DIS-Parity: Physics Beyond the Standard Model with Parity NonConserving Deep Inelastic Scattering

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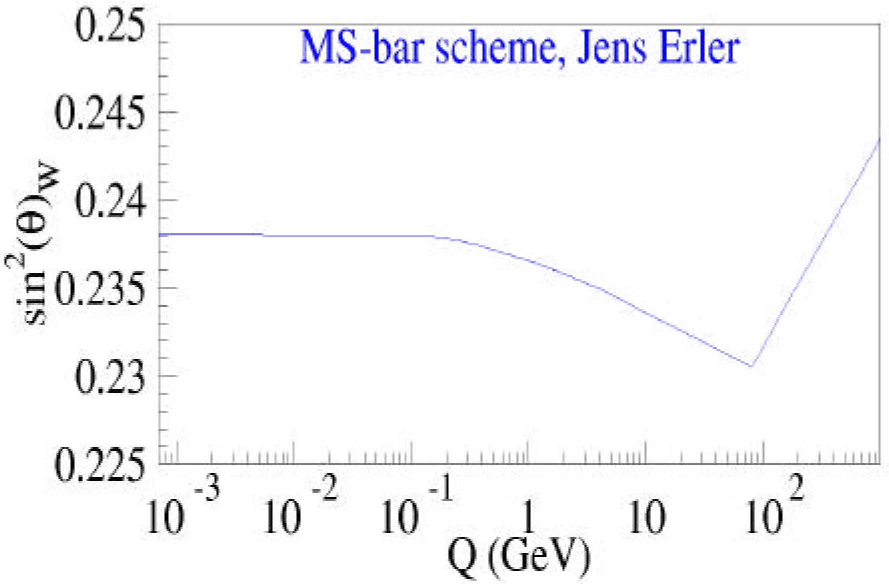
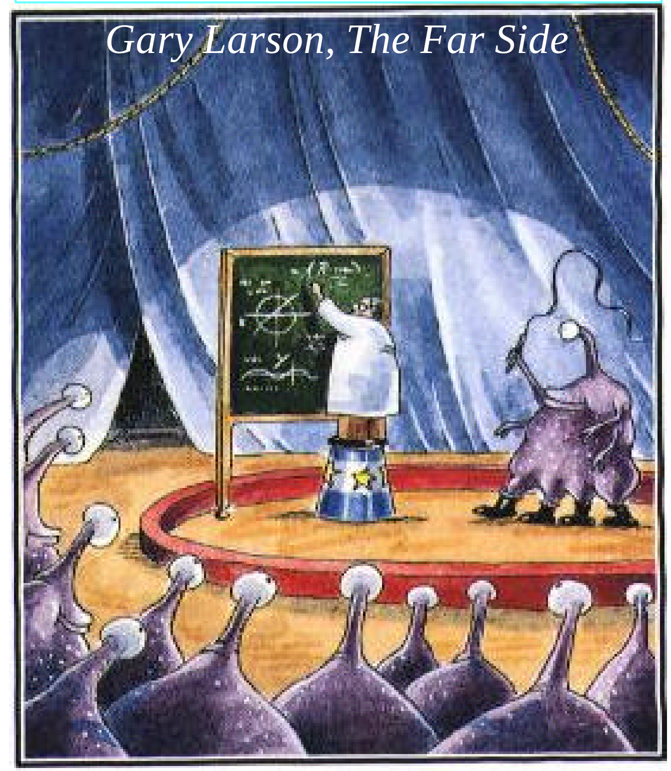
- Introduction: Weinberg-Salam Model and $\sin^2(\theta_W)$
- Parity NonConserving Electron Deep Inelastic Scattering
- 11 GeV Measurement at Jefferson Laboratory



Work done in collaboration with Peter Bosted, Dave Mack *et al.*

Weinberg-Salam model and $\sin^2(\theta_W)$

Remember—I'm not the expert. . .



Abducted by an alien circus company, Professor Doyle is forced to write calculus equations in center ring.

Unification of Weak and E&M Force

- SU(2)—weak isospin—Triplet of gauge bosons
- U(1)—weak hypercharge—Single gauge boson

Electroweak Lagrangian:

$$\mathcal{L} = g\vec{J}_\mu \cdot \vec{W}_\mu + g' J_\mu^Y B_\mu \qquad J_\mu^Y = J_\mu^{\mathrm{EM}} - J_\mu^{(3)}$$

J_m, J_m^Y isospin and hypercharge currents
g, g' couplings between currents and fields

$$\begin{aligned} W_\mu^\pm &= \tfrac{1}{\sqrt{2}}\left(W_\mu^{(1)} \pm iW_\mu^{(2)}\right) && \text{Weak CC} \\ A_\mu &= \tfrac{1}{\sqrt{g^2+g'^2}}\left(g'W_\mu^{(3)} + gB_\mu\right) && \text{EM NC} \\ Z_\mu^0 &= \tfrac{1}{\sqrt{g^2+g'^2}}\left(g'W_\mu^{(3)} - gB_\mu\right) && \text{Weak NC} \end{aligned}$$

θ_w , relative strength of the SU(2) and U(1) couplings:

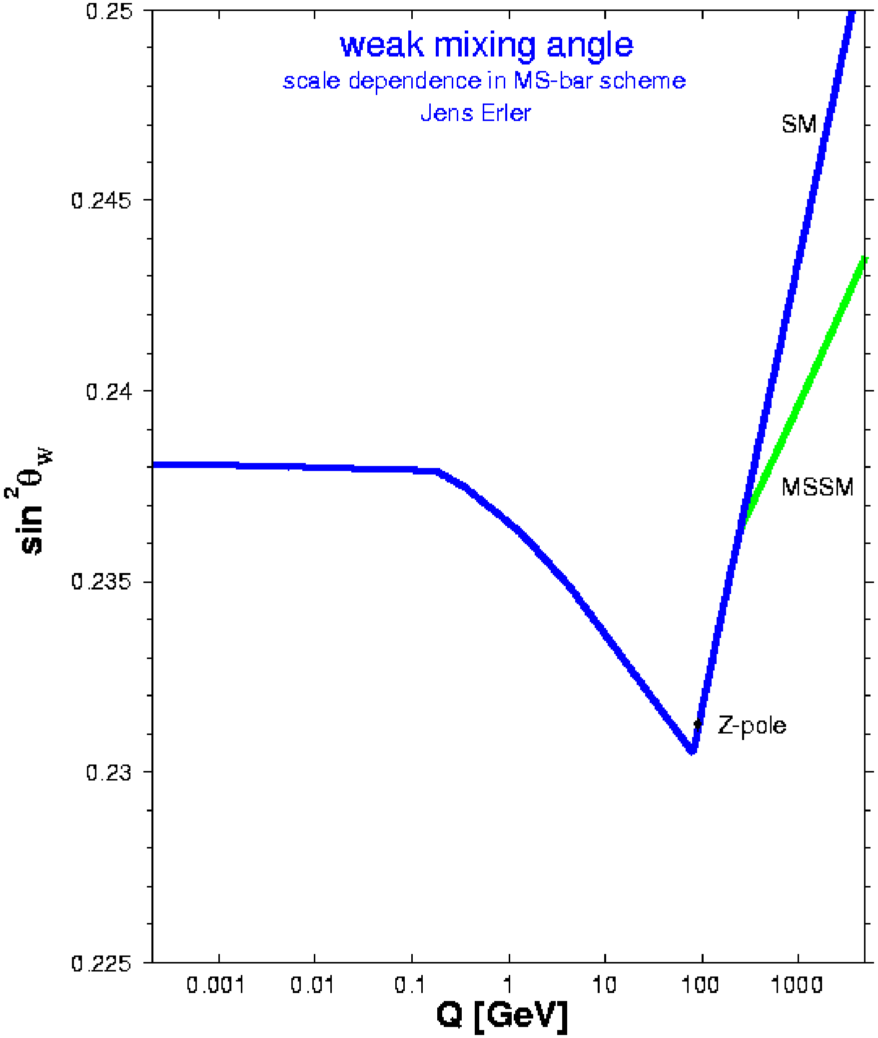
$$\tan\theta_W = \frac{g'}{g} \qquad \sin\theta_W = \frac{g'}{\sqrt{g'^2+g^2}}$$

$$\cos\theta_W = \frac{g}{\sqrt{g'^2+g^2}}$$

- Observables:
  - $Q_{EM} \equiv e = g\sin(\theta_W)$
  - $\sin^2(\theta_W) = 1 - M_W^2/M_Z^2$.

