Studying Strong and Electroweak Interactions Using Electron Scattering at JLab

Xiaochao Zheng
Univ. of Virginia
February 6, 2009

- Introduction — electron scattering and nucleon structure
- Parity Violating DIS
  - E08-011 using a 6 GeV beam – Physics and preparation status;
  - Program at the 12 GeV Upgrade
- Nucleon resonances study from pion electroproduction
- Summary of research program and outlook
# Four Interactions of Our Nature

<table>
<thead>
<tr>
<th>Gravitational</th>
<th>$10^{-38}$</th>
<th>General relativity</th>
<th>Well understood at large distances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-Magnetic</td>
<td>$1/137$</td>
<td>SU(2) x U(1) gauge theory</td>
<td>EM, weak: fully understood, but there is room for New Physics</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-5}$</td>
<td>SU(3), QCD</td>
<td>less understood, and no analytical calculation</td>
</tr>
<tr>
<td>Strong</td>
<td>$10^{-1}$ - $10^{0}$</td>
<td>SU(3), QCD</td>
<td></td>
</tr>
</tbody>
</table>

**Electron scattering has been widely used to study**

- Structure of the nucleon — strong interactions, pQCD;
- (Recently) parity violation electron scattering:
  - strange-quark content of the nucleon (elastic)
  - Electroweak interactions (DIS)
Electrons (μ's) interact with the target by exchanging a “virtual” photon;

Two variables to describe how the target behaves: 1/Q^2 and ν;
The cross section:

\[ \frac{d^2 \sigma}{d \Omega \, dE'} = \sigma_{Mott} \left[ \alpha F_1(Q^2, \nu) + \beta F_2(Q^2, \nu) \right] \]

For point-like target
Exploring Nucleon Structure Using Electron Scattering

Elastic, quasi-elastic, resonances, deep inelastic

➔ (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body

\[ Q^2 = 2M_{T(N)}^2 \]

➔ Resonance region – quarks inside the nucleon react coherently

➔ Deep Inelastic Scattering (DIS):

- Quarks start to react incoherently (start to see constituents of the nucleon)
- Can test pQCD

(highly non-pertubative, phenomenology models)
Exploring Nucleon Structure Using Electron Scattering

Elastic, quasi-elastic, resonances, deep inelastic

→ (Quasi-) elastic – the nucleus (nucleon) appears as a rigid body

→ Resonance region – quarks inside the nucleon react coherently

→ Deep Inelastic Scattering (DIS):
  • Quarks start to react incoherently (start to see constituents of the nucleon)
    (Can test pQCD)

\[
Q^2 = \frac{2MT}{N}
\]
Current Knowledge of Nucleon Unpolarized Structure

\[
\frac{d^2 \sigma}{d \Omega \, dE'} = \sigma_{\text{Mott}} \left[ \alpha F_1(Q^2, x) + \beta F_2(Q^2, x) \right]
\]

\[
F_1 = \frac{F_2(1+y^2)}{2x \left( 1 + R(Q^2, x) \right)} \quad x_{\text{Bj}} = \frac{Q^2}{2M \nu}
\]

Proton

Deuteron

\begin{align*}
F_2(x, Q^2) &= c(x) \\
0.1 & 1.0 & 10 & 10^2 & 10^3 & 10^4 & 10^5 & 10^6
\end{align*}

\begin{align*}
Q^2(\text{GeV}^2)
0.1 & 1.0 & 10 & 10^2
\end{align*}
After four decades of DIS experiments, the unpolarized structure of the nucleon is reasonably well understood (for moderate $x_{Bj}$ region);

**Similar status for spin structure of the nucleon from polarized DIS.**
Weak Interaction in DIS
(Parity Violating DIS)
What is Parity Violation

- The parity symmetry: the physical laws behind all phenomena must be the same as those behind their mirror images;
- However this symmetry is broken in weak interactions.

1957 Nobel Prize in Physics:
"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"
Parity Violating Electron Scattering

- Electromagnetic observables — $\sigma, A...$
- Weak observables — parity violating asymmetries ($A_{PV}$)
  (polarized beam + unpolarized target)
Parity Violating Electron Scattering

- Electromagnetic observables — $\sigma, A$...
- Weak observables — parity violating asymmetries ($A_{PV}$)

(polarized beam + unpolarized target)

VS.

\[ \text{(polarized beam + unpolarized target)} \]
Parity Violating Electron Scattering

Electromagnetic observables — $\sigma, A$...

