Global Fits to Precision Electroweak Data

- Precision Experiments: Historical Perspective
- LEP/SLC Physics
- Probing the Standard Model
- Beyond the Standard Model
The $Z$, the $W$, and the Weak Neutral Current

- Primary prediction and test of electroweak unification
- WNC discovered 1973 (Gargamelle, HPW)
- 70's, 80's: weak neutral current experiments (few %)
  - Pure weak: $\nu N, \nu e$ scattering
  - Weak-elm interference in $eD, e^+e^-$, atomic parity violation
  - $SU(2) \times U(1)$ group/representations; $t$ and $\nu_\tau$ exist; hint for SUSY unification; limits on TeV scale physics
- $W$, $Z$ discovered directly 1983 (UA1, UA2)
● 90's: $Z$ pole (LEP, SLD), 0.1%; lineshape, modes, asymmetries

● LEP 2: $M_W$, Higgs, gauge self-interactions

● Tevatron: $m_t$, $M_W$

● 4th generation weak neutral current experiments

● Implications
  – SM correct and unique to zeroth approx. (gauge principle, group, representations)
  – SM correct at loop level (renorm gauge theory; $m_t$, $\alpha_s$, $M_H$)
  – TeV physics severely constrained (unification vs compositeness)
  – Precise gauge couplings (gauge unification)
The LEP/SLC Era

- **Z Pole:** $e^+e^- \rightarrow Z \rightarrow \ell^+\ell^-, \; q\bar{q}, \; \nu\bar{\nu}$
  - LEP (CERN), $2 \times 10^7 Z'$s, unpolarized (ALEPH, DELPHI, L3, OPAL);
    SLC (SLAC), $5 \times 10^5$, $P_{e^-} \sim 75\%$ (SLD)

- **Z pole observables**
  - lineshape: $M_Z, \Gamma_Z, \sigma$
  - branching ratios
    * $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$
    * $q\bar{q}, c\bar{c}, b\bar{b}, s\bar{s}$
    * $\nu\bar{\nu} \Rightarrow N_\nu = 2.983 \pm 0.009$ if $m_\nu < M_Z/2$
  - asymmetries: FB, polarization, $P_\tau$, mixed
  - lepton family universality
The $Z$ Lineshape

Basic Observables: $e^+ e^- \rightarrow f \bar{f}$ \hspace{1em} (f = e, \mu, \tau, s, b, c, hadrons) \hspace{1em} (s = \notE_{CM}^2)

$$\sigma_f(s) \sim \sigma_f \frac{s \Gamma_Z^2}{(s - M_Z^2)^2 + \frac{s^2 \Gamma_Z^2}{M_Z^2}}$$

(plus initial state rad. corrections)

Peak Cross Section:

$$\sigma_f = \frac{12\pi}{M_Z^2} \frac{\Gamma(e^+ e^-) \Gamma(f \bar{f})}{\Gamma_Z^2}$$
Partial Widths:

\[
\Gamma(f\bar{f}) \sim \frac{C_f G_F M_Z^3}{6\sqrt{2}\pi} \left[|\bar{g}_{Vf}|^2 + |\bar{g}_{Af}|^2\right]
\]

(plus mass, QED, QCD corrections; \(C_\ell = 1\), \(C_q = 3\); \(\bar{g}_{V,Af} = \) effective coupling (includes ew)).

At tree level:

\[
\bar{g}_{Af} = \pm \frac{1}{2}, \quad \bar{g}_{Vf} = \pm \frac{1}{2} - 2\sin^2 \theta_W q_f
\]

where \(\sin^2 \theta_W \equiv 1 - \frac{M_W^2}{M_Z^2}\) is the weak angle, \(\pm \frac{1}{2}\) is the weak isospin (\(+\) for \((u, \nu)\), \(-\) for \((d, e^-)\)), and \(q_f\) is the electric charge.
Ratio of Hadronic to Leptonic Width

Experiment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH</td>
<td>20.729 ± 0.039</td>
</tr>
<tr>
<td>DELPHI</td>
<td>20.730 ± 0.060</td>
</tr>
<tr>
<td>L3</td>
<td>20.809 ± 0.060</td>
</tr>
<tr>
<td>OPAL</td>
<td>20.822 ± 0.044</td>
</tr>
<tr>
<td>LEP</td>
<td>20.767 ± 0.025</td>
</tr>
</tbody>
</table>

