Parity-Violating Electron Scattering at 11 GeV

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Nuclear Science and the New Standard Model: Fundamental Symmetries and Neutrinos in The Next Decade

+ parity-violating electron scattering

Recent Accomplishments: Highlights

- Tight bounds on the strange sea in the nucleon (HAPPEX, G0, A4, SAMPLE)
- Precision measurement $\sin^2\theta_W$ away from the Z^0 resonance (E158)

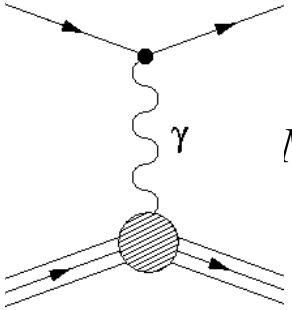
Ongoing Project

- Determination of the neutron skin in ^{208}Pb nucleus (PREX)
- Precision measurement $\sin^2\theta_W$ away from Z^0 resonance (semileptonic) (QWeak)

New Opportunities with the JLab Upgrade

- Precision measurement of $\sin^2\theta_W$ away from the Z^0 resonance (Moller)
- Measurement of quark axial-vector couplings (C_{2q}s) (PV-DIS)
- Electroweak probe of the strong interaction (PV-DIS)

Parity Violating Electron Scattering

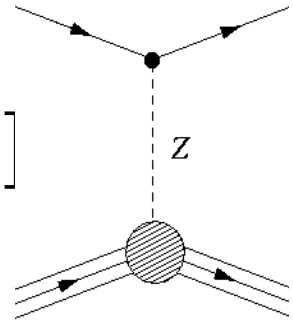


$$M^{EM} = \frac{4\pi\alpha}{Q^2} Q_\ell \, \ell^\mu J_\mu^{EM}$$

…but G_F is $10^{-6}*\alpha$

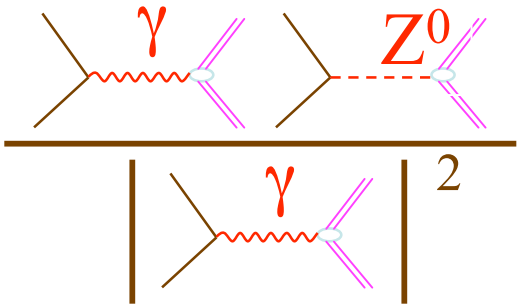
NC vector current probes same hadronic structure, with different couplings

$$M_{PV}^{NC} = \frac{G_F}{2\sqrt{2}} \left[g_A^e \ell^{\mu 5} J_\mu^{NC} + g_V^e \ell^\mu J_{\mu 5}^{NC} \right]$$



Scatter longitudinally polarized electrons off unpolarized target

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto$$

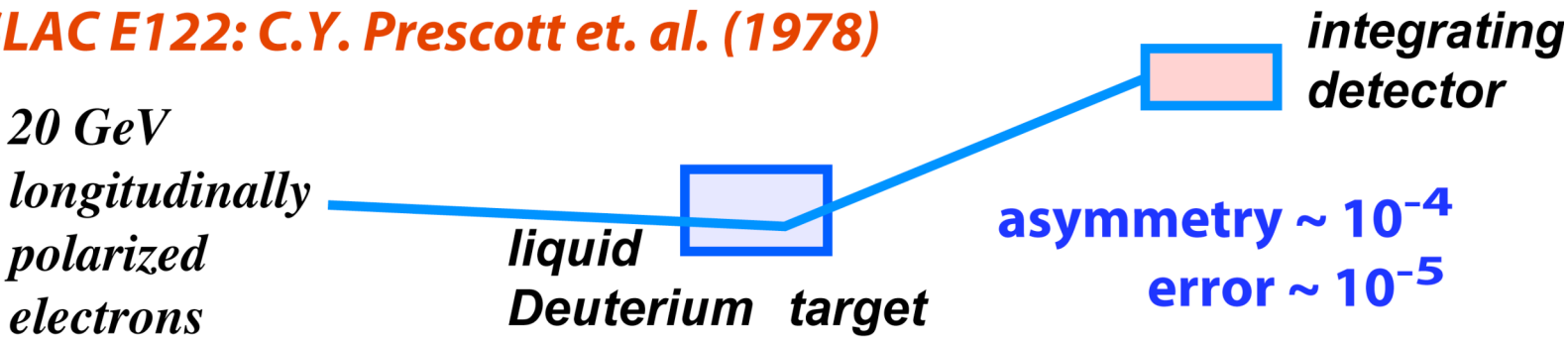


$$\propto \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \approx 10^{-7} - 10^{-3} \quad \textbf{for} \quad Q^2 \approx 0.01 - 10 \ \textbf{GeV}^2$$

E122 at SLAC (1978)

SLAC E122: C.Y. Prescott et. al. (1978)



$$A_D = \frac{3\, G_F\, Q^2}{10\sqrt{2\pi\,\alpha}}\left[a(x) + b(x)\, Y\right]$$

At high x:

$$a(x) = 2C_{1u} - C_{1d}$$

$$b(x) = 2C_{2u} - C_{2d}$$

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

$$R(x, Q^2) = \sigma_L/\sigma_R \approx 0.2$$

$$C_{1u} = -\tfrac{1}{2} + \tfrac{4}{3}\sin^2(\theta_W) \approx -0.19, \quad C_{1d} = \tfrac{1}{2} - \tfrac{2}{3}\sin^2(\theta_W) \approx 0.35,$$

$$C_{2u} = -\tfrac{1}{2} + 2\sin^2(\theta_W) \approx -0.04, \quad C_{2d} = \tfrac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

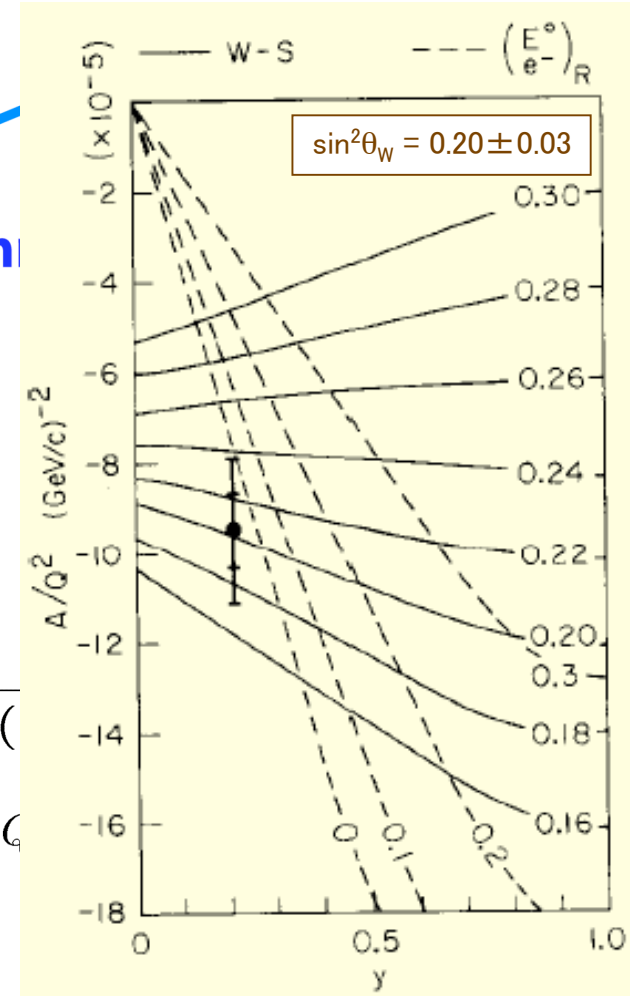
E122 at SLAC (1978)

SLAC E122: C.Y. Prescott et. al. (1978)

20 GeV longitudinally polarized electrons

liquid Deuterium target

asym



$$A_D = \frac{3\, G_F\, Q^2}{10\sqrt{2\pi\,\alpha}}\left[a(x) + b(x)\, Y\right]$$

$$Y = \frac{}{1+(}$$

$$R(x, Q$$

At high x:

