EPJ manuscript No.
(will be inserted by the editor)

Outlook for an Improved Measurement of Parity Violation in Moeller Scattering at Jefferson Laboratory

the e2ePV experiment

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Received: date / Revised version: date

Abstract. Jefferson Laboratory has the potential to make a dramatically improved measurement of parity violation in Moeller scattering($e + e \rightarrow e + e$). In the context of the Standard Model, the measurement would yield the best determination of $\sin^2\theta_W$ at low energy ($\Delta\sin^2\theta_W = \pm 0.00025$), and one of the best at any energy scale. As a new physics search via the running of the weak mixing angle, the experiment would have unparalleled sensitivity to new parity-violating $e-e$ interactions, probing electron substructure to 29 TeV (95% CL). In terms of specific models, pulls of 6σ are allowed in R-parity violating SUSY, about 5σ in E6 Z', and almost 3σ in R-parity conserving SUSY. The latter makes an improved Moeller measurement complementary to searches for SUSY loop-induced Electric Dipole Moments. Interpretability limits are well below the projected experimental error. A conceptual design for a 12 GeV JLab experiment is presented.

PACS. 11.30.Er Charge conjugation, parity, time reversal, and other discrete symmetries – 11.30.Pb Supersymmetry – 12.15.-y Electroweak interactions – 13.60.Fz Elastic and Compton scattering

1 Introduction

The SLAC E158 collaboration recently completed the first measurement of parity violation in Moeller scattering ($e+e \rightarrow e+e$).[1]. This pioneering experiment, summarized by K. Kumar at this conference, was not only an impressive technical achievement but is the clearest confirmation of the predicted running of the weak mixing angle, $sin^2\theta_W$. It also sets the highest limits on compositeness in the $e-e$ sector. However, the final error bar was too large to play a significant role in the global average of $\sin^2\theta_W$ or to provide significantly improved constraints on most models of new $e-e$ interactions. A greatly improved measurement could take place at the upgraded Jefferson Laboratory which would possess discovery-class sensitivity by measuring $\sin^2\theta_W$ at low energy with an error on par with the best individual collider measurements.

2 Motivation for the New Experiment

2.1 an important new $\sin^2\theta_W$ measurement

The Z^0 pole precision data for $\sin^2\theta_W$ are shown in Figure 1 [2]. Since statistical weights are proportional to the inverse *square* of the error, the present world value of $\sin^2\theta_W$ is largely determined by the two apparently inconsistent points with the smallest errors: one leptonic from SLD, the other semileptonic from LEP. The SLD experiment suggests a low value of the Higgs mass, while the LEP experiment suggests a much higher value of the Higgs mass. While there is only a small chance that the 3σ discrepancy is due to statistics, global analyses nevertheless average these data, yielding the small error bar seen in the figure. If one of the two measurements has a significantly underestimated systematic error, then the uncertainty on $\sin^2\theta_W$ at the Z^0 pole is larger than this naive weighted average implies. This has implications for Higgs mass searches, as well as for new physics searches via the apparent running of $\sin^2\theta_W$. Additional data of high precision are needed, and Fermilab is expected to make a significant contribution in the next few years.[3]

Low energy experiments can also determine $\sin^2\theta_W$. The first two entries in Table 1 are existing data from the weak charge of Cs and the electron. The remaining entries in the table are for hypothetical experiments. While the error from a potential nuclear elastic $0^+ \rightarrow 0^+$ measurement would be far too large to be useful, future precise measurements of the proton and the electron weak charge could make significant improvements in the low energy situation due to their proportionality to the suppressed quantity $1-4\sin^2\theta_W$.

