

## EW PRECISION ANALYSIS AND THE HIGGS MASS\*

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Two topics on the standard electroweak theory are discussed based on its remarkable success in precision analyses. One is a test of structure of the radiative corrections to the weak-boson masses as a further precision analysis. The other is an indirect Higgs-boson search through the radiative corrections to the various quantities measured at LEP.

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**1. Introduction**

The discovery of the top quark [1] has completed the fermion world in the three generation scheme. In the framework of the standard (minimal) electroweak theory, we now have only one yet-undiscovered ingredient left: the Higgs boson. Combining this with the fact that the electroweak theory (with the radiative corrections) has been quite successful in precision analyses through LEP, SLC, Tevatron and lots of other experimental information, we find ourselves in a position to proceed to further more detailed studies of this theory.

At this Symposium, I would like to discuss two topics under this circumstance based upon some of our recent works [2, 3]: One is a test of structure of the EW radiative corrections via  $W/Z$  masses. The other is a Higgs-boson search through the radiative corrections and precision LEP data. The latter has already been a popular subject, and there are a lot of related papers (see [4–6] and references cited therein). I do not mean that we developed some new technique to analyze the data. However, it is quite significant for future experiments to draw any information on the

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Higgs mass, and I wish to show some results which Consoli and I obtained lately.

Before stepping into actual discussions, let me briefly explain what I intend to talk about. First, EW corrections consist of several parts with different properties, and I examined via  $\alpha$ ,  $G_F$  and  $M_{W,Z}$  what would happen if each of them would not exist. For example, there are top-quark corrections which do not decouple, *i.e.*, become larger and larger as  $m_t$  increases. Studying them are significant not only because it is a test of the EW theory as a renormalizable field theory but also because the existence of such effects is a characteristic feature of theories in which particle masses are produced through spontaneous symmetry breakdown plus large Yukawa couplings.

Next, on the Higgs search. Stimulated by the first CDF report on the top-quark evidence, Najima and I considered if there is not any problem in the EW theory. We then found that the Higgs mass needs to be 1.1–1.2 TeV in order for  $M_W|_{m_t=174 \text{ GeV}}$  to reproduce the central value of  $M_W^{\text{exp}}$ , contrary to some other analyses using the LEP/SLC data which prefer a lighter Higgs boson:  $m_\phi \lesssim 300 \text{ GeV}$  [4, 6]. At present, it is not that serious since such a lighter Higgs is also allowed if we take into account the size of  $\Delta m_t^{\text{exp}}$  and  $\Delta M_W^{\text{exp}}$ , but this motivated us to analyze the LEP data our own way.

The first subject is discussed in Section 2, and the second one is in Section 3. Section 4 is for brief summary and discussions.

## 2. Structure of EW corrections

Through the  $O(\alpha)$  corrections to the muon-decay amplitude, the  $W$  mass is calculated as

$$M_W = M_W(\alpha, G_F, M_Z, \Delta r). \quad (2.1)$$

Here  $\Delta r$  expresses the corrections, and it is also a function of  $\alpha$ ,  $G_F$ ,  $M_Z$ ,  $m_f$  and  $m_\phi$ . This formula, the  $M_W$ - $M_Z$  relation, is the main tool of my analyses in this section<sup>1</sup>.

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<sup>1</sup> Over the past several years, some corrections beyond the one-loop approximation have been computed. They are two-loop top-quark corrections [7] and QCD corrections up to  $O(\alpha_{\text{QCD}}^2)$  for the top-quark loops [8] (see [9] as reviews). As a result, we have now a formula including  $O(\alpha\alpha_{\text{QCD}}^2 m_t^2)$  and  $O(\alpha^2 m_t^4)$  effects. In the following,  $M_W$  is always computed by incorporating all of these higher-order terms as well, although I will express the whole corrections with these terms also as  $\Delta r$  for simplicity.

