SUPERSYMMETRIC CORRECTIONS TO
MASSES AND WIDTHS

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Abstract

Supersymmetric radiative corrections to the partial width $\Gamma(\tau \to e\nu\bar{\nu})$ and the masses of the $W$ and $Z$ gauge bosons are calculated in different renormalization schemes. The importance of the non-universal contributions is analyzed.
1 INTRODUCTION

The minimal supersymmetric standard model (MSSM) is one of the most interesting extensions of the standard model of the electroweak interactions (SM) \[1\]. Although the SM, a gauge theory based on a spontaneously broken $SU(2) \times U(1)$ describes successfully all observed phenomena, it leaves several theoretical questions unanswered. Some of these problems, such as the hierarchy problem, could be solved by supersymmetry (SUSY) \[2, 3\]. Unfortunately, no supersymmetric particle has been detected, and we do not even know if SUSY has anything to do with the real world. However, if SUSY is realized in nature, it could be possible to detect supersymmetric signals through radiative effects.

Several analysis of SUSY radiative corrections already exist in the literature (see, for example, \[4, 5, 6, 7, 8\] and references therein). In this paper, we focus our attention on universal and full one loop radiative corrections to the partial width $\Gamma(\tau \rightarrow e\nu\bar{\nu})$ and the masses of the $W$ and $Z$ gauge bosons in different renormalization schemes. Sleptons and -inos (gauginos and higgsinos) will be included in the analysis. The phenomenological bounds

$$m_{\tilde{l}^+} \geq 45 \text{ GeV}, \ m_{\tilde{\nu}} \geq 30 \text{ GeV}, \ M_{\Phi^+} \geq 45 \text{ GeV}$$

will be respected. In the -ino sector, we assume the GUT relation

$$M' = \frac{5}{3} \tan^2(\theta) M.$$  \hspace{1cm} (2)

The charged sleptons of each family are supposed to be degenerate in mass. Their mass is related to the sneutrino mass through

$$m_{\tilde{l}^+}^2 = m_{\tilde{\nu}}^2 + M_W^2 \frac{\tan^2(\beta) - 1}{\tan^2(\beta) + 1},$$  \hspace{1cm} (3)

where $\tan(\beta)$ is the ratio of the v.e.v. of the Higgs giving mass to the up quarks and the v.e.v. of the Higgs giving mass to the down quarks. We do not consider squark contributions, but they can easily be included: Once their masses and mixing angles are given, one just adds their (universal) contributions $\delta M_W^{\text{squarks}}$ and $\delta M_Z^{\text{squarks}}$ to the given results. As we will see in sec. 4, $\Gamma(\tau \rightarrow e\nu\bar{\nu})$ is not affected by squark contributions.

This paper is organized as follows: In section 2, radiative corrections to the $W$ mass are computed in the popular $(\alpha, G_{\mu}, M_Z)$ scheme. In section 3, we consider radiative corrections to the $Z$ mass in the $(\alpha, G_{\mu}, M_W/M_Z \equiv \cos(\theta))$ scheme. Clearly, some steps in these directions have already been done (see, for example \[4\]). However, analyses including process dependent contributions (i.e. vertex and box diagrams, as well as external wave function renormalization effects), which could be important \[4, 8\] are, to my knowledge, still missing. In section 4, we say a few words on $\tau$ decays, and finally, section 5 will be devoted to the discussions and conclusions.
2 RADIATIVE CORRECTIONS TO $M_W$

Suppose we are given the fine structure constant $\alpha$, the Fermi constant $G_\mu$ and the mass of the $Z$ boson $M_Z$. Then, at tree-level, the following relation holds [14]:

$$ M_W^2 = \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4\pi \alpha}{\sqrt{2} G_\mu M_Z^2}} \right). \quad (4) $$

After inclusion of radiative corrections, eq. (4) will be modified, but it still holds for bare quantities. Let us now introduce

$$ s_{12}^2 = \frac{1}{2} \left( 1 - \sqrt{1 - \frac{4\pi \alpha}{\sqrt{2} G_\mu M_Z^2}} \right), \quad c_{12}^2 + s_{12}^2 = 1, \quad (5) $$

$$ M_W^2 = M_W^0 + \Pi_W(M_W^2) \equiv M_W^0(1 + \delta_W), \quad (6) $$

$$ M_Z^2 = M_Z^0 + \Pi_Z(M_Z^2) \equiv M_Z^0(1 + \delta_Z), \quad (7) $$

$$ \alpha = \alpha^0(1 + \delta_{\alpha}), \quad (8) $$

$$ G_\mu = G_\mu^0(1 + \delta_\mu). \quad (9) $$

After substituting the bare quantities $M_W^0$, $M_Z^0$, $\alpha^0$ and $G_\mu^0$ in eq. (4) and doing some algebra, we find

$$ M_W^2 = M_Z^2 c_{12}^2 \left\{ 1 - \frac{s_{12}^2}{c_{12}^2 - s_{12}^2}(\delta_\mu - \delta_{\alpha}) - \frac{c_{12}^2}{c_{12}^2 - s_{12}^2}\delta_Z + \delta_W \right\}. \quad (10) $$