In both the electron and proton cases, the small asymmetry makes these measurements not only systematically challenging but statistically challenging. The case of the proposed 4% Jefferson Lab Q^p_W measurement, currently under construction and reviewed at this conference by S. Page, has been studied in great detail and appears to

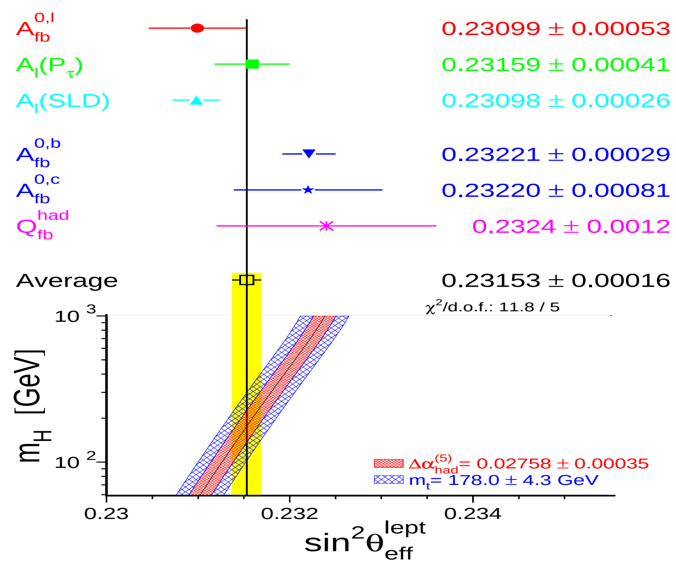

Fig. 1. The Z^0 pole values of $\sin^2\theta_W(eff)$ from purely leptonic and semi-leptonic reactions.[2]

Table 1. Summary of existing and potential low energy $\sin^2\theta_W$ experiments. For a generic tree-level weak charge, $Q_W = A + B\sin^2\theta_W$, the magnification from the relative error on the weak charge to the relative error on $\sin^2\theta_W$ is $\frac{A+B\sin^2\theta_W}{B\sin^2\theta_W}$.

Experiment	$\frac{\Delta Q_W}{Q_W}$	Error Mag.	$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W}$	$\Delta\sin^2\theta_W$
data:				
Q_W^{Cs}[4]	0.5%	1.4	0.7%	0.0016
Q_W^{e}[1]	13.1%	0.041	0.5%	0.0013
future:				
Q_W^{e}	2.5%	0.041	0.1%	0.00025
Q_W^{p}[5]	4%	0.078	0.3%	0.00072
$Q_W(0^+ \rightarrow 0^+)$	1%	0.93	0.9%	0.0022

be both feasible[5] and interpretable[6]. However, due to hadronic dilutions, and the fact that statistical and systematic errors are already well-matched, it is not possible to significantly reduce this error. The situation for Q_W^e has not been examined in the same detail, but assuming similar systematic errors, a 2.5% measurement of the electron's weak charge appears possible. Due to differences in electroweak radiative corrections which cause the electron asymmetry to be even further suppressed than the proton asymmetry, the error magnification is also a factor of 2 smaller for the electron. Thus, the electron measurement can yield an error on $\sin^2\theta_W$ which 3 times smaller than the proton measurement, on par with the best individual measurements at the Z^0 pole.

To better understand how JLab is able to mount a competitive Moeller scattering experiment, it is helpful to examine the dependence of the statistical figure of merit on beam energy. In a hopefully obvious notation, taking $\sigma A^2 It$ as our statistical figure of merit, and using the fact that $\sigma \propto 1/E$ and $A \propto E$, where E is the beam energy, one finds the figure of merit is proportional to EIt or the total integrated beam power.[1] Although JLab and SLAC can both produce O(1) MWatt beams, SLAC invested only about 0.07 MWatt-Years in the E158 experiment, while a JLab Moeller experiment would require 0.5 MWatt-Years. Significantly smaller statistical errors than the 2.5% JLab measurement under discussion here would require either a new facility with multi-MWatt beams (*e.g.* the measurement K. Kumar has proposed for the exhaust beam at the NLC[7]) or much longer integration times. However, the fixed target Moeller scattering technique requires an absolute measurement of a PV asymmetry, and is ultimately limited by a systematic error floor.

