# Parity Violating Electron Scattering at Jefferson Lab

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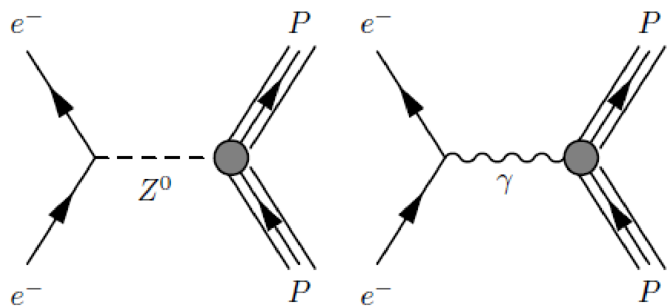
# Outline

- Parity Violating Electron Scattering (PVES) overview
- Testing the Standard Model (SM) with PVES
  - Qweak, SoLID-PVDIS and MOLLER
- Nuclear structure physics with PVES
  - PREX/CREX
- PVES as a probe of nucleon structure
  - SoLID-PVDIS EMC proposal

# Parity Violating Electron Scattering



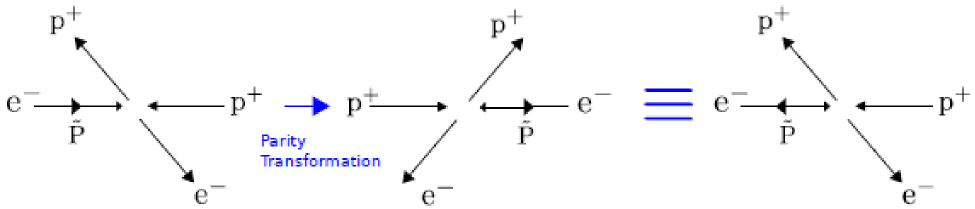

$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell l^\mu J_\mu^{EM}$$

$$M^{NC} = \frac{-G_F}{2\sqrt{2}} (g_V^\ell l^\mu + g_A^\ell l^{\mu 5})(J_\mu^{NC} + J_{\mu 5}^{NC})$$

Differential scattering cross section,

$$\frac{d\sigma}{d\Omega} \propto |M^{Total}|^2 \simeq |M^{EM}|^2$$

Due to PV nature of the neutral current, the differential cross section is dependent on the helicity of the electron




The difference in helicity correlated scattering cross section is known as the PV asymmetry,

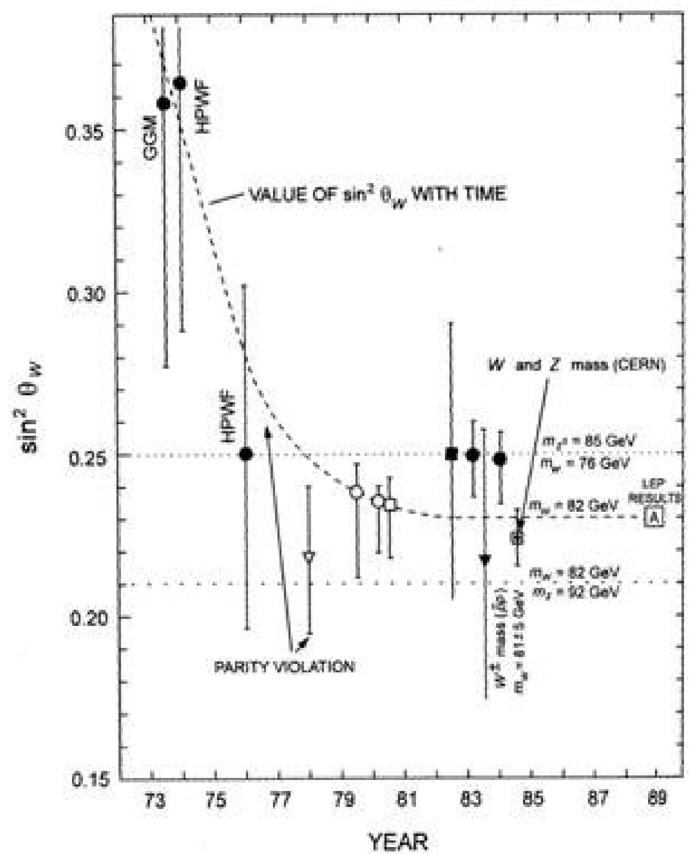
$$A_{PV} = \frac{\frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega}}{\frac{d\sigma^R}{d\Omega} + \frac{d\sigma^L}{d\Omega}} \propto \frac{M^{EM} \cdot M^{NC}}{|M^{EM}|^2}$$

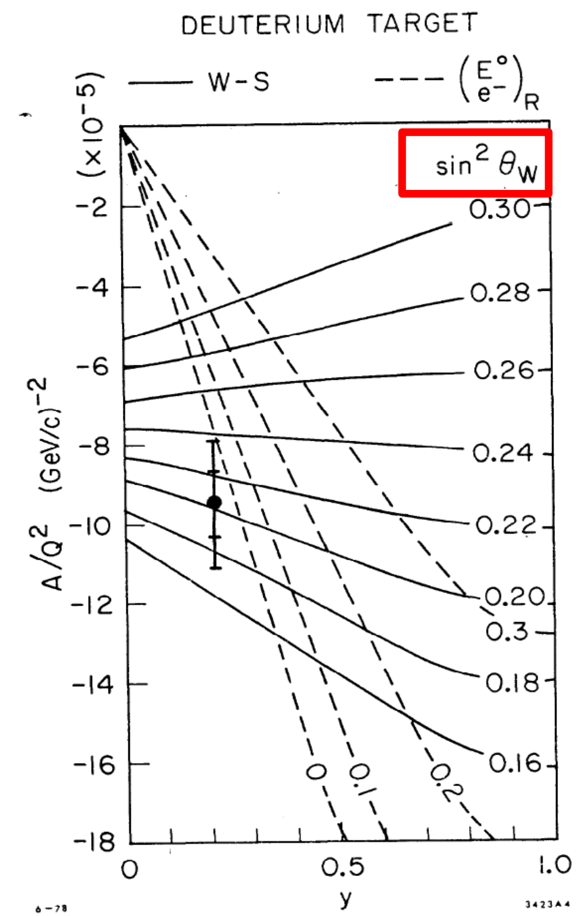
# PVES Applications

- Testing the Standard Model (SM)
  - Qweak (e-p), MOLLER (e-e), SoLID-PVDIS (e-q) experiments
- Nuclear Structure
  - Neutron density measurements with PREX/CREX experiments (e-$^{208}$Pb and e-$^{48}$Ca)
- Nucleon Structure
  - EMC with SoLID-PVDIS experiment using e-$^{48}$Ca
  - Strangeness in proton (HAPPEX, G0 experiments) and etc.

# PVES Historical Significance

- Confirmation of the EW SM from the first PVES experiment at SLAC by Prescott et. al.
- First measurement of parity-violation in the neutral weak current!
  - Which they found the weak mixing angle to be around 1/4 that amount to a small axial vector(e) **X** vector(f) weak neutral interaction!



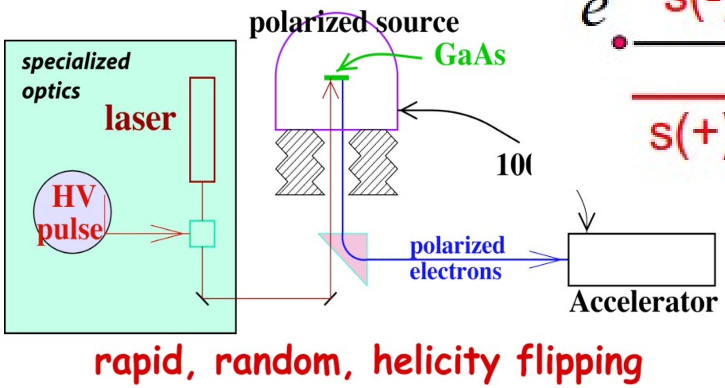



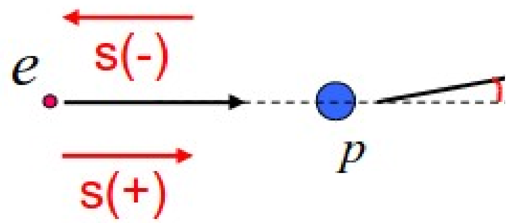

1[st] PVDIS at SLAC!
first result in 1978:
Prescott et al., PLB 77, 347 (1978)
Prescott et al., PLB 84, 524 (1978)

# Unique Nature of a PVES Experiment

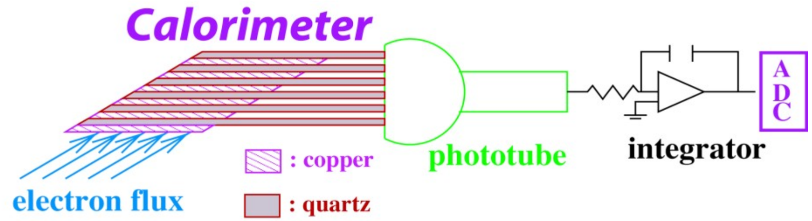
- The Injector + Accelerator + Apparatus or “The Whole Machine” becomes parts of the experiment
- Complete understanding of all the backgrounds is the key to successful PVES
- Monitor PVES asymmetries real-time to find issues and fix them
  - No second chance at offline after the experiment

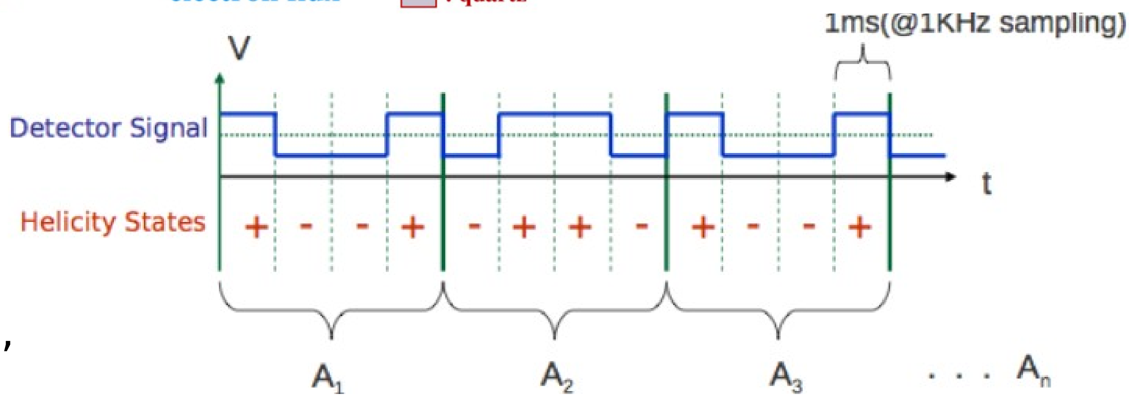
# How to Do A PVES Experiment



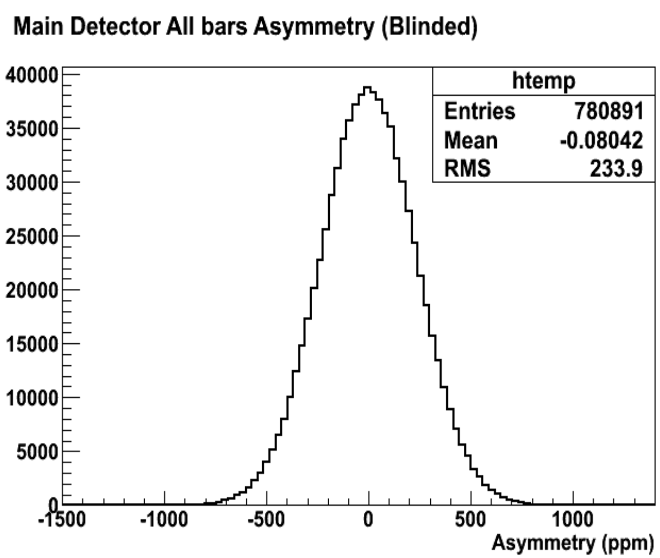




Helicity of electron beam flipped periodically, delayed helicity reporting to prevent direct electrical pick up of reversal signal by detectors




Detector signal integrated for each helicity window and asymmetry formed by quartet




| Contribution | Expected width (ppm) |
|---|---|
| **Pure statistics** | **201** |
| Detector resolution | 92 |
| Current monitor resolution | 50 |
| Target boiling | 57 |
| **Total** | **233.7** |

$$\delta A = \frac{\sigma_A}{\sqrt{N_{QRT}}}$$

$\sigma_A$ = 230-260 ppm

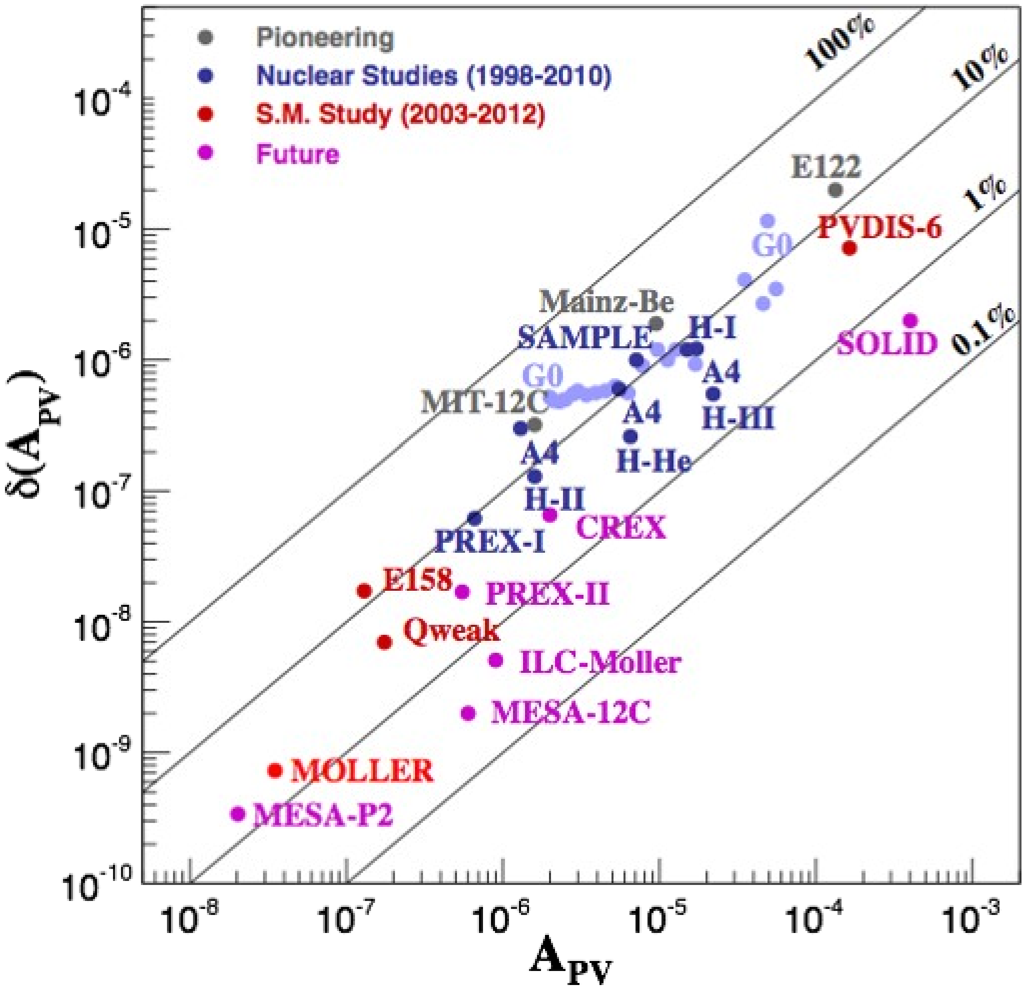
$A_{Phys}$ = -0.200 ppm

**$\delta A_{Phys}$ = 0.006 ppm**

# PVES Progress

Looking to Future : Technical challenges :