$\delta^SUSY_{\alpha}$, $\delta^SUSY_{\mu}$, $\delta^SUSY_Z$ and $\delta^SUSY_Z$ are given by

$$ \delta^SUSY_{\alpha} = \begin{cases} \Pi_{\gamma\gamma}(k^2)^{SUSY} \\ k^2 \to 0 \end{cases}, \quad (11) $$

$$ \delta^SUSY_{\mu} = -\frac{\Pi_W(0)^{SUSY}}{M_W^2} + \delta^NSE_{\mu(SUSY)}; \quad (12) $$

$$ \delta^SUSY_W = \frac{\Pi_W(M_W^2)^{SUSY}}{M_W}, \quad (13) $$

$$ \delta^SUSY_Z = \frac{\Pi_Z(M_Z^2)^{SUSY}}{M_Z^2}, \quad (14) $$

where $\delta^NSE_{\mu(SUSY)}$ is a process-dependent contribution which depends on $m_{\tilde{\nu}_e}$, $m_{\tilde{\nu}_\mu}$, the electron masses and mixing angles, the smuon masses and mixing angles, $\tan(\beta)$, and the -ino masses and mixing-matrices. The formulæ for $\Pi_\gamma(k^2)$, $\Pi_W(k^2)$, $\Pi_Z(k^2)$ and $\delta^NSE_{\mu(SUSY)}$ can
be found in the literature \cite{9,10} and will not be listed here. The universal contributions to the mass shift $\delta M_W \equiv M_W - \bar{M}_W$ are given by

$$ (\delta M_W^{\text{SUSY}})_{\text{UNIV}} = \frac{M_W}{2} \left\{ \frac{s_1^2}{c_1^2 - s_1^2} \left( \frac{\Pi_W(k^2)}{M_W^2} + \frac{\Pi_{\gamma\gamma}(k^2)}{k^2} \right) + \frac{\Pi_Z(k^2)}{M_Z^2} + \frac{\Pi_W(M_W^2)}{M_W^2} \right\} \left. \right|_{k^2 \to 0},$$

(15)

the non-universal contributions are given by

$$ (\delta M_W^{\text{SUSY}})_{\text{NON-UNIV}} = -\frac{M_W}{2} \frac{s_1^2}{c_1^2 - s_1^2} \delta^{\text{NSE}}_{\mu(SUSY)},$$

(16)

and the full contributions read

$$ \delta M_W^{\text{SUSY}} = \frac{M_W}{2} \left\{ -\frac{s_1^2}{c_1^2 - s_1^2} (\delta^{\text{SUSY}} - \delta^{\text{SUSY}}_{\alpha}) - \frac{c_1^2}{c_1^2 - s_1^2} \delta^{\text{SUSY}}_Z + \delta^{\text{SUSY}}_W \right\}. $$

(17)

In fig.1, we show the universal (fig.1.a) and full (fig.1.b) contributions to $\delta M_W$ for $\tan(\beta) = 2$ and $m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} = m_{\tilde{\nu}_\tau} = 50$ GeV. The masses of the charged sleptons are given in eq.(3). The blank regions are phenomenologically excluded by the mass limit $M_{\Psi^+} \geq 45$ GeV. Comparison of fig.1.a and fig.1.b shows that the non-universal contributions turn out to be small.

In the main range of the allowed $(\mu, M)$ space the full corrections (fig.1.b) lie between $\sim 60$ and $\sim 120$ MeV, mainly due to the universal contributions (eq.(13)), which are about one order of magnitude bigger than the non-universal contributions (eq.(16)). Similar analyses, with heavier sleptons, show that the mass shift decreases as the sfermions become heavier. For example, for $m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} = m_{\tilde{\nu}_\tau} = 200$ GeV and $\tan(\beta) = 2$, the full corrections lie between $\sim -10$ and $\sim 50$ MeV (in the main range of the allowed $(\mu, M)$ space). In this case, the non-universal contributions turn out to be very small. They are not bigger than 20 MeV in the whole allowed space, and not bigger than 10 MeV in a wide region. These mass shifts lie below the present experimental uncertainty $\Delta M_W = 250$ MeV. However, $M_W$ will be measured with an accuracy of $\sim 100$ MeV in the near future and thus, the experimental uncertainty and SUSY mass shifts will become comparable, provided the sparticles are light enough and squarks have been included in the analysis.

