The $G^0$ Forward-Angle Measurement of Parity Violating Asymmetries in $\bar{e}p$ Elastic Scattering

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for the $G^0$ Collaboration

Workshop on Precision ElectroWeak Interactions
College of William and Mary
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Virtually all slides are from Doug Beck's 17-June-2005 data release seminar at JLab.
G0 Collaboration


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Experimental setup
G0 Experiment Overview

- Measure $G_E^Z, G_M^Z$
- different linear combination of $u$, $d$, and $s$ contributions
- strange quark contributions
- recoil protons for forward measurement
- electrons for backward measurements
- elastic/inelastic for $^1$H, elastic for $^2$H

Forward measurements complete (101 Coulombs)

- Measure $G_E^Z, G_M^Z$
- different linear combination of $u$, $d$, and $s$ contributions
- strange quark contributions
- recoil protons for forward measurement
- electrons for backward measurements
- elastic/inelastic for $^1$H, elastic for $^2$H
Polarized Injector/Accelerator

- Challenging specifications – all met!
  - 32 ns pulse spacing for t.o.f.
  - 40 µA beam current
    - higher bunch charge
  - run concurrently with small energy spread for Hall A

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Achieved</th>
<th>“Specs”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge asymmetry</td>
<td>-0.14 ± 0.32 ppm</td>
<td>1 ppm</td>
</tr>
<tr>
<td>x position differences</td>
<td>3 ± 4 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>y position differences</td>
<td>4 ± 4 nm</td>
<td>20 nm</td>
</tr>
<tr>
<td>x angle differences</td>
<td>1 ± 1 nrad</td>
<td>2 nrad</td>
</tr>
<tr>
<td>y angle differences</td>
<td>1.5 ± 1 nrad</td>
<td>2 nrad</td>
</tr>
<tr>
<td>Energy differences</td>
<td>29 ± 4 eV</td>
<td>75 eV</td>
</tr>
</tbody>
</table>

New Tiger laser system for G0

JLab polarized injector

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Leakage Beam Measurement

- Use "cut0" region in actual data to measure leakage yield, asymmetry throughout run
- Cut0 certified during test runs with only leakage beam
  - Uncertainty determined in 3 ways
    - Compare lumi monitor (direct) measurements to cut0
    - Cut3 asymmetry independent of beam current (10, 20, 40 μA)
    - Variation of corrected cut3 asymmetry (should be constant over run)
  - Methods consistent at 20% level
- $\delta A_{\text{false, leak}} = -0.71 \pm 0.14$ ppm

<table>
<thead>
<tr>
<th>I (μA)</th>
<th>$A_{3,\text{meas}}$ (ppm)</th>
<th>$A_{3,\text{corr}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>$0.14 \pm 0.43$</td>
<td>$-2.5 \pm 0.43$</td>
</tr>
<tr>
<td>20</td>
<td>$-29.6 \pm 2.1$</td>
<td>$-7.2 \pm 2.1$</td>
</tr>
<tr>
<td>10</td>
<td>$-51.3 \pm 3.9$</td>
<td>$-9.5 \pm 3.9$</td>
</tr>
</tbody>
</table>

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Beam Polarization

- Beam polarization measured with interleaved Möller measurements
  - std Hall C polarimeter
    (M. Hauger, et al. NIM A462 (2001) 382.)
  - apply for groups of runs as shown
  - average: $P = 73.7\%$

<table>
<thead>
<tr>
<th>Source</th>
<th>Rel. uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>0.42</td>
</tr>
<tr>
<td>Leakage</td>
<td>0.2</td>
</tr>
<tr>
<td>Current extrap’n</td>
<td>1</td>
</tr>
<tr>
<td>Beam</td>
<td>0.52</td>
</tr>
<tr>
<td>Levchuk</td>
<td>0.3</td>
</tr>
<tr>
<td>Detection</td>
<td>0.35</td>
</tr>
<tr>
<td>Total</td>
<td>1.32</td>
</tr>
</tbody>
</table>
Timing in the Experiment

