Structure of Electroweak Radiative Corrections

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ABSTRACT

Looking into the inside of radiative corrections is an interesting subject as a deeper study of the standard electroweak theory after its remarkable success in the precision analyses. I will discuss here a test of “structure” of the EW radiative corrections to the weak-boson masses, and show that we can now analyze several different parts separately.

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§1. Introduction

The standard electroweak theory has been excellently successful in describing a lot of low- and high-energy precision data, by taking into account radiative corrections (see [1, 2] and references cited therein). This means that the theory has been well tested as a renormalizable field theory. Looking into the inside of the EW radiative corrections is an interesting theme as one of its next-step studies. At this School, I would like to discuss “structure” of the EW corrections to the $W$ and $Z$ masses based on my recent work [3].

There is no room for an objection on using $M_Z^{\text{exp}} (= 91.1884 \pm 0.0022 \text{ GeV})$ [4], while the reason why I focus on the $W$ mass among others is as follows: First of all, the weak-boson mass relation derived from the radiative corrections to $G_F$ (the $M_W-M_Z$ relation) has the advantage of being freest from gluon effects. In addition, all the other high-energy precision data are those on $Z$ boson or those at $\sqrt{s} \simeq M_Z$, and their accuracy is now reaching the highest level, while $M_W$, which is already known with a good precision, will be determined much more precisely at LEP II. For comparison, the present $Z$ width is $\Gamma_Z^{\text{exp}} = 2.4963 \pm 0.0032 \text{ GeV}$ [4], i.e., $\pm 0.13 \%$ precision. On the other hand, $M_W^{\text{exp}}$ by UA2+CDF+D0 is $80.26 \pm 0.16 \text{ GeV} (\pm 0.20 \% \text{ precision})$ [4], i.e., already comparable to $\Gamma_Z^{\text{exp}}$, and its precision reaches $\pm 0.06 \%$ once $\Delta M_W^{\text{exp}} = \pm 50 \text{ MeV}$ is realized at LEP II [4]. Therefore, we can expect very clean and precise tests through the $M_{W,Z}$ measurements.

I wish to proceed as follows: First of all, I will explain what I mean by “structure of …” and what we should do in order to test it in section 2. Then, a brief review of the EW corrections to the weak-boson masses is given in § 3. In § 4, fermionic corrections are studied. What I study there are the (QED-)improved-Born approximation and the non-decoupling top-quark effects. Testing the latter one is particularly important 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. In §5, on the other hand, I will study other-type corrections from $W, Z$ and the Higgs, i.e., bosonic contributions. Since the top quark was found to be very heavy [7], we have a good chance to detect the bosonic contribution. This is because the fermionic leading-log terms and the non-decoupling top-quark terms work to cancel each other, and consequently the role of the non-fermionic corrections becomes relatively more significant. The final section is for a summary and brief discussions.

§2. What “Structure · · ·” Means

EW radiative corrections to physical quantities consist of several parts with different properties. For example, one-loop corrections to the muon-decay amplitude are usually expressed as $\Delta r$, and can be written as follows:

$$\Delta r = \Delta \alpha + \Delta r[m_t] + \Delta r[m_{\phi}] + \Delta r[\alpha].$$

(2.1)

Here $\Delta \alpha$ is the leading-log terms from the light charged fermions

$$\Delta \alpha = -\frac{2\alpha}{3\pi} \sum_{f(\neq t)} \left\{ Q_f^2 \ln \left( \frac{m_f}{M_Z} \right) + \frac{5}{6} \right\},$$

(2.2)

$\Delta r[m_t]$ and $\Delta r[m_{\phi}]$ express the non-decoupling top-quark and Higgs-boson effects respectively

$$\Delta r[m_t] = -\frac{\alpha}{16\pi s_W^2} \left\{ \frac{3}{s_W^2 M_Z^2} m_t^2 + 4 \left( \frac{c_W^2}{s_W^2} - \frac{1}{3} - \frac{3m_b^2}{s_W^2 M_Z^2} \right) \ln \left( \frac{m_t}{M_Z} \right) \right\},$$

(2.3)

$$\Delta r[m_{\phi}] = \frac{11\alpha}{24\pi s_W^2} \ln \left( \frac{m_{\phi}}{M_Z} \right),$$

(2.4)

where $c_W \equiv M_W/M_Z$ and $s_W^2 = 1 - c_W^2$, and $\Delta r[\alpha]$ is the remaining $O(\alpha)$ non-leading terms.