Given the large facility investment that will be required to achieve errors on $\sin^2\theta_W$ of ±0.00025, and the potential difficulties in reducing the systematic errors by more than a factor of several, it seems likely any further breakthroughs will eventually have to come from non-accelerator experiments. One technique for reducing uncertainties in atomic parity violation experiments is to cancel the correlated errors by measuring isotope ratios.[8] From a low-order expansion of the atomic weak charge, one can easily show the seemingly paradoxical result that isotope ratios experiments measure the *proton* weak charge[9]. The same expansion reveals the factor $\frac{<N>}{\Delta N} \simeq O(10)$ which magnifies any remaining uncorrelated errors. Fortunately, laser quanta are cheap, so high statistical precision is possible. There is also an effort at Jefferson Laboratory to measure the neutron radius of ^{208}Pb, reviewed at this conference by R. Michaels and J. Piekarewicz, to help calibrate relevant models. Finally, D. Budker at this conference reported that his group's decade-long program of preparatory measurements on Yb is complete, and that they are ready to begin searching for the predicted enhancement of parity violation in selected transitions of that atom.

2.2 constraining new e-e interactions

Strangely enough, even though $\sin^2\theta_W$ is a free parameter in the Standard Model, a precision measurement at low energies can constrain new interactions beyond the Standard Model. In a neutral weak measurement, after the known Standard Model reaction- and hadronic structure-dependent electroweak box diagrams are regressed out, the value of $\sin^2\theta_W$ still "runs" from low to high energy scales due to the γZ mixing diagram. (See the solid curve in Figure 2.[13]) Because any parity violating interactions beyond the Standard Model must also contribute to the virtual particle spectrum of the vacuum, they may reveal themselves through a deviation from this expected running. Note that the theoretical uncertainty on the running has recently been reduced to only ±0.00007[14], hence the

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[1] For fixed beam power, if the energy drops too low, then the target refrigeration requirements become excessive. It is assumed here that we can provide the 5+ kWatts of target refrigeration needed at 12 GeV.

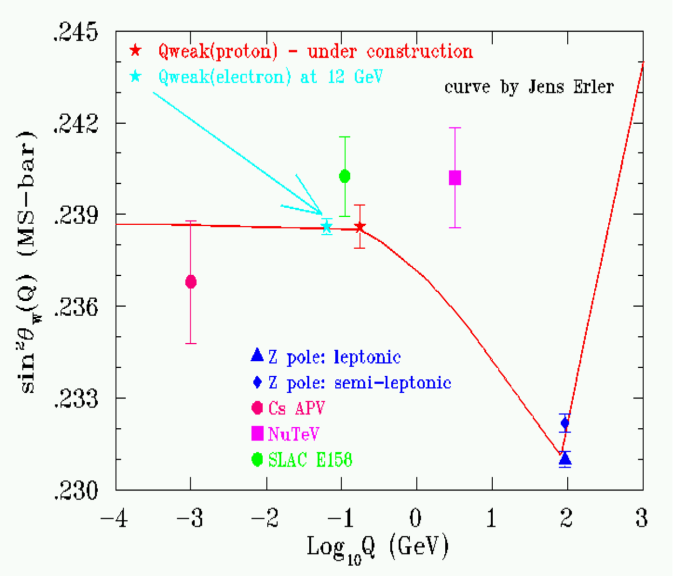

Fig. 2. The running of $\sin^2\theta_W$. Curve from reference [13]. The normalization is defined by the experimental data at the Z^0 pole. The scale dependence is a property of the vacuum and is due to the γZ mixing diagrams. As in the case of the running of the electromagnetic fine structure constant α, at low energies the strength increases with increasing energy due to reduced screening. However, the strength decreases again once W^+W^- threshold is crossed.