Accelerator pulse structure

Beam Helicity

1/30 s

~500 μs

“Macropulse”

“Quartet”

Helicity +---+ or -+++ (random)

Measurement timing

Typical t.o.f. spectrum
20 cm LH$_2$, aluminum target cell
longitudinal flow, $v \sim 8$ m/s, $P > 1000$ W!
negligible density change < 1.5%
measured small boiling contribution
  - 260 ppm/1200 ppm statistical width
Spectrometer Optics

- zero magnification along beam axis
- elastic protons dispersed in $Q^2$ along focal surface

- acceptance $0.12 < Q^2 < 1.0$ GeV$^2$ for 3 GeV incident beam

- detector 15 acceptance: $0.44 - 0.88$ GeV$^2$
  - 3 $Q^2$ bins at 0.51, 0.63 and 0.78 GeV$^2$
- detector 14: $Q^2 = 0.41, 1.0$ GeV$^2$
- det. 16: no elastic acceptance
  - important for measuring backgrounds
Detectors

- 16 detectors per octant
- Arc shape (const. $Q^2$), protons at normal incidence
  - Each detector: scintillator pair
    - BC408: 0.5, 1.0 cm thick
    - 1/8 in. shielding in-between
  - PMT at each end of each scintillator
    - XP2262B (NA), XP2282B (Fr)
  - Signal: mean-time-front AND mean-time-back
- Assembled with ~ 2 mm accuracy
- Octants in light-tight enclosures

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Electronics

- Measure time-of-flight target to detectors
- Counting rates $\leq$ 4 MHz per scintillator pair
- Fast time encoding
  - NA: dual 500 MHz shift registers $\rightarrow$ scalers (1 ns resolution)
    - “latching time digitizer” (LTD)
  - Fr: flash TDC $\rightarrow$ DSP $\rightarrow$ scalers (1/4 ns resolution)

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Electronics Deadtime Corrections

- Residual effect on asymmetry
  - scale factor

\[
A_{\text{meas}} = \frac{R_+ (1 - \tau R_+) - R_- (1 - \tau R_-)}{R_+ (1 - \tau R_+) + R_- (1 - \tau R_-)}
\]

\[
\approx A \left( 1 - \tau \frac{R_+ + R_-}{2} \right)
\]

- \( A \) is sum of physics and charge asymmetries
  - helicity-correlated beam current changes corrected in linear regression analysis
  - correction for residual effect \( \sim 0.05 \pm 0.05 \) ppm (pt-pt systematic unc.)

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Analysis
Analysis Overview

Blinding Factor

- Raw Asymmetries, $A_{\text{meas}}$

  "Beam" corrections:
  - Leakage beam asymmetry
  - Helicity-correlated beam properties
  - Deadtime
  - Beam polarization

Background correction

Unblinding

- $Q^2$

Elastic form factors

$G_E^s + \eta G_M^s$
Forward Data Summary

• 101 Coulombs of parity-quality beam
  - cuts on helicity-correlated beam parameter are
    4 x std. dev. for given run:

    | Quantity               | Std. dev. |
    |------------------------|-----------|
    | charge asymmetry       | 600 ppm   |
    | x, y position differences | 8, 10 µm |
    | x, y angle difference  | 0.6, 1.1 µrad |
    | energy difference      | 7.5 keV   |

• Includes running with both Hall A and Hall B (leakage beam asymmetry measured satisfactorily)

• Corresponds to: 701 h at 40 µA
  19 x 10^6 quartets
  76 x 10^6 MPS

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Statistical Properties of the Data

- Asymmetry distributions very clean over range of $10^5$

- Measured and expected widths agree at few % level
Helicity-Correlated Beam Parameters

- Response of spectrometer to beam changes well understood
- Average helicity-correlated beam parameters very small
- False asymmetries due to helicity-correlated beam parameters very small
  - overall about \(-0.02\) ppm
  - largest is \(0.01\) ppm from residual charge asymmetry
  - uncertainties small as well: \(0.01\) ppm