- Statistics
  - High rate, beam polarization, beam current, high-power target, large acceptance detectors
- Noise
  - Electronics, target density fluctuations, detector resolution
- Systematics
  - Helicity-correlated beam asymmetry (false asym.), backgrounds, precision beam polarimetry, precise $Q^2$ determination




Precision vs smaller asymmetry

# PVES Progress

| Beam property | MOLLER spec. | Qweak observed |
|---|---|---|
| Intensity | < 1000 ppm | 500 ppm |
| Energy | < 108 ppm | 6.5 ppm |
| Position | < 47 µm | 48 µm |
| Angle | < 4.7 µrad | 1.4 µrad |

Courtesy of Mark Pitt

## Looking to Future : Technical challenges :

- Random beam fluctuations limits : present (Qweak) vs. Future (MOLLER)
- Beamline monitor precision : present (Qweak) vs. Future (MOLLER)

| Monitor type | MOLLER spec. | Qweak observed |
|---|---|---|
| Beam charge | 10 ppm | 65 ppm |
| Beam position | 3 µm | 6 µm |

Courtesy of Mark Pitt

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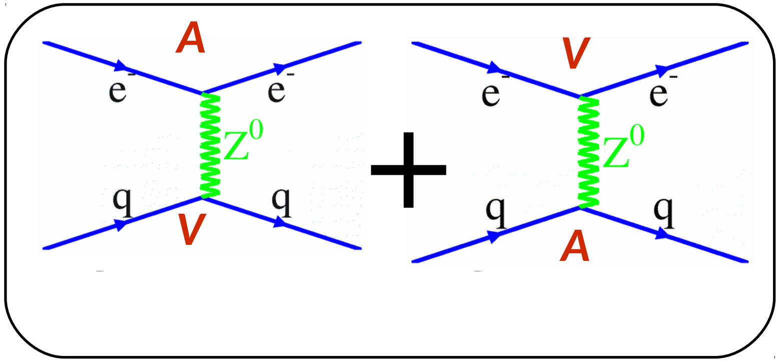
# Electron-Quark Couplings

EW neutral current interaction + New Physics

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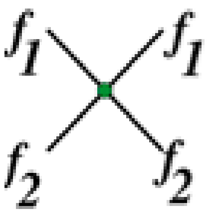



$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

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

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

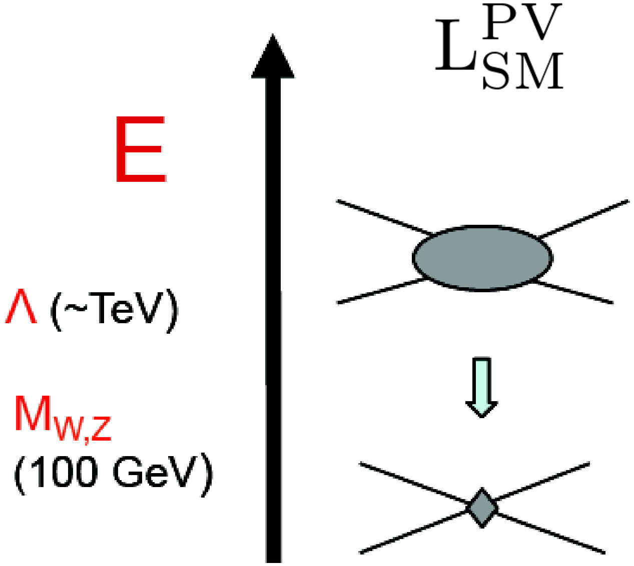
Involve vector hadronic currents:PV elastic e-p scattering, Atomic parity violation

Involve axial hadronic currents: PV deep inelastic scattering

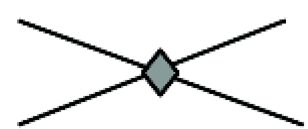
# PVES in Search for New Physics

- New physics at high energies can be detected through precision PVES at low energies
  - At low energies new physics appear as a new contact interaction

$$L_{eff}^{PV} = \underbrace{-\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \cdot \sum_q C_{1q}\bar{q}\gamma^\mu q}_{L_{SM}^{PV}} + \underbrace{\frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q\bar{q}\gamma^\mu q}_{L_{new}^{PV}}$$




These could be Heavy Z's or neutrinos, Technicolor, SUSY, etc



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

For Λ ~ TeV scale

# PVES vs Colliders: Neutral Currents

- Both colliders and PVES can access $\Lambda$ > 10 TeV but...
- In PVES : both New physics and EW physics amplitudes interference with electromagnetic amplitude

$$|A_\gamma + A_Z + A_{New}|^2 \to A_\gamma^2 \left[1 + 2\left(\frac{A_Z}{A_\gamma}\right) + 2\left(\frac{A_{New}}{A_\gamma}\right)\right]$$

Can observe PV new physics interactions!

- In colliders : No interference

$$|A_Z + A_{New}|^2 \to A_Z^2 \left[1 + \left(\frac{A_{New}}{A_Z}\right)^2\right]$$

At Z resonance $A_Z$ is imaginary and no interference observed!

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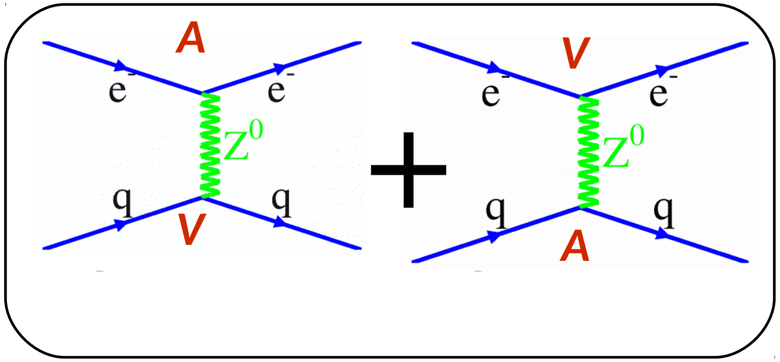


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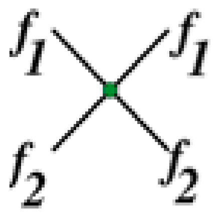


$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$

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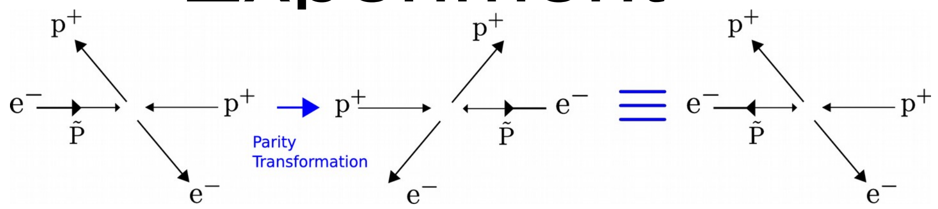
→ Involve vector hadronic currents:PV elastic e-p scattering, Atomic parity violation

→ Involve axial hadronic currents: PV deep inelastic scattering

# Parity Violating Asymmetry for the Qweak Experiment




The Qweak experiment determines the proton's weak charge by measuring the PV asymmetry in elastic scattering of longitudinally polarized electrons on unpolarized protons

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

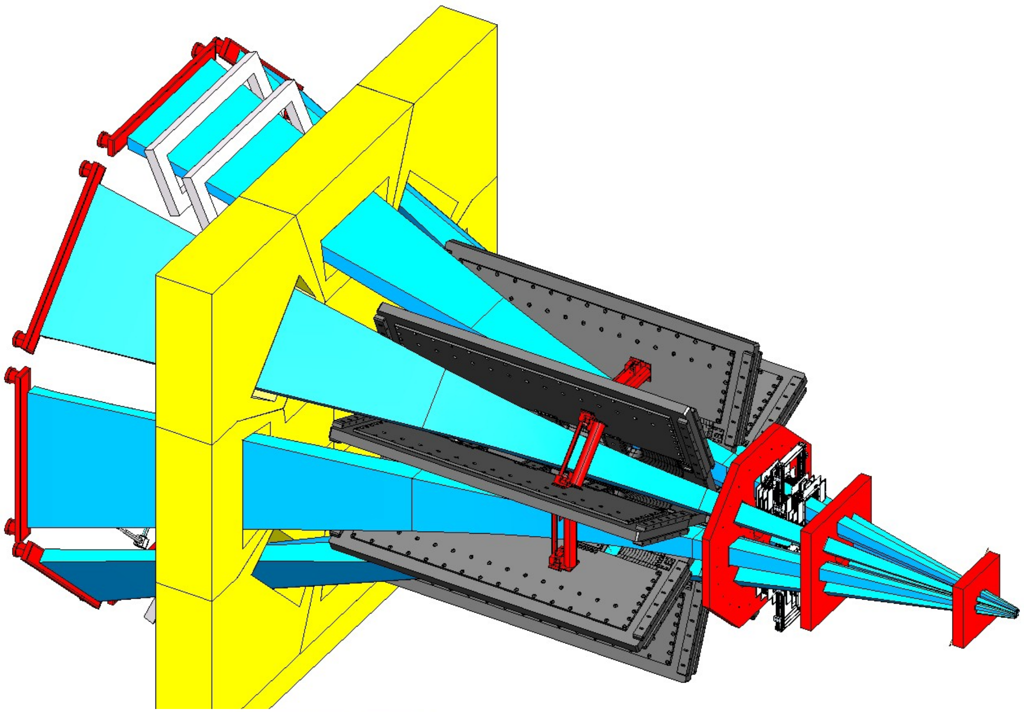
At forward angles and very small $Q^2$,

$$A_{PV}(\vec{e}p) = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W^P + F(Q^2,\theta)\right] = A_{Q_W^P} + A_{Had}$$

Proton's weak charge, $Q_W^p = 2g_V^u \cdot g_A^e + g_V^d \cdot g_A^e = 1 - 4\cdot\sin^2\theta_W$

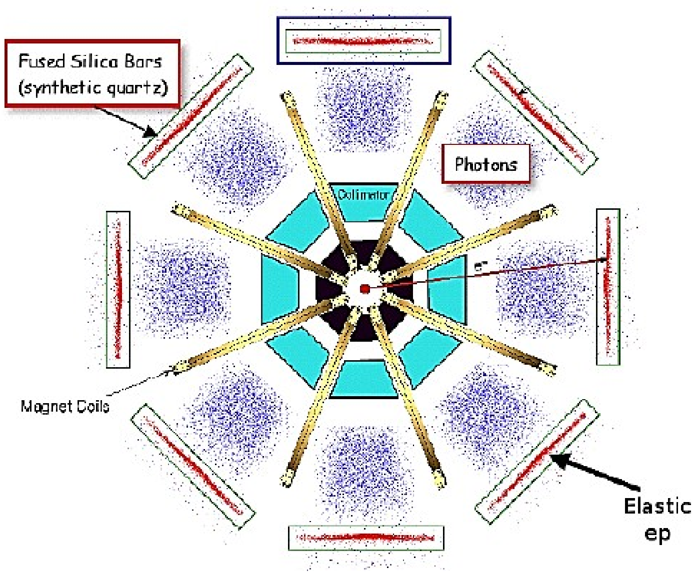
Form factor term due to finite proton size → Hadron structure (~ 30% of the asymmetry) By running the experiment at very small $Q^2$, sensitivity to the effects of the "Hadron structure" is minimized

