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8/12/98

Precision Electroweak Measurements and "New Physics"

Outline

1. Natural Relations and EW Radiative Corrections

$$\sin^2\theta_W^0 = \frac{e_0^2}{g_{Z_0}^2} = 1 - (m_W^0/m_Z^0)^2$$

2. Precision Measurements - Status + Commentary

   i) α, G_μ, m_Z, m_W, $\sin^2\theta_W$, Γ_Z ...

   ii) $\nu_\mu N$, Atomic P.V., ...

3. "New Physics" - Implications

   i) Higgs Mass + SUSY ($m_H \lesssim 130$ GeV)

   ii) S, T, U (Peskin + Takeuchi)

   iii) Z′ Bosons (GUTS, ...) Not enough time

   iv) W^*, $Z^*_{2,1}$ (Extra Dimensions) (see Arkani-Hamed Talk) (Like S, T, U)

4. Conclusion + Outlook

1. Natural Relations and EW Radiative Corrections

Standard $SU(2)_L \times U(1)_Y$ Theory: Renormalizable
Custodial $SU(2)_V$ sym.

$$\sin^2\theta_W^0 = \frac{e_0^2}{g_{z_0}^2} = 1 - (m_W^0/m_Z^0)^2$$

Natural Relations

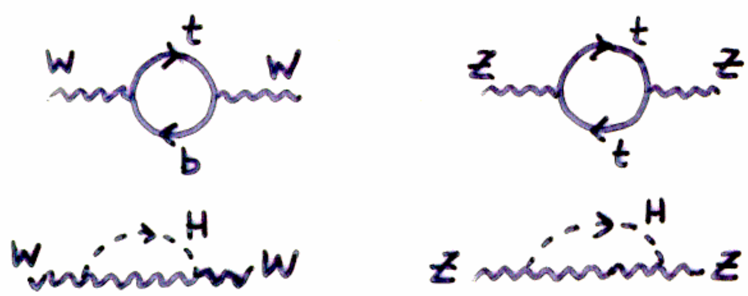
Satisfied by renormalized parameters, up to

Finite Calculable Radiative Corrections!

Quantum Loops Depend on m_t, m_{Higgs}, "New Physics"
SUSY
Technicolor (S, T, U)

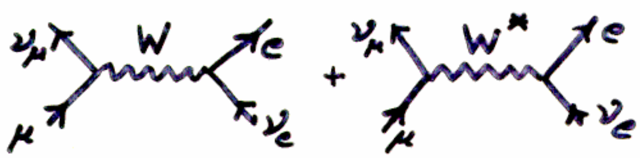
Also, heavy new particles can affect tree level: 

Z', W^*, Z^*, Leptoquarks... Compositeness
string excitations
large dimensions ~ 10^{-17} cm?



Heavy Fermions, SUSY

etc.



High vs Low Energy
explore $m_{W^*} \gtrsim$ 1-2 TeV

Renormalized Relations

$q^2=0$ $\quad \alpha = e^2/4\pi$, $\quad G_\mu = g_2^2/4\sqrt{2}m_W^2$ (Muon Decay)

m_W , m_Z Real Part of Pole in Propagator

(Z pole) $\sin^2\theta_W^{eff} = \sin^2\theta_W(m_Z)_{\overline{MS}} + 0.0003$

Radiative Corrections Depend on: $m_t = 173.8 \pm 5\,\text{GeV}$

$m_H = ?$ ($\gtrsim 89\,\text{GeV}$ LEP II)

some α_s dependence

$$\frac{e_0^2}{g_{2_0}^2} = 1-(m_W^0/m_Z^0)^2 \rightarrow \boxed{\frac{\pi\alpha}{\sqrt{2}G_\mu m_W^2} = \left(1-\frac{m_W^2}{m_Z^2}\right)(1-\Delta r(m_t,m_H))}$$

$$\frac{e_0^2}{g_{2_0}^2} = \sin^2\theta_W^0 \rightarrow \boxed{\frac{\pi\alpha}{\sqrt{2}G_\mu m_W^2} = \sin^2\theta_W(m_Z)_{\overline{MS}}(1-\Delta r(m_Z)_{\overline{MS}})}$$

$$\sin^2 2\theta_W^0 = \frac{4e_0^2}{g_{2_0}^2}\frac{m_W^{0\,2}}{m_Z^{0\,2}} \rightarrow \boxed{\frac{4\pi\alpha}{\sqrt{2}G_\mu m_Z^2} = \sin^2 2\theta_W(m_Z)_{\overline{MS}}(1-\Delta\hat{r}(m_t,m_H))}$$

$\Delta r(m_t,m_H)$, $\Delta r(m_Z)_{\overline{MS}}$, $\Delta\hat{r}(m_t,m_H)$ Finite + Calculable!

($\Delta r(m_Z)_{\overline{MS}}$: rather insensitive to m_t + m_H)

$m_W^2\sin^2\theta_W(m_Z)_{\overline{MS}} = \text{constant}$

$\Delta r(m_t,m_H) \simeq 0.035$, $\quad \Delta r(m_Z)_{\overline{MS}} \simeq 0.070$, $\quad \Delta\hat{r}(m_t,m_H) \simeq 0.060$

Need ±1% to confirm (some hadronic unc.)