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Background Overview

- Measure yield and asymmetry of entire spectrum
- Correct asymmetry according to

\[ A_{\text{meas}} = (1 - f)A_{\text{el}} + fA_{\text{back}} \]

where \( A_{\text{el}} \) is the raw elastic asymmetry,

\[ f = \frac{Y_{\text{back}}}{Y_{\text{meas}}} \]

- Actual analysis: \( f = f(t) \)
  - det. 1-14
    - fit \( Y_{\text{back}} \) (polynomial of degree 4), Gaussian for elastic peak
    - then fit \( A_{\text{back}} \) (polynomial of degree 2), constant \( A_{\text{el}} \)
  - det. 15
    - interpolate over detectors for \( Y_{\text{back}}, A_{\text{back}} \)
    - fit 3 constants for \( A_{\text{el}} \)
Det 1-14 Background

- Results of 2-step fitting procedure: det 8
  - fit $Y_{\text{back}}$ (poly$^l$ of degree 4), Gaussian for elastic peak
  - then fit $A_{\text{back}}$ (poly$^l$ of degree 2), constant $A_{\text{el}}$
  - example fits
    - yield: $\chi^2 = 31.1/40$
    - asym: $\chi^2 = 37.5/44$
  - $f$ determined from $Y_{\text{back}}$, $Y_{\text{meas}}$ in subsequent analysis
    - don’t use detailed shape of elastic peak

- Det 14 similar except it has 2 elastic peaks
  - $Q^2 = 0.41, 1.0 \text{ GeV}^2$
Det. 1-14 Background Uncertainty

- Statistical uncertainty includes that from $A_{el}$ and from $A_{back}$

\[ A_{meas} = (1 - f)A_{el} + fA_{back} \]

- Systematic uncertainty: general philosophy
  - vary background yield and asymmetry over plausible ranges
  - consider distributions of results for $A_{el}$
    - unweighted
    - weighted by $\chi^2$
    - systematic uncertainty is average of std. dev. of these two distributions
Det. 1-14 Background Uncertainty

- Background yield varied within “lozenge”
  - use a variety of shapes

- Similar approach for asymmetry
  - vary throughout range
Correlations in Det 1-14 Backgrounds

- Separate point-to-point (pt-pt) uncertainties in background correction from global uncertainties
  - e.g. changing from linear to quadratic model for background asymmetry changes all det. 1-14 asymmetries downward on average

- Again using the distributions of results for $A_{e;i}$
  - calculate correlation coefficient
  - correlated uncertainty is change in centroid of distribution for given background model compared to width of overall distribution

\[
\Delta^2 A_{e;i,pt} = \Delta^2 A_{e;i,pt-rt} + \frac{3}{4} \Delta^2 A_{e;i,sys,rt} = \frac{3}{4} \Delta^2 A_{e;i,sys,pt}
\]

For det. 1-14
Det. 15 Background Yields

- Elastic protons shifted to lower t.o.f.
- Elastic peak broadened because of increased $Q^2$ acceptance
- Interpolate over detector range 12-14, 16
  - take out changing acceptance first

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Positive Background Asymmetries

- Det. 12-16 see smoothly varying peak in background asymmetries
  - maximum magnitude ~ +45 ppm

- Source is protons from hyperon weak decay scattering inside spectrometer
  - GEANT simulation with generator for hyperon production based on CLAS data
  - simulate both $\Lambda$ and $\Sigma^{+\,0}$ decays
    - polarization transfer for $\Lambda$ 100%
    - assume 70% for $\Sigma^+$
    - $\Sigma^0$ asymmetry scaled by further factor of $-1/3$ (CG coefficient)
  - simulation explains source; use measured data for actual analysis
Positive Background Asymmetries: GEANT

Det 13

Det 14

Det 15

Det 16

\[ \text{Asymmetry (ppm)} \]

\[ \text{ToF (ns)} \]

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Det. 15 Background Asymmetry

- Use smoothed interpolation of $A_{\text{back}}$ from det. 12-14, 16
- Uncertainties are $\pm 1$ detector AND $\pm 0.5$ ns time shift

