High Rate Neutrino Detectors for Neutrino Factories

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Three types of high rate neutrino detectors for neutrino interaction physics at neutrino factories are discussed. High performance general-purpose detectors might collect event samples on the order of a billion events or more. This could greatly improve on existing analyses of neutrino interactions and also lead to new and important analysis topics including, for example, precise determinations of the CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$. The potential of such general purpose detectors is illustrated with reference to a previously discussed detector that is structured around a novel and compact vertexing and tracking neutrino target comprising a stack of CCD pixel devices. Design ideas and prospects are also discussed for two types of specialized detectors: (i) polarized targets filled with polarized solid protium-deuterium (HD), for unique and powerful studies of the nucleon’s spin structure, and (ii) Fully active liquid tracking targets with masses of several tonnes for precise determinations of the weak mixing angle, $\sin^2 2\theta_W$, from the total cross-section for neutrino-electron scattering. All three detector types pose severe technical challenges but their utilization could add significantly to the physics motivation for neutrino factories.

1 Introduction

Muon colliders and other proposed high-current muon storage rings can be collectively referred to as neutrino factories. As well as the long baseline neutrino oscillation studies that are currently garnering much of the attention, neutrino factories also have considerable potential for wide-ranging studies involving the physics of neutrino interactions. Exciting and unique high rate (HR) neutrino physics could be performed using detectors placed as close as is practical to the storage ring in order to maximize the event rate and to subtend the neutrino beam with the narrowest possible target. Rather than studying the properties of the neutrinos themselves, such experiments would instead investigate their interactions with the quarks inside nucleons and with electrons. HR detectors needed for these studies form the topic of this paper.

The advantages of neutrino beams from stored muons over traditional neutrino beams are in some ways even more notable for HR experiments than for oscillation studies. In particular, the increased neutrino flux and the much smaller transverse extent close to production allows the collection of unprecedented event statistics even in compact fully-active tracking targets backed by high-rate, high-performance detectors.

The small transverse extent of the beam at the HR detectors derives from the production method in neutrino factories. Muon decays,

$$\mu^- \to \nu_\mu + \bar{\nu}_e + e^-,$$

Presented at the ICFA/ECFA Workshop "Neutrino Factories based on Muon Storage Rings" (νFACT’99), Lyon, France, 5–9 July, 1999.
in the production straight sections of the muon storage ring will produce pencil beams of neutrinos with unique two-component flavor compositions. The beams from $\mu^-$ and $\mu^+$ decays will be denoted as ($\nu_\mu\bar{\nu}_e$) and ($\bar{\nu}_\mu\nu_e$) in the rest of this paper. From relativistic kinematics, the forward hemisphere in the muon rest frame is boosted into a narrow cone in the laboratory frame with a characteristic opening half-angle, $\theta_\nu$, given in obvious notation by

$$\theta_\nu \simeq \sin \theta_\nu = \frac{1}{\gamma_\mu} = \frac{m_\mu c^2}{E_\mu} \simeq \frac{0.106}{E_\mu [\text{GeV}]}.$$  

For example, the neutrino beams from 50 GeV muons will have an opening half-angle of approximately 2 mrad and a radius of only 20 cm at 100 meters downstream from the center of the production straight section. (This neglects corrections due to the non-zero width of the muon beam and the length of the production straight section.) As an additional advantage besides the increased beam intensity, the decay kinematics for equations 1 are precisely specified by electroweak theory. This enables precisely modeled and completely pure two-component neutrino spectra for HR physics at neutrino factories, which is a substantial advantage over conventional neutrino beams from pion decays, particularly for high-statistics precision measurements.

Analysis topics at these novel beams and detectors at neutrino factories might extend well beyond traditional neutrino physics topics and should complement or improve upon many analyses in diverse areas of high energy and nuclear physics. Section 2 presents an example of a high performance general purpose detector whose excellent event reconstruction capabilities should address almost all such analyses, and gives a brief overview of the physics benefits of these analyses. There are two important physics topics that might be much better conducted using specialized detectors. Polarized targets for spin physics are discussed in section 3, and section 4 introduces the options for high mass detectors to study neutrino-electron scattering.