Example, in large m_t, m_H limits

$$\Delta r(m_t, m_H) \sim \frac{\alpha}{\pi \sin^2\theta_W} \left\{ \underbrace{\frac{-3}{16} \frac{m_t^2}{m_W^2} \cot^2\theta_W}_{-3\%} + \underbrace{\frac{11}{48} \ln\left(\frac{m_H^2}{m_Z^2}\right)}_{0 \sim 1\%} \right\}$$

Input: $\alpha, G_\mu, m_Z \xrightarrow[m_t, m_H]{} m_W$, $\sin^2\theta_W(m_Z)_{\overline{MS}}$ Predicted

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$m_t = 173.8$ GeV (± 5GeV $\rightarrow \Delta m_W = \pm 0.035$GeV, $\Delta \sin^2\theta_W = \mp 0.0002$)

m_H (GeV)	m_W (GeV)	$\sin^2\theta_W(m_Z)_{\overline{MS}}$ ($= \sin^2\theta_W^{eff} - 0.0003$)
65	80.402	0.23097
100	80.379	0.23118
300	80.305	0.23176
600	80.252	0.23214
1000	80.212	0.23242

Need $\pm 0.1\%$ Measurements of $\sin^2\theta_W^{eff}$ or m_W^2

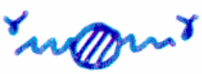
to probe m_t to ± 5GeV or m_H to $\pm 40\%$

Goals: $\Delta \sin^2\theta_W = \pm 0.0002$ ✓ (or $\Delta\Gamma_Z / \Gamma_Z \simeq \pm 0.1\%$) ✓

$\Delta m_W = \pm 40$ MeV

Roughly State of Current Measurements

(Theoretical Uncertainties?)

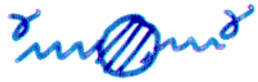
Hadronic Vac. Pol.  Δr to $\pm 0.0010 \rightarrow \pm 0.0002$!

Two Loop Effects (Largest accounted for)

2. Precision Measurements - Status + Commentary

i) α, G_μ, m_Z (Very Precise)

$\alpha^{-1} = 137.03599944(57)$ [From $g_e - 2$]

Need Vacuum Pol.  $q^2 = 0 \rightarrow q^2 = m_Z^2$ (for Δr)

$$\alpha^{-1}(m_Z) \simeq \underbrace{\alpha^{-1}}_{137.036} - \underbrace{\frac{2}{3\pi} \sum_f Q_f^2 \ln(m_Z/m_f)}_{\text{Hadronic Unc.}} + \cdots \quad \approx 6\% \text{ change}$$

Use Dispersion Rel. + $e^+e^- \rightarrow$ hadrons ($\tau \rightarrow \nu_\tau$ + hadrons)

eg. Eidelman + Jegerlehner (1995) $\alpha^{-1}(m_Z) = 128.896 \pm 0.090$ {Mainly e^+e^- data}

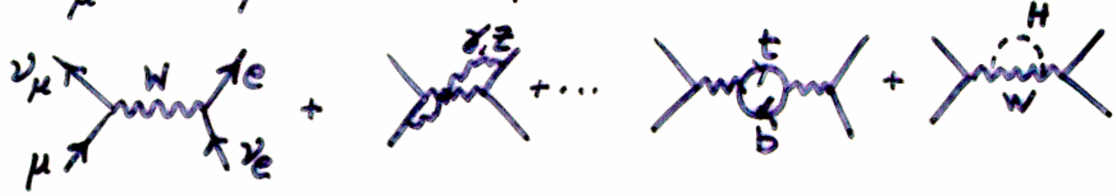
Davier + Höcker (1998) $\alpha^{-1}(m_Z) = 128.933 \pm 0.021$!!

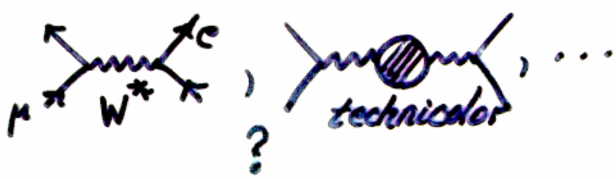
Improved Precision - Pert. QCD, Moments, ... (see fig.)

$\rightarrow \pm 0.016\%$ (Impressive) $\rightarrow \Delta r$ to ± 0.0002

$G_\mu = 1.16639(1) \times 10^{-5}\,\text{GeV}^{-2}$ $\quad \frac{\Delta G_\mu}{G_\mu} \simeq \pm 0.001\%$!!

$\tau_\mu^{-1} = \Gamma(\mu \rightarrow e \nu \bar{\nu}) + \Gamma(\mu \rightarrow e \nu \bar{\nu} \gamma) + \cdots$



+ "New Physics" 

All in τ_μ!

From Davier + Höcker (May 1998)