What I have so far studied is to see by using experimental data if each of them must exist or not. I am afraid, however, this statement will not be enough clear. From a purely theoretical point of view, it may seem to be stupid to
ask, e.g., if the data need the bosonic effects. Everyone knows that $W^\pm$ and $Z$ exist, and since we are studying in the framework of renormalizable field theories, their loop effects must of course exist. Then, how about the Higgs contribution? This may also sound a meaningless question. If it would not exist, the theory becomes non-renormalizable, and the precision analyses performed so far must face immediately a quite serious difficulty. More generally, it is easy in many cases to judge pure-theoretically if some terms under consideration are necessary or not. That is, removing the corresponding terms would break some symmetries and/or renormalizability. In this sense, we can say that they must exist.

From a phenomenological point of view, however, it is totally a different story. As an example, let us consider the meaning of testing the triple gauge-boson couplings. Also in this case, it will not be meaningful pure-theoretically, since if the size of the coupling differs from the one predicted by the gauge principle, the theory becomes again non-renormalizable. In other words, the success of the electroweak theory in precision analyses means that all the couplings are already known. Nevertheless, testing these couplings is a very significant phenomenological analysis. We need to observe them directly in order for the theory to be established. Testing the neutral current structure has also a quite similar significance. These show the reason why I believe studying the structure of the EW corrections are indispensable.

Finally, let me summarize what we have to do in actual analyses. Suppose we are trying to test in a theory the existence of some effects phenomenologically. Then, we have to show that the following two conditions are simultaneously satisfied:

- The theory cannot reproduce the data without the terms under consideration, no matter how we vary the remaining free parameters.

- The theory can be consistent with the data by adjusting the free parameters appropriately (i.e., within experimentally- and theoretically-allowed range),
once the corresponding terms are taken into account.

Needless to say, we have to have data and theoretical calculations precise enough to distinguish these two clearly. In those analyses it is safer to be conservative: That is, when we check the first criterion, the less we rely on data, the more certain the result is. On the contrary, for checking the second criterion, it is most trustworthy if we can get a definite conclusion after taking into account all the existing data, preliminary or not.

§3. Corrections to the Weak-Boson Masses

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

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

The explicit expression of Eq.(3.1) at one-loop level with resummation of the leading-log terms is

$$M_W = \frac{1}{\sqrt{2}} M_Z \left[ 1 + \sqrt{1 - \frac{2\sqrt{2} \alpha}{M_Z^2 G_F(1 - \Delta r)}} \right]^{1/2}.$$ (3.2)

When we apply the first criterion mentioned in the previous section to the fermionic corrections, this formula is enough precise. However, over the past several years, some corrections beyond the one-loop approximation have been computed to it. They are two-loop top-quark corrections and QCD corrections up to $O(\alpha^2 QCD)$ for $\Delta r[m_t]$, and $O(\alpha QCD)$ corrections for the non-leading terms \[8, 9\] (see \[10\] as reviews). As a result, we have now a formula including $O(\alpha \alpha^2 QCD m_t^2)$ and $O(\alpha^2 m_t^4)$ effects:

$$M_W = \sqrt{\frac{\rho}{2}} M_Z \left[ 1 + \sqrt{1 - \frac{2\sqrt{2} \alpha(M_Z)}{\rho M_Z^2 G_F(1 - \Delta r_{rem})}} \right]^{1/2},$$ (3.3)

$$\rho = 1/(1 - 3\sqrt{2} G_F m_t^2/16\pi^2 + \Delta),$$

$$\Delta r_{rem} = (\Delta r - \Delta \alpha + 3\sqrt{2} G_F c_W^2 m_t^2/16\pi^2 s_W^2 + \Delta').$$
where $\Delta$ and $\Delta'$ are the above mentioned higher-loop terms.

If $\Delta r_{\text{rem}}$, the non-leading corrections, were to be zero, Eq. (3.3) would be unambiguous within the present approximation. However, it is indeed not negligible. Concerning how to handle it, there are several possible ways. I compute $M_W$ these several ways and use the average of the results as the central value, while the difference among them is taken into account as part of the theoretical error. This problem is discussed in detail in [11]. Anyway I use Eq. (3.1) in the following to express both Eqs. (3.2) and (3.3) for simplicity.

