

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

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We propose a new high-resolution neutrino experiment within a dipole magnetic field, HiResMv. This experiment will run along with long-baseline neutrino oscillation experiments (LBLv) such as NOvA, a large-cavity detector at DUSEL, or a Liquid-Argon detector in the Medium-Energy (ME) configuration of the NuMI-beam. The $4 \times 4 \times 7 \text{ m}^3$ detector, inside a dipole magnetic field of $B \approx 0.4 \text{ T}$, will have the density of liquid hydrogen, $\rho \approx 0.1 \text{ gm/cm}^3$, with a nominal fiducial mass of 7.4 tons. Assuming the 120 GeV Main Injector proton intensities we anticipate 140(50) million ν_μ ($\bar{\nu}_\mu$) Charged-Current (CC) events in the fiducial volume, for 3(4)-year run with the ME (anti)neutrino beam. Alternatively, the same statistics could be collected in just 1(1.5) year with the High Energy (HE) beam configuration. The goals of HiResMv are twofold. It will measure the relative abundance and the energy spectrum of ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$ CC-interactions, which are directly relevant to LBLv. It will serve as an 'Event-Generator' of real neutrino interactions to estimate backgrounds and efficiencies in LBLv. As such, it will provide a quantitative determination of the overall energy-scale of neutrino CC interactions and of hadronic multiplicities for all CC and Neutral-Current (NC) event topologies. In addition, it will perform precise measurements of electroweak parameters, of (semi)exclusive processes such as quasi-elastic, resonance, $\pi^0/K_S^0/\Lambda$ /charm-hadron production, as well as of the hadronic structure of nucleons and nuclei. We expect to reach a sensitivity of about 0.2% on the weak mixing angle by combining different channels. The new experiment will also perform searches for new physics beyond the Standard Model.

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1. High Intensity Neutrino Beam

A new high intensity proton facility, Project-X, is planned to support a major program in neutrino and flavor physics at Fermilab [1]. Project X is based on a new 8 GeV superconducting linac, paired with the existing (but modified) Main Injector and Recycler Ring, to provide in excess of 2 MW of beam power throughout the energy range 60-120 GeV. The linac utilizes technology in common with the International Linear Collider over the energy range 0.6-8.0 GeV. The project would allow to achieve an intensity of 1×10^{18} protons/hour for the Main Injector 120 GeV beam. Assuming $(365/\pi)$ days of operation in a year, that corresponds to about 30×10^{20} protons/year available for the MI neutrino beam.

We propose a new neutrino experiment, HiResMv, which, taking advantage of the unprecedented (anti)neutrino fluxes available with Project-X, should combine high resolution in the reconstruction of neutrino events and large statistics. The experiment will run along with the LBLV experiments at the Near Detector site. This fact is an imperative to achieve the highest precision in the discovery of the elements of the neutrino mass matrix. The LBLV's will run in both neutrino and anti-neutrino modes. Assuming the Medium Energy spectrum of the existing NuMI beam and a modest fiducial mass of 7.4 tons, we plan to collect 140 million ν_μ CC events and 50 million $\bar{\nu}_\mu$ CC events in a 3-year and 4-year run, respectively. It is worth noting the running time required to collect the same statistics would be reduced by about a factor of three with the High Energy configuration of the NuMI beam.

2. High Resolution Detector

Building upon the NOMAD-experience [2], we propose a low-density tracking detector as neutrino target. The active target tracker will have a factor of two more sampling points along the z -axis (ν -direction) and a factor of six more sampling points in the plane transverse to the neutrino compared to the NOMAD experiment. Figure 1 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 proposed experiment, HiResMv, will further enhance the resolving power: an order of magnitude more points in tracking charged particles, and coverage for side-exiting neutrals and muons.