Let me show first by using this formula how the theory with the full corrections is successful, though it is already a well-known fact. We thereby have

$$M_W^{(0)} = 80.9404 \pm 0.0027 \text{ GeV} \quad \text{and} \quad M_W = 80.36 \pm 0.09 \text{ GeV} \quad (2.2)$$

for  $M_Z^{\text{exp}} = 91.1887 \pm 0.0022 \text{ GeV}$  [10], where  $M_W^{(0)} \equiv M_W(\alpha, G_F, M_Z, \Delta r = 0)$  and  $M_W$  is for  $m_t^{\text{exp}} = 180 \pm 12 \text{ GeV}$  [1],  $m_\phi = 300 \text{ GeV}$  and  $\alpha_{\text{QCD}}(M_Z) = 0.118$ . Concerning the uncertainty of  $M_W$ , 0.09 GeV, I have a little overestimated for safety. From these results, we can find that the theory with the corrections is in good agreement with the experimental value  $M_W^{\text{exp}} = 80.27 \pm 0.14 \text{ GeV}$  [11], while the tree prediction fails to describe it at about  $4.8\sigma$  (99.9998 % C.L.).

We are now ready. First, let us see if taking only  $\alpha(M_Z)$  into account is still a good approximation (so-called “improved-Born approximation”), which was shown to be quite successful in [12]. The  $W$  mass is calculated within this approximation by putting  $\Delta r = 0$  and replacing  $\alpha$  with  $\alpha(M_Z)$  in Eq. (2.1), where  $\alpha(M_Z) = 1/(128.92 \pm 0.12)^2$ . The result is

$$M_W[\text{Born}] = 79.964 \pm 0.017 \text{ GeV}, \quad (2.3)$$

which leads to

$$M_W^{\text{exp}} - M_W[\text{Born}] = 0.31 \pm 0.14 \text{ GeV}. \quad (2.4)$$

This means that  $M_W[\text{Born}]$  is in disagreement with the data now at  $2.2\sigma$ , which corresponds to about 97.2 % C.L.. Although the precision is not yet sufficiently high, it indicates some non-Born terms are needed which give a positive contribution to the  $W$  mass. It is noteworthy since the electroweak theory predicts such positive non-Born type corrections unless the Higgs is extremely heavy (beyond TeV scale). Similar analyses were made also in [15].

The next test is on the non-decoupling top-quark effects. Except for the coefficients, their contribution to  $\Delta r$  is

$$\Delta r[m_t] \sim \alpha(m_t/M_Z)^2 + \alpha \ln(m_t/M_Z). \quad (2.5)$$

According to my strategy, I computed the  $W$  mass by using the following  $\Delta r'$  instead of  $\Delta r$  in Eq.(2.1):

$$\Delta r' \equiv \Delta r - \Delta r[m_t]. \quad (2.6)$$

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<sup>2</sup> Recently three papers appeared in which  $\alpha(M_Z)$  is re-evaluated from the data of the total cross section of  $e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons}$  [13] (their updated results are given in [14]). Here I simply took the average of the maximum and minimum among them.

The resultant  $W$  mass is denoted as  $M'_W$ . The important point is to subtract not only  $m_t^2$  term but also  $\ln(m_t/M_Z)$  term, though the latter produces only very small effects as long as  $m_t$  is not extremely large.  $\Delta r'$  still includes  $m_t$  dependent terms, but no longer diverges for  $m_t \rightarrow +\infty$  thanks to this subtraction. I found that  $M'_W$  takes the maximum value for the largest  $m_t$  and the smallest  $m_\phi$ . That is, we get an inequality

$$M'_W \leq M'_W[m_t^{\max}, m_\phi^{\min}]. \quad (2.7)$$

We could use  $m_t^{\text{exp}} = 180 \pm 12$  GeV [1] and  $m_\phi^{\text{exp}} > 65.1$  GeV [16] in the right-hand side of the above inequality, *i.e.*,  $m_t^{\max} = 180 + 12$  GeV and  $m_\phi^{\min} = 65.1$  GeV, but I first take  $m_t^{\max} \rightarrow +\infty$  and  $m_\phi^{\min} = 0$  in order to make the result as data-independent as possible. The accompanying uncertainty for  $M'_W$  is estimated at most to be about 0.03 GeV. We have then

$$M'_W < 79.950(\pm 0.030) \text{ GeV} \quad \text{and} \quad M_W^{\text{exp}} - M'_W > 0.32 \pm 0.14 \text{ GeV}, \quad (2.8)$$

