DIS-Parity: Measuring $\sin^2?_W$ with Parity Violating Deep Inelastic Scattering

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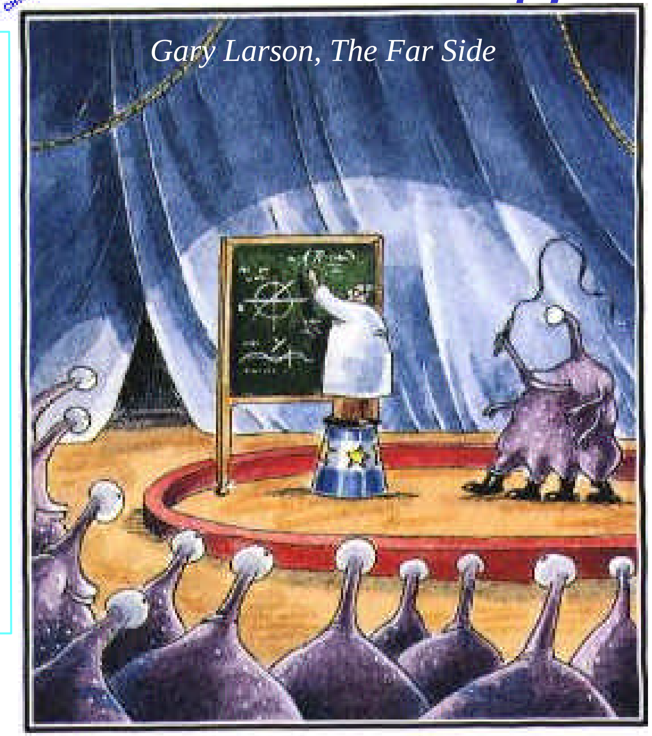
- Introduction: Weinberg-Salam Model and $\sin^2(\theta_W)$
- Parity NonConserving Electron Deep Inelastic Scattering
- Possibilities at SLAC End Station A

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

Remember—I'm not the expert here.



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:

$$\mathcal{L} = g\vec{J}_\mu \cdot \vec{W}_\mu + g' J^Y_\mu B_\mu$$

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

J_m, J_m^Y isospin and hypercharge currents

g, g′ couplings between currents and fields

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^{(1)}_\mu \pm iW^{(2)}_\mu\right) \quad \text{Weak CC}$$

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu + gB_\mu\right) \quad \text{EM NC}$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2+g'^2}}\left(g'W^{(3)}_\mu - gB_\mu\right) \quad \text{Weak NC}$$

$$\tan\theta_W = \frac{g'}{g}$$

Standard Model parameters:

- Charge, $e \Leftrightarrow \alpha_{em}$
- $g \Leftrightarrow G_F$ from μ lifetime
- M_Z
- $\sin^2(\theta_W)$

Charge

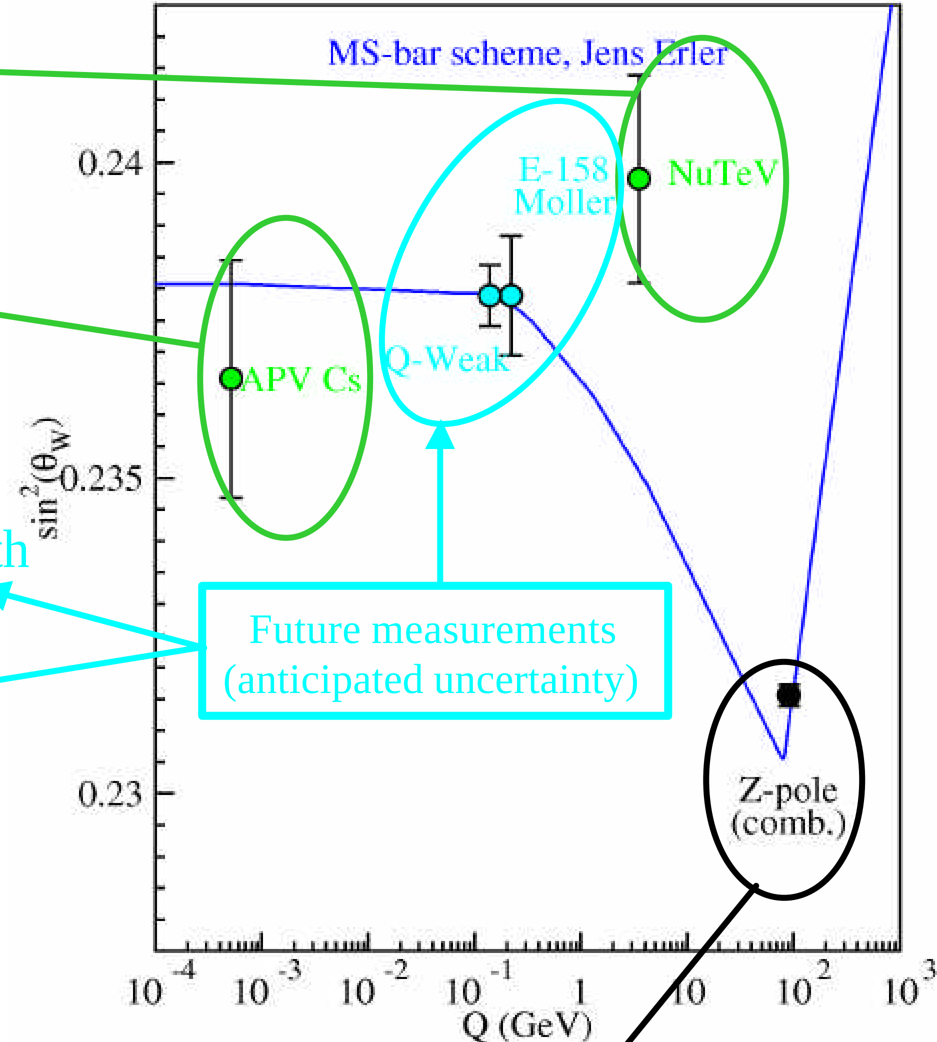
Vector: $g^i_V = t_{3L}(i) - 2q_i \sin^2(\theta_W)$

Axial: $g^i_A = t_{3L}(i)$

Weak isospin

$\sin^2(\theta_W)$ 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.
- SLAC E158-Møller [Q_{weak} (electron)]:
  - Preliminary (low stat.) result agrees with Standard Model (large uncertainties)
  - Final run this summer
- Jefferson Lab Q_{weak} (proton)
  - Elastic ep scattering
  - Data in 2008??
- DIS-Parity:
  - Deep Inelastic Scattering Parity Violation on Deuterium
  - SLAC LOI now, data in 2006-2007??
  - $\langle Q^2 \rangle = 20$ GeV^2



- Z-Pole measurements
  - Combined from many expts.

