Symmetry Tests in Nuclear Physics

Krishna Kumar

University of Massachusetts

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Opportunities for Symmetry Tests at 12 GeV

- *Strong Interaction*
  - Chiral symmetry breaking
  - Charge symmetry violation
  - Spin-Flavor symmetry breaking
- *Electroweak Interaction*
  - TeV scale physics

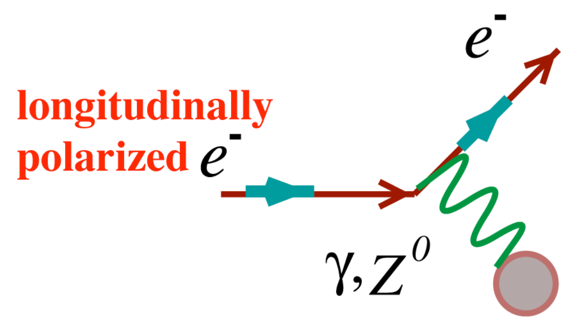
Outline

- *Parity-Violating Electron Scattering*
  - Brief Overview
  - Weak Neutral Current Interactions at $Q^2 << M_Z^2$
- *Parity-Violating Deep Inelastic Scattering*
  - New Physics at 10 TeV in Semileptonic Sector
  - Charge Symmetry Violation
  - d/u at High x
  - Higher Twist Effects
- *Parity-Violating Møller Scattering*
  - Ultimate Precision at $Q^2 << M_Z^2$: 25 TeV reach

PV Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 << M_Z^2$

Longitudinally Polarized Electron Scattering off Unpolarized Fixed Targets



$$\sigma \;\; \alpha \; | \, A_\gamma + A_{\text{weak}} |^2$$

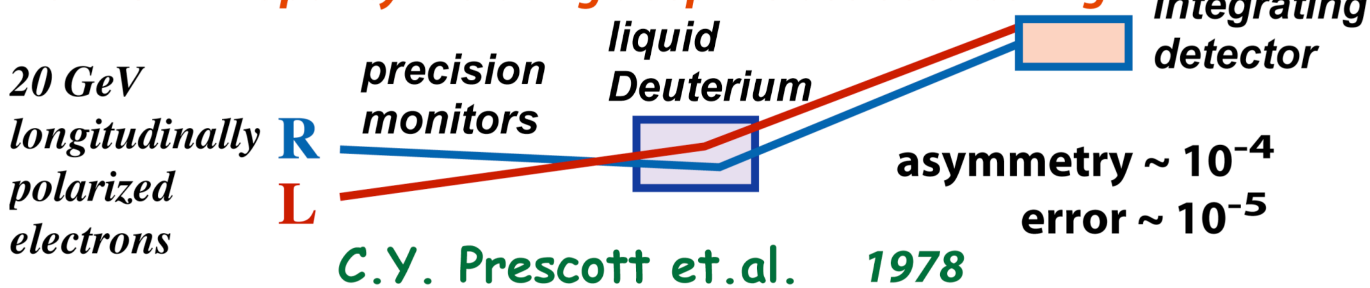
$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{\text{weak}}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

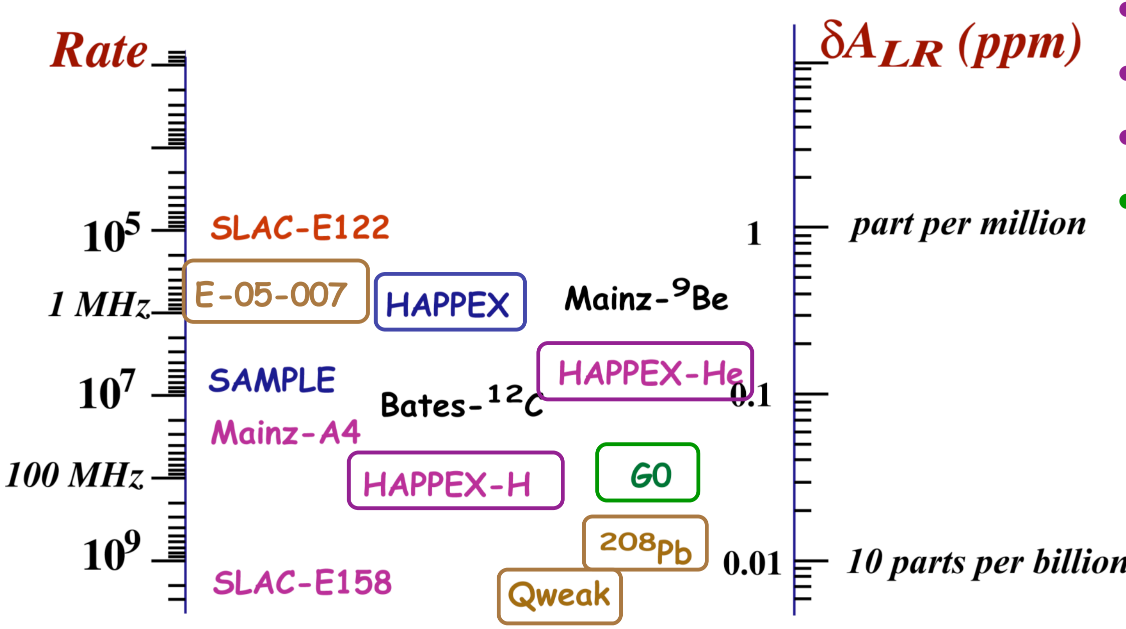
- *The couplings g depend on electroweak physics as well as on the weak vector and axial-vector hadronic current*
- *With specific choice of kinematics and targets, one can probe new physics at high energy scales*
- *With other choices, one can probe novel aspects of hadron structure*

A_{PV} Measurements

$$A_{PV} \sim 10^{-5} \cdot Q^2 \text{ to } 10^{-4} \cdot Q^2 \Rightarrow$$ **0.1 to 100 ppm**

SLAC E122: parity-violating deep inelastic scattering





- *Steady progress in technology*
- *part per billion systematic control*
- *1% normalization control*
- *JLab now takes the lead*
  - *-New results from HAPPEX*
  - *-Photocathodes*
  - *-Polarimetry*
  - *-Targets*
  - *-Diagnostics*
  - *-Counting Electronics*

The Annoying Standard Model

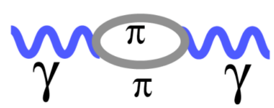
(it just wont break!)