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Det. 15 Asymmetry

- Compare interpolated background asymmetry and data
Correlations in Det. 15 Backgrounds

- Separate point-to-point (pt-pt) uncertainties in background correction from global uncertainties
  - in det. 15, correlations larger because bins are contiguous

- Consider distributions of results for $A_{el}$
  - for variety of randomly generated models determine correlation coefficient

- For det. 15

\[ \Delta^2 A_{el,sys} = \Delta^2 A_{el,pt-pt} + \Delta^2 A_{el.glob} \]

\[ \Delta^2 A_{el,pt-pt} = \frac{1}{2} \Delta^2 A_{el,sys} \]

\[ \Delta^2 A_{el.glob} = \frac{1}{2} \Delta^2 A_{el,sys} \]
Dilution factor and Background Asymmetry

- Smooth, systematic progression
  - dilution factor
  - background asymmetry
  - both averaged over t.o.f. for demonstration
GO results
Experimental Results

- $A_{\text{phys}}$ corrected for all beam, electronics, background factors

<table>
<thead>
<tr>
<th>Det</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$A_{\text{phys}}$ (ppm)</th>
<th>$\Delta A_{\text{stat}}$ (ppm)</th>
<th>$\Delta A_{\text{sys,pt}}$ (ppm)</th>
<th>$\Delta A_{\text{sys,glob}}$ (ppm)</th>
<th>$f$ (ppm)</th>
<th>$\Delta A_{\text{meas}}$ (ppm)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>0.122</td>
<td>-1.513</td>
<td>0.436</td>
<td>0.224</td>
<td>0.176</td>
<td>0.061</td>
<td>-1.380</td>
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<tr>
<td>2</td>
<td>0.128</td>
<td>-0.972</td>
<td>0.409</td>
<td>0.198</td>
<td>0.173</td>
<td>0.084</td>
<td>-1.070</td>
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<tr>
<td>3</td>
<td>0.136</td>
<td>-1.298</td>
<td>0.424</td>
<td>0.174</td>
<td>0.170</td>
<td>0.085</td>
<td>-1.340</td>
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<tr>
<td>4</td>
<td>0.144</td>
<td>-2.707</td>
<td>0.433</td>
<td>0.183</td>
<td>0.176</td>
<td>0.077</td>
<td>-2.670</td>
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<tr>
<td>5</td>
<td>0.153</td>
<td>-2.223</td>
<td>0.431</td>
<td>0.284</td>
<td>0.214</td>
<td>0.096</td>
<td>-2.460</td>
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<tr>
<td>6</td>
<td>0.164</td>
<td>-2.880</td>
<td>0.434</td>
<td>0.324</td>
<td>0.234</td>
<td>0.100</td>
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<td>7</td>
<td>0.177</td>
<td>-3.949</td>
<td>0.426</td>
<td>0.251</td>
<td>0.205</td>
<td>0.110</td>
<td>-4.470</td>
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<tr>
<td>8</td>
<td>0.192</td>
<td>-3.850</td>
<td>0.485</td>
<td>0.218</td>
<td>0.192</td>
<td>0.110</td>
<td>-5.010</td>
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<td>9</td>
<td>0.210</td>
<td>-4.683</td>
<td>0.475</td>
<td>0.258</td>
<td>0.212</td>
<td>0.116</td>
<td>-5.730</td>
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<td>10</td>
<td>0.232</td>
<td>-5.267</td>
<td>0.505</td>
<td>0.301</td>
<td>0.232</td>
<td>0.136</td>
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<td>11</td>
<td>0.262</td>
<td>-5.260</td>
<td>0.520</td>
<td>0.108</td>
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<td>0.154</td>
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<tr>
<td>12</td>
<td>0.299</td>
<td>-7.715</td>
<td>0.602</td>
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<td>0.349</td>
<td>0.174</td>
<td>-5.400</td>
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<tr>
<td>13</td>
<td>0.344</td>
<td>-8.400</td>
<td>0.676</td>
<td>0.850</td>
<td>0.521</td>
<td>0.182</td>
<td>-3.650</td>
</tr>
<tr>
<td>14 a</td>
<td>0.410</td>
<td>-10.25</td>
<td>0.674</td>
<td>0.895</td>
<td>0.551</td>
<td>0.180</td>
<td>-1.700</td>
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<td>15 a</td>
<td>0.511</td>
<td>-16.81</td>
<td>0.889</td>
<td>1.478</td>
<td>1.498</td>
<td>0.190</td>
<td>-5.800</td>
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<tr>
<td>15 b</td>
<td>0.631</td>
<td>-19.96</td>
<td>1.112</td>
<td>1.277</td>
<td>1.306</td>
<td>0.200</td>
<td>-9.740</td>
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<tr>
<td>15 c</td>
<td>0.788</td>
<td>-30.83</td>
<td>1.857</td>
<td>2.556</td>
<td>2.589</td>
<td>0.400</td>
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<tr>
<td>14 b</td>
<td>0.997</td>
<td>-37.93</td>
<td>7.237</td>
<td>9.000</td>
<td>0.519</td>
<td>0.780</td>
<td>4.210</td>
</tr>
</tbody>
</table>
Asymmetry with EW Radiative Corrections

