C_{3q} Measurement Using Polarized e^+/e^- Beams

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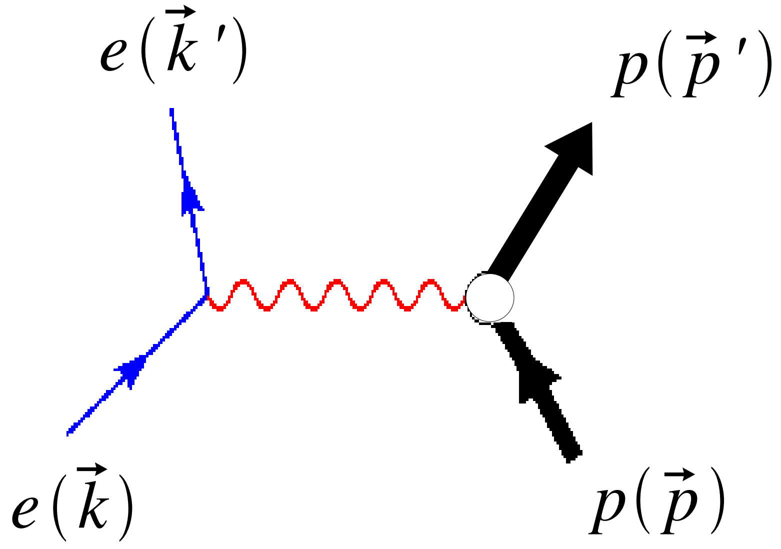
- Introduction — Standard Model of Electroweak Interaction
- Neutral Weak Coupling Constants
- Test of the Standard Model
- Access to C_{3q} Using Electron vs. Positron Scattering
- Summary

Electroweak Interaction – A Historical View

- Let's start from electromagnetic interaction (QED, 1920's):



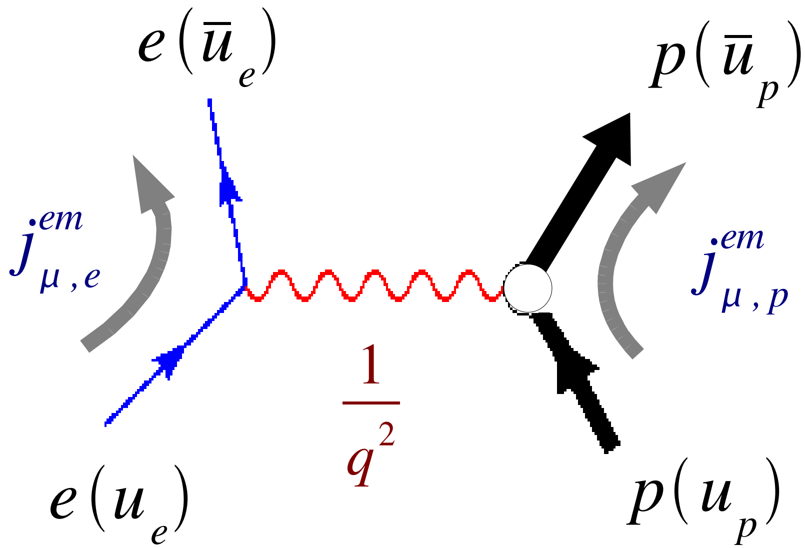
Electroweak Interaction – A Historical View

- Let's start from electromagnetic interaction (QED):

$$M = -\frac{e^2}{q^2}\left(j_\mu^{em}\right)_p\left(j^{em,\mu}\right)_e$$

$$= \left(e\bar{u}_p\gamma^\mu u_p\right)\left(\frac{-1}{q^2}\right)\left(-e\bar{u}_e\gamma_\mu u_e\right)$$

$$|M|^2 \Rightarrow \sigma$$



We can calculate many electromagnetic interactions using QED

Electroweak Interaction – A Historical View

- Charged pion and muon decay:

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \qquad \tau = 2.6\times 10^{-8} s$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \qquad \tau = 2.2\times 10^{-6} s$$

  - Much longer than strong (10^{-23} s) or electromagnetic (10^{-16} s) decays
  - Indicate a 4th interaction: "weak"

