Parity Violation Measurments for 12 GeV Hall A at JLab

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Outline

- Introduction
- Experimental Program
    - PVDIS with SoLID
    - Moller
    - Neutron Skin Measurements

eN DIS

- 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

$$\begin{aligned}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E'} &= \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(W_2(\nu,Q^2)\cos^2\frac{\theta}{2} + 2W_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right)\\ &= \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(\frac{1}{\nu}F_2(x)\cos^2\frac{\theta}{2} + \frac{2}{M}F_1(x)\sin^2\frac{\theta}{2}\right)\end{aligned}$$

Callan-Gross

$$F_L = F_2 - 2xF_1 \approx 0$$

$$F_2 = x\sum_q e_q^2(q+\bar{q})$$

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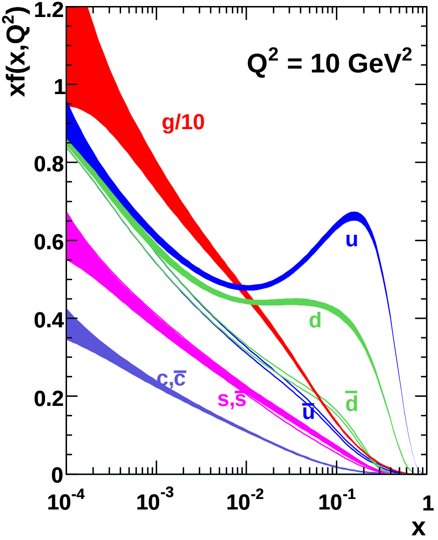

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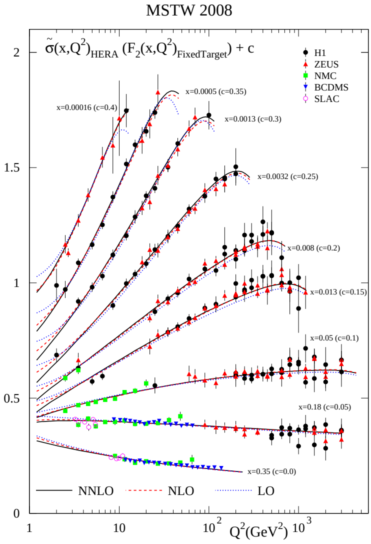
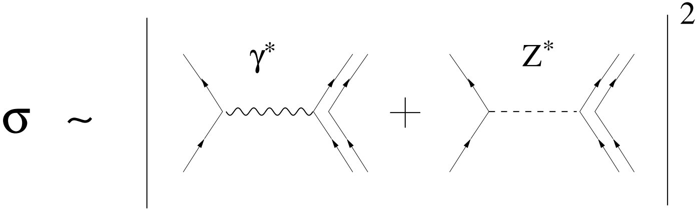


PV DIS

- Parity-violating studies provide additional handle on eN scattering
- Exploit γZ inteference which provides parity violating term



Sensitive to different couplings to PDFs...

$$\begin{aligned} F_2^{\gamma Z} &= x \sum_q 2 e_q g_V^q (q + \bar{q}) \\ F_3^{\gamma Z} &= x \sum_q 2 e_q g_A^q (q - \bar{q}) \end{aligned}$$

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\end{aligned}
$$

$$
\begin{aligned}
g_V^q &= \pm\frac{1}{2} - 2 e_q \sin^2\theta_W (g_V^u \approx 0.19, g_V^d = -0.35) \\
g_A^q &= \pm\frac{1}{2}
\end{aligned}
$$

In principle have F_i^Z terms as well, but these are supressed by Q^2/M_Z^2

PV Asymmetry

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

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

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

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

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

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

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

PV Asymmetry

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- For $Q^2 \ll M_Z^2$, ignoring Q^2 dependence:

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

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 → look for deviations
- Looking at range in x tests PDF cancellation assumptions

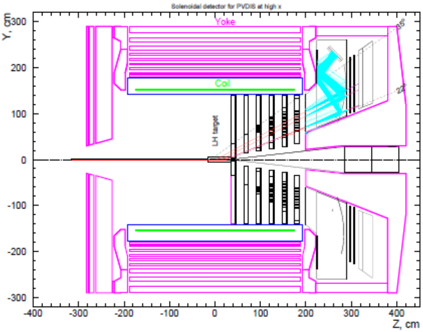
PVDIS Measurements - SoLID

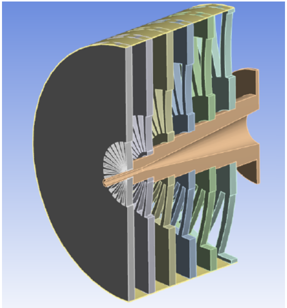
PVDIS with e' has been explored at various facilities

