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INITIAL STUDIES OF GEANT and COMPARISONS with EGS

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1 Introduction

The present UCI and Queens Monte Carlos use SLAC's EGS program to propagate electrons and gammas in the detector. This is arguably the best such program around but unfortunately does not propagate muons or hadrons. GEANT, developed at CERN primarily for the current complex high energy detectors, does propagate muons and hadrons, as well as electromagnetic showers. This report presents some of the results of initial studies of GEANT and comparisons with EGS.

2 Material Generation

EGS defines the media and calculates such quantities as radiation length by generating a so-called PEGS file. This is a one time operation and all future calculations using EGS simply read this file. If new material are added at a later date, then the PEGS filed must be regenerated. GEANT has built in the properties of 15 basic elements (^1H, ^2H, He, Li, Be, C, N, Ne, Al, Fe, Cu, W, Pb and U) and has the ability to generate the properties of other elements and compounds with a call to a subroutine whose input requires the chemical composition and density of the compound. These routines are a permanent part of the MC program and are called each time the MC is run. D_2O, H_2O and Acrylic ($C_5H_8O_2$) were generated and comparison of the radiation lengths and absorption lengths with the APS blue book values are shown in Table I.

3 Geometry Definition

It will be in this phase of the MC that the greatest incompatibilty will occur when one tries to switch between EGS and GEANT. When using EGS it is the programmers responsibility to keep track of where and in what medium any given particle is via user written programs called AUSGAB and HOWFAR. It is in these two routines that the major programming effort is made when applying EGS.

GEANT defines the geometry with calls to subroutines which define a wide assortment of shapes including spheres, cones, cylinders, parallelopipeds, tetrahedrons etc, and what material each region is filled with. GEANT then transports particles (hadrons, muons, electrons and gammas) through the detector, automatically tracking which region the particle is in and generating the various interactions and energy losses. Should new particles be generated in an interaction, GEANT will place them on a stack and return to them later in the event. GEANT requires the ZEBRA dynamical memory management programs, but it is transparent to the user.

Neither EGS or GEANT transports Cerenkov photons, which is just as well since the user generated Cerenkov photon transportation code should be independent of which code is used and will make any EGS/GEANT comparison more direct.

4 GEANT-EGS Comparison for Electromagnetic Showers

Table II compares the physics input to GEANT and EGS for the various electromagnetic processes. The number of Cerenkov photons generated by 5-2000 MeV/c electrons traversing H_2O were calculated using EGS and GEANT, with the results presented in Fig 1 as a ratio. The two programs agree to 1% or better with a slight systematic shift occuring below 100 MeV/c. Since the percentage difference between the two programs exceeds the energy resolution by about an order of magnitude, GEANT can be used for low energy electron and photon events.

5 Transportation of Hadrons and Muons with GEANT

GEANT has the ability to generate and track hadronic events such as

$$\pi + {}^{16}\mathrm{O} \rightarrow \text{pions} + \text{protons} + \text{neutrons}$$

One such interaction is shown in Fig 2 which shows GEANT tracking the $\pi \rightarrow \mu \rightarrow e$ decay chain, the Michel electron shower, neutrons and protons from the nuclear breakup, and a subsequent (n,γ) reaction.

High energy muon events from cosmic rays ($\approx$ 0.1/minute), and from neutrino interactions ($\approx$ 1/day) will occur in SNO, and a Monte Carlo will be required to study these events. Results are presented for the range, range straggling, lateral spread and δ ray production for 200-2000 MeV/c muons traversing various materials. GEANT has the ability to turn δ ray production on and off, and studies are made for both cases, since 10% of the Cerenkov photons generated by muons come from δ ray production. This is shown in Fig 3, where the total number of Cerenkov photons as a function of momentum is shown along with the δ ray contribution for muons traversing H_2O.

Fig 4 shows the GEANT calculated range of muons in H_2O as a function of momentum. At 2 GeV/c the ranges differ by 5% with the δ rays turned on and off. A simple integration of dE/dx for muons in water gives a result in agreement with the δ ray off result. In an attempt to determine which calculation is more reliable, the GEANT range results for muons in scintillator are compared with the calculations of Martin Barger of the NBS. Fig 5 shows the percentage difference between the ranges calculated by Barger and GEANT both with δ ray production on and off. Here the GEANT calculations with δ ray production turned on yields the better agreement by about a factor of two over the δ ray off result. The agreement is within 3.5% of Barger's calculation at the lower momenta and improves with increasing muon momentum. Another comparison was made for protons in scintillator, and here much better agreement with Barger is obtained when GEANT turns on the δ rays , as shown in Fig 6. The agreement is within 5% for low kinetic energy protons (250 MeV) and improves to 2% at higher energies. Digging up some range straggling data taken at LBL (LBL-791) a comparison is made with the GEANT predictions with and without δ rays . This is shown in Fig 7, with the data falling between the δ ray on/off calculations with the δ ray off calculation being favored.

The net result of all this is that it is not clear whether or not the δ ray production in GEANT produces the more reliable results. δ ray production produces better agreement with Barger's calculations, but turning δ ray production off produces better agreement with some old LBL data, and a simple integration of the muon dE/dx function.

The lateral spread of muons after traversing 10 cm of scintillator is compared with the calculations using APS blue book formula.

$$\Delta z = (\frac{1}{\sqrt{3}})(\frac{14.1}{p\beta})L\sqrt{\frac{L}{42.4}}[1+\frac{1}{9}log_{10}(\frac{L}{42.4})]$$

As can be seen in Fig 8 the agreement is excellent. The GEANT calculations used the Moliere theory of multiple scattering, but is also capable of using a Gaussian distribution for the lateral scattering. This was tried and as can be seen in Fig 9 the agreement with the blue book is poorer.