Polarized e^- *deuterium* DIS

$$Q^2 = -q^2 = 2(EE' - \mathbf{k}\cdot\mathbf{k}) - m_l^2 - m_l^2 \approx 4EE'\sin^2(\theta/2)$$

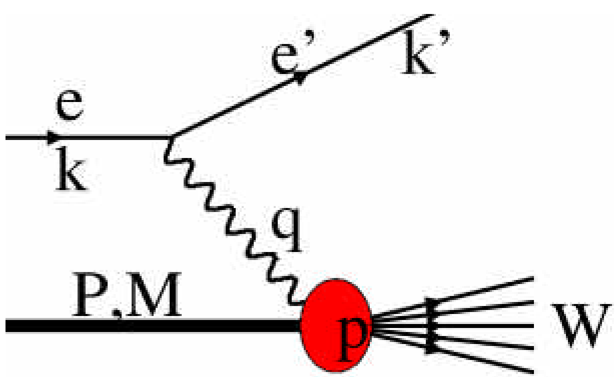
$$\nu = \mathbf{q}\cdot\mathbf{P}/M = E - E'$$

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

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

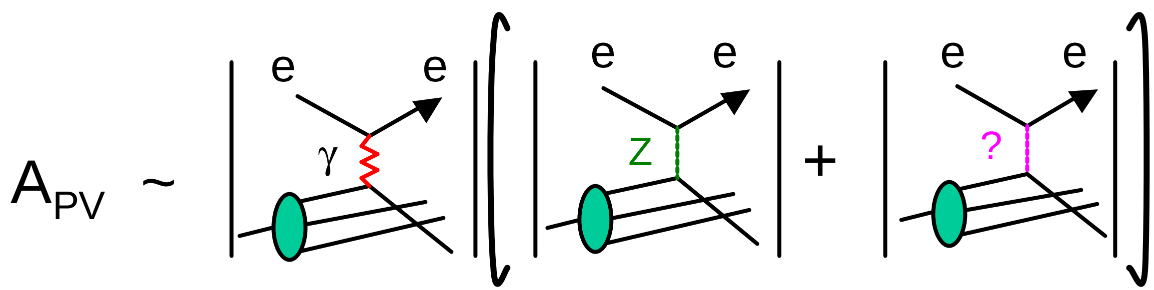
$$W^2 = (\mathbf{P} + \mathbf{q})^2 = M^2 + 2M\nu - Q^2$$

$$s = (\mathbf{k} + \mathbf{P})^2 = Q^2/xy + M^2 + m_l^2$$



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

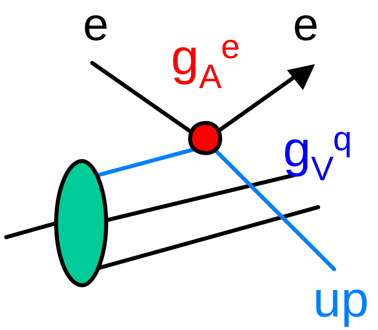
- Asymmetry caused by interference between Z^0 and γ diagrams.



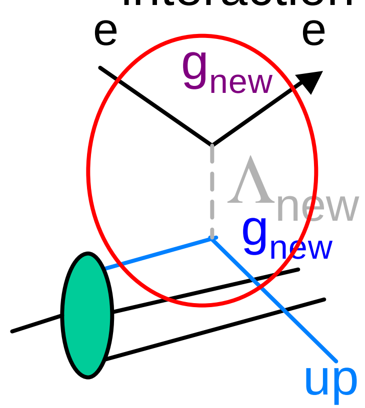
- Use deuterium target: $u(x) \equiv d(x)$
- Large asymmetry: $A_d \approx 10^{-4} \times Q^2$
- Cahn and Gilman **PRD** 17, 1313 (1978)

Standard Model Extensions

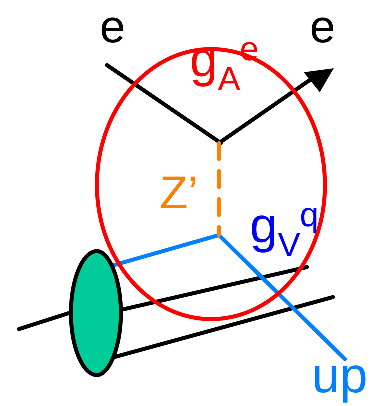
4-Fermi Contact



Heavy short range interaction

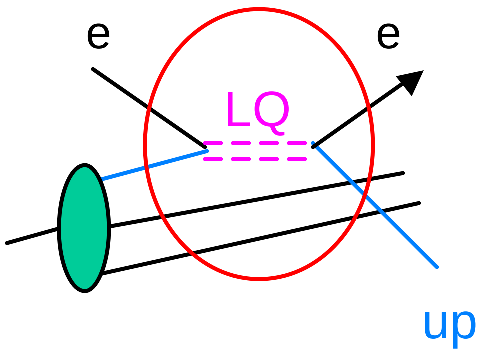


New Z'

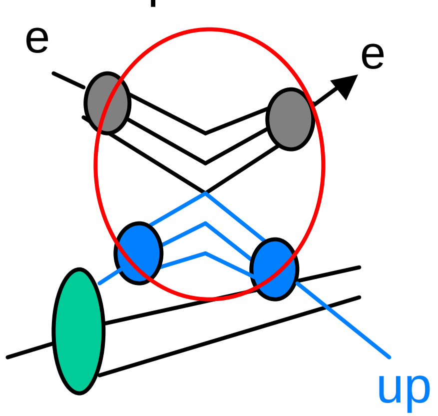


Z′ mass limit of 1.5TeV

Leptoquarks

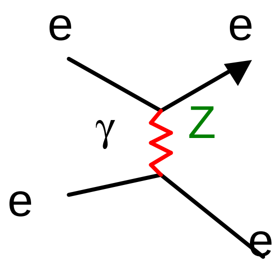


Compositeness



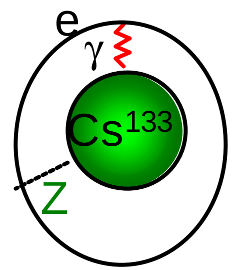
How does DIS-Parity fit in?

SLAC E158/Møller



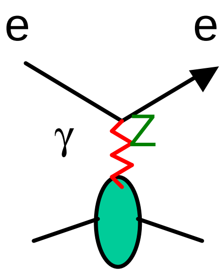
- Purely Leptonic—no quark interactions
- Complete in 2003

Atomic Parity Violation



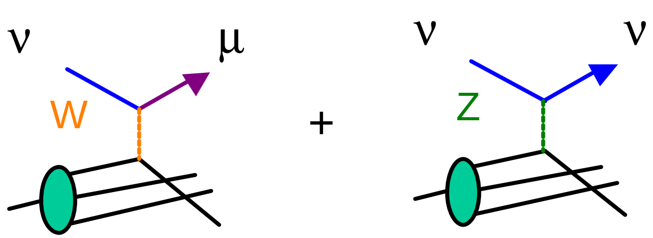
- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Q-Weak (JLab)



- Coherent quarks in Proton
- Results in ~2008
- $2(2C_{1u}+C_{1d})$

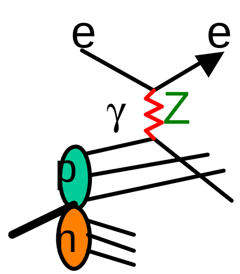
NuTeV (Fermilab)



- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Expt. Probe different parts of Lagrangian

SLAC DIS-Parity



- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

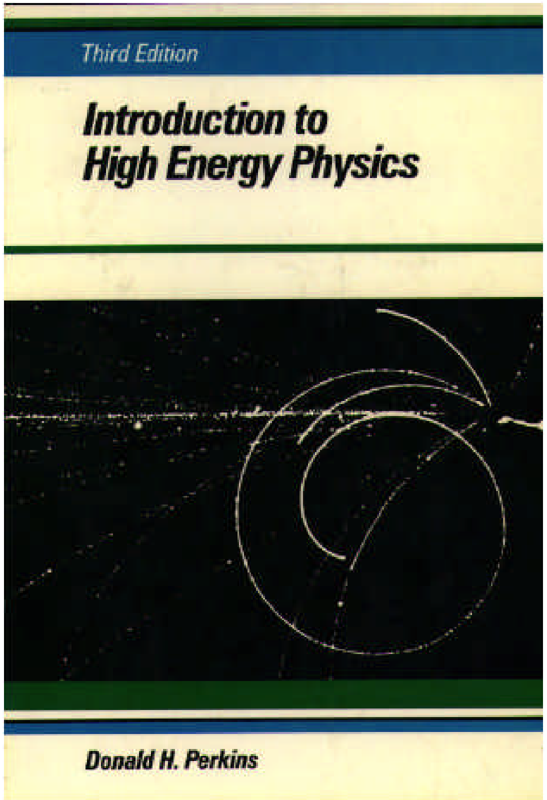
Textbook Physics: Polarized e^- d scattering

