Future Parity Violation Program at JLab

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Hadron-China2016, CCNU, Wuhan, China, August 8 – August 11, 2016

- Introduction: Parity Violating Electron Scattering
- MOLLER/QWeak: precision test of SM (search BSM)
- **Parity Violating Electron Scattering Experiments with SoLID**
  - **PVDIS on deuteron**: precision test of SM (search BSM)
    - Precision study of hadron physics: charge symmetry, higher twist
  - PVDIS on proton: d/u at high-x
  - PVDIS on ^{48}Ca: isoscaler EMC effect
  - PVDIS pol ^{3}He: total quark contribution, spin-flavor (Δs)
- PREX/CREX: neutron-skin

Thanks to McKeown, Kumar, Riordan, Souder, Y. Zhao and Zheng for providing slides.

Discovery of Parity Violation

Symmetries play a central role in physics.
Parity, Time Reversal, Charge Conjugation, …,
were naturally assumed to be conserved until

T.D. Lee and C.N. Yang suggested parity violation. Awarded Nobel Prize 1957 after experimental confirmation.

"for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles"

C. S. Wu led the experiment confirmed parity violation (in weak interaction).


Tsung-Dao Lee

（李政道）


Chen-Ning Yang

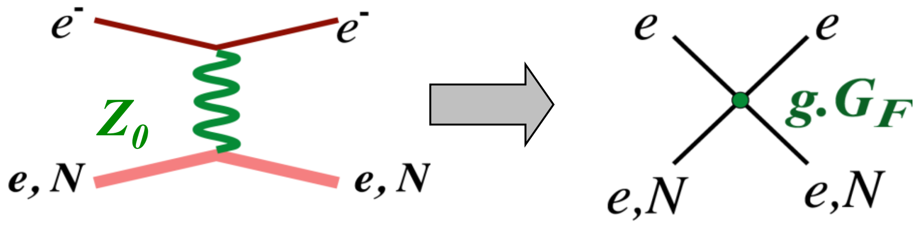
（杨振宁）


Chien-Shiung Wu

（吴健雄）

Weak Neutral Current (WNC) Interactions

Low energy Weak NC interactions ($Q^2 << M_Z^2$)



Historical Context:

- **1960s: An Electroweak Model of Leptons (and quarks)**
  - **$SU(2)_L$ X $U(1)_Y$ gauge theory predicted the Z boson**
- **1973: antineutrino-electron scattering**
  - **First weak neutral current observation**
- **Mid-70s: Does the Weak Neutral Current interfere with the Electromagnetic Current?**
  - **Central to establishing $SU(2)_L$ X $U(1)_Y$**

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

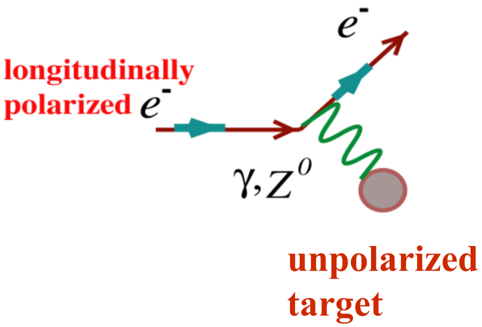
Parity is conserved

Consider fixed target electron scattering

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

Parity is violated

Parity-Violating (PV) Electron Scattering



$$\sigma \;\alpha\; |A_\gamma + A_{\mathrm{weak}}|^2 \;\sim |A_{\mathrm{EM}}|^2 + 2A_{\mathrm{EM}}A^*_{\mathrm{weak}} + \ldots$$

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{\mathrm{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} g$$

$$g = g_A^e g_V^T + \beta g_V^e g_A^T$$

$$A_{PV} \sim 10^{-5} \times Q^2 \quad \text{to} \quad 10^{-4} \times Q^2$$

- g_V and g_A are function of $\sin^2\theta_W$
- β is a kinematic factor
- Q^2 is the 4-momentum transfer
- g^T affected by QCD physics

A_{PV} in Deep Inelastic Scattering off liquid Deuterium: $Q^2 \sim 1$ (GeV)^2

E122 at the Stanford Linear Accelerator Center (SLAC) (1978)

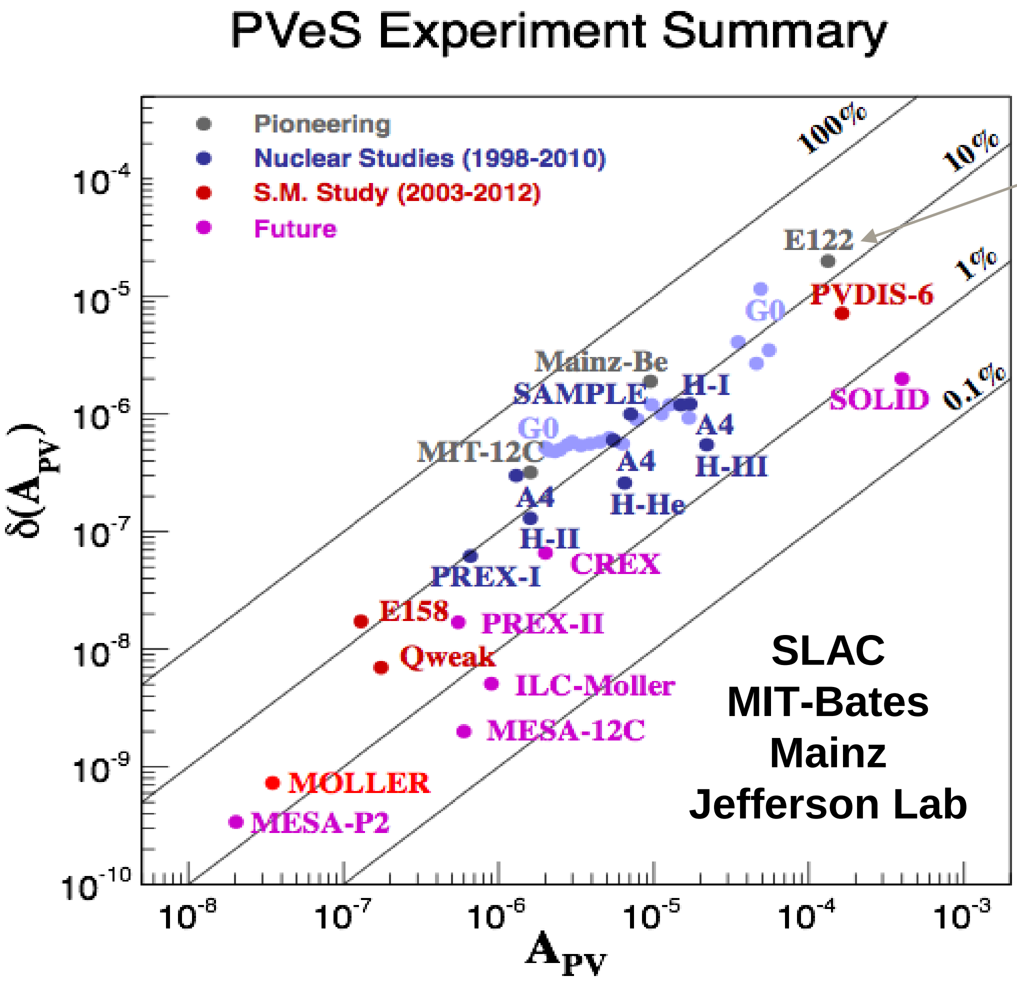
20 GeV polarized electron beam on a 30 cm LD_2 target

- *Established experimental technique: $\delta(A_{PV}) < 10$ ppm*
- *Cleanly observed weak-electromagnetic interference*
- *$\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering*

4 Decades of Progress

Parity-violating electron scattering has become a precision tool

Continuous interplay between probing hadron structure and electroweak physics



SLAC
MIT-Bates
Mainz
Jefferson Lab

Pioneering PV DIS experiment SLAC E122

State-of-the-art:

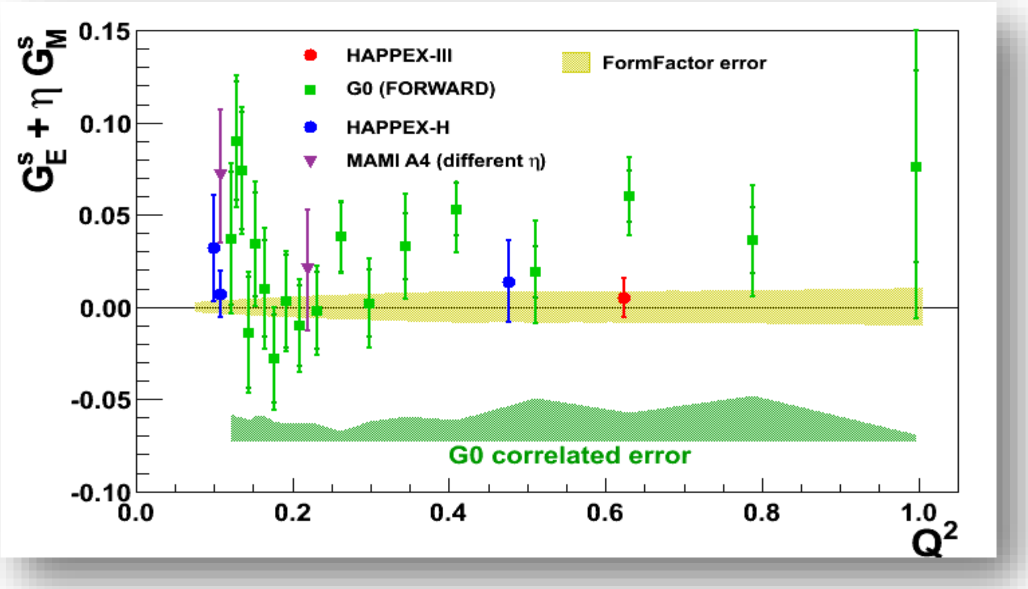
- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

Physics Topics

- ***Strange Quark Form Factors***
- ***Neutron skin of a heavy nucleus***
- ***Indirect Searches for New Interactions***
- ***Novel Probes of Nucleon Structure***

Parity Violation at JLab

- Nucleon Strangeness Form Factors (complete)
  - HAPPEX (Hall A)
  - G0 (Hall C)