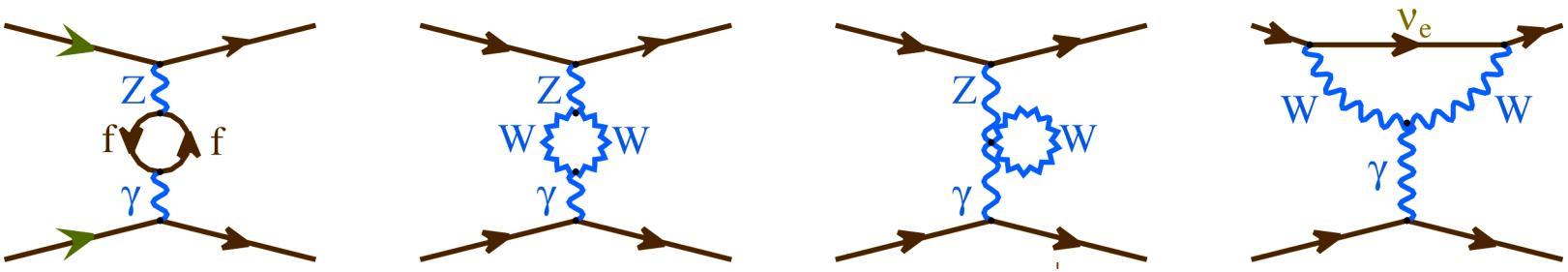
$$a(x) = 2C_{1u} - C_{1d}$$

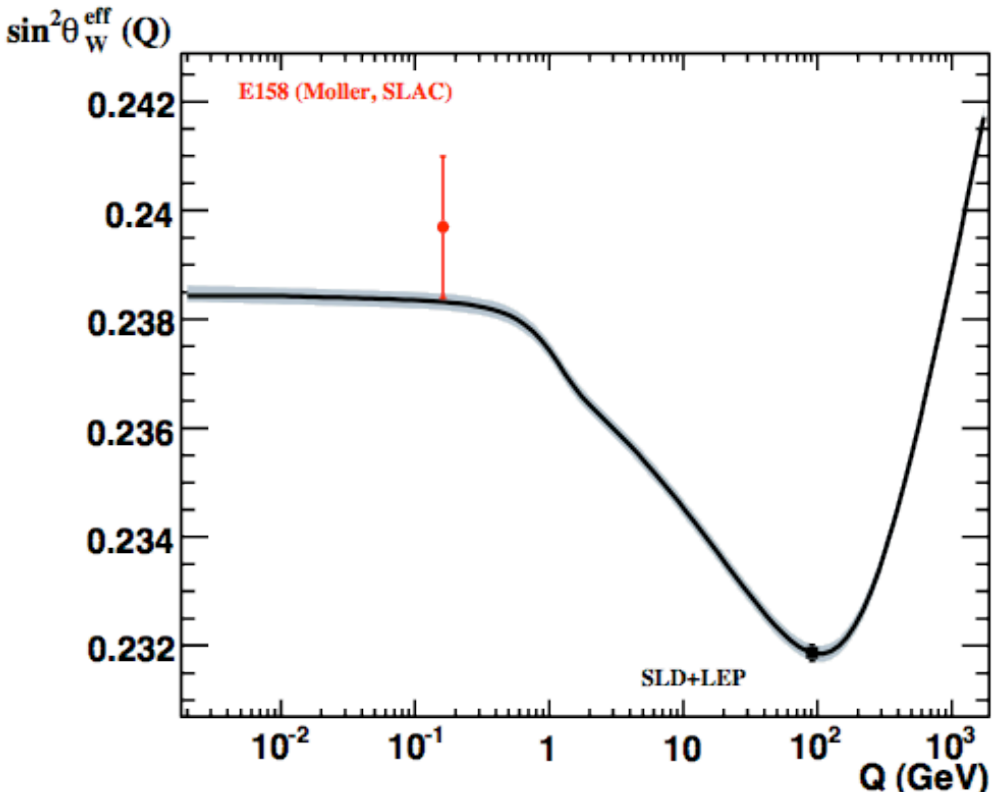
$$b(x) = 2C_{2u} - C_{2d}$$

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

$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) \approx -0.04, \quad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) \approx 0.04.$$

$\sin^2\theta_W$



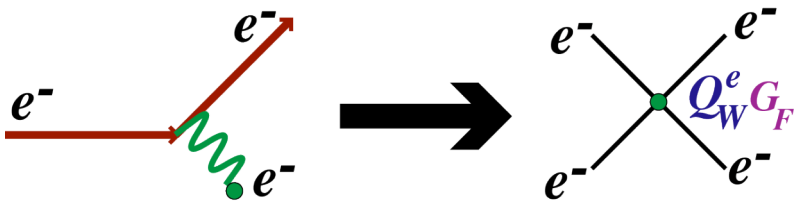


Renormalization scheme ($\overline{MS}$) defines $\sin^2\theta_W$ at the Z-pole.

γ-Z mixing and other diagrams are absorbed into the coupling constant

Precision measurements at low-Q^2 test this running under the Standard Model

E-158 at SLAC (2005)



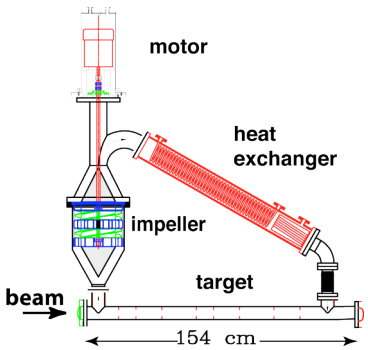
Purely leptonic reaction

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

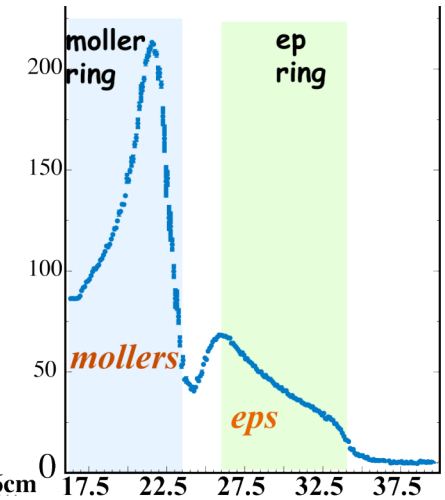
$$A_{PV} \propto E_{lab} Q_W^e$$

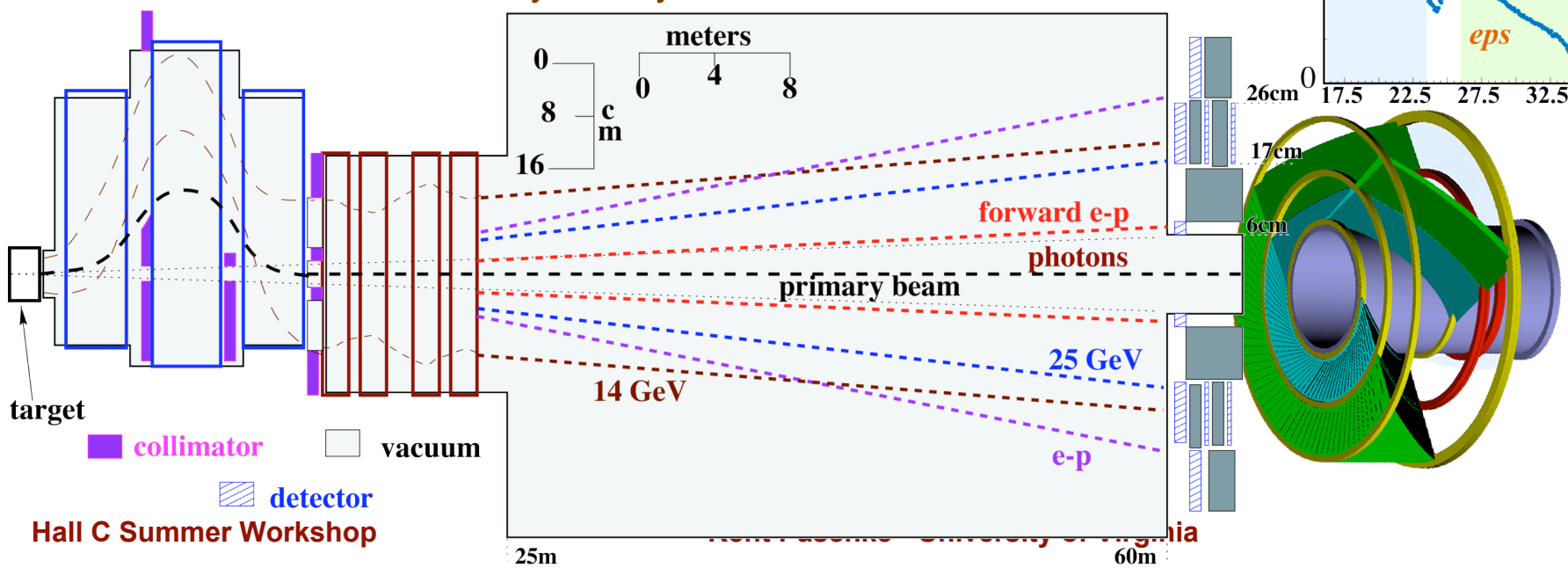
$$\frac{\delta(\sin^2\vartheta_W)}{\sin^2\vartheta_W} \sim 0.05 \frac{\delta(A_{PV})}{A_{PV}}$$

