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PROPOSAL TO MEASURE $\sin^2\theta_W$ IN SEMILEPTONIC νFe INTERACTIONS WITH HIGH PRECISION

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1. INTRODUCTION

A precise determination of the electroweak mixing angle $\sin^2\theta_W$ is of interest for three reasons. It is the only free parameter of the minimal SU(2) × U(1) theory which predicted correctly the masses of the $W^\pm$ and Z^0, and describes successfully all experimental results in a large variety of weak neutral current phenomena. It is also one of the parameters in theories which attempt to unify electroweak and strong interactions. Finally, a precise measurement of $\sin^2\theta_W$ might enable, for the first time, a determination of higher order corrections which can be compared with theoretical predictions, and hence test the renormalizability of the electroweak theory. This latter argument was put forward by Marciano and Sirlin[1)] and Llewellyn-Smith[2)].

At present, the most precise measurement of $\sin^2\theta_W$ comes from the ratio of neutral-current (NC) to charged-current (CC) events in semileptonic νN interactions, where N denotes an isoscalar nucleus. The analysis of such semileptonic reactions necessarily involves a hadronic model whose uncertainties limit the "theoretical" precision in the extraction of $\sin^2\theta_W$. In a contribution to the SPS Fixed Target Workshop held at CERN in December 1982, Llewellyn-Smith[2)] pointed out that this theoretical uncertainty is small provided an isoscalar target nucleus is used. For such nuclei the largest contributions to the CC and NC cross-sections are related by isospin invariance alone. The quark-parton model is only needed for minor corrections, and introduces uncertainties in $\sin^2\theta_W$ which are of the order of 1%. Llewellyn-Smith concluded that there is no theoretical obstacle to measuring $\sin^2\theta_W$ to ±0.005 in semileptonic νN interactions.

Analysing such an experiment in the Born approximation, the value of $\sin^2\theta_W$ would predict a Z^0 mass which is $\sim$ 4.5 GeV lower than its actual value[3)]. If the Z^0 mass is measured with a precision of ±1 GeV, a significant determination of the higher order correction is possible at the 3.7 σ level if $\sin^2\theta_W$ is measured to ±0.005. If the Z^0 mass is measured to ±0.1 GeV, the correction is tested at the level of 6.6 σ.

Our Collaboration has acquired a quite detailed experience in the study of NC phenomena in $\overset{(-)}{\nu}$Fe interactions. In 1977, the ratios $R_\nu = (NC/CC)_\nu$ and $\bar{R}_\nu = (NC/CC)_{\bar{\nu}}$ were measured and gave strong support to the electroweak theory; a value of $\sin^2\theta_W = 0.24 \pm 0.02$ was published[4)] which was quite different from the then commonly accepted value. Further, a study of the y-distribution ($y = E_{had}/E_\nu$) was presented[5)], which showed for the first time the space-time structure of the NC scattering off isoscalar nuclei to be dominantly V-A, with evidence for a small V+A component at the 4 σ level.

Recently, the analysis of 200 GeV narrow-band beam (NBB) data taken in 1978/79, has been completed and gave the following results[6]:

$$\left.\begin{aligned} R_\nu &= 0.300 \pm 0.005\ \text{(stat.)} \pm 0.005\ \text{(syst.)} \\ R_{\bar\nu} &= 0.357 \pm 0.010\ \text{(stat.)} \pm 0.012\ \text{(syst.)} \end{aligned}\right\}\ \text{for } E_{had} > 10\ \text{GeV} .$$

The (preliminary) value of $\sin^2\theta_W$, corrected for electroweak radiative effects according to Wheater and Llewellyn-Smith[7], is then

$$\sin^2\theta_W = 0.232 \pm 0.012 ,$$

which is the most precise experimental value obtained so far.

With our improved apparatus, which has been in operation since 1982, the precision of $\sin^2\theta_W$ can be increased further. An experimental error on $\sin^2\theta_W$ of ± 0.005 can be achieved with optimal beam and data-taking conditions.

2. APPARATUS

Our improved apparatus consists of 10 new iron core magnets ("modules") with 2.5 cm sampling, 5 old magnets with 5 cm sampling, and 6 old magnets with 15 cm sampling (see Fig. 1). The magnets have a toroidal field oriented so that the muons originating from CC neutrino interactions are focused towards the axis of the detector.

The layout of the 10 new modules is shown in Fig. 2. The module consists of 20 iron plates each 25 mm thick. The iron is sampled with 15 cm wide scintillator strips -- 24 across the diameter of the module. Five successive strips along the axis are viewed by one phototube. The module thus consists of 4 planes, each made up of 2 × 24 independent scintillator forks. Successive planes are oriented at right angles. This structure allows the determination of the lateral position of a hadronic shower with a resolution of ∿ 3 cm, and constitutes the most relevant improvement to the old apparatus as far as the NC analysis is concerned.