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 exp. (30 years later) w/better statistics and systematics:

- Beam current 17 μA vs. 4 μA at SLAC in '78 — × 4 stat
- 100 cm target vs. 30 cm target — × 3 stat
- Higher Q^2 (beam energy) ⟨18⟩ vs ⟨1.6⟩ GeV — × 11 stat
- P_e (electron polarization) = 80% vs. 37% — × 2 stat
- $\delta P_e \approx$ 0.3% vs. 6% — × 20 sys
- Better understanding of QCD (parton distributions/higher twist)
- Better control of beam systematics (polarization)

DIS Formalism

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

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

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

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

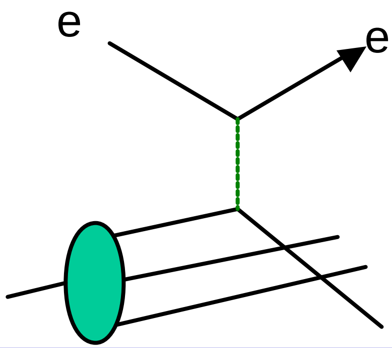
$$R_s(x) = \frac{2s(x)}{u(x)+d(x)} \xrightarrow{\text{large } x} 0$$

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

$C_{1q} \Rightarrow$ NC vector coupling to *q* $\times$ NC axial coupling to *e*

$C_{2q} \Rightarrow$ NC axial coupling to *q* $\times$ NC vector coupling to *e*

C_{ia} provide sensitivity to $\sin^2(\theta_W)$



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

Sensitivity to $\sin^2(\theta_W)$

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

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

$$\text{with } \sin^2(\theta_W) \approx 0.23$$

$$A_d \approx 10^{-4}Q^2\left[\frac{3}{2}(1+Y) - \left(\frac{10}{3} + 6Y\right)\sin^2(\theta_W)\right]$$

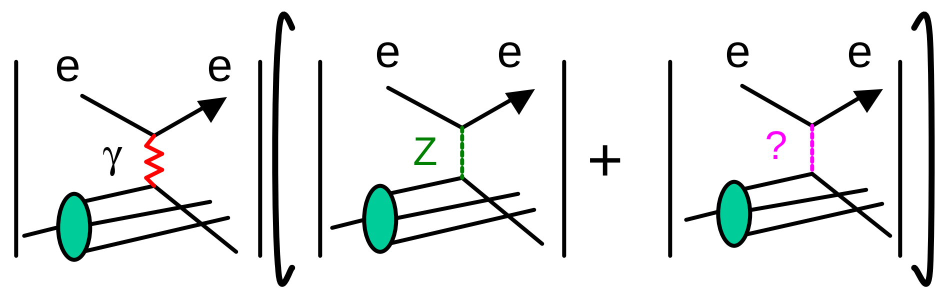
Large asymmetry
$Q^2 = 20$ GeV^2, $A_d = 0.002$

$$\frac{\delta\sin^2(\theta_W)}{\sin^2(\theta_W)} \approx \frac{0.91 + 0.12Y}{1 + 1.8Y}\left(\frac{\delta A_d}{A_d}\right)$$

$$\approx 0.4\left(\frac{\delta A_d}{A_d}\right) \quad \text{at } Y \approx 0.82$$

Gain factor of 2 in $\delta\sin^2(\theta_W)$ over δA_d

A_{PV} ~



Look for interference between Large photon term and New Physics

Experimental Constraints and Kinematics

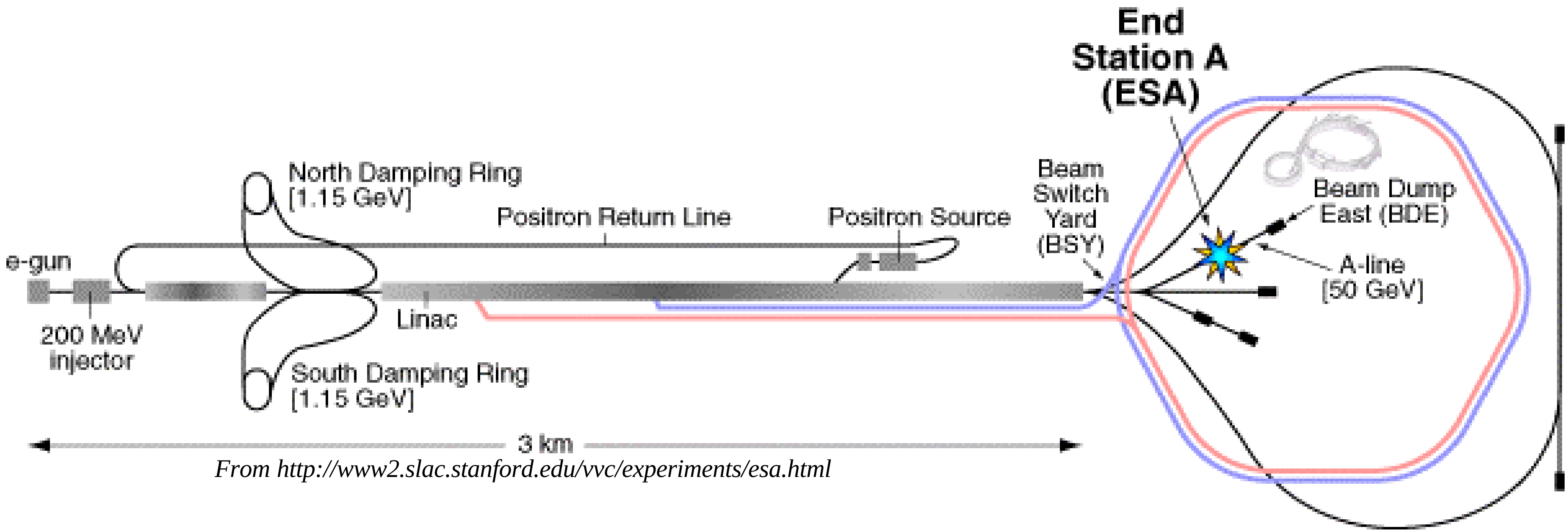
- DIS region ⇒ $Q^2 > 2.0$ GeV^2
  ⇒ $W^2 > 2.0$ GeV^2
- Small sea quark uncertainties ⇒ $x > 0.3$
- Minimize higher twist ⇒ $Q^2 > 10$ GeV^2
  ⇒ $x < 0.7$
- Better sensitivity to $\sin^2(\theta_W)$ ⇒ Large Y
- d(x)/u(x) uncertainties ⇒ deuterium target
- Minimize π backgrounds ⇒ $E'/E > 0.3$ ($y < 0.7$)
- Reasonable rates ⇒ determine Q^2 event by event
  ⇒ realistic run time

In fact, well matched to available beam at SLAC with spectrometer built from (mostly) pre-existing components.

