The MOLLER Experiment:
"An Ultra-precise Measurement of the Weak Charge of the Electron using Møller Scattering"

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Parity Violating Electron Scattering (PVES) is an extremely successful precision frontier tool that have been used for testing the Standard Model (SM) and understanding nucleon structure. Several generations of highly successful PVES programs at SLAC, MIT-Bates, MAMI-Mainz, and Jefferson Lab have contributed to understanding of nucleon structure and testing the SM. But missing phenomena like matter antimatter asymmetry, neutrino flavor oscillations, and dark matter and energy suggest that the SM is only a low energy effective theory. The MOLLER experiment at Jefferson Lab will measure the weak charge of the electron, $\mathrm{Q_W^e} = 1 - 4\sin^2\theta_\mathrm{W}$, with a precision of 2.4% by measuring the parity violating asymmetry in electron-electron (Møller) scattering and will be sensitive to subtle but measurable deviations from precisely calculable predictions from the SM. The MOLLER experiment will provide the best contact interaction search for leptons at low OR high energy makes it a probe of physics beyond the Standard Model with sensitivities to mass scales of new PV physics up to 7.5 TeV.

I. OVERVIEW

The Standard Model (SM) of particle physics has been build on decades of experimental evidences [1]. But unexplained observations including: why observable universe is mostly matter not antimatter? why neutrino oscillations (mixed states)? why there are only three families of quarks and leptons? why no comprehensive theory to unify SM with gravity and dark matter? suggest that the SM is only a low energy effective theory.

Parity Violating Electron Scattering (PVES) is an extremely successful precision frontier tool where a precision measurement of the SM predicted quantities or nuclear property can be used to test the SM or understanding the nucleon structure, respectively [2]. Historically, 1978 pioneering Prescott experiment at SLAC was the first successful PVES experiment [3] that provided the first measurement of parity-violation in the neutral weak current. Several generations of highly successful PVES programs have contributed to testing the SM and understanding the nucleon structure (SAMPLE [4], A4 [5, 6], E158 [7], HAPPEX [8–10], G0 [11], PREX [12] and Qweak [13]). The current and next generation PVES experiments provide measurements of SM predicted quantities that can be used to constrain or discover new physics beyond the SM. The proposed MOLLER experiment is one of the next generation PVES experiment.

The MOLLER experiment [14] will utilize the 11 GeV polarized electron beam at Jefferson Lab to extract the weak charge of the electron, $\mathrm{Q_W^e} = 1 - 4\sin^2\theta_\mathrm{W}$, with a precision of 2.4% by measuring the parity violating (PV) asymmetry in electron-electron (Møller) scattering. The measured asymmetry will be sensitive to faint but measurable deviations from precisely calculable predictions from SM. The MOLLER experiment will provide the best contact interaction search for leptons at low or high energy making it a probe of physics beyond the SM with sensitivities to mass scales of new PV physics up to 7.5 TeV. The proposed measurement provide a factor of five improvement in the precision over the only previous measurement by the E158 experiment at SLAC [7].

In order to measure a very small PV asymmetry of the order of 10^{-9} (ppb) to a high precision, the MOLLER experiment will have a unique spectrometer to accept the full azimuthal coverage of scattered and recoiled electrons from the high intensity highly polarized electron beam incident on a liquid hydrogen target.

II. PHYSICS MOTIVATIONS

The precision measurement of the weak mixing angle, $\sin^2\theta_\mathrm{W}$ at $Q^2 \ll M_Z^2$ (low energy scale) allows testing the Standard Model (SM) at the level of electroweak radiative corrections. The consistency of such a measurement with the SM can be used to constrain the physics beyond the SM. The best estimations of weak mixing angle at low energy scales were provided by SLAC E158 Møller measurement [7] and the weak charge of ^{133}Cs [15] via atomic parity violation. The final results from Qweak experiment will soon provide a precision measurement of the $\sin^2\theta_\mathrm{W}$ via a precise measurement of the weak charge of the proton. So far Qweak published an initial result [13]. The proposed $\sin^2\theta_\mathrm{W}$ measurement from MOLLER will be the most precise low energy measurement to match the best precision at Z-boson resonance energy scale (see FIG 1). The set of $\sin^2\theta_\mathrm{W}$ measurements from high energy to low energy will test the SM electroweak radiative correction that used to obtain the running of weak mixing angle with Q^2 (FIG 2). There is a significant potential