$\chi^2 / \text{dof} = 3.5 / 3$

$\alpha_S = 0.118 \pm 0.003$

Linearly added to

$M_t = 178.0 \pm 4.3 \text{ GeV}$

Common error 0.007
Z-Pole Asymmetries

- Effective axial and vector couplings of $Z$ to fermion $f$

$$
\bar{g}_{A_f} = \sqrt{\rho_f} t_{3_f} \\
\bar{g}_{V_f} = \sqrt{\rho_f} \left[ t_{3_f} - 2 \bar{s}_f^2 q_f \right]
$$

where $\bar{s}_f^2$ the effective weak angle,

$$
\bar{s}_f^2 = \kappa_f s^2_W \quad \text{(on-shell)} \\
= \hat{\kappa}_f \hat{s}_Z^2 \sim \hat{s}_Z^2 + 0.00029 \quad (f = e) \quad \text{(MS)},
$$

$\rho_f, \kappa_f, \text{ and } \hat{\kappa}_f$ are electroweak corrections, $q_f = \text{electric charge}$, $t_{3_f} = \text{weak isospin}$

WIN 05 (June 10, 2005)  Paul Langacker (Penn)
• $A^0 = \text{Born asymmetry}$ (after removing $\gamma$, off-pole, box (small), $P_{e-}$)

forward – backward: $A_{FB}^{0f} \simeq \frac{3}{4} A_e A_f$

($A_{FB}^{0e} = A_{FB}^{0\mu} = A_{FB}^{0\tau} \equiv A_{FB}^{0\ell} \rightarrow \text{universality}$)

$\tau$ polarization: $P_{\tau}^0 = -\frac{A_\tau + A_e \frac{2z}{1+z^2}}{1 + A_\tau A_e \frac{2z}{1+z^2}}$

($z = \cos \theta$, $\theta = \text{scattering angle}$)

