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SMR.1508 - 17

SUMMER SCHOOL ON PARTICLE PHYSICS

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THE STANDARD MODEL AND HIGGS PHYSICS

Lecture IV

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More on the Higgs Mass & Precision Measurements

$$\mathcal{O}\left(\frac{\alpha}{\pi}\ln\frac{m_H}{m_Z}\right) \text{ effects!}$$

contained in m_W, G_μ, m_Z

Comparison of G_μ, m_W with $m_Z \longrightarrow m_H$ { For given $\alpha, m_t \ldots$

Global Fit to all precision data:

$$m_H \simeq 86^{+49}_{-32}\ \text{GeV} \qquad < 185\ \text{GeV (95\% CL)}$$

$m_H^{exp} > 114.4\ \text{GeV}$

Some Conflicting Results

$$m_H = \left(86^{+31}_{-23}\ {}^{+11}_{-9}\ \text{GeV}\right)\exp\left[\frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.23104}{0.0005225}\right]$$

↑ Δm_t unc ↑ Had. Vac. Pol. unc.

A_{LR} & other leptonic Z pole Asym. $\longrightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2308(2)$

$$m_H = 54^{+19}_{-14}\ {}^{+7}_{-6}\ {}^{+[illegible]}_{-[illegible]}\ \text{GeV}$$

$Z \to b\bar{b}$ FB Asym. $\longrightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3)$

$$m_H = 540^{+195}_{-144}\ {}^{+69}_{-56}\ {}^{+420}_{-236}\ \text{GeV}$$

m_H exhibits sensitive dependence on $\sin^2\theta_W(m_Z)_{\overline{MS}}$!

Translate other precision observables into $\sin^2\theta_W(m_Z)_{\overline{MS}}$

$m_W = 80.451(33)\,GeV \rightarrow \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2304(5) \rightarrow$ light Higgs

$\Gamma(Z \rightarrow \ell^+\ell^-) = 83.984(86)\,MeV \rightarrow \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2314(8) \rightarrow$ Heavier Higgs

It would be wonderful to have a very precise determination of $\sin^2\theta_W(m_Z)_{\overline{MS}}$ to ± 0.00002 ! i.e. a $\pm 0.01\%$ value!

Giga Z: An e^+e^- collider with $\sqrt{s} = 91.1875\,GeV$

with High Luminosity $\rightarrow$ 100 Z/sec!

A Z Boson Factory $\rightarrow 10^9$ Z/yr! or more!

Remeasure all Z boson properties with 1/10 stat. error

Do $b\bar{b}$ physics studies: CP, Rare Decays... τ Physics...

$A_{LR} \rightarrow \Delta\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq \pm 0.00001$ statistically

Systematics $\rightarrow$ Beam Polarization Unc.

$$\frac{\Delta P}{P} = \pm 0.1\% \longrightarrow \Delta\sin^2\theta_W(m_Z) = \underbrace{\pm 0.00002}_{\text{very good goal}}$$

Can $\pm 0.1\%$ Polarization Be Achieved?

b Physics at the Z Pole

$10^8, 10^9, 10^{10}$ or 10^{11} Z Decays
(How Ambitious?)

$BR(Z \to b\bar{b}) \simeq 0.15$

$b \to \bar{B}_d^0$ 40%

$b \to B^+$ 40%

$b \to \bar{B}_s$ 12%

$b \to \Lambda_b$ 8%

$b \to b\bar{c} \sim 10^{-4}$

$b \to bcq \sim 10^{-5}$

Study CP in many modes eg. $\overset{(-)}{B}_s \to J/\psi\,\phi$

Utilize LRFB Asymmetry $x = \cos\theta$

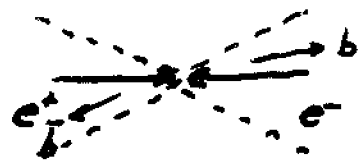
$$\frac{dN(e^+e^- \to b\bar{b})}{dx} = \frac{3}{8} N_B \left(1 - P_+P_-\right)\left(1 + P_{eff} A_{LR}\right)\left(1 + x^2 + \frac{8}{3} A_{eff}\, x\right)$$

$$P_{eff} = \frac{P_+ - P_-}{1 - P_+P_-}$$

↗ $(1+x)^2$ distribution

$$A_{eff} = \frac{A_{FB} + P_{eff} A_{LR}^{FB}}{1 + P_{eff} A_{LR}}$$

$A_{eff} \simeq 0.75$ for $P_{eff} \sim 1$



Flavor Tag

From
Kamal, Parsa, & W.M.

