Precise Electroweak Measurements and the Higgs Mass

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Introduction

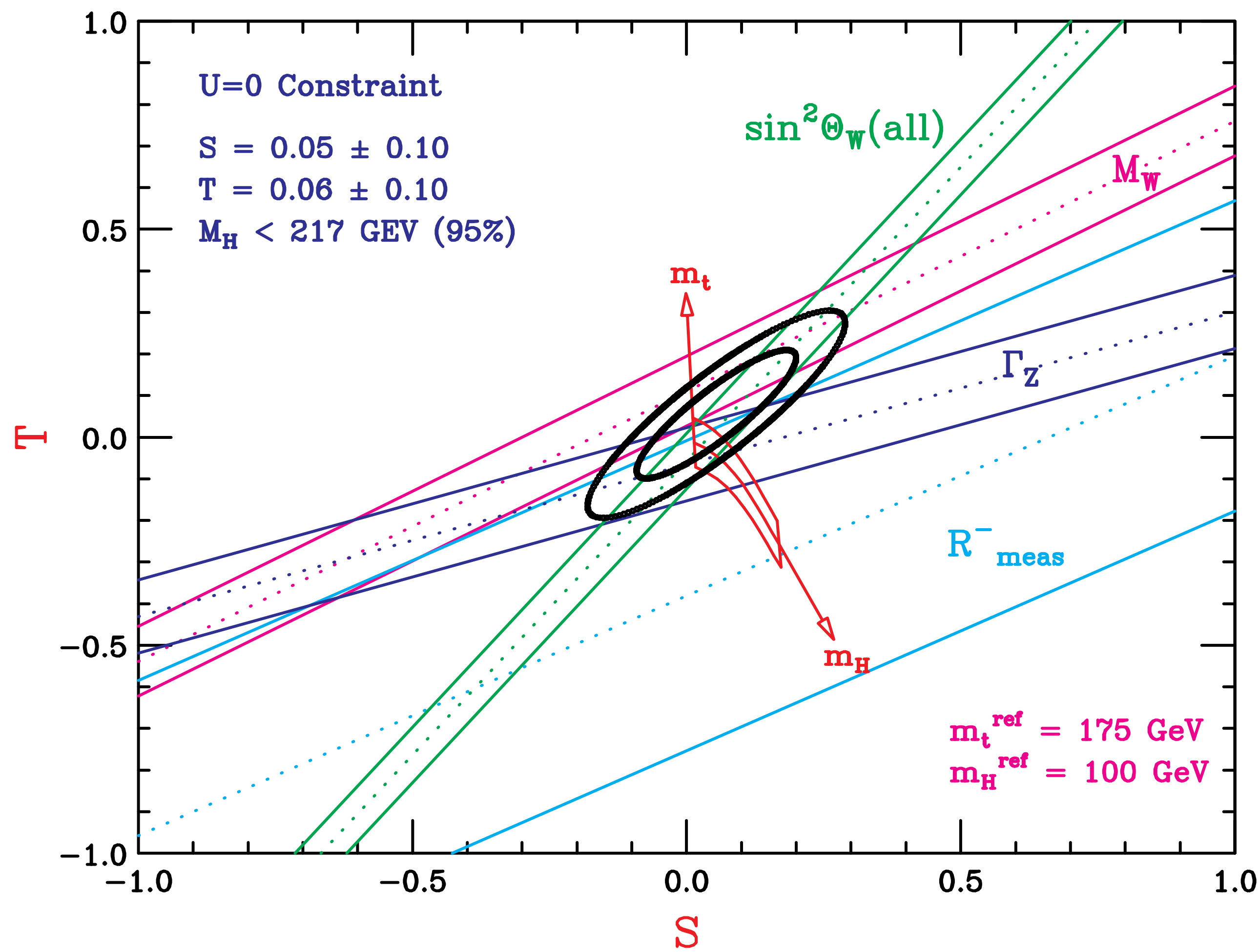
Over the last decade, there has been an active program of precise electroweak measurements at LEP, SLC, and Tevatron. It's main purpose has been to test the Minimal Standard Model (MSM):

- Does the MSM describe an array of precise measurements?
  - If NO, $\longrightarrow$ very exciting result ... learn a bit about the "correct" theory.
  - If YES, $\longrightarrow$ can infer information about unobserved parameters of the MSM.
- Unfortunately, only a NO can be unambiguously established. Finite measurement uncertainties and unknown/uncertain parameters can always mask small deviations from MSM:
  - Extracting unknown parameters (like m_H) requires that we assume that the MSM is correct (certainly an incorrect assumption ... but possibly a numerically accurate one).
  - Given our state of ignorance, the consumer should be aware that unquoted uncertainties are always present.
  - field of precise EW measurements will be more interesting after a Higgs or (Higgses) are discovered.

Is the MSM "Correct"?

A standard Higgs (and many undiscovered "new" states) would affect all currently measured electroweak observables primarily through vacuum polarization corrections to W and Z propagators:

Use Peskin-Takeuchi ST parameters to test theory (assumes vertex corrections are small and $\rho \simeq 1$),



- Intrinsic sensitivity of an observable is given by orthogonality of ST band and m_H axis: $\sin^2\theta_W^{\mathrm{eff}}$, M_W, and Γ_Z are best for light Higgs

- Smallest bands (most precisely measured observables) are: $\sin^2\theta_W^{\mathrm{eff}}$, M_W, and Γ_Z

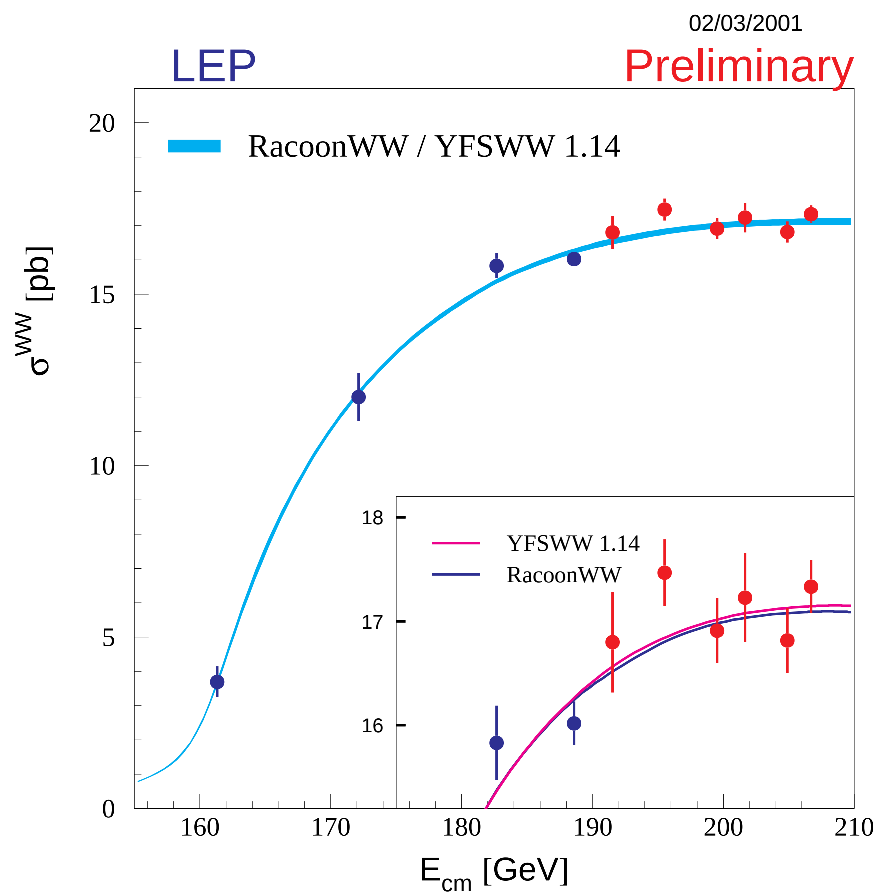
- Data agree with Standard Model → "light" Higgs favored
  - We can use MSM predict m_H ... keeping caveats in mind
  - Most of what we know about m_H comes from $\sin^2\theta_W^{\mathrm{eff}}$ and M_W.