The layout of the old modules is shown in Fig. 3. Every scintillator plane consists of 8 scintillators each 45 cm wide. The vertical shower position is determined by weighting coordinates of the scintillator sheets with their energy response. The horizontal shower position is calculated from the ratio of pulse heights at the right and left scintillator edge, making use of the light absorption in the scintillator sheets. The radial position of a shower has a resolution of ∿ 20 cm.

In order to use the good spatial resolution in the new modules the fiducial volume is restricted to module 2 until the middle of module 10. The fiducial mass is then 177 t, with a radial cut of R < 1.3 m. The first module serves as absorber of incoming neutral hadrons.

3. METHOD OF MEASUREMENT

NC events are distinguished from CC events by their "length" L in iron, defined as the distance from the event vertex to the end point of the most penetrating particle of the event, projected onto the z-axis of the detector. The length is expressed in cm of iron. A typical example of the length distribution is shown in Fig. 4. NC events are given by the hadronic shower length and cluster around short lengths. CC events are dominantly defined by the outgoing penetrating muon, and tend to have large values of length. Only a minor fraction of CC events constitutes a background to the NC signal.

It is important to notice that the separation of NC and CC events in the variable L is not complete but safe. The analysis deals with global numbers of events defined by suitable cuts in the range distribution. The cuts are chosen so that any reliance on the understanding of the hadronic cascade is avoided. The only thing that really matters is the understanding of the trajectory of a muon of given momentum in the specific magnetic field and geometry of our apparatus.

A NC candidate is defined by the requirement $L < L_{cut}$ ("NC signal region") where L_{cut} is typically about 200 cm, and is logarithmically dependent on the hadron shower energy. A CC candidate is defined by the requirement $L \geq L_{cut}$ ("CC signal region").

Short CC events ($L < L_{cut}$) are to be subtracted from the number of NC candidates, and to be added to the number of CC candidates. Their number is determined on the basis of the observed CC events in a "monitor region", defined by $L_{cut} + 75$ cm $< L < 526$ cm. The extrapolation from the monitor region into the NC signal region is done with a Monte Carlo simulation program.

For events with $L > L_{cut}$, the length L is determined by the outgoing muon. The extrapolation gives the number of events with projected muon length $L < L_{cut}$ based on the number of observed events in the monitor region. It is important to notice that the length distribution of CC events simply reflects the y-distribution ($y = E_{had}/E_\nu$). The extrapolation is rather safe since it relates CC events at large y (in the monitor region) to CC events at even larger y (in the NC signal region). Since the y-distribution is nearly flat at large y, also the L-distribution is in first approximation flat and uncritical.

The hadron energy is measured in a "box" of 1.5 m length of iron, starting at the event vertex. To obtain the genuine hadronic energy for CC events, the energy $E_\mu^{box} \sim 3$ GeV which is dissipated by the outgoing muon has to be subtracted from the measured global shower energy. This leads, in practice, to a cut-off of, say, 10 GeV for the NC signal region and the NC monitor region, and a cut-off of 10 GeV + E_μ^{box} for the CC signal region and its associated CC monitor region.

Near $\sin^2\theta_W = 0.23$ only R_ν is sensitive to $\sin^2\theta_W$ whereas $R_{\bar{\nu}}$ is insensitive to $\sin^2\theta_W$. The errors in R_ν and $\sin^2\theta_W$ are related by $\Delta R_\nu \simeq -0.7\ \Delta \sin^2\theta_W$. Hence, an error $\Delta \sin^2\theta_W = 0.005$ requires a measurement of R_ν to ± 0.003. We will try to achieve this overall error of 0.003, and expect that it will be composed of equal statistical and systematic errors of 0.002.

Table 1 gives a breakdown of the event numbers which have been used in our last R_ν analysis. The data are from a NBB with 200 GeV/c parent momentum, which is close to the experimental situation proposed here. The individual subtractions are discussed in detail in Section 5.

For the cross-section of neutrinos scattering off an isoscalar nucleus, the cross-section ratio of neutral to charged currents is according to Llewellyn-Smith[2)] given by

$$R_\nu = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left[1 + r\right] + \text{small corr. terms} ,$$

where $r = \sigma_{CC}^{\bar{\nu}}/\sigma_{CC}^{\nu}$ with the same cut-off in E_{had} as for neutral current events. For $\sin^2\theta_W = 0.23$, we have $\Delta R_\nu \simeq 0.03\ \Delta r$. A measurement of r to 4% is sufficient to reduce the uncertainty of R_ν to 0.2%. According to Table 1, a few times 10^{17} protons in an antineutrino exposure would suffice to achieve the required precision of r. The dominant part of data taking will be in a neutrino exposure.