Finally a comparison is made between the Kamioka Monte Carlo and GEANT for the number of Cerenkov photons generated by muons traversing water. The comparison is presented as a ratio in Fig 1 where it is seen that there are differences ranging between -2.5% and +6% between the two calculations. Using the GEANT result would mitigate the atmospheric ν_μ deficiency claimed by Kamioka since the momentum calibration is now altered.

6 Summary

GEANT and EGS agree to $\approx$ 1.0% in the calculation of the number of Cerenkov photons generated by electrons between 5 and 2000 MeV/c. There are some inconsistency problems at the 5% level for muons when the δ ray production is turned on and it is not clear if turning δ ray production on yields more reliable results. It is important that the δ ray production be calculated properly for muons since it accounts for 10% of the total number of Cerenkov photons generated by a muon, and doing it improperly can work towards producing physics results such as atmospheric ν_μ deficiencies. The geometrical definition of the detector is handled very differently in EGS and GEANT, and will require considerable effort to be able to easily switch back and forth in a Monte Carlo simulation.

TABLE I

GEANT/APS Blue Book Comparison

Material	Rad Len (cm)		Abs Len (cm)	
	GEANT	APS	GEANT	APS
H_2	865	865	790	718
H_2O	35.7	36.1	95.0	84.9
D_2O	39.1	-	92.8	-
Lucite	34.0	34.4	79.5	70.8

	EGS	GEANT
Medium	Any chamical element compound or mixture	Same
Energy region	0.1 MeV - 100 GeV	Same
Pair production	Bethe-Heitler theory with Coulomb and empirical corrections Average angle	Semiempirical total cross-section, others are same
Compton scattering	Klein-Nishina formula	Empirical total, Klein-Nishina differential cross-section
Photoeffect	Cross-section from Storm, Israel $E_e = E_\gamma - E_k(Z) + m$	Empirical cross-section (fitted to Storm's data) $E_e = E_\gamma - E_k(Z) + m$
Bremsstrahlung	Bethe-Heitler with with Coulomb and empirical corrections Average angle Continuous energy loss from soft photons	Semiempirical total cross-section, others are same
δ-rays	Moller-Bhabha cross-sections	Same
e^+e^- annihilation	Heitler's formula	Same
Ionisation	Restricted stopping power formula of Berger and Seltzer	Same
Multiple scattering	Moliere theory, lateral deviation in position neglected	Gaussian distribution, lateral deviation calculated

Table II

Comparison of EGS and GEANT (e.m. physics)

Figure Captions

- Fig 1) a) EGS/GEANT ratio of the number of Cerenkov photons generated by electrons traversing water as a function of momentum. b) Kam II MC/GEANT ratio of the number of Cerenkov photons generated by muons.
- Fig 2) Hadronic $\pi + {}^{16}O$ event generated by GEANT.
- Fig 3) Relative number of Cerenkov photons generated by electrons, muons, and δ rays from muons in water.
- Fig 4) Muon range in H_2O vs momentum with δ ray production on and off.
- Fig 5) Range difference in percent between NBS and GEANT calculations for muons in scintillator, with δ ray production on and off.
- Fig 6) Range difference in percent between NBS and GEANT calculations for protons in scintillator, with δ ray production on and off.
- Fig 7) RMS range straggling of muons.
- Fig 8) Transverse spread of muons after passing through 10 cm of scintillator. Comparison of GEANT using Moliere theory and the Blue Book formula.
- Fig 9) Transverse spread of muons after passing through 10 cm of scintillator. Comparison of GEANT using a Gaussian transverse distribution and the Blue Book formula.