- 1932, based on QED, Fermi proposed:

$$M^{EM} = \left(e\bar{u}_p\gamma^\mu u_p\right)\left(\frac{-1}{q^2}\right)\left(-e\bar{u}_e\gamma_\mu u_e\right)$$

$$M^{weak} = G\left(\bar{u}_n\gamma^\mu u_p\right)\left(\bar{u}_{\nu_e}\gamma_\mu u_e\right)$$

arbitrary strength (→ G)

- assuming same current as in EM force
- charge lowering (raising) - "weak charged current"

Electroweak Interaction – A Historical View

- 1956, when Parity violation was first proposed (and tested in 1957), the only modification needed is:

$$M^{weak} = G\left(\bar{u}_n \gamma^\mu u_p\right)\left(\bar{u}_{\nu_e} \gamma_\mu u_e\right)$$

$$M^{weak} = G\left(\bar{u}_n \gamma^\mu (1-\gamma^5) u_p\right)\left(\bar{u}_{\nu_e} \gamma_\mu (1-\gamma^5) u_e\right)$$

$$= \frac{4G}{\sqrt{2}} J^\mu J_\mu^+$$

- (A mixture of γ^μ and $\gamma^\mu\gamma^5$ automatically violate parity)
- select only left-handed ν's

- If further assume that weak interaction occurs by exchanging a (*W*) particle, similar to the photon in electromagnetic interactions, then

$$M^{CC} = \left(\frac{g}{\sqrt{2}} \bar{u}_{\nu_\mu} \gamma^\mu \frac{1}{2}(1-\gamma^5) u_\mu\right) \frac{1}{M_W^2 - q^2} \left(\frac{g}{\sqrt{2}} \bar{u}_e \gamma_\mu \frac{1}{2}(1-\gamma^5) u_{\nu_e}\right)$$

$$\frac{G}{\sqrt{2}} \xrightarrow{q^2 \ll M_W^2} \frac{g^2}{8 M_W^2}$$

Electroweak Interaction – Neutral Current

- 1973, with developement of ν beams, found:

$$\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^- \qquad \nu_\mu N \to \nu_\mu X \qquad \bar{\nu}_\mu N \to \bar{\nu}_\mu X$$

  - cannot be explained by CC;
  - magnitude of strength indicates a "Neutral Current".

$$M^{CC} = \frac{4G}{\sqrt{2}} J_\mu^{CC} J^{CC,\mu} \longrightarrow M^{NC} = \frac{4G}{\sqrt{2}} (2\rho) J_\mu^{NC} J^{NC,\mu}$$

$$J_\mu^{NC}(\nu) = \frac{1}{2}\left(\bar{u}_\nu \gamma_\mu \frac{1}{2}(1-\gamma^5) u_\nu\right)$$

$$J_\mu^{NC}(q) = \left(\bar{u}_q \gamma_\mu \frac{1}{2}(c_V^q - c_A^q \gamma^5) u_q\right)$$

vector and axial-vector coupling constants

Electroweak Interaction – The Standard Model

- 1961, construct a $SU(2)_L$ group using charged currents, with weak isospin T.
  - Provide CC weak interactions carried by W^+, W^-;
  - Linear combination of the two is a neutral current, but it couples only to Left-handed fermions, while experimentally observed neutral currents exist for both R- and L-handed fermions;
  - On the other hand, EM $(U(1)_\gamma)$ also couple to both R- and L-H fermions.

- Suggest: Combine Neutral Current from $SU(2)_L$ and $U^{EM}(1)_\gamma$

$$\frac{G}{\sqrt{2}} \rightarrow \frac{g^2}{8(M_W^2 - q^2)} \Leftrightarrow \frac{e^2}{q^2}$$

(weak interaction is much weaker than EM because M_W is large, not because $g<<e$)

Electroweak Interaction – The Standard Model

- 1961, construct a $SU(2)_L$ group using charged currents, with weak isospin T.
- Combine Neutral Current from $SU(2)_L$ and QED ($U^{EM}(1)_\gamma$) to construct:

$$j_\mu^{em} \quad J_\mu^{NC} \quad \Leftrightarrow \quad J_\mu^3 \quad j_\mu^Y$$