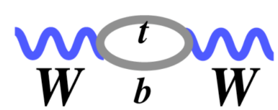
Nuclear Physics Long Range Plan:
What is the new standard model?

Low Q^2 offers unique and complementary probes of new physics

- ***Rare or Forbidden Processes*** - *Double beta decay..*
- ***Symmetry Violations*** - *neutrinos, EDMs..*
- ***Electroweak One-Loop Effects*** - *Muon g-2, beta decay..*

α_{QED} G_F





M_Z

σ_Z M_W A_f

- ***Precise predictions at level of 0.1%***
- ***Indirect access to TeV scale physics***

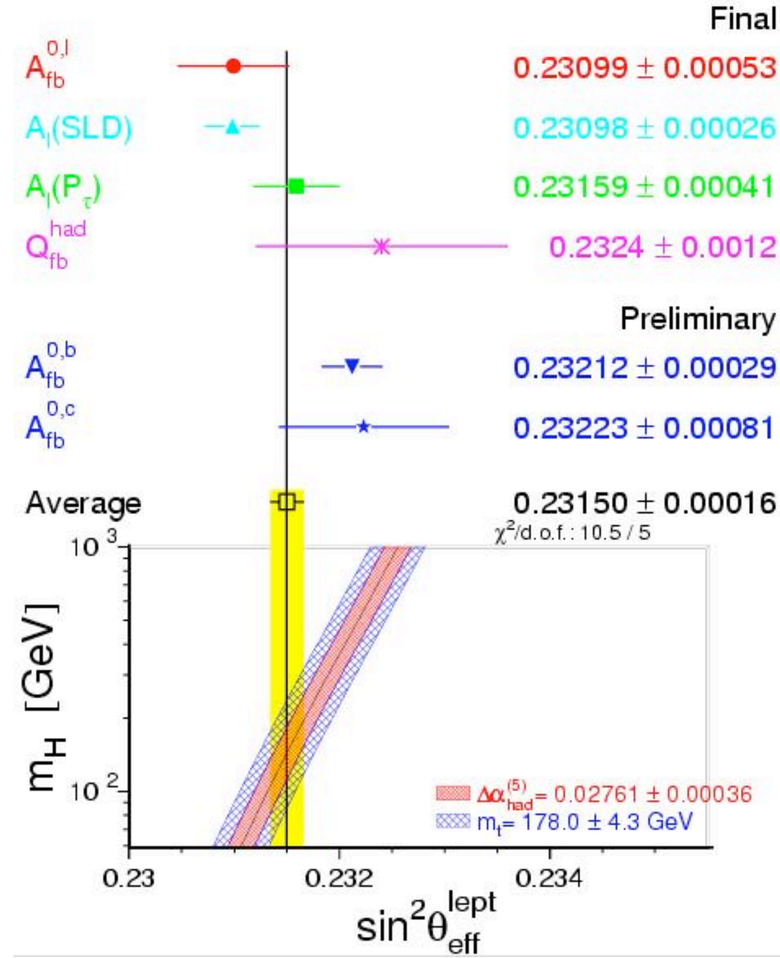
Low energy experiments are again players in the neutral current sector

World Electroweak Data

16 precision electroweak measurements:

χ^2/dof ~ 25.4/15

Probability < 5%



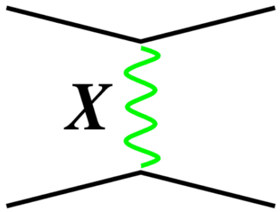
Leptonic and hadronic
Z couplings seem inconsistent

Perhaps there are bigger deviations lurking elsewhere

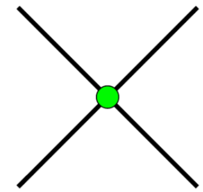
Electroweak Physics at Low Q^2

$Q^2 \ll$ scale of EW symmetry breaking

consider



$$A_X \;\alpha\; \frac{1}{Q^2 - M_X^2} \;\sim\; \frac{4\pi}{\Lambda^2}$$



Contact interaction

$Q^2 \sim M_Z^2$ **on resonance:** A_Z *imaginary* $\longrightarrow A_Z^2\left[1 + \frac{A_X^2}{A_Z^2}\right]$

no interference!