4. NEUTRINO BEAM

The requirements for the neutrino beam are: high rate of events to achieve the necessary statistical accuracy; high average energy to work as much as possible in the deep inelastic region far above the charm production threshold; a good knowledge of the K/π ratio of the hadron parents (which is important for the K_{e3} subtraction, see Section 5); a spectrum of E_{had} which falls with energy as little as possible (which is important for the correction for the muon energy loss, see Section 5); good beam intensity monitoring devices; and finally a good understanding of the intensity and energy profile of the neutrino flux over the front-face of the apparatus.

The CERN standard 200 GeV NBB meets all the above criteria, except the high event rate, and offers the best chances for a high-precision determination of $\sin^2\theta_W$ from the systematic point of view: the average neutrino energy is of the order of 100 GeV; the K^+/π^+ ratio can be measured with a precision of ∿ 2%; the flux spectrum is flat with energy; good beam monitoring equipment exists; the intensity and energy profiles are *a priori* known from the optical beam parameters and the two-body decay kinematics of π and K, and are checked by measuring fully reconstructed charged current events.

In order to increase the neutrino flux considerably, Grant and Mauguin[8] have proposed a modification of the N3 neutrino beam line. The acceptance of the beam line for secondary hadrons is increased by changing the optical properties of the initial group of quadrupoles such that the effective centre of the lens moves closer to the target. The limitation in the maximum field gradient of the quadrupoles however implies a reduction of the nominal parent momentum of 200 GeV/c to 160 GeV/c. At this setting, a maximum neutrino event rate is found using only the first four of the seven quadrupoles at the start of the beam. The remaining three quadrupoles are switched off. The remainder of the beam optics is scaled down from the nominal 200 GeV/c beam optics.

With 450 GeV/c protons on target, the gain in event rate at event radius $R < 1.3$ m is ~ 1.9 as compared to the 200 GeV/c NBB with 400 GeV/c protons on target.

Scaling from the observed event rates given in Table 1, which give $R_\nu = 0.300 \pm 0.005$ (stat.), we need a factor of $(2.5)^2 = 6.25$ more events than observed in the 1978/79 exposure with 1.1×10^{18} protons of 400 GeV/c and event radius $R < 1.2$ m, to achieve a statistical error of 0.002 in R_ν. This can be achieved with 6×10^{18} protons of 450 GeV/c on target, which corresponds to 110 days of running with an *average of* 1.1×10^{13} *protons per burst, 12 s SPS cycle and 70% overall efficiency*. Out of the total of 6×10^{18} protons, about 0.3×10^{18} protons will be used for the antineutrino exposure.

5. SYSTEMATIC ERROR SOURCES

Table 1 is a list of the subtractions to be made to obtain R_ν. This section is concerned with a discussion of the systematic accuracy of each of the subtractions. We will focus our attention on the "Short CC" subtraction, which is the largest and hence of particular importance.

5.1 Cosmic subtraction

The number of cosmic background events is measured in a separate time window outside the beam spill. The only source of systematic error is the small difference in dead-time in spill and out of spill. The beam is extracted in a fast-slow resonance mode (FWHM $\sim$ 0.3 ms), and the effective spill gate width is 1.5 ms. The fast-slow spill is chosen to minimize the dead-time and hence loss of protons, and to minimize the chance of event and/or SPS muon overlays which cause problems for the analysis.

The cosmic background, which is a 1% subtraction in Table 1, will be increased by a factor of 1.5 ms/100 μs = 15. The dead-time is of the order of 5%, measured to better than 10% of its value. Hence the systematic error of the cosmic-background subtraction is 15% × 0.5% and therefore negligible. The increase of the statistical error of R_ν due to a 15% cosmic-background subtraction is 8%, which is tolerable.

If the background due to SPS muons turns out to be very low, a multi-turn fast extraction mode could be employed.

5.2 Wide-band beam subtraction

The wide-band beam (WBB) background arises from decays of π and K before momentum and sign selection, from decays of π and K originating in interactions of selected parent particles along the beam line, and from prompt ν_μ and ν_e from charm production and subsequent semileptonic decay in the target and in the proton dump. This background constitutes a 2.7% correction, which can be known with a systematic accuracy of 5% of its value.

Firstly, the optimum fraction of $\sim$ 15% of the total running time must be devoted to background measurements. Secondly, we propose to rearrange the end of the N3 beam line (Fig. 5 shows the present and the proposed layout).

The large beam current transformer (BCT) is moved close to the last quadrupole, whose vacuum pipe is extended to the BCT. It serves for absolute normalization of the parent flux. It is followed by the Cherenkov counter needed for the measurement of the K/π ratio. The small BCT, which is movable on a common support with two beam position monitors, is replaced by a beam dump (made of copper, 110 cm long, 30 cm in diameter, 0.7 t in weight) which can be moved into the beam line by external control.