3 RADIATIVE CORRECTIONS TO $M_Z$

Suppose now that we are given the fine structure constant $\alpha$, the Fermi constant $G_\mu$ and the ratio of the masses of the $W$ and the $Z$ bosons, $M_W/M_Z \equiv \cos(\theta)$. Then, at tree-level,
the following relation holds:

\[ M_Z^2 = \frac{\pi \alpha}{\sqrt{2} G_\mu \sin^2(\theta) \cos^2(\theta)} \]  \hspace{1cm} (18)

As in the previous section, eq. (18) will get modified when radiative corrections are included, but it still holds for bare quantities. Substituting bare quantities in eq. (18), we find (see also [11])

\[ M_Z^2 = \frac{\pi \alpha}{\sqrt{2} G_\mu \sin^2(\theta) \cos^2(\theta)} \left\{ 1 - \delta_\alpha + \delta_\mu + \frac{2 s_2^2 - 1}{s_2^2} \delta_W + \frac{1 - s_2^2}{s_2^2} \delta_Z \right\}, \]  \hspace{1cm} (19)

where \( s_2 = \sin(\theta) \). The universal contributions to \( \delta M_Z \equiv M_Z - \bar{M}_Z \) are given by

\[ (\delta M_Z^{SUSY})_{UNIV} = \frac{M_Z}{2} \left\{ \frac{\Pi_{\gamma\gamma}(k^2)^{SUSY}}{k^2} - \frac{\Pi_W(k^2)^{SUSY}}{M_W^2} \right\} + \frac{2 s_2^2 - 1}{s_2^2} \frac{\Pi_{\gamma\gamma}(k^2)^{SUSY}}{M_W^2} + \frac{1 - s_2^2}{s_2^2} \frac{\Pi_W(k^2)^{SUSY}}{M_Z^2} \right\} \]  \hspace{1cm} (20)

the non-universal contributions are given by

\[ (\delta M_Z^{SUSY})_{NON-UNIV} = \frac{M_Z}{2} \delta^{NSE\mu(SUSY)}, \]  \hspace{1cm} (21)

while the full contributions read

\[ \delta M_Z^{SUSY} = \frac{M_Z}{2} \left\{ -\delta_\alpha^{SUSY} + \delta_\mu^{SUSY} + \frac{2 s_2^2 - 1}{s_2^2} \delta_W^{SUSY} + \frac{1 - s_2^2}{s_2^2} \delta_Z^{SUSY} \right\}. \]  \hspace{1cm} (22)

In fig.2, \((\delta M_Z^{SUSY})_{UNIV}\) (fig.2.a) and \((\delta M_Z^{SUSY})_{FULL}\) (fig.2.b) are displayed for \( \tan(\beta) = 2 \) and \( m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} = m_{\tilde{\nu}_\tau} = 50 \text{ GeV} \). The masses of the charged sleptons are given in eq. (3). The blank regions are phenomenologically excluded by the mass limit \( M_{\Psi^+} \geq 45 \text{ GeV} \). Comparison of fig.2.a and fig.2.b shows that, the non-universal contributions turn out to be small. As in the previous section, the universal contributions (eq. (20)) are about one order of magnitude bigger than the non-universal contributions (eq. (21)).

The full mass shifts (fig.2.b) lie between \( \sim -150 \) and \( \sim -310 \text{ MeV} \) in the main region of the allowed \((\mu, M)\) space. Similar analyses show that these mass-shifts decrease for heavier sleptons, e.g., for \( m_{\tilde{\nu}_e} = m_{\tilde{\nu}_\mu} = m_{\tilde{\nu}_\tau} = 200 \text{ GeV} \) and \( \tan(\beta) = 2 \), the radiative corrections lie between \( \sim 30 \) and \( \sim -110 \text{ MeV} \) (in the main range of the allowed \((\mu, M)\) space). As in the previous section, the non-universal contributions are found to be small. For light sleptons, these mass shifts are bigger than the present experimental error \( \Delta M_Z = 20 \text{ MeV} \) [18]! Unfortunately, at tree-level \( M_Z \) can only be predicted with a precision of \( \sim 670 \text{ MeV} \). This tree-level error is due to the present experimental uncertainty \( \Delta M_W = 250 \text{ MeV} \). However, for light sparticles, SUSY mass-shifts and the tree-level uncertainty will become comparable in the future, once \( M_W \) is measured with an accuracy of \( \sim 100 \text{ MeV} \) and squarks have been included in the analyses.
4 \ \ \ \tau \ \text{decays}