Table 1, which is reproduced from reference [1], displays parameters for examples of the three types of detectors discussed in the following sections. It also gives realistic but very approximate integrated luminosities and event sample sizes for 2 illustrative neutrino factory energies: 50 GeV and 500 GeV. A muon beam energy of about 50 GeV is a likely choice for a dedicated muon storage ring [2], with default specifications of $10^{20}$ muon decays per year in the production straight section. Five hundred GeV muons correspond to a 1 TeV center-of-mass muon collider such as, for example, that discussed in reference [1].

The event samples in table 1 are truly impressive. It is seen that high performance detectors with fully-active tracking neutrino targets might collect and precisely reconstruct data samples with of order billions of neutrino-nucleon DIS interactions – more than three orders of magnitude larger than any of the data samples collected using today’s much larger and cruder neutrino targets. Each of the three detector types in table 1 will now be discussed further in the following sections.
Table 1: Specifications, integrated luminosities and event rates for the HR targets discussed in this paper and for 50 GeV (500 GeV) muon storage rings. The approximation is made that the target is situated 100 m (1 km) downstream from the center of a straight section that has $N_{\mu} = 10^{20}$ decays of 50 GeV (500 GeV) muons. This corresponds to average neutrino energies of 32.5 GeV (325 GeV) and to approximately 1 (2) years running for storage ring parameters given previously in the literature [2, 1].

| target purpose | general | polarized | $\nu - e$ scatt. |
|----------------|---------|-----------|-----------------|
| material       | Si CCD’s | solid HD | liquid CH$_4$   |
| ave. density   | 0.5 g.cm$^{-3}$ | 0.267 g.cm$^{-3}$ | 0.717 g.cm$^{-3}$ |
| length         | 2 m     | 0.5 m    | 20 m            |
| mass/area, $l$ | 100 g.cm$^{-2}$ | 13.4 g.cm$^{-2}$ | 1434 g.cm$^{-2}$ |
| radius         | 0.2 m   | 0.2 m    | 0.5 m           |
| mass           | 126 kg  | 16.8 kg  | 11.25 tonnes    |
| $\int L dt$   | $6.0 \times 10^{45}$ cm$^{-2}$ | $8.1 \times 10^{44}$ cm$^{-2}$ | $8.6 \times 10^{46}$ cm$^{-2}$ |
| no. DIS events:|         |          |                 |
| at 50 GeV      | $1.4 \times 10^9$ | $1.9 \times 10^8$ | $2.0 \times 10^{10}$ |
| at 500 GeV     | $1.4 \times 10^{10}$ | $1.9 \times 10^9$ | $2.0 \times 10^{11}$ |
| no. $\nu$-$e$ events:| |          |                 |
| at 50 GeV      | $3.5 \times 10^5$ | NA          | $7 \times 10^6$ |
| at 500 GeV     | $3.5 \times 10^6$ | NA          | $7 \times 10^7$ |

2 Example design for a neutrino detector to study DIS

Figure 1 shows a general purpose high rate neutrino detector that might be well matched to the intense neutrino pencil beams at neutrino factories. This specific example is reproduced from reference [3] and it illustrates the design considerations that might be shared by other HR detector designs at neutrino factories. A brief overview of its capabilities will be given in this section; the reader is referred to the references [3, 1, 4] for more in-depth presentations of its anticipated performance capabilities.

