Precision Measurement of the Weak Mixing Angle in Møller Scattering

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We report on a precision measurement of the parity-violating asymmetry in fixed target electron-electron (Møller) scattering: $A_{\rm PV} = [-131 \pm 14({\rm stat}) \pm 10({\rm syst})] \times 10^{-9}$, leading to the determination of the weak mixing angle $\sin^2\theta_{\rm W}^{\rm eff} = 0.2397 \pm 0.0010({\rm stat}) \pm 0.0008({\rm syst})$, evaluated at $Q^2 = 0.026~{\rm GeV}^2$. Combining this result with the measurements of $\sin^2\theta_{\rm W}^{\rm eff}$ at the Z^0 pole, the running of the weak mixing angle is observed with over 6σ significance. The measurement sets constraints on new physics effects at the TeV scale.

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Precision measurements of weak neutral current processes at low energies rigorously test the standard model of electroweak interactions. Such measurements are sensitive to new physics effects at TeV energies, and are complementary to searches at high energy colliders.

One class of low-energy electroweak measurements involves scattering of longitudinally polarized electrons from unpolarized targets, allowing for the determination of a parity-violating asymmetry $A_{\rm PV} \equiv (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$, where $\sigma_{R(L)}$ is the cross section for incident right (left)-handed electrons. $A_{\rm PV}$ arises from the interference of the weak and electromagnetic amplitudes [1] and is sensitive to the electroweak coupling constants and thus the weak mixing angle $\theta_{\rm W}$.

The electroweak parameter $\sin^2\theta_{\rm W}^{\rm eff}$ is defined as the ratio of the electromagnetic to the weak isospin coupling constants [2]. Possible new physics contributions at very high energy scales can be expressed in terms of their impact on the measured value of $\sin^2\theta_{\rm W}^{\rm eff}$. Measurements at low momentum transfers $Q^2 \ll M_Z^2$ can have sensitivity comparable to high energy collider searches for new physics provided $\sin^2\theta_{\rm W}^{\rm eff}$ is measured to better than 1%.

At such a precision, the variation of the coupling constants with momentum transfer, a fundamental property of gauge interactions referred to as running [3], must be taken into account. While the running of the electromagnetic and strong coupling constants has been clearly established, it has not been unambiguously observed for $\sin^2\theta_{\rm W}^{\rm eff}$ so far. The variation of $\sin^2\theta_{\rm W}^{\rm eff}$ from $Q^2 \approx 0$ to $Q^2 = M_Z^2$ is due to higher order amplitudes involving virtual weak vector bosons and fermions in quantum loops, referred to as electroweak radiative corrections [4,5].

To date, the most precise low-energy determinations of the weak mixing angle come from studies of parity violation in atomic transitions [6] and measurements of the neutral current to charge current cross section ratios in neutrino-nucleon deep inelastic scattering [7]. In this Letter, we present a measurement of the weak mixing angle in electron-electron (Møller) scattering, a purely leptonic reaction with little theoretical uncertainty. We have previously reported the first observation of $A_{\rm PV}$ in Møller scattering [8]. Here, we report on a significantly improved measurement of $A_{\rm PV}$ resulting in a precision determination of $\sin^2\theta_{\rm W}^{\rm eff}$ at low momentum transfer.

At a beam energy of $\simeq 50$ GeV available at End Station A at SLAC and a center-of-mass scattering angle of 90°, A_{PV} in Møller scattering is predicted to be $\simeq 320$ parts per billion (ppb) at tree level [9]. Electroweak radiative corrections [4,5] and the experimental acceptance reduce the measured asymmetry by more than 50%.

The principal components of the experimental apparatus are the polarized electron beam, beam diagnostics, the liquid hydrogen target, the spectrometer/collimator system, and detectors. They are described in our previous publications [8,10,11]; we discuss them briefly here.

The high-intensity polarized electron beam, delivered in $\sim$270 ns pulses at the rate of 120 Hz, passes through a 1.57 m long cylindrical cell filled with liquid hydrogen [12]. Scattered particles with $4.4 < \theta_{lab} < 7.5$ mrad over the full range of the azimuth are selected by the magnetic spectrometer [10], while the primary beam and forward angle photons pass unimpeded to the beam dump.

Sixty meters downstream of the target, scattered Møller electrons in the range 13–24 GeV form an azimuthally-symmetric ring, spatially separated from electrons scattered from target protons (ep scattering). The charged particle flux is intercepted by the primary copper/fused silica fiber sandwich calorimeter. The asymmetry is measured by extracting the fractional difference in the integrated calorimeter response for incident right- and left-handed beam pulses.

The calorimeter provides both radial and azimuthal segmentation. Four radial rings are uniformly covered in the azimuth by 10, 20, 20, and 10 photomultipliers, respectively. The three Inner rings, referred to as the Inner, Middle, and Outer Møller rings are predominantly sensitive to Møller scattered electrons. The Outermost or EP ring intercepts the bulk of the ep scattering flux.

