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# Measurement of $\sin^2\theta_W$ at the First Muon Collider [1]

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**Abstract.** This report summarizes the study of the possibility of measuring $\sin^2\theta_W$ using the intense neutrino beam expected from the straight sections of the First Muon Collider ring. This study is based on realistic error calculations from the CCFR and the NuTeV experiments. Using a neutrino detector that is capable of identifying and distinguishing electrons and muons, along with a light isoscalar target, it is conceivable to measure $\sin^2\theta_W$ to the precision equivalent to the $W$ mass uncertainty (experimental) of 30 MeV.

## I INTRODUCTION

The weak mixing angle, $\sin^2\theta_W$, is one of the fundamental parameters in the electro-weak sector of the Standard Model (SM). Neutrino-nucleon deep inelastic scattering experiments provide excellent testing field of the theory due to their wide range of $q^2$ accessibility. However, since neutrinos interact weakly, the interaction rate is very low, and in the past neutrino fixed target experiments have used dense material as neutrino targets in order to increase the interaction rates per given cycle. While these heavy target detectors increase the interaction rates, the calorimetric nature of the targets did not allow one to distinguish electron neutrino induced charged current interactions (CC) from neutral current (NC) interactions.

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## II CURRENT $\nu$-N EXPERIMENTS

The CCFR experiment used ratios of the cross sections of NC to CC interactions, expressed in the following Llewellyn-Smith formula [1] :

$$R^{\nu(\overline{\nu})} = \frac{\sigma_{NC}^{\nu(\overline{\nu})}}{\sigma_{CC}^{\nu(\overline{\nu})}} = \rho^2 \left( \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left( 1 + \frac{\sigma_{CC}^{\overline{\nu}(\nu)}}{\sigma_{CC}^{\nu(\overline{\nu})}} \right) \right). \qquad (1)$$

to extract $\sin^2\theta_W$, assuming the SM expectation for $\rho$ [2].

The NuTeV (E815) experiment just finished taking its data, totalling $\sim 3 \times 10^{18}$ protons on target. During the run, the experiment used the Sign-Selected-Quadrupole-Train (SSQT) [3] to run separately with neutrinos or anti-neutrinos at a given running period by reversing the magnet polarities. The beam line optics was set so that for the given mode ($\nu$ or $\overline{\nu}$) the polarities of all secondary magnets can be reversed, selecting only the secondary particles with desired charge. This capability of sign selection was necessary for the experiment to utilize the Paschos-Wolfenstein relationship [4]:

$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\overline{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\overline{\nu}}} = \frac{R_\nu - rR_{\overline{\nu}}}{1-r} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W\right), \qquad (2)$$

where $r = \frac{\sigma(\overline{\nu},CC)}{\sigma(\nu,CC)}$, to minimize the measurement uncertainty due to the mass threshold effect in CC charm production. The main reason for sign-selection was the inability of the NuTeV detector to distinguish $\nu_\mu$ induced NC events from the $\overline{\nu}_\mu$ induced NC events.

Table 1 compares various uncertainties on the $\sin^2\theta_W$ measurements from CCFR and NuTeV, along with the expected First Muon Collider (FMC) uncertainties. There were two dominant systematic uncertainties in the CCFR experiment: 1) $\nu_e$ flux and 2) CC charm production. These two major systematic uncertainties in CCFR have been reduced in the NuTeV experiment, utilizing the SSQT, so that the remaining dominant uncertainty is the statistical uncertainty.

Using the FMC beam parameters for the mean muon energy of 200GeV to give a mean neutrino energy of 178GeV [5] and a $10m$ long straight section. we expect approximately 94k neutrino events per year per cm of $H_2$ target with a radius of 150 cm. This results in $\sim$ 20million $\nu_\mu$ induced events per year, for a 1 m long $D_2$ target with 1 m radius located $\sim$ 500 m away from the end of the straight section of the FMC, because 90% of the beam is contained within 60 cm radius for this energy [6]. With a detector that can distinguish electrons and muons resulting from CC interactions, the effective neutrino interaction statistics double, resulting in a total of 40 million events per year. Since the number of neutrino events from the NuTeV experiment is of the order of 1 million events for $\nu_\mu$, the expected 40 million events per year from the FMC would cause a reduction in the statistical uncertainty by a factor of