e$^-\text{polarization (SLD)} : A_{LR}^0 = A_e$

mixed (SLD): $A_{LR}^{0FB} = \frac{3}{4} A_f$

$A_f \equiv \frac{2 g_{VF} \bar{g}_{Af}}{\bar{g}_{VF}^2 + \bar{g}_{AF}^2}$
## The $Z$ Pole Observables: LEP and SLC (01/03)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Group(s)</th>
<th>Value</th>
<th>Standard Model</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_Z$ [GeV]</td>
<td>LEP</td>
<td>$91.1876 \pm 0.0021$</td>
<td>$91.1874 \pm 0.0021$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>LEP</td>
<td>$2.4952 \pm 0.0023$</td>
<td>$2.4972 \pm 0.0011$</td>
<td>−0.9</td>
</tr>
<tr>
<td>$\Gamma(had)$ [GeV]</td>
<td>LEP</td>
<td>$1.7444 \pm 0.0020$</td>
<td>$1.7436 \pm 0.0011$</td>
<td>—</td>
</tr>
<tr>
<td>$\Gamma(inv)$ [MeV]</td>
<td>LEP</td>
<td>$499.0 \pm 1.5$</td>
<td>$501.74 \pm 0.15$</td>
<td>—</td>
</tr>
<tr>
<td>$\Gamma(\ell^+\ell^-)$ [MeV]</td>
<td>LEP</td>
<td>$83.984 \pm 0.086$</td>
<td>$84.015 \pm 0.027$</td>
<td>—</td>
</tr>
<tr>
<td>$\sigma_{had}$ [nb]</td>
<td>LEP</td>
<td>$41.541 \pm 0.037$</td>
<td>$41.470 \pm 0.010$</td>
<td>1.9</td>
</tr>
<tr>
<td>$R_e$</td>
<td>LEP</td>
<td>$20.804 \pm 0.050$</td>
<td>$20.753 \pm 0.012$</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_\mu$</td>
<td>LEP</td>
<td>$20.785 \pm 0.033$</td>
<td>$20.753 \pm 0.012$</td>
<td>1.0</td>
</tr>
<tr>
<td>$R_\tau$</td>
<td>LEP</td>
<td>$20.764 \pm 0.045$</td>
<td>$20.799 \pm 0.012$</td>
<td>−0.8</td>
</tr>
<tr>
<td>$A_{FB}(e)$</td>
<td>LEP</td>
<td>$0.0145 \pm 0.0025$</td>
<td>$0.01639 \pm 0.00026$</td>
<td>−0.8</td>
</tr>
<tr>
<td>$A_{FB}(\mu)$</td>
<td>LEP</td>
<td>$0.0169 \pm 0.0013$</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>$A_{FB}(\tau)$</td>
<td>LEP</td>
<td>$0.0188 \pm 0.0017$</td>
<td></td>
<td>1.4</td>
</tr>
<tr>
<td>Quantity</td>
<td>Group(s)</td>
<td>Value</td>
<td>Standard Model</td>
<td>pull</td>
</tr>
<tr>
<td>---------------------</td>
<td>----------------</td>
<td>---------------------</td>
<td>----------------------</td>
<td>-------</td>
</tr>
<tr>
<td>$R_b$</td>
<td>LEP/SLD</td>
<td>$0.21664 \pm 0.00065$</td>
<td>$0.21572 \pm 0.00015$</td>
<td>1.1</td>
</tr>
<tr>
<td>$R_c$</td>
<td>LEP/SLD</td>
<td>$0.1718 \pm 0.0031$</td>
<td>$0.17231 \pm 0.00006$</td>
<td>−0.2</td>
</tr>
<tr>
<td>$R_{s,d}/R_{(d+u+s)}$</td>
<td>OPAL</td>
<td>$0.371 \pm 0.023$</td>
<td>$0.35918 \pm 0.00004$</td>
<td>0.5</td>
</tr>
<tr>
<td>$A_{FB}(b)$</td>
<td>LEP</td>
<td>$0.0995 \pm 0.0017$</td>
<td>$0.1036 \pm 0.0008$</td>
<td>−2.4</td>
</tr>
<tr>
<td>$A_{FB}(c)$</td>
<td>LEP</td>
<td>$0.0713 \pm 0.0036$</td>
<td>$0.0741 \pm 0.0007$</td>
<td>−0.8</td>
</tr>
<tr>
<td>$A_{FB}(s)$</td>
<td>DELPHI/OPAL</td>
<td>$0.0976 \pm 0.0114$</td>
<td>$0.1037 \pm 0.0008$</td>
<td>−0.5</td>
</tr>
<tr>
<td>$A_b$</td>
<td>SLD</td>
<td>$0.922 \pm 0.020$</td>
<td>$0.93476 \pm 0.00012$</td>
<td>−0.6</td>
</tr>
<tr>
<td>$A_c$</td>
<td>SLD</td>
<td>$0.670 \pm 0.026$</td>
<td>$0.6681 \pm 0.0005$</td>
<td>0.1</td>
</tr>
<tr>
<td>$A_s$</td>
<td>SLD</td>
<td>$0.895 \pm 0.091$</td>
<td>$0.93571 \pm 0.00010$</td>
<td>−0.4</td>
</tr>
<tr>
<td>$A_{LR}$ (hadrons)</td>
<td>SLD</td>
<td>$0.15138 \pm 0.00216$</td>
<td>$0.1478 \pm 0.0012$</td>
<td>1.7</td>
</tr>
<tr>
<td>$A_{LR}$ (leptons)</td>
<td>SLD</td>
<td>$0.1544 \pm 0.0060$</td>
<td>$0.1478 \pm 0.0012$</td>
<td>1.1</td>
</tr>
<tr>
<td>$A_\mu$</td>
<td>SLD</td>
<td>$0.142 \pm 0.015$</td>
<td>$0.142 \pm 0.015$</td>
<td>−0.4</td>
</tr>
<tr>
<td>$A_\tau$</td>
<td>SLD</td>
<td>$0.136 \pm 0.015$</td>
<td>$0.136 \pm 0.015$</td>
<td>−0.8</td>
</tr>
<tr>
<td>$A_e(Q_{LR})$</td>
<td>SLD</td>
<td>$0.162 \pm 0.043$</td>
<td>$0.162 \pm 0.043$</td>
<td>0.3</td>
</tr>
<tr>
<td>$A_\tau(P_{\tau})$</td>
<td>LEP</td>
<td>$0.1439 \pm 0.0043$</td>
<td>$0.1439 \pm 0.0043$</td>
<td>−0.9</td>
</tr>
<tr>
<td>$A_e(P_{\tau})$</td>
<td>LEP</td>
<td>$0.1498 \pm 0.0048$</td>
<td>$0.1498 \pm 0.0048$</td>
<td>0.4</td>
</tr>
<tr>
<td>$Q_{FB}$</td>
<td>LEP</td>
<td>$0.0403 \pm 0.0026$</td>
<td>$0.0424 \pm 0.0003$</td>
<td>−0.8</td>
</tr>
</tbody>
</table>
LEP 2