- SLAC
- 6 GeV JLab, Hall A

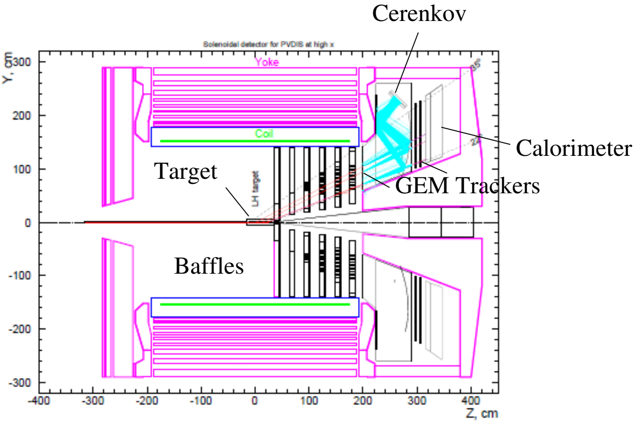
12 GeV Hall A has SoLID - enormous increase in acceptance

- $2 < p < 8\ \mathrm{GeV}$
- $2 < Q^2 < 10\ \mathrm{GeV}^2$
- $0.2 < x_{\mathrm{bj}} < 1$
- Acceptance $\sim 40\%$



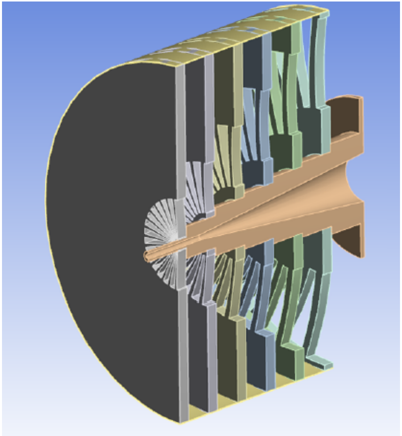


Proposed Setup



- Unique experiment - true "counting mode" PV measurement
- Divide into 30 independent sectors
- Necessary rate > 200 kHz presents challenges for analysis

Baffle System

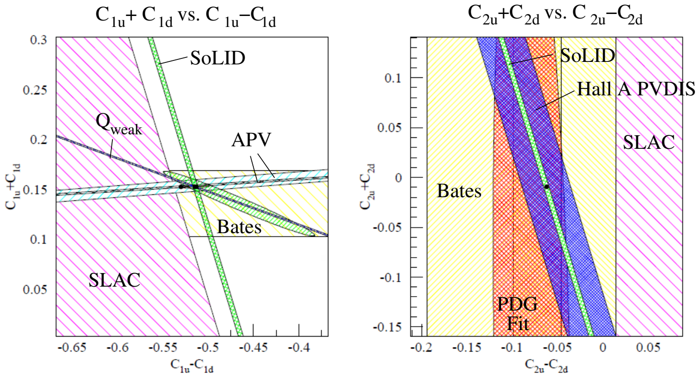


- Lead/tungsten baffles provide low energy filter
- Also very important to blocking line of sight to target

PVDIS Physics - Precision

- 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 $\sin^2\theta_W$, $\Lambda \sim \text{few TeV}$