Let us now say a few words on \( \tau \) decays. The \( \tau \) lifetime, \( \tau_\tau \), which can be derived from direct measurements of the impact parameter, can also be calculated from the measured branching ratio

\[
B(\tau \to e\nu\bar{\nu}) = \frac{\Gamma(\tau \to e\nu\bar{\nu})}{\Gamma(\tau \to \text{all})},
\]

where \( \Gamma(\tau \to e\nu\bar{\nu}) \) (electroweak radiative corrections are included, \[17\]) is given by

\[
\Gamma(\tau \to e\nu\bar{\nu}) = \frac{G_\mu^2 m_\tau^5}{192\pi^3} f\left(\frac{m_e^2}{m_\tau^2}\right) \left(1 + \frac{3}{5} \frac{m_\tau^2}{M_W^2}\right) \left(1 + \frac{\alpha(m_\tau)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right),
\]

and \( f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log(x) \). Since both results for \( \tau_\tau \) should agree, it is expected that

\[
R_\tau \equiv \frac{\Gamma(\tau \to e\nu\bar{\nu})}{B(\tau \to e\nu\bar{\nu})\Gamma(\tau \to \text{all})} = 1
\]

holds. However, eq.(24) may be affected by non-electroweak corrections. Supersymmetric corrections to eq.(24) can be included by introducing a new Fermi constant \( G_\tau \),

\[
G_\tau = G_\mu^o (1 + \delta_\tau^{\text{SUSY}}),
\]

where \( \delta_\tau^{\text{SUSY}} = \delta_\mu^{\text{SUSY}}(\mu \leftrightarrow \tau) \). Combining eq.(9) and eq.(26), we find

\[
G_\tau = G_\mu^o (1 + \delta_\tau^{\text{SUSY}} - \delta_\mu^{\text{SUSY}}).
\]

Thus, if supersymmetric corrections are included, the partial width \( \Gamma(\tau \to e\nu\bar{\nu}) \) reads

\[
\Gamma(\tau \to e\nu\bar{\nu}) = \frac{G_\mu^2 m_\tau^5}{192\pi^3} f\left(\frac{m_e^2}{m_\tau^2}\right) \left(1 + \frac{3}{5} \frac{m_\tau^2}{M_W^2}\right) \left(1 + \frac{\alpha(m_\tau)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right), \quad (28)
\]

and \( R_\tau \) (eq.(23)) will deviate from 1. Supersymmetric corrections to \( R_\tau \), i.e.,

\[
\delta R_\tau^{\text{SUSY}} = 2(\delta_\mu^{\text{SUSY}} - \delta_\tau^{\text{SUSY}}),
\]

where \( \delta_\tau^{\text{SUSY}} \) is a process-dependent contribution which depends on \( m_{\tilde{\nu}_e} \), \( m_{\tilde{\nu}_\tau} \), the electron mass-electron masses, and mixing angles, the stau masses and mixing angles, \( \tan(\beta) \), and the -ino masses and mixing-matrices, will arise if \( m_{\tilde{\nu}_\tau} \neq m_{\tilde{\nu}_e} \) (and \( m_\tau \neq m_{\tilde{\mu}} \), eq.(3)). Thus, \( R_\tau \) is sensitive to mass splittings between the \( \tilde{\nu}_\mu \) and the \( \tilde{\nu}_\tau \) (and between the smuon and the stau). Notice that there are no universal contributions to \( \delta R_\tau^{\text{SUSY}} \). Furthermore, as already pointed out in the introduction, \( R_\tau \) is not affected by squark contributions. Combining eqs.(24), (27), (28) and (29), we find

\[
\Gamma(\tau \to e\nu\bar{\nu}) = \Gamma(\tau \to e\nu\bar{\nu})_\mu (1 - \delta R_\tau^{\text{SUSY}}) \quad (30)
\]
and
\[
\delta \Gamma(\tau \to e\nu\bar{\nu})^{SUSY} = -\Gamma(\tau \to e\nu\bar{\nu})\delta R_{\tau}^{SUSY}.
\]

Substituting the updated (and preliminary) data \[12\]
\[
m_\tau = (1777.1 \pm 0.5)\text{MeV},
\]
\[
\tau_\tau = (295.7 \pm 3.2)\text{fs},
\]
\[
B_\tau = (17.76 \pm 0.15)\%,
\]
in eq.(25) and eq.(28), we find
\[
R_\tau = 1.020 \pm 0.014.
\]

