Experiments of Weak Interaction
" Neutrino Reaction "

Yorikiyo NAGASHIMA

KEK

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CONTENTS

Chapter 1 Introduction

§ 1 Weak Hamiltonian

Most of the low energy weak interactions so far are mainly decay interactions and can be described by the single effective Hamiltonian

$$H_W = \frac{G}{\sqrt{2}} J_\mu^+ J_\mu \tag{1}$$

where

$$J_\mu = \{\cos\theta_c J_\mu \ (\Delta s = 0,\ \Delta I = 1 \text{ Hadronic current}) + \sin\theta_c J_\mu \ (\Delta s = 1,\ \Delta I = 1/2 \text{ Hadronic current}) + \bar{\mu}\gamma_\mu (1+\gamma_5)\nu_\mu + \bar{e}\gamma_\mu (1+\gamma_5)\nu_e\} \tag{2}$$

In eq.(1) are contained the following rules :

1) Cabbibo theory
2) Universality
3) V-A interaction
4) Conserved Vector Current (CVC) hypothesis
5) $\Delta S / \Delta Q = 1$ for strangeness changing interaction
6) $\Delta I = 1/2$

Eq. (1) explains most of the decay interactions. The exceptions are CP-violating phenomena, some possible rare decay modes, and possibly high energy neutrino interactions. The low energy neutrino reactions at CERN are described by eq. (1), too. To see it we proceed as follows.

§ 2 Kinematics of the lepton-hadron interaction

We define the relevant kinematics variables as shown on Fig. 1.

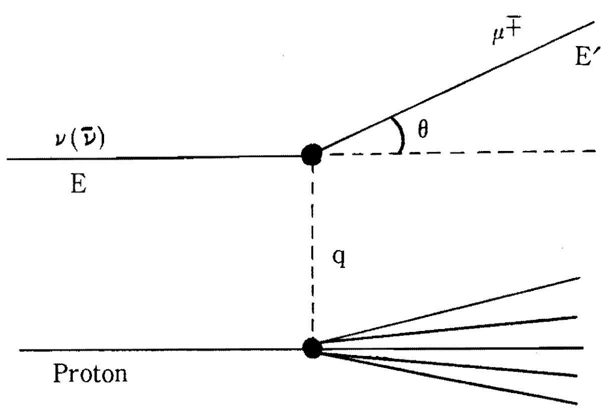


Fig. 1

The inelastic crosssections by neutrinos (antineutrinos) are defined as

$$\frac{\pi}{EE'} \frac{d^2\sigma_{\nu\bar{\nu}}}{d\Omega\, dE'} = M\frac{d^2\sigma_{\nu\bar{\nu}}}{dq^2 d\nu} = \frac{E'G^2}{E\ 2\pi}\left(\cos^2\frac{\theta}{2} W_2^{\nu\bar{\nu}} + 2\sin^2\frac{\theta}{2} W_1^{\nu\bar{\nu}} \mp \frac{E+E'}{M}\sin^2\frac{\theta}{2} W_3^{\nu\bar{\nu}}\right) \tag{3}$$

where

$$M : \text{Proton mass}$$
$$q^2 = 2EE' \sin^2\frac{\theta}{2}$$
$$\nu = q \cdot p = M(E - E')$$
$$G : \text{Weak coupling constant} = 10^{-5} \times M^{-2} \tag{4}$$

W_1, W_2, W_3 are form factors which depend only on q^2 and ν.

Notice here that electron proton interactions can also be described by eq. (3) if we make the following replacements :

$$\frac{G^2}{2\pi} \longrightarrow \frac{4\pi\alpha^2}{q^4} \tag{5}$$

$$W_3 = 0$$

q is the 4-momentum carried by the weak current[*1] or by the photon.

We can further define the following quantities.

$$\sigma_R = \frac{\pi}{\nu + \frac{q^2}{2}} \left[W_1 + \frac{1}{2}\sqrt{\frac{\nu^2}{M^4} - \frac{q^2}{M^2}}\, W_3 \right]$$

$$\sigma_L = \frac{\pi}{\nu + \frac{q^2}{2}} \left[W_1 - \frac{1}{2}\sqrt{\frac{\nu^2}{M^4} - \frac{q^2}{M^2}}\, W_3 \right]$$

$$\sigma_S = \frac{\pi}{\nu + \frac{q^2}{2}} \left[W_2 \left(\frac{\nu^2}{-q^2 M^2} + 1 \right) - W_1 \right] \tag{6}$$

σ_R σ_L ,σ_S can be interpreted as the absorption cross-sections by the right-handed, left-handed and scaler weak currents (or by the W boson if it exists). For the electromagnetic interaction

$$\sigma_L = \sigma_R = \sigma_T \tag{7}$$

where σ_T is the absorption cross section by the transversely polarized photons.

From the properties of W_1, W_2, W_3 we can prove that σ_R, σ_L, σ_S are positive quantities.

Let us now define the new variables which are more convenient in describing the deep inelastic reactions. We write

$$x = \frac{1}{\omega} = \frac{q^2}{2\nu}$$

$$y = \frac{\nu}{E} \tag{8}$$

here x and y range between 0 and 1.

(*1) If intermediate W-boson exists, it is interpreted as W-boson and the analogy with the electromagnetic interaction is better. In that case, however, W-boson propbgator $(1 + q^2 / m_W^2)^{-2}$ has to be multiplied to the expression.

The " Scaling " means that in the deep inelastic limit, namely when E, ν, q go to infinity with x fixed, the form fadtors are functions of only x. That is

for $E, \nu, q \rightarrow \infty$ with x fixed,

$$\begin{aligned} MW_1 \quad (q^2, \nu) &\longrightarrow F_1(x) \\ \frac{\nu W_2}{M}(q^2, \nu) &\longrightarrow F_2(x) \\ \frac{\nu W_3}{M}(q^2, \nu) &\longrightarrow F_3(x) \end{aligned} \tag{9}$$

The scaling was observed to hold in the deep inelastic e-p scattering at SLAC.

§ 3. Parton Model

There are many ways to interpret the scaling. The most popular interpretation is that of Feynman. He considers a proton that consists of many hard point-like objects (partons). To see how it came we consider e-p scattering in their center of mass (CM) system. See Fig. 2

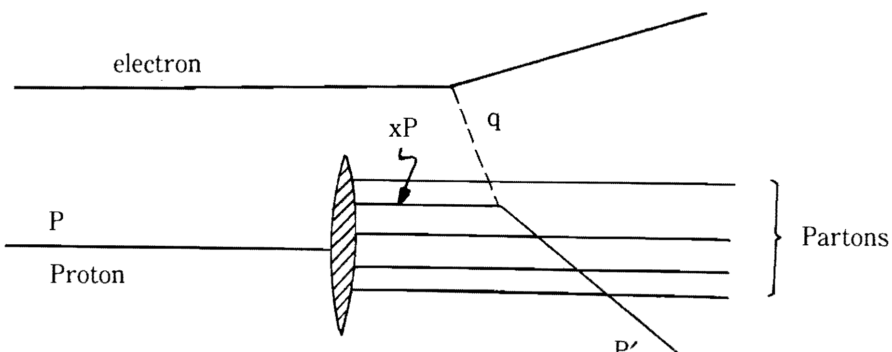


Fig. 2

In the limit $P \rightarrow \infty$, the proton becomes flat like a pan-cake bedause of the relativistic effect. The interaction time (τ_{int}) is proportinal to that the electron passes throngh the pan-cake and goes like

$$\tau_{int.} \sim \frac{1}{P} \tag{10}$$

On the other hand the virtual life time (τ_{life}) that the protons are separated to several free partons goes like

$$\tau_{life} \sim P$$

Then the impulse approximation is valid. Namely the electron is scattered off by one " free " parton and the rest of the partons fly unaffected. The partons subsequently decay into pions and other hadrons. Requiring that the parton is free before and after the interaction and that the parton has fractional momentum $x\dot{P}$ and mass xM we obtain

$$P'^2 = (q + xP)^2 = (xM)^2$$

$$\text{or} \quad x = \frac{q^2}{2\nu} \tag{11}$$

We can write the elastic electron scattering crosssetion as

$$\left.\frac{d\sigma}{d\Omega}\right|_{el.} \sim \left\{ Q\cdot F(q^2) \right\}^2 \times \left.\frac{d\sigma}{d\Omega}\right|_{point} \tag{12}$$

where Q is the charge of the proton and $F(q^2)$ is the elastic form factor. If the proton is point like, $F(q^2) = 1$. If the proton has a hard core

$$\lim_{q^2 \to \infty} F(q^2) = \text{constant} \tag{13}$$

Experimentally $F(q^2) \to 0$ as $q^2 \to \infty$, hence it does not have a single hard core. Does it have many cores then, or is it a soft object like jam? If the parton model is correct

$$\left.\frac{d\sigma}{d\Omega}\right|_{in\ el.} \sim \Sigma_i \left.\frac{d\sigma}{d\Omega}\right|_{el.,parton}$$

$$\sim \left.\frac{d\sigma}{d\Omega}\right|_{point} \Sigma_i Q_i^2 \rho_i(x)\, dx \tag{14}$$

where Q_i is the charge of the i-th parton and $\rho_i(x)$ is the probability that it has the fractional momentum x. Eq. 14 has the exact expression as the scaling requires. So a proton is soft but it has many cores like a strawberry jam. The eq. (14) tells us that the form factors F_i have a simple meaning like the avrerage square charge of the partons. In the parton model we have

$$\int_0^1 F_2(x)\, dx = \sum_N P_N \sum_{i=1}^{N} \frac{Q_i^2}{N} \tag{15}$$

where P_N is the probability that there are N partons. In the neutorino interaction the physical interpretation of the form factor is not the electric charge but some combinations of iso-spin and hyper charge.