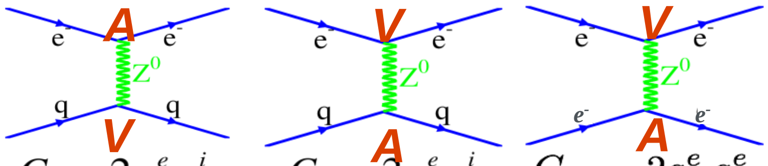
- Neutron Skin
  - PREX
  - CREX

- Precision Tests of Standard Model
  - Qweak (Under analysis)
  - MOLLER
  - SoLID

Precision Test of Standard Model

Parity Violating Electron Scattering:
e-e (Moller), Elastic and DIS

Weak Neutral Current Couplings



$C_{1i} \equiv 2g_A^e g_V^i$ $C_{2i} \equiv 2g_V^e g_A^i$ $C_{ee} = 2g_V^e g_A^e$

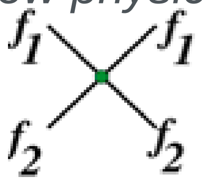
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d) + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W &\approx& -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W &\approx& 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W &\approx& -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W &\approx& 0.04 \end{aligned}$$

$$\boxed{C_{ee} = \frac{1}{2} - 2\sin^2\theta_W \approx 0.02}$$

+

new physics



$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i}\bar{f}_{2j}\gamma_\mu f_{2j}$$

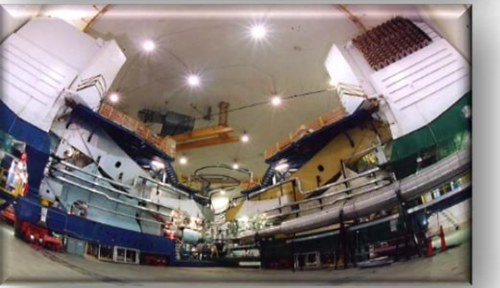
Two equivalent notations!

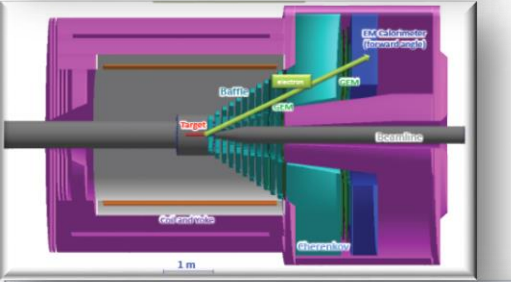
$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ PV elastic e-p scattering,
Atomic parity violation

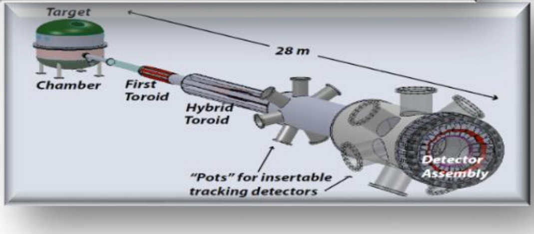
$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$ ⇨ PV deep inelastic scattering

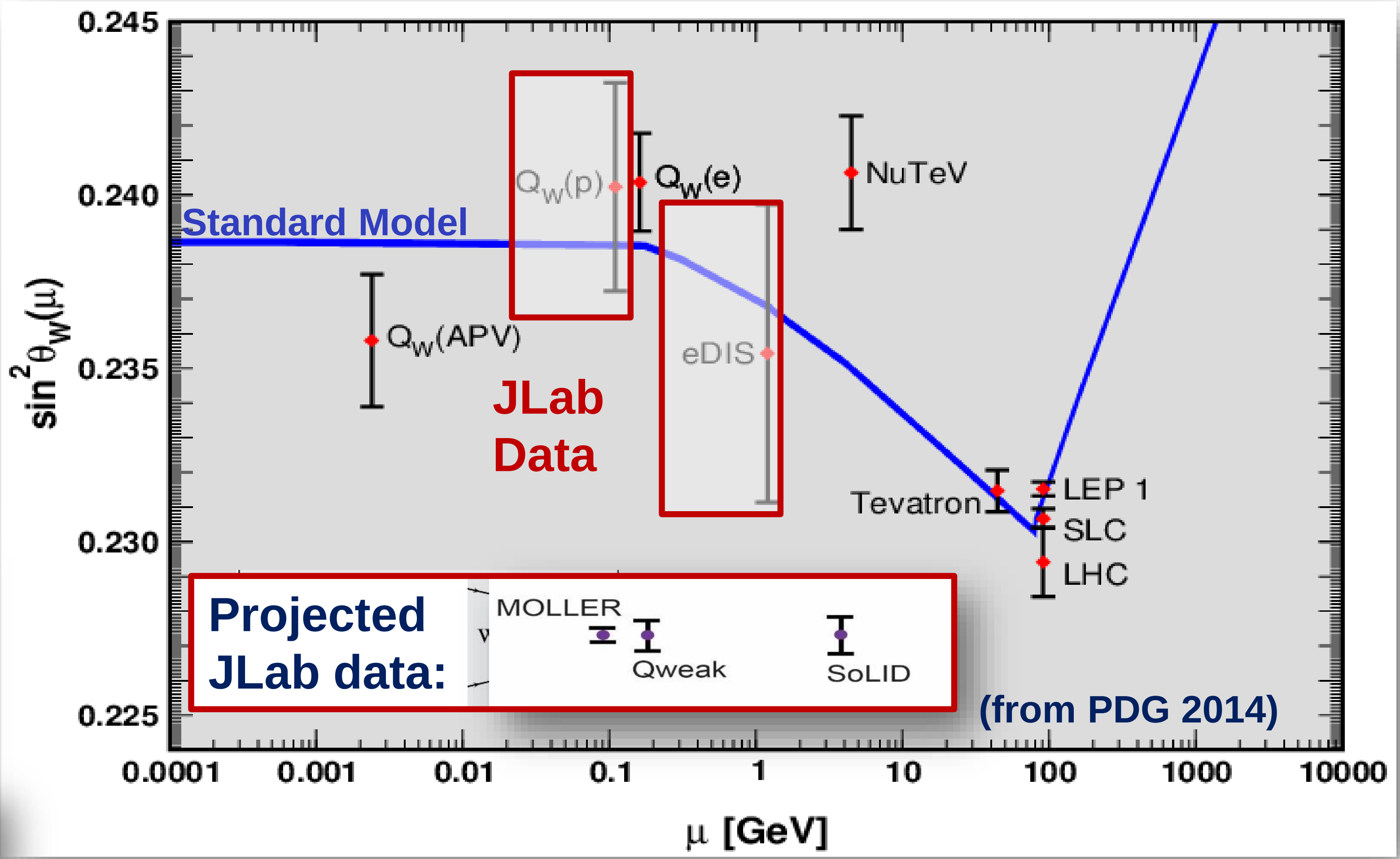
$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2$ ⇨ PV Møller scattering

Testing the Standard Model at JLab

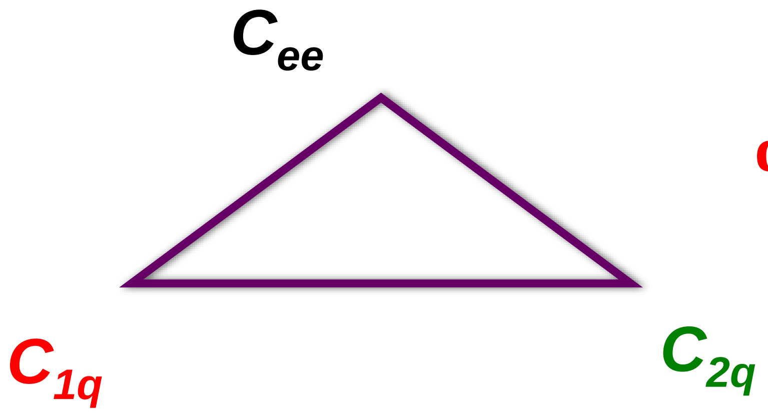








PVES Initiatives: Complementarity



Different experiments address different vertices of the triangle which in turn address different new physics.

SUSY Loops	✓	✓	✓	→	*Q_W^e and $Q_W^{p:}$:same absolute shift, smaller for others*
GUT Z'	✓	✓	✓	→	*High for Q_W(Cs), Q_W^e(relative), smaller for others*
Leptophobic Z'			✓	→	*axial-quark couplings (C_2's) only*
RPV SUSY	✓	✓	✓	→	*Different for all four in sign and magnitude*
Leptoquarks		✓	✓	→	*semi-leptonic only; different sensitivities*
H++•	✓			→	*Q_W^e only*

Precision Test of SM

MOLLER:PV e-e Scattering

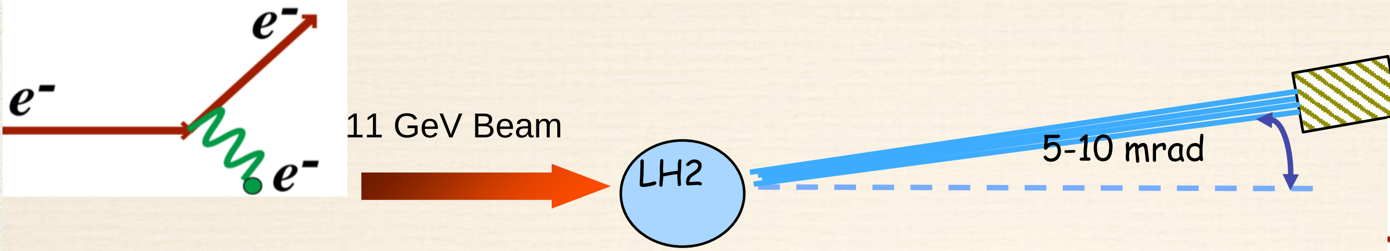
Weak Charge of the Proton: Qweak and P2 @ MESA

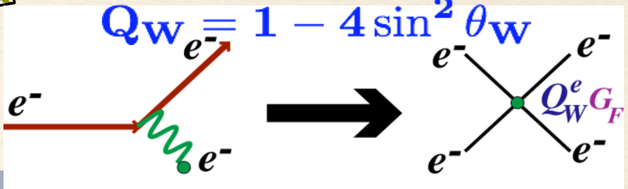
Using Møller scattering (purely leptonic!), improve on E158 by a factor of 5