$A_{PV} = (-131 \pm 14 \pm 10)$ ppb



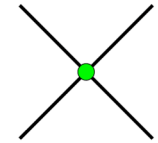
- High beam polarization and current
- High-power (1kW) LH_2 target
- Dipole chicane + quadrupole spectrometer
- Stringent control of helicity-dependent systematics.
- Passive asymmetry reversals





Why PVeS doesn't (just) measure $\sin^2\theta_W$

$$L_{eq}^{\mathrm{PV}} = L_{\mathrm{SM}}^{\mathrm{PV}} + L_{\mathrm{new}}^{\mathrm{PV}} = -\frac{G_\mu}{2\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q Q_W^q\bar{q}\gamma^\mu q + \frac{g^2}{4\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e\sum_q h_V^q\bar{q}\gamma^\mu q$$



Contact interaction

Ramsey-Musolf(1999)

Λ: new physics scale O(1)

Take δQ_W^p=4%

$$\frac{\Lambda}{g} \sim \frac{1}{\sqrt{\sqrt{2}G_\mu|\Delta Q_W^p|}} \sim 4.6\,\mathrm{TeV}$$

- Non-perturbative theory $g \sim 2\pi$ $\Lambda \sim 29$ TeV
- Extra Z' (GUT) $g \sim 0.45$ $m_{Z'} \sim 2.1$ TeV

Measurements at the Z-pole don't have this sensitivity

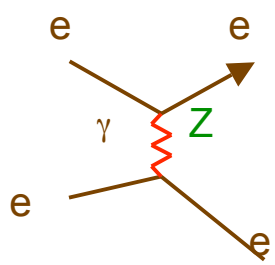
on resonance: A_Z *imaginary* $\longrightarrow A_Z^2\left[1 + \frac{A_X^2}{A_Z^2}\right]$ *no interference!*

Complementary to (parity-conserving) couplings sought at high-energy colliders

Discovery, or help determine couplings of LHC discovery

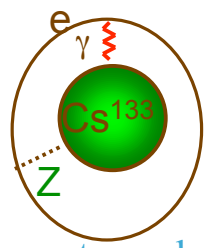
Complementary sensitivity to new Physics

Møller Scattering



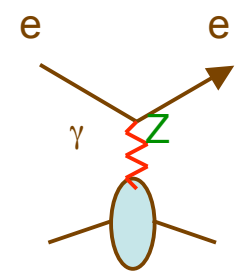
Purely Leptonic—no quark interactions

Atomic Parity Violation



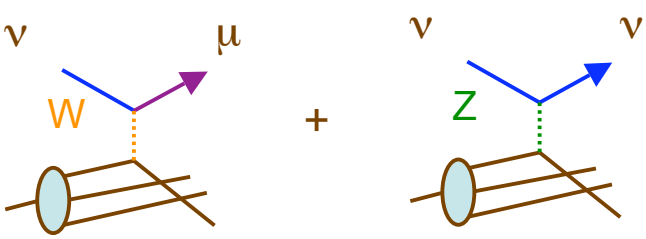
Coherent quarks from entire nucleus

Q-Weak (JLab)



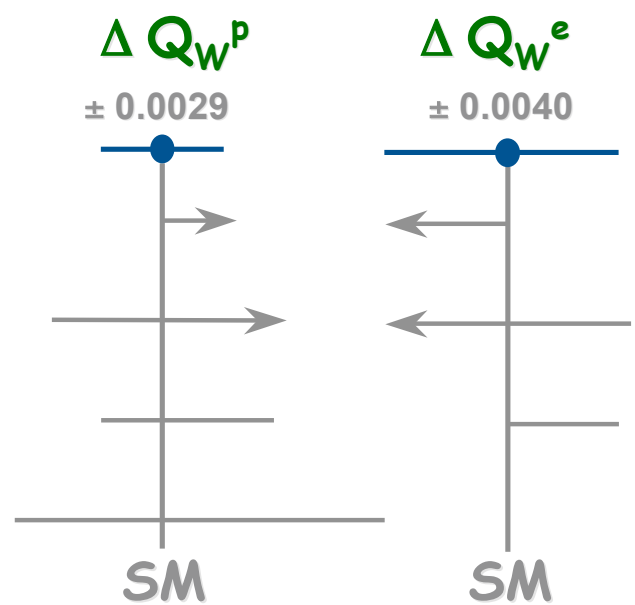
Coherent quarks in Proton

Neutrino DIS



Quark scattering (from nucleus)

- **exp**
- **MSSM:**
- **extra Z':**
- **RPV SUSY**
- **leptoquark**



Erler, Kurylov and Ramsey-Musolf (2003)

DIS at high x

$$A_d = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{\{2C_{1u} - C_{1d}[1 + R_s(x)]\} + Y\,(2C_{2u} - C_{2d})\,R_v(x)}{5 + R_s(x)}$$

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

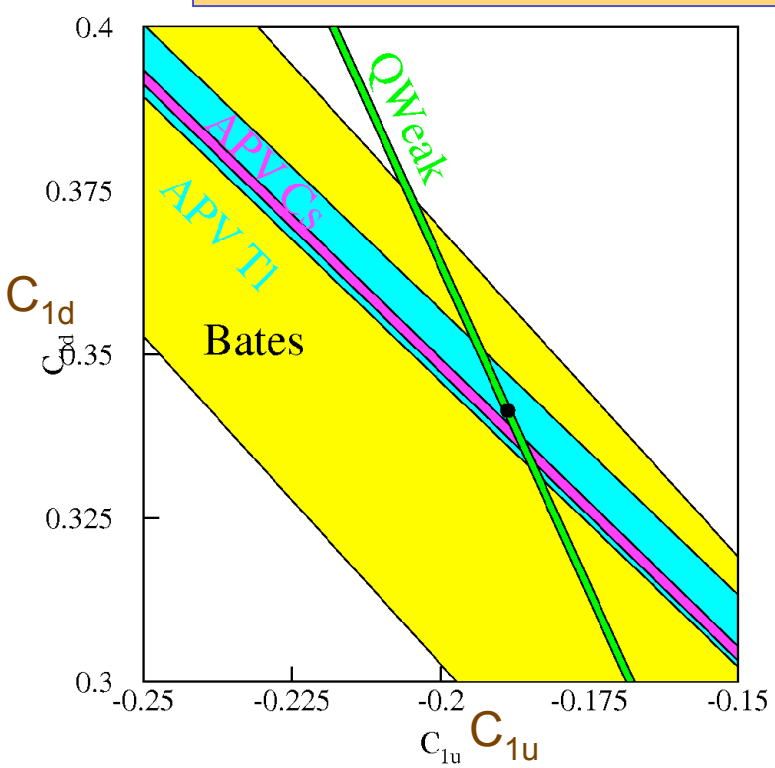
$$R(x, Q^2) = \sigma_L/\sigma_T \approx 0.2$$

