A High Resolution Neutrino Experiment in a Magnetic Field for Project-X

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Abstract

We propose for Project-X a high-resolution neutrino experiment within a dipole magnetic field, HiResMν. This experiment will run along with long-baseline neutrino oscillation experiments (LBLν) such as NOνA, or DUSEL, or a Liquid-Argon detector in the Medium-Energy (ME) configuration of the NuMI-beam. The $4 \times 4 \times 7$ m$^3$ detector, inside a dipole magnetic field of $B \approx 0.4$ T, will have the density of liquid hydrogen, $\rho \approx 0.1$ gm/cm$^3$, with a nominal fiducial mass of 7.4 tons. Assuming the 120 GeV Main Injector proton intensity of $1 \times 10^{18}$ protons/hr for Project-X, for a 3-year neutrino-run (365/$\pi$ days/year) we anticipate 140 million $\nu_\mu$ Charged-Current (CC) events in the fiducial volume. For an additional 4-year anti-neutrino run, we anticipate 50 million $\bar{\nu}_\mu$-CC events. The goals of the proposed experiment are:

• [1]: Determination of the relative abundance and the energy spectrum of the four species of neutrinos in NuMI: $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$ and $\bar{\nu}_e$ CC-interactions. This is directly relevant to LBLν.
• [2]: An ‘Event-Generator’ measurement for the LBLν including the complete hadronic multiplicity ($\pi^\pm$, $K^\pm$, $\pi^0$ & $p$) comprising all topologies of CC and Neutral-Current (NC) events.

• [3]: A quantitative determination of the energy-scale of neutrino CC interactions, a serious error in the $\Delta m^2$ measurement.

• [4]: Measurement of the weak-mixing angle, $\sin^2\theta_w$ with a cumulative precision approaching 0.2% using two independent channels: $\nu(\bar{\nu})q$ (DIS), $\nu(\bar{\nu})e^-$, and Coherent-$\pi^0$-vs- $\pi^+/-\pi^-$ interactions.

• [5]: Precise determination of (semi)exclusive processes such as quasi-elastic, resonance, $\pi^0/K^0_S/\Lambda$/charm-hadron production; and precision measurement of the nucleon structure functions and nuclear effects.

• [6]: Search for new physics with unprecedented sensitivity.

The proposed experiment, with an approximate cost of $15M, is very rich in physics, and will provide powerful constraints on the systematics associated with the discovery of the neutrino mass matrix elements by the LBLν.
The HiResMν is an evolving idea. The projected precisions in this document are preliminary. Where uncertain we have qualified the numbers as tentative.
So audacious is the anticipated proton intensity for Project-X that a light, low-density \( \rho \approx 0.1 \text{gm/cm}^3 \), high-resolution neutrino detector in a dipole magnetic field \((B \approx 0.4 \text{T})\) with an ability to precisely measure, \(e^\pm, \mu^\pm, \pi^\pm, K^\pm, \text{protons, } \pi^0 \text{ and } K^0_S \) will usher in a new standard of precision in neutrino physics. Such an experiment will serve as an ‘Event-Generator’ measurement for the massive long-baseline neutrino oscillation experiments (LBL\(\nu\)) comprising all topologies: – \(\nu\)-induced inclusive charge-current (CC) and neutral-current (NC) interaction, non-scaling processes such as quasi-elastic, resonance, and diffractive/coherent meson production. The LBL\(\nu\) proposals include NO\(\nu\)A, DUSEL water Cerenkov detector, and Liquid Argone (LAr) at Soudan or Homestake mine.

1 Working Assumptions

The ideas presented in this document assume the following:

(A) The Proton Intensity: Based upon the guidelines presented in Page-21: “http://www.fnal.gov/pub/directorate/steering/pdfs/SGR2007.pdf”, the MI 120 GeV proton intensity will be \(1 \times 10^{18}\) protons/hour. Assuming \((365/\pi)\) days of operation in a year, we expect about \(30 \times 10^{20}\) protons/year.

(B) The Neutrino Beam: The experiment will run along with the LBL\(\nu\) experiments at the Near Detector site. This is a not just choice of convenience but, we believe, an imperative to achieve the highest precision in the discovery of the elements of the neutrino mass matrix. The LBL\(\nu\)’s will run in neutrino and anti-neutrino modes. In the following, we have assumed a 3-year run with neutrino (focusing positives), and a 4-year run with anti-neutrino (focusing negatives).

(C) The MIPP Upgrade: Most precision neutrino measurements, be it a cross-section or an Electroweak or an oscillation measurement, have ultimately suffered from a lack of knowledge of the neutrino flux, \(i.e.\) the error in the production cross-section and propagation through the beam elements of the secondary mesons, \(\pi^\pm, K^\pm, \text{ and } K^0_L \) that decay into neutrinos. The principal reason for this has been, to quote one of our colleagues not on MIPP, “..everyone wants to eat the pie, but no one wants to do the tilling, sowing, ...”. Regardless of the fate of this proposal, we hope that the Lab and the community will have the wisdom to support
and help bring the Main Injector Particle Production (MIPP) program, this most useful of experiments to the HEP/Nuclear community, to a successful conclusion.

2 The Detector

The Medium Energy (ME) neutrino beam in NuMI is flat within ±3m in X- and Y-dimension. (This is valid for the Low Energy or the High Energy beams as well.) Accordingly, the proposed on-axis detector, pictured in Figure 1, will have dimensions of 400 × 400 × 700 cm³ and will be embedded in a dipole magnet with $B \approx 0.4$ T.

Building upon the NOMAD-experience [1, 2, 3], a low-density tracking detector will be the neutrino target. In NOMAD [1], light drift chambers provided the target and the tracker. For the HiResMν we are proposing an active target tracker with a factor of two more sampling points along the z-axis ($\nu$-direction) and a factor of six more sampling points in the plane transverse to the neutrino compared to the NOMAD experiment. Figure 2 juxtaposes the resolving power of the NOMAD detector with the massive CCFR/NuTeV calorimeter. One sees a stark contrast for an NC event candidate in the NuTeV experiment compared with one in the NOMAD experiment. The HiResMν will further the resolving power compared to NOMAD: an order of magnitude higher data points in tracking charged particles, and coverage for side-exiting neutrals.

Taking advantage of the existing design and production details for the ATLAS Transition Radiation Tracker [7, 8, 9] and the COMPASS detector [10, 11], we are proposing straw-tube trackers (STT) for HiResMν. In what follows, we take the STT a default option for the active neutrino target. We would consider other technologies, but we are committed to a low-density, $\rho \leq 0.1$ gm/cm³, precision tracker.

Figure 3 presents a schematic of a straw-tube module based upon the COMPASS design. The nominal fiducial volume (FV) for CC analysis is: $350 \times 350 \times 600$ cm³ corresponding to 7.4 tons of mass. We have quantified the improvements over the NOMAD measurements. These include:

(1) **Full Carolimetric Coverage:** The tracking volume will be surrounded by an electromagnetic calorimeter (ECAL) on the four sides and at the downstream end. The ECAL will have transverse and longitudinal segmentation. (The granularity will be decided after detailed calculations.) And the sides of the dipole magnet will be instrumented for muon-detection.
Figure 1: Sketch of the proposed detector showing the inner straw tube tracker (STT), the electromagnetic calorimeter (EM CALO) and the magnet with the muon range detector (MRD). The internal magnetic volume is $4m \times 4m \times 7m$. 
Figure 2: Candidate NC Event in NuTeV and NOMAD. In tracking charged particles, HiResM will provide a factor of two higher segmentation along the z-axis and a factor of six higher segmentation in the transverse plane compared to NOMAD.

