E158 Goal: $\Delta \sin^2 \theta_W = +/- 0.001$

Best measurement of $\theta_W$ away from the Z-pole
Physics Beyond the Standard Model

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

Complementary Approaches

\( \alpha_{QED} \quad G_F \quad \gamma \pi \gamma \quad W^+_b W \quad M_Z \quad \sigma_Z \quad M_W \quad A_f \)
## Latest World Electroweak Data

### Summer 2004

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>0 $\sigma_{\text{meas}}$</th>
<th>1 $\sigma_{\text{meas}}$</th>
<th>2 $\sigma_{\text{meas}}$</th>
<th>3 $\sigma_{\text{meas}}$</th>
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</thead>
<tbody>
<tr>
<td>$\Delta\alpha^{(S)}_{\text{had}}(m_Z)$</td>
<td>0.02761 ± 0.00036</td>
<td>0.02769</td>
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<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
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<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4966</td>
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<tr>
<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.481</td>
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<tr>
<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.739</td>
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<tr>
<td>$A_{tb}^{0,l}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01650</td>
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<tr>
<td>$A_{tb}^{0,b}$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1483</td>
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<tr>
<td>$A_{tb}^{0,c}$</td>
<td>0.1723 ± 0.0031</td>
<td>0.1723</td>
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<tr>
<td>$A_{tb}^{0,b}$</td>
<td>0.0998 ± 0.0017</td>
<td>0.1040</td>
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<td>$A_{tb}^{0,c}$</td>
<td>0.0706 ± 0.0035</td>
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<tr>
<td>$A_{tb}$</td>
<td>0.923 ± 0.020</td>
<td>0.935</td>
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<tr>
<td>$A_{tb}$</td>
<td>0.670 ± 0.026</td>
<td>0.668</td>
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<tr>
<td>$A_{tb}$ (SLD)</td>
<td>0.1513 ± 0.0021</td>
<td>0.1483</td>
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<tr>
<td>$\sin^2\theta_{\text{eff}}(Q_{tb})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
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<tr>
<td>$m_W$ [GeV]</td>
<td>80.425 ± 0.034</td>
<td>80.394</td>
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</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.133 ± 0.069</td>
<td>2.093</td>
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<tr>
<td>$m_t$ [GeV]</td>
<td>178.0 ± 4.3</td>
<td>178.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Final              | 0.23099 ± 0.00053 |                           |                           |                           |                           |
| Preliminary        | 0.23098 ± 0.00026 |                           |                           |                           |                           |
|                   | 0.23159 ± 0.00041 |                           |                           |                           |                           |
|                   | 0.2324 ± 0.0012   |                           |                           |                           |                           |
|                   | 0.23210 ± 0.00030 |                           |                           |                           |                           |
|                   | 0.23223 ± 0.00081 |                           |                           |                           |                           |
|                   | 0.23147 ± 0.00017 |                           |                           |                           |                           |
| $\chi^2$/d.o.f.   | 97 / 5            |                           |                           |                           |                           |

**P = 8.4%**

David Relyea, E158 Results
• Precision Z observables establish anchor points for SM
• Low energy observables probe interference between SM and new physics
• Current low energy experiments access scales beyond 10 TeV
• Eventually push to energies above the Z resonance (but for now...)
Measuring the Weak Neutral Current at Low $Q^2$

Purely leptonic reaction $Q^e_W \sim 1 - 4\sin^2\theta_W$

Fixed Target Möller Scattering

E158

Caltech, 01/05/2005

David Relyea, E158 Results
E158 Collaboration / Timeline

- UC Berkeley
- Caltech
- Jefferson Lab
- Princeton
- Saclay

- SLAC
- Smith College
- Syracuse
- UMass
- Virginia

SLAC

ESA

A-Line
Weak-Electromagnetic Interference in Electron Scattering

\[ -A_{LR} = A_{PV} = \frac{\sigma - \sigma}{\sigma + \sigma} \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4 \pi \alpha} \]

\[ Q^2 \sim 0.01 - 1 \text{ GeV}^2 \]

\[ A_{PV} \lesssim 10^{-7} - 10^{-4} \]

**SLAC E122: lepton-nucleon deep inelastic scattering**

20 GeV longitudinally polarized electrons

precision monitors

liquid Deuterium

integrating detector

asymmetry \( \sim 10^{-4} \)

error \( \sim 10^{-5} \)