C_{2q} not as well contrained



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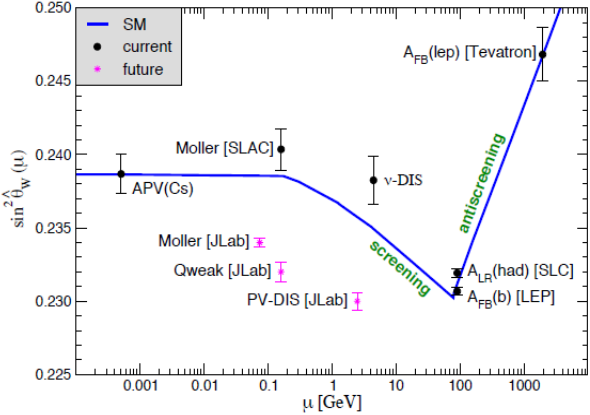
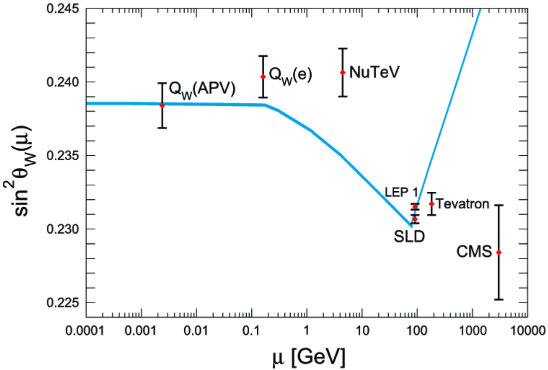


Aside - New PDG Plot



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.

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 anamoly, but not well contrained by present parametrizations

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

$$
\begin{aligned}
R_{\mathrm{PW}} &= \frac{\sigma^{\nu A}_{\mathrm{NC}} - \sigma^{\bar{\nu} A}_{\mathrm{NC}}}{\sigma^{\nu A}_{\mathrm{CC}} - \sigma^{\bar{\nu} A}_{\mathrm{CC}}} \\
&= \frac{\left(\frac{1}{6} - \frac{4}{9}\sin^2\theta_W\right)\langle x_A u_A^- \rangle + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)\langle x_A d_A^- \rangle}{\langle x_A d_A^- \rangle - \frac{1}{3}\langle x_A u_A^- \rangle} \\
\lim_{N=Z} &\quad \frac{1}{2} - \sin^2\theta_W
\end{aligned}
$$

Charge Symmetry Violation

- CSV always present to some level from EM effects and quark masses
- Measurement at valence parton level would be very exciting
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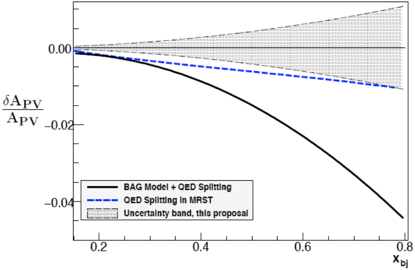
Sensitive to CSV

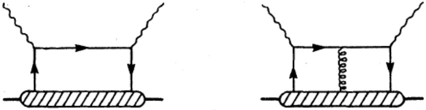


- Uncertainties in MRST broad enough to fix or make NuTeV worse - constraint can be important!

Higher Twist

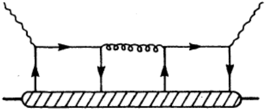
Large kinematic reach allows for evaluation of higher twist

- Beyond DGLAP, additional Q^2 dependence gives information on quark-quark and quark-gluon correlations
- In asymmetry measurment, 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



Leading Order

Quark–gluon



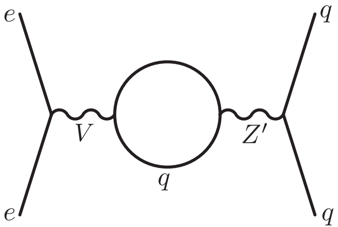
Diquark

Leptophobic Z'

- 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 $M'_Z \approx 100 - 200\ \mathrm{GeV}$ range

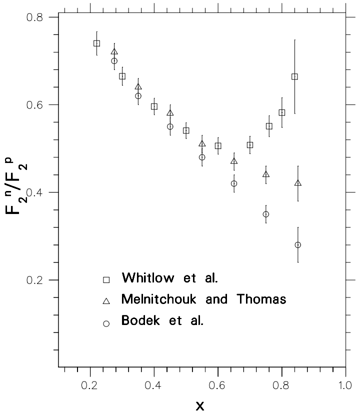
M.R. Buckley *et al.*, Phys Lett B 712, 261 (2012)

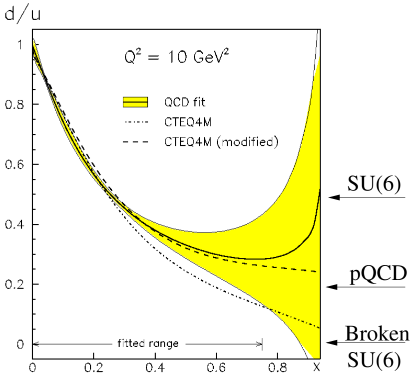
$$\begin{aligned} C_{1q} &= 2g^e_A g^q_V \\ C_{2q} &= 2g^e_V g^q_A \end{aligned}$$