Logical to push to higher energies, away from the Z resonance

LEPII, Tevatron, LHC access scales greater than $\Lambda \sim 10$ TeV

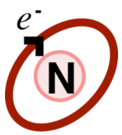
$$\frac{\delta A_Z}{A_Z} \;\alpha\; \frac{\pi/\Lambda^2}{g\,G_F} \longrightarrow \begin{array}{c} \delta(g)/g \sim 0.1 \\ \Lambda \sim 10\ \text{TeV} \end{array}$$

$$\frac{\delta(\sin\theta_W)}{\sin^2\theta_W} \lesssim 0.01$$

Complementary: **Parity Violating vs Parity Conserving**

WNC Low Q^2 Processes

Atomic Parity Violation (APV) → ***series of isotopes***

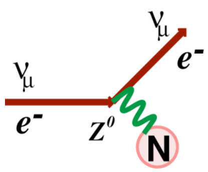


APV on Cs

•Limited by theory: Atomic structure; Neutron Halo

Semi-Leptonic → ***PV Elastic electron-proton scattering at JLab***

PV Deep Inelastic Scattering at upgraded JLab



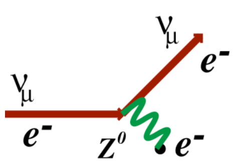
NuTeV

- *PV DIS experiment feasible within scope of HMS/SHMS upgrade*
- *Unique, complementary probes of New Physics*
- *Theoretical issues are interesting in themselves:*

Unique, outstanding opportunity for a dedicated apparatus with JLab upgrade

Leptonic → ***ν-e scattering in reactor***

Møller scattering at upgraded JLab



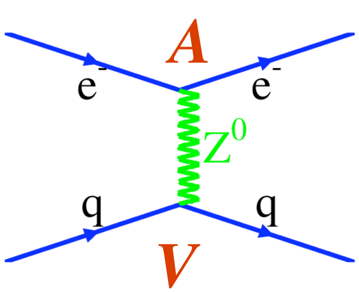
E158

•Reactor experiment cannot do better than SLAC E158

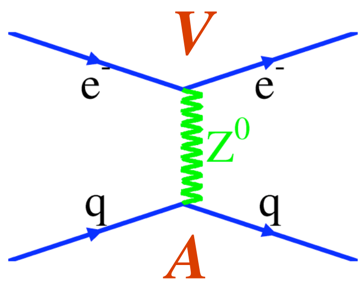
•Dedicated new apparatus at upgraded JLab can do significantly better:

Best low energy measurement until Linear Collider or ν-Factory

Electron-Quark Phenomenology



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



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

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) \approx -0.19$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) \approx 0.35$$
$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04$$
$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

C_{1u} and C_{1d} will be determined to high precision by other experiments

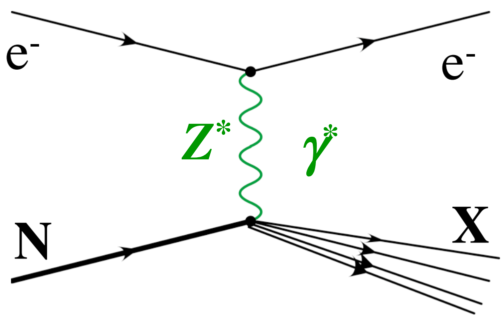
C_{2u} and C_{2d} are small and poorly known: can be accessed in PV DIS

New physics such as compositeness, new gauge bosons:

Deviations to C_{2u} and C_{2d} might be fractionally large

Proposed JLab upgrade experiment will improve knowledge of $2C_{2u}$-C_{2d} by more than a factor of 20

Parity Violating Electron DIS



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

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad y \equiv 1 - E'/E$$

$f_i(x)$ are quark distribution functions

For an isoscalar target like ^2H, structure functions largely cancel in the ratio:

Provided $Q^2 >> 1$ GeV^2 and $W^2 >> 4$ GeV^2 and $x \sim 0.2 - 0.4$

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots \qquad b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

Must measure A_{PV} to fractional accuracy better than 1%

- *11 GeV at high luminosity makes very high precision feasible*
- *JLab is uniquely capable of providing beam of extraordinary stability*
- *Systematic control of normalization errors being developed at 6 GeV*

^{2}H Experiment at 11 GeV

E': 5.0 GeV ± 10%

$\theta_{lab} = 12.5^{o}$

$I_{beam} = 90\ \mu A$

60 cm LD_2 target

- *Use both HMS and SHMS to increase solid angle*
- *~2 MHz DIS rate, π/e ~ 2-3*

$A_{PV} = 217$ ppm

$x_{Bj} \sim 0.235$, $Q^2 \sim 2.6\ GeV^2$, $W^2 \sim 9.5\ GeV^2$

1000 hours

$\delta(A_{PV})$=0.65 ppm

$\delta(2C_{2u}-C_{2d})=\pm0.0086\pm0.0080$

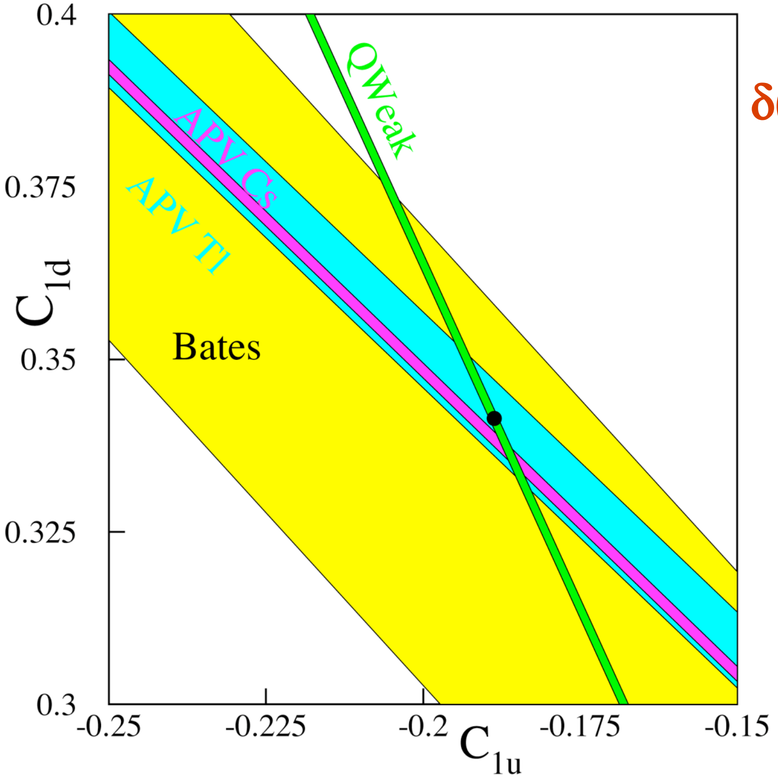
Advantages over 6 GeV:

- *Higher Q^2, W^2, f(y)*
- *Lower rate, better π/e*
- *Better systematics: 0.7%*

Theory: +0.0986

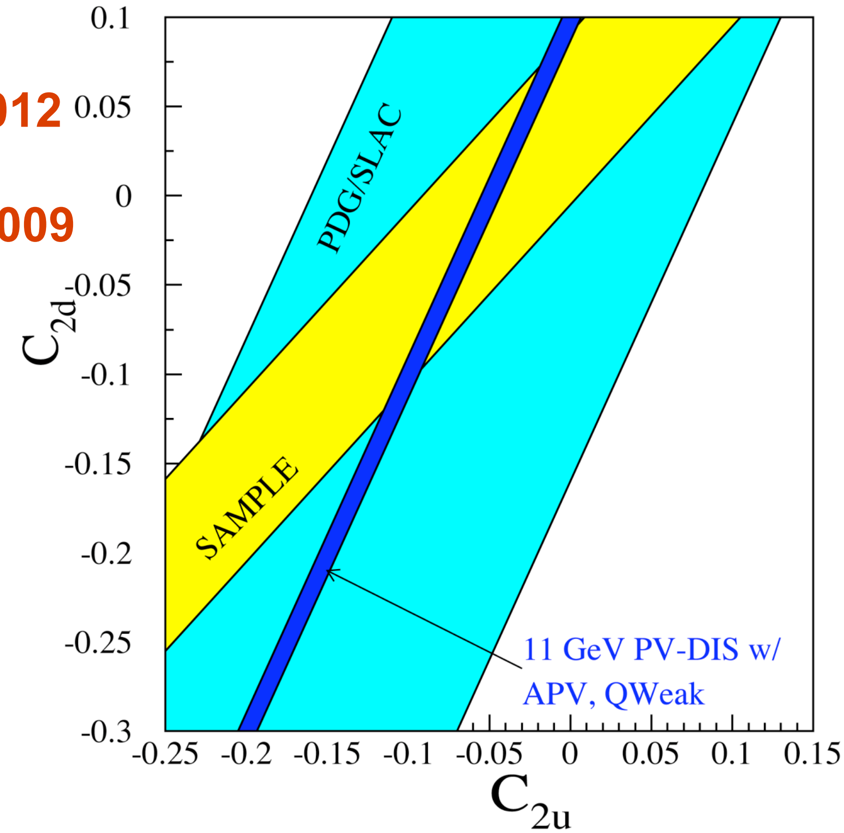
PDG (2004): -0.08 ± 0.24

Physics Implications



$\delta(2C_{2u}-C_{2d})=0.012$

$\delta(\sin^2\theta_W)=0.0009$



Unique, unmatched constraints on axial-vector quark couplings:

→ *Complementary to LHC direct searches*

Examples:

- *1 TeV extra gauge bosons (model dependent)*
- *TeV scale leptoquarks with specific chiral couplings*

PV DIS and Nucleon Structure

- *Analysis assumed control of QCD uncertainties*
  - Higher twist effects
  - Charge Symmetry Violation (CSV)
  - d/u at high x
- *NuTeV provides perspective*
  - Result is 3σ from theory prediction
  - Generated a lively theoretical debate
  - Raised very interesting nucleon structure issues: cannot be addressed by NuTeV
- *JLab at 11 GeV offers new opportunities*
  - PV DIS can address issues directly
    - *Luminosity and kinematic coverage*
    - *Outstanding opportunities for new discoveries*
    - *Provide confidence in electroweak measurement*

Search for CSV in PV DIS

$u^p(x) = d^n(x)?$

$d^p(x) = u^n(x)?$

- u-d mass difference
- electromagnetic effects

$\delta u(x) = u^p(x) - d^n(x)$

$\delta d(x) = d^p(x) - u^n(x)$

- *Direct observation of parton-level CSV would be very exciting!*
- *Important implications for high energy collider pdfs*
- *Could explain significant portion of the NuTeV anomaly*

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

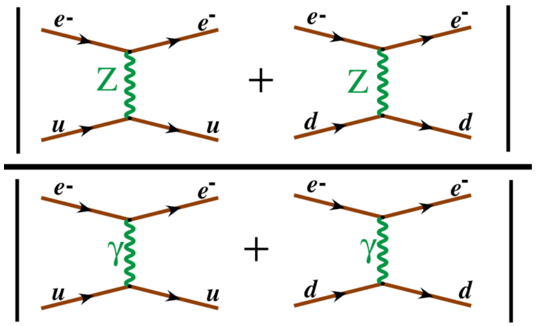
$$\frac{\delta A_{PV}}{A_{PV}} = 0.28 \frac{\delta u - \delta d}{u + d}$$

Sensitivity will be further enhanced if u+d falls off more rapidly than δu-δd as $x \to 1$