As the most striking feature of the detector, the neutrino pencil beam allows a compact, fully-active precision vertexing target in place of the kilotonne-scale coarse-sampling calorimetric targets often used for past and present high rate neutrino experiments. For example, a 2 meter long stack of equally-spaced CCD tracking planes with a radius to match the beam width could contain 1500 planes of 300 micron thick silicon CCD’s, corresponding to a mass per unit area of approximately 100 g.cm$^{-2}$, which is about 5 radiation lengths or one interaction length. According to table 1, even such a modest detector volume might well correspond to unprecedented neutrino event samples of order a billion, or even 10 billion, interactions per year.

The relatively small interaction region of the CCD target is backed by a hermetic detector that is reminiscent of many collider detector designs and serves much the same functions. The enveloping time projection chamber (TPC) provides track-following, momentum measurements and particle identification for all charged tracks emanating from the interactions. Further particle ID might be provided by a mirror reflecting Cherenkov light to an instrumented back-plane directly upstream from
Figure 1: Example of a general purpose neutrino detector, reproduced from reference [3]. Its scale is illustrated by a human figure in the lower left corner. The neutrino target is the small horizontal cylinder at mid-height on the right hand side of the detector. Its radial extent corresponds roughly to the radial spread of the neutrino pencil beam, which is incident from the right hand side. The illustration is partially schematic in that the geometries of the calorimeters and dipole magnet have been simplified for illustrative purposes.

the target. Downstream from these, electromagnetic and hadronic calorimeters use total absorption to measure the energies of individual particles and particle jets and, lastly, iron-core toroidal magnets will identify muons that have filtered through the calorimetry.

Rather than attempting to derive the performance of this detector for specific physics topics, the rest of this section will simply present plausibility arguments for its potentially wide-ranging physics capabilities at neutrino factories, then quote some more specific conclusions taken from reference [3].

The dominant interaction processes that provide the physics content are the charged current (CC) and neutral current (NC) deep inelastic scattering (DIS) of (anti-) neutrinos off nucleons (\(N\), i.e. protons and neutrons) with the production of several hadrons (\(X\)):

\[
\begin{align*}
\nu(\bar{\nu}) + N &\rightarrow \nu(\bar{\nu}) + X & (NC) \\
\nu + N &\rightarrow l^- + X & (\nu - CC) \\
\bar{\nu} + N &\rightarrow l^+ + X & (\bar{\nu} - CC),
\end{align*}
\]

where the charged lepton, \(l\), is an electron if the neutrino is an electron neutrino and a muon for muon neutrinos. At the many-GeV energies of neutrino factories, these interactions are well described as the quasi-elastic (elastic) scattering of neutrinos off one of the many quarks (and anti-quarks), \(q\), inside the nucleon through the
exchange of a virtual W (Z) boson:

\[ \nu(\overline{\nu}) + q \rightarrow \nu(\overline{\nu}) + q \quad (NC) \]
\[ \nu + q^{(-)} \rightarrow l^- + q^{(+)} \quad (\nu - CC) \]
\[ \overline{\nu} + q^{(+)} \rightarrow l^+ + q^{(-)} \quad (\overline{\nu} - CC), \]

where all quarks, \( q \), participate in the NC process but the CC interactions convert negatively charged quarks to positive ones for neutrinos and vice versa for anti-neutrinos, as denoted by \( q^{(-)} \in d, s, b, \overline{u}, \overline{c} \) and \( q^{(+)} \in u, c, d, s, b \).

It is clear from our experience with collider detectors that the detector of figure 1 could reconstruct DIS events with at least comparable accuracy and completeness to, for example, the reconstruction of Z or W decay events at an e+e- collider detector. The charged leptons from CC interactions would of course be well measured and, more crucially, the properties of the struck quark could be inferred from reconstruction of the hadronic jet it produces. In particular, the favorable geometry of closely spaced CCD’s in the neutrino target along with their \( \sim 3.5 \mu m \) typical hit resolutions should provide vertexing of charm and beauty decays that would be superior to any current or planned collider detector.