- Full form of asymmetry used to extract $G_E^s + \eta G_M^s$

$$A = -\frac{G_F^e Q^2}{4\pi\alpha\sqrt{2}} \frac{1}{\varepsilon G_E^p + \tau G_M^p} \left\{ \left(1 - 4\sin^2 \theta_W \right) \left(\varepsilon G_E^p G_E^p + \tau G_M^p G_M^p \right) \left(1 + R_V^p \right) \right\} - \left(\varepsilon G_E^p G_E^n + \tau G_M^p G_M^n \right) \left(1 + R_V^n \right) - \left(\varepsilon G_E^p G_E^s + \tau G_M^p G_M^s \right) \left(1 + R_V^{(0)} \right) - \varepsilon' \left(1 - 4\sin^2 \theta_W \right) G_M^p G_A^e \right\}$$

where

$$G_A^e = -G_A^p \left(1 + R_A^{T=1} \right) + \left[ \frac{1}{2} \left(3F - D\right) R_A^{T=0} + \Delta s \left(1 + R_A^{(0)} \right) \right] G_A^{dip}$$

and

$$G_A^p = g_A G_A^{dip} = (F + D) G_A^{dip} = \frac{g_A}{\left(1 + \frac{Q^2}{\Lambda_A^2} \right)^2}$$

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Standard Parameters

- use Zhu, et al. $R_A^{T=1}$, $R_A^{T=0}$ including anapole
- incident energy 3.028 GeV

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$1/137.03599976$</th>
<th>$R_V^p$</th>
<th>$-0.0447091$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_W$</td>
<td>0.2312</td>
<td>$R_V^n$</td>
<td>$-0.011789$</td>
</tr>
<tr>
<td>$G_F$</td>
<td>0.00000116639 GeV$^2$</td>
<td>$R_V^{(0)}$</td>
<td>$-0.011789$</td>
</tr>
<tr>
<td>$m_p$</td>
<td>0.938272 GeV</td>
<td>$R_A^{T=1}$</td>
<td>$-0.259163$</td>
</tr>
<tr>
<td>$\mu_p$</td>
<td>2.79285</td>
<td>$R_A^{T=0}$</td>
<td>$-0.23826$</td>
</tr>
<tr>
<td>$\mu_n$</td>
<td>$-1.91304$</td>
<td>$R_A^{(0)}$</td>
<td>$-0.551753$</td>
</tr>
<tr>
<td>$\Lambda^2$</td>
<td>0.711 GeV$^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_A^2$</td>
<td>1.00 GeV$^2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$g_A/g_V$</td>
<td>1.2695</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$3F-D$</td>
<td>0.585</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

http://www.npl.uiuc.edu/exp/G0/Forward

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Strange Quark Contribution

- Strange quark contribution to asymmetry

\[ G_E^s + \eta G_M^s = \frac{4\pi\alpha\sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^p}{G_E^p(1+R_V^{0})} \left( A_{\text{phys}} - A_{\text{NVS}} \right) + \tau G_M^p \]

\[ \eta(Q^2, E_i) = \frac{\tau G_M^p}{\varepsilon G_E^p} \]

\[ Q^2 (\text{GeV}^2) \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \quad 1 \]
$A_{NV}$ Sensitivities

