Parity Violation Measurements for 12 GeV Hall A at JLab

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Introduction

Experimental Program
  - PVDIS with SoLID
  - Moller
  - Neutron Skin Measurements
DIS provides information on longitudinal nucleon structure
Has proven to be crucial in realizing quarks and asymptotic freedom
pQCD has been very successful for these processes

\[
\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( W_2(\nu, Q^2) \cos^2 \frac{\theta}{2} + 2W_1(\nu, Q^2) \sin^2 \frac{\theta}{2} \right)
\]


\[
= \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{1}{\nu} F_2(x) \cos^2 \frac{\theta}{2} + \frac{2}{M} F_1(x) \sin^2 \frac{\theta}{2} \right)
\]

Callan-Gross

\[F_L = F_2 - 2xF_1 \approx 0\]

\[F_2 = x \sum_q e_q^2 (q + \bar{q})\]
DIS provides information on longitudinal nucleon structure

Has proven to be crucial in realizing quarks and asymptotic freedom

pQCD has been very successful for these processes
DIS provides information on longitudinal nucleon structure

Has proven to be crucial in realizing quarks and asymptotic freedom

pQCD has been very successful for these processes
Parity-violating studies provide additional handle on eN scattering

Exploit $\gamma Z$ interference which provides parity violating term

\[
\sigma \sim |\gamma^*| |Z^*|^2
\]

Sensitive to different couplings to PDFs...

\[
F_2^{\gamma Z} = x \sum_q 2e_q g_V^q (q + \bar{q})
\]

\[
F_3^{\gamma Z} = x \sum_q 2e_q g_A^q (q - \bar{q})
\]
Parity-violating studies provide additional handle on eN scattering

Exploit $\gamma Z$ interference which provides parity violating term

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F_2^{\gamma Z} = x \sum_q 2e_q g_V^q (q + \bar{q})
\]

\[
F_3^{\gamma Z} = x \sum_q 2e_q g_A^q (q - \bar{q})
\]

\[
g_V^q = \pm \frac{1}{2} - 2e_q \sin^2 \theta_W (g_V^u \approx 0.19, g_V^d = -0.35)
\]

\[
g_A^q = \pm \frac{1}{2}
\]

In principle have $F_i^Z$ terms as well, but these are suppressed by $Q^2/M_Z^2$.
PV Asymmetry

- Parity violating asymmetry between electron helicity states separates $\gamma^*$ and $\gamma^* - Z$
- For $Q^2 \ll M_Z^2$, ignoring $Q^2$ dependence:

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ Y_1 a_1(x) + Y_3 a_3(x) \right]$$

For $Q^2 \gg M^2$:

$$Y_1 \approx 1, \quad Y_3 \approx \frac{1 - (1 - y)^2}{1 + (1 - y)^2}, \quad y = \frac{\nu}{E}$$

$$a_1(x) = g_A^e \frac{F_1^{\gamma Z}}{F_1} = 2 \sum C_{1i} e_q (q + \bar{q}) \frac{e_q^2 (q + \bar{q})}{\sum e_q^2 (q + \bar{q})}$$

$$a_3(x) = \frac{g_V^e}{2} \frac{F_3^{\gamma Z}}{F_1} = 2 \sum C_{2i} e_q (q - \bar{q}) \frac{e_q^2 (q + \bar{q})}{\sum e_q^2 (q + \bar{q})}$$

$a_3$ term suppressed! $g_A^e = -0.5, \quad g_V^e \approx -0.04$; $y$ coverage limited
PV Asymmetry

- Parity violating asymmetry between electron helicity states separates $\gamma^*$ and $\gamma^*-Z$
- For $Q^2 \ll M_Z^2$, ignoring $Q^2$ dependence:

$$A_{PV} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha} \left[ Y_1 a_1(x) + Y_3 a_3(x) \right]$$

Isoscalar, high $x$ (suppress sea), lots of cancellations!