Under normal operation, the beam dump is rolled out of the beam line, and only the entrance window of the decay tunnel, the remaining gas in the evacuated decay tunnel, and the hadron stopper at the end of the decay tunnel create WBB background. These contributions are switched off when the beam dump is rolled in. On the other hand, the beam dump now creates WBB background which does not exist in normal running.

Compared to the WBB background from the hadron stopper, the contribution from the remaining gas in the decay tunnel is negligible (3%) if the pressure is kept below 0.1 Torr (note that a pressure of 0.02 Torr was achieved in beam-dump running in 1982). Similarly, the contribution from the entrance window of the decay tunnel can be kept at 20% of the contribution from the hadron stopper if a very thin window of 0.1 mm thick Ti with a diameter of 15 cm is used.

The contributions from the beam dump in front of the decay tunnel and the hadron stopper after the decay tunnel differ by a factor of 2.4 because of the different acceptance. The fraction of the overall WBB background which is due to the hadron stopper is poorly known and estimated at the level of 15%. The correction compared to the case when the beam dump is rolled in can be calculated on the basis of the measured rates in the 1979 and 1982 beam-dump exposures. Ideally, however, one would install a movable beam dump with average interaction length chosen such that the integral WBB contributions from the beam dump in front of the decay tunnel, on the one hand, and from the entrance window plus remaining gas in the tunnel plus the hadron stopper, on the other hand, cancel out. A study is under way as to whether the last quadrupole can be moved from its present position. This would allow sufficient space for the installation of a somewhat diluted beam dump.

The hadron stopper at the end of the decay tunnel must be placed as close as possible (a few cm) to the window of the tunnel. In the present configuration, after the beam-dump running of 1982, an empty space of about 10 m exists after the window, which would constitute an untolerably large source of WBB background.

In order to cut down the cosmic background in the WBB background running the 23 μs single-turn extraction mode will be employed.

In any case, a systematic precision of the WBB background subtraction given by the differences in the WBB background discussed above, the normalization, and the differences in dead-time, at the level of 5% of its value is possible.

5.3 Short charged-current subtraction

As can be seen from Table 1, this subtraction constitutes a 18.5% correction to the ratio of muonless to muonic events, and hence must be known to 2.5% of the correction.

The subtraction is due to CC events where the outgoing muon has so low an energy that it is hidden in the hadronic shower, or the muon is emitted at large angle and leaves the detector by the side. In the first case we deal with CC events with y close to unity, whereas in the latter case also lower y are concerned. Owing to the small cut in event radius, $R < 1.3$ m, compared to the detector radius of 1.88 m, and the focusing property of the magnetic field, only the first case of stopping muons plays a significant role.

As outlined above, the number of CC events in the NC signal region, $L < L_{cut}$, is determined from a Monte Carlo extrapolation on the basis of the observed number of events in the monitor region. Notice that the extrapolation on the basis of the monitor events is statistically poorer but systematically safer than an extrapolation based on all CC events with $L > L_{cut}$.

The Monte Carlo must reproduce correctly the geometrical properties of our detector, the bending of the muon in the magnetic field, the energy loss of muons in iron, and the energy and intensity profile of the neutrino beam over the front-face of the detector. All this is in principle straightforward and can be done with the necessary accuracy.

Since the NC signal region is ∿ 200 cm long, and the short CC subtraction (which is to first order flat in the variable L) is to be precise to ±2.5%, the event length must be precise to 5 cm on an average.

Backscattering of $\pi^{\pm}$ and photons from π^0 decay at the primary vertex increases L by 1-2 cm of iron on an average, according to our present understanding. This effect will be studied further with BEBC film from νNe interactions (G. Myatt, spokesman of WA47, has kindly agreed to make this data available to us).

The efficiency per scintillator slab to detect a minimum ionizing track is at present 95%. This will be increased by raising the HV of the phototubes by 100 V. This is possible in a 160 GeV NBB exposure without saturating the upper end of the dynamical range of the pulse-height measuring chain. The efficiency of scintillators can be determined from the data themselves, and is adequate for the required precision.

Problems due to random noise in the scintillators can be avoided by evaluating the projected length L by pattern recognition of the muon track in space (the previous analyses of R_{ν} have relied on the integrated pulse height per scintillator plane only).

The NC and CC rates must refer to the same cut-off in hadronic energy, which we expect to choose near 10 GeV. As already outlined above, the measured shower energy always contains in the case of CC events a portion E_{μ}^{box}, of the order of 3 GeV, which comes from the muon energy deposit in the hadronic "shower box". This contribution E_{μ}^{box} must be known to 10%, in order to keep the effect on the number of CC events below 0.3%. The muon energy loss will be determined from the data themselves, since there are many scintillators which are traversed by a muon of known momentum. The average muon energy loss, expressed in terms of our pulse-height units per scintillator slab, can certainly be determined to better than 10%.