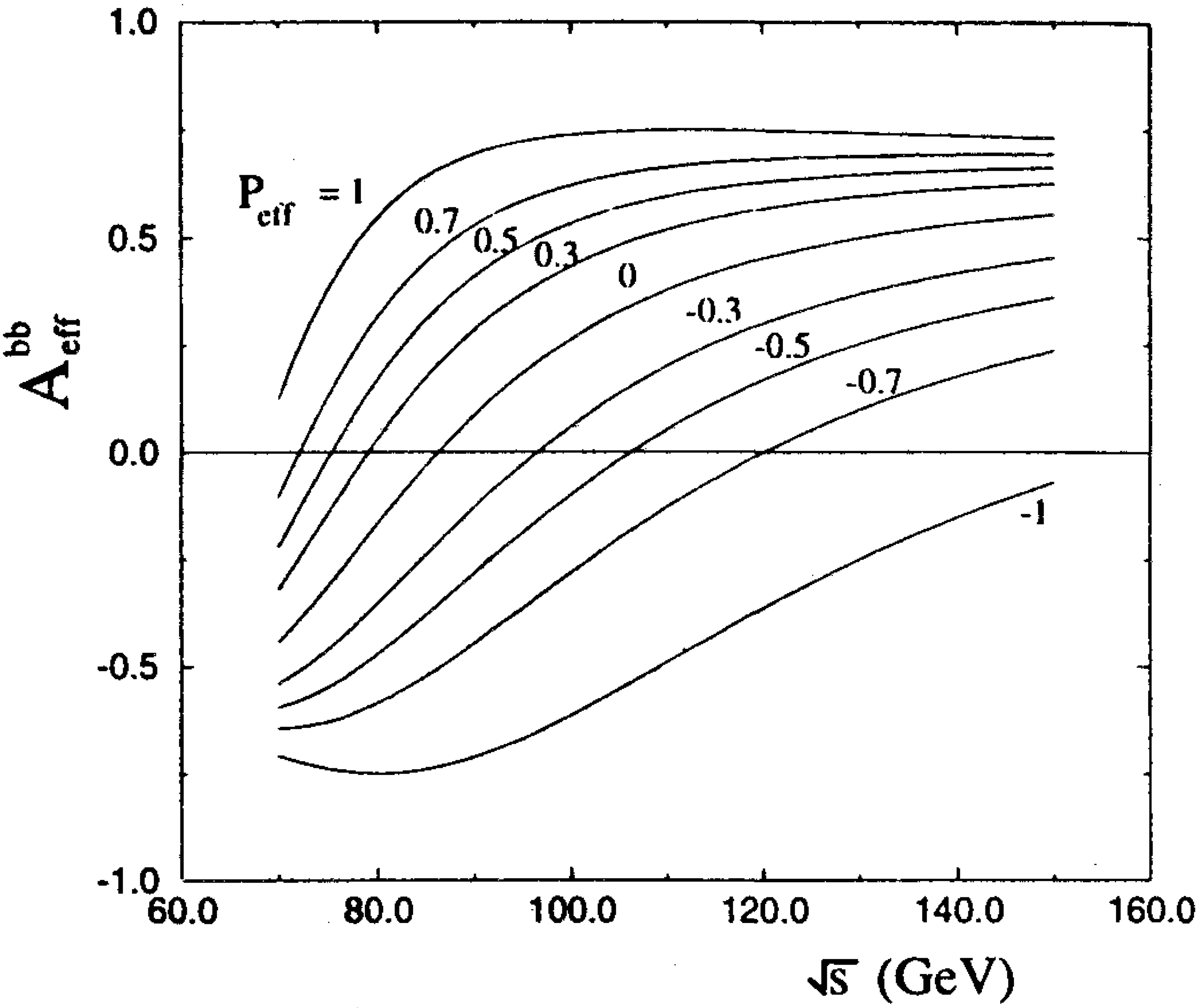


FIGURE 3. Effective forward-backward asymmetry for $\mu^- \mu^+ \to b\bar{b}$

Expect electron polarization $\underline{P_{e^-} \simeq 0.9}$, $\frac{\Delta P_{e^-}}{P_{e^-}} \simeq 0.004$
achieved at SLAC

Polarized Positrons? (Hard) May be possible

with $\underline{P_{e^+} = 0.7 \pm 0.007}$ i.e. $\frac{\Delta P_{e^+}}{P_{e^+}} \simeq \pm 1\%$

Effective Polarization, $\underline{P = (P_{e^-} + P_{e^+})/(1 + P_{e^-} P_{e^+})}$

(Polarizations add like Rel. Velocities!)