Let us see here what we can say about the whole radiative corrections as a simple example of applications of the $M_W$-$M_Z$ relation and the two criterions given in §2. Through Eq. (3.1), we have

$$M_W^{(0)} = 80.9400 \pm 0.0027 \text{ GeV} \quad \text{and} \quad M_W = 80.36 \pm 0.09 \text{ GeV} \quad (3.4)$$

where $M_W^{(0)} \equiv M_W(\alpha, G_F, M_Z, \Delta r = 0)$ and $M_W$ is for $m_t^{\text{exp}} = 180 \pm 12 \text{ GeV}$ [7], $m_\phi = 300 \text{ GeV}$ and $\alpha_{\text{QCD}}(M_Z) = 0.118$. Concerning the uncertainty of $M_W$, 0.09 GeV, I have a little overestimated for safety.

As is easily found from Eq. (3.2), $M_W^{(0)}$ depends only on $\alpha$, $G_F$ and $M_Z$. So, we conclude from $M_W^{(0)} - M_W^{\text{exp}} = 0.68 \pm 0.16 \text{ GeV}$ and $M_W - M_W^{\text{exp}} = 0.10 \pm 0.18 \text{ GeV}$ that

- $M_W^{(0)}$ is in disagreement with $M_W^{\text{exp}}$ at about 4.3$\sigma$ (99.998 % C.L.),
- $M_W$ is consistent with the data for, e.g., $m_\phi = 300 \text{ GeV}$, which is allowed by the present data $m_\phi > 65.1 \text{ GeV}$ [12].

That is, the two criterions are both clearly satisfied, by which the existence of radiative corrections is confirmed. Radiative corrections were established at 3$\sigma$ level already in the analyses in [13], but where one had to fully use all the available low- and high-energy data. We can now achieve a much higher accuracy via the weak-boson masses alone. Analyses in the following sections are performed in
the same way as this, so I do not repeat the explanation on the second criterion below since it is common to all analyses.

§4. Fermionic Corrections

It is known that all the precision data up to 1993 are reproduced at 1σ level by using $\alpha(M_Z) (= \alpha/(1 - \Delta \alpha))$ instead of $\alpha$ in tree quantities [13], where $\alpha(M_Z)$ is known to be $1/(128.92 \pm 0.12)$.\footnote{Recently three papers appeared in which $\alpha(M_Z)$ is re-evaluated from the data of the total cross section of $e^+e^- \rightarrow \gamma^* \rightarrow \text{hadrons}$ [15] (the latest results are given in [16]). Here I simply took the average of the maximum and minimum among them.} I examine first whether this (QED-)Improved-Born approximation still works or not.

The $W$ mass is calculated within this approximation as

$$M_W[\text{Born}] (\equiv M_W(\alpha(M_Z), G_F, M_Z, 0)) = 79.963 \pm 0.017 \text{ GeV}, \quad (4.1)$$

which leads to

$$M_W^{\text{exp}} - M_W[\text{Born}] = 0.30 \pm 0.16 \text{ GeV}. \quad (4.2)$$

This means that $M_W[\text{Born}]$ is in disagreement with the data now at 1.9σ, which corresponds to about 94.3 % C.L.. Although the precision is not yet sufficiently high\footnote{The effective mixing angle in the $\bar{\ell}\ell Z$ vertex, $\sin^2 \theta^{\ell\ell\ell}_{\ell\ell\ell}$, is also a (almost) gluon-free quantity. Within this approximation, $\sin^2 \theta^{\ell\ell\ell}_{\ell\ell\ell}[\text{Born}]$ is given by $1 - (M_W[\text{Born}]/M_Z)^2 = 0.23105 \pm 0.00033$. So, when $\sin^2 \theta^{\ell\ell\ell}_{\ell\ell\ell} = 0.23186 \pm 0.00034$ by LEP [4] is taken into account, we will have a higher precision. In fact, the total $\chi^2$ becomes 6.58, which means that non-Born effects are required at 96.3 % C.L.. However, when the SLD data via the LR-asymmetry are incorporated, the average becomes $\sin^2 \theta^{\ell\ell\ell}_{\ell\ell\ell} = 0.23143 \pm 0.00028$, and we can no longer get a better precision. This is why I did not use this quantity in my analysis.} 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 [14].

