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THE HIGH-ENERGY NEUTRINO BEAM IN AREA 1

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ABSTRACT

The 500-GeV high-energy neutrino beam has been tentatively designed in Area 1. On the basis of the new beam parameters muon flux distributions, neutrino energy distributions, and event rates are presented. A possibility of a low-energy beam is discussed.

I. INTRODUCTION

The 500 GeV high energy neutrino beam designed at NAL enables the operation of counter spark chamber experiments up to 500 GeV and for the operation of the 15' bubble chamber up to 400 GeV primary proton energy. The area design can be characterized by five distinct regions. The first region is comprised of a 200 feet long steel box within which the proton beam strikes a target and the secondary hadrons are focussed by magnetic elements. These hadrons enter the second region which is a 1400 feet long pipe whose diameter is 3 feet. Within this pipe a fraction of the hadrons decay to neutrinos. A 30 feet long steel box containing a high power hadron beam dump is located at the end of the decay pipe. All hadrons are stopped within this third region. Neutrinos and muons penetrate this beam dump and enter the fourth region. In this region the high energy muons are stopped by the normal ionization process. We have chosen 3300 feet of soil for this purpose. Finally emerging from the back of this soil shield the beam of neutrinos enters the final region where the bubble chamber and electronic detectors are located.

The beam will create 1 event per picture in the 15' hydrogen bubble chamber with the machine operating at 400 GeV. The requirement of analysis of high energy neutrino events in the bubble chamber is likely to demand the installment of an electronic muon detection system at the exit of the bubble chamber at a very early stage.

It should be noted that the beam design described cannot provide a high intensity low energy neutrino beam to the bubble chamber simply because of incompatibility of neutrino decay angle and the beam length. It has been suggested that an independent low energy neutrino beam be constructed at a later stage to provide a low energy neutrino beam of maximum flux to the bubble chamber.

In subsquent sections we present results of calculations.

II. MUON FLUX DISTRIBUTIONS

The muon flux calculations have been initiated by Keefe[1] in conjunction with 200 GeV Accelerator Design Study, and recently sophisticated computer programs have been developed independently by Keefe and Noble[2] and Alsmiller et. al.[3] For the latter a calculation for the tunnel geometry has been reported in TM-207. Here we have used Alsmiller's computer program to calculate and study muon flux distributions in Area 1.

He gives for a muon flux at a given depth Z, and a radial distance R from the proton direction

$$F(Z,R) = 2\pi \int_{o}^{E_o} dE_\mu \int_{o}^{\theta_{max}} d(\cos\theta) \int_{E_{\mu\,min}}^{E_{\mu\,max}} \frac{d^2N}{dp_\pi d\Omega} \left(1 - e^{-\frac{m_\pi}{p_\pi}\frac{r}{\tau_\pi \cos\theta}}\right)$$

$$\times \frac{\cos\theta}{2A_2\left(E_\mu, \frac{Z}{\cos\theta}\right)} \left[I_o \frac{2(Z+r)\ R\sin\ \cos\theta}{4A_2\left(E_\mu, Z/\cos\theta\right)} \right]$$

$$\times \exp\left\{-\frac{1}{4A_2\left(E_\mu,\frac{Z}{\cos\theta}\right)}\left(R^2\cos^2\theta+(Z+r)^2\sin^2\theta\right)\right\}$$

/ unit area . interacting proton

where E_μ = muon kinetic energy

E_o = maximum muon energy, i.e. incident proton energy

θ = pion production angle

$\frac{d^2n}{dp_\pi d\Omega}$ = double differential production spectrum of pions in a closed form. The Trilling model was used with a new set of parameters[4].

m_π = the rest mass of a pion

τ_μ = the lifetime of a pion

r = the radius of the decay tunnel

I_o = a modified Bessel function

A_2 = the mean square deviation of the Coulomb scattering distribution in the Eiges formula (Gaussian)[5]

Assuming a small angle approximation and a constant energy loss the above formula is reduced to a simpler one, which is identical to the formula used by Keefe and Noble.

Muon isoflux distributions around the decay tunnel are shown in Figs. 1, 2 and 3 resulting from the two programs for the same geometry. The agreement is good. The small difference is due to different muon energy loss data and other different parameter value (radiation length).

In both calculations, a Gaussian shape of the Coulomb scattering was used rather than a Moliere type. This approximation will have least effect in the beam direction. Independent calculations indicate there is a small increase of the flux laterally if the Moliere theory is used.

The range straggling is not included in this calculation but according to Sternheimer's theory[6] the muon range straggling increases steadily with energy up to 100 GeV and then flattens out (8.4% at 500 GeV). In Fig. 4 we show a calculation up to muon energy of 500 GeV. We have reserved 20% of the shielding thickness against the straggling effect. Thus we anticipate the present beam design is adequate for approximately 400 GeV bubble chamber operation and for 500 GeV counter-spark chamber operation.

In Figs. 5 and 6 we show muon isoflux distributions for 200 GeV and 500 GeV operations. For 500 GeV operation an appropriate earth shield would be of radius 6 m, assuming a muon flux level of 10^5 muons/m^2 pulse laterally.

The kaon contribution to isoflux curves has not been included in these calculations but it is estimated to increase somewhat the lateral shielding.

III. NEUTRINO FLUX DISTRIBUTIONS AND EVENT RATES

In Fig. 7 we show neutrino flux distributions for 200 GeV, 300 GeV, 400 GeV and 500 GeV operations, respectively. The beam parameters used are as follows: decay length =

450 m, shield length = 1000 m, bubble chamber to end of shield distance = 22.5 m, decay tunnel radius = 0.5 m, and detector radius = 1.35 m. We assumed perfect focusing for simplicity. A neutrino flux for real focusing is in practice obtained by roughly 0.5 times the flux for perfect focusing. We mean by this that a real magnetic focusing device can be built which achieves essentially 50% efficiency in directing neutrinos through the bubble chamber.

The Hagedorn-Ranft particle production model was used in the above calculation. The pion spectrum by this model is probably over estimated at the higher energies.[7] It also predicts pion multiplicity and K to π ratio. The values of multiplicity and K to π ratio at 400 GeV is 6.5 and 0.28, respectively. The recent cosmic ray data gives 5.4 for total multiplicity at 400 GeV.[8] However, this K to π ratio of 0.28 is somewhat higher than the value of 0.20, which is indicated in the cosmic ray experiments. It should be emphasized that the high energy flux contributed from the K decays should be considered with reservation. For example, the C.K.P. particle production model predicts approximately a hundred times fewer 300 GeV neutrinos than the Hagedorn-Ranft model.

We observe in Fig. 7 that there is a substantial reduction in neutrino flux at 200 GeV operation compared with 400 GeV operation despite the fact that the particle multiplicity increase from 200 GeV to 400 GeV is only 12%. This is primarily due to a high production rate of low energy neutrinos at 200 GeV and the low efficiency of low energy neutrinos hitting a detector.

In Fig. 8 and 9 we show event rate distributions as a function of neutrino energy for 200 GeV and 400 GeV, respectively. The target materials are H_2 (0.06 g/cc), D_2 (0.12 g/cc), Neon (1.2 g/cc) and TST (H_2) and the fiducial volume was assumed to be 20 m^3 except TST (4.7m^3). The total cross section is assumed to be $0.8 \times 10^{-38} E_\nu cm^2$.

