Fixed Target Møller Scattering at the NLC*

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ABSTRACT

I discuss the measurement of the parity violating left-right asymmetry in the scattering of high energy polarized electrons from the atomic electrons in a liquid hydrogen target. The asymmetry, due to the interference between the weak and electromagnetic amplitudes, measures the product of the vector and axial-vector couplings of the electron to the Z boson, and is thus proportional to $1-4\sin^2\theta_{\rm W}$. The statistical power on the measurement of $\sin^2\theta_{\rm W}$ for a given luminosity increases linearly with the incident beam energy. At NLC energies, one could achieve $\delta(\sin^2\theta_{\rm W}) = 0.00006$ in 2×10^7s, which would be precise enough to probe the electroweak symmetry breaking sector at the quantum loop level. This would complement direct high energy collider searches, provide an important crosscheck of the electroweak theory and probe electron compositeness up to an interaction scale of 50 TeV.

I. INTRODUCTION

Over the past two decades, experiments measuring weak neutral current interactions have taken the lead in the study of electroweak radiative corrections, providing the best indirect probes to new high energy physics. Precision measurements in $\rm e^+e^-$ and $\rm p\bar{p}$ colliders as well as fixed target experiments are continuing to probe for physics beyond the standard model through virtual effects and have provided important tests of the electroweak theory at the quantum loop level. It would be a significant achievement if such indirect measurements were pushed to a level where they became sensitive to the mass generating mechanism of the electroweak theory.

However, studies have shown that it will be difficult to probe the higgs sector of the theory through its manifestation in quantum loop effects. Assuming that the mass of the top quark is known to high precision from future collider experiments, a significant measurement of the Higgs boson mass (assuming one elementary Higgs scalar) through its manifestation in quantum loop effects requires the measurement of the weak mixing angle $\sin^2\theta_{\rm W}$ to an accuracy better than 0.0001 or a measurement of the W boson mass to an accuracy better than 20 MeV. Such measurements will be challenging in any existing or future collider.

In this paper, I describe a precision electroweak measurement at $Q^2 \ll M_{\rm Z}^2$ which has the potential to provide a measurement of the weak mixing angle $\sin^2\theta_{\rm W}$ with an accuracy of 0.00006. This would be achieved via a precision measurement of the left-right asymmetry ($A_{\rm LR}$) in the reaction $\rm e^-e^- \to e^-e^-$, using the high energy polarized electron beam at the NLC scattering off electrons in a liquid hydrogen target.

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II. PHYSICS MOTIVATION

One of the major goals of future high energy accelerators is to search for new particles and interactions and elucidate the nature of the particles and interactions that give rise to masses for the fermions and gauge bosons. Whereas some physics signals have the desirable feature of direct observation of an unambiguous signature in a high energy collision, others produce only small statistical samples with uncertain background contaminations. These searches, especially the latter, are significantly complemented and enhanced by probing for the virtual effects of new particles and interactions in electroweak processes at energies much lower than the scale of new physics.

Since the standard model is a renormalizable field theory, it is possible to make accurate predictions for experimental observables at the level of electroweak radiative corrections. At the loop level, particles that are much heavier than the energy scale of the experiment can contribute to the corrections. Moreover, due to the fact that the electroweak gauge symmetry is spontaneously broken, these effects do not vanish even if the Q^2 of the experiment becomes much smaller than the scale of the relevant high energy physics. A recent example of the success of this technique is the agreement between the direct measurement of the top quark mass[1] and the indirect measurements extracted from the partial width and asymmetry measurements from the LEP/SLC experiments[2].

By the end of the LEP-II and Fermilab collider programs, precision measurements would have achieved significant sensitivity to new physics at the TeV scale. However, the lack of significant deviation does not necessarily rule out all sources of new virtual effects at the TeV scale. Further, such loop measurements would have shed little light on the nature of electroweak symmetry breaking, which requires precision measurements which are a factor of five better than current measurements. Improved precision electroweak measurements would become especially significant if new physics is found at a high energy collider.

A. Probing Higgs Physics at the Loop Level

It is likely that experiments at new high energy colliders, if they are built, will provide clues to the mechanism of mass generation. However, while they would provide information on origin of W/Z mass generation, there would have to be significant accumulation of data from more than one collider before it is possible to demonstrate that the same mechanism is responsible for fermion mass generation as well.