which show that  $M'_W$  is in disagreement with  $M_W^{\text{exp}}$  at about  $2.3\sigma$  ( $=97.9\%$  C.L.). This means that 1) the electroweak theory is not able to be consistent with  $M_W^{\text{exp}}$  *whatever values  $m_t$  and  $m_\phi$  take* if  $\Delta r[m_t]$  would not exist, and 2) the theory with  $\Delta r[m_t]$  works well, as shown before, for experimentally-allowed  $m_t$  and  $m_\phi$ . Combining them, we can summarize that the latest experimental data of  $M_{W,Z}$  demand, *independent of  $m_\phi$* , the existence of the non-decoupling top-quark corrections. The confidence level of this result becomes higher if we use  $m_t^{\max} = 180 + 12$  GeV and  $m_\phi^{\min} = 65.1$  GeV:

$$M'_W < 79.863(\pm 0.030) \text{ GeV} \quad \text{and} \quad M_W^{\text{exp}} - M'_W > 0.41 \pm 0.14 \text{ GeV}, \quad (2.9)$$

that is, almost  $3\sigma$  level.

Finally, let us look into the bosonic contribution. It was pointed out in [17] by using various high-energy data that such bosonic electroweak corrections are now required. I studied whether we could observe a similar evidence in the  $M_W$ - $M_Z$  relation. In this case, we have to compute  $M_W$  taking account of only the pure-fermionic corrections  $\Delta r[f](\equiv \Delta r - \Delta r[\text{boson}])$ . Since  $\Delta r[f]$  depends on  $m_t$  strongly, it is not easy to develop a quantitative analysis of it without knowing  $m_t$ . Therefore, I used  $m_t^{\text{exp}}$ . I express thus-computed  $W$  mass as  $M_W[f]$ . The result became

$$M_W[f] = 80.48 \pm 0.09 \text{ GeV}. \quad (2.10)$$

This value is of course independent of the Higgs mass, and leads to

$$M_W[f] - M_W^{\text{exp}} = 0.21 \pm 0.17 \text{ GeV}, \quad (2.11)$$

which tells us that some non-fermionic contribution is necessary at  $1.2\sigma$  level.

It is of course too early to say from Eq.(2.11) that the bosonic effects were confirmed. Nevertheless, this is an interesting result since we could observe nothing before: Actually, the best information on  $m_t$  before the first CDF report (1994) was the bound  $m_t^{\text{exp}} > 131$  GeV by D0 [18], but we can thereby get only  $M_W[f] > 80.19 (\pm 0.03)$  GeV (*i.e.*,  $M_W[f] - M_W^{\text{exp}} > -0.04 \pm 0.18$  GeV). We will be allowed therefore to conclude that “the bosonic effects are starting to appear in the  $M_W$ - $M_Z$  relation”.

### 3. Indirect Higgs search

Here I wish to discuss what information on the Higgs we can get from precision LEP data. As a matter of fact, it is not that easy to draw its indirect information from existing experimental data since the Higgs mass  $m_\phi$  enters EW radiative corrections only logarithmically at one-loop level [19]. Therefore, at present, one can only hope to separate out the heavy Higgs-mass range (say  $m_\phi \sim 500$ -1000 GeV) from the low mass regime  $m_\phi \sim 100$  GeV as predicted, for instance, from supersymmetric theories. Such analyses are, however, still very important and indispensable for future experiments at, *e.g.*, LHC/NLC. For our analysis, we used in [3] the disaggregated data, just as presented by the experimental Collaborations, without taking any average of the various results. This type of analysis is interesting by itself to point out the indications of the various sets of data since even a single measurement, if sufficiently precise, can provide precious information. At the same time, since the LEP data are becoming so precise, before attempting any averaging procedure one should first analyze the various measurements with their errors and check that the distribution of the results fulfills the requirements of gaussian statistics. Without this preliminary analysis one may include uncontrolled systematic effects which can sizably affect the global averages<sup>3</sup>.