Next, I study the non-decoupling top-quark contribution. According to my strategy, I computed the $W$ mass by using the following $\Delta r'$ instead of $\Delta r$ in
\[ \Delta r' \equiv \Delta r - \Delta r[m_t]. \]

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 unless \( m_t \) is extremely large. \( \Delta r' \) still includes \( m_t \) dependent terms, but no longer diverges for \( m_t \to +\infty \) thanks to this subtraction. I found that \( M'_W \) takes the maximum value for the largest \( m_t \) and the smallest \( m_\phi \) (as long as the perturbation theory is applicable\(^\text{♯3} \)). That is, we get an inequality

\[ M'_W \leq M'_W [m_{\text{max}}^t, m_{\text{min}}^\phi]. \]

We can use \( m_t^{\text{exp}} = 180 \pm 12 \text{ GeV} \) \[^6\] and \( m_\phi^{\text{exp}} > 65.1 \text{ GeV} \) \[^12\] in the right-hand side of the above inequality, i.e., \( m_{\text{max}}^t = 180 + 12 \text{ GeV} \) and \( m_{\text{min}}^\phi = 65.1 \text{ GeV} \), but I first take \( m_{\text{max}}^t \to +\infty \) and \( m_{\text{min}}^\phi = 0 \) 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

\[ M'_W < 79.950(\pm0.030) \text{ GeV and } M^{\text{exp}}_W - M'_W > 0.31 \pm 0.16 \text{ GeV}, \]

which show that \( M'_W \) is in disagreement with \( M^{\text{exp}}_W \) at about 1.9\( \sigma \). This means that 1) the electroweak theory is not able to be consistent with \( M^{\text{exp}}_W \) \textit{whatever values} \( m_t \) \textit{and} \( m_\phi \) \textit{take if} \( \Delta r[m_t] \) \textit{does 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 the existence of the non-decoupling top-quark corrections. This shows that we could know something about the existence of the top even if we would know nothing about \( m_t \) and \( m_\phi \). Of course, it never means that the present information on them is not useful: The confidence level of this result becomes

\[^{23}\text{We do not know what will happen for, e.g., } m_\phi = 10 \text{ TeV.}\]
higher if we use $m_t^{\text{max}} = 180 + 12 \text{ GeV}$ and $m^{\phi}_{\text{min}} = 65.1 \text{ GeV}$:

$$M'_W < 79.863(\pm 0.030) \text{ GeV} \quad \text{and} \quad M^{\text{exp}}_W - M'_W > 0.40 \pm 0.16 \text{ GeV}, \quad (4.6)$$

that is, $2.5\sigma$ level.

§5. Corrections Including Bosonic Effects

I wish to examine in this section non-fermionic contributions to $\Delta r$ (i.e., the Higgs and gauge-boson contributions). It has been pointed out in [18] by using various high-energy data that such bosonic electroweak corrections are now inevitable. I study here whether we can observe a similar evidence in the $M_W-M_Z$ relation.

For this purpose, we have to compute $M_W$ taking account of only the pure-fermionic corrections $\Delta r[f]$. 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 $m_t^{\text{exp}}$ from the beginning in this case. I express thus-computed $W$-mass as $M_W[f]$. The result became

$$M_W[f] = 80.48 \pm 0.09 \text{ GeV}. \quad (5.1)$$

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

$$M_W[f] - M^{\text{exp}}_W = 0.22 \pm 0.18 \text{ GeV}, \quad (5.2)$$

which tells us that some non-fermionic contribution is necessary at $1.2\sigma$ level. It is of course too early to say from this result 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 $m_t^{\text{exp}} > 131 \text{ GeV}$ by D0 [19], but we can thereby get only $M_W[f] > 80.19 (\pm 0.03) \text{ GeV}$ while $M^{\text{exp}}[94]$ was $80.23 \pm 0.18 \text{ GeV}$ (i.e., $M_W[f] - M^{\text{exp}}_W > -0.04 \pm 0.18 \text{ GeV}$).

For comparison, let us make the same computation for $\Delta M^{\text{exp}}_W = \pm 0.05 \text{ GeV}$ and $\Delta m_t^{\text{exp}} = \pm 5 \text{ GeV}$, which will be eventually realized in the future at Tevatron
and LEP II. Concretely, $\Delta m_t^{\text{exp}} = \pm 5$ GeV produces an error of $\pm 0.03$ GeV in the $W$-mass calculation. Combining this with the theoretical ambiguity $\Delta M_W = \pm 0.03$ GeV, we can compute $M_W[\ldots] - M_W^{\text{exp}}$ with an error of about $\pm 0.07$ GeV. Then, $M_W[\ell] - M_W^{\text{exp}}$ becomes $0.22 \pm 0.07$ GeV if the central value of $M_W^{\text{exp}}$ is the same, by which we can confirm the above statement at $3\sigma$ level.