Strategy:

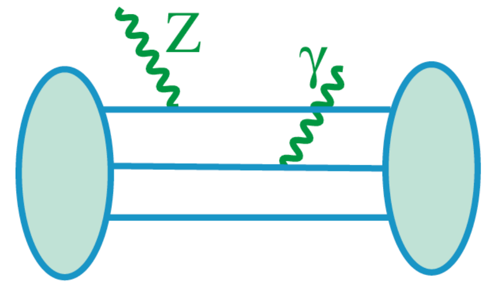
- *measure or constrain higher twist effects at x ~ 0.5-0.6*
- *precision measurement of A_{PV} at x ~ 0.7 to search for CSV*

Higher Twist Effects

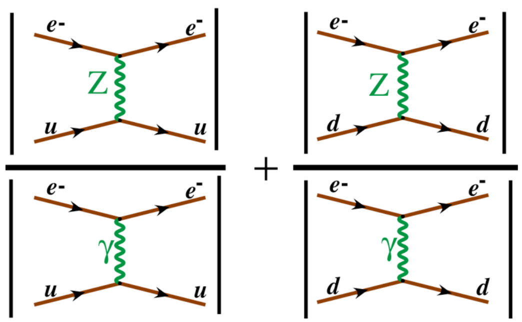


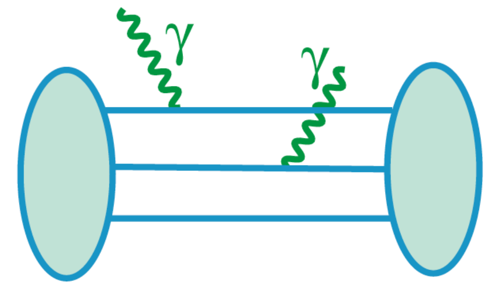
$$F_2(x,Q^2) = F_2(x)(1 + D(x)/Q^2)$$

$$A_{PV}(x,Q^2) = A_{PV}(x)(1 + C(x)/Q^2)$$



$\neq$





- ***A_{PV} sensitive to diquarks: ratio of weak to electromagnetic charge depends on amount of coherence***
- ***If Spin 0 diquarks dominate, likely only $1/Q^4$ effects.***
- ***Novel interference terms might contribute***
- ***On the other hand, higher twist effects may cancel, so A_{PV} may have little dependence on Q^2.***

A_{PV} in DIS on ^{1}H

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

$$a(x) = \frac{3}{2}\left[\frac{2C_{1u}u(x) - C_{1d}(d(x) + s(x))}{4u(x) + d(x) + s(x)}\right]$$

$$b(x) = \frac{3}{2}\left[\frac{2C_{2u}u_v(x) - C_{2d}d_v(x)}{4u(x) + d(x) + s(x)}\right]$$

$$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)} \quad + \text{small corrections}$$

- *Allows d/u measurement on a single proton!*
- *Vector quark current! (electron is axial-vector)*

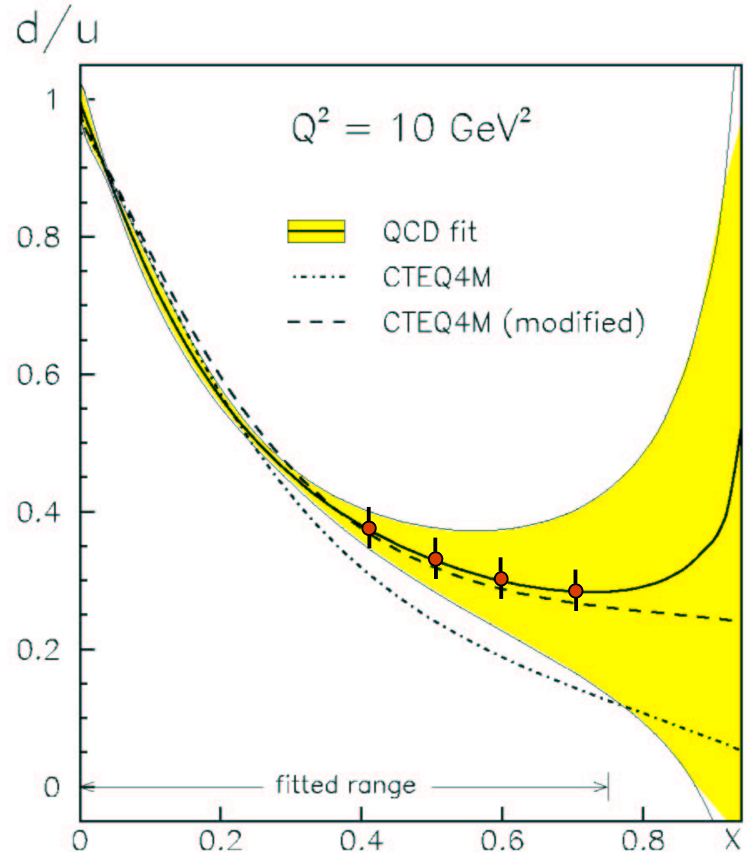
- *Determine that higher twist is under control*
- *Determine standard model agreement at low x*
- *Obtain high precision at high x*

d/u at High x

Deuteron analysis has nuclear corrections

A_{PV} for the proton has no such corrections

Must simultaneously constrain higher twist effects



The challenge is to get statistical and systematic errors ~ 2%

PV DIS Program

- *Hydrogen and Deuterium targets*
- *Better than 2% errors*
  - It is unlikely that any effects are larger than 10%
- *x-range 0.25-0.75*
- *W^2 well over 4 GeV^2*
- *Q^2 range a factor of 2 for each x point*
  - (Except x~0.7)
- *Moderate running times*

