Strange Quark Contributions to Parity-Violating Electron Scattering Asymmetries in the Backward Angle $G^0$ Experiment

Mathew Muether - University of Illinois
for the G0 Collaboration
Hadron 2009
Outline

• Strange quark contributions to the nucleon
• $G^0$ Backward angle measurement and analysis
• Strange and Axial Form Factor Results
Why strange quarks in the nucleon?
Why strange quarks in the nucleon?

What’s in a proton?

- Scalar matrix element
- Momentum
- Spin
- Vector matrix elements
Why strange quarks in the nucleon?

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Valence quarks carry baryon number and account for 1% of total mass (u, d)
Why strange quarks in the nucleon?

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sea of strongly coupled self interacting gluons and associated quark-antiquark pairs (u,d and ... s)
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- scalar matrix element
- momentum
- spin
- vector matrix elements

\[
2 \langle N | s \bar{s} | N \rangle / \langle N | u \bar{u} + d \bar{d} | N \rangle \sim 0.1 - 0.4
\]
\[
2s / (u + d) = 0.42 \pm 0.07 \pm 0.06
\]
\[
\Delta s_{0.02} = 0.006 \pm 0.029 \pm 0.007
\]
\[
G \sim \langle N | \sum_i e_i \bar{q}_i \Gamma_\mu q_i | N \rangle
\]
Flavored Form Factors
Flavored Form Factors

\[ G_{E,M}^{\{\gamma,Z\},\{p,n\}} = q_{u}^{\gamma,Z} G_{E,M}^{u,\{p,n\}} + q_{d,s}^{\gamma,Z} (G_{E,M}^{d,\{p,n\}} + G_{E,M}^{s,\{p,n\}}) \]

where

\[ \frac{1}{3} \{ q_{u}^{\gamma}, q_{d,s}^{\gamma}, q_{u}^{Z}, q_{d,s}^{Z} \} = \{ 2, -1, 3 - 8 \sin^{2} \theta_{W}, -3 + 4 \sin^{2} \theta_{W} \} \]
\[ G_{E,M}^{\{\gamma,Z\},\{p,n\}} = q^{\gamma,Z}_{u} G_{E,M}^{u,\{p,n\}} + q^{\gamma,Z}_{d,s} (G_{E,M}^{d,\{p,n\}} + G_{E,M}^{s,\{p,n\}}) \]

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\]

plus charge symmetry

\[
\{ G_{E,M}^{u,p}, G_{E,M}^{d,p}, G_{E,M}^{s,p} \} = \{ G_{E,M}^{d,n}, G_{E,M}^{u,n}, G_{E,M}^{s,n} \}
\]

(see G. A. Miller PRC 57 (98) 1492.; B. Kubis and R. Lewis, PRC (74) , 015204)
Flavored Form Factors

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(see G. A. Miller PRC 57 (98) 1492.; B. Kubis and R. Lewis, PRC (74), 015204)

Note: Charge symmetry breaking effects are typically small (~1%) compared to the experimental precision
Flavored Form Factors

\[ G_{E,M}^{s,p} = (1 - 4 \sin^2 \theta_w) G_{E,M}^{\gamma,p} - G_{E,M}^{\gamma,n} - G_{E,M}^{Z,p} \]
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Electromagnetic form factors and the weak mixing angle are well measured quantities in this context.
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Measurements of the neutral weak form factors are needed for flavor separation. Elastic e-p cross sections are sensitive to both Υ and Z exchange but ....
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Measurements of the neutral weak form factors are needed for flavor separation. Elastic e-p cross sections are sensitive to both \( \Upsilon \) and \( Z \) exchange but \( \Upsilon \) dominates!

\[ \sim 1 \]  
\[ + 2 \]  
\[ \sim 2 \times 10^{-4} \]  
\[ + \sim 9 \times 10^{-9} \]
Accessing Neutral Weak Currents

The parity violating cross term allows one to form an observable which is sensitive to $G^Z$:

$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \sim \frac{2M^*_\gamma M^{PV}_Z}{|M_\gamma|^2}$$

$$= -\frac{G_F Q^2}{4\sqrt{2\pi\alpha}} \frac{\epsilon G_\gamma^E G^Z_E}{\epsilon(G_\gamma^E)^2 + \tau(G_\gamma^M)^2} + \tau G_\gamma^M G^Z_M - (1 - 4\sin^2\theta_W)\epsilon' G_\gamma^M G^e_A$$

