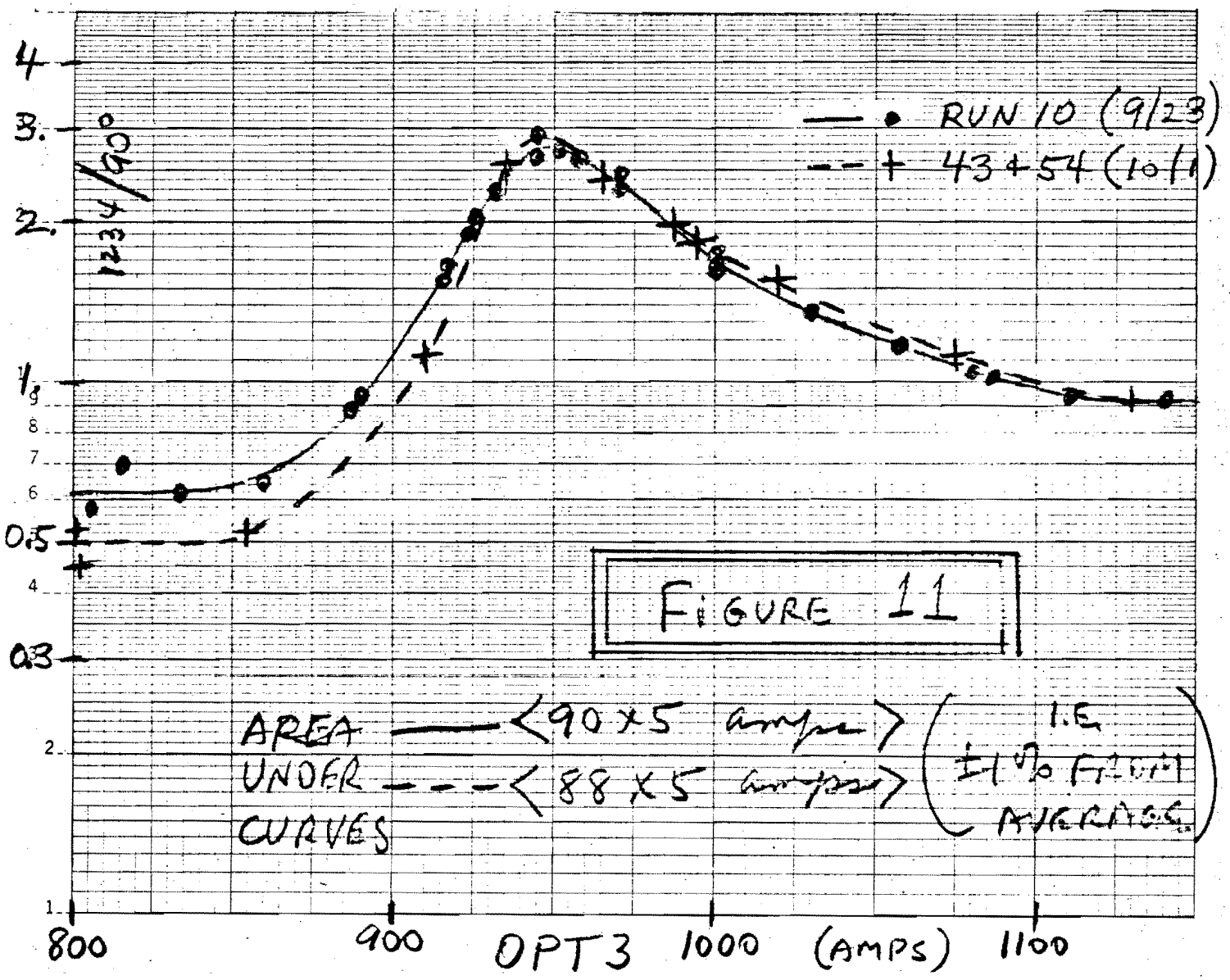
4
3.
2.
1
0.5
0.3
1234/90°
RUN 10 (9/23)
43+54 (10/1)
AREA UNDER CURVES
<90 x 5 amps>
<88 x 5 amps>
I.E. ±1% FROM AVERAGE
800
900
OPT 3
1000
(AMPS)
1100