Current Knowledge of M_W

The best W boson mass measurements have been performed at LEP II and the Tevatron:

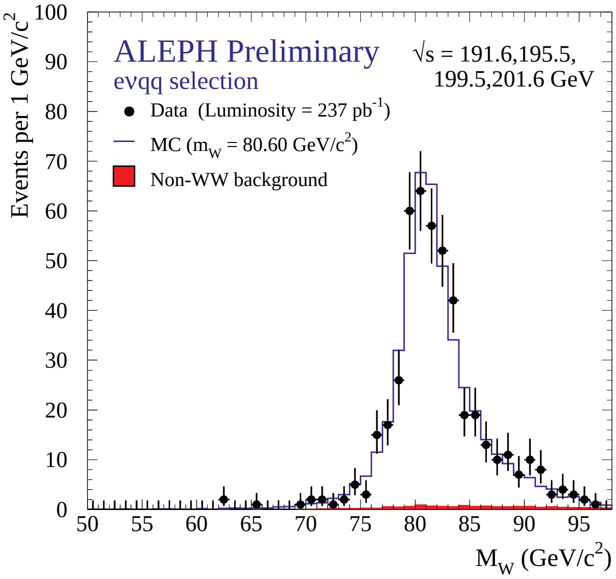
1. LEP II:

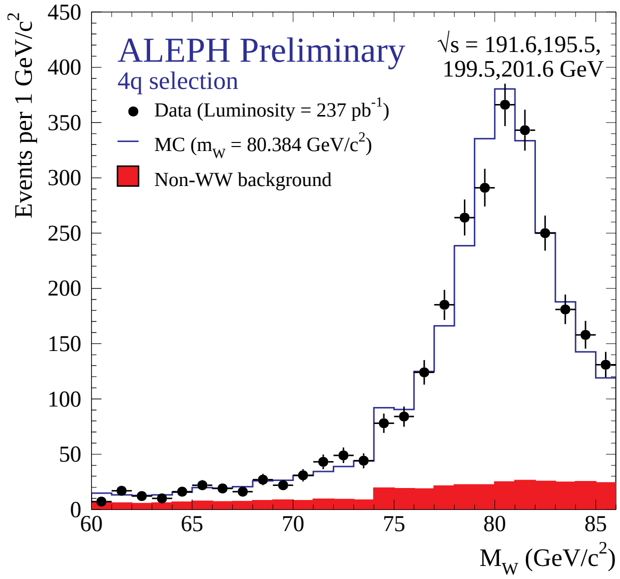
(a) A statistically imprecise measurement is extracted from the W^+W^- cross section at threshold (assumes that Γ_W is given by MSM):



$$M_W = 80.40 \pm 0.20(\text{stat}) \pm 0.07(\text{syst}) \pm 0.03(\text{LEP})\ \text{GeV}$$

(b) **Much more precise measurements are performed by reconstructing M_W from $q\bar{q}q\bar{q}$ and $q\bar{q}\ell\bar{\nu}_\ell$ final states:**





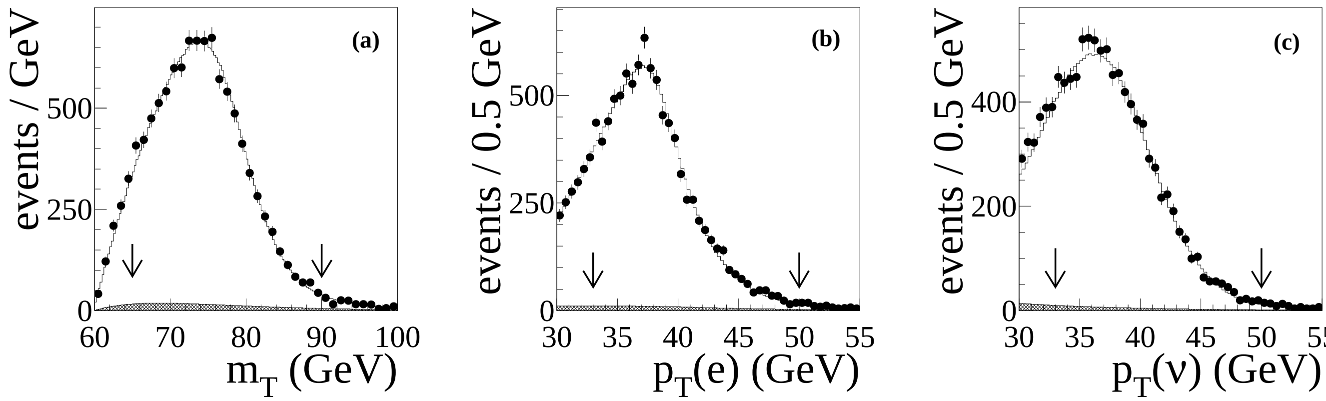
$$M_W = \mathbf{80.428} \pm \mathbf{0.030}(\mathrm{stat}) \pm \mathbf{0.036}(\mathrm{syst})\ \mathrm{GeV}$$

where the systematic uncertainties are:

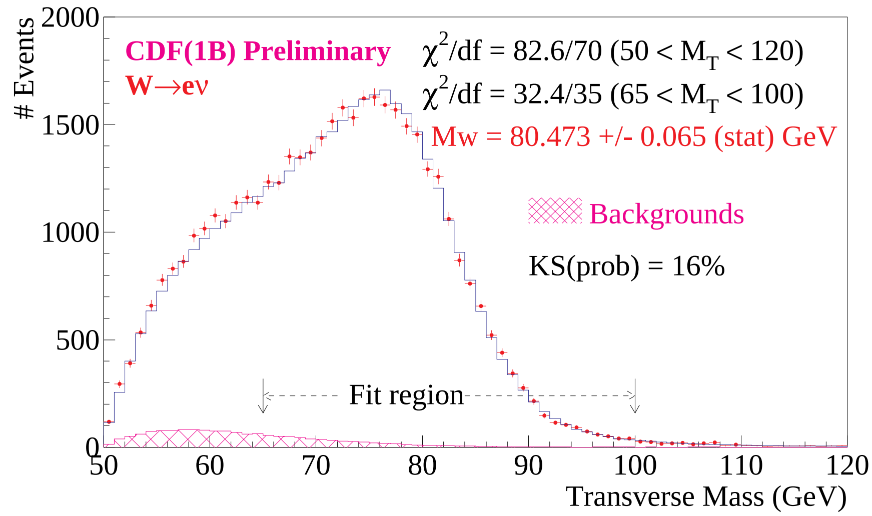
Source	Systematic Error on M_{W} (MeV)		
	$q\bar{q}\ell\bar{\nu}_\ell$	$q\bar{q}q\bar{q}$	Combined
ISR/FSR	8	10	8
Hadronisation	26	23	24
Detector Systematics	11	7	10
LEP Beam Energy	17	17	17
Colour Reconnection	—	50	13
Bose-Einstein Correlations	—	25	7
Other	5	5	4
Total Systematic	35	64	36
Statistical	38	34	30
Total	51	73	47

2. **Tevatron** - the W mass is extracted from the transverse mass distributions of final state leptons from $p\bar{p} \longrightarrow W \longrightarrow \ell\nu$:

D0

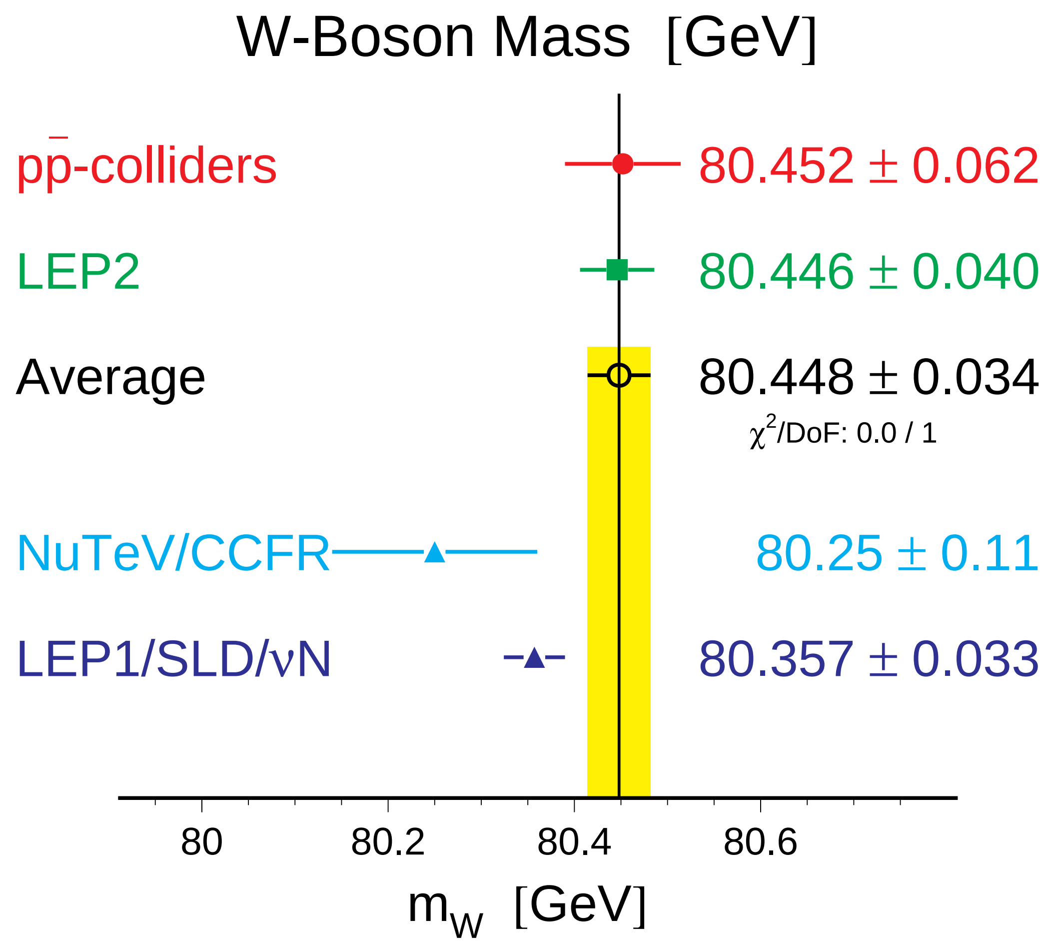


CDF



Experiment	M_W (GeV)
CDF Run 1A ($e\nu$, $\mu\nu$)	80.410±0.180
CDF Run 1B ($e\nu$, $\mu\nu$)	80.470±0.089
CDF Combined	80.433±0.079
D0 Run 1A ($e\nu$)	80.350±0.270
D0 Run 1B ($e\nu$)	80.498±0.095
D0 Combined	80.482±0.091
Tevatron	80.454±0.063

and the world average value of M_W **is**



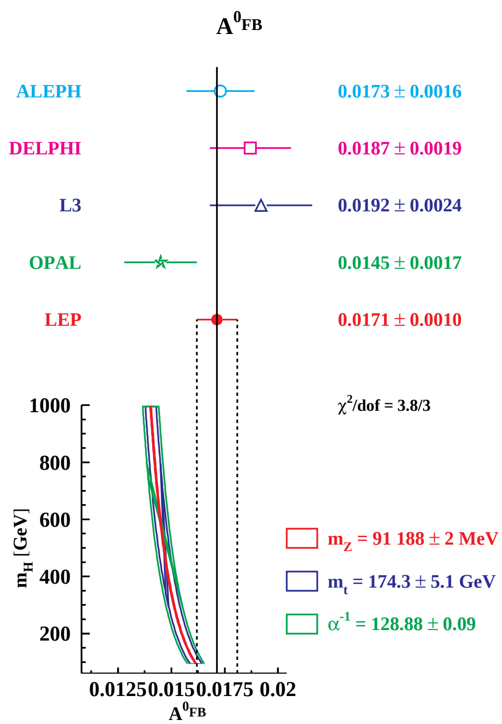
Current Knowledge of $\sin^2\theta_W^{\text{eff}}$

The effective weak mixing angle for the Z-$\ell^+\ell^-$ coupling is defined in terms of the vector and axial vector effective couplings, $\sin^2\theta_W^{\text{eff}} = (1 - v_\ell/a_\ell)/4$. It is also related to the left-right coupling asymmetry:

$$A_\ell = \frac{(g_L^\ell)^2 - (g_R^\ell)^2}{(g_L^\ell)^2 + (g_R^\ell)^2} = \frac{2v_\ell a_\ell}{v_\ell^2 + a_\ell^2} = \frac{2\left(1 - 4\sin^2\theta_W^{\text{eff}}\right)}{1 + \left(1 - 4\sin^2\theta_W^{\text{eff}}\right)^2}$$