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\[
A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \approx \frac{2\mathcal{M}_\gamma^* \mathcal{M}_Z^{PV}}{|\mathcal{M}_\gamma|^2}
\]

\[
= -\frac{G_F Q^2}{4\sqrt{2\pi\alpha}} \frac{\epsilon G^Z \epsilon' G^Z}{\epsilon (G^\gamma_E')^2 + \tau (G^\gamma_M)^2} - (1 - 4 \sin^2 \theta_W) \frac{\epsilon' G^\gamma_M G^e_A}{\epsilon (G^\gamma_E')^2 + \tau (G^\gamma_M)^2}
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\]

\[
= - \frac{G_F Q^2}{4\sqrt{2\pi\alpha}} \left( \epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z \right) - (1 - 4\sin^2\theta_W) \epsilon' G_M^\gamma G_A^e
\]

\[
\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2
\]

\( A_{PV} \) is sensitive to axial form factors at backward angles

Accessing Neutral Weak Currents

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$$A_{PV} = \frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L} \sim \frac{2M^*_\gamma M^{PV}_Z}{|M_\gamma|^2} \sim 10^{-5}$$

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \epsilon G_E^\gamma (G_E^Z) + \tau G_M^\gamma (G_M^Z) - (1 - 4\sin^2 \theta_W) \epsilon' G_M^\gamma G_A^e \frac{\epsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}{\epsilon (G_E^\gamma)^2}$$

$A_{PV}$ is sensitive to axial form factors at backward angles

Axial Current Contribution

\[ G^e_A = G_A \tau_3 + \eta F_A + R_e + \Delta s \]
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\( G_A \), from \( \gamma_\mu \gamma_5 \), probes the spin–isospin distribution of the nucleon and has been measured in neutrino scattering.
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Nucleon anapole form factor from the effective parity-violating coupling between real photons and nucleons.
PVES Measurements

3 measurements at a given $Q^2$ are needed to separate the form factors.
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e-p scattering at forward angles
PVES Measurements

3 measurements at a given $Q^2$ are needed to separate the form factors.

e-$p$ scattering at forward angles

$e-p$ scattering at backward angles
PVES Measurements

3 measurements at a given $Q^2$ are needed to separate the form factors.

- e-p scattering at forward angles
- e-p scattering at backward angles
- and e-d scattering at backward angles

$$A_D = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \times \frac{Num_n + Num_p}{Denom_n + Denom_p}$$

Sensitive to the axial form factor
## PVES Measurements

<table>
<thead>
<tr>
<th>Expt/Lab</th>
<th>Target/Angle</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$A_{\text{phy}}$ (ppm)</th>
<th>$s$ Sensitivity</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAMPLE/Bates</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>SAMPLE I</td>
<td>LH$_2$/145</td>
<td>0.1</td>
<td>-6</td>
<td>$\mu_s + 0.4G_A$</td>
<td>2000</td>
</tr>
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<td>SAMPLE II</td>
<td>LD$_2$/145</td>
<td>0.1</td>
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<td>0.04</td>
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<td>HAPPEx</td>
<td>LH$_2$/12.5</td>
<td>0.47</td>
<td>-15</td>
<td>$G_E + 0.39G_M$</td>
<td>2001</td>
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<tr>
<td>HAPPEx II, III</td>
<td>LH$_2$/6</td>
<td>0.11</td>
<td>-1.6</td>
<td>$G_E + 0.1G_M$</td>
<td>2006, 2007</td>
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<td>HAPPEx He</td>
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**Note:** The table represents measurements of PVES (Polarized Vector Electromagnetic Structure) in different experiments and laboratories, detailing various parameters such as $Q^2$, $A_{\text{phy}}$, $s$ sensitivity, and status.
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</table>

Provides a complete measurement at $Q^2$ larger than 0.1 GeV$^2$
G⁰ Collaboration

Graduate Students:
C. Capuano (W&M), A. Coppens (Manitoba), C. Ellis (Maryland), J. Mammei (VaTech), M. Muether (Illinois), J. Schaub (New Mexico State), M. Versteegen (Grenoble); S. Bailey (Ph.D. Jan. 07 W&M)

Analysis Coordinator:
F. Benmokhtar - Carnegie Mellon (Maryland)

Caltech, Hendricks College, Orsay, LA Tech, Ohio, JLab, TRIUMF, Kentucky, Manitoba, Winnipeg, Zagreb, Yerevan Physics Institute
CEBAF at JLab

- Helicity changed every 1/30 sec (MPS).
- Form a pseudo-random quartet structure in helicity (+--+ or -++-).
- Excellent “parity quality” $A_q < 0.3$ ppm, $\Delta(x,y) < 20$ nm, $\Delta\Theta(x,y) < 1$ nrad, $\Delta E < 3$ eV
- Beam Polarization 85.8%
Detection scheme
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20 cm cryo-target
Detection scheme

