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STRUCTURE OF ELECTROWEAK RADIATIVE CORRECTIONS*

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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 $M_Z^{exp}(= 91.1884 \pm 0.0022$ 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

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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 $\Gamma_Z^{\rm exp} = 2.4963 \pm 0.0032$ GeV [4], *i.e.*, ± 0.13 % precision. On the other hand, $M_W^{\rm exp}$ by UA2+CDF+D0 is 80.26 ± 0.16 GeV (± 0.20 % precision) [5], *i.e.*, already comparable to $\Gamma_Z^{\rm exp}$, and its precision reaches ± 0.06 % once $\Delta M_W^{\rm exp} = \pm 50$ MeV is realized at LEP II [6]. 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 $\cdots$" 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 Section 3. In Section 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 Section 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 $\cdots$" 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 Δr, and can be written as follows:

$$\Delta r = \Delta\alpha + \Delta r[m_t] + \Delta r[m_\phi] + \Delta r[\alpha] \,. \tag{2.1}$$

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

$$\Delta\alpha = -\frac{2\alpha}{3\pi} \sum_{f(\neq t)} \left\{ Q_f^2 \ln\left(\frac{m_f}{M_Z}\right) + \frac{5}{6} \right\}, \tag{2.2}$$

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

$$\Delta r[m_t] = -\frac{\alpha}{16\pi s_W^2} \left\{ \frac{3}{s_W^2 M_Z^2} m_t^2 + 4\left(\frac{c_W^2}{s_W^2} - \frac{1}{3} - \frac{3m_b^2}{s_W^2 M_Z^2} \right) \ln\left(\frac{m_t}{M_Z}\right) \right\}, \tag{2.3}$$

$$\Delta r[m_\phi] = \frac{11\alpha}{24\pi s_W^2} \ln\left(\frac{m_\phi}{M_Z}\right), \tag{2.4}$$

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

$$M_W = M_W(\alpha, G_F, M_Z, \Delta r)\,. \tag{3.1}$$

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

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

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 $O(\alpha_{\rm QCD}^2)$ for $\Delta r[m_t]$, and $O(\alpha_{\rm QCD})$ corrections for the non-leading terms [8, 9] (see [10] as reviews). As a result, we have now a formula including $O(\alpha\alpha_{\rm QCD}^2 m_t^2)$ and $O(\alpha^2 m_t^4)$ effects:

$$\begin{aligned} M_W &= \sqrt{\frac{\rho}{2}} M_Z \left\{ 1 + \sqrt{1 - \frac{2\sqrt{2}\pi\alpha(M_Z)}{\rho M_Z^2 G_F (1-\Delta r_{\bf rem})}} \right\}^{1/2}, \\ \rho &= 1/(1 - 3\sqrt{2}G_F m_t^2/16\pi^2 + \Delta)\,, \\ \Delta r_{\bf rem} &= (\Delta r - \Delta\alpha + 3\sqrt{2}G_F c_W^2 m_t^2/16\pi^2 s_W^2 + \Delta')\,, \end{aligned} \tag{3.3}$$

where Δ and Δ' are the above mentioned higher-loop terms.

If $\Delta r_{\bf rem}$, 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 Section 2. Through Eq. (3.1), we have

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

where $M_W^{(0)} \equiv M_W(\alpha, G_F, M_Z, \Delta r = 0)$ and M_W is for $m_t^{\rm exp} = 180 \pm 12$ GeV [7], $m_\phi = 300$ GeV and $\alpha_{\rm QCD}(M_Z)$=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 α, G_F and M_Z. So, we conclude from $M_W^{(0)} - M_W^{\rm exp} = 0.68 \pm 0.16$ GeV and $M_W - M_W^{\rm exp} = 0.10 \pm 0.18$ GeV that

- $M_W^{(0)}$ is in disagreement with $M_W^{\rm exp}$ at about 4.3σ (99.998 % C.L.),
- M_W is consistent with the data for, *e.g.*, $m_\phi = 300$ GeV, which is allowed by the present data $m_\phi > 65.1$ 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 3σ 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 α in tree quantities [14], where $\alpha(M_Z)$ is known to be $1/(128.92 \pm 0.12)$[1]. I examine first whether this (QED-)Improved-Born approximation still works or not.

The W mass is calculated within this approximation as

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

which leads to

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

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[1] Recently three papers appeared in which $\alpha(M_Z)$ is re-evaluated from the data of the total cross section of $e^+e^- \to \gamma^* \to$ *hadrons* [15] (the latest results are given in [16]). Here I simply took the average of the maximum and minimum among them.

This means that M_W[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[2],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 [17].