§ 4 Electron Data

For e-p scattering we have experimental data

$$\int_0^1 F^{\gamma}_{2p}(x)\, dx = 0.16 \pm 0.02 \qquad \text{for proton}$$

$$\int_0^1 F^{\gamma}_{2n}(x)\, dx = 0.12 \pm 0.02 \qquad \text{for neutron} \tag{16}$$

and

$$R = \frac{\sigma_S}{\sigma_T} = 0.18 \pm 0.10 \tag{17}$$

R should be zero for sqin ½ partons. Eq. 17 tells us that it is almost true.

In the quark model we have

$$P_N = 1 \text{ for } N = 3$$

$$Q_i = 2/3,\ 2/3,\ 1/3 \qquad \text{for proton}$$

$$= 2/3,\ 1/3,\ 1/3 \qquad \text{for neutron} \tag{18}$$

Therefore

$$\int F^{\gamma}_{2p}(x)\,dx = {}^{1}/3 \qquad \text{for proton}$$

$$\int F^{\gamma}_{2n}(x)\,dx = {}^{2}/9 \qquad \text{for neutron} \tag{19}$$

The experimental values are smaller than the quark model predictions (19). We need some neutral objects (gluons ?) other than charged quarks.

§ 5 Total Crosssection

5-1 Total crossection by neutrinos

we rewrite the eq. (3), using the scaling variable.

$$\frac{d^2\sigma^{\nu\bar{\nu}}}{dxdy} = \frac{G^2ME}{\pi}\left[\left\{1 - y\left(1 + \frac{Mx}{E}\right)\right\}F_2(x) + \frac{y^2}{2}\left\{2xF_1(x)\right\} \mp y\left(1 - \frac{y}{2}\right)\left\{xF_3(x)\right\}\right] \tag{20}$$

In the scaling limit, the term Mx/E in the square bracket drops out. By integrating with x and y we obtain

$$\sigma_{Tot} = \int dxdy \frac{d^2\sigma^{\nu\bar{\nu}}}{dxdy} \sim \text{constant} \times E \tag{21}$$

The crosssection increase, linearly with energy if the scaling is true !

5-2 CERN-Gargamelle experiments

The neutrino experiment at CERN was done using the Gargamelle Bubble Chamber. It was a size of 4.5 m × 1.5 m and is filled with Freon (CF_3Br). The neutron to proton ratio of the Freon is about 1.19. The data consist of 1000 neutrino events and 1000 anti- neutrino events. We show the total crosssection by neutrinos (antineutrinos) in Fig. 3.

Fig. 3 See Separate sheet

The data fit well with the linear approximation

$$\sigma^{\nu} = \alpha E_{\nu}$$
$$\sigma^{\bar{\nu}} = \alpha^{\bar{\nu}} E_{\bar{\nu}} \qquad 1 < E_{\nu,\bar{\nu}} < 10\text{GeV} \tag{22}$$

where

$$\alpha_{\nu} = 0.69 \pm 0.14$$
$$\alpha_{\bar{\nu}} = 0.27 \pm 0.05 \tag{23}$$

The experiment clearly shows that the scaling is good in the neutrrino interaction at energies as low as 1 GeV.

5-3 Comparison between neutrino and electron data

We saw that the scaling is apparently true in the low energy (< 10 GeV) neutrino reactions. An important question is to what extent the coefficient α, the slope parameter of the total crosssection, really represents the high energy scaling behavior in electron scattering.

As the electron data suggest, we will assume the spin ½ parton in the following. Then

1) Parton has spin ½ → $2xF_1 = F_2$

Further assume

2) $\cos\theta_c = 1$

From iso spin symmetry

3) $F_i^{\bar{\nu}p} = F_i^{\nu n}$

$$F_i^{\nu p} = F_i^{\bar{\nu}n} \tag{24}$$

Then for the neutron-proton average

$$F_i^{\nu N} = \frac{1}{2}\left(F_i^{\nu n} + F_i^{\nu p}\right) = F_i^{\bar{\nu}N} \tag{25}$$

Integrating eq. (20) we have

$$\frac{d\sigma^{\nu N,\bar{\nu}N}}{dy}=\frac{G^2ME}{\pi}\left[\int_0^1 F_2^{\nu N}dx\right]\left\{1-(1\mp B)\left(y-\frac{y^2}{2}\right)\right\} \tag{26}$$

where B is defined as

$$B=-\frac{\int_0^1 xF_3^{\nu N}(x)\,dx}{\int_0^1 F_2^{\nu N}(x)\,dx} \tag{27}$$

If we add ν and $\bar{\nu}$ crosssection, the B term drops out. Integrating over y, we then get

$$\sigma^{\nu}\equiv\sigma^{\nu N}+\sigma^{\bar{\nu}N}=\frac{G^2ME}{\pi}\frac{4}{3}\int_0^1 F_2^{\nu}dx \tag{28}$$

$$\therefore\quad \int_0^1 F_2^{\nu N}(x)\,dx=\frac{3\pi}{4G^2M}(\alpha^{\nu}+\alpha^{\bar{\nu}})=0.47\pm0.07 \tag{29}$$

Two corrections have to be made on the value

1) $\cos\theta_c$ is not exactly zero $\rightarrow +5$ %

2) n/p in Freon = 1.19 $\rightarrow -1.5$ %

with the above corrections made, we finally obtain

$$\int F_2^{\nu N}dx=0.49\pm0.07$$

: from neutrino total cross section (30)

Next we consider what we will get from the e-p scattering data. The isospin average of eq. (16) gives

$$\int F_2^{\nu N}dx=\frac{1}{2}\int(F_2^{\gamma p}+F_2^{\gamma n})\,dx=0.14\pm0.02 \tag{31}$$

Now let us assume

1) Conserved Vector Current (CVC)

that is , isovector part of the electromagnetic current is proportional to I_3, whereas the isovector part of the weak current to $I_{\pm}$. Then for the isovector part

$$\int F_2^{\nu}dx=4\int F_2^{\gamma}dx \tag{32}$$

2) Pure V-A

3) 10 % iso-scaler contribution in the electromagnetic interaction which is true in the high energy photo-productions.

Then we can derive

$$\int F_2^{\nu}dx=0.52\pm0.08 \tag{33}$$

: prediction from e-p scattering data

The agreement between (30) and (33) is excellent. It gives a strong support to the notion that the scaling behavior in the low energy neutrino crosssection is indeed a representation of the true scaling which is expected to appear in the high energy region.

§ 6 The ratio $\sigma_{\bar{\nu}}/\sigma_{\nu}$

From eq. (26) we can have for the ratio

$$R = \frac{\sigma_{\bar{\nu}}}{\sigma_{\nu}} = \frac{2 - B}{2 + B} \qquad (34)$$

B would be less than 1 for V-A theory.

B = 1 if

1) Scattering from spin ½ parton only
2) No contribution from antipartons
3) Pure V-A.

The experimental data of R is shown in Fig. 4.

Fig. 4 See separate sheet

The value of R is very close to $^1/_3$ which corresponds to B = 1.

Experimentally $B = 0.86 \pm 0.04$ (35)

It means there is not very much contributions from anti-partons. We cannot, however, exclude the possibility that there are large number of the so-called " wee " anti-partons, since their x value $\simeq 0$ and do not contribute much to B.

§ 7 Y-distribution

Eq. (26) gives the y-distribution for the neutrinos (anti-neutrino) crosssection. There are data of only anti-neutrino distribution.

From eq. (26), we have

$$\frac{dN}{dy} = 1 - (1 + B)\left(y - \frac{y^2}{2}\right) \qquad (36)$$

$$\frac{dN}{dy} = 0 \qquad \text{at } y = 1,\ B = 1$$

The experimental data are shown on Fig. 5

Fig. 5 See separate sheet

The number of events at y = 1 is not quite zero reflecting the fact tihat B is not exactly 1. The peak at $y \lesssim 0.1$ comes from the quasi elastic scattering and will presumably disappear at higher energy.

§ 8 Summary of Chapter 1

1) $\sigma^{\nu,\bar{\nu}}_{tot} = \alpha^{\nu,\bar{\nu}} E_{\nu}$ $\qquad 1 < E_{\nu} < 10$ GeV

consistent with the scaling.

2) α^{ν} (neutrino experiment) = α (prediction from e-p)

with CVC, V-A hypothesis

3) Parton Model

a) Parton has spin ½
b) The contribution of anti-parton is small.

