• Moller scattering: intro
• Previous measurement: SLAC E158
• MOLLER: new physics reach
• Experimental Concept and Challenges
• Status & Timeline

Many slides courtesy of K. Kumar, K. Paschke, J. Mammei, M. Dalton, etc....
Moller Scattering

MOLLER: Measurement Of Lepton Lepton Elastic Reaction
Proposed new experiment at 11 GeV at Jefferson Lab (after the upgrade)

Measure target weak vector coupling = weak charge: $Q_W^e$

$$A_{PV} = -m_e E_{lab} \frac{G_F}{\sqrt{2\pi\alpha}} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q_W^e$$

Derman and Marciano (1978)

$A_{PV} = \frac{N_R - N_L}{N_R + N_L} \propto m_e E_{lab} (1 - 4 \sin^2 \theta_W)$

$$\frac{\delta(\sin^2 \theta_W)}{\sin^2 \theta_W} \approx 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

Purely leptonic probe
- no hadronic corrections
- complementary to semileptonic expts
- Spokespersons: E. Hughes, K. Kumar, P. Souder
- Stanford Linear Accelerator Center (SLAC): used 45 and 48 GeV e\(^-\) beams
- electron beam \(\approx 80\%\) polarized (longitudinal) 120 Hz 11 μA
- 3 data-taking runs: 2002-2003
- \(A_{PV} \approx 130\) ppb (280 ppb at tree level)

\[ A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9} \]

*Phys. Rev. Lett.* **95** 081601 (2005)
E158: Implications

Running of $\sin^2 \theta_W$ established at 6σ level

if BSM physics: “bookkeeping” plot

doubly charged scalar exchange $0.01 \cdot G_F$
Flavor Diagonal Interactions

Consider \( f_i f_1 \rightarrow f_2 f_2 \) or \( f_i f_2 \rightarrow f_1 f_2 \)

\[
L_{f_i f_2} = \sum_{i,j=L,R} \frac{4\pi}{\Lambda^2} \eta_{ij} \bar{f}_i \gamma_\mu f_i \bar{f}_j \gamma^\mu f_j
\]

Many new physics models give rise to such terms:
Heavy Z's, compositeness, extra dimensions, SUSY...

One goal of neutral current measurements at low energy AND colliders:
Access \( \Lambda > 10 \text{ TeV} \) for as many \( f_i f_2 \) and \( L,R \) combinations as possible

Precision of proposed experiment:

\[
\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}
\]

best contact interaction reach at low \( Q^2 \)
MOLLER: if SUSY seen at LHC...

\[ P_R = (-1)^{3(B-L)+2s} \]

MSSM sensitivity if light super-partners

MOLLER: if Z' seen at LHC...

- Virtually all GUT models predict new Z’s (E6, SO(10)...): LHC reach ~ 5 TeV
- With high luminosity at LHC, 1-2 TeV Z’ properties can be extracted

Suppose a 1 to 2 TeV heavy Z’ is discovered at the LHC...

\[
\sqrt{2}G_F \delta(Q_W^e) = \frac{1}{(7.5 \text{ TeV})^2}
\]

\[
= \frac{|g_{RR}^2 - g_{LL}^2|}{\Lambda^2} = \frac{e_R^2 - e_L^2}{M_{Z'}^2}
\]

LHC data can extract the mass, width and \(A_{FB}(s)\)

MOLLER: resolve signs on \(e_R, e_L\)
MOLLER: Weak Mixing Angle (1)
MOLLER: Weak Mixing Angle (2)

MOLLER
$A_{fb}^{0,1}$
$A_{l}(P_{\tau})$
$A_{l}(SLD)$

$A_{fb}^{0,b}$
$A_{fb}^{0,c}$
$Q_{l fb}$

Average

$0.23099 \pm 0.00053$
$0.23159 \pm 0.00041$
$0.23098 \pm 0.00026$

$0.23221 \pm 0.00029$
$0.23220 \pm 0.00081$
$0.2324 \pm 0.0012$

$0.23153 \pm 0.00016$

Proposed MOLLER error bar $\approx$ most precise Z-pole data

Precise enough to affect the central value of the world average

$\chi^{2}$/d.o.f.: 11.8 / 5

$m_{H}$ [GeV]

$\sin^{2}\theta_{\text{eff}}$

$\Delta\alpha_{\text{had}}^{(5)}=0.02758 \pm 0.00035$

$m_{t}=172.7 \pm 2.9$ GeV
**MOLLER: Overview**

*How to improve on E158 precision?*

Go to JLab @ 11 GeV (Hall A)

- take hit in figure of merit (factor 4) because of $E_{\text{lab}}$
- gain in Luminosity by order of magnitude (85 μA, 1.5 m target)
- gain in beam quality/stability
- spectrometer design: improve signal/background separation

\[
\theta_{\text{lab}} = 0.25^\circ - 1.1^\circ \quad E' = 1.8 - 8.8 \text{ GeV}
\]

*Detected Rate:* 150 GHz!

