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Polarized Electron Scattering

(Past, Present + Future)

Outline

1.) Ancient History: APV, eD and $\nu_\mu N$

* 2.) $m_t - m_W - \sin^2\theta_W - m_H$ - SUSY - Technicolor Connection

3.) e^-e^- Moller Scattering: EW Radiative Corrections
see A. Czarnecki's Talk

4.) E158 $\sin^2\theta_W(0.026\,GeV^2) = 0.2397(10)(8)$ Implications

5.) Future Goals + Possibilities

E158 Tour de force

$$A_{LR} = \frac{\sigma(e_L^-e^- \to e^-e^-) - \sigma(e_R^-e^- \to e^-e^-)}{\sigma(e_L^-e^- \to e^-e^-) + \sigma(e_R^-e^- \to e^-e^-)} = 131(14)(10) \times 10^{-9}\ !!$$

$Q^2 = 0.026\,GeV^2$

1.) Ancient History: APV vs eD (E122) + $\nu_\mu N$

1975: $SU(3)_c \times SU(2)_L \times U(1)_Y$ Standard Model ~ in Place

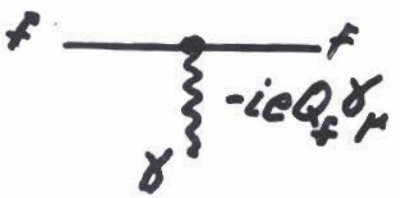
$$Z_\mu = W_\mu^3 \cos\theta_W^0 - B_\mu \sin\theta_W^0$$

$$A_\mu = W_\mu^3 \sin\theta_W^0 + B_\mu \cos\theta_W^0 \quad \text{massless photon}$$

SU(5), SO(10) GUTS → $\sin^2\theta_W^0 \propto 3/8 \xrightarrow{\text{run}} 0.20 \sim 0.21$

γ with $X, Y, W \rightarrow \frac{\alpha}{\pi} \ln m_X/m_W$

Weak Neutral Currents Seen in ν-Scattering $\sin^2\theta_W \sim 3/8$

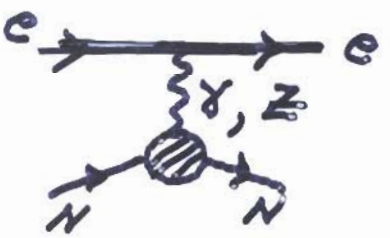


$$\frac{-ig_Z}{2\cos\theta_W}\gamma_\mu\left(T_{3f} - 2Q_f \sin^2\theta_W - T_{3f}\gamma_5\right)$$

$T_{3f} = \pm 1/2$

Violates Parity

Atomic Parity Violation



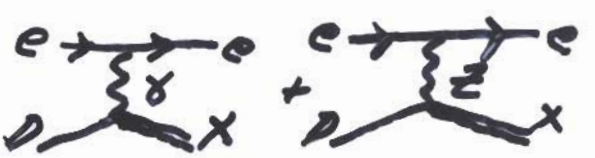
$Q_W(Z,N) = Z(1-4\sin^2\theta_W) - N$ weak Charge

Not Seen in Bi Exps (Seattle + Oxford)!

Standard Model Ruled Out?

1978 SLAC Pol eD → eX $E_e \simeq 24$ GeV Prescott, Hughes...

$$A_{LR} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L + d\sigma_R}$$



P.V.A

$E_e \simeq 20\,GeV$, $\langle x \rangle = 0.2$, $\langle y \rangle = 0.2$, $\langle Q^2 \rangle = 1.6\,GeV^2$

$$A_{ep} \simeq -15 \pm 1.5 \times 10^{-5}$$

SM Prediction $A_{ep} \simeq -32(1 - 2.5\sin^2\theta_W)$

$\rightarrow$ $\sin^2\theta_W = 0.22 \pm 0.02$! $\pm 10\%$ Precision!

Spectacular Confirmation of SM ! (No Serious Discrep. Since)

Good Agreement with SU(5) GUT! (Accident?)

As $\pm 10\% \rightarrow \pm 1 \sim 2\%$ $\rightarrow$ ERA of Precision EW Studies

Electroweak Radiative Corrections Required !

W.M. + A. Sirlin 1979, 1980, 1981...

