W. Marciano
6/21/06

Electroweak Physics

$SU(3)_c$ QCD is a perfect theory - No Free Parameters!

Rich Dynamics: Confinement, Asy Freedom, Spectroscopy ...

BNL is a QCD Laboratory

RHIC - Pol. pp - Lattice Gauge Th.

$SU(2)_L \times U(1)_Y$ EW is not a perfect theory

but very accommodating!

Many Arbitrary Parameters

$g_1, g_2 \rightarrow \alpha, \sin^2\theta_W$

$\mu^2, \lambda \rightarrow m_H, v \simeq 250\,GeV$

Higgs Yukawa $\rightarrow$ 12 Parameters - 20 observables

+ ...

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!

Potential For Lots Of "New Physics"

Supersymmetry, Technicolor ...

Probes: * **Precision Measurements:** m_W, $\sin^2\theta_W$, $g_\mu - 2$ ...

Flavor Violation: $\mu \to e\gamma$, $\mu^- N \to e^- N$

EDMs: Atoms, Neutron, D, p^+ ... $\bar{\theta}_{QCD}$ (New Source of $\not{CP}$)

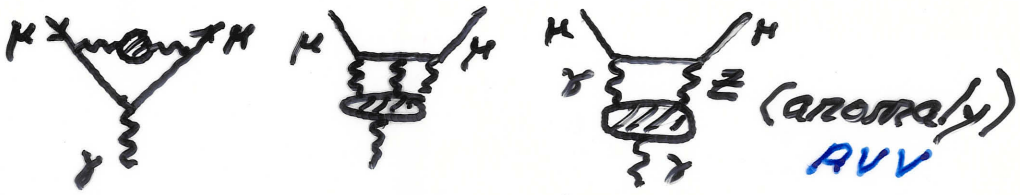
Colliders: Best Bet LHC, ILC

Higgs? susy? strong Dynamics?

Lattice Has A Major Role To Play

ε'/ε, B_K, B_b, $f_+(0)$, f_K, f_π, f_B, f_D ...

$a_\mu \equiv \frac{g_\mu - 2}{2}$



(anomaly) AVV

7000×10^{-11} 120×10^{-11}

small (∞) $\to 2 \times 10^{-11}$

but good practice

$$a_\mu^{exp} - a_\mu^{SM} = 268\,(63)_{Exp}\,(59)_{VP}\,(35)_{LBL}\,(2)_{EW} \times 10^{-11} \quad 2.9\sigma$$

CKM Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + \underbrace{|V_{ub}|^2}_{\sim 1\times 10^{-5}\ \text{tiny}} = 1$

$0^+ \to 0^+$ Beta Decays $V_{ud} = 0.97377(11)(15)(19)_{RC}$

$\to V_{us} = \sin\theta_c = 0.2275(11)$ Indirect

$K \to \pi l \nu_l$ $(K_{l3}) \to V_{us} = 0.2261(8)\left(\frac{0.961}{f_+(0)}\right)$ Vector

$\frac{K\to\mu\nu}{\pi\to\mu\nu}$ $\left(\frac{K_{\mu 2}}{\pi_{\mu 2}}\right) \to V_{us} = 0.2245(5)\left(1.198\,\frac{f_\pi}{f_K}\right)$ Axial

Also, Hyperon Decays, $s \to u\, l^-\, \bar{\nu}_l$

Now a lattice problem: $f_+(0)$ & f_K/f_π

I will concentrate on $\sin^2\theta_W(m_Z)_{\overline{MS}}$ $\to m_H$ + "New Physics"

The Most Important EW Parameter!

Natural Relations: $\sin^2\theta_W^0 = \frac{e_0^2}{g_{Z_0}^2} = 1 - (m_W^0/m_Z^0)^2$ SU(2) Custodial sym.

Radiative Corrections (finite & calculable)

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

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

The Weak Mixing Angle Problem (Mini-Crisis)

Two Best Z Pole Determinations

A_{LR} SLD $\rightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3)$

$A_{FB}(Z \rightarrow b\bar{b})$ $\rightarrow$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3)$

} 3σ!

Discrepancy Lost in Averaging $\rightarrow$ $0.2312(2)$

Very Different Implications

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3) \rightarrow m_H = 35^{+26}_{-17}$ GeV Ruled Out!

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3) \rightarrow m_H = 480^{+350}_{-230}$ GeV Heavy!