$P_{eff} = 0.9816 \pm 0.0008$, $\frac{\Delta P}{P} \simeq 0.09\%$!

What could we do with a determination of $\sin^2\theta_W(m_Z)_{\overline{MS}}$ to ± 0.00002?

Determine m_H from loop effects $\frac{\Delta m_H}{m_H} \simeq \pm 4\%$
spectacular

Look for effects of "New Physics" in loops, tree level etc $m_{W^*} + m_{Z^*} \to 10\,\text{TeV}$! } After m_H Directly Measured

A Giga Z Factory Should Have Already Been Built!

5.) Some Other Precision Studies (Low $q^2 \ll m_Z^2$)

Polarized $e^- D$ $\quad A_{LR}$ (Classic SLAC Exp)

Atomic Parity Violation (Cs) $\sim \pm 1\%$ Precision

Deep-Inelastic $\nu_\mu N$ scattering Some discrepency

New → Polarized $e^- e^-$ Möller Scattering at SLAC → A_{LR}

etc.

extract $\sin^2\theta_W(m_Z)_{\overline{MS}}$ to $\sim \pm 1\%$ via weak NC (or better) $\pm 0.3\%$

violates parity

depends on $\sin^2\theta_W$

Very good probes of Z' bosons, Extra dim ...

Complementary to Z pole studies (Competitive?)

eg. Currently Probe $m_{Z'} \lesssim 1$ TeV

Brief Comment on NuTeV at Fermilab (Anomaly)

Measure $R_\nu \equiv \dfrac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu X)}$ $+ R_{\bar\nu}$

→ $m_W = 80.16\,(8)$ GeV Too Low → "Very" Heavy Higgs

"New Physics" or Exp. Problem

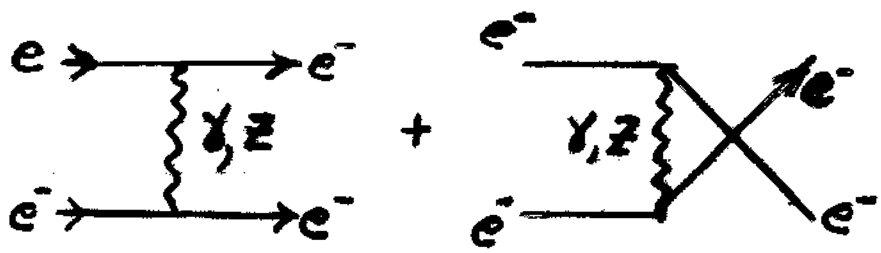
ii) Polarized e^-e^- (SLAC) E158 Experiment

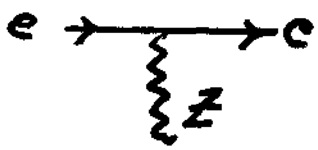
Möller Scattering $e^-e^- \to e^-e^-$

Use a polarized 50GeV e^- beam on a fixed target (Hydrogen)

Measure the P.V. Asymmetry

$$A_{LR} = \frac{\sigma(e_L^- e^- \to e^- e^-) - \sigma(e_R^- e^- \to e^- e^-)}{\sigma(e_L^- e^- \to e^- e^-) + \sigma(e_R^- e^- \to e^- e^-)}$$



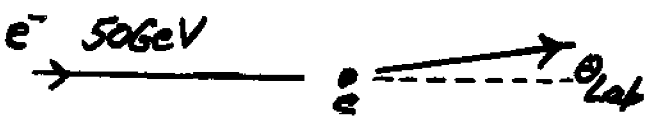


$$\frac{i g_0 \gamma_\mu}{4\cos\theta_W^0}\left(1 - 4\sin^2\theta_W^0 - \gamma_5\right)$$

↑ vector ↑ axial-vector

Parity Violation Requires VA → $1-4\sin^2\theta_W$ Factor

Asymmetry Very Small $1-4\sin^2\theta_W \simeq 0.08$



$y = \frac{1-\cos\theta_{cm}}{2}, \quad 0 \le y \le 1$

$Q^2 = -q^2 = yS = 0.05y\ \mathrm{GeV}^2$

$S = 2 \times 50 \times \underbrace{0.5\times10^{-3}}_{m_e}\ \mathrm{GeV}^2$

$$A_{LR}(e^-e^-) = \frac{G_\mu s}{\sqrt{2}\,\pi\alpha}\,\frac{y(1-y)}{1+y^4+(1-y)^4}\,(1-4\sin^2\theta_W^0) \underset{y=1/2}{\sim} \underbrace{3\times10^{-7}}_{\text{tiny}} \quad \Big\{ \text{Need } 10^{16} \text{ events}$$