$A_{PV} = 35.6 \text{ ppb}$

**Goal** (5000 hrs running): $\delta(A_{PV}) = 0.73 \text{ ppb}$

\[
\delta(Q^e_W) = \pm 2.1 \text{ (stat.)} \pm 1.0 \text{ (syst.) \%}
\]

\[
\delta \sin^2 \theta_W = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.)} \quad \sim 0.1\%
\]
MOLLER: Experimental Challenges

150 GHz Rate:
- flip Pockels cell at ~2 kHz
- 80 ppm pulse-to-pulse statistics
  need 10 ppm or smaller electronic noise and target density fluctuations
- need beam monitoring resolution at 10 ppm and few μm level at 1 kHz
- Flux integration; radiation-hard, highly-segmented detectors

85 μA on 150 cm $\ell H_2$ target
- 5 kW target  \textit{(twice power of QWeak target)}

Beam Quality
- 0.5 nm & 0.05 nrad helicity-correlated beam fluctuations on target

Electron Beam Polarimetry
- require 0.4% precision  \textit{(SLD achieved 0.5%)}
- redundant techniques: Compton and Atomic Hydrogen Moller polarimetry

Full Azimuthal Acceptance
- small $\theta_{\text{lab}}$ wide range of scattered energies
- novel spectrometer magnet design: two toroids
- complicated collimation, alignment, shielding design

Backgrounds
MOLLER: Kinematics

- Peak Figure of Merit at $\theta_{\text{CM}} = 90^\circ$ (maximize $A_{PV}$)

Normally: want to avoid double-counting (both electrons)
Instead, exploit: odd number of magnet coils: throw away half of $\varphi$ acceptance!

All of those rays of $\theta_{\text{CM}} = [90,120]$ that you don’t get here...

... are collected as $\theta_{\text{CM}} = [60,90]$ over here!

Full azimuthal acceptance, broad kinematic coverage
Spectrometer: Two warm toroids
150 kW of photons from target – reject superconductors
MOLLER: Spectrometer Concept

Also: azimuthal defocusing: different $\varphi$ - different $\theta_{CM}$ bins
MOLLER: Hybrid Toroid Design

Present design:
- 1.4 Tm
- 820 kW
- 243 A per conductor
- double pancake
- water cooling (*tricky...*)
- $J = 1550 \text{ A/cm}^2$
**MOLLER: Detectors**

**Main Detectors:**
- fused silica
- air lightguides & PMTs
- highly segmented in $r$ and $\varphi$

![Diagram of MOLLER detectors](image)

- Lead shield
- PMTs
- Air Light-guides
- Beam of neutrals from target

**Diagram Notes:**
- e+e
- e+p
MOLLER: Target

Choose: liquid hydrogen \( (as \ did \ E158) \)

Why?
- Most thickness for least radiation length
- Easy to assure is unpolarized
- No complex nucleus to scatter from

\[
\frac{10.7 \text{ g}}{\text{cm}^2} \quad X_0 = 17.5\% \quad \text{benchmark simulation with tracking detectors}
\]

\[
150 \text{ cm long, 3” diameter Al cell}
\]

\[
0.005” \text{ nipples in windows}
\]

\[
\text{Fluid flow}
\]

\[
\text{Beam}
\]

\[
\text{Contours of temperature}
\]

\[
7.8 \text{ litres}
\]

\[
1 \text{ kg/s}
\]

\[
35 \text{ psia} \quad 20 \text{ K}
\]

\[
5000 \text{ W cooling power}
\]

Design with CFD (Fluent)
\( \text{as was done for QWeak} \)

Fluctuation scaling suggests:
\( 26 \text{ ppm at 2 kHz} \)
MOLLER: Backgrounds

- Elastic e-p scattering
  - well-understood, measurable in data
  - 8% dilution, 7.5±0.3% correction

- Inelastic e-p scattering
  - <1% dilution
  - large EW coupling, 4.0±0.4% correction
  - $A_{PV}$ varies with $r$ and $\phi$

- Photons and Neutrons
  - mostly 2-bounce collimation system
  - special runs to measure “blocked” response of detectors

- $\pi$’s and $\mu$’s
  - real & virtual photo-production and DIS
  - continuous parasitic measurement
  - estimate: $A_{PV}$ 0.5 ppm 0.1% dilution
Two Photon Exchange: Beam normal single spin asymmetry; if electron beam has transverse component $\varphi$ dependence

$A_T \sim 14$ ppm ($>10^4$ our precision goal)

- need to average this down to tolerable correction...