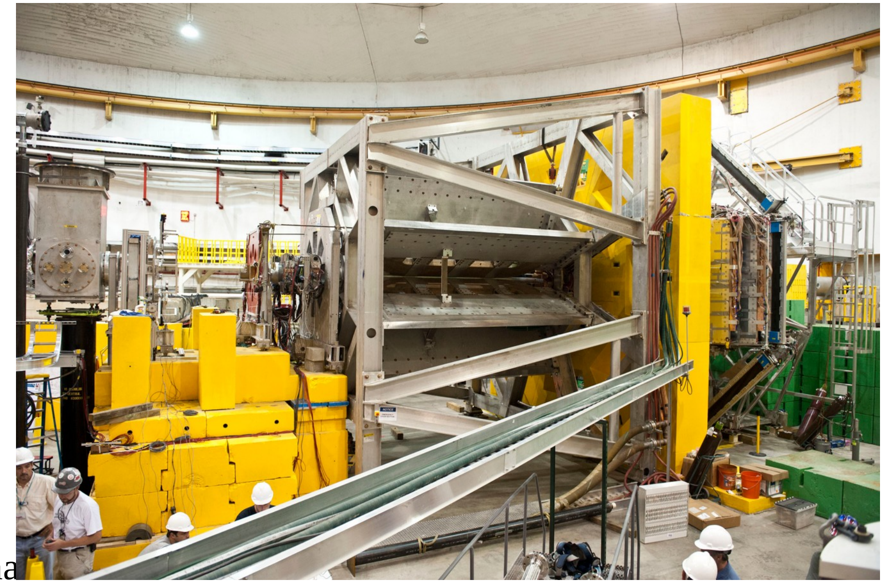
# Qweak Experimental Apparatus



## Parameters

- $E_{beam}$ = 1.165 GeV
- $\langle Q^2 \rangle$ = 0.025 GeV$^2$
- $\langle \theta \rangle$ = 7.9 ± 3
- φ coverage = 50% of 2π
- $I_{beam}$ = 180 μA
- Integrated rate = 6.4 GHz
- Beam polarization = 88%
- Target = 35 cm
- Cryo-power = 3 kW

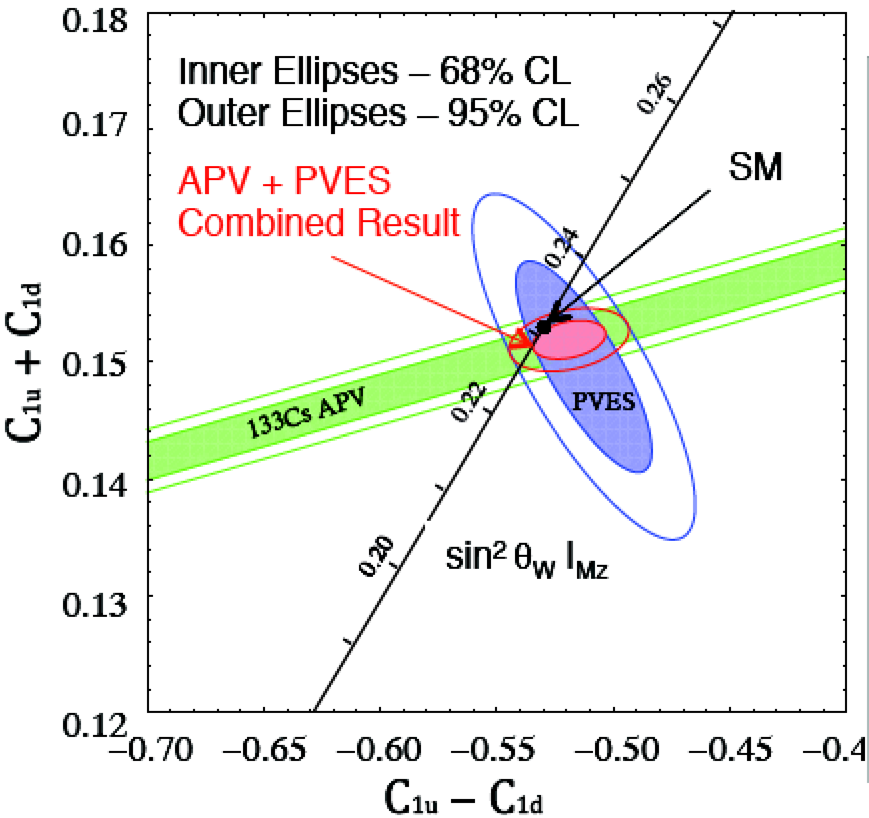


# Qweak Commissioning Run

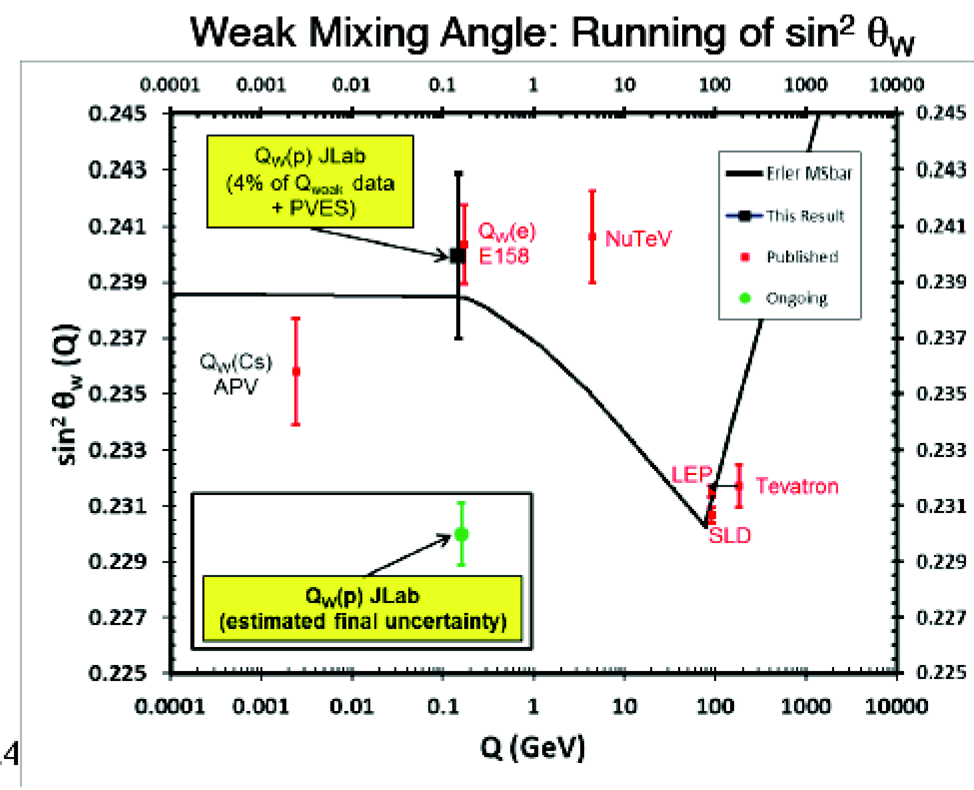
**Combined Analysis**

**Extract: $C_{1u}$, $C_{1d}$, $Q^n_W$**




**Qweak + Higher $Q^2$ PVES**

**Extract: $Q^p_W$, $\sin^2\theta_W$**




$Q^n_W = -2\,(C_{1u} + 2\,C_{1d})$
$= -0.975 \pm 0.010$

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$

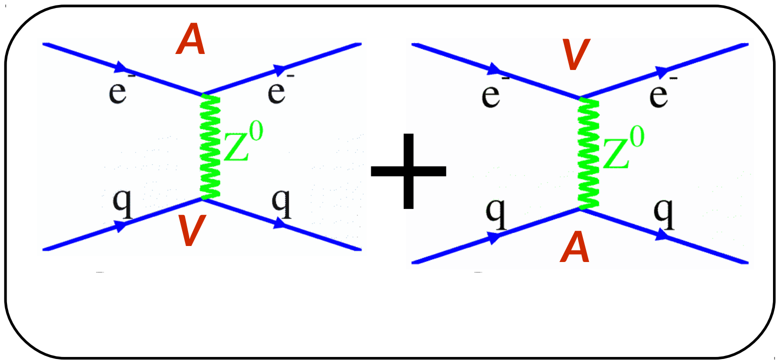
$Q^p_W = -2\,(2\,C_{1u} + C_{1d})$
$= 0.064 \pm 0.012$
SM prediction = 0.0710(7)

Publication : PRL 111, 141803 (2013)

More production data is still being analyzed : expect final results in 2016!

# Electron-Quark Couplings

EW neutral current interaction + New Physics

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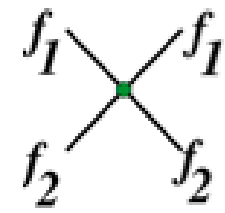


$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^{\mu}\gamma_5 e(C_{1u}\bar{u}\gamma_{\mu}u + C_{1d}\bar{d}\gamma_{\mu}d) + \bar{e}\gamma^{\mu}e(C_{2u}\bar{u}\gamma_{\mu}\gamma_5 u + C_{2d}\bar{d}\gamma_{\mu}\gamma_5 d)]$$

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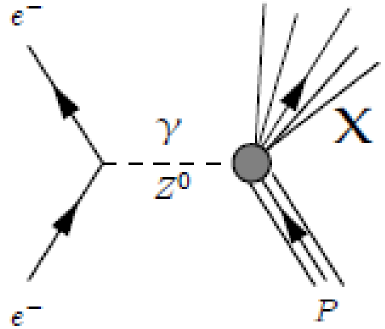
Involve axial hadronic currents: PV deep inelastic scattering

# PV Deep Inelastic Scattering




*Off the simplest isoscalar nucleus (deuterium) at high Bjorken x*

$$A_{PV}^{DIS} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[2g_A^e Y_1(y)\frac{F_1^{\gamma Z}}{F_1^Z} + 2g_V^e Y_3(y)\frac{F_3^{\gamma Z}}{F_1^Z}]$$

At high x, deuterium PV asymmetry becomes independent of PDFs, x and W, with well defined SM predictions for given $Q^2$ and y = 1 – E'/E

For $Q^2 >> 1\ GeV^2$ and $W^2 > 4\ GeV^2$

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

$$\text{Where, } Y_1 \simeq 1; Y_3 \simeq \frac{1-(1-y)^2}{1+(1-y)^2}$$

$$a_1^D(x) = \frac{6}{5}(2C_{1u} - C_{1d})(1 + \frac{0.6s^+}{u^+ + d^+})$$

$$a_3^D(x) = \frac{6}{5}(2C_{2u} - C_{2d})(\frac{u^- + d^-}{u^+ + d^+})$$

Where $f_i^{\pm} = f_i \pm \bar{f}_i, y = \frac{E-E'}{E}$

Interplay with QCD,

- Flavor dependent quark distributions (u,d, and s)
- Charge symmetry violations (CSV)
- Higher twist effects (HT)
- Nuclear medium effects (EMC)

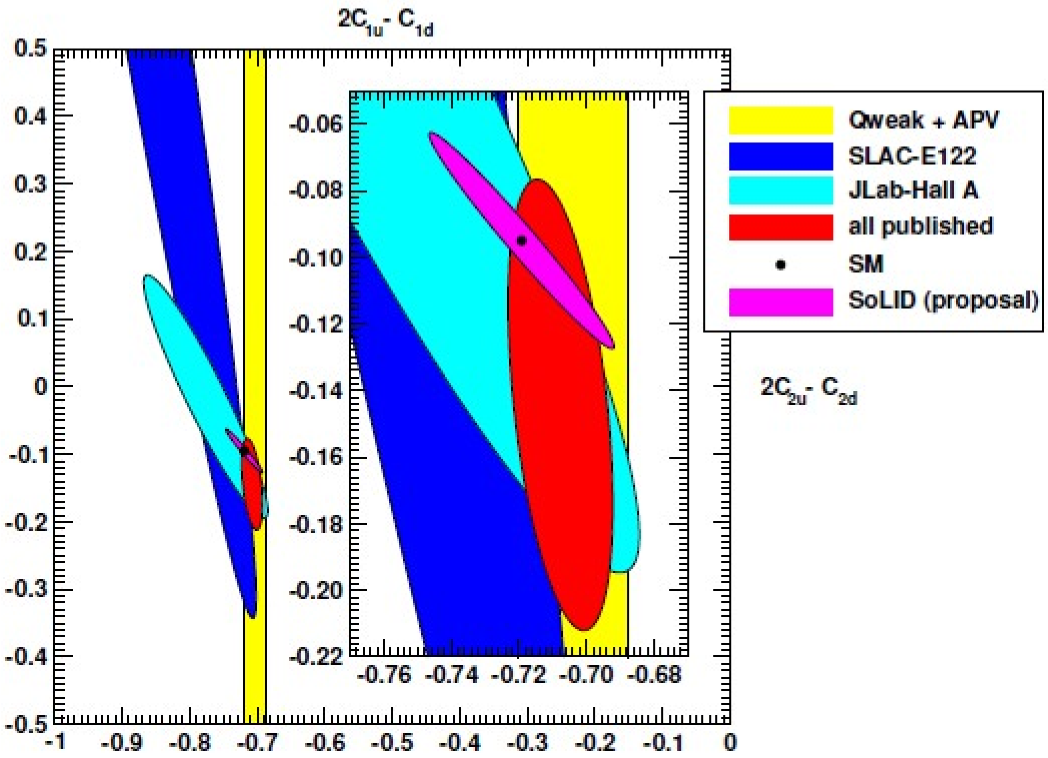
# SoLID-PVDIS Physics Motivation

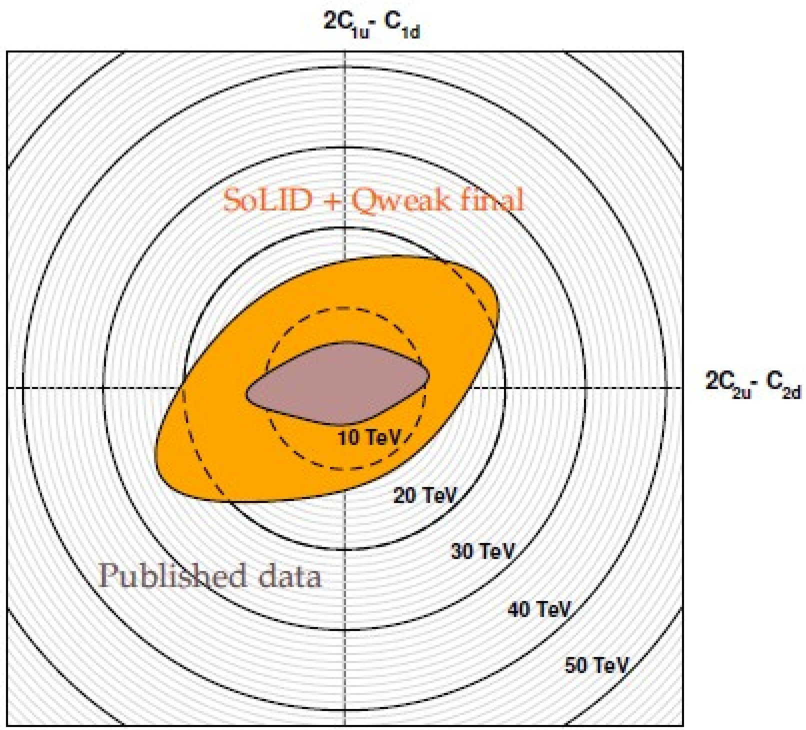
- A precision test of the Standard Model
- Search for Charge Symmetry Violation (CSV)
- Test of QCD higher twist corrections (quark quark correlations)
- Measurement of d/u quark ratio for proton