**Massive Calo (NuTeV)**

**Precise Tracker (NOMAD)**

HiResMv: order of magnitude higher segmentation
Figure 3: One module for the proposed straw tube tracker (STT). Two planes of straw tubes are glued together and held by an Al frame. In front of each module a plastic radiator made of many thin foils provides 85% of the total mass of the detector and can be adjusted according to the required resolution and statistics. The module design is taken from the COMPASS experiment.
(2) Tracking Detector: The tracker will be composed of straw tubes with 1 cm diameter. Vertical \((Y)\) and horizontal \((X)\) straws will be alternated and arranged in modules - each module containing a double straw layer - as shown in Figure 3. We plan to have readout at both ends of the straws to resolve ambiguities in the hit assignment. Compared to NOMAD, there will be a factor of 6 more tracking points in the plane perpendicular to the incident \(\nu\) and a factor of two more points in the plane parallel to the incident \(\nu\) for a charged particle of given momentum. Figure 4 shows the longitudinal radiography of NOMAD — the measured \(Z\)-position of the \(\nu\)-vertex. It reveals the Kevlar skins, the Honeycomb, and the Gas gap within the tracking drift-chambers. The proposed detector will yield a more precise reconstructed vertex resolution approaching 100 \(\mu\)m. In front of each module plastic foils, the “radiators”, provide 85\% of the mass and allow a measurement of the transition radiation (TR) which will yield continuous identification of electrons through the tracking volume. We propose to use Xe-gas in the straw tubes (Xe/CO\(_2\)) to maximise the TR capability. Finally, unlike NOMAD, we shall measure \(dE/dx\) enabling the identification of protons, charged pions and kaons. The identification of individual tracks as protons is especially important for the neutrino Quasi-Elastic (QE) and resonance interactions. We iterate that such straw tube detectors are deployed in ATLAS [7, 8, 9] and COMPASS [10, 11].

(3) Improved Muon-Identification: We propose to tag 95\% of the emergent muon in the \(\nu_\mu\)-CC sample in contrast with the 85\% efficiency in NOMAD. Instrumentation in the magnet yoke and the muon detector coverage outside the magnet will enable this improvement. The muon detectors will be inexpensive RPC’s following the designs in BELLE and INO.

(4) Trigger: Unlike NOMAD, the trigger will not be based upon the geometry or charge-bias. We aim to have \(\approx 100\%\) trigger efficiency for any event with \(\geq 100\) MeV of visible energy in the tracker or ECAL.

3 The Expected Detector Performance

For the straw tube tracker we assume a resolution of 200 \(\mu\)m on individual spacepoints. For reference, the ATLAS tracker archives \(\sim 130\mu\)m resolution with testbeam particles [8], and COMPASS [10] gets about 175 \(\mu\)m with straws of similar dimensions.

As baseline we consider the same density \(\rho \sim 0.1g/cm^3\) and magnetic field \(B = 0.4T\) as in NOMAD. The neutrino target would be mainly composed of carbon, and a radiation length \(X_0\)
Figure 4: A neutrino radiograph of the NOMAD drift chambers shows the internal structure of the tracking volume. It illustrates the high resolution of the $z$-position of the vertex.

deep corresponding to about 5 m. With the above parameters multiple scattering contributes 0.05 to the $\Delta p/p$ for tracks 1 m long. Given the proposed granularity, the corresponding systematic measurement error would be 0.006, for a $p = 1$ GeV, 1 m long tracks ($N \sim 50$ spacepoints).

The proposed detector will measure track position, $dE/dx$, and Transition Radiation (with Xe filling) over the entire instrumented volume of $3.5 \times 3.5 \times 6.4m^3$. The unconverted photon energy will be measured in the forward and side calorimeters with a target energy resolution of $\sim 10%/\sqrt{E}$. The expected capabilities of HiResM$\nu$ include:

- Full reconstruction of charged particles and $\gamma$'s;
• Identification of $e$, $\pi$, $K$, and $p$ from $dE/dx$;
• Electron (positron) identification from TR ($\gamma > 1000$);
• Full reconstruction and identification of protons down to 250 MeV/c;
• Reconstruction of electrons down to 80 MeV from curvature in $B$ field.

The maximum drift time for a $Xe/CO_2$ gas mixture over a distance of $5 \ mm$ is 125 ns, as measured in a testbeam and compatible with the expected rates.

We emphasize that the proposed design provides both redundancy of measurements and flexibility. The redundancy is crucial to achieve high resolution in the reconstruction of neutrino events. Moreover, most of the target mass (85%) is represented by the radiators, which are independent from the straws. This will allow us to change the fiducial mass without affecting the construction of the tracking devices.

4 The Expected Event Samples

Table 1 presents the expected number of events induced by $\nu_\mu$ in a 3-year run: Inclusive-CC, QE, NC, Coherent-$\pi^0$ and -$\pi^+$, inverse-muon decay (IMD), and $\nu_\mu$-e NC. Also included are the CC events induced by the inherent ‘contaminant’ neutrinos in the beam: $\nu_e$, $\bar{\nu}_e$, and $\nu_\mu$. The following Table 2 presents the expected number of events in a 4-year anti-neutrino run.

5 Physics

The proposed experiment will measure the energy and relative composition of $\nu_\mu^-$, $\bar{\nu}_\mu^-$, $\nu_e^-$, and $\bar{\nu}_e$-CC interactions. It will identify and determine the energy and angle of the emergent leading lepton, $\mu^\pm$ & $e^\pm$. It will measure the momentum-vectors of the the particles composing the hadronic jet in CC and NC interactions. Uniquely, the detector will measure kinematic variables in the plane transverse to the neutrino direction. Figure 5 presents a conspectus of kinematic variables available in HiResM$\nu$. With the particle-ID’s, the kinematic variables and the statistics in Table 1, it is easy to chart the Physics goals of the proposal.
<table>
<thead>
<tr>
<th>Interaction</th>
<th>Events</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
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<td>Inclusive $\nu_\mu$-CC</td>
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<td>FV</td>
</tr>
<tr>
<td>$\nu_\mu$-QE</td>
<td>$12 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>Inclusive $\nu_\mu$-NC</td>
<td>$19 \times 10^6$</td>
<td>FV &amp; $E_{Had} \geq 3$ GeV</td>
</tr>
<tr>
<td>Coherent-$\pi^0$</td>
<td>$0.7 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>Coherent-$\pi^+$</td>
<td>$1.4 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>IMD</td>
<td>$15 \times 10^3$</td>
<td>FV &amp; $E_\nu \geq 11$ GeV</td>
</tr>
<tr>
<td>$\nu_\mu$-e NC</td>
<td>$3 \times 10^3$</td>
<td>FV &amp; $E_e \geq 0.1$ GeV</td>
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<tr>
<td>Contaminant CC’s</td>
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<td></td>
</tr>
<tr>
<td>$\nu_e$-CC</td>
<td>$2 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>$\bar{\nu}_e$-CC</td>
<td>$0.3 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$-CC</td>
<td>$3.5 \times 10^6$</td>
<td>FV</td>
</tr>
</tbody>
</table>

Table 1: Expected Events in a 3-Year $\nu$-Run: Events in the fiducial volume for various interactions are shown.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Events</th>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive $\bar{\nu}_\mu$-CC</td>
<td>$50 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>Inclusive $\bar{\nu}_\mu$-NC</td>
<td>$4 \times 10^6$</td>
<td>FV &amp; $E_{Had} \geq 3$ GeV</td>
</tr>
<tr>
<td>Coherent-$\pi^0$</td>
<td>$0.4 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>Coherent-$\pi^+$</td>
<td>$0.8 \times 10^6$</td>
<td>FV</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$-e NC</td>
<td>$17 \times 10^3$</td>
<td>FV &amp; $E_e \geq 0.1$ GeV</td>
</tr>
</tbody>
</table>