Finally just for curiousity we tabulate the various quark model predictions together with the experimental values.

Table 1 See separate sheet.

The table tells us that the original Gell-Mann-Zweig version of the 3-quark model is most consistent with the experiment.

Chapter 3 Neutrino experiment at NAL

§ 9 Problems at high energy neutrino interactions

The Hamiltonian given by eq. (1) of chapter 1 is OK for most decay processes. It also describes the low energy neutrino reactions correctly with the scattering assumption. The total crosssection goes linearly with the total energy S where S is the total center of mass energy squared

$$S = (\text{ Total CM energy })^2 = 2M\, E\nu(\text{ inlab }) \qquad (37)$$

$$\sigma \sim G^2 S$$

The eq. (37) cannot hold for arbitrary large S, since the S-wave unitarity limits the crosssection from above

$$\sigma \sim \frac{1}{S}$$

At $S \sim \frac{1}{G} = (300 \text{ GeV})^2$, the crosssection reaches the unitary limit. In this energy region the higher order term contribution is non-negligible. The eq. (37) no longer holds. Notice here that eq. (37) is true so long as we assume

1) The 1st order weak interaction
2) Scaling
3) No intermediate W-boson exists

The condition (3) is necessary since it gives another multiplicative factor $(1 + q^2/m_w^2)^2$ in the eq. (3) and (20).

From a theoretical point of view the Hamiltonian (1) gives a badly divergent result even if we take the higher order terms. The introduction of W improves the high energy behavior somewhat, though it still gives a divergent result at $S \to \infty$. In other words the weak interaction is unrenormalizable. Recently there appeared some theoretical trials to make the theory renormalizable by utilizing the gauge theory with spontaneous breakdown and combining the weak and electromagnetic theory[*2]. The theory requires $W^{\pm}$ and neutral W boson and/or heavy leptons.

The neutrino experiment at NAL can investigate the several alternative-treatment of the weak interaction.

1) $\sigma = \text{const.} \times E$

Does this relation still hold at NAL energy ? If not with which of the 3 causes mentioned above is responsible ?

2) $R = \sigma_{\bar{\nu}} / \sigma_{\nu}$

3) $\frac{d^2\sigma}{dxdy}$, $\frac{d\sigma}{dy}$ etc

4) Check of scaling at different q^2 and ν

1), 2), 3), 4) can be investigated for $E_\nu \lesssim 300$ GeV, $q^2 \lesssim 300$.

The scaling can be checked for wider range of ν and q^2 than is possible at SLAC. See Fig. 6.

Fig. 6 (Separate sheet Kinematic Region)

5) Search for $W^{\pm}$ $M_W \leqq 15$ GeV

(*2) S. Weinberg Phys. Rev. Letters. 19. 1264 (1967) and many others

6) Search for heavy lepton $M_y \leqq 10$ GeV

7) Search for neutral currents

8) Other tests like the existence of the diagonal term $\nu_\mu \mu \rightarrow \nu_\mu \mu$ and Adler's sum rule, which I will not describe here.

§ 10 Neutrino beam

The neutrino interaction is a weak process. The interaction rate is so low that maximization of the neutrino flux and the target material is of absolute necessity. For this purpose a horn and a bulky target like hundreds of tons of iron have been used in the past experiments. To distinguish the 2nd type of the beam which will be described later, the horn beam is reffered as wide band neutrino beam. The schematics of the wide band beam is described in Fig. 7. (a)

Fig. 7 Horn beam

The neutrino is obtained primarily from $K\mu\nu$ and $\pi\mu\nu$ decay. In order to maximize the neutrino flux we have to maximize the pion and kaon flux. Ideally we should collect the all 2ndary positive pions and kaons produced at the target. The horn almost does it. The current through the horn produces a circular magnetic field and bends all the positive particles back into the forward direction. The negative particles are bent in the backward direction and do not contribute much. However some of them go in the forward direction without going through the horn field. They are the source of the antineutron backgrounds. Since the horn does not select the momentum, the energy spectrum of the beam looks like as Fig. 7 (b). The peak is at lower energy side. The energy of the neutrino is undefined. This kind of the neutrino beam has been used throughout the past experiments and all the experiments at NAL as well, except the one being done by CALTECH-NAL group. Since I am involved in the experiment and this is the only one that gives any meaningful data at NAL so far I will concentrate my talk on this experiment in the following.

We use the so-called narrow band neutrino beam. The beam layout is schematically described in Fig. 8 (a).

Fig. 8 Narrow band ν beam

The 2ndary π and K beam is first sign selected and momentum selected by a set of quadrupole and bending magnets. Then it is focussed into a sharp parallel pencil beam. Since the neutrino is made primarily via two body decay, there is a unique relation between the angle and the energy of the deday neutrino. The spectrum is shown in Fig. 8 (b). It has two peaks corresponding to K and π decays. Theoretically, there are no antineutrino contributions, although we cannot avoid some coming from upstream of the target or beam stoppers.

There is a great advantage of using an energy defined, antineutrinoless neutrino beam, in measuring the total crosssection and in looking into rare events that cannot ordinarily be produced by the neutrinos. The price to pay for them is the flux. There are some limitations on the experiments that can be done using the narrow band beam.

§ 11 CALTECH-NAL Experiments

Fig. 9 shows the CALTECH-NAL group setup at NAL

Fig. 9 CALTECH NAL exp. setup

It is a typical counter-spark chamber neutrino experiment with the following features.

1) Anti-counter at the upstream end to prevent the background μ-ons
2) Bulky iron target -detecter (160 tons) to produce interactions
3) Iron core magnet to analyse the muon momentum. The muon is identified as the particle that penetrates the iron for many interaction lengths.
4) More than 80 scintillation counters and more than 23 wire spark chambers are interspaced between the irons and behind the magnet too.
   The counters also identify the hadron showers.

A typical event will look like the following picture.

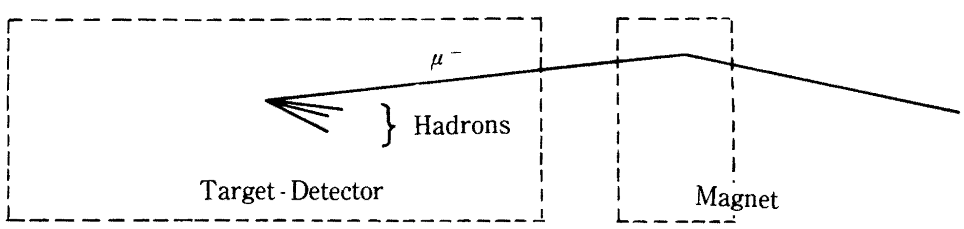


Fig. 10

corresponding to the processs

$$\nu + {n \atop p} \rightarrow \mu^- + \text{ many hadrons}$$

μ^- produces a long track accompanied by a hadron shower. A multi-tracks in the spark chamber and/or a large pulse height in some counters identify showers.

The information from counters and chambers are then sent to the electronics logical circuits and to the on-line computer. The events are displayed on the scope and the results are printed.

During a prelininary run in January, 1973, we obtained 2.7×10^{16} protons on target. Some parameters of the experiments are listed below.

Proton energy	300 GeV
No. of protons	2.7×10^{16}
Secondary particle momenta	160 GeV
$\Delta p/p$	± 11 %
$<E_\nu>$ from K	$\simeq 145$ GeV
$<E_\nu>$ from π	$\simeq 50$ GeV
Total Number of events	167

The number of neutrino events are then reduced to 112 by requiring that they are within the fiducial volume and that they are kinematically reconstructable. Of the 112 events only one event had μ^+ and all others were μ^- events.

§ 12 Search for W-boson

If a W-boson exists, it has spin 1, charged and is supposed to mediate the weak interactions. Its decay modes are

$$
\begin{aligned}
W^{\pm} &\rightarrow e^{\pm}\nu \\
&\rightarrow \mu^{\pm}\nu \\
&\rightarrow \pi^{\pm}\pi^{0} \\
&\rightarrow \text{Many hadrons}
\end{aligned}
$$

The coupling constant g is related to the usual weak coupling constant G by

$$\frac{g^2}{m_W^2} = \frac{G}{\sqrt{2}}$$

that is to say the process coupled with W is semi-weak. The 2nd order process gives an ordinary weak interaction given by eq. (1).

If W exists, the following process as in Fig. 11 is possible

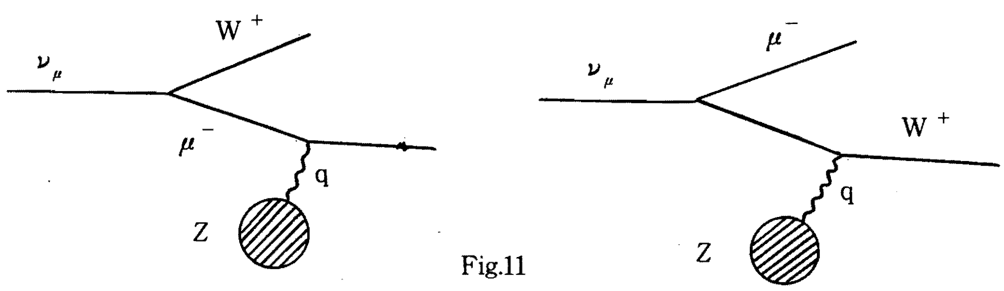


Fig.11

It is a semi-weak process with 2nd order electromagnetic interaction. The reduction factor e^2 by the electromagnetic coupling is almost compensated by using a large Z material. The crosssection is large for the coherent production (the neucleus does not break up) by a factor Z than for the incoherent production. Experimentally the signal looks like Fig. 12.