Average transverse asymmetry, energy weighted detectors
**MOLLER: Systematics**

<table>
<thead>
<tr>
<th>source of error</th>
<th>% error</th>
</tr>
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<tbody>
<tr>
<td>absolute value of $Q^2$</td>
<td>0.5</td>
</tr>
<tr>
<td>beam second order</td>
<td>0.4</td>
</tr>
<tr>
<td>longitudinal beam polarization</td>
<td>0.4</td>
</tr>
<tr>
<td>inelastic $e-p$ scattering</td>
<td>0.4</td>
</tr>
<tr>
<td>elastic $e-p$ scattering</td>
<td>0.3</td>
</tr>
<tr>
<td>beam first order</td>
<td>0.3</td>
</tr>
<tr>
<td>pions and muons</td>
<td>0.3</td>
</tr>
<tr>
<td>transverse polarization</td>
<td>0.2</td>
</tr>
<tr>
<td>photons and neutrons</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.0</strong></td>
</tr>
</tbody>
</table>

Dedicated Tracking & Scanner detectors

Laser spot-size control at $10^{-4}$ level
Slow flips via Wien-filter & g-2 beam energy

Active feedback:
intensity, position and angle

Monitor online: kinematic separation
Slow feedback using Wien-filter
MOLLER: Compton Polarimetry

SLD: achieved 0.5% precision

**Systematics:** 2 points of well-defined energy:
- end-point and A=0 crossing
- electron detector: integrate between these to minimize error on analyzing power
- photon detector: independent analysis normalizable to 0.5% (tag via e detector) (SLD did not have)

Techniques being developed (PREx, Qweak...)
MOLLER: Atomic Hydrogen Moller Polarimetry

Virgin territory: Redundant technique, equal precision to Compton


Moller polarimetry from polarized atomic hydrogen gas, stored in ultra-cold magnetic trap

- 100% electron polarization - Brute force
- tiny error on polarization
- thin target (sufficient rates but no dead time)
- Non-invasive
- high beam currents allowed
- no Levchuk effect

\[ \frac{n_+}{n_-} = e^{-2\mu B / kT} \approx 10^{-14} \]

10 cm \( \rho = 3 \times 10^{15} \text{cm}^3 \)
B = 7T \( T = 300 \text{ mK} \)

Ambitious development project
Adopt high-field solid target Moller as fall-back plan
MOLLER: Collaboration

Proposal: ~100 authors, 30 institutions;
experience from E158, HAPPEx, PV-A4, G0, PREx, Qweak

Steering Committee:

Working Groups & Conveners:
– Polarized Source: G. Cates
– Beam & Beam Instrumentation: M. Pitt
– Target: G. Smith
– Spectrometer: K. Kumar
– Integrating Detectors: D. Mack
– Tracking Detectors: D. Armstrong
– Polarimetry: K. Paschke
– Electronics/DAQ: R. Michaels
– Simulations: N. Simicevic / K. Grimm

Expressions of interest – not finalized

<table>
<thead>
<tr>
<th>sub-system</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>polarized source</td>
<td>UVa, JLab, Miss. St.</td>
</tr>
<tr>
<td>Target</td>
<td>JLab, VPI, Miss. St.</td>
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<tr>
<td>Spectrometer</td>
<td>Canada, ANL, MIT, UVa</td>
</tr>
<tr>
<td>Integrating Detectors</td>
<td>Syracuse, Canada, JLab, FIU, UNC A&amp;T, VPI</td>
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<tr>
<td>Luminosity Monitors</td>
<td>VPI, Ohio U.</td>
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<tr>
<td>Pion Detectors</td>
<td>UMass/Smith, LATech</td>
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<td>Tracking Detectors</td>
<td>William &amp; Mary, Canada, INFN Roma</td>
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<tr>
<td>Electronics</td>
<td>Canada, JLab</td>
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<tr>
<td>Beam Monitoring</td>
<td>VPI, UMass, JLab</td>
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<tr>
<td>Polarimetry</td>
<td>UVa, Syracuse, JLab, CMU, ANL, Miss. St., Claremont-Ferrand, Mainz</td>
</tr>
<tr>
<td>Data Acquisition</td>
<td>Ohio U., Rutgers U.</td>
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<tr>
<td>Simulations</td>
<td>LATech, UMass/Smith, Berkeley, UVa</td>
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</table>

Collaboration seeks to grow!
MOLLER: Timeline

- Project received PAC approval: Jan 2009
- Director’s review of physics goals and concept: Jan 2010
- Aim to develop project funding (US + foreign): 2011-12
- Aim to install at JLab after 12 GeV upgrade: late 2015

Daunting challenges... pushes precision in both absolute and relative terms
MOLLER: Summary

• Projected Result from an $A_{PV}$ measurement in Moller Scattering:
  \[ \delta(Q^e_W) = \pm 2.1 \text{ (stat.)} \pm 1.0 \text{ (syst.) \%} \]
  \[ \delta(\sin^2\theta_W) = \pm 0.00026 \text{ (stat.)} \pm 0.00012 \text{ (syst.) \ ~ 0.1\%} \]

• Opportunity with high visibility and large potential payoff
  - The weak mixing angle is a fundamental parameter of EW physics
  - A cost-effective project has been elusive until now
    - expensive ideas reach perhaps 0.2\% (reactor or accelerator ν’s, LHC Z production...)
    - sub-0.1\% requires a new machine (e.g. Z- or ν-factory, linear collider....)
  - physics impact on nuclear physics, particle physics and cosmology
    - pin down parameter for other precision low energy measurements
    - help decipher new physics signals at LHC
    - critical part of the web of “Precision Frontier” measurements (e.g. see MRM’s talk)

• 11 GeV JLab beam is a unique instrument that makes this feasible

Grazie!