The potential richness of neutrino interactions as a probe of both the nucleon and the weak interaction is apparent from the 3 experimentally distinguishable processes of equations 4 through 6, comprising 3 different weightings of the quark flavors probed through weak interactions involving both the W and Z. Consider, for comparison, that only a single and complementary weighting of quarks is probed by the photon exchange interactions of analogous charged lepton scattering experiments. Past and present neutrino experiments with the more diffuse neutrino beams from pion decays have suffered from either insufficient event statistics (e.g. bubble chambers) or inadequate detector performance (e.g. iron-scintillator sampling calorimeters) to exploit this rich physics potential. High rate experiments at neutrino factories will certainly not lack for statistics – as evidenced by table 1 – so high performance detectors should provide the final piece of the puzzle in realizing the considerable potential of HR neutrino physics.

Beyond the plausibility arguments given above, more detailed analyses suggest the following physics capabilities for general purpose high rate detectors at neutrino factories:

- the only realistic opportunity, in any physics process, to determine the detailed quark-by-quark breakdown of the internal structure of the nucleon
- some of the most precise measurements and tests of perturbative QCD
- some of the most precise tests of the electroweak theory through measurements of the electroweak mixing angle, \( \sin^2 \theta_W \), in neutrino-nucleon deep inelastic scattering, with uncertainties that might approach a 10 MeV equivalent uncertainty in the W mass – i.e. comparable with, and complementary to, the best measurements predicted for determinations at future colliders
- unique measurements of the elements of the CKM quark mixing matrix that will be interesting for lower energy neutrino factories (\( |V_{cd}| \) and \( |V_{cs}| \)) and
will become extremely important ($|V_{ub}|$ and $|V_{cb}|$) at muon beam energies of order 100 GeV and above

- a new realm to search for exotic physics processes
- as a bonus outside neutrino physics, a charm factory with unique capabilities.

3 Polarized Nucleon Targets

Neutrinos have intrinsic promise for polarization studies because they are 100% longitudinally polarized: neutrinos are always "left-handed" or "backward" polarized and anti-neutrinos are "right-handed" or "forward" polarized. Despite this, no past or present neutrino beam has yet been intense enough or collimated enough for polarized targets, so polarized neutrino-nucleon DIS appears to have even more to gain from the improved neutrino beams at neutrino factories than the non-polarized case presented in the preceding section.

Until now, the main tool for spin physics studies has been charged lepton scattering with either polarized electrons or muons [6]. The capabilities of these experiments are limited by several factors:

1. the polarization state of the leptons is never 100%
2. the photon exchange interaction provides only a single probe of the nucleon, as was mentioned in the preceding section
3. beam heating of the cryogenic polarized targets places serious restrictions on their design.

Very little consideration has yet been given to the design of a polarized target for neutrino factories or, for that matter, to the design of the detector that would surround it. The simplest design solution is to copy the targets used in charged lepton spin experiments. For example, another contribution to this workshop [7] discussed designs based on the butanol target used with polarized muons by the NMC collaboration. The problem with such a target is that most of its mass resides in unpolarized nuclei (carbon, in this case) rather than in the interesting hydrogen atoms so the effective polarization of the target is diluted by typically an order of magnitude. It is hoped [1] that the absence of significant target heating from the beam will allow the use of polarized solid protium-deuterium (HD) targets such as have been used in experiments with low intensity neutron or photon beams. The preparation of such targets is a detailed craft [6] involving doping the targets with ortho-hydrogen and holding them for long periods of time at very low temperatures and high magnetic fields, e.g. 30-40 days at 17 T and 15 mK. In order to avoid building an entire new detector around the target, an economical solution would be to place the polarized target immediately upstream from another detector, such as the general purpose detector described in the preceding section.