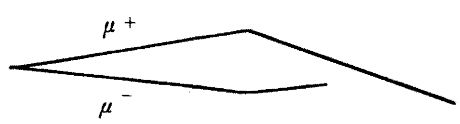


Fig. 12

In our apparatus only the $W \rightarrow \mu\nu$ decay mode is directly observable. Since we observed no $\mu^+\mu^-$ pairs, we did not see any W-boson. However in the process shown in Fig.11., typically high energy μ^+ and low energy μ^- are produced. The negative muon could have escaped the observation. Therefore we could not exclude the possibility that one observed μ^- event is indeed the W-event.

The production rate of W is calculable relative to the ordinary neutrino reaction as a function of W-bosn mass. So the potential one W-event gives the lower bound for the W^+ boson mass. We give it in Fig. 13

Fig. 13 W mass

as a function of the branching ratio into $\mu\nu$; another unknown parameter. Quoting a single number we say $M_W > 4.6$ GeV/c^2 for $B = 0.5$ with 90 % confidence level. This is a significant improvement over the past experimental knowledge, that is, $M_W > 2$ GeV/c^2.

Theoretically it is hardly surprising a result, since the gauge theory of weak interaction tells that $M_W > 37.3$ GeV/c^2. Whethere we believe the theory or not, certainly the experimental search for W-boson with mass below 37 GeV should continue.

§ 13 Search for Heavy Muon

There are many kinds of heavy leptons. The one required by the unified gauge theory of the weak and electromagnetic interaction proposed by Georgi - Glashow(*3) and others have the following properties

1) It has charge of either $+1$ or 0

2) It has the same quantum number as μ or e

Let us denote the heavy muon as Y. Then Y^+ has the following decay modes

$$
\begin{aligned}
Y^+ &\rightarrow \nu_\mu + \mu^+ + \nu_\mu \\
&\rightarrow \nu_\mu + e^+ + \nu_e \\
&\rightarrow \nu_\mu + \pi^+ \\
&\rightarrow \nu_\mu + \text{many hadrons}
\end{aligned}
\tag{40}
$$

If Y^0 is lighter than Y^+, then Y^+ also decays into

$$Y^+ \rightarrow Y^0 + \ldots\ldots\ldots\ldots \tag{41}$$

So far we only know that any heavy lepton, if it exists, should be heavior than K meson. Y^+ would be produced via a process

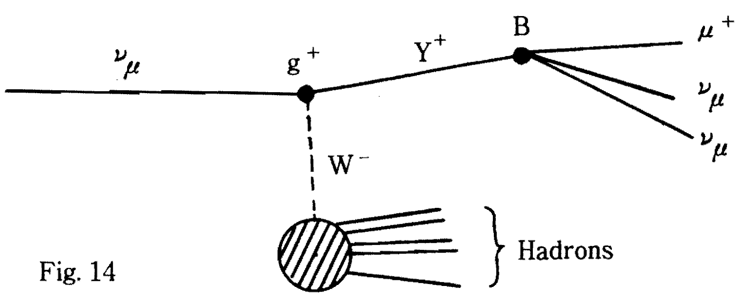


Fig. 14

Hear g^+ is the ν - W - Y coupling constant and B is the branching ratio into $\mu^+ \nu_\mu \nu_\mu$. Experimentally it would appear as

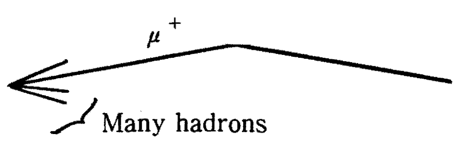


Fig. 15

The important point here is that the beam should not have any anti - neutrino components. Otherwise a plenty of μ^+ would be produced by ordinary anti - neutrino interactions. Although we have several reasons to believe the one μ^+ event observed is indeed produced by the anti - neutrino background in the beam, it sets an upper limit for the possible heavy muon production.

Like W - boson production, the crosssection to produce heavy muon can be calculated (*4) relative to the ordinary process assuming spin ½ partons. The parameters are mass of the heavy muon M_Y, the coupling constant g + and the branching ratio B. We can calculate the expected number of μ^+ for our experimental apparatus. The results are shown in Fig. 14. Now, g+ is equal to g with the ordinary gauge theories

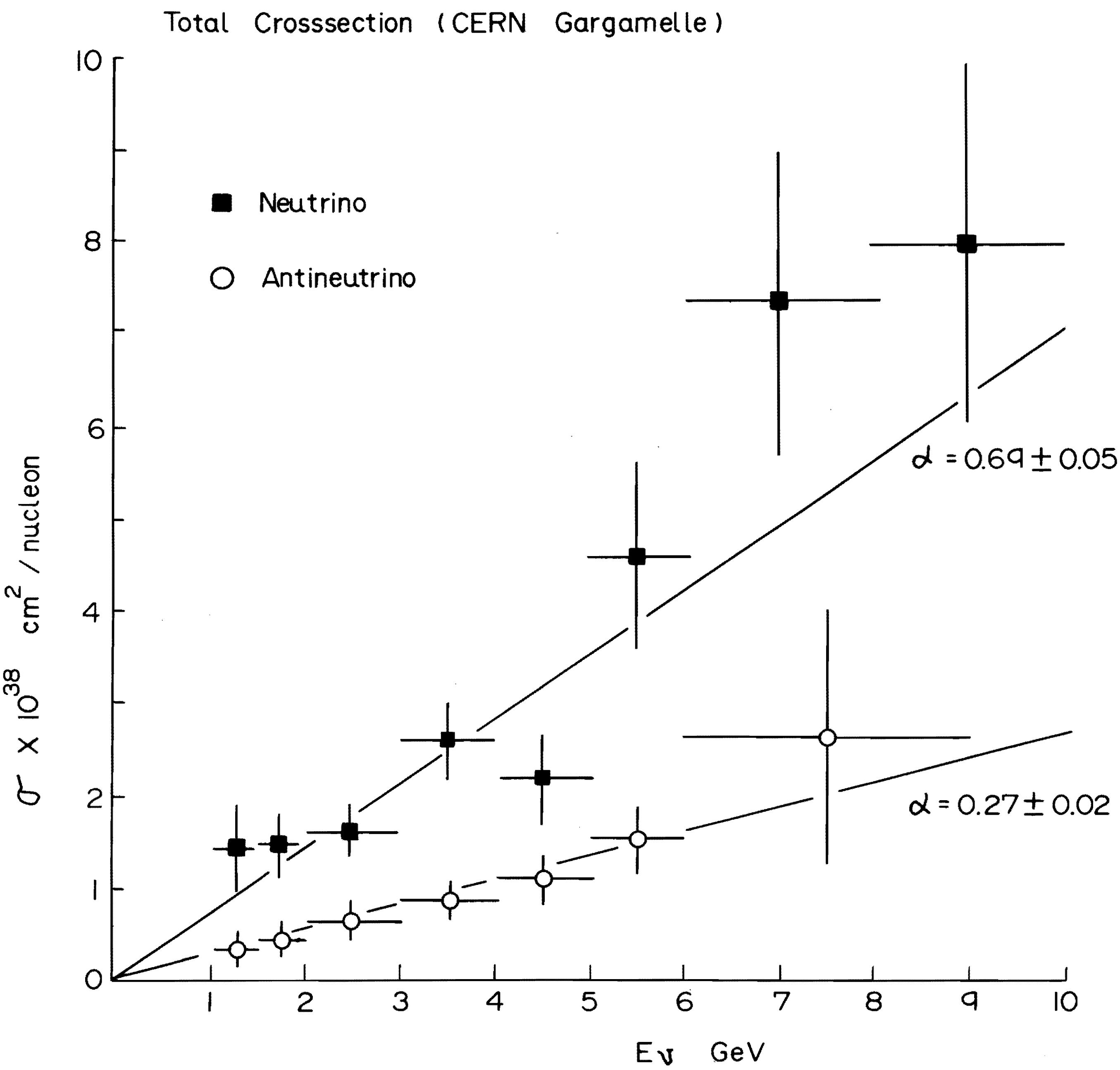
(*3) H. George, S. L. Glashow Phys. Rev. Letters 28, 1494 (1972)

(*4) J. D. Bjorken, C. H. Llewellyn - Smith, SLAC - PUB - 1107

B is more model dependent, close to 0.3 if Y^+ decay modes are limited to those listed in (40). Asking that the probability to observe one event is less 10 %, we can say that the heavy muon is not lighter than 2 GeV if it exists.

