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Precision Measurements & "New Physics"

Outline

I. Standard Model and Beyond (Overview)

II. Electroweak Precision - Quantum Loop Effects

* i) $\alpha, G_F, m_Z, m_t + m_W, \sin^2\theta_W, \Gamma_Z \ldots \rightarrow m_H$ (Higgs)

ii) S & T Parameters — Supersymmetry as Technicolor

* III. A Tale Of Two Numbers (3.2 sigma difference)

i) $A_{LR}(Z) \rightarrow \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23070(26) \rightarrow$ Supersymmetry

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

III. Outlook

i) Polarized e^-e^- at JLab — $\Delta\sin^2\theta_W(m_Z)_{\overline{MS}} \simeq 0.0002$!
(Post LHC) (This week's workshop)

I. Standard Model and Beyond

"We are the symmetries of Nature"

Poincaré Inv + $SU(3)_c \times SU(2)_L \times U(1)_Y$ + Higgs Mechanism

$|spin, mass\rangle$ | 8 gluons, $W^\pm$, Z, γ | $V(\phi) = -\lambda(\phi^2 - v^2/2)^2$

general coor inv | + 3 Generations of Fermions | ϕ = complex $S=0$ doublet

$\left(\begin{matrix}\nu_e \\ e\end{matrix}\right)_L e_R \cdots \left(\begin{matrix}u \\ d\end{matrix}\right)_L u_R d_R \cdots$

$v = 250\,GeV$

Scale of EW Sym Br.

↓ SUSY, Strings, Extra Dim.

Gravity

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} w_1 + i w_2 \\ H + v + i z \end{pmatrix}$$

12 Gauge Fields

45 (48) Chiral Fermion

[12 Doublets, 21-24 Singlets]

All Discovered!

~30 years of Testing!

Where is H?

$m_H^{Exp} > 114\,GeV$

$SU(3)_c$ = Quantum Chromodynamics (QCD)

Perfect Theory! - No Parameters!

$SU(2)_L \times U(1)_Y + Higgs$ = Electroweak

$\underbrace{\quad}_{U(1)_{EM}}$

Many Parameters: g_2, g_1, λ, v

+ > 72 Yukawa Couplings!

Potential For "New Physics": $SU(2)_R, U(1)', SU(N)_{TC} \rightarrow W_R^\pm, Z' \ldots$

SUPERSYMMETRY, Technicolor

Extra Dimensions ... - $Z^*, \gamma^*, \mu^*, \ldots$

QCD exhibits rich dynamics { low energies, high Temp. + Density

Non-Linear + Strong Coupling

- Quark Confinement
- Asymptotic Freedom $\alpha_3(91GeV) \simeq 0.118$
- Hadron Spectroscopy
- Nuclear Physics
- Proton Structure (Spin)
- Chiral Sym. Br
- $\langle 0|\bar{q}q|0\rangle \neq 0$ Breaks EW! $m_W \simeq 80MeV$?
- Dynamical Mass Generation
- Exotics - Glueballs
- Color Superconductivity
- Quark-Gluon Plasma
- ⋮

} All $SU(3)_c$ Dynamics!

QCD is a major scientific triumph of 20th Century

It completely solved strong interaction physics which had been a big mess!

Next Major Step: LHC $p\bar{p} \to X$ at 14 TeV, $\mathcal{L} \simeq 10^{34}\,cm^{-2}s^{-1}$

* Find Higgs Scalar, SUSY, Extra Dim.? Technicolor? ...

or Bust

Light Higgs $\lesssim$ 135 GeV Favors Supersym.

Heavy Higgs $\gtrsim$ 400 GeV Suggests Strong Dynamics (Technicolor)

What is the Higgs Mass? $\gtrsim$ 114.4 GeV (Exp)

Precision EW Data + Quantum Loops $\to$ $m_H = 85^{+39}_{-28}$ GeV < 161 GeV (95% CL)

SUSY To Follow?

Good Bet

or

Major Disappointment

II. Electroweak Precision - Quantum Loops

EW Parameters: $g_2^0, g_1^0, v_0, \lambda^0 \rightarrow \alpha_0, G_F^0, m_Z^0, m_H^0$

$\alpha_0 = e_0^2/4\pi$

$G_F^0 = g_{2\,0}^2/4\sqrt{2}\, m_W^{0\,2}$

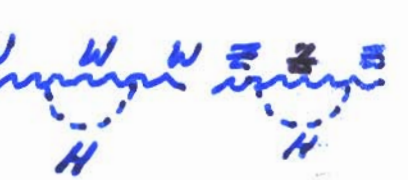
* Bare Parameters Connected:

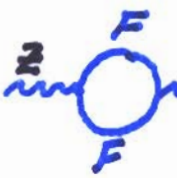
$$\sin^2\theta_W^0 = \frac{e_0^2}{g_{2\,0}^2} = 1 - m_W^{0\,2}/m_Z^{0\,2}$$

Natural Relations
custodial symmetry

Loop Corrections Finite & Calculable!