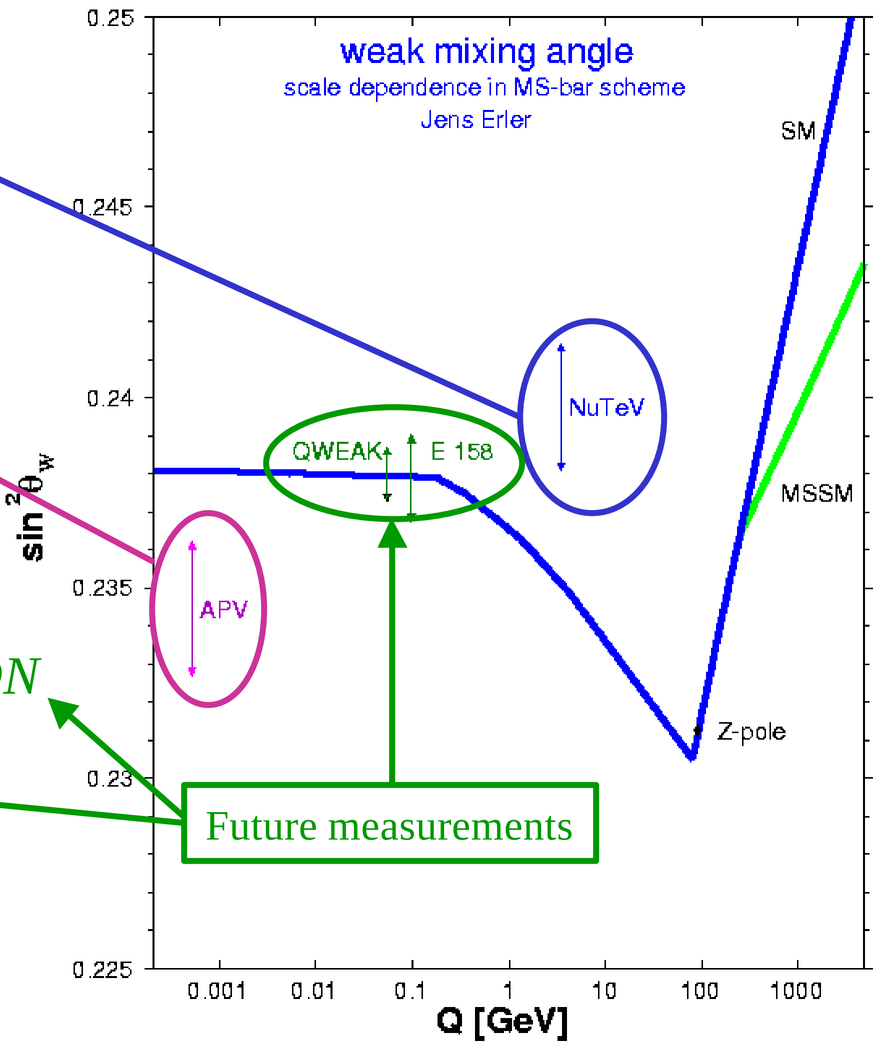
$\sin^2(\theta_W)$ vs. Q^2

- Standard Model predicts $\sin^2(\theta_W)$ varies (runs) with Q^2
  - Well measured at Z-pole, but not at other Q^2.
  - Running sensitive to non-Standard Model Physics.
  - Different measurements sensitive to *different* non-S.M. physics.
- $\sin^2(\theta_W)$ is *scheme dependent* observable—it's value depends on the renormalization scheme.

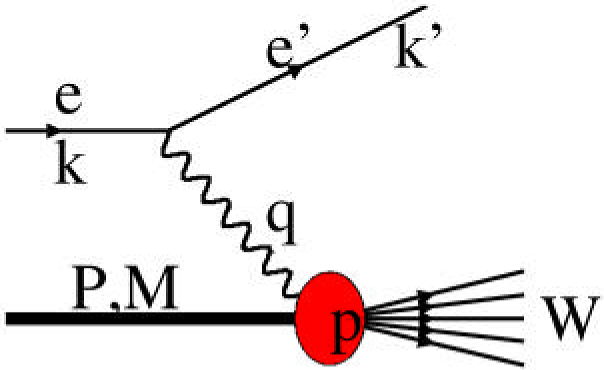


$\sin^2(\theta_W)$ measurements below Z-pole

- NuTeV νA scattering:
  - 3σ from Standard Model!!!
  - *Fe* target: PDF's in iron? Nuclear corrections—NC vs. CC?
- Atomic Parity Violation (APV):
  - Good measurement, hard to understand theoretically.
  - *Appears* to differ from S.M.??
- Q_{weak} (Jlab)
  - Q_{weak} *PROTON*
  - ¼ 2005-07
- E158-Moller
  - Q_{Weak} *ELECTRON*
  - *Final run 2004*
- DIS-Parity:
  - 11 GeV JLab Deep Inelastic Scattering Parity violation.
  - Deuterium/Hydrogen target.
  - $Q^2 = 3.5\ \mathrm{GeV}^2$ ($Q = 1.9$ GeV)



Polarized e^- *deuterium* DIS



$Q^2 = -q^2 = 2(EE^0 - \mathbf{k}$¢ $\mathbf{k})$

$- m_l^2 - m_l^2$

¼ $4EE^0 \sin^2(\theta/2)$

$\nu = \mathbf{q}$¢ $\mathbf{P}/M = E - E^0$

$x = Q^2/2M\nu$

$y = \mathbf{q}$¢ $\mathbf{P}/\mathbf{k}$¢ $\mathbf{P} = \nu / E$

$W^2 = (\mathbf{P} + \mathbf{q})^2$

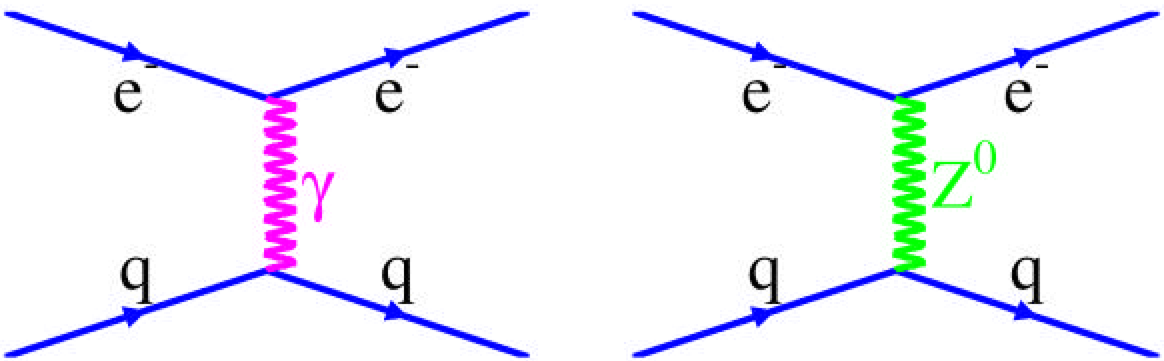
$= M^2 + 2M\nu - Q^2$

$s = (\mathbf{k} + \mathbf{P})^2$

$= Q^2/xy + M^2 + m_l^2$

Look for left-right asymmetry in polarized eD deep inelastic scattering

•Asymmetry caused by interference between Z^0 and γ diagrams.