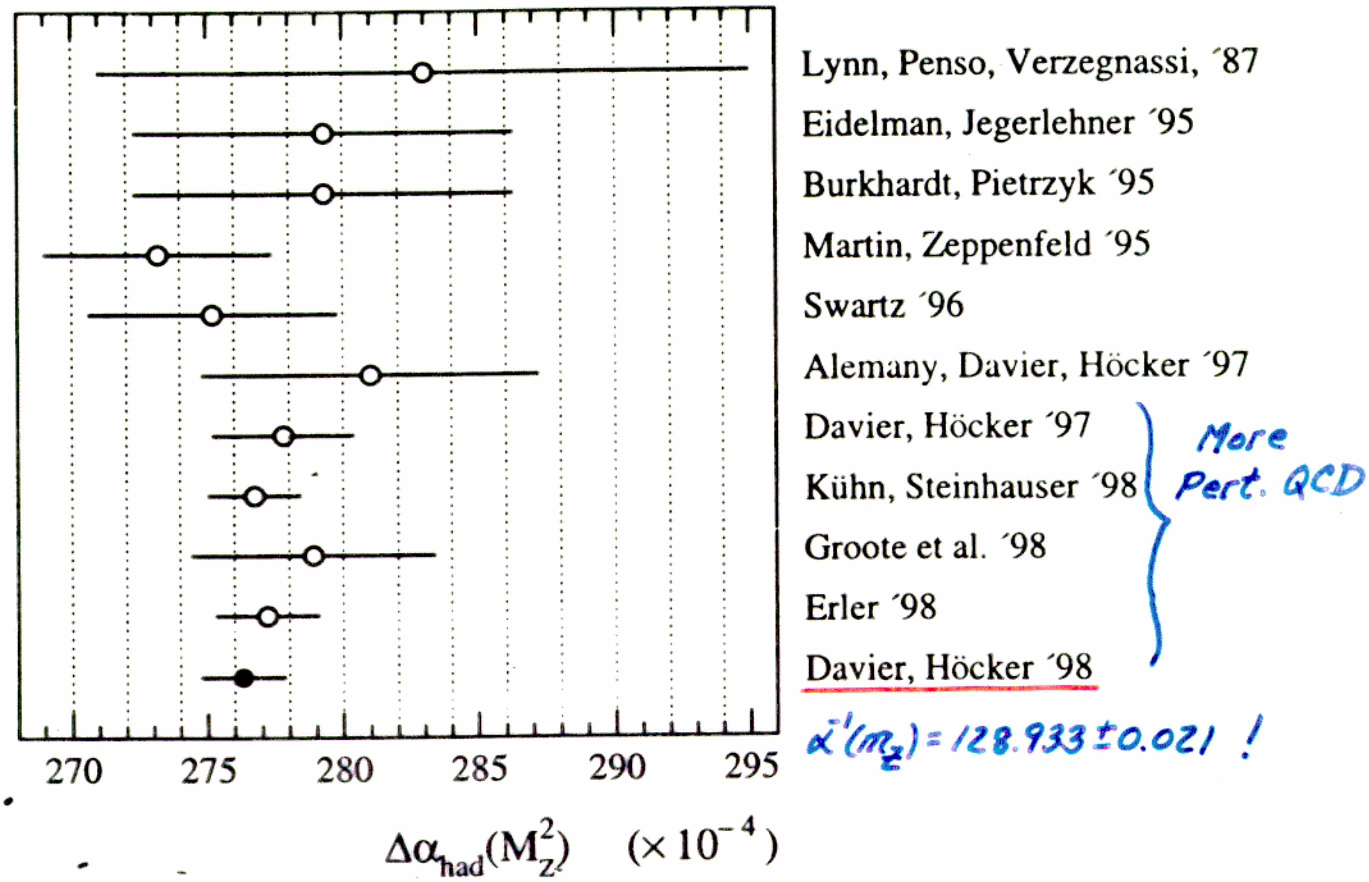


Figure 2: *Comparison of $\Delta\alpha_{\rm had}(M_Z^2)$ evaluations. The values are taken from Refs.* [29, 22, 30, 31, 32, 1, 2, 24, 37] *and from this work.*

For comparison, in 1979 $\alpha^{-1}(m_Z) \simeq 128.5 \pm 1.0$

$$\tau_\mu^{-1} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} f\left(\frac{m_e^2}{m_\mu^2}\right)\left(1+\frac{3}{5}\frac{m_\mu^2}{m_W^2}\right)\left\{1 + \frac{\alpha}{2\pi}\left(\frac{25}{4}-\pi^2\right)\left(1+\frac{2}{3}\frac{\alpha}{\pi}\ln\left(\frac{m_\mu}{m_e}\right)\right)\right\}$$

R.C. in Four Fermion Th. V-A

Most loops + "New Physics" → G_μ

$\tau_\mu = 2.197035 \pm 0.000040\,\mu\text{sec} \rightarrow G_\mu = 1.16639(1) \times 10^{-5}\,\text{GeV}^{-2}$

Proposals for factor 10 improvement : BNL, PSI, RIKEN

$m_Z = 91.1867(21)$ GeV   LEP

$\frac{\Delta m_Z}{m_Z} = \pm 0.0046\%$ Very Precise

W$^\pm$ Mass

pp colliders $m_W = 80.41 \pm 0.09$ GeV

LEP II $m_W = 80.37 \pm 0.09$ GeV

Ave $m_W = 80.39 \pm 0.06$ GeV

} Direct

CCFR $\nu_\mu N \rightarrow m_W^2/m_Z^2 \longrightarrow m_W = 80.26 \pm 0.11$ GeV   (Indirect)