Attractive PVDIS feature

- Large PV asymmetries with manageable backgrounds
- Ability to reach higher precision beam polarimetry with 11 GeV electron beam energies

# Projected Coupling Constraints from PVDIS



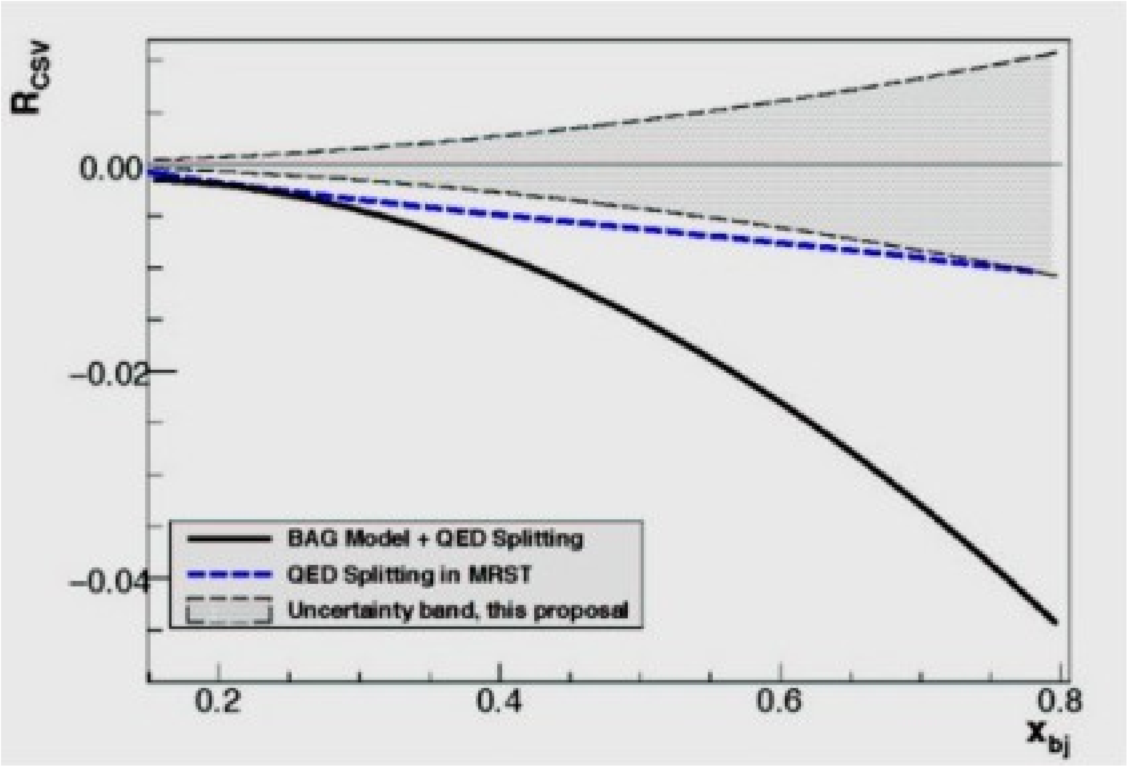

Constraint on quark coupling constants and updated limits on new physics beyond SM using SoLID-PVDIS projections

# Charge Symmetry Violations

Sensitivity to CSV

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

Where $\delta u \equiv u^p - d^n; \delta d \equiv d^p - u^n;$

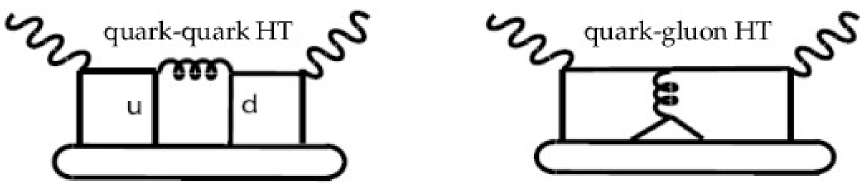


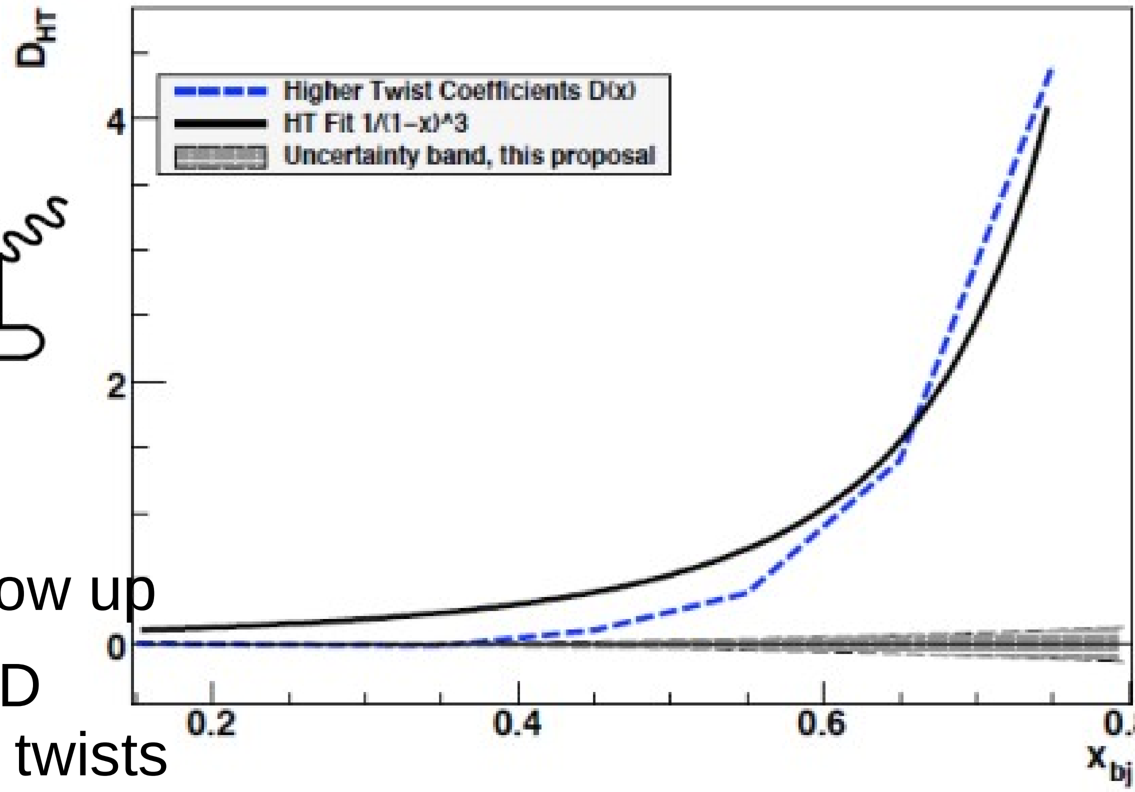

Direct observation of parton level CSV

- Charge symmetry → $u^p = d^n$; $d^p = u^n$
- Fractional change in APV due to CSV from different models shown
- The uncertainty band using PVDIS figure-of-merit is  plotted

# Higher Twists effects in PVDIS

- In QCD, additional $Q^2$ dependence gives information on quark-quark and quark-gluon correlations
  - Higher Twist (HT) terms

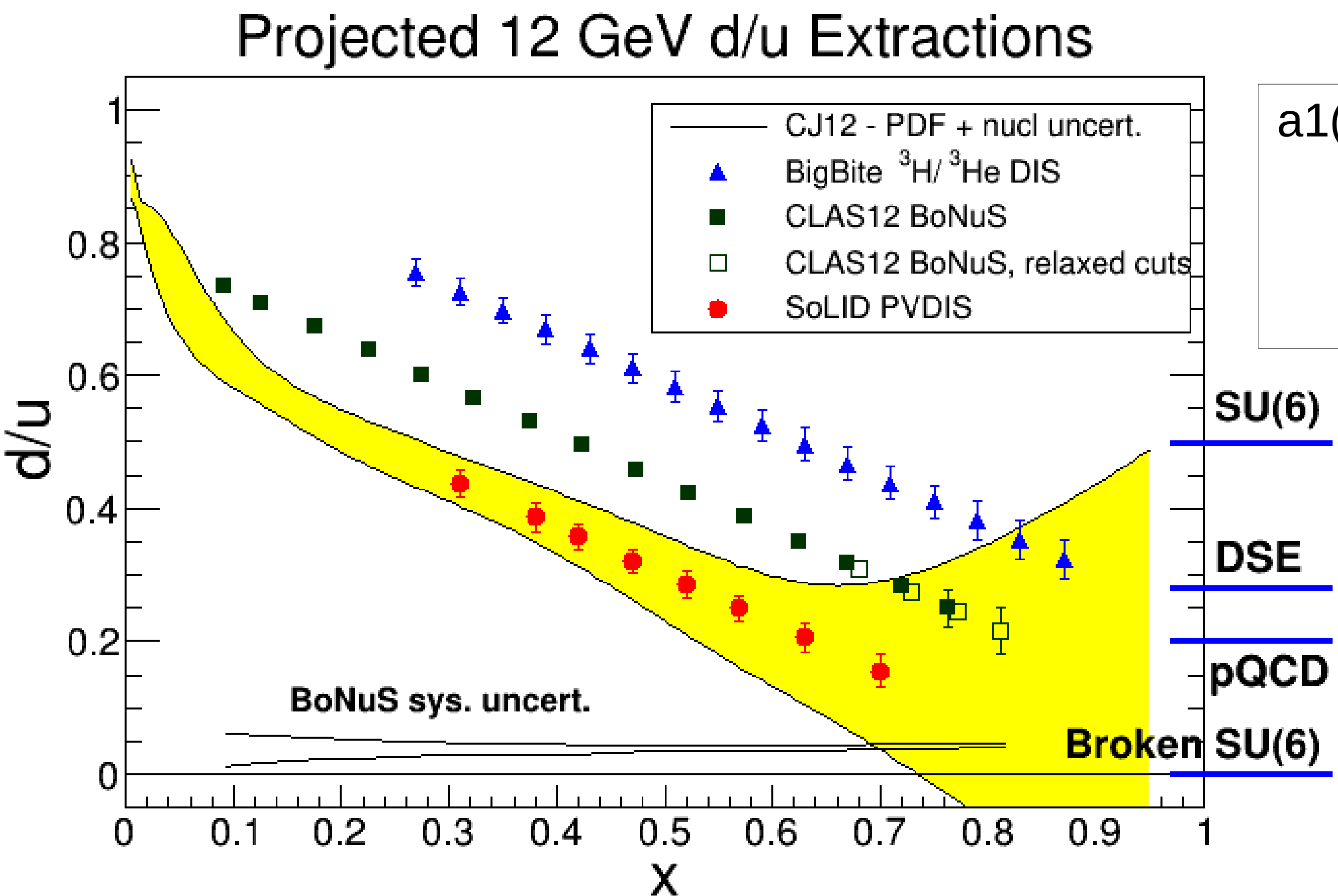



- With PVDIS asymmetry measurements, only $Q^2$ dependence of q-q HT can show up
- Large kinematic reach in SoLID allows for evaluation of higher twists
- PVDIS signature is the variation of $Y_1 a_1$ term (of the APV) with x and $Q^2$

# Quark Flavor Dependent Effects on Proton

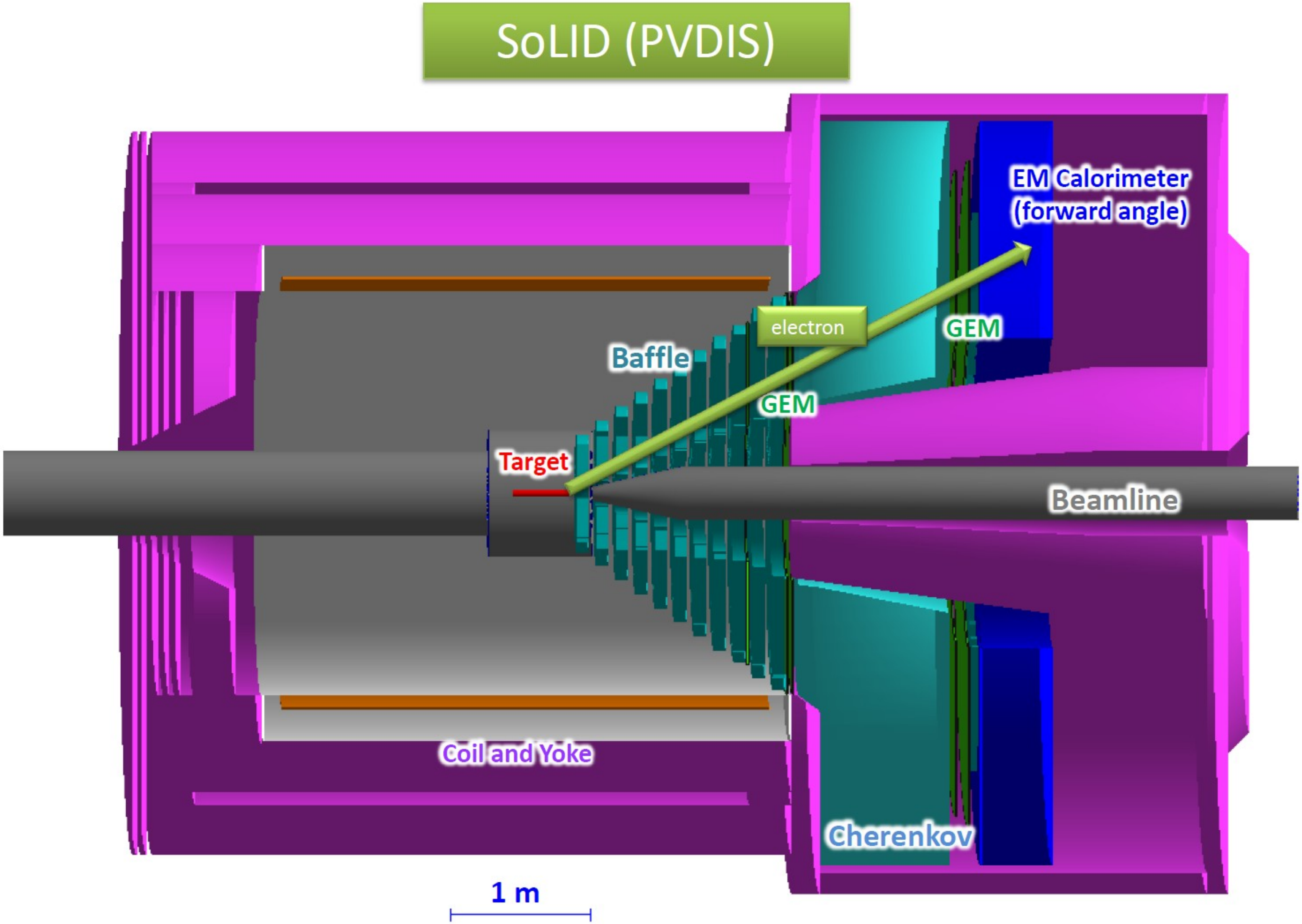
- Measurement of d(x)/u(x) ratio for the proton at high x
- A clean measurement free from any nuclear corrections
- Uncertainties of set of PVDIS measurements are shown in the plot (red points)
    - Provides a high precision measurements in range of x