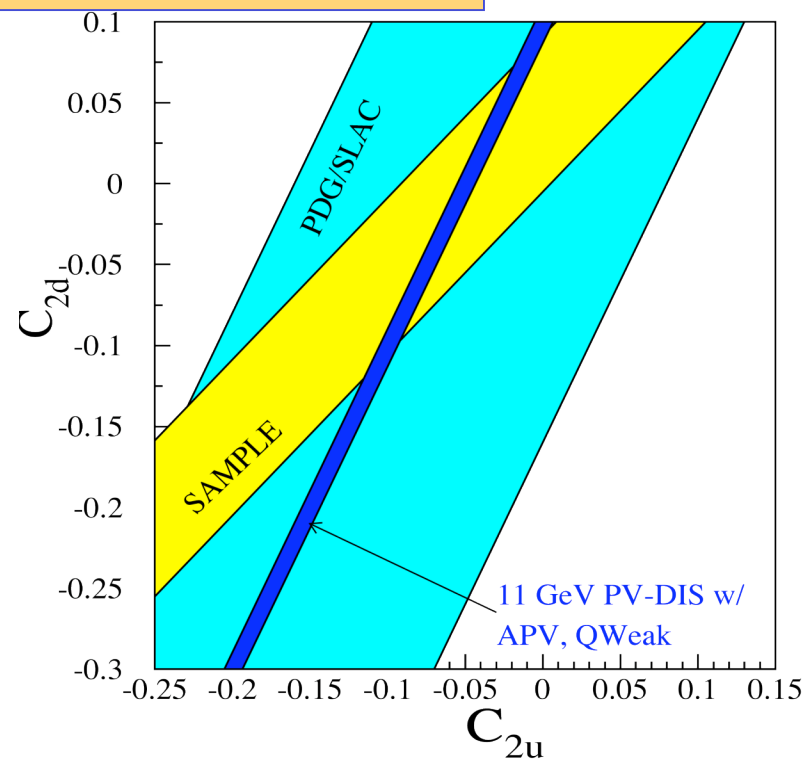
$$R_s(x) = \frac{2\,[s(x) + \bar{s}(x)]}{u(x) + d(x)} \xrightarrow{\text{large x}} 0$$

$$R_v(x) = \frac{u_v(x) + d_v(x)}{u(x) + d(x)} \xrightarrow{\text{large x}} 1$$

$$A_D \sim -\frac{3\,G_F\,Q^2}{10\sqrt{2}\,\pi\,\alpha}\left[2C_{1u} - C_{1d} + Y\left(2C_{2u} - C_{2d}\right)\right]$$

High precision DIS from isoscaler target gives unique access to quark axial WNC coupling C_{2q}



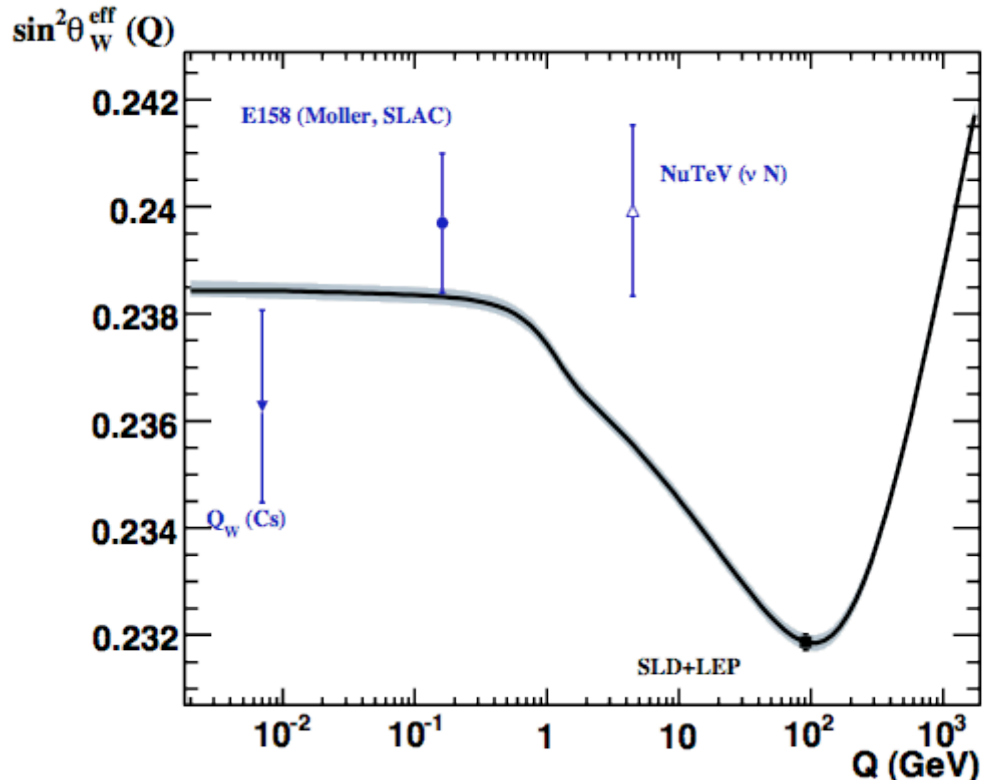


NuTeV, and the Trouble with Nuclear Targets

NuTeV sits 3σ from the Standard Model

Many questions have come up about what may be in their observable (Pachos-Wolfenstein ratio), besides SM couplings, such as:

- partonic isospin symmetry
- include only light (u, d) quarks
- nuclear effects (parton shadowing, EMC, ….)
- higher twist effects
- radiative corrections



With precise kinematic resolution, these effects can be studied. NuTeV can not resolve reaction kinematics.

Any SM test will need to understand such issues, but don't forget:

QCD is more than just a background to the Standard Model !

Charge Symmetry

Charge symmetry

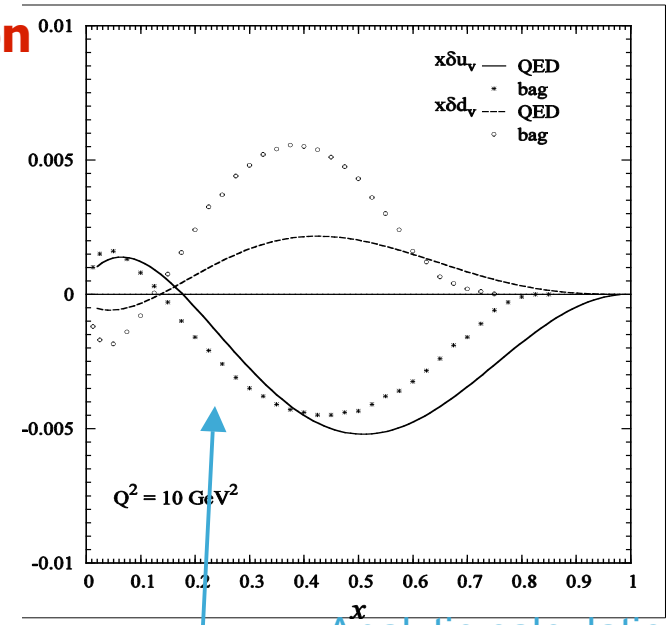
$$u^p(x) = d^n(x)$$

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

Charge Symmetry Violation

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

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



Quark Mass effects:

- Analytic Quark Model Approximation (Sather)
- QCD Bag model (Rodionov, Londergan, Thomas)

"**QED** Splitting" (MRST, Glueck et al.)