NC/CC

$\sin^2\theta_W(m_Z)_{\overline{MS}} = \sin^2\theta_W^{eff} - 0.0003$

LEP Ave $\sin^2\theta_W^{eff} = 0.23187 \pm 0.00024$

SLD A_{LR} $\sin^2\theta_W^{eff} = 0.23101 \pm 0.00031$

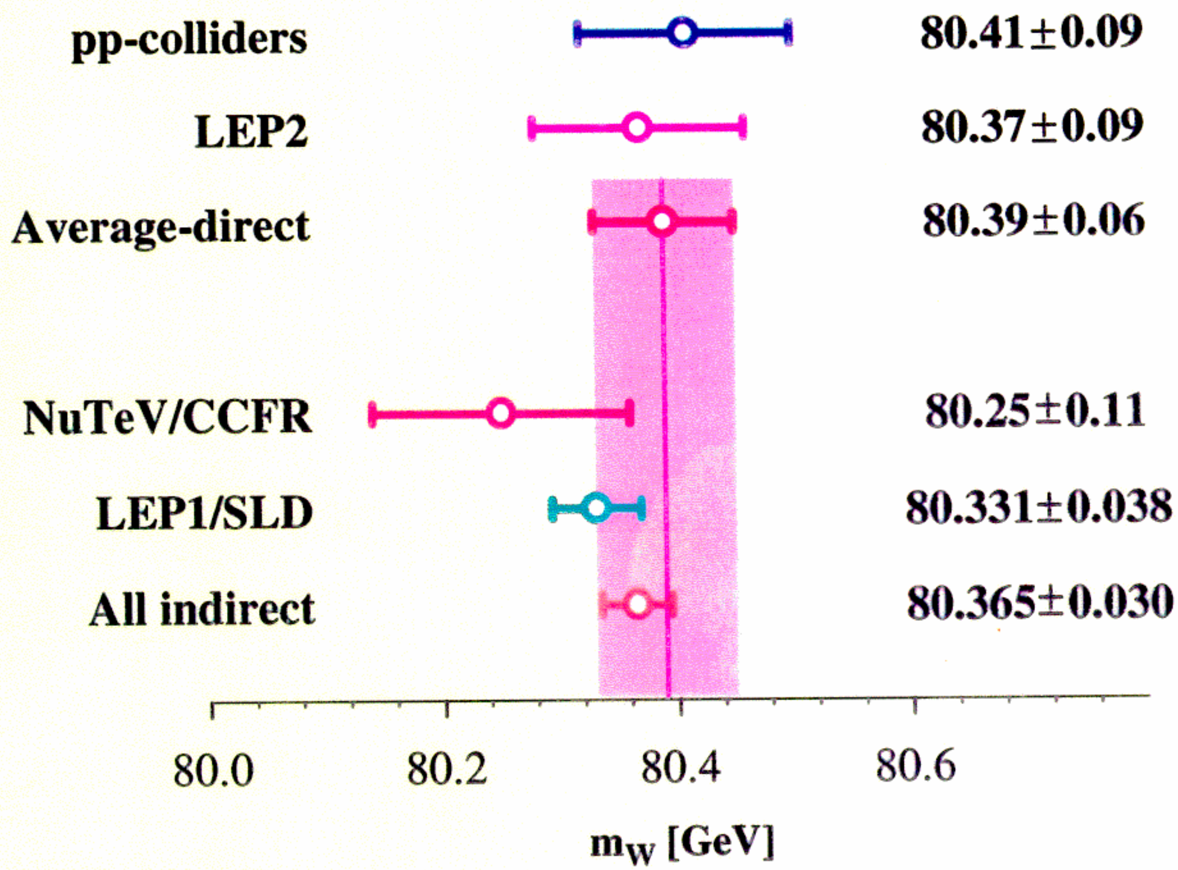
} Preliminary Differ by 2.2σ

Ave LEP+SLD $\sin^2\theta_W^{eff} = 0.23155 \pm 0.00019$

$\Delta s^2/s^2 \simeq \pm 0.08\%$

W mass summary

W-boson Mass [GeV]



ICHEP 98

Dean Karlen / Carleton University

From D. Karlen ICHEP 98

Low Energy Experiments

$\nu_\mu N$, Atomic P.V., Neutral Currents $\sim \pm 1\%$

β-decay, τ Decays, Charged Currents $\sim \pm 0.1\%$