Weak observables — parity violating asymmetries ($A_{PV}$)

(polarized beam + unpolarized target)

$$A_{PV} = \begin{array}{c}
\begin{array}{ccc}
\text{e} & \gamma & \text{e} \\
\text{e} & \equiv & \approx Q^2 \\
\end{array}
\end{array} + \begin{array}{c}
\begin{array}{ccc}
\text{e} & z & \text{e} \\
\approx & M_Z^2 & \approx 120 \text{ ppm} \\
\end{array}
\end{array}$$

at $Q^2 = 1 (GeV/c)^2$

$(ppm= "parts per million" = 10^{-6})$
Parity Violating Electron Scattering

Electromagnetic observables — \( \sigma, A \)...

Weak observables — parity violating asymmetries (\( A_{PV} \))

(polarized beam + unpolarized target)

\[
A_{PV} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \approx \frac{Q^2}{M_Z^2} \approx 120 \text{ ppm}
\]

at \( Q^2 = 1 (\text{GeV} / c)^2 \)

study hadron structure

- elastic scattering: strange form factors
- DIS: higher twist effects, charge symmetry violation...

- test the electroweak standard model

\[ A_{PV} = + \]

\[ A_{LR} \equiv \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \approx \frac{Q^2}{M_Z^2} \approx 120 \text{ ppm} \]

\[ at \ Q^2 = 1 (\text{GeV} / c)^2 \]

A4(MAINZ), G0, HAPPEX (JLab), SAMPLE (MIT/Bates)

E158(SLAC), Qweak(JLab)
ElectroWeak Standard Model

- SM works well at present energy range;

- Conceptual reasons for new physics:
  - What happens in the "high-energy desert"?
  - Data exist: cannot be explained by the SM (m, NuTeV anomaly);
  - (250 GeV, ~ 5 x 10^{14} GeV ~ 2.4 x 10^{18} GeV)?
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(250 \text{ GeV} \sim 5 \times 10^{14} \text{ GeV} \sim 2.4 \times 10^{18} \text{ GeV})?
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- Data exist: cannot be explained by the SM (\(m_\nu\), NuTeV anomaly...);
**ElectroWeak Standard Model**

- SM works well at present energy range;
- Conceptual reasons for new physics:
  
  What happens in the “high-energy desert”?

**Search for Physics beyond the Standard Model**

- Indirect searches: E158, NuTeV, Qweak, PVDIS
- Direct searches: LEP, LHC

(250 GeV \sim 5 \times 10^{14} \text{ GeV} \sim 2.4 \times 10^{18} \text{ GeV})?
Testing the EW Standard Model – Running of $\sin^2 \theta_W$ and the NuTeV Anomaly
Neutral Weak Couplings in Electron DIS

\[ A_{PV} = \]

\[ \frac{1}{2} \bar{e} \gamma_{\mu} (g^e_V - g^e_A \gamma^5) e \]

\[ \frac{1}{2} \bar{q} \gamma_{\mu} (g^q_V - g^q_A \gamma^5) q \]

- axial electron * vector quark:

- vector electron * axial quark:

\[ L_{SM}^{PV} = -\frac{G_F}{\sqrt{2}} e \gamma_{\mu} \gamma^5 e \sum_q C_{1q} q \gamma_{\mu} q \]

\[ L_{SM}^{PV} = -\frac{G_F}{\sqrt{2}} \bar{e} \gamma_{\mu} e \sum_q C_{2q} \bar{q} \gamma_{\mu} \gamma^5 q \]

\[ C_{1u} = g^e_A g^u_V = -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W) \]

\[ C_{2u} = g^e_V g^u_A = -\frac{1}{2} + 2 \sin^2(\theta_W) \]

\[ C_{1d} = g^e_A g^d_V = \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W) \]

\[ C_{2d} = g^e_V g^d_A = \frac{1}{2} - 2 \sin^2(\theta_W) \]
PVDIS Asymmetries

\[
A_{PV} = \frac{2C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2C_{2u} - C_{2d})R_V(x)}{5 + R_S(x) + 4R_C(x)}
\]

- Deuterium:

\[
A_d = (540 \text{ ppm})Q^2 C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2C_{2u} - C_{2d})R_V(x)
\]
**PVDIS Asymmetries**

\[ A_{PV} = \]

\[ + \]

\[ + \]