C.Y. Prescott et al. 1978
Parity Violation in Møller Scattering

- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure
  \[ A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]
- Small tree-level asymmetry
  \[ A_{ee} = mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{16\sin^2 \theta}{(3 + \cos^2 \theta)^2} \left( \frac{1}{4} - \sin^2 \theta W \right) \]
- At tree level, \( A_{ee} (Q^2 = 0.03) \approx 3.2 \times 10^{-7} \) (320 ppb)
- Higher order corrections reduce asymmetry to 130 ppb
E158 New Physics Reach

- **LEP II**
  - $e R e R e^2 + e L e L e^2$

- **Fermilab**
  - $q \cdots Z' e$

- **E158**
  - $e R e R e^2 - e L e L e^2$

- 15 TeV
  - Compositeness

- 0.5-1.0 TeV
  - GUTs

- 0.5-2.5 TeV
  - Extra dimensions

- $\frac{g^2}{2M_\Delta^2} < 0.01 G_F$
  - Lepton flavor violation

*Caltech, 01/05/2005*
Experimental Technique

• Scatter polarized electrons off atomic electrons
  • High cross section (14 µBarn)
  • High intensity electron beam, ~85% polarization
  • 1.5 m LH2 target (0.18 r.l.)
    ➡️ Luminosity 4*10^{38} cm^{-2}s^{-1}
  • High counting rates (~2 GHz) ⇒ flux-integrating calorimeter

• Principal backgrounds:
  elastic and inelastic $ep$ scatters

• Main systematics:
  • Helicity-correlated beam effects
  • Backgrounds
  • Beam polarization
Parity-Violating Asymmetry

1. Measure asymmetry for each pair of pulses,
\[ A_{\text{exp}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \]

2. Correct for detector response to beam helicity differences:
\[ A_{\text{raw}} = A_{\text{exp}} - \sum a_i \cdot x_i \]
beam intensity, position, angle, energy
R-L differences

coefficients determined by 1. fitting detector asymmetry to beam R-L differences, or
2. “dithering” beam and observing detector response

3. Obtain physics asymmetry:
\[ A_{\text{PV}} = \frac{1}{P_b} \frac{A_{\text{raw}} - f_{\text{bkg}} A_{\text{bkg}}}{1 - f_{\text{bkg}}} \]
backgrounds
beam polarization
Experimental Challenges

0. Measure a 100 ppb effect with a 10 ppb error

1. Electron Beam
   i) high intensity
      - 500 kW beam!
   ii) stability
      - intensity jitter <1%
      - spotsize jitter <10%
      - position jitter <10%
   iii) small left-right helicity differences
      - intensity
      - position/angle
      - energy
   iv) high (>80%) polarization

2. Electron Beam monitoring
   i) toroid resolution: < 30 ppm per pulse
   ii) BPM resolution: < 1 µm per pulse
   iii) energy resolution: < 50 ppm per pulse

\[
A_I = \frac{\langle I \rangle_R - \langle I \rangle_L}{\langle I \rangle_R + \langle I \rangle_L} < 2 \cdot 10^{-7}
\]
\[
A_x = \langle x \rangle_R - \langle x \rangle_L < 10 \text{ nm}
\]
\[
A_E = \frac{\langle E \rangle_R - \langle E \rangle_L}{\langle E \rangle_R + \langle E \rangle_L} < 2 \cdot 10^{-8}
\]

3. Liquid Hydrogen Target
   i) target density fluctuations: <10^{-4} per pulse
   ii) 18% radiation length
      - absorbs 500W beam power
   iii) Safety (largest LH2 target in the world)

4. Detectors
   i) detector resolution: <100 ppm per pulse
   ii) multiple backgrounds
   iii) radiation damage
   iv) linearity < 1%
Beam helicity is generated pseudo-randomly at 120 Hz
• Use electro-optical Pockels Cell in Polarized Light Source
• Sequence of pulse quadruplets:

Beam R-L differences reduced using feedbacks
• Charge and position R-L differences nullified using electro-optical Pockels Cells in Source

Physics asymmetries can be reversed
• Insertable Halfwave Plate in Source
• (g-2) spin precession in A-Line (45 GeV and 48 GeV data)