Powerful For Z', Leptoquarks ... Probe $\gtrsim 1$ TeV (roughly)

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3. "New Physics" - Implications

i) Higgs Mass + SUSY

Standard Model Stability $m_H \gtrsim 130$ GeV (How Solid?)

SUSY $h, H, A, H^\pm$ $m_h \lesssim 130\ (150)$ GeV

Strong Coupling "m_H" $\gtrsim \mathcal{O}(800\text{ GeV})$

LEP II $e^+e^- \to ZH$ $m_H \gtrsim 89$ GeV (Hope to reach ~ 100 GeV)

Tevatron $pp \to ZHX$ go to 120 ~ 130 GeV

Precision Measurements (Favor Relatively Light Higgs)

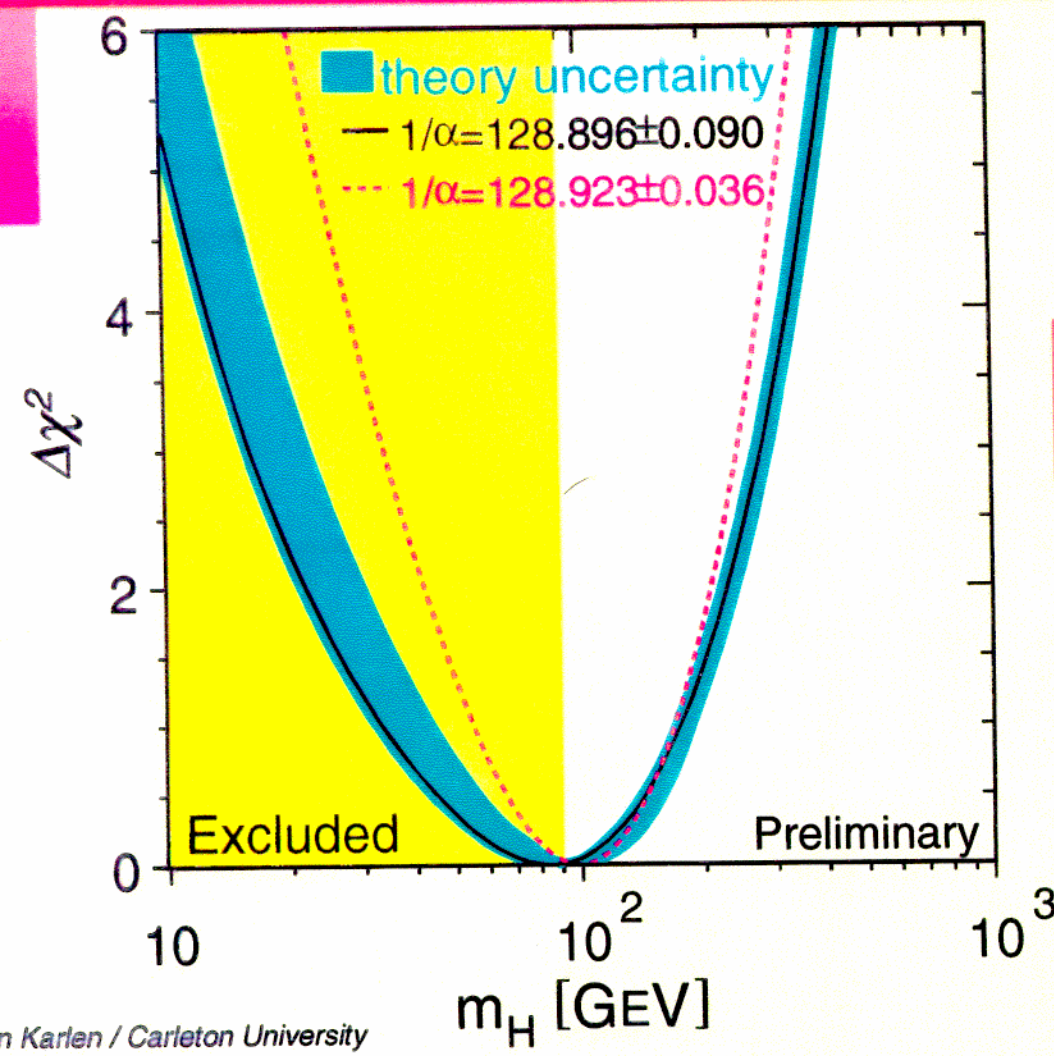
(see figs.) $m_H \simeq 90^{+90}_{-45}$ GeV, $m_H < 280$ GeV (95% CL)

