Parity Violation in Møller Scattering

First Results from SLAC E158

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- Physics Motivation
- Experimental Technique
- Results and Interpretations
- Outlook
Beyond the Standard Model

- High Energy Colliders
- Rare or Forbidden Processes
- Symmetry Violations
- Electroweak One-Loop Effects

Complementary Approaches

- Precise predictions at level of 0.1%
- Indirect access to TeV scale physics
Parity Violation in Möller Scattering

- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure \( A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_{LR} \)
- Small tree-level asymmetry

\[
A_{PV} = -mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} \left( \frac{1}{4} - \sin^2 \theta_W \right)
\]

- At tree level, \( A_{PV} \approx 280 \cdot 10^{-9} \)
- Raw asymmetry about 130 ppb
  - Goal is to measure it with precision of 8% (10 ppb)
  - Most precise measurement of \( \sin^2 \theta_W \) at low \( Q^2 \) with \( \sigma(\sin^2 \theta_W) < 0.001 \)
Electroweak Physics
E158: New Physics Impact

Compositeness

Neutral currents (GUTs, extra dims)

Scalar interactions (LFV)

➔ Unique window of opportunity
➔ Complementary to collider searches

Λ ~ 15 TeV

M_{Z'} ~ 1 TeV

\[ \frac{g^2}{2M^2} < 0.01G_F \]
E158 Collaboration

Institutions

Caltech        Syracuse
Princeton      Jefferson Lab
SLAC           UC Berkeley
CEA Saclay     UMass Amherst
Smith College  U. of Virginia

60 physicists, 7 Ph.D. students

Chronology:  Sept 1997:  PAC approval
             1998:  Polarized Beam Instrumentation R&D
             1999:  Spectrometer and Detector Design
             2000:  Construction Funds and Test Beams
             2001:  Commissioning Run
             Spring 2002:  Physics Run I
             Fall 2002:  Physics Run II
             Summer 2003:  Physics Run III (final statistics)
Parity-Violating Asymmetry

Measure pulse-pair flux asymmetry:

$$A_{exp} = \frac{F_R - F_L}{F_R + F_L}$$

Correct for difference in R/L beam properties:

$$A_{raw} = A_{exp} - \sum \alpha_i \Delta x_i$$

charge, position, angle, energy
R-L differences
coefficients determined experimentally

Physics asymmetry:

$$A_{PV} = \frac{1}{P_b} \frac{A_{raw}}{1 - f_{bkg}} f_{bkg} A_{bkg}$$

backgrounds
beam polarization
Statistical and Systematic Fluctuations

Detector D, Current I: \( F = D/I \)

\[
A_{\text{pair}} = \frac{F_R - F_L}{F_R + F_L}
\]

Integrate
Detector response: Flux Counting

\[
= \frac{\Delta F}{2F} + \text{fluctuations}
\]

- \( \frac{\Delta I}{2I} \)
- \( \frac{\Delta D}{2D} \)
- \( \frac{\Delta E}{2E} \)

20 million Moller electrons per spill

jitter (ppm) 200
accuracy (ppm)
cumulative (ppb) 110 +/- 9

linac tune

5000 1000 500
30 30 50
200 20 10
+/-1 +/-2 +/-2

precision monitoring and control of electron beam fluctuations

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Minimizing Beam Systematics

At the start:

→ ~1000 ppm charge, ~2 μm position asymmetries

1) Passive setup:

- Careful work at the polarized source
- Beam helicity flipped pseudo-randomly at 120 Hz
- Decouple source electrically from the detector

→ ≤100 ppm, ~0.5 μm

2) Active suppression with feedbacks:

→ ~few ppb, nm level

3) Slow asymmetry reversals:

- Physics asymmetries \( \lambda/2 \) plates (2), energy (g-2 precession)
- Beam asymmetry inverter

☞ Cancellation of systematics, and stringent cross-check. Multiple reversals are essential!
Key Ingredients

- High beam polarization and current
- Largest high-power LH2 target in the world
- Spectrometer optimized for Møller kinematics
- Stringent control of helicity-dependent systematics
Polarized Electron Source

"strain" boosts polarization, but introduces anisotropy in response

<table>
<thead>
<tr>
<th>Parameter</th>
<th>E158</th>
<th>NLC-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge/Train</td>
<td>$6 \times 10^{11}$</td>
<td>$1.43 \times 10^{11}$</td>
</tr>
<tr>
<td>Train Length</td>
<td>270ns</td>
<td>260ns</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>0.3ns</td>
<td>1.4ns</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>120Hz</td>
<td>120Hz</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>45 GeV</td>
<td>250 GeV</td>
</tr>
<tr>
<td>e⁻ Polarityation</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

High doping for 10-nm GaAs surface overcomes charge limit.

