Chapter 15

Detectors

15.1 Introduction

The Neutrino Factory will open up a regime of neutrino physics that is inaccessible at existing facilities. When combined with a multi-kiloton detector located at a large distance, the proposed accelerator will allow the study of a number of unexplored neutrino oscillation parameters and a significant reduction in uncertainty of previously measured neutrino mass differences and mixing angles. The Neutrino Factory, plus its long-baseline detector, will have a physics program that is a logical continuation of current and near-future neutrino oscillation experiments in the U.S., Japan and Europe [1]. The facility will potentially enable physicists to determine values for all remaining unknown physical constants associated with current neutrino oscillation theory.

Features of the facility that allow these challenging oscillation measurements are a high neutrino intensity, a well-collimated beam, precise understanding of beam composition and spectra, and optimized energy. In addition, detector facilities located in experimental areas near the neutrino source will have access to integrated neutrino intensities 10^4–10^5 times larger than previously available (10^{20} neutrinos per year compared with 10^{15}–10^{16}). Standard neutrino physics at this facility could include physics topics such as precision $\sin^2\theta_W$, structure functions, high precision neutrino total charge current (CC) cross sections at low $\sqrt{s}$ (a few GeV), nuclear effects (shadowing at low x, anti-shadowing...), pQCD, and neutrino magnetic moments. These topics have relevance for standard model physics, nuclear physics, astrophysics and physics beyond the standard model. Finally, the Neutrino Factory will serve as a test accelerator for a high intensity muon collider and so is an R&D facility that is a significant step toward a muon collider in the future.

15.2 Beam Parameters

Neutrino beams produced at the Neutrino Factory are either (ν_μ,$\bar{\nu_e}$) or ($\bar{\nu_\mu}$,ν_e) depending on whether the machine is running μ^- or μ^+. The characteristics of the machine design guarantee that the beam is pure, with no contamination from anti-particles of the same neutrino flavor. The design intensity is 10^{20} μ decays/year, where a year is defined as 1×10^7 s. The angular dispersion of the ν-beam is $\Delta\theta/\theta = 5.3$ mrad with a momentum spread $\Delta p/p = 30\%$. The primary long-baseline target site considered in this report is the Waste Isolation Pilot Plant (WIPP) located in Carlsbad, New Mexico [2]. WIPP is located 2900 km from Brookhaven National Laboratory and requires a 13.1° dip angle in the muon storage ring. An alternative site with a smaller baseline, but with an already existing detector, Soudan, Minnesota, is discussed in the Appendix B.6. Most recently, a new alternative site has been suggested, the Homestake Mine in Lead, SD, that has been recommended as the site for the National Deep Underground Laboratory [3].

Based on design parameters in this report, the expected event rate at the WIPP site is given in Table 15.1.

Table 15.1: Event rates WIPP.

E_μ (GeV)	Baseline (km)	E_{ν_μ}	E_{ν_e}	$N(\nu_\mu$ CC) (per kt-year)	$N(\nu_e$ CC) (per kt-year)
$20_{\text{BNL-WIPP}}$	2900	15	13	740	330

15.3 Physics Signals

As discussed in detail in Section 1.3, neutrino mixing can be described by the lepton CKM matrix:

$$U = U_{23}U_{13}U_{12} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\exp^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}\exp^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(The possibility of light sterile neutrinos is not considered here). Three-flavor neutrino oscillations can be described by seven parameters: three $\Delta m_{ij}{}^2$ terms; three mixing angles θ_{ij}; and a CP violating term δ. The mass parameters are related by the simple identity $\Delta \mathrm{m}_{12}{}^2 + \Delta \mathrm{m}_{23}{}^2 + \Delta \mathrm{m}_{31}{}^2 = 0$. SuperKamiokande (SuperK) [4] has measured what appears to be non-zero values for $\Delta m_{23}{}^2$ and θ_{23} in atmospheric neutrinos. Over the next few years both K2K [5] and MINOS [6] will try to confirm the SuperK observation with accelerator-based experiments and obtain accurate values for $\Delta\mathrm{m}_{23}{}^2$ and θ_{23}. The ν-oscillation parameters $\Delta\mathrm{m}_{12}{}^2$ and θ_{12} are the province of solar and reactor-based experiments, either now running or planned for the next several years. The values of these parameters, hopefully, will be measured over the next 5–10 years. A long-baseline experiment at the Neutrino Factory will be able to measure θ_{13}, the sign of $\Delta m_{23}{}^2$ and possibly the CP violation term δ, providing θ_{13} is large enough. Depending on the values of the various neutrino parameters, it is conceivable that the Neutrino Factory will be in a position to measure all the remaining outstanding neutrino mixing parameters. Additionally, a long-baseline neutrino detector should be able to make the first direct measurement of the neutrino-matter oscillation effect (MSW). It would study MSW and could make a model-independent measurement of the matter parameter A, where $A = \sqrt{2}G_F n_e$. Measurements of A with 10% accuracy are possible, and may even be of interest to geophysicists.