S Parameter

$$S = 118\left[2\,\frac{m_W - 80.366\,\text{GeV}}{80.366\,\text{GeV}} + \frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.23117}{0.23117}\right]$$

use $m_W = 80.410(32)$ GeV

Standard Model + SUSY $\rightarrow$ $S \simeq 0$ Expected

Heavy Fermion Chiral Doublets $\rightarrow$ $S \simeq +\frac{1}{6\pi} N_D \simeq 0.05\,N_D$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3) \rightarrow S = -0.11(9)(15)$

$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2320(3) \rightarrow S = +0.55(9)(15)$ 3σ

Room for $\sim N_D = 10$ Heavy Chiral Doublets!

New Life For Technicolor

Mirror Fermions, 4th Gen. . . .

Supersymmetric GUTS (SU(5), SO(10), E_6)

1982 W.M. & G. Senjanovic, M. Einhorn & D.R.T. Jones

Input $\alpha^{-1}(m_Z) = 127.8$, $\alpha_s(m_Z) = 0.12$, $m_{SUSY} \simeq 100\,GeV$

$\alpha_1(m_X) = \alpha_2(m_X) = \alpha_3(m_X)$, $N_H = 2$ doublets

Predict: $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.233 - 0.234$ (High)

$m_X \simeq 2 \times 10^{16}\,GeV$

$\tau(p \to e^+\pi^0) \simeq 2 \times 10^{36}\,yr$ (Exp $\gtrsim 10^{34}\,yr$)

$\sin^2\theta_W(m_Z)_{\overline{MS}}$	m_{SUSY} (GeV)	m_X (GeV)	$\tau(p \to e^+\pi^0)$ yr.
0.2320	450	1.6×10^{16}	8×10^{35}
0.2312	1500	1.4×10^{16}	5×10^{35}
0.2307	3,200	1.2×10^{16}	3×10^{35}

Observable

How will $\sin^2\theta_W(m_Z)_{\overline{MS}}$ discrepency be resolved?

* LHC? $pp \to Z \to \mu^+\mu^-$ FB Asym Hard (± 0.00008)

ILC? Giga Z Factory (Z pole) A_{LR} in e^+e^-
$\Delta \sin^2\theta_W \to \pm 0.00002$ Pol. $\pm 0.1\%$? Hard
Other $\to \pm 0.0002$ (Long Wait ~15yr)

What about low Q^2 experiments?

Atomic Parity Violation $Q_W(Cs) = -72.66(46)$
Pol. Electron Scattering $e^-e^- \to e^-e^-$ Moller $A_{LR} \simeq 1.3\times10^{-7}$
($\propto (1-4\sin^2\theta_W)$) $e^-p \to e^-p$ $Q_W(p)$ A_{LR}

Current Status (After Rad. Corr.)

APV $\to$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2290(20)$
Moller (E158) $\to$ $\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2330(14)$
} 1.5σ

Again below and above world average

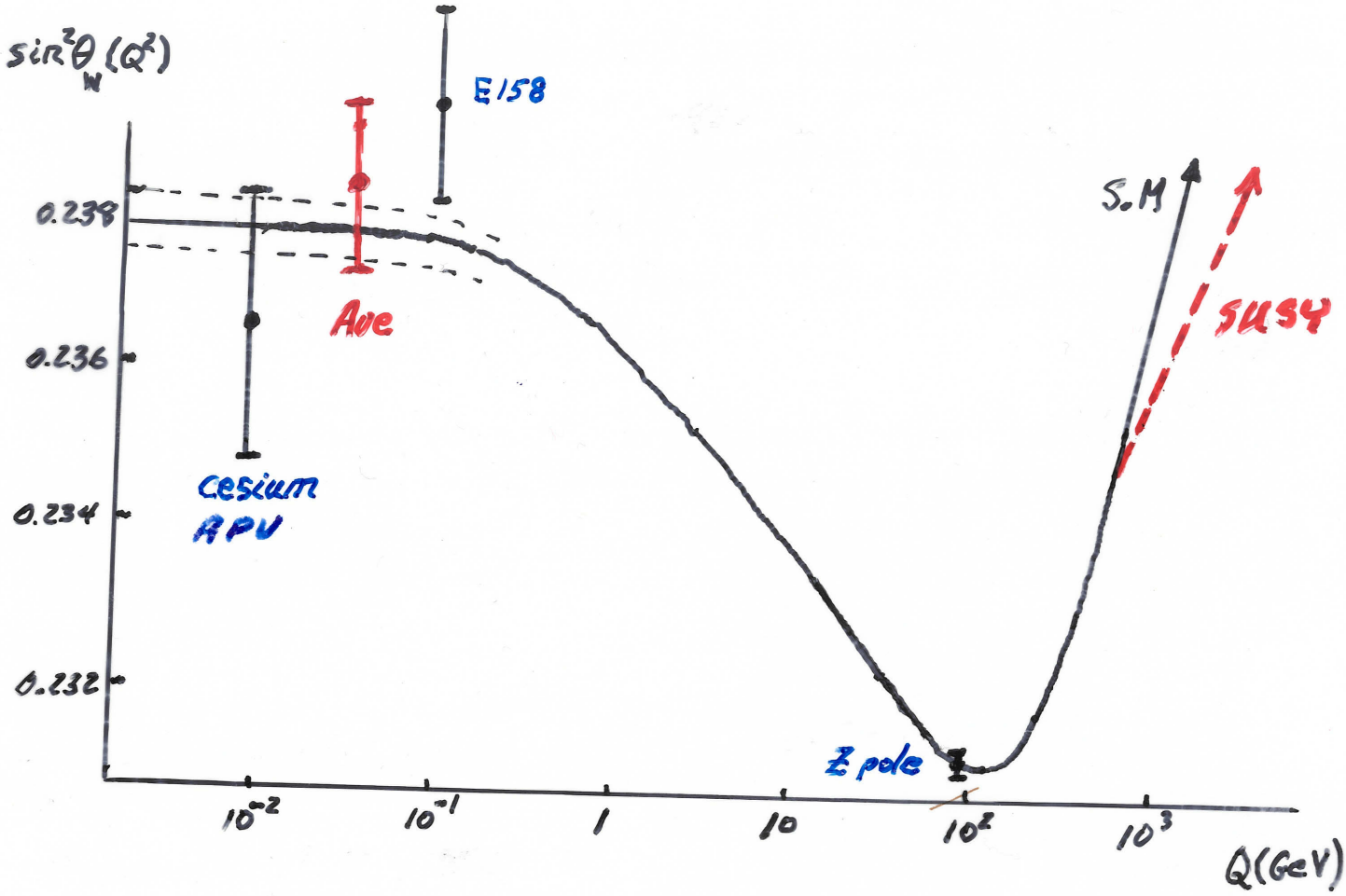
Nice confirmation of SM Quantum Loops & Running