Let us now turn to the numerical analysis. In fig.3, \(\delta_{NSE}\tilde{l}_{(SUSY)}\), \(\bar{l} = \bar{\mu}, \bar{\tau}\) is displayed for \(\mu = -50\text{ GeV}, M = 100\text{ GeV}\) and \(\tan(\beta) = 2\). The masses of the charged sleptons are given in eq.(3). By combining eq.(29) and the results in fig.3, we easily obtain the value of \(\delta R_\tau\), which turns out to be small (\(|\delta R_\tau| \leq 0.25\%\)). Similar analyses show that \(|\delta_{NSE}\tilde{l}_{(SUSY)}|\) (and thus, \(|\delta R_{\tau}^{SUSY}|\) and \(|\delta \Gamma(\tau \to e\nu\bar{\nu})^{SUSY}|\)) decrease as \(|\mu|\) and \(|M|\) increase.

I would not like to conclude this section without saying a few words on the \(\tau\)-decay puzzle. For the averages \(m_\tau = 1784.1^{+2.7}_{-3.6}\) MeV and \(\tau_\tau = (0.305 \pm 0.006)\times10^{-12}\) sec, \[18\] the experimental branching ratios for \(\tau\) decays were found to be smaller than the theoretical predictions by a factor 0.95 \pm 0.02. Several attempts have been made to solve this puzzle with help of new physics \[13, 15, 16\]. Supersymmetric contributions to \(\Gamma(\tau \to e\nu\bar{\nu})\), and thus, to \(B(\tau \to e\nu\bar{\nu})\) are too small to solve the \(\tau\) puzzle. However, the most recent measurements of the \(\tau\) mass and lifetime (eqs.(32) and (33), see also ref.\[12\]) seem to resolve these discrepancies.

5 CONCLUSIONS

Supersymmetric one loop corrections to the partial width \(\Gamma(\tau \to e\nu\bar{\nu})\) and the masses of the \(W\) and \(Z\) gauge bosons have been calculated. All the contributions (i.e. universal and non-universal) have been taken into account. \(\Gamma(\tau \to e\nu\bar{\nu})\) is only affected by non-universal contributions, which turn out to be very small.

The mass shifts \(\delta M_W^{SUSY}\) (\(\delta M_Z^{SUSY}\)) where found to lie below the present experimental (tree-level) errors, but in the future they might become comparable to these uncertainties, once \(M_W\) is measured with a precision of \(\sim 100\) MeV. When the top quark mass will be known and squarks have been included in the analyses, SUSY might produce visible signals through both, \(M_W\) and \(M_Z\) mass shifts, which go in opposite directions. Thus, a deviation of the standard model prediction for \(M_W\) (in the \((\alpha, G_\mu, M_Z)\) scheme) from the measured
value $M_W$ and a deviation, in opposite direction, of the standard model prediction for $M_Z$ (in the $(\alpha, G_\mu, M_W/M_Z)$ scheme) from the measured value $M_Z$ could be an indication for new physics (not necessarily supersymmetry), even if the deviations are not big. The sign and size of these deviations would contain valuable information.

For light sparticles, the computed mass shifts are dominated by universal contributions, which, are about one order of magnitude bigger than the non-universal contributions (we have found a small region, easily explorable at LEP II, where the non-universal contributions are about 30% of the universal contributions), while for heavier sparticles, both, the universal and the non-universal contributions turn out to be small (I have checked that this also holds for $\tan(\beta) \neq 2$). The fact that $(\delta M_W^{SUSY})_{\text{NON-UNIV}} - (\delta M_Z^{SUSY})_{\text{NON-UNIV}}$ is not big can also be seen by combining eq.(16) (eq.(21)) and the results displayed in fig.3.

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Figure Captions

fig.1. Contour plots of $\delta M_{\text{SUSY}}^W$ (MeV) for $m_{\tilde{\nu}} = 50$ GeV and $\tan(\beta) = 2$. In fig.1.a only universal contributions are displayed, while in fig.1.b all contributions have been taken into account. The blank regions are phenomenologically excluded by $M_{\Psi^+} \geq 45$ GeV.

fig.2. Contour plots of $\delta M_{\text{SUSY}}^Z$ (MeV) for $m_{\tilde{\nu}} = 50$ GeV and $\tan(\beta) = 2$. In fig.2.a only universal contributions are displayed, while in fig.2.b all contributions have been taken into account. The blank regions are phenomenologically excluded by $M_{\Psi^+} \geq 45$ GeV.

fig.3. Contour plots for $\delta^{\text{NSE}}_{\tilde{l}(\text{SUSY})}$ (%) for $\mu = -50$ GeV, $M = 100$ GeV and $\tan(\beta) = 2$. 