The MOLLER Experiment
Measurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction

An Ultra-precise Measurement of the Weak Mixing Angle
using Møller Scattering

E12-09-005 Update submitted to PAC 49

The MOLLER Collaboration
(https://moller.jlab.org/DocDB/0007/000757/002/210616_MOLLER_Collaboration.pdf)

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Executive Summary

The MOLLER experiment is designed to measure the parity-violating asymmetry A_{PV} in polarized electron-electron (Møller) scattering. In the Standard Model, A_{PV} arises from the interference between the electromagnetic amplitude and the weak neutral current amplitude, the latter being mediated by the Z^0 boson. The goal is to measure A_{PV}, predicted to be ≈ 33 parts per billion (ppb) at our kinematics, to an uncertainty of 0.8 ppb. The result would yield a measurement of the weak charge of the electron Q^e_W to a fractional uncertainty of 2.4% at an average Q^2 of 0.0056 GeV^2. With the sensitivity to the interference of the electromagnetic amplitude with new neutral current amplitudes as weak as $\sim 10^{-3} \cdot G_F$ from as yet undiscovered dynamics beyond the Standard Model, MOLLER's discovery reach is unmatched by any proposed experiment measuring a flavor- and CP-conserving process in the foreseeable future. The result would thus provide a unique window to new physics from MeV to multi-TeV scales, complementary to direct searches at high energy colliders.

The conceptual design of the experiment and the physical parameters of the apparatus including the polarized instantaneous luminosity, analyzing power and overall statistical and systematic goals are largely unchanged since the last update to PAC37. Substantial progress has been made in retiring technical risk and in developing a preliminary engineering design of the apparatus in recent years. The science motivation was reviewed by the Office of Nuclear Physics at the Department of Energy (DOE) in September 2014 and DOE Mission Need (CD-0) was awarded in December 2016. Director's reviews in December 2016 and April 2019 monitored technical progress and reviewed cost and schedule estimates. A project team to manage the construction of the apparatus was put in place beginning in January 2019.

The principal funding for the apparatus is via a DOE Major Item of Equipment (MIE) project, which was awarded CD-1 status in December 2020 with a cost range of 42M$ to 60M$. Two other major sources of funding are now also in place, namely an NSF Physics Midscale Award and a Canadian Foundation for Innovation (CFI) Award. The DOE MIE project team has overall oversight responsibility for the construction project. Broadly speaking, the DOE MIE funding delivers the quantum state to be measured i.e. the requisite flux (~ 134 GHz) of Møller scattered electrons focused into a background-free region, and the laboratory infrastructure required to carry out the A_{PV} measurement. The CFI award funds the detectors and electronics that will measure the relative scattered flux with the required precision (~ 91 ppm in 1 ms) while the NSF award funds the auxiliary and diagnostic tools required to calibrate the signal and irreducible backgrounds and validate the requisite normalization accuracy (1.1%) on A_{PV}.

The project team is integrated into a strong collaboration that has extensive experience in previous successful measurements using similar techniques. A comprehensive set of physics requirements has been developed and led to the conceptual design that forms the basis for the development and execution of the construction project. The collaboration is working intensively on the engineering design, and looking forward to the construction and deployment of the apparatus and to data collection and analysis at the completion of the MIE project. Project planning calls for achieving CD-2 status in late 2022 and completion of construction by mid-2024 to be ready for installation when Hall A is available. Current funding profile guidance from DOE, NSF and CFI is consistent with such a technically-driven schedule, which would result in the start of experiment commissioning in the latter half of 2025.

1 Science Motivation

1.1 Physics Context

The MOLLER experiment [1, 2] proposes to significantly expand the sensitivity reach to discover new dynamics beyond the Standard Model of electroweak interactions both at low energy scales ($\sim$ 100 MeV) as well as at high energy (multi-TeV). It is one of a small handful of projects worldwide designed to carry out ultra-precise measurements of electroweak observables well below the scale of electroweak symmetry breaking, and which are theoretically calculable to high accuracy. Specifically, MOLLER measures the parity-violating asymmetry A_{PV} in the scattering of longitudinally polarized electrons off unpolarized electrons, using the 11 GeV beam in Hall A at Jefferson Laboratory (JLab), to an overall fractional accuracy of 2.4%. Such a result would constitute more than a factor of five improvement in fractional precision over the only other measurement of the same quantity by the E158 experiment at SLAC [3].