15.4 Long Baseline Oscillation Experiment

The characteristics of a Neutrino Factory beam, $\nu_\mu, \bar{\nu_e}$ with no $\bar{\nu_\mu}, \nu_e$ contamination, naturally lend themselves to a neutrino appearance experiment. Since a μ^- beam at the Neutrino Factory will not result in any initial production of $\bar{\nu_\mu}$, a $\bar{\nu_\mu}$ signal will be due to $\bar{\nu_e} \rightarrow \bar{\nu_\mu}$ oscillations. An experiment designed to look for $\bar{\nu_\mu}$ CC events measures $P(\bar{\nu_e}\rightarrow\bar{\nu_\mu})$, where

$$P(\bar{\nu_e}\rightarrow\bar{\nu_\mu}) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2(\Delta m^2{}_{13} L/4E)$$

A program to study both $P(\bar{\nu_e}\rightarrow\bar{\nu_\mu})$ and $P(\nu_e\rightarrow\nu_\mu)$ not only gives us access to θ_{13} but also tells us the sign of the $\Delta\mathrm{m}_{23}{}^2$ and allows us to measure the matter parameter A (Fig. 15.1).

It is interesting to note that the matter parameter becomes accessible only when the beam has passed through a significant amount of material. Calculations show that the BNL-WIPP distance of 2900 km is far enough for the MSW effect to be measurable.

As stated earlier, if both the CP violating term, δ, and θ_{13} are large enough, they may be disentangled in these measurements. In addition, a spectral scan on the oscillation probabilities would potentially improve the precision of the $\Delta m_{23}{}^2$ and θ_{23} measurements by nearly an order of magnitude [7].

The experiment's concept is to start with the muon storage ring filled with μ^-, which produces a ν_μ,$\bar{\nu_e}$ beam, and look for a $\bar{\nu_\mu}$ appearance at the distant detector. The experiment would take sequential data sets with both μ^- and μ^+ storage ring fills, enabling