- **Deuterium:**
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- **New physics sensitivity:**
  \[ L = L_{SM}^{PV} + L_{NEW}^{PV} \]

\[ L_{SM}^{PV} = \frac{-G_F}{\sqrt{2}} \bar{\epsilon} \gamma_\mu e \sum_q C_{2q} \bar{q} \gamma_\mu \gamma^5 q \]

\[ L_{NEW}^{PV} = \frac{g^2}{4 \Lambda^2} \bar{\epsilon} \gamma_\mu e \sum_f h_A^q \bar{q} \gamma_\mu \gamma^5 q \]

- \( g \): coupling constant, \( \Lambda \): mass limit, \( h_A^q \): effective coefficient
PV DIS Asymmetries

\[ A_{PV} = A_d + A_{\gamma} + A_z + A_e \]

**Deuterium:**

\[ A_d = (540 \text{ ppm}) Q^2 \frac{2 C_{1u} [1 + R_C(x)] - C_{1d} [1 + R_S(x)] + Y (2 C_{2u} - C_{2d}) R_V(x)}{5 + R_S(x) + 4 R_C(x)} \]

**New physics sensitivity:**

\[ L = L_{PV}^{SM} + L_{PV}^{NEW} \]

\[
L_{PV}^{SM} = -G_F \frac{\bar{e} \gamma_\mu e}{\sqrt{2}} \sum_q C_2 q \bar{q} \gamma_\mu \gamma_5 q
\]

\[
L_{PV}^{NEW} = \frac{g^2}{4 \Lambda^2} \bar{e} \gamma_\mu e \sum_f h_A^q \bar{q} \gamma_\mu \gamma_5 q
\]

\( g \): coupling constant, \( \Lambda \): mass limit, \( h_A^q \): effective coefficient

**Sensitive to:** Z' searches, compositeness, leptoquarks

**Mass limit:**

\[
\frac{\Lambda}{g} \approx \left[ \sqrt{8 G_F} \left| \Delta \left( 2 C_{2u} - C_{2d} \right) \right| \right]^{-1/2}
\]
PV DIS and Other SM Test Experiments

**E158/Moller (SLAC)**
- Purely leptonic

**Qweak (JLab)**
- $2 \left( 2C_{1u} + C_{1d} \right)$
- Coherent quarks in the proton

**Atomic PV**
- Coherent Quarks in the Nucleus
  - Purely leptonic
- $\text{Cs}^{133}$

**NuTeV (FNAL)**
- Weak CC and NC difference
- Nuclear structure?
- Other hadronic effects?

**PVDIS (JLab)**
- Isoscalar quark scattering
- $\left( 2C_{1u} - C_{1d} \right) + \gamma \left( 2C_{2u} - C_{2d} \right)$

**Different Experiments**
- Probe Different Parts of Lagrangian,
  - PVDIS is the only one accessing $C_{2q}$

Cartoons borrowed from R. Arnold (UMass)
PVDIS Asymmetries

\[ A_{PV} = \]

\[ R_S(x) = \frac{2[s(x) + \bar{s}(x)]}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \quad R_C(x) = \frac{2[c(x) + \bar{c}(x)]}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \quad R_V(x) = \frac{u_V(x) + d_V(x)}{u(x) + \bar{u}(x) + d(x) + \bar{d}(x)} \]

Deuterium:

\[ A_d = (540 \text{ ppm}) Q^2 \frac{2 C_{1u} [1 + R_C(x)] - C_{1d} [1 + R_S(x)] + Y (2 C_{2u} - C_{2d}) R_V(x)}{5 + R_S(x) + 4 R_C(x)} \]

Also sensitive to:

- quark-gluon correlations (higher-twist effects)
- Charge symmetry violation
  \[ u^p(x) \neq d^n(x) \quad d^p(x) \neq u^n(x) \]
PVDIS Experiment – Past, Present and Future


PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.
PVDIS Experiment – Past, Present and Future


- PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.

- (Re)start PVDIS at JLab 6 & 12 GeV

- Difficulty: separate New Physics and hadronic effects
PVDIS Experiment – Past, Present and Future


- PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/CSV ...... However, hasn't been done since 1978.

- Do a first measurement at JLab 6 GeV:
  - If observe a significant deviation from the SM value, it will definitely indicate something exciting;
  - *Indicate either electroweak new physics, or current understanding of strong interaction is worse than we thought*

- New electroweak Physics
- Non-perturbative QCD (higher-twist) effects
- Charge symmetry violation

At the 6 GeV precision:

- Likely to be small, but need exp confirmation
- Small from MRST fit (90% CL ~1%)

PVDIS asymmetry has the potential to explore New Physics, study hadronic effects/Csv ...... However, hasn't been done since 1978.