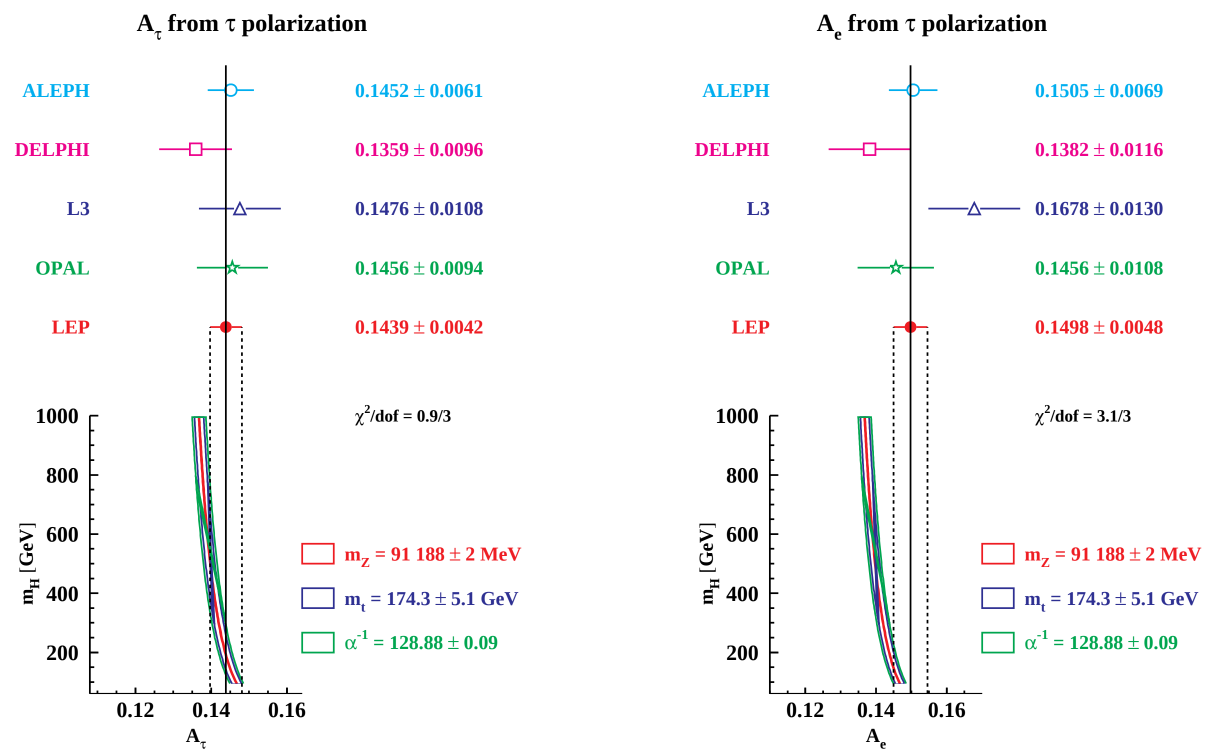
In recent years, $\sin^2\theta_W^{\text{eff}}$ has been determined from a number of Z-pole asymmetry measurements performed at LEP and the SLC:

1. Leptonic FB asymmetries - $A_{FB}^\ell = 3A_\ell^2/4$:



$$\sin^2\theta_W^{\text{eff}} = 0.23099 \pm 0.00053$$

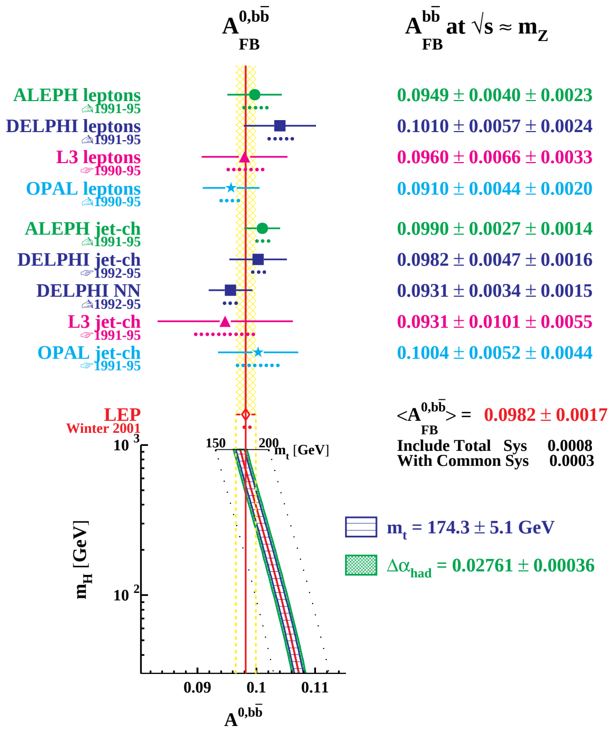
2. Tau polarization - $< P_\tau >= A_\ell$, $P_\tau^{FB} = 3A_\ell/4$:



$\sin^2\theta_W^{\rm eff} = 0.23192 \pm 0.00052$ $\sin^2\theta_W^{\rm eff} = 0.23117 \pm 0.00061$

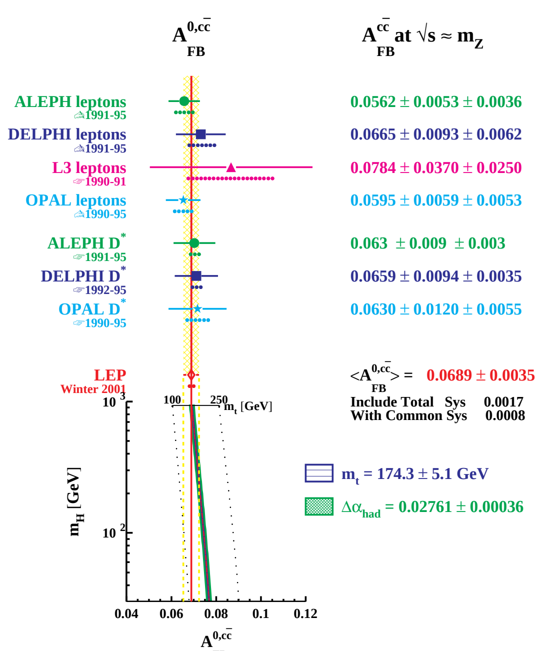
3. b-quark FB asymmetry - $A_{FB}^b = 3A_\ell A_b/4$:
ALEPH and DELPHI have recently updated their measurements of A_{FB}^b:

- DELPHI uses neural network for b-charge tag based on: vertex charge, jet charge, leptons, and kaons
- ALEPH uses neural network for b-flavor tag (30% increase in sample size)
- both use double-tag methods to reduce analyzing power uncertainties
- most precise class of unpolarized Z pole meas.
- New results decrease A_{FB}^b and increase $\sin^2\theta_W^{\rm eff}$



$$\sin^2 \theta_W^{\rm eff} = 0.23240 \pm 0.00031$$

4. c-quark FB asymmetry - $A_{FB}^c = 3 A_\ell A_c / 4$: much harder and less precise than b-quark measurements:



$$\sin^2 \theta_W^{\rm eff} = 0.23262 \pm 0.00080$$

5. Left-Right Asymmetry - $A^0_{LR} = A_\ell$: performed by SLD over7 years

Year	A^0_{LR}
1992	$0.100 \pm 0.044 \pm 0.004$
1993	$0.1656 \pm 0.0071 \pm 0.0028$
1994/5	$0.15116 \pm 0.00421 \pm 0.00112$
1996	$0.15929 \pm 0.00573 \pm 0.00101$
1997/8	$0.14906 \pm 0.0037 \pm 0.00096$
Total	0.15138 ± 0.00216

A^0_{LR} is entirely equivalent to the effective weak mixing angle,

$$\sin^2\theta_W^{\rm eff} = 0.23097 \pm 0.00027$$

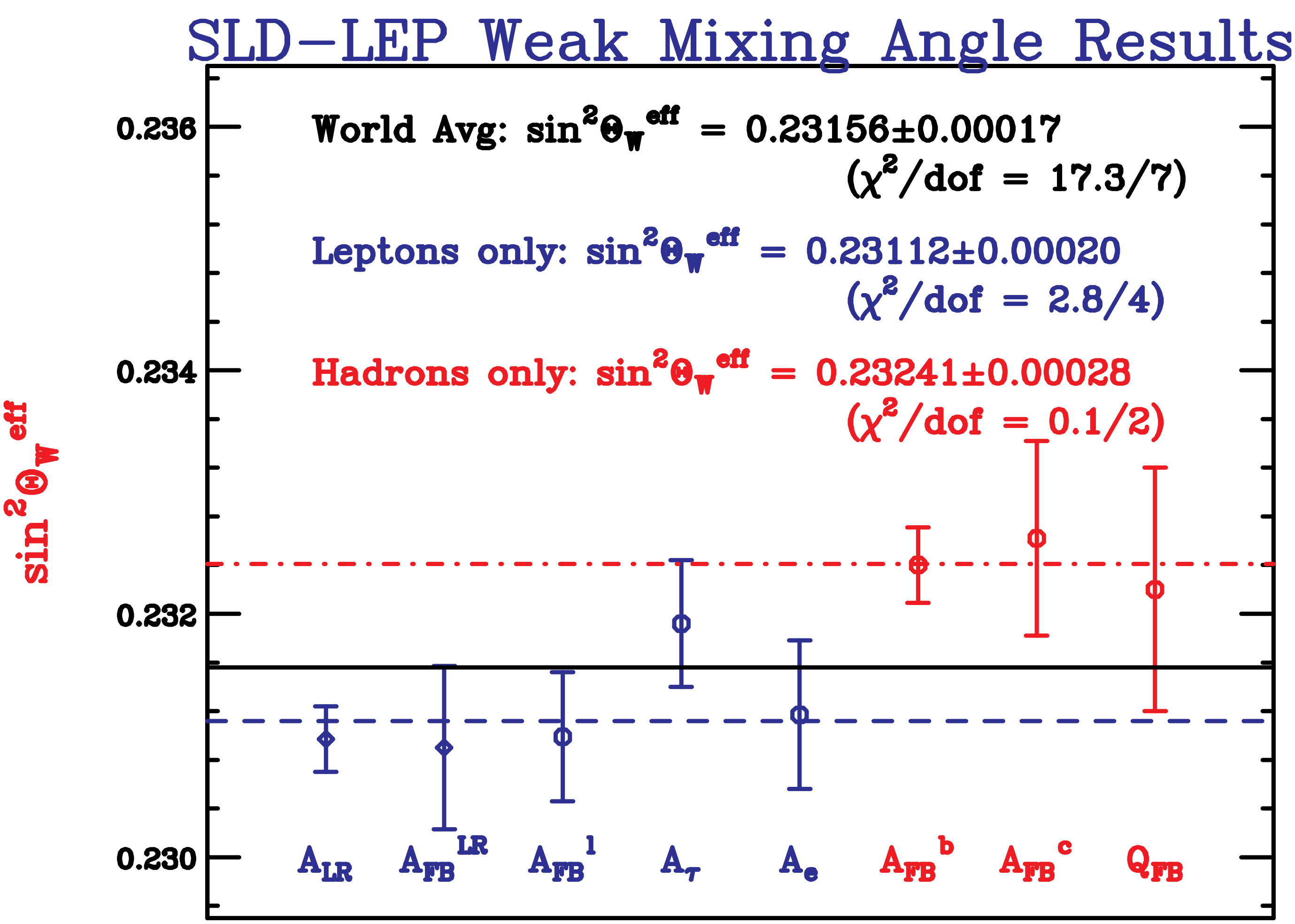
Note that the total statistical error is still about twice as large as the systematic uncertainty:

Uncertainty	1992	1993	1994/5	1996	1997/8
Polarimetry	2.7%	1.3%	0.64%	0.50%	0.50%
Energy Scale	—	—	0.33%	0.37%	0.39%
Chromatic Effects	—	1.1%	0.17%	0.16%	0.15%
Bkgd., Det., ...	2.4%	0.1%	0.06%	0.05%	0.07%
Total Systematic	3.6%	1.7%	0.75%	0.63%	0.64%
Statistics	44%	4.3%	2.8%	3.7%	1.6%

6. Polarized leptonic FB asymmetries: $\tilde{A}^{\ell}_{FB} = 3A_{\ell}/4$: derives information from beam polarization asymmetry and the angular distribution of final state leptons

$$\sin^2\theta_W^{\rm eff} = 0.23090 \pm 0.00067$$

Summary of $\sin^2\theta_W^{\rm eff}$ Measurements



- Shift in A^b_{FB} has increased world average by 1×10^{-4}!
- Leptonic and hadronic determinations disagree by 3.2σ.