In Table I we give events/hr and events/picture for 400 GeV and 200 GeV operations, respectively. The proton intensity was assumed to be 3×10^{13} interacting protons per pulse.

If we assume that all the neutrino events are equally interesting, the 400 GeV operation is superior to the 200 GeV in the event rate per hour (60% better) and event rate per picture (three times better). For the first operation of the bubble chamber the hydrogen target is likely to be used because other targets are expensive. Thus the first operation of the H_2 bubble chamber at 400 GeV will yield about one event/picture and ~ 100,000 events/week. At 400 GeV operation about 60% of events will be found in the energy region less than 35 GeV. Due to the difficulty of muon identification at these high energies a hybrid system will be required at a very early stage.

IV. LOW ENERGY NEUTRINO BEAM

The beam which we have designed contains low energy neutrinos (less than 15 GeV) at a much reduced rate compared with an optimally designed low energy neutrino beam using a short iron shield. This is due to the fact that low energy neutrino decay angles are too large for neutrinos to hit the detector in most cases.

We have designed an independent beam for 100 GeV primary protons and show the neutrino energy distribution in Fig. 10 and event rate distributions for H, D and TST in Fig. 11. The over-all event rates are added in Table I. We also compared event rates with other cases which are presented in Fig. 12.

The event rate is superior to the high energy beam in the energy range of 2.5 to 18 GeV, and is better at 5 GeV by a factor of 30 compared with 200 GeV operation of our chosen design for the neutrino beam. Certainly, this kind of low energy beam is ideal for exploring in detail with excellent statistics, the physics of neutrino interactions at less than 18 GeV.

V. CONCLUSIONS

We conclude the following features in this high energy neutrino beam:

1) The event rate for 400 GeV operation:
one event/picture and one event/three pictures for H_2 and TST (H_2), respectively. For neon filling of the bubble chamber the beam intensity may have to be substantially lowered.

2) The soil shield can be built with minimum cost and with the minimum uncertainty in the level of the background muon flux around the bubble chamber.

We acknowledge the installment of Alsmiller's computer program at NAL by M. Awschalom and D. Theriot, Radiation Physics Section, and appreciate A. Nelson's help in programming.

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EVENT RATE

		H_2	D_2	Neon	TST
400 GeV D = 450 m S = 1000 m	Event/hr	673	1346	13460	221.7
	Event/picture	1.12	2.24	22.4	0.36
200 GeV D = 450 m S = 1000 m	Event/hr	425	851	8508	119.4
	Event/picture	0.36	0.72	7.2	0.1
100 GeV D = 200 m S = 75 m	Event/hr	1415	2829	28290	583
	Event/picture	0.78	1.56	15.6	0.33