Table 2: Expected Events in a 4-Year $\bar{\nu}$-Run: Events in the fiducial volume for various interactions are shown.
5.1 The Traditional Neutrino Physics

The proposed experiment will measure the relative abundance, the energy spectrum, and the detailed topologies for $\nu_\mu/\bar{\nu}_\mu/\nu_e/\bar{\nu}_e$ induced interactions including the momentum vectors of negative, positive, and neutral ($\pi^0$ and $K^0_S/\Lambda/\bar{\Lambda}$) particles composing the hadronic jet. (We are exploring the possibility of measuring the neutron yield using charge-exchange process.) The experiment will provide topologies, on an event-by-event basis, of various interactions that will serve as ‘generators’ for the LBL$\nu$ experiments. A glance at $\nu_\mu$ CC and $\bar{\nu}_e$ CC event candidates in NOMAD, shown in Figure 6 and Figure 7, gives an idea of the precision with which the

Figure 5: Diagram illustrating various kinematic measureables in the proposed detector.
charged-particles, the emergent positron, and the forward-\(\gamma\) were measured. The proposed experiment will have substantially better resolution than NOMAD.

The excellent resolution of the detector inside a calibrated dipole B-field will allow a precise determination of the overall neutrino energy scale, a crucial scale in precisely determining the neutrino oscillation parameters in LBL\(\nu\). The energy scale of charged particles and the B-field calibration can be checked from the mass constraint of the reconstructed \(K^0_S\). In Figure 8 we show a sample of reconstructed \(K^0_S\) as measured in NOMAD [4, 5], with momenta greater than 1 GeV, compared with the Monte Carlo. With a total sample of 30,000 reconstructed \(K^0_S\) the charged track energy scale was determined to better than 0.2%. Similarly, the hadron energy scale was constrained to 0.5% level from the reconstructed charged tracks and from the muon measurement. Both uncertainties were limited by the statistics and resolution, respectively, of the available control samples [6]. In the proposed experiment, we expect to reconstruct over \(2 \times 10^6\) \(K^0_S\) in the \(\nu\)-mode and we will collect overall a factor of 200 more \((\nu + \bar{\nu})\) events than in NOMAD.

Because this experiment and the LBL\(\nu\) experiments will utilize the same neutrino beam, our irreducible errors in measured cross sections, in the NC/CC ratio, in the species composition of hadronic secondaries, and in the \((x_F & P_T)\) of hadronic secondaries will not propagate to the determination of the oscillation parameters of significance to LBL\(\nu\).

This is the ‘service’ aspect of the proposed experiment to the LBL\(\nu\) programme. It is also a textbook measurement of neutrino interactions.

### 5.2 The Weak Mixing Angle

One goal of the proposed experiment is to measure the weak mixing angle, \(\sin^2 \theta_W\), with a precision approaching 0.2\%, i.e. \(\delta \sin^2 \theta_W \approx \pm 0.00045\) (on-shell), a precision comparable to the PDG value [17]. The current PDG precision on \(\sin^2 \theta_W\) derives from the LEP/SLC/CDF/D0 measurements. The proposed \(\nu\)-experiment, the only direct probe to \(\nu\)-Z coupling, aims to measure this quantity at values of \(Q^2\) that are 1/1000 of those at colliders with commensurate precision. Finally, the NuTeV experiment has reported an anomalous value of \(\sin^2 \theta_W\) that is 3\(\sigma\) higher than the ‘world average’ [12]. The HiRes\(\nu\) will provide a decisive check of this anomaly.

In HiRes\(\nu\), two different channels permit precise measurements of \(\sin^2 \theta_W\) with independent
Figure 6: A $\nu_\mu$ CC Event Candidate in NOMAD. The HiRes$\nu$ will have more sampling points and better muon coverage.
Figure 7: A $\bar{\nu}_e$ CC Event Candidate in NOMAD. The positron track with bremsstrahlung photons are clearly visible. The HiResM$\nu$ will have more sampling points, TR, and better $\gamma$ acceptance.
Figure 8: Reconstructed $K_S^0$ in NOMAD: Shown are the invariant mass distribution of the $\pi^+\pi^-$ pairs in Data (Symbols) and Monte Carlo (Histogram). The efficiency of $K_S^0$ was about 27%; the purity was about 96%.

systematics and at different scales ($Q^2$).

5.2.1 $R^\nu$, $R^\bar{\nu}$, and $\sin^2\theta_W$ using DIS Events

The experiment will permit a measurement of $R^\nu$, the NC/CC ratio in a $\nu$-beam, and of $R^\bar{\nu}$, the NC/CC ratio in a $\bar{\nu}$-beam. We will also exploit the Paschos-Wolfenstein relation [13] to constrain the systematic errors.
With a cut on the hadronic energy $E_{\text{Had}} \geq 3$ GeV, the NC and the CC samples in the NuMI-ME beam are almost entirely composed of deep-inelastic scattering (DIS) events. The number of NC events in the $\nu$-mode is $19 \times 10^6$, and that in the $\bar{\nu}$-mode is $4 \times 10^6$ (see Tables 1 and 2). Thus, the statistical error on the $R^\nu$ and $R^{\bar{\nu}}$ will be a factor of two below the total projected error. Table 3 summarises the anticipated uncertainties in $\sin^2 \theta_W$.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\delta \sin^2 \theta_W / \sin^2 \theta_W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
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<tr>
<td>Experimental systematics</td>
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<tr>
<td>Model systematics</td>
<td>0.0014</td>
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<tr>
<td>TOTAL</td>
<td>0.0019</td>
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</table>

Table 3: Estimated uncertainties for the extraction of $\sin^2 \theta_W$ from DIS events.

The total experimental error on $R^\nu$ ($R^{\bar{\nu}}$) in the proposed experiment will be a factor of 4 smaller than those quoted for the NuTeV-experiment [12] due to the high resolution and statistics of the proposed experiment.

In the DIS-channel, $\sin^2 \theta_W$ can be extracted using either $R^\nu$ or $R^-$ (Paschos-Wolfenstein). For $R^\nu$ measurement, flux is almost a non-issue. For the $R^-$, we will constrain the energy-integrated $\bar{\nu}_\mu/\nu_\mu$ flux ratio using the Low-$\nu^0$ method of determining relative flux [29] in concert with the measurements by MIPP-II and NA49. We will ensure that the beam simulation is driven by a precise data-base comprising secondary/tertiary interactions as measured by MIPP-II, and the precisely surveyed, and, where applicable, monitored, parameters of the beam-elements such as alignment, horn-current, the B-field of the horn, inert elements, and the primary proton beam characteristics. We will also use the knowledge of the extant $\bar{\nu}_\mu$-CC and $\nu_\mu$-CC data. Such an all encompassing effort will yield a precision of better than 1% on the cumulative $\bar{\nu}_\mu/\nu_\mu$ flux. Appendix-C explains the rational behind this assumption.