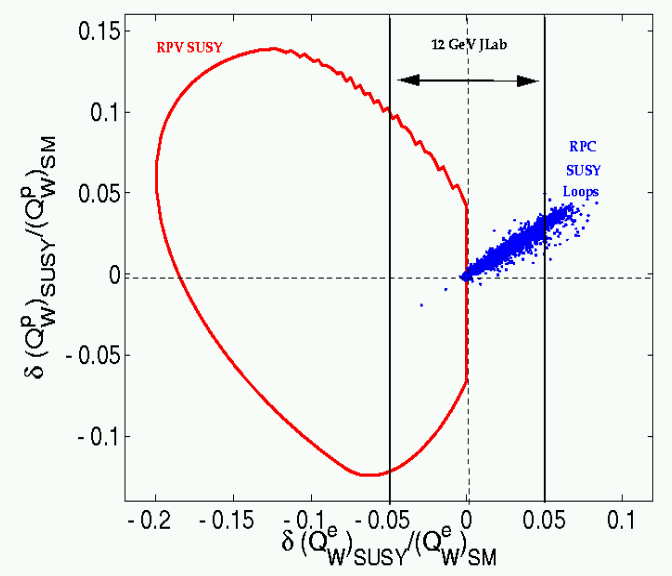

Fig. 3. The correlation between the allowed shifts of the electron and proton weak charges due to R-parity violating SUSY (red contour) and R-Parity conserving SUSY (ellipse of dots).[16] The Standard Model corresponds to the origin at (0,0). If the 2.5% JLab Q^e_W measurement were to agree exactly with the Standard Model, the parameter space outside the vertical lines would be excluded at 95% confidence level.

interpretability is currently limited by the normalization of the curve at the Z^0 pole which is arguably as small as the ± 0.00016 .

Existing data and projected uncertainties are also shown in Figure 2. The Q^{Cs}_W and E158 results are both consistent with the predicted SM running. However, because the E158 result is so highly interpretable and so obviously inconsistent with the Z^0 pole value, it provides the single most convincing demonstration of the predicted running of $\sin^2\theta_W$. The NuTeV[15] result was reviewed by T. Londergan at this conference. Since "ambiguous Standard Model test" is an oxymoron, it probably doesn't belong on this plot. But in contrast to the rapid resolution by the atomic theory community of problems in the interpretability of the Q^{Cs}_W experiment, it may take decades to clear the hadronic interpretability cloud which hangs over the NuTeV value for the weak mixing angle.

It's probably worth noting that each separate low energy reaction on Figure 2 is complementary in that it is sensitive to new physics in a different manner. Thus, the future JLab Q^p_W experiment is complementary to Q^{Cs}_W because they measure different isospin combinations of $e-q$ couplings. The Q^e_W experiments are complementary in that they alone are sensitive to new $e-e$ interactions. It's a case of size doesn't matter, as long as you're not redundant.

Such complementarities are better reflected in specific models, a few of which are listed in Table 2. Although one has to be cautious about interpreting the value of an experiment in terms of a small subset of models, the importance of the Q^{Cs}_W experiment in constraining new $e-q$ interactions (particularly new $e-d$ quark interactions) is very impressive. This measurement needs to be confirmed, yet we were told by M. Lintz at this conference that the Paris effort, after a great deal of groundwork, is no longer funded. The E158 result is without parallel as a constraint on electron compositeness, but does not exceed collider limits for E6 Z' models. By the end of the decade, the Q^p_W experiment should nicely complement the existing Q^{Cs}_W result, yielding roughly balanced constraints on new $e-u$ and $e-d$ interactions.

In the contact interaction formalism of reference [6], because the sensitivity to the new physics mass-to-coupling ratio Λ/g is proportional to $1/\sqrt{\Delta Q_W}$, the E158 error bar would have to be reduced by a factor of 4 to bring $e-e$ constraints into line with anticipated $e-q$ constraints. In a mature program of measurements, this level of improvement in experimental technique could take a whole generation. Fortunately, these measurements are still in the pioneering stage and we believe a JLab measurement of 2.5% is possible. By the end of the JLab weak charge program, compositeness for electrons and the two lightest quarks would be probed to about 28 TeV (at 95% confidence level).[2]

Figure 3 shows the correlation between the allowed phase space for SUSY perturbations on Q^p_W and Q^e_W.[16] The electron weak charge has the potential to place very

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[2] As for a potential 1% $Q_W(0^+ \rightarrow 0^+)$ measurement, it would nicely complement the Cs and proton measurements since it is sensitive to an intermediate isospin combination and has essentially no axial contributions.