Depend on m_t, m_H 

m_H 

Depend on "New Physics" 

Heavy Fermions Eg. Technicolor, 4th Gen...

$$\Delta r(m_t, m_H, \text{New Phys}) = \blacksquare\ 1 - \frac{\pi\alpha}{\sqrt{2}G_F m_W^2 (1 - m_W^2/m_Z^2)}$$

$$\Delta\hat{r}(m_t, m_H, \text{New Phys}) = 1 - \frac{2\sqrt{2}\pi\alpha}{G_F m_Z^2 \sin^2 2\theta_W(m_Z)_{\overline{MS}}}$$

$$\Delta r \simeq 0.07 + \frac{\alpha}{\pi}\left\{-\frac{3}{16}\frac{m_t^2}{m_Z^2}\frac{1}{s^4} + \frac{11}{48 s^2}\ln\frac{m_H^2}{m_Z^2}\right\} \cdots$$

α, G_F, m_Z, m_t + m_W or $\sin^2\theta_W(m_Z)_{\overline{MS}} \longrightarrow m_H$

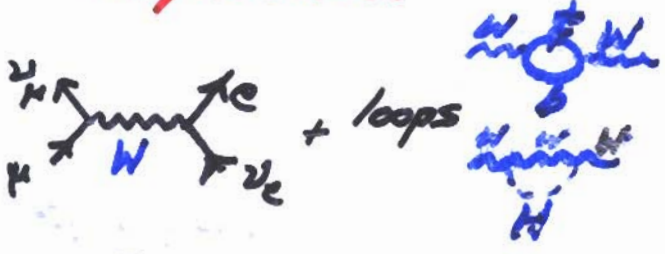
Electron Anomalous Magnetic Moment $a_e = g_e - 2/2$

$a_e^{exp} = 1159652180.85(76) \times 10^{-12}$ G. Gabrielse et al. (2006)

$a_e^{SM} = \frac{\alpha}{2\pi} - 0.328478444\left(\frac{\alpha}{\pi}\right)^2 + 1.181234\left(\frac{\alpha}{\pi}\right)^3 - 1.7502\left(\frac{\alpha}{\pi}\right)^4 \ldots$

* $\alpha^{-1} = 137.035999710(96)$ Very Precise!

Muon Lifetime $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$



* $G_F = \frac{g_2^2}{4\sqrt{2}\, m_W^2} = 1.16637(1) \times 10^{-5}\ GeV^{-2}$

New Exp PSI Underway
1/10 Reduction

Z Pole Studies at CERN $e^+e^- \to Z$

* $m_Z = 91.1875(21)\ GeV$

Top Quark Mass FNAL $p\bar{p} \to t\bar{t} + X$ $t \to Wb$

* $m_t = 171.4(2.1)\ GeV$

Recent Reduction
174.3 → 178 → 172.7 → 171.4!
Somewhat Low?

Other $m_W^{aoc} = 80.405^{(30)}$ GeV (Recent Reduction) Still High

$\sin^2\theta_W(m_Z)^{aoc}_{\overline{MS}} = 0.23125(16)$ Many Z pole meas.

Best Individual: $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23070(26)$ $A_{LR}(e^+_L e^-_R \to Z)$

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

Differ by 3.2 sigma!

Other Precision: $\Gamma(Z \to e^+e^-) = 83.985(86)$ MeV, Γ_Z ...

Global Fit To All Data + 1+2 Loop Quantum Loops

Erler + Langacker PDG

$m_H = 85^{+39}_{-28}$ GeV < 161 GeV (95% CL)

$m_H^{exp} > 114.4$ GeV $e^+e^- \to Z + H$

"New Physics": $m_{Z_\chi} \gtrsim 1$ TeV (SO(10)) ...

Heavy Fermions $\begin{pmatrix} F \\ F' \end{pmatrix}_L$ F_R, F'_R ... N_D doublets

eg $N_D = 4$ (4th Gen.)