The theoretical uncertainty in the NuTeV measurement is dominated by errors from charm production and strange sea followed by the errors from the longitudinal structure function ($F_L$) and higher-twist effects. First, there are $\approx 15,000$ charm-induced dimuons in the NOMAD experiment (on-going analysis). A global analysis of the charm production and strange sea, including the NOMAD, CCFR, and NuTeV data, will reduce the NuTeV error by a factor of 2. Importantly, we expect to measure in situ $\approx 200,000$ charm-induced dileptons ($e^+$ and
\( \mu^+ \), with \( E_{\text{Had}} \geq 3 \text{ GeV} \) corresponding to an assumed 20% dilepton detection efficiency. The detector will also permit direct measurements of exclusive charmed hardons, which will be reconstructed from their decay kinematics. Therefore, we can expect that the charm/strange-sea error will be a factor of 3 less than that quoted by NuTeV. The estimate of the other theoretical uncertainties is based upon the current understanding of structure functions [19, 20, 21, 22, 23, 24], and the on-going \( \sin^2 \theta_W \) analysis in NOMAD (\( E_{\text{Had}} \geq 3 \text{ GeV} \)). Some of these errors will be further reduced by the J-Lab measurements, and measurements conducted in HiResM\( \nu \) experiment. Appendix-B presents the status of theoretical models which are anchored in the fits to the existing experimental data. These models deal with higher twist, longitudinal structure function, and bound state effects. We expect the total model error on \( \sin^2 \theta_W \) to be \(< 0.0003 \).

In Table 4 we present a detailed breakdown of the anticipated systematic errors. The tabulation of the projected errors in this document uses the published results of NOMAD (\( \nu \)-species measurement, vertex and momentum resolution, CC, dimuon, charm-hadron, strange hadron production, etc.), the NuTeV publication on the anomalous \( \sin^2 \theta_W \) [12], and the on-going \( \sin^2 \theta_W \) analysis in NOMAD.

In summary, we believe that measurements of \( R^e \) and \( R^\mu \), with all other attendant analyses (CC, charm production, strange sea, charm sea, \( F_L \)), will allow a measurement of \( \sin^2 \theta_W \) with 0.2% precision.

### 5.2.2 \( \nu_\mu - e^- \) and \( \bar{\nu}_\mu - e^- \) NC Scattering

The \( \nu - e^- \) scattering, via CC or NC, evinces a clean signal in this experiment. The signal is a single \( e^- \) (\( \mu^- \)) emerging at zero-mrad in the NC (CC) reaction. The relevant measurable that characterizes the signal is \( E_L \theta_L^2 \) where \( E_L \) and \( \theta_L \) are the energy and angle (with respect to the neutrino direction) of the emergent lepton. (The relevant measurable characterizing the backgrounds from low-\( Q^2 \) \( \nu-N \) interactions is \( E_L^2 \theta_L^2 \).) Thus, it is the resolution of \( \theta_L \) that controls the purity and efficiency of the \( \nu - e^- \) sample.

The IMD events are virtually background free. Since the IMD cross-section can be precisely calculated, and the background precisely measured using \( \nu_\mu \)-CC and \( \bar{\nu} \)-CC, we will have an absolute \( \nu_\mu \)-flux calibration with a precision of \( \leq 1\% \) above \( E_\nu \geq 11 \text{ GeV} \). As discussed in the previous section, and detailed in Appendix-C, the relative \( \bar{\nu}_\mu / \nu_\mu \) flux can be constrained to a precision of better than 1% in HiResM\( \nu \).
<table>
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<th>Source of uncertainty</th>
<th>$\delta X/\chi$</th>
<th>$\delta R^\nu/R^\nu$</th>
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<td><strong>Total Statistics</strong></td>
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<td>Other</td>
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<td>Charm sea</td>
<td>0.00044</td>
<td>0.00013</td>
<td>0.00010</td>
<td>n.a.</td>
</tr>
<tr>
<td>$r = \sigma^D/\sigma^\nu$</td>
<td>0.00097</td>
<td>0.00018</td>
<td>0.00064</td>
<td>0.0005</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.00048</td>
<td>0.00013</td>
<td>0.00015</td>
<td>0.0001</td>
</tr>
<tr>
<td>Non-isoscalar target</td>
<td>0.00022</td>
<td>0.00010</td>
<td>0.00010</td>
<td>N.A.</td>
</tr>
<tr>
<td>Higher twists</td>
<td>0.00061</td>
<td>0.00031</td>
<td>0.00032</td>
<td>0.0003</td>
</tr>
<tr>
<td>$R_L$</td>
<td>0.00141</td>
<td>0.00115</td>
<td>0.00249</td>
<td>$(F_2,F_T,xF_3)$ 0.0005</td>
</tr>
<tr>
<td><strong>Model systematics</strong></td>
<td><strong>0.00281</strong></td>
<td><strong>0.00258</strong></td>
<td><strong>0.00523</strong></td>
<td><strong>0.0014</strong></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.00711</strong></td>
<td><strong>0.00332</strong></td>
<td><strong>0.00672</strong></td>
<td><strong>0.0019</strong></td>
</tr>
</tbody>
</table>

Table 4: Summary of uncertainties on the extraction of the weak mixing angle ($\chi = \sin^2 \theta_W$) based upon the Pascos-Wolfenstein relation. The first three columns refer to the published NuTeV errors [12] while the last column indicates the corresponding projection for our experiment.
The key to measuring the $\nu-e^-$ NC interaction is the presence of B-field and resolution in $\theta_e$. The background, almost entirely caused by photon conversion, is charge independent. Thus, we will measure the background to the $\nu-e^-$ NC process by measuring forward $e^+$. We will not rely upon the systematically difficult interpolation to the low values of $E_e\theta_e^2$ as in the CHARM-II measurement. Moreover, the energy and the angle of the scattered $e^-$ will be measured with high resolution in HiResM$\nu$.

We posit that the dominant error will be the statistical error of the $\nu-e^-$ sample. The ratio of $\sigma(\overline{\nu}_\mu e^-)$ and $\sigma(\nu_\mu e^-)$ gives a measure of $\sin^2 \theta_W$. Since we aim to measure $R_{\nu e}$ to a relative precision of about 1.0%, the corresponding error on $\sin^2 \theta_W$ will be about 0.56%.

5.2.3 Coherent-$\pi^0$ and Coherent-$\pi^+/\pi^-$ Processes

We expect a large sample of coherent-$\pi$ events in the $\nu$-NC and CC events. About 25% of the $\pi^0$ will have both photons convert in the tracking volume; an additional 25% will have one photon convert in the tracking volume and other measured in the ECAL. Figure 9 shows a coherent $\pi^0$ event candidate in NOMAD with two photons converted in the tracker. In HiResM$\nu$ the use of at least one converted photon, corresponding to about half the $\pi^0$ produced, will provide the pointing direction for a precise reconstruction of the primary vertex.

The definition of coherence will be applied identically to the neutral and charged pion samples by “removing” the accompanying muon in the CC-interaction. The statistical error in the Coherent-$\pi$ sample will be small. The principal concern in the WMA extraction using this channel is the theoretical uncertainties [14]. We have requested some of our theory-colleagues to investigate the model-error in this analysis.

Even if the model systematics on WMA extraction using the Coherent-$\pi$ sample prove formidable, the channel will offer new data-point for the Electroweak studies. At the most pessimistic, we will have the most accurate measurement of the coherent-$\pi$ production cross section and associated kinematic characteristics.