Table I

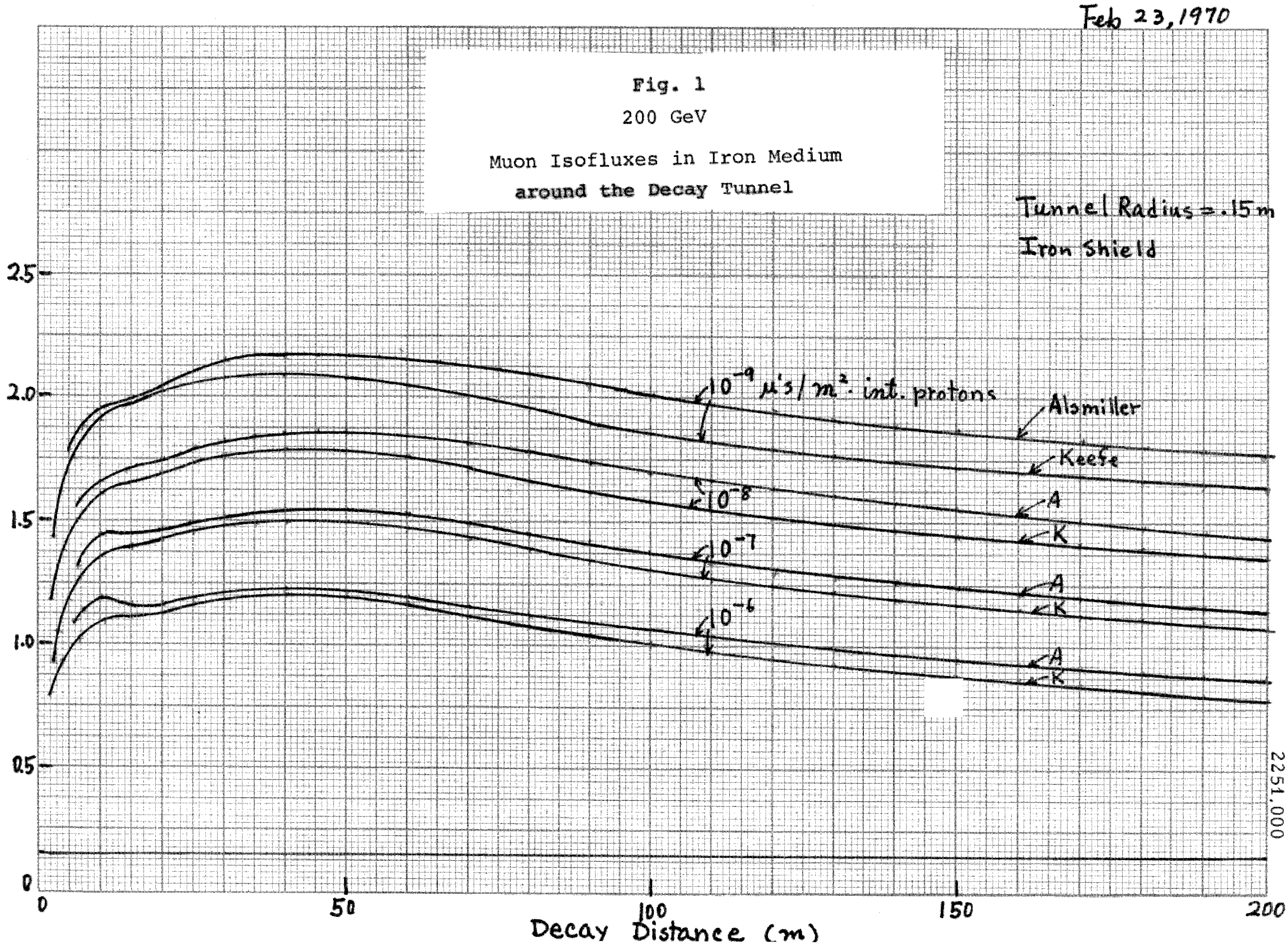

Fig. 1
200 GeV
Muon Isofluxes in Iron Medium
around the Decay Tunnel

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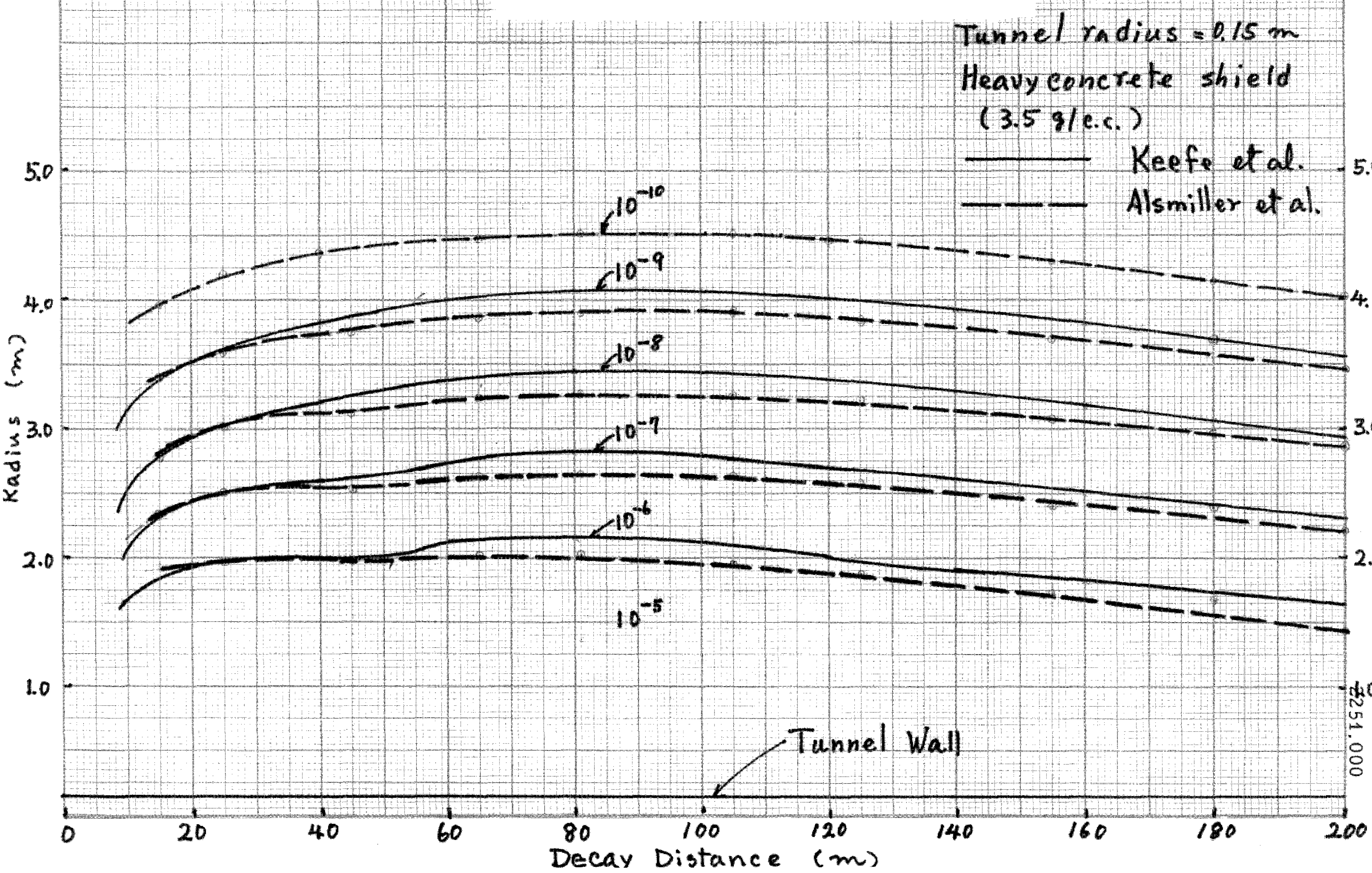
Fig. 2
200 GeV
Muon Isofluxes in Heavy Concrete
around the Decay Tunnel



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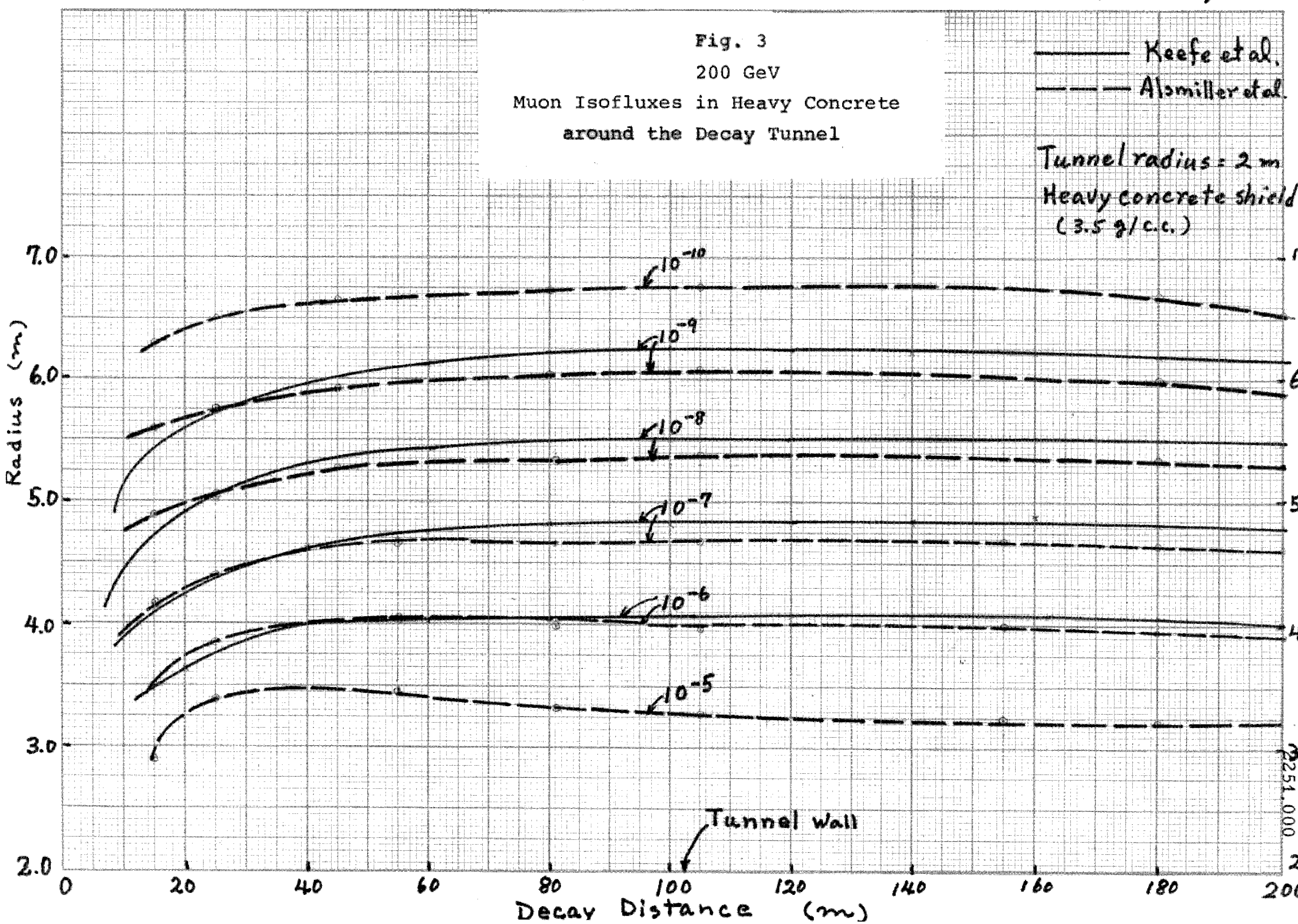