But Errors Not Competitive With Z Pole

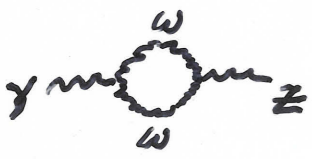
Constraints: $m_{Z_X} > 1\,TeV$
$m_{comp.} \gtrsim 10\,TeV$
$g^2/m_H^2 < 0.01\,G_\mu$
...

Together
$S \simeq 0.4(6)$
$\sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2317(12)$

Running of $\sin^2\theta_W(Q^2)$ ($\sim 6\sigma$ confirmation) E158
($\sim 8\sigma$ E158 + APV)



$$\sin^2\theta_W(0) = 1.0301(25)\,\sin^2\theta_W(m_Z)_{\overline{MS}}$$



Future JLAB Program

A_{LR} in $ep \to ep$ $\quad Q_W(p) \to \Delta \sin^2\theta_W \to \pm 0.0008$

12 GeV Upgrade $\quad$ Moller $\to \Delta \sin^2\theta_W \to \pm 0.0003$

Very Competitive

Resolve Discrepancy or See New Physics $Z' \ldots H^{--}, S$

K. Kumar $\quad$ Fixed Target at ILC $\quad e^- \xrightarrow[250\,GeV]{} \cdot e^-$

A_{LR} $\quad e^-e^- \to e^-e^-$

High Energy $\quad$ 250 GeV
High Current
High Pol.

$\Delta \sin^2\theta_W \to \pm 0.00006$ $\quad$ Spectacular

Probes $\quad Z_\chi \simeq 2.5$ TeV

$\Lambda_{comp.} \simeq 50$ TeV

$\Delta S \simeq 0.05 \quad (m_W + \sin^2\theta_W (MR_Z)_{\overline{MS}})$

Probes $N_D = 1$

Conclusion: $\sin^2\theta_W(m_Z)$ most important parameter for:

Higgs Mass (via loops)
S Parameter
Grand Unification
⋮

Present Situation Unacceptable

Need $Q_W(p)$, e^-e^- at JLab

e^-e^- + Giga Z at ILC → $\Delta s^2 \simeq \pm 0.00006, 0.00002$

+ LHC + other e^+e^- efforts

Very Complementary to Direct "New Physics" Discovery

Lattice:

vs $e^+e^- \to$ hadrons data

easier than $g_\mu - 2$

LHC: $pp \to Z + X$ $\quad Z \to \mu^+\mu^- \to$ $\delta\sin^2\theta_W \simeq \pm 0.00008$

(Best Bet)

Can Pol pp help overcome had. unc → ±0.0002?

or Z/W at LHC