5.2.4 Outlook on $\sin^2 \theta_W$ Measurement

In summary we shall have two independent and well established channels to determine the weak-mixing angle, $\sin^2 \theta_W$. The channels have largely independent systematics. The most promising channel for the $\sin^2 \theta_W$ measurement is the DIS with a precision approaching 0.2%. It
Figure 9: A coherent $\pi^0$ event candidate in NOMAD with both photons from the $\pi^0$ decay converting in the tracker. The HiRes$\nu$ will have a superior resolution than shown.
Figure 10: Running of the weak mixing angle as a function of the momentum transfer $Q$, as predicted by the Standard Model [15]. The data points are from Atomic Parity Violation [16, 17], Moeller scattering (E158 [18]), $\nu$ DIS (NuTeV [12]) and the combined $Z$ pole measurements (LEP/SLC) [17]. The projected sensitivity of our experiment is shown for comparison.

is followed by the $\nu$-e scattering where a precision of 0.56% appears feasible. Further constraints for Electroweak physics could be obtained from coherent-like processes once theoretical issues have been addressed. Figure 10 presents the world measurement of $\sin^2\theta_W$ as a function of $Q$; the projected HiResM$\nu$ measurements will offer an in situ check of the running of $\sin^2\theta_W$. These measurements will provide a powerful constraint on this important parameter using processes different from, and at an energy scale much smaller than, the collider experiments.
5.3 Standard Measurements

A sample of 140 Million $\nu_\mu$-CC and 50 Million $\bar{\nu}_\mu$-CC, with an experiment capable of conducting measurements with a precision such as outlined above, offers an entire programme of text-book physics: from exclusive cross-sections of QE and resonance, coherent-$\pi$, -$\rho$, -Charmed-mesons/baryons, to $J/\psi$-production in NC, to inclusive cross-sections, to strange mesons, to hyperons and polarization measurements of hyperons. To illustrate the power of this experiment, we show a NOMAD event with three reconstructed $K_S^0$ in Figure 11. Figure 8 shows the reconstructed $K_S^0$ mass in NOMAD ($E_{K_S^0} \geq 1$ GeV). In the proposed experiment, we expect to reconstruct over 2 Million $K_S^0$ in the $\nu$-mode. Another example of the tracking capability is Figure 12, showing the reconstructed kinematics for a Quasi-Elastic CC event in NOMAD.

Figure 11: A reconstructed $\nu_\mu$ CC event candidate in NOMAD containing 3 $V^0$ vertices identified as $K_S^0$. The scale on this plot is given by the size of the vertex boxes ($3 \times 3 cm^2$). The HiResM$\nu$ will have finer resolution.

For the study of nuclear effects in neutrino interactions possibilities abound. An arrangement of nuclear targets positioned upstream of the detector, as shown in Figure 13, could provide the desired sample. For example, a single 1mm thick Pb-sheet, at the upstream end of the detector, will provide about $2.5 \times 10^6$ $\nu_\mu$-CC interactions.

5.4 New Physics

When $200 \times 10^{20}$ protons collide and one has a large magnetized $4 \times 4 \times 7$ m$^3$ volume with precise tracking, search for unexpected phenomena — leading to new physics —, can be conducted
The HiResM will have much better resolution to track the emergent proton.

Figure 12: A Quasi-Elastic $\nu_e$ CC event candidate in NOMAD with reconstructed kinematics.

- $E_y = 23.65$ GeV
- $Q^2 = 0.39$ GeV$^2$
- $W^2 = 1.07$ GeV$^2$
- $P_{\text{mis}} = 0.20$ GeV

Proton track: $P = 0.54$ GeV; $\theta = 54^\circ$

Muon track: $P = 23.34$ GeV; $\theta = 1.52^\circ$
Figure 13: Sketch of a basic STT module for the measurement of nuclear effects. Several modules can be placed in the upstream magnetic volume with different target materials (Pb, Fe etc.) of the same thickness in radiation length.
with unprecedented precision.

We wish to state that the neutrino sector has few no-go theorems and anomalies in neutrino experiments are plentiful. The NuTeV collaboration has reported an observation of 3 anomalous dimuon events with an estimated background of $0.069 \pm 0.010$ [25]. The anomaly remains unconfirmed. If confirmed this result could herald new physics. Other examples include the NuTeV $\sin^2 \theta_W$ result, and the excess of $\nu_e$-like events below 400 MeV in MiniBOONE [26]. Once an anomaly appears the experimental challenge is to attain the statistics, resolution, and redundancy that would establish the effect.

The proton intensity of Project-X permits us to propose an experiment with high resolution and in built redundancy to establish new physics, if at all observed. The proposed experiment will be highly sensitive to a long-lived weakly interacting particle, which might decay in the tracking volume. This program combines good sensitivity to electronic, hadronic, or muonic decay modes of such a hypothetical particle with powerful discrimination for Standard Model background. The neutrino Minimal Standard Model ($\nu$MSM) [27], for example, introduces three light singlet right-handed fermions. Attractive features of this model are that it is consistent with data on neutrino oscillation, that it provides a candidate for dark matter — the highest singlet fermion (sterile neutrino) — and, that it can explain the baryon asymmetry of the universe. Secondary hadrons, produced in the interaction of the primary proton beam may decay to these heavy neutrino-like particles ($M > 10$ eV), and then decay inside the tracking detector of our experiment. Figure 14 shows the expected number of sterile neutrino decays in HiResM$\nu$ after one year of data taking [28]. We can see that already after one year we can be sensitive to singlet fermion masses up to $M_N \sim 2$ GeV. We will further study the sensitivity of HiResM$\nu$ to such particles.

### 5.5 Composite Physics Potential

The HiResM$\nu$ will be rich in Physics. Some salient topics we have discussed in the sections above. We have compiled a more complete but still preliminary list of physics topics — papers and thesis topics — in Appendix A. In few instances in this list we have collapsed several topics into one. Judging from the publication record of NOMAD, NuTeV, and CCFR, the HiResM$\nu$ should yield over 100 papers in the refereed journals.
Figure 14: Number of sterile neutrino decays which can be detected in the HiResMν STT volume after one year run, as a function of the sterile neutrino mass $M_N$. Black, dark gray and light gray lines refer to different benchmark models. In phenomenologically viable models the number of decay events are confined by the corresponding thin (upper limits) and thick (lower limits) curves [28]. These numbers should be multiplied by a factor 7 to obtain the sensitivity of HiResMν after the completion of the data taking. Effects of beam divergence, horn focusing, and detailed background errors have not been included.

6 Cost and Feasibility

Our cost estimates for HiResMν are of necessity preliminary. Nevertheless, we have relatively firm estimates on the two most critical items: the dipole magnet and the STT detector. The dipole estimate is based upon the design and fabrication of the UA1 and LHCb magnets. The dipole cost breakdown, obtained from G. Petrucci (CERN), is shown in Appendix D. The total cost, assuming a rate 1UDS=1.1CHF, is: 4.5 M$. The UA1 and LHCb magnets were both more complex and designed for a higher maximal field (0.8T) than would be required in the
The STT cost estimates are based upon the ATLAS and COMPASS designs. Appendix E shows the breakdown of the STT cost. We estimate the STT to cost 5.2 M$. It includes the tight requirements on mechanical precision, rates, and radiation hardness imposed by the ATLAS and COMPASS environment. The benign environment of HiResM$^{\nu}$ implies looser requirements.

We are investigating detailed costs for the electromagnetic calorimeter and the RPC’s for the muon detection. Overall, we project the total cost of HiResM$^{\nu}$ to be about 15 M$, with an additional 25% contingency.

We note that the proposed design is based upon established technologies: similar detectors are operational in the ATLAS [7, 8, 9] and COMPASS [10, 11] experiments at CERN. No critical R&D would then be required for HiResM$^{\nu}$. The construction could benefit from the ATLAS and COMPASS experience and the corresponding production centers.

7 Future Plans

First we solicit constructive criticism of these ideas from all quarters. If the community and Project-X management encourage further development of this proposal, we will collaborate with management to develop a roadmap for the follow-on work.