- ***With HMS/SHMS: search for TeV physics***
- ***With larger solid angle apparatus: higher twist, CSV, d/u…***

Large Acceptance: Concept

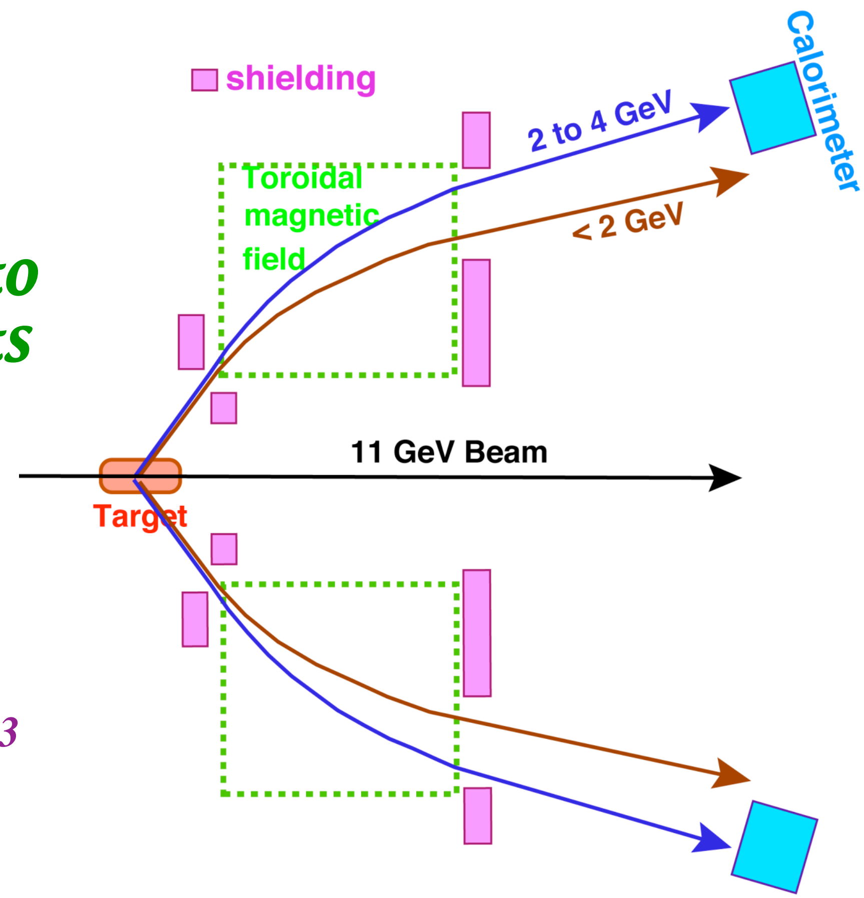
JLab Upgrade ⇨

- CW 90 μA at 11 GeV
- 40-60 cm liquid H_2 and D_2 targets
- Luminosity > $10^{38}/cm^2/s$

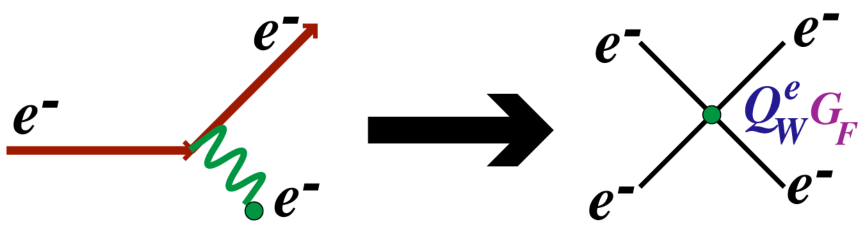
- Need high rates at high x
- For the first time: sufficient rates to make precision PV DIS measurements

⇩

- solid angle > 200 msr
- Count at 100 kHz
- online pion rejection of 10^2 to 10^3



Fixed Target Møller Scattering



Purely leptonic reaction

Weak charge of the electron:

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

$$A_{PV} \propto m_e E_{lab} (1 - 4\sin^2\vartheta_W)$$

$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \cong 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

$$\sigma \propto \frac{1}{E_{lab}}$$

Figure of Merit rises linearly with E_{lab}

- Maximal at 90° in COM ($E' = E_{lab}/2$)

SLAC E158 → - Highest possible E_{lab} with good $P^2 I$

Jlab at 12 GeV → - Moderate E_{lab} with LARGE $P^2 I$

Unprecedented opportunity: The best precision at $Q^2 << M_Z^2$ with the least theoretical uncertainty until the advent of a linear collider or a neutrino factory