The background within the Møller rings is estimated to be $\simeq 8\%$. It is dominated by radiative ep scattering, while neutral particles and charged pions contribute less than 1%. Quartz detectors placed behind the Møller detector and shielding record the charged pion asymmetry. Target density fluctuations and spurious asymmetries are monitored by intercepting charged particles at $\theta_{lab} \approx 1$ mrad with gas ionization chambers [13].

The data sample consists of 2.9×10^8 and 3.7×10^8 pulses at beam energies of 45.0 and 48.3 GeV, respectively, collected over three data runs in 2002 and 2003. Roughly 60% of the data were accumulated in the 2003 run, which featured a novel "superlattice" photocathode [14] with $\approx 90\%$ beam polarization.

Data were collected at 120 Hz, with $\sim$1 Hz of pulses blanked to measure baseline signals. Alternate triggers fall into two 60 Hz fixed-phase "time slots." Within these time slots, right-left pulse pairs are formed for independent asymmetry analyses. The helicity sequence in each pulse pair was chosen pseudorandomly. In addition to the fast helicity flips, the sign of the electron polarization was passively reversed in two independent ways. First, the state of a half-wave plate in the laser line was toggled each day, guarding against helicity-correlated electronics cross talk. Second, spin precession in the 24.5° bend after acceleration created opposite helicity orientations at 45 and 48 GeV beam energies. For each of the 2002 runs the beam energy was changed once, while the change was made roughly every four days during the 2003 run. Roughly equal statistics were accumulated with opposite signs of the measured asymmetry, suppressing many classes of systematic effects.

We select pulses with beam charge greater than 10^{11} electrons and require that the beam crosses each beam position monitor (BPM) within 1 mm of its geometric center. We also require that the beam position and charge for each pulse be within 6 standard deviations from the running mean value. Typically, the beam charge per pulse varies between (4–6) $\times 10^{11}$ electrons with 0.3% pulse-to-pulse jitter, and the beam position is within 100 μm of each BPM center, with jitter on the order of 50 μm. In order to avoid helicity-dependent biases, we reject several pulses before and after a pulse which fails a cut. Other than the demand that the beam charge asymmetry measured by two independent monitors agree to within 10^{-3}, no helicity-dependent cuts are made.

The right-left asymmetry in the integrated detector response for each pulse pair is computed by normalizing to incident charge and then correcting for beam fluctuations. To first order, six correlated parameters describe the beam trajectory: charge, energy, and horizontal and vertical position and angle. Each parameter is measured by two independent monitors, such that device resolution and systematic effects can be studied.

Two methods are used to calibrate the detector sensitivity to each beam parameter and remove beam-induced random and systematic effects from the raw asymmetry. One method uses a calibration subset (4%) of the pulses, where each beam parameter is modulated periodically around its average value by an amount large compared to nominal beam fluctuations. The other method applies an unbinned least squares linear regression to the pulses used for physics analysis. They yield statistically consistent results to within 3 ppb. Final results are obtained with the latter, statistically more powerful technique.

Additional bias to the measured asymmetry may arise from asymmetries in higher order moments of beam distributions, such as temporal variations of the beam position or energy within a 270 ns beam pulse, coupled to the intrapulse variation of position or energy asymmetries. Such higher order biases are small for the Inner and Middle Møller detector rings, but are observed to be significant for the Outer ring.

During the physics runs, great care was taken to minimize the residual time structure of the beam position at the target, keeping it typically within 1 mm. In order to measure the possible bias due to such effects, six BPMs were instrumented with 23 additional readout channels before the 2003 run. Thus, in addition to the average beam parameters for each pulse, BPM signals for charge, energy, positions, and angles are each digitized in four independent time slices (three slices for energy). Corrections due to intrapulse variation of beam asymmetries are computed by linearly regressing Møller asymmetries against the beam asymmetries in time slices.

For the 2003 data, the regression analysis limits the possible contribution to the detector asymmetry due to the intrapulse variations to 3 ppb. Since time slice data were not available for 2002 data, the Outer Møller ring channels are only used in the 2003 data samples. For the 2002 data sets, these channels set a limit on the maximum possible bias in the two innermost Møller rings (containing the bulk of the statistical weight) of less than 5 ppb.

After linear regression, the integrated responses of all the selected rings are averaged to form the raw asymmetry $A_{\rm raw}$. Near-perfect azimuthal symmetry reduces the sensitivity to beam fluctuations and right-left beam asymmetries. The $A_{\rm raw}$ pulse-pair distribution has an average rms of 215 ppm for the 2002 data and 185 ppm for the 2003 data. The cumulative beam asymmetry correction is -9.7 ± 1.4 ppb. A correction due to an azimuthal modulation of $A_{\rm raw}$ [15] from a small nonzero transverse component of the beam polarization is found to be -3.8 ± 1.5 ppb.