As has been recently pointed out[3], precision measurements of electroweak radiative corrections would provide new information since they would be sensitive to the mass and couplings of all new scalars. For example, radiative corrections could provide additional evidence from which to determine whether the correct theory of nature is supersymmetric. Assuming the existence of a single elementary Higgs scalar and assuming that the top quark mass will be known in the future with a precision of 1 GeV, a mass of the Higgs scalar could be determined with a fractional precision of 10% with a measurement of the weak mixing angle $\delta(\sin^2\theta_{\rm W}) = 0.00006$[3].

A measurement of $\sin^2\theta_{\rm W}$ with such precision or alternatively the measurement of the W mass with equivalent precision will be very difficult in high energy collisions ($Q^2 \geq M_{\rm Z}^2$) in currently envisioned colliders. It is therefore interesting to consider electroweak measurements with fixed targets, such as the measurement considered in this paper.

B. New Contact Interactions

A large class of new physics effects are just new four-Fermi contact interactions at low energy and cannot therefore be accounted for by the oblique correction formalism of the previous section. Since the amplitudes of such contact interactions are real, they do not interfere with the purely imaginary electroweak amplitude on the Z pole and thus cannot be easily observed at LEP and SLC. Important examples of such new interactions are those produced by new Z$'$ bosons with negligible mixing to the Z^0, fermion substructure and leptoquarks[4]. Certain supersymmetric models can also produce low energy contact interactions, if for example there are significant differences between the masses of left- and right-handed superparticles[5]. To search for such interactions efficiently, additional precision experiments must be carried out far from the Z^0 resonance with comparable sensitivity.

We use the formalism for new four-fermion contact interactions as that discussed more than a decade ago in the context of quark and lepton substructure[6]. The formalism is primarily used to provide a framework to evaluate the sensitivity of different experiments. Considering only helicity and flavor conserving interactions, the general four-fermion contact interaction Lagrangian takes the form

$$\mathcal{L}_{ab} = \sum_{\rm h1,h2=\mathit{L},\mathit{R}} k_{ab}\frac{4\pi}{\Lambda_{ab}^2}\left[\eta_{\rm h1h2}(\bar\psi^a_{\rm h1}\gamma_\mu\psi^a_{\rm h1})(\bar\psi^b_{\rm h2}\gamma^\mu\psi^b_{\rm h2})\right] \tag{1}$$

where $\psi_L = \frac{1}{2}(1-\gamma_5)\psi$ and $\psi_R = \frac{1}{2}(1+\gamma_5)\psi$ are the usual chirality projections of the fermion spinors. Λ_{ab} is the compositeness scale for contact interactions between flavors a and b and $k_{ab} = \frac{1}{2}$ for $a = b$ and $k_{ab} = 1$ otherwise. One can distinguish new physics scenarios corresponding to various linear combinations of the couplings η.

The sensitivity of high energy electroweak measurements to contact interactions arises from interference terms in the cross section between the electroweak and new contact interaction amplitudes[6]:

$$\frac{\Delta\sigma}{\sigma} \sim \frac{\pi/\Lambda^2}{4\pi\alpha/Q^2} = \frac{Q^2}{4\alpha\Lambda^2}. \tag{2}$$

Measurement of a weak neutral current amplitude $A_{\rm Z}$ at low Q^2 is also sensitive to contact interactions due to the fact that one is looking for a deviation from a small quantity:

$$\frac{\Delta|A_{\rm Z}|}{|A_{\rm Z}|} \sim \frac{\pi/\Lambda^2}{G_{\rm F}/\sqrt{2}} = \frac{\pi\sqrt{2}}{G_{\rm F}\Lambda^2}. \tag{3}$$

From the two relations given above, it is apparent that the sensitivity of low energy weak neutral current amplitudes to contact interaction scales is similar to high energy collisions with a center of mass energy of about 100 GeV. If specific low energy processes are chosen where the effective electroweak coupling is small, the relative sensitivity is further enhanced. Furthermore, asymmetry measurements are capable of measuring weak neutral current amplitudes with fractional accuracies much better than 1%. Thus, carefully chosen low energy measurements could have higher sensitivity than that envisioned in current and future colliders. For the measurement considered in this paper, the contact interaction scales that are probed are of the order of 50 TeV.