A_{PV} in Møller scattering is directly proportional to the weak charge of the electron Q^e_W, which is in turn proportional to the product of the electron's vector and axial-vector couplings to the Z^0 boson. The electroweak theory prediction at tree level in terms of the weak mixing angle is $Q^e_W = 1 - 4\sin^2\theta_W$; this is modified at the 1-loop level [4–6] and becomes dependent on the energy scale at which the measurement is carried out, *i.e.* $\sin^2\theta_W$ "runs". The prediction for A_{PV} for the proposed experimental design is ≈ 33 parts per billion (ppb) and the goal is to measure this quantity with an overall uncertainty of 0.8 ppb and thus achieve a 2.4% measurement of Q^e_W. Under the assumption of a SM Higgs boson mass of 126 GeV, the theoretical prediction for the MOLLER A_{PV} is calculable to better than 0.2 ppb accuracy. The purely leptonic Møller A_{PV} is a rare low-energy observable whose theoretical uncertainties, especially due to hadronic effects, are well under control.

The electron beam energy, luminosity and stability at Jefferson Laboratory are uniquely suited to carry out such a measurement. The 11 GeV JLab beam provides a compelling new opportunity to achieve a new benchmark in sensitivity. The physics motivation has two important aspects:

1. New neutral current interactions are best parameterized model-independently at low energies by effective four-fermion interactions using the quantity Λ/g, where g characterizes the strength and Λ is the scale of the new dynamics. The proposed A_{PV} measurement is sensitive to interaction amplitudes as small as 1.5×10^{-3} times the Fermi constant, G_F, which corresponds to a sensitivity of $\Lambda/g = 7.5$ TeV. A coupling g of order one probes the TeV scale with new and unique sensitivity, while for $\Lambda \sim 100$ MeV, there is extraordinary new sensitivity approaching $10^{-3} \cdot \alpha_{QED}$. This would be *the* most sensitive probe of new flavor and CP-conserving neutral current interactions in the leptonic sector until the advent of a linear collider or a neutrino factory, and would have 5σ discovery potential in the discovery space allowed within the existing most stringent low and high energy constraints.

2. Within the Standard Model, weak neutral current amplitudes are functions of the weak mixing angle $\sin^2\theta_W$. The two most precise independent determinations of $\sin^2\theta_W$ differ by 3σ. The world average is consistent with the theoretical prediction for the weak mixing angle assuming the 126 GeV scalar resonance observed at the LHC is the Standard Model (SM) Higgs boson. However, choosing one or the other central value ruins this consistency and implies very different new high-energy dynamics. The proposed A_{PV} measurement, which would achieve a sensitivity of $\delta(\sin^2\theta_W) = \pm 0.00028$, has the same level of precision and interpretability: the best among projected sensitivities for new measurements at low Q^2 or at colliders over the next decade.

1.2 Precision Goal

The parity-violating asymmetry in the scattering of longitudinally polarized electrons on unpolarized target electrons A_{PV}, due to the interference between the photon and Z^0 boson exchange diagrams is given at tree level by [7]

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q^e_W = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q^e_W \tag{1}$$

where Q^e_W is the weak charge of the electron (proportional to the product of the electron's vector and axial-vector couplings to the Z^0 boson), α is the fine structure constant, E is the incident beam energy, m is the electron mass, θ is the scattering angle in the center of mass frame, $y \equiv 1-E'/E$ and E' is the energy of one of the scattered electrons. The experimental apparatus is designed for full acceptance of Møller-scattered electrons in the range $0.3 < y < 0.7$, leading to $A_{PV} \sim 34$ ppb for a 11 GeV beam.

The electroweak theory prediction at tree level in terms of the weak mixing angle is $Q^e_W = 1-4\sin^2\theta_W$; this is modified at the 1-loop level [4–6] and increases by approximately 3% compared to its value at the scale of the Z^0 boson mass, M_Z; this and other radiative corrections reduce Q^e_W to 0.0435, a $\sim 42\%$ change of its tree level value of ~ 0.075 (when evaluated at M_Z). The consequent reduction in the numerical value of Q^e_W leads to increased fractional accuracy in the determination of the weak mixing angle, $\sim 0.1\%$, matching the precision of the single best such determination from measurements of asymmetries in Z^0 decays in the $\mathrm{e}^+\mathrm{e}^-$ colliders LEP and SLC.