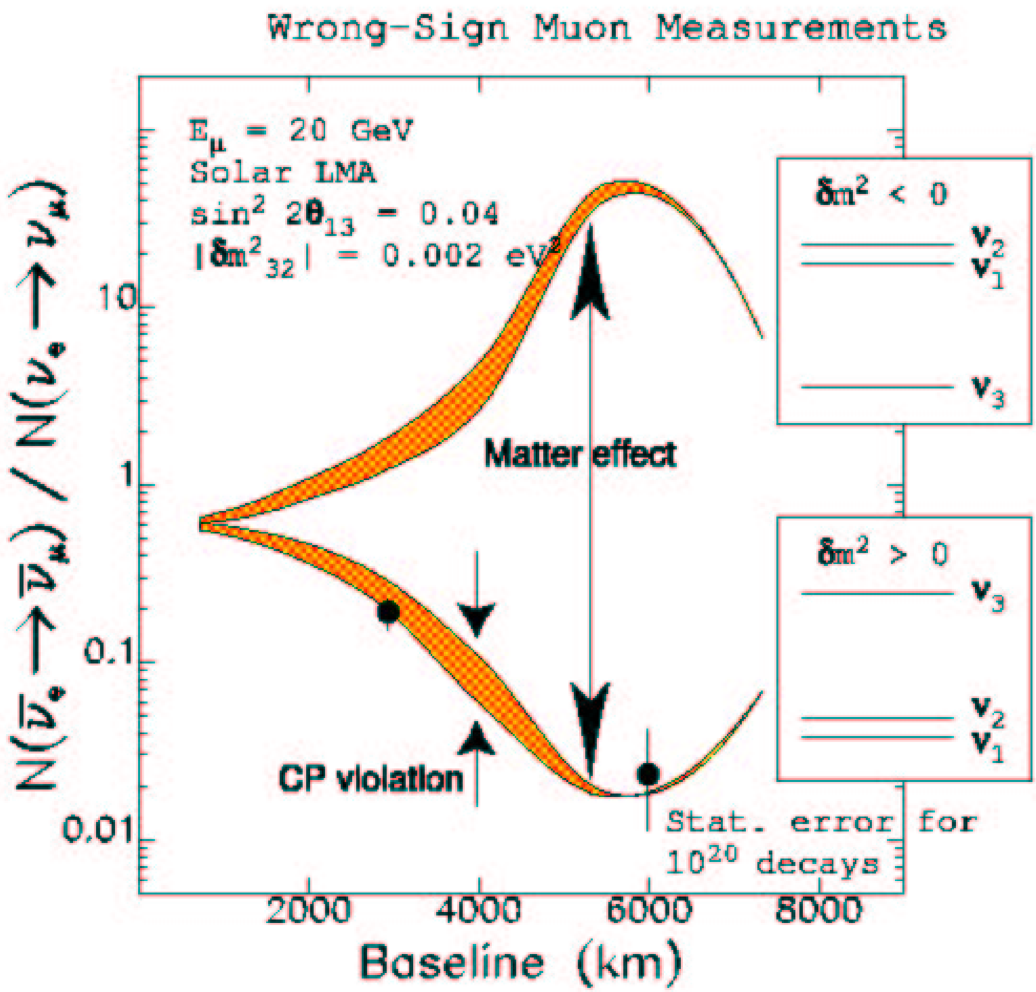

Figure 15.1: Measuring the ratio of $P(\bar{\nu_e}\to\bar{\nu_\mu})$ to $P(\nu_e\to\nu_\mu)$ enables measuring the sign of $\Delta m_{23}{}^2$ and the value of the matter parameter A.

the study of both the neutrino-matter oscillation effect and neutrino CP violations. Measuring $P(\nu_e \rightarrow \nu_\mu)$ and $P(\bar{\nu_e} \rightarrow \bar{\nu_\mu})/P(\nu_e \rightarrow \nu_\mu)$ gives access to the oscillation parameters described above.

$\bar{\nu_\mu}$ appearance experiment is typically done by looking for the leading μ^+ from the $\bar{\nu_\mu}$ CC reaction in the detector. The challenges in a search for $\bar{\nu_\mu}$ events are threefold: i) distinguishing μ^+ from the μ^- coming from the non-oscillating ν_μ's; ii) separating μ^+'s from π^+ punch-throughs; and iii) rejecting μ^+'s coming from hadronic decays. Another potential background, which depends on the detector environment, is accidentals from either cosmics or some background radiation.

There are a number of hadronic decay backgrounds for the μ^+ signal. They are:

- ν_μ CC where the primary μ^- is missed and the μ^+ from hadronic decay of the π^+, K^+, or D^+ is observed

- ν_e CC where the primary e^+ is missed and the μ^+ from hadronic decay of the π^+ or K^+ is observed (The D^+ is not a significant concern here)

- ν_μ,ν_e NC, where π^+ and K^+ again cause problems

The requirement to both measure the signal and reject the background determines a number of the detector's characteristics. Measurement of the sign of the muon is critical to the experiment, which means the detector must contain a magnetic field. Obtaining the muon spectrum is also important and can be done either through bending in the spectrometer or by range, using $\frac{dE}{dx}$. Separation of μ's from π's is accomplished through range-out in many interaction lengths of material. Rejection of hadronic backgrounds requires a combination of momentum, p_t, and isolation cuts. A detailed investigation of these backgrounds was carried out in Study-I [8]. It was determined that, to make the background manageable, a detector requires both momentum resolution and transverse segmentation (See Figs. 15.2, 15.3, 15.4). Rejection of accidental backgrounds can be handled by a detector with moderate timing resolution. Timing resolutions on the order of 100 ns would allow the experiment to only take events in phase with the machine time structure, and so reject accidentals by a factor of 200. A timing resolution of 10 ns gains an additional factor of two in background rejection by allowing a direction cut. Finally, the neutrino event rates seen in Table 15.1 indicate the need for the detector to be large, multiple ktons.