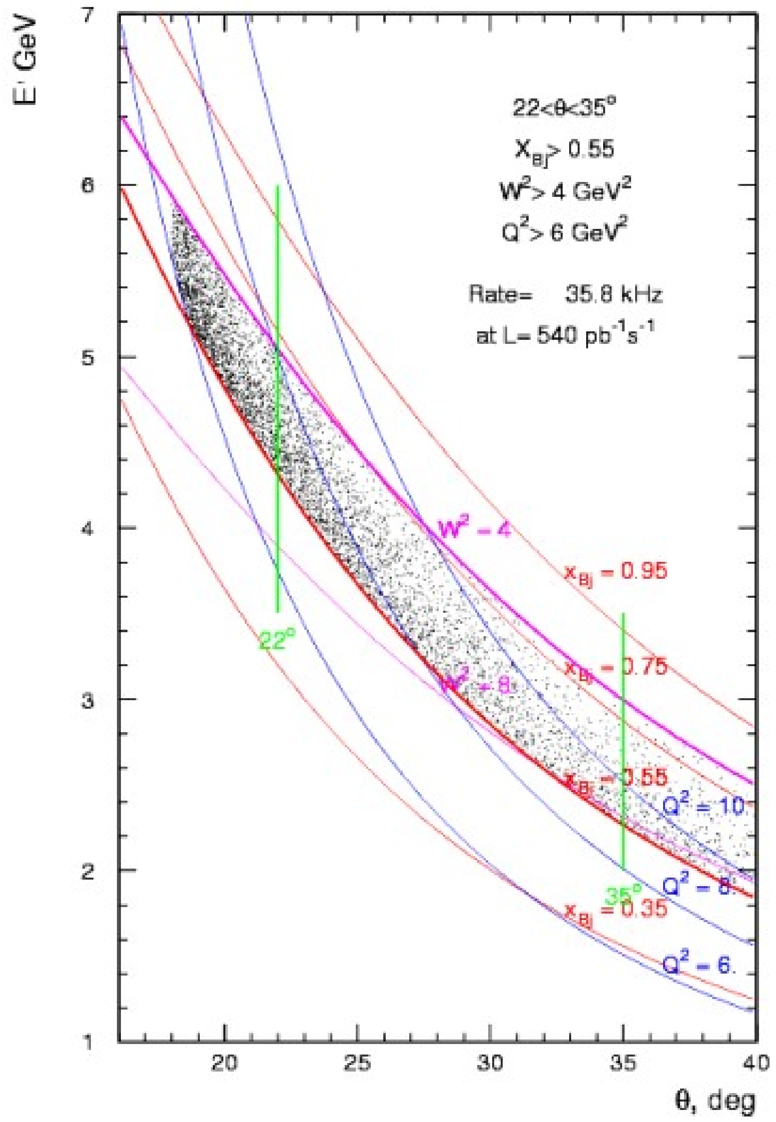

a1(x) term of the PVDIS asymmetry

$$a_1^p(x) \sim \frac{u(x) + 0.912d(x)}{u(x) + 0.25d(x)}$$

# Solenoidal Large Intensity Device (SoLID) Apparatus

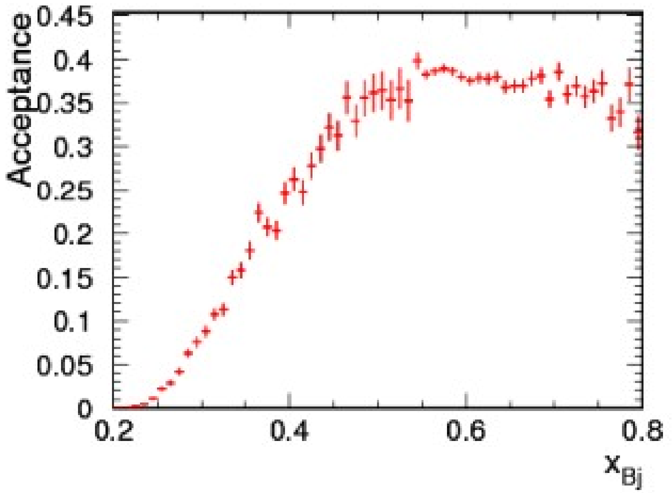


# Solenoidal Large Intensity Device (SoLID) Acceptance




<u>SoLID Specs. and Figure-Of-Merit</u>

- High Luminosity ($10^{39}$ $cm^2/s$)
- Beam current 50 uA and polarization 85%
- Large scattering angles for high x and y access




- With moderate running times,
  - X-range of 0.25 to 0.75
  - $W^2$ > 4 $GeV^2$
  - $Q^2$ range a factor of 2 for each x

# SOLID-PVDIS Figure-Of-Merit

## Sub. 1% precision over broad range of kinematic range: *A Standard Model test and a detailed study of hadronic structure contributions*

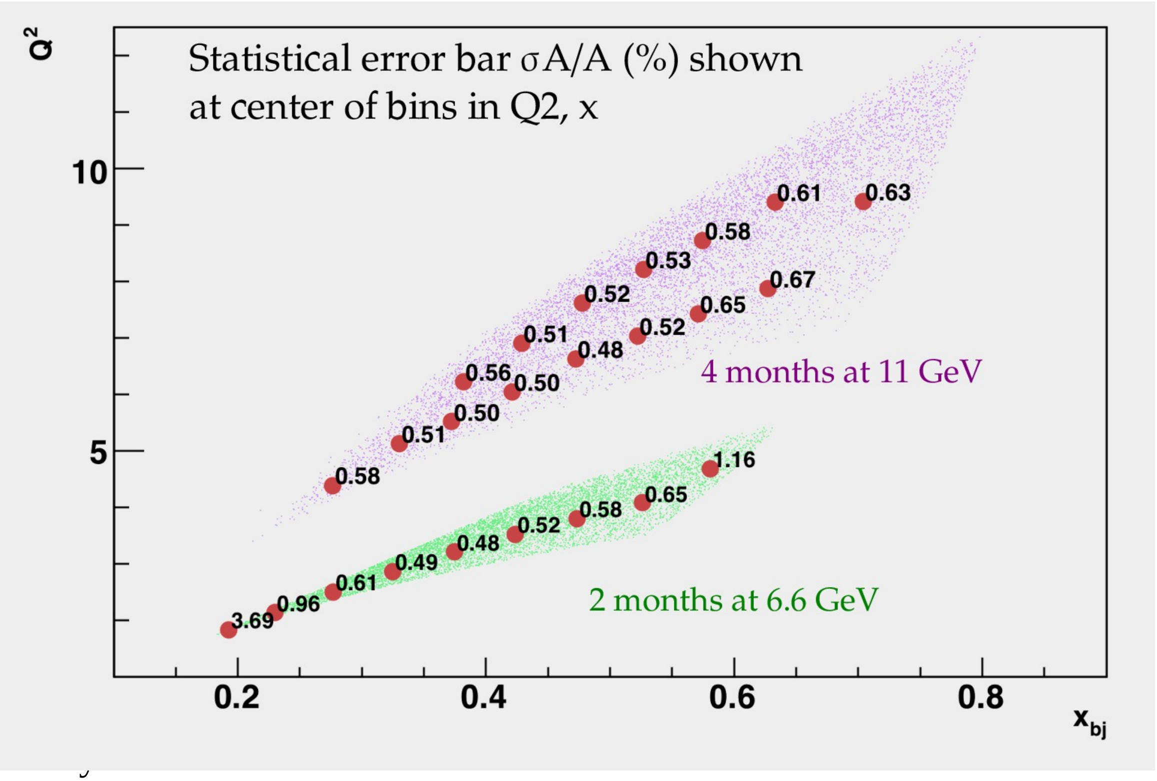
If no CSV, HT, quark sea, or nuclear effects, All (Q2, x) bins should give the asymmetry within statistics and kinematic factors

Fit to data :

$$A_{PV}^{D} = A_{PV}^{EW}(1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2)$$

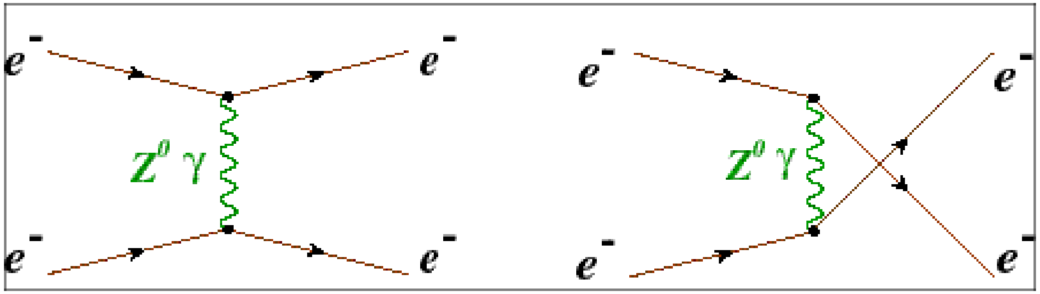
Kinematics dependence of Physics

| | x | y | $Q^2$ |
|---|---|---|---|
| New Physics | | YES | |
| CSV | YES | | |
| Higher Twist | YES | | YES |



# PV in MØller Scattering

A Search for New Physics at the TeV Scale




- Proposed MOLLER experiment will be the best contact interaction search for leptons at low OR high energy
  - Best current limit on contact interaction scales available from LEP2
    - LEP2 only sensitive to parity conserving quantities ($g^2_{RL}$ and $g^2_{RR}+g^2_{LL}$)

Where $g_{ij}=g^*_{ij}$ are contact interaction coupling constants for chirality projections of the electron spinor

  - Model independent mass scale for parity violating interactions :

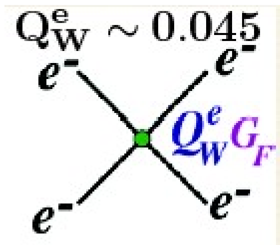
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \qquad \frac{\Lambda}{(g_{RR}^2 - g_{LL}^2)} = 7.5 \text{ TeV}$$

The MOLLER measurement will extend the current sensitivity of 4-electron contact interactions,both qualitatively and quantitatively