The proposed MOLLER measurement will make a precision (2.4% relative) measurement of a suppressed Standard Model observable ($Q^e_W \sim 0.0435$) resulting in sensitivity to new neutral current amplitudes as weak as $\sim 10^{-3} \cdot G_F$ from as yet undiscovered dynamics beyond the Standard Model. The fact that the proposed measurement provides such a sensitive probe of TeV-scale dynamics beyond the SM (BSM) is a consequence of a very precise experimental goal ($\sim 10^{-3} \cdot G_F$), the energy scale of the reaction ($Q^2 \ll M_Z^2$), and the ability within the electroweak theory to provide quantitative predictions with negligible theoretical uncertainty. The proposed measurement is likely the only practical way, using a purely leptonic scattering amplitude at $Q^2 \ll M_Z^2$, to make discoveries in important regions of BSM space in the foreseeable future at any existing or planned facility worldwide.

An important point to note is that, at the proposed level of measurement accuracy of A_{PV}, the Standard Model (SM) prediction must be carried out with full treatment of one-loop radiative corrections and leading two-loop corrections. The current uncertainty associated with radiative corrections for MOLLER is estimated to be less than 0.5 ppb [13], smaller than the expected 0.8 ppb overall precision. There has been recent progress to investigate several classes of diagrams beyond one-loop [14, 15], and ongoing efforts are studying the complete set of two-loop corrections at MOLLER kinematics; such corrections are already estimated to be smaller than the statistical uncertainty goal for MOLLER. The theoretical uncertainties for the purely leptonic Møller PV are thus well under control, and the planned future work will aim to reduce the uncertainty on the A_{PV} prediction, including the effects of the apparatus, to less than 0.2 ppb.

1.3 Summary of Physics Motivation

1.3.1 Electroweak Physics

The weak mixing angle $\sin^2\theta_W$ has played a central role in the development and validation of the electroweak theory, especially testing it at the quantum loop level, which has been the central focus of precision electroweak physics. A key feature of MOLLER is that the A_{PV} measurement will be carried out at $Q^2 \ll M_Z^2$. Since $\sin^2\theta_W$ "runs" as a function of Q^2 due to electroweak radiative corrections, one can use $\sin^2\theta_W$ as a bookkeeping parameter to compare the consistency of the full Q^2 range of weak neutral current measurements, as shown in Fig. 1. The theory error in the low energy extrapolation is comparable to the width of the line in the figure [6]. MOLLER A_{PV} would be the first low Q^2 measurement to match the precision of the single best high energy measurement at the Z^0 resonance. The proposed MOLLER A_{PV} measurement would achieve a sensitivity of $\delta(\sin^2\theta_W) = \pm 0.00028$. That is the most precise anticipated weak mixing angle measurement currently proposed over the next decade at low or high energy.