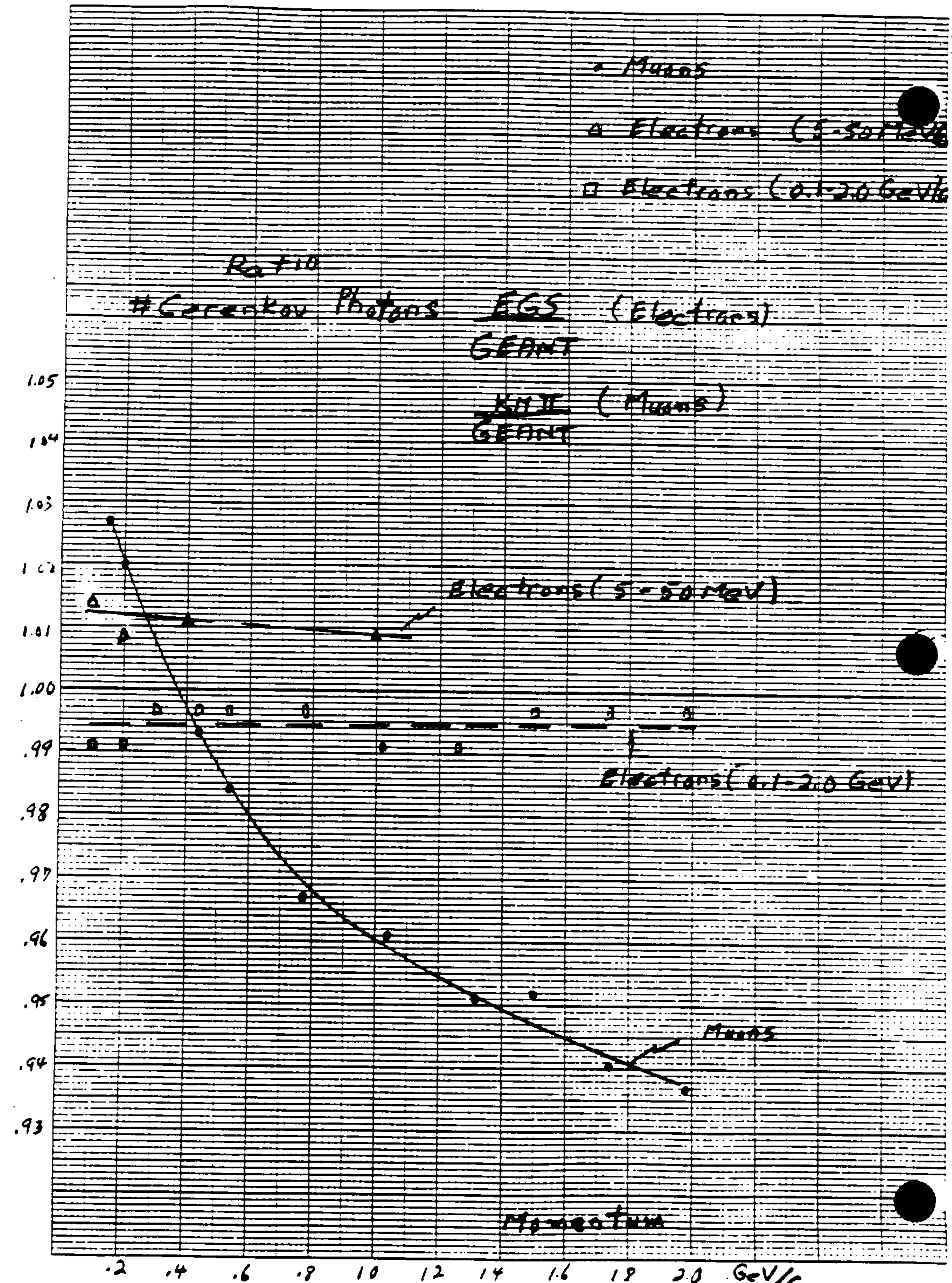

• Muons
△ Electrons (5-50 MeV)
□ Electrons (0.1-2.0 GeV)
Ratio
Cerenkov Photons EGS/GEANT (Electrons)
KMII/GEANT (Muons)
1.05
1.04
1.03
1.02
1.01
1.00
.99
.98
.97
.96
.95
.94
.93
Electrons (5-50 MeV)
Electrons (0.1-2.0 GeV)
Muons
Momentum
.2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 GeV/C
10 20 30 40 50 MeV/C

Fig 1

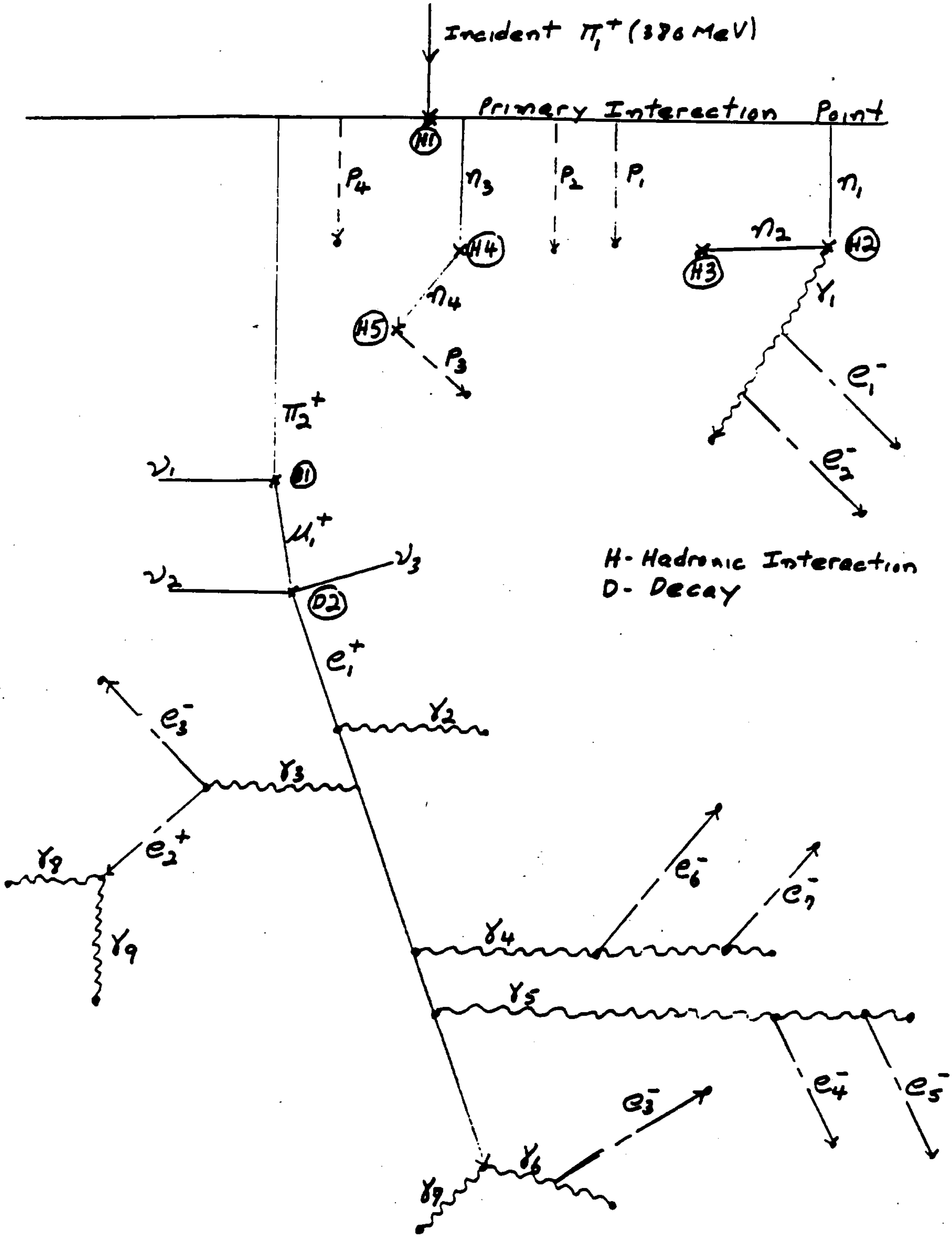

Incident π₁⁺ (380 MeV)
Primary Interaction Point
H1
p4
n3
p2
p1
n1
n2
H4
H2
H3
n4
H5
γ1
p3
e1⁻
π2⁺
e2⁻
ν1
D1
μ1⁺
ν3
ν2
D2
H- Hadronic Interaction
D- Decay
e1⁺
e3⁻
γ2
γ3
e2⁺
γ9
γ9
e6⁻
e7⁻
γ4
γ5
e4⁻
e5⁻
e3⁻
γ6
γ9