$G_F^0 M_{cc}^0 \rightarrow \rho^{cc} G_\mu M_{cc}$ $\quad G_\mu = 1.16637 \times 10^{-5} GeV^{-2}$, $\rho^{cc} = 1 + O(\alpha)$

$G_F^0 M_{NC}^0 \rightarrow \rho^{NC} G_\mu M_{NC}(\kappa \sin^2\theta_W^R)$ $\quad \rho^{NC} = 1 + O(\alpha)$, $\kappa = 1 + O(\alpha)$

Renormalized Weak Mixing Angle

(1980) $\sin^2\theta_W \equiv 1 - M_W^2/M_Z^2$ On Shell (m_t^2) $\frac{\alpha}{\pi}\frac{m_t^2}{m_W^2}$ corr.

or

(1981) $\sin^2\theta_W(m_Z)_{\overline{MS}} = \dfrac{e^2(m_Z)_{\overline{MS}}}{g_2^2(m_Z)_{\overline{MS}}}$ Good for GUTS running

1980s $R_\nu \equiv \dfrac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)}$ well measured at CERN

$\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq 0.230$ → Favored SUSY SUSY)

top mass dependence $m_t \lesssim 180\,GeV$ 

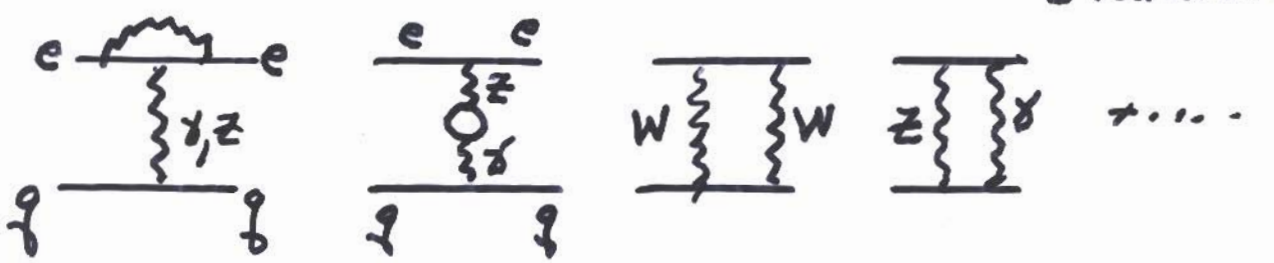
Atomic Parity Violation "The Carl Wieman Story"

(1988...) $Q_W(Cs)^{exp} = -72.69 \pm 0.48$

SM $Q_W(Cs) = -73.19 \pm 0.14$ After R.C.

Powerful Constraint on "New Physics" 

S Parameter

SM RC 

$G_F^0 \to \rho\, G_\mu \qquad \rho = 1 + \mathcal{O}(\alpha)$

$\sin^2\theta_W^0 \to \kappa \sin^2\theta_W(m_Z)_{\overline{MS}} \qquad \kappa = 1 + \mathcal{O}(\alpha)$

+ Box Diagrams (partly absorbed into ρ, κ)

$$Q_W(Z,A) = (Z-A)\rho_{PV} + Z\rho_{PV}\left(1 - 4\kappa_{PV}\sin^2\theta_W(m_Z)_{\overline{MS}}\right)$$

$$\rho_{PV} = 1 - \frac{\alpha}{2\pi} + \frac{\alpha(m_z)}{2\pi}\left\{\frac{3}{8s^2}\frac{m_t^2}{m_W^2} + \frac{3}{8s^4}\ln c^2 + \frac{3\xi}{8s^2}\left(\frac{\ln c^2/\xi}{c^2-\xi} + \frac{1}{c^2}\frac{\ln\xi}{1-\xi}\right)\right.$$

$$\left. - \frac{1}{s^2} - 4(1-4s^2)\left(\ln\frac{m_z^2}{m^2} + \frac{3}{2}\right) - \frac{9}{16s^2}(1-\tfrac{16}{9}s^2)\left(1+(1-4s^2)^2\right)\right\}$$

WW box — γZ box — ZZ box

$$s^2 = 1-c^2 = \sin^2\theta_W(m_z)_{\overline{MS}}$$

$$\xi = m_H^2/m_z^2$$

$$\kappa_{PV} = 1 - \frac{\alpha}{2\pi s^2}\left\{\frac{1}{3}\sum_f (T_{3f}Q_f - 2s^2Q_f^2)\ln\frac{m_f^2}{m_z^2} + \dots\right\}$$

γZ Mixing

evaluated using $e^+e^- \to$ hadrons data

Large $\kappa \to 1.03$

$\kappa \sin^2\theta_W(m_z)_{\overline{MS}} \to \sim 0.239$!

Largely cancelled by WW box!

$$\left.\begin{aligned} Q_W\left({}^{133}_{55}Cs\right) &= -73.19(14) - 0.85 \\ Q_W^{exp} &= -72.69(48) \end{aligned}\right\} \quad S = -0.6 \pm 0.6$$

Rosner & W.M.