Superconducting Magnetic Spectrometer

20 cm cryo-target
Detection scheme

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Lead Collimators

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2 scintillator arrays (FPD/CED) providing kinematic selection

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2 scintillator arrays (FPD/CED) providing kinematic selection

Cerenkov detector for e/pion separation 1:85 rejection factor

20 cm cryo-target
Electron Yields

LH2, 687 MeV

LD2, 687 MeV

LH2, 362 MeV

LD2, 362 MeV
Electron Yields

LH2, 687 MeV

LH2, 362 MeV

LD2, 687 MeV

LD2, 362 MeV

Elastic
Electron Yields

LH2, 687 MeV

LD2, 687 MeV

LH2, 362 MeV

LD2, 362 MeV

Elastic

Inelastic
Electron Yields

LH2, 687 MeV

LD2, 687 MeV

LH2, 362

LD2, 362 MeV

Elastic

Inelastic

Background
Asymmetries

Each pseudorandom quartet in each cell in each octant,

\[ A_{meas} = \frac{Y_+ - Y_- - Y_- + Y_+}{Y_+ + Y_- + Y_- + Y_+} \]
Asymmetries

Each psuedorandom quartet in each cell in each octant,

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Asymmetries

Each pseudo-random quartet in each cell in each octant,

$$A_{meas} = \frac{Y_+ - Y_- - Y_- + Y_+}{Y_+ + Y_- + Y_- + Y_+}$$

Insertable half waveplate allows manual control of asymmetry sign for systematics control.

$\sim 100M$ quartets collected for each data set
Asymmetries

Each pseudorandom quartet in each cell in each octant,

\[ A_{\text{meas}} = \frac{Y_+ - Y_- - Y_- + Y_+}{Y_+ + Y_- + Y_- + Y_+} \]

Elastic locus average for each octant, IHWP (H687)

Insertable half waveplate allows manual control of asymmetry sign for systematics control.

\~100M quartets collected for each data set
Analysis Strategy

<table>
<thead>
<tr>
<th>H, D Raw Asymmetries, $A_{\text{meas}}$</th>
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<tbody>
<tr>
<td><strong>Instrumental &amp; Beam corrections:</strong></td>
</tr>
<tr>
<td>Electronic Deadtime/Randoms</td>
</tr>
<tr>
<td>Helicity-correlated beam properties</td>
</tr>
<tr>
<td>Beam polarization</td>
</tr>
<tr>
<td><strong>Background corrections:</strong></td>
</tr>
<tr>
<td>Dilution Factors</td>
</tr>
<tr>
<td>Backgrounds from target</td>
</tr>
<tr>
<td>Pion Contamination</td>
</tr>
</tbody>
</table>

| LH2 $A_{\text{phys}}$ | LD2 $A_{\text{phys}}$ |

Forward angle results

$G_E^s + \eta G_M^s$

- $Q^2$ Determination
- Radiative Corrections
- Electromagnetic Form Factors

\[ G_E^s \quad G_M^s \quad G_A^e \]
Instrumental Corrections

Helicity-correlated beam false asymmetries $\sim 0.1$ ppm

Electronic Deadtime/Randoms

Simulated full electronics chain and studied via current scans

- LH2, 687 MeV, 60 μA $\sim 7\%$
- LH2, 362 MeV, 60 μA $\sim 6\%$
- LD2, 687 MeV, 20 μA $\sim 9\%$
- LD2, 362 MeV, 35 μA $\sim 13\%$

Beam polarization

$$A_{el} = \frac{1}{P} \times A_{meas} + K_s$$

$I/P = 1/1.858 +/-.02$ (ppm)

$K_s$: correction for transverse beam component $<.04$ ppm
Ordinary Radiative effects

\[ R_c = \frac{A_{\text{tree}}}{A_{\text{RC}}} \]

Found to be \( \sim 1.035 \) from simulation

Tsai 71

2-boson corrections (Arrington, Blunden, Melnitchouk, et al.; Zhou, Kao & Yang, priv. comm.) found to contribution less than .3 ppm
Backgrounds: Field Scans

Use simulation *shapes* to help determine dilution factors

\[ A_{el} = \frac{A_{meas} - f_{al} A_{Al} - f_{pi} - A_{pi} - f_{other} A_{other}}{1 - f_{al} - f_{pi} - f_{other}} \]