The contamination of events in the monitor region due to π and K decay (which would shift NC events into CC events) can be estimated from the rate of like-sign dimuon events, which is $\sim 5 \times 10^{-4}$ for $p_{\mu} > 5$ GeV. Assuming that all such events fall into the monitor region, and taking a ratio of monitor events to all CC events of 0.05, we obtain a 1% change of the number of monitor events due to π and K decay. This is at the edge of being dangerous, but can easily be corrected for.

5.4 Long neutral-current subtraction

The cut-off in L is designed such that 99% of all NC events are included. The cut-off is not designed for the statistical optimum of the subtraction, but for the best systematic accuracy while maintaining the NC signal region as short as possible. The cut-off correction of the order of 1% can be determined from a comparison of the data with the predicted Monte Carlo distribution in L to 20% accuracy (note that the Monte Carlo only deals with CC events, and L is there defined as the projected length of the outgoing muon).

5.5 K_{e3} subtraction

The K_{e3} subtraction is due to the ν_e contamination in the NBB which arises from K_{e3} decay. Both CC and NC interactions of ν_e appear as neutral currents in our sample. To achieve the required precision on this 8% correction to R_ν, the K/π ratio must be known to 4%. This is possible since the relative K to π yield of a Be target has been measured precisely[9], and the Cherenkov counter installed in the N3 beam line measures K^+/π^+ ratios with an error of $\sim$ 2%.

The difference in response to electrons and hadrons in our calorimeter has been measured[10], but is of minor importance since K_{e3} CC events will all be above the cut-off of 10 GeV.

6. SUMMARY AND REQUEST FOR BEAM TIME

We aim for a measurement of R_ν with ±0.002 (stat.) and ±0.002 (syst.) errors. To achieve this, we need 88,500 NC and 295,000 CC events after corrections.

The estimated systematic error sources are (expressed as percentage error of R_ν):

- Cosmic-background subtraction	< 0.1%
- WBB-background subtraction	0.3%
- Determination of event length L	0.4%
- Muon energy loss in shower box	0.3%
- Long neutral currents	0.2%
- K_{e3} subtraction	0.3%
- Uncertainty from r (see Section 3)	0.2%
Overall systematic error of R_ν	0.7%

The experiment can be carried out with practically no cost for new equipment. Minor changes in the WA1 apparatus and in the N3 beam line can be covered by the normal support budgets.

We need 110 days of running with an average of 1.1×10^{13} protons on the neutrino target with a total of 6×10^{18} protons. The beam is a specially designed 160 GeV NBB. The normal extraction mode is fast-slow spill. About 15% of the time has to be spent for WBB background measurements, in 23 μs single-turn extraction mode. About 3×10^{17} protons are devoted for $\bar{\nu}$ running.

We would like to carry out the proposed experiment during the fixed target running in 1984. We see no possibility to do the experiment at a later time.

REFERENCES

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Table 1

Data reduction of R_ν analysis in 200 GeV NBB (1978/79 exposure, Ref. 6;
E_{had} > 10 GeV; event radius R < 1.2 m; fid. mass 280 t)

	Neutrinos (1.1×10^{18} protons)				
	NC		CC		Correction factor to NC/CC ratio
	Signal region	Monitor region	Signal region	Monitor region	
Raw	18176	2421	44224	2295	-
Cosmics	-181	-0.6	-4	-0.6	0.990
WBB	-641	-199	-404	-117	0.973
Short CC	-2356		+2643		0.815
Long NC	+150		-150		1.013
K_{e3}	-991		+857		0.918
	14157		47166		
	Antineutrinos (3.0×10^{18} protons)				
Raw			14411	413	
Cosmics			-2	-0.2	
WBB			-382	-33	
Short CC			+526		
Long NC			-53		
K_{e3}			+133		
			14633		

Figure captions

Fig. 1 : Improved WA1 neutrino detector.

Fig. 2 : Layout of new modules.

Fig. 3 : Layout of old modules.

Fig. 4 : Projected length of νFe interactions.

Fig. 5 : Present and proposed layout of the instrumentation in the N3 beam line in front of the decay tunnel.