III. PARITY VIOLATING ELECTRON SCATTERING

Polarized electron scattering off unpolarized targets provides a clean window to study weak neutral current interactions. One measures an asymmetry defined by

$$A_{\rm LR} = \frac{\sigma_R - \sigma_L}{\sigma_L + \sigma_L} \tag{4}$$

where σ_R (σ_L) is the scattering cross-section from incident right (left) handed electrons. A non-zero asymmetry constitutes parity nonconservation and signals the presence of pseudo-scalar terms in the cross-section. At $Q^2 \ll M_{\rm Z}^2$, the pseudo-scalar terms are dominated by the interference between the weak and electromagnetic amplitudes. $A_{\rm LR}$ is thus proportional to the ratio of these amplitudes, and rises with Q^2[7]. At $Q^2 \sim 1$ GeV^2, $A_{\rm LR} \simeq 10^{-4}$.

The experimental techniques necessary to measure such small asymmetries have been established in past experiments using nuclear targets[8, 9, 10]. In this paper, I consider the Møller scattering of polarized electrons off atomic electrons, a purely leptonic reaction which is calculable to high accuracy in the electroweak theory. This process has recently been investigated with the aim of developing an experimental proposal using the 50 GeV polarized electron beam at SLAC[11]. The total unpolarized cross section is given by

$$\frac{d\sigma}{d} = \frac{\alpha^2}{2mE}\frac{(3+\cos^2\Theta)^2}{\sin^4\Theta} \tag{5}$$

where α is the fine structure constant, E is the incident beam energy, m is the electron mass and Θ is the scattering angle in the center of mass frame. The parity-violating asymmetry $A_{\rm LR}$ is given by

$$A_{\rm LR} = mE\frac{G_{\rm F}}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}g_{\rm ee}. \tag{6}$$

where $G_{\rm F}$ is the Fermi coupling constant, Θ is the scattering angle in the center of mass frame, and

$$g_{\rm ee} \equiv \rho_{\rm eff}\cdot g_{\rm Ve}\cdot g_{\rm Ae} = \frac{1}{2} - 2\sin^2\theta_{\rm W} \tag{7}$$

is the effective weak neutral current coupling governing Møller scattering.

We summarize the salient features of the experimental measurement below:

- The cross-section for Møller scattering is large, providing the high rates required to obtain a small statistical error in a reasonable length of time.
- This reaction is a clean and independent test of electroweak radiative corrections and is complementary to collider measurements carried out at the electroweak scale.
- The asymmetry $A_{\rm LR}$ in Møller scattering measures $1 - 4\sin^2\theta_{\rm W}$ which is small,[1] leading to less stringent requirements on the systematics of the beam polarization, determination of the experimental $< Q^2 >$ and other normalization uncertainties.
- The small numerical value of $g_{\rm ee}$ results in enhanced sensitivity to $\sin^2\hat\theta_{\rm W}(0)$. The predicted value of $\sin^2\theta_{\rm W}$ at $Q^2 = 0$ is about 0.2373. Therefore, for Møller scattering,

$$g_{\rm ee} \propto 1 - 4\sin^2\hat\theta_{\rm W}(0) \Longrightarrow \frac{\delta(\sin^2\hat\theta_{\rm W}(0))}{\sin^2\hat\theta_{\rm W}(0)} \simeq 0.06\frac{\delta g_{\rm ee}}{g_{\rm ee}}. \tag{8}$$

- For electrons from a hydrogen target, the only relevant background is elastic electron-proton scattering at very low Q^2, which is well understood and can be kinematically suppressed.
- The accuracy in the measurement of the weak mixing angle could possibly be the best ever from a single process.

$A_{\rm LR}$ for Møller scattering rises linearly with the beam energy and the beam polarization. The viability of this measurement is thus improved dramatically by the availability of polarizations in excess of 80% and by the high available beam energy. Even so, the raw asymmetry is small, $\sim 2\times10^{-6}$, and the goal is to reach a statistical error better than 10^{-8}. The challenge is to achieve this statistical error as well as keep the systematic error to a few parts per billion (ppb). This is possible by devising several methods of reversing the sign of the asymmetry and by incorporating techniques developed in previous experiments[8, 10] to control systematic errors.