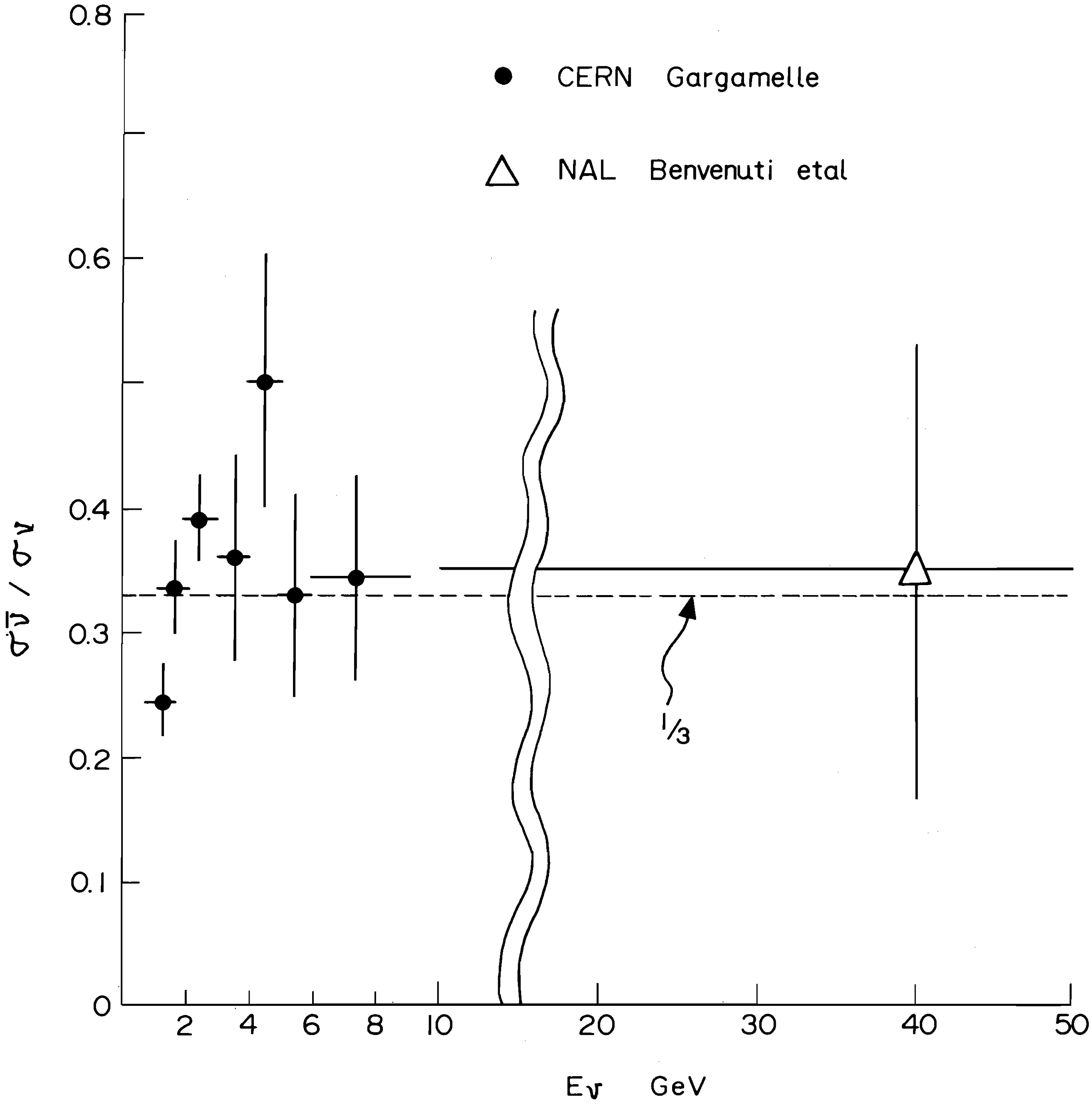
The limit is expected to go up to $\sim$ 8 GeV in the near future.

Fig. 16



Total Crosssection (CERN Gargamelle)
Neutrino
Antineutrino
α = 0.69 ± 0.05
α = 0.27 ± 0.02
σ × 10^38 cm^2 / nucleon
Eν GeV
0
1
2
3
4
5
6
7
8
9
10

Fig. 3



Antineutrino / Neutrino Crosssection Ratio

Fig. 4

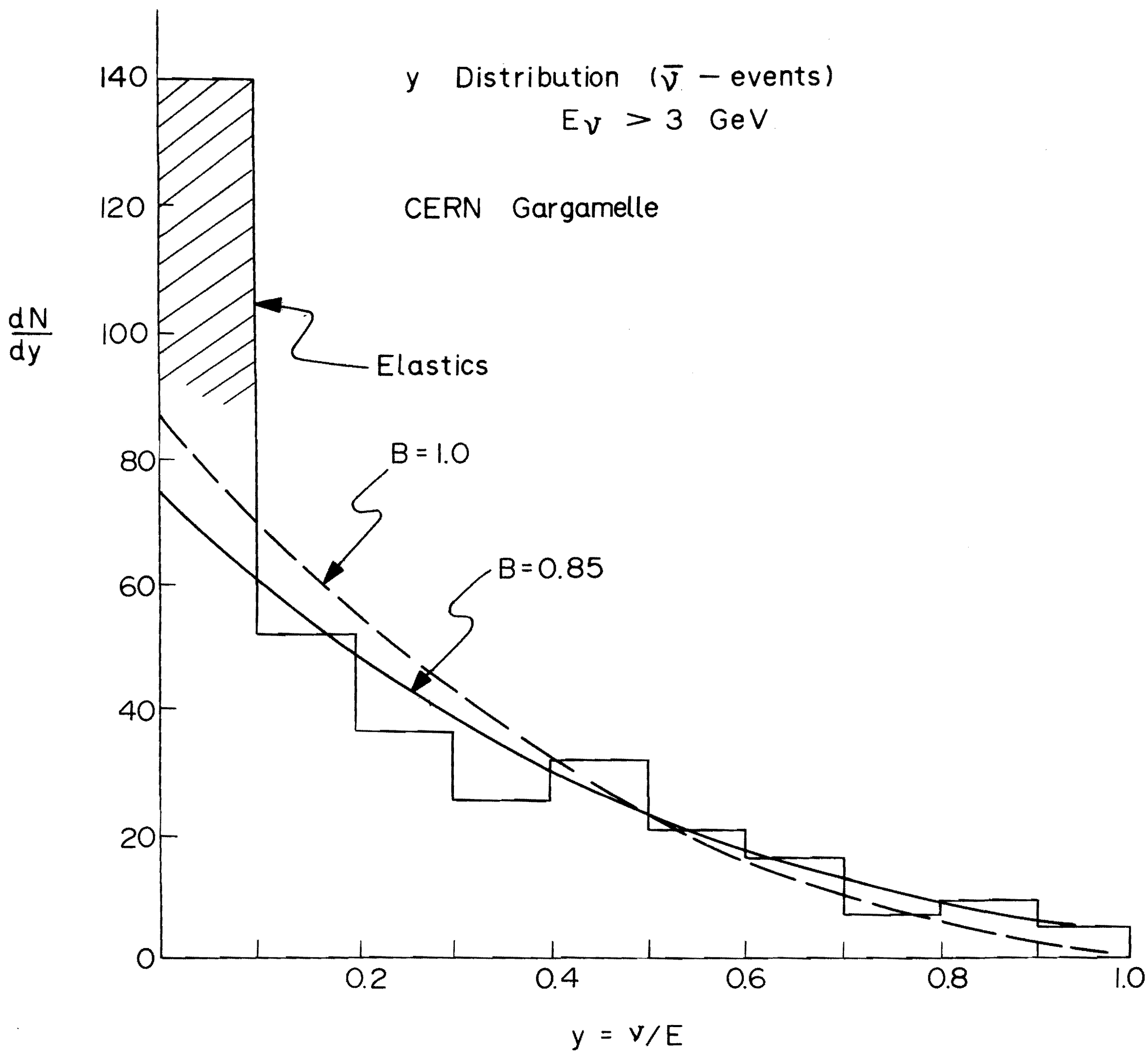

y Distribution ($\bar{\nu}$ − events)
E_ν > 3 GeV
CERN Gargamelle
$\frac{dN}{dy}$
140
120
100
80
60
40
20
0
Elastics
B = 1.0
B = 0.85
0.2
0.4
0.6
0.8
1.0
y = ν/E

Fig. 5

Table I

Quark Model Predictions (All Spin $1/2$)

Model	Partons are	$\dfrac{\int F_2^{\nu}\, dx}{\int F_2^{\gamma}\, dx}$	$\sigma^{\bar{\nu}}/\sigma^{\nu}$	F_2^{rn}/F_2^{rp} $x=1 \rightarrow 0$
Gell-Mann -3 weig	3-fractional charge quarks	3.6 $=\frac{18}{5}$	$1/3$	$\frac{1}{4} \rightarrow 1$
	+ Many $\theta\bar{\theta}$'s	~ 3.0	~ 1.0	~ 1
Han - Nambu	3-integral charge triplets	≤ 3.3	$1/3$	$\frac{1}{2} \rightarrow 1$
Integral charge (SAKATA, HARA)	Integral charge triplet or quartet	≤ 2.0	$1/2$	$0 \rightarrow \infty$
Experiment		3.4 ± 0.7	0.38	$\sim 0.25 \rightarrow 1$