$\langle x \rangle = 0.41$ $\langle Q^2 \rangle = 19.1$ GeV^2

$\langle Y \rangle = 0.82$ $\langle W^2 \rangle = 29.0$ GeV^2

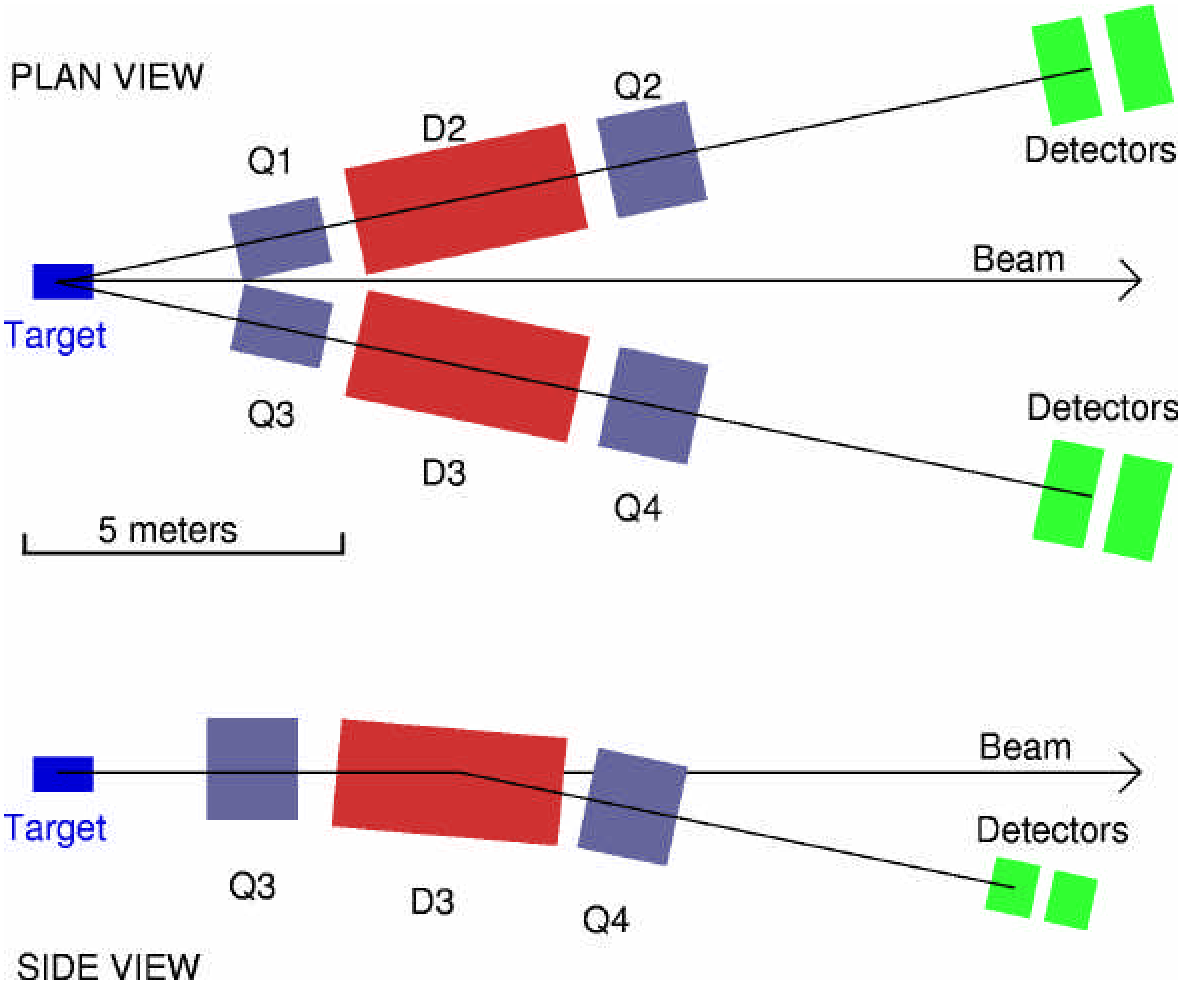
Experimental Setup/Electron Beam



From http://www2.slac.stanford.edu/vvc/experiments/esa.html

- Experiment located at SLAC End Station A
- *Helicity related beam problems are already solved for E-158 Møller*
- 35.6, 38.8 GeV beam—π rotation in (g-2) precession in beam line.
- 9×10^{11} e^-/spill at 120 Hz; 5×10^{8} spills
- 80-85% Beam polarization; unpolarized deuterium target

DIS-Parity Spectrometer



- Pair of identical spectrometers at 12°
- Electron focus of 9-20 GeV
- Acceptance:
  - ±8 mr at 9 GeV
  - ±12 mr at 20 GeV
- Lead-glass array
  - $\delta E/E \approx 4.5\%$
  - Used in E155
- Rates require new flash ADC system
  - (Kamland/Berkeley design)

Use existing magnets/spectrometer design

SLAC DIS-Parity Collaboration

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and others. . .

Uncertainties in A_d and $\sin^2(\theta_W)$

	$\delta A_d/A_d$ (%)	$\delta\sin^2(\theta_W)$ (abs $\times 10^{-3}$)
Statistical	*0.6%*	*0.6*

Experimental Syst. Uncertainties	$\delta A_d/A_d$ (%)	$\delta\sin^2(\theta_W)$ (abs $\times 10^{-3}$)
Beam polarization	0.3%	0.3
δQ^2	0.3%	0.3
Electromagnetic Radiative Corrections	0.3%	0.3
False Asymmetries	0.1%	0.1
Pion Contamination	0.1%	0.1
Pair symmetric bkg	0.1%	0.1
Target Purity/Density	0.1%	0.1
Electronics/pile up	0.1%	0.1
Total	*0.6%*	*0.6*