Clean Measurement of d/u

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

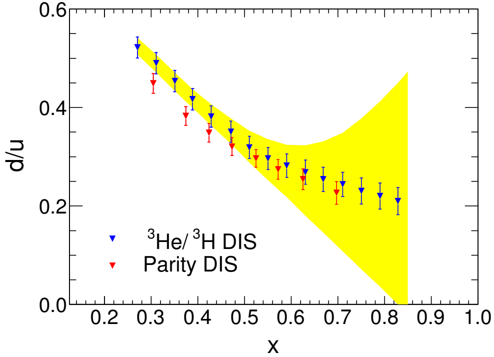




Clean Measurement of d/u

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

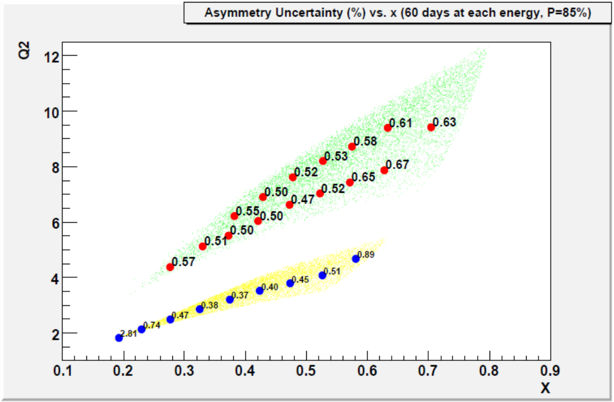
$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] = \left[\frac{u(x) - 0.912d(x)}{u(x) + 0.25d(x)}\right]$$



Approved Measurement

- Approved for 169 days (requested 338)

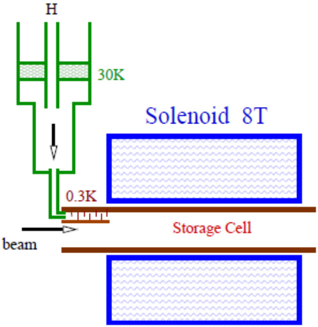
LD_2, 120 days:



- 120 days on LD_2 (60 at 11 GeV, 60 at 6.6 GeV)
- Also, 90 days on LH_2 11 GeV

Polarimetry

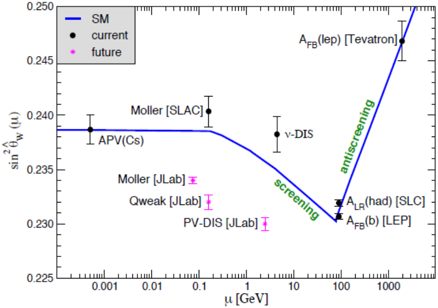
- Polarimetery required on the level of 0.4%
- Both Compton and Moller give 1% separately now
  - Run Compton electron and photon independently, must understand systematics - each $\sim$ 0.4%
  - Moller limited to about 0.8% systematics with brute force iron foils
- Atomic H_2 provides huge reduction in systematics
  - Use RF disassociation and trap in large $8\mathrm{T}$ solenoid
  - Could provide necessary 0.4% required
  - Enormous R&D effort required



PbPVDIS - Potential new experiment

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 $|N - Z|$

Now on arxiv! Cloet *et al.* arXiv:1202.6401 [nucl-th]

Changes to Paschos-Wolfenstein

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

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- Excess of neutrons pushes *d* to higher *x*
- Fe Z/N is only ~ 0.87, Maximizes near Pb ~ 0.65

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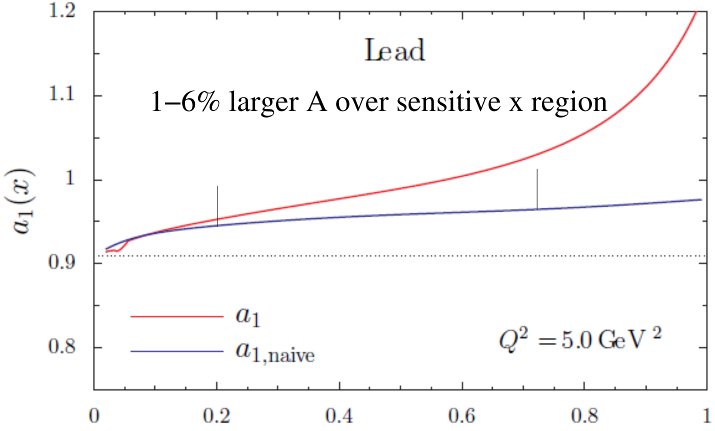


