The status of the standard model is briefly reviewed in the light of the most recent set of experimental data, with particular emphasis to the limits on the Higgs boson mass. The search for a light Higgs boson at LEP 2 is also briefly analyzed.
Since new electroweak data from the LEP Collaborations have been made available for the winter conferences we can attempt a partial updating of the corresponding theoretical predictions. The first and preliminary question that we can address is: what have the theorists been doing in 1995-96?

- Most of the experts have been moving from MULTI-LOOP TWO-FERMION Physics to TREE-LEVEL FOUR-FERMION Physics

Also of some relevance is the following question: what are they planning to do next?

- To move from TREE-LEVEL FOUR-FERMION Physics to either ONE-LOOP FOUR-FERMION (relevant for LEP 2 and beyond) or to TREE-LEVEL SIX-FERMION Physics (relevant for the NLC).

Therefore what to say about THEORY versus EXPERIMENT after the recent upgrading of the experimental accuracy? The most sensible thing to do is perhaps to present the facts strictly separated from the opinions and to be as pragmatic as possible. In other words we will offer the most advanced standard model (MSM) technology and try to find out where we are without any interpretation of the data and with no prejudice.

The foundations to discuss estimates of the theoretical error have been set by the Working Group on Precision Calculations for the Z-resonance. How do we compare today with the data? This is better illustrated in Table 1 where we have reported for some of the most relevant quantities the 1995 and 1996 experimental error. Moreover we have added the ratio $\Delta_c$ between the world average of the estimate of the theoretical error and the corresponding experimental one. In the last column of Table 1 we have added the most recent evaluation of some of the sub-leading corrections as computed in ref. [3].

From this table we can easily conclude that the experiments are closing the gap and the only new piece of calculation is about sub-leading $\Delta\rho$ [3]. Of course the main question remains

- Do the experimental data accept the MSM?

- Are we setting sail for the land beyond the edge of the world, where New Physics roam?

Again we will try to present facts and no opinions, i.e. to show a poor (standard) man fit* obtained with the help of TOPAZ0 [4]. In Table 2 we have shown a typical result of a fit with the Higgs boson mass fixed at 90(400) GeV with the SLD $A_{LR}$ measurement included(excluded). The uncertainty due to the error on $\alpha(M_Z)$ and $m_b$ is fully propagated in the theoretical part of the $\chi^2$. For the given $M_H$ the corresponding $\chi^2$ has been obtained by minimizing the $\chi^2$ function with respect to $M_Z$, $m_t$ and $\alpha_s(M_Z)$. Experimental results will include LEP lineshape + $A_{FB}$ data and their correlation, LEP asymmetry data, LEP + SLD heavy flavor data and their correlation, the SLD $A_{LR}$, the $M_W$ measurement and the $m_t$ measurement.

*Real fits to be found somewhere else
| \( M_W \) (MeV) | \( \Gamma_Z \) (GeV) | \( R_l \) | \( R_b \) | \( R_c \) | \( A^L_{FB} \) | \( A^b_{FB} \) | \( A^c_{FB} \) | \( \sin^2 \theta_{eff} \) |
|----------------|----------------|--------|--------|--------|-------------|-------------|-------------|-------------|
| 180            | 3.8            | 0.04   | 0.002  | 0.0098 | 0.0016      | 0.0038      | 0.0091      | 0.0004      |
| 150            | 3.2            | 0.032  | 0.0016 | 0.0070 | 0.0011      | 0.00275     | 0.0051      | 0.0005      |
| 2.5\times10^{-2}| 3.9\times10^{-2}| 1.0\times10^{-1}| 3.3\times10^{-2}| 0.2\times10^{-2}| 5.6\times10^{-2}| 7.8\times10^{-2}| 2.5\times10^{-2}| 1.4\times10^{-1}|
| 3.0\times10^{-2}| 4.6\times10^{-2}| 1.3\times10^{-1}| 4.1\times10^{-2}| 0.28\times10^{-2}| 8.1\times10^{-2}| 1.1\times10^{-1}| 4.5\times10^{-2}| 1.1\times10^{-1}|
| \( \text{m}_{t} \) at CDF+D0 value | \( 100 \text{ GeV} \leq M_{\mu} \leq 300 \text{ GeV} \) | \( 9.5\times10^{-2} - 8.3\times10^{-2} \) | \( 4.6\times10^{-2} \) | \( 1.3\times10^{-1} \) | \( 4.1\times10^{-2} \) | \( 1.1\times10^{-1} \) | \( 4.5\times10^{-2} \) | \( 1.1\times10^{-1} \) |