We first restricted to a fixed value of the top-quark mass  $m_t = 180$  GeV. As input data, we used the available, individual results  $\Gamma_Z$ ,  $\sigma_{\text{had}}$ ,  $R_\ell$ ,  $A_{\text{FB}}(\ell)$  and  $A_{e,\tau}$  from the four Collaborations as quoted in [10], where  $R_\ell \equiv \Gamma_{\text{had}}/\Gamma_\ell$  and  $A_\ell \equiv 2g_V^\ell g_A^\ell / \{(g_V^\ell)^2 + (g_A^\ell)^2\}$  ( $\ell = e, \mu, \tau$ , and  $g_{V,A}^\ell$  are the vector and axial-vector couplings of  $\ell$  to  $Z$ ). The theoretical computations

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<sup>3</sup> We did not consider the LR asymmetry by SLD [20] since it is already known that its present value demands a very heavy top (around 240 GeV) when the lower bound on  $m_\phi$  is taken into account, or conversely  $m_\phi$  must be much lower than this bound when  $m_t^{\text{exp}}$  is used within the standard EW theory (see, *e.g.*, Ellis et al. in [4]).

have been performed with the computer code TOPAZ0 [21], and the main results are given in Table I. There we do not see any specific indication on  $m_\phi$ , but a heavy Higgs seems to be a little bit favored by the total  $\chi^2$ .

TABLE I

Total  $\chi^2$  for the four Collaborations.

$\alpha_{\text{QCD}}(M_Z)$	0.113	0.125	0.127	0.130
$m_\phi(\text{GeV})$	100	100	500	1000
ALEPH	11.2	15.2	13.9	14.7
DELPHI	5.1	7.9	6.7	7.2
L3	11.6	6.0	8.0	9.2
OPAL	19.4	13.9	8.5	6.9
Total $\chi^2$	47.3	43.0	37.1	38.1

We, however, found some problems in the  $\tau$  forward-backward asymmetry as shown below. Let us consider the global averages

$$A_{\text{FB}}^{\text{exp}}(e) = 0.0154 \pm 0.0030, \tag{3.1}$$

$$A_{\text{FB}}^{\text{exp}}(\mu) = 0.0160 \pm 0.0017, \tag{3.2}$$

$$A_{\text{FB}}^{\text{exp}}(\tau) = 0.0209 \pm 0.0024, \tag{3.3}$$

and transform the averages for  $A_e$  and  $A_\tau$

$$A_e^{\text{exp}} = 0.137 \pm 0.009, \quad A_\tau^{\text{exp}} = 0.140 \pm 0.008 \tag{3.4}$$

into “effective” F-B asymmetries by using

$$A_{\text{FB}}^{\text{eff}}(e) = \frac{3}{4}(A_e^{\text{exp}})^2, \quad A_{\text{FB}}^{\text{eff}}(\tau) = \frac{3}{4}A_e^{\text{exp}}A_\tau^{\text{exp}}, \tag{3.5}$$

which hold in the electroweak theory. We find

$$A_{\text{FB}}^{\text{eff}}(e) = 0.0141 \pm 0.0019, \quad A_{\text{FB}}^{\text{eff}}(\tau) = 0.0144 \pm 0.0018 \tag{3.6}$$

in very good agreement with Eqs.(3.1) and (3.2) but not with Eq.(3.3). Therefore, there might be some problem in the direct measurement of  $A_{\text{FB}}(\tau)$  since all other measurements are in excellent agreement with each other.

Just to have an idea of the effect, we computed the  $\chi^2$  without  $A_{\text{FB}}^{\text{exp}}(\tau)$ . The results are illustrated in Table II, which should be compared with Table I. We find that the tendency toward a heavy Higgs becomes stronger

and the best values of the  $\chi^2$  are obtained for a large value of  $m_\phi$ , just as in the case of the  $W$  mass mentioned in Sec. 1. It is still not easy to get a definite conclusion from this, but the “bulk” of the LEP data, namely those well consistent with each other, show no preference for a light Higgs boson, to say the least of it.

TABLE II

Total  $\chi^2$  for the four Collaborations by excluding the data for  $A_{\text{FB}}^{\text{exp}}(\tau)$ .