Table 2. Miscellaneous model sensitivities (all 95% confidence level lower mass limits in units of TeV). The potentially most sensitive measurement in a given column has been marked in bold (which isn't very fair to the published experiments). Sensitivities of low energy PV experiments are from reference [9] with some rescaling to reflect the latest values of the final or projected experimental errors. Collider limits for new Z's are from reference [10] while leptoquark limits are from reference [11]. With its present integrated luminosity of 2 fb^{-1}, FNAL Run II should be able to raise $e-q$ compositness limits to 6-10 TeV.[12]

Experiment	Z'		Leptoquarks		Compositeness (LL)	
	$M(Z_\chi)$	$M(Z_{LR})$	$M_{LQ}(up)$	$M_{LQ}(down)$	e-q	e-e
Collider Limits	.67	.80	"1.5"	"1.5"	2.5-3.7	2.2-2.4
low energy PV data:						
0.5% Q_W^{Cs}[4]	1.2	**1.3**	**4.0**	3.8	**28**	—
13.1% Q_W^e[1]	.66	.34	—	—	—	13
future experiments:						
2.5% Q_W^e	**1.5**	.77	—	—	—	**29**
4% Q_W^p[5]	.95	.45	3.1	**4.3**	**28**	—
1% $Q_W(0^+ \rightarrow 0^+)$	.91	.92	3.0	3.0	22	—

strong limits on RPV SUSY models, and pulls of 6σ are allowed. Effects due to RPC SUSY loops would be manifested more subtly, but pulls of almost 3σ are still allowed. The cancellation of SUSY loop pulls between u and d quarks in hadronic targets leads to depressingly small net pulls which may be only significantly addressable in the future by APV isotope ratios. Thus Q_W^e, along with $(g-2)_\mu$ and potentially APV isotope ratios, may be complementary to searches for Electric Dipole Moments which require CP violation.

The fact that precision electroweak measurements set higher limits than present day colliders will seem quaint in a few years when the LHC acquires the ability to materialize TeV-scale particles. Yet low energy measurements will remain important. If the LHC does not find anything in this region, precision measurements will continue to probe masses above LHC limits albeit in the model space of larger couplings. If the LHC does observe a heavy neutral particle, precision electroweak measurements may help identify it.

Table 3. Nominal parameters for the e2ePV experiment.

Parameter	12 GeV JLab
E	12 GeV
E'	3-6 GeV
Beam polarization	85%
$< Q^2 >$	.008 $(GeV/c)^2$
θ_{cm}	90°-120°
θ_{lab}	0.53°-0.92°
$< A_{pv} >$	40 ppb
$< A_{expt} >$	34 ppb
σ	$64 \cdot 10^{-29}$ cm^2
Current	100 μA
Target Length	150 cm
Luminosity $cm^{-2}sec^{-1}$	$4.4 \cdot 10^{39}$
Time	4000 hours
Luminosity*Time	$6.4 \cdot 10^{46}$ cm^{-2}
Rate	282 GHz (35 GHz/octant)
Counting Statistics	23 ppm/pair at 300 Hz reversal
$\Delta A(stat) = \frac{1}{P}\frac{1}{\sqrt{N}}$	0.58 ppb
$\frac{\Delta A}{A}(stat)$	1.7%

3 Conceptual Design

The 13% error on Q_W^e from E158 needs to be reduced by a factor of 4-5 to have a significant impact on the world $\sin^2\theta_W$ database or to raise $e-e$ compositeness limits to the same level as $e-q$ limits expected by the end of the decade. Table 3 lists parameters for a potential JLab Q_W^e experiment which would yield a counting statistical error of 1.7%. Assuming an approximate matching of statistical and systematic errors, and some allowance for excess noise in the detectors, a final error of about 2.5% on Q_W^e appears possible. A 4000 hour integration period corresponds to a year of JLab operations, assuming 32 weeks of operation per year and an overall accelerator and endstation equipment efficiency of 75%. Of course, a detailed examination will find efficiencies to be slightly lower, and additional time would be needed for installation and commissioning, so the experiment would realistically have to occupy one of JLab's high luminosity endstations for 2-3 years.