Table 1: Ratios of theoretical uncertainties versus experimental errors. Data
| O          | Exp. | Theory                        | Comments                  |
|------------|------|-------------------------------|---------------------------|
| $M_{\mu}$ (GeV) | –    | 90(400) (fixed)               |                           |
| $\chi^2$  |      | 21.5/14(20.2/13)              |                           |
| $m_t$ (GeV) | 175 ± 9 | 169 ± 8(176 ± 8)             | penalty in the fit         |
| $\alpha^{-1}(M_Z)$ | 128.896 ± 0.09 | 128.926 ± 0.099(128.961 ± 0.098) | th. err. not included      |
| $\alpha_s(M_Z)$ | –    | 0.1210 ± 0.0047(0.1242 ± 0.0046) |                           |
| $m_b$ (GeV) | 4.7 ± 0.2 | 4.67 ± 0.26(4.67 ± 0.25) |                           |
| $\sin^2 \theta^e_{eff}$ | 0.23049 ± 0.00050 | 0.23137 ± 0.00027(0.23188 ± 0.00029) |                           |
| $\sin^2 \theta^b_{eff}$ | 0.2320 ± 0.0010 | 0.2326 ± 0.0002(0.2332 ± 0.0002) |                           |
| $R_b$      | 0.2211 ± 0.0016 | 0.2159 ± 0.0003(0.2156 ± 0.0003) | correlated                |
| $R_c$      | 0.1598 ± 0.0070 | 0.1723 ± 0.0001(0.1724 ± 0.0001) | ”                         |

Table 2: Theory versus Experiments(with/without SLD).
As it is well known the non standard result is $R_b$ and less significantly $R_c$, especially in the light of the new data. For the fun of it let us consider a Transfer Function $G$, the probability of reconstructing the true pair $R_b, R_c$ given the event contained the pair of $\overline{R}_b, \overline{R}_c$. For the sake of simplicity let us also assume that $G$ is a simple rotation ($\theta$) in the $R_b, R_c$ plane. We assume to believe in a light Higgs(100 GeV) and perform a fit to $M_Z, m_t, \alpha_s$ and $\theta$ and obtain

\[
\begin{align*}
    m_t &= 171 \\
    \alpha_s(M_Z) &= 0.1211 \\
    \theta &= 1.27^\circ
\end{align*}
\]

(1)

giving

\[
\begin{align*}
    R_b &\mid 0.2159 \rightarrow 0.2195(1.0 - \sigma), \\
    R_c &\mid 0.1723 \rightarrow 0.1675(1.1 - \sigma),
\end{align*}
\]

(2)

which is not bad since they are $1.0 \sigma$ and $1.1 \sigma$ away from the experimental value. New Physics should be compatible with rotating $b - c$ of about $1^\circ$.

Back to Orthodoxy it is perhaps opportune to re-iterate that so far no realistic calculation exists for the $\overline{b}b$ cross section which should take into account as much as possible the experimental setup chosen to extract $R_b$. Every realistic calculation should interface the two-fermion final state with the four-fermion one since by now we know how to include the exact $\overline{b}c\overline{c}c$ cross section into $\sigma(\overline{b}b)$ and $\sigma(\overline{c}c)$. This is most likely not going to account for deviations but we need the real thing and we should not go for anything less. Thus we have shown in Fig. 1 the ratio $\sigma(\overline{b}c\overline{c}c)/\sigma(\overline{b}b)$ as a function of $\sqrt{s}$ as computed by TOPAZ0-WTO [5].