**TABLE 1.** $sin^2\theta_W$ uncertainties (not all the errors from NuTeV are available).

| SOURCE OF UNCERTAINTY | CCFR | NuTeV | $\mu$-Col (20M) |
|---|---|---|---|
| data statistics | 0.0019 | 0.0019 | 0.0004 |
| Monte Carlo statistics | 0.0004 | | |
| **TOTAL STATISTICS** | 0.0019 | 0.0019 | 0.0004 |
| $\nu_e$ flux | 0.0015 | 0.0006 | $<< 0.0004$ |
| Cosmic Ray Background | <0.0001 | < 0.0001 | |
| Transverse Vertex | 0.0004 | 0.0004 | $\sim 0$ |
| Energy Measurement | | | |
| Hadron Energy Scale (1%) | 0.0004 | 0.0004 | 0.0004 |
| Muon Energy Loss in Shower | 0.0003 | 0.0002 | $\sim 0.0001$ |
| Muon Energy Scale (1%) | 0.0002 | 0.0002 | $\sim 0.0002$ |
| Hadron Energy Resolution | 0.0001 | | < 0.0001 |
| NC/CC $E_{\mathrm{had}}$ Difference | 0.0001 | | < 0.0001 |
| $e/\pi$ ratio | <0.0001 | | |
| Event Length | | | Irrelevant |
| Hadron Shower Length | 0.0007 | 0.0001 | |
| Counter Fiducial Size | 0.0005 | 0.0004 | |
| Counter Efficiency | 0.0004 | 0.0001 | |
| Counter Noise | 0.0001 | 0.0002 | |
| Vertex Determination | 0.0003 | 0.0007 | |
| **TOTAL EXP. SYST.** | 0.0019 | 0.0012 | < 0.0004 |
| Charm Production, $\overline{s}$ | | | |
| ($m_c = 1.31 \pm 0.24$ GeV) | 0.0027 | $\sim 0$ | $\sim 0$? |
| Higher Twist | 0.0010 | 0.0006 | Need to be controlled |
| Longitudinal Cross-Section | 0.0008 | N/A | Need to be measured |
| Charm Sea, (±100%) | 0.0006 | 0.0004 | Need to be measured |
| Non-Isoscalar Target | 0.0004 | 0.0004 | $\sim 0$ for $D_2$ |
| Structure Functions | 0.0002 | 0.0001 | 0.0001 |
| Rad. Corrections | 0.0001 | | |
| $\sigma^{\overline{\nu}}/\sigma^{\nu}$ | <0.0001 | N/A | |
| **TOTAL PHYSICS MODEL** | 0.0030 | ~0.0008 | << 0.0008? |
| **TOTAL UNCERTAINTY** | 0.0041 | 0.0024 | < 0.0010 |
| $\Delta M_W$ | 0.21 $GeV/c^2$ | 0.11$GeV/c^2$ | $< 0.050 GeV/c^2$<br>$0.030 GeV/c^2$ (EXP) |

6. This enormous increase in statistical power also helps to minimize many of the systematic uncertainties in table 1 dramatically.

The remaining error of 0.0004 due to $\nu_e$ flux no longer exists for a detector that is capable of distinguishing CC interactions of $\nu_e$ from hadronic showers resulting from NC interactions by identifying the outgoing electrons. The uncertainties resulting from energy scale can also be minimized by carefully planned calibration runs. The errors in event length, in principle, do not exist, because with the detector described in the following section, one can distinguish CC from NC interactions on an event-by-event basis. The above expectations will enable the experiment to reduce the statistical and experimental systematic uncertainties on $\sin^2\theta_W$ to the equivalent $M_W$ uncertainty of 30 MeV.

## III DETECTOR AND BEAM REQUIREMENTS

It is crucial to be able to reverse the polarity of the ring so that one accepts $\nu_\mu$ and $\overline{\nu}_e$ or $\overline{\nu}_\mu$ and $\nu_e$ at a given time. This capability also provides the opportunity for studying possible systematics coming from the beam of a given sign.

The beamline also needs sweeping magnets or sufficient thickness of shielding to filter out electrons or electromagnetic (EM) shower particles resulting from the muon decay in the FMC ring. Due to the intensity of neutrino beam, some neutrino interactions would occur in the shielding. Thus, one requires adequate veto counters before the target in order to flag the charged particles that come from upstream neutrino interactions.