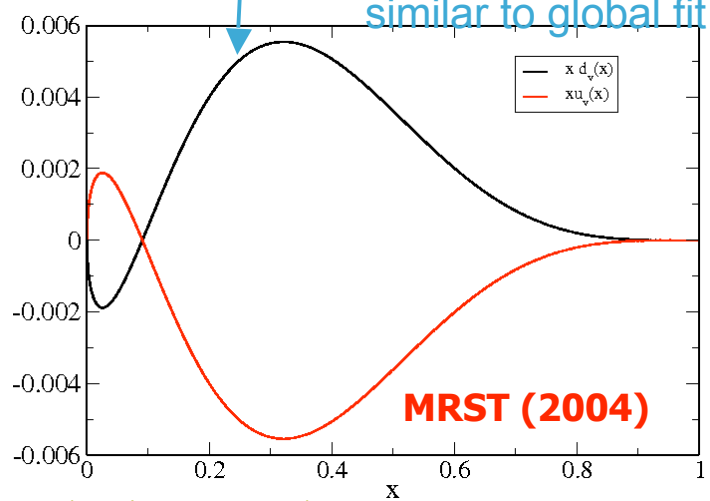
- EM correction independent of δm
- MRST incorporated QED splitting into global PDF fit (2005)

Analytic calculation similar to global fit

Separately: MRST PDF global with *fit* of CSV

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

Chose restricted form for parton CSV (contains both QED and QCD splitting)

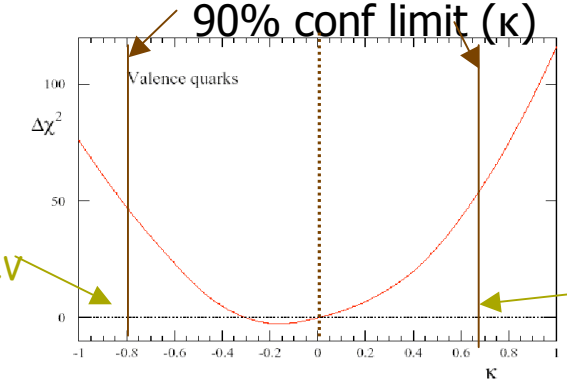


Broad minimum

κ= [-0.8,0.65]

(90% C.L.)

90% conf limit (κ)



fully explains NuTeV

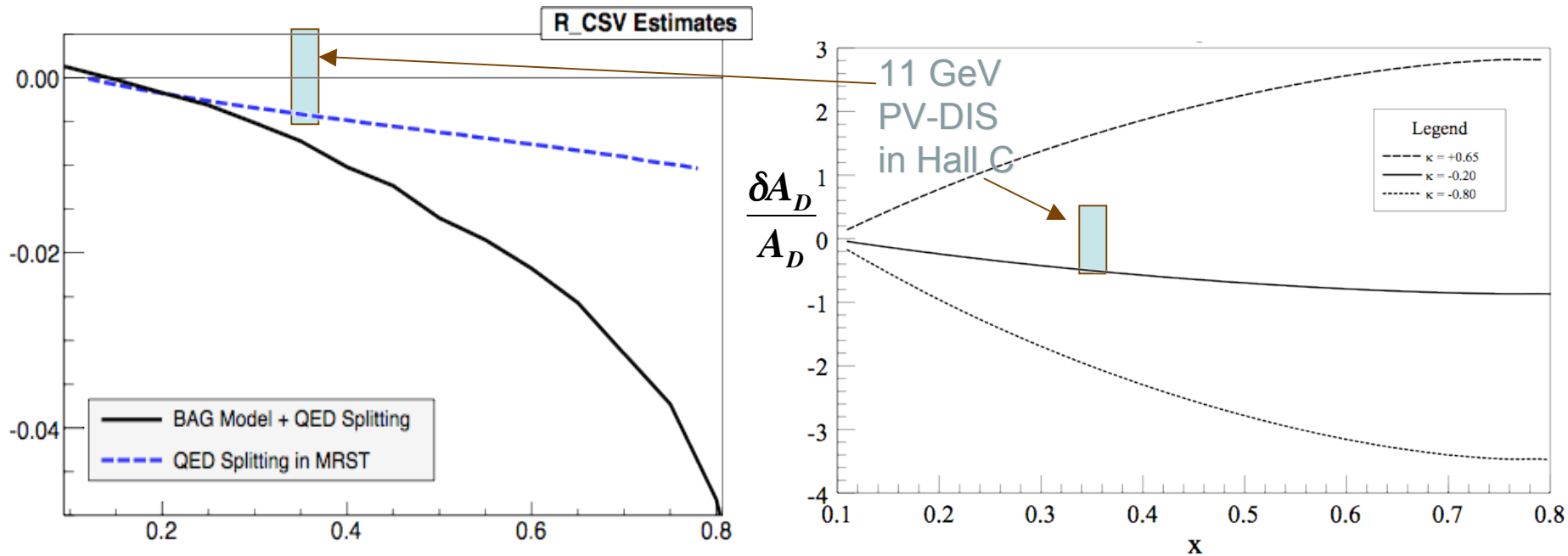
doubles NuTeV deviation

CSV and PV-DIS

- *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 PV-DIS from ^{2}H: $$\frac{\delta A_D}{A_D} \sim 0.3 \frac{\delta u - \delta d}{u + d}$$

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



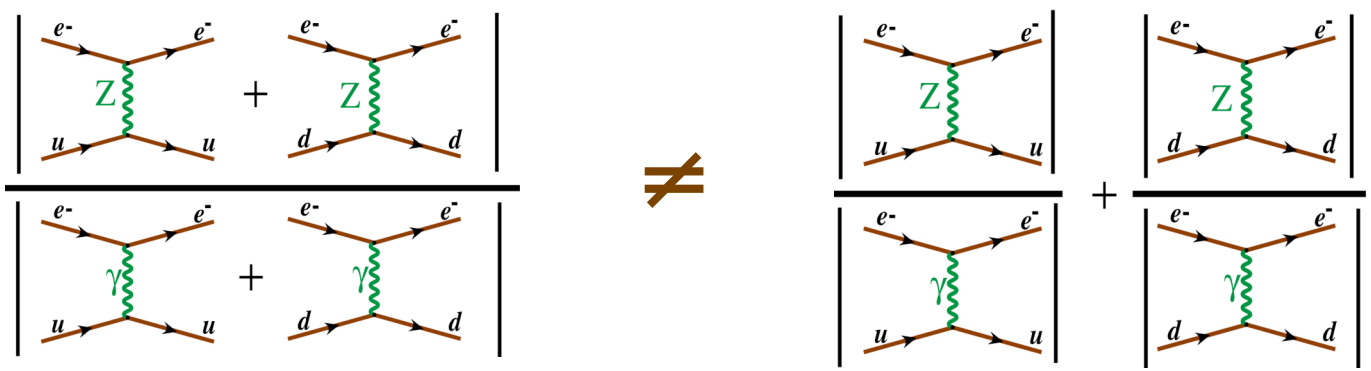
Higher Twist

Does higher twist fully cancel from the asymmetry?

$$A_d = -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{\{2C_{1u} - C_{1d}[1 + R_s(x)]\} + Y(2C_{2u} - C_{2d})R_v(x)}{5 + R_s(x)}$$

Trivially, higher twist is potentially important when x is low enough that sea quarks matter

At higher x, a more interesting higher twist effect may be evident:



- A_{PV} sensitive to diquarks: ratio of weak to electromagnetic charge depends on amount of coherence
- Do diquarks have twice the x of single quarks?
- If Spin 0 diquarks dominate, likely only $1/Q^4$ effects

Coherent Program of PV-DIS Study

To achieve a high precision constraint on axial-vector quark couplings, first study hadronic physics