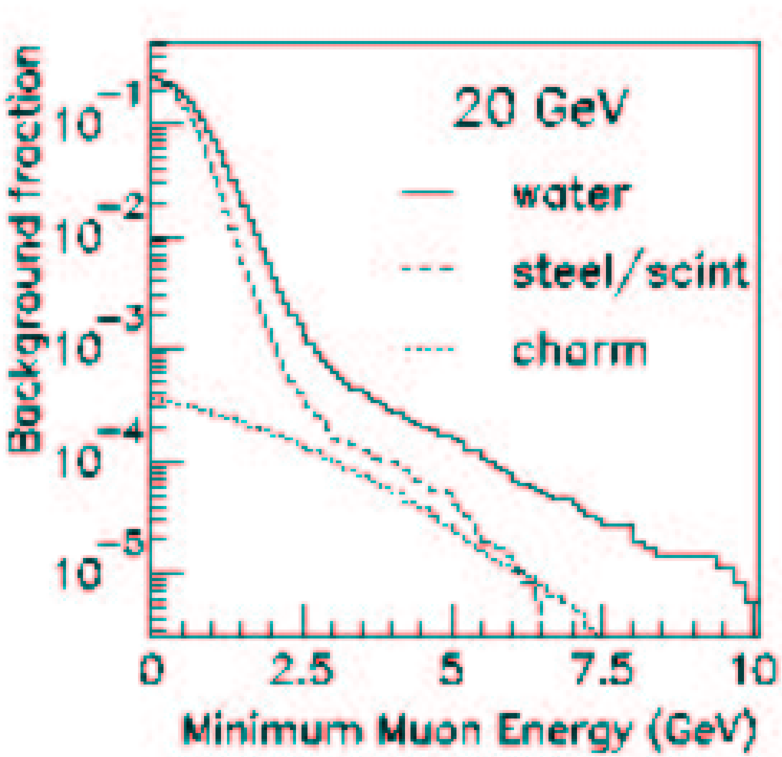

Figure 15.2: Fraction of neutrino events that produce a background signal as a function of minimum muon energy. Background sources include π and K decays, π punch-through, and charm decays.

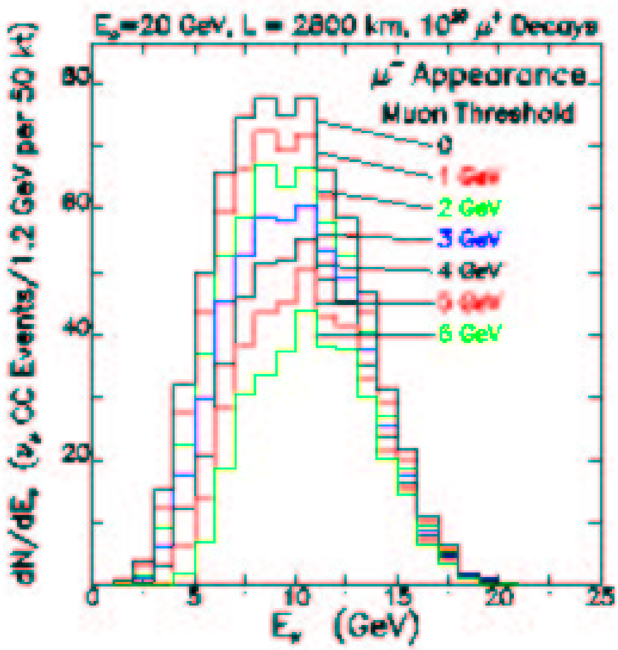

Figure 15.3: Reconstructed neutrino energy distribution for several different minimum muon energy cuts. Note that a minimum muon cut at 4 GeV reduces the signal by 30–35%.

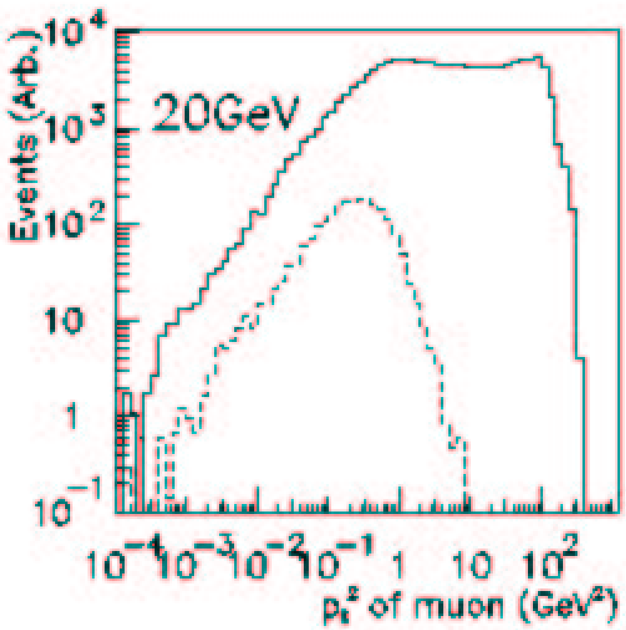

Figure 15.4: Distributions of the square of the muon momentum component transverse to the hadronic shower, p_t^2, for ν_μ CC events (solid line) and background muons (dashed line). The effectiveness of a transverse cut can be seen.