Cross-Section in Enormous & $\mathcal{L}_{eff} \simeq 4\times10^{38}\,\mathrm{cm}^{-2}/\mathrm{s}$ luminosity

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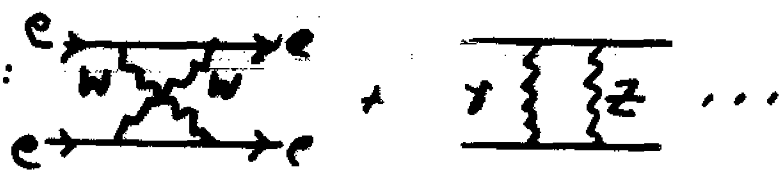
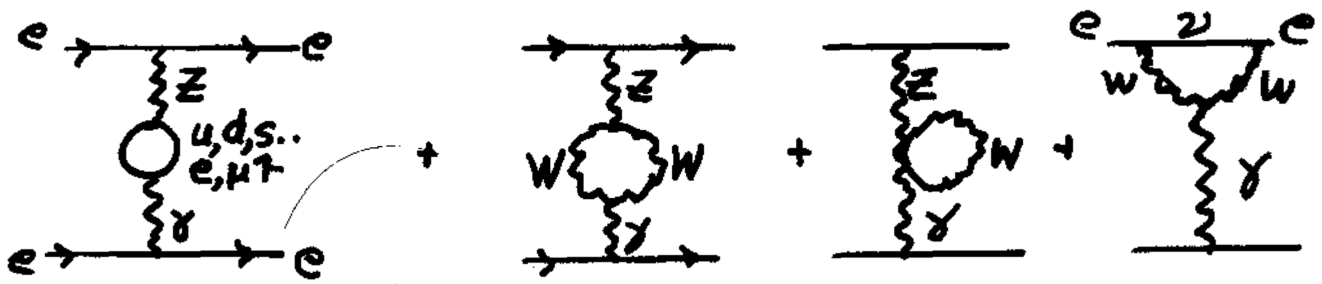
E158 Goal → Measure $\sin^2\theta_W(m_Z)_{\overline{MS}}$ to ± 0.0007

Become Best Low Q^2 Measurement

Radiative Corrections Very Large $\gtrsim 40\%$ A. Czarnecki + WM

examples: 

Main Correction γZ Mixing at low Q^2



Hadronic Part Large

$$\sin^2\theta_W(m_Z)_{\overline{MS}} \longrightarrow \sin^2\theta_W(Q^2) = \kappa(Q^2)\,\sin^2\theta_W(m_Z)_{\overline{MS}}$$

$$\kappa(Q^2 \simeq 0.025\,\mathrm{GeV}^2) = 1.03 \pm 0.0025 \quad \text{large shift}$$

Exp → $\sin^2\theta_W(Q^2 \simeq 0.025\,\mathrm{GeV}^2) \simeq 0.238(2)$ Preliminary

$$\rightarrow \sin^2\theta_W(m_Z)_{\overline{MS}} \simeq 0.231(2)$$

E158 will be completed this Summer. Expect $\Delta s^2 \simeq 0.0007$?

So far it is right on the SM value from Z pole. (A_{LR})

No Confirmation of NuTeV Anomaly (But not yet in
or $Z \to b\bar{b}$ FB real conflict)

Long Term Future — Fixed Target e^-e^- at NLC
(K. Kumar Snowmass 1996)