- $M_W, \Gamma_W, B$ (also hadron colliders)
- $M_H$ limits (hint?)
- $WW$ production (triple gauge vertex)
- Quartic vertex
- SUSY/exotics searches
Other: atomic parity (Boulder); $\nu e$; $\nu N$ (NuTeV); polarized Møller asymmetry (SLAC E158); $M_W$, $m_t$ (Tevatron)
## Non-$Z$ Pole Precision Observables (1/03)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Group(s)</th>
<th>Value</th>
<th>Standard Model</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$ [GeV]</td>
<td>Tevatron</td>
<td>$174.3 \pm 5.1$</td>
<td>$174.4 \pm 4.4$</td>
<td>0.0</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>LEP</td>
<td>$80.447 \pm 0.042$</td>
<td>$80.391 \pm 0.018$</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Tevatron /UA2</td>
<td>$80.454 \pm 0.059$</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>$g_L^2$</td>
<td>NuTeV</td>
<td>$0.30005 \pm 0.00137$</td>
<td>$0.30396 \pm 0.00023$</td>
<td>$-2.9$</td>
</tr>
<tr>
<td>$g_R^2$</td>
<td>NuTeV</td>
<td>$0.03076 \pm 0.00110$</td>
<td>$0.03005 \pm 0.00004$</td>
<td>0.6</td>
</tr>
<tr>
<td>$R^\nu$</td>
<td>CCFR</td>
<td>$0.5820 \pm 0.0027 \pm 0.0031$</td>
<td>$0.5833 \pm 0.0004$</td>
<td>$-0.3$</td>
</tr>
<tr>
<td>$R^\nu$</td>
<td>CDHS</td>
<td>$0.3096 \pm 0.0033 \pm 0.0028$</td>
<td>$0.3092 \pm 0.0002$</td>
<td>0.1</td>
</tr>
<tr>
<td>$R^\nu$</td>
<td>CHARM</td>
<td>$0.3021 \pm 0.0031 \pm 0.0026$</td>
<td></td>
<td>$-1.7$</td>
</tr>
<tr>
<td>$R^\nu$</td>
<td>CDHS</td>
<td>$0.384 \pm 0.016 \pm 0.007$</td>
<td>$0.3862 \pm 0.0002$</td>
<td>$-0.1$</td>
</tr>
<tr>
<td>$R^\nu$</td>
<td>CHARM</td>
<td>$0.403 \pm 0.014 \pm 0.007$</td>
<td></td>
<td>$1.0$</td>
</tr>
<tr>
<td>$R^\bar{\nu}$</td>
<td>CDHS 1979</td>
<td>$0.365 \pm 0.015 \pm 0.007$</td>
<td>$0.3816 \pm 0.0002$</td>
<td>$-1.0$</td>
</tr>
</tbody>
</table>