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 Δr in Eq. (3.1):

$$\Delta r' \equiv \Delta r - \Delta r[m_t]\,. \tag{4.3}$$

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_ϕ (as long as the perturbation theory is applicable[3]). That is, we get an inequality

$$M'_W \;\leq\; M'_W[m_t^{\mathbf{max}}, m_\phi^{\mathbf{min}}]\,. \tag{4.4}$$

We can use $m_t^{\mathbf{exp}} = 180 \pm 12$ GeV [7] and $m_\phi^{\mathbf{exp}} > 65.1$ GeV [12] in the right-hand side of the above inequality, *i.e.*, $m_t^{\mathbf{max}} = 180 + 12$ GeV and $m_\phi^{\mathbf{min}} = 65.1$ GeV, but I first take $m_t^{\mathbf{max}} \to +\infty$ and $m_\phi^{\mathbf{min}} = 0$ 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

$$M'_W < 79.950(\pm 0.030)\ \text{GeV} \quad \text{and} \quad M_W^{\mathbf{exp}} - M'_W > 0.31 \pm 0.16\ \text{GeV}\,, \tag{4.5}$$

which show that M'_W is in disagreement with $M_W^{\mathbf{exp}}$ at about 1.9σ. This means that 1) the electroweak theory is not able to be consistent with $M_W^{\mathbf{exp}}$

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[2] The effective mixing angle in the $\bar{\ell}\ell Z$ vertex, $\sin^2\theta_\ell^{\rm eff}$, is also a (almost) gluon-free quantity. Within this approximation, $\sin^2\theta_\ell^{\rm eff}$[Born] is given by $1 - (M_W[\text{Born}]/M_Z)^2 = 0.23105 \pm 0.00033$. So, when $\sin^2\theta_\ell^{\rm eff} = 0.23186 \pm 0.00034$ by LEP [4] is taken into account, we will have a higher precision. In fact, the total χ^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 $\sin^2\theta_\ell^{\rm eff} = 0.23143 \pm 0.00028$, and we can no longer get a better precision. This is why I did not use this quantity in my analysis.

[3] We do not know what will happen for, *e.g.*, $m_\phi = 10$ TeV.

whatever values m_t *and* m_ϕ *take* if $\Delta r[m_t]$ does not exist, and 2) the theory with $\Delta r[m_t]$ works well, as shown before, for experimentally-allowed m_t and m_ϕ.

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_ϕ. Of course, it never means that the present information on them is not useful: The confidence level of this result becomes higher if we use $m_t^{\mathbf{max}} = 180+12$ GeV and $m_\phi^{\mathbf{min}} = 65.1$ GeV:

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

that is, 2.5σ level.

5. Corrections including bosonic effects

I wish to examine in this section non-fermionic contributions to Δr (*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 $m_t^{\mathbf{exp}}$ from the beginning in this case. I express thus-computed W-mass as $M_W[\mathrm{f}]$. The result became

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

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

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

which tells us that some non-fermionic contribution is necessary at 1.2σ 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 $m_t^{\mathbf{exp}} > 131$ GeV by D0 [19], but we can thereby get only $M_W[\mathrm{f}] > 80.19$ (± 0.03) GeV while $M_W^{\mathbf{exp}}[94]$ was 80.23 ± 0.18 GeV (*i.e.*, $M_W[\mathrm{f}] - M_W^{\mathbf{exp}} > -0.04 \pm 0.18$ GeV).

For comparison, let us make the same computation for $\Delta M_W^{\mathbf{exp}} = \pm 0.05$ GeV and $\Delta m_t^{\mathbf{exp}} = \pm 5$ GeV, which will be eventually realized in the future at Tevatron and LEP II. Concretely, $\Delta m_t^{\mathbf{exp}} = \pm 5$ GeV produces an error of ± 0.03 GeV in the W-mass calculation. Combining this with the theoretical ambiguity $\Delta M_W = \pm 0.03$ GeV, we can compute $M_W[\cdots] - M_W^{\mathbf{exp}}$ with an error of about ± 0.07 GeV. Then, $M_W[\mathrm{f}] - M_W^{\mathbf{exp}}$ becomes 0.22 ± 0.07 GeV if the central value of $M_W^{\mathbf{exp}}$ is the same, by which we can confirm the above statement at 3σ 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 $\int_0^1 dx \ln\{m_\phi^2(1-x) + M_Z^2 x - M_Z^2 x(1-x)\}$ in powers of M_Z/m_ϕ. 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 $\Delta M_W^{\mathbf{exp}} = \pm 0.05$ GeV and $\Delta m_t^{\mathbf{exp}} = \pm 5$ 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_ϕ terms in the two-loop top-quark corrections were also eliminated. This inequality leads us to $M_W'' - M_W^{\mathbf{exp}} > 0.20 \pm 0.07$ GeV.