•Use deuterium target: u(x) ´ d(x)

•Large asymmetry: A_d¼ 10^{-4}

DIS Formalism

Longitudinally polarized electrons on unpolarized isoscaler (deuterium) target (derivation is problem for listener).

$$A_d = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

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

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

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

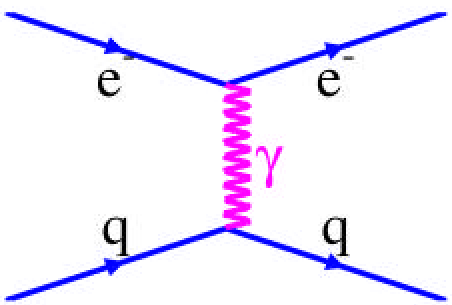
$$R_s(x) = \frac{2s(x)}{u(x)+d(x)} \xrightarrow{\text{large x}} 0$$

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

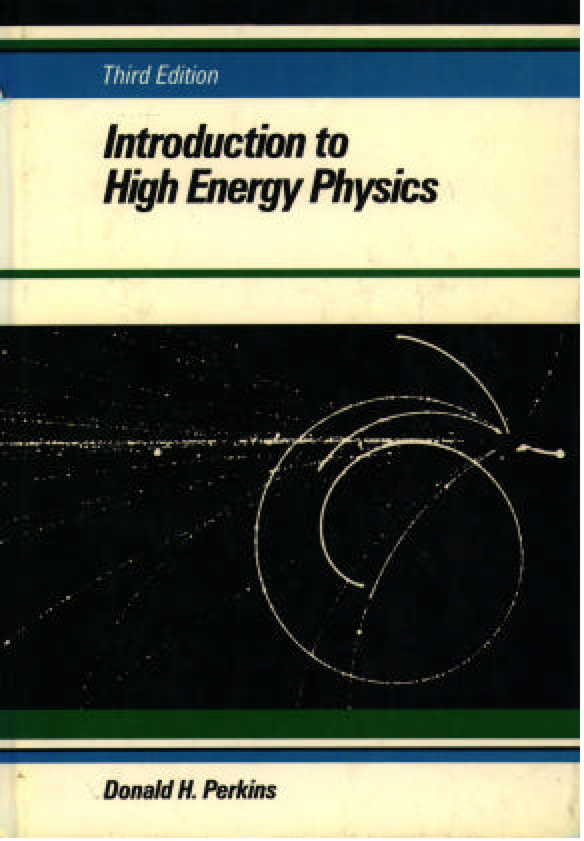
C_{1q}) NC vector coupling to *q*
£ NC axial coupling to *e*

C_{2q}) NC axial coupling to *q*
£ NC vector coupling to *e*

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



Note that each of the C_{ia} are sensitive to *different* possible S.M. extensions.



Textbook Physics: Polarized e$^-$ d scattering

9.7. Experimental Tests of Neutral Currents in the Weinberg-Salam Model 333

9.7.4. Asymmetries in the Scattering of Polarized Electrons by Deuterons

Finally we discuss a very delicate experiment to detect tiny parity-violation effects (asymmetries) due to the interference between Z^0 and γ-exchange in inelastic scattering of polarized electrons by deuterons. The experiment was carried out with beams of electrons of 16–22-GeV/c momentum at SLAC, the reaction being

$$e^-_{L,R} + d_{\text{unpolarized}} \to e^- + X,$$

Repeat SLAC experiment (30 years later) with better statistics and systematics at 12 GeV Jefferson Lab:

- Beam current 100 μA vs. 4 μA at SLAC in '78 £ 25 stat
- 60 cm target vs. 30 cm target £ 2 stat
- P_e (=electron polarization) = 80% vs. 37% £ 4 stat
- δP_e ¼ 1% vs. 6% £ 6 sys

Experimental Constraints and Kinematics

- Small sea quark uncertainties) $x > 0.3$
- Better sensitivity to $\sin^2(\theta_W)$) Large Y
- DIS region, minimize higher twist) $Q^2 > 2.0$ GeV^2
) $W^2 > 4.0$ GeV^2
- d(x)/u(x) uncertainties) deuterium target
- Pion and other backgrounds) $E^0/E > 0.3$ ($y < 0.7$)

Quick calculations show that these conditions are best matched with an 11 GeV beam and an electron scattering angle of approximately 10±-15± (12.5±).

hxi = 0.45 hQ²i = 3.5 GeV²

hYi = 0.46 hW²i = 5.23 GeV²

$$\left.\frac{\delta \sin^2\theta_W}{\sin^2\theta_W}\right|_{Y=0.46} \approx \frac{1}{2}\left(\frac{\delta A_d}{A_d}\right) \qquad A_d \approx 2.9\times 10^{-4}$$

Detector and Expected Rates

- Expt. Assumptions:
  - 60 cm ld_2/lH_2 target
  - 11 GeV beam @ 90μA
  - 75% polar.
  - 12.5$^{\pm}$ central angle
  - 12 msr dΩ
  - 6.8 GeV § 10% momentum bite

- Rate expectations:
  - 1MHz DIS
  - π/e ¼ 1) 1 MHz pions
  - 2 MHz Total rate
  - dA/A = 0.5%) 345 hrs (ideal) plus time for H_2 and systematics studies.

- *Will work in either Hall C (HMS +SHMS) or Hall A (MAD)*
- π/e separation requires gas Cherenkov counters ¼ 6 GeV thresh.
- Ignore tracking in detectors
- Rate requires flash ADC's on Cherenkov and Calorimeters—this is a counting experiment!!

Uncertainties in A_d

- Beam Polarization:
  - QWeak also needs 1.4% polarization accuracy.
  - Hall C Moller has achieved 0.5% polarization accuracy.
- Higher twists may enter in at this low of Q^2:
  - Check by taking additional data at lower Q^2
  - 12.5±—11 GeV and 15±—8 GeV data
  - Possible 6 GeV experiment?
- EMC effect in d_2
  - Check with proton data in region where d/u is known.

Statistical	0.5%
Beam polarization	1.0%
δQ^2	0.5%
Radiative corr.	<1%
$\delta R = \delta(\sigma_L/\sigma_T) =$ § 15%	<0.02%
$\delta s(x) =$ § 10%	<0.03%
Higher Twist	????
EMC Effect	????

Expected $\sin^2(\theta_W)$ Results

$$A = f\left[\alpha + \beta \sin^2(\theta_W)\right] \qquad A = 1.1 \times 10^{-4} Q^2 \left[2.2 - 6.1 \sin^2(\theta_W)\right]$$

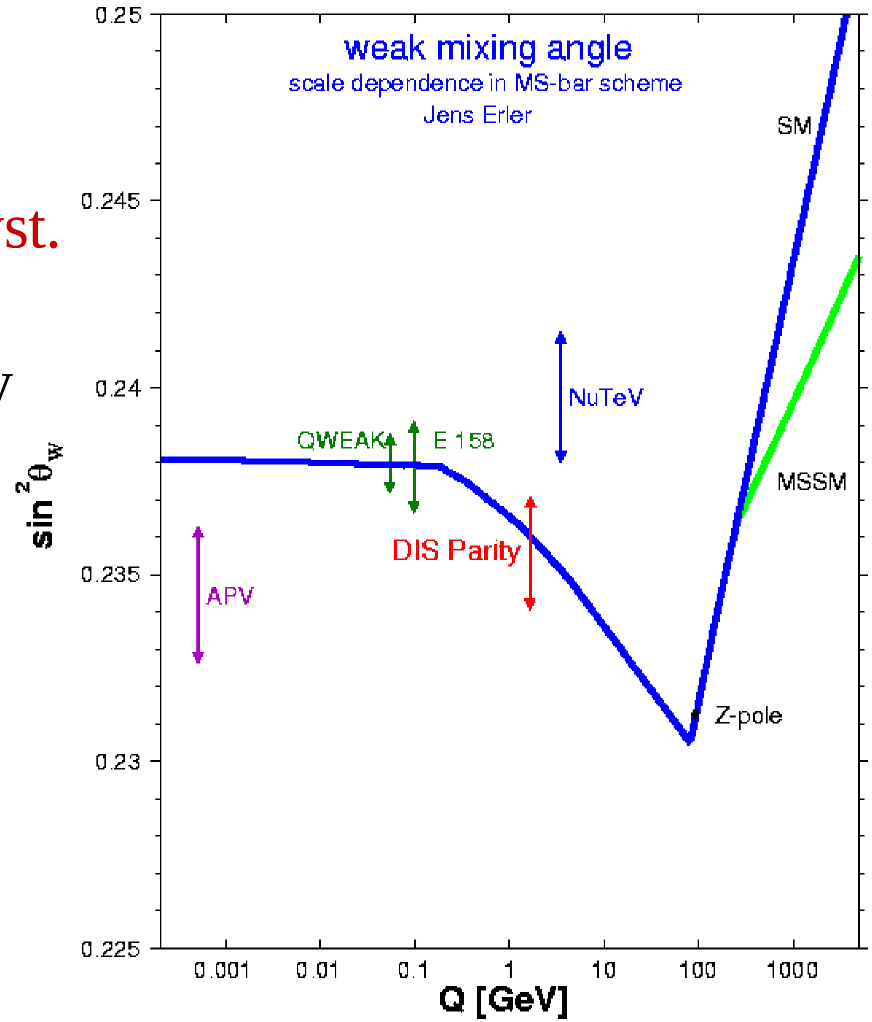
$$\frac{\delta \sin^2(\theta_W)}{\sin^2(\theta_W)} = \frac{\delta A}{A}\frac{1}{\beta}\frac{\alpha + \beta \sin^2(\theta_W)}{\sin^2(\theta_W)}$$