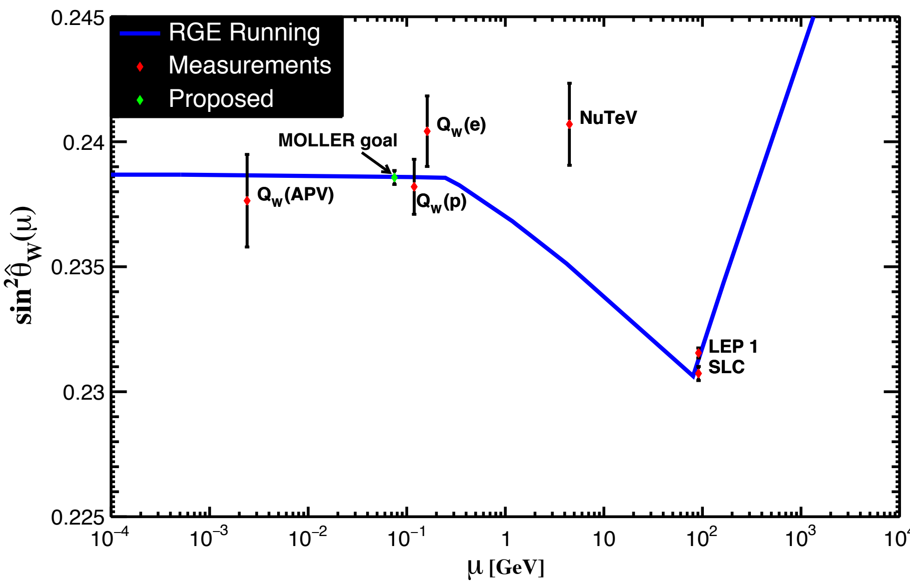

Figure 1: *The four most precise measurements of the weak mixing angle measurements vs. the energy scale μ are shown as red diamonds with error bars; the curve is reproduced from the PDG [8]. The APV point reflects the reanalysis of the original result [9] in Ref. [10]. The $Q_W(e)$ point is the E158 result [3]. The $Q_W(p)$ point is the $\mathrm{Q_{weak}}$ result [11]. The NuTeV point is the extracted value from the original publication result [12]. The proposed MOLLER measurement is shown at the appropriate μ value and the proposed error bar with the nominal SM prediction as the central value.*

1.3.2 New Physics Beyond the Standard Model

The MOLLER experiment measures a unique observable with a precision goal that would result in the most sensitive discovery reach for flavor- and CP- conserving scattering amplitudes in the next decade; see recent reviews that situate the measurement in broader contexts [16–18]. It is very complementary to other precision low-energy experiments and the energy frontier efforts at the LHC. If the LHC continues to agree with the Standard Model with high luminosity running at the full 14 TeV energy, then MOLLER will be a significant component of a global strategy to discover signatures of a variety of physics that could escape LHC detection. Examples include hidden weak-scale scenarios such as compressed supersymmetry [19], lepton-number violating amplitudes such as those mediated by doubly charged scalars [20], and light MeV-scale dark matter mediators such as the "dark" Z [22, 23].

If the LHC observes an anomaly, then MOLLER will have the sensitivity to be part of a few select measurements that will provide important constraints to choose among possible beyond the Standard Model (BSM) scenarios to explain the anomaly. Examples of such BSM scenarios that have been explicitly considered for MOLLER include: new particles predicted by the Minimal Supersymmetric Standard Model observed through radiative loop effects (R-parity conserving) or tree-level interactions (R-parity violating) [24, 25] and TeV-scale Z's [26] which arise in many BSM theories.

A fairly general and model-independent way to quantify the energy scale of BSM high-energy dynamics (that MOLLER is sensitive to) is to express the resulting new amplitudes at low energies in terms of contact interactions (dimension-6 non-renormalizable operators) among leptons and quarks [27]. Specializing here to vector and axial-vector interactions between electrons and/or positrons, the interaction Lagrangian is characterized by a mass scale Λ and coupling constants g_{ij} labeled by the chirality of the leptons. For the MOLLER A_{PV} measurement with 2.4% total uncertainty (and no additional theoretical uncertainty) the resulting sensitivity to new 4-electron contact interaction amplitudes can be expressed as:

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} \simeq \frac{246.22 \text{ GeV}}{\sqrt{0.023 Q_W^e}} = 7.5 \text{ TeV}. \quad (2)$$

For example, models of lepton compositeness are characterized by strong coupling dynamics. Taking $\sqrt{|g_{RR}^2 - g_{LL}^2|} = 2\pi$ shows that mass scales as large as $\Lambda = 47$ TeV can be probed, far beyond the center of mass energies of any current or planned high energy accelerator. This allows electron substructure to be studied down to the level of 4×10^{-21} m.

The remarkable feature of the MOLLER sensitivity to four-lepton flavor-conserving contact interactions has been emphasized [28]. Not only does the contact interaction scale reach exceed those at LEP-200, the highest energy electron-positron collider to collect data, but there is unique sensitivity to a specific linear combination of left- and right-handed four electron operators to which all other collider measurements happen to be insensitive. Indeed, in the current global analysis, the E158 result [3] is used to break the degeneracy. The MOLLER measurement will allow the extension of the current limits for these operators from about 2 TeV to more than 7 TeV.

The importance of improving sensitivity over the entire multi-dimensional space of new operators is particularly important if higher sensitivity searches at the LHC yield no new discoveries. For example, in hidden weak-scale scenarios such as compressed supersymmetry [19], one of the superpartner masses could be relatively light, likely if the super-partner masses are nearly degenerate. In that scenario, the LHC signatures would be very challenging to disentangle from QCD backgrounds. Another example is a lepton number violating amplitude mediated by doubly-charged scalars. The MOLLER measurement is one of the rare low Q^2 observables with sensitivity to such amplitudes, which naturally arise in extended Higgs sector models containing complex triplet representations of SU(2). In a left-right symmetric model, for example, the proposed MOLLER measurement would lead to the most stringent probe of the left-handed charged scalar and its coupling to electrons, with a reach of 5.3 TeV, significantly above the LEP 2 constraint of about 3 TeV. Moreover, such sensitivity is complementary to other sensitive probes such as lepton-flavor violation and neutrinoless double-beta decay searches [20, 21].