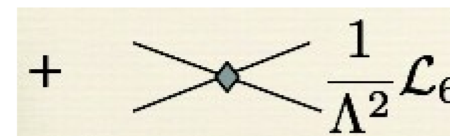
# PV in MØller Scattering

A Search for New Physics at the TeV Scale

- Measure weak charge of electron precisely




$$\frac{\delta Q_W^e}{Q_W^e} = 2.4\% \rightarrow A_{new} \sim 0.001 \cdot G_F$$



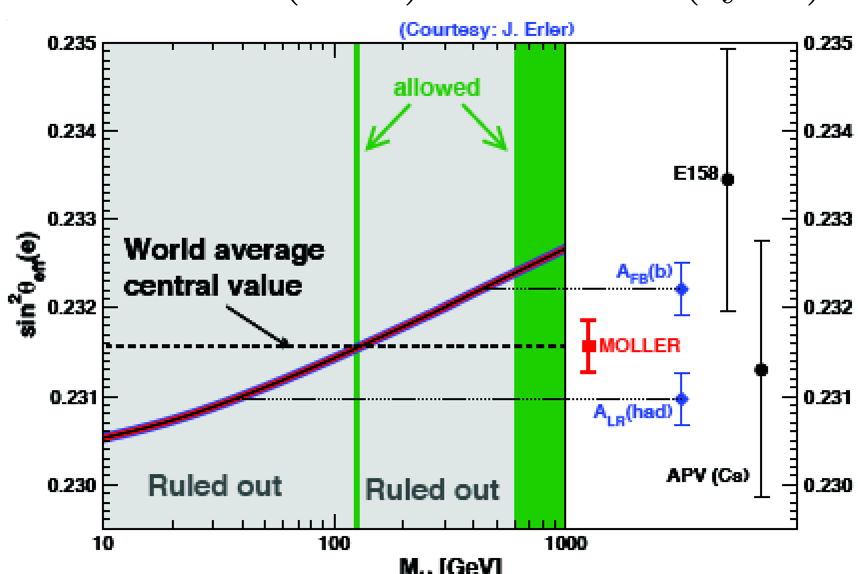

$$\frac{\Lambda}{\sqrt{(g_{RR}^2 - g_{LL}^2)}} = 7.5\ \mathrm{TeV}$$

  - Unprecedented sensitivity

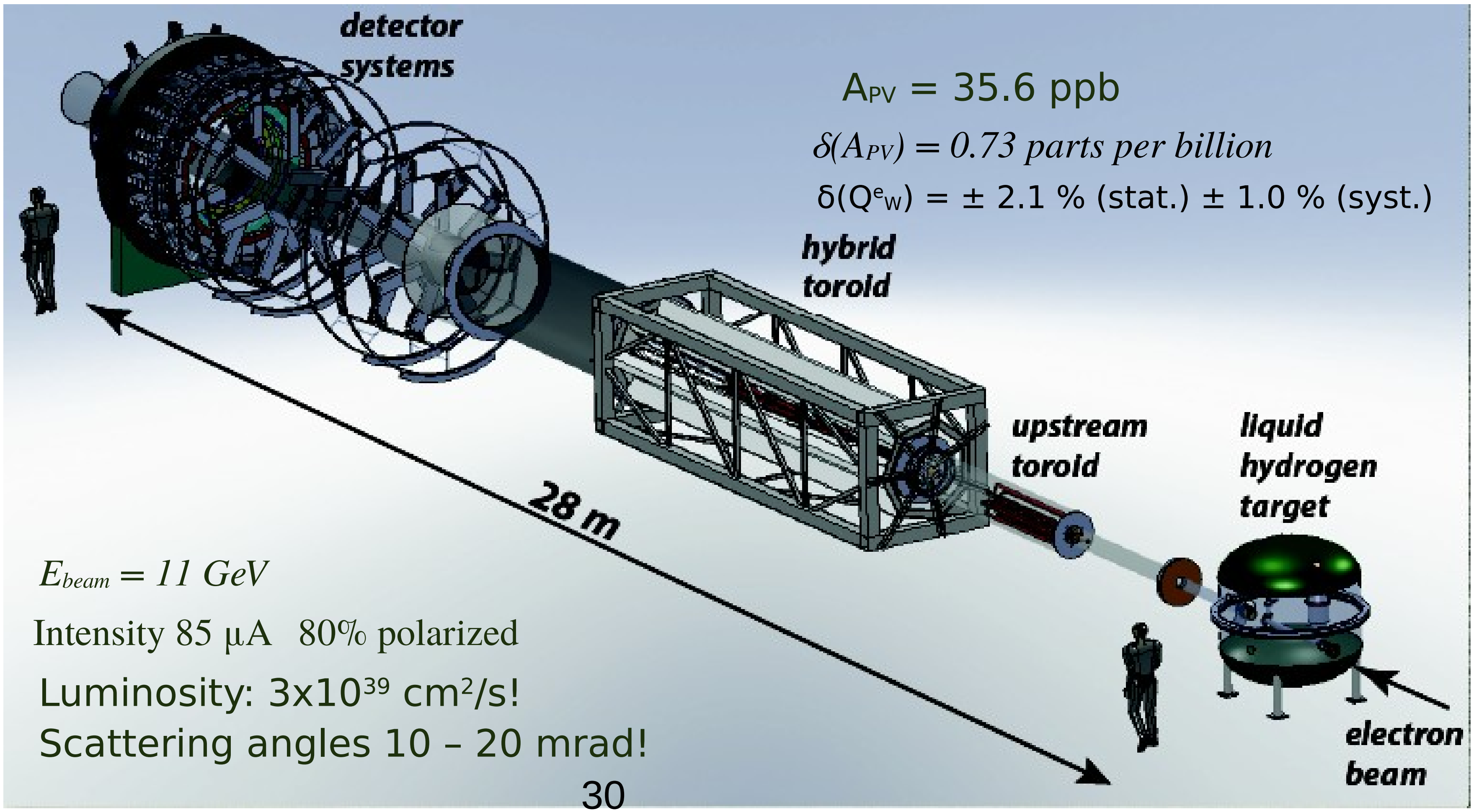
- Provide best projected uncertainty weak mixing angle at any energy scale

$$\delta \sin^2\theta_W = \pm 0.00024\ (\mathrm{stat.}) \pm 0.00013\ (\mathrm{syst.}) \rightarrow \sim 0.1\%$$

use standard model electroweak radiative corrections to evolve best measurements to Q ~ MZ



# MOLLER Apparatus




$A_{PV}$ = 35.6 ppb

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

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

$E_{beam} = 11$ *GeV*

Intensity 85 μA 80% polarized

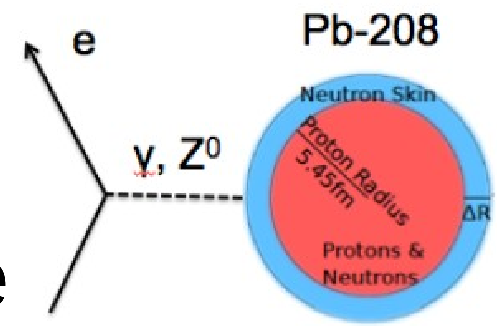
Luminosity: $3\text{x}10^{39}$ $cm^2/s$!

Scattering angles 10 – 20 mrad!

# MOLLER Context Summary

- Best contact interaction reach for leptons at any energy
  - Similar to LHC reach with semi-leptonic amplitudes
  - To do better for a 4-lepton contact interaction would require:
    - Giga-Z factory, linear collider, neutrino factory or muon collider
- If LHC sees any anomaly in runs 2 and 3 (~ 2022)
  - The unique discovery capability in MOLLER will be very important
- MOLLER also provides discovery scenarios beyond LHC signatures
  - Hidden weak scales
  - Lepton number violating interactions
  - Light dark matter mediators

# PREX/CREX : Neutral Current as a Probe of the Neutron




- Weak neutral current : A clean probe couples mainly to neutrons

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

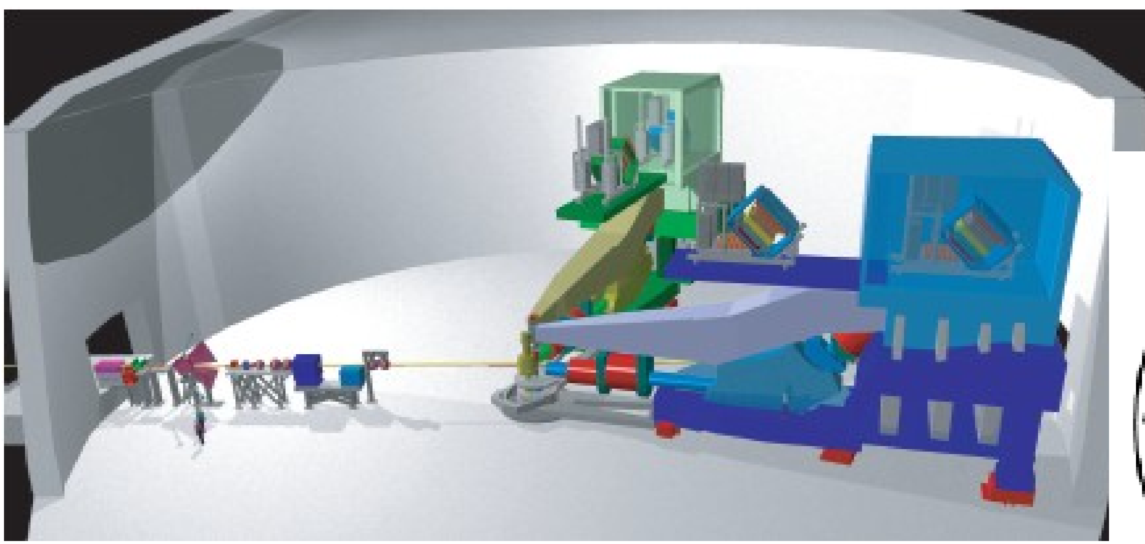
$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.076 \qquad Q^n_{weak} \sim -1 \qquad A_{PV} \rightarrow 10^{-6}$$

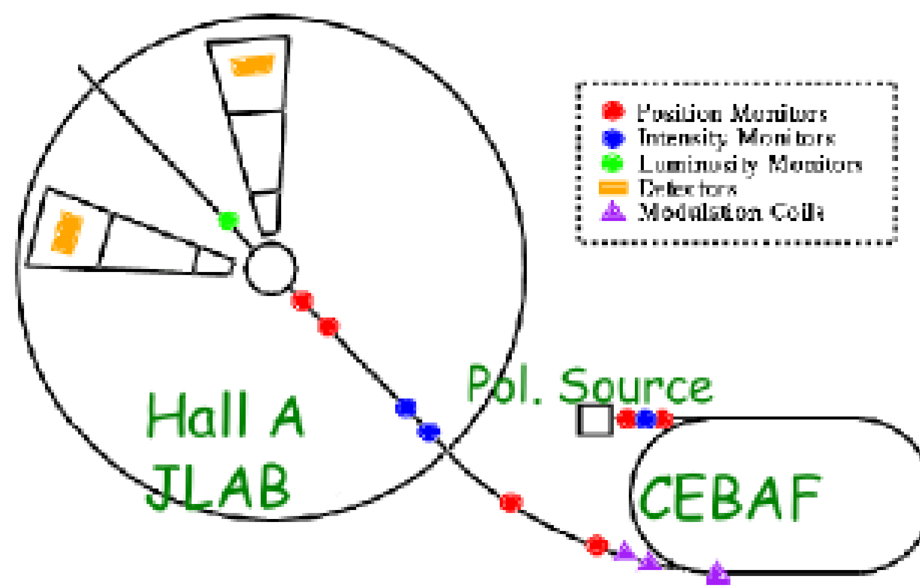
- It provides theoretically clean method to measure neutron radius and skin thickness

$$A_{PV} \rightarrow F_W(Q^2) \rightarrow R_n \rightarrow (R_n - R_p)$$

# Experimental Setup

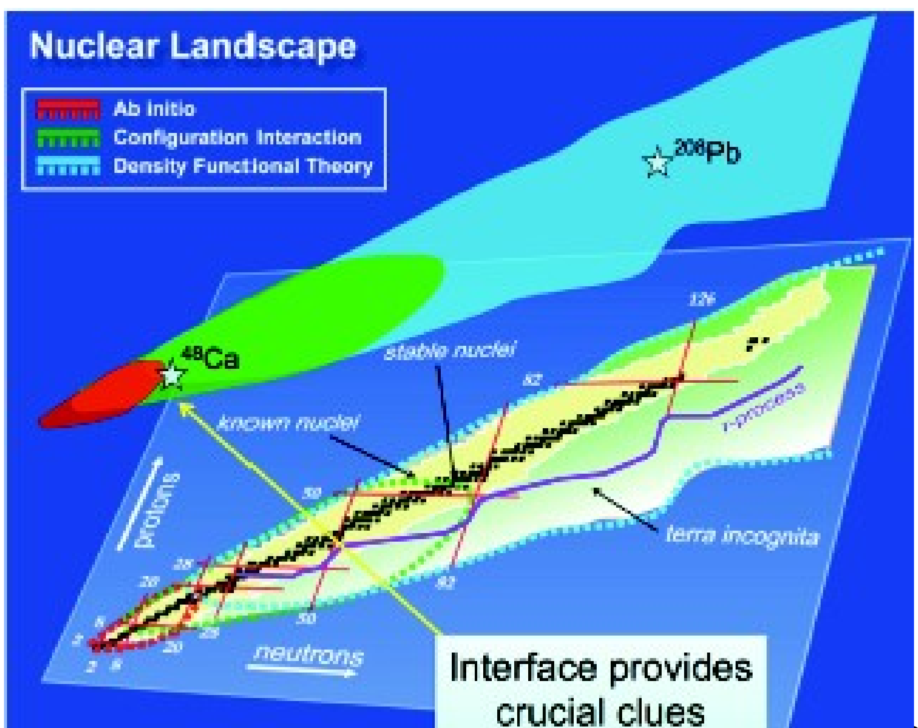
- Two High Momentum Spectrometers (HRS) to run simultaneously
  - Will require a Septum magnet to reach our acceptance
- PREX acceptance at about 5$^{o}$ Using E = 1.1 GeV beam
- CREX acceptance at about 4$^{o}$ Using E = 2.2 GeV beam
- Both $^{208}$Pb and $^{48}$Ca provide large inelastic separation with HRS and have very long life time for a neutron excess nuclei

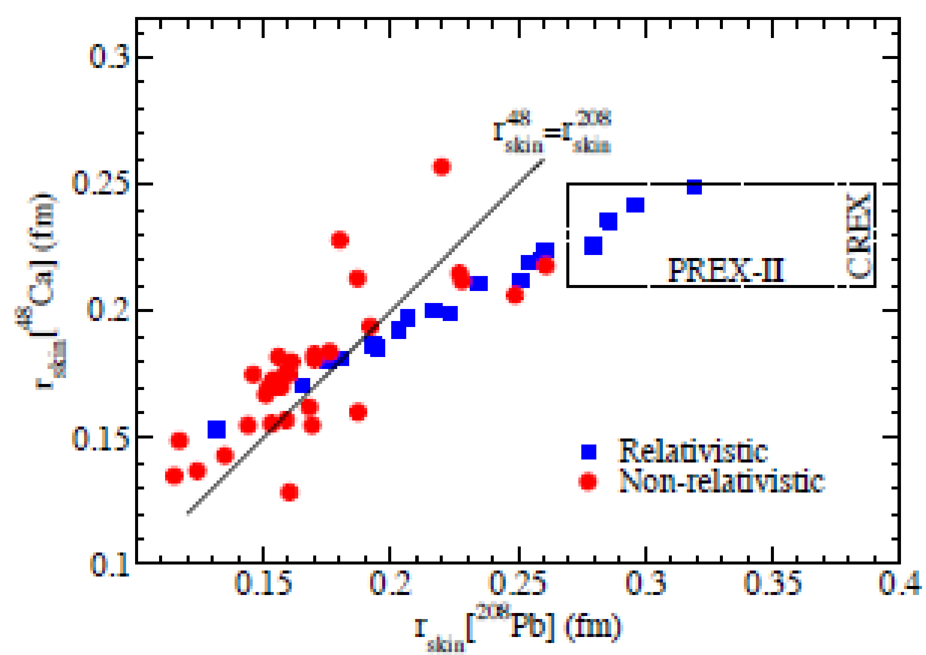




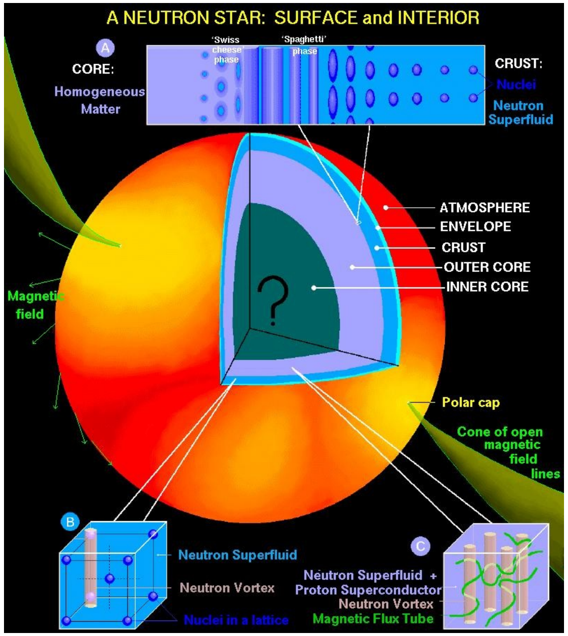
# Why Two different Nuclei?