15.5 Detector Options

Specifications for the long-baseline Neutrino Factory detector are rather typical for an accelerator-based neutrino experiment. However, because of the need to maintain a reasonable neutrino rate at these long distances, the detectors considered here are between 3 and 10 times more massive than those in current neutrino experiments.

Large-mass detector designs are driven primarily by the cost of the absorbers. Limiting the detector's cost drives us to two basic options: steel-based and water-based designs. The two detector options considered for the WIPP site in this study are a 50 kton Steel/Scintillator/Proportional Drift Tube (PDT) detector and a Water Cerenkov Detector. The detector considered for the Soudan site, a 15 kton PDT detector is discussed in Section B.6.

The PDT detector would resemble MINOS, having steel absorber plates of 10–20 cm thickness, being magnetized with a toroidal field to 1–1.5 T. A combination of PDT's and scintillator slats would be interleaved with the absorber to provide longitudinal and transverse position resolution and coarse timing. In addition, the scintillator layers provide the experiment with its trigger. The thickness of the steel absorber and the ratio of PDT to scintillator slats would be optimized for momentum resolution and background rejection. The estimated electronics channel count would be of the order $1 - 5 \times 10^5$. With a neutrino event rate of a few mHz, the electronics could be highly multiplexed to reduce cost and complexity. Phototube magnetic shielding in these detector geometries has been solved by both MINOS and predecessor experiments, and so should not be an issue. Figure 15.5 shows a 50 kton detector with dimension 8 m $\times$ 8 m $\times$ 150 m. This geometry would be convenient for access and services, though designs that maximize fiducial-volume-to-edge ratios are possible. A detector of this size would record up to 4×10^4 ν_μ events/year.

A large water Cerenkov counter would be similar to SuperK but with either a magnetized water volume or toroids separating smaller water tanks. The detector could be the large water-Cerenkov UNO detector [9], currently proposed to study both proton decay and cosmic neutrinos. UNO would be a 650 kton water-Cerenkov detector segmented into a minimum of three tanks (Fig. 15.6). The gaps between the tanks may contain toroidal magnets, or perhaps large-gap dipoles to provide the B field needed to identify the charge of the leading muon (Fig. 15.7). The detector provides sufficient muon/hadron separation and muon containment up to 30 GeV/c. A water-Cerenkov detector would have background rejection of the same order as a steel/scintillator/PDT detector, though results from Study-I (Fig. 15.2) suggest muon p_t cuts would need to be 1.0–1.5 GeV/c higher in a water-Cerenkov counter to obtain the same rejection levels. UNO would be read out with 70,000 phototubes, a combination of the 20-inch SuperK tubes and 8-inch tubes.

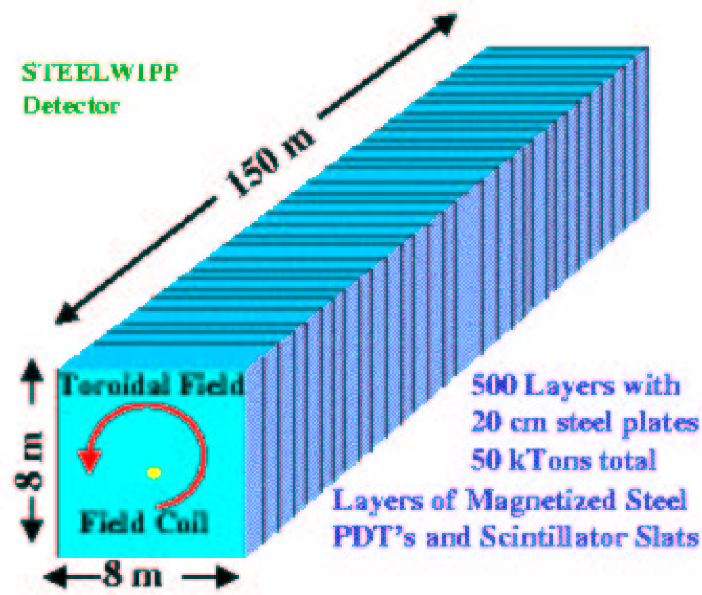

Figure 15.5: A possible 50 kton Steel/Scintillator/PDT detector at WIPP.

