Supersymmetric contributions to muon $g - 2$ and the electroweak precision measurements

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Abstract

In view of the recent measurement of the muon $g - 2$ and finalization of the LEP electroweak data, we re-examine all the new particle contributions to those observables in the MSSM. The SM fits the latest electroweak data excellently with the observed top-quark mass and the Higgs-boson mass of around 100 GeV, and so does the MSSM in the decoupling limit. The MSSM gives a slightly better fit to the data than the SM ($\Delta \chi^2_{\text{min}} \sim -2$) when relatively light left-handed sleptons of mass $\sim 200$ GeV and a light chargino of mixed higgsino-wino character ($\mu/M_2 \sim 1$) with mass $\sim 100$ GeV co-exist. The improvement in the fit diminishes quickly for wino- or higgsino-dominant charginos, for heavier charginos, and for lighter sleptons. We find that the MSSM contributions to the muon $g - 2$ is most efficient when the light chargino has a mixed character. If $\tan \beta < 10$, the set of a light mixed chargino and light sleptons that is favored by the electroweak data is also favored by the $g - 2$ data for $\mu > 0$. Models with light gauginos ($\mu/M_2 > 10$) or light higgsinos ($\mu/M_2 < 0.1$) give significant contributions to muon $g - 2$ only for large $\tan \beta (\gtrsim 15)$. 
Looking for signatures of supersymmetry (SUSY) at high energy experiments is one of the most important tasks of particle physics. Since the LEP experiments have been completed without finding any evidences of new physics beyond the Standard Model (SM), the chance to discover the superparticles at the energy frontier has been postponed to the next stage, at the Tevatron Run-II or at the LHC. However, we may find important constraints on, or an indication of, the supersymmetric models from precise measurements of the SM particles which are sensitive to the interactions of superparticles. In this letter, we would like to examine the superparticle contributions to the muon $g - 2$ in the light of its recent measurement \[1\] and the finalization of the LEP electroweak data \[2\].

The precise measurement of the muon $g - 2$ has been achieved at BNL \[1\] where the experimental uncertainty has been reduced by about factor 3 from the previous measurement \[3\]. The current world average of the muon $g - 2$ is then given by

$$a_\mu(\text{exp.}) = 11659203(15) \times 10^{-10}.$$ \hspace{1cm} (1)

The comparison of the data with the SM prediction is

$$a_\mu(\text{exp.}) - a_\mu(\text{SM}) = 43(16) \times 10^{-10},$$ \hspace{1cm} (2)

where the experimental and theoretical errors are added in quadrature. The theoretical uncertainty is dominated by the hadronic vacuum polarization effect. The SM prediction in eq. (2) has been obtained by using the estimate of ref. \[4\]. Although consensus among experts should yet to emerge on the magnitude and the error of the SM prediction \[4\], we adopt the estimate of eq. (2) as a distinct possibility. The purpose of this letter is to examine if this possible inconsistency of the data and the SM can be understood naturally in the context of minimal supersymmetric SM (MSSM), when taking account of the electroweak precision data.

The enormous data of the electroweak measurements at LEP1 have been analyzed after its completion in 1995. The final combination of the results from four collaborations – ALEPH, DELPHI, L3 and OPAL– has been available on the $Z$-line shape and the leptonic asymmetry data \[6\]. The electroweak precision measurements consist of 17 $Z$-pole observables from LEP1 and SLC, and the $W$-boson mass from Tevatron and LEP2.

Let us first summarize the constraints on the MSSM parameters \[7\] from the electroweak data. The supersymmetric particles affect these observables radiatively through the oblique corrections which are parametrized by $S_Z, T_Z, m_W$, and
the \(Z_{ff}\) vertex corrections \(g^f_\lambda\), where \(f\) stands for the quark/lepton species and \(\lambda = L\) or \(R\) stands for their chirality. The parameters \(S_Z\) and \(T_Z\) are related to the \(S\)- and \(T\)-parameters as:

\[
\Delta S_Z = S_Z - 0.955 = \Delta S + \Delta R - 0.064x_\alpha + 0.67\frac{\Delta G}{\alpha}, \quad (3a)
\]

\[
\Delta T_Z = T_Z - 2.65 = \Delta T + 1.49\Delta R - \frac{\Delta G}{\alpha}, \quad (3b)
\]