Higher energy 50GeV → 250 or 500 GeV
Higher Intensity
Longer Running

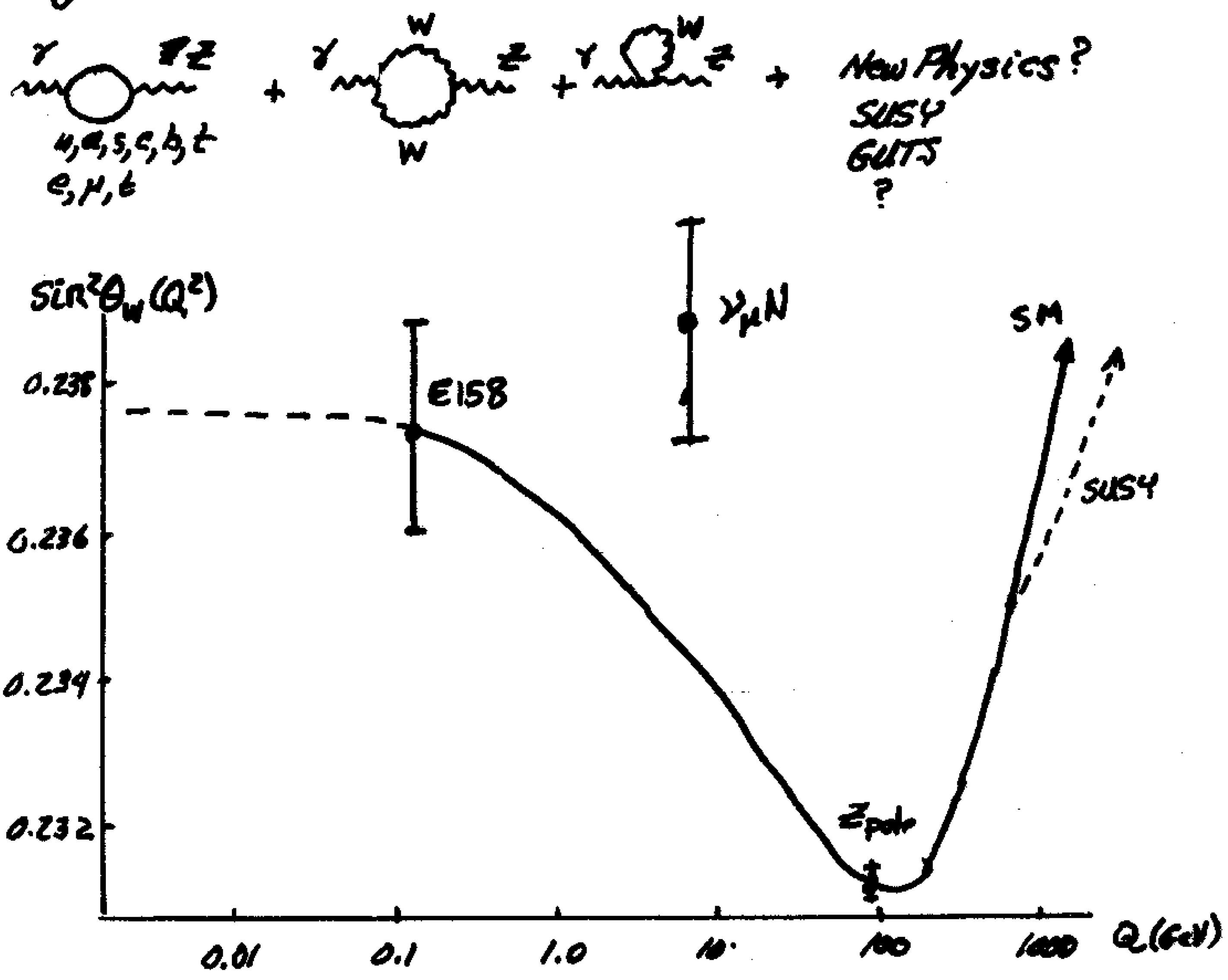
→ $\Delta \sin^2\theta_W \simeq \pm 0.00006$! — Pol. Unc Very Small
(Had. Loop Effects ?)

Probes: $\frac{\Delta m_H}{m_H} \simeq \pm 12\%$, $m_{Z_\chi}(SO(10)) \simeq 2.5$ TeV . . .

Alternative e^-e^- at $\sqrt{s} \simeq 500-1000$ GeV Collider

Not as good for $\sin^2\theta_W$
but better Probe of "New Physics"

Running $\sin^2\theta_W(Q^2)$ from γ-Z Mixing



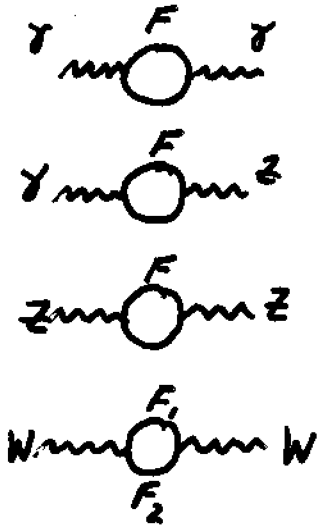
6) "New Physics" Effects

i) S, T, U Parametrization of Peskin + Takeuchi

Dynamical Sym. Breaking Generally Requires __Heavy__ New Fermions

$\begin{pmatrix} F_1 \\ F_2 \end{pmatrix}_L \quad F_{1_R} \quad F_{2_R} \rightarrow$ Effective Bound State Higgs
eg Technicolor
$\pi^{\pm}_{TC}$, π^{0}_{TC}, σ_{TC} (Heavy + Broad) $\mathcal{O}$(1TeV)