$$a_1(x) \approx \frac{3}{10} (2C_{1u} - C_{1d})$$

$$a_3(x) \approx \frac{3}{10} (2C_{2u} - C_{2d})$$

- Powerful method to get at couplings
- Broad reach in $Q^2$ tests scaling behavior $\rightarrow$ look for deviations
- Looking at range in $x$ tests PDF cancellation assumptions
PVDIS with $e'$ has been explored at various facilities
- SLAC
- 6 GeV JLab, Hall A

12 GeV Hall A has SoLID - enormous increase in acceptance
- $2 < p < 8 \text{ GeV}$
- $2 < Q^2 < 10 \text{ GeV}^2$
- $0.2 < x_{bj} < 1$
- Acceptance $\sim 40\%$
Unique experiment - true "counting mode" PV measurement
Divide into 30 independent sectors
Necessary rate > 200 kHz presents challenges for analysis
Lead/tungsten baffles provide low energy filter
Also very important to blocking line of sight to target
Deuterium powerful, since $q(x)$ cancel for large $x$

Measuring $A_{PV}$ across this region puts enormous constraints on $C_{1q}$ and $C_{2q}$ compared to present world data

Alternatively, gives us $\sin^2 \theta_W$, $\Lambda \sim$ few TeV

$C_{2q}$ not as well contrained

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**Figure**: Diagram showing the constraints on $C_{1q}$ and $C_{2q}$ from various experiments and fits.

- $C_{1u} + C_{1d}$ vs. $C_{1u} - C_{1d}$
- $C_{2u} + C_{2d}$ vs. $C_{2u} - C_{2d}$

Experiments: 
- Bates
- SoLID
- PDG
- Hall A PVDIS
- SLAC

Fits: 
- Bates
- SoLID
- SLAC

Weak $Q$-Bates fit.
Deuterium powerful, since $q(x)$ cancel for large $x$
Measuring $A_{PV}$ across this region puts enormous constraints on $C_{1q}$ and $C_{2q}$ compared to present world data
Alternatively, gives us $\sin^2 \theta_W$, $\Lambda \sim \text{few TeV}$
The Tevatron measurements are strongly dominated by invariant masses of the final state dilepton pair of $O(M_Z)$ and can thus be considered as additional $Z$ pole data points. However, for clarity we displayed the point horizontally to the right. Similar remarks apply to the first measurement at the LHC by the CMS collaboration.
CSV always present to some level from EM effects and quark masses

Measurement at valence parton level would be very exciting

Important in explaining at least part of NuTeV anomaly, but not well constrained by present parametrizations

Paschos-Wolfenstein ratio for N=Z: neutrino NC/CC

\[
R_{PW} = \frac{\sigma_{\nu A}^{NC} - \sigma_{\bar{\nu} A}^{NC}}{\sigma_{\nu A}^{CC} - \sigma_{\bar{\nu} A}^{CC}}
= \frac{\left(\frac{1}{6} - \frac{4}{9}\sin^2\theta_W\right)\langle x_A u_A^- \rangle + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)\langle x_A d_A^- \rangle}{\langle x_A d_A^- \rangle - \frac{1}{3}\langle x_A u_A^- \rangle}
\]

\[
\lim_{N=Z} \frac{1}{2} - \sin^2\theta_W
\]
Charge Symmetry Violation

- CSV always present to some level from EM effects and quark masses
- Measurement at valence parton level would be very exciting
- Important in explaining at least part of NuTeV anomaly, but not well constrained by present parametrizations

Sensitive to CSV

- Uncertainties in MRST broad enough to fix or make NuTeV worse - constraint can be important!
Higher Twist