False asymmetry reversals
• Insert a four lens “-I/+I” inverter in the Source
• Reverses beam R-L differences
• Leaves physics asymmetry intact

‘Null Asymmetry’ cross-check is provided by a Luminosity Monitor
• measure very forward angle e-p (Mott) and Møller scattering
Electron Beam: Diagnostics

Put 2 Mile Accelerator Here

Thermionic Source

BPMs (3)

Toroids (2)

Dithering Magnets

Polarized Source

Momentum Defining Slits

Angle BPMs (2)

Position BPMs (2)

Wire Array

Toroids (2 pair)

Dispersive (Energy) BPMs (2)

1 GeV

48 GeV

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

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

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

Pulse-to-pulse monitoring of beam helicity differences and resolutions:

\[ x^2 = 0.83 \]

\[ x^2 = 1.01 \]

Caltech, 01/05/2005
Experimental Layout: Spectrometer

- **Dipole chicane** allows clean collimation of photons and positrons from target interactions
- **Quadrupoles** separate Møller and ep flux at detector face (see inset)
- **Main acceptance collimator** (upper right corner) accepts Møller scatters in desired momentum/radial range
- **Synchrotron collimators** (not shown) block synchrotron radiation
Experimental Layout: Detectors

Møller, ep are (copper/fused silica fiber) calorimeters
Pion is a quartz bar Cherenkov
Luminosity is an ion chamber with Al pre-radiator

All detectors have azimuthal segmentation, and have photomultiplier tube (PMT) readout to a 16-bit ADC

\[ \sigma_{MOLLER} \propto \frac{1}{E\theta^4} \quad \sigma_{MOTT} \propto \frac{1}{E^2\theta^4} \]

\[ \left\langle \theta_{lab}^{LUMI} \right\rangle = 1.5 \text{ mrad} \]
\[ \left\langle \theta_{lab}^{MOLLER} \right\rangle = 6.0 \text{ mrad} \]
E158 Runs

Run 1: Spring 2002
Run 2: Fall 2002
Run 3: Summer 2003
Møller Statistics and Fluctuations

observed left-right asymmetry distribution

For each detector channel,

Raw channel asymmetry
Beam helicity differences:
Intensity, Energy, Position

raw asymmetry distribution in one PMT

RMS ~ 3460 ppm

distribution regressed for energy, position, angle in one PMT

1.8 Million electrons/pulse
σ = 527 ppm

charge normalized distribution in one PMT

RMS ~ 1108 ppm

grand width

15 Million electrons/pulse
σ = 194 ppm
Caltech, 01/05/2005

David Relyea, E158 Results

**Raw Asymmetry Statistics**

- **Per pulse pair (2 days, Run I only):**
  \[
  A_i - \langle \overline{A} \rangle
  \]
  \[
  \sigma_i \sim 200 \text{ ppm}
  \]
  \[
  N = 85 \text{ Million}
  \]

- **Per run (Run I only):**
  \[
  A_i - \langle \overline{A} \rangle
  \]
  \[
  \sigma_i \sim 600 \text{ ppb}
  \]
  \[
  N = 818
  \]
Raw Asymmetry Systematics

• First order systematic effects
  ❑ False asymmetry in electronics
    ➩ Measured to be smaller than 1 ppb
  ❑ Errors in correction slopes
    ➩ Measured by comparing two timeslots
    ➩ Beam-induced asymmetries of ~1 ppm corrected to below stat errors of 50 ppb in multiple data samples

• Higher-order corrections
  ❑ Beam size fluctuations
    ➩ Measured by wire array
  ❑ Correlation between beam asymmetry and pulse length (intra-spill asymmetries)
    ➩ New electronics in Run III
SLICES: Temporal Beam Profile

• SLICES readout in 10 bit ADCs
  Q : bpm31Q (4)
  E : bpm12X (3)
  X : bpm41X (4)
  Y : bpm41Y (4)
  dX : bpm31X (4)
  dY : bpm31Y (4)

Integration time:
S1: 0 - 100 ns
S2: 100 - 200 ns
S3: 200 - 300 ns
S4: 300 - 1000 ns
Additional Corrections