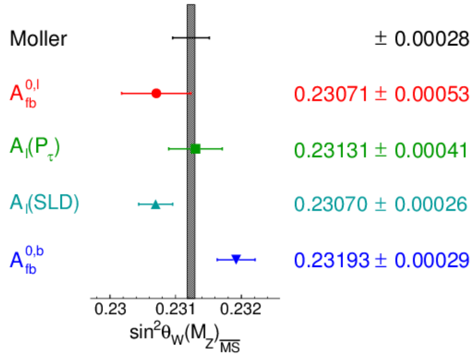

FIG. 1. Four of the best $\sin^2\theta_W$ measurements and the projected error of the MOLLER proposal. The black band represents the theoretical prediction based on Higgs mass, $m_H = 126$ GeV.

to discover beyond the SM interactions at low Q^2 due to electroweak radiative effect on weak mixing angle while having a reduced impact on measurements done at Z resonance. The FIG 3 shows the Higgs mass dependence of the weak mixing angle evolved to $Q^2 \rightarrow M_Z$. There is about $\pm 10\ \sigma$ discovering potential for the projected MOLLER results in the phase-space currently allowed by E158 and APV measurements.

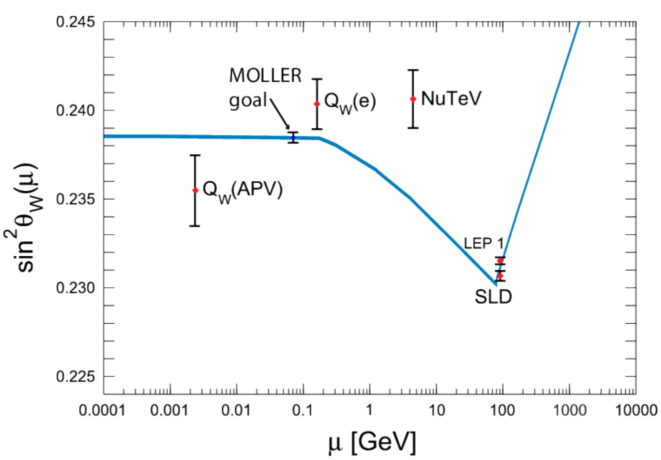

FIG. 2. *The most precise measurements of the weak mixing angle measurements vs. the energy scale μ are shown in red diamonds; the weak mixing angle running curve is reproduced from the PDG [16]. The $Q_W(APV)$ is the reanalysis of the ^{133}Cs atomic PV data [15]. The $Q_W(e)$ is the E158 result [7]. The original result of the NuTeV data [17] is shown. The proposed MOLLER measurement is shown at the appropriate μ value with the proposed error bar.*

The proposed MOLLER measurement will achieve a sensitivity of $\delta(\sin^2\theta_W) = \pm 0.00028$, the best projected sensitivity for weak mixing angle at low or high energy for the next decade. The neutral current interactions at low energies can be model independently parametrized using an effective four fermion couping. The Standard Model (SM) couping is characterized by fermi constant,G_F and

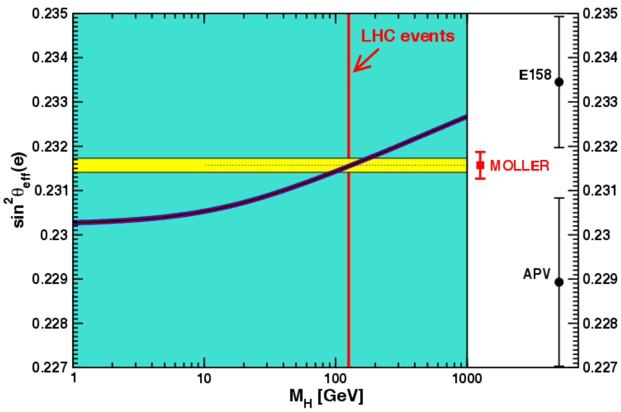

FIG. 3. $\sin^2\theta_W$ *vs* m_H. *The yellow band is the world average. The black points are the two most precise measurements at $Q^2 \ll M_Z^2$. The projected MOLLER error is shown in red [14].*