Measure A_d to § 0.5% stat § 1.1% syst. (1.24% combined)

- Measurement uncertainties driven by polarization uncertainties

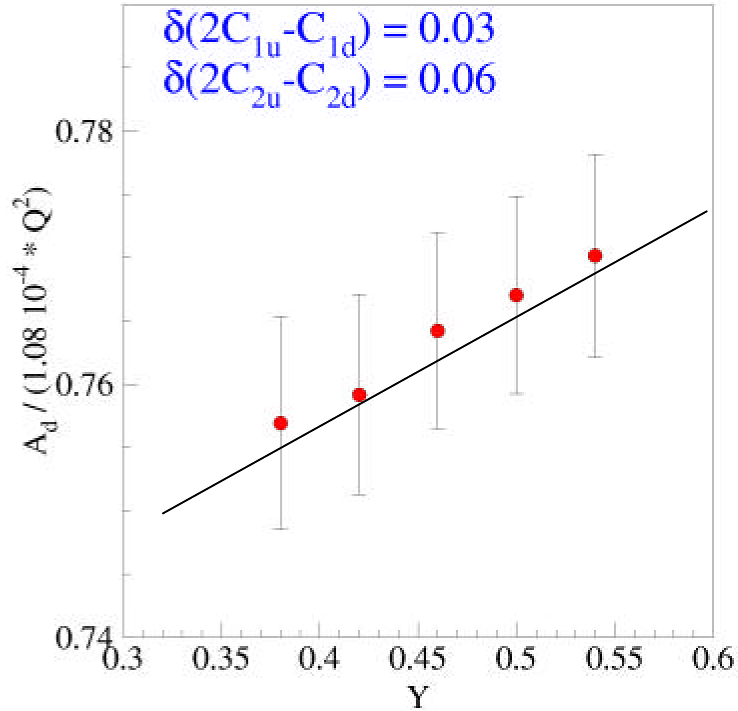
$$\left.\frac{\delta \sin^2 \theta_W}{\sin^2 \theta_W}\right|_{Y=0.46} = 0.56 \left(\frac{\delta A_d}{A_d}\right)$$
$$= 0.7\%$$

What about C_{iq}'s?



Extracted Signal—It's all in the binning

$$\frac{A_d}{1.1 \times 10^{-4} Q^2} \approx -\left[(2C_{1u} - C_{1d}) + Y\,(2C_{2u} - C_{2d})\right]$$



PDG: C_{1u}= –0.209 § 0.041 highly
C_{1d}= 0.358 § 0.037 correlated

$2C_{2u} – C_{2d}$ = –0.08 § 0.24

This measurement:

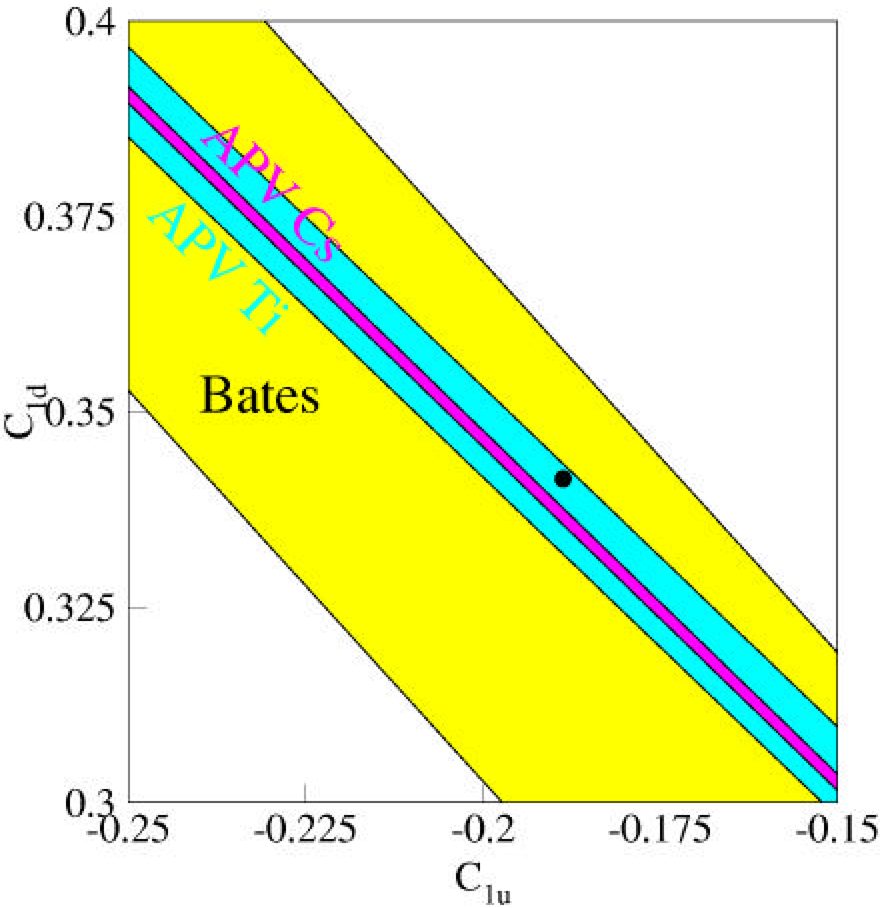
$\delta(2C_{1u} – C_{1d}) = 0.03$ (stat.)