Fig 2

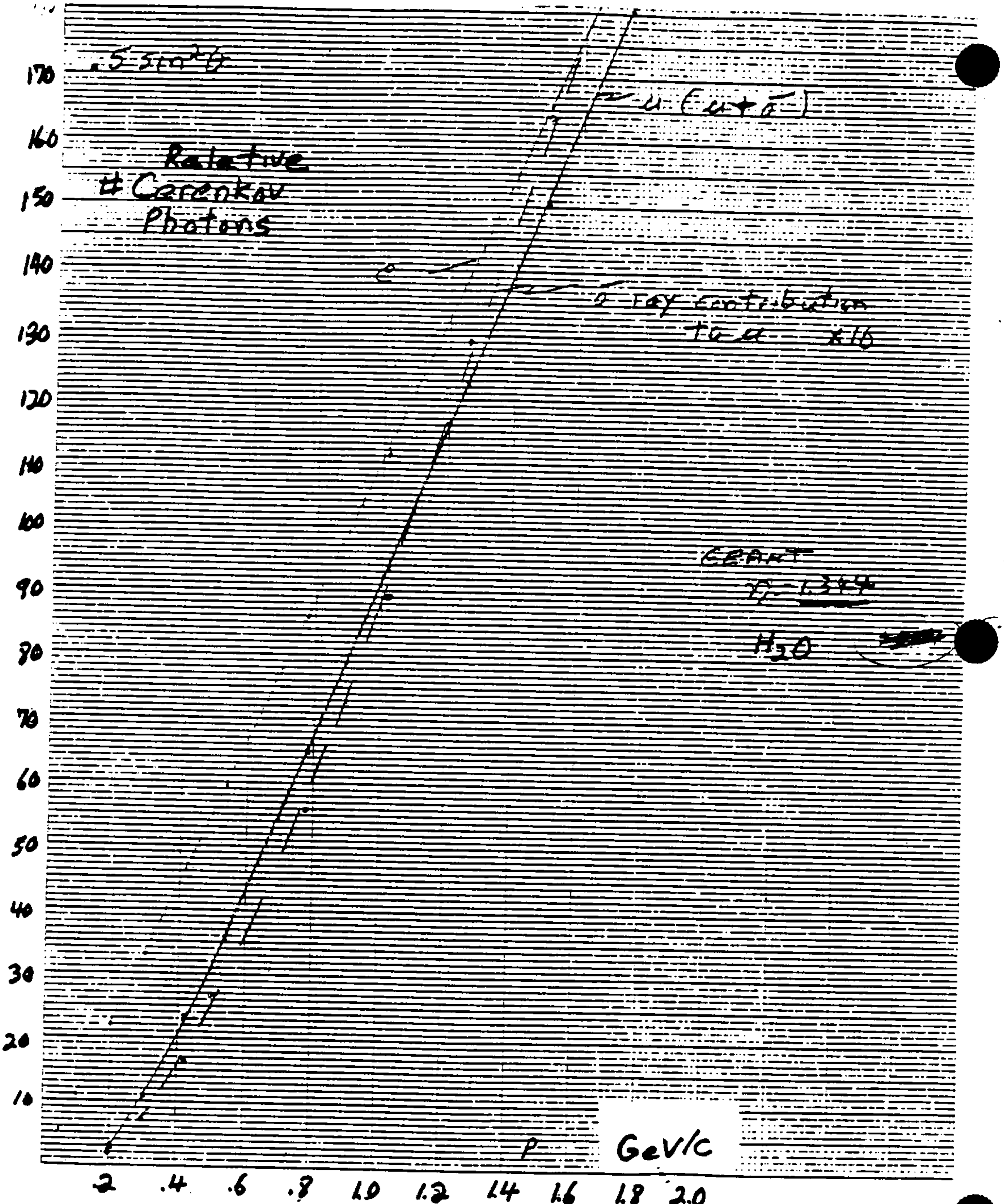

Relative
Cerenkov
Photons
H2O
GeV/c
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10