The next question will be of course about supersymmetry, i.e. how do we compare the MSM with the MSSM? Data are still changing a little and a new plot of DATA/MSSM is not yet available. However things do not change dramatically in the data from 1995 to 1996 and the old conclusions remain valid to a very large extent. Thus 50% of the discrepancy on $R_b$ will go away with MSSM but nothing will be gained in $R_c$ where however the data have been changing a little moving towards the theoretical predictions.

All of this is really peanuts, the edge of the world is the Higgsland since a light Higgs is most likely supersymmetric while a heavy Higgs means troubles for almost everybody. We have attempted several fits but before discussing the outcome we would like to stress the following facts:

- The main problem is to understand when the $\chi^2$ shape as a function of $M_\mu$ is unstable with respect to normal fluctuations of the experimental data in the large $M_\mu$ tail.
- Very stringent bounds on $M_\mu$, i.e. much less than 500 GeV, look more like a symptom of the clash between SLD and LEP.
• The $\chi^2$ shape depends heavily on the introduction of penalty functions which constrain $m_t$ and/or $\alpha_s$.

• $\chi^2_{\text{min}}(M_H)$ has an unnatural tendency to be in the forbidden region, thus requiring the unnatural introduction of yet another penalty function.

In all fits we have used the most recent electroweak data \[1\] with or without the exclusion of some sub-set. We have fixed the Higgs boson mass, fully propagated the uncertainty on $\alpha(M_Z)$ and $m_b$ in the fit and determined $M_Z$, $m_t$ and $\alpha_s(M_Z)$. After that the $\chi^2(M_H)$ curve or the $\Delta \chi^2(M_H)$ curve has been constructed and the 95% C.L. one-sided upper bound has been determined ($\Delta \chi^2 = 2.7$).

In Fig. 2 we have shown the effect of including the theoretical error in the fit, at least according to TOPAZ0. Therefore the two solid lines account for different options in treating higher order corrections as equivalent treatments of resummation techniques, momentum transfer scale for vertex corrections and factorization schemes. As depicted here the one-sided upper bound on $M_H$ has become quite less than the mythical $1-1.5$ TeV of some year ago. Fig.3 is telling us what the effect will be of lowering the experimental error on the top quark mass or on $M_W$. Clearly it is not only a question of reducing the experimental error but also the effect of the central value is of some relevance for the goodness of the fit, which is not of the highest quality anyway. In Fig. 4 we have attempted to understand the effects of single measurements on the determination of the Higgs boson mass. It emerges that the exclusion of $R_b$, $R_c$ but especially of $A_{LR}$ will move up $M_H$ considerably. The only statement that should be made today is that while we are well below the 1 TeV wall (with this set of data) it is still premature to give something more precise than a vague estimate $M_H \leq 400 - 500$ GeV at 95% of confidence level. In particular we find somehow unsatisfactory the large jump in the upper bound when a single measurement is removed from the set of data.

Even more important we have analyzed the question of stability of the $\chi^2$ high $M_H$ tail. The procedure is standard, by going at the minimum of the $\chi^2$ we use that value of $M_H$ to compute the electroweak observables according to the MSM (as seen by TOPAZ0). This set of numbers, hereafter termed fixed theory (FT), is subsequently used instead of the experimental data (E) for a new fit. Thus the difference between the solid and the dashed line in Fig. 5 gives terms linear in $T$-$FT$ ($E$-$FT$ drops out of the $\Delta \chi^2$) which are noise, i.e. normal fluctuations. As a matter of fact the goodness itself of the fit is not completely satisfactory. Whenever a penalty on $m_t$ is included, accounting for the CDF+D0+UA2 constraint, we see that the two minima of $\Delta \chi^2$ for $T$-$FT$ or $T$-$E$ are slightly shifted. This is due to the fact that while repeating the fit for $T$-$FT$ the theory prefers to adjust first the constraint of the penalty paying a much lesser price on the rest of the residuals. This again we interpret as suggesting some caution in establishing a very precise upper bound on $M_H$ in the region below $400 - 500$ GeV. Thus our only conclusion will be $M_H \leq 500$ GeV from the present set of data (average among the four LEP Collaborations) and the present correlation matrix.