FIGURE 11

TABLE II

Train[+] and Flux Data and Event Rates

	Momentum (GeV/c)	Effective Aperture[++] (μsr-%)	Relative[+++] π^+ yield	Kycia's K/π Ratio	Relative K^+ yield	Relative π^+ Events	Relative K^+ Events
	70	160	1.7	.12	0.20	.8	.09 (.18*)
	95	135	1.8	.14	0.26	1.2	.20
	120	120	1.7	.16	0.27	1.4	.35
	145	100	1.35	.18	0.24	1.25	.55
(reference)	170	90	1.0	.23	0.23	1.0	.55
	190	80	.75	.30	0.22	.8 (.4*)	.60

\+ The train has a geometric aperture of about 684 μsr% with the Δp/p slit fully open; we will run with it half closed at ∿ 246 μsr%.

++ The effective aperture is the geometric aperture times a factor that accounts for the fact that all particles are not produced at the nominal momentum at 0 milliradians. Most of the loss is due to falloff of the yield with transverse momentum in the horizontal plane.

+++ Wang formula and Kycia beam survey (see Fig. 13).

* These event rates represent those of interest for the conditions under which we propose to run (slit 1/4 closed for 70-GeV K's and .6m fiducial volume cut for 190-GeV π's).

protons required to reach the statistics required in Table I. We find we need 0.4×10^{18} protons for + 190 GeV running, 1.0×10^{18} for +70 GeV running and anticipate 0.1×10^{13} for test and tune-up, for a total of 1.5×10^{18} protons.

Figure 12 shows the neutrino energy spectra for both 190 GeV π's and 70 GeV K's. Note that by cutting the fiducial volume of π neutrinos at 190 to a .6m square the peak of both spectra are at 68 GeV although the 190 GeV π spectrum is 28 GeV wide (FWHM) while the 70 GeV K spectrum is only 18 GeV wide. One can therefore anticipate widening the momentum slit at 70 GeV to increase the rate by a factor of about 2 and match the 190 GeV π spectrum more closely. These conditions should yield about 600 ν_π and 600 λ_K events.

Our estimates are based on Wang's parameterization of π^+ production[2] and our model of the beam line. Figure 13 shows the Wang prediction for 3.6 mr (per interacting proton) superimposed on the beam survey of Kycia[4] (per incident proton). The ratio of (Kycia/Wang) is 0.5 ± 0.2, which is presumably the ratio of (protons interacting/protons incident) and thus the Wang formula combined with the interaction ratio gives reasonable results for 3.6 mr production. Furthermore the K/π ratio measured by Kycia (used in our estimates) agrees well with CalTech's measurements at 95 GeV and 120 GeV.[5]

We have compared the ν flux predicted by our estimates with that measured by CalTech[5] and it appears that the Wang formula gives too large a flux when extrapolated for our 0° production situation. We have therefore scaled all our estimates down by this factor. We find good agreement, after this scaling, with our muon flux measurements at 170 GeV. Our estimate of 600 ν_π events at 190 GeV and 600 λ_K events at 70 GeV includes the above