Taking advantage of the existing design and production details for the ATLAS Transition Radiation Tracker [4] and the COMPASS detector [5], we are proposing straw-tube trackers (STT) for the active neutrino target of HiResMv. 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. In front of each module a plastic radiator made of many thin foils allows the identification of electrons through their Transition Radiation. The nominal fiducial volume (FV) for CC analysis is: $350 \times 350 \times 600 \text{ cm}^3$, corresponding to 7.4 tons of mass with an overall density $\rho \leq 0.1 \text{ gm/cm}^3$. The STT will be surrounded by an electromagnetic calorimeter (sampling Pb/scintillator) covering the forward and side regions. Both sub-detectors will be installed inside a dipole magnet providing a magnetic field of $\sim 0.4 \text{ T}$. An external muon detector based upon Resistive Plate Chambers (RPC) will be placed outside of the magnet.

The neutrino target would be mainly composed of carbon, and a radiation length is about 5 m . The spacepoint resolution is expected to be $< 200\mu m$, consistent with the performance of ATLAS [4] and COMPASS [5] trackers. Multiple scattering contributes 0.05 to the $\Delta p/p$ for tracks 1 m long, while the measurement error would be 0.006 for $p = 1$ GeV tracks. The proposed detector will measure track position, dE/dx , and Transition Radiation (with Xe filling) over the entire instrumented volume. The unconverted photon energy will be measured in the calorimeters with a target energy resolution of $\sim 10\%/\sqrt{E}$. The expected capabilities of HiResMv include:

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

The proposed design provides both redundancy of measurements and flexibility. The redundancy is crucial for high resolution in the reconstruction of neutrino events. Furthermore, most of the target mass (85%) is represented by the radiators, which are independent from the straws. This fact allows a change in the fiducial mass without affecting the construction of the trackers.

3. Reduction of Systematics for LBLV

The sensitivity to the oscillation parameters (θ_{13} , δ_{CP}) which can be achieved by the next generation LBLV experiments will depend upon systematic uncertainties from intrinsic flux contaminations and from the knowledge of (anti)neutrino cross-sections and background topologies. 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 (π^0 and $K_S^0/\Lambda/\bar{\Lambda}$) particles composing the hadronic system. The experiment will provide topologies, on an event-by-event basis, of various interactions that will serve as 'generators' for the simulation of LBLV experiments. A glance at the NC event candidate in NOMAD, shown in Figure 1, gives an idea of the precision with which the charged-particles and the forward- γ were measured. The proposed experiment will have substantially better resolution than NOMAD.

The excellent resolution of the detector inside a calibrated dipole \mathbf{B} -field will allow a precise determination of the overall neutrino energy scale, a crucial scale in precisely determining the neutrino oscillation parameters in LBLV. The energy scale of charged particles and the B-field calibration can be checked from the mass constraint of the reconstructed K_S^0 . With a total sample of 30,000 reconstructed K_S^0 in NOMAD 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 of the available control samples [3]. In the proposed experiment, we expect to reconstruct over 2×10^6 K_S^0 in the ν -mode and we will collect overall a factor of 200 more ($\nu + \bar{\nu}$) events than in NOMAD.

Because this experiment and the LBLV 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 in the LBLV.