Fig. 3
200 GeV
Muon Isofluxes in Heavy Concrete
around the Decay Tunnel

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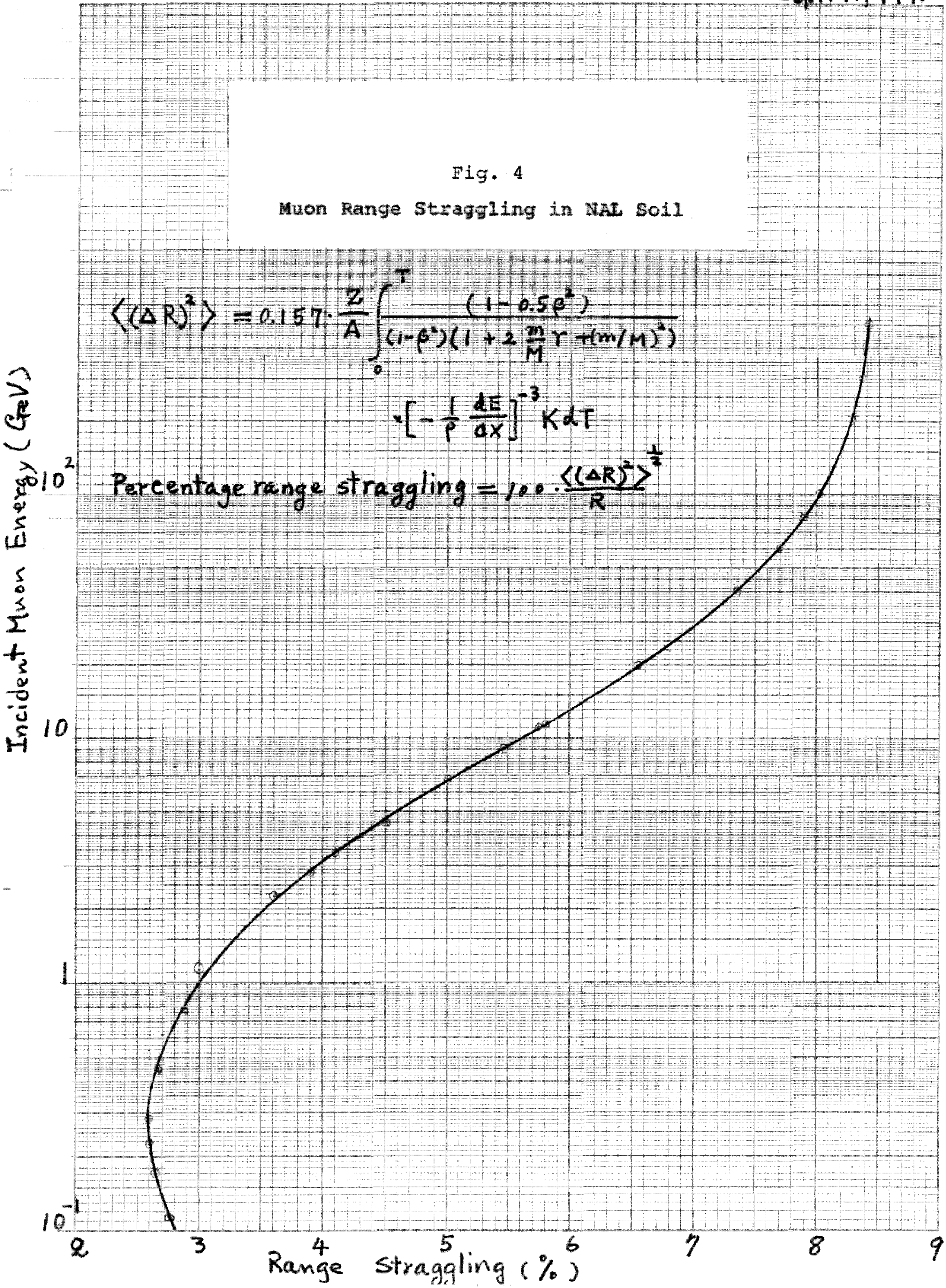