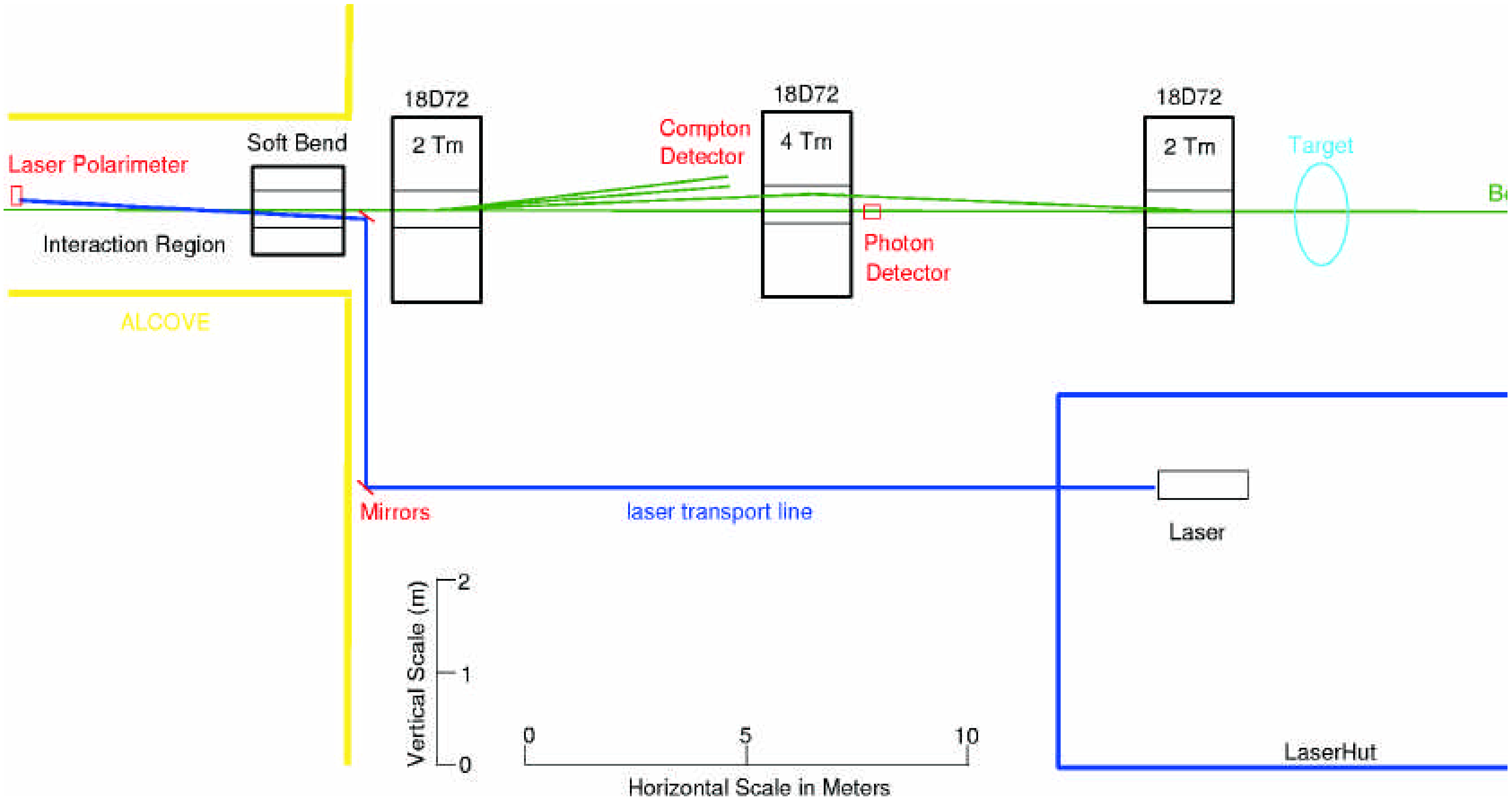
Theoretical Systematic Uncertainties	$\delta\sin^2(\theta_W)$ (abs $\times 10^{-3}$)
Dynamic Higher Twist	0.1
Electroweak Radiative Corrections	0.2
Quark distributions	0.2
Charge Symmetry Violation	0.2
$\delta R\ (=\sigma_L/\sigma_T)$	0.1
Total	*0.4*

$$\left.\frac{\delta \sin^2\theta_W}{\sin^2\theta_W}\right|_{Y=0.82} \approx 0.4\left(\frac{\delta A_d}{A_d}\right)$$

Total Uncertainty:
$\delta A/A = \pm 0.8\%$
$\delta\sin^2(\theta_W) = \pm 0.0009$

Beam Polarization Measurement

Compton Polarimeter



Based on SLD polarimeter (0.5%—we want 0.3%)

- Detect both scattered electron and photon (independent measurement)
- High Power Laser: $P_\gamma = 99.8 \pm 0.1\%$, 10^{17} photons/pulse (50mJ)
- Small (< 0.1%) radiative corrections

Q^2 Uncertainty

$$Q^2 = 4\, EE' \sin^2(\theta/2)$$

E:

• $\delta E < 0.1\%$—calibration of beam line magnets

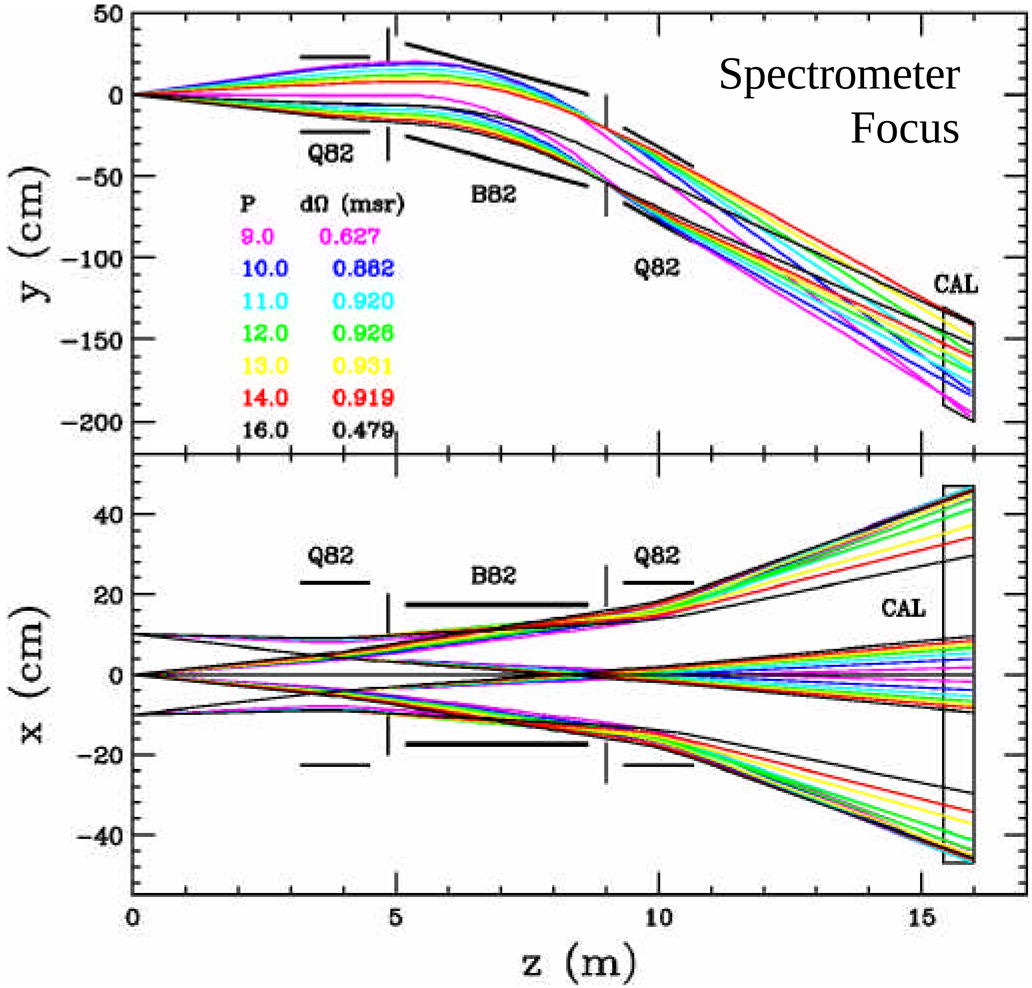
•Zero point of longitudinal beam polarization defines 37.22 GeV

$E' \sin^2(\theta/2)$

•Optics Measurements for E′ (0.2%) and θ (0.2mr)

•Floating Wire calibration in E140 achieved this

- –Central angle ± 0.05 mr
- –Central Momentum ($\delta E'/E'$) ± 0.03



Other:

•"Point" Targets/masks

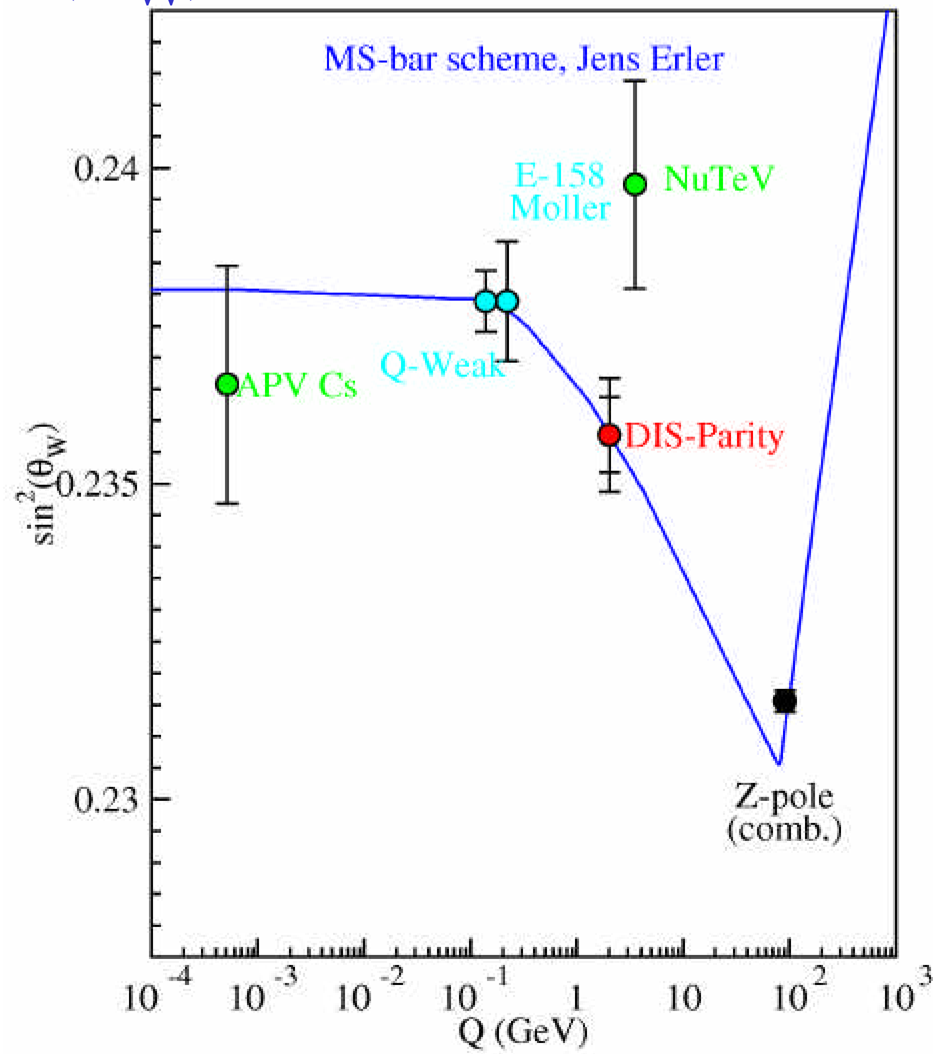
•Quad off measurements

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

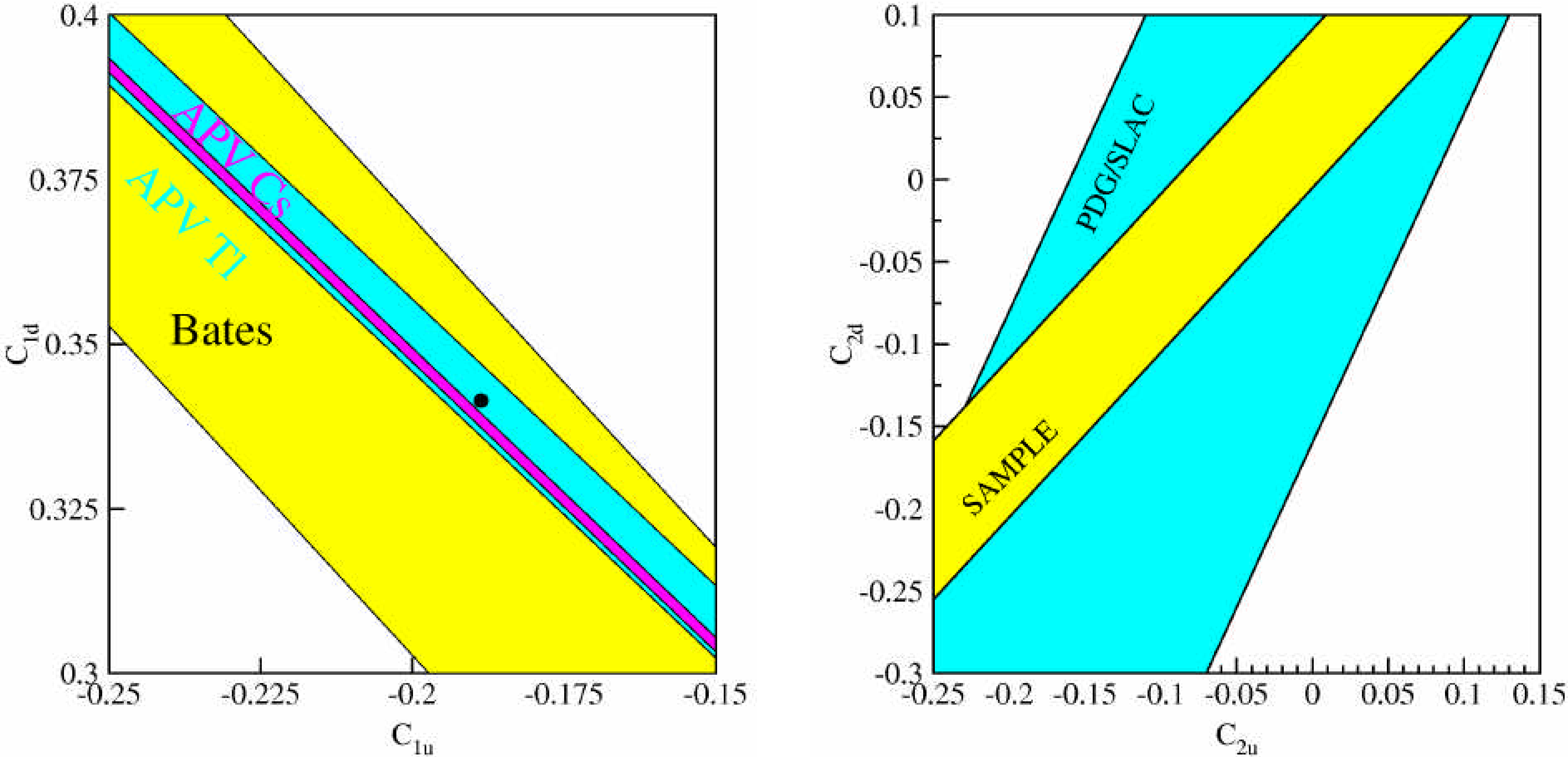
$\delta A_d/A_d = \pm 0.6\%$ (stat)
$\pm 0.6\%$ (syst)
($\pm$ 0.8% combined)

$\delta \sin^2(\theta_W) = \pm$ 0.0003 (stat)
$\pm$ 0.0003 (sys)
$\pm$ 0.0004 (theory)
($\pm$ 0.0009 combined)

What about C_{iq}'s?