Finally, the interesting possiblity of a light MeV-scale dark matter mediator known as the “dark” Z [22, 23] has been recently investigated. It is denoted as Z_d with mass m_{Z_d}, and it stems from a spontaneously broken $U(1)_d$ gauge symmetry associated with a secluded “dark” particle sector. The Z_d boson can couple to SM particles through a combination of kinetic and mass mixing with the photon and the Z^0-boson, with couplings ε and $\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$ respectively. In the presence of mass mixing ($\delta \neq 0$), a new source of “dark” parity violation arises [22] such that it has negligible effect on other precision electroweak observables at high energy, but is quite discernable at low Q^2 through a shift in the weak mixing angle [23].

In summary, the discovery reach of the proposed MOLLER experiment is unmatched by any proposed experiment measuring a flavor- and CP-conserving process over the next decade. It results in a unique window to new physics at MeV and multi-TeV scales, complementary to direct searches at high energy colliders such as the Large Hadron Collider (LHC).

2 Experiment Overview

The MOLLER experiment (E12-09-005) was approved by PAC34 [31] in January 2009. An update was presented to PAC37 [32] in January 2011, resulting in a scientific rating of A and a beamtime allocation of the full request of 344 PAC days. Since that time, the collaboration and project team have made substantial progress in retiring technical risk and developing a preliminary engineering design of the apparatus. The project has undergone numerous reviews, a full project structure has been developed, and funding has been allocated. A comprehensive set of documents related to the experiment (including all of the documents mentioned in the text below) can be found at the website [33] prepared for the recent DOE Office of Project Assessment CD-1 review of the MOLLER project.

2.1 Reviews, Funding, and Collaboration Structure

Since the last update to PAC37, the experiment and the project established for the construction of the MOLLER apparatus have been reviewed on numerous occasions. A summary is presented below.

- September 2014: Science Review organized by the DOE Office of Nuclear Physics - endorsed the goals of the MOLLER experiment and emphasized the strong and unique science impact
- December 2016: Jefferson Lab Director's review focused on physics, technical and project aspects - this review was followed by the award of DOE Mission Need (CD-0) in December 2016
- April 2019: Jefferson Lab Director's review focused on technical readiness, risk assessment and cost
- November-December 2019: Internal MOLLER Cost Review and Conceptual Design Review
- January 2020: Jefferson Lab Director's review focused on evaluating whether the project was ready to move to the next stage of preliminary design towards CD-2
- August 2020: Jefferson Lab Director's review to assess the readiness of the MOLLER project for the anticipated DOE CD-1 review
- October 2020: DOE OPA CD-1 review - review to determine if the project had fulfilled the requirements for CD-1; Alternative Selection and Cost Range approval was awarded in December 2020

Funds for construction of the MOLLER apparatus have been obtained from three sources, with the principal funding coming from DOE and two other major sources of funding from the Canadian Foundation for Innovation (CFI) and the National Science Foundation (NSF). Each agency is funding well-defined subsystems of the experiment that have critical roles to achieve a successful measurement.
• **DOE Major Item of Equipment (MIE)** provides the infrastructure and Hall apparatus (beamline, target, spectrometer, shielding) to prepare the quantum state to be measured: requisite flux of scattered Møller electrons directed to a background-free region. The current point estimate is $48.2M including contingency.
• **Canadian Foundation for Innovation (CFI) and Research Manitoba (RM)** provides the apparatus (fused silica integrating detectors and the associated electronics chain) to measure the raw Møller flux asymmetry and achieve the requisite statistical error. The grant was awarded for $3.7M (USD) in March 2021.
• **NSF Physics Division Midscale** provides the apparatus for the Normalization and Systematic Control needed to achieve the systematic error goals. The grant was awarded for $5.7M in March 2021 for the construction of the tracking system, background detectors, main detector mechanics, auxiliary asymmetry measurements, the data acquisition system, and certain aspects of beam monitoring and polarimetry.