The timing provided by the PMT's would allow UNO to gate events in time with the Neutrino Factory beam structure. This enables UNO to work simultaneously as both a long-baseline neutrino experiment and a proton-decay experiment. The multi-faceted nature of the UNO physics program is an appealing aspect of this detector option. However, geometry of the water tanks does not provide a straightforward way to contain the spectrometer magnet fringe field, so magnetic shielding of the PMT's could be a technical challenge. UNO's active volume is large, 60 m $\times$ 60 m $\times$ 180 m (w $\times$ h $\times$ l), which implies an experiment hall of substantial dimensions. To provide reasonable access, the hall would need to be at least 100 m $\times$ 80 m $\times$ 300 m, and perhaps more. The detector would have an active fiducial mass of 440 ktons and would record up to 3×10^5 ν_μ events/year from the Neutrino Factory beam.

15.6 WIPP Site

The WIPP facility is the U.S. Department of Energy's Waste Isolation Pilot Plant located in Carlsbad, New Mexico. It is a large, underground depository for the storage of low-level radioactive waste and has been in operation since 1999 (Fig. 15.8).

The WIPP site is approximately 2900 km from Brookhaven National Laboratory. The active depository is located 650 m underground in a deep salt formation. Space is potentially available for a large underground physics facility at depths of 740–1100 m and discussions are under way between DOE and the UNO project on the possible development of such a facility. Infrastructure, such as elevator access and electricity, is currently available at the waste storage levels but new excavation and infrastructure installation would need to take place for the creation of an underground physics facility. The area should be considered a green field, albeit a very salty one.

It is worth asking here whether these experiments need to be as deep underground as proposed, or even underground at all. The effort and expense to build an experiment 700+ m underground adds significantly to the challenge of the experiment. Certainly for the UNO detector option, the experiment must be deep underground. A proton decay experiment that is searching for events with maximum rates of a few per year can tolerate little cosmic ray background. The ν interaction rate in a 50 kton steel-based detector is a few mHz at beam design intensity. At the surface, the cosmic ray interaction rate in the 50 kton detector is a few 100 kHz. These event rates would not provide significant data loading to the Data Acquisition System from either a bandwidth or archiving perspective. The main issue is the signal-to-noise (S/N) ratio of $10^{-7} - 10^{-8}$, which would be improved by gating with the Neutrino Factory beam structure, and providing a veto array around the detector. These techniques should allow the S/N to be improved to $10^{-3} - 10^{-2}$.

