Search for New Physics Using Parity Violation in DIS

K. Hafidi, R.J. Holt, P.E. Reimer
Argonne National Laboratory, Argonne, Illinois 60439

P. Bosted
University of Massachusetts, Amherst, Massachusetts 01003

R. Ent
Thomas Jefferson National Laboratory, Newport News, Virginia 23606

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The weak mixing angle, θ_W is one of the fundamental parameters of the Standard Model. The tangent of the weak mixing angle represents the relative coupling strength of the SU(2) and U(1) groups (g and g'). At the Z resonance, the value of $\sin^2(\theta_W)$ has been well established through a number of measurements; however, there have been very few measurements made of $\sin^2(\theta_W)$ away from $Q^2 = M_Z^2$. One important consequence of the Standard Model is that the value of $\sin^2(\theta_W)$ will vary (run) as a function of Q^2. Deviations from the predicted running are sensitive to possible extensions of the Standard Model. The running of $\sin^2(\theta_W)$ is illustrated in Fig. 1 [1].

Two measurements which have been made away from the Z-pole come from atomic parity violation (APV) and νA scattering. In APV the most sensitive measurements come from the cesium atom [2, 3]. Unfortunately, the interpretation of APV results have been somewhat controversial and the extracted value for the weak charge, $Q_W = 1 - 4\sin^2(\theta_W)$, has changed as the understanding of atomic structure has advanced. The most recent calculations of cesium APV appear to disagree with the measured values by approximately two standard deviations [4]; however, this conclusion is by no means universal and there is still considerable ongoing discussion in the literature about these values [5]. At higher energies using neutrino scattering on iron, the NuTeV collaboration at Fermilab recently reported $\sin^2\theta_W^{\mathrm{on-shell}} = 0.2277 \pm 0.001(\mathrm{stat}) \pm 0.0009(\mathrm{syst})$, three standard deviations above the Standard Model predictions [6]. Naturally, this deviation has been interpreted in terms of physics beyond the Standard Model (new propagator or couplings, dimension six operators, extra U(1) gauge bosons, etc) [7]. However, there are also more conventional explanations, including nuclear effects in the iron target [8] and QCD effects [7]. Clearly, in order to observe and understand deviations from the standard model, more and theoretically better-understood high precision measurements are needed.

One such measurement is SLAC Experiment 158, which is using parity nonconservation in Møller scattering to measure $\sin^2(\theta_W)$ at an average Q^2 of 0.03 $(\mathrm{GeV/c})^2$. This experiment has compltete its first run with an expected uncertainty of $\delta\left[\sin^2(\theta_W)\right] \approx 0.0025$ By