Fig. 4

Muon Range Straggling in NAL Soil

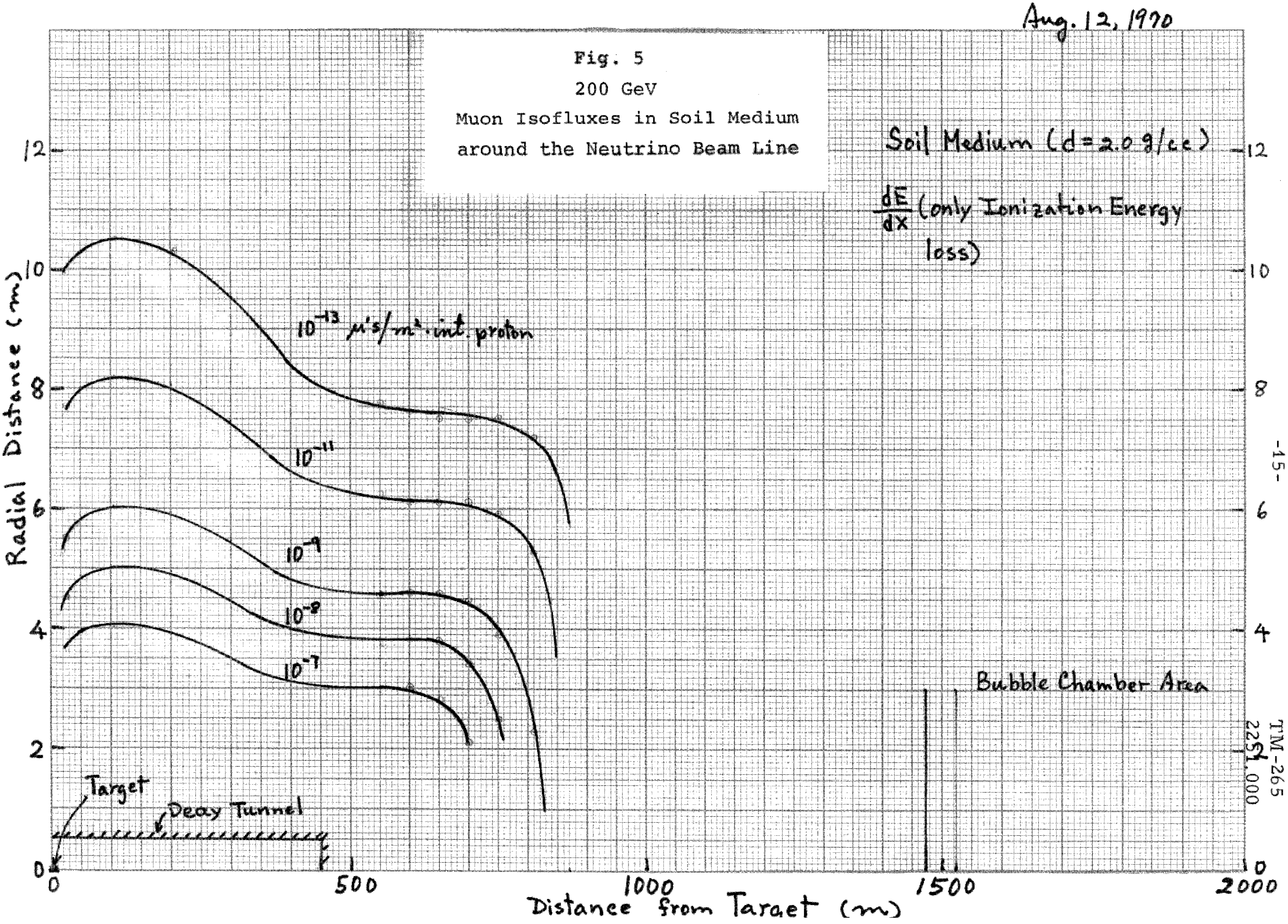


Fig. 5
200 GeV
Muon Isofluxes in Soil Medium
around the Neutrino Beam Line

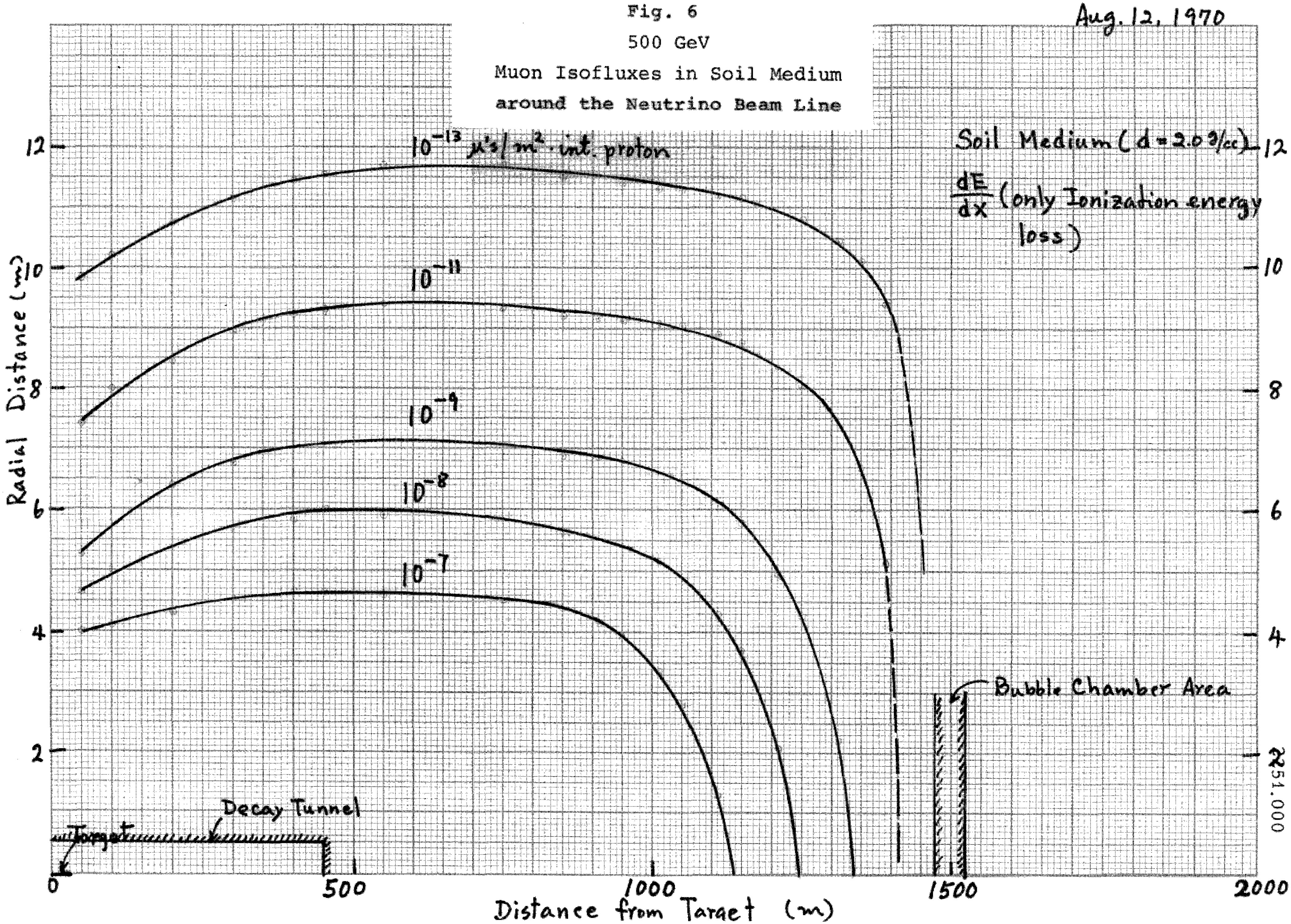
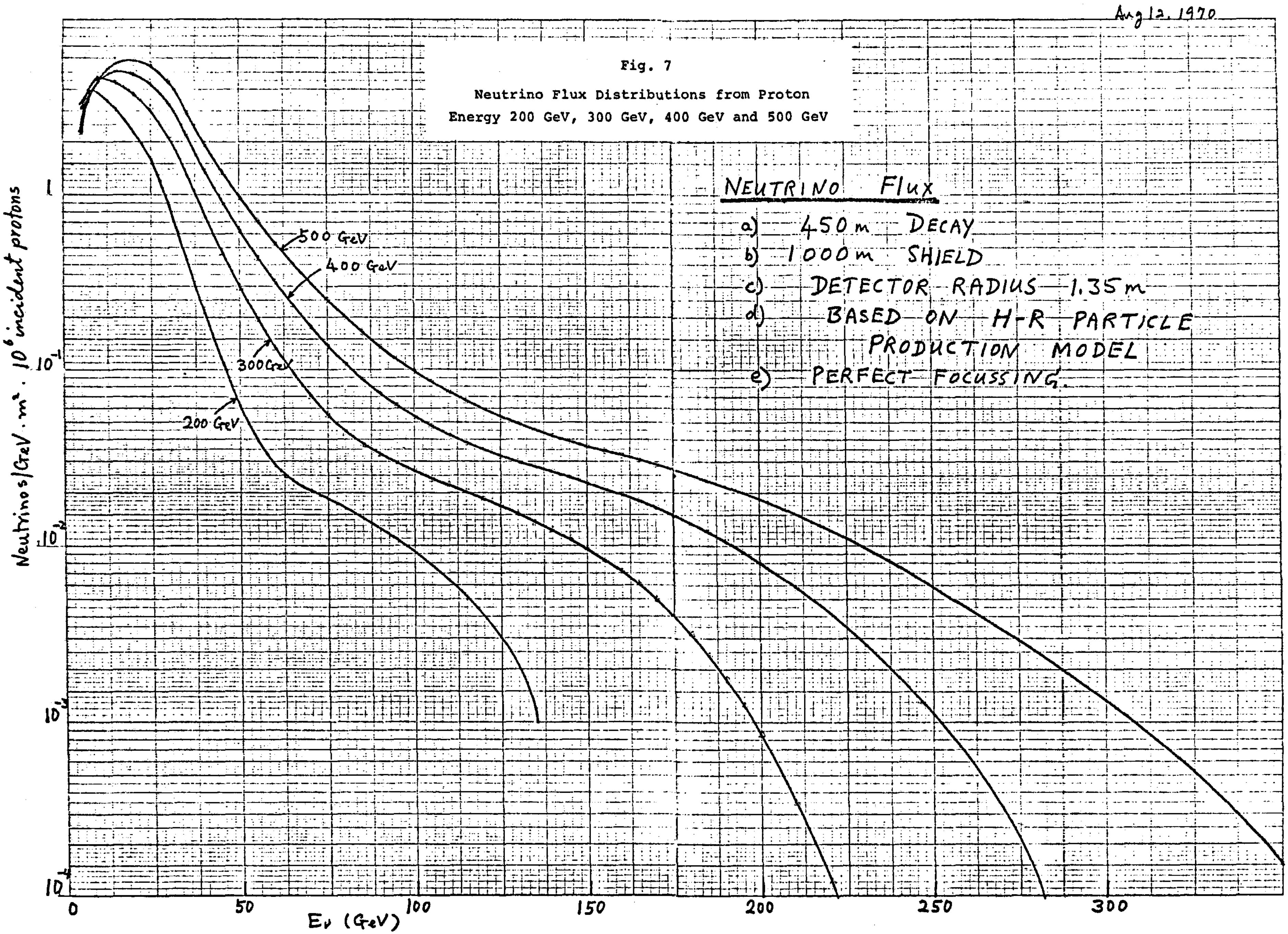