- OUT detector at edge of Møller acceptance most sensitive to beam systematics
- Use it to set limits on the grand asymmetry
Backgrounds

**High Energy Electrons:**
- "ep" detector flux and asymmetry measurements

**High Energy Pions:**
- Measure calibrated response to quartz-bar detectors behind 15 cm of copper + 20 cm of lead

**High Energy Photons:**
- Negligible due to collimation

**Multibounce Photons:**
- Quads off/on data with main detector & profile detector

**Soft Photons and Neutrons:**
- Quads off/on data with "blinded" PMTs

**Synchrotron Photons:**
- "target out" runs

Integrating calorimeter: All dilutions and asymmetries must be measured or bounded
ep Asymmetry

elastic scattering
At low $Q^2 : A_{LR} \sim 10^{-5} \times Q^2$
in the ep detector:
$Q^2 \sim 0.06 \text{ GeV}^2$:
$A_{\text{Raw}} \sim 0.4 +/- 0.2 \text{ ppm}$

- radiative tail dominated by elastic scattering: $\sim 8\%$ under Moller peak
- additional 1% contribution from inelastic scattering
**Ratio of asymmetries:**

$$A_{PV}(48 \text{ GeV}) / A_{PV}(45 \text{ GeV}) = 1.25 \pm 0.08 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

**Consistent with expectations for inelastic ep asymmetry**
Transverse Asymmetries

Beam-Normal Asymmetry in elastic electron scattering

Electron beam polarized transverse to beam direction

\[ A_T \equiv \frac{2\pi}{\sigma^+ + \sigma^-} \frac{d(\sigma^+ - \sigma^-)}{d\phi} \propto S_e \cdot (k_e \times k'_e) \propto \sin \phi \]

Interference between one- and two-photon exchange

\[ A_T \propto \frac{\alpha m_e}{\sqrt{s}} = -3.5 \text{ ppm} \cdot \sin \phi \]

for Møller scattering at 43/46 GeV

Theory References:
1. A. O. Barut and C. Fronsdal, (1960)
2. L. L. DeRaad, Jr. and Y. J. Ng (1975)
   *(Included bremsstrahlung corrections: few percent)*
Observe ~ 2.5 ppm asymmetry
First measurement of single-spin transverse asymmetry in e-e scattering.

i) Interesting signal
ii) Potential background for $A_{PV}$ measurement
   ➢ Data carefully re-weighted to maintain azimuthal symmetry
iii) Studying its utility for calibration of polarization scale
\( A_T^{ep} \) at E158

- Raw asymmetry!
- Has the opposite sign! (preliminary)
- Polarization & background corrections
- ~ 25% inelastic ep
- Few percent pions (asymmetry small)
  ✓ Proton structure at E158!

\( \phi \) (Azimuthal angle)

\begin{itemize}
  \item \( A_T^{ep} \) at E158
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\[ \phi \] (Azimuthal angle)

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  \item Few percent pions (asymmetry small)
  \item ✓ Proton structure at E158!
\end{itemize}
Møller Asymmetry

- Over 330M pulse pairs over 3 separate runs (2002-2003) at $E_{\text{beam}} = 45$ and 48 GeV
- Passively flip helicity of electrons wrt source laser light ~every day to suppress spurious helicity-correlated biases

Physics asymmetry

$A_{PV} = -128 \pm 14 \text{ ppb}$

$\chi^2/df = 74.3/74$
The Weak Mixing Angle

- General agreement between low $Q^2$ experiments, although NuTeV is still $3\sigma$ high compared to SM fit
- Stringent limits on new interactions at multi-TeV scales
- Parameterize as limit on 4-fermion contact term $\Lambda_{LL}$: 6-14 TeV limits for E158 alone (95% C.L.)
- Limit on SO(10) Z' at 900 GeV
Running of the Weak Mixing Angle

\[ \sin^2 \theta_w^{\text{eff}} (Q) \]

- E158 (Preliminary)
- Qw(Cs)
- NuTeV
- Czarnecki & Marciano (2000)
- SLD+LEP

7σ
Summary: Physics Results

Electro-weak parity violation

- first observation of parity violation in Møller scattering (8σ)
- running of the weak mixing angle established (7σ)
- Probing TeV-scale physics: ~10 TeV limit on $\Lambda_{LL}$,
  ~900 GeV limit on SO(10) Z’
- inelastic e-p asymmetry consistent with quark picture