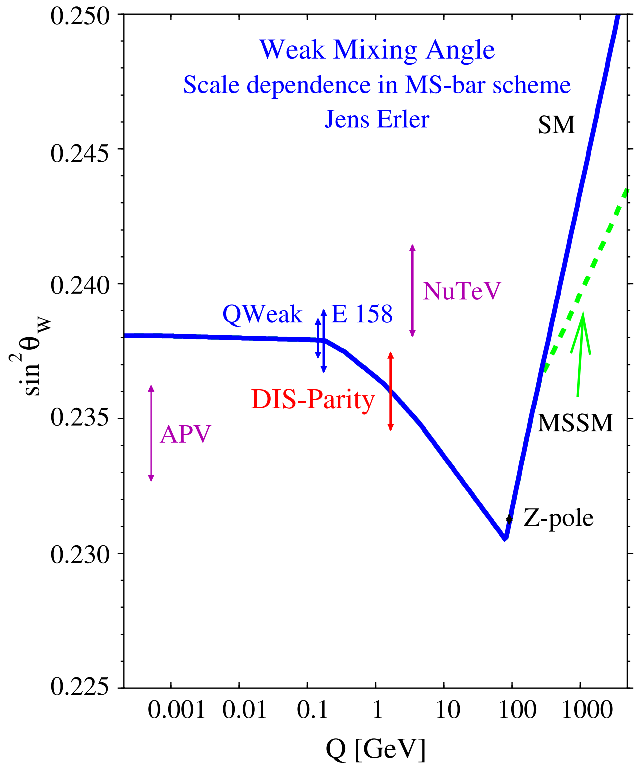

Figure 1: The running of $\sin^2\theta_W$ shown as a function of Q^2. The proposed combined statistical and systematic precision of the DIS parity violation experiment (DIS-Parity) is shown in red. Also shown are the existing APV cesium [2, 3] and neutrino DIS (NuTeV) [6] measurements along with expected uncertainty of the approved Jefferson Laboratory $Q_{\rm weak}$ [10] and running SLAC E-158 Møller [9] experiments.

the completion of its second run in 2003, E-158 should acheive a precision corresponding to $\delta\left[\sin^2(\theta_W)\right] \approx 0.0007$ [9]. The Jefferson Laboratory experiment $Q_{\rm weak}$ will provide a complimentary measurement of $\sin^2(\theta_W)$. $Q_{\rm weak}$ will determine the weak charge on the *proton* by measuring the parity violating asymmetry in elastic *ep* scattering, also at an average Q^2 of 0.03 $(\mathrm{GeV/c})^2$. The experiment anticipates a precision of 4% in Q_W, roughly corresponding to $\delta\left[\sin^2(\theta_W)\right] \approx 0.0005$ [10].

Here we present another possible measurement of $\sin^2(\theta_W)$ using parity nonconserving deep inelastic electron-deuterium scattering. The measurement would use the upgraded 11 GeV beam at Jefferson Lab, and could be staged in either Hall A or Hall C. The relative merits of each are under study. Since this experiment would use a deuterium target, it will not suffer from the uncertainties in nuclear effects and nuclear parton distributions that the NuTeV measurement on iron did. It is important to note that the sensitivity to different "new physics" scenarios of the three new experiments, Møller, $Q_{\rm weak}$ and this proposed measurement, is not the same [11], and to fully explore the range of possible extensions to the Standard Model, these experiments form a complementary program.

1 Formalism for DIS

The parity-violating asymmetry for scattering longitudinally polarized electrons from an unpolarized isoscalar target such as a deuteron (assuming isospin symmetry) is given by [12, 13]

$$\begin{aligned} A_d &= \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \\ &= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right) \frac{2C_{1u} - C_{1d}\left[1 + R_s(x)\right] + Y(2C_{2u} - C_{2d})R_v}{5 + R_s(x)} \end{aligned}$$

where, taking $\sin^2(\theta_W) \approx 0.23$,

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) &\approx& -0.19, \\ C_{1d} &= \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) &\approx& 0.35, \\ C_{2u} &= -\tfrac{1}{2} + 2\sin^2(\theta_W) &\approx& -0.04 \quad \text{and} \\ C_{2d} &= \tfrac{1}{2} - 2\sin^2(\theta_W) &\approx& 0.04. \end{aligned}$$

Also

$$Y = \frac{1 - (1-y)^2}{1 + (1-y)^2 - y^2 R/(1+R)} \quad \text{and}$$
$$y = \nu/E.$$

Here, $\nu = E - E'$ is the energy lost by an incident electron of energy E scattering to an electron of energy E', and the ratio $R = \sigma_L/\sigma_T \approx 0.2$ depends on x and Q^2. The ratios $R_s(x)$ and $R_v(x)$ depend on the quark distribution functions:

$$R_s(x) = \frac{2s(x)}{u(x) + d(x)} \text{ and } R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + d(x)}.$$

At high x, where sea quark contributions vanish, $R_v = 1$ and $R_s = 0$, and using $\sin^2(\theta_W) \approx 0.23$ for C_{1u}, C_{1d}, C_{2u} and C_{2d} from above, we find

$$A_d \approx 10^{-4} Q^2 (0.72 + 0.12Y).$$

The sensitivity to $\sin^2(\theta_W)$ is approximately given by

$$\frac{d\sin^2(\theta_W)}{\sin^2(\theta_W)} = \left(\frac{dA}{A}\right)\left(\frac{0.96 + 0.16Y}{1.0 + 1.8Y}\right).$$

Even for large Y, for which the sensitivity is greatest, competitive measurements of $\sin^2(\theta_W)$ require a combined systematic and statistical error on (dA/A) below 2%.