Fig. 6
500 GeV
Muon Isofluxes in Soil Medium
around the Neutrino Beam Line



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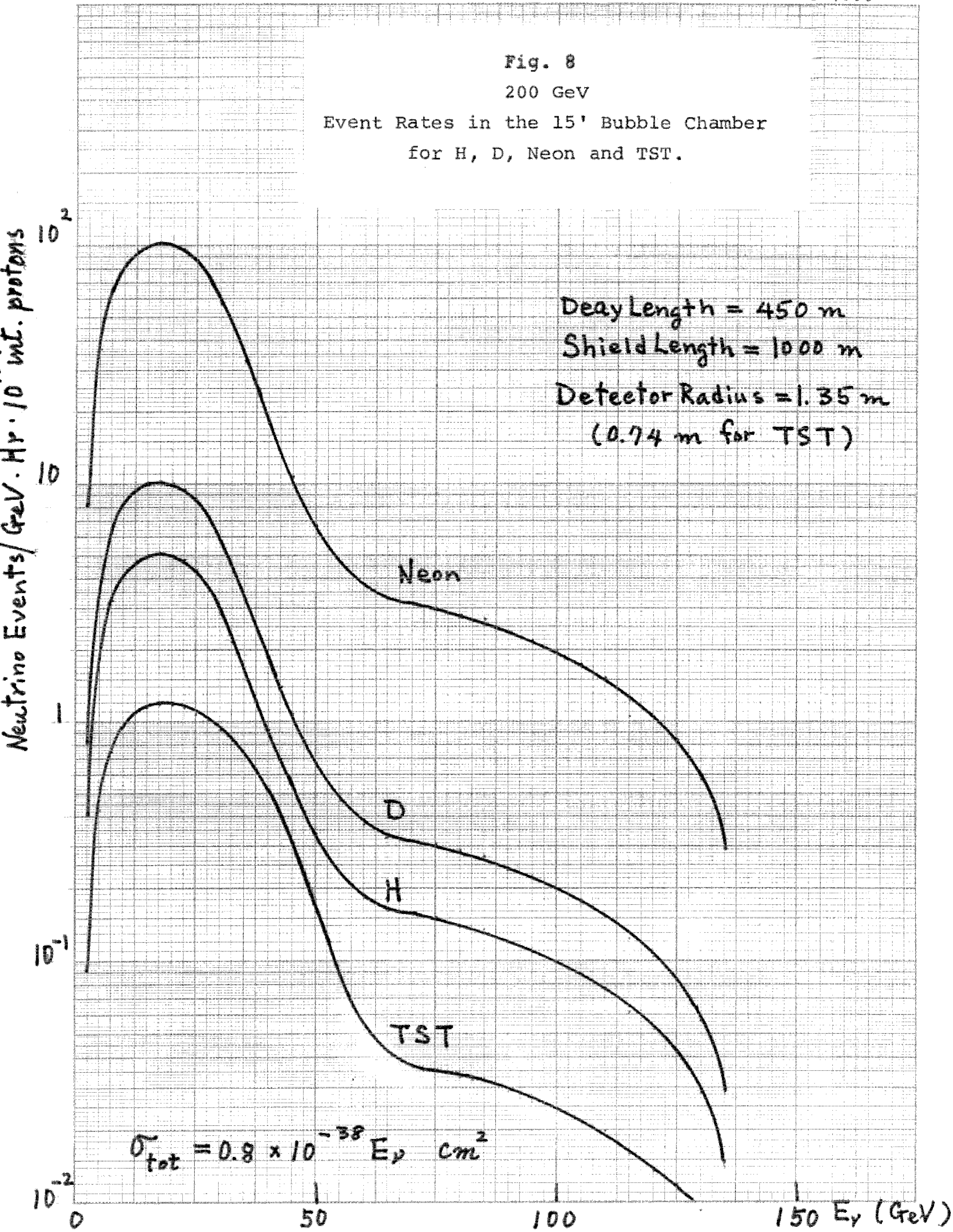

Fig. 8
200 GeV
Event Rates in the 15' Bubble Chamber
for H, D, Neon and TST.