Negative

Technicolor $S \simeq \frac{+1}{6\pi} N_D\ (\times 2) \sim +0.5 \sim 2.0$

Ruled Out!

APV Should be improved (if possible)

2. $m_t - m_W - \sin^2\theta_W - m_H$ - SUSY - Technicolor Connection

Natural Relations (Custodial SU(2))

$$\sin^2\theta_W^0 = \frac{e_0^2}{g_{Z0}^2} = 1 - m_W^{0\,2}/m_Z^{0\,2}$$

$$\Delta r(m_t, m_H, S, T \ldots \text{new physics}) = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu m_W^2 (1 - m_W^2/m_Z^2)}$$

$$\Delta\hat{r}(m_t, m_H, S, T \ldots \text{new physics}) = 1 - \frac{2\sqrt{2}\pi\alpha}{G_\mu m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{MS}}}$$

EW Rad. Corr.

+ SUSY loops + ... Other New Phys.

$\alpha^{-1} = 137.035999710(96)$

$G_\mu = 1.16637(1) \times 10^{-5}\,\text{GeV}^{-2}$

$m_Z = 91.1875(21)\,\text{GeV}$

m_W, $\sin^2\theta_W(m_Z)_{\overline{MS}}$ predicted as functions of $m_t, m_H, S, T \ldots$

Remember $S = \frac{1}{6\pi} \times N_D$ $\quad N_D = 4$ (fourth generation + 12 Mirror Fermions

Rad → $m_t \sim 170\,\text{GeV}$

1995: Top Discovered at Fermilab

$m_t = 174.3(5.1)\,GeV \xrightarrow[2004]{} 178.0(4.3)\,GeV \xrightarrow[2005]{} 172.7(2.9)\,GeV$

$\xrightarrow[2006]{} 171.4(2.1)\,GeV$ (smaller) Will it increase?

$m_W^{ave} = 80.405(30)\,GeV$ Will it decrease?

$\sin^2\theta_W^{Ave}(m_z)_{\overline{MS}} = 0.23125(16)$

Erler + Langacker Global Fit to all data (Rad. Corr.)

$m_N = 85^{+39}_{-28}\,GeV \quad < 161\,GeV\ (95\%\,CL)$

$S \simeq -0.1 \pm 0.1 \qquad T \simeq -0.1 \pm 0.1$ No Heavy Doublets

Suggestive of Supersymmetry

But two best $\sin^2\theta_W(m_z)_{\overline{MS}}$ inconsistent (3.2σ)

$A_{LR}(e\bar{e} \to z \to had.) \to \sin^2\theta_W(m_z)_{\overline{MS}} = 0.23070(26) \to m_N = 30^{+33}_{-18}\,GeV$

$A_{FB}(z \to b\bar{b}) \to \sin^2\theta_W(m_z)_{\overline{MS}} = 0.23193(29) \to m_N \simeq 450^{+300}_{-190}\,GeV$

Either taken alone rules out SM!

$X = \ln \frac{m_H}{115\,GeV}$, $S + T$ $\qquad m_H^{exp} > 114.4\,GeV$

$m_W(GeV) = 80.354(13) - 0.065X - 0.01X^2 - 0.29S + 0.45T$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23129(7) + 0.00048X + 0.00002X^2 + 0.0036S - 0.0026T$

$$S \simeq 120\left\{ 2\,\frac{m_W - 80.354}{80.354} + \frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.23129}{0.23129} - 7.1\times10^{-4}X + 1.6\times10^{-4}X^2 \right\}$$

A_{LR} m_W $m_H \simeq 115\,GeV \rightarrow S \simeq -0.16$, $T \simeq +0.06$ SUSY?

A_{FB} + $m_W \rightarrow m_H \simeq 500\,GeV$, $S \simeq 0.4$ $T \simeq 0.6$ Technicolor?

* Will the real $\sin^2\theta_W(m_Z)_{\overline{MS}}$ stand up!

A New Definitive $\sin^2\theta_W(m_Z)_{\overline{MS}}$ Needed!