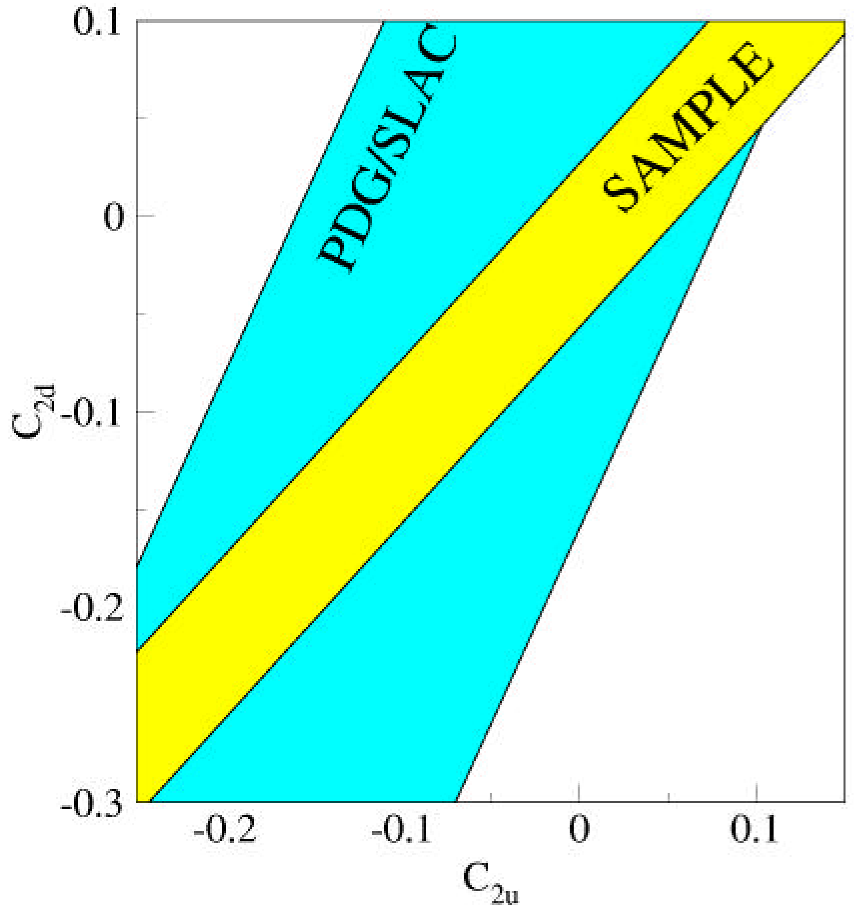
$\delta(2C_{2u} – C_{2d}) = 0.06$ (stat.)

(with out considering other expts.)

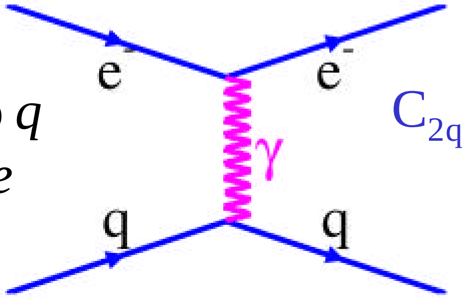
Note—Polarization uncertainty enters as in slope and intercept
$A_{obs} = PA_d$ / $P(2C_{1u}–C_{1d})$ +
$P(2C_{2u}–C_{2d})Y]$
but is correlated

Constraints with DIS-Parity



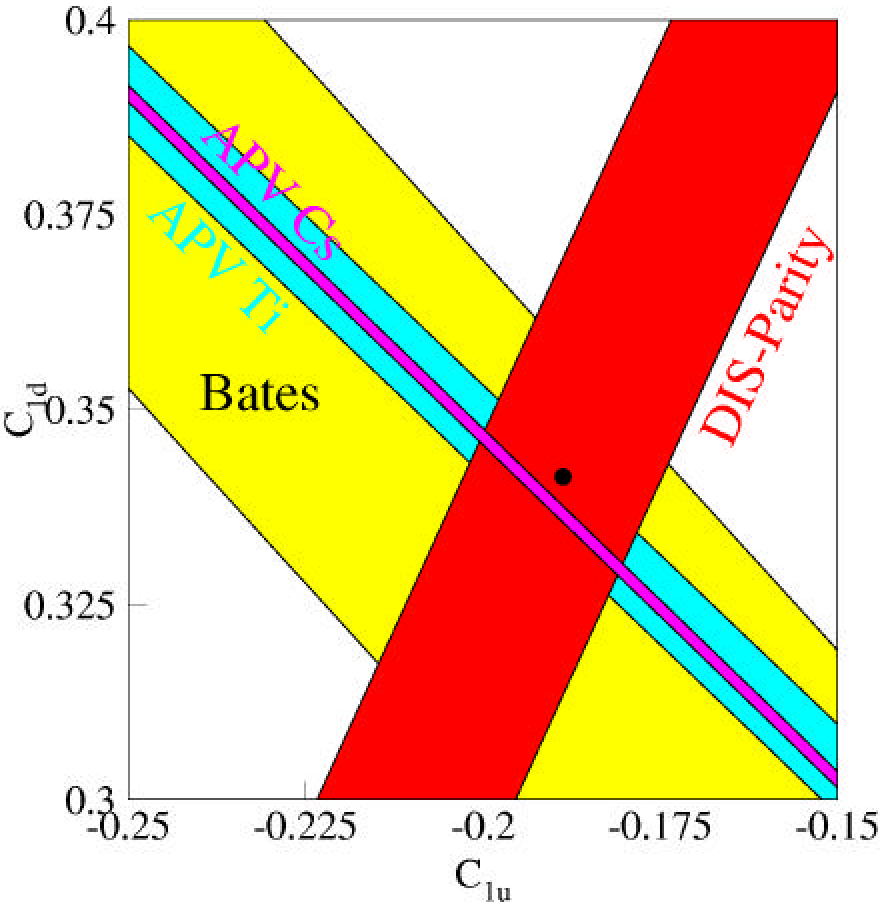


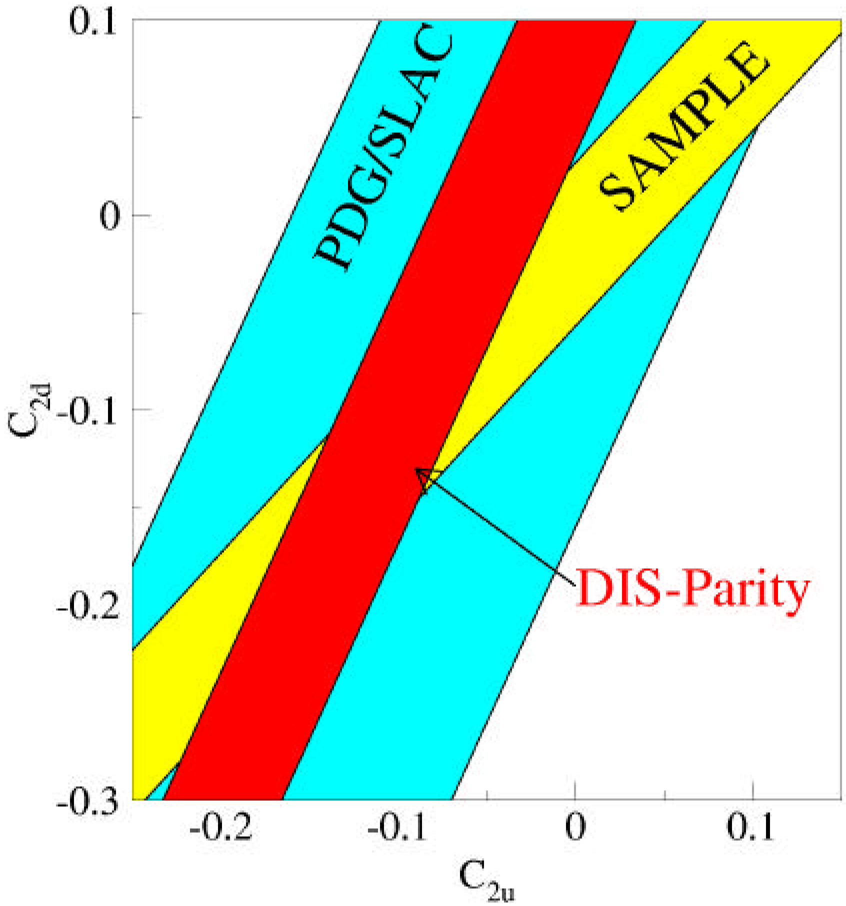
C_{1q}) NC vector coupling to *q*
£ NC axial coupling to *e*