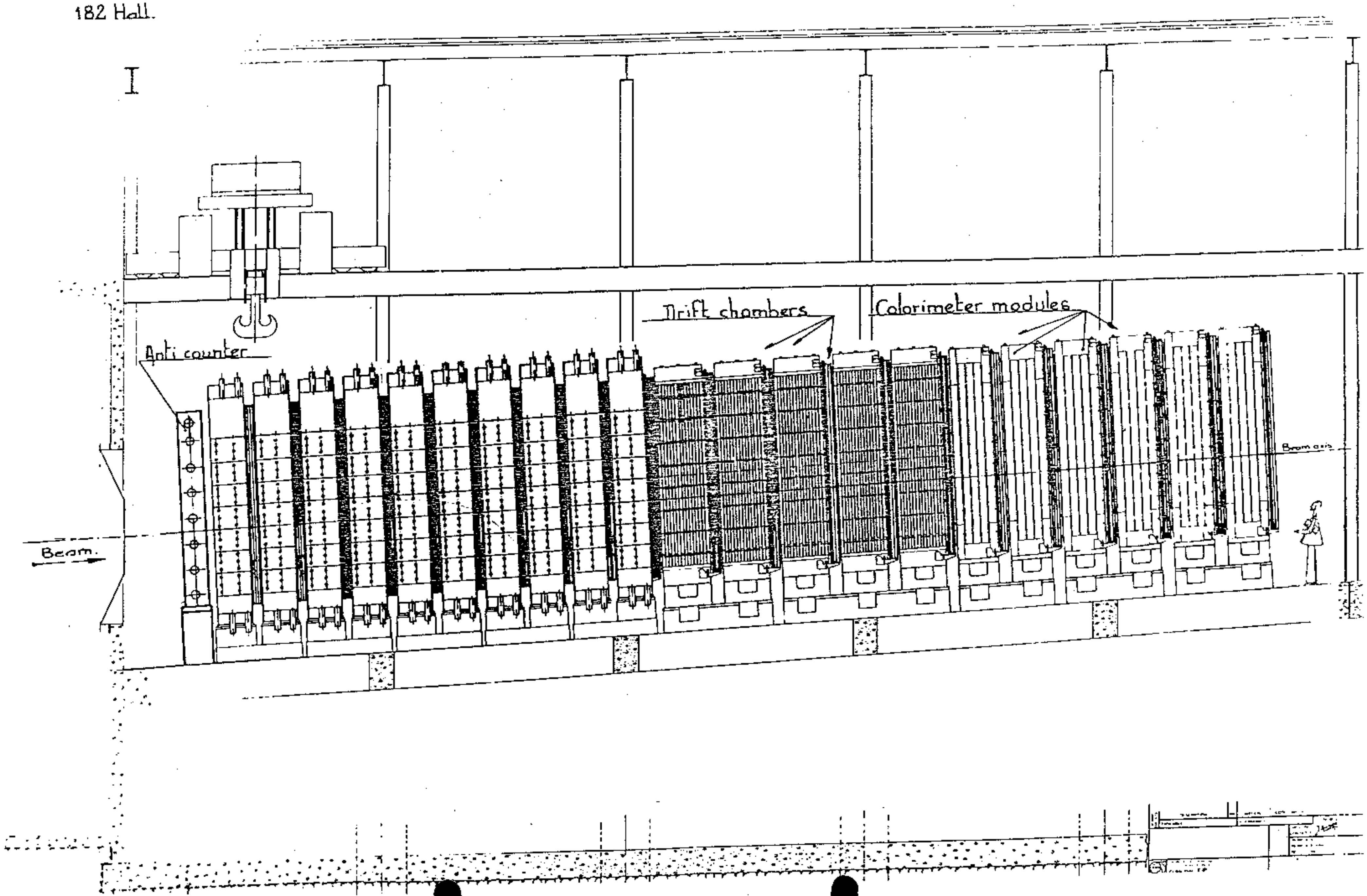
182 Hall.
I
Anti counter
Drift chambers
Colorimeter modules
Beam.
Beam axis