The average electron beam polarization is $P_b = 0.89 \pm 0.04$, measured every few days by a polarimeter using Møller scattering of beam electrons off a magnetized foil. The linearity of the calorimeter response is determined to be $\epsilon = 0.99 \pm 0.01$ from special calibration runs.

The physics asymmetry $A_{\rm phys}$ is formed from $A_{\rm raw}$ by correcting for background contributions, detector linearity and beam polarization

$$A_{\rm phys} = \frac{1}{P_b \epsilon} \frac{A_{\rm raw} - \Sigma_i \Delta A_i}{1 - \Sigma_i f_i}.$$

Asymmetry corrections ΔA_i and dilutions f_i for various background sources are listed in Table I.

TABLE I. Corrections ΔA_i and dilutions f_i to $A_{\rm raw}$ and associated systematic uncertainties.

Source	ΔA (ppb)	f
Beam (first order)	-10 ± 1	
Beam (higher order)	0 ± 3	
Transverse polarization	-4 ± 2	
e^- from $e^- + p \to e^- + p(\gamma)$	-7 ± 1	0.056 ± 0.007
e^- from $e^-(\gamma) + p \to e^- + X$	-22 ± 4	0.009 ± 0.001
e^- from $\gamma + e^- \to e^- + \gamma$	0 ± 1	0.005 ± 0.002
High energy photons	3 ± 3	0.004 ± 0.002
Synchrotron photons	0 ± 1	0.002 ± 0.001
Pions	1 ± 1	0.001 ± 0.001

Figure 1 shows $A_{\rm phys}$ for all data, divided into 75 sequential samples in runs I, II (2002), and III (2003). Each $A_{\rm phys}$ measurement has sign reversals depending on the beam energy and the state of the half-wave plate. $A_{\rm PV}$ is obtained by correcting each result by the appropriate sign. The combined result is

$$A_{\rm PV} = -131 \pm 14({\rm stat}) \pm 10({\rm syst})\ {\rm ppb}.$$

In the context of the standard model, we interpret the measurement of $A_{\rm PV}$ in terms of the effective weak mixing angle $\sin^2\theta_W^{\rm eff}(Q)$ [4]:

$$A_{\rm PV} = -\mathcal{A}(Q^2, y)\rho^{(e;e)}[1 - 4\sin^2\theta_W^{\rm eff}(Q) + \Delta].$$

The average values of the kinematic variables are $Q^2 = 0.026\ {\rm GeV}^2$ and $y = Q^2/s \simeq 0.6$, where s is the square of the center-of-mass energy.

$$\mathcal{A}(Q^2, y) = \frac{G_F Q^2}{\sqrt{2}\pi\alpha(Q)} \frac{1 - y}{1 + y^4 + (1 - y)^4} \mathcal{F}_{\rm QED}$$

is the effective analyzing power, G_F and $\alpha(Q)$ are the Fermi and fine structure constants, respectively [16], $\rho^{(e;e)}$ is the low-energy ratio of the weak neutral and charge current couplings, $\mathcal{F}_{\rm QED} = 1.01 \pm 0.01$ is a QED radiative correction factor that includes kinematically weighted hard initial and final state radiation effects and y-dependent contributions from the $\gamma\gamma$ and γZ box and vertex diagrams [17]. Δ contains residual $\mathcal{O}(\alpha)$ electroweak corrections. The effective analyzing power $\mathcal{A} = 3.25 \pm 0.05$ ppm is determined from a Monte Carlo simulation that accounts for energy losses in the target and systematic uncertainties in the spectrometer setup.

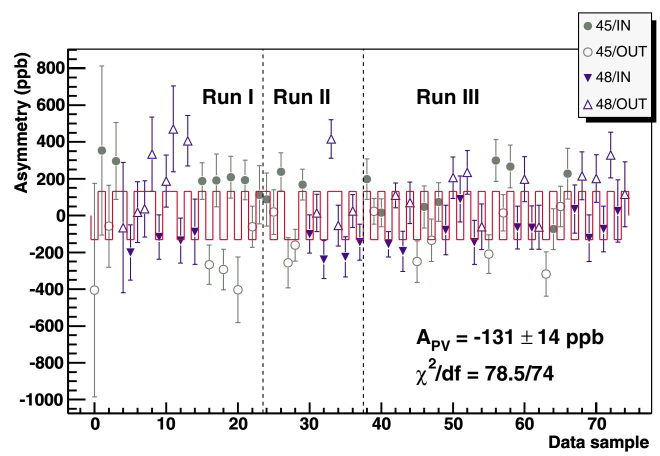

FIG. 1 (color online). $A_{\rm phys}$ for each of 75 data samples. Data collected with half-wave plate inserted (removed) at a beam energy of 45 (48) GeV are shown as solid (open) circles (triangles). The solid line represents the grand average, with the expected modulation of the asymmetry sign for each beam energy and half-wave plate state. Only statistical uncertainties are shown.