If the Higgs boson is in the range of LEP 2 we should stop worrying about Tails&Fits and start to understand how it will look like in a real environment. Already a large amount of work has been done in this direction \[3\] and here we will briefly summarize the present theoretical situation by using the result of WTO. All the results have been obtained by
including the $H \to gg$ channel in the total Higgs width. This treatment will therefore evolve $\alpha_s$ to the scale $\mu = M_H$, evaluate the running $b, c$-quark masses and compute

$$\Gamma_H = \frac{G_F M_H^4}{4 \pi} \left\{ 3 \left[ m_b^2(M_H) + m_c^2(M_H) \right] \left[ 1 + 5.67 \frac{\alpha_s}{\pi} + 42.74 \left( \frac{\alpha_s}{\pi} \right)^2 \right] + m_t^2 \right\} + \Gamma_{gg},$$

$$\Gamma_{gg} = \frac{G_F M_H^3}{36 \pi} \frac{\alpha_s^2}{\pi^2} \left( 1 + 17.91667 \frac{\alpha_s}{\pi} \right). \tag{3}$$

Finally the Higgs boson signal is multiplied by

$$\delta_{QCD} = 1 + 5.67 \frac{\alpha_s}{\pi} + 42.74 \left( \frac{\alpha_s}{\pi} \right)^2,$$

$$\alpha_s = \alpha_s(M_H). \tag{4}$$

In Fig. 6 we have shown the $e^+e^- \to \mu^+\mu^-\mu^-\mu^-$ total cross section as a function of $\sqrt s$ for three possibilities: no Higgs, $M_H = 80$ GeV and $M_H = 100$ GeV. At LEP 2 a large fraction of events will be of the type $\nu\bar{\nu}b\bar{b}$ and we have shown the corresponding cross section (summed over all neutrinos) in Fig. 7 with a simple set of kinematical cuts, $|M_{\mu\mu}(M_{\nu\nu}) - M_Z| \leq 25 \text{GeV}$ and $M_{b\bar{b}} \geq 50 \text{ GeV}$. To show the potentialities of the dedicated electroweak codes we have presented in Fig. 8 and 9 the $M_{b\bar{b}}$ distribution for $e^+e^- \to \mu^+\mu^-\mu^-\mu^-$ at two energies, 175 GeV and 190 GeV and two values of $M_H = 80, 100$ GeV. Actually in Fig. 8 and 9 we have shown the ratio

$$R = \frac{M_H}{\sigma} \frac{d\sigma}{dM_{b\bar{b}}}. \tag{5}$$

Finally in Fig. 10 we have compared the invariant mass distribution $d\sigma/dM(b\bar{b})$ with the corresponding histogram reporting the number of events/0.5 GeV.

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Figure 1: The ratio $\sigma(\bar{b}b\bar{c}c)/\sigma(\bar{b}b)$ at LEP 1 energies.
Figure 2: The $\chi^2(M_H)$ curve inclusive of the estimate of the theoretical error.
Figure 3: The $\chi^2(M_H)$ curve with projected experimental errors on $m_t$ and $M_W$. 
Figure 4: The $\chi^2(M_H)$ curve with the exclusion of some sub-set of experimental data.
Figure 5: The normal fluctuations in the $\Delta \chi^2(M_H)$ curve.
Figure 6: The cross section for $e^+e^- \rightarrow \mu^+\mu^- b\bar{b}$. 

Figure 6: The cross section for $e^+e^- \rightarrow \mu^+\mu^- b\bar{b}$. 
Figure 7: The cross section for $e^+e^- \rightarrow \mu^+\mu^- (\sum \nu\bar{\nu})bb$. 
Figure 8: The $M_{\bar{b}b}$ distribution for $e^+e^- \rightarrow \mu^+\mu^-\bar{b}b$ at $M_H = 80$ GeV.
Figure 9: The $M_{\mu\mu b\bar{b}}$ distribution for $e^+e^- \rightarrow \mu^+\mu^- b\bar{b}$ at $M_H = 100$ GeV.
Figure 10: The $M_{\bar{b}b}$ distribution for $e^+e^- \rightarrow \mu^+\mu^-\bar{b}b$ versus events/0.5 GeV.