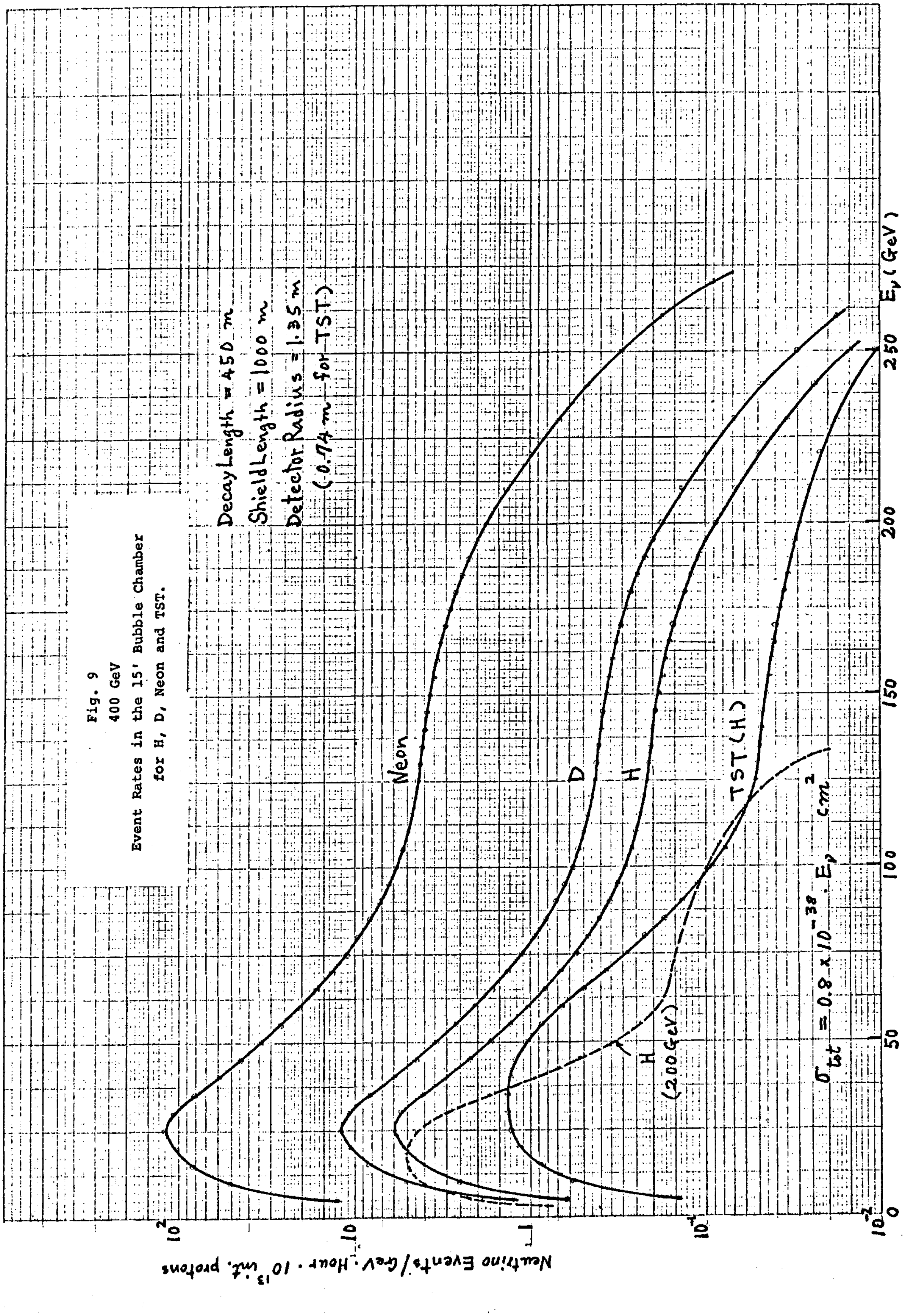

Fig. 9
400 GeV
Event Rates in the 15' Bubble Chamber
for H, D, Neon and TST.