In the above formalism, $C_{1u(d)}$ represents the axial Z-electron coupling times the vector Z-u quark (d quark) coupling, while the $C_{2u(d)}$ are the vector Z-electron coupling times the axial Z-u quark (d quark) coupling. Each of the C_{ia} terms is sensitive to physics beyond the Standard Model in different ways.

2 Counting Rates and Expected Uncertainties

To have good sensitivity to new physics beyond the Standard Model, we would like $x > 0.2$ so that uncertainties in the sea quark distributions are sufficiently small, $Q^2 > 2$ GeV^2 to minimize higher twist contributions, Y as large as possible to improve the sensitivity to $\sin^2(\theta_W)$, and a deuterium target to avoid the uncertainty due to the $d(x)/u(x)$ ratio. It is also important to keep $E'/E > 0.3$ to avoid large rates of pions and pair-symmetric backgrounds in the detectors.

It is quickly apparent that the highest available beam energy is optimal. Assuming 11 GeV, one finds the best figure-of-merit for an electron scattering angle of 10 to 15 degrees. Picking a typical value of 12.5 degrees, the optimum central momentum is about 5.5 GeV, corresponding to $x = 0.27$, $Q^2 = 2.8$ GeV^2, $W^2 = 8.6$ GeV^2 (well above the resonance region), and $Y = 0.64$. This happens to be quite well matched to the combination of the existing HMS and planned SHMS spectrometers in Hall C or to the MAD spectrometer in Hall A. The target length acceptance at 12.5 degrees is about 60 cm, corresponding to 10 g/cm^2 and 8% radiation length of LD2. It is not desirable to use a much longer target than this because radiative corrections become difficult to calculate.

Assuming a beam current of 90 μA corresponding to the maximum power level for the planned Q_{weak} target in Hall C, a momentum bite of ±12%, and an average solid angle of 11 msr for the combined HMS and SHMS spectrometers, or the MAD spectrometer on its own, the total count rate is on the order of 1 MHz. Assuming a beam polarization of 0.8, this leads to a relative statistical error on the asymmetry of 0.5% in about 250 hours of "perfect" data collection. The resulting statistical error on $\sin^2(\theta_W)$ would be about 0.0006, or a 0.25% relative error. To help understand systematic effects, it would be desirable to also take data at higher (x, Q^2) by going to approximately 15 degree scattering angle, and at fixed x but lower Q^2 by lowering the beam energy to 8 GeV. For the central point, it is desirable to take additional data with a proton target to look for nuclear effects in deuterium that are larger than the uncertainty in the d/u ratio of the proton. Approximately 50 days of running time would be needed for the complete program.

The largest systematic error is expected to be from the beam polarization (of order 1%). Experience using a Compton polarimeter at the SLD at SLAC has shown the error can be reduced to below 1% with sufficient effort. The error due to radiative corrections should be well under 1%, and the error due to the determination of the average Q^2 should be under 0.5%. The error due to R is about 0.2%. A more difficult class of systematic error relates to the interpretation, because higher twist effects may not be negligible at the relatively low Q^2 of about 3 GeV^2. This will be partially addressed by making an additional measurement at lower Q^2, and another at higher Q^2 and x. Possible breaking of isospin symmetry in the deuteron could lead to corrections, as could effects such as nuclear shadowing, and the "EMC Effect" in the deuteron. These can be addressed by also making measurements with a proton target, if the d/u quark ratio is sufficiently well known at the desired kinematics from other experiments. Significant theoretical support will be needed to control all of these uncertainties to the desired level. Because the asymmetry is several orders of magnitude larger than the Q_{weak} and G0 experiments, control of helicity-correlated beam parameters should be adequate if they can be maintained at G0 levels when the beam energy is upgraded.