C_{2q}) NC axial coupling to *q*
£ NC vector coupling to *e*

Constraints with DIS-Parity



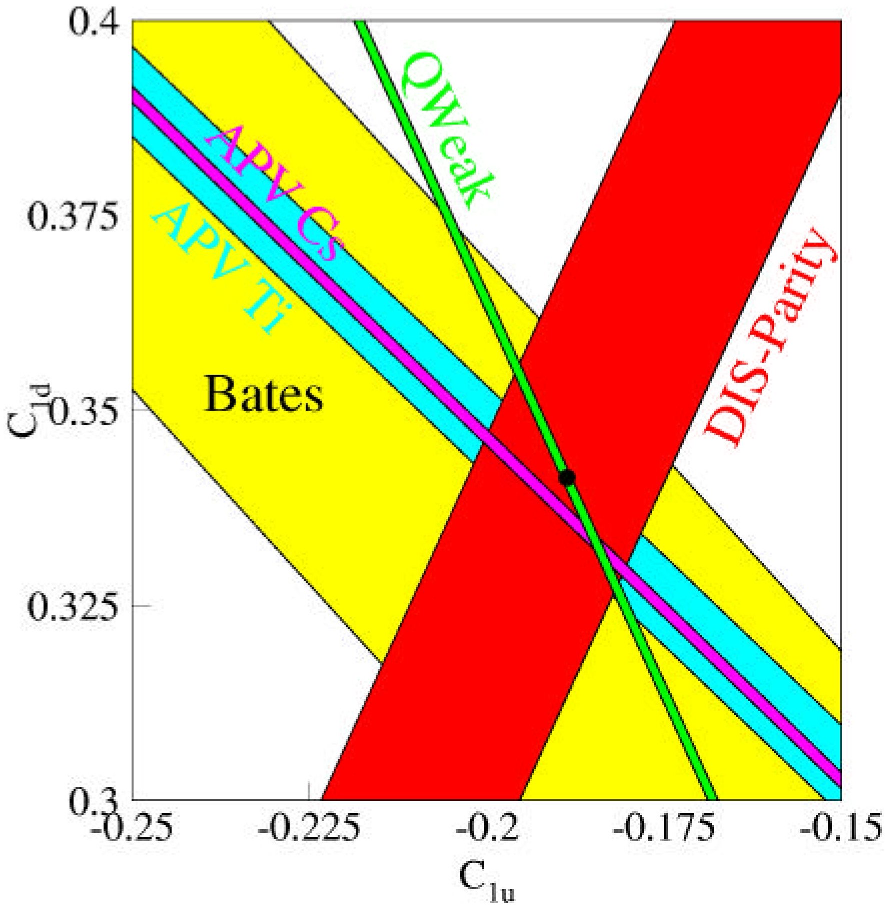


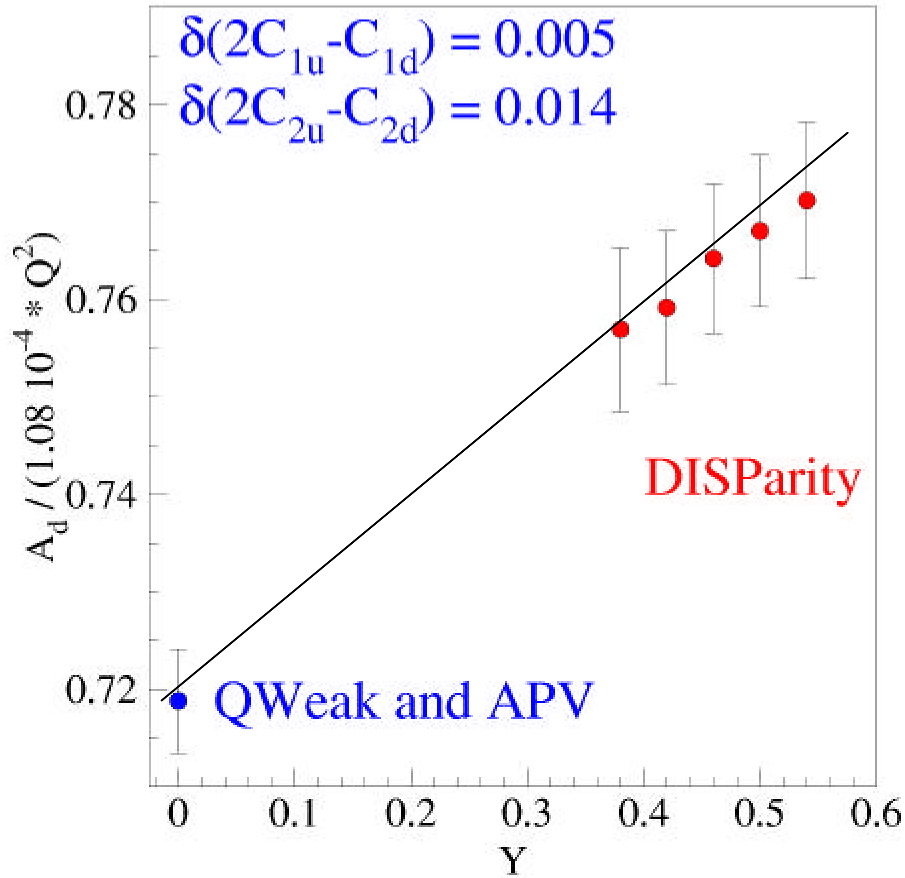
DIS-Parity provides intersecting constraints on C_{ia} parameters:

$\delta(2C_{1u} - C_{1d}) = 0.03$ (stat.) $\delta(2C_{2u} - C_{2d}) = 0.06$ (stat.)

(1σ limits)

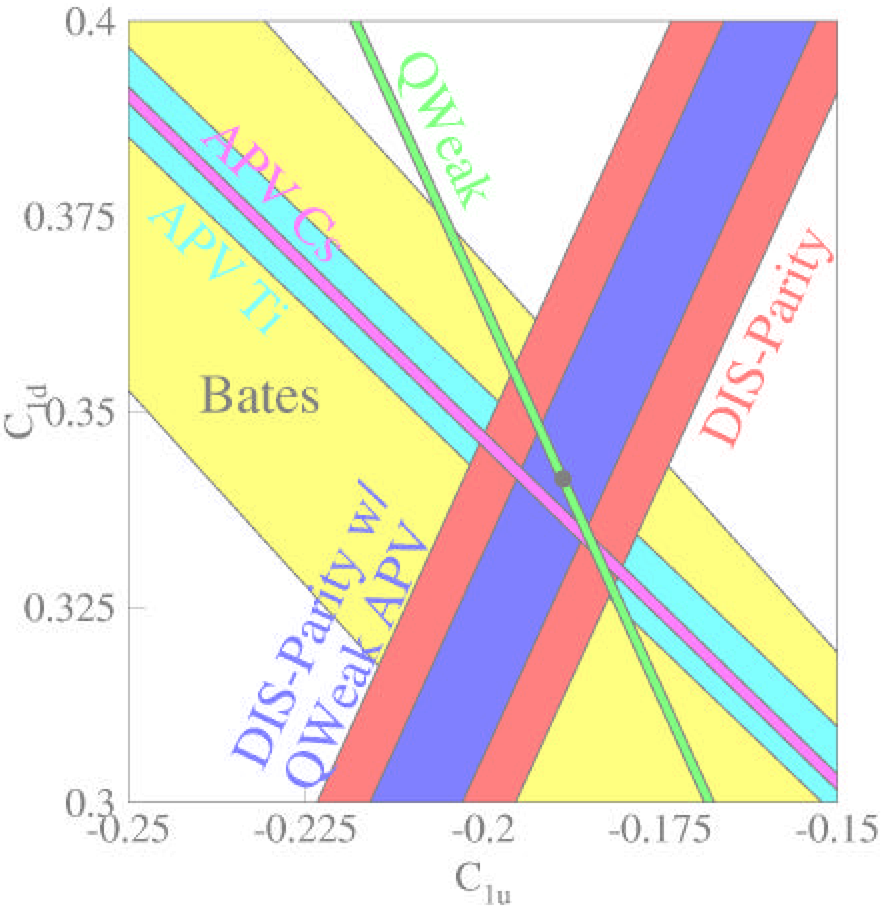
QWeak & APV will Constrain C_{1u} & C_{1d}