11 GeV Møller scattering

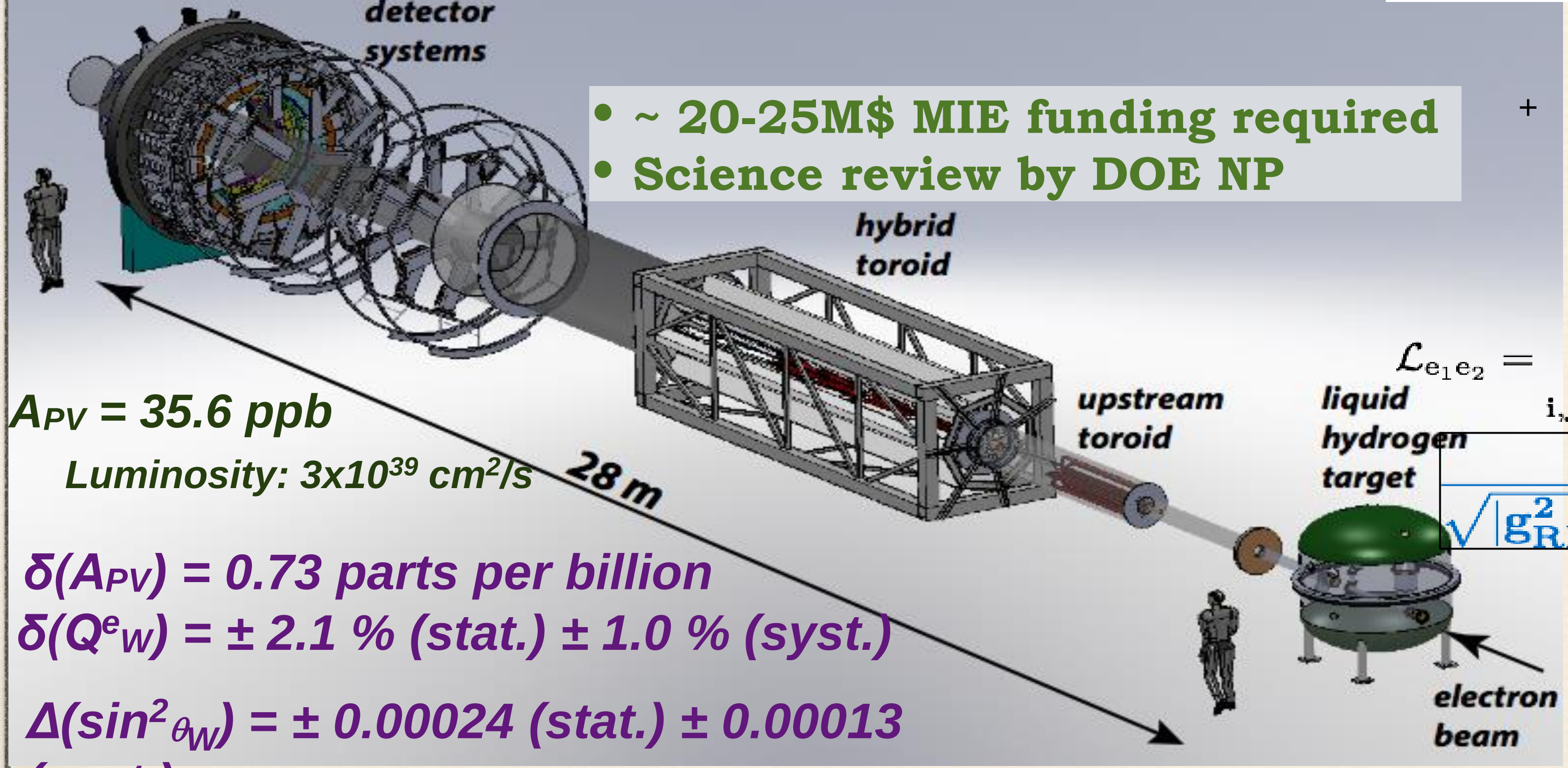
MOLLER at JLab

Measurement **O**f **L**epton **L**epton **E**lectroweak **R**eaction

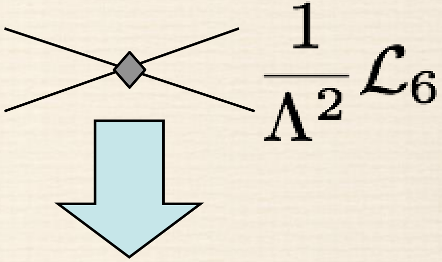




$Q_W = 1 - 4\sin^2\theta_W$



- ~ 20-25M$ MIE funding required
- Science review by DOE NP



$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g^2_{ij}}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5 \text{ TeV}$$

$A_{PV} = 35.6$ ppb

Luminosity: 3×10^{39} cm^2/s

$\delta(A_{PV}) = 0.73$ parts per billion

$\delta(Q^e_W) = \pm 2.1\,\%$ (stat.) $\pm 1.0\,\%$ (syst.)

$\Delta(\sin^2\theta_W) = \pm 0.00024$ (stat.) ± 0.00013 (syst.)

The Weak Charge of the Proton

Qweak see **Jie Pan**'s talk

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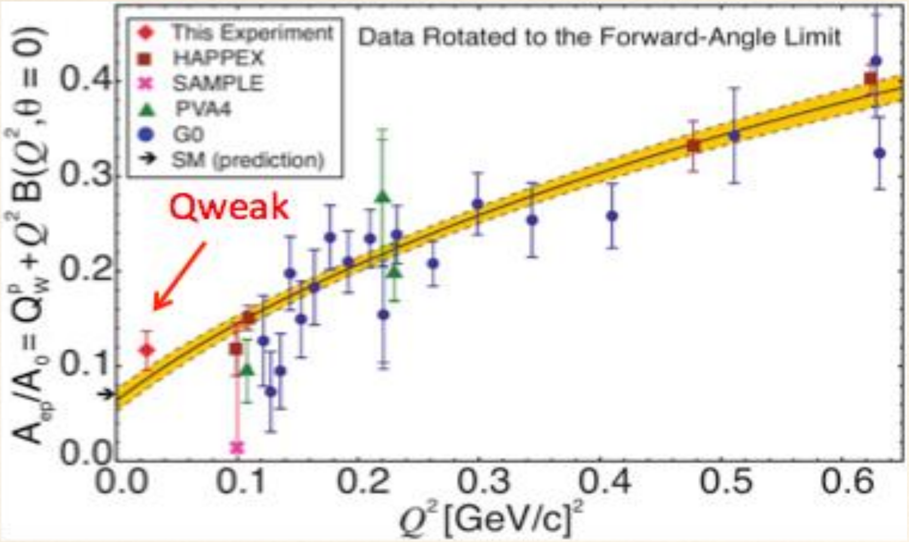
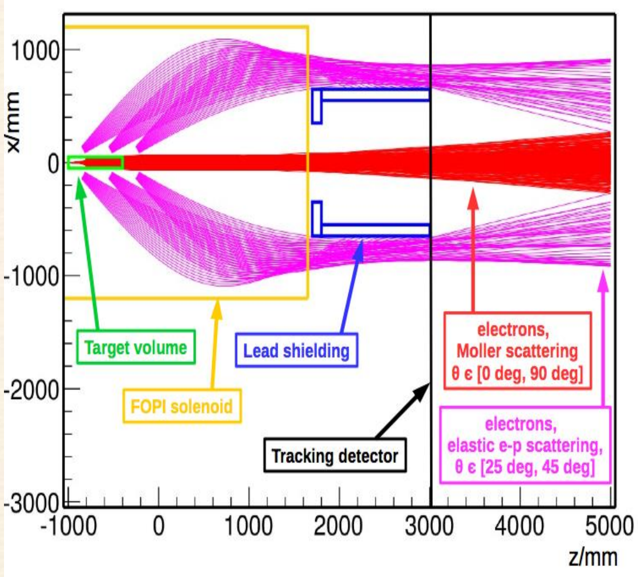


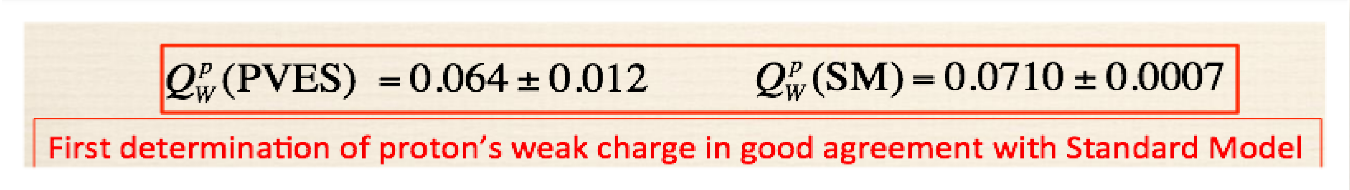
$$Q^p_{weak} = 2C_{1u} + C_{1d} \quad \propto 1 - 4\sin^2\vartheta_W$$



Two Production Runs: Feb-May '11, Nov '11-May '12

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\text{stat}) \pm 31(\text{syst})\ \text{ppb} \quad \text{at} \quad \langle Q^2 \rangle = 0.0250\ (\text{GeV}/c)^2$$



$$Q_W^p(\text{PVES}) = 0.064 \pm 0.012 \qquad Q_W^p(\text{SM}) = 0.0710 \pm 0.0007$$

First determination of proton's weak charge in good agreement with Standard Model

P2 at MESA at Mainz

Parity Violating Deep-Inelastic Scattering

Precision Test of Standard Model

Signature of Neutral Weak Interaction in Electron Scattering - Parity Violation Asymmetry

- In the Standard Model,
  - weak interaction current = V(vector) minus A(axial-vector)

- PV comes from the product V×A

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

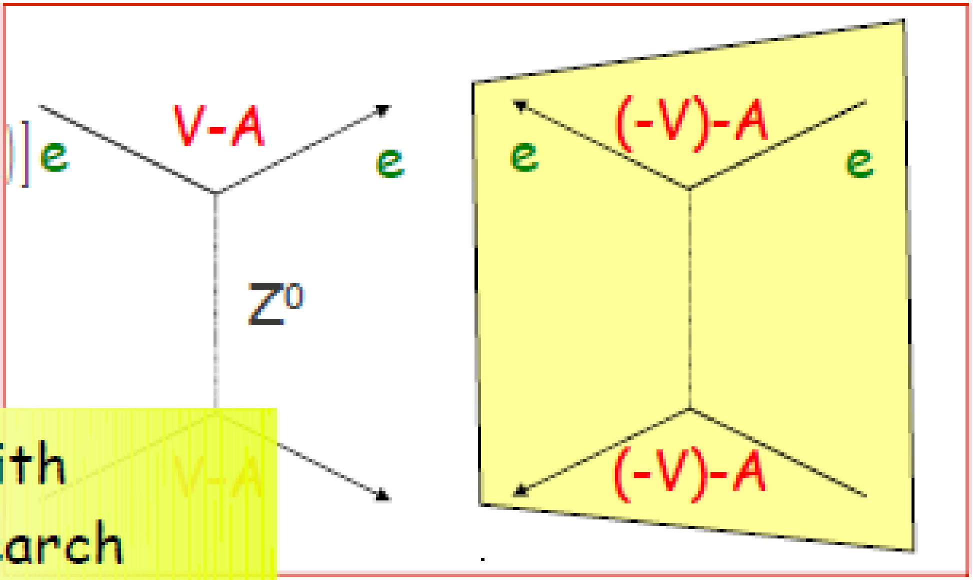
fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$