Transverse asymmetries

- First measurement of e-e transverse asymmetry (QED)
- e-p transverse asymmetry measured (QCD)

Weak Mixing Angle

Preliminary Results using all data

$$A_{PV} (\text{Møller}) = (-128 \pm 14 \pm 12) \text{ ppb}$$

$$\sin^2 \theta_W^{MS}(M_Z^2) = 0.2330 \pm 0.0011 \text{ (stat)} \pm 0.0010 \text{ (syst)}$$

Best measurement of the weak mixing angle away from the Z-pole!
Outlook

- **Next set of precision measurements on the horizon**
  - **Neutrino-electron scattering**
    - Reactor experiments (in conjunction with $\theta_{13}$): cross section measurements to 0.7-1.3% would translate in $\sigma(\sin^2\theta_W)$ down to ~0.001
    - Ultimate measurements at the neutrino factory
  - **Atomic parity violation**
    - Ratios of APV in isotopes and hydrogenic ions could reach sensitivity of $\sigma(\sin^2\theta_W) \sim 0.001$
  - **PV in electron scattering**
    - Active program planned for JLab: PV in elastic ep scattering (~2007), Møller scattering, and DIS eD scattering (~2010) could reach below $\sigma(\sin^2\theta_W) \sim 0.001$ per experiment
  - $e^+e^-$ and $e^-e^-$ at the Linear Collider
Selected Future Measurements

\[ \sin^2(\theta_W) \]

0.238

0.236

0.234

0.232

0.01 GeV

0.1 GeV

1 GeV

10 GeV

100 GeV

1 TeV

168\text{Yb} - 176\text{Yb} PNC Isotopic Chain

SLAC E158 Möller Scattering

NuTeV Neutrino-Nucleon Scattering

JLab DIS-parity

JLab Proton Weak Charge

133\text{Cs} PNC Single Isotope

Linear Collider In $e^+ e^-$ and $e^- e^-$ Modes

LEP + SLAC Measurements At Z Pole

Caltech, 01/05/2005

David Relyea, E158 Results
EW Corrections to $A_{LR}$ (Czarnecki-Marciano)

- **LO expression:**
  
  $g/Z$ mixing, anapole moment (factor of 1.03 in $\sin^2\theta_W$, -40% change in $A_{LR}$)

**EW Boxes**

(4% change in $A_{LR}$)

\[ A_{LR}(e^+e^-) = \frac{\rho G_F q^2}{\sqrt{2\pi \alpha}} \frac{1-y}{1+y^4 + (1-y)^4} \times \left\{ 1 - 4\alpha(0) \sin^2\theta_W (m_Z)_{MS} + \frac{\alpha(m_Z)}{4\pi s^2} \right\} \]

where

\[ + F_1(y, Q^2) + F_2(y, Q^2) \]

FIG. 2. $\gamma-Z$ mixing diagrams (a) and (b), $W$-loop contribution to the anapole moment (c).
Eliminating Beam Helicity Effects

\[ A_{\text{exp}} = A_N - A_I + A_E + \sum \alpha_i X_i \]

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

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

Integrate
Detector response:
Flux Counting

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

\[ A_{\text{pair}} \approx \frac{\Delta D}{2D} - \frac{\Delta I}{2I} + \frac{\Delta E}{2E} + \alpha_i \Delta X_i \]

- **Jitter (ppm)**: 200
- **Accuracy (ppm)**: 200
- **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
Polarized Laser + GaAs cathode = Polarized Electron Beam
Polarized Source: GaAs cathode

"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>$14.3 \times 10^{11}$</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>$e^-$ Polarization</td>
<td>80%</td>
<td>80%</td>
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</tbody>
</table>

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

Low doping for most of active layer yields high polarization.