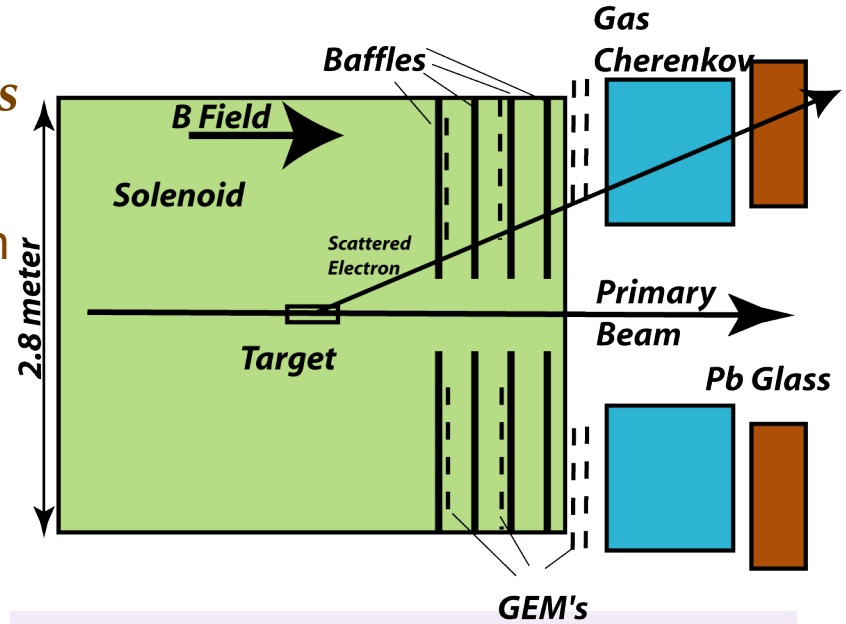
Strategy: requires precise kinematics and broad range

- Measure A_D in narrow bins of x, Q2 with 1% 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, and Y dependence to measure C_{2q}'s

- Continue with ^1H for additional HT study, d/u and proton structure functions

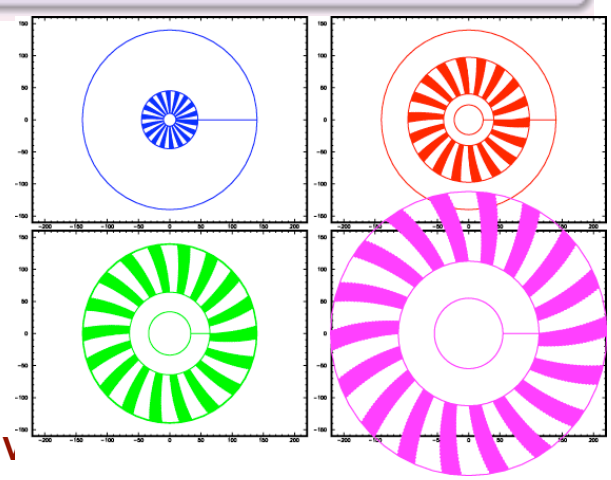
A Design for Precision PV DIS Physics

- ***High Luminosity on LH_2 & LD_2 Cryotargets***
- ***Better than 1% errors***
  - It is unlikely that any effects are larger than 5-6%
- ***x-range 0.25-0.75***
- ***W^2 well over 4 GeV^2***
- ***Q^2 range a factor of 2 for each x***
  - (Except x~0.75)
- ***Moderate running times***
  - *Need BaBar, CDF or CLEOII Solenoid*
  - *state-of-the art fast tracking, particle ID and "parity" counting electronics*
  - *precision polarimetry (-> 0.5%)*
  - *diverse physics topics addressed*
    Standard Model test, CSV, d/u, nuclear EMC effect, semi-inclusive physics, detailed studies of spin structure functions…

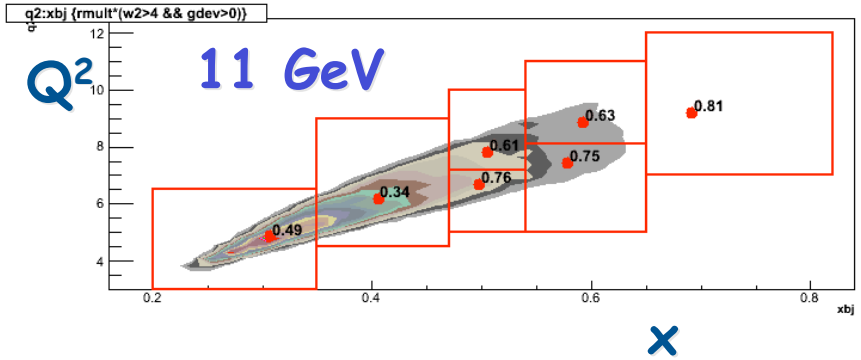


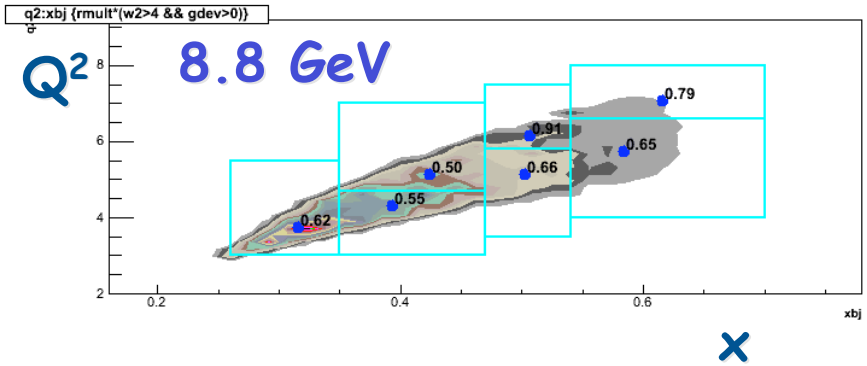
Existing solenoids which may fit

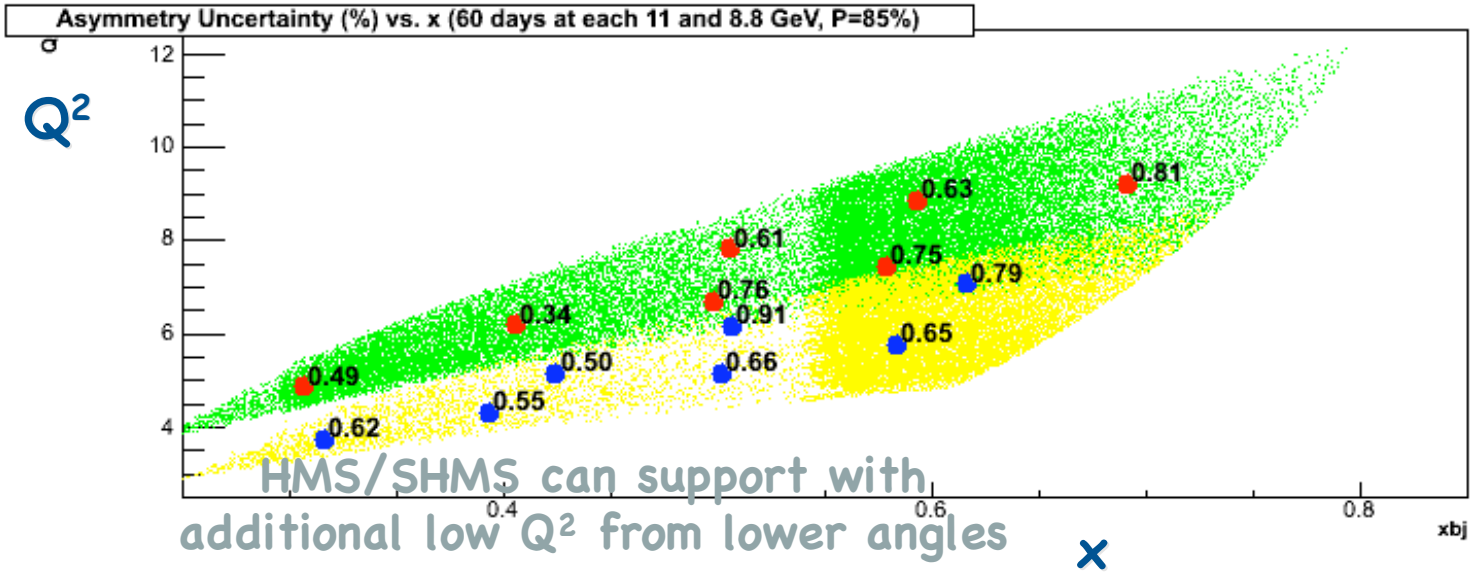
Experiment	B, T	Bore D, m	Length, m	MJ	X_0
BaBar	1.5	2.80	3.46	27	<1.4
Cleo-II	1.5	2.90	3.80	25	2.5