- In the valence quark region:

$a_1 = \frac{6}{5}\left[2C_{1u} - C_{1d}\right] \qquad a_3 = \frac{6}{5}\left[\left(2C_{2u} - C_{2d}\right)\right]$

$$\boxed{C_{1q} \equiv 2 g_A^e g_V^q, \quad C_{2q} \equiv 2 g_V^e g_A^q}$$

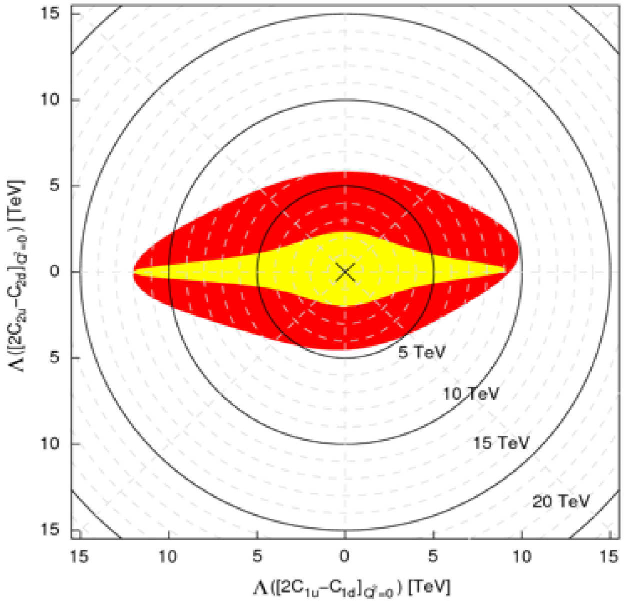
e-q contact terms, both with potential in new physics search

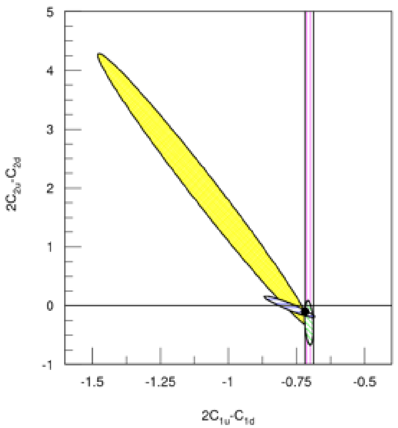


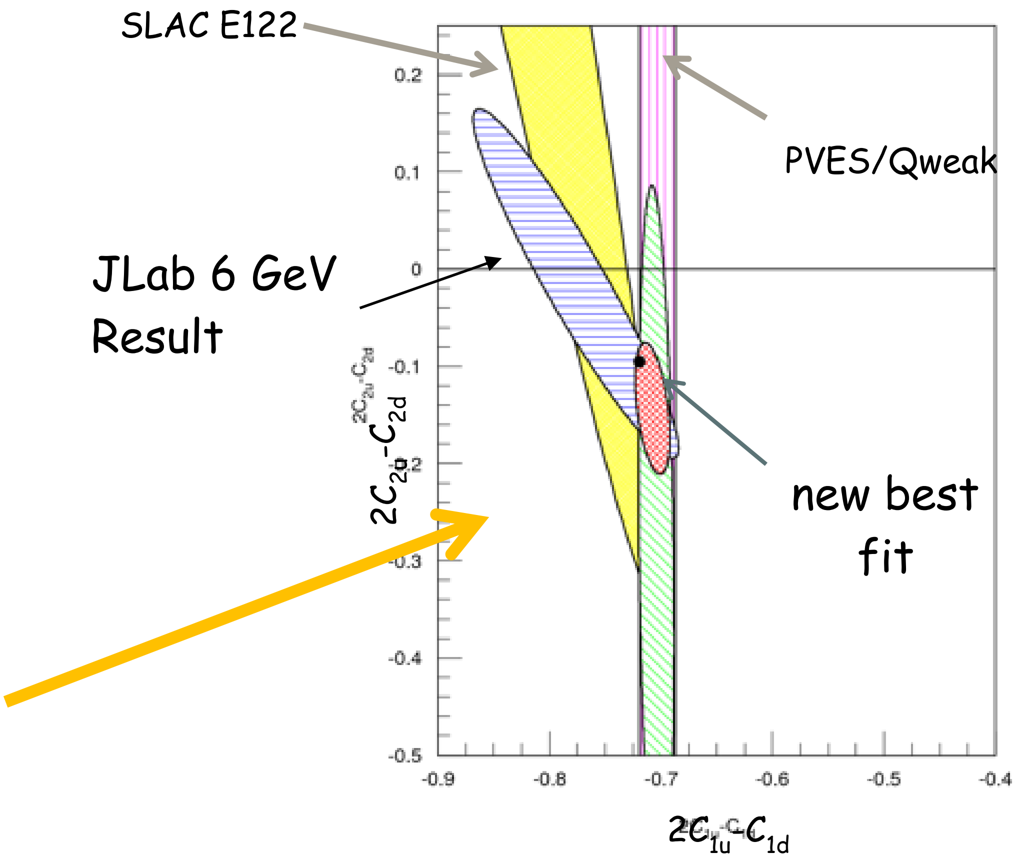
JLab 6 GeV PVDIS Results

nature International weekly journal of science

D. Wang et al., Nature 506, no. 7486, 67 (2014)



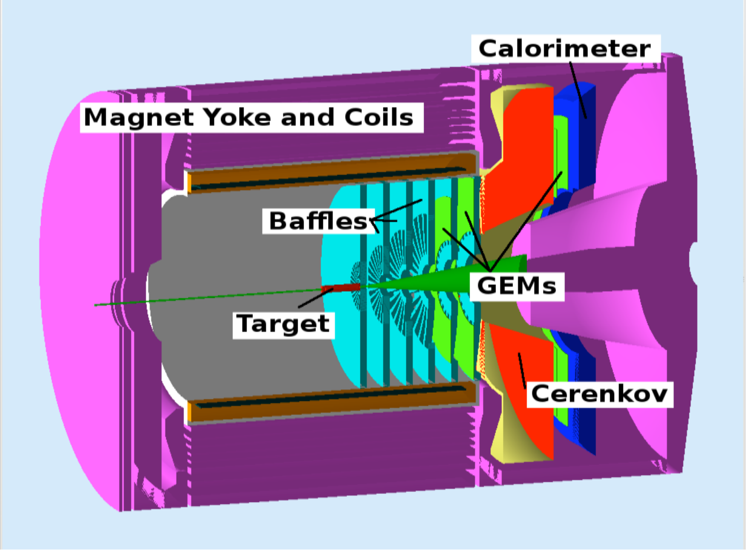




first experimental determination that an axial quark coupling combination is non-zero (as predicted)

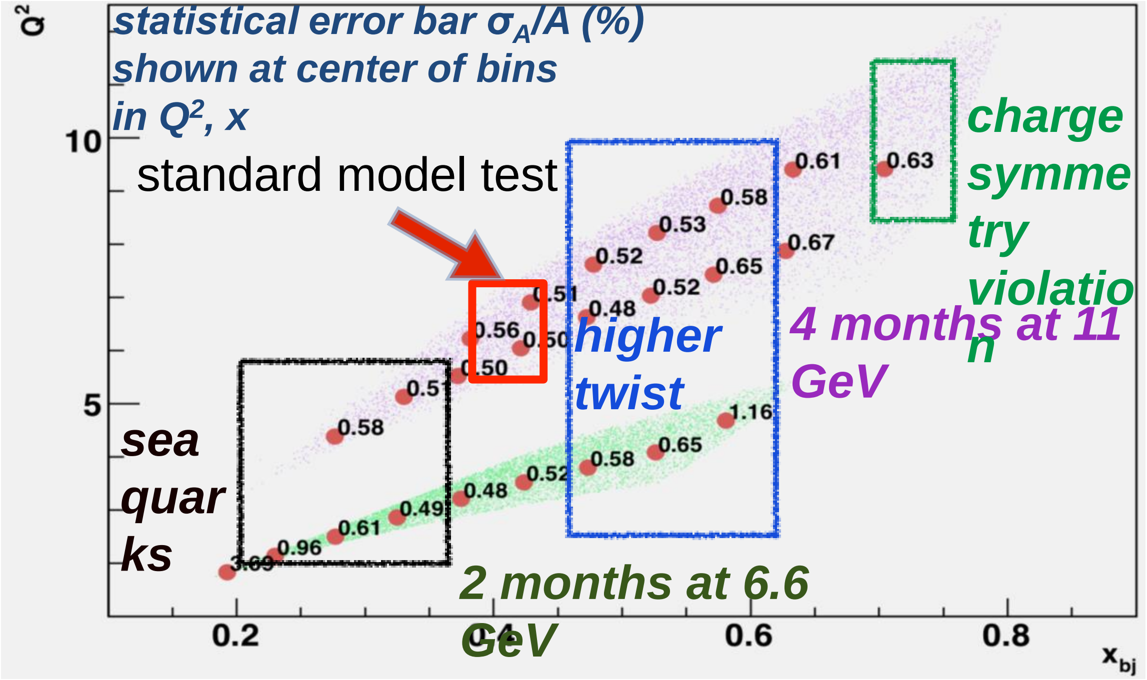
12 GeV Upgrade: Extraordinary opportunity to do the ultimate PVDIS Measurement