Unc. ~ Factor 2, Does well because central value low

Note $A_{LR} \to \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.2307(3) \to m_H \simeq 35^{+40}_{-20}$ GeV

(Hint of SUSY loops?)

implications for m_H



$m_H = 84^{+91}_{-51}$ GeV

$m_H < 280$ GeV
95% C.L.

direct search results not included in 95% CL.

mH precision depends strongly on $\alpha(m_Z)$

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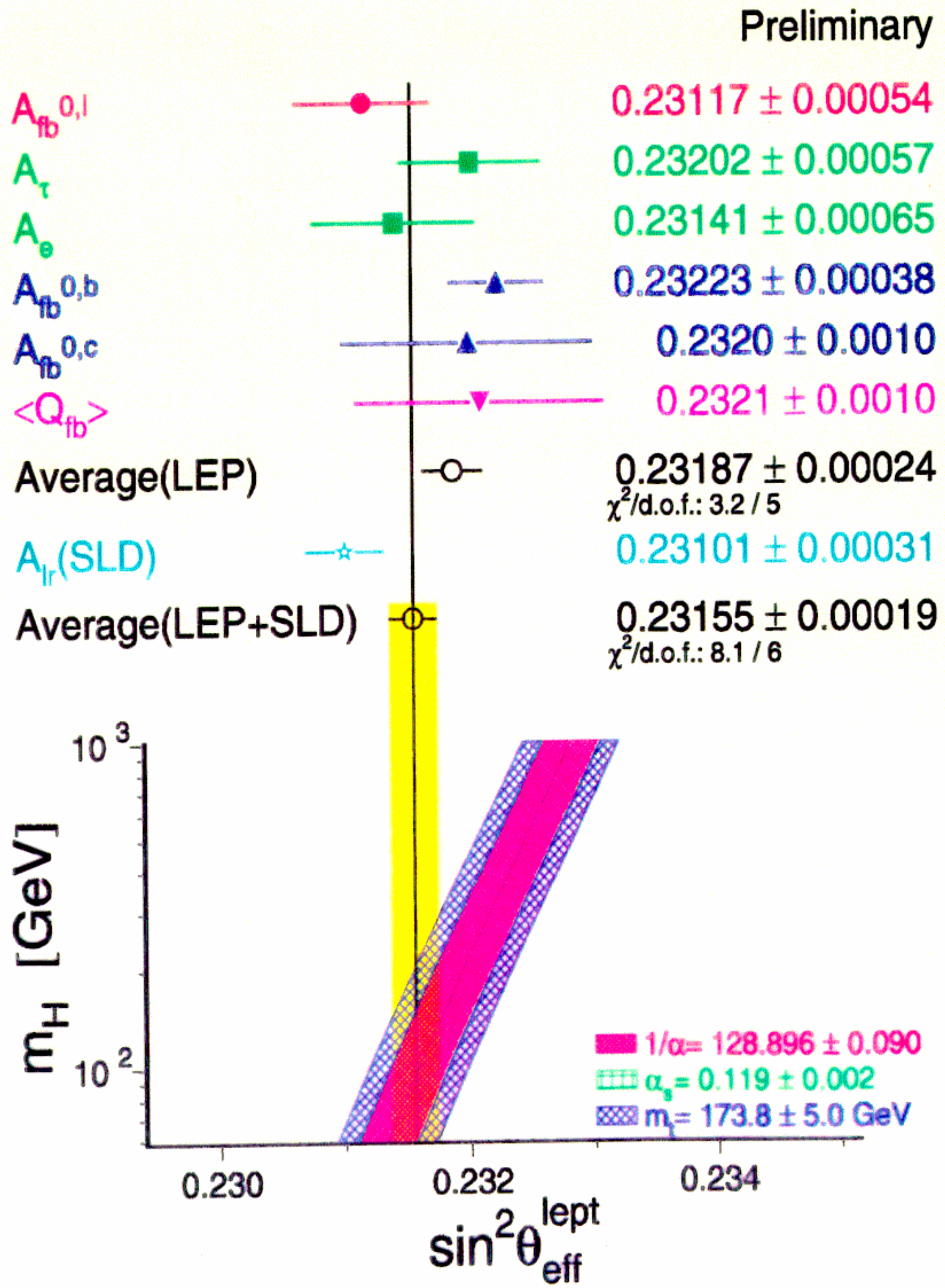
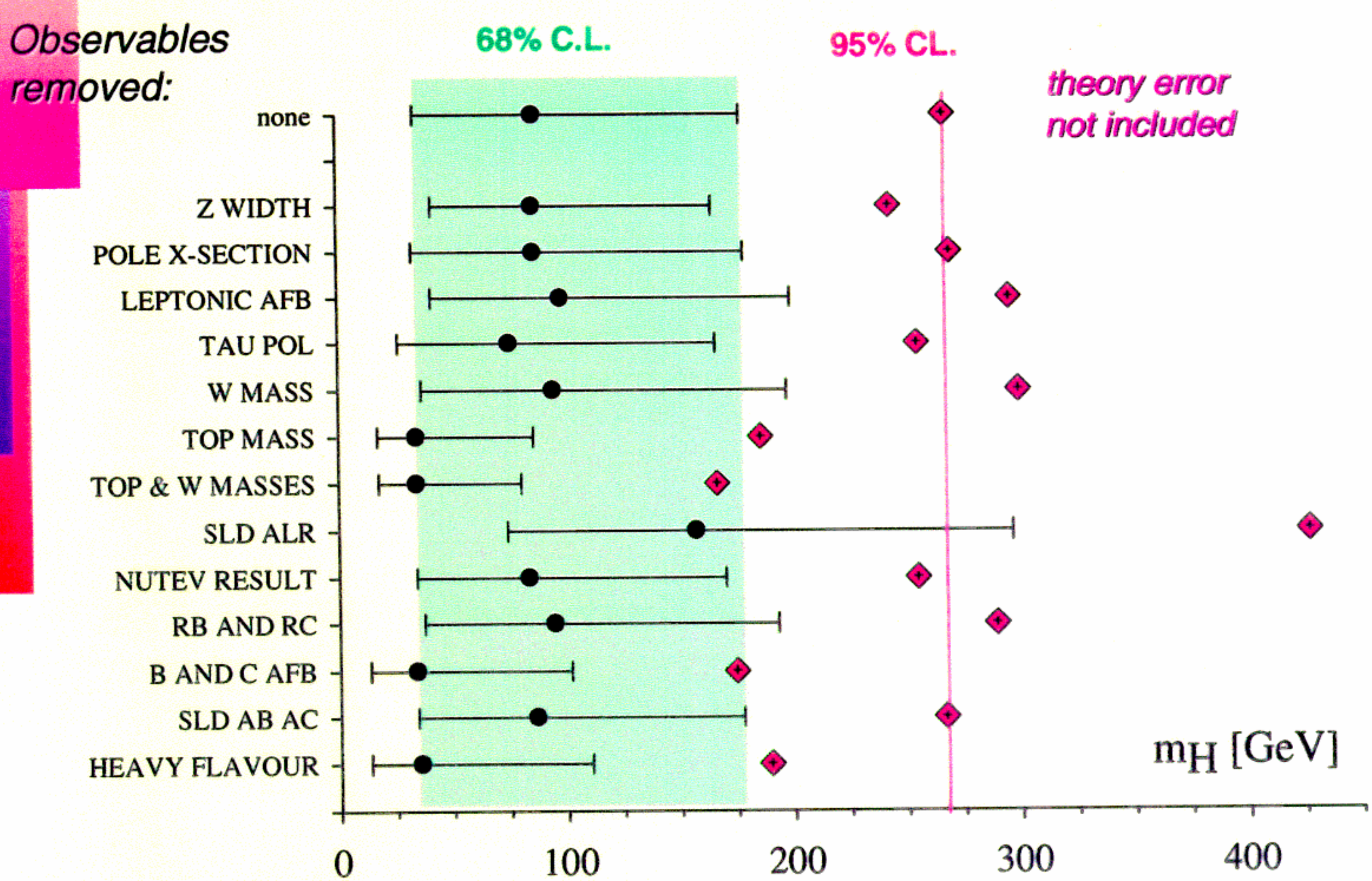
 From D. Karlen ICHEP 98