any new interactions by the quantity Λ/g, where g characterizes the strength and Λ is the scale of the new dynamics. The sensitivity to new physics beyond the SM using the projected 2.4% A_{PV} measurement from MOLLER can be shown,

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} \simeq 7.5 \text{ TeV}.$$

Where the new physics Lagrangian is characterized by coupling constants g_{ij} (chirality of the leptons) and mass scale Λ. MOLLER results will probe mass scales as large as 47 TeV assuming coupling constants are about 2π [2].

An important subset of beyond SM physics includes Minimal Supersymmetric Standard Model (MSSM) that could be observed through radiative loop effects [18]. MSSM effects are predicted to have signatures both at high energy collider (LHC) and in the MOLLER measurement. A light MeV-scale dark matter mediator known as the dark Z (Z_d) has been postulated to explain the dark matter and its interaction with SM particles. The Z_d can couple to SM particles via kinetic and mass mixing with the photon and the Z^o-boson. The Z_d boson is predicted to generate a new source of parity violation that can shift the weak mixing angle at low Q^2 [19]. The expected shift of the weak mixing angle due to dark sector mixing is shown in FIG 4 for Z_d masses of 100 and 150 MeV.

MOLLER experiment will provide the best projected uncertainty for the weak mixing angle at any energy scale with potential to discover new physics from MeV to few-TeV scales that are complimentary to direct searches at high energy colliders including at the LHC.

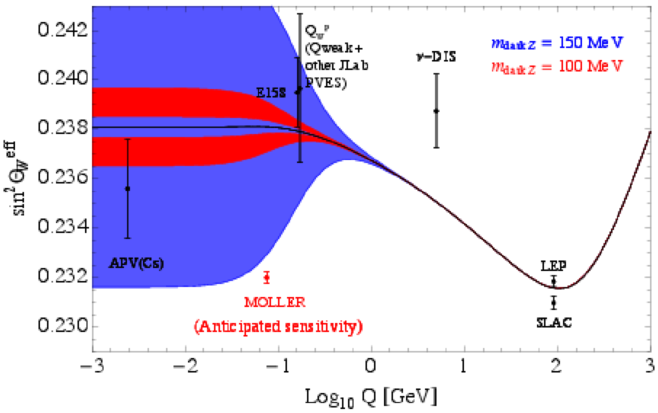

FIG. 4. *The potential deviations of* $\sin^2\theta_W(Q)$ *under a scenario for a light* Z_d *using two different masses (*100 and 150 MeV*). The projected error bar for the MOLLER measurement is shown at the appropriate Q value*

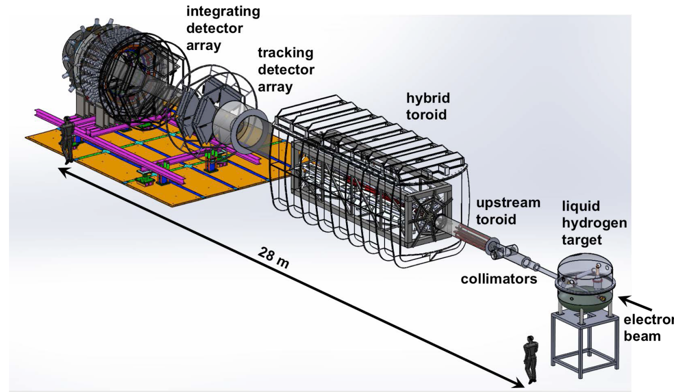

FIG. 5. Conceptual view of the MOLLER apparatus

III. MOLLER APPARATUS

The MOLLER apparatus will be built in Hall A at JLab. A highly polarized 11 GeV beam will be incident on a liquid hydrogen target. The scattered electrons are focused in to set of detectors using a spectrometer consisting of system of magnets for steering the scattered electrons, and collimators for defining the angular and radial acceptance. The spectrometer is an open geometry design in a toroidal configuration with 7-fold symmetry to achieve full azimuthal coverage. The conceptual view of the MOLLER apparatus is shown in the Figure 5 and main experimental parameters are listed in the Table I.