Large kinematic reach allows for evaluation of higher twist

- Beyond DGLAP, additional $Q^2$ dependence gives information on quark-quark and quark-gluon correlations
- In asymmetry measurement, $Q^2$ dependence from HT in $qq$ correlations can show up while effects such as DGLAP cancel and $q(x)$ cancel for isoscalar targets
- Prevalence of diquark-type structures are an interesting topic in terms of nucleon structure
New physics could be hiding in $C_{2q}$ and not $C_{1q}$

Leptophobic $Z'$ could mix with photon through $q\bar{q}$ loops, requires vector coupling with $ee'\gamma$

PVDIS could have sensitivity within some models to detect at $3\sigma$ level with

$M_Z' \approx 100 - 200$ GeV range

Clean Measurement of $d/u$

- $d/u$ as $x \to 1$ gives information on valence quarks - models give varying predictions on behavior

![Graph showing $d/u$ vs. $F_2$ for different experiments]

- Theoretical uncertainties since no free neutron targets, e.g. fermi smearing insufficient.
- Three experiments at JLab access this directly: BONuS, SBS Tritium, SoLID
- SoLID using LH2 has no nuclear uncertainties

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12 GeV Parity at JLab
Clean Measurement of $d/u$

- With proton data, $d/u$ as $x \to 1$ is accessible

\[ a^p_1(x) = \left[ \frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)} \right] = \left[ \frac{u(x) - 0.912d(x)}{u(x) + 0.25d(x)} \right] \]
Approved Measurement

- Approved for 169 days (requested 338)
- LD$_2$, 120 days:

  - 120 days on LD$_2$ (60 at 11 GeV, 60 at 6.6 GeV)
  - Also, 90 days on LH$_2$ 11 GeV
Polarimetry

- Polarimetry required on the level of 0.4%
- Both Compton and Møller give 1% separately now
  - Run Compton electron and photon independently, must understand systematics - each $\sim 0.4$
  - Møller limited to about 0.8% systematics with brute force iron foils
- Atomic $\text{H}_2$ provides huge reduction in systematics
  - Use RF disassociation and trap in large 8T solenoid
  - Could provide necessary 0.4% required
  - Enormous R&D effort required
PV DIS on $A$ with large isospin in very interesting!

- NuTeV anomaly showed 3 sigma deviation without CSV - CSV shifts about $\sim 1\sigma$ down

New physics or unconsidered effects?

Mean field calculations by Cloet et al. show EMC effect dependence on nuclei with large $|N - Z|$

Excess of $p$ or $n$ creates additional distortions in $u$ and $d$ beyond standard isoscalar EMC effect

$$R_{PW} = \frac{\sigma_{\nu A}^{NC} - \sigma_{\bar{\nu} A}^{NC}}{\sigma_{\nu A}^{CC} - \sigma_{\bar{\nu} A}^{CC}}$$

$$= \left( \frac{1}{6} - \frac{4}{9} \sin^2 \theta_W \right) \langle x_A u_A^- \rangle + \left( \frac{1}{6} - \frac{2}{9} \sin^2 \theta_W \right) \langle x_A d_A^- \rangle$$

$$\langle x_A d_A^- \rangle - \frac{1}{3} \langle x_A u_A^- \rangle$$

$$\lim_{N=Z} \frac{1}{2} - \sin^2 \theta_W$$

Excess of neutrons pushes $d$ to higher $x$

Fe $Z/N$ is only $\sim 0.87$, Maximizes near Pb $\sim 0.65$
Changes to Paschos-Wolfenstein

- Excess of \( p \) or \( n \) creates additional distortions in \( u \) and \( d \) beyond standard isoscalar EMC effect
- Excess of neutrons pushes \( d \) to higher \( x \)
- Fe \( Z/N \) is only \( \sim 0.87 \), Maximizes near Pb \( \sim 0.65 \)

![Graph showing lead with 1–6% larger A over sensitive x region](image-url)
High Impact Physics

- JLab Physics
  - New feature on classic understanding of medium modification!
  - Ties to short range correlations