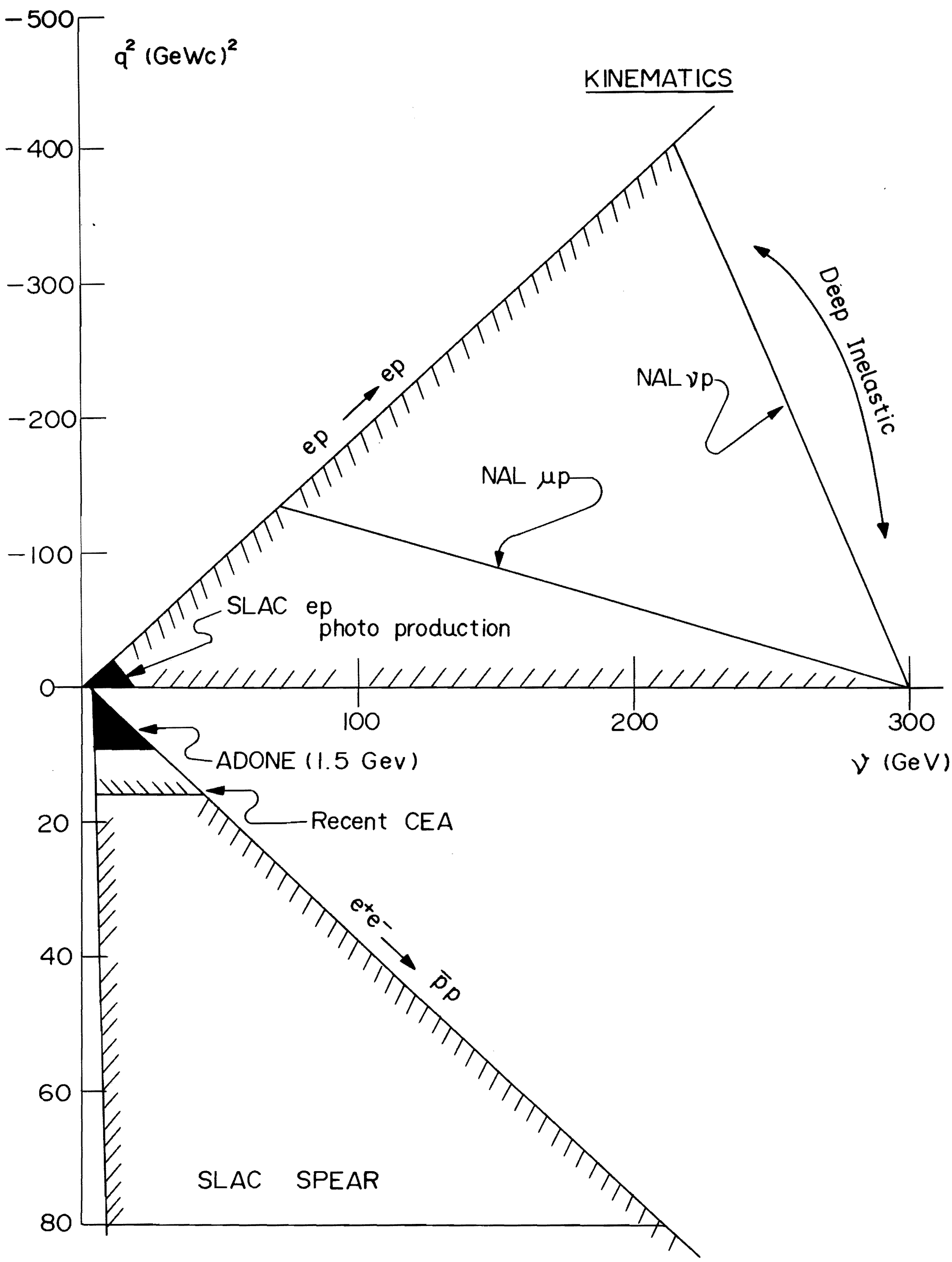
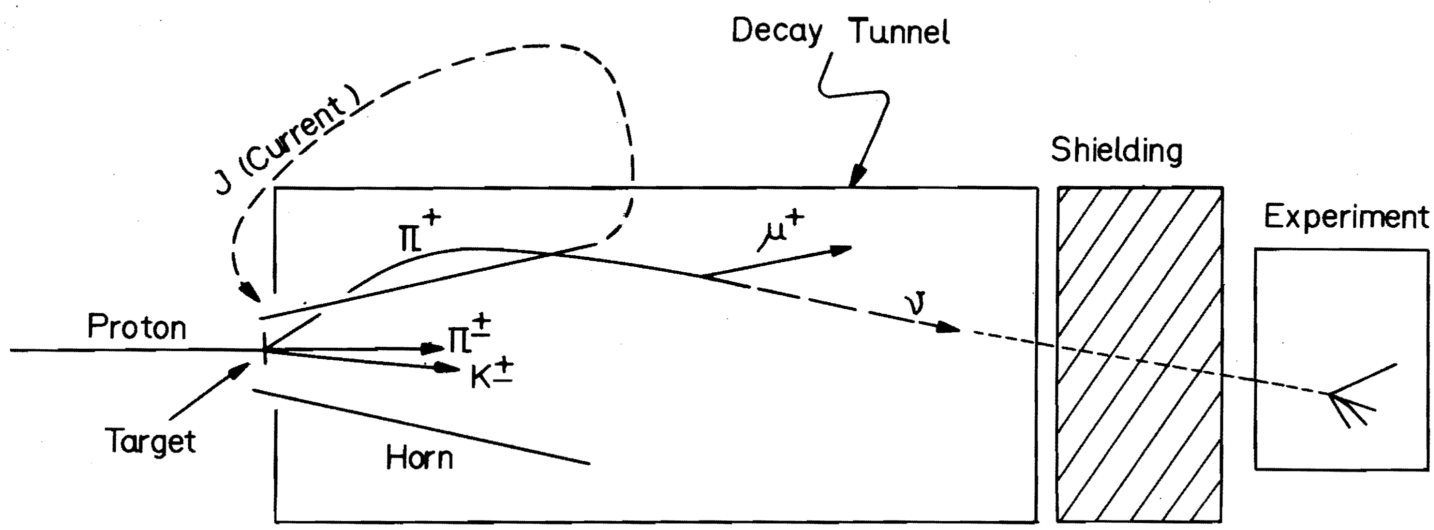
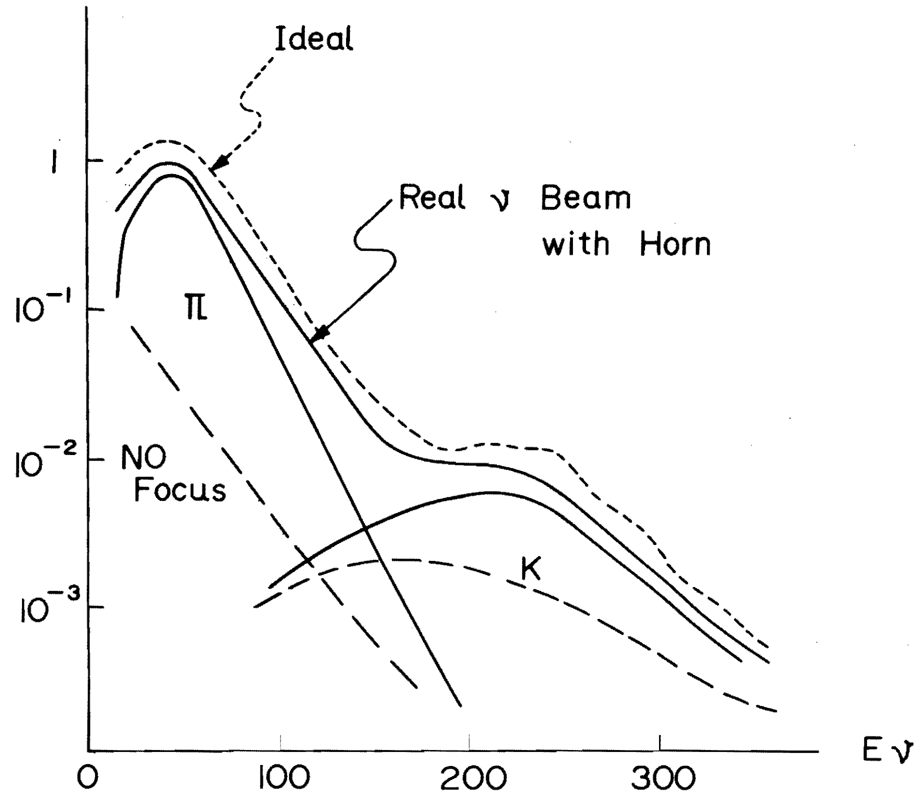