WIN 05 (June 10, 2005)  Paul Langacker (Penn)
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Group(s)</th>
<th>Value</th>
<th>Standard Model</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g^\nu e_V$</td>
<td>CHARM II</td>
<td>$-0.035 \pm 0.017$</td>
<td>$-0.0398 \pm 0.0003$</td>
<td>—</td>
</tr>
<tr>
<td>$g^\nu e_V$</td>
<td>all</td>
<td>$-0.041 \pm 0.015$</td>
<td></td>
<td>-0.1</td>
</tr>
<tr>
<td>$g^\nu e_V$</td>
<td>CHARM II</td>
<td>$-0.503 \pm 0.017$</td>
<td>$-0.5065 \pm 0.0001$</td>
<td>—</td>
</tr>
<tr>
<td>$g_A^\nu e_V$</td>
<td>all</td>
<td>$-0.507 \pm 0.014$</td>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>$Q_W(Cs)$</td>
<td>Boulder</td>
<td>$-72.69 \pm 0.44$</td>
<td>$-73.10 \pm 0.04$</td>
<td>0.8</td>
</tr>
<tr>
<td>$Q_W(Tl)$</td>
<td>Oxford/Seattle</td>
<td>$-116.6 \pm 3.7$</td>
<td>$-116.7 \pm 0.1$</td>
<td>0.0</td>
</tr>
<tr>
<td>$10^3 \frac{\Gamma(b\to s\gamma)}{\Gamma_{SL}}$</td>
<td>BaBar/Belle/CLEO</td>
<td>$3.48^{+0.65}_{-0.54}$</td>
<td>$3.20 \pm 0.09$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\tau_\tau$ [fs]</td>
<td>direct/$B_e/B_\mu$</td>
<td>$290.96 \pm 0.59 \pm 5.66$</td>
<td>$291.90 \pm 1.81$</td>
<td>-0.4</td>
</tr>
<tr>
<td>$10^4 \Delta\alpha^{(3)}_{\text{had}}$</td>
<td>$e^+e^-/\tau$ decays</td>
<td>$56.53 \pm 0.83 \pm 0.64$</td>
<td>$57.52 \pm 1.31$</td>
<td>-0.9</td>
</tr>
<tr>
<td>$10^9 (\alpha_\mu - \frac{\alpha}{2\pi})$</td>
<td>BNL/CERN</td>
<td>$4510.64 \pm 0.79 \pm 0.51$</td>
<td>$4508.30 \pm 0.33$</td>
<td>2.5</td>
</tr>
</tbody>
</table>
New Inputs, Anomalies, Things to Watch

- New CDF $m_t$ from Run II (lepton + jets)
  - $m_t = 173.5^{+4.1}_{-4.0}$ GeV, lower than previous Tevatron average
    - $178.0 \pm 4.3$ GeV (dominated by reanalysis of D$\bar{0}$ Run)
  - More precise than previous average
  - Will lower the $M_H$ prediction
• $A_{FB}^b = 0.0995(17)$ is $2.4\sigma$ below expectation of $0.1032(8)$ for $M_H = 114$ GeV

  – Favors large $M_H$. New physics or fluctuation/systematics lead to smaller $M_H$
  
  – $A_{FB}^b = \frac{3}{4} A_l A_b$; $A_b$ agrees with SM, $A_l$ (SLC) is $1.9\sigma$ high

  – New physics in $A_{FB}^b$ would require compensation of $L$ and $R$ couplings (to preserve $R_b$)

  – 5% effect, but $\sim 25\%$ in $\kappa \rightarrow$ probably tree level affecting third family

  – New physics possibilities include $Z'$ with non-universal couplings, or $b_R$ mixing with $B_R$ in doublet with charge $-4/3$
\[ \langle A_{0, b\bar{b}}^{0, b\bar{b}} \rangle_{FB} = 0.0992 \pm 0.0016 \]

\[ m_t = 178.0 \pm 4.3 \text{ GeV} \]

\[ \Delta\alpha_{\text{had}} = 0.02761 \pm 0.00036 \]

\[ m_H = 150 \text{ to } 200 \text{ GeV} \]

\[ A_b = 0.0978 \pm 0.0030 \pm 0.0015 \]

\[ A_{l} = 18.3 \text{ to } 95.5 \% \text{ CL} \]

\[ A_{l} = 0.8 \text{ to } 0.9 \]

\[ A_{l} = 0.14 \text{ to } 0.145 \]

\[ A_{l} = 0.15 \text{ to } 0.155 \]

\[ \text{SM} \]

\[ \text{WIN 05 (June 10, 2005) Paul Langacker (Penn)} \]
\( a_\mu = (g_\mu - 2)/2 \)

- More sensitive than \( a_e \) to new physics
- BNL (2004) + other: \( a_\mu^{\text{exp}} = 11659208(6) \times 10^{-10} \)
- Hadronic light by light has settled down, but considerable uncertainty from \( a_\mu^{\text{Had}} \)
- \( a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (24 \pm 10) \times 10^{-10} \) (2.4\( \sigma \)) (using \( e^+e^- \) data for \( a_\mu^{\text{Had}} \)) \( \rightarrow 0.9\sigma \) (using \( \tau \) decay data. Theory uncertainties?)