JLAB Moller $\Delta\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq \pm 0.00025$

Must Do If Possible

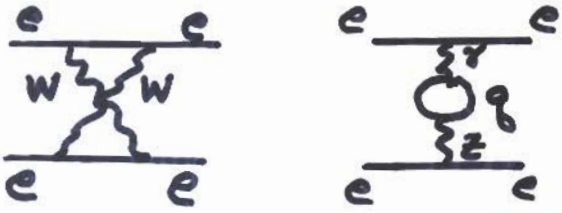
3. e^-e^- Moller Scattering $\qquad e \rightarrow \qquad Q^2 = ys \propto 2m_e E_e y$

$$A_{LR} = \frac{G_\mu Q^2}{\sqrt{2}\pi\alpha}\,\frac{1-y}{1+y^4+(1-y)^4}\,(1 - 4\sin^2\theta_W)$$

Purely leptonic, High Statistics $\sim \frac{1}{Q^2}$, Sensitive to $\sin^2\theta_W$

Radiative Corr. - Very Important A. Czarnecki + W.M.

Some loops not suppressed by $1-4\sin^2\theta_W$



very large → 40% Reduction in R_{LR}!

Better!

Pol. Unc. less important

$\sin^2\theta_W \rightarrow \kappa(0)\sin^2\theta_W(m_z)_{\overline{MS}}$

$\kappa(0) \simeq 1.0301 \pm 0.0025$

Expect $\kappa(0)\sin^2\theta_W(m_z)_{\overline{MS}} \simeq 0.2382$

4. E158 Result $A_{LR}(e\bar{e}\rightarrow c\bar{c}) = 131 \pm 14 \pm 10 \times 10^{-9}$!

$\kappa(0)\sin^2\theta_W(m_z)_{\overline{MS}} = 0.2397(10)(8)$

$\sin^2\theta_W(m_z)_{\overline{MS}} = 0.2330(14)$ error ~5x Z Pole A_{LR}

Better Agreement with $A_{FB}(Z\rightarrow b\bar{b})$

Note: NuTeV $R_\nu \rightarrow \sin^2\theta_W(m_z)_{\overline{MS}} \simeq 0.2361(17)$

E158 Implications: 1) 6σ running $\sin^2\theta_W(Q^2)$

2) $m_{Z_\chi} \gtrsim 1$ TeV

3) 10 TeV Compositeness Probed

4) $\frac{g^2}{m_N^2} \lesssim 0.01 G_\mu$

⋮

5. Future Goals + Possibilites

What is $\sin^2\theta_W(m_Z)_{\overline{MS}}$?

We left Z pole too early!

$\sin^2\theta_W(m_Z)^{Ave}_{\overline{MS}} = 0.23125(16)$ $\quad m_H \simeq 115\,GeV$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23070(26)$ $\quad A_{LR}$ consistent with m_W

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23193(29)$ $\quad A_{FB}(b\bar{b})$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23300(130)$ $\quad$ Moller

$\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq 0.233$ $\quad$ SUSY SU(5)

Present Situation Unacceptable!

LHC $\quad pp \to Z+X \quad A_{FB}(Z \to \mu^+\mu^-) \to \Delta\sin^2\theta_W \simeq \pm 0.00008_{stat.}$ systematics ?

JLAB $\quad Q_{weak} \quad ep \to ep \quad \Delta\sin^2\theta_W \simeq \pm 0.0008$

JLAB $\quad 12\,GeV \quad e\bar{e} \to e\bar{e} \quad \Delta\sin^2\theta_W \simeq \pm 0.00025$!

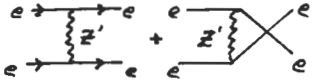
Must Do IF Feasible

Someday $\quad$ ILC $\to$ ± 0.00002 $\quad$ Z Factor

Fixed Target ± 0.00006 $\quad$ K. Kumar

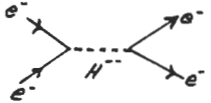
New Physics Probed by $e^-e^- \to e^-e^-$:

Z' Bosons (eg Z_χ of $\frac{SO(10)}{SU(5)\times U(1)_\chi}$)



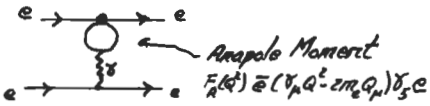
$$A_{LR}^{SM} \to A_{LR}^{SM}\left(1 + 7\frac{m_Z^2}{m_{Z'}^2}\right)$$

H^{--}



$\begin{pmatrix} H^0 \\ H^- \\ H^{--} \end{pmatrix}$ triplet $\quad \Delta L = 2$

Loop Effects



X parameter $\quad (S, T, U, V, W, X)$

$X = 0.38 \pm 0.59$ (1996 constraint)

$$A_{LR}^{SM} \to A_{LR}^{SM}(1 - 0.6 X)$$

etc.

$$\frac{4\pi}{\Lambda^2}\,\bar{e}\gamma_\mu e\,\bar{e}\gamma^\mu\gamma_5 e$$

Compositeness ...

Future Precision $\to m_H$ ... vs α, G_μ, m_Z + loops