Effective electroweak mixing angle



-12- From D. Karlen ICHEP 98

Influence of individual observables on m_H



W Boson Mass   Direct $m_W = 80.39 \pm 0.06$ GeV

Implies $m_H \simeq 80^{+130}_{-50}$ GeV

Becoming Competitive

Data very consistent → Relatively Light Higgs

"m_H" $\simeq O(800\,\text{GeV})$ Very Unlikely (see fig.)

$m_H < 130$ GeV or > 130 GeV Still Open

Note, other "New Physics" could easily influence observables at the $\pm 0.1\%$ level. eg. SUSY loops

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Warning From M. Chanowitz

Direct Search $m_H \gtrsim 89$ GeV conflicts with A_{LR} ($+ A_{FB}^{\tau}$)

Rescale Errors (PDG)

$m_H \simeq 200$ GeV $m_H \lesssim 750$ GeV (95% CL)

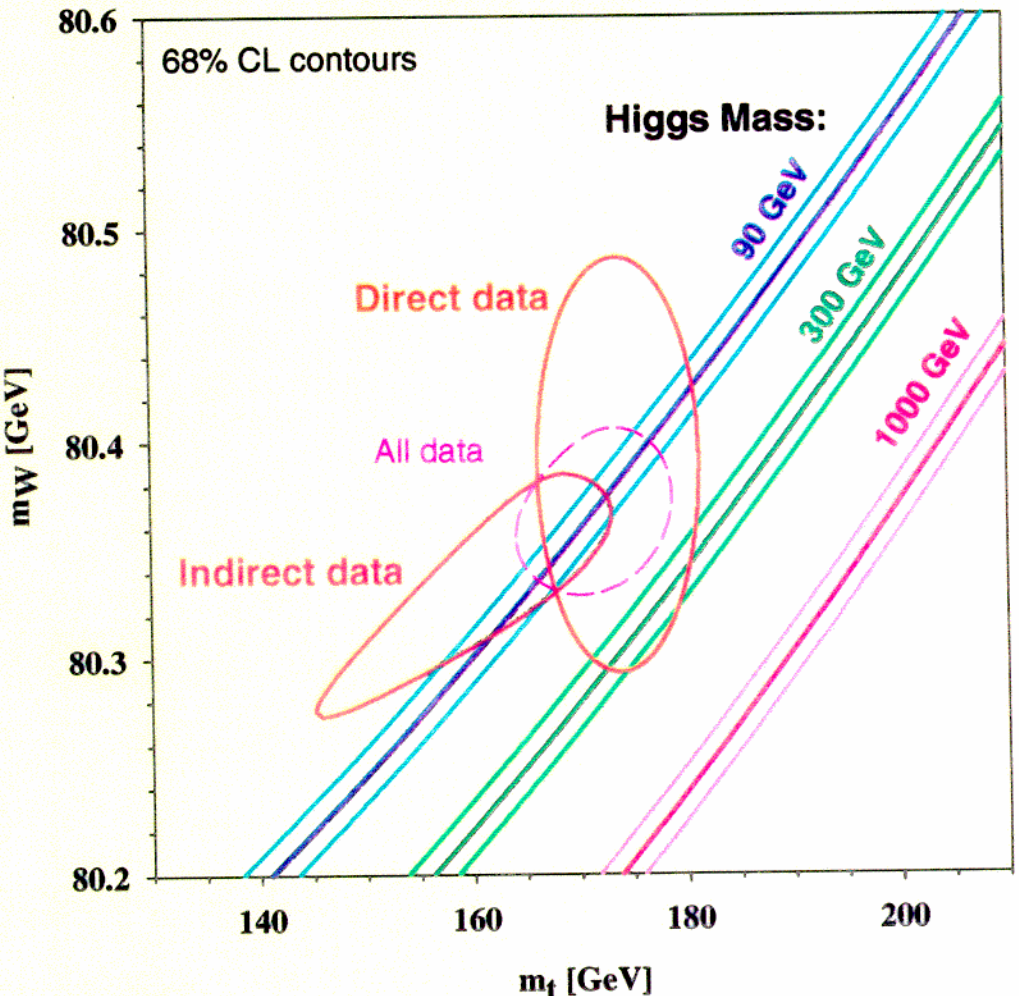
But it implies A_{LR} is incorrect

(A_{LR} is driving low mass Higgs (SUSY) Interpretation!)

A_B issue?   "New Physics" in $Z\bar{b}b$?
Leptophobic $Z'-Z$ mixing?

 From D. Karlen ICHEP 98

Check indirect estimates of m_W & m_t



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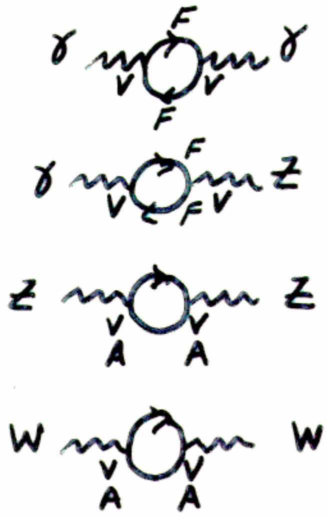
ii) S, T, + U Parameters (Peskin + Takeuchi)

Heavy Fermions (eg. Techni-Fermions) effect on self-energies



6 self-energies

$3 \to \alpha, G_\mu, m_Z$

3 Observables $\Delta r, \Delta r(m_Z)_{\overline{MS}}, \Delta \hat{r}$

or S, T, U

$$\frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} = \frac{\alpha}{4\sin^2\theta_W} S_W = Z_W - 1$$

$$\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} = \frac{\alpha}{4\sin^2\theta_W\cos^2\theta_W} S_Z = Z_Z - 1$$

$$\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} = \alpha T = \rho - 1$$

Peskin + Takeuchi

$S = S_Z$

$T = T$

$U = S_W - S_Z$ (small)

For $m_H = 100\,GeV$

$\to \sin^2\theta_W(m_Z)_{\overline{MS}} = 0.23118 + 0.0365\,S - 0.00261\,T$

$m_W = 80.379 - 0.29\,S_W$ [redacted] $+ 0.45\,T$ GeV

$\Gamma_Z = \Gamma_Z^{SM}(1 - 0.0038\,S + 0.0105\,T)$

etc.

Global Fit (PDG98) (Becoming Very Precise)

($m_H = 100$ GeV)

$S = -0.16 \pm 0.14$

$T = -0.21 \pm 0.16$

$U = 0.25 \pm 0.24$

if $m_H = 1$ TeV $S = -0.29 \pm 0.14$

$T = 0.03 \pm 0.16$

$U = 0.25 \pm 0.24$

Generic Technicolor $S \sim +1$, $T > 0$

No Signal For Heavy Fermions (chiral)

Note m_W vs $\sin^2\theta_W(m_Z)_{\overline{MS}} \rightarrow S_W = S + U$ (From $\alpha + G_\mu$)

$$S_W = 118 \left\{ 2\left(\frac{m_W - 80.379\text{GeV}}{80.379\text{GeV}}\right) + \frac{\sin^2\theta_W(m_Z)_{\overline{MS}} - 0.23118}{0.23118} \right\}$$

Exp $\rightarrow$ $S_W = 0.07 \pm 0.20$ (Consistent with zero)

(Compares m_W direct vs m_W in Muon Decay)

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iv) Extra Dimensions? Kaluza-Klein, Superstrings $R_{Pl} \sim 10^{-32}$cm

What if $R_{\text{extra dim.}} \sim 10^{-17}$cm $\rightarrow$ $m = 1/R \simeq 1$ TeV

Source of EW + SUSY Breaking?

Spectacular Phenomenology

Some Refs.