Fig. 1

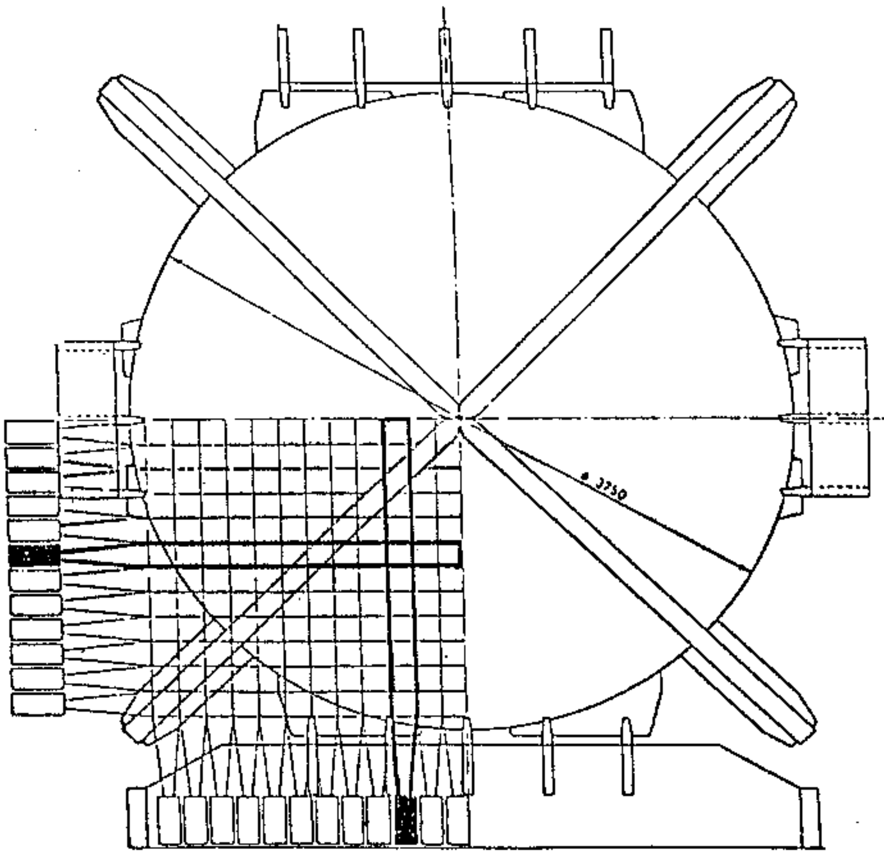

Fig. 2

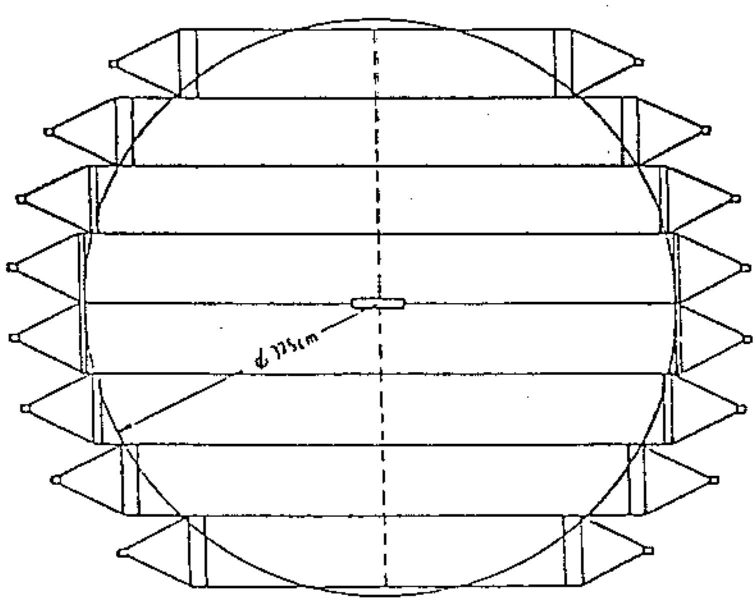

Fig. 3

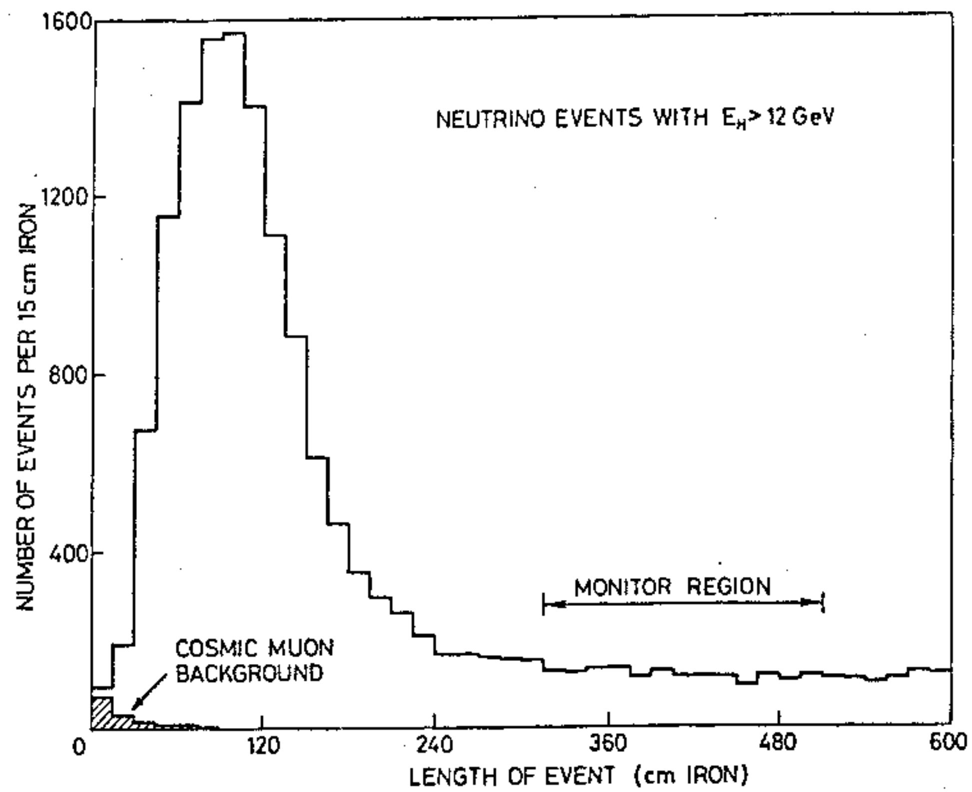
NEUTRINO EVENTS WITH E_H > 12 GeV
NUMBER OF EVENTS PER 15 cm IRON
1600
1200
800
400
0
120
240
360
480
600
LENGTH OF EVENT (cm IRON)
MONITOR REGION
COSMIC MUON BACKGROUND