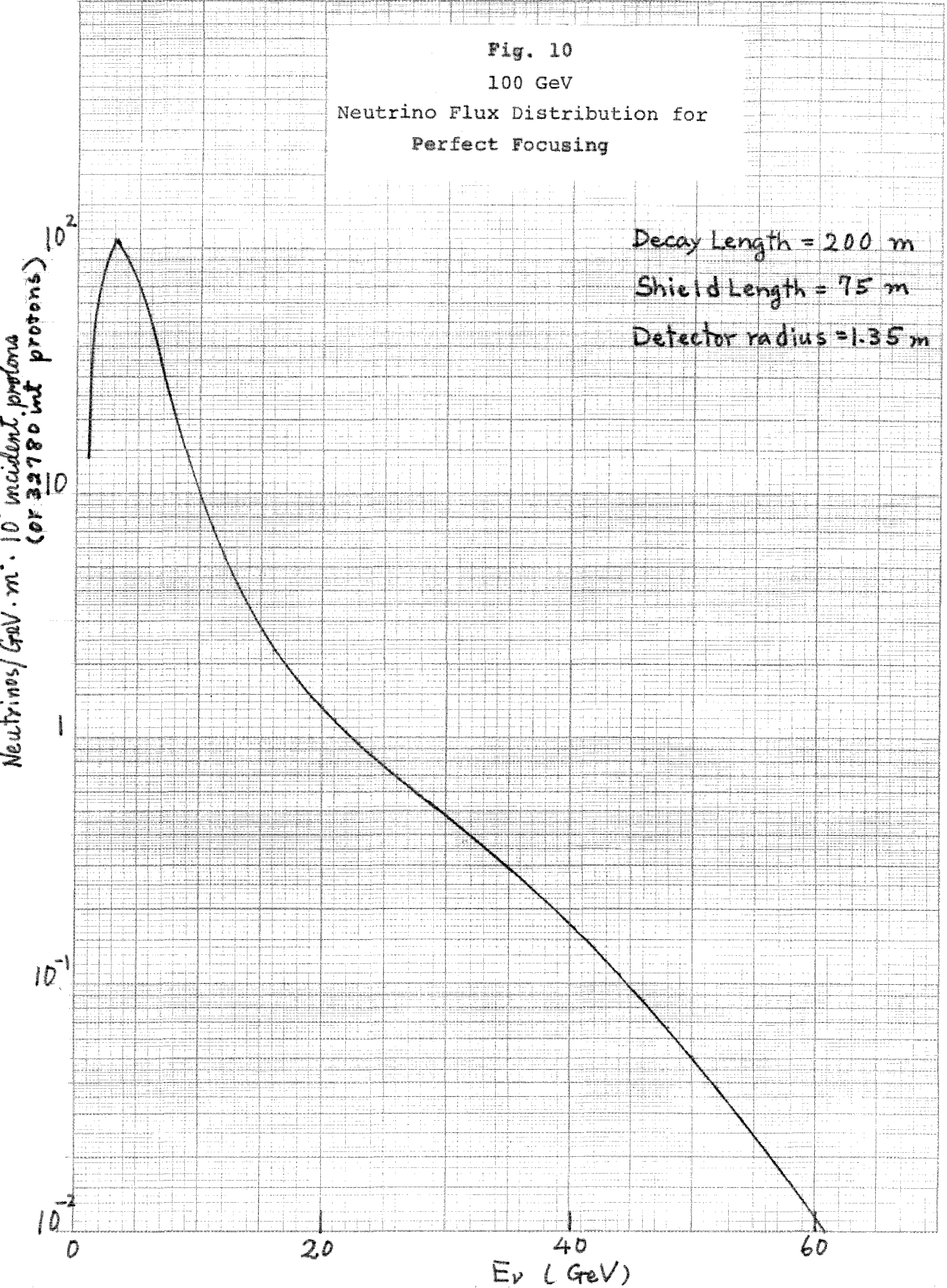

Fig. 10

100 GeV

Neutrino Flux Distribution for

Perfect Focusing

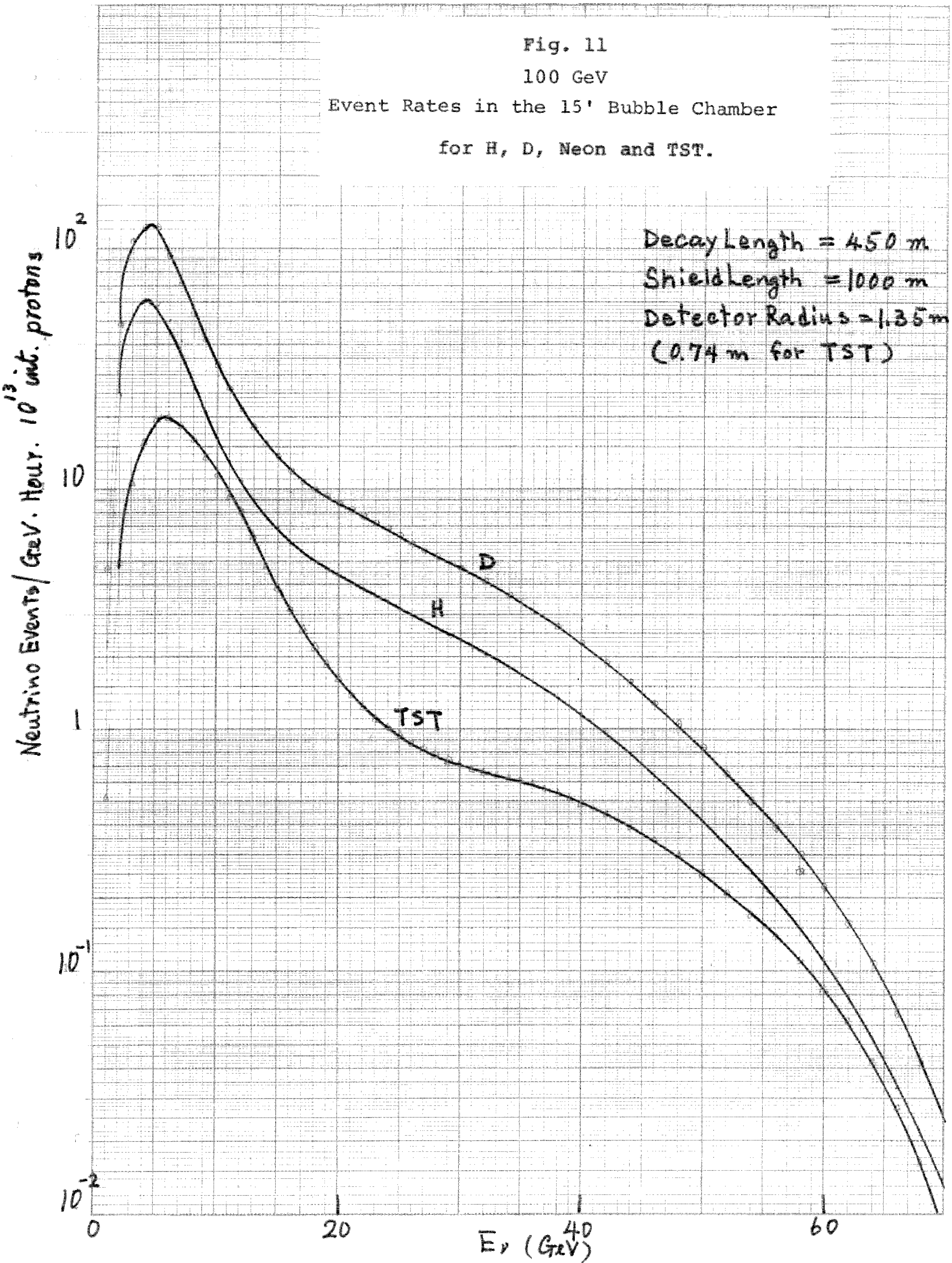
Fig. 11
100 GeV
Event Rates in the 15' Bubble Chamber
for H, D, Neon and TST.
Decay Length = 450 m
Shield Length = 1000 m
Detector Radius = 1.35 m
(0.74 m for TST)
D
H
TST
Neutrino Events / GeV. Hour. 10^13 int. protons
10^2
10
1
10^-1
10^-2
0
20
40
60
Eν (GeV)

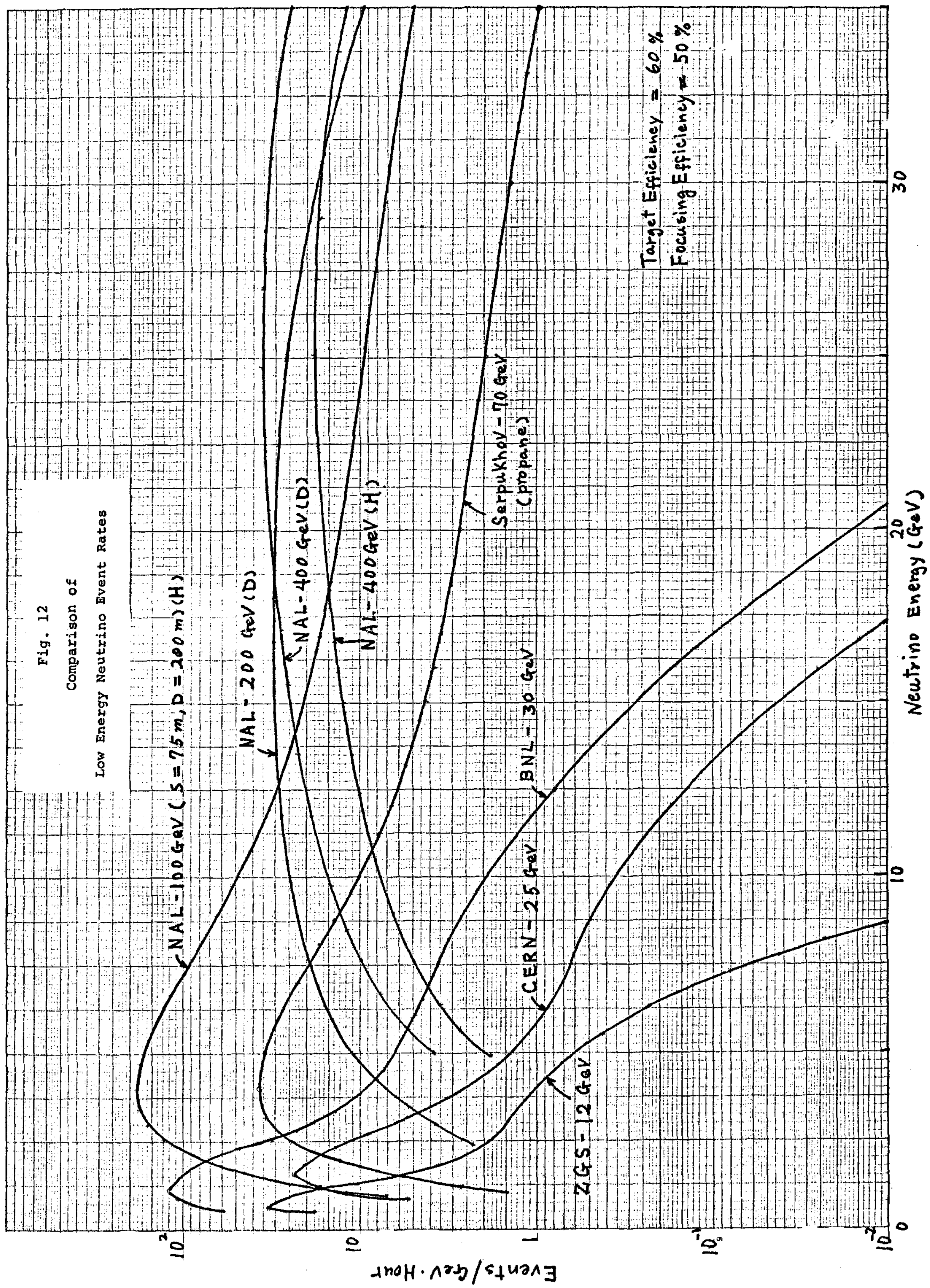

Fig. 12
Comparison of
Low Energy Neutrino Event Rates