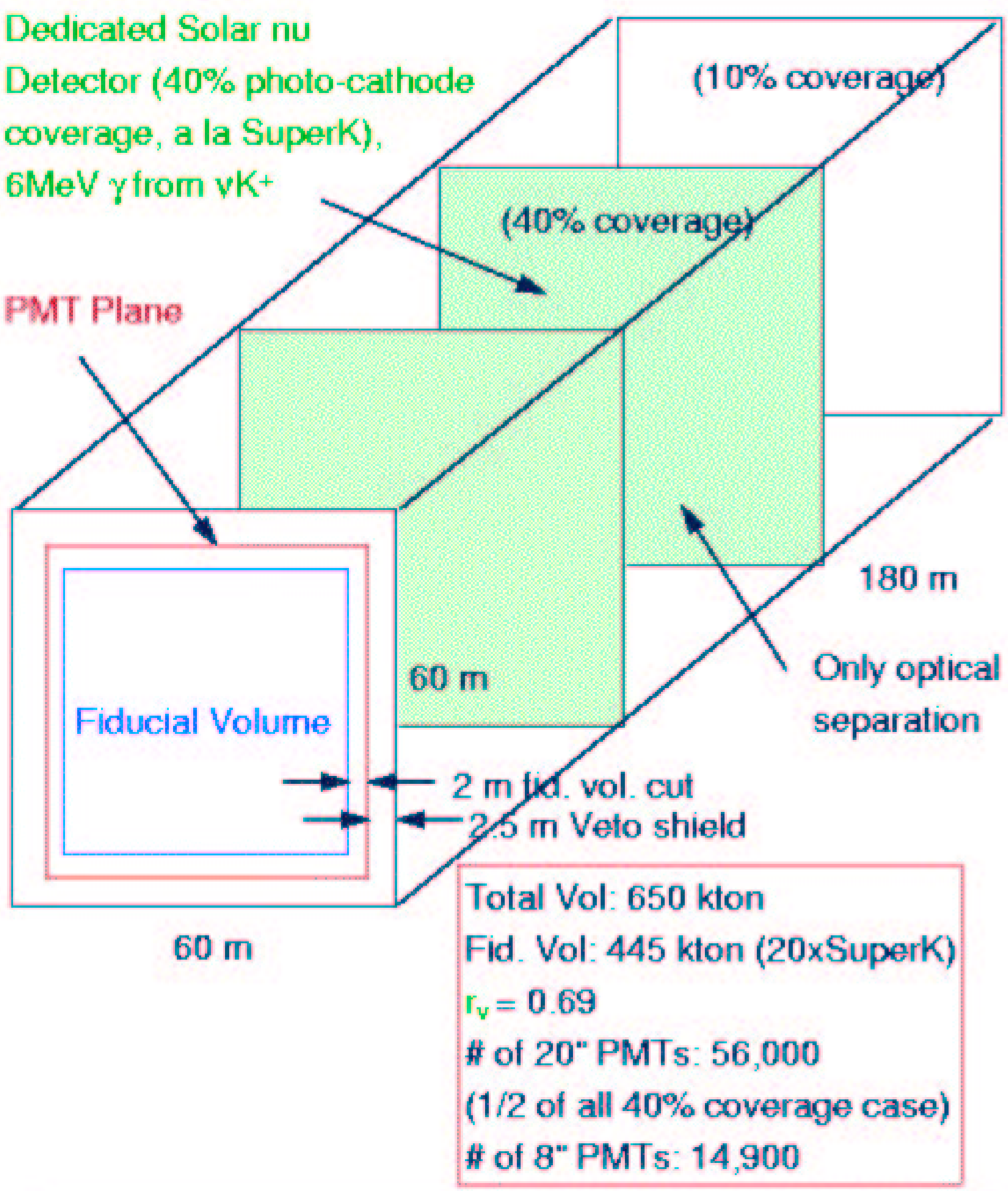

Figure 15.6: Block schematic of the UNO detector, including initial design parameters.

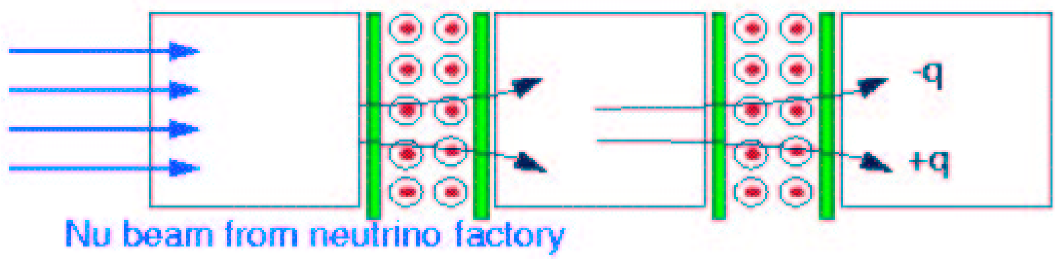

Figure 15.7: Concept of multi-water tank Cerenkov counter with magnetic field included.

Higher level software triggers could further reduce backgrounds by making cuts on event topology. A Monte Carlo study would be necessary to determine whether the remaining cosmic ray background events could be removed through data analysis.

15.7 The Near Detector

Detector facilities located on-site at the Neutrino Factory would have access to unprecedented luminosities of pure neutrino beams, well focussed with narrow energy spectra. A detector positioned 50 m from the end of the muon storage ring straight-away could expect ν-fluxes 10^4–10^5 times higher than currently available from accelerator sources. These luminosities would allow neutrino detectors to be much more compact, with higher precision in particle momentum and energy measurements. This in turn would enable standard neutrino physics studies such as $\sin^2\theta_W$, structure functions, ν cross sections, nuclear shadowing and pQCD to be performed with much higher precision than previously obtainable.