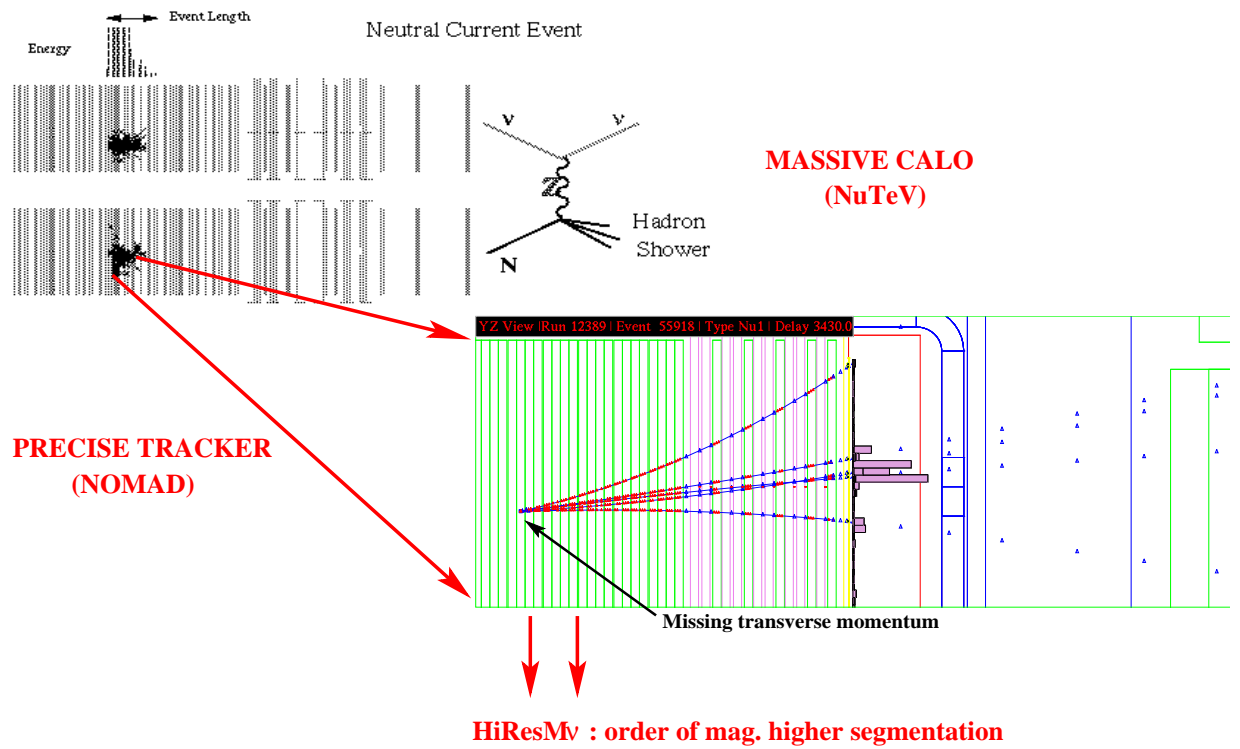


Figure 1: Candidate NC Event in NuTeV and NOMAD. In tracking charged particles HiResMv will provide a factor of two higher segmentation along z-axis and a factor of six higher segmentation in the transverse-plane compared to NOMAD.

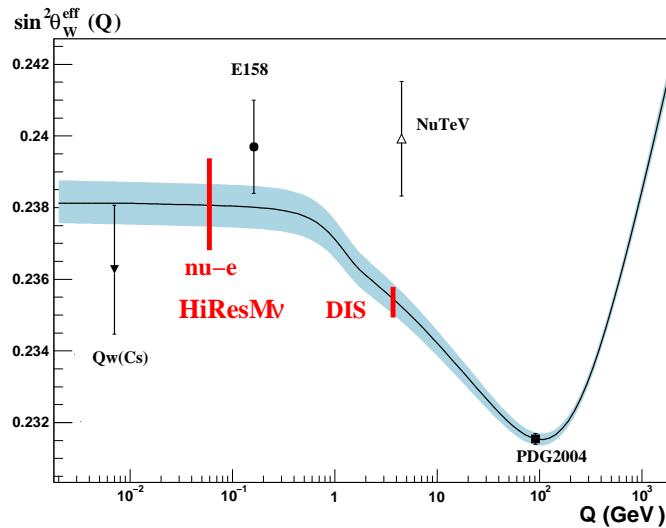


Figure 2: Running of the weak mixing angle as a function of the momentum transfer Q , as predicted by the Standard Model [8]. The data points are from Atomic Parity Violation [9], Moeller scattering (E158 [11]), ν DIS (NuTeV [6]) and the combined Z pole measurements (LEP/SLC). The projected sensitivity of our experiment is shown for comparison.