The fundamental task of such targets at neutrino factories will be to probe and quantify the quark and gluon contributions to the longitudinal spin component, $S_N^z$, of the nucleon. The overall spin component for forward polarized nucleons is, of
course, 1/2 in fundamental units ($\hbar = 1$) and the potential component contributions are summarized in the helicity sum rule:

$$S_z^N = \frac{1}{2} = \frac{1}{2} (\Delta u + \Delta d + \Delta s) + L_q + \Delta G + L_G,$$

(7) where the quark contribution is $\Delta \Sigma = \Delta u + \Delta d + \Delta s$, $\Delta G$ is the gluon spin and $L_q$ and $L_G$ are the possible angular momentum contributions from the quarks and gluons circulating in the nucleon. (In this notation, $\Delta q \equiv q^{\uparrow \uparrow} - q^{\downarrow \downarrow}$ is the difference between quarks of type $q$ polarized parallel to the nucleon spin and those polarized anti-parallel, and similarly for gluons.) The motivation for measuring the individual terms in equation (7) has strengthened following the experimental observation [9] in 1989 that only a small fraction of the nucleon spin is contributed by the quarks, $\Delta \Sigma \ll 1/2$, which has been considered counter-intuitive and is often referred to as the nucleon spin crisis.

Independent of the details of the polarized target, the experimental procedure for extracting the $\Delta q$'s at neutrino factories will be rather analogous to the more familiar extraction of the quark 4-momentum distributions in conventional non-polarized targets that was alluded to in the preceding section. The spin “structure functions” $g_1$ and $g_5$ will be extracted from differences in the DIS CC differential cross-sections for the target spin aligned with, and then opposite to, the neutrino spin direction. These structure functions correspond to linear combinations of the quark spin contributions: the parity conserving structure function, $g_1$, is the sum of quark and anti-quark contributions (analogous to the 4-momentum contributions of quarks to the non-polarized structure function $F_1$) while the parity violating $g_5$ is the difference of quark and anti-quark contributions (analogous to the non-polarized structure function $F_3$).

As was the case in the preceding section, the extraction of the quark-by-quark contributions from the structure functions should benefit greatly from the richness of neutrino interactions, with 8 independent structure functions to be measured: $g_1$ and $g_5$ from both neutrinos and antineutrinos and for both protons and neutrons.

The relative advantage over polarized DIS experiments with charged leptons is particularly evident for the parity-violating spin structure functions, $g_5$, since these can only be measured in CC weak interactions. The only other future opportunity to measure $g_5$ that has been widely discussed is the possibility of eventually polarizing the proton beams in the HERA e-p collider. Because of kinematic constraints on reconstructing events, a polarized HERA would be able to make less precise measurements $[10]$ for protons in a complementary kinematic region that will not be accessible to neutrino factories. It would not provide measurements for neutrons, of course.

The above method for extracting the various quark spin distributions is called “inclusive” because it sums over all hadronic final states. Additionally, neutrino factories should also provide novel and extended capabilities for “semi-inclusive” measurements. In particular, the semi-muonic tagging of charm production is sensitive to the spin contribution from the strange quarks in the nucleon, $\Delta s$. In some kinematic regions it may also provide sensitivity to the spin contribution of the gluon, $\Delta G$. Such a capability, if realized, would be very valuable in helping to solve
the spin crisis since $\Delta G$ is extremely difficult to measure and yet it is the leading suspect for providing the bulk of the nucleon’s spin.

4 Neutrino detector for neutrino-electron elastic scattering

The other physics topic that would benefit from a specialized detector is the precise determination of the weak mixing angle, $\sin^2 \theta_W$, from the measurement of the cross-section for neutrino-electron scattering:

$$\nu e^- \rightarrow \nu e^-.$$  \hfill (8)

This is an interaction between point elementary particles with a precise theoretical prediction for its cross section as a function of $\sin^2 \theta_W$ so statistical and experimental uncertainties will always dominate over the theoretical uncertainty.