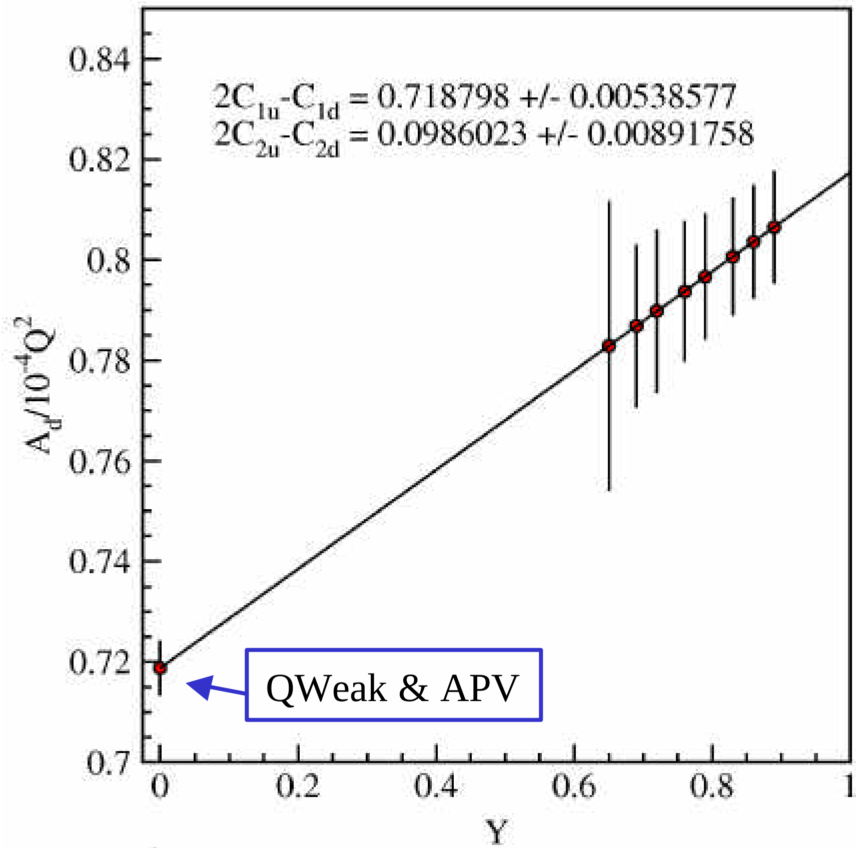


Exp. Constraints on C_{1u}, C_{1d}, C_{2u} and C_{2d}



Present experimental constraints are wide open, except for APV
(1 standard deviation limits shown)

Extracted Signal—It's all in the binning



Fit Asymmetry data as fn. of Y

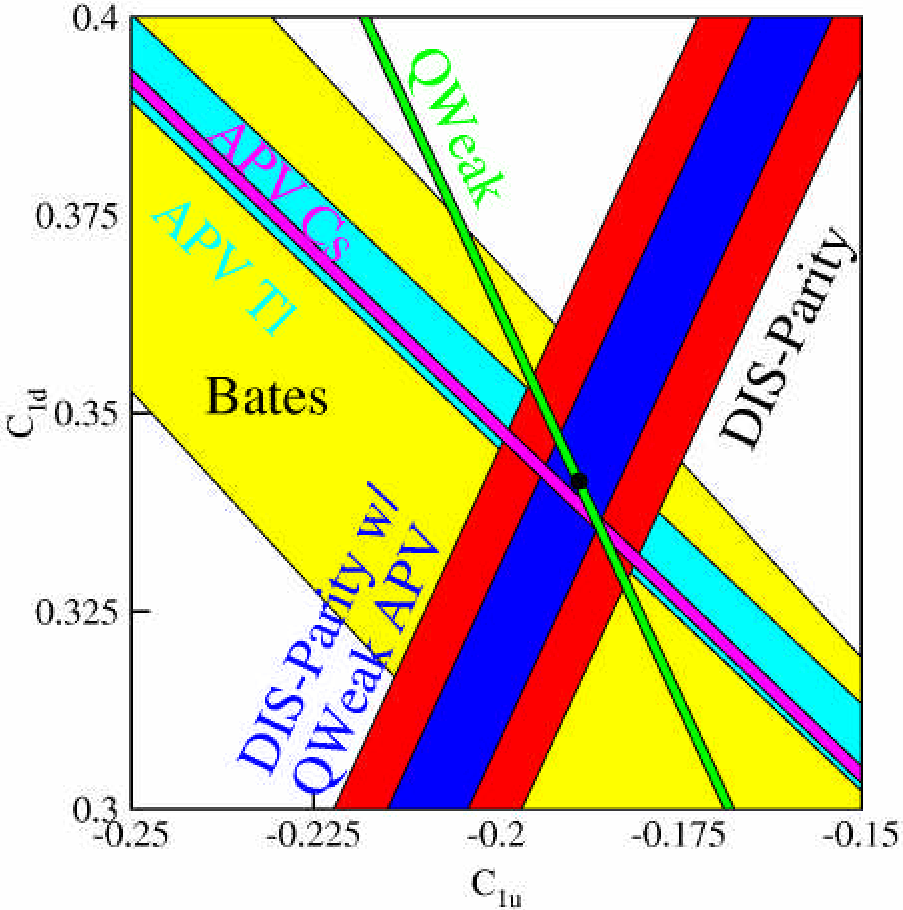
intercept = $2C_{1u} – C_{1d}$

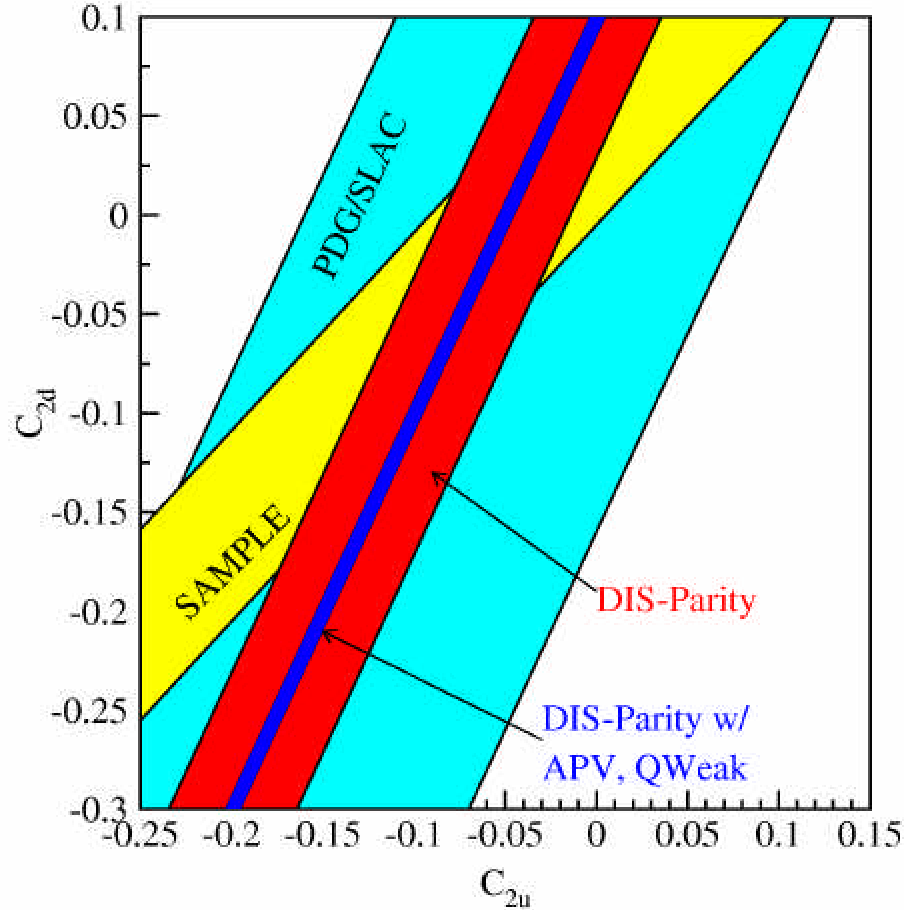
slope = $2C_{2u} – C_{2d}$

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

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

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 $\delta(2C_{2u}$–$C_{2d})$ = ± 0.009

× 27 improvement (S.M $2C_{2u}$ – C_{2d} = 0.0986)

Additional Possibilities with H_2

- Asymmetry in σ_d-$2\sigma_p$
  - Interpretation does not require knowledge of parton distributions (except charge symmetry).