$\Delta\rho^{New} \sim 1 = \frac{\alpha}{4\sin^2\theta_W} S$ $S = \frac{N_D}{6\pi}$, $T \sim \frac{|m_F^2 - m_{F'}^2|}{m_W^2}$

Global Fit → $S \simeq -0.1 \pm 0.1$ $\quad T \simeq -0.1 \pm 0.1$

No evidence for Heavy Chiral Doublets

No 4th Gen, No Technicolor? ...

* Supersymmetry $S \simeq 0$ Favored

Dependence on $X = \ln\left(\frac{m_H}{115\,GeV}\right)$, S, T

$$m_W\,(GeV) = 80.354(13) - 0.055X - 0.01X^2 - 0.29S + 0.45T$$

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

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

III A Tale Of Two Numbers (use $m_W = 80.405(30)$ GeV)

$A_{LR} \rightarrow \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23070(26) \rightarrow m_H \simeq 30\,GeV\,^{+23}_{-18}$

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

Individually, both inconsistent with SM + m_W + $m_H > 114$

A_{LR} for $m_H \simeq 115$GeV → $S \simeq -0.16$, $T \simeq 0.06$, smaller m_W

Easily Accomodated by SUSY

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

Incarsistent with m_W + SM

but Consistent with

$m_H \simeq 500\,GeV$
$S \simeq 0.4$ $\quad N_D \simeq 4 \sim 12$!
$T \simeq 0.6$

} 3σ evidence? Technicolor (Randall-Sundrum) Suggestive!

Is it possible? Other measurements wrong? Γ_Z, A_{LR}

Low Q^2 Moller $e_L^- e^- \to e^- e^-$ $A_{LR} \to \sin^2\theta_W(M_Z)_{\overline{MS}} = 0.2330(13)$

Error too large

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

IV Outlook

Precision data very suggestive of Supersymmetry
low Higgs Mass (see a_μ) 3.4sigma

* Expect Higgs + SUSY Discoveries

But, what about $A_{FB}(Z \to b\bar{b})$? → Technicolor? (New Life?)

$\sin^2\theta_W(M_Z)_{\overline{MS}}$ incorsistency unacceptable!

LHC: $pp \to Z + X$ $\quad A_{FB}(Z \to \mu^+_{e^+}\mu^-_{e^-})$

$\Delta \sin^2\theta_W \simeq \pm 0.00008$ stat. (systematics hard!)

JLAB: 12GeV Pol. Electrons $A_{LR}(\vec{e}_R e^- \to e^- e^-)$

$\Delta \sin^2\theta_W(m_Z)_{\overline{MS}} \simeq \pm 0.00025$ (Non-Pole)

ILC: (Giga Z option) A_{LR} with 10^9 Zs!

$\Delta \sin^2\theta_W \simeq \pm 0.00002$! (2026?)

WAIT and See

Next stop LHC (H, SUSY...?)

(Also, watch m_W at Fermilab)(m_t)

Do R_{LR} Studies!

Polarized $e\vec{e}^- \to e\vec{e}^-$

E158 at SLAC $E_e \simeq 50$GeV on Fixed Target

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

13% measurement!

$A_{LR} \sim (1 - 4\sin^2\theta_W) \to \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2330(14)$

Compare with Z pole ave = 0.23125(16) 1.25σ diff

Constrain "New Physics"

$\Lambda_{compositeness} \gtrsim 10$ TeV

$m_{Z'}(SO(10)) \gtrsim 1$ TeV

$\Lambda_{ExtraDim} \gtrsim$ few TeV

⋮

Goals at JLab

1) Qweak $Pol\ e^- p \to e^- p$ $A_{LR} \sim (1 - 4\sin^2\theta_W) Q^2$

$$\Delta \sin^2\theta_W(m_Z)_{\overline{MS}} \simeq \pm 0.0008$$

Constrains "New Physics"

Develop pol. asym. program at JLab

Moller at 12GeV JLab $e^-e^- \to e^-e^-$ A_{LR} to $\pm 2.5\%$ (Moller)

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

Will it be important in 2015? Post LHC Pre ILC

Higgs Discoved, SUSY Seen or Not, Z'boson ~1-3TeV

Other Hints

eg Suppose $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23300(25)$

$m_W = 80.405(20)$GeV

Now $\sin^2\theta_W^{ave}(m_Z)_{\overline{MS}} = 0.23176(13)$

$\to m_H \simeq 295^{+83}_{-66}$ GeV Agree with LHC?

$m_W + \sin^2\theta_W \to S = 0.4 \pm 0.1$ Technicolor? 4th gen

More likely Z' or Z* ~5 TeV

Seen at LHC? Wait for ILC $\sqrt{s}$=?

"JLab discovers evidence for physics beyond the (supersymmetric) standard model"

Very Exciting