TABLE I. *Nominal design parameters for the MOLLER experiment.*

Parameter	Value
E [GeV]	$\approx$ 11.0
E' [GeV]	1.7 - 8.5
θ_{cm}	46°-127°
θ_{lab}	0.23°-1.1°
$< Q^2 >$ [GeV^2]	0.0058
Maximum Current [μA]	85
Target Length (cm)	150
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$3.4{\cdot}10^{39}$
σ [μBarn]	$\approx$ 40
Møller Rate [GHz]	$\approx$ 140
Statistical Width(2 kHz flip) [ppm/pair]	$\approx$ 83
Target Raster Size [mm]	5 x 5
ΔA_{raw} [ppb]	$\approx$ 0.6
Background Fraction	$\approx$ 0.09
P_{beam}	$\approx$ 85%
$< A_{pv} >$ [ppb]	$\approx$ 35
$\Delta A_{stat}/ < A_{expt} >$	2.0%
$\delta(\sin^2\theta_W)_{stat}$	0.00023

The JLab polarized source can routinely provide beam polarization around 90% with up to 200μA beam current. The MOLLER apparatus will be designed to accept maximum of 85 μA The polarized electrons are generated using laser-induced photoemission from a GaAs wafer, a techniques first developed at SLAC. The sign of the electron longitudinal polarization (helicity) is determined by the incident LASER and the polarization flip rate up to 2 kHz bunches has been tested. MOLLER experiment will use helicity time windows at 1.92 kHz and the helicity reversal will be done in pseudo-random basis to eliminate certain periodic random noises. Starting from the HAPPEX experiments, then PREX-I and Qweak have made important progress in understanding and controlling changes in the beam properties (intensity, position, profile). These Helicity-correlated beam asymmetries (HCBAs) must be kept below certain specifications for MOLLER experiment. The operational experience and lessons learned during PREX-I and Qweak as well as near fututre PREX-II running will guide towards reaching the expected MOLLER specifications for HCBA.

The 11 GeV polarized electrons will be incident on a liquid hydrogen (LH2) target that act as the source of target electrons for Møller scattering. To reach the statistical goal for parity violating asymmetry for Møller scattering, a maximum luminosity of $3.4{\times}10^{39}$ cm^{-2}sec^{-1} is required and this is achieved with a 150 cm LH2 target cell. The LH2 target will require a cryogenic system capable of handling a heat load of about 5 kW. This is about twice as large as the LH2 target for the Qweak experiment. Initial studies have shown that the E158 target design is the best starting point for the proposed LH2 target.

The MOLLER spectrometer consists of set of magnets to steer scattered electrons and set of collimators to define the angular and radial acceptance for the apparatus. The goal of the spectrometer is to focus Møller scattered electrons into a background minimized location where main set of detectors are placed using a set of resistive, water-cooled copper coils. The spectrometer has a 7-fold symmetry with 100% azimuthal acceptance for Møller electrons due to identical-particle scattering.

Electrons that are scattered to forward angles have corresponding backward angle scattered electrons. The spectrometer utilize this symmetry to accept the forward and backward angle scattered electrons in opposite sectors (FIG 6). A beam intercepting collimator and photon blocking collimator will minimize the electromagnetic radiation and neutrons reaching the detector region. Localized shielding around the target and the collimators will further reduce the background contribution to the detector area as well as radiation to the experimental hall.