- Base calculation uses Kelly electromagnetic form factors and uncertainties
  - PRC 70 (2004) 068202
    - "Rosenbluth" fit for $G_E^p, G_M^p$
    - Kelly for $G_E^n, G_M^n$

- Key factors, uncertainties

$$\frac{\Delta G_A^p}{G_A^p} = 2.2\%$$
$$R_A^{T=0} = -0.24 \pm 0.20$$
$$R_A^{T=1} = -0.26 \pm 0.35$$
$$R_A^{(0)} = -0.55 \pm 0.55$$
$$3F - D = 0.585 \pm 0.025$$
Electromagnetic Form Factors

- Use Kelly parameterization for baseline results
  - omits Rosenbluth data for $G_E^D$, $Q^2 > 1 \text{ GeV}^2$
  - omits some neutron data using associate particle calibration
Electromagnetic Form Factor Uncertainties

- Use slightly modified Kelly uncertainties

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G0 Sensitivities for $G_E^s$

\[
\frac{\partial G_E^s}{\partial p}:
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Det 1</th>
<th>Det 8</th>
<th>Det 14a</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\text{meas}}$ (1/ppm)</td>
<td>$8.344 \times 10^{-2}$</td>
<td>$5.068 \times 10^{-2}$</td>
<td>$2.113 \times 10^{-2}$</td>
</tr>
<tr>
<td>$E_i$ (1/GeV)</td>
<td>$-1.911 \times 10^{-3}$</td>
<td>$-3.021 \times 10^{-3}$</td>
<td>$-6.755 \times 10^{-3}$</td>
</tr>
<tr>
<td>$Q^2$ (1/GeV$^2$)</td>
<td>$1.680$</td>
<td>$1.575$</td>
<td>$8.718 \times 10^{-1}$</td>
</tr>
<tr>
<td>$G_E^{\gamma p}$</td>
<td>$-2.396 \times 10^{-1}$</td>
<td>$-3.909 \times 10^{-1}$</td>
<td>$-6.987 \times 10^{-1}$</td>
</tr>
<tr>
<td>$G_M^{\gamma p}$</td>
<td>$5.488 \times 10^{-2}$</td>
<td>$6.063 \times 10^{-2}$</td>
<td>$1.010 \times 10^{-1}$</td>
</tr>
<tr>
<td>$G_E^{\gamma n}$</td>
<td>$-1.000$</td>
<td>$-1.000$</td>
<td>$-1.000$</td>
</tr>
<tr>
<td>$G_M^{\gamma n}$</td>
<td>$-9.839 \times 10^{-2}$</td>
<td>$-1.559 \times 10^{-1}$</td>
<td>$-3.407 \times 10^{-1}$</td>
</tr>
<tr>
<td>$G_A^{\gamma p}$</td>
<td>$3.992 \times 10^{-3}$</td>
<td>$6.471 \times 10^{-3}$</td>
<td>$1.516 \times 10^{-2}$</td>
</tr>
<tr>
<td>$G_A^s$</td>
<td>$-1.721 \times 10^{-3}$</td>
<td>$-2.472 \times 10^{-3}$</td>
<td>$-4.140 \times 10^{-3}$</td>
</tr>
<tr>
<td>$R_V^p$</td>
<td>$6.896 \times 10^{-2}$</td>
<td>$6.589 \times 10^{-2}$</td>
<td>$5.861 \times 10^{-2}$</td>
</tr>
<tr>
<td>$R_V^n$</td>
<td>$9.440 \times 10^{-2}$</td>
<td>$1.307 \times 10^{-1}$</td>
<td>$2.060 \times 10^{-1}$</td>
</tr>
<tr>
<td>$R_V^{(0)}$</td>
<td>$-3.739 \times 10^{-2}$</td>
<td>$-2.846 \times 10^{-3}$</td>
<td>$-5.320 \times 10^{-2}$</td>
</tr>
<tr>
<td>$R_A^0$</td>
<td>$-1.123 \times 10^{-3}$</td>
<td>$-1.613 \times 10^{-3}$</td>
<td>$-2.702 \times 10^{-3}$</td>
</tr>
<tr>
<td>$R_A^1$</td>
<td>$4.875 \times 10^{-3}$</td>
<td>$7.002 \times 10^{-3}$</td>
<td>$1.173 \times 10^{-2}$</td>
</tr>
<tr>
<td>$R_A^{(0)}$</td>
<td>$3.226 \times 10^{-4}$</td>
<td>$4.633 \times 10^{-4}$</td>
<td>$7.759 \times 10^{-4}$</td>
</tr>
<tr>
<td>$3F-D$</td>
<td>$4.575 \times 10^{-4}$</td>
<td>$6.571 \times 10^{-4}$</td>
<td>$1.100 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Experimental Asymmetries