It is extremely important for the detector to distinguish electrons from muons that are coming from neutrino CC interactions. The detector should also be capable of distinguishing the combination of electron and hadron induced showers from purely hadronic ones. Traditional heavy target neutrino detectors could not distinguish $\nu_e$ induced CC interactions from NC interactions.

It also is necessary to use light isoscalar targets for the charm and strange sea measurements from the same experiment as this will be very useful in reducing the remaining systematic uncertainties.

In order to satisfy the above requirements, the detector needs to have:

- Good EM and hadronic shower identification.
- High electron detection efficiency along with high efficiency particle identification.
- Good charged particle momentum measurement.
- Good EM and hadronic shower energy containment and measurement.
- Muon identification and momentum measurement.

# Neutrino Detector

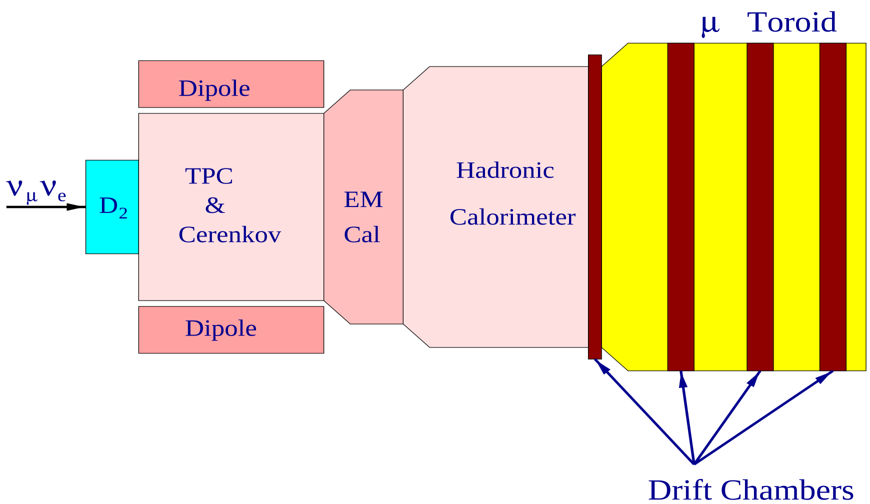


**FIGURE 1.** A schematic drawing of a conceptual detector design for the $\sin^2\theta_W$ measurement. This detector is essentially the same as B.J. King's conceptual design.

Figure 1 shows a conceptual design of a neutrino detector [7]. The components of the detector in the figure are discussed in the following section.

## A Detector Components

This section summarizes the suggested components of the detector to meet the requirements discussed in the previous section.

- Target : $D_2$, $r = 1$ m, $l = 1$ m (light isoscalar)
- Vertex chamber for the interaction vertex determination.
- TPC and Čerenkov counter : particle-ID and momentum measurement.
- EM calorimeter :
  - Good longitudinal segmentation and multiple depth readout
  - Fine transverse granularity (enhanced at the shower max) for shower shape analysis.
  - More than 21 $X_0$ depth for the full EM shower containment. (The depth has to be optimized so that the hadronic showers do not deposit too much energy in the EM section.)
  - Energy resolution : $\frac{\sigma}{E} = \frac{15\%}{\sqrt{E}}$
- Hadron calorimeter :

  - More than $3 \sim 4$ layer longitudinal readout.
  - Some transverse granularity in order to determine shower direction.
  - $10 \sim 20\ \lambda_0$ deep (168 cm to 333 cm Fe equivalent)
  - Energy resolution : $\frac{\sigma}{E} = \frac{50\%}{\sqrt{E}}$

- $\mu$ Toroid magnet interspersed with drift chambers for muon momentum measurements with its field magnitude to be determined.

It is premature at this point to discuss the detailed technologies for the various elements of the detector. However, the above functionality is necessary to identify electrons and muons in CC interactions.

## IV BACKGROUNDS AND DIFFICULTIES

We discuss expected backgrounds and some difficulties to be overcome for the precise measurement of $\sin^2\theta_W$, using the conceptual detector discussed in the previous section.

- $\pi \& K$ from hadron shower decaying in-flight in the particle-ID system, faking CC events.
- $\pi^0$ conversions resulting in electrons.
- Electrons from upstream $\nu_e$ interactions.

All of the above backgrounds have to do with identification of CC interactions. One may be able to enhance the detector to overcome these backgrounds.

We also expect the following minor difficulties from the CCFR or NuTeV type measurements of $\sin^2\theta_W$.