Fig 3

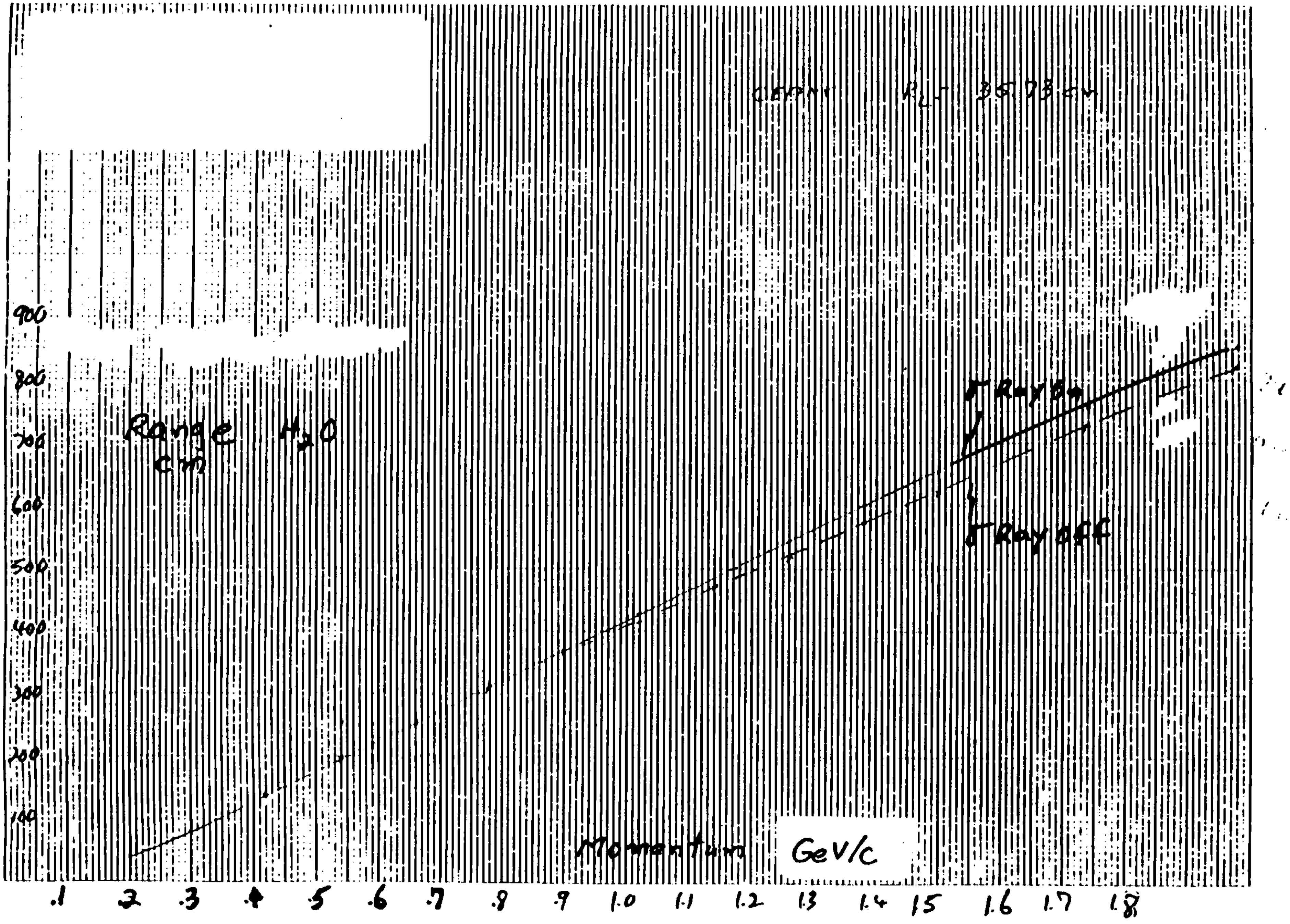

Range H2O cm
Ray on
Ray off
Momentum GeV/c
900
800
700
600
500
400
300
200
100
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
p