J_μ^3 ← completes $SU(2)_L$

j_μ^Y ← $U(1)_Y$, Y: weak hyper charge

$$Q = T^3 + \frac{Y}{2}$$

observable | theory

Electroweak Interaction – The Standard Model

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observable | theory

photon → A_μ

Z^0 → Z_μ

$$A_\mu, \; Z_\mu \quad \Leftrightarrow \quad W_\mu^3, \; B_\mu$$

Electroweak Interaction – The Standard Model

- Mixing of the $SU(2)_L$ and $U^{EM}(1)_\gamma$ is giving by: ... the Weak Mixing angle θ_W

theory		observable
W^3_μ	$\Leftrightarrow$	A_μ
B_μ		Z_μ

$$A_\mu = B_\mu \cos\theta_W + W^3_\mu \sin\theta_W \qquad (m=0)$$

$$Z_\mu = -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W \qquad (m\neq 0)$$

Electroweak Interaction – The Standard Model

- Mixing of the $SU(2)_L$ and $U^{EM}(1)_\gamma$ is giving by: ... the Weak Mixing angle θ_W

theory		observable
W^3_μ	$\Leftrightarrow$	A_μ
B_μ		Z_μ

left-handed fermions only → W^3_μ

both left- and right-handed fermions → B_μ

$$A_\mu = B_\mu \cos\theta_W + W^3_\mu \sin\theta_W \qquad (m=0)$$

$$Z_\mu = -B_\mu \sin\theta_W + W^3_\mu \cos\theta_W \qquad (m\neq 0)$$

In the Standard Model

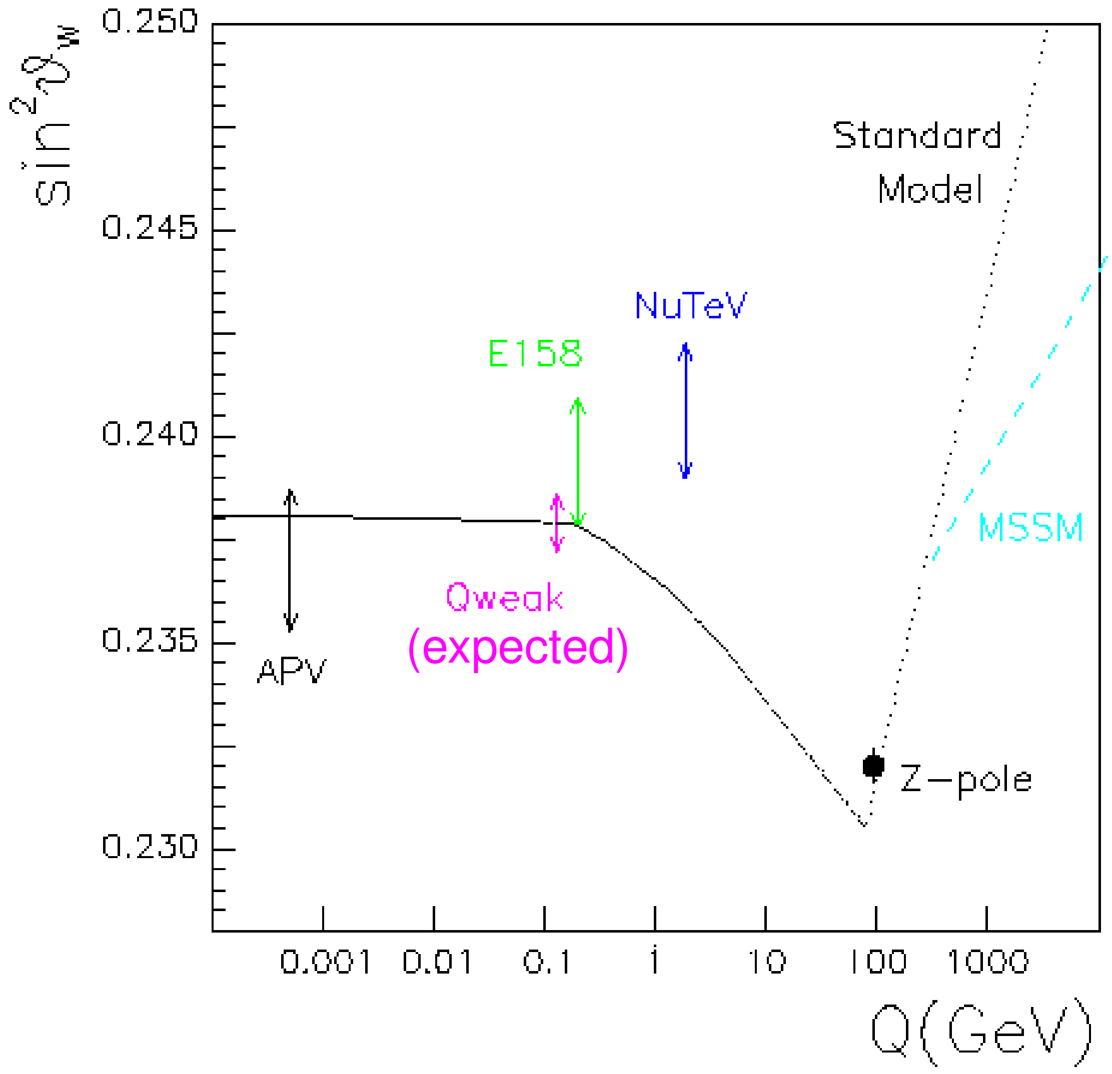
fermions	c^f_A	c^f_V
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$