PVDIS with SoLID @ JLab12

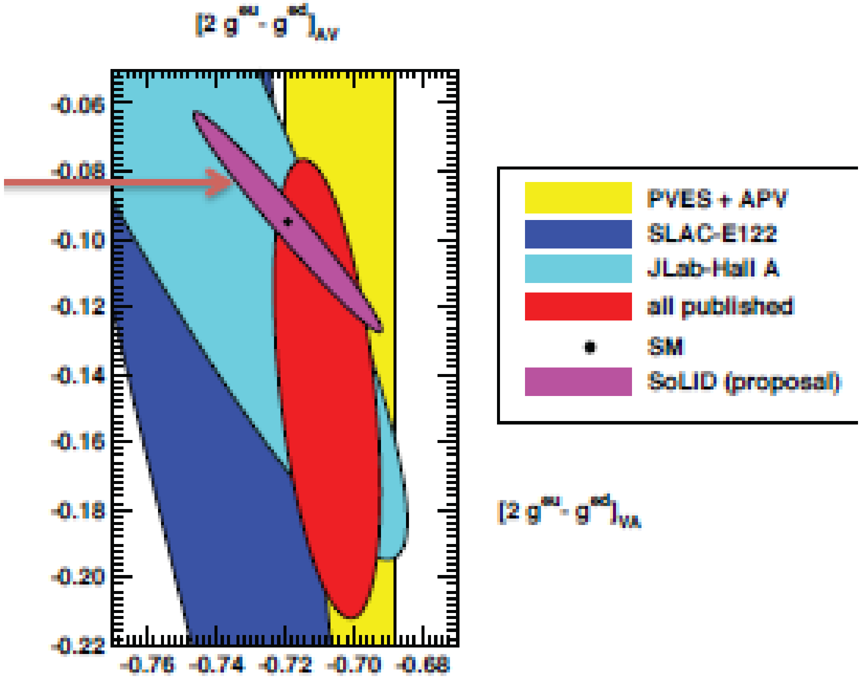


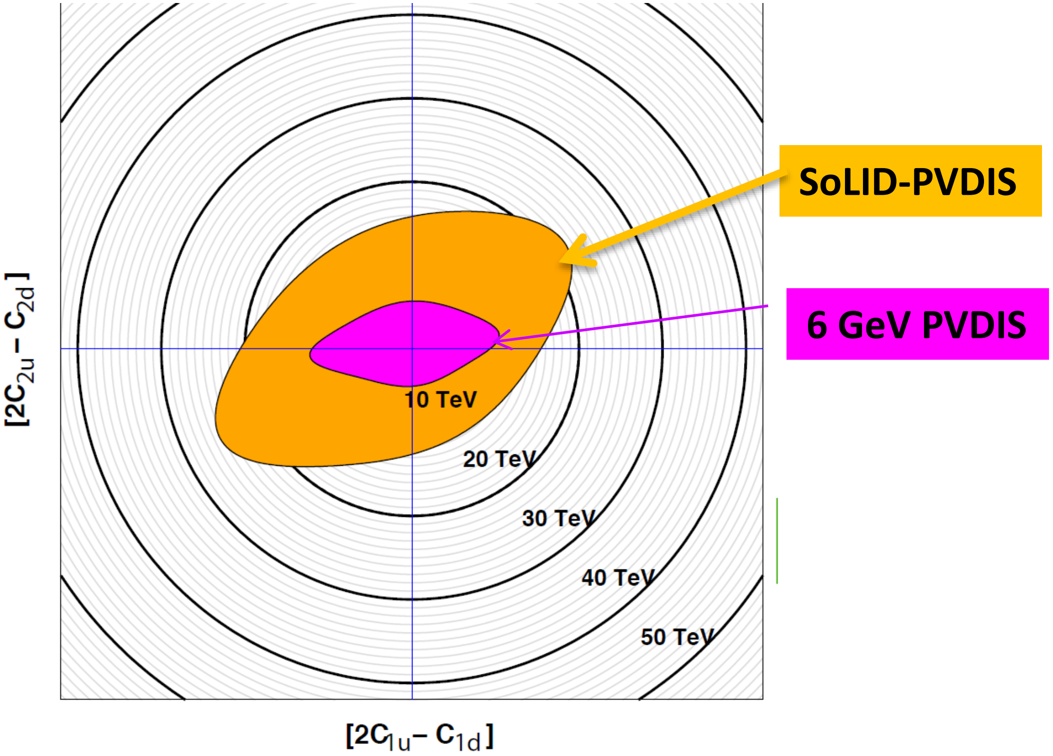
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - charge symmetry violation
  - quark-gluon correlations
  - d/u at large-x



Parity Violation with SoLID





PVDIS asymmetry has two terms:

1) C_{2q} weak couplings, test of Standard Model

2) Unique precision information on **quark structure of nucleon**

Mass reach in a composite model, SoLID-PVDIS ~ 20 TeV, sensitivity match LHC reach with complementary Chiral and flavor combinations

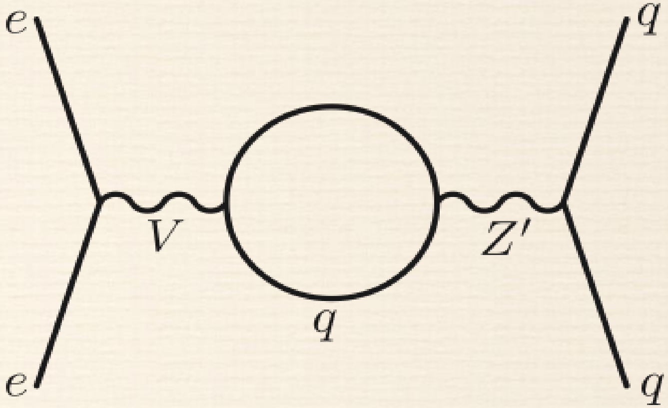
Unique SoLID Sensitivity

Leptophobic Z'

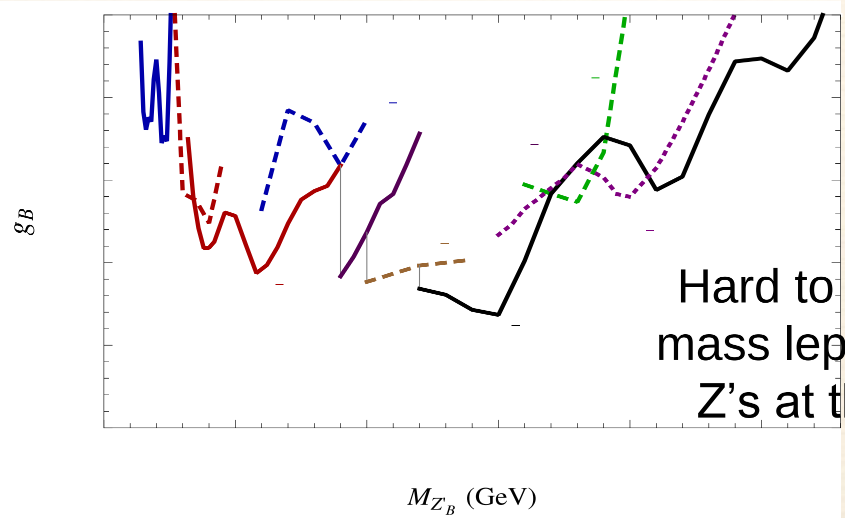
- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *Little sensitivity if Z' doesnt couple to leptons*
- *Leptophobic Z' as light as 120 GeV might escape detection*
- *Leptophobic Z' might couple to dark matter*

arXiv:1203.1102v1

Buckley and Ramsey-Musolf



Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect ***C_{2q}'s***



Hard to see low mass lepto-phobic Z's at the LHC

SOLID can improve sensitivity: 100-200 GeV range

Parity Violating Deep-Inelastic Scattering

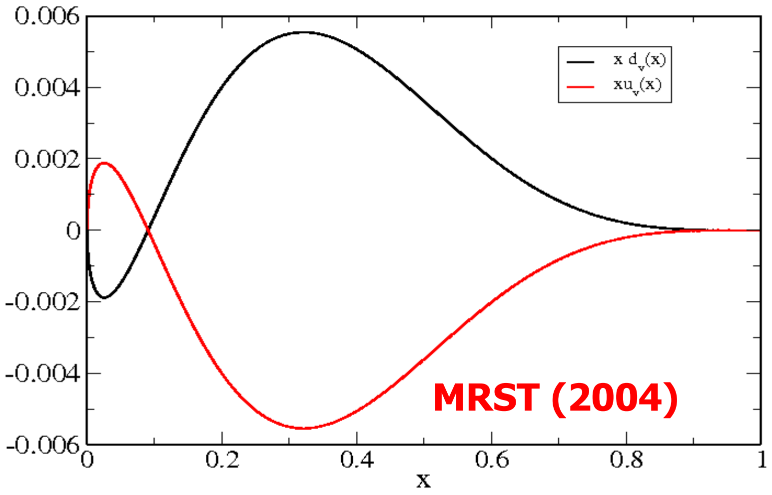
Unique Window to Probe Nucleon Structure

QCD: Charge Symmetry Violation

We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

- Direct observation of CSV—very exciting!
- Important implications for PDF’s
- *Could be a* partial explanation of the NuTeV anomaly



MRST (2004)

$$u^p(x) \overset{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$

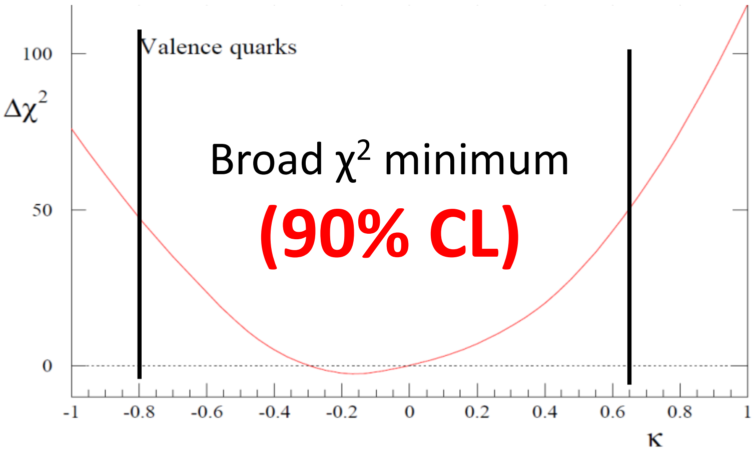
$$d^p(x) \overset{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

For A_{PV} in electron-^{2}H DIS:

MRST PDF global with fit of CSV

Martin, Roberts, Stirling, Thorne Eur Phys J C**35**, 325 (04)



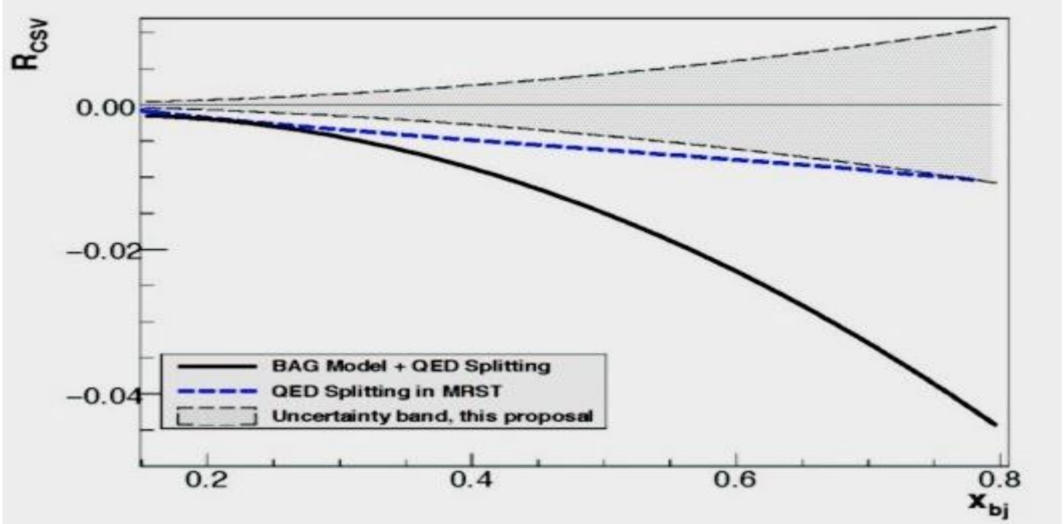
Broad χ^2 minimum

(90% CL)

QCD Physics with PVDIS

$$u^p(x) \overset{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$
$$d^p(x) \overset{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

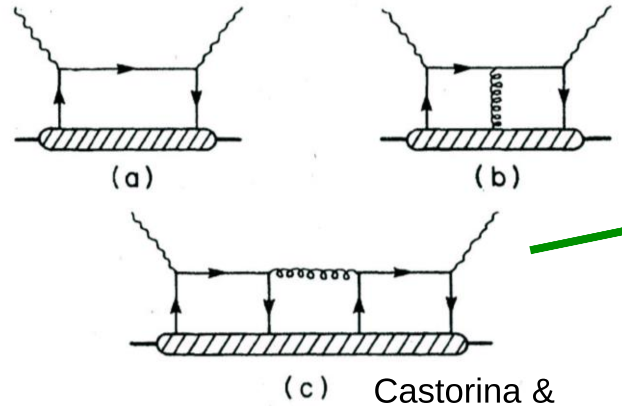
$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$



We already know CSV exists:

- u-d mass difference $\delta m = m_d - m_u \approx 4$ MeV
  $\delta M = M_n - M_p \approx 1.3$ MeV
- electromagnetic effects

- **Direct sensitivity to parton-level CSV**
- **Important implications for PDF's**
- ***Could be* partial explanation of the NuTeV anomaly**



Castorina & Mulders, '84

$$\langle VV \rangle - \langle SS \rangle = \langle (V-S)(V+S) \rangle \propto l_{\mu\nu} \int \langle D | \bar{u}(x)\gamma^{\mu} u(x) \bar{d}(0) \gamma^{\nu} d(0) \rangle e^{iqx} d^4x$$

Zero in quark-parton model

Higher-Twist valence quark-quark correlation

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Kinematic dependence of physics topics

	x	Y	Q^2
New Physics	**none**	**yes**	**small**
CSV	**yes**	**small**	**small**
Higher Twist	**large?**	**no**	**large**

- ***Measure A_d in narrow bins of x, Q^2 with 0.5% precision***
- ***Cover broad Q^2 range for x in [0.3,0.6] to constrain HT***
- ***Search for CSV with x dependence of A_d at high x***
- ***Use x > 0.4, high Q^2 to measure a combination of the C_{iq}'s***

Fit data to:

$$A_{\mathrm{Meas.}} = A_{\mathrm{SM}}\left[1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3\,Q^2} + \beta_{\mathrm{CSV}}\,x^2\right]$$

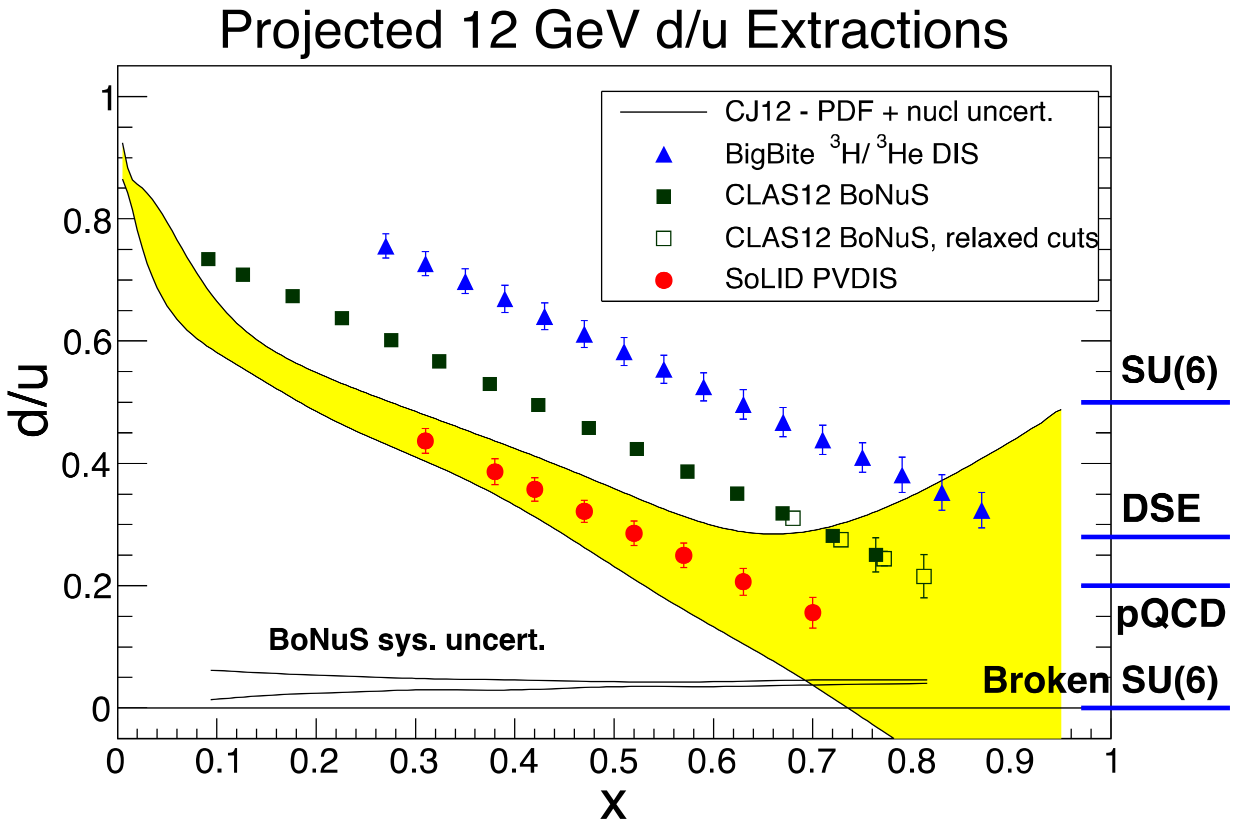
PVES on proton

Precision determination of d/u @ high-x
without nuclear effect

Clean Measurement of d/u with PVDIS

For high x on proton target:

$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$


Projected 12 GeV d/u Extractions

- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3\mathrm{H}/^3\mathrm{He}$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*
- Disagreement would also signal CSV

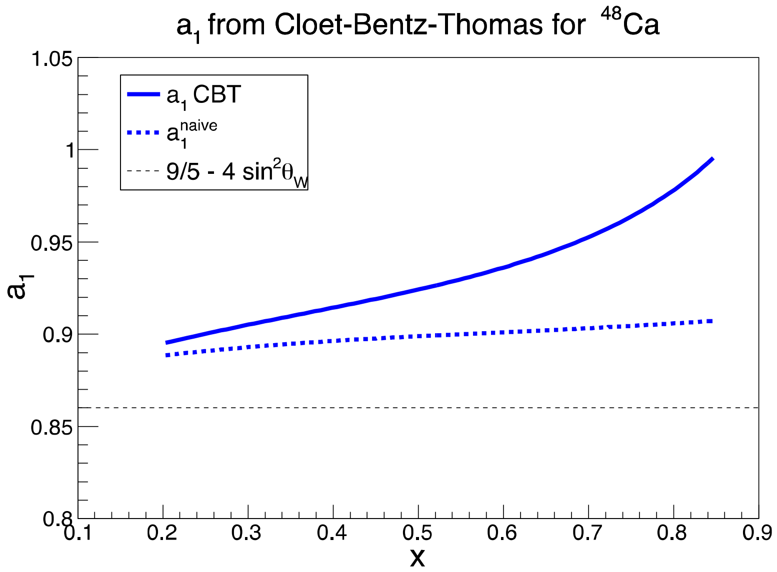
PVES on ^{48}Ca

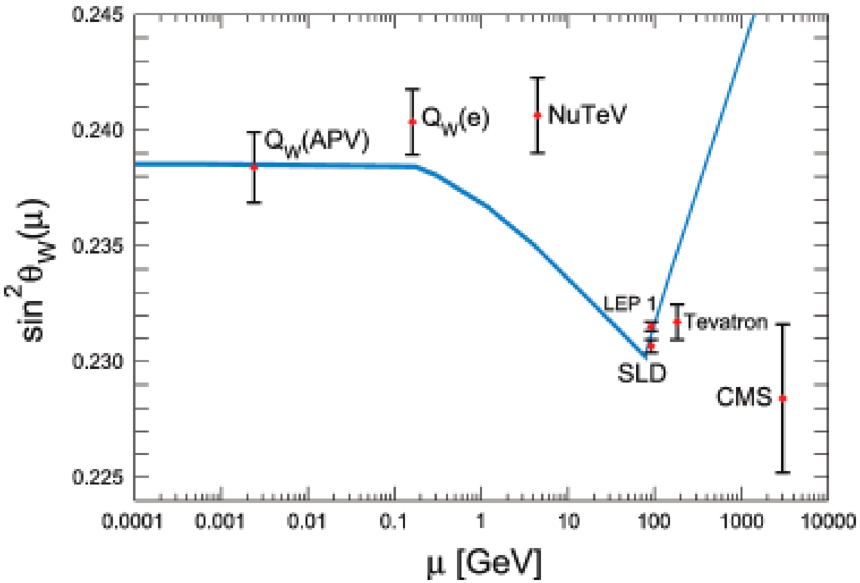
Study Isoscaler EMC effect

EMC Effect Flavor Dependence

S. Riordan, et al., new proposal - 48Ca PVDIS

- Flavor dependence of EMC effect and be probed with PVDIS
- Relevant for nuclear modification, short-range correlations, neutrinos, BSM, ...