The main parity violating (PV) asymmetry measurement for Møller scattering and PV asymmetry contribution due to background will be performed using an array of signal integrating detectors (main detectors). The MOLLER apparatus will consist many different detectors required for the main measurement as well as dedicated particle tracking configuration. The FIG 7 shows conceptual design of the main detector systems. The main detectors will be designed to operate in two modes, the main measurement mode and in an event counting mode for particle tracking. The spectrometer will focus scattered electrons into a plane 28.5 cm downstream of the target between 70 to 120 cm in radially with respect to the beam line center. The radial distribution of the scattered electrons is shown in the FIG 8. The Møller electrons are focused in to ring 5 (100 ± 16 cm). The elastic electron-proton events are focused to rings 1-3 and in 6 while inelastic e-p events peak in ring 2 with a long radiative tail. Detectors will be placed in all the rings to measure these electrons events and the main measurement will be done using Møller electrons from the ring 5. The detector rates at maximum beam current varies from 10 to 100 MHzcm^{-2} at the Møller and elastic e-p rings requiring to integrate the scattered electron signal of many events within a single helicity window. Internally reflecting Cerenkov light detectors based on artificial fused silica will be used for integrating detectors due to radiation hardness and low background sensitivity.

A supplemental energy weighted measurement of the Møller electrons at ring 5 will be performed using set of detectors (Shower-Max detectors) placed downstream of the main detector plane. These detectors will count electrons by inducing an electromagnetic shower and then detecting the Cerenkov light of the shower.

Simulation studies have shown about 0.1% pion and other hadron contamination at the Møller ring due to potentially large analyzing power to beam polarization. Therefore an auxiliary hadron (mainly pion) detection system will be located behind the main detectors that will provide hadron dilution and PV asymmetry. The detector system will consist of a calorimeter style hadron detector and particle tracking with Gas Electron Multipier (GEM) detectors.

Based on experience from previous PVES experiments, it is very important to monitor false asymmetries generated by primary scattered electron beam interacting with materials in downstream of the target (collimators, shielding, beam pipes and etc). Therefore scattered beam monitors (SMB) will be installed at various locations along the downstream beam pipe. These detectors will be similar to Shower-Max detectors discussed above.

The Cerenkov light from each radial bin detector will be read using quartz glass photomultiplier tubes (PMT) with a high quantum efficiency (QE) in the UV region (peak at 280 nm). A preamplifier system will be used to convert the PMT output current to a voltage signal and send to the data acquisition system based on custom ADCs. The DAQ will sample the detector signal over the helicity period to produce a mean, a RMS and minimum/maximum for that time period.

A particle tracking system that only works at very low beam current (about 100 pA) will be installed within the MOLLER apparatus. The main detectors will be reconfigured to detect single events at low beam current while two pairs of GEM detectors will be inserted into the acceptance at downstream of the MOLLER spectrometer. The GEM detectors will be capable of rotating to the each of the seven azimuthal acceptance. The tracking system will provide background evaluation, background dilutions, spectrometer optics, and kinematical factors relevant for extracting the PV asymmetry. A focal plane scanner operable at both main measurement and at tracking mode will measure the scattered electron rate distribution across the one of the seven azimuthal acceptance at the detector plane. Such detector was developed for many different previous PVES experiments including the Qweak experiment [20].

The electron beam polarization is required to be measured to about 0.4% precision while continuously monitoring for variation in time due to the measured PV asymmetry is proportional to the electron beam polarization. The Hall A Compton polarimeter [21] will provide the non-destructive continuous measurements and the Hall A Møller polarimeter will provide high precision cross check for the Compton polarimeter. Compton polarimeter will a receive detector upgrade and progress towards the reduction of the systematic errors before the MOLLER experiment. The main challenge for the Møller polarimeter is to control systematic effects to reach high precision required for the MOLLER experiment.