Design for 12 GeV

E': 3-6 GeV

$I_{beam} = 90\ \mu A$

$\theta_{lab} = 0.53^\circ$-$0.92^\circ$

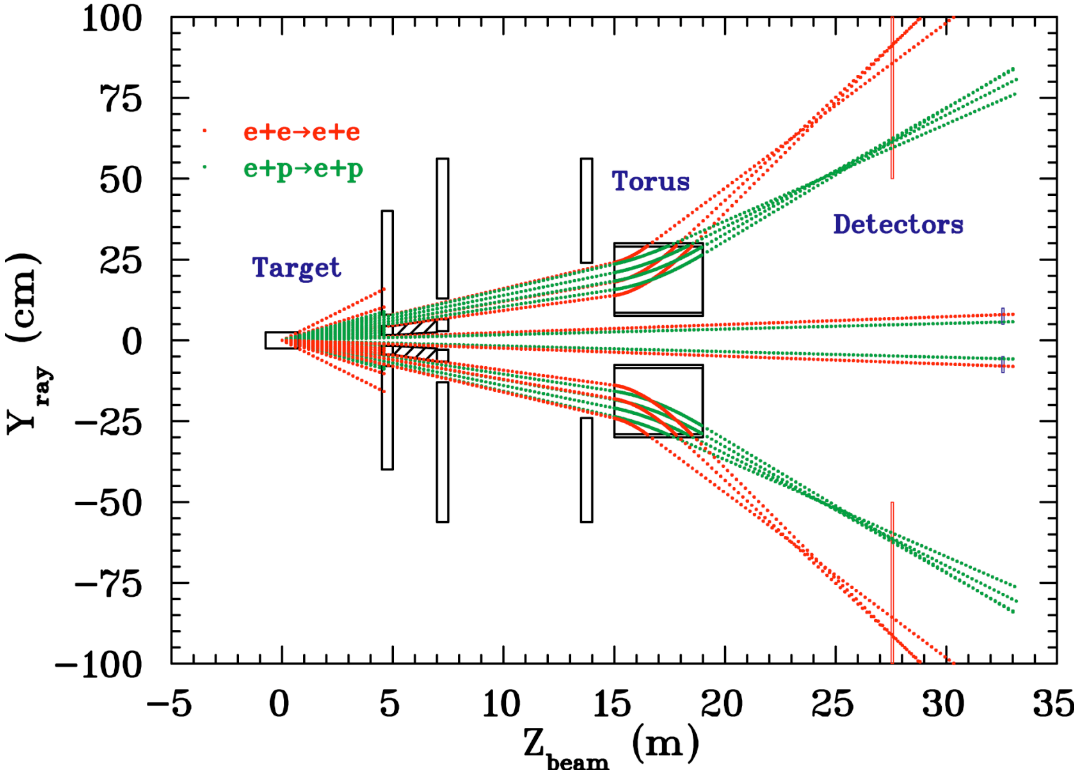
150 cm LH_2 target

$A_{PV} = 40$ ppb

4000 hours

$\delta(A_{PV})=0.58$ ppb

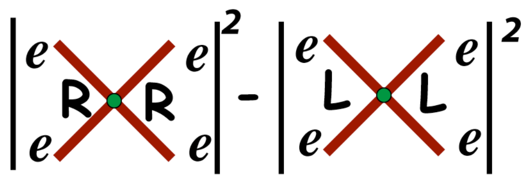
Toroidal spectrometer → ring focus



- *Beam systematics: steady progress (E158 Run III: 3 ppb)*
- *Focus alleviates backgrounds:*

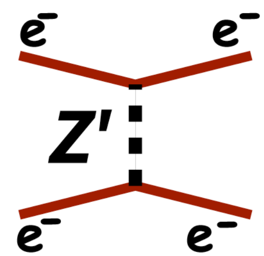
  $ep \rightarrow ep(\gamma),\ ep \rightarrow eX(\gamma)$
- *Radiation-hard integrating detector*
- *Normalization requirements similar to other planned experiments*
- *Cryogenics, density fluctuations and electronics will push the state-of-the-art*

New Physics Reach

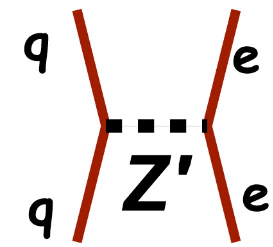


JLab Møller

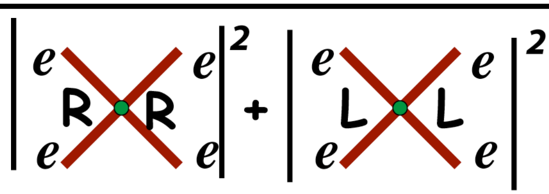
$\Lambda_{ee} \sim 25$ TeV



New Contact Interactions



LHC



LEP200

$\Lambda_{ee} \sim 15$ TeV

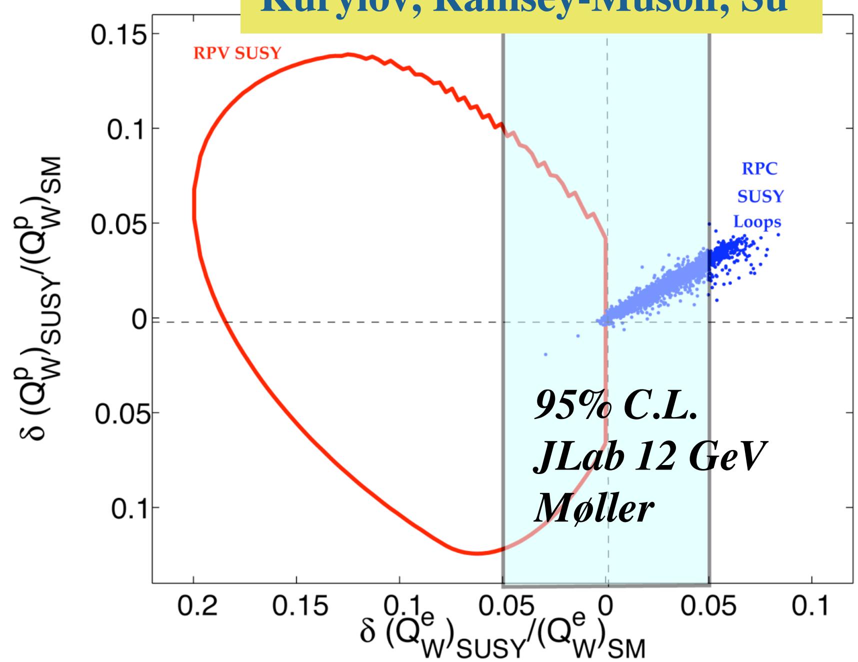
Complementary; 1-2 TeV reach

Does Supersymmetry (SUSY) provide a candidate for dark matter?