IV. EXPERIMENTAL DESIGN

The behavior of the differential cross section (Eqn. 5), dominated by one photon exchange, is shown in Fig. 1. The energy E' of the scattered electron in the laboratory frame is related to the beam energy E and the center of mass scattering angle Θ by $E' = \frac{1}{2}E(1+\cos\Theta)$. The cross-section has a minimum at $E' = \frac{1}{2}E$ ($\cos\Theta = 0$) and diverges at $E' = 0$ and $E' = E$. For $E = 250$ GeV, $E' = 125$ GeV and 100% beam polarization, $A_{\rm LR}$ is 1.4×10^{-6}. Radiative corrections reduce this asymmetry by more than 40%[12].

[1] We use the definitions $\sin^2\hat\theta_{\rm W}(0) \equiv \sin^2\theta_{\rm W}(Q^2 \ll M_Z^2)$ and $\sin^2\hat\theta_{\rm W}(M_Z) \equiv \frac{1}{4}(1 - g_{\rm Ve}/g_{\rm Ae})$, where the couplings are measured at $Q^2 = M_Z^2$. For the purposes of estimating the error on $\sin^2\theta_{\rm W}$, the specific choice of definition of $\sin^2\theta_{\rm W}$ is unimportant.

As shown in Fig. 1, the asymmetry is maximal at $E' = E/2$ ($\cos\Theta = 0$) and falls to zero at $E' = 0$ and $E' = E$. For the experimental design, an important parameter is the figure of merit (f.o.m.), which quantifies the variation of the achievable statistical error for fixed luminosity. For Møller scattering, the f.o.m. varies slowly with $\cos\Theta$ and is maximal at $E' = E/2$. It is therefore possible to design an experiment to accept a large scattered energy bite, making a small statistical error feasible.

A. General Considerations

The polarized source at NLC would generate 6×10^{11} electrons per pulse train with 80% beam polarization at a repetition rate of 180 Hz, with the ability to assign the sign of the beam polarization on a pulse train to pulse train basis. The experimental asymmetry would be measured by rapidly flipping between the two possible electron beam helicity states while keeping all other experimental parameters virtually unchanged and then averaging the fractional difference in the cross-section over many such complementary pairs of pulses.

The critical requirement in an asymmetry measurement is the control of the differences in the beam characteristics between left- and right-handed pulses to a negligible level. Another important aspect is the reversal of the sign of the experimental asymmetry by several independent methods. The relevant experimental techniques have been developed and employed successfully in previous measurements[8, 10].

Since we need to achieve a statistical error better than 10^{-8} on $A_{\rm LR}$, more than 10^7 scattered electrons must be detected every beam pulse. Liquid hydrogen is the natural choice to provide a dense electron target thickness. It provides the least amount of

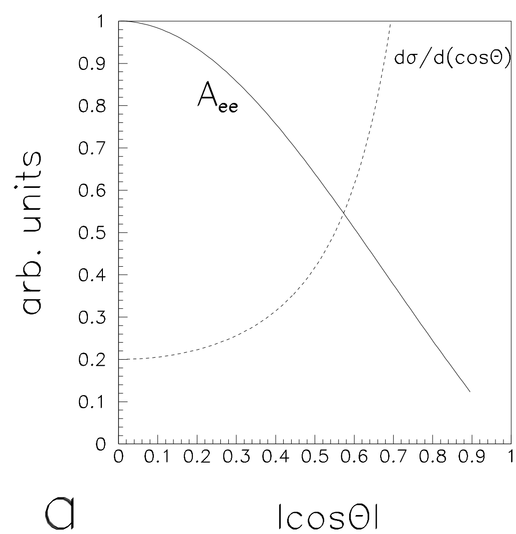

Figure 1: The behaviour of the asymmetry, and the differencital cross-section is shown as a function of $|\cos\Theta|$, the scattering angle in the center of mass frame.

radiation loss for a given target electron thickness. Further, the dominant background for a hydrogen target at $Q^2 \sim 0.1$ GeV^2 is elastic electron-proton scattering, which is well understood and has a small electroweak asymmetry. To achieve the necessary rate, scattered electrons from a 1.5 meter hydrogen target in the energy range from 50 to 125 GeV in the full range of the azimuth must be detected. The luminosity for such a target with NLC Ib parameters is $7.6 \times 10^{38}/\mathrm{cm}^2/\mathrm{sec}$ and the total cross section is 4 μBarn.