Do a first measurement at JLab 6 GeV:

- If observe a significant deviation from the SM value, it will definitely indicate something exciting;

- *Indicate either electroweak new physics, or current understanding of strong interaction is worse than we thought*

At 12 GeV, a larger, well-planned PVDIS program could separate all three: New Physics, HT, CSV, *important information for both EW and Strong interaction study.*
JLab 6 GeV Experiment 08-011

Co-spokesperson & contact: X. Zheng
Co-spokesperson: P.E. Reimer, R. Michaels

(Hall-A Collaboration Experiment, approved by PAC27, re-approved by PAC33 for 32 days, rated A-)

Use 85μA, 6 GeV, 80% polarized beam on a 25-cm LD2 target;

Two Hall A High Resolution Spectrometers detect scattered electrons;

Measure PV asymmetry $A_d$ at $Q^2=1.10$ and 1.90 GeV$^2$ to 2.7% (stat.);

$A_d$ at $Q^2=1.10$ will limit the higher twist effects;

If HT is small, can extract $2C_{2u}-C_{2d}$ from $A_d$ at $Q^2=1.90$ to ±0.04 (or with reduced precision if higher twists are un-expectedly large)
Current Knowledge on $C_{1,2q}$

<table>
<thead>
<tr>
<th>$C_{1u} - C_{1d}$</th>
<th>$C_{2u} - C_{2d}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT/Bates</td>
<td>SLAC/Prescott</td>
</tr>
<tr>
<td>Cs APV</td>
<td>Ti APV</td>
</tr>
<tr>
<td>R. Young (combined)</td>
<td>R. Young (PVES)</td>
</tr>
<tr>
<td>Qweak (expected)</td>
<td></td>
</tr>
</tbody>
</table>

PDG best fit

Best: $\Delta(2C_{2u} - C_{2d}) = 0.24$

all are $1\sigma$ limit

MIT/Bates

SLAC/Prescott

Cs APV

Ti APV

R. Young (combined)

SAMPLE

PDG 2006 fit

R. Young (combined)

Xiaochao Zheng, February 2009, Colloquium at UVa
Best: $\Delta(2C_{2u} - C_{2d}) = 0.24 \to 0.04$ (factor of six improvement);

New physics mass limit:

$$\frac{\Lambda}{g} \approx \left[ \sqrt{8} G_F \Delta (2C_{2u} - C_{2d}) \right]^{-1/2} \approx 0.9\,\text{TeV}$$
TheAccelerator(CEBAF)
Experimental Hall A
Overview of the Experimental Setup in Hall A

Pol $e^-$ beam, 6.0 GeV, 85uA, 80%

Electrons detected by the two spectrometers independently
In Addition to the Standard Setup

- New method being developed (photon integration): provide 1% precision on $P_{\text{beam}}$
- Regular HRS DAQ up to 4KHz (expect: 500KHz)
- Integration method won't work for DIS
- Need a new fast-counting DAQ, design goal: 1MHz, on-line PID; Never been done before!

Also needed for two other approved PV experiments in Hall A

- Compton Polarimeter
- Moller Polarimeter
- LD$_2$ Target
- Luminosity Monitor
- Left Spectrometer
- Right Spectrometer
The Collaboration


The Hall A Collaboration

ANL, Calstate, FIU, JLab, Kentucky, Louisiana Tech, U. of Ljubljana (Slovenia), MIT, UMD, UMass, UNH, Universidad Nacional Autonoma de Mexico, Ohio U., Randolph-Mason C., Smith C., Syracuse, Temple U., TsingHua U. (China), UVa, W&M, Yerevan Phys. Inst.(Armenia)
Design and Structure for the Fast Counting DAQ

- **Scaler-based:**
  - A double-layered lead-glass counter (PID)
  - A gas cherenkov detector (PID)
  - Scintillators (suppress background)
  - Helicity-gated scalers count $e^-$ and $\pi$

- **Deadtime measured by multiple methods (goal: 0.3%)**
  - Two resolution times (20, 100ns)
  - “tagger”, TDC system

- Cross-check with regular DAQ at low rate (PID performance)