Fig 4

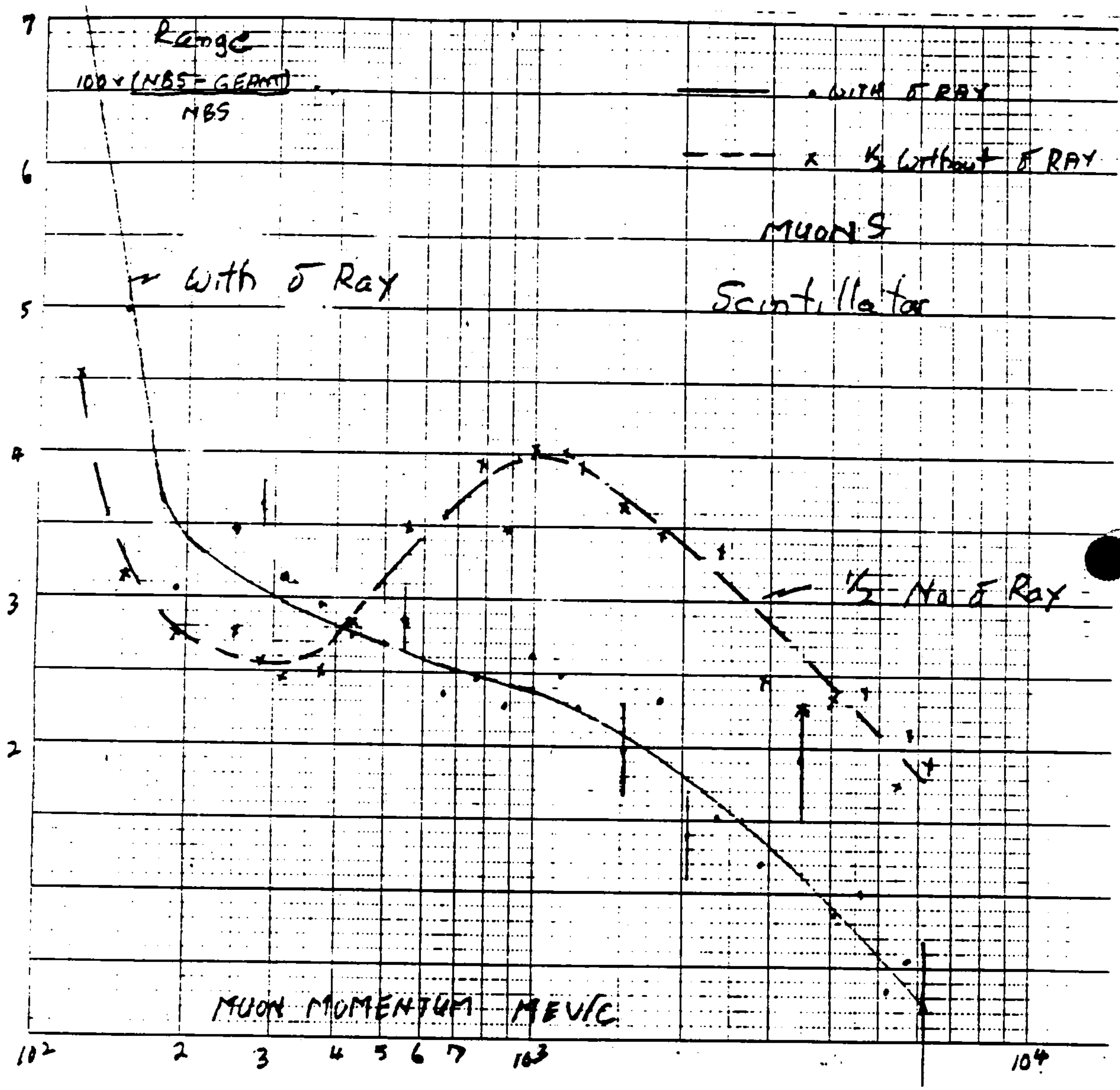
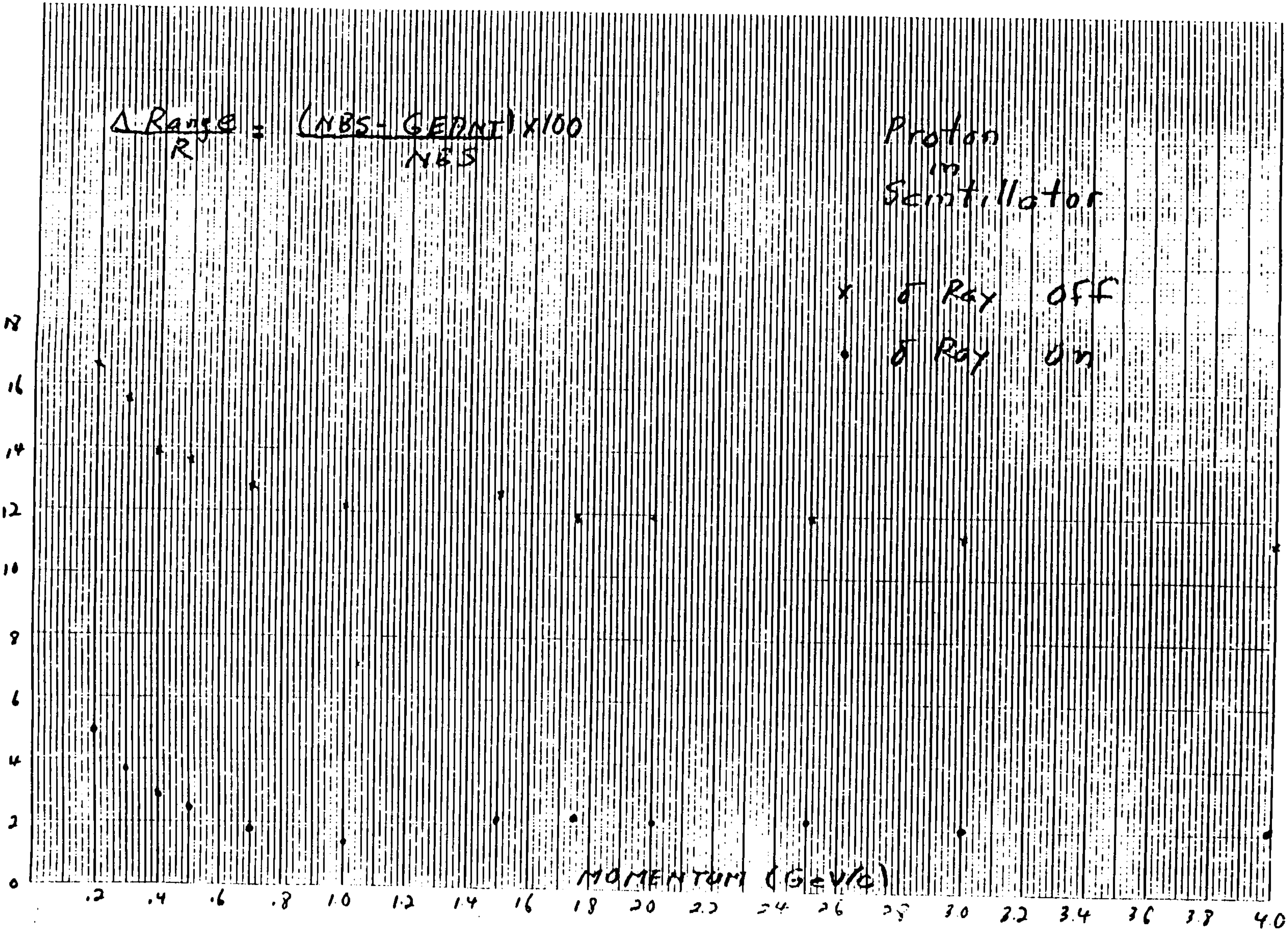

Range
100 × (NBS − GEANT) / NBS
• WITH δ RAY
× ½ Without δ RAY
MUONS
Scintillator
With δ Ray
½ No δ Ray
MUON MOMENTUM MEV/C
7
6
5
4
3
2
10²
2
3
4
5
6
7
10³
10⁴

Fig 5



$\frac{\Delta Range}{R} = \frac{(NBS - GEANT)}{NBS} \times 100$
Proton in Scintillator
× δ Ray Off
• δ Ray On
MOMENTUM (GeV/c)
0
2
4
6
8
10
12
14
16
18
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0