Determination of the absolute cross section for the process of equation 8 provides a less traditional way of measuring $\sin^2 \theta_W$ with neutrinos than the neutrino-nucleon DIS scattering method mentioned in section 2 and is complementary since the two measurements have different sensitivities to exotic physics processes. The best measurement so far from neutrino-electron scattering was performed with a finely segmented sampling calorimetric target by the CHARM II collaboration at CERN, with the result:

$$\sin^2 \theta_W = 0.2324 \pm 0.0058(\text{stat}) \pm 0.0059(\text{syst}).$$  \hfill (9)

The systematic component of the 3.6% total uncertainty is due mainly to beam normalization and background uncertainties. Background uncertainties at this level may well be intrinsic to sampling calorimetric targets so the new approach of a tracking detector is probably required to obtain much more precise measurements at neutrino factories.

The experimental signature for the process in a tracking detector is a single electron track with a very low transverse momentum with respect to the beam direction, $p_t < \sqrt{2m_e E_\nu}$, and no other activity in the detector. The two experimental challenges that motivate a dedicated detector are:

1. the cross section for neutrino interactions with electrons is three orders of magnitude below the dominating process of DIS interactions with nucleons. Even at neutrino factories this would require a relatively massive detector – perhaps several tonnes – to obtain sufficiently large event samples.

2. the crucial measurement of the electron $p_t$’s must be obtained before the electron initiates an electromagnetic shower and this distance scale is characterized by the radiation length of the tracking medium. This effectively restricts the target to elements with particularly low atomic numbers ($Z$) because the radiation length scales inversely as $Z^2$.

Other desirable characteristics for the detector are a fully-active tracking medium with good position resolution, a magnetic field to verify the negative charge of the electrons and a fast read-out to minimize pile-up from the DIS background events.
An attractive target/detector option is a cylindrical tank containing a low-Z liquid that can form tracks of ionization electrons and drift them to an electronic read-out. The choice of the liquid requires a more detailed survey of low-Z liquid properties than has so far been conducted. Working up from the lowest Z, liquid hydrogen (Z=1) is unfortunately ruled out because of insufficient electron mobility. Liquid helium (Z=2) also suffers from poor mobility and potentially difficult operation because it lacks the ability to self-quench.

Liquid methane and other saturated alkanes appear to be good candidates for the tracking medium as they contain only carbon (Z=6) and hydrogen (Z=1) and sufficiently pure samples are capable of transporting electrons over large distances. Experimental studies of electron transport in methane have been successful enough to suggest its use in TPC detectors of up to several kilotons. It is liquid at atmospheric pressure between –182.5 and –161.5 degrees centigrade and has a density of 0.717 g/cm³ and a radiation length of 65 cm. Heavier alkanes that are liquid at room temperature, such as octane, would be superior for safety and convenience if they can be maintained at sufficient purity for good electron transport, and this deserves further study. Finally, liquid argon (Z=18) also deserves further consideration despite having a radiation length of only 14 cm since its suitability as a large-volume tracking medium has been convincingly demonstrated through prototyping for the multi-kilotonne ICANOE neutrino oscillation detector.

Example monte carlo-generated event pictures for neutrino-electron scattering events in liquid methane are shown in figures 2 and 3. Essentially all of the p_t and charge sign information on the electron is contained in the initial track at the upstream (left hand side) of the display.

![Figure 2: Monte-carlo generated picture of a neutrino-electron scattering interaction in liquid methane. The view is perpendicular to both the beam direction and the magnetic field. The red tracks are electrons or positrons. The blue tracks are photons, and these won’t actually be seen in the detector.](image)
A time projection chamber (TPC), as used in ICANOE, is the best established readout option but may run into problems with event pile-up due to the large drift distances characteristic of this readout geometry. A faster read-out alternative that has been suggested by Rehak [15] uses printed-circuit kapton strips to provide more channels and, hence, shorter drift distances.

The two other big experimental challenges for the measurement besides event pile-up are background rejection and benchmarking the signal event rate to precisely predictable flux normalization processes, which will now be discussed in turn.