Higgs Mass Dependence of M_W and $\sin^2\theta_W^{\rm eff}$

The dependence of M_W and $\sin^2\theta_W^{\rm eff}$ upon m_H is well-approximated by the following expressions due to Degrassi et al [PL B418, 209 (1998)],

$$
\begin{aligned}
M_W &= 80.3805 - 0.0581 \ln\frac{m_H}{100\ \text{GeV}} \\
&- 0.0078 \ln^2\frac{m_H}{100\ \text{GeV}} - 0.518\left[\frac{\Delta\alpha^5_{\rm had}}{0.0280} - 1\right] \\
&+ 0.537\left[\left(\frac{m_t}{175\ \text{GeV}}\right)^2 - 1\right] - 0.085\left[\frac{\alpha_s(M_Z)}{0.118} - 1\right] \\
\sin^2\theta_W^{\rm eff} &= 0.231540 + 5.23\cdot 10^{-4}\ln\frac{m_H}{100\ \text{GeV}} \\
&+ 0.00986\left[\frac{\Delta\alpha^5_{\rm had}}{0.0280} - 1\right] - 0.00268\left[\left(\frac{m_t}{175\ \text{GeV}}\right)^2 - 1\right] \\
&+ 4.4\cdot 10^{-4}\left[\frac{\alpha_s(M_Z)}{0.118} - 1\right].
\end{aligned}
$$

- **EW observables depend upon $\ln m_H$. All m_H uncertainties are therefore multiplicative (they scale with the central value of the fit).**

- **Must know the other parameters ($\Delta\alpha^5_{\rm had}$, m_t, $\alpha_s(M_Z)$) with adequate precision .**

It is instructive to calculate the uncertainty on each quantity that corresponds to the current experimental uncertainties on the two quantities,

Parameter	δM_W	$\delta \sin^2\theta_W^{\rm eff}$	Current
$\delta \ln m_H$	$\pm$0.585	$\pm$0.325	—
$\delta\Delta\alpha_{\rm had}^5$	$\pm$0.0018	$\pm$0.00048	$\pm$0.0002
δm_t	$\pm$5.5 GeV	$\pm$5.5 GeV	$\pm$5.1 GeV
$\delta\alpha_s(M_Z)$	$\pm$0.047	$\pm$0.046	$\pm$0.003

- $\delta M_W = 19$ **MeV needed to equal current** $\sin^2\theta_W^{\rm eff}$ **information**
- **theoretically-oriented determinations of** $\Delta\alpha_{\rm had}^5$ **are adequate to extract all information**
- m_t **information is already limiting the interpretation of the data**

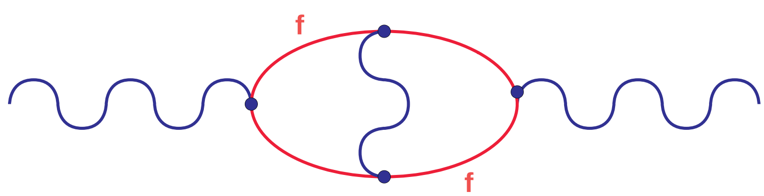
What about $\Delta\alpha_{\mathrm{had}}(M_Z^2)$?

Can represent the running of α_{em} as follows:

$$\Delta\alpha(q^2) = \frac{\alpha(q^2) - \alpha_0}{\alpha(q^2)} = \Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0).$$

where $\alpha_0 = 1/137.0359895(61)$. At the Z-mass-scale, $\Delta\alpha$ is approximately 0.06 which leads to 100% corrections in the magnitudes of some Z-pole asymmetries! It is clear that $\Delta\alpha(M_Z^2)$ must be determined very accurately.

$\Delta\alpha$ receives first-order contributions from all charged fermions,



The leptonic contributions have been calculated to three loops using field theoretical methods,

$$\Delta\alpha_{lept}(M_Z^2) = 314.98 \times 10^{-4}$$

The hadronic contributions involve potentially large QCD corrections and historically have been determined using analytic techniques and the optical theorem applied to the amplitude for s-channel Bhabha scattering. This yields a dispersion integral involving the cross section for the process $e^+e^- \longrightarrow \gamma^* \longrightarrow \mathrm{hadrons}$ (σ_{had}),

$$\begin{aligned}
\Delta\alpha_{\mathrm{had}}(q^2) &= \frac{1}{\pi}\mathrm{P}\int_{4m_\pi^2}^{\infty} ds \frac{q^2}{s^2(s-q^2)} \mathrm{Im}\Pi_{\gamma\gamma}^{had}(s) \\
&= \frac{\alpha_0}{3\pi}\mathrm{P}\int_{4m_\pi^2}^{\infty} ds \frac{q^2}{s(q^2-s)} R_{had}(s)
\end{aligned}$$

where $R_{had}(s) = \sigma_{had}/\sigma_{\mu\mu}(s)$.

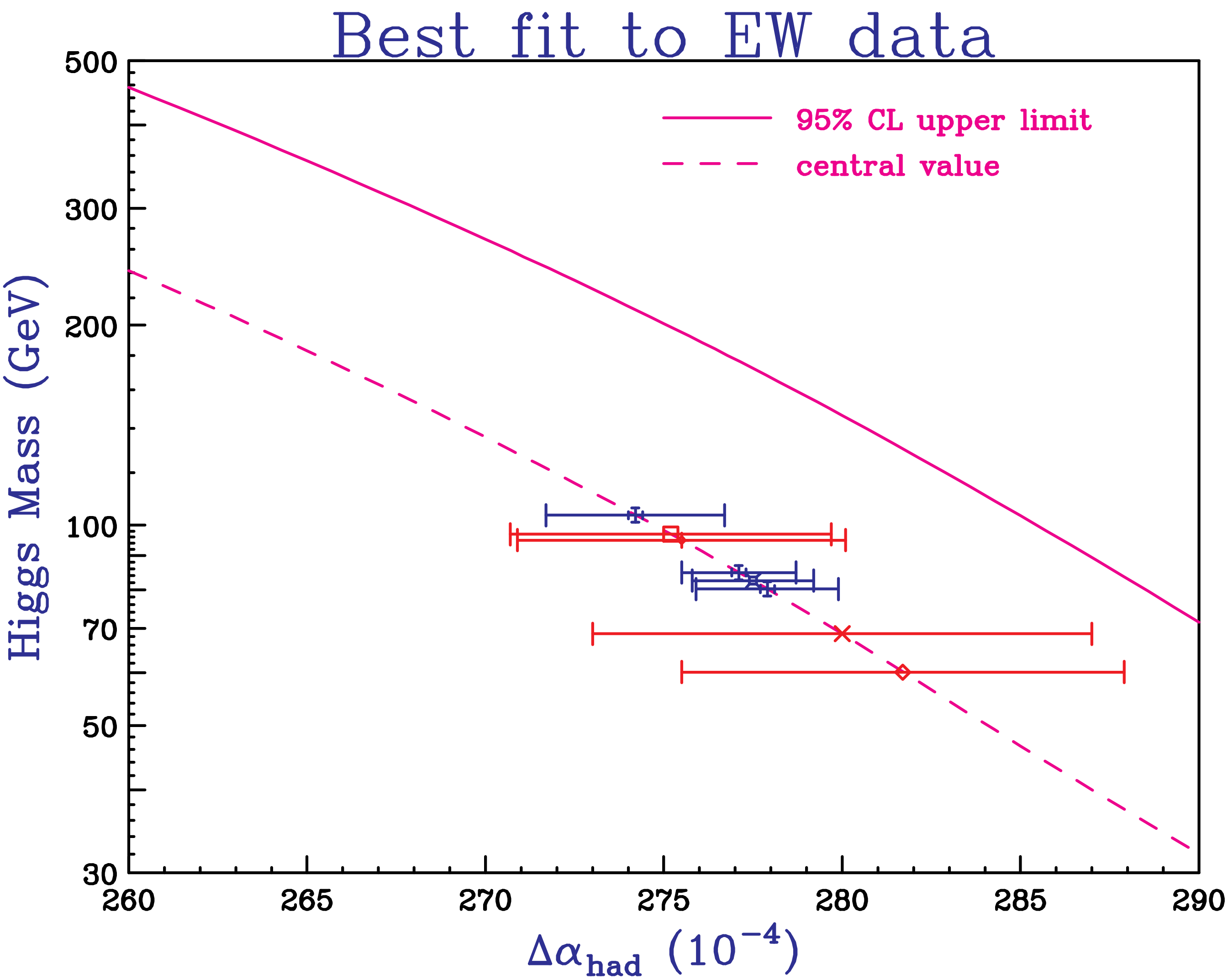
There have been many determinations of $\Delta\alpha_{had}(M_Z^2)$ over the last 13 years. In general, the earlier ones were based more strongly upon experimental measurements and later ones have increased their dependence upon theory, Since the contribution of the top quark was completely unknown until its discovery in 1995 and since it now has a well-determined and small effect ($\Delta\alpha_t(M_Z^2) = -0.76 \times 10^{-4}$), the top quark has not generally been included in determinations of $\Delta\alpha_{had}(M_Z^2)$. Most results are quoted for the contributions of 5-flavors,