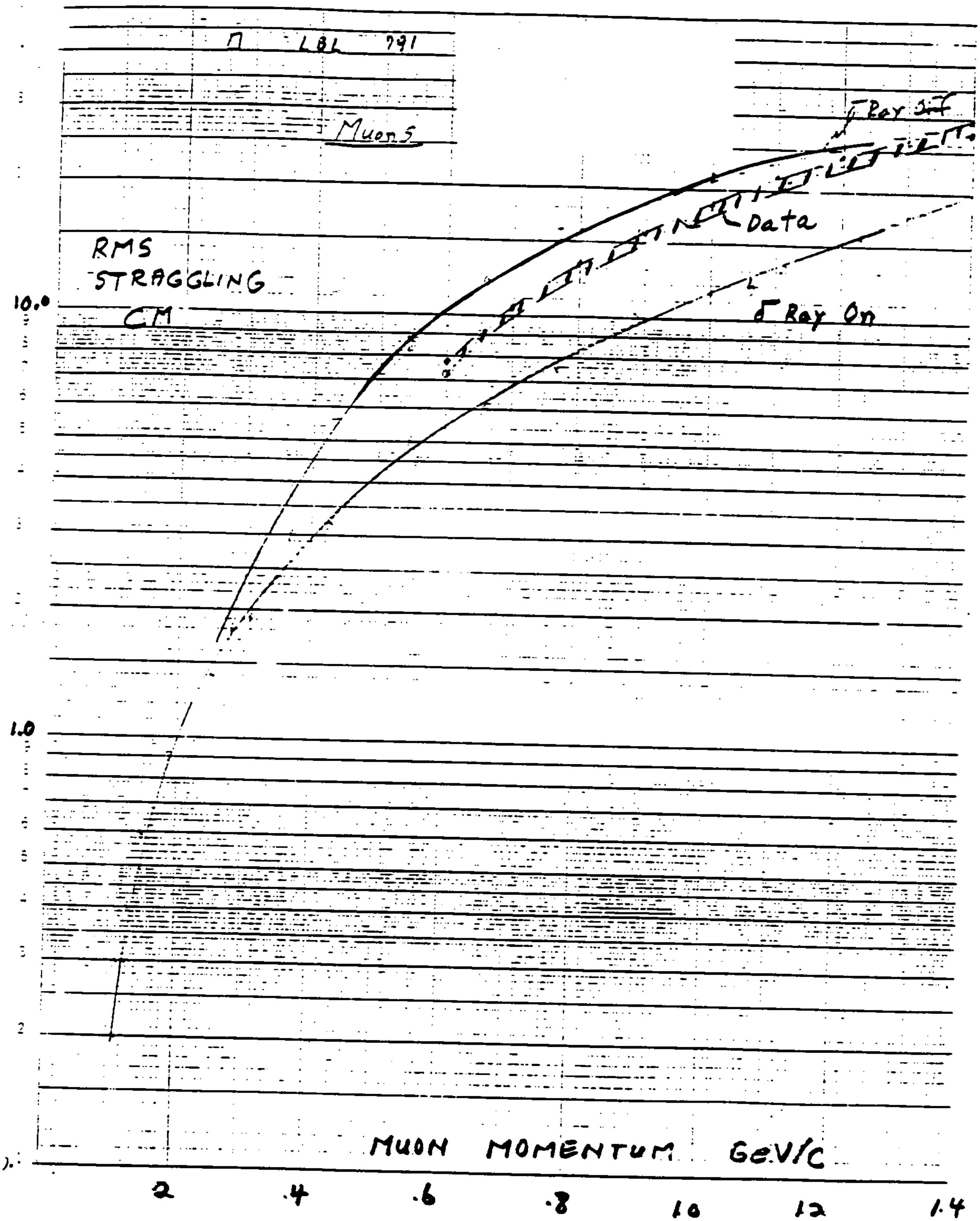

LBL 791
Muons
RMS STRAGGLING CM
10.0
1.0
Data
δ Ray Off
δ Ray On
MUON MOMENTUM GeV/C
.2
.4
.6
.8
1.0
1.2
1.4