Fig. 4

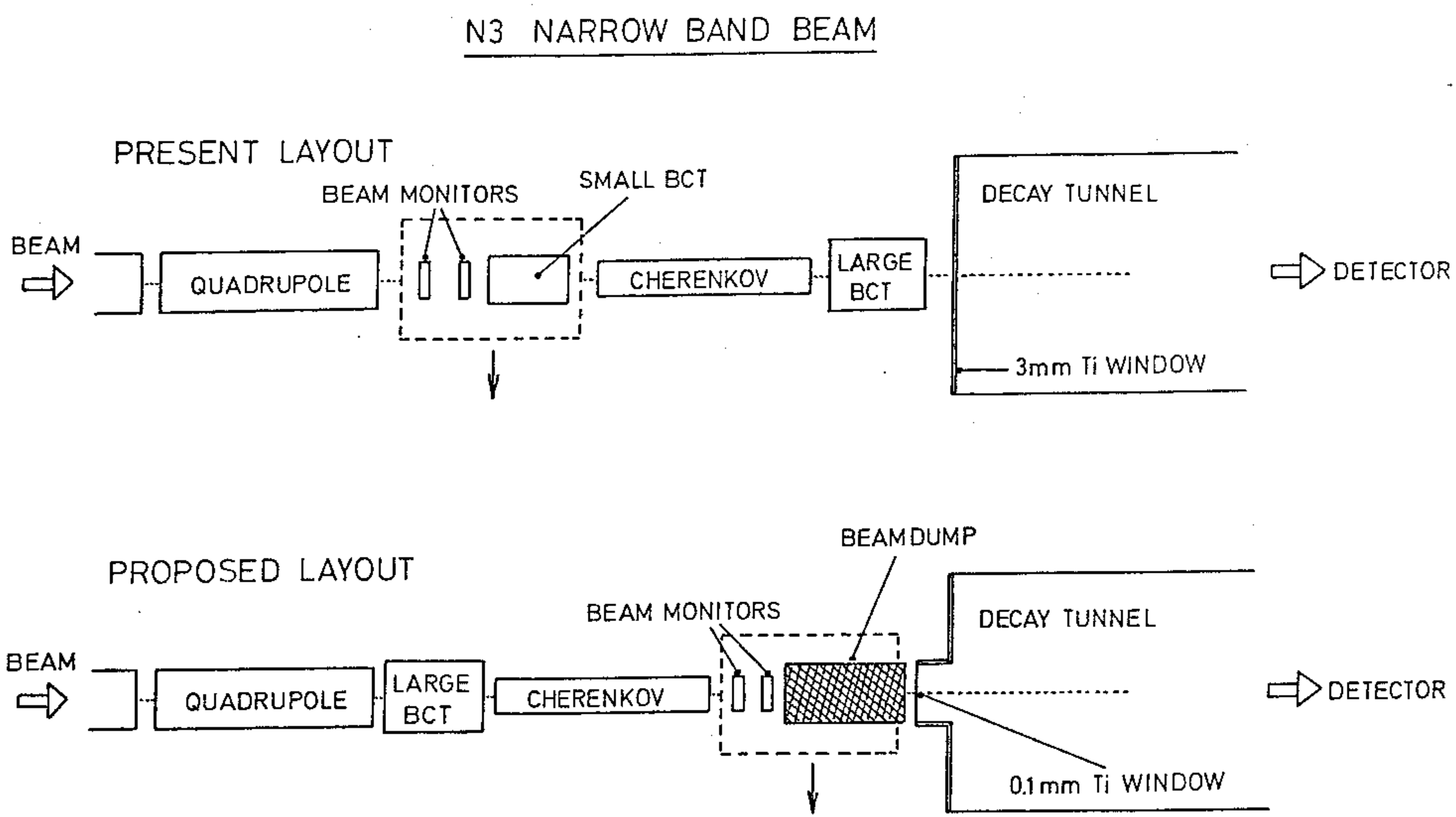
N3 NARROW BAND BEAM
PRESENT LAYOUT
BEAM MONITORS
SMALL BCT
BEAM
QUADRUPOLE
CHERENKOV
LARGE BCT
DECAY TUNNEL
3mm Ti WINDOW
DETECTOR
PROPOSED LAYOUT
BEAMDUMP
BEAM MONITORS
BEAM
QUADRUPOLE
LARGE BCT
CHERENKOV
DECAY TUNNEL
0.1mm Ti WINDOW
DETECTOR

Fig. 5