$$J^{NC}_\mu(q) = \left(\bar{u}_q \gamma_\mu \frac{1}{2}(c^q_V - c^q_A \gamma^5) u_q\right)$$

Test of The Standard Model

- Standard Model works well at present energy range (~250GeV?); But, conceptual reasons for "theory of everything", hence new physics up to $10^{(14\text{-}18)}$ GeV.
- Test of the Standard Model:
  - Direct searches (LHC)
  - Indirect searches:
    - New physics modify: $\sin^2\theta_W, c_V^e, c_A^e, c_V^q, c_A^q$ at low energies;
    - Search for forbidden processes (ββ-decay, EDM ... ...).

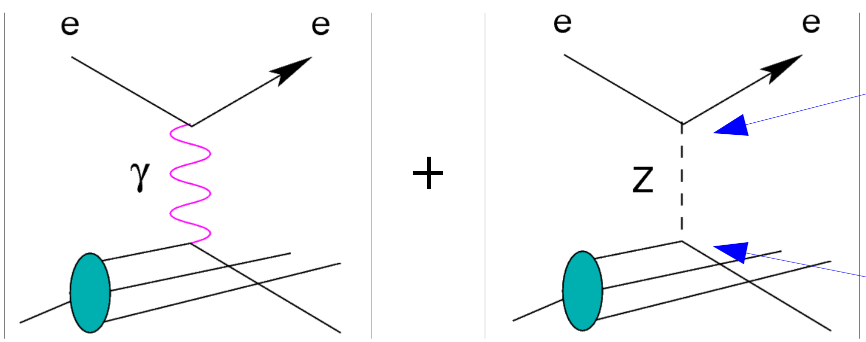
Testing the EW Standard Model – Running of $\sin^2\theta_W$ and the NuTeV Anomaly



Neutral Weak Couplings

- Asymmetries (ratios) in charged lepton-N scattering can be used to measure products of $c^e_{V,A}, c^q_{V,A}$

$$L^{lepton\ scatt.}_{NC} = \sum_q \left[c^l_A c^q_V \bar{l}\gamma^\mu\gamma_5 l\bar{q}\gamma_\mu q + c^l_V c^q_A \bar{l}\gamma^\mu l\bar{q}\gamma_\mu\gamma_5 q + c^l_A c^q_A \bar{l}\gamma^\mu\gamma_5 l\bar{q}\gamma_\mu\gamma_5 q \right]$$