We believe the proposed high resolution tracking detector using the impressive proton intensity of Project-X offers compelling neutrino physics program. We seek your support and welcome participation in this exciting programme!
APPENDIX A: Physics Potential of HiResM$\nu$

Below we enumerate some physics topics which can be studied with the proposed experiment and can be the subject of PhD theses. The list is not complete. It is intended to illustrate the outstanding physics potential of HiResM$\nu$.

About NuMI and Service to LBL$\nu$

1: The energy scale and relative flux of $\nu_\mu$ Flux in NuMI
2: The $\bar{\nu}_\mu$ relative to $\nu_\mu$ as a function of $E_\nu$ in NuMI
3: Relative abundance of $\nu_e$ and $\bar{\nu}_e$ -vs- $\nu_\mu$ and $\bar{\nu}_\mu$ in NuMI
4: An empirical parametrization of $K_L^0$ yield in NuMI using the $\nu_e$ data
5: Redundancy check on the MIPP $\pi^+$, $K^+$, $\pi^-$, $K^-$, and $K_L^0$ yields in NuMI using the $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$, and $\bar{\nu}_e$ induced charged current interactions

Neutral-Pion Production in $\nu$-Interactions

6: Coherent and single $\pi^0$ production in $\nu$-induced neutral current interactions
7: Multiplicity and energy distribution $\pi^0$ production in neutral current and charged current processes as a function of hadronic energy
8: The cross section of $\pi^0$ production as a function of $X_F$ and $P_T$ in the $\nu$-CC interactions

Charged-Pion, Kaon and Proton Production in $\nu$-Interactions

9: Coherent and single $\pi^\pm$ production in $\nu$-induced charged current interactions
10: Charged $\pi/K/\text{Proton}$ production in the the neutral current and charged current interactions as a function of hadronic energy
11: The cross section of $\pi^\pm/K^\pm$/proton production as a function of $X_F$ and $P_T$ in the $\nu$-CC interactions

Neutrino-Electron Scattering

12: Measurement of inverse muon decay and absolute normalization of the NuMI flux above $E_\nu > 11$ GeV with $\leq 1\%$ precision
13: The $\nu_\mu$-$e^-$ and $\bar{\nu}_\mu$-$e^-$ neutral current interaction and determination of $\sin^2 \theta_W$

14: Measurement of the chiral couplings, $g_L$ and $g_R$ using the $\nu_\mu$-$e^-$ and $\bar{\nu}_\mu$-$e^-$ neutral current interactions

**$\nu$-Nucleon Neutral Current Scattering**

15: Measurement of neutral current to charged current ratio, $R^\nu$, as a function of hadronic energy in the range $0.25 \leq E_{Had} \leq 20$ GeV

16: Measurement of neutral current to charged current ratio, $R^\nu$ and $R^\bar{\nu}$, for $E_{Had} \geq 3$ GeV and determination of the electroweak parameters $\sin^2 \theta_W$ and $\rho$.

**Non-Scaling Charged Current Processes**

17: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ quasi-elastic interaction and determination of $M_A$

18: Measurement of the axial form-factor of the nucleon from quasi-elastic interactions

19: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ induced resonance processes

20: Measurement of resonant form-factors and structure functions

21: Study of the transition between scaling and non-scaling processes

22: Constraints on the Fermi-motion of the nucleons using the 2-track topology of neutrino quasi-elastic interactions

23: Coherent $\rho^\pm$ production in $\nu$-induced charged current interactions

**Inclusive Charged Current Processes**

24: Measurement of the inclusive $\nu_\mu$ and $\bar{\nu}_\mu$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

25: Measurement of the inclusive $\nu_e$ and $\bar{\nu}_e$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

26: Measurement of the differential $\nu_\mu$ and $\bar{\nu}_\mu$ charged current cross-section as a function of $x_{bj}$, $y_{bj}$ and $E_\nu$.

27: Determination of $xF_3$ and $F_2$ structure functions in $\nu_\mu$ and $\bar{\nu}_\mu$ charged current interactions
28: Measurement of the longitudinal structure function, $F_L$, in $\nu_\mu$ and $\bar{\nu}_\mu$ charged current interactions and test of QCD

29: Determination of the gluon structure function, bound-state and higher twist effects

30: Precise tests of sum-rules in QPM/QCD

31: Measurement of $\nu_\mu$ and $\bar{\nu}_\mu$ charged current differential cross-section at large-$x_{bj}$ and -$y_{bj}$

32: Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino charged current interactions

33: Search for rapidity gap in neutrino charged current interactions.

34: Verification of quark-hadron duality in (anti)neutrino interactions

35: Verification of the PCAC hypothesis at low momentum transfer

36: Determination of the behavior of $R = \sigma_L/\sigma_T$ at low momentum transfer

**Nuclear Effects**

37: Measurement of nuclear effects on $F_2$ in (anti)neutrino scattering from ratios of Pb,Fe and C targets

38: Measurement of nuclear effects on $xF_3$ in (anti)neutrino scattering from ratios of Pb,Fe and C targets

39: Study of (anti)shadowing in neutrino and antineutrino interactions and impact of axial-vector current

40: Measurement of axial form-factors for the bound nucleons from quasi-elastic interactions on Pb, Fe and C

41: Measurement of hadron multiplicities and kinematics as a function of the atomic number

**Semi-Exclusive and Exclusive Processes**

42: Measurement of charmed hadron production via dilepton ($\mu^-\mu^+$, and $\mu^-e^+$) processes

43: Determination of the nucleon strange sea using the (anti)neutrino charm production and
QCD evolution

44: Measurement of $J/\psi$ production in neutral current interactions

45: Measurement of $K^0_S$, $\Lambda$ and $\overline{\Lambda}$ production in (anti)neutrino CC and NC processes

46: Measurement of exclusive strange hadron and hyperon production in (anti)neutrino charged and neutral current

47: Measurement of the $\Lambda$ and $\overline{\Lambda}$ polarization in (anti)neutrino charged current interactions

48: Inclusive production of $\rho^0(770)$, $f_0(980)$ and $f_2(1270)$ mesons in (anti)neutrino charged current interactions

49: Measurement of backward going protons and pions in neutrino CC interactions and constraints on nuclear processes

50: $D^{*+}$ production in neutrino charged current interactions

51: Determination of the $D^0, D^+, D_s, \Lambda_c$ production fractions in (anti)neutrino interactions

52: Production of $K^*(892)^+\,-$ vector mesons and their spin alignment in neutrino interactions

Search for New Physics and Exotic Phenomena

53: Search for heavy neutrinos using electronic, muonic and hadronic decays

54: Search for eV (pseudo)scalar penetrating particles

55: Search for the exotic $\Theta^+$ resonance in the neutrino charged current interactions

56: Search for heavy neutrinos mixing with tau neutrinos

57: Search for an anomalous gauge boson in $\pi^0$ decays at the 120 GeV p-NuMI target

58: Search for anomaly mediated neutrino induced photons

59: Search for the magnetic moment of neutrinos

60: A test of $\nu_\mu - \nu_\tau$ universality down to $10^{-4}$ level
APPENDIX B: Modeling DIS interactions

The estimate of systematic uncertainties for the HiResMν measurement of \( \sin^2 \theta_W \) in DIS interactions is based upon the extensive modeling work performed for the NOMAD \( \sin^2 \theta_W \) analysis. Studies on structure functions include the improvement on the parton distribution functions, the extraction of higher twist contributions [19, 20], electroweak corrections [21, 22] and the analysis of nuclear effects [23, 24]. In this Appendix we provide a status of the principal results.