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

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

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

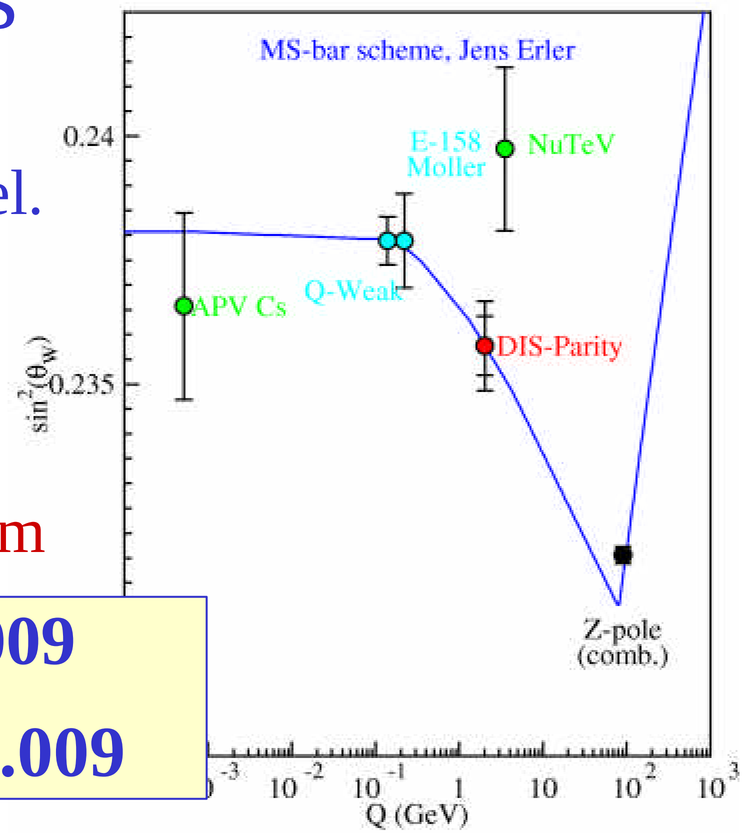
- Ratio of asymmetries: A_p/A_d
  - If C_{1a}'s are known, measures $r(x) \approx d(x)/u(x)$ at large x.
  - Polarization cancels out.

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

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

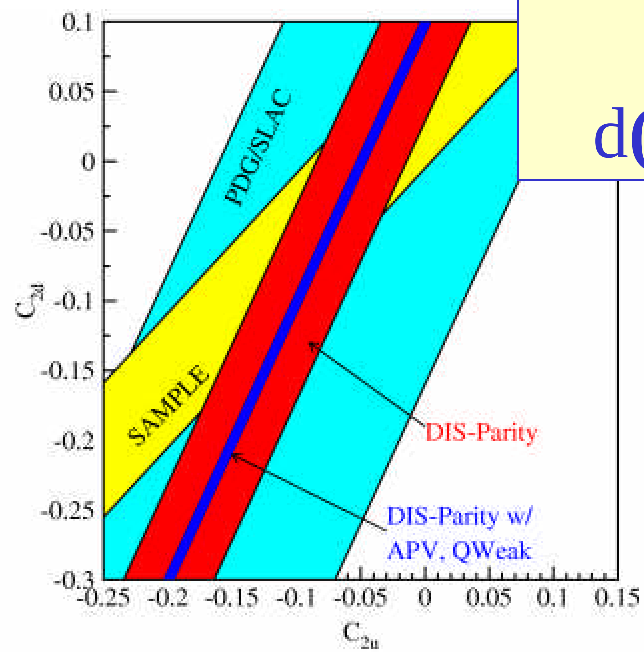
DIS-Parity: Conclusions

- 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 in at SLAC in the near term future.



$d\sin^2(q_W) = 0.0009$

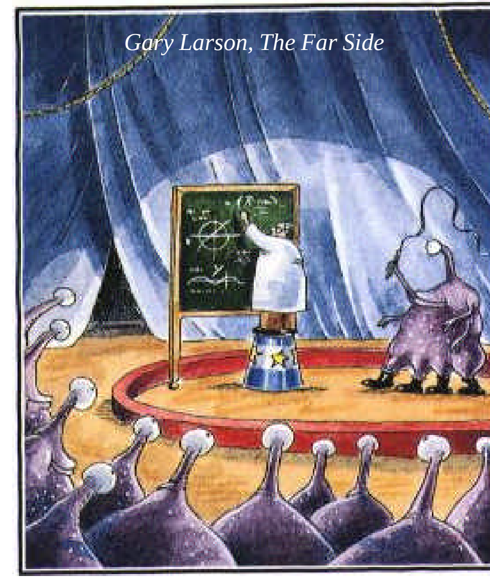
$d(2C_{2u} - C_{2d}) = 0.009$



Status:

- LOI submitted to SLAC EPAC
- Presentation to EPAC on 12 June
- Full Proposal in Fall 2003

Aside: Renormalizations Schemes



Definition of $\sin^2(\theta_W)$ depends on renormalization scheme which is used.

- Well defined relationships for converting between schemes depending on m_t and m_H.

On Shell	Z Mass	$\overline{\text{MS}}$	Effective (Z-Pole)
$s_W^2 \equiv \left(1 - \frac{M_W^2}{M_Z^2}\right)$	$s_{M_Z}^2\left(1 - s_{M_Z}^2\right) \equiv \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$	$\hat{s}_Z^2 \equiv \frac{\hat{g}'^2(M_Z)}{\hat{g}'^2(M_Z)+\hat{g}^2(M_Z)}$	$\bar{s}_f^2 \equiv \frac{1}{4}\left(1 - \frac{\bar{g}_{Vf}}{\bar{g}_{Af}}\right)$
$s_W^2 = 0.22272(38)$	$s_{M_Z}^2 = 0.23105(8)$	$\hat{s}_Z^2 = 0.23107(16)$	$\bar{s}_l^2 = 00.23136(15)$

On Shell:
- Familiar, simple
- Large m_t, M_H dependence

Z Mass:
- Most precise—No m_t, M_H dependence
- m_t, M_H reenter w/other observables

$\overline{\text{MS}}$:
- Based on coupling constants—theorist's definition
- Not conceptually simple
- Determined through global fits

Effective (Z-Pole):
- Simple
- Phenomenological definition

See PDB "Electroweak Model" (J. Erler and P. Langacker) for a better discussion.

Detector and Expected Rates

	x	E′ (GeV)	Y	Q^2 (GeV^2)	W^2 (GeV^2)	π/e	Rate (/spill)	$\delta A_d/A_d$ (%)	$\delta\sin^2(\theta_W)$ (× 100)
	0.31	15.8	0.89	9.8	36.1	3.10	4.4	1.39	0.14
	0.36	17.5	0.86	10.8	32.4	0.40	3.6	1.41	0.15
	0.41	19.3	0.83	11.9	28.7	0.10	2.9	1.47	0.16
	0.47	21.0	0.79	13.0	25.0	0.03	2.2	1.58	0.17
	0.53	22.7	0.76	14.0	21.3	0.00	1.5	1.76	0.20
	0.59	24.4	0.72	15.1	17.6	0.00	1.0	2.06	0.24
	0.67	26.1	0.69	16.2	13.9	0.00	0.5	2.60	0.30
	0.75	27.8	0.65	17.2	10.2	0.00	0.2	3.68	0.44
Average	0.41	19.1	0.82	11.82	28.97	0.94			
Total							16.3	0.6	0.09