- Some channels with flash-ADC, allowing full sampling of signals (PID performance and pileup effects)

\[
A_{PV} = \frac{A_{\text{measured}}}{P_b \eta_{DT}}
\]
E08-011 DAQ Status (Jan.-Aug. 2008)

- Half-system assembled in EEL Rm 122
- Three deadtime measurements performed
E08-011 DAQ Status (Jan.-Aug. 2008)

Method I

- Three deadtime measurements performed

Method II

Method III
E08-011 DAQ Status (Jan.-Aug. 2008)

Method I

\[ DT \text{ from Scaler- and TDC-data} \]

Method II

\[ DT \text{ from input and output trigger rates} \]

Measured induced asymmetry, width as expected \( \sqrt{1/RT} \)

✔ Installed in Right HRS in Hall A — Aug. 2008

✔ Parasitic test using cosmics — until Nov. 2008

✔ Parasitic test using low rate electrons and pions — Dec. 2008 - Feb. 2009:

✔ All detectors working;

✔ Can measure large (induced) asymmetries from beam;

✔ Communicating with two existing DAQs.
E08-011 Plan (Mar. - Dec. 2009)

- DAQ Parasitic test using medium-rate electrons and pions — Mar-May 2009
  - Cross-checking with regular HRS DAQ for PID performance, determine system characteristics;
- Duplicate the system to install in the Left HRS — June-July 2009;
- Test performance with very high rate electrons (a few MHz) during HAPPEX-III — Aug.-Oct.2009.
- Data analysis, publishing results: 1 ~ 2 years
Best: $\Delta(2C_{2u} - C_{2d}) = 0.24 \rightarrow 0.04$ (factor of six improvement);

New physics mass limit:

$$\frac{\Lambda}{g} \approx \left[ \sqrt{8} G_F |\Delta(2C_{2u} - C_{2d})| \right]^{-1/2} \approx 0.9 \text{TeV}$$
PVDIS Program at JLab 12 GeV

Higher precision, possibly sensitive to 1) New Physics beyond the SM; 2) Charge Symmetry Violation (CSV)

Two approaches (conditionally approved):

  - 1% on $A_d$, extraction of $C_{2q}$, $\sin^2\theta_W$ (if higher-twist and CSV are negligible);

- Hall A large acceptance “solenoid” device: PR09-012
  - Measure $A_d$ to 1% for a wide range of $(x,Q^2,y)$, clean separation of New Physics (via $C_{2q}$ and $\sin^2\theta_W$), HT and CSV possible;
  - Extract $d/u$ at large $x$ from PVDIS on a proton target, free of nuclear effects;
  - Other hadronic physics study possible: $A_1^n$ at large $x$, Semi-inclusive DIS.
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**Graph:**
- $\sin^2(\theta_W)$ vs. $Q$ (GeV)
- Data points and error bars indicating experimental results and theoretical predictions.
- Key data for E-158 Moller, NuTeV, QWeak, APV Cs, DISParity JLab 12 GeV, and $A_{f0}$.

**Additional Points:**
- Higher precision, possibly sensitive to 1) New Physics beyond the SM; 2) Charge Symmetry Violation (CSV)
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Nucleon Resonances Study from Doubly Polarized Electron Scattering
Extraction of Double and Single Spin Asymmetries for pion electroproduction from NH$_3$ and ND$_3$ targets using JLab EG4 data

Co-spokespeople: Xiao-chao Zheng (UVa), Angela Biselli (Fairfield U.), Peter Bosted (JLab) and Gail Dodge (ODU)

Physics Motivation;

EG4 Run Overview;

Preliminary asymmetries from 3 GeV NH$_3$ data

Acknowledgment:

EG4 spokespeople: M. Battaglieri, R. De Vita, A. Deur, G. Dodge, M. Ripani, K. Slifer

CAA Review committee: D. Carman, P. Eugenio, C. Smith, M. Ungaro
Physics Motivation

- Nucleon resonances form an important part of strong interaction study;
  - Mostly non-perturbative, cannot use pQCD;
  - Too light for lattice calculation;
- Must use effective theories or models:
  - Constituent Quark Model: resonance amplitudes, helicity structure... (not on interference terms)
  - Phenomenology models: MAID, SAID, DMT, JANR, Sato-Lee (Δ) ... ...
  - *May compare to Chiral Perturbation Theory (very low Q^2 only).*
- Spin observables (asymmetries) provide constraints on: spin-dependent amplitudes, interference terms...
Observables in Pion Electroproduction