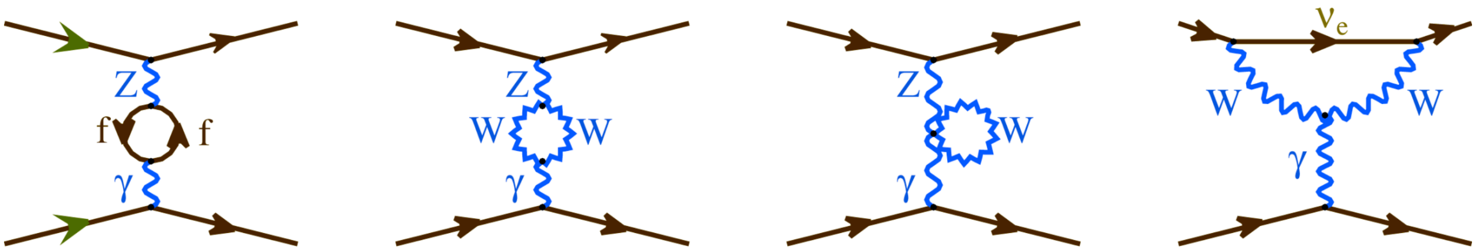
•Lightest SUSY particle (neutralino) is stable if baryon (B) and lepton (L) numbers are conserved

•However, B and L need not be conserved in SUSY, leading to neutralino decay (RPV)

Kurylov, Ramsey-Musolf, Su



Electroweak Physics

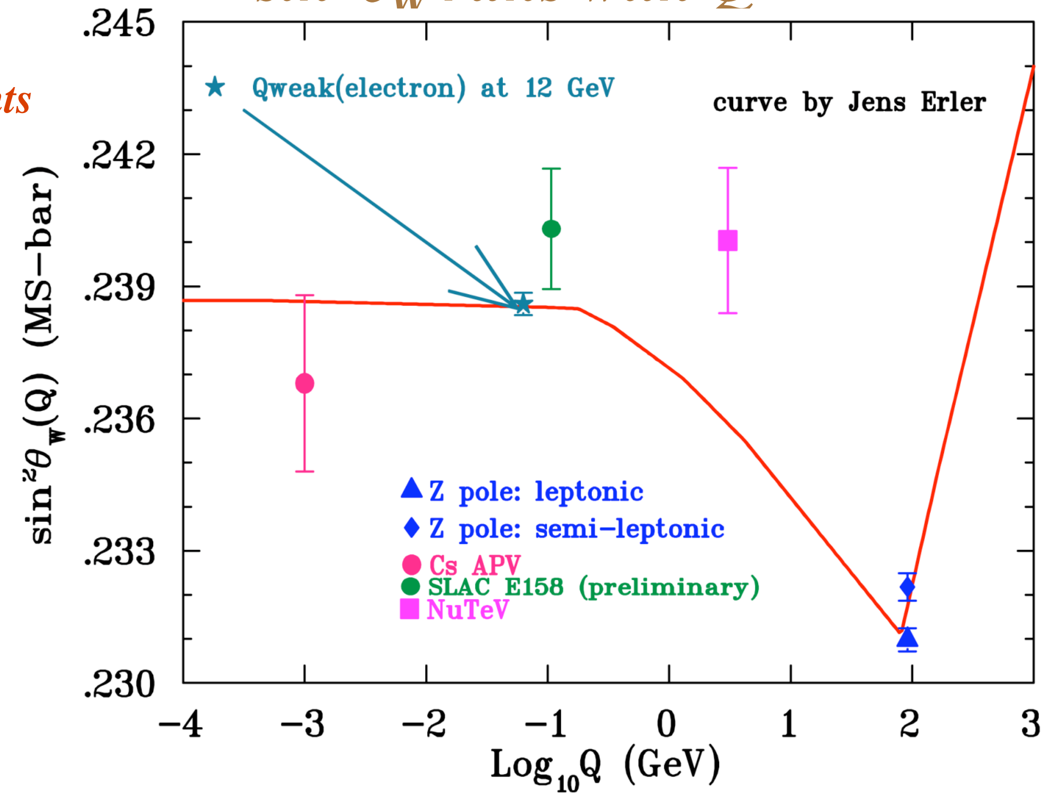


Q_W^e modified

$\sin^2\theta_W$ runs with Q^2

$\delta(\sin^2\theta_W) \sim 0.0003$

Comparable to single collider measurements



- ***Semileptonic processes have theoretical uncertainties***
- ***E158 established running, probing vector boson loops***
- ***JLab measurement would have impact on discrepancy between leptonic and hadronic Z-pole measurements***

Summary

- *12 GeV Upgrade*
  - Opens unique opportunities for new PV measurements
  - Hall configuration must support dedicated apparatus
    - *Large solid angle toroid/calorimeter for PV DIS*
    - *Superconducting solenoid for Møller scattering*
- *Science in the first five years*
  - Complete TeV physics search in DIS with SHMS/HMS
    - *Important complement to direct LHC searches*
  - Address new questions raised:
    - *Develop experimental tools for PV DIS at high x*
    - *Major potential for new discoveries in nucleon structure*
  - Launch electron weak charge measurement
    - *Best low energy probe of TeV scale physics for decades*