The organization structure for the MOLLER experiment is shown in Fig. 2. The spokesperson is Krishna Kumar (UMass, Amherst) and the DOE MIE project manager is Jim Fast (JLab). Members of the collaboration have been designated as Technical Leads and Experimental Contacts within the MIE project. They are for the various subsystems: Target (D. Meekins), Spectrometer (J. Mammei), Integrating Detectors (M. Gericke), Tracking Detectors (D. Armstrong), Hall Infrastructure and Integration (C. Gal and D. McNulty), DAQ/Online (P. King), Beam Diagnostics/Monitoring (M. Pitt), Offline (R. Beminiwattha), Polarized Beam (G. Cates), Polarimetry (K. Paschke).

The collaboration has a Working Group (WG) structure with conveners. The current focus is on the physics requirements and subsequent focus will be on individual subsystem commissioning and performance once the construction project is completed. These working groups and conveners are Polarized Source (G. Cates - Virginia and K. Paschke- Virginia), Beam Instrumentation (M. Pitt - Virginia Tech), Hydrogen Target (S. Covrig - JLab), Spectrometer (J. Mammei - Manitoba), Integrating Detectors (M. Gericke - Manitoba and D. McNulty - Idaho State), Tracking Detectors (D. Armstrong - William and Mary and N. Liyanage - Virginia), Hall Integration (C. Gal - Stony Brook, D. McNulty - Idaho State and P. Souder - Syracuse), Polarimetry (K. Paschke - Virginia and J. Napolitano - Temple), Electronics/DAQ/Offline (P. King - Ohio and R. Michaels - JLab), Simulations (R. Beminiwattha - Louisiana Tech), and Physics Extraction (Y. Kolomensky - UC Berkeley).

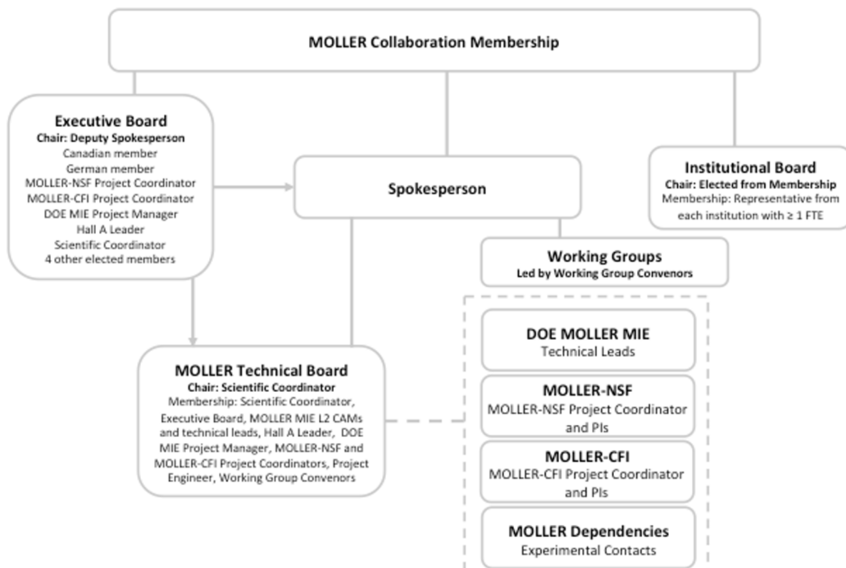

Figure 2: *MOLLER collaboration organization and the construction project: solid lines describe oversight from the box above; arrows indicate advisory input. Lab Management and Funding Agencies oversee the self-contained project within the dashed box; the Technical Board is the principal line of communication.*

2.2 MOLLER Apparatus Update

The 11 GeV longitudinally polarized electron beam in Hall A will be incident on a 1.25 m liquid hydrogen target. Møller electrons (beam electrons scattering off target electrons) in the full range of the azimuth and spanning the polar angular range 5 mrad $< \theta_{lab} <$ 21 mrad, are separated from background and brought to a ring focus $\sim$ 26.5 m downstream of the target by a spectrometer system consisting of precision collimators and a pair of toroidal magnet assemblies. The Møller ring is intercepted by a system of fused silica detectors; the resulting Cherenkov light provides a relative measure of the scattered flux. The experimental techniques for producing an ultra-stable polarized electron beam, relative scattered flux measurement at counting statistics, systematic control at the ppb level, and sub-percent normalization control including the longitudinal electron beam polarization have been continuously improved over two decades of development at Jefferson Lab. A list of the nominal parameters that characterize this design is shown in Table 1. A complete description of the conceptual design can be found in the MOLLER Conceptual Design Report [34].