$A =$ 

$$J^{NC}_\mu(e) = \left(\bar{u}_e\gamma_\mu\frac{1}{2}(c^e_V - c^e_A\gamma^5)u_e\right)$$

$$J^{NC}_\mu(q) = \left(\bar{u}_q\gamma_\mu\frac{1}{2}(c^q_V - c^q_A\gamma^5)u_q\right)$$

$$c^{e,q}_{V,A} \Leftrightarrow g^{e,q}_{V,A}$$

Neutral Weak Couplings

- Charged lepton-N scattering can be used to measure products of $c^{e}_{V,A}, c^{q}_{V,A}$

$$L_{NC}^{lepton\ scatt.} = \sum_q \left[c^l_A c^q_V \bar{l}\gamma^\mu\gamma_5 l\,\bar{q}\gamma_\mu q + c^l_V c^q_A \bar{l}\gamma^\mu l\,\bar{q}\gamma_\mu\gamma_5 q + c^l_A c^q_A \bar{l}\gamma^\mu\gamma_5 l\,\bar{q}\gamma_\mu\gamma_5 q \right]$$

C_{1q} C_{2q} C_{3q}

- parity-violating
- e_L, e_R cross sections

- lepton charge conjugate-violating
- e_L, e^+_R cross sections

Current Knowledge on Weak Coupling Coeffecients

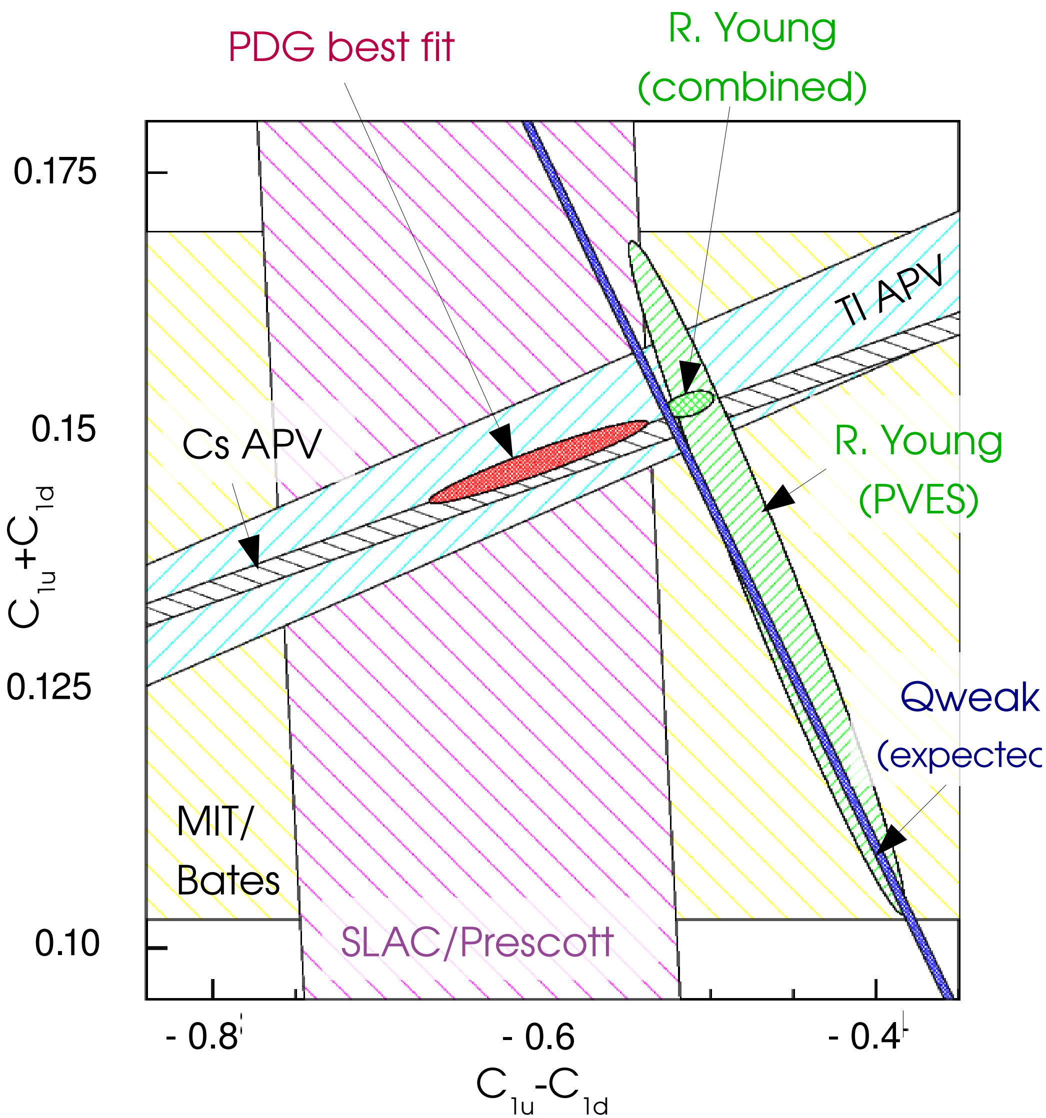
$C_{1q} = g_A^e g_V^q$ $C_{2q} = g_V^e g_A^q$ $C_{3q} = g_A^e g_A^q$ J. Erler, M.J. Ramsey-Musolf, Prog. Part. Nucl. Phys. **54**, 351 (2005)