Fig 7

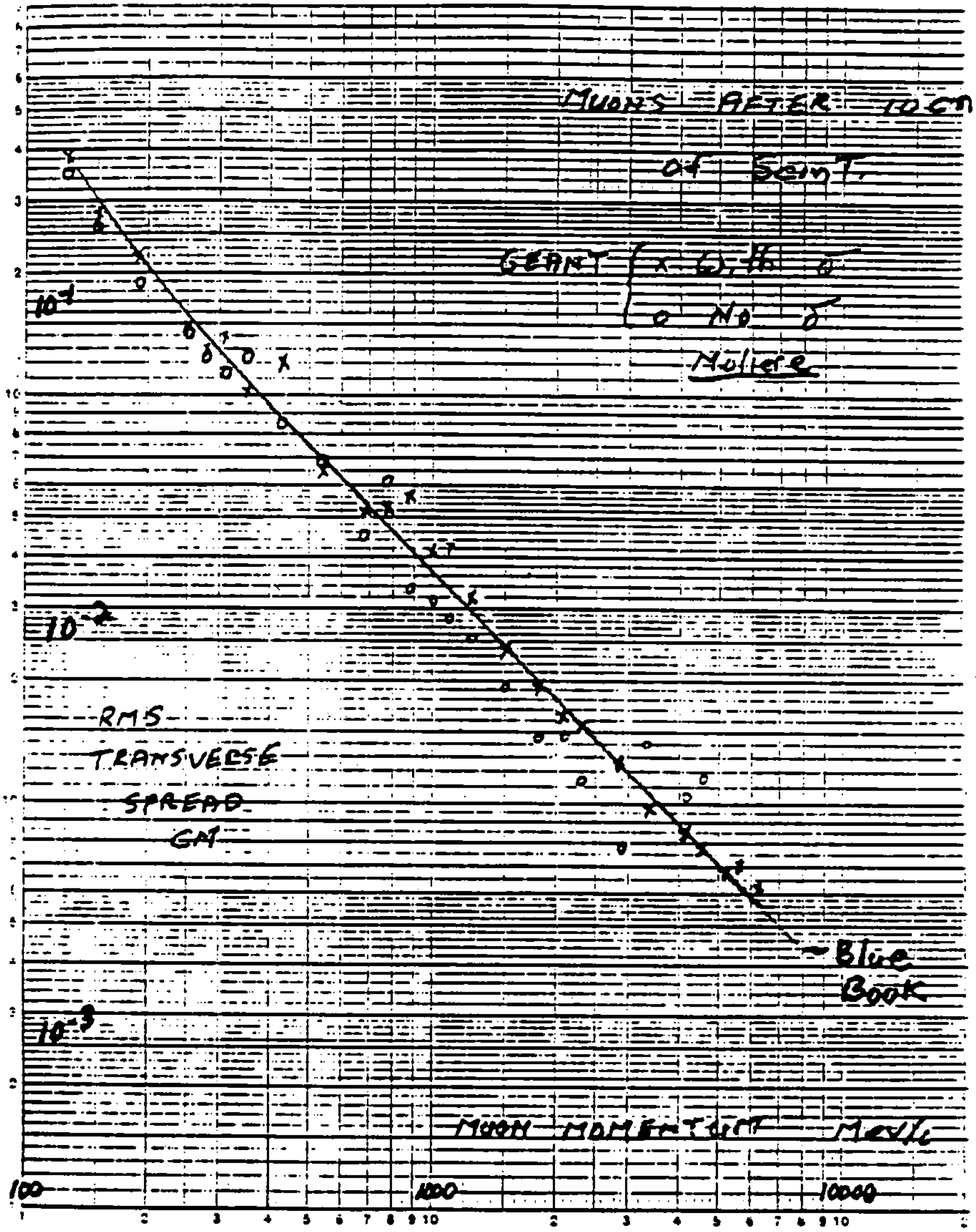

MUONS AFTER 10 CM
OF SCINT.
GEANT
x Δ, H δ
o NO δ
Moliere
RMS
TRANSVERSE
SPREAD
CM
Blue Book
MUON MOMENTUM MeV/c
10⁻¹
10⁻²
10⁻³
100
1000
10000

Fig 8

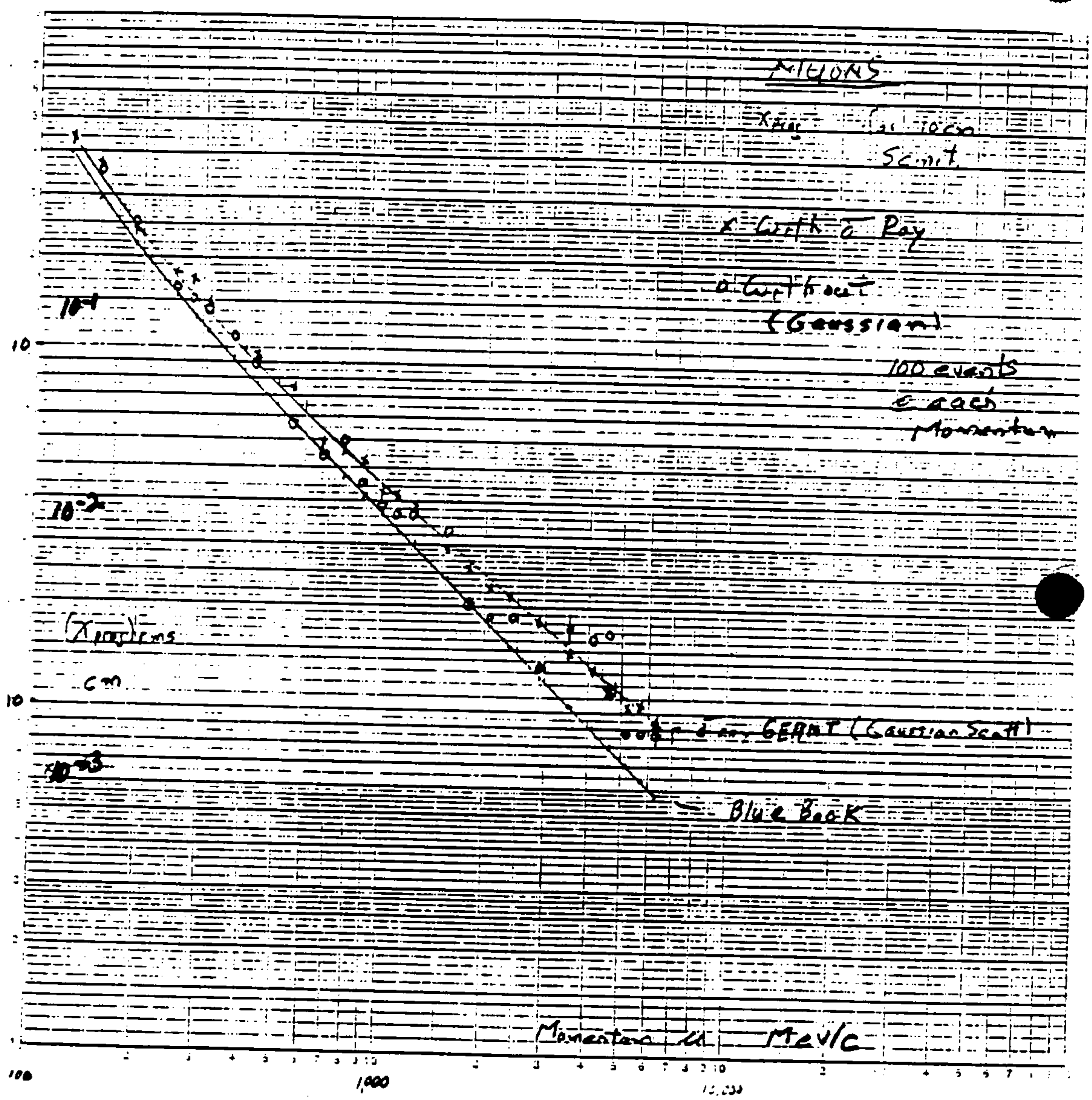

MUONS
Scint.
x With δ Ray
o Without (Gaussian)
100 events each Momentum
GEANT (Gaussian Scatt)
Blue Book
10⁻¹
10⁻²
10⁻³
cm
Momentum in MeV/c
100
1000
10,000

Fig 9