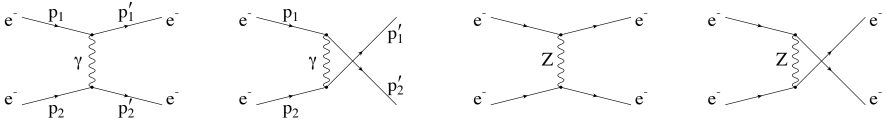
1–6% larger A over sensitive x region

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 - MINERνA 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

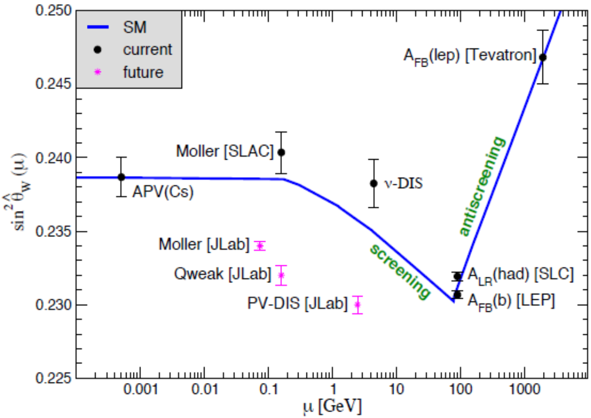


- Provides indirect tests to new potential new physics
- *Low energy, but high precision sensitive to high energy physics*

$$A_{PV} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q_W^e$$

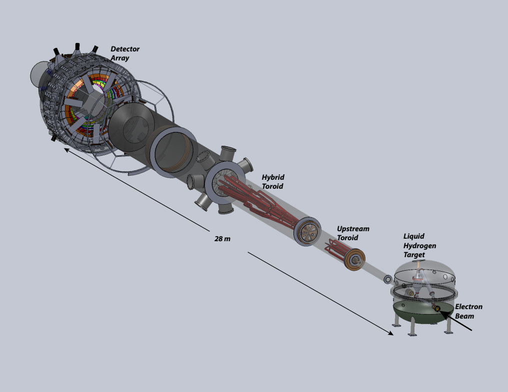
$Q_W^e = 1 - 4\sin^2\theta_W$

$\sin^2\theta_W$ Projections



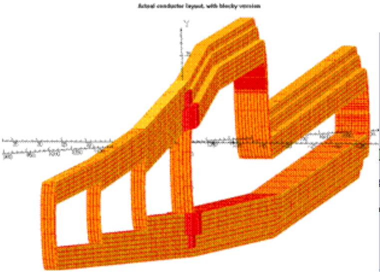
- A_{PV} to 0.73 ppb gives Q_W^e to 2.3%, or similar accuracy to best collider determination
- Sensitive to new physics on the multi-TeV level

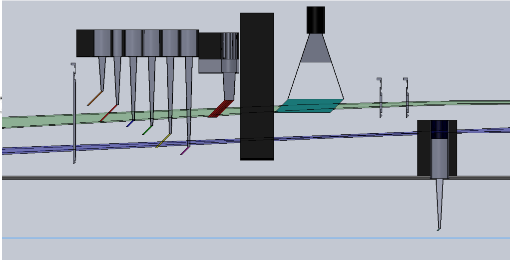
Moller Apparatus



- $Q^2 \approx 0.0056\ \mathrm{GeV}^2$, $A_{PV} \approx 35\ \mathrm{ppb}$
- $150\ \mathrm{cm}$ long LH_2 target
- $150\ \mathrm{GHz}$ Moller e^- rate
- Toroidal spectrometer with quartz for signal integration

Moller Apparatus





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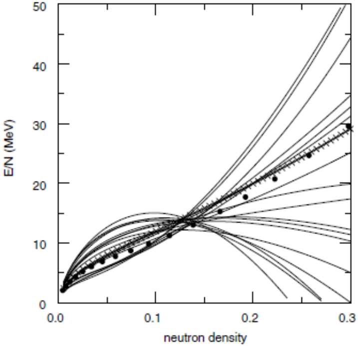
Neutron Distribution Theoretical Overview