- New physics? Supersymmetry: \( (\tilde{m} \sim 70 \text{ GeV} \sqrt{\tan \beta}) \)
NuTeV

\[
\begin{align*}
\bar{\nu}_\mu N &\rightarrow \bar{\nu}_\mu X \\
\nu_\mu N &\rightarrow \mu^+ X
\end{align*}
\]

- Little c threshold uncertainty
- \( s_W^2 = 0.2277(16) \), 3.0\( \sigma \) above SM value 0.2228(4)
- Possible QCD effects: large \( \bar{s} - s \) asymmetry (CTEQ); large isospin breaking in sea (MRST; Glück, Jimenez-Delgado, Reya)
- Need new analysis
- Future NOMAD
SLAC E158 Polarized Møller Asymmetry

- $e^-e^-$ asymmetry, $P \sim 90\%$
- $\sin^2 \theta_W^{eff}(Q) = 0.2397 \pm 0.0013$ at $Q^2 = 0.026$ GeV$^2$
• Atomic Parity Violation
  
  – Very precise measurement (0.4%) in cesium (single electron outside tightly bound core)
  
  – Previous hint (2.2σ) of discrepancy, but theory-dominated error
  
  – Surprisingly large (O(1%)) radiative corrections: Breit, vacuum polarization, vertex, self-energy have now stabilized
  
  – Now excellent agreement: 
    \[ Q_W(Cs) = -72.69(48) \text{ (SM: } -73.19(3) \text{)} \]

• CKM Unitarity
  
  – Expect \( \Delta \equiv 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = 0 \)
  
  – PDG 2002: \( \Delta = 0.0042 \pm 0.0019 \)
  
  – Superallowed (0\(^+\)→0\(^+\)): \( |V_{ud}| = 0.9740(5) \) under control
  
  – Recent BNL865 \( K^+ \), KTEV \( K_L \), KLOE, NA48 give higher \( |V_{us}| \), consistent with unitarity
Global Standard Model Fit Results

- **PDG 2004 (12/93)** (Erler, PL)
  - Fully $\overline{MS}$
  - Good agreement with LEPEWWG up to known effects
  - Update for PDG 2006 in progress

\[
\begin{align*}
M_H &= 113^{+56}_{-40} \text{ GeV}, \\
m_t &= 176.9 \pm 4.0 \text{ GeV}, \\
\alpha_s &= 0.1213 \pm 0.0018, \\
\hat{\alpha}(M_Z)^{-1} &= 127.906 \pm 0.019 \\
\hat{s}_Z^2 &= 0.23120 \pm 0.00015, \\
\hat{s}_W^2 &= 0.22280 \pm 0.00035 \\
\Delta \alpha_{\text{had}}^{(5)}(M_Z) &= 0.02801 \pm 0.00015
\end{align*}
\]
• $m_t = 176.9 \pm 4.0$ GeV

- $172.4^{+9.8}_{-7.3}$ GeV from indirect (loops) only (direct: $178.0 \pm 4.3$)
- New CDF Run II, $m_t = 173.5^{+4.1}_{-4.0}$ GeV, not included
• $\alpha_s = 0.1213 \pm 0.0018$

  - Higher than $\alpha_s = 0.1187(20)$ (Hinchliffe (PDG) 2004), because of $\tau$ lifetime