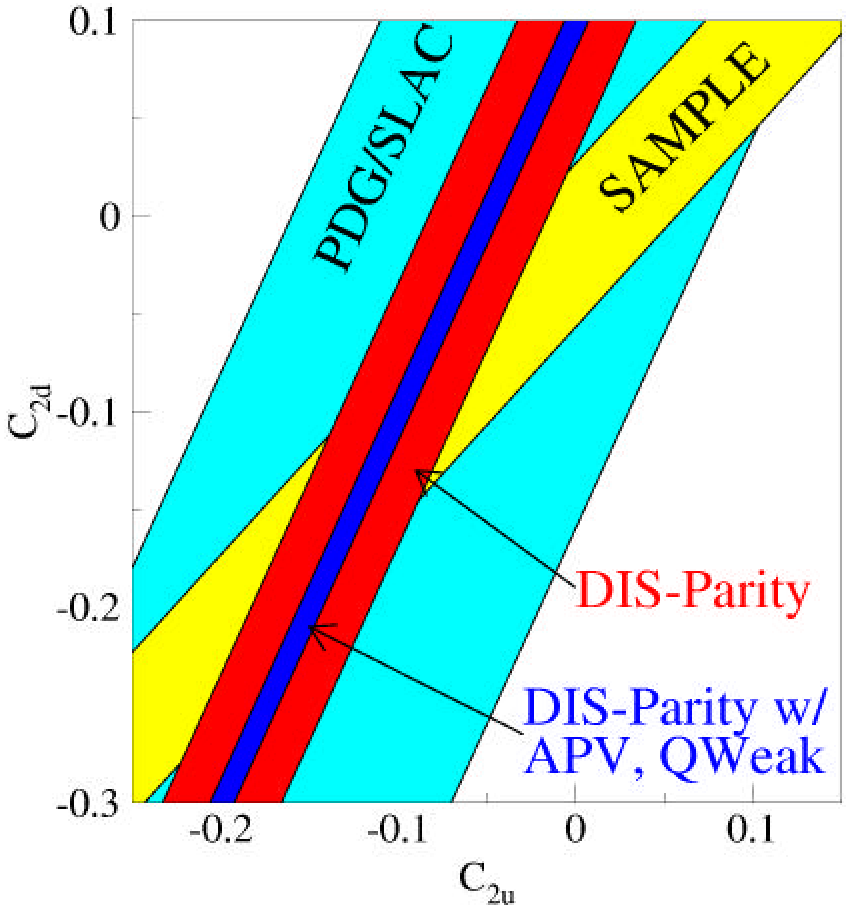




Combined expected Qweak (proton) and APV measurements give a better value for C_{1u} and C_{1d}. Will provide an "anchor" point for fit. Very useful in determining $2C_{2u}– C_{2d}$.

DIS-Parity determines $2C_{2u}-C_{2d}$





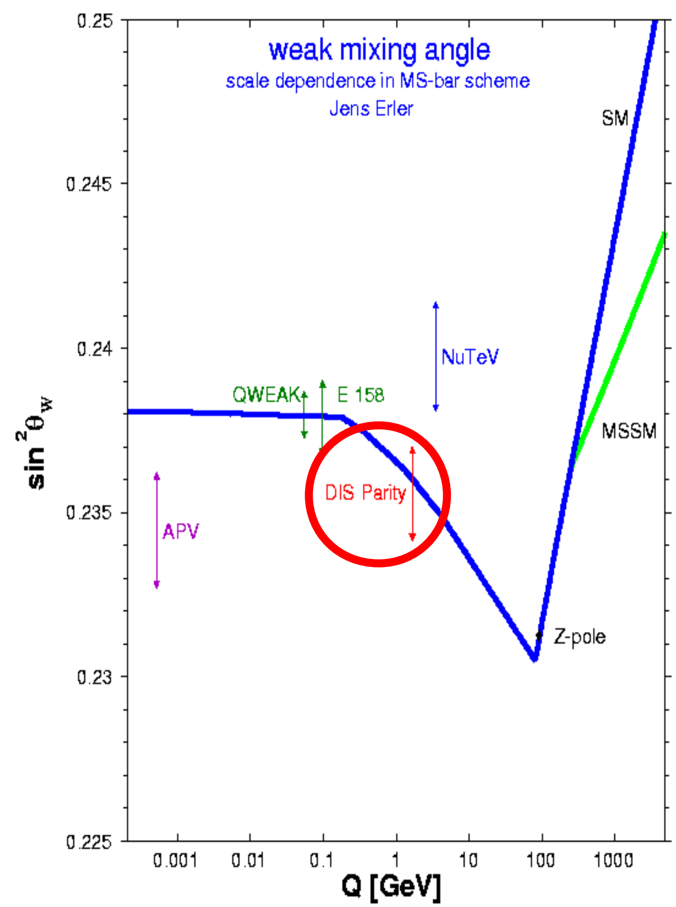
Combined result significantly constrains $2C_{2u}–C_{2d}$.

PDG $2C_{2u}–C_{2d}$ = –0.08 § 0.24 Combined $\delta(2C_{2u}–C_{2d})$ = § 0.014

£ 17 improvement (S.M $2C_{2u} – C_{2d} = 0.0986$)

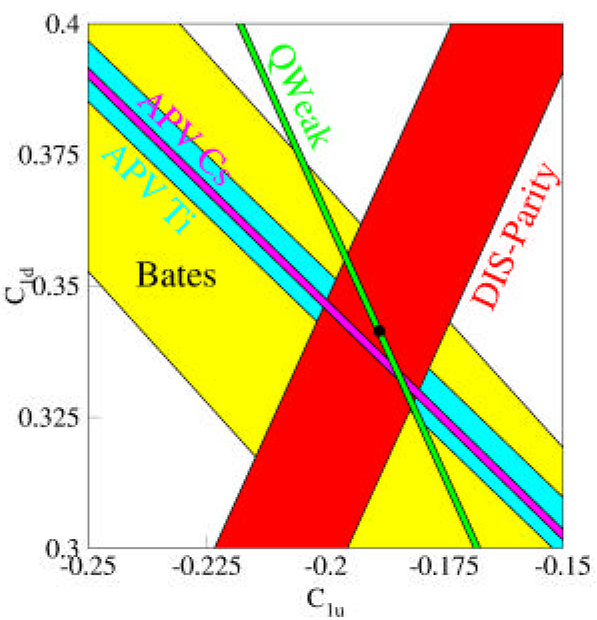
DIS-Parity: Conclusions

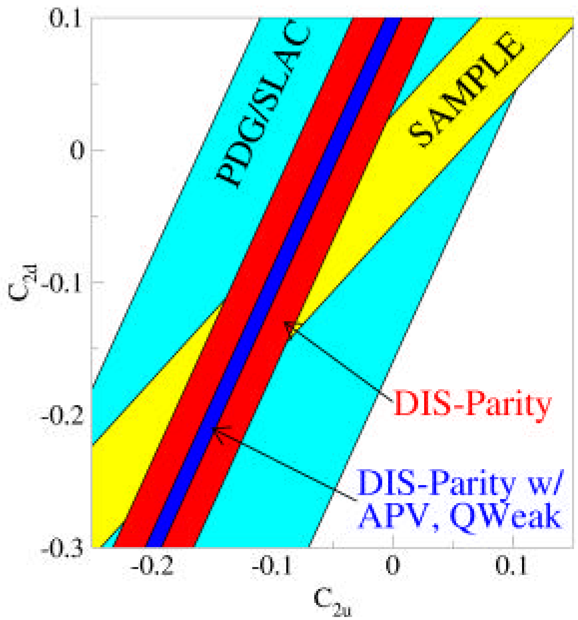
- Measurements of $\sin^2(\theta_W)$ below M_Z provide strict tests of the Standard Model.
- Parity NonConserving DIS provides complimentary sensitivity to other planned measurements.
- DIS-Parity Violation measurements can be carried out at Jefferson Lab with the 12 GeV upgrade (beam and detectors) in either Hall A or Hall C.