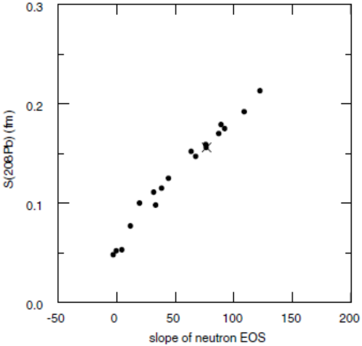
PREX and CREX: Measuring neutron distributions in nuclei

- 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





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

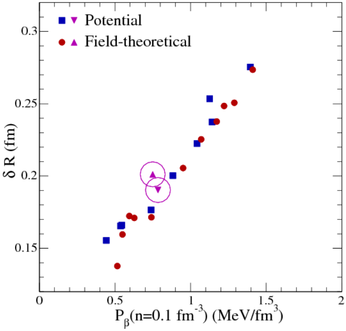
- Slope of EOS can be used to constrain potential models

Neutron Stars

A. W. Steiner *et al.*,

Phys Rep 411, 325 (2005)

- 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 $\delta R_{Pb} = 0.15 \pm 0.02\ \mathrm{fm}$
- Structure can influence properties such as gravity waves



- Additionally, symmetry energy governs proton fraction
  - Direct Urca cooling depends on processes

$$
\begin{aligned}
n &\rightarrow p + e^- + \bar{\nu} \\
e^- + p &\rightarrow n + \nu
\end{aligned}
$$

  - Larger symmetry energy gives larger proton fraction

Parity Violating Electron Scattering

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

$$Q_{\mathrm{weak}}^{\mathrm{proton}} \propto 1 - 4\sin^2\theta_{\mathrm{W}} \approx 0.076, \quad Q_{\mathrm{weak}}^{\mathrm{neutron}} \propto -1$$

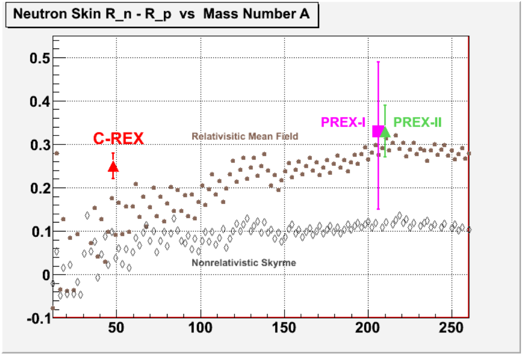
- Detectable in parity violating asymmetry of electrons with different helicity
- In Born approximation, $Q^2 \ll M_Z^2$, from $\gamma - Z$ interference:

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

- For fixed target exp., typical $A_{\mathrm{PV}} \sim 10^{-7} - 10^{-4}$

CREX and PREX

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



All experiments are statistics limited

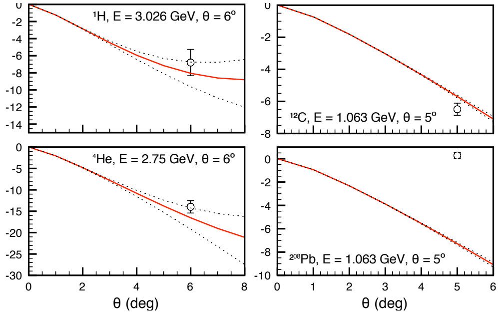
Conclusion

- 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

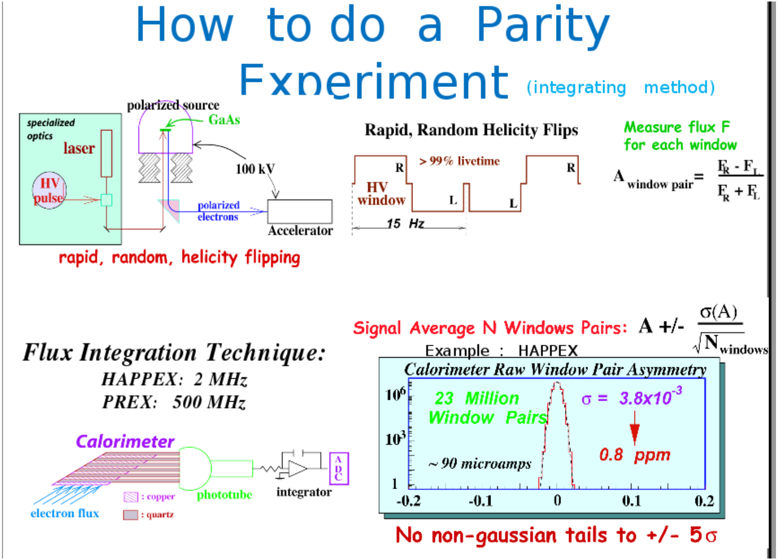
Transverse Asymmetries

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



- 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)