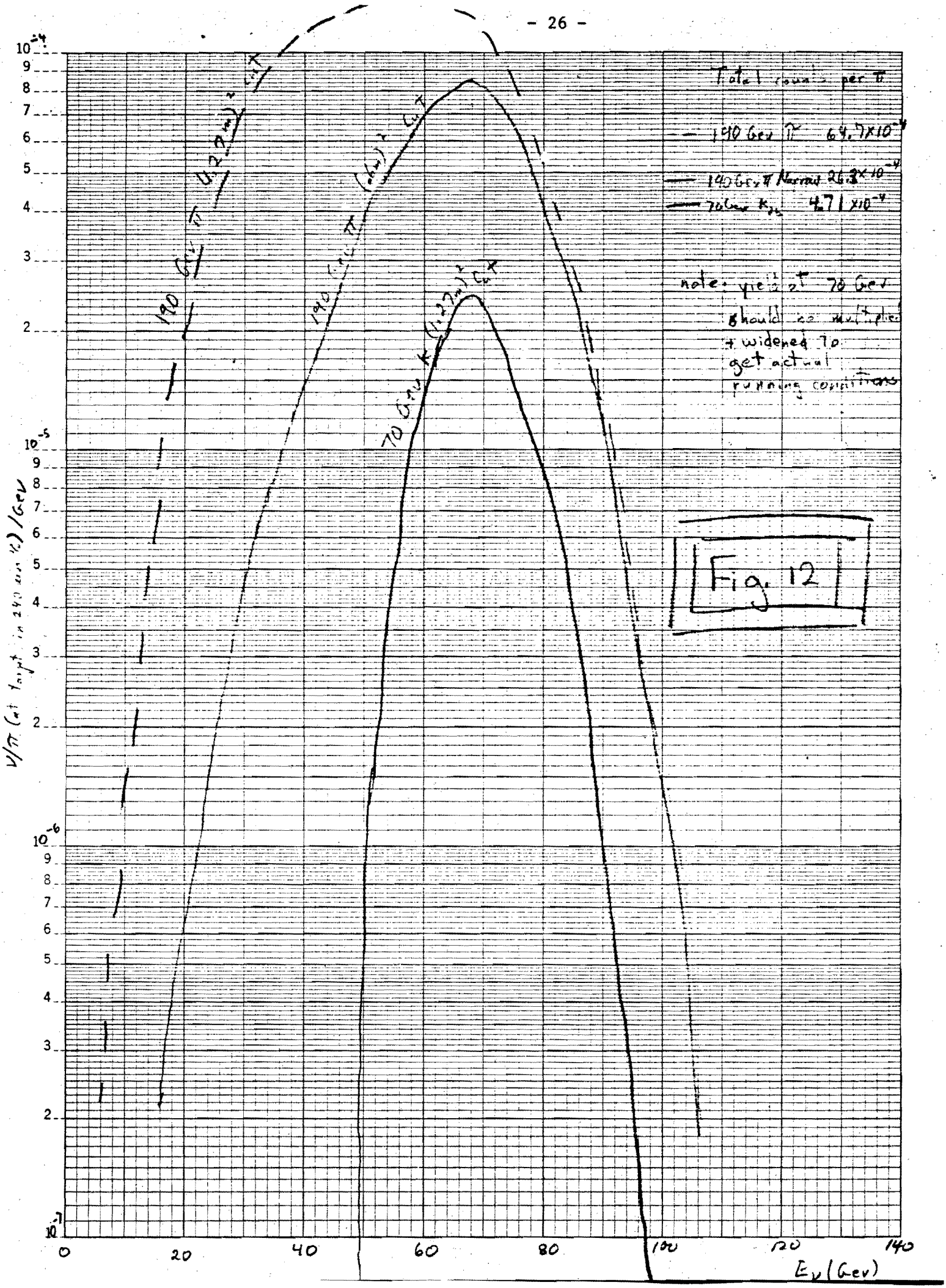

Fig. 12

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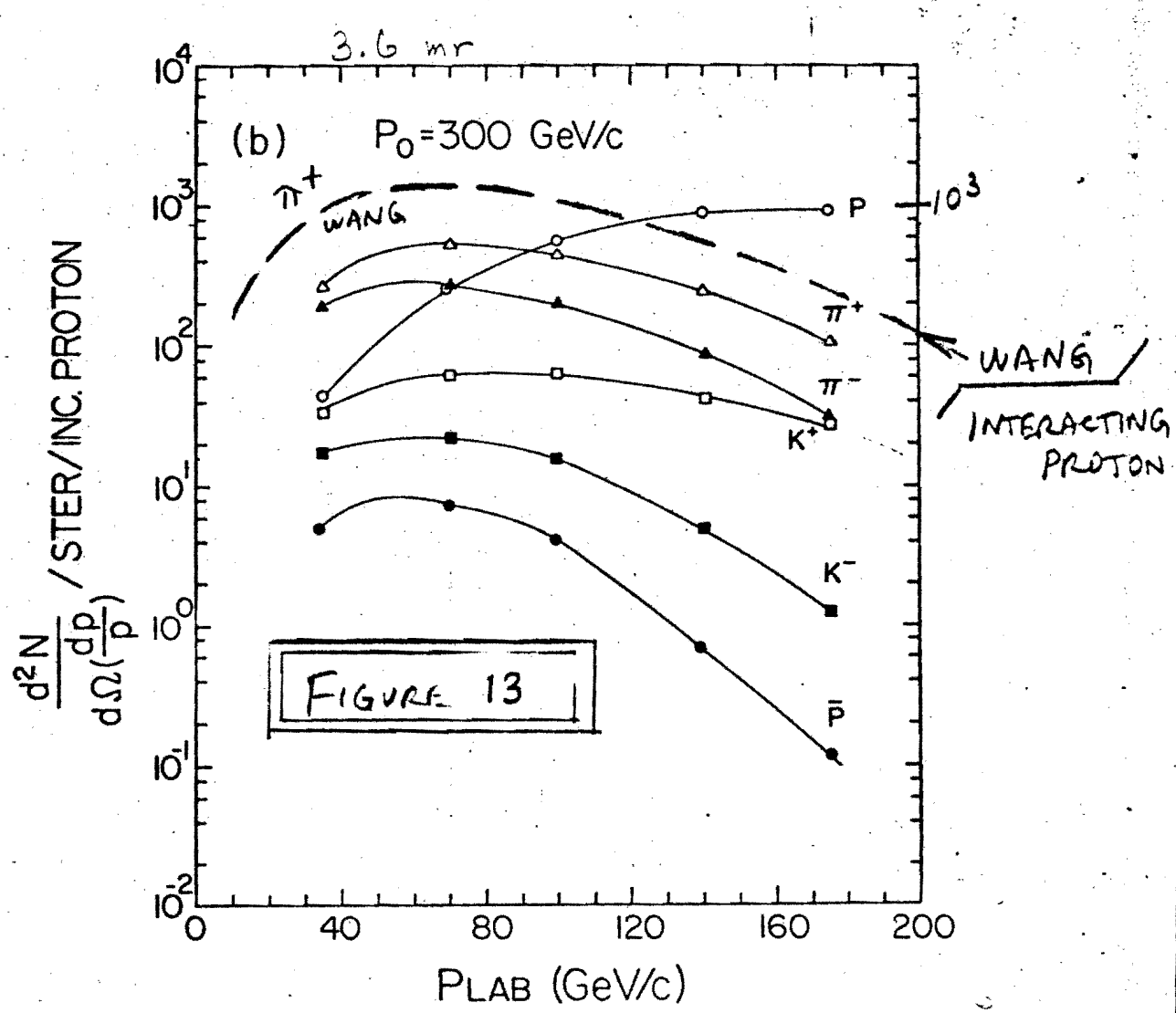

FIGURE 13

mentioned scaling, which appears to work at 120 GeV and 170 GeV. It also includes the ν detector efficiency, a .6m square fiducial cut for 190-GeV π 's and an increased aperture (246 to 465 μsr %) at 70 GeV. It seems possible to increase the aperture at 70 GeV to what it is now (684 μsr %) without badly affecting the ν_π-λ_K energy separation for a 50% increase in statistics.

Summary

We have observed muon distributions and yields which generally agree with our calculations. The five sources can be isolated and measured. Iteration of the calculations to a best fit will then allow "inversion" of the measured muon flux to the neutrino flux incident on the detector. We expect this to be estimated to 6-7% as outlined in Table I, essentially all systematics. Data runs with overall 5-6% statistics, using 1.5×10^{18} protons, will allow a direct test of the distinguishability of the neutrinos ν_π and λ_K to $\pm 8\%$ in the ratio R of $\nu_\pi N$ and $\lambda_K N$ interactions. This is, in our opinion, a great improvement over the indirect results, currently at an accuracy of ± 30-$\pm 40\%$. After execution of this experiment, it should be possible to prescribe the conditions to improve the accuracy which might be attained in "second generation" experiments.