Table:

<table>
<thead>
<tr>
<th>Doping</th>
<th>Thickness</th>
<th>Electron Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs$<em>{0.95}$P$</em>{0.05}$</td>
<td>10 nm</td>
<td>$5 \times 10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>GaAs$<em>{0.66}$P$</em>{0.34}$</td>
<td>90 nm</td>
<td>$5 \times 10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>GaAs$_{1-y}$P$_y$</td>
<td>2.5 µm</td>
<td>$y = 0 \rightarrow 0.34$</td>
</tr>
<tr>
<td>GaAs substrate</td>
<td>2.5 µm</td>
<td></td>
</tr>
</tbody>
</table>

Graph:

- **New cathode**: No sign of charge limit!
- **Old cathode**:
Liquid Hydrogen Target

- Refrigeration Capacity: 1 kW
- Operating Temperature: 20 K
- Length: 1.5 m
- Flow Rate: 5 m/s
- Vertical Motion: 6 inches

Caltech, 01/05/2005
Kinematics

Quadrupole Quadruplet

- primary & scattered electrons enclosed in quadrupoles
- Mollers (e-e) focused, Motts (e-p) defocused
- full range of azimuth

Caltech, 01/05/2005

David Relyea, E158 Results
Møller Detector

Basic Idea:
- 20 million electrons/pulse at 120 Hz
- 100 MRad radiation dose
- Copper/fused silica fiber sandwich
- state of the art in calorimetry at ultra-high flux
- challenging cylindrical geometry

- single Cu plate
- "ep" ring
- "moller" ring
- end plate
- light guide
- lead shield
- PMT holder

quartz
copper
electron flux
air
shielding
light guide
fiber bundle
PMT holder
Profile Detector

- 4 Quartz Cherenkov detectors with PMT readout
  - insertable pre-radiators
  - insertable shutter in front of PMTs

- Radial and azimuthal scans
  - collimator alignment, spectrometer tuning
  - background determination
  - $Q^2$ measurement

![Graph showing radial distance from beamline (cm) with quadrupoles on and off.](image)
Scattered Flux Profile

Møller peak scan: data vs Monte Carlo

Møller scattering kinematics:
\(<Q^2> = 0.026 \text{ GeV}^{-2}\)
\(<y> = 0.6\)

- ~2 mm geometry
- 1% energy scale
- Radiative tail
- <1% background
84.9 +/- 4.4 % polarization throughout Run I
Pion Detector

- ~ 0.5% pion flux
- ~ 1 ppm asymmetry
- < 5 ppb correction
Luminosity Monitor

Segmented ion chamber detector with aluminum preradiator

500W incident power
(50W from synchrotron radiation)

Signal: eps and high energy Møllers
350M electrons per pulse;
\( <E> \sim 40 \text{ GeV} \)
\( \theta_{\text{lab}} \sim 1 \text{ mrad} \)

• Null asymmetry measurement
• Enhanced sensitivity to beam and target density fluctuations
# Asymmetry Corrections and Systematics

<table>
<thead>
<tr>
<th>Correction</th>
<th>( f_{\text{bkg}} )</th>
<th>( \sigma(f_{\text{bkg}}) )</th>
<th>( A_{\text{corr}} ) (ppb)</th>
<th>( \sigma(A_{\text{corr}}) ) (ppb)</th>
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<tr>
<td>Beam asymmetries</td>
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<td>Beam spotsize</td>
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<tr>
<td>Pions</td>
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<tr>
<td>TOTAL</td>
<td>0.082</td>
<td>0.009</td>
<td>-27</td>
<td>8</td>
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</tbody>
</table>

- Scale factors:
  - Average Polarization 88 ± 5%
  - Linearity 99 ± 1%
  - Radiative corrections: 1.016 ± 0.005
Preliminary Results

\[ A_{PV}(e^-e^- \text{ at } Q^2=0.026 \text{ GeV}^2) = -128 \pm 14 \text{ (stat)} \pm 12 \text{ (syst)} \text{ ppb} \]

→ Significance of parity non-conservation in Møller scattering: 8 \( \sigma \)

\[ \sin^2\theta_{\text{eff}}(Q^2=0.026 \text{ GeV}^2) = 0.2403 \pm 0.0010 \text{ (stat)} \pm 0.0009 \text{ (syst)} \]

→ Most precise measurement at low \( Q^2 \)
→ Significance of running of \( \sin^2\theta_W \): 7 \( \sigma \)

\[ \sin^2\theta_W^{\overline{\text{MS}}}(M_Z) = 0.2330 \pm 0.0011 \text{ (stat)} \pm 0.0010 \text{ (syst)} \]

→ Standard Model pull: +1.2 \( \sigma \)