Determinations of $\Delta\alpha^5_{had}(M_Z^2)$

Authors	Year	$\Delta\alpha^5_{had}(M_Z^2)$ (10^{-4})
Lynn, et al.	1987	??
Burkhardt et al.	1987	288±9
Jegerlehner	1991	282±9
Martin and Zeppenfeld	1994	273.2±4.2
Swartz	1994/5	275.2±4.5
Eidelman and Jegerlehner	1995	280±7
Burkhardt and Pietrzyk	1995	280±7
Alemany, Davier, and Hocker	1997/8	281.7±6.2
Kuhn and Steinhauser	1998	277.5±1.7
Davier and Hocker	1998	277.1±1.6
Erler	1998/9	277.9±2.0
Martin, Outhwaite, and Ryskin	2000	274.2±2.5
Pietrzyk	2000	275.5±4.6
Burkhardt and Pietrzyk	2001	276.1±3.6

Note that red results are mostly data-driven and blue results are mostly theory driven.

We do care about the central value,



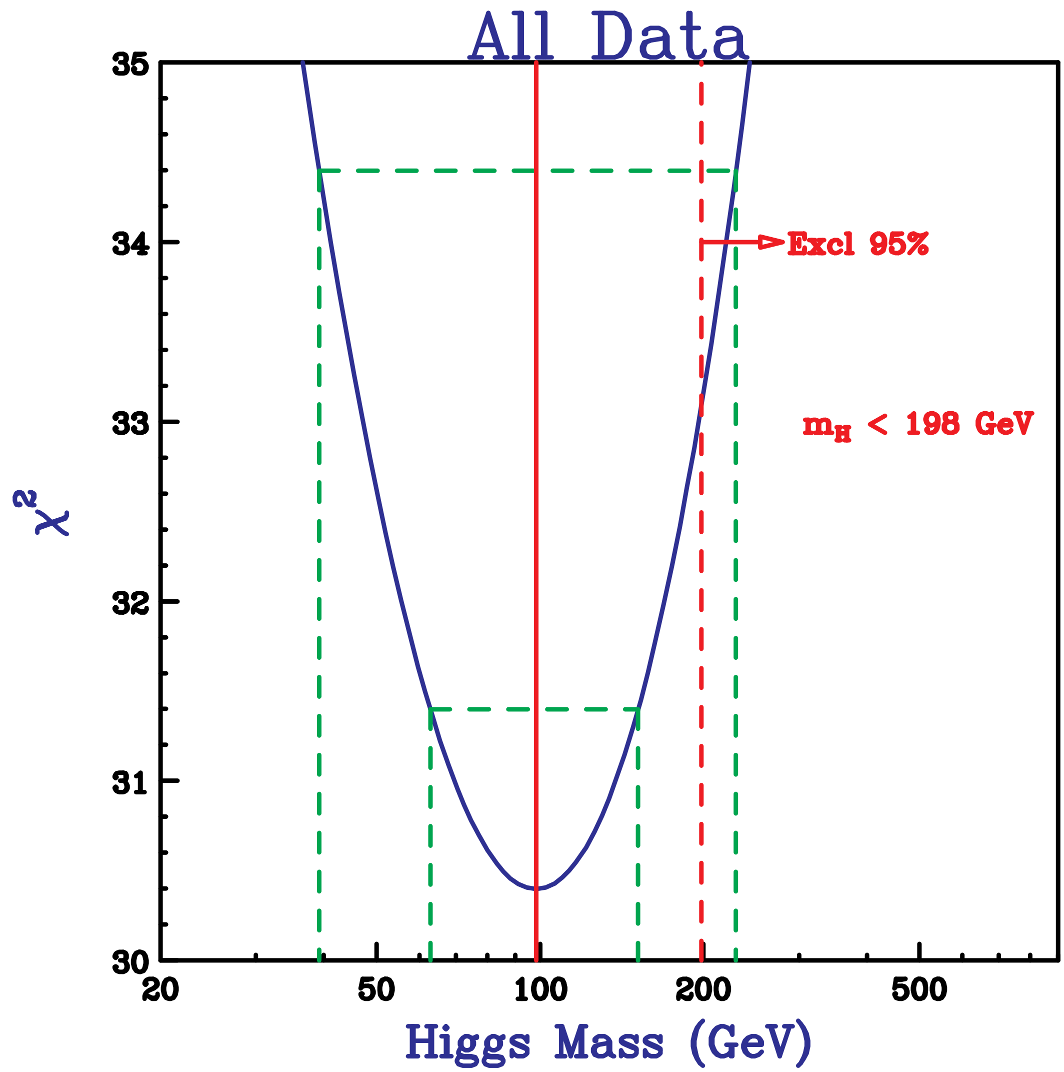
The central value of M_H varies by 44 GeV and the 95% upper limit varies by about 60 GeV with our choice of central value of $\Delta\alpha^5_{had}(M_Z^2)$.