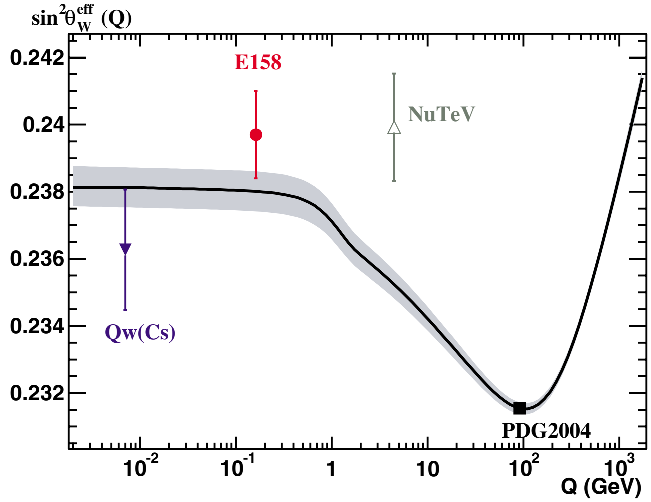

FIG. 2 (color online). Predicted variation [18] of $\sin^2\theta_W^{\rm eff}$ as a function of momentum transfer Q (solid line) and its estimated theoretical uncertainty (shaded area). Results of prior low-energy experiments [6,16] (closed triangle, shown at an arbitrarily higher Q) and [7] (open triangle) are overlaid together with the Z^0 pole value [16] (square) and this measurement (circle).

A number of definitions of the low-energy weak mixing angle exist [5,18] and differ in the way various corrections of order $\mathcal{O}(\alpha)$ are distributed between terms $\sin^2\theta_W^{\rm eff}(Q)$, $\rho^{(e;e)}$, and Δ. Here we adopt a definition of the coupling $\sin^2\theta_W^{\rm eff}(Q)$ [18] which reproduces the effective leptonic coupling $\sin^2\theta_W^{\rm eff}(M_Z) \equiv \bar{s}_l^2 = 0.23149 \pm 0.00015$ [16] at Z^0 pole. This implies $\rho^{(e;e)} = 1.0012 \pm 0.0005$ and $\Delta = -0.0007 \pm 0.0009$. We determine at $Q^2 = 0.026$ GeV^2

$$\sin^2\theta_W^{\rm eff}(Q) = 0.2397 \pm 0.0010({\rm stat}) \pm 0.0008({\rm syst}).$$

Our value is consistent with the standard model expectation [4,16] $\sin^2\theta_W^{\rm eff}(Q) = 0.2381 \pm 0.0006$ and is 6.2σ away from $\sin^2\theta_W^{\rm eff}(M_Z)$ (Fig. 2). Interpreting our result as a measurement of the electroweak coupling parameter $\sin^2\theta_W(M_Z)_{\overline{\rm MS}}$ yields

$$\sin^2\theta_W(M_Z)_{\overline{\rm MS}} = 0.2330 \pm 0.0011({\rm stat}) \pm 0.0009({\rm syst}) \pm 0.0006({\rm theory}). \quad (1)$$

The last uncertainty is from the evolution to M_Z.

Our measurement of $A_{\rm PV}$ can also be used to set limits on the size of possible new contributions beyond the standard model. Quite generally, we set a limit on the scale $\Lambda_{\rm LL}$ of a new left-handed contact interaction characterized by a term in the Lagrangian [19] $\mathcal{L} = \pm(4\pi/2\Lambda_{\rm LL}^{\pm 2})(\bar{e}_L\gamma_\mu e_L)$. At 95% C.L. a tree-level calculation yields $\Lambda_{\rm LL}^+ \geq 7$ TeV and $\Lambda_{\rm LL}^- \geq 16$ TeV, for potential positive and negative deviations, respectively. As an example of a specific model, the 95% C.L. on the mass of Z_χ boson appearing in the grand unified model with SO(10) symmetry [4,19] is $M_{Z_\chi} \geq 1.0$ TeV.

In summary, we have reported a new measurement of $A_{\rm PV}$ in Møller scattering with an accuracy of 17 ppb. This leads to a precise determination of $\sin^2\theta_W^{\rm eff}$ at low momentum transfer. The running of the weak mixing angle is observed with over 6σ significance. The consistency of the result with the standard model prediction provides significant new limits on TeV scale physics, comparable in sensitivity and complementary to the best current limits from high energy colliders.

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