**Table**

<table>
<thead>
<tr>
<th>Tar</th>
<th>( Q^2_{\text{GeV}^2} )</th>
<th>( f_{al} )</th>
<th>( f_{pi} )</th>
<th>( f_{other} )</th>
<th>( f_{total} )</th>
</tr>
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<tbody>
<tr>
<td>H</td>
<td>0.22</td>
<td>0.129 ± 0.064</td>
<td>0 ± 0.001</td>
<td>0.003</td>
<td>0.132 ± 0.064</td>
</tr>
<tr>
<td>D</td>
<td>0.22</td>
<td>0.099 ± 0.050</td>
<td>0 ± 0.002</td>
<td>0.005</td>
<td>0.104 ± 0.050</td>
</tr>
<tr>
<td>H</td>
<td>0.628</td>
<td>0.110 ± 0.055</td>
<td>0 ± 0.001</td>
<td>0.023</td>
<td>0.133 ± 0.060</td>
</tr>
<tr>
<td>D</td>
<td>0.628</td>
<td>0.061 ± 0.031</td>
<td>0.04 ± 0.015</td>
<td>0.029</td>
<td>0.13 ± 0.045</td>
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\( A_{pi/other} \sim 0 \)

\( A_{Al} \sim A_{D} \) with 15% uncer.

\( f_{pi} \)- from t.o.f./Cer. studies

\( f_{Al} \) from empty target
In addition

- Starting from asymmetries, need deuterium model (Schiavilla, priv. comm.)
  electromagnetic form factors (Kelly PRC 70 (2004))
- Interpolation of G0 forward angle measurement (D. S. Armstrong et al., PRL 95, 092001)
Results

Error bars: statistical and statistical plus point-to-point systematic; shaded bars show global systematic uncertainties (for $G^0$ points).

For $G_E^s$ and $G_M^s$, an extraction at $Q^2 = 0.1 \text{ GeV}^2$ from Liu as well as the results of the PVA4 (Mainz) experiment are shown.

Note: PVA4 assumes GeA value based on Zhu and dipole

Lattice calculations from Adelaide and Kentucky groups are shown.

For $G_A^e$, results from the SAMPLE experiment are shown together with the calculation of Zhu, et al.
Conclusions

• We have measured backward angle parity-violating asymmetries in elastic electron-proton and quasi-elastic electron-deuteron scattering at $Q^2 = 0.221$ and 0.628 GeV$^2$.

• From the asymmetries we have determined $G_E^s$, $G_M^s$ and $G_A^e$ which indicate that the strange quark contributions to the nucleon form factors are <10%, and provide the first information on the $Q^2$ dependence of $G_A^e$.

• Additional forward angle experiments at $Q^2 = 0.63$ GeV$^2$ are planned at Jefferson Lab and Mainz to further improve the precision of these determinations.

-Thank you
Backup Slides
Forward Angle Result

\[ G_E^S + iG_M^S \]

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

- Blue squares: \( G^0 \), Kelly F.F.
- Dashed line: Baseline, Arrington, Meinlouchouk & Tjon
- Dotted line: Baseline, Friedrich & Walcher
Transverse Asymmetries

- Elastic scattering:
  Second order e.m. effects generate single-spin asymmetries

\[ A_n \propto \frac{M_\gamma \text{Im} M_{\gamma\gamma}}{|M_\gamma|^2} \]

- Real part of \( M_{2\gamma} \) related to important contribution to longitudinal scattering: \( G_E/G_M \) ratio
Deuterium Model

\[ A_{\text{phys}} = a_0 + a_1 G_E^s + a_2 G_M^s + a_3 G_A^e \]

- Calculation from R. Schiavilla
Contributions to Overall Form Factors
Measured Asymmetries

LH$_2$ 362 MeV

LD$_2$ 362 MeV

LH$_2$ 687 MeV

LD$_2$ 687 MeV
# Asymmetry Uncertainties

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<thead>
<tr>
<th>Correction</th>
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# Asymmetry Uncertainties

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## Asymmetry Uncertainties

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Comparison to theory
Scaler Counting issue

- An occasional bit drop in a North American scaler was traced down to trigger electronics. At high rates: LD2 target at 362 MeV. This was fixed during the run (Jan07)

- Problem blind to helicity.

- Test by cutting data; compare with French octants.
- Confirmed by unchanged asymmetry

\[ \text{Uncut} \quad 7\sigma \quad 6\sigma \quad 5\sigma \quad 4\sigma \quad 3\sigma \]

5\(\sigma\) cut removes \(\sim 1\)% of our data for 362\(\text{MeV}\) LD2, which is the worst case!