B. Spectrometer

For Møller scattering, there is a kinematical correlation between the scattered electron energy E' and the laboratory scattering angle. For an incident beam energy of 250 GeV, the range of scattering angles for $50 < E' < 200$ GeV is 1 to 4 mrads. Since we are dealing with identical particles, a good event gives rise to an electron at an azimuthal angle ϕ with energy E' simultaneously with another electron at an azimuthal angle of $\pi - \phi$ with energy $E - E'$. The full available solid angle in the azimuth for scattered electrons from 50 to 200 GeV is thus obtained by detecting 50 to 125 GeV electrons over 2π radians in ϕ.

Since the scattering angles are small, the spectrometer can be designed with quadrupoles, the scattered beam always staying within the magnet apertures. A quadrupole doublet or triplet would bring the scattered electrons to a compact ring focus downstream. The background consists of high energy electrons ($\sim$ 250 GeV) from elastic scattering of the primary beam off protons in the target. Additionally, some of the primary electrons radiate high energy photons before scattering off the protons, giving rise to a background of low energy electrons ($\sim 10 - 50$ GeV) as well.

We have investigated the spectrometer design using a GEANT[13] Monte Carlo simulation of 1.6×10^8 250 GeV electrons traversing a 1.5 meter hydrogen target. Figure 2 shows the energy distribution of signal and elastic e$-$p scattering background electrons in the scattered angular range $2 < \theta_{\mathrm{lab}} < 4$ mrad in the full range of the azimuth. A quadrupole spectrometer would be designed to select the momentum range between 40 and 125 GeV. Within this range, the background from electron-proton scattering is about 15% and the loss of signal due to radiation in the target is 12%.

C. Statistical and Systematic Errors

The integrated Møller cross-section for scattered electrons over the range 40 to 125 GeV is 4.1 μbarns for an incident beam energy of 250 GeV and the loss of rate due to the thick target is 12%. The scattering rate for an incident beam of 6×10^{11} electrons is 1.5×10^7 per pulse. The subtraction of the 10% background will degrade the statistical error by 5% and appropriate reweighting of the scattered flux should keep the cumulative figure of merit to within 85% of the maximum (at 125 GeV).

The largest source of experimental normalization error is expected to be due to the beam polarization measurement. The current limit of the technology of compton polarimetry, based on experience at the SLD experiment is expected to be about 0.3%. The dominant background of elastic e$-$p scattering would be suppressed to be below 10% of the signal. The asymmetry is not very sensitive to the background fraction, since the standard model prediction for the low energy effective neutral current coupling for e$-$p scattering is the same as for Møller scattering.

Radiative corrections to A_{LR} in Møller scattering has been recently investigated[12]. The authors found that the tree level prediction is reduced by more than 40%. This has no direct impact on the projected statistical sensitivity of the measurement. In fact, it alleviates the systematic error from normalization uncertainties such as the beam polarization. The estimation of the hadronic loop uncertainties, however, will have to be significantly better than is currently known, and will have to be improved before the measurement can be interpreted.

The salient features of the measurement and the projected errors are summarized in Table I. It can be seen that one year runs, each at 250 GeV and 500 GeV, provides a cumulative measurement of $\sin^2\theta_{\mathrm{W}}$ with an accuracy of 0.00006.

V. NEW PHYSICS REACH

In the presence of new contact interactions, the deviation in the effective coupling measured in polarized Møller scattering can be expressed as

$$g_{\mathrm{ee}}(\mathrm{meas.}) - g_{\mathrm{ee}}(\mathrm{S.M.}) = \pm \frac{\pi\sqrt{2}}{G_{\mathrm{F}}} \frac{(\eta_{RR} - \eta_{LL})}{\Lambda_{\mathrm{ee}}^2}. \qquad (9)$$