One concern is the target will consist of a 150 cm long liquid H_2 cell with over 5 kW of cooling power. Assuming the cooling power is made available, then density fluctuations will be managed by a combination of rapid beam polarization reversal and normalization via a low noise luminosity monitor. The Q_W^p experiment, which will employ a shorter target with a 2 kW heat load, already plans to use a faster 300 Hz reversal to help "freeze" target density fluctuations. Another concern is false beam asymmetries since we have to make a precision measurement of an asymmetry of 40 parts per billion! This will require even tighter control of helicity-correlated changes in the polarized source and perhaps a new generation of beam diagnostics to measure changes in the beam spot size, etc. However, qualitatively similar problems are presented by the Q_W^p and ^{208}Pb radius experiments currently under construction (with somewhat larger asymmetries of roughly 250 ppb and 500 ppb, respectively). The success of the ongoing 3rd generation of JLab parity violation experiments will make possible the 4th generation Moeller experiment.

My view of lessons from E158 is that it would be helpful to have a spectrometer which achieves a better focus for Moeller electrons to minimize backgrounds. The detector should also have finer binning in position to allow a more detailed comparison between simulation and experimental yields and asymmetries. Bending a primary electron beam after it has passed through a 17% radiation length target, as was done in the E158 spectrometer, will inevitably produce severe backgrounds and so should be avoided. The desire to keep a minimum of 2 bounces between the target and detectors is also not controversial, but this admittedly requires field integrals which are much easier to produce at 12 GeV than at 48 Gev.

The 12 GeV conceptual design consists of a toroidal spectrometer with 8 resistive coils and a focal plane instrumented with Position Sensitive Ion Chamber (PSIC) detectors. The $1/R$ field profile of a toroidal spectrometer is a natural way to produce a θ_{scatt}-dependent hardware corrections needed to focus the Moeller electrons. Initial studies have already confirmed that a 2-bounce system with a cm-scale Moeller focus can be obtained over the large required momentum bite (at least on the mid-plane between adjacent coils as shown in Figure 4). Well-designed PSIC detectors with 4.5 radiation length pre-radiators should allow highly linear, low noise, and extremely radiation resistant operation with better than cm-scale resolution. But much more work needs to be done. For example, azimuthal defocusing in the toroidal spectrometer must be brought under control, and trim coils probably need to be designed which allow a robust tuning capability in the face of coil fabrication errors and small misalignments between the target and collimator and toroidal spectrometer. PSIC detectors must also be thoroughly tested for sensitivity to soft backgrounds.[17]

We are in the process of assembling an international collaboration to tackle this measurement. Other conceptual designs are possible, and the collaboration will have to select one as a reference design. Once JLab calls for 12 GeV proposals for non-standard equipment, we will have about one year to write our Letter of Intent.

4 Acknowledgements

I would like to acknowledge Jens Erler and William Marciano for recent discussions which were crucial to refining the physics focus, the other members of the e2ePV working group for extensive input and encouragement, and the PAVI06 organizers and support staff for a tremendously stimulating and well organized conference on the beautiful island of Milos.

The Southern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

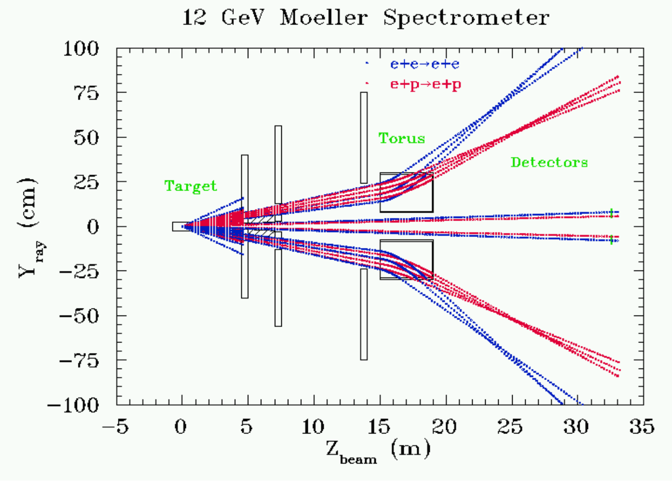

Fig. 4. Conceptual design for a toroidal, Moeller-focusing spectrometer. (Note the change in units between horizontal and vertical axes.) In addition to the Moeller focus at roughly 75 cm radius, there is a good quality $e+p$ elastic focus at about 55 cm.

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