A compact Liquid Argon TPC (similar to the ICARUS detector [10]), cylindrically-shaped with a radius of 50 cm and a length of 1 m would have an active volume of 10^3 kg and a neutrino event rate O(10 Hz). The detector provides tracking, an EM energy resolution of $3\%/\sqrt{E} + 1\%$ and hadronic energy resolution of $20\%/\sqrt{E} + 5\%$. The TPC could be combined with a downstream magnetic spectrometer for muon and

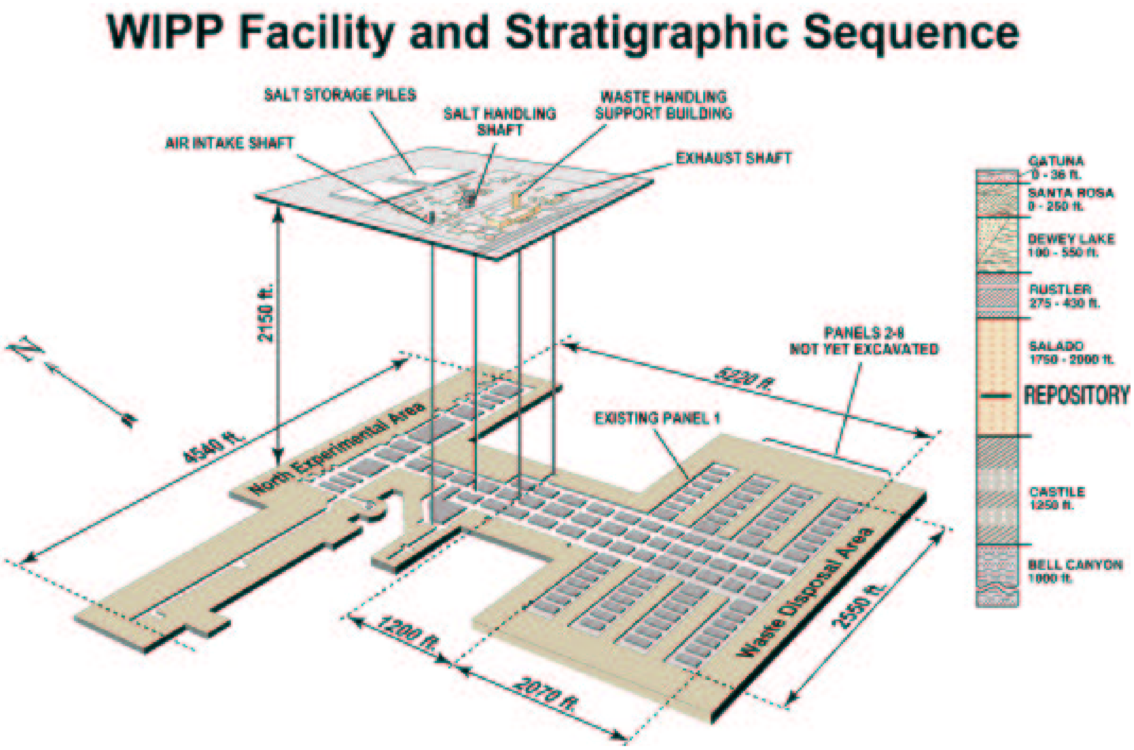

Figure 15.8: The WIPP area.

hadron momentum measurements. At these ν-luminosities it is even possible to have an experiment with a relatively thin Pb target (1 L_{rad}) followed by a standard fixed target spectrometer containing tracking chambers, time-of-flight and calorimetry with a event rate O(1 Hz). Backgrounds from neutrino interactions in the upstream shield must be considered, but should be manageable with accurate tracking to the target.

15.8 Summary

The Neutrino Factory, combined with a long-baseline detector, will allow a number of neutrino oscillation parameters to be measured (θ_{13}, sign of $\Delta m_{23}{}^2$, δ, A), some for the first time. There is the potential that by the time the factory comes online, the long-baseline experiment would be able to measure all the outstanding neutrino oscillation parameters. The experiment site considered in this study, WIPP, has space available 700+ m underground with some associated infrastructure. Detector options for the experiment include a steel/scintillator/PDT detector similar to MINOS and its progenitors, and weighing tens of ktons. The proposed 650 kton water-Cerenkov detector, UNO, is also an option. Both choices are technically feasible, though the water-Cerenkov approach has a number of outstanding technical questions. Conventional neutrino physics is also accessible at the Neutrino Factory with ν beam intensities many orders of magnitude higher than previously available at accelerator facilities.

15.8. Summary

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