Cross section:

\[
\frac{d\sigma}{d\Omega^{*}_{\pi}} \sim \frac{d\sigma_{unp}}{d\Omega^{*}_{\pi}} + P_e \frac{d\sigma_e}{d\Omega^{*}_{\pi}} + P_t \frac{d\sigma_t}{d\Omega^{*}_{\pi}} + P_e P_t \frac{d\sigma_{et}}{d\Omega^{*}_{\pi}}.
\]

Three independent asymmetries:

- Single-beam
  \[
  A_e = \frac{d\sigma_e}{d\sigma_{unp}} = \frac{\sigma(+h_e) - \sigma(-h_e)}{\sigma(+h_e) + \sigma(-h_e)}
  \]
  accessible from unpolarized target data

- Single-target
  \[
  A_t = \frac{d\sigma_t}{d\sigma_{unp}} = \frac{\sigma(+h_N) - \sigma(-h_N)}{\sigma(+h_N) + \sigma(-h_N)}
  \]
  only accessible from polarized target data

- Double beam-target
  \[
  A_{et} = \frac{d\sigma_{et}}{d\sigma_{unp}} = \frac{\sigma(+h_e, +h_N) + \sigma(-h_e, -h_N) - \sigma(+h_e, -h_N) - \sigma(-h_e, +h_N)}{\sigma(+h_e, +h_N) + \sigma(-h_e, -h_N) + \sigma(+h_e, -h_N) + \sigma(-h_e, +h_N)}
  \]
EG4 Exclusive Channel Analysis

- Extract $A_t$ and $A_{et}$ from EG4 data for:
  - NH3 target: $\vec{e} \, \vec{p} \rightarrow e' \pi^+ n$ and $\vec{e} \, \vec{p} \rightarrow e' \pi^0 p$
  - ND3 target: $\vec{e} \, \vec{n} \rightarrow e' \pi^- p$ and $\vec{e} \, \vec{p} \rightarrow e' \pi^+ n$

- Study dependence on $Q^2$, $W$, $\phi^*$ and $\cos \theta^*$—(binned in 4 simultaneously)

- Previous/other analyses: EG1a, EG1b;

- Our new results will help to constrain models at low $Q^2$;
  - Can compare to future real photon experiment, study transition from virtual to real photons;
  - Data on the neutron are rare.
EG4 Kinematic Coverage

- **NH$_3$ target**
- **ND$_3$ target**

Extensive running at 1.3 GeV.
Analysis and Very Preliminary Results for

$\bar{e} \, p \rightarrow e' \, \pi^+ \cdot n$

using 3 GeV NH3 Data
Charged Pion Exclusive Analysis Flow Charts (CLAS/EG4) 3 GeV NH3 Runs

Experiment: E03-006
CLAS runs
Feb-May 2006

Calibrations

Combining Runs

PbPt

Dilution factors

Extracted Asymmetries

Polarized N backgd e⁺ corrections

Radiative Corrections

Systematic Errors

Models

RESULTS

Event selection, basic cuts

Momentum corrections

Acceptance Corrections

Run & file quality checks

Electron fiducial cuts

Radiative Corrections

Event selection, basic cuts

Momentum corrections

Acceptance Corrections

Models

Systematic Errors

Not yet started

In progress

Completed

Legends:
Very Preliminary
Very Preliminary
Aet vs. $W$, $\text{H}_3$, 3 GeV runs, $\pi^+n$, $Q^2=(0.266,0.452)$

Very Preliminary

Data; MAID2007; DMT; MAID2007(P11off); MAID2007(S11off); MAID2007(D13off)

Aet, $\text{NH}_3$, 3 GeV runs, $\pi^+n$, $Q^2=(0.452,0.77)$
At vs. $\phi^*$

**At, NH$_3$, 3 GeV, $\pi^+ n$, W=1.1,1.34**

- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.0919, 0.156)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.0919, 0.156)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.156, 0.266)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.266, 0.452)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.452, 0.77)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.77, 1.31)$

**At, NH$_3$, 3 GeV, $\pi^+ n$, W=(1.34,1.58)**

- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.054, 0.0919)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.054, 0.0919)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.0919, 0.156)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.0919, 0.156)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.156, 0.266)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.156, 0.266)$
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- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.266, 0.452)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.452, 0.77)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.452, 0.77)$
- $\phi^*$, $\cos\theta^* = (0.5, 0.5)$, $Q^2 = (0.77, 1.31)$
- $\phi^*$, $\cos\theta^* = (0.5, 1)$, $Q^2 = (0.77, 1.31)$