Broad Kinematic Acceptance



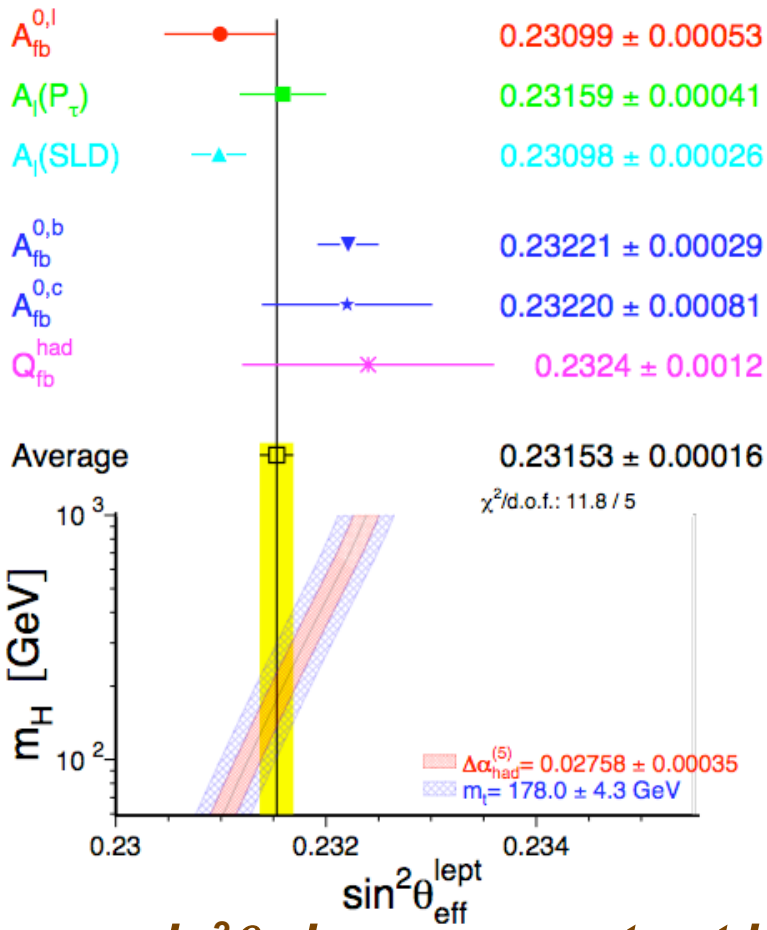




HMS/SHMS can support with additional low Q^2 from lower angles

JLab 11GeV can provide new probe of nucleon structure and unique measure of Weak axial-vector quark couplings

How well do we know $\sin^2\theta_W$?



"well measured" weak mixing angle $\sin^2\theta_W$ key in global electroweak fits

- prediction for Higgs mass
- favors SUSY
- rules out Technicolor

3σ discrepancy with consquences

A_{LR}

(also APV in Cs)

$\sin^2\theta_W = 0.2310(3)$

↓

$m_H = 35\ ^{+26}_{-17}$ GeV

S= -0.11 ± 17

Rules out the SM!

A_{FB} (Z→ bb)

(also Moller @ E158)

$\sin^2\theta_W = 0.2322(3)$

↓

$m_H = 480\ ^{+350}_{-230}$ GeV

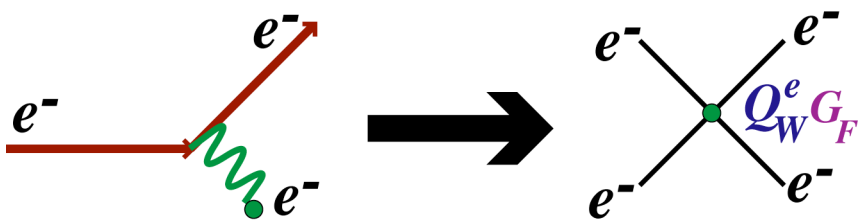
S= +0.55 ± 17

Rules out SUSY!

Favors Technicolor!

- ***$\sin^2\theta_W$ improvements at hadron colliders very challenging***
- ***"Giga-Z" option of ILC or neutrino factory: powerful but far future***
- ***Is there any other method in the next decade?***

Back to Møller Scattering



Purely leptonic reaction

$A_{PV} \propto Q_W{}^e \sim 1 - 4\sin^2\theta_W$

Theoretically very clean

Big amplification factor for $\sin^2\theta_W$ precision

E158 stopped with $\delta[\sin^2\theta_W(M_Z{}^2)] = 0.0011$ stat, 0.0009 syst.

Running time, Polarimetry, Inelastic ep and photon backgrounds

These can all be improved!

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

Figure of Merit proportional to beam power

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

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

$\delta(\sin^2\theta_W) \sim 0.00025$

Matches best collider (Z-pole) measurement!