- CC-charm error $\Rightarrow 0$ (This error can be reduced by measuring the CC production of charm directly from the same experiment, using oppositely charged dimuon or di-electron final states.)
- Is it straightforward to measure $R^-$?

$$R_\nu = \frac{\sigma(\nu_\mu, NC) + \sigma(\overline{\nu}_e, NC)}{\sigma(\nu_\mu, CC) + \sigma(\overline{\nu}_e, CC)}$$

$$R_{\overline{\nu}} = \frac{\sigma(\overline{\nu}_\mu, NC) + \sigma(\nu_e, NC)}{\sigma(\overline{\nu}_\mu, CC) + \sigma(\nu_e, CC)}$$

- Are the higher twist effects going to be under better control? (It is extremely important to reduce this error, because this error will be the dominant uncertainty.)
- Is the CC to NC identification error close to 0?
- Are there any other theoretical effects we need to worry about?

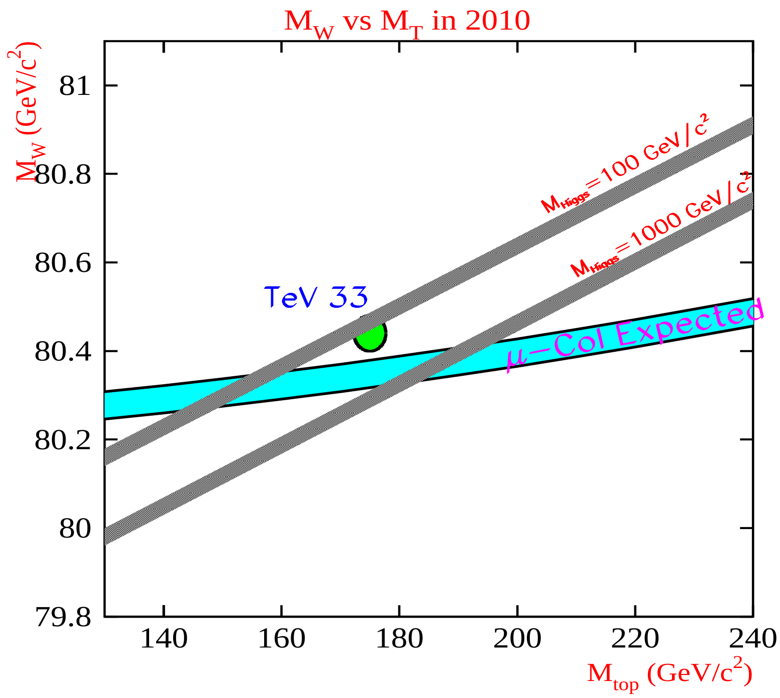


**FIGURE 2.** Expected uncertainties of TeV 33 and FMC $M_W$ vs $M_T$ in the year 2010.

## V EXPECTED $M_W$ STATUS IN 2010

Figure 2 shows the expected status of various W mass measurements in the year 2010. The most precise measurement is expected from direct measurements of the TeV33 project. The contour represents the 68% confidence level from the TeV33 expectations of $\delta M_W = 30$ MeV and $\delta M_t = 2$ GeV, with $\int \mathcal{L} dt = 10 fb^{-1}$ using the traditional $M_T$ method [8]. The FMC measurements of the W mass would be of similar precision after one year of running with the beam parameters provided to us. As can be seen in figure 2, since the errors from both the direct measurements and the FMC are going to be extremely small, and the FMC measurement provides the SM based band in $M_W$-$M_T$ plane, the measurements would be complementary to each other in testing the SM and nailing down the SM Higgs mass.

## VI CONCLUSIONS

We have investigated the possibility of measuring $\sin^2\theta_W$ in an FMC neutrino experiment. With a suitable detector that uses a light isoscalar target along with excellent electron and muon identification, one can expect collecting 40 million events per year, due to the utilization of both $\nu_\mu$ and $\nu_e$ induced events resulting from the FMC beam. Using this high intensity neutrino beam, along with theoretical help in reducing higher twist effects, we expect the precision of $\sin^2\theta_W$ to be equivalent to 30 MeV on the W mass in the on-shell scheme.

Since the statistical and experimental systematic uncertainties will reduce dramatically using the proper apparatus, it becomes crucial to reduce the remaining theoretical uncertainties. Calculations to minimize the higher twist effects and the uncertainties from longitudinal structure function, $R_L$, need to be dealt with.

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