Very Preliminary

Data; MAID2007; DMT; MAID2007(P11off); MAID2007(S11off); MAID2007(D13off)
Data: MAID2007; DWT; MAID2007 (P11off); MAID2007 (S11off); MAID2007 (D13off)
Aet, NH$_3$, 3 GeV, $\pi^+ n$, W=(1.1,1.34)

Very Preliminary

Data; MAID2007; DMT; MAID2007(P11off); MAID2007(S11off); MAID2007(D13off)
Very Preliminary
Summary (2009-2013)

Parity Violating DIS has the potential to study the Electro-weak Standard Model, and nucleon structure/QCD:

First step — JLab 6 GeV (E08-011): measure $A_d$ at two $Q^2$ to $\sim 2.7\%$ (stat.), could extract $\Delta(2C_{2u}-C_{2d}) = 0.04$ (impact on EW SM test);

- DAQ construction and tests underway;

Extraction of $A_{et}$ and $A_t$ for single-pion electro-production $\vec{e} \ p \rightarrow e' \ \pi^+ \ n$ from NH3 and $\vec{e} \ n \rightarrow e' \ \pi^- \ p$ from ND3 using CLAS EG4 data;

- Analysis tools developed; preliminary asymmetries at the highest beam energy look very promising;
- Will complete the analysis for 4 lower energies before 2012/13; Contribute to low $Q^2$ resonance structure study; May compare to chiral perturbation theory.
Summary (2013 - )

- Measurement of neutron asymmetry $A_1^n$ in the valence quark region at JLab 12 GeV
  - Flagship experiment
  - Will be one of the first experiments to run (~2014?)

- PVDIS at 12 GeV
  - Ultimate goal: clean separation of New Physics and CSV (2015 or later?)
## Current Knowledge on Weak Coupling Coefficients

\[ C_{1q} = g_A^e g_V^q \quad C_{2q} = g_V^e g_A^q \quad C_{3q} = g_A^e g_A^q \]

<table>
<thead>
<tr>
<th>Facility</th>
<th>Process</th>
<th>Q^2</th>
<th>( C_{1q} ) Combination</th>
<th>Result</th>
<th>SM Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC</td>
<td>e^-D DIS</td>
<td>1.39</td>
<td>(2C_{1u} - C_{1d})</td>
<td>-0.90 ± 0.17</td>
<td>-0.7185</td>
</tr>
<tr>
<td>SLAC</td>
<td>e^-D DIS</td>
<td>1.39</td>
<td>(2C_{2u} - C_{2d})</td>
<td>0.62 ± 0.81</td>
<td>-0.0983</td>
</tr>
<tr>
<td>CERN</td>
<td>(\mu^\pm)-D DIS</td>
<td>34</td>
<td>0.66((2C_{2u} - C_{2d})) + 2(C_{3u} - C_{3d})</td>
<td>1.80 ± 0.83</td>
<td>1.4351</td>
</tr>
<tr>
<td>CERN</td>
<td>(\mu^\pm)-D DIS</td>
<td>66</td>
<td>0.81((2C_{2u} - C_{2d})) + 2(C_{3u} - C_{3d})</td>
<td>1.53 ± 0.45</td>
<td>1.4204</td>
</tr>
<tr>
<td>MAINZ</td>
<td>e^-Be QE</td>
<td>0.20</td>
<td>(2.68C_{1u} - 0.64C_{1d} + 2.16C_{2u} - 2C_{2d})</td>
<td>-0.94 ± 0.21</td>
<td>-0.8544</td>
</tr>
<tr>
<td>Bates</td>
<td>e^-C elastic</td>
<td>0.0225</td>
<td>(C_{1u} + C_{1d})</td>
<td>0.138 ± 0.034</td>
<td>0.1528</td>
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<tr>
<td>Bates</td>
<td>e^-D QE</td>
<td>0.1</td>
<td>(C_{2u} - C_{2d})</td>
<td>-0.042 ± 0.057</td>
<td>-0.0624</td>
</tr>
<tr>
<td>Bates</td>
<td>e^-D QE</td>
<td>0.04</td>
<td>(C_{2u} - C_{2d})</td>
<td>-0.12 ± 0.074</td>
<td>-0.0624</td>
</tr>
<tr>
<td>JLab</td>
<td>e^-p elastic</td>
<td>0.03</td>
<td>(2C_{1u} + C_{1d})</td>
<td>approved</td>
<td>-0.0357</td>
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<tr>
<td>133Cs APV</td>
<td></td>
<td>0</td>
<td>(-376C_{1u} - 422C_{1d})</td>
<td>-72.69 ± 0.48</td>
<td>-73.16</td>
</tr>
<tr>
<td>205TI APV</td>
<td></td>
<td>0</td>
<td>(-572C_{1u} - 658C_{1d})</td>
<td>-116.6 ± 3.7</td>
<td>-116.8</td>
</tr>
</tbody>
</table>