Global QCD fits for \( Q^2 \geq 1 \text{ GeV}^2 \) and \( W > 1.8 \text{ GeV} \) are performed including the power corrections. The analyzed data set consists of the world charged-leptons DIS cross section data for proton and deuteron targets by the SLAC, BCDMS, NMC, FNAL-E-665, H1, and ZEUS experiments supplemented by the fixed-target Drell-Yan data. The latter constrain the sea quark distribution, which is poorly determined by the DIS data alone. The charm dimuon data from CCFR and NuTeV are used to define the strange sea quark distributions. In addition, the recent neutrino and antineutrino cross-section data from the CHORUS experiment are added to the global fit for \( Q^2 > 1.0 \text{ GeV}^2 \) and \( x \geq 0.045 \), mainly to constrain the corresponding HT terms. The analysis is performed in the NNLO QCD with the target mass corrections taken into account and the dynamical twist-4 (twist-6) terms parameterized in the additive form as model independent spline functions \( H(x) \).

The \( d \)-quark distribution is determined within few per cent at \( x \sim 0.2 \) comparable to the precision of the \( u \)-quark distribution. This allows an improvement by a factor of five in the precision on \( x_1/x_0 \) where \( x_1 \) and \( x_0 \) are the integrals over \( x \) of the iso-vector and iso-scalar combinations of the valence quarks, respectively. A better separation between Leading (LT) and Higher Twists (HT) is also achieved. An enhancement in the gluon distribution at \( x \sim 0.3 \) is observed as a consequence of a more accurate determination of \( R = \sigma_L/\sigma_T \).

No evidence is found for sizeable twist-6 contributions to structure functions. The High Twist contribution to \( F_T \) is remarkably similar to the one in \( F_2 \), despite the two terms are fitted independently. As a result the HT term in \( F_L \), defined as \( H_L = H_2 - H_T \), is comparable to zero within the uncertainties. Results indicate the HT contribution to the structure function \( R = \sigma_L/\sigma_T \) is also small in the entire considered range of \( x \). Furthermore, the ratio \( H_2/F_2^{LT} \) is remarkably similar for both (anti)neutrinos and charged leptons over the entire \( x \) range. Overall \( H_3 \) provides a negative contribution to the Gross–Llewellyn-Smith integral is consistent
with prediction.

The total contribution of the HT terms into the DIS cross section turns out to be small compared to the leading-twist (LT) part. For a realistic DIS kinematics the ratio of the HT and LT terms is \( \lesssim 10\% \), which justifies the use of the twist expansion. No strong dependence on the order of QCD calculation is observed.

A detailed phenomenological study of nuclear structure functions is performed for a wide kinematical region of \( x \) and \( Q^2 \). The model takes into account a number of different nuclear effects including nuclear shadowing, Fermi motion and binding effects, nuclear pion excess and off-shell correction to bound nucleon structure functions. Within this approach a statistical analysis of available data is performed on the ratio of the nuclear structure functions \( F_2 \) for different nuclei in the range from the deuteron to the lead. An excellent overall agreement between calculations and data in the entire kinematic range is achieved. Existing data constrain model uncertainties. Calculations for (anti)neutrino scattering are obtained and compared with NOMAD, CCFR, NuTeV and CHORUS data.
APPENDIX C: Flux Determination in the Horn Focused NuMI Beam

The absolute flux will be determined by the inverse muon decay measurement at high $E_\nu$ of about 25 GeV. The relative flux, i.e. the relative number of neutrinos in $E_\nu$ bins, and of $\overline{\nu}_\mu$ to $\nu_\mu$ in energy bins, will be determined by the Low-$\nu^0$ method. This method will be valid for small of $\nu^0$ or $E_{\text{Had}}$-cut provided the cut has meaning in a given detector. Smaller the $\nu^0$-cut, smaller the correction. The excellent momentum and energy resolution of HiResM$\nu$ and the high statistics allow to use events with $\nu^0 < 0.5$ GeV. The low value of $\nu^0$-cut is in contrast with the case of massive calorimeter like CCFR/NuTeV that are limited by poor hadronic energy resolution below 5 GeV due to the coarse Fe sampling. We have worried about systematic errors affecting the relative flux determination using the low-$\nu^0$ technique such as arising from $B/A$ and $C/A$ determination, radiative correction, energy resolution, iso-scalar correction, etc.. We will constrain the relative flux and the energy-integrated $\overline{\nu}_\mu/\nu_\mu$ flux ratio using the Low-$\nu^0$ method of determining relative flux in concert with the measurements by MIPP-II and NA49. We will ensure that the beam simulation is driven by a precise data-base comprising secondary/tertiary interactions as measured by MIPP-II, and the precisely surveyed, and, where applicable. monitored, parameters of the beam-elements such as alignment, horn-current, the $B$-field of the horn, inert elements, and the primary proton beam characteristics. We will also use the knowledge of the extant $\overline{\nu}_\mu$-CC and $\nu_\mu$-CC data. Such an all encompassing effort will yield a precision of better than 1% on the cumulative $\overline{\nu}_\mu/\nu_\mu$ flux. We do not see any fundamental systematic impediment which will prevent us from determining the relative flux with high accuracy from the Low-$\nu^0$ events.

The NC-background at $E_\nu$ of about 5 GeV was < 1% in NOMAD. The resulting error after correcting for the NC-contamination was negligible. This is because the NC-events were in NOMAD, and will be in HiResM$\nu$, kinematically identified on an event-by-event basis, and, hence, tightly constrained. Indeed, the non-prompt backgrounds contaminating the $\nu_\mu$-CC and $\overline{\nu}_\mu$-CC at low-$\nu^0$ are not an issue in the HiResM$\nu$.

The $\nu^0$-method relies on excellent energy calibration and this is one of the strength of HiResM$\nu$. We do not need a dedicated calibration beam for the detector, although having such a redundancy will be desirable. To begin with, the charged particle momenta will be measured to a very high precision. In NOMAD, the systematic error on the charged-particle momentum was $\leq 0.2\%$ by using the $K_S^0$ mass constraint.
Role of MIPP

We should take into account the important impact of the upgraded MIPP on the HiResμν
Physics and the larger NuMI neutrino programme. In particular, two aspects of the MIPP
measurements are relevant to NuMI Physics.

A: Charged Pion Measurement in the NuMI Target

The region $1 \leq E_\nu \leq 10$ GeV is almost entirely dominated by neutrinos from pion-decay. (The
$\nu_e$ arising from the $\mu^+$-decay are tightly constrained by the $\pi^+$.). The corresponding energy
region for pions is, thus, $2.5 \leq E_\pi \leq 25$ GeV produced in the 120 GeV p-C (NuMI Target)
collision. The pions are copiously produced in this in this region which roughly corresponds
to $0.01 \leq x_F \leq 0.1$; the contamination from kaons in this region is small, i.e. the particle-ID
distinction between pion and kaon is not so critical. The proton versus pion distinction is clean
in this energy region. We therefore believe that the charged-pion yield at the primary target,
measured event-by-event, in MIPP will go a long way to provide an accurate constraint on $\bar{\nu}_\mu$
and $\nu_\mu$ yield.

B: Secondary/Tertiary Pion Yield

About 7% of $\nu_\mu$ come from secondary/tertiary pion production while focussing positives (Neutri-
nino-Run). The estimate for $\bar{\nu}_\mu$ from secondary/tertiary interactions is about 15% (Antineutrino-
Run). Here the second class of MIPP measurements come into play. MIPP will measure the
pion/kaon yield using proton/pion/kaon beams, at various energies (10 GeV to 120 GeV), on
a variety of targets spanning the periodic table. The beam transport computation will be
based upon an empirical cross-section matrix comprising various beam-projectile, momenta,
and nuclear targets as measured by MIPP. We will have to precisely survey/monitor the inert
material in the beam line, the horn-current and magnetic field, and the alignment. The eventual
error on the relative flux could be controlled to 2% level. A case in point is the NOMAD $\nu_\mu$-N
cross-section measurement where the $\nu_\mu$ relative flux was entirely determined from the SPY,
and to a lesser degree Atherton, measurement.