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4. Electroweak Measurements

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 [10]. The current PDG precision on $\sin^2\theta_W$ derives from the LEP/SLC/CDF/D0 measurements. The proposed ν -experiment, the only direct probe to ν -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 about 3σ higher than the ‘world average’ [6]. The HiResMv will provide a decisive check of this anomaly.

In HiResMv, two different channels permit precise measurements of $\sin^2\theta_W$ with independent systematics and at different scales (Q^2), as shown in Figure 2. The most promising channel for the $\sin^2\theta_W$ measurement is the Deep Inelastic Scattering (DIS) with a precision approaching 0.2%. It is followed by the ν -e scattering where a precision of 0.56% can be achieved.

4.1 Deep Inelastic Scattering off quarks

The experiment will permit a measurement of R^ν , the NC/CC ratio in a ν -beam, and of $R^{\bar{\nu}}$, the NC/CC ratio in a $\bar{\nu}$ -beam. We will also exploit the Paschos-Wolfenstein relation [7] to constrain the systematic errors. With a cut on the hadronic energy $E_{Had} \geq 3$ 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 ν -mode is 19×10^6 , and that in the $\bar{\nu}$ -mode is 4×10^6 . Thus, the expected statistical uncertainty on $\sin^2\theta_W$ is 0.08%.

The total experimental errors on R^ν ($R^{\bar{\nu}}$) in the proposed experiment will be a factor of 4 smaller than those quoted for the NuTeV-experiment [6] due to the higher resolution and statistics. The overall expected experimental systematics on $\sin^2\theta_W$ is 0.1%, mainly dominated by the muon identification and by the kinematic analysis like in the NOMAD experiment. For R^ν measurement, flux is almost a non-issue. For the $R^{\bar{\nu}}$, we will constrain the energy-integrated $\bar{\nu}_\mu/\nu_\mu$ flux ratio using the Low- ν^0 method of determining relative flux [15] in concert with the measurements by MIPP-II and NA49. We will also use the knowledge of the extant $\bar{\nu}_\mu$ -CC and ν_μ -CC data. Such an effort will yield a precision of the order of 1% on the cumulative $\bar{\nu}_\mu/\nu_\mu$ flux.

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 $\sim 15,000$ 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* $\sim 200,000$ charm-induced dileptons (e^+ and μ^+). The detector will also permit direct measurements of exclusive charmed hadrons (~ 5 million), which will be reconstructed from their decay kinematics. The estimate of the other theoretical uncertainties is based upon the current understanding of neutrino-nucleus structure functions [12, 13, 14], and the on-going $\sin^2\theta_W$ analysis in NOMAD ($E_{Had} \geq 3$ GeV). The theoretical models used for our calculations are anchored in the fits to the existing experimental data. These models deal with higher twist, longitudinal structure function, bound state effects in nuclei and electroweak corrections. Some of the uncertainties will be further reduced by J-Lab measurements, and measurements conducted in HiResMv experiment. We expect the model uncertainty on $\sin^2\theta_W$ to be about 0.14%.

4.2 Elastic Scattering off electrons

The ν - e^- scattering, via CC or NC, results in a clean signal in this experiment. The signal is a single e^- (μ^-) emerging at zero-angle in the NC (CC) reaction. The relevant measurable that characterizes the signal is $E_L \theta_L^2$ where E_L and θ_L are the energy and angle (with respect to the neutrino direction) of the emergent lepton. Thus, the key to measuring the ν - e^- NC interaction is the presence of B-field and resolution in θ_e . The background, almost entirely caused by photon conversion, is charge independent. Thus, we will measure the background to the ν - e^- NC process by measuring forward e^+ . Moreover, the energy and the angle of the scattered e^- will be measured with high resolution in HiResMv.

We posit that the dominant error will be the statistical error of the ν - e^- sample. The ratio of $\sigma(\bar{\nu}_\mu e^-)$ 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%.

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