It must be very interesting if we can find moreover the existence of the non-decoupling Higgs effects since we still have no phenomenological indication for the Higgs boson. Then, can we in fact perform such a test? It depends on how heavy the Higgs is: If it is much heavier than the weak bosons, then we may be able to test it. If not, however, that test will lose its meaning essentially, since $\Delta r[m_\phi]$ comes from the expansion of terms like $\int_0^1 dx \ln\left\{m_\phi^2(1-x) + M_Z^2 x - M_Z^2 x(1-x)\right\}$ in powers of $M_Z/m_\phi$. Here, let us simply assume as an example that we have gained in some way (e.g., at LHC) a bound $m_\phi > 500$ GeV. At the same time, I assume $\Delta M_W^{\text{exp}} = \pm 0.05$ GeV and $\Delta m_t^{\text{exp}} = \pm 5$ GeV, since $M_W$ and $m_t$ will have been measured at least at this precision by the time we get a bound like $m_\phi > 500$ GeV. Then, for $\Delta r'' \equiv \Delta r - \Delta r[m_\phi]$, the $W$ mass (written as $M_W''$) satisfies $M_W'' > 80.46 \pm 0.04$ GeV, where the non-decoupling $m_\phi$ terms in the two-loop top-quark corrections were also eliminated. This inequality leads us to $M_W'' - M_W^{\text{exp}} > 0.20 \pm 0.07$ GeV.

It seems therefore that we may have a chance to get an indirect evidence of the Higgs boson even if future accelerators fail to discover it.

\section{Summary and Discussions}

A lot of experimental and theoretical effort has so far been made to analyze the electroweak theory, and now we know that including the radiative corrections is indispensable in these analyses. Based on this success, I have carried out a further study of the theory and its radiative corrections \[3\], and reported here its main results: They are analyses on (1) pure-fermionic and (2) bosonic corrections in the weak-boson mass relation.
On the former part, I tested the improved-Born approximation and the non-decoupling top corrections. There we could conclude that non-Born type corrections and non-decoupling $m_t$ contribution are required respectively at about 1.9σ and 2.5σ level by the recent data on $M_{W,Z}$. This is a clean, though not yet perfect, test of those corrections which has the least dependence on hadronic contributions.

Concerning the latter part, we could observe a small indication for non-fermionic contributions (at 1.2σ level), which can be interpreted as the bosonic ($W/Z$ and the Higgs) corrections. Furthermore, it seemed to be possible to test the non-decoupling Higgs effects if the Higgs boson is heavy (e.g., $\gtrsim$ 500 GeV). These results (except for the last one) are visually represented in the Figure.

**Figure**

On the bosonic corrections, however, supplementary discussions are necessary. That is, the corresponding result is still somewhat “unstable”. I used in section 5 the present world average $M_{W}^{\text{exp}} = 80.26 \pm 0.16$ GeV, but if the preliminary D0 data $M_{W}^{\text{exp}[D0]} = 79.86 \pm 0.40$ GeV and the early-stage CDF data $M_{W}^{\text{exp}[\text{CDF}(90)]} = 79.91 \pm 0.39$ GeV are not incorporated, the average becomes $M_{W}^{\text{exp}} = 80.40 \pm 0.16$ GeV (CDF[92/93]+UA2). This value might be more reliable, and in this case

$$M_{W}[f] - M_{W}^{\text{exp}} = 0.08 \pm 0.18 \text{ GeV},$$

by which the bosonic effects become again totally unclear. On the contrary, our conclusion on the fermionic corrections becomes thereby much stronger: the non-Born effects and the non-decoupling $m_t$ effects are required respectively at 2.8σ (99.5 % C.L.) and 3.4σ (99.9 % C.L.).

More precise measurements of the top-quark and $W$-boson masses are therefore considerably significant for studying this issue, 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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Figure

Deviations of $W$ masses calculated in various approximations from $M_W^{\text{exp}} = 80.26 \pm 0.16$ GeV. $M'_W[a]$ is for $m_t^{\text{max}} = +\infty$ and $m_\phi^{\text{min}} = 0$ GeV, and $M'_W[b]$ is for $m_t^{\text{max}} = 192$ GeV and $m_\phi^{\text{min}} = 65.1$ GeV. The last $M_W$ (the one with the full corrections) is for $m_\phi = 300$ GeV. Only $M_W - M_W^{\text{exp}}$ crosses the “happy” line.