The combined statistical and systematic uncertainties for the measurement of the asym-

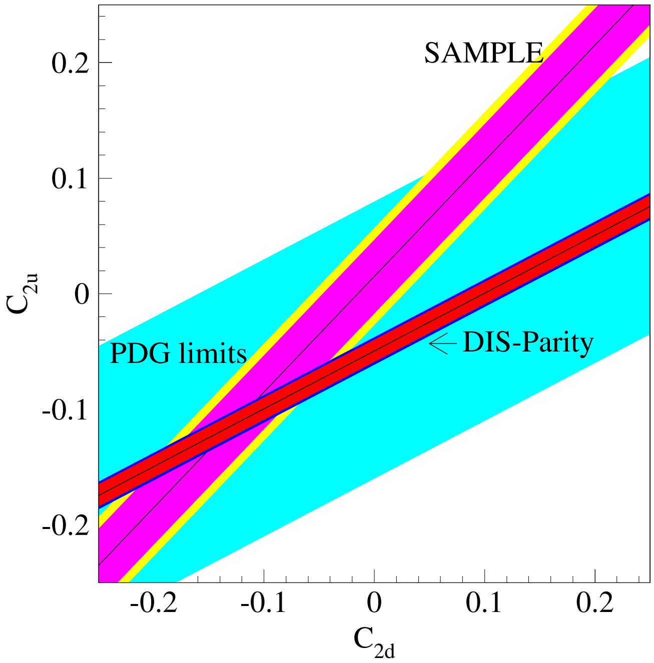

Figure 2: The limits on C_{2u} and C_{2d} listed by the particle data group [15], by the SAMPLE experiment [14] and by the proposed experiment.

metry, A_d are at the 1.2% level. This gives a uncertainty on $\sin^2(\theta_W)$ of roughly 0.6%. This uncertainty is shown in Fig 1. This experiment is sensitive to "new physics" in both $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$. The sensitivity to the $2C_{2u} - C_{2d}$ makes the experiment quite unique. Assuming the successful completion of the Q_{weak} experiment, an absolute uncertainty of $\Delta C_{1u(d)} = 0.005$ may be obtained. With this, the proposed experiment places an absolute uncertainty of $\delta(C_{2u} - \frac{1}{2}C_{2d}) = 0.012$. When taken together with the results from the SAMPLE experiment [14] much tighter bounds are placed on C_{2u} and C_{2d} than were previously available [15] as illustrated in Fig. 2.

3 Detection of Electrons

At the above kinematics the principal additional source of particles will be pions, at about 0.8 the rate of inelastic electrons. Thus the total rate will be about 2 MHz, which is tolerable for the lead glass spectrometer detectors. To separate pions from electrons, it is probably sufficient to demand a coincidence between the Cherenkov and lead glass counters, and ignore the wire chamber and time-of-flight information. The Cherenkov counter will have to be adjusted (gas mixture, pressure) to have a threshold about 6 GeV for pions. For each lead glass plus Cherenkov coincidence, the pulse height information would be recorded so that cuts could be placed off-line to optimize the efficiency versus purity, and for optimizing the lead glass energy resolution.

The equipment planned for Hall A (MAD spectrometer) has approximately the same acceptance at the optimal angle of about 12 degrees as the HMS plus SMHS. The well-defined optics of the HMS and SHMS might allow a for a better determination of the average Q^2 of the electrons, and potentially lower backgrounds. The infrastructure needed for the high-power target will be in place in Hall C from the Q_{weak} experiment. There is no compelling reason to prefer one Hall over the other, at this stage of planning.

4 Conclusion

A competitive search for physics beyond the Standard Model can be made using DIS parity violation at Jefferson Lab using the upgraded 11 GeV beam. An experiment has been presented which would measure $\sin^2(\theta_W)$ to an 0.5% relative error. The proposed experiment is complimentary to both the Møller and Q_{weak} experiments in its sensitivity to extensions of the Standard Model.

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