- Ab initio calculations only reach as far as medium nuclei such as $^{48}Ca$
  - Experimental data from $^{208}Pb$ and $^{48}Ca$ will provide a bridge between medium nuclei ab initio calculations and heavy nuclei Density Functional Theory (DFT) calculations.
- Correlations predicted between neutron skin of $^{208}Pb$ and $^{48}Ca$ need experimental validations



# PREX Implications : Neutron Stars



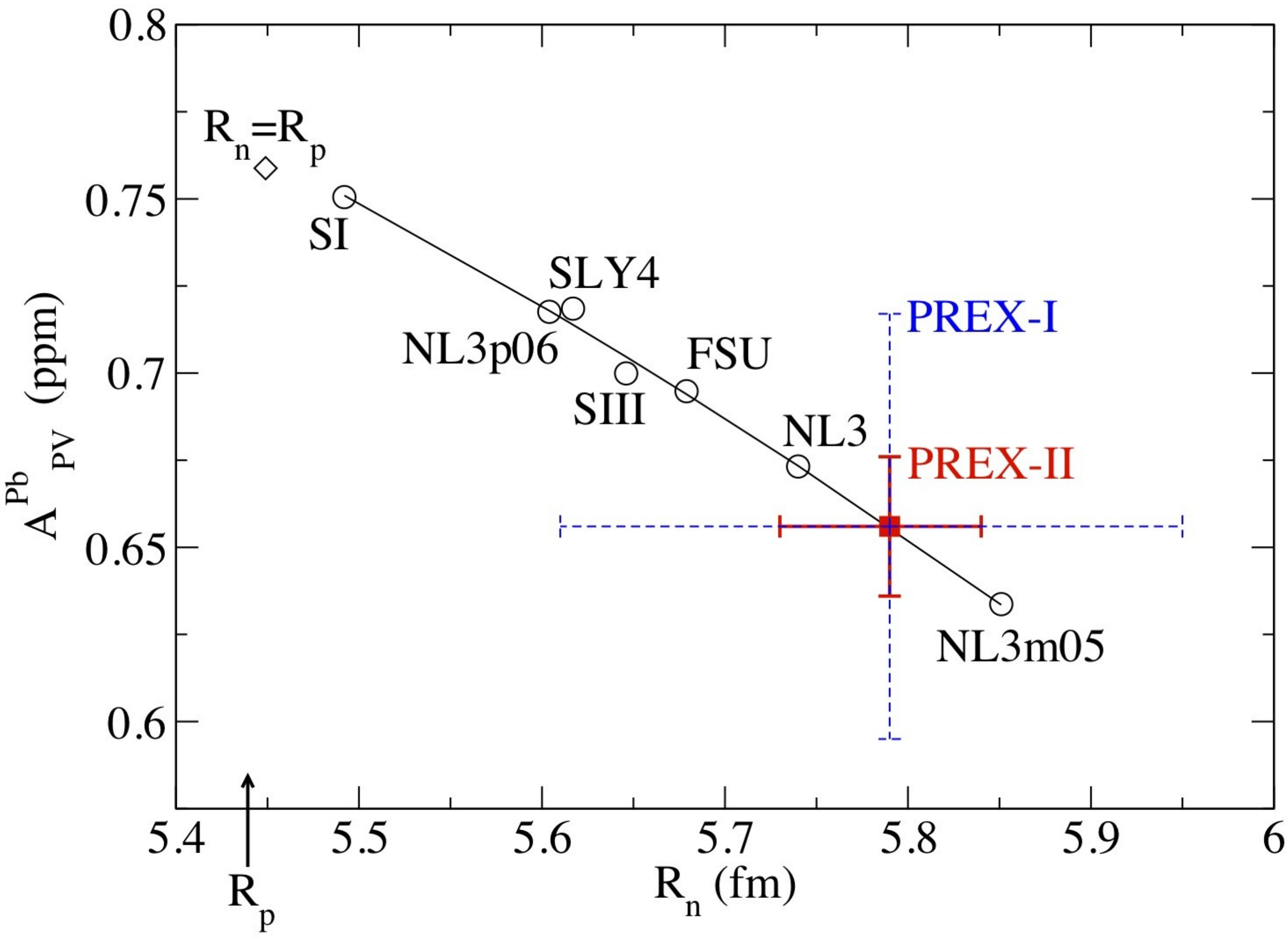

Courtesy of C.J. Horowitz and J. Piekarewicz

- $R_N$ calibrates equation of state (pressure vs density) of Neutron rich matter
- Combine PREX $R_N$ with observed neutron star radii
  - Phase transition to “Exotic” Core?
    - Strange star? Quark star?
- Some neutron stars seem too cold
  - Explained by cooling by neutrino emission (URCA process)?
  - Only if $(R_N - R_p) \rightarrow 0.2$ fm : URCA is probable

Crab Pulsar

# PREX : Earlier Results

Neutron Skin = $R_N$ - $R_P$ = 0.33 + 0.16 - 0.18 fm




Spokespersons

K. Kumar
R. Michaels
K. Paschke
P. A. Souder
G. Urciuoli

# PREX/CREX : Next Run

- PREX-II is on its way to make many improvements over several PREX-I radiation damage issues
  - Damaging neutron (0.1 < E < 10 MeV) dose is reduced by 78% compared to PREX-I
  - High energy (E>10 MeV) photon dose is reduced by 80%
  - Collimator design is almost ready
  - Neutron radiation shielding optimization is underway
  - Final design will further improve dose reduction
- Neutron density measurements for $^{208}$Pb and $^{48}$Ca will provide necessary support for better nuclear structure theory models
  - For nuclei to neutron stars with implications on nuclear structure studies to astrophysics

# PVES as a Probe of EMC effect

- PVDIS offers a picture into partonic distributions by probing new flavor combinations
- Expanding the $a_1$ term about the isoscalar limit
- $$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$ Where $u_A$ = u in p and d in n
- PVDIS asymmetry is sensitive to differences in the quark flavors
  - For isoscalar targets the asymmetry becomes a test for charge symmetry violation

For $Q^2 >> 1\ \mathrm{GeV}^2$ and $W^2 > 4\ \mathrm{GeV}^2$

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

$$\text{Where, } Y_1 \simeq 1; Y_3 \simeq \frac{1-(1-y)^2}{1+(1-y)^2}$$

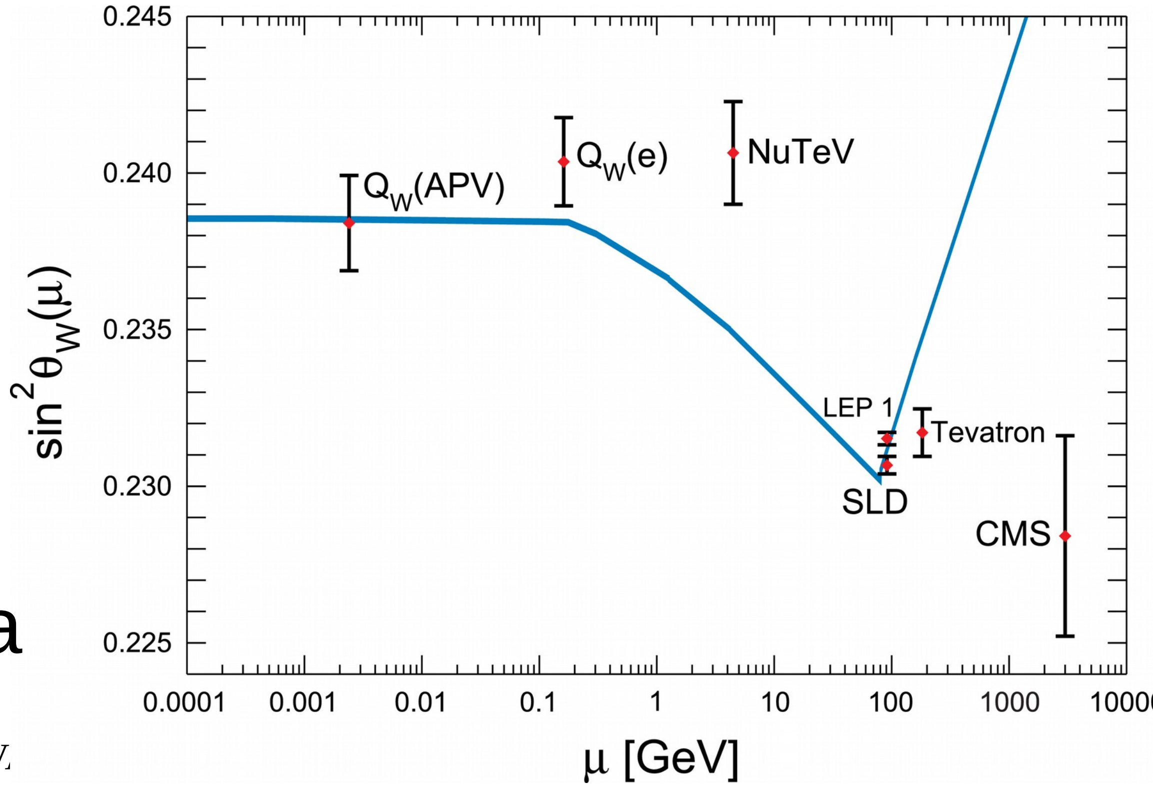
# Isovector dependence of EMC effect

NuTeV results from Fermilab

- Neutrino scattering is sensitive to different flavor combinations
- Asymmetry nuclei (iron target used in NuTeV) need corrections
- CSV or isovector EMC effects could play significant role and not well constrained by data

Pachos-Wolfenstein relation:

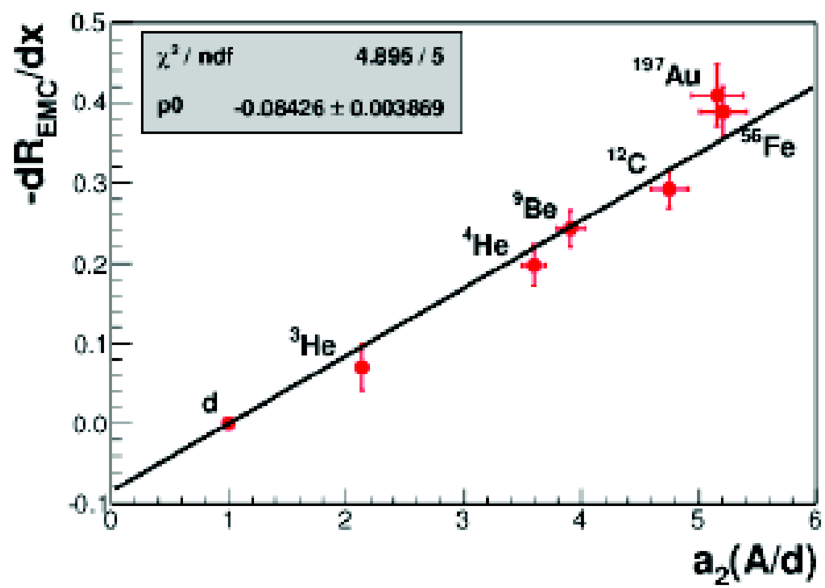
$$R_{\rm PW} \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)} = \lim_{\to \rm i.s.} \frac{1}{2} - \sin^2\theta_W$$

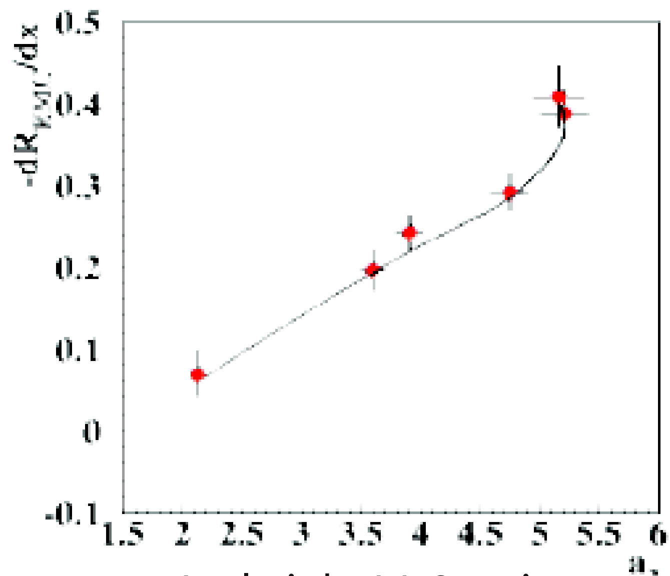


# Isovector dependence of EMC effect

<u>Short range correlations and EMC effect</u>

- SRC show strong preference  to n-p pairs over p-p/n-n
  - SRCs generated by interactions in short-distance (high density)
- EMC effect correlates with SRC
  - EMC effect driven by high-density nucleon configurations (pairs, clusters)
- Preliminary models make predictions for asymmetry nuclei
  - (Z – N) boost by isovector enhancement?