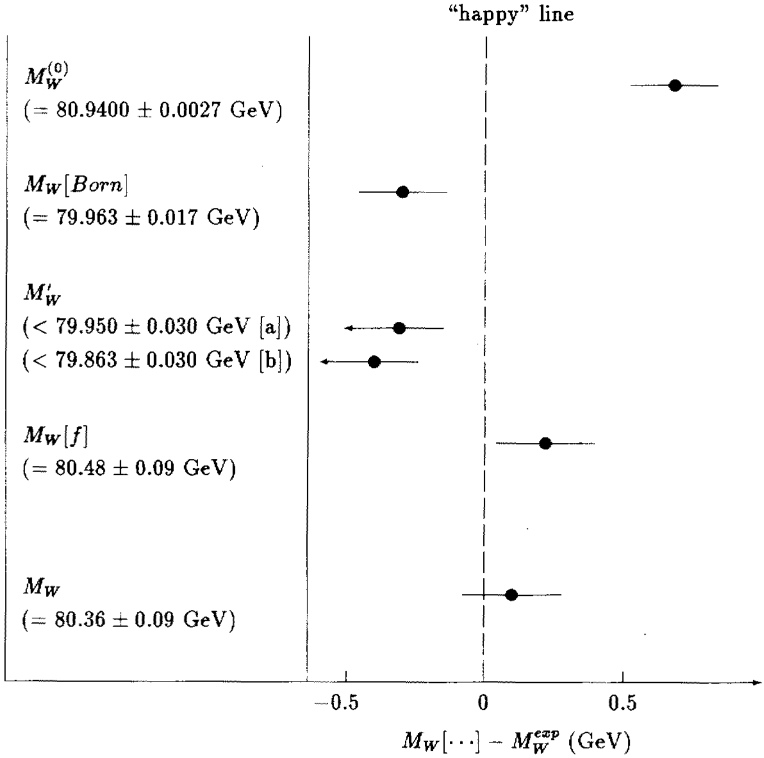
It seems therefore that we may have a chance to get an indirect evidence of the Higgs boson even if future accelerators fail to discover it.

6. 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.



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

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 $M_W^{\bf exp} = 80.26 \pm 0.16$ GeV, but if the preliminary D0 data $M_W^{\bf exp}[{\rm D0}] = 79.86 \pm 0.40$ GeV and the early-stage CDF data $M_W^{\bf exp}[{\rm CDF(90)}] = 79.91 \pm 0.39$ GeV are not incorporated, the average becomes $M_W^{\bf exp} = 80.40 \pm 0.16$ GeV (CDF[92/93]+UA2). This value might be more reliable, and in this case

$$M_W[{\rm f}] - M_W^{\bf exp} = 0.08 \pm 0.18 \text{ GeV}\,, \tag{6.1}$$

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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REFERENCES

[1] J. Ellis, G.L. Fogli, E. Lisi, Preprint CERN-TH/95-202 – BARI-TH/211-95 (hep-ph/9507424); P.H. Chankowski, S. Pokorski, Preprint MPI-Ph/95-39 – IFT-95/6 (hep-ph/9505308); G. Montagna, O. Nicrosini, G. Passarino, F. Piccinini, *Phys. Lett.* **B335**, 484 (1994); S. Matsumoto, Preprint KEK-TH-418 (hep-ph/9411388); K. Kang, S.K. Kang, Preprint BROWN-HET-968 (hep-ph/9412368) and BROWN-HET-979 (hep-ph/9503478).

[2] P. Langacker, in: Proceedings of 22nd INS International Symposium "Physics with High Energy Colliders", March 8-10, 1994, INS, Univ. Tokyo, Japan, ed. by S. Yamada and T. Ishii (World Scientific, 1995), p.107; K. Hagiwara, S. Matsumoto, D. Haidt, C. S. Kim, *Z. Phys.* **C64**, 559 (1994).

[3] Z. Hioki, *Phys. Rev.* **D45**, 1814 (1992); *Phys. Lett.* **B340**, 181 (1994); *Int. J. Mod. Phys.* **A10**, 3803 (1995); Z. Hioki, R. Najima, *Mod. Phys. Lett.* **A10**, 121 (1995).

[4] D. Schaile, Lecture at this School.

[5] CDF Collaboration : F. Abe *et al.*, *Phys. Rev. Lett.* **75**, 11 (1995); M. Demarteau, H. Frisch, U. Heintz, R. Keup, D. Saltzberg, Joint CDF note/D0 note CDF/PHYS/CDF/PUBLIC/2552 and D0NOTE 2115.