Chapline + Slansky Nucl. Phys. 1982

Antoniadis PL 1990

Antoniadis, Muñoz, Quiros (1993)

Antoniadis, Benakli (1994)

⋮

Arkani-Hamed, Dimopoulos, Dvali (Mar. 1998)
Antoniadis, Arkani-Hamed, Dimopoulos, Dvali (Apr. 1998)
Dienes, Dudas, Ghergetta (June 1998)

} Imaginative & Stimulating

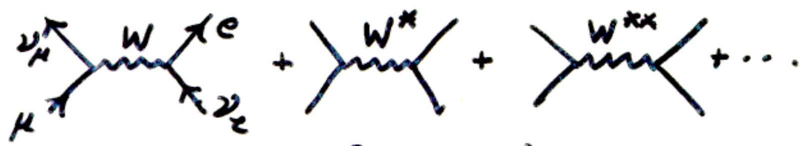
G. Kane (Physics Today) \$5,000! $\gamma^* + Z^*$ at LHC ~1.1 TeV

Excitations: W^*, Z_2^*, Z_1^* $\quad m^2 = m_0^2 + \frac{n^2}{R^2}$

Searches by CDF + DØ $\quad m_{W^*} > 720\,\text{GeV}$, $m_{Z^*} > 690\,\text{GeV}$ } assumes same couplings as W + Z

Low energy exps feel W^*, Z_2^*, Z_1^*

eg Muon Decay



$$\frac{g_2^2}{m_W^2} + \frac{g_2^{*2}}{m_{W^*}^2} + \frac{g_2^{*2}}{4m_{W^*}^2} + \cdots$$

$$\frac{1}{m_W^2} \rightarrow \frac{1}{\langle m_W^2 \rangle}$$ Parallel Resistors $\langle m_W^2 \rangle < m_W^2$

$$\frac{1}{\langle m_W^2 \rangle} = \frac{1}{m_W^2}\left[1 + \frac{\pi^2}{6}\frac{g_2^{*2}}{g_2^2}\frac{m_W^2}{m_{W^*}^2}\right]$$ acts like $Z_W = 1 + \frac{\alpha}{4\sin^2\theta_W} S_W$

i.e. $\frac{\alpha}{4\sin^2\theta_W} S_W \simeq \frac{\pi^2}{6}\frac{g_2^{*2}}{g_2^2}\frac{m_W^2}{m_{W^*}^2}$

similar correspondence between S_Z + $\frac{g_2^{*2}}{m_{Z_2^*}^2}$, $\frac{g_1^{*2}}{m_{Z_1^*}^2}$

$m_W,\ \sin^2\theta_W(m_Z) \rightarrow S_W = 0.07 \pm 0.20$

$$\text{or} \quad \frac{\pi^2}{6}\left(\frac{g_2^*}{g_2}\right)^2 \frac{m_W^2}{m_{W^*}^2} = 0.0084\,(0.07 \pm 0.20)$$

$$\rightarrow \quad m_{W^*} > 24.5\left(\frac{g_2^*}{g_2}\right) m_W = \frac{g_2^*}{g_2} \times 2\,\text{TeV}\,!$$

Much Better than direct searches ~ 1 TeV

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4. Conclusion + Outlook

Standard Model is an Outstanding Success

Tested at Quantum Loop Level ~ ±1% → ±0.1% !

Consistent with $m_t = 173.8$ GeV (~ 3% loop effect)

Points to Relatively Light Higgs (< 280 GeV)

~ 90-100 GeV Favored

Hint of SUSY? (mainly A_{LR}) Eye of the beholder

No Evidence for Strong Dynamics (Technicolor)

Z', Leptoquarks, Compositeness.

Extra Dimension $R \lesssim 10^{-17}$ cm

$1/R \gtrsim \frac{g_2^*}{g_2} \times 2\,\text{TeV}$!

Near Term Expectations: $\sin^2\theta_W^{eff}$ Updates

m_W improvements → ±30 MeV

Atomic P.V., e^-e^-, $g_\mu - 2$, ..

Direct Higgs + SUSY Searches at LEP II + TeVatron

$m_H \lesssim 89\,GeV \rightarrow 100\,GeV \rightarrow 120\,GeV \rightarrow$ LHC

Future Goals (High Precision)

Aim for $\pm 0.01 - 0.02\%$!
Spectacular

m_Z + G_μ already there
$\alpha(m_Z)$ at $\pm 0.016\%$ (better e^+e^-)

$$\left.\begin{array}{l} \Delta \sin^2\theta_W(m_Z)_{\overline{MS}} = \pm 0.00002 \\ \Delta m_W = \pm 4\,MeV \end{array}\right\} \rightarrow \left.\begin{array}{l} \frac{\Delta m_H}{m_H} \sim \pm 5\% ! \\ \Delta S, \Delta T \text{ to } \pm 0.02 ! \end{array}\right\} \text{Figs. of Merit}$$

example: probes extra dim. $1/R \gtrsim 6$ TeV

How? NLC $\sqrt{s} \simeq m_Z$ - 500 GeV Stage I (or first $\mu^+\mu^-$)

$\sin^2\theta_W(m_Z)$) High Statistics Z pole A_{LR} to $\pm 0.1\%$ (Polarization)

$e^+e^- \rightarrow t\bar{t} \rightarrow \Delta m_t < 0.5\,GeV$

$e^+e^- \rightarrow W^+W^- \rightarrow \Delta m_W = \pm 4\,MeV$ (?)

also $e^+e^- \rightarrow \mu^+\mu^-$ $A_{LR} = \frac{4}{5}(1 - 4\sin^2\theta_W)$ at high $\sqrt{s}$

Probes $m_{Z^*} \simeq 7$ TeV or better

furthermore $e^+e^- \rightarrow ZH$ measure m_H to $\pm 1\,GeV$ (Directly)

Push as Far as Possible
(Just Beginning)