Analysis by M. Sargsian

# PVDIS Constraints on EMC Effect

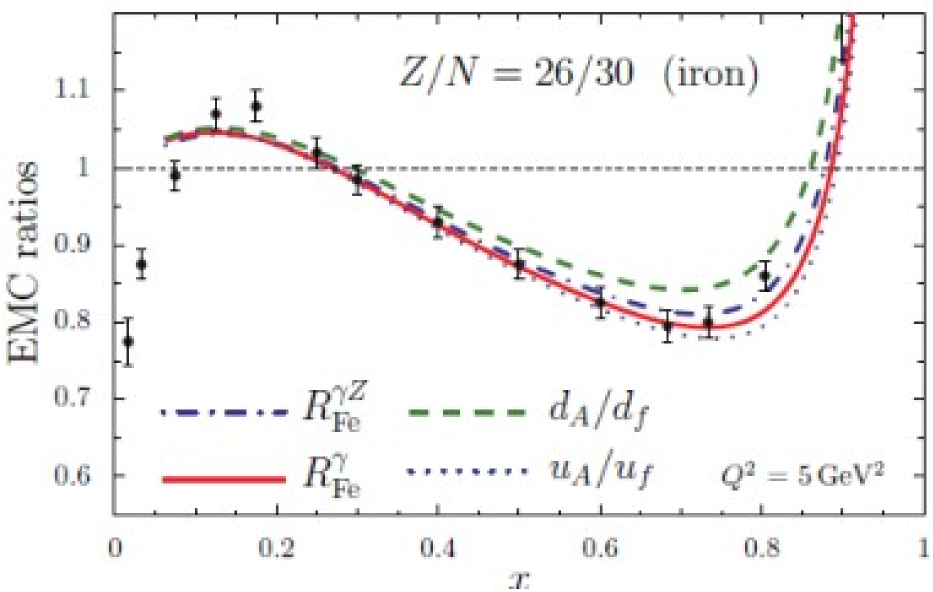
- PVDIS on asymmetric target ($^{48}$Ca or $^{9}$Be) will test isovector dependence,
  - Larger A → larger EMC and larger (Z – N) gives an boost to isovector enhancement
  - PV asymmetry is independent of overall size of EMC effect; only sensitive to difference in EMC effect for u and d quarks
- $^{48}$Ca DIS Rates and backgrounds are comparable for deuterium DIS
- Therefore isovector observables on an asymmetric target is doable with SoLID-PVDIS
- 60 days production will offer powerful constraints, help resolve the NuTeV anomaly, and test leading models to several sigma

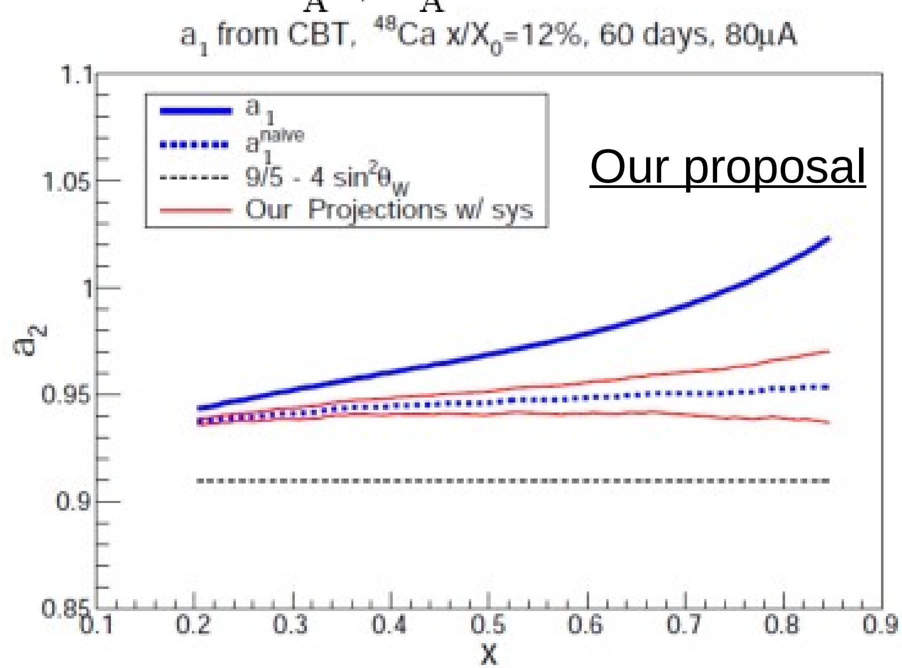
# Flavor Dependent Model EMC Predictions

PVDIS with neutron rich nuclei $^{48}$Ca can constrain possible flavor-dependent nuclear medium modification effects on quarks

- PVDIS asymmetry is a direct measurement of differences in the quark flavors

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




Cloet et al. PRL102 252301 (2009), Cloet et al. PRL109 182301 (2012)

# Conclusions

- Jlab is a great facility to do PVES
  - Polarized Continuous electron beam
- PVES provides unique information for nuclear physics
  - Nucleons : EMC effect, strangeness, weak form factors
  - Nuclei : PREX/CREX
- PVES is a precision frontier of testing the SM and physics beyond SM
  - Qweak, SoLID-PVDIS and MOLLER
  - Complementary to LHC

# Random Beam Fluctuations and Beamline Instrumentation

Use Qweak experience (@ 1 kHz data rate) $\longrightarrow$

Assess MOLLER specifications (@ 2 kHz data rate) for beam fluctuations/monitoring

Random beam fluctuations ("jitter") @2 kHz:

If 12 GeV machine is as "quiet" as 6 GeV machine, these will be easily satisfied!

| Beam property | MOLLER spec. | Qweak observed |
|---|---|---|
| Intensity | < 1000 ppm | 500 ppm |
| Energy | < 108 ppm | 6.5 ppm |
| Position | < 47 μm | 48 μm |
| Angle | < 4.7 μrad | 1.4 μrad |

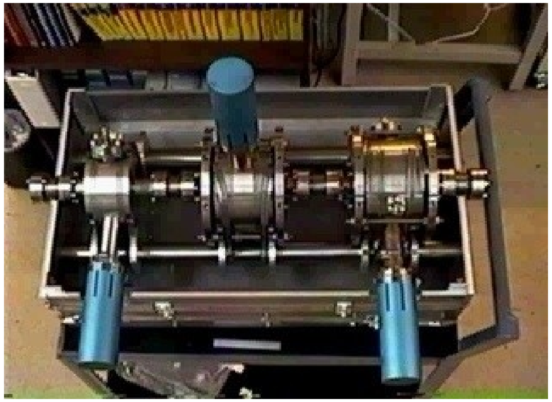
Beamline monitor precision @2 kHz:

| Monitor type | MOLLER spec. | Qweak observed |
|---|---|---|
| Beam charge | 10 ppm | 65 ppm |
| Beam position | 3 μm | 6 μm |

- Position nearly satisfied
- Charge monitoring will require further developments

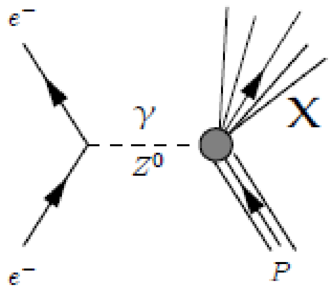
➔ Start with BCM digital receiver studies

**NEW: actually BPM spec is probably already achieved**



# PV Deep Inelastic Scattering

*Off the simplest isoscalar nucleus (deuterium) at high Bjorken x*




$$A_{PV}^{DIS} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}[2g_A^e Y_1(y)\frac{F_1^{\gamma Z}}{F_1^Z} + 2g_V^e Y_3(y)\frac{F_3^{\gamma Z}}{F_1^Z}] \qquad \text{Where, } Y_1 \simeq 1; Y_3 \simeq \frac{1-(1-y)^2}{1+(1-y)^2}$$

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

At high x, deuterium PV asymmetry becomes independent of PDFs, x and W, with well defined SM predictions for given $Q^2$ and y = 1 – E'/E

$$A_{PV}^{D} = \frac{\sigma^L - \sigma^R}{\sigma^L + \sigma^R} \qquad \text{For } Q^2 >> 1 \text{ GeV}^2 \text{ and } W^2 > 4 \text{ GeV}^2$$

$$= -\left(\frac{3G_F Q^2}{2\pi\alpha\sqrt{2}}\right)\frac{(2C_{1u} - C_{1d})(1+R_s) + Y(2C_{2u} - C_{2d})R_\nu)}{5 + R_s}$$

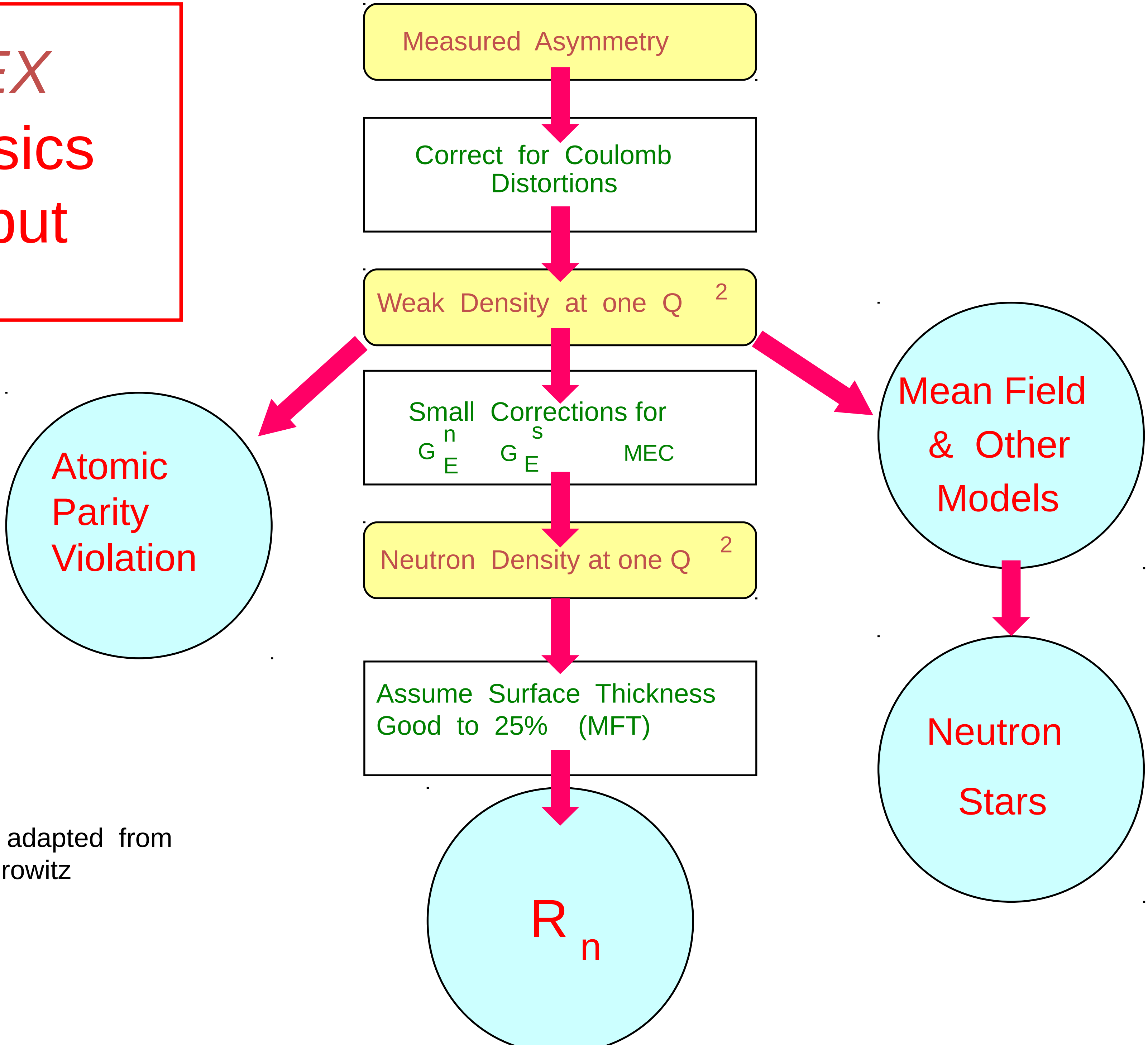
$$Y = \frac{1-(1-y)^2}{1+(1-y^2) - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \frac{\sigma^L}{\sigma^R} \simeq 0.2$$

Interplay with QCD,

- Flavor dependent quark distributions (u,d, and s)
- Charge symmetry violations (CSV)
- Higher twist effects (HT)
- Nuclear medium effects (EMC)

# *PREX* Physics Output




Slide adapted from C. Horowitz

# Anticipated Errors

PREX-II at E = 1.1 GeV ; $A_{PV}$ = 0.6 ppm

| Systematic Error | Contribution |
|---|---|
| Charge normalization | 0.1% |
| Beam asymmetries | 1.1% |
| Detector non-linearity | 1.0% |
| Transverse | 0.2% |
| Polarization | 1.1% |
| Inelastic contribution | < 0.1% |
| Effective Q2 | 0.4% |
| **Total** | **2%** |

CREX at E = 2.2 GeV; $A_{PV}$ = 2 ppm

| Systematic Error | Contribution |
|---|---|
| Charge normalization | 0.1% |
| Beam asymmetries | 0.3% |
| Detector non-linearity | 0.3% |
| Transverse | 0.1% |
| Polarization | 0.8% |
| Inelastic contribution | 0.2% |
| Effective Q2 | 0.8% |
| **Total** | **1.2%** |

# SoLID-PVDIS Error Budget

Error budget for PVDIS asymmetry at x=0.4

| Source | Error (%) |
|---|---|
| Statistics | 0.3 |
| Polarimetry | 0.4 |
| $Q^2$ | 0.2 |
| Radiative corrections | 0.3 |
| Total | 0.6 |