[6] T. Kawamoto, in: Proceedings of the ICEPP Symposium "From LEP to the Planck World", Dec. 17-18, 1992, Univ. of Tokyo, ed. by K. Kawagoe and T. Kobayashi, ICEPP, Univ. of Tokyo, Dec. 1993, p.55; T. Sjöstrand, V.A. Khoze, *Phys. Rev. Lett.* **72**, 28 (1994).

[7] CDF Collaboration: F. Abe *et al.*, *Phys. Rev. Lett.* **73**, 225 (1994); *Phys. Rev.* **D50**2966 (1994); *Phys. Rev. Lett.* **74**, 2626 (1995); D0 Collaboration : S. Abachi *et al.*, *Phys. Rev. Lett.* **74**, 2632 (1995).

[8] R. Barbieri, M. Beccaria, P. Ciafaloni, G. Curci, A. Viceré, *Nucl. Phys.* **B409**, 105 (1993); J. Fleischer, O. V. Tarasov, F. Jegerlehner, *Phys. Lett.* **B319**, 249 (1993); M. Consoli, W. Hollik, F. Jegerlehner, *Phys. Lett.* **B227**, 167 (1989).

[9] A. Djouadi, C. Verzegnassi, *Phys. Lett.* **B195**, 265 (1987); F. Halzen, B.A. Kniehl, *Nucl. Phys.* **B353**, 567 (1991); K.G. Chetyrkin, J.H. Kühn, M. Steinhauser, *Phys. Lett.* **B351**, 331 (1995); L. Avdeev, J. Fleischer, S. Mikhailov, O. Tarasov, *Phys. Lett.* **B336**, 560 (1994); B.A. Kniehl, A. Sirlin, *Nucl. Phys.* **B371**, 141 (1992); *Phys. Rev.* **D47**, 883 (1993); B.H. Smith, M.B. Voloshin, *Phys. Rev.* **D51**, 5251 (1995).

[10] S. Fanchiotti, B. Kniehl, A. Sirlin, *Phys. Rev.* **D48**, 307 (1993); W. Hollik, in: Precision tests of the Standard Model, Advanced series on directions in high-energy physics, ed. by Paul Langacker World Scientific, Singapore 1995, p.37; B.A. Kniehl, *Int. J. Mod. Phys.* **A10**, 443 (1995).

[11] D. Bardin *et al.*, in: Reports of the Working Group on Precision Calculations for the Z Resonance, CERN 95-03), ed. by D. Bardin, W. Hollik and G. Passarino, CERN, 1995, p.7.

[12] A. Sopczak, Preprint CERN-PPE/95-46 (hep-ph/9504300).

[13] U. Amaldi, A. Böhm, L.S. Durkin, P. Langacker, A.K. Mann, W.J. Marciano, A. Sirlin, H.H. Williams, *Phys. Rev.* **D36**, 1385 (1987); G. Costa, J. Ellis, G.L. Fogli, D.V. Nanopoulos, F. Zwirner, *Nucl. Phys.* **B297**, 244 (1988).

[14] V. A. Novikov, L.B. Okun, M.I. Vysotsky, *Mod. Phys. Lett.* **A8**, 2529 (1993); M. Bilenky, K. Kołodziej, M. Kuroda, D. Schildknecht, *Phys. Lett.* **B319**, 319 (1993); G. Altarelli, Preprint CERN-TH.7045/93, Talk at the EPS Conference on High Energy Physics, Marseille, France, July 1993.

[15] M.L. Swartz, Preprint SLAC-PUB-6710 and SLAC-PUB-95-7001 (hep-ph/9411353 and 9509248); A. D. Martin, D. Zeppenfeld, *Phys. Lett.* **B345**, 558 (1995); S. Eidelman, F. Jegerlehner, *Z. Phys.* **C67**, 585 (1995).

[16] T. Takeuchi, Preprint FERMILAB-CONF-95/173-T (hep-ph/9506444).

[17] V.A. Novikov, L.B. Okun, A.N. Rozanov, M.I. Vysotsky, *Mod. Phys. Lett.* **A9**, 2641 (1994); K. Kang, S.K. Kang, Preprint BROWN-HET-940 (hep-ph/9403406 and 9509431).

[18] S. Dittmaier, D. Schildknecht, K. Kołodziej, M. Kuroda, *Nucl. Phys.* **B426**, 249 (1994); P. Gambino, A. Sirlin, *Phys. Rev. Lett.* **73**, 621 (1994); S. Dittmaier, D. Schildknecht, G. Weiglein, Preprint BI-TP 95/31 (hep-ph/9510386).

[19] D0 Collaboration: S. Abachi *et al.*, *Phys. Rev. Lett.* **72**, 2138 (1994).