rapid, random, helicity flipping

Rapid, Random Helicity Flips

Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

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

Example : HAPPEX

Flux Integration Technique:

HAPPEX: 2 MHz

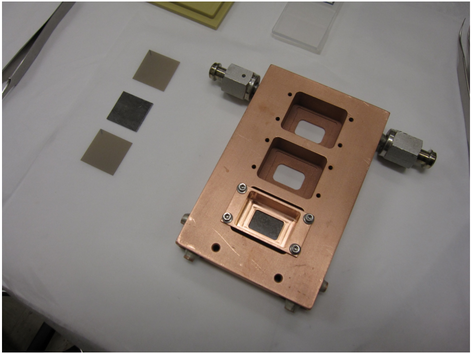
PREX: 500 MHz

No non-gaussian tails to +/- 5σ

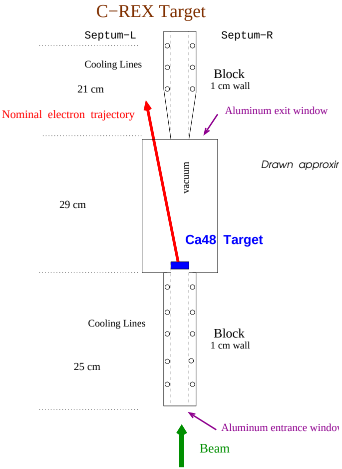
Stolen from R. Michaels

Lead/Diamond Targets

- 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



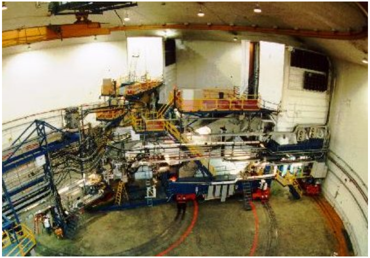
^{48}Ca Target

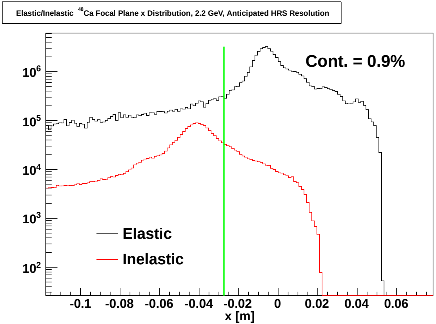


- 1 $\mathrm{g/cm^2}$, 5% radiator (much less than PREX!)
- Oxidizes when exposed to air, must remain isolated
- End windows contribute background with excited states, must remove from acceptance
- Collimators degrade e^- energy by 20 MeV
- Prototype and test with ^{40}Ca target, add in to ladder during PREx-II

HRS and Quartz Detectors

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





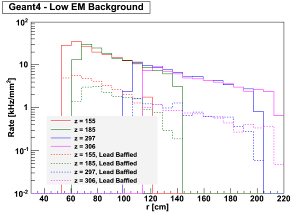
- Place quartz Cerenkov detectors to minimize inelastics
- Several states, but kept to $< 1\%$. Asymmetries calculable to some level and subtracted

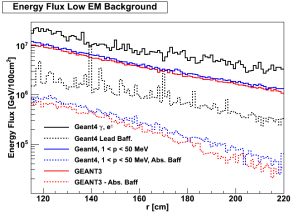
SoLID Design

- Considerable effort is presently being made in completing the design of this spectrometer
- Broadening purpose for several different types of experiments

- Need coherent, detailed simluations to cover complete experiment
  - Modeling DIS events, optics, acceptance, FOMs
  - Backgrounds - detectors and damage
  - Fast, high rate tracking - trigger/sector $\sim 10\ \mathrm{kHz}$, GEM up to $5\ \mathrm{kHz/mm}^2$