NOMAD $\nu_\mu$-N Cross-Section Measurement

NOMAD collaboration has recently published the $\nu_\mu$-N cross-section in the region $2.5 \leq E_\nu \leq
40$ GeV region [6]. The relevance of this result is the measurement of $\sigma(\nu - N)/E_\nu$ in $10 \leq E_\nu \leq
30$ GeV with 2.6% precision and in $2.5 \leq E_\nu \leq 10$ GeV with a 4% precision. The neutrinos
were focussed by a horn [34]. The relative $\nu_\mu$-flux was determined using the SPY measurement of $\pi^+$ [35, 30, 31, 32]. (The $K^+$ measurement was of little relevance to this $\sigma(\nu - N)/E_\nu$ result.) The best SPY data were around 45 GeV secondary hadron setting [30, 31, 32]. The 2.6% error in cross-section with $E_\nu \approx 20$ GeV is clearly dominated by the precision of the SPY measurement at 45 GeV.

The current error on the $\bar{\nu}_\mu/\nu_\mu$ flux in MINOS is about 5-7%. This has no input from MIPP. Furthermore, the MINOS resolution is much poorer than that of NOMAD, or the projected resolution of HiResM$\nu$ which will have a much higher resolution than NOMAD. We believe that the input from MIPP, and those from NA49, will have significant impact on the the $\bar{\nu}_\mu/\nu_\mu$ flux-ratio as NOMAD/SPY analyses demonstrate.

**Determination of $\nu_e/\nu_\mu$ in NuMI**

In NuMI, the $\nu_e/\nu_\mu$ in the region $1 \leq E_\nu \leq 10$ GeV is known to about 6% precision. It is done by constraining the $\pi^+$ using the low-$E_{\text{Had}}$ $\nu_\mu$-CC data, which in turn fixed the $\mu^+$ giving rise to the majority of $\nu_e$ in the above energy region. The largest contribution to the $\pm 6\%$ comes from the error in the $\nu_\mu$-acceptance in the near detector. The error in the $\nu_\mu$-acceptance in NOMAD is at $\pm 0.15\%$ level; in HiResM$\nu$ this error will be negligible.

Thus in HiResM$\nu$ one will know precisely the $\nu_e/\nu_\mu$. Uniquely, using the anti-$\nu_e$ data, we will constrain the $K^0_L$ contribution to a very high precision. (The anti-$\nu_e$ is dominated by the $K^0_L$ contribution.)
APPENDIX D: Cost of the Dipole Magnet

Table 5: Cost for the original UA1 dipole magnet with a total magnetic volume of $3.0 \times 3.0 \times 7.0 \ m^3$ (courtesy G. Petrucci, CERN). The maximal $B$ field was $0.8 \ T$.

<table>
<thead>
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<th>Item</th>
<th>Description</th>
<th>kCHF</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoke</td>
<td>2.0 CHF/kg</td>
<td>2,870</td>
<td></td>
</tr>
<tr>
<td>Winding</td>
<td>Al, 54.5 mm x 54.5mm, 31tons, about 30 CHF/kg</td>
<td>750</td>
<td>Expensive: hole for beam pipe</td>
</tr>
<tr>
<td>Power supply</td>
<td>6 MW with 4 existing units in parallel</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>Water cooling</td>
<td></td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Supports, tracks,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>connections, safety</td>
<td></td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Cables (10000A) and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water cooling pipes</td>
<td></td>
<td>250</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>5,370</strong></td>
</tr>
</tbody>
</table>

Table 6: Cost for the LHCB dipole magnet with a total magnetic volume of about $3.5 \times 4.2 \times 5.0 \ m^3$ (courtesy W. Flegel, CERN). Integrated field $\int B dl = 4Tm$.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>kCHF</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yoke</td>
<td>Lamination 100mm, 1500tons</td>
<td>1,958</td>
<td>Complex shape</td>
</tr>
<tr>
<td>Winding</td>
<td>Al, 50mm x 50mm, 50tons</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>Conductor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td>1,134</td>
<td></td>
</tr>
<tr>
<td>Special clamps and</td>
<td></td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>support</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>4 MW</td>
<td>638</td>
<td></td>
</tr>
<tr>
<td>Tracks and mechanical</td>
<td></td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bus-bar, water cooling</td>
<td></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Magnet control system</td>
<td></td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>and safety</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary equipment</td>
<td></td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>for assembly and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>manipulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnet moving system</td>
<td></td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Regie manpower</td>
<td></td>
<td>120</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4,996</strong></td>
</tr>
</tbody>
</table>
APPENDIX E: Cost of the Straw Tube Tracker

Table 7: Cost estimate (as of 2004) for the proposed Straw Tube Tracker (STT) assuming an instrumented active volume of $3.5 \times 3.5 \times 6.4 \text{ m}^3$. The total number of channels is 112,000, arranged in 160 double layers. The numbers are taken from the actual production costs of ATLAS and COMPASS detectors. A conservative calculation is assumed to allow some contingency.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>kCHF</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straws + wire + endplugs + crimp tubes etc.</td>
<td>Material, winding, wire 6.7 CHF/straw other plastic &amp; metallic parts 6.0 CHF/straw</td>
<td>1,422</td>
<td>Use kapton (high quality) For mylar reduced to 1,156 CHF</td>
</tr>
<tr>
<td>Global mechanics frames + supports</td>
<td>Al structure (COMPASS) 6000 CHF/double layer</td>
<td>960</td>
<td>Possible to use C-fibre COMPASS prototypes Including high precision COMPASS requirements</td>
</tr>
<tr>
<td>Gas system</td>
<td>Closed circuit (Xe/CO$_2$)</td>
<td>300</td>
<td>Upper limit (same cost as ATLAS with triple mixture)</td>
</tr>
<tr>
<td>Cooling system</td>
<td></td>
<td>200</td>
<td>Upper limit (same cost as ATLAS)</td>
</tr>
<tr>
<td>Assembly (Russia)</td>
<td>700USD/month/person ~ 20 persons, 2.5 years</td>
<td>500</td>
<td>Prices paid 400USD/month/person</td>
</tr>
<tr>
<td>Tooling for assembly</td>
<td></td>
<td>200</td>
<td>Cost depending upon parallelization required (schedule)</td>
</tr>
<tr>
<td>FE electronics + ASIC</td>
<td>Analog readout 5.3 CHF/straw</td>
<td>1,187</td>
<td>Very conservative estimate assuming ATLAS prices (costly because rate &amp; radiation problems)</td>
</tr>
<tr>
<td>HV power supplies</td>
<td>0.78 CHF/straw</td>
<td>87</td>
<td>Use one layer/HV channel</td>
</tr>
<tr>
<td>LV power supplies</td>
<td>1.0 CHF/straw</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>Cabling</td>
<td>2.4 CHF/straw</td>
<td>269</td>
<td>Very conservative due to material problems in ATLAS</td>
</tr>
<tr>
<td>Patch panels</td>
<td>0.44 CHF/straw</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5,757</strong></td>
<td></td>
</tr>
<tr>
<td>Xe filling (70%)</td>
<td>0.62 CHF/straw</td>
<td></td>
<td>69</td>
</tr>
</tbody>
</table>
References


[34] G. Acquistapace et al., CERN-ECP/95-14