- High Energy
  - Resolution of high precision discrepancy in $\sin^2 \theta_W$
  - Relevant to neutrino physics - MINER$\nu$A gets NC through jets, this has no ambiguities, should have agreement

- Low Energy, Astrophysics
  - Relevant to nuclear symmetry energy
  - EOS of nuclear matter can be derived in this model: Use symmetry energy to constrain
  - Implications on PREx-type physics, such as neutron stars
PV Moller - High precision $\sin^2 \theta_W$

- Moller scattering has no direct hadronic interactions - clean test of weak interaction couplings

- Provides indirect tests to new potential new physics

- *Low energy, but high precision sensitive to high energy physics*

\[
A_{PV} = mE \frac{G_F}{\sqrt{2\pi\alpha}} \frac{2y(1 - y)}{1 + y^4 + (1 - y)^4} Q^e_W
\]

\[
Q^e_W = 1 - 4 \sin^2 \theta_W
\]
$\sin^2 \theta_W$ Projections

- $A_{PV}$ to 0.73 ppb gives $Q^e_W$ to 2.3%, or similar accuracy to best collider determination
- Sensitive to new physics on the multi-TeV level
Moller Apparatus

- $Q^2 \approx 0.0056 \text{ GeV}^2$, $A_{PV} \approx 35 \text{ ppb}$
- 150 cm long LH$_2$ target
- 150 GHz Moller $e^-$ rate
- Toroidal spectrometer with quartz for signal integration
Moller Apparatus

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- Toroidal spectrometer with quartz for signal integration
PREX and CREX: Measuring neutron distributions in nuclei

- Both proton and neutron structure is important to understanding the strong nuclear force
- Calculations are difficult due to non-pQCD regime complicated by many-body physics
- Interesting for
  - Fundamental nuclear structure
  - Isospin dependence and nuclear symmetry aspects
  - Dense nuclear matter and neutron stars
- Proton radius is relatively easy - electromagnetic probes
- Neutron radius is difficult
  - Weakly couples to electroweak probes
  - Hadronic probes have considerable uncertainty
  - Theory has range of $R_n - R_p$ for various nuclei
Importance of Neutron Densities

- Constraints on neutron EOS

![Graph 1](image1.png)

![Graph 2](image2.png)

B. Alex Brown, PRL 85, 5296 (2000)

- Slope of EOS can be used to constrain potential models
Neutron Stars

- Neutron star structure is also better understood with measurements on $R_n$
- Larger $R_n$ correlates with larger pressure
- X-ray observations from neutron stars predict $\delta R_{Pb} = 0.15 \pm 0.02$ fm
- Structure can influence properties such as gravity waves
  - Additionally, symmetry energy governs proton fraction
    - Direct Urca cooling depends on processes
      $$ n \rightarrow p + e^- + \bar{\nu} $$
      $$ e^- + p \rightarrow n + \nu $$
  - Larger symmetry energy gives larger proton fraction

• $e^-$ also exchange $Z$, which is parity violating
• Primarily couples to neutron:

\[
Q_{\text{weak}}^{\text{proton}} \propto 1 - 4 \sin^2 \theta_W \approx 0.076, \quad Q_{\text{weak}}^{\text{neutron}} \propto -1
\]

• Detectable in parity violating asymmetry of electrons with different helicity
• In Born approximation, $Q^2 \ll M_Z^2$, from $\gamma - Z$ interference:

\[
A_{\text{PV}} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ 1 - 4 \sin^2 \theta_W - \frac{F_n(Q^2)}{F_p(Q^2)} \right]
\]

• For fixed target exp., typical $A_{\text{PV}} \sim 10^{-7} - 10^{-4}$
CREX and PREX

- PREX Measurement on $^{208}$Pb published in December gave $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm
- PREX-II approved to reduce error bars to 0.06 fm
- CREX will give errors of 0.03 fm, conditionally approved pending theoretical development

All experiments are statistics limited
Parity violation provides unique handles for JLab and Hall A to exploit in tapping into unexplored nucleon features.