How would they impact precision measurements
Contribute to Gauge Boson Self-Energies



$\pi_{\gamma\gamma}(q^2) \longrightarrow \alpha$

$\pi_{\gamma Z}(q^2) \longrightarrow \sin^2\theta_W$

$\pi^{VV}_{ZZ}(q^2), \pi^{AA}_{ZZ}(q^2) \longrightarrow m_Z$

$\pi^{VV}_{WW}(q^2), \pi^{AA}_{WW}(q^2) \longrightarrow m_W$

} Related by Natural Rel.!

$$\alpha T = \frac{\pi^{New}_{WW}(0)}{m_W^2} - \frac{\pi^{New}_{ZZ}(0)}{m_Z^2}, \quad \frac{\alpha}{\sin^2 2\theta_W} S = \frac{\pi^{New}_{WW}(m_W^2) - \pi^{New}_{WW}(0)}{m_W^2}$$

$$\frac{\alpha}{4\sin^2\theta_W}(S+U) = \frac{\pi^{New}_{ZZ}(m_Z^2) - \pi^{New}_{ZZ}(0)}{m_Z^2}$$

U small (violates isospin)

$S, T \sim \mathcal{O}(1)$
Dynamical Sym Br.

<u>Technicolor</u> (QCD like with $SU(N)_{TC}$ and $\Lambda_{TC} \simeq 1000\,\Lambda_{QCD}$)

$\begin{pmatrix} U^i \\ D^i \end{pmatrix}_L \quad U^i_R,\, d^i_R \quad i=1,2..N_{TC}$ Techniquarks + Technileptons

Goldstone Bosons $\pi^\pm_{TC}, \pi^0_{TC} \to W^\pm_L, Z_L$ $\quad W^- \; \pi^-_{TC} \; W^-$

Spectrum of $\rho_{TC}, A_{TC} \ldots$ at $\sim 1\,\text{TeV}$

$$S \simeq +(1\sim 2) \times \frac{1}{6\pi} \times \underbrace{\text{No. of heavy technidoublets}}_{\gtrsim 8} \gtrsim O(1)$$

Positive

Effectively $m_H \sim O(1\,\text{TeV}) \to m_W + \sin^2\theta_W(m_Z)_{\overline{MS}}$ predictions change (way off)

$$S \simeq 118 \left\{ 2\,\frac{m_W - 80.209\,\text{GeV}}{80.209\,\text{GeV}} + \frac{\sin^2\theta_W(m_Z) - 0.23232}{0.23232} \right\}$$ Nice Test

$$\left.\begin{array}{l} m_W = 80.451(33) \\ s^2 = 0.2308(2) \end{array}\right\} \to \underline{S = -0.06 \pm 0.1 \pm 0.1}$$

No Sign of Technicolor

Using $\alpha, G_\mu, m_Z, m_t, (m_H \sim 1\,\text{TeV}) \ldots$ as input

Predict m_W + $\sin^2\theta_W(m_Z)_{\overline{MS}}$

$$m_W = \text{S.M.} + (0.45T - 0.29S + 0.34U)\,\text{GeV}$$

$$\sin^2\theta_W^{\overline{MS}}(m_Z) = \text{S.M.} + 0.00365S - 0.00261T$$

Global Fits → (crudely)

$$S \simeq -0.1 \pm 0.1$$
$$T \simeq +0.1 \pm 0.1$$

} No Evidence For New Physics

Each Heavy Fermion Doublet → $\Delta S = \frac{1}{6\pi}$

A Heavy 4th Generation → $\frac{4}{6\pi} \simeq 0.2$ (Ruled Out ?)

No evidence for <u>$S \simeq +1$</u> As Expected in dym. models (generic)

With Giga Z → $\Delta\sin^2\theta_W \simeq 0.00002$, we would probe

$$\boxed{\Delta S \simeq \pm 0.02} \quad \text{besides } \frac{\Delta m_H}{m_H} \sim \pm 4\%$$

Spectacular Probe of Heavy Loop Effects !

Next Lecture Higgs Phenomenology