**new**

### PDG2002 (best):

\((2C_{2u} - C_{2d}) = ±0.24\)

Some New Physics can affect \(C_{2q}\), but not \(C_{1q}\)

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Xiaochao Zheng, February 2009, Colloquium at UVa
Current Knowledge on $C_{1,2q}$

Best: PDG2002 $\Delta(2C_{2u} - C_{2d}) = 0.24$
Dilutions

Dilution factor measures fraction of events from polarized nucleons (p in NH3 and D in ND3)

With momentum corrections, expect to have sharper peak and higher $f$;
Studying kinematic dependence of $f$ with higher statistics.

$\text{f} = 0.207 \pm 0.015$
Aet vs. $Q^2$

- (integrated over $\phi^*$ and $\cos\theta^*$)
- 0.20: overall “dilution factor”
Physics Motivation (cont.)

- Example: Roper \(P_{11}^{(1440)}\) -- Least understood and most controversial
  - Radial excitation of 3q: \((1s)^2(2s)^1\) predicted by CQM;
  - Hybrid: 3qG with relativistic effect; Favored by the recent CLAS ana. PRC71, 015201 (2005) PRC72, 058202(2005)
  - Sensitivity of Aet \((n\pi^+)\) to \(P_{11}^{(1440)}\):

Eb=1.34  
Q2=0.1  
\(\cos\theta^*=0.4\)  
\(\phi^*=20^\circ\)

Figure credit: C. Smith

(2003) PRC67, 015209
Physics Motivation (cont.)

- Sensitivity of $A_t(n\pi^+)$ to $P_{11}(1440)$:

![Graph](image)

$Eb=1.34$

$Q^2=0.1$

$\cos\theta^*=0.4$

$\phi^*=60^\circ$

Figure credit: C. Smith

(MAID2000)

(JANR) PRC67, 015209 (2003)
Physics Motivation (cont.)

Sensitivity of $A_t$ ($p\pi^0$) to $P_{11}(1440)$:

Spin observables may help to remove some model dependence in extraction of amplitudes -> better determination of the nature of $P_{11}(1440)$.

Figure credit: C. Smith

$E_b = 1.34$
$Q_2 = 0.1$
$\cos \theta^* = -0.8$
$\phi^* = 50^\circ$

(MAID2000)  
(JANR)  
PRC67, 015209  
(2003)
EG4 Kinematic Coverage

- eg1b coverage: (for comparison)

- Lowest Eb: 1.6 GeV
EG4 Kinematic Coverage

- Extensive running at 1.3 GeV;
- Better ND₃ polarization
Electron Selection

EG4 had Cerenkov only in sector 6, use forward EC for $e'$, will add Cerenkov cut in the final analysis.
Pion Selection

- Offline TOF calibration close to final (have not excluded non-working paddles yet)
- Used TOF cut $|t-t_\pi|<1\text{ns}$

$M = 0.3, 0.7, 1.2 \text{ GeV}$
Pion Selection

- Offline TOF calibration close to final
  (have not excluded non-working paddles yet)

- Used TOF cut $|t-t_\pi| < 1 \text{ns}$

- Pion mass: $0.1497 \pm 0.064 \text{ GeV/c}^2$

TOF cuts: $1.0, 0.5 \text{ ns}$
Missing neutron (proton) selection

NH$_3$ target, ep $\rightarrow$ e$'$$\pi^+$n

Cut used in analysis:
0.85<$M_{miss}$<1.05 GeV
Missing neutron (proton) selection

NH₃ target, ep -> e⁺π⁺n

Cut used in analysis: 0.85 < Mmiss < 1.05 GeV

Also checked: e'p(π⁻), but not as good

ND₃ target, en -> e⁻π⁻p

Have good channel selection
Dilutions

Dilution factor measures fraction of events from polarized nucleons (p in NH3 and D in ND3)

Figure from R. de Vita, Ph.D. thesis