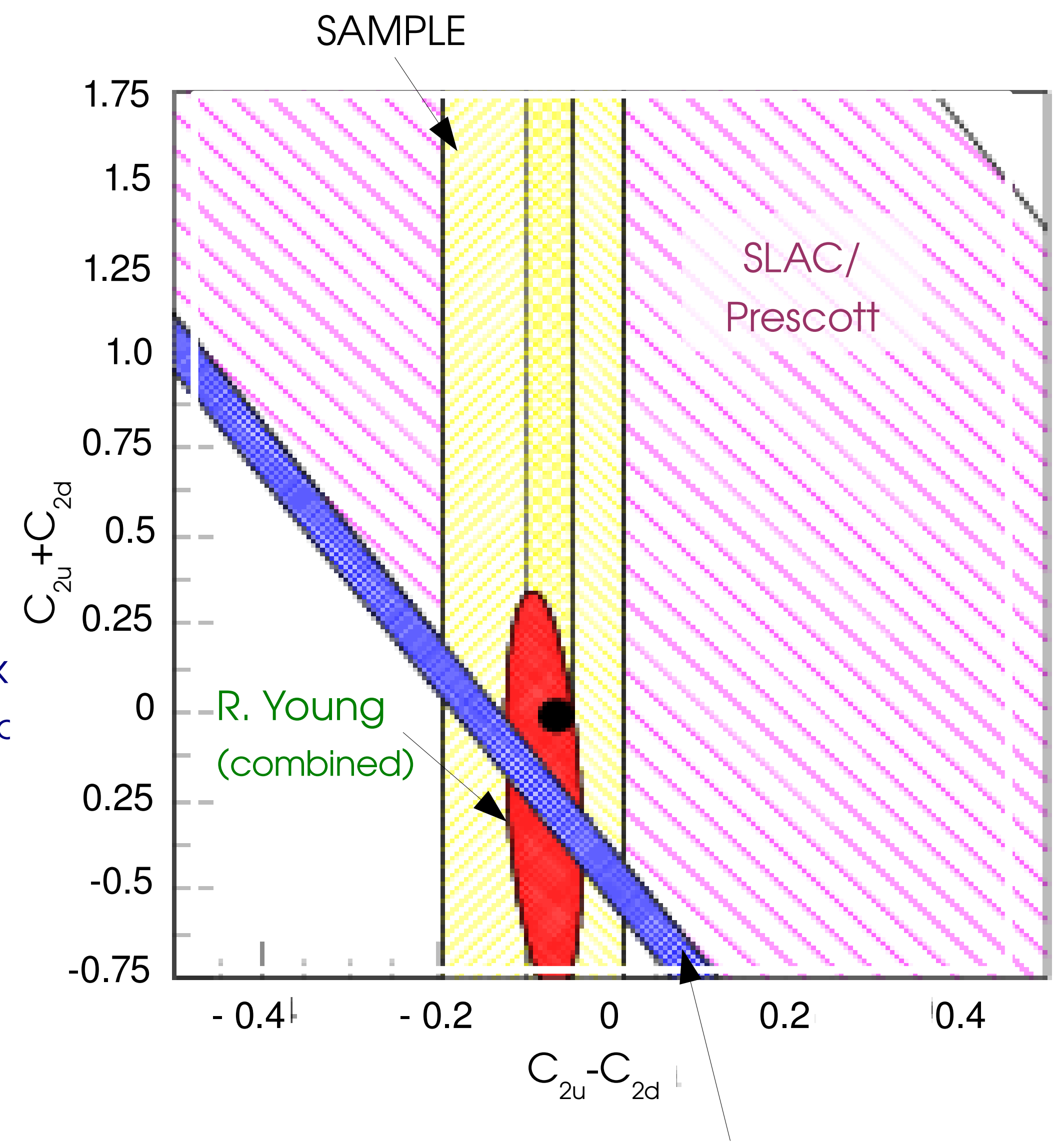
Facility	Process	Q^2	C_{iq} Combination	Result	SM Value
SLAC	e^--D DIS	1.39	$2C_{1u}-C_{1d}$	-0.90± 0.17	-0.7185
SLAC	e^--D DIS	1.39	$2C_{2u}-C_{2d}$	0.62± 0.81	-0.0983
CERN	$\mu^\pm$-D DIS	34	$0.66(2C_{2u}-C_{2d})+2C_{3u}-C_{3d}$	1.80± 0.83	1.4351
CERN	$\mu^\pm$-D DIS	66	$0.81(2C_{2u}-C_{2d})+2C_{3u}-C_{3d}$	1.53± 0.45	1.4204
MAINZ	e^--Be QE	0.20	$2.68C_{1u}-0.64C_{1d}+2.16C_{2u}-2C_{2d}$	-0.94± 0.21	-0.8544
Bates	e^--C elastic	0.0225	$C_{1u}+C_{1d}$	0.138±0.034	0.1528
Bates	e^--D QE	0.1	$C_{2u}-C_{2d}$	-0.042± 0.057	-0.0624
Bates	e^--D QE	0.04	$C_{2u}-C_{2d}$	-0.12± 0.074	-0.0624
JLab	e^--p elastic	0.03	$2C_{1u}+C_{1d}$	approved	-0.0357
	^{133}Cs APV	0	$-376C_{1u}-422C_{1d}$	-72.69±0.48	-73.16
	^{205}Tl APV	0	$-572C_{1u}-658C_{1d}$	-116.6±3.7	-116.8
Fit	e^--A	low	$C_{1u}+C_{1d}$	0.1358±0.0326	0.1528
All			$C_{1u}-C_{1d}$	-0.4659±0.0835	-0.5297
PVES			$C_{2u}+C_{2d}$	-0.2063±0.5659	-0.0095
Data			$C_{2u}-C_{2d}$	-0.0762±0.0437	-0.0621