  - insensitive to oblique new physics

  - very sensitive to non-universal new physics (e.g., $Zb\bar{b}$ vertex)
• Higgs mass $M_H = 113^{+56}_{-40} \text{ GeV}$
  - LEPEWWG (12/94): $114^{+69}_{-45}$
  - direct limit (LEP 2): $M_H \gtrsim 114.4 (95\%) \text{ GeV}$
  - SM: $115 (\text{vac. stab.}) \lesssim M_H \lesssim 750 (\text{triviality})$
  - MSSM: $M_H \lesssim 130 \text{ GeV} (150 \text{ in extensions})$
  - indirect: ln $M_H$ but significant
    * fairly robust to new physics (except $S < 0, T > 0$)
    * however, strong $A_{FB}(b)$ effect
    * $M_H < 246 \text{ GeV at 95\%}, \text{ including direct}$
WIN 05 (June 10, 2005) Paul Langacker (Penn)
WIN 05 (June 10, 2005) Paul Langacker (Penn)
\begin{align*}
\Delta \chi^2 &= \text{Theory uncertainty} \\
M_t &= \text{Run-1 average} \\
\text{CDF-II preliminary}
\end{align*}

\begin{align*}
\text{LEP1, SLD data} \\
\text{LEP2 (prel.), pp data (CDF-II m_t)} \\
68\% \text{ CL}
\end{align*}

\begin{align*}
m_H \ [\text{GeV}] &= 114, 300, 1000 \\
m_t \ [\text{GeV}] &= 150, 175, 200
\end{align*}

\text{WIN 05 (June 10, 2005)}

Paul Langacker (Penn)
Beyond the standard model

- $\rho_0; \ S, T, U$: Higgs triplets, nondegenerate fermions or scalars; chiral families (ETC)

$$S = -0.13 \pm 0.10(-0.08)$$
$$T = -0.17 \pm 0.12(+0.09)$$
$$U = 0.22 \pm 0.13(+0.01)$$

for $M_H = 117 (300)$ GeV

- $\rho_0 = 1 + \alpha T = 0.9998^{+0.0008}_{-0.0005}$ and $114.4 \text{ GeV} < M_H < 193$ GeV (for $S = U = 0$)

- Can evade Higgs mass limit for $S < 0, \ T > 0$ (Higgs doublet/triplet loops, Majorana fermions)
Oblique Parameters

constraints on gauge boson self-energies

\[ M_H = 117 \text{ GeV} \]
\[ M_H = 340 \text{ GeV} \]
\[ M_H = 1000 \text{ GeV} \]
- Supersymmetry
  - decoupling limit ($M_{new} \gtrsim 200 - 300$ GeV): only precision effect is light SM-like Higgs
  - little improvement on SM fit

- SUSY parameters constrained
• A TeV scale $Z'$?
  
  – Expected in many string theories, grand unification, dynamical symmetry breaking, little Higgs
  
  – Natural solution to $\mu$ problem
  
  – Implications
    * Exotics
    * FCNC (especially in string models)
    * Non-standard Higgs masses, couplings (doublet-singlet mixing)

    * Non-standard sparticle spectrum
    * Neutrino mass, BBN, structure
    * Enhanced possibility of EW baryogenesis

  – Typically $M_{Z'} > 500 - 800$ GeV (Tevatron, LEP 2, WNC), $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$ (Z-pole)
• Other
  – Exotic fermion mixings
  – Large extra dimensions
  – New four-fermi operator
  – Leptoquark bosons

• Gauge unification: GUTs, string theories
  – \( \alpha + \hat{s}^2_Z \rightarrow \alpha_s = 0.130 \pm 0.010 \)
  – \( M_G \sim 3 \times 10^{16} \text{ GeV} \)
  – Perturbative string: \( \sim 5 \times 10^{17} \text{ GeV (10\% in } \ln M_G) \). Exotics: \( O(1) \) corrections.
M unification
$M_Z, m_b, \mu, e$

$\alpha_1(\alpha, \sin^2 \theta_W)$

$\alpha_2(G_F, M_W)$

$\alpha_3$
Conclusions

- WNC, $Z$, $W$ are primary predictions and test of electroweak unification

- SM correct and unique to first approx. (gauge principle, group, representations)

- SM correct at loop level (renorm gauge theory; $m_t$, $\alpha_s$, $M_H$)

- Watershed: TeV physics severely constrained (unification vs compositeness)
  - unification (decoupling): expect 0.1%
  - TeV compositeness: expect several % unless decoupling

- Precise gauge couplings (gauge unification)