References

1. R.E. Marshak, Riazzudin and C.P. Ryan, Theory of Weak Interactions in Particle Physics, (John Wiley, New York, 1969).
2. C.L. Wang, Phys. Rev. D7, 2609 (1973).
3. G.W. Bennett, et al., Particle Accelerators 4, 229 (1973).
4. W.F. Baker, et al., NALREP, February 1974.
5. B. Barish, F. Sciulli, et al., private communication.

G.R. Kalbfleisch, J. Alspector, E.C. Fowler, and N. Baggett
6/11/74

APPENDIX: NAL #254

Muon Monitoring - Preliminary Measurements

Summary

Muon monitoring was envisaged in the proposal to be made in enclosure #100 immediately after the secondary hadron stopper at the end of the 350-meter decay region. We report here the feasibility of such a muon monitor which can operate at least to a beam level of 7×10^{12} protons (per pulse) per second (with the ≈ 50 MHz RF structure).

Two measurements were made: the first, December 7, 1973, with the narrow-band train load, $1.5\text{-}2 \times 10^{12}$ ppp with 10' of steel in the stopper and the protons dumped on the train; the second, June 8, 1974, with the μ98 triplet quad train, $4\text{-}8 \times 10^{12}$ ppp with 15' of steel in the stopper and an 18" Al production target with the unabsorbed ≈ 2×10^{12} ppp being dumped in the upstream end of the steel stopper.

The muon monitor will consist of eight 5-fold telescopes, each of 0.05 in.^{2} cross-section, which will monitor muons (and accidentals) pulse by pulse.

The Measurements

Two measurements of the fluxes immediately after the enclosure 100 secondary hadron stopper were made. The first, with the narrow-band beam, was made December 7, 1973, at $1.5\text{-}2 \times 10^{12}$ ppp. With the rapid five-fold increase of the intensity of the FNAL accelerator this spring, a second measurement was indicated. This was carried out June 8, 1974, with the μ98 triplet train at $4\text{-}8 \times 10^{12}$ ppp.

The December measurement was done at one radial position (≃ 9" from beam centerline) at four train momenta (95, 120, 145 and 170 GeV), and for both positive and negative beam (simultaneously with monitor calibrations being made by ν21). The June measurement was done at various radial positions (7" to 12" from centerline) at one momentum, 150 GeV/c positive beam, during μ98 data taking.

Telescope

December: Three 1/2" x 1/2" x 1/2" cubes of scintillator were viewed through 36"-long air light guides (conical tubes of aluminized mylar). The scintillators were aligned on an Al bar mounted normal to the end plate of the enclosure 100 beam stopper.

June: Four scintillators, 0.75" long x 0.05 in^2 area (0.2" x 0.25"), were used. The telescope was movable via remote control over a 7" travel.

The tubes used were 56 AVP's. For the June run, the resistor string carried 4 ma at 2000 volts, and the last two dynodes were "boosted," i.e. held at constant voltage, with 3 ma and 10 ma of current supplied to the respective dynodes of each tube by auxiliary power supplies during pulses with a singles counting rate of $\sim 10^7$/second. No "sagging" of the pulses occurs with "boosting" at these rates.

Electronics

Three- or four-fold real coincidence and accidental coincidences with appropriate gate. The accidentals are with delays of 0, 1, 2, and 3 times one RF bunch (∿ 18.5 ms) in each of the four inputs. The gate was 0.1

second per spill at the beginning of the spill for the December run (to avoid possible "sagging" during the measurement period) and 0.2 seconds near the middle of the spill for the June run (in between the 0.25-second spaced 30" beam "pings" to exclude that "fast" spill).

The coincidences, accidentals, and the "90° monitor" were scaled. The 90° monitor is failing as of June but still is proportional to beam: in December there were approximately four 90° monitor counts per 10^9 protons (via SEM) whereas there were $\sim$ 1 in June.

Single Counting Rates

December 1973: 0.25 in^2 area, 2-6 MHz at 10^{12} protons/second.

June 1974: 0.05 in^2 area, 10 MHz at 5×10^{12} protons/second with minimal discrimination. The large length/transverse size ratio ($\sim$ 3) in June setup gives "coincidence" pulses which are $\gtrsim$ 2 times the "accidental" pulses. Thus with proper discrimination (efficiency to be measured and corrected for in actual monitor of course), the singles counting rate was measured to be $\lesssim$ 5 MHz /7.5×10^{12} protons per pulse ($\sim$ 1 second duration), of which a substantial fraction is due to true "coincidence" pulses. The singles rates decrease somewhat ($\sim$ factor of two) with change of radius 7" to 12".