$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} = 0.7\%$$

$$\delta(2C_{1u} - C_{1d}) = 0.005$$
$$\delta(2C_{2u} - C_{2d}) = 0.014$$





Weinberg-Salam model and $\sin^2(\theta_W)$

Unification of Weak and E&M Force

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Electroweak Lagrangian:

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$$J^Y_\mu = J^{\mathrm{EM}}_\mu - J^{(3)}_\mu$$

J_m, $J^y{}_m$ isospin and hypercharge currents

g, g^0 couplings between currents and fields

$$\begin{aligned} W^\pm_\mu &= \frac{1}{\sqrt{2}}\left(W^{(1)}_\mu \pm iW^{(2)}_\mu\right) && \text{Weak CC} \\ A_\mu &= \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu + gB_\mu\right) && \text{EM NC} \\ Z^0_\mu &= \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu - gB_\mu\right) && \text{Weak NC} \end{aligned}$$

$$\tan\theta_W = \frac{g'}{g} \qquad \sin\theta_W = \frac{g'}{\sqrt{g'^2+g^2}}$$

$$\cos\theta_W = \frac{g}{\sqrt{g'^2+g^2}}$$

- Observables: Q_{EM} ´ $e = g\sin(\theta_W)$

  $\sin^2(\theta_W) = 1 - M_W{}^2/M_Z{}^2$.

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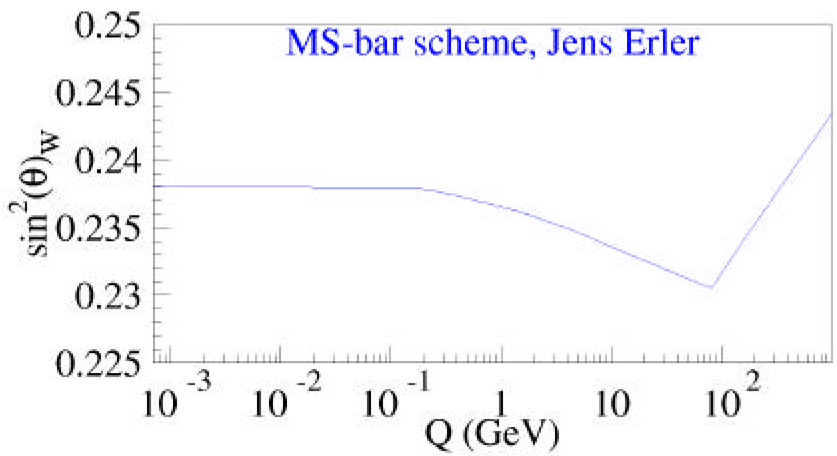


  - Running sensitive to non-Standard Model Physics.
  - Different measurements sensitive to *different* non-S.M. physics.
- $\sin^2(\theta_W)$ is *scheme dependent* observable—it's value depends on the renormalization scheme.

Additional Possibilities with H_2

- Asymmetry in σ_d-$2\sigma_p$
  - Interpretation does not require knowledge of parton distributions.

$$A_{d2p} = \frac{\sigma_d^L - \sigma_d^R - 2\left(\sigma_p^L - \sigma_p^R\right)}{\sigma_d^L + \sigma_d^R - 2\left(\sigma_p^L + \sigma_p^R\right)}$$

$$= \left(\frac{G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\left[-\frac{1}{2} + 2\sin^2(\theta_W)\right] \times [1+Y]$$

$$\approx -0.65 \times 10^{-5} Q^2 (1+Y)$$

- Ratio of asymmetries: A_p/A_d
  - If C_{1a}'s are known, measures r(x) ¼ d(x)/u(x) at large x.
  - Polarization cancels out.

$$\left(\frac{A_p}{A_d}\right) = \left(\frac{2C_{1u} - r(x)C_{1d}}{2C_{1u} - C_{1d}}\right)\left(\frac{5}{4 + r(x)}\right)$$

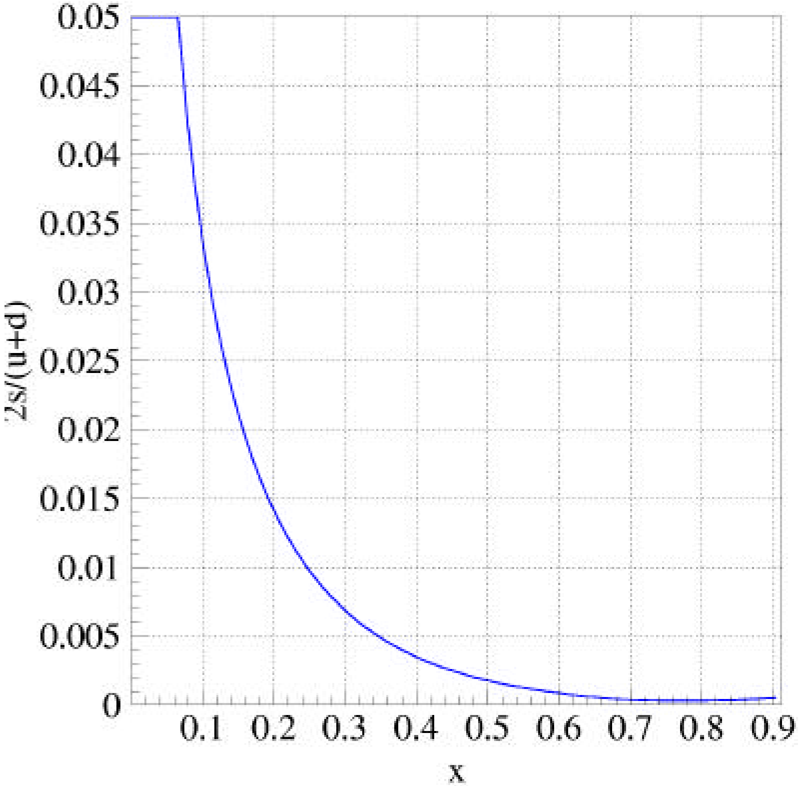
$$r(x) \approx d(x)/u(x)$$

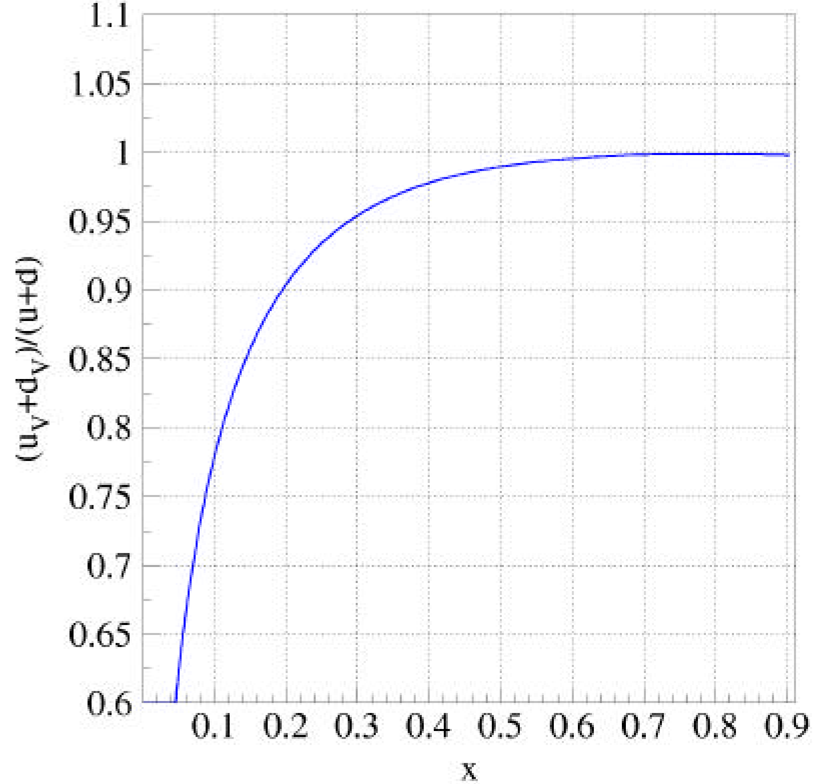
- s-quark distribution at low x: A_p
  - Q^2 possibly not high enough at Jlab 11 GeV.

$R_s(x)$ and $R_V(x)$

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

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





Uncertainties in PDF's are now known and would be factored into overall error budget.