$\alpha_{\text{QCD}}(M_Z)$	0.113	0.125	0.127	0.130
$m_\phi(\text{GeV})$	100	100	500	1000
ALEPH	10.2	14.3	12.1	12.5
DELPHI	4.7	7.5	5.9	6.2
L3	8.4	2.8	3.9	4.8
OPAL	19.4	13.8	8.0	6.1
Total $\chi^2$	42.7	38.4	29.9	29.6

Finally, to see the  $m_t$ -dependence of  $\chi^2$ , I show in Tables III and IV the total  $\chi^2$  for  $m_t=170, 180$  and  $190$  GeV including all data or excluding  $A_{\text{FB}}^{\text{exp}}(\tau)$ . By increasing (decreasing) the top-quark mass, a larger (smaller) value of  $m_\phi$  is favored and the shape of the  $\chi^2$  is well consistent with all values of the Higgs mass. For a heavier top  $m_t \gtrsim 180$  GeV, however, Tables 3 and 4 give rather different information and it becomes crucial to include the problematic data for  $A_{\text{FB}}^{\text{exp}}(\tau)$  to accommodate  $m_\phi \sim 100$  GeV.

TABLE III

Total  $\chi^2$  for the four Collaborations at various values of  $m_t$ .

## ALEPH+DELPHI+L3+OPAL

$\alpha_{\text{QCD}}(M_Z)$	0.113	0.125	0.127	0.130
$m_\phi(\text{GeV})$	100	100	500	1000
$m_t(\text{GeV})= 170$	46.3	38.4	38.3	41.2
$= 180$	47.3	43.0	37.1	38.1
$= 190$	51.8	50.4	38.9	37.5

TABLE IV

Total  $\chi^2$  for the four Collaborations at various values of  $m_t$  by excluding the data for  $A_{\text{FB}}^{\text{exp}}(\tau)$ .

ALEPH+DELPHI+L3+OPAL

$\alpha_{\text{QCD}}(M_Z)$	0.113	0.125	0.127	0.130
$m_\phi(\text{GeV})$	100	100	500	1000
$m_t(\text{GeV})=170$	40.7	32.8	29.7	31.2
$=180$	42.7	38.4	29.9	29.6
$=190$	50.1	46.6	32.9	30.3

We have no mind to claim that Tables II and IV represent a more faithful representation of the real physical situation than Tables I and III. Most likely, our results suggest only that further improvement in the data taking is necessary for a definitive answer. We may, however, conclude thereby that it is not a good idea to focus on a light-mass region in Higgs searches at future experiments.

#### 4. Summary and discussions

Let us briefly summarize and discuss what I have talked. In Section 2, I have shown that we can now test not only (1) the whole EW corrections but also their various parts separately: (2) the light-fermion leading-log corrections which lead to the improved-Born approximation, (3) the non-decoupling  $m_t$  corrections and (4) the bosonic corrections. Studying corrections (1) is a test of the theory as a renormalizable field theory, while (2)–(4) are more detailed tests.

The improved-Born approximation succeeded to a certain extent, which is related to the fact that the EW theory unifies the weak interaction (with  $q^2 \simeq M_W^2$  scale) and the electromagnetic interactions (with  $q^2 \simeq 0$  scale). We, however, have seen that some non-Born corrections are now starting to appear. Next we observed that the non-decoupling  $m_t$  corrections are also required, which is a test as a theory with spontaneous symmetry breakdown plus large Yukawa couplings. Similar way we also tested the bosonic corrections and found some small indication for them.

Based on this excellent success, we are able to explore the remaining unknown area, *i.e.*, the Higgs sector, which I discussed in Section 3. Concerning such a Higgs search, there are already a lot of papers. Unfortunately, the  $m_\phi$ -dependence of one-loop quantities are only logarithmic in the minimal scheme and therefore it is not easy to get any strong restriction on



the Higgs mass, but we have so far obtained some quantitative information. Such information is of course extremely important for future experimental projects like LHC/NLC. Several papers pointed out that the Higgs will be rather light, say less than about 300 GeV [4]. We have found, however, there is also an indication for a rather heavy Higgs through our analysis of LEP and  $W$ -mass data.

Due to the reason mentioned above, our results cannot be strong either, but at least we can say it is risky to concentrate our attention on a light-mass region in Higgs searches at future experiments, though I am not a fan of a heavy Higgs boson. More precise measurements of the top-quark and  $W$ -boson masses are considerably significant for studying this problem (and also for searching any new-physics effects), and I wish to expect that the Tevatron and LEP II will give us a good answer for it in the very near future.

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