All "accidental" coincidence rates measured check out with the singles rates measured using the $\simeq$ 50 MHz structure of the proton beam.

Coincidence Counting Rates

December 1973: (2-40) thousand/10^{12} protons for momenta 170-95 GeV/c at $\simeq$ 9" radius, 0.25 in^2. Fig. 5 of the NAL 254 proposal expected $\sim$ 50K at 7" radius and a factor of a few less at a somewhat larger radius. The true centering of the counter telescope in these runs relative to the beam is uncertain, but the rates are in the correct ballpark. In addition the energy dependence, shown in Fig. 1, is roughly correct (relative to Expt. 104's measurements (Kycia, et al.)).

June 1974: 2.5 MHz /pulse of 7.5×10^{12} pps at 7" radius and 0.5 MHz at 12" radius with $\leq$ 10% accidentals.

These coincidences are presumably due almost entirely to muons produced in the stopper. The secondary hadron beam incident on the stopper is $\sim$ few x 10^9/pulse; about 10% decay to muons over an $\sim$ 100 in^2 area, i.e. roughly $\sim$ 0.3 MHz μ/0.05 in^2 of telescope area. A large fraction of the protons pass through the target and were dumped on the upstream end of the stopper (since the train dump is inoperative at this time), i.e. some 2×10^{12} protons. The hadron feedthrough is less than 10^{-8}-10^{-9} for 15' of steel and is negligible. But the 2×10^{12} of 300-GeV protons will produce $\sim 2 \times 10^{13}$ pions of some 30 GeV each (on average); each will have > 0.2 meters in which to decay (on average), i.e. > 10^{-4} probability. This gives a plug produced μ flux of the order of > 2×10^9 over $\sim$ 100 in^2, i.e. $\gtrsim$ 1 MHz/ 0.05 in^2 area of the telescope at the close-in radius of $\sim$ 7". Also, the μ98 experiment was keeping the proton beam spray through the 4"x4" hole in the center of the stopper to less than a few $\times 10^{10}$ (measured downstream with a SEM). The "spray" from these protons in the walls of the hole and elsewhere should give a substantial singles rate (not "coincident" since

telescope "views" edges of hole only thru greater than 7' or so of steel). This spray, $\sim 10^{10}$ per ~ 100 in^2 should give a singles rate $\sim$ 5 MHz in telescope, comparable to what was seen.

Discussion

These measurements show the feasibility of μ monitoring in enclosure 100 for slow spill narrow-band running. With the anticipated 20' of stopper (15' of steel + 5' of aluminum), the hadron leakage should yield even lower singles rates at the telescope. With only secondary hadrons in the decay pipe, the plug produced muons will be nearly negligible ($\lesssim 10^{-3}$ of 2.5 MHz measured in June run) as expected. Thus the μ's from π and K decay will dominate the counting rate seen by the telescope. The accidentals should be less than 10% for intensities about 7×10^{12}ppp:

$$\text{accidental rate} = 50\ \text{MHz}\ \left(\frac{\lesssim 5\text{MHz singles}}{50\ \text{MHz RF}}\right)^5$$

$$= 0.5\ \text{KHz (at most a factor of 10 higher at smaller radii)}$$

vs. coincidence rate ≈ 70 KHz at small radii for μ from π decay and vs. at large radii ≈ 7 KHz for μ from K decay.

Detailed calculations of the radial dependence of the μ flux arising from π,K decays in the 350m decay pipe and interactions in the stopper will be checked against careful test run data to be made after approval of this proposal. Careful attention to leakage of protons from the train dump and construction of the telescope may lead to sufficient reductions in the singles rates such that even higher proton intensity can be utilized. However, a maximum of $\sim 7\times10^{12}$ ppp appears reasonable in any case. It is to be noted

that no deterioration of scintillators or phototubes at these rates (10^7/second) for 10^6 pulses has been observed by us in an experiment at the AGS; at 10^{14} particles, this may change, but it is comfortably adequate; we will remove the μ telescopes from the beam when slow spill narrow-band running is <u>not</u> in progress.