-500
q² (GeWc)²
KINEMATICS
-400
-300
-200
-100
0
20
40
60
80
100
200
300
ν (GeV)
ep → ep
NAL νp
Deep Inelastic
NAL μp
SLAC ep
photo production
ADONE (1.5 Gev)
Recent CEA
e⁺e⁻ → p̄p
SLAC SPEAR

Fig. 6

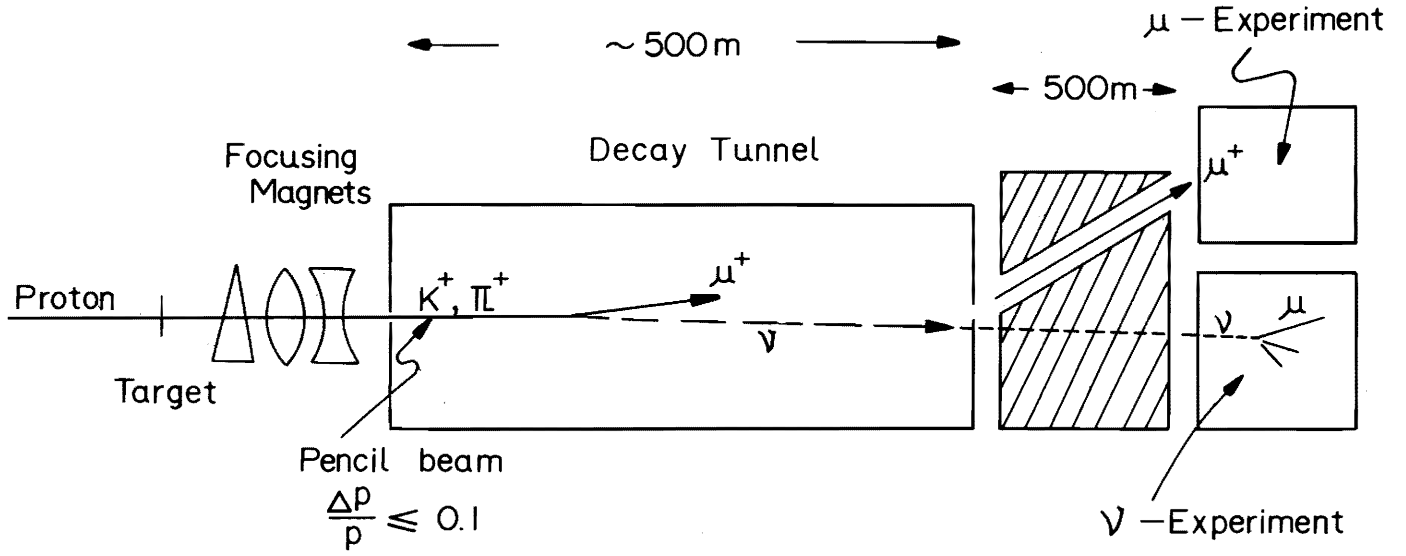


Wide band Neutrino beam
(a)

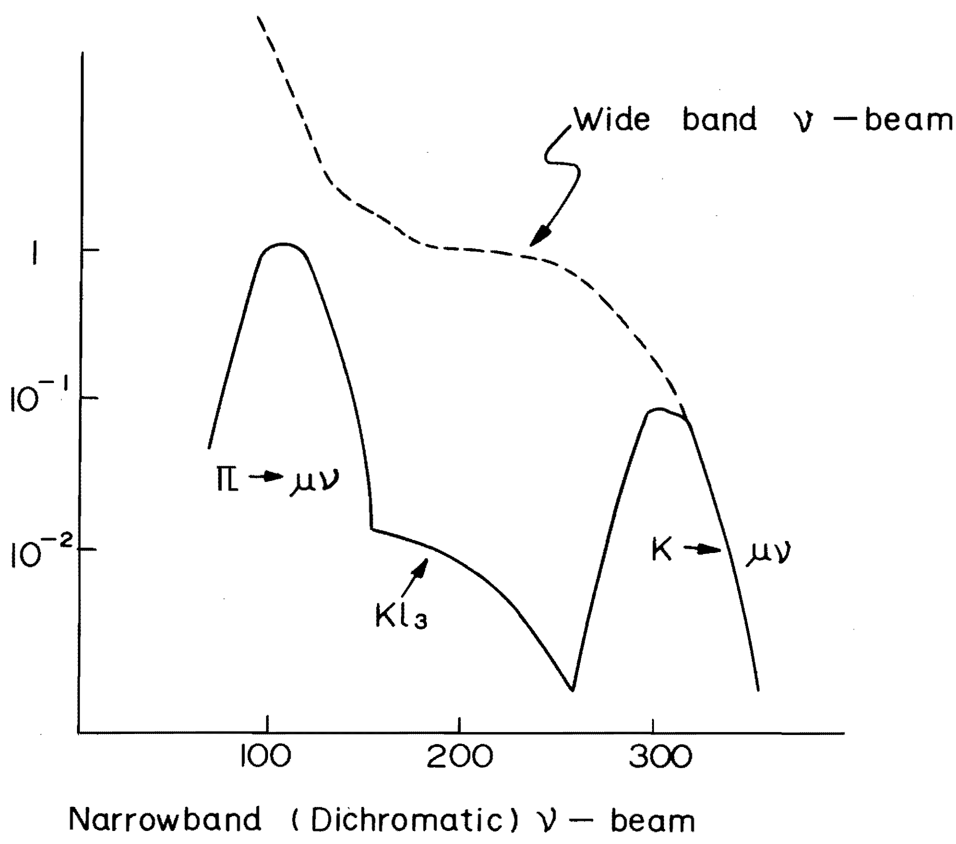


Wideband Neutrino Beam
(b)

Fig. 7

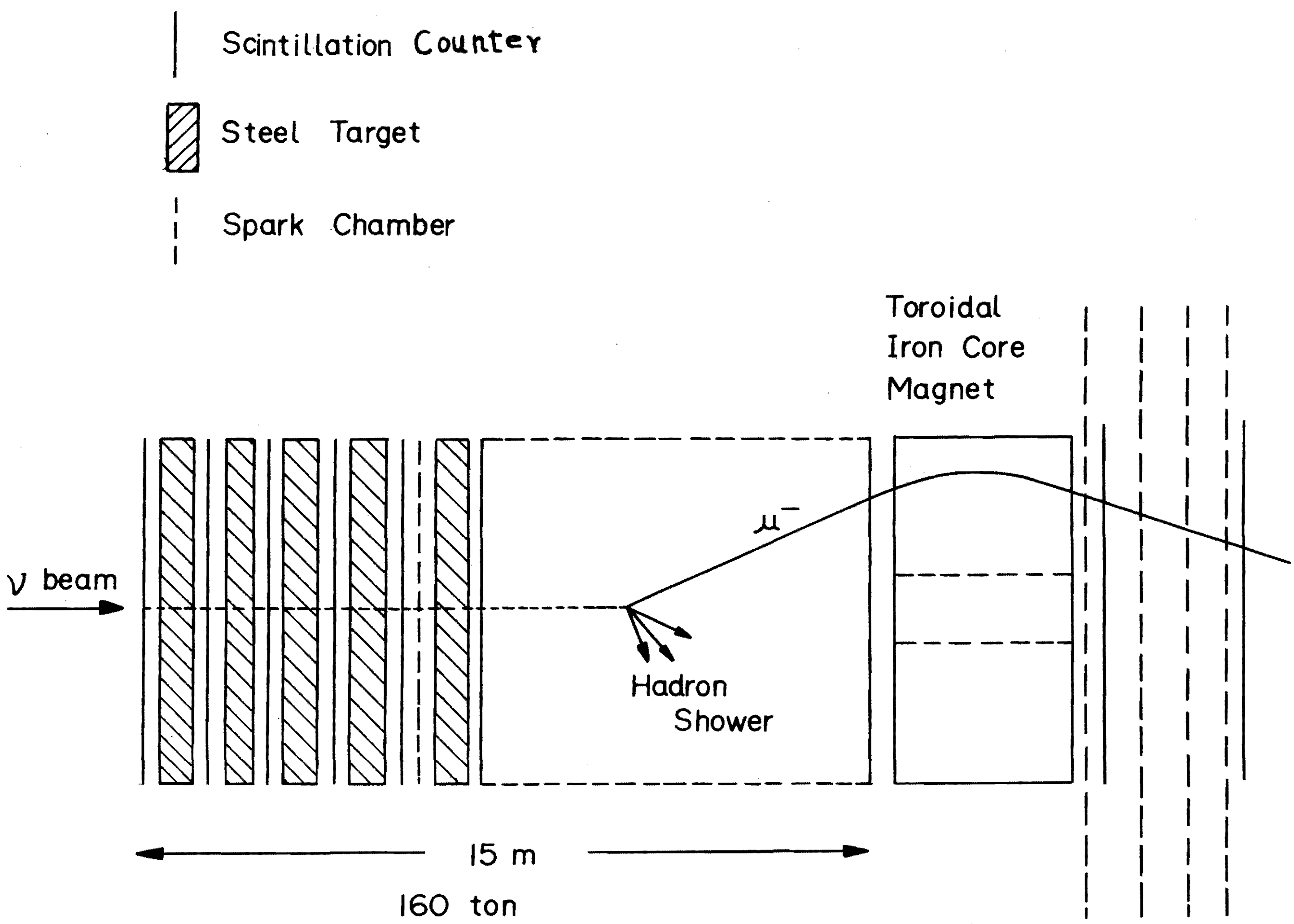

μ − Experiment
~ 500 m
500m
Focusing
Magnets
Decay Tunnel
μ+
Proton
K+, π+
μ+
ν
ν
μ
Target
Pencil beam
Δp/p ≤ 0.1
ν −Experiment