- “no vector strange” asymmetry, $A_{NVS}$, is $A(G_E^s, G_M^s = 0)$
- inside error bars: stat, outside: stat & pt-pt

![Graph showing $A$ (ppm) vs $Q^2$ (GeV$^2$)](http://www.npl.uiuc.edu/exp/G0/Forward)
Experimental Asymmetries

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Strange Quark Contribution to Proton

$G_E^s + \eta G_M^s$

$Q^2 (\text{GeV}^2)$

$\Delta A_{\text{glob}}$

$\Delta A_{\text{model}}$

http://www.npl.uiuc.edu/exp/G0/Forward

DHB, 17 June 2005
Strange Quark Contribution to Proton

\[ G_E^s + \eta G_M^s \]

- **G0**
- **HAPPEX**
- **Arrington**
- **Friedrich & Walcher**

\[ Q^2 (\text{GeV}^2) \]

http://www.npl.uiuc.edu/exp/G0/Forward

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Speculation
Simple Fits to World Hydrogen Data

- Fit

\[ G_E^s(Q^2) + \eta(Q^2, E_i)G_M^s(Q^2) = \]
\[ \frac{4\pi\alpha\sqrt{2}}{G_F Q^2} \frac{\varepsilon G_E^p}{\varepsilon G_E^p (1 + R_V^{(0)})} \left( A_{phys} - A_{NVS}(Q^2, E_i) \right) \]

with simple forms for \( G_E^s \), \( G_M^s \)

\[ G_E^s(Q^2) = \frac{c_2 Q^4}{1 + d_1 Q^2 + d_2 Q^4 + d_3 Q^6} \]

à la Kelly

\[ G_M^s(Q^2) = \frac{G_M^s(Q^2 = 0)}{\left(1 + Q^2 / \Lambda_M^s \right)^2} \]

with

\[ G_M^s(Q^2 = 0) = 0.81 \]

from \( Q^2 = 0.1 \text{ GeV}^2 \) plot, dipole ff

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“Fit” to World Hydrogen Data

- $\chi^2 = 31/20$
“Fit” to World Hydrogen Data

\[ c_2 = -0.51 \pm 0.25 \]
\[ d_1 = -8.5 \pm 0.9 \]
\[ d_2 = 24 \pm 6 \]
\[ d_3 = 1 \]
\[ \Lambda_M^s = \Lambda^2 / 1.3 \]

Remember the factor of \(-1/3\)
G0 Summary

- First measurement of parity-violating asymmetries over broad $Q^2$ range
- Excellent performance of accelerator, experimental equipment
- Conservative estimates of uncertainties
  - careful assessment of backgrounds

- Results consistent with previous measurements

- Emerging picture
  - $G_M^S > 0$ at low $Q^2$
  - $G_E^S < 0$ at medium $Q^2$ a possibility
  - $G_E^S + \eta G_M^S$ positive at higher $Q^2$