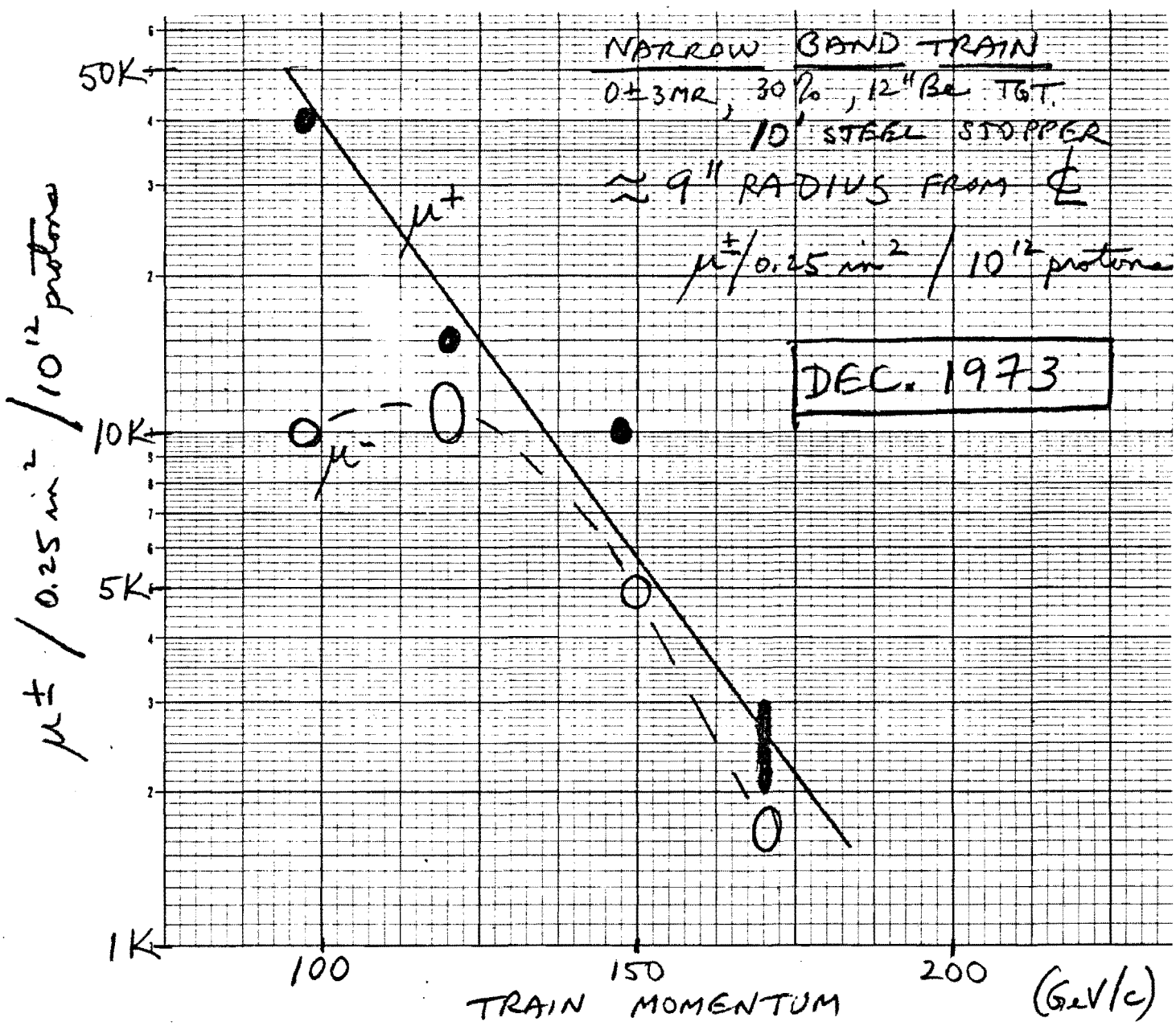

Fig 1.