Parity Violation in Møller Scattering

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Abstract. We have carried out a precision of the parity-violating asymmetry $A_{\rm PV}$ in the scattering of longitudinally polarized electrons off electrons in a liquid hydrogen target. The measurement was performed with the 50 GeV beam line at SLAC. The final result with the full data set collected in three production runs is $A_{\rm PV} = -131 \pm 14$ (stat) ± 10 (syst) parts per billion. The result leads to new limits on possible contact interactions at the TeV scale.

Keywords: Parity Violation, Møller Scattering, Weak Neutral Current Interactions
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INTRODUCTION

Precision measurements of weak neutral current (WNC) interactions, mediated by the Z boson, play a central role in tests of the electroweak theory and in the search for new dynamics at very high energy scales. One class of WNC experiments involves measurements of the fractional difference in the cross-section for longitudinally polarized electrons scattering off unpolarized nuclear targets. A non-zero asymmetry ($A_{\rm PV}$) is a signature of parity violation and arises from the interference between the WNC and electromagnetic amplitudes[1]. $A_{\rm PV}$ thus rises linearly with the 4-momentum transfer Q^2. For the range of Q^2 typical for fixed target scattering, $A_{\rm PV}$ ranges from 10^{-4} to as small as 10^{-7}, depending on the WNC couplings of the particles involved.

Measurements of WNC amplitudes can test the standard model by comparing the extracted value of the weak mixing angle $\sin^2\theta_W$ in each case (evolved to the same energy scale) to the precise value obtained in high energy collider expectation. A deviation would be a signature of new contact interactions at the TeV scale, such as a new Z′ boson or compositeness. Since fixed target WNC measurements are carried out at $Q^2 \ll M_Z^2$, such new physics amplitudes can interfere with the electromagnetic amplitude, unlike the case of WNC measurements at the Z resonance[2]. In order for such low Q^2 WNC measurements to provide new information, it is necessary to measure $\sin^2\theta_W$ to fractional accuracy better than 1%[3].

Two measurements have reached such sensitivity: the weak charge measurement in atomic Cesium[4] and the NuTeV neutrino deep-inelastic scattering measurement[5]. In this paper we discuss a measurement of $A_{\rm PV}$ in electron-electron (Møller) scattering[6], a purely leptonic reaction with little theoretical uncertainty[7]. The E158 experiment at the Stanford Linear Accelerator Center (SLAC) was designed to use the longitudinally polarized 50 GeV electron beam to measure $A_{\rm PV}$ to a relative accuracy of 10%, which enabled a measurement of $\sin^2\theta_W$ to an accuracy of 0.001.

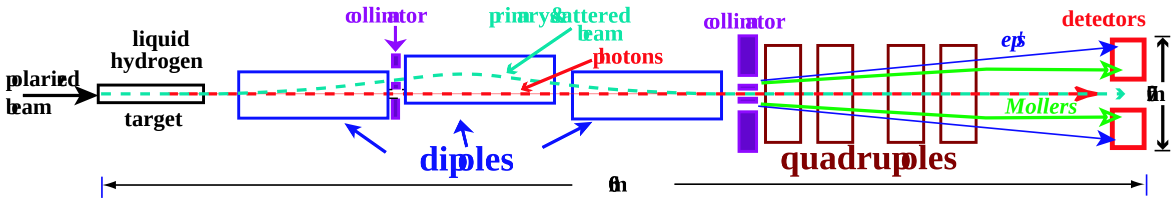

FIGURE 1. Schematic Overview of the E158 Apparatus

EXPERIMENTAL OVERVIEW

Target electrons, in a 1.54 m long cell of liquid hydrogen (10.5 gm/cm^2), are bombarded by a 48 GeV electron beam, the longitudinal polarization of which is changed pseudo-randomly, keeping all other beam parameters unchanged. Møller electrons, i.e., beam electrons scattering from target electrons, are isolated by a forward magnetic spectrometer consisting of 3 dipole "chicane" and 4 quadrupole magnets, oriented with their magnetic axes along the primary beam direction. Møller electrons of interest in the full range of the azimuth (spanning the polar angular range 4.5 mrad $< \theta_{lab} <$ 8 mrad) traverse through the bores of the quadrupoles and are brought to focus in a ring on a calorimeter located 60 m downstream of the target. A schematic overview of the apparatus is shown in Fig. 1.