new (R. Young, R. Carlini, A.W. Thomas, J. Roche, PRL 99, 122003 (2007) & priv. comm.)

Current Knowledge on $C_{1,2q}$

all are 1 σ limit





Expected: JLab 6 GeV PV-DIS E08-011
(assuming small hadronic effects)

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PDG2002 (best): $(2C_{2u}-C_{2d})=\pm 0.24$ →

$$2C_{3u}-C_{3d}=\pm 0.490 \quad (SM:-3/2)$$

Accessing C_{3q} from Electron, Positron Scatterings

- Not in the textbook   S.M. Berman, J. R. Primack, *Phys. Rev. D* **9**, 2171 (1974)

$A(l_L^- - l_R^+)$ ← sensitive to C_{3q}

Accessing C_{3q} from Electron, Positron Scatterings

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$A(l_L^- - l_R^+)$ ← sensitive to C_{3q}

$A(l_L^- - l_R^-)$ ← "PV-DIS" asymmetry, SLAC E122 and JLab 6 & 12 GeV

$$A_d^{PV-DIS} = \left(\frac{3 G_F Q^2}{\pi \alpha 2\sqrt{2}}\right) \frac{2 C_{1u}[1+R_C(x)] - C_{1d}[1+R_S(x)] + Y(2 C_{2u} - C_{2d}) R_V(x)}{5 + R_S(x) + 4 R_C(x)}$$

$$R_S(x) = \frac{2[s(x)+\bar{s}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \qquad R_C(x) = \frac{2[c(x)+\bar{c}(x)]}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)} \qquad R_V(x) = \frac{u_V(x)+d_V(x)}{u(x)+\bar{u}(x)+d(x)+\bar{d}(x)}$$

(small) (very small) (~1)

Accessing C_{3q} from Electron, Positron Scatterings

- proton target:

$$\left[\frac{A(l_L^- - l_R^+)}{A(l_L^- - l_R^-)}\right]_p = \frac{y(2-y)}{2}\frac{2C_{2u}u_V - C_{2d}d_V + 2C_{3u}u_V - C_{3d}d_V}{2C_{1u}u - C_{1d}(d+s) + Y(2C_{2u}u_V - C_{2d}d_V)} \qquad y=\frac{\nu}{E}$$

$$\Rightarrow A_p(e_L^- - e_R^+) = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{2C_{2u}u_V - C_{2d}d_V + 2C_{3u}u_V - C_{3d}d_V}{4u+d+s}$$

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not well known (C_{3u}, C_{3d})

Accessing C_{3q} from Electron, Positron Scatterings

- proton target:

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- deuteron target:

$$\left[\frac{A(l_L^- - l_R^+)}{A(l_L^- - l_R^-)}\right]_d = \frac{y(2-y)}{2}\frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d})R_V}{2C_{1u} - C_{1d} + Y(2C_{2u} - C_{2d})R_V}$$

$$\Rightarrow A_d(e_L^- - e_R^+) = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d})R_V}{5+R_s+4R_c}$$

$2C_{2u} - C_{2d}$: ≈ -0.1

$2C_{3u} - C_{3d}$: ≈ -1.5 (dominant)

Accessing C_{3q} from Electron, Positron Scatterings

- proton target:

$$\left[\frac{A(l_L^- - l_R^+)}{A(l_L^- - l_R^-)}\right]_p = \frac{y(2-y)}{2}\frac{2C_{2u}u_V - C_{2d}d_V + 2C_{3u}u_V - C_{3d}d_V}{2C_{1u}u - C_{1d}(d+s) + Y(2C_{2u}u_V - C_{2d}d_V)} \qquad y = \frac{\nu}{E}$$

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≈ -0.1 ≈ -1.5 (dominant)

$$\Rightarrow A_d(e_L^- - e_R^+) = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{\left(\boxed{2C_{2u} - C_{2d}} + \boxed{2C_{3u} - C_{3d}}\right)R_V}{5 + R_s + 4R_c}$$

$$\approx (108\,ppm)\frac{y(2-y)}{2}(2C_{3u} - C_{3d})Q^2 R_V$$

Accessing C_{3q} from Electron, Positron Scatterings

- Start from: $e^-_{L,R}$ (PV-DIS) at JLab 12 GeV (two approaches)
  - Hall A large acceptance "solenoid" device: PR09-012
  - Hall C "baseline" SHMS+HMS: PR12-07-102 (P.E. Reimer, X. Z, K. Paschke)
    - E=11.0 GeV, E'=6.0 GeV, Q^2=3.3 GeV^2, W^2=7.3 GeV^2, x_{Bj}=0.34
    - can achieve 1% (0.5% stat) on A_d from 28 PAC days of 85uA 80% e-beam on a 40cm liquid D2 target, extraction of C_{2q}, $\sin^2\theta_W$
- Using PR12-07-102 kinematics, $A_d(e^-_L - e^+_R) \approx$ -169ppm (~3/4 of A_d^{PVDIS}) assuming e^+ luminosity is 5 times lower, can determine $2C_{3u}$-C_{3d} to +/-0.05 (factor of 10 improvement) using 28 PAC days.
- Use proton target, can provide a different combination of C_{3q}.
- Problems: luminosity? systematics? two-photon effects? other hadronic effects?

Summary

- Neutral current couplings are fundamental quantities of the Standard Model.
- Comparison of polarized e+, e- DIS cross sections can access C_{3q}.