Design for e2e, 12 GeV

E': 3-6 GeV

θ_{lab} = 0.53°-0.92°

A_{PV} = -40 ppb

I_{beam} = 100 μA

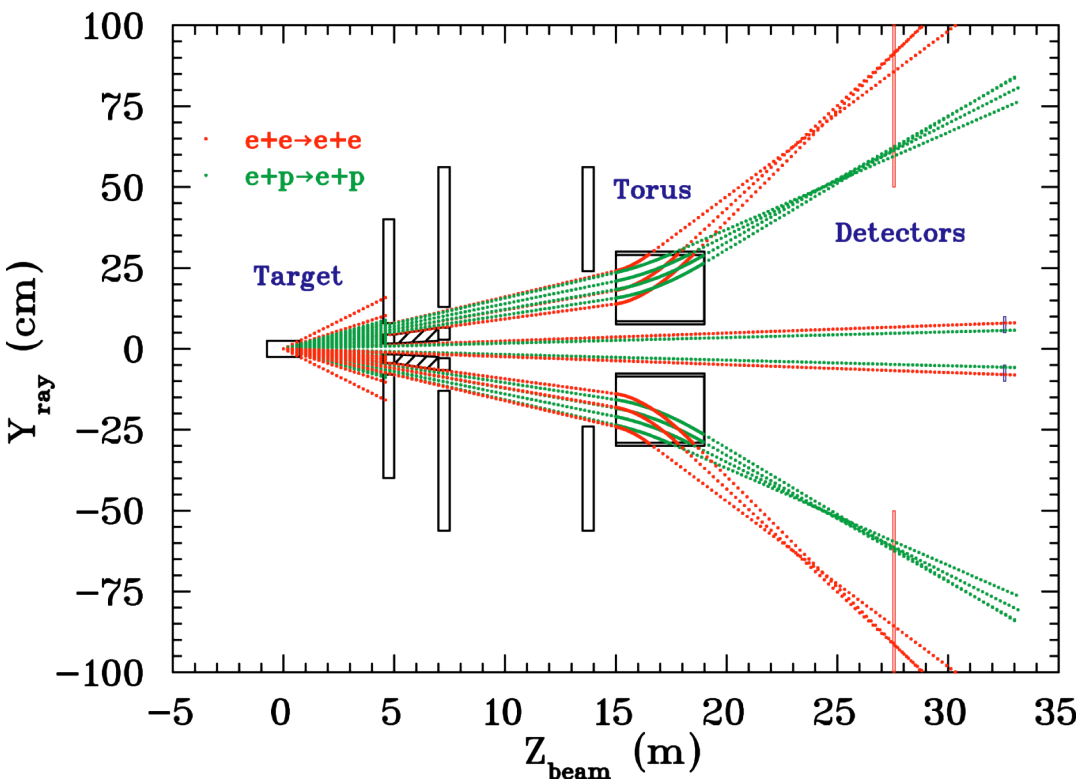
150 cm LH_2 target

4000 hours, P=85%

Width = 23 ppm at 300Hz

Toroidal spectrometer → *ring focus*

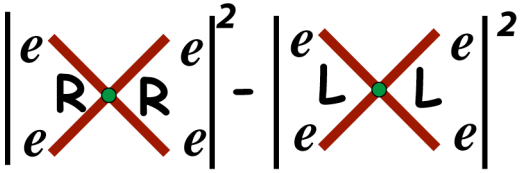
$\delta(A_{PV})$=0.58 ppb



- 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

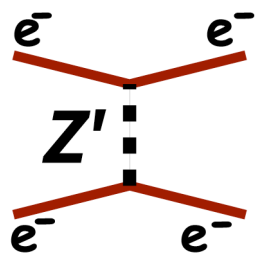
New Physics Reach

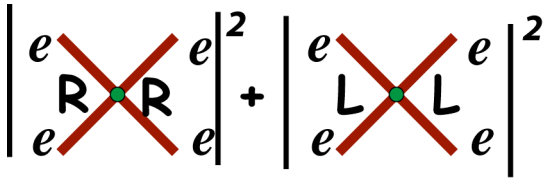


Jlab Møller

$\Lambda_{ee} \sim 25$ TeV

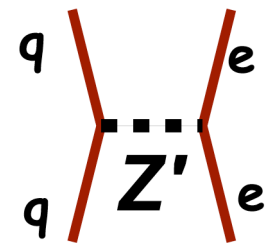
New Contact Interactions





LEP200

$\Lambda_{ee} \sim 15$ TeV

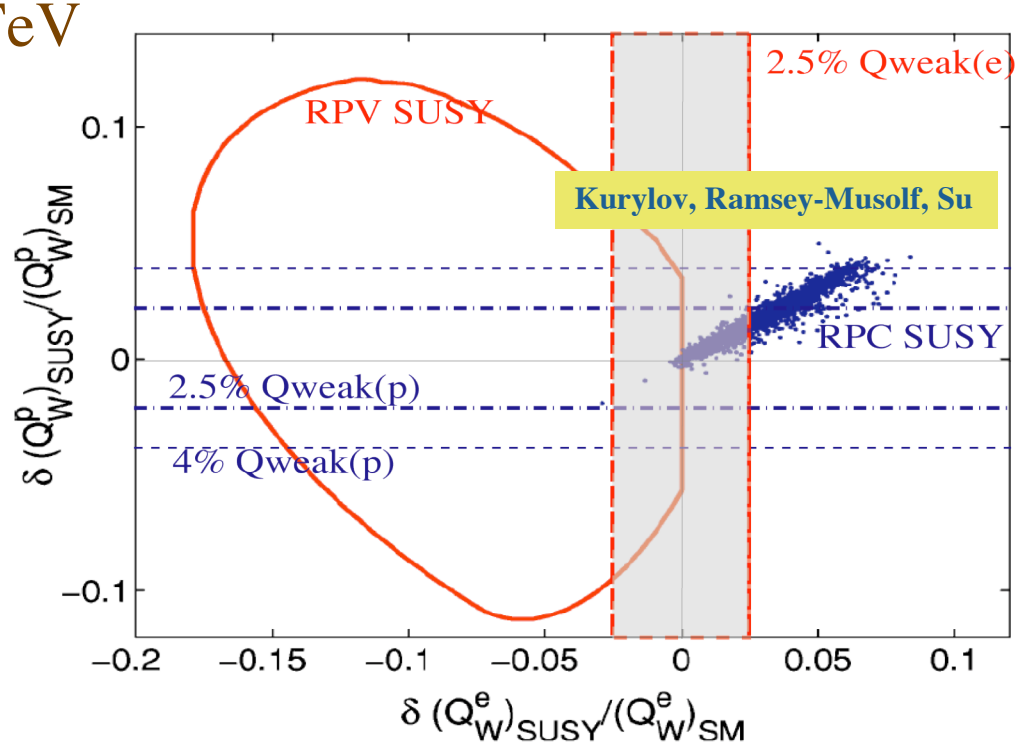


LHC

Complementary

- SUSY provides a dark matter candidate if baryon (B) and lepton (L) numbers are conserved

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



Q^e_W and Q^p_W would have new contributions from RPV

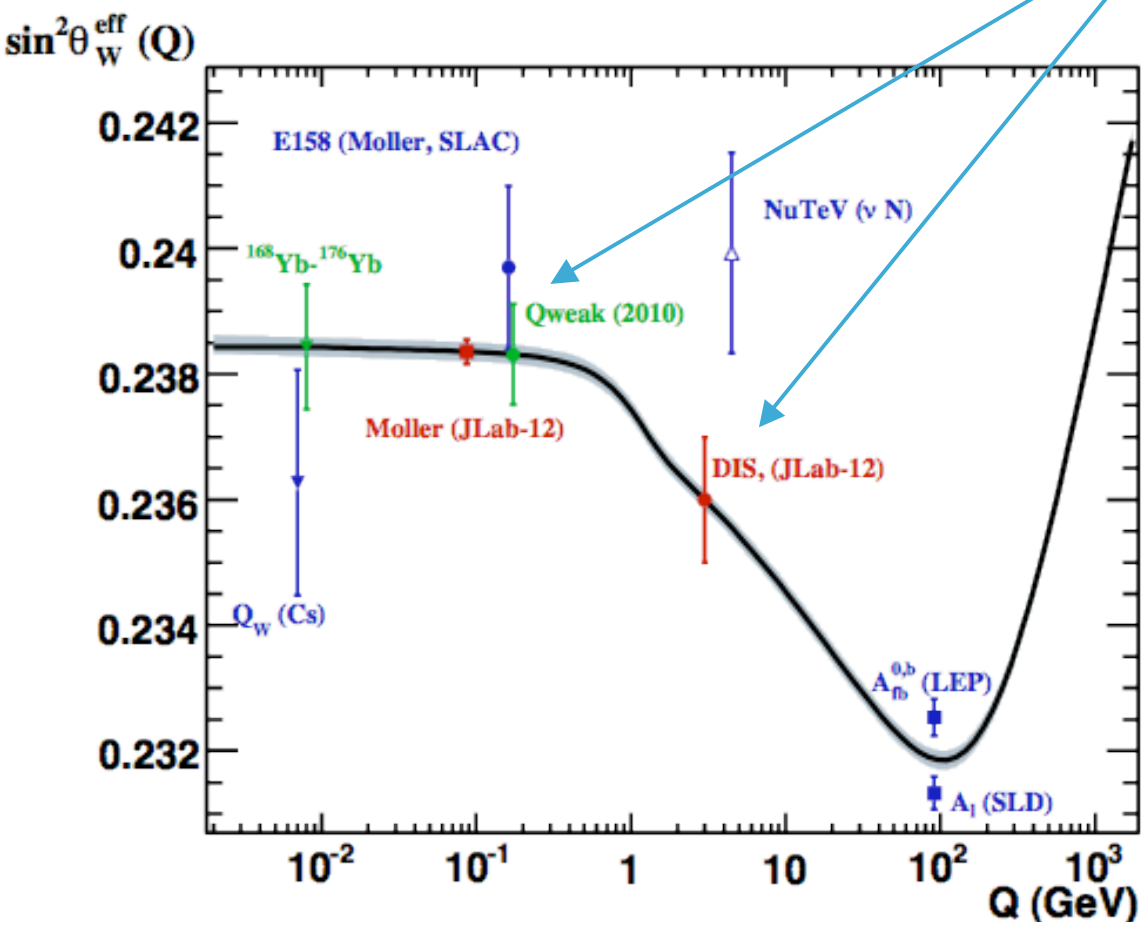
Summary

- ***Future Parity-Violating Electron Scattering Expts:***
  - New precision tests of the Standard Model
  - Important complement to confront LHC Data
- ***Parity-Violating Deep Inelastic Scattering***
  - Necessary component of a comprehensive search for "New Physics"
- ***12 GeV Upgrade of Jefferson Laboratory***
  - Beam quality and luminosity enables world-class electroweak program
  - Enables novel tests of nucleon structure and QPM picture
- ***Solenoidal Spectrometer Package***
  - Provides unprecedented acceptance and resolution at x ~ 0.7
  - Many other physics topics would benefit
    - d/u at high x
    - SIDIS with focus on TMDs
    - Nuclear EMC Effect
    - g_3 and g_5 structure functions

Weak Mixing Angle

Plot not truly appropriate for QWeak (proton) and PV-DIS (or APV or NuTeV…)

… they test for different terms in the Lagrangian



12 GeV Moller helps settle ambiguity in the mixing angle, plus opens door to new contributions in radiative corrections.