The experimental asymmetry is measured by averaging the fractional difference in the cross-section over many complementary pairs of beam pulses of opposite helicity. In order to achieve the desired statistical precision of 10 parts per billion (ppb) in a reasonable length of time, the intergrated signal of more than 20 million electrons must be detected each beam pulse.

The calorimeter provides both radial and azimuthal segmentation. Four radial rings are uniformly covered in the azimuth by a total of 60 photomultiplier tubes (PMTs). The three inner rings are predominently sensitive to Møller electrons while the outermost ring intercepts the bulk of the flux from electron-proton (*ep*) scattering. The radiative tail of the *ep* flux is the main background in the Møller rings, totalling $\approx$ 8%. Other charged and neutral particles contribute less than 1%.

Data were collected over three run periods in 2002 and 2003. The longitudinally polarized electron beam is generated via photoemission of a GaAs photocathode by circularly polarized laser light. This facililated rapid reversal of the electron beam polarization. In addition, spurious asymmetries were suppressed by passively reversing the sign of the helicity asymmetry by two independent methods. First, the state of a half-wave plate in the laser line was toggled each day. Second, spin precession in the 24.5° bend after beam acceleration created opposite helicity orientation at 45 GeV and 48 GeV beam energies. Roughly equal statistics were accumulated with opposite signs of the measured asymmetry.

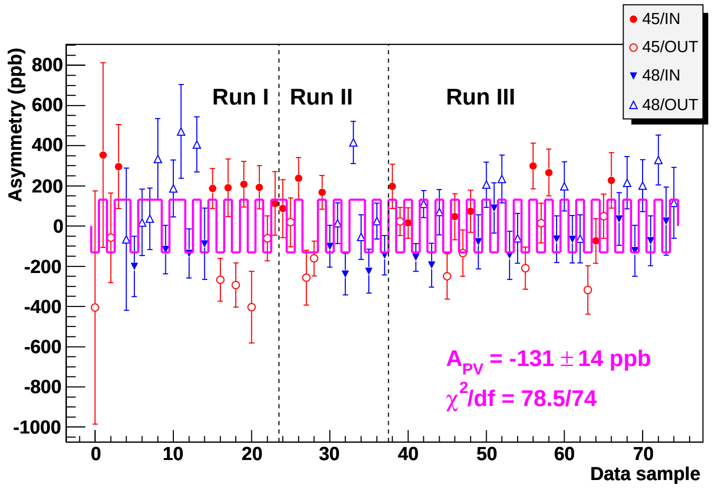

FIGURE 2. A_{PV} for 75 data samples

RESULTS AND IMPLICATIONS

Figure 2 shows the parity-violating asymmetry as a function of data-set number. Each data-set constitutes about two days of data, after which either the beam energy or the state of the half-wave plate were changed to flip the sign of the measured asymmetry. The grand average result for the parity-violating asymmetry in Møller scattering at $Q^2 = 0.03$ GeV^2 was found to be:

$$A_{\mathrm{PV}} = -131 \pm 14(\mathrm{stat}) \pm 10(\mathrm{syst}) \quad (\mathrm{ppb}). \tag{1}$$

From this measurement, the value of $\sin^2\theta_W$ can be extracted within the context of the Standard Model. Using a definition which reproduces the effective leptonic couplings at the Z pole, we determine:

$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff}} = 0.2397 \pm 0.0010(\mathrm{stat}) \pm 0.0008(\mathrm{syst}). \tag{2}$$

Figure 3 shows the E158 result, which establishes the "running" of $\sin^2\theta_W$[8] by more than 6 standard deviations. Also shown are the two other precise low energy $\sin^2\theta_W$ determinations mentioned earlier. It can be seen that the atomic Cesium result and the E158 result are consistent with the standard model expectation. The deviation of the NuTeV result thus implies that either there are new contact interactions specific to neutrino interactions or that there are additional strong interaction effects that are unaccounted for in neutrino deep inelastic scattering. One leading candidate is charge symmetry violation in the parton distribution functions[9].