Symmetric nucleus limit

$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+} + \dots$$

PVES on polarized ^{3}He

γ-Z interference (spin) structure functions

PV Structure Functions: New LOI by Y. Zhao et al.

---γ-Z interference structure functions

pol. electron & unpol. nucleon:

$$A_{beam} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A^e \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e \frac{Y_-}{2Y_+}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$F_1^{p,\,\gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_1^{n,\,\gamma Z} \approx \frac{1}{9}(u + \bar{u} + d + \bar{d} + s + \bar{s} + c + \bar{c})$$

$$F_3^{p,\,\gamma Z} = \frac{2}{3}(u_V + c - \bar{c}) + \frac{1}{3}(d_V + s - \bar{s})$$

$$F_3^{n,\,\gamma Z} = \frac{2}{3}(d_V + s - \bar{s}) + \frac{1}{3}(u_V + c - \bar{c})$$

unpol. electron & pol. nucleon:

$$A_L = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V^e \frac{g_5^{\gamma Z}}{F_1^{\gamma}} + g_A^e \frac{Y_-}{Y_+}\frac{g_1^{\gamma Z}}{F_1^{\gamma}}\right]$$

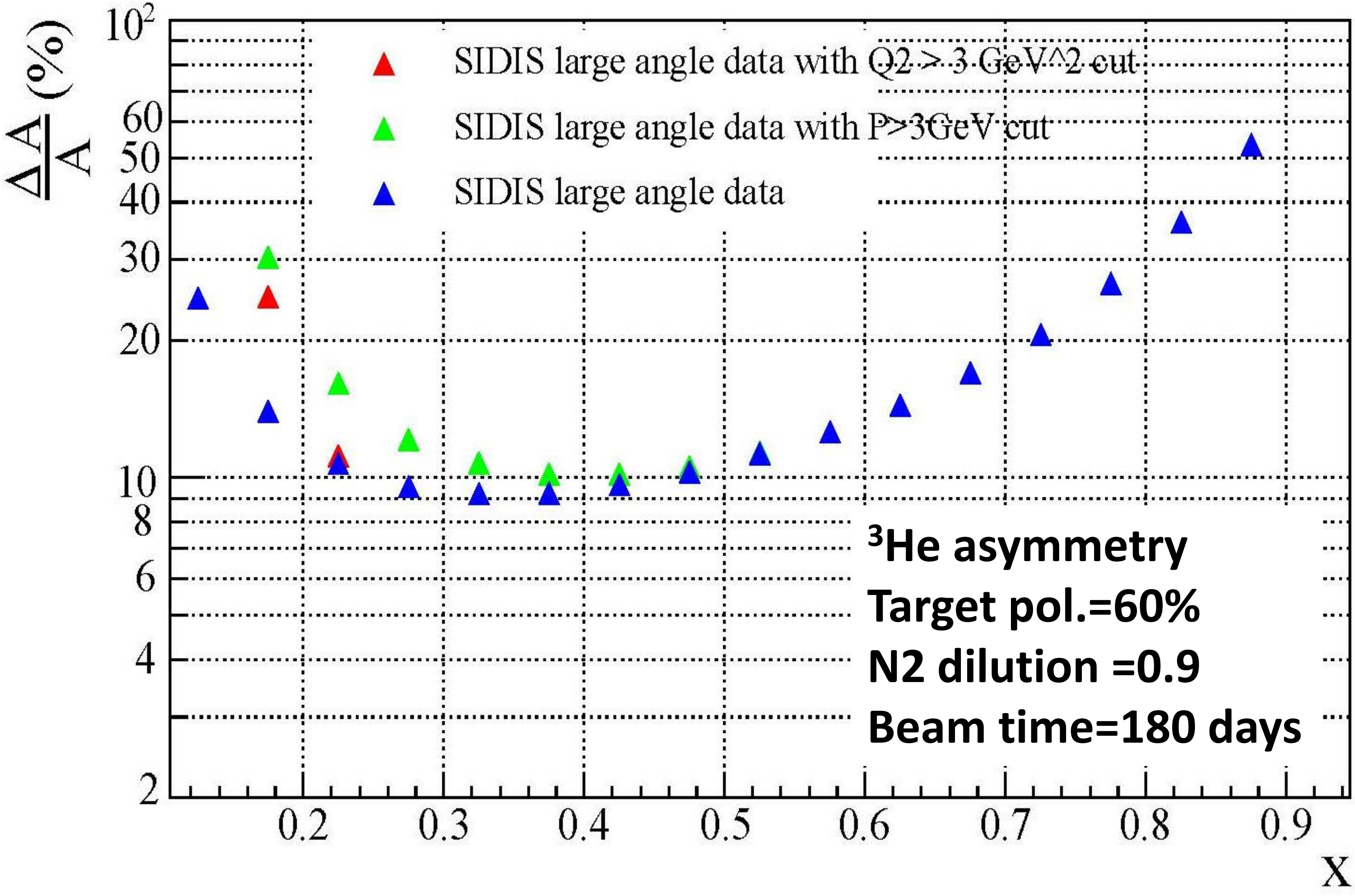
$$g_1^{p,\,\gamma Z} \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \Delta c + \Delta\bar{c})$$

$$g_1^{n,\,\gamma Z} \approx \frac{1}{9}(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} + \Delta c + \Delta\bar{c})$$

$$g_5^{p,\,\gamma Z} = \frac{1}{3}(\Delta u_V + \Delta c - \Delta\bar{c}) + \frac{1}{6}(\Delta d_V + \Delta s - \Delta\bar{s})$$

$$g_5^{n,\,\gamma Z} = \frac{1}{3}(\Delta d_V + \Delta s - \Delta\bar{s}) + \frac{1}{6}(\Delta u_V + \Delta c - \Delta\bar{c})$$

Projections: unpolarized beam on high luminosity pol. 3He



^{3}He asymmetry

Target pol.=60%

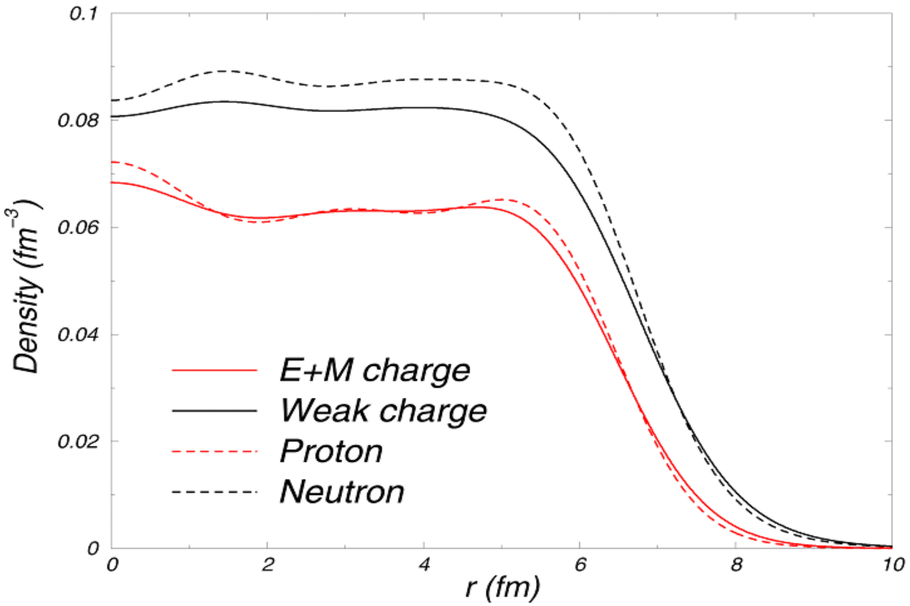
N2 dilution =0.9

Beam time=180 days

PVES on ^{208}Pb (PREX) and ^{48}Ca (CREX)