Arbitrarily choose the Kuhn-Steinhauser value (in the middle of the theory pack):

$$\Delta\alpha^5_{\rm had}(M_Z^2) = (277.5 \pm 1.7) \times 10^{-4}$$

Current Higgs Mass Information

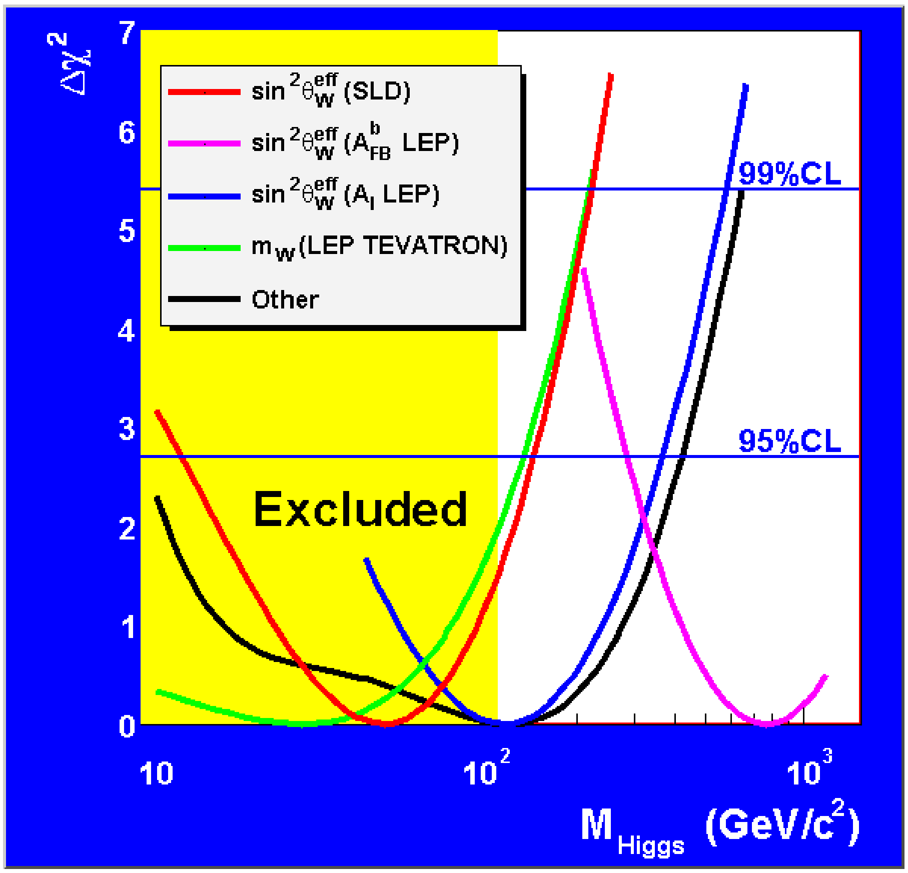
Performing a 5-parameter (m_H, m_t, M_Z, $\Delta\alpha^5_{\rm had}$, and α_s) to 21 electroweak measurements (with 3 constraints: m_t, M_Z, $\Delta\alpha^5_{\rm had}$),



$$
\begin{aligned}
\ln m_H &= 4.5900^{+0.4311}_{-0.4499} \qquad m_H = 98.5^{+53.1}_{-35.7}\ \text{GeV} \\
m_t &= 174.4 \pm 4.4\ \text{GeV} \\
\Delta\alpha^5_{\rm had} &= (277.7 \pm 1.7) \times 10^{-4} \\
\alpha_s(M_Z^2) &= 0.1186 \pm 0.0027
\end{aligned}
$$

What about the $\sin^2\theta_W^{\rm eff}$ discrepancy?

A_{FB}^b is consistent with the MSM (and a heavy Higgs) but is not consistent with the fairly "pristine" leptonic measurements (favor a light Higgs),



Excluding the hadronic determinations of $\sin^2\theta_W^{\rm eff}$,

$$\ln m_H = 3.7104^{+0.5370}_{-0.5348} \qquad m_H = 40.9^{+29.1}_{-16.9}\ \text{GeV}$$

and the 95% upper limit is

$$m_H < 97.8\ \text{GeV}$$

Is the MSM Excluded??

The Future

The near/medium-term future of particle physics is fairly easy to project: Run II at the Tevatron will continue until the LHC takes over (2006-2008?), LHC will run for many (15?) years, and (I hope) that there will be a Linear Collider somewhere in the world in the second decade of the century.

1. **Tevatron Run II** Unless the Tevatron run goes very well, the Higgs could still remain an interesting but elusive beast through Run II. In that instance, improved electroweak measurements would continue to be interpreted as indirect Higgs mass measurements until LHC is fully operational and definitive searches become possible. The electroweak capabilities of Run II were studied by a CDF/D0 working group which reported it's findings in December [hep-ex/0011009]. Of particular significance to determining m_H, the following was projected:

$$\begin{aligned} \delta m_W &\simeq 30 \text{ Mev} \\ \delta m_t &\simeq 2 \text{ GeV} \\ \delta \sin^2\theta_W^{\text{eff}} &\simeq 0.00028 \end{aligned}$$

where the measurement of $\sin^2\theta_W^{\text{eff}}$ comes from the measurement of the forward-backward asymmetry of

$\ell^+\ell^-$ final states in the Z mass region. We can expect that the uncertainty on $\ln m_H$ is reduced by 33%,

$$\delta \ln m_H = \pm \mathbf{0.45}\ (2001) \ \rightarrow\ \pm \mathbf{0.30}\ (2006)$$

2. **LHC** We have already noted that (hopefully) precision EW studies will have moved beyond m_H by the LHC era and that ew physics will be involved in more interesting testing. Nevertheless, let's keep our current language and take the projections of the LHC EW working group [hep-ph/0003275] at face value,

$$\begin{aligned} \delta m_W &\simeq \mathbf{15}\ \mathrm{Mev} \\ \delta m_t &\simeq \mathbf{1}\ \mathrm{GeV} \\ \delta \sin^2 \theta_W^{\mathrm{eff}} &\simeq \mathbf{0.00014} \end{aligned}$$

We can expect that the uncertainty on $\ln m_H$ is further reduced by a factor of 3.4,

$$\delta \ln m_H = \pm \mathbf{0.30}\ (2006) \ \rightarrow\ \pm \mathbf{0.089}\ (2010)$$

3. **LC** Finally, we note that truly remarkable electroweak measurements have been discussed for a Linear Collider

operating at the Z and at W-pair threshold [see K. Monig, hep-ex/0101005]. Using polarized electrons and positrons, the following measurements have been projected,

$$\begin{aligned} \delta m_W &\simeq 6 \text{ Mev} \\ \delta m_t &\simeq 0.1 \text{ GeV} \\ \delta \sin^2 \theta_W^{\text{eff}} &\simeq 0.000013 \end{aligned}$$

Assuming an additional improvement of 3 in the determination of $\Delta\alpha^5_{\text{had}}(M_Z^2)$, we can project that the uncertainty on $\ln m_H$ is further reduced by a factor of 3.9,

$$\delta \ln m_H = \pm 0.089 \ (2010) \ \rightarrow \ \pm 0.023 \ (2015)$$

Comparing the current result with an LC-based one,