The E158 measurement can be used to set limits on the size of possible new contributions beyond the standard model. Assuming a new contact interaction scale[10] characterized by Λ_{LL}, the 95% C.L. limit is 7 TeV or 16 TeV depending on the sign of the contact interaction term.

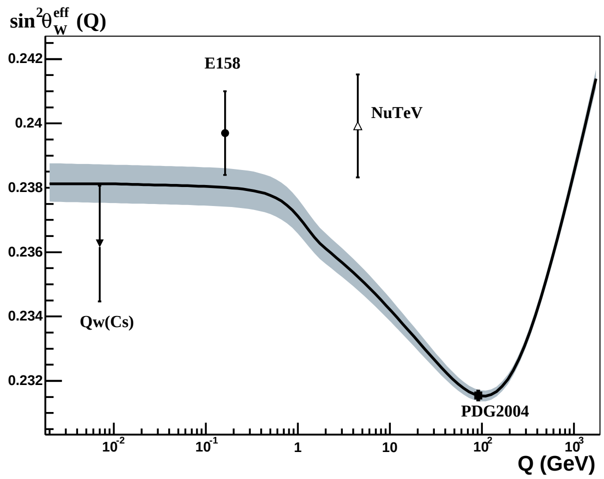

FIGURE 3. $\sin^2\theta_W$ as a function of Q^2

FUTURE PROSPECTS

The figure of merit on the achievable precision on the WNC amplitude in Møller scattering rises with incident beam energy. It is therefore possible to contemplate improved new measurements of A_{PV} at future facilities[11]. One possibility is to carry out a new measurement at Jefferson Laboratory after it is upgraded to 12 GeV, where it is potentially possible to achieve a factor of 5 improvement over the reported measurement. The ultimate measurement could be carried out at the proposed International Linear Collider, using the electron beam downstream of the primary collider interaction region. More than an order of magnitude improvement is possible [12], which competes very favorably with future collider determinations of the weak mixing angle and measurements of the W boson mass.

REFERENCES

1. Ya.B. Zel'dovich, *Sov.Phys.JETP* **94**, 1959, pp. 262-263.
2. K.S. Kumar et. al, *Mod.Phys.Lett.* **A10**, 1995, 2979.
3. M.J. Ramsey-Musolf, *Phys.Rev.* **C60**, 1991, 015501.
4. S.C. Bennett and C.E. Wieman, *Phys.Rev.Lett.* **82**, 1999, 2484-2487.
5. G.P. Zeller et. al, *Phys.Rev.Lett.* **88**, 2002, 0918802.
6. A. Czarnecki and W.J.Marciano, *Phys.Rev.* **D53**, 1996, 1066.
7. P.L. Anthony et.al, *Phys.Rev.Lett.* **92**, 2004, 181602.
8. A. Czarnecki and W.J. Marciano, *Int.J.Mod.Phys.* **A15**, 2000, 2365; J. Erler, A. Kurylov and M.J. Ramsey-Musolf, *Phys.Rev.* **D68**, 2003, 016006; A. Ferroglia, G. Ossola, and A. Sirlin, *Eur.Phys.J.* **C34**, 2004, 165; J. Erler and M.J. Ramsey-Musolf, hep-ph/0409169, 2004; F.J. Petriello, *Phys.Rev.* **D68**, 2003, 033006.
9. J.T. Londergan and A.W. Thomas, hep-ph/0407247, 2004, and references therein.
10. E.J. Eichten, K.D. Lane, and M.E. Peskin, *Phys.Rev.Lett* **50**, 1983, 811.
11. K.S. Kumar, *Eur.Phys.J.* **A24**, s2, 2005, 191-195.
12. K.S. Kumar, in *DPF/DPB Summer Study on New Directions in High Energy Physics*, econf **C960625**, 1996, NEW168.