The projected statistical error and estimated systematics errors are summarized in the Table II

IV. OUTLOOK AND SUMMARY

The 2007 and 2015 long range plan reports [22, 23] discussed MOLLER experiment as an opportunity for new sensitive indirect probe beyond SM that fit into Fundamental Symmetries subfield. One of the important question that defines this subfield is: "What are the unseen forces that were present at the dawn of the universe but disappeared from view as the universe evolved?". As an important part of addressing this question and ad-

TABLE II. *Summary of projected relative statistical and systematic errors.*

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	0.3
Transverse polarization	0.2
Neutral background (soft photons, neutrons)	0.1
Total systematic	**1.1**

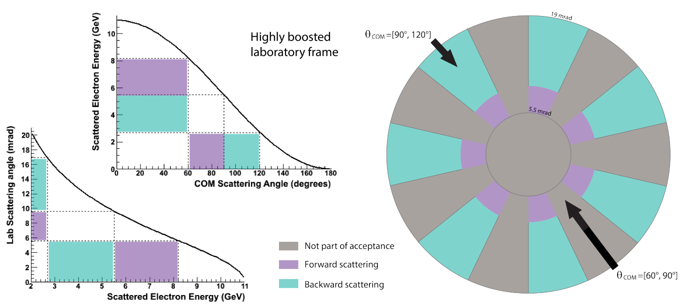

FIG. 6. *Left:center of mass (COM) and lab frame scattering angle vs. scattered electron energy for $E_{beam} = 11$ GeV are illustrated in the two plots. Right: Using the primary acceptance collimator design, a 100% acceptance is achieved for each azimuthal sector (ϕ).*

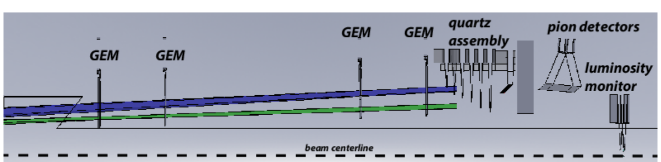

FIG. 7. *The main integrating and tracking detector layout is shown. An elastically scattered electrons from target protons (green) and Møllerelectrons (blue) are also shown.*

dressing one of the principal recommendation regarding capitalization of the CEBAF upgrade at Jefferson Lab (JLab), 2015 NSAC long range plan advocated for new investments including MOLLER experiment. MOLLER experiment has received the highest rating from the JLab Program Advisory Committee (PAC) when the experiment was first proposed in 2009. The JLab then organized the director's review chaired by Charles Prescott [9] in 2010 which endorsed the MOLLER experiment. The NSAC subpanel on the implementation of the Long Range Plan (the Tribble Subcommittee)[10] has strongly

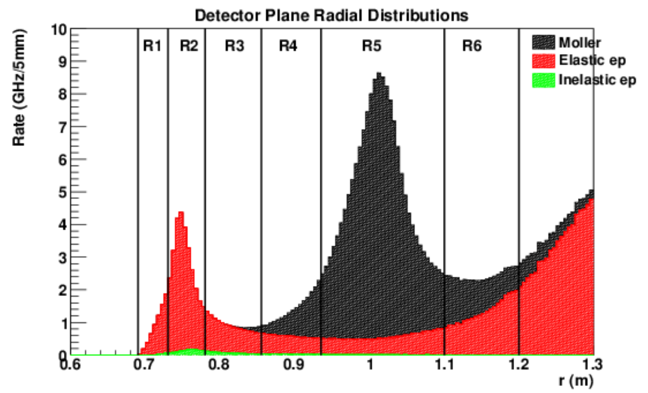

FIG. 8. *Radial distribution of Møller (black), ep elastic (red), and ep inelastic electrons at 28.5 m downstream of the target. The vertical black lines separate the proposed radial segmentation into 6 rings (R1 through R6). The main asymmetry measurement will be carried out in ring R5.*

endorsed the experiment in 2012 as an important investments for the fundamental symmetries. The science review of the MOLLER experiment was conducted by DOE in 2014 and collaboration is currently undergoing a review of the technical feasibility of the proposed measurement. Over 120 collaborators from 30 institutions from 6 countries currently provide pre-R&D activities expecting construction funding approval will be obtained by fiscal year 2018. According to current plan construction and installation is expected to be completed in 2020. The experimental commissioning and first physics data could then be expected by the end of 2020.

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