(a)


Wide band ν −beam
1
10⁻¹
10⁻²
π → μν
Kl3
K → μν
100
200
300
Narrowband (Dichromatic) ν − beam

(b)

Fig. 8 (a) (b)



Neutrino Experiment at NAL
(CALTECH — NAL)

Fig. 9

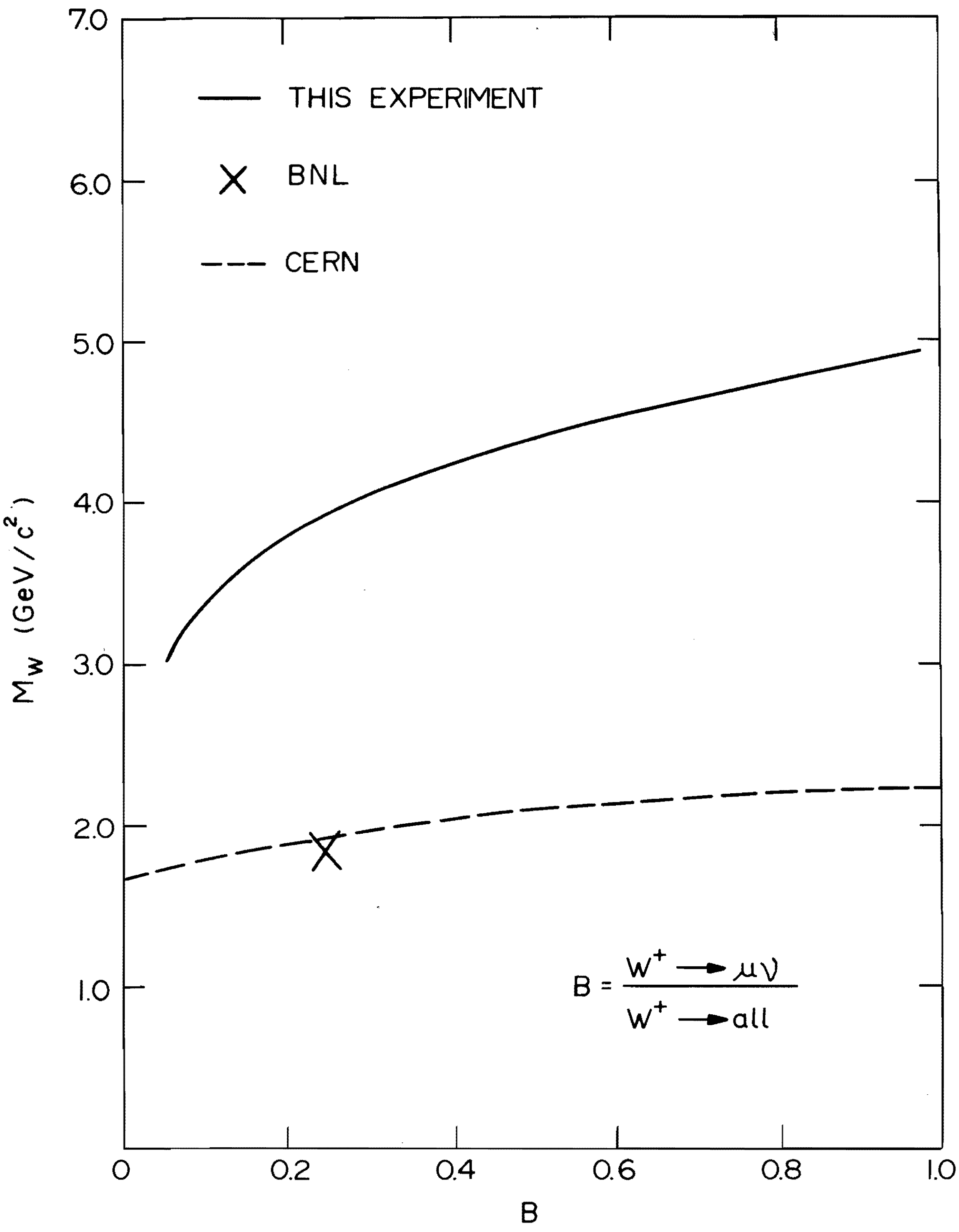
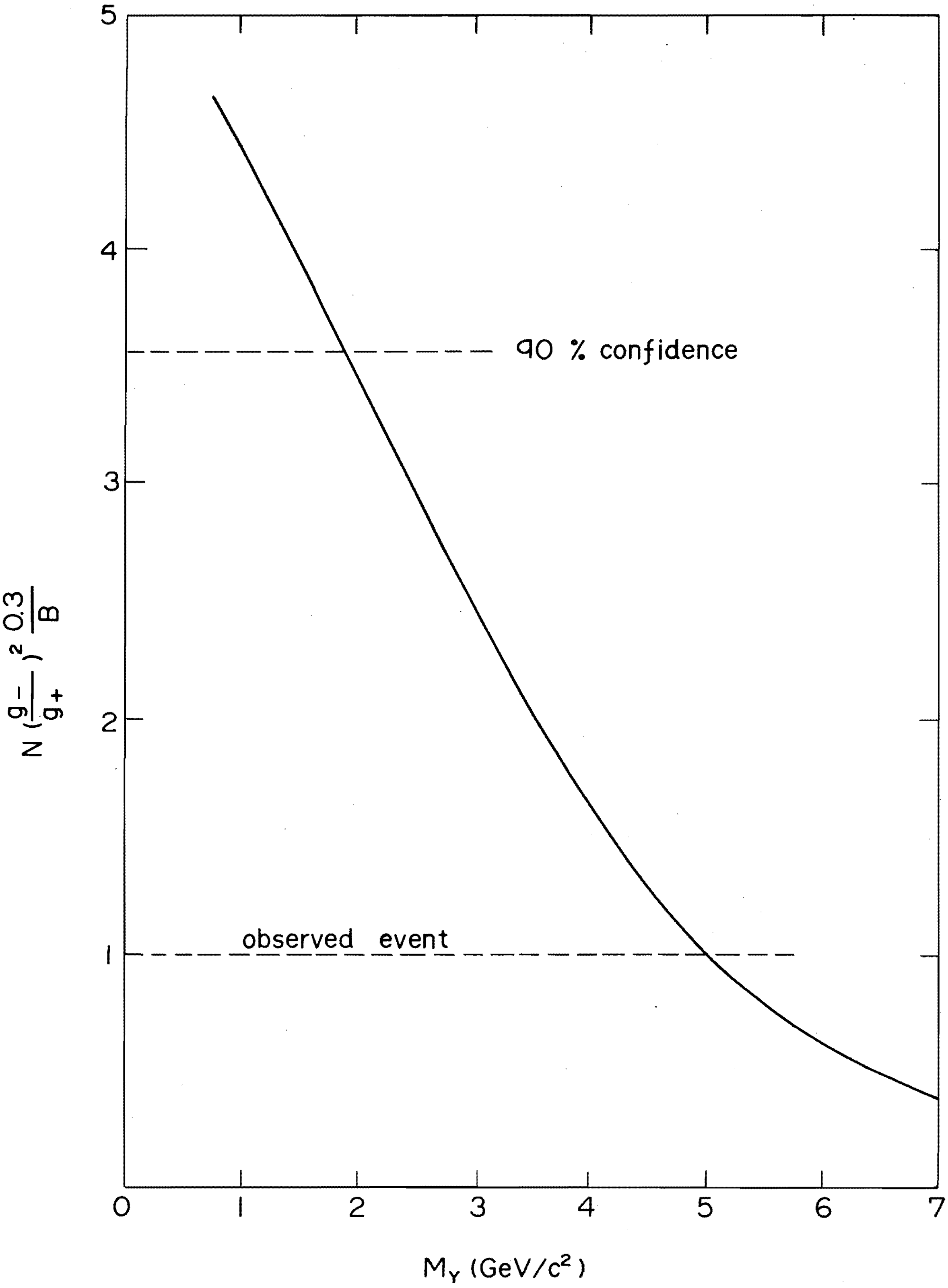

7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0.2
0.4
0.6
0.8
1.0
B
M_W (GeV/c^2)
THIS EXPERIMENT
BNL
CERN
$B = \frac{W^+ \to \mu\nu}{W^+ \to all}$

Fig. 13



5
4
3
2
1
0
1
2
3
4
5
6
7
90 % confidence
observed event
$N\left(\frac{g_-}{g_+}\right)^2 \frac{0.3}{B}$
M_Y (GeV/c^2)

Fig. 16