The minimum data needed to form an asymmetry are two adjacent data samples with opposite electron beam helicities at the planned 1.92 kHz data-taking rate. This is referred to as a pulse-pair asymmetry, and

Table 1: *Nominal parameters for the conceptual design of the MOLLER experimental apparatus.*

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
θ_{cm}	50°-130°
θ_{lab}	0.26°-1.2°
$< Q^2 >$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
Møller Rate @ 65 μA [GHz]	≈ 134
Statistical Width(1.92 kHz flip) [ppm/pair]	≈ 91
Production running time	344 PAC-days = 8256 hours
ΔA_{raw} [ppb]	≈ 0.54
Background Fraction	≈ 0.10
P_{beam}	$\approx 90\%$
$< A_{pv} >$ [ppb]	≈ 32
$\Delta A_{stat}/ < A_{expt} >$	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.00023

the width of this distribution is what determines the statistical uncertainty on the asymmetry after averaging over all pairs. The experiment is designed to keep all sources of random noise small compared to the counting statistics width of 82 ppm, associated with the number of scattered electrons counted at design luminosity in a pulse pair. The projected random noise width for the conceptual design is 91 ppm.

The raw asymmetry is corrected for correlations with beam fluctuations and leakage from residual transverse polarization to yield the measured asymmetry, which is in turn corrected for background processes, beam polarization, and a normalization factor accounting for the kinematic factor and radiative corrections. The projected systematic uncertainties associated with these corrections are shown in Table 2. The resulting total error uncertainty on the parity-violating asymmetry, dominated by statistical fluctuations, is 2.4%.

A layout of the MOLLER apparatus to be placed in Hall A at JLab is shown in Fig. 3. Here we briefly describe the function of each subsystem.

- **Polarized Beam:** MOLLER relies on delivery of up to 70 μA of 90% longitudinally polarized, 11 GeV beam. The desired output was exceeded at Jefferson Lab during the $\mathrm{Q_{weak}}$ experiment [11], where ~ 180 μA of $\sim 89\%$ polarized beam was routinely delivered.
- **Beam Polarimetry:** Precision electron beam polarimetry at the level of 0.4% is required. A Compton polarimeter will provide a continuous measure of the beam polarization and will be cross-checked with periodic measurements with a Møller polarimeter using ferromagnetic foil targets.
- **Liquid Hydrogen (LH2) and Solid Targets:** The 125 cm long LH2 target requires a cryogenic system capable of handling ~ 4.0 kW, the highest-power LH_2 target to be ever constructed. It will build on the experience with the $\mathrm{Q_{weak}}$ target, which successfully operated up to 180 μA with a total power of 2.9 kW. Numerous auxiliary targets will facilitate optics, background and normalization calibrations.
- **Spectrometer:** The subsystem, consisting of 7-fold symmetry toroidal magnets and collimators, defines the acceptance and optimizes the signal to background ratio while facilitating the deconvolution of the Møller asymmetry from raw asymmetry measurements that include irreducible and soft backgrounds.
- **Tracking Detectors:** The tracking system provides the diagnostics to calibrate the primary detectors,

Table 2: *Summary of projected fractional statistical and systematic errors on the parity-violating asymmetry.*