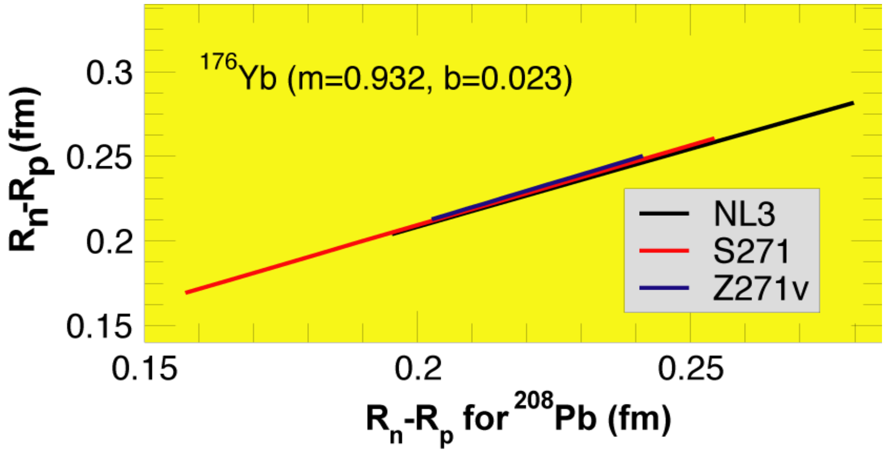
Precision Study of Neutron Skin

Probing Neutron-Rich Matter



Piekerewicz, Michaels

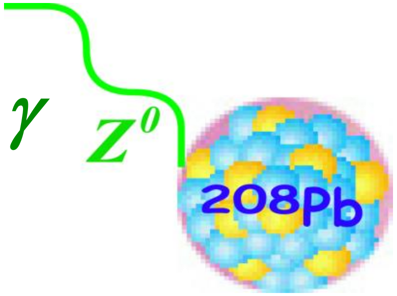
Constrain neutron halo for APV

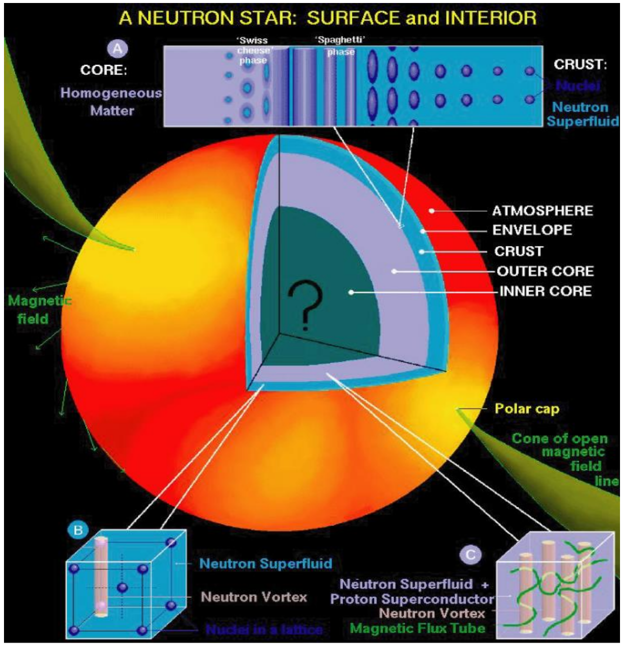


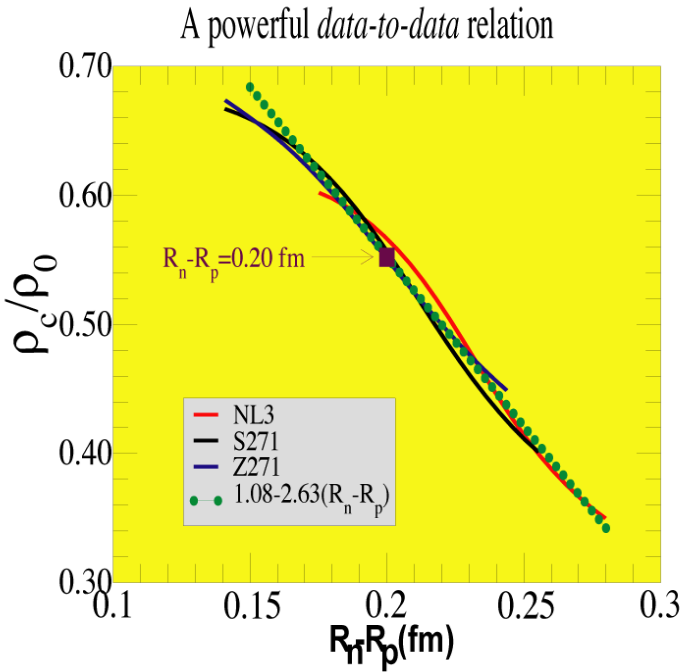
Constrain neutron star crust thickness

Q^p_{EM} ~ 1 Q^n_{EM} ~ 0

Q^n_W ~ 1 $Q^p_W \sim 1 - 4\sin^2\theta_W$

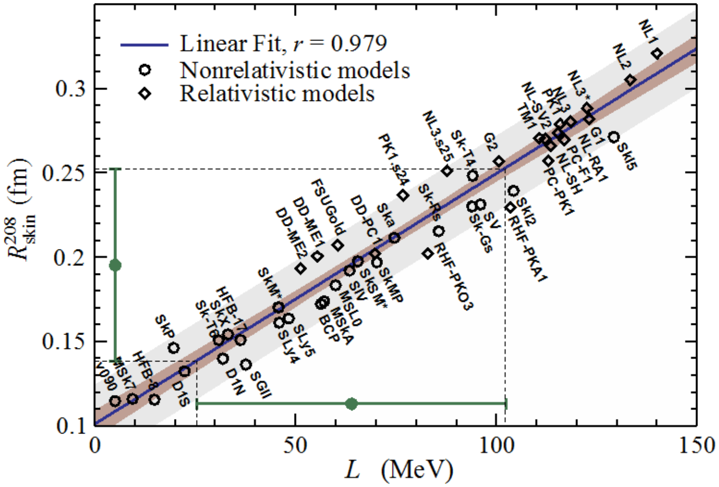






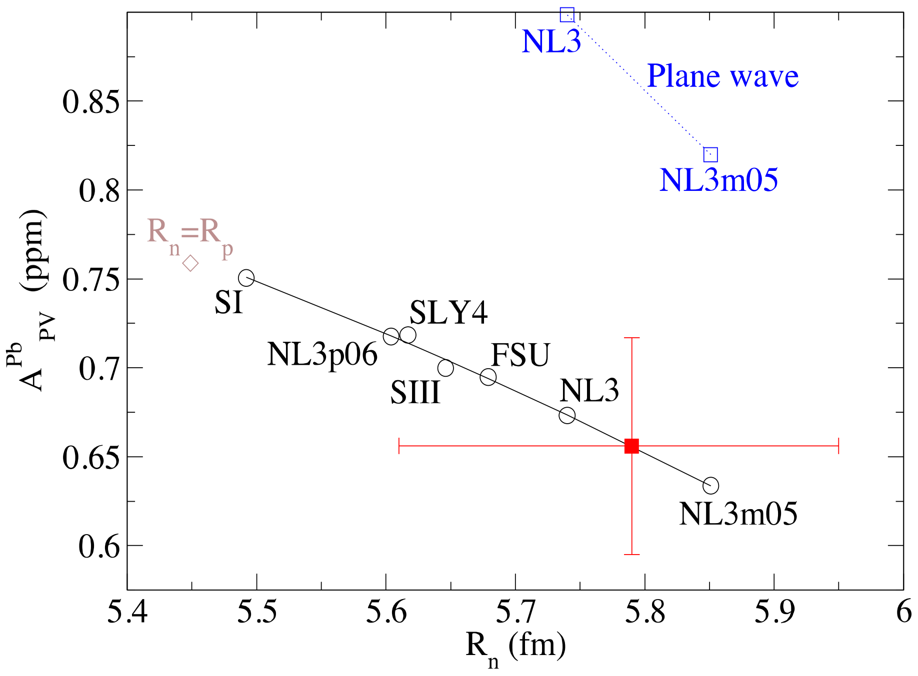
PREX - Neutron Radius of ^{208}Pb

- Ultimate goal to measure R_n (□0.2 fm) to 0.06 fm
- Ran Spring 2010 in Hall A at JLab
- ^{208}Pb because
  - Large neutron excess
  - Doubley-magic nucleus
  - Spin 0
  - Large separation from first inelastic excited state



X. Roca-Maza *et al.*, PRL 106 252501 (2011)

Symmetry Energy



- Set 95% CL on existence of neutron skin
- $R_n - R_p = 0.34 + 0.15 - 0.17$ fm
- Goal of 2% systematics (polarimetry, detector linearity, beam asymmetries each $\sim 1\%$) reached!
- Publications
  - S. Abrahamyan *et al.* Phys. Rev. Lett. 108, 112502 (2012)
  - C.J Horowitz *et al.* Phys. Rev. C 85, 032501(R) (2012)

Near Future!

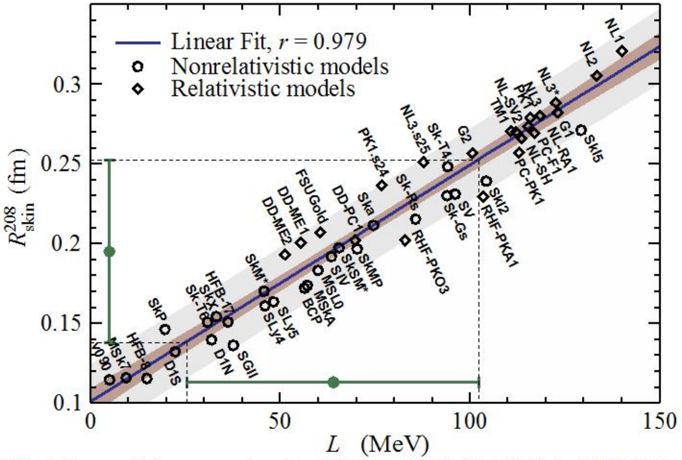
Next round of experiments for fall of 2017!

PREX-II - ^{208}Pb

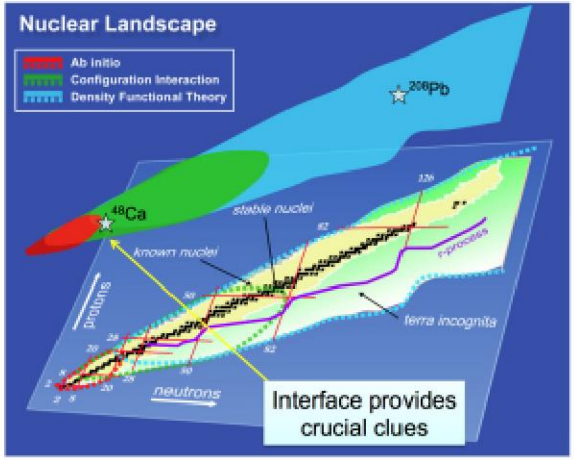
- Aims to each goal of δR_n □ 0.06 fm
- Improved shielding ar more advanced target allow for full running
- Will provide reliable constraints on slope of symmetry energy

CREX - ^{48}Ca

- Measurements on ^{48}Ca to 0.02 fm
- Gives broader reach over periodic table
- Contributing systematics slightly different
- A □ 40 now within reach of microscopic calculations



X. Roca-Maza *et al.*, PRL 106 252501 (2011)



Interface provides crucial clues

Summary

- Parity Violating Electron Scattering:
  a precision tool to test Standard Model and
  a precision tool to study hadron/nuclear physics
- MOLLER/Qweak: precision test of SM
- PVDIS on deuteron: precision test of SM
  Precision study of CSV, higher-twist
- PVDIS on other targets
  p: d/u at high-x
  ^{48}Ca: isoscaler EMC Effects
  Pol. ^{3}He: spin-flavor structure
- PVES on ^{208}Pb and ^{48}Ca: neutron skin

Parity Violation with EIC