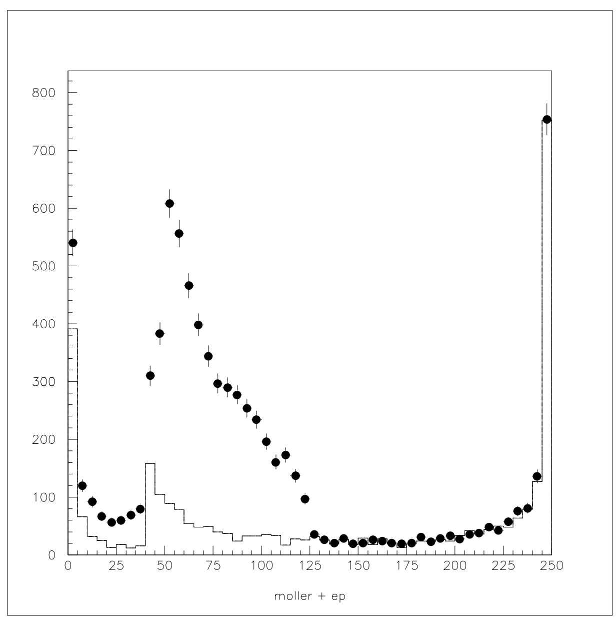

Figure 2: The simulated energy spectrum from Møller and elastic proton scattered electrons from 1.6×10^8 incident 250 GeV electrons on a 1.5 meter long liquid hydrogen target is shown in the angular range $2 \le \theta_{\mathrm{lab}} \le 4$ mrad. The points show the total contribution while the histogram shows the contribution from the e$-$p background.

Table I: The important parameters of the $A_{\rm LR}$ measurement are shown, assuming a run of 10^7s at each beam energy, 90% beam polarization and a polarimetry systematic error of 0.3%.

	NLC Ib	NLC IIb
$E_{\rm beam}$ (GeV)	250	500
$\sigma_{\rm tot}$ (μBarn)	4	2
Rate (Hz)	2.8×10^9	1.4×10^9
$A_{\rm LR}$	1.4×10^{-6}	2.9×10^{-6}
$\delta(A_{\rm LR}(\rm stat))$	6.0×10^{-9}	8.5×10^{-9}
$\delta(A_{\rm LR}(\rm syst))$	2.5×10^{-9}	5.0×10^{-9}
$\delta(\sin^2\theta_{\rm W})$	0.000092	0.000082

This would lead to a 95% confidence level limit of 63 TeV for $\Lambda_{\rm ee}$ for the specific combination of couplings $\eta_{LL} = -\eta_{RR} = \pm 1$. This limit is better than that achievable at the NLC $\rm e^+e^-$ collider and compares well with the limits obtainable at a high energy $\rm e^-e^-$ collider.

As an example of the discovery potential of low Q^2 measurements to new gauge bosons, we consider the effect on $A_{\rm ee}$ of a new neutral boson Z_χ[14], which arises in SO(10) and $\rm E^6$ grand unified theories. If we assume that any mixing with the $\rm Z^0$ is negligibly small, the contact interaction mediated by a new vector boson of mass $M_{\rm Z'}$ will give rise to a contribution to the asymmetry which can be quantified as

$$\frac{4\pi}{\Lambda_{\rm ee}^2}(\eta_{RR} - \eta_{LL}) = 8\frac{G_{\rm F}}{\sqrt{2}}\left(\frac{M_{\rm Z}}{M_{\rm Z'}}\right)^2\left(\frac{g_2}{g_1}\right)^2(g'^2_{\rm Re} - g'^2_{\rm Le}), \quad (10)$$

where g_2/g_1 is the ratio of the gauge couplings of the interactions mediated by the $\rm Z'$ and $\rm Z^0$ bosons and $g'_{\rm Re}$ ($g'_{\rm Le}$) is the coupling of right- (left-) handed electrons to the $\rm Z'$ boson. For the Z_χ model, $\Lambda_{\rm ee} \sim$ 63 TeV corresponds to $M_{Z_\chi} \sim$ 2.7 TeV.

VI. CONCLUSIONS

A fixed target experiment measuring the parity violating asymmetry in the process $\rm e^-e^- \to e^-e^-$ would nicely complement the physics program at the NLC. Such a measurement would probe the electron compositeness scale at the level of 50 TeV. The experiment has the potential to provide the single best measurement of the weak mixing angle, $\delta(\sin^2\theta_{\rm W}) = 0.00006$, better than that achievable in precision measurements in future high energy colliders. Such a measurement would thus probe the symmetry breaking sector of the electorweak theory at the quantum loop level and provide important clues towards the ultimate theory of nature.

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