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

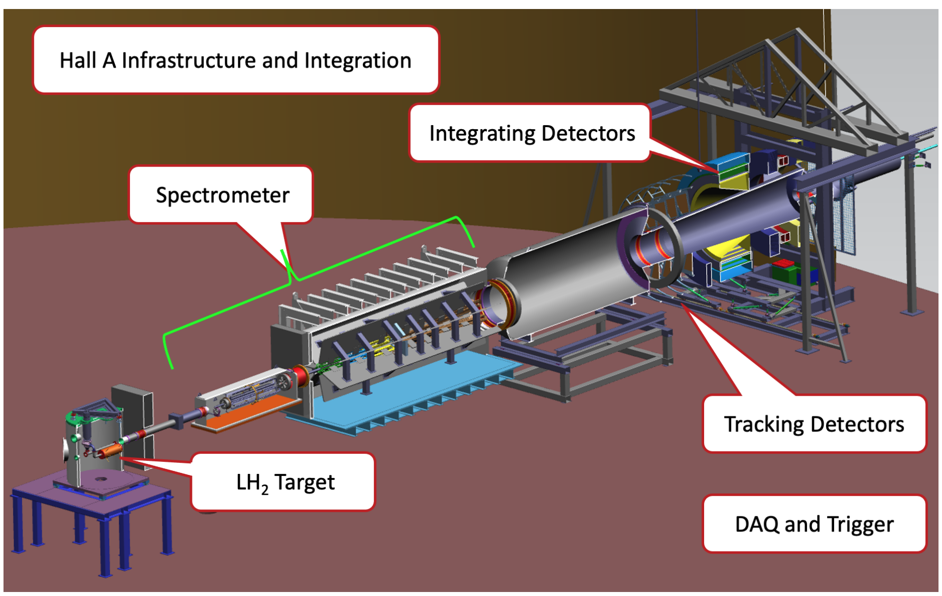

Figure 3: *MOLLER Experimental Apparatus Overview: Layout of the target, spectrometer, and detectors.*

the spectrometer optics, and the background processes over the full relevant radial and azimuthal ranges. It also provides the capability to measure the acceptance function of the primary Møller-scattered electrons. It consists of Gas Electron Mulitplier (GEM) detectors, trigger scintillators, pion detectors based on acrylic Cherenkov detectors, and scanner systems.

• **Main Integrating Detectors:** This array of fused silica ("quartz") tiles operates at full beam current and provides full azimuthal and radial coverage of the scattered flux, with segmentation optimized to facilitate deconvolution of signal and background asymmetry contributions. An integrating quartz-tungsten electromagnetic sampling calorimeter array behind the Møller ring provides a redundant asymmetry measurement.

Run Period	1kHz Width (ppm)	% Stat. Error	Stat. Error (ppb)	PAC Days (Prod.)	Eff. %	Notional Calendar Weeks (Prod.)	Notional Comm. Weeks	Notional Total Weeks
I	101	11.4	2.96	14	40	5	6	11
II	96	4.2	1.08	95	50	27	3	30
III	91	2.5	0.65	235	60	56	4	60
		2.1	0.55	**344**			**13**	101

Table 3: *Summary of the estimated beam time and projected performance (65 μA, $P_e = 90\%$).*

- **Data Acquisition and Trigger:** This subsystem allows for operation in both the high beam-current integrating mode and low beam-current counting mode. The integrating mode DAQ system primarily interfaces with the integrating ADC modules to record the detector and beam monitor signals during high current physics data collection. The counting mode DAQ is used for low beam-current measurements in which individual electron-scattering events can be recorded.
- **Beam Diagnostics and Monitoring:** Beam position and intensity are measured with existing beamline monitors, with improvements planned for the beam intensity measurements. A beam modulation system is used to generate controlled variations in the position, angle, and energy of the electron beam to measure the response of the detection system to those variations. Scattered beam monitors are deployed to monitor potential false asymmetries from background resulting from primary scattered beam interactions in downstream collimators, beampipe, and shielding.
- **Infrastructure and Integration:** The MOLLER experiment will be installed and collect data in experimental Hall A along with the requisite upgrades integrated into the existing infrastructure.

2.3 Timeline

Since DOE CD-1 approval, the collaboration and project team are in the engineering design phase with the goal of achieving CD-2 status in late 2022. In the project schedule, completion of the construction of the apparatus is expected in mid-2024, to be ready for installation at about the currently anticipated time that Hall A will become available. Installation planning is part of the current effort; the technically driven schedule is expected to result in the ability to start experiment commissioning in the second half of 2025.

While the MOLLER apparatus is being designed for a beam current of 70 μA at 11 GeV, JLab management has requested that we assume a beam current of 65 μA and a beam polarization of 90% to project performance. In order to ensure the technical success of this challenging measurement, the collaboration developed a notional run plan divided into three separate run periods as shown in Table 3. These run periods ensure that not only important technical milestones are met, but also that each run will provide publishable results that will significantly add to our knowledge of electroweak physics. For example, the precision from the short Run Period 1 is comparable to the precision of the published E158 result [3]. An important constraint is the need for a 3 - 5 month break between Run Period 1 and 2 in order to allow time to study the data for unexpected asymmetry background sources and plan for any required modifications. The total allotted time of 344 PAC days for production running and 13 commissioning weeks over the three running periods notionally totals just over 100 weeks, which can be accommodated in 3 years.

References

[1] MOLLER Experiment Homepage:

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