Studying weak couplings can yield information on potential new interactions.

Studying neutron distributions help compose a complete picture of nuclear structure, provide constraints to a broad program of physics.
BACKUP SLIDES
Transverse Asymmetries

- Vertically transverse beam asymmetries sensitive to two photon effects
- Asymmetries are highly suppressed, few ppm for $Q^2 \sim 10^{-2}$ GeV$^2$

![Graphs showing asymmetry data for different nuclei and energies.]

- Very latest calculations: agreement with measurements on low $Z$ nuclei
- $^{208}$Pb is significantly off - Coulomb distortions?
Typical Experiment

How to do a Parity Experiment (integrating method)

Flux Integration Technique:
HAPPEX: 2 MHz
PREX: 500 MHz

Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Calorimeter Raw Window Pair Asymmetry

Stolen from R. Michaels
0.15 mm thick diamond, 0.5 mm thick Pb
Cryogenically cooled frame (30 W)
Beam is rastered by two fast magnets upstream to diffuse beam on surface
- **48Ca Target**

- 1 g/cm², 5% radiator (much less than PREX!)
- Oxidizes when exposed to air, must remain isolated
- End windows contribute background with excited states, must remove from acceptance
- Collimators degrade e⁻ energy by 20 MeV
- Prototype and test with ⁴⁰Ca target, add in to ladder during PREx-II
HRS and Quartz Detectors

- HRS with septum has hardware resolution $10^{-3}$, use to separate inelastic states

- Place quartz Cerenkov detectors to minimize inelastics

- Several states, but kept to < 1%. Asymmetries calculable to some level and subtracted
SoLID Design

- Considerable effort is presently being made in completing the design of this spectrometer
- Broadening purpose for several different types of experiments
  - Need coherent, detailed simulations to cover complete experiment
    - Modeling DIS events, optics, acceptance, FOMs
    - Backgrounds - detectors and damage
    - Fast, high rate tracking - trigger/sector $\sim 10$ kHz, GEM up to $5$ kHz/mm$^2$
  - Work beginning on development of GEM systems
  - Looking at acquiring CLEO magnet

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Microscopic calculations for $^{48}\text{Ca}$ are just now becoming available.

Indirect calculations show a 0.03 fm difference in radius is induced by three neutron forces.

CREX would help test these assumptions, and provide some constraint.
Accessing Neutron Radii in Nuclei

Hadronic Probes
- Elastic $pN$, $\bar{p}N$, $nN$, $\pi^\pm N$
- Alpha scattering
- GDR/dipole polarizability
- Antiproton scattering

Have uncertainty in extraction due to strong force interactions

Electroweak Probes
- Parity violating electron scattering
- Atomic parity violation
- “Clean” measurements, fewer systematics

Technically challenging due to small weak force interactions
Electron scattering $\gamma$ exchange provides $R_p$ through nucleus FFs, spin 0:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} F^2(Q^2)$$
Non-Parity Violating Electron Scattering

Electron scattering $\gamma$ exchange provides $R_p$ through nucleus FFs, spin 0:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} F^2(Q^2)$$

- In limit of small $Q^2$
  
  $$F(Q^2) \approx F(0) + \frac{dF}{dQ^2} \bigg|_{Q^2=0} + ... = \int \rho(\vec{x}) d^3x - \frac{1}{6} Q^2 \langle r^2_{\text{charge}} \rangle$$

- So small $Q^2$ measurements give RMS radius ($R_{n/p}$)
208\text{Pb} is more direct measurement for dense nuclear matter

Models show correlation between predictions of skin
- 1\% on 208\text{Pb} is about 1\% on 48\text{Ca}
- Uncorrelated uncertainties give advanced precision

48\text{Ca} can have microscopic calculations performed
- Directly tests assumptions/parameters based into models
- Different Z, allows more reliable extrapolation between nuclei