Low doping for most of active layer yields high polarization.

New cathode

No sign of charge limit!

Old cathode

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Beam Diagnostics

Pulse-to-pulse monitoring of beam asymmetries and resolutions:

\[ \sigma_{\text{toroid}} \leq 30 \text{ ppm} \]

\[ \sigma_{\text{BPM}} \leq 2 \text{ microns} \]

\[ \sigma_{\text{energy}} \leq 1 \text{ MeV} \]
Beam Asymmetries

Charge asymmetry at 1 GeV

Energy difference in A line

Position differences < 20 nm

Position agreement ~ 1 nm

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Møller Polarimetry

- Møller scattering off polarized valence electrons in Fe foil
  - Large QED asymmetry: \( A_{\text{QED}} \sim \frac{7}{9} P_{\text{beam}} P_{\text{target}} \approx 0.05 \)
  - Same kinematics as PV measurement
  - Dedicated small acceptance movable detector (control backgrounds)

\[ \text{Polarimeter signal} \]

\[ \text{Raw Asymmetry} \]

\(~ 85\% \) polarization throughout Run I, ~80\% for Run 2
Detector Concept

* 4 integrating detectors
* profile detectors for calibration
Scattered Flux Profile

Møller peak scan: data vs Monte Carlo

Møller scattering kinematics:
\(<Q^2> = 0.0266 \text{ GeV}^{-2}\)
\(<y> = 0.6\)

- ~2 mm geometry
- 1% energy scale
- Radiative tail
- <1% background

Data
Monte Carlo
MOLLER Statistics and Fluctuations

- **Raw Asymmetry Distribution in one PMT**
  - RMS $\approx 3460$ ppm

- **Charge Normalized Distribution in one PMT**
  - RMS $\approx 1108$ ppm

- **Distribution Regarded for Energy, Position, Angle in one PMT**
  - $\approx 1.8$ Million electrons/pulse
  - $\sigma = 527$ ppm

- **Grand Width**
  - $\approx 15$ Million electrons/pulse
  - $\sigma = 194$ ppm

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### Physics Runs

<table>
<thead>
<tr>
<th>Run</th>
<th>Energy</th>
<th>#days @120Hz</th>
<th># Peta-Electron</th>
<th>#spills</th>
<th>Average Charge</th>
<th>Production Efficiency*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td>45.6 GeV</td>
<td>19.2</td>
<td>67K</td>
<td>125M</td>
<td>5.5 x 10^{11}</td>
<td>63%</td>
</tr>
<tr>
<td>Run I</td>
<td>48.8 GeV</td>
<td>14.8</td>
<td>37K</td>
<td>105M</td>
<td>3.5 x 10^{11}</td>
<td>69%</td>
</tr>
<tr>
<td>Run II</td>
<td>45.6 GeV</td>
<td>15.2</td>
<td>56K</td>
<td>113M</td>
<td>5.2 x 10^{11}</td>
<td>72%</td>
</tr>
<tr>
<td>Run II</td>
<td>48.8 GeV</td>
<td>19.0</td>
<td>63K</td>
<td>153M</td>
<td>4.3 x 10^{11}</td>
<td>78%</td>
</tr>
</tbody>
</table>

*Efficiency is avg. delivered rate normalized to 119Hz

**Run I**: April 23 12:00 – May 28 00:00 (this result)

**Run II**: October 10 08:00 – November 13 16:00

- Run I with PEP II, Run II dedicated
- One g-2 flip in each run
- $\lambda/2$ flip roughly once in two days
- Asymmetry inverter flip once a week
- Run I data divided into 24 “slugs”

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Raw Asymmetry Statistics

Asymmetry pulls per pulse pair:

- Moller Detector Pull, All Pairs
  - Nent = $8.58631 \times 10^7$
  - Mean = $3.147 \times 10^{-6}$
  - RMS = 0.9998

Asymmetry pulls per run:

- Moller Pull
  - Nent = 818
  - Mean = 0.00489
  - RMS = 1.02
  - Constant = $128 \pm 5.691$
  - Mean = $0.01049 \pm 0.03551$
  - Sigma = $0.9948 \pm 0.02699$

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Sensitivity to Beam Systematics

- Detector divided into 3 rings of PMTs: Inner, Middle and Outer

Various linear combinations used to study systematics

Current systematic error: 18 ppb
Transverse Asymmetry

~ 3 ppm up-down asymmetry with 85% transverse polarization

Two-photon exchange QED effect: probe of QED to $O(\alpha^3)$

~5% residual transverse polarization in production data:
Data carefully re-weighted to maintain azimuthal symmetry
Luminosity Monitor Data

- Null test at level of 20 ppb
- Density fluctuations small
- Limits on second order effects

Chi2 = 2.751
Mean = -0.021 +/- 0.016

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Consistent with expectations for inelastic ep asymmetry, but hard to interpret in terms of fundamental parameters
Raw Asymmetry Result

Moller Detector, Asymmetry vs Slug

Chi2 / ndf = 18.71 / 23
Prob = 0.718
p0 = -0.1654 ± 0.02191
Systematic Uncertainties

- Total correction to $A_{PV} - 47 \pm 24$ ppb
  - Also $0.84 \pm 0.05$ normalization correction (beam polarization)
- Uncertainty currently dominated by
  - Beam asymmetry systematics
    - $18$ ppb, statistics limited
  - EP background subtraction
    - $11$ ppb, reduced in Run II with additional collimator
  - Soft photon background
    - $9$ ppm, reduced in Run II with additional collimator
  - Beam polarization
    - $6\%$, work ongoing
- Conservative estimates
  - Plan to reduce systematic error in Run I to $\sim 15$ ppb
  - Run II corrections will be of order $25$ ppb with smaller errors
Significance of parity non-conservation in Møller scattering: $3.6 \sigma$

$A_{PV}(e^{-}e^{-} \text{ at } Q^2 = 0.027 \text{ GeV}^2)$:

-152 ± 29 (stat) ± 32 (syst) parts per billion

(preliminary)
The Weak Mixing Angle

\[ \sin^2 \theta_{\text{eff}}(Q^2=0.027 \text{ GeV}^2) = 0.2371 \pm 0.0025 \text{ (stat)} \pm 0.0027 \text{ (syst)} \] (preliminary)

Standard Model prediction: 0.2387 \pm 0.0006
(Czarnecki, Marciano, 2000)

Convert to \( \sin^2 \theta_{\text{MS}}^W(M_Z^2) \) for comparison with other experiments:

\[ \sin^2 \theta_{\text{MS}}^W(M_Z^2) = 0.2296 \pm 0.0038 \] (preliminary)

PDG2002: 0.2311 \pm 0.0006
(error includes running of \( \sin^2 \theta_{\text{eff}} \) from low energy to \( M_Z \))

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Implications

- Parity is violated in Møller scattering
- Limit on $\Lambda_{LL}$ at the level of 3-4 TeV (90% C.L.)
- Limits on extra Zs at the level of 400-500 GeV
- Limit on lepton-flavor violating coupling $\sim 0.02 \, G_F$

These numbers are currently on par with collider limits

Clearly need to reduce statistical and systematic errors
Outlook

First measurement of Parity Violation in Møller Scattering
- Preliminary result on $A_{PV} = -152 \pm 29 \pm 32 \text{ ppb}$
- $\sin^2 \theta_{\text{eff}} = 0.2371 \pm 0.0025 \pm 0.0027$ (preliminary)

Experiment poised to achieve proposal goals
- Nontrivial constraints on New Physics at TeV scale with $\sigma(\sin^2\theta_W) \sim 0.001$
  - Unique window of opportunity, complementary to FNAL Run II
- E158 Run II data are being analyzed, will double statistics
- Final physics Run III July-August 2003
  - Beam to ESA on Monday for checkout and systematics studies