- Work beginning on development of GEM systems
- Looking at aquiring CLEO magnet

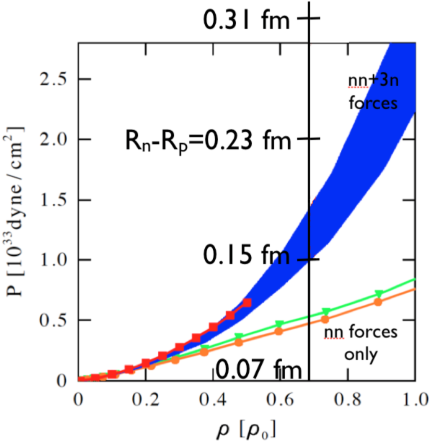




Three Neutron Forces

- Microscopic calculations for ^{48}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

P vs *ρ* for
uniform neutron matter



Accessing Neutron Radii in Nuclei

Hadronic Probes

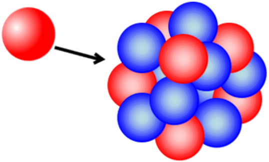
- Elastic pN, $\vec{p}N$, nN, $\pi^{\pm}N$
- Alpha scattering
- GDR/dipole polarizability
- Antiproton scattering

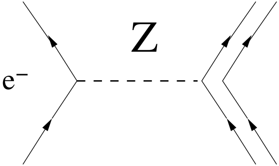
Have uncertainty in extraction due to strong force interactions

Electroweak Probes

- Parity violating electron scattering
- Atomic parity violation
- "Clean" measurements, fewer systematics

Technically challenging due to small weak force interactions

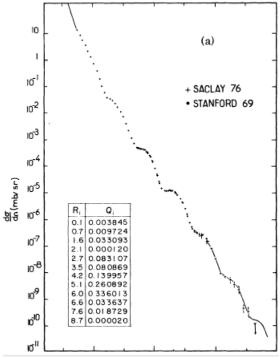




Non-Parity Violating Electron Scattering

Electron scattering γ exchange provides R_p through nucleus FFs, spin 0:

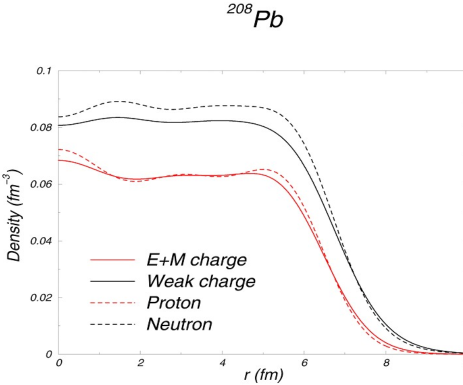
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}} F^2(Q^2)$$



R_i	Q_i
0.1	0.003845
0.7	0.009724
1.6	0.033093
2.1	0.000120
2.7	0.083107
3.5	0.080869
4.2	0.139957
5.1	0.260892
6.0	0.336013
6.6	0.033637
7.6	0.018729
8.7	0.000020

q $[fm^{-1}]$

→



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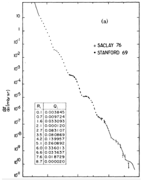

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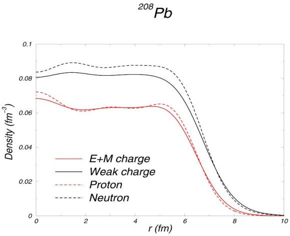


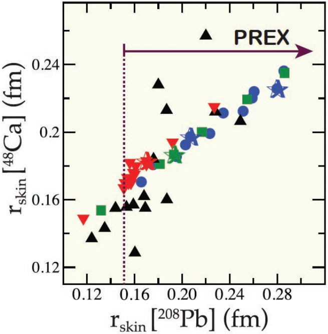
- In limit of small Q^2

$$F(Q^2) \approx F(0) + \left.\frac{dF}{dQ^2}\right|_{Q^2=0} + \ldots = \int \rho(\vec{x}) d^3x - \frac{1}{6} Q^2 \langle r^2_{\mathrm{charge}} \rangle$$

- So small Q^2 measurements give RMS radius ($R_{n/p}$)

^{48}Ca vs. ^{208}Pb

- ^{208}Pb is more direct measurement for dense nuclear matter
- Models show correlation between predictions of skin
    - 1% on ^{208}Pb is about 1% on ^{48}Ca
    - Uncorrelated uncertainties give advanced precision



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