The dominant DIS background events will usually be readily distinguishable from the signal due to their high track multiplicity at the primary vertex. Instead, the most difficult backgrounds will come from low-multiplicity neutrino-nucleon scattering events such as quasi-elastic neutrino-nucleon scattering:

$$\nu N \rightarrow l^\pm N',$$  \hspace{1cm} (10)

where $N'$ is an excited state of the nucleon $N$. A tracking detector with very good $p_t$ resolution is needed to resolve the signal peak from the much broader background distributions from such events.

Flux normalization [1] should be less difficult for the ($\nu_\mu \nu_e$) beam due to the availability of two theoretically predictable normalization processes involving muon production off electrons:

$$\nu_\mu e^- \rightarrow \nu_e \mu^-$$  \hspace{1cm} (11)

$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-.$$  \hspace{1cm} (12)

The ($\bar{\nu}_\mu \nu_e$) beam is more problematic, probably requiring an additional stage of relative flux normalization back to the ($\nu_\mu \nu_e$) flux using the relative sizes of the event

Figure 3: Monte-carlo generated picture of a neutrino-electron scattering interaction in liquid methane. Same event as the immediately preceding figure except that the view is now parallel to the magnetic field.
samples for the quasi-elastic neutrino-nucleon scattering process of equation 10. This requires the detector to also measure very low-\(p_t\) muons from the processes of equation 12 and 10 which should in practice be less difficult than the signal process for the detectors under consideration.

Table 1 gives signal event sample sizes in the range of millions to tens-of-millions of events for an 11-tonne liquid methane detector. This corresponds to the impressive limiting statistical uncertainties of \(\Delta \sin^2 \theta_W = 0.0003\) and 0.0001 for the \((\nu_\mu \nu_e)\) and \((\bar{\nu}_\mu \nu_e)\) beams, respectively, at the 50 GeV neutrino factory, and to \(\Delta \sin^2 \theta_W = 0.001\) and 0.00003 for the 500 GeV neutrino factory. With negligible theoretical uncertainties for this process the experimental challenge in approaching these statistical limits rests largely on the design of a specialized detector that can minimize the experimental uncertainties.

5 Conclusions

The prospects for short-baseline high rate neutrino physics at future neutrino factories is substantial and is tightly coupled to the development of novel high performance neutrino detectors that exploit the uniquely intense and collimated neutrino beams at these facilities.

Three types of high rate neutrino detectors have been discussed in this paper:

1. general purpose detectors featuring, for example, a fully active CCD vertexing and tracking target and with a backing detector of similar complexity and performance to some collider detectors. Such detectors would have wide-ranging potential for extending neutrino physics well beyond its traditional bounds.

2. polarized targets that might map out the quark-by-quark spin structure of the nucleon and, perhaps, also determine the gluon contribution to the nucleon’s spin. Cryogenic targets of solid hydrogen might have much superior performance to the conventional polarized targets used in charged lepton scattering if their considerable design challenges can be negotiated.

3. fully active tracking targets comprising several tonnes of low atomic number liquids hold promise for one of the most precise tests of the electroweak interaction, through the determination of the weak mixing angle, \(\sin^2 \theta_W\), from the total cross-section for neutrino-electron scattering.

The designs for all three detector types are both exciting and very challenging. Designs for general purpose detectors have been presented only at the conceptual level and those for the two specialized target types have not even proceeded that far. Given the levels of complexity and challenge, there is both an opportunity and a need to soon begin the design work towards realizing these detector options at the first neutrino factory facility. The expected experimental conditions at neutrino factories are so novel and impressive that there are sure to be many surprises along the way.
6 Acknowledgments

The author has benefitted from many discussions with his co-authors on reference [1]. A discussion on spin physics with M. Velasco was also valuable. The organizers and secretariat of NUFACT99 are to be commended for a well-organized and stimulating workshop.

This work was performed under the auspices of the U.S. Department of Energy under contract no. DE-AC02-98CH10886.

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