where \(\Delta S_Z\) and \(\Delta T_Z\) measure the shifts from the reference SM prediction point, \((S_Z, T_Z) = (0.955, 2.65)\) at \(m_t = 175\) GeV, \(m_{H_{SM}} = 100\) GeV, \(\alpha_s(m_Z) = 0.118\) and \(1/\alpha(m^2_Z) = 128.90\). The \(R\)-parameter, which accounts for the difference between \(T\) and \(T_Z\), represents the running effect of the \(Z\)-boson propagator corrections between \(q^2 = m^2_Z\) and \(q^2 = 0\) \([7]\). The parameter \(x_\alpha \equiv (1/\alpha(m^2_Z) - 128.90)/0.09\) allows us to take account of improvements in the hadronic uncertainty of the QED coupling \(\alpha(m^2_Z)\). \(\Delta G\) denotes new physics contribution to the muon lifetime which has to be included in the oblique parameters because the Fermi coupling \(G_F\) is used as an input in our formalism \([4, 9]\). The third oblique parameter \(\Delta m_W = m_W - 80.402\) (GeV) is given as a function of \(\Delta S, \Delta T, \Delta U, x_\alpha\) and \(\Delta G\) \([7]\). The explicit formulae of the oblique parameters and the vertex corrections \(\Delta g^f_\lambda\) in the MSSM can be found in ref. \([7]\).

We study constraints on the oblique parameters from the electroweak data. In addition to the three oblique parameters, the \(Zb_Lb_L\) vertex correction, \(\Delta g^b_L\), is included as a free parameter in our fit because non-trivial top-quark-mass dependence appears only in the \(Zb_Lb_L\) vertex among all the non-oblique radiative corrections in the SM. By using all the electroweak data \([2]\) and the constraint \(\alpha_s(m_Z) = 0.119 \pm 0.002\) \([10]\) on the QCD coupling constant, we find from a five-parameter fit \((\Delta S_Z, \Delta T_Z, \Delta m_W, \Delta g^b_L, \alpha_s(m_Z))\) the following constraints on the oblique parameters:

\[
\begin{align*}
\Delta S_Z - 25.1\Delta g^b_L &= 0.002 \pm 0.104 \\
\Delta T_Z - 45.9\Delta g^b_L &= -0.041 \pm 0.125
\end{align*}
\]

\(\rho = 0.88, \quad (4)\)

\(\Delta m_W\) (GeV) = 0.032 \pm 0.037,

for \(\Delta g^b_L = -0.00037 \pm 0.00073\). The \(\chi^2\) minimum of the fit is \(\chi^2_{\text{min}} = 22.6\) for the degree-of-freedom (d.o.f.) \(19 - 5 = 14\).

Through the expression \([34]\) of \(\Delta S_Z\), the QED coupling \(\alpha(m^2_Z)\) affects theoretical predictions for the electroweak observables. The LEP electroweak working
group has adopted the new estimate \[11\]

\[
\frac{1}{\alpha(m_Z^2)} = 128.936 \pm 0.046 \quad (x_\alpha = 0.4 \pm 0.51),
\]

which takes into account the new $e^+e^-$ annihilation results from BEPC \[12\]. Using the central value of $\alpha(m_Z^2)$ in eq. (5), $x_\alpha = 0.4$, the SM best fit is found given at $(m_t\text{ (GeV)}, m_{H_{SM}}\text{ (GeV)}, \alpha_s(m_Z)) = (175.1, 116, 0.118)$. The $\chi^2$ minimum is $\chi^2_{\text{min}} = 24.4$ for the d.o.f. $20 - 3 = 17$. At the SM best fit point, the oblique parameters are given by $(\Delta S_Z - 25.1\Delta g_H^b, \Delta T_Z - 45.9\Delta g_L^b, \Delta m_W) = (-0.010, -0.020, -0.009)$, which shows an excellent agreement with the data. Although the SM fit is already good, the further improvement of the fit may be found if new physics gives slightly positive $\Delta m_W$. On the other hand, new physics contribution which gives large negative $\Delta S_Z$ and positive $\Delta T_Z$ is disfavored from the data.

The supersymmetric contributions to the oblique parameters have been studied in ref. \[7\] in detail. In the MSSM, the oblique corrections are given as a sum of the individual contributions of (i) squarks, (ii) sleptons, (iii) Higgs bosons and the (iv) ino-particles (charginos and neutralinos). Squarks always give $\Delta S_Z \sim 0$ and $\Delta T_Z > 0$ while sleptons give $\Delta S_Z \lesssim 0$ and $\Delta T_Z > 0$. Both of them give $\Delta m_W > 0$ which is favored from the data but the improvement is more than compensated by the disfavored contributions to $\Delta S_Z$ and $\Delta T_Z$. The contributions from the MSSM Higgs bosons are similar to that of the SM Higgs boson whose mass is around that of the lightest CP-even Higgs boson, as long as the CP-odd Higgs mass is not too small; $m_A \gtrsim 300 \text{ GeV}$ \[7\]. We find no improvement of the fit through the oblique corrections in the Higgs sector.

The ino-particles give $\Delta T_Z < 0$, owing to the large negative contribution to the $R$-parameter when there is a light chargino of mass $\sim 100 \text{ GeV}$ \[7\]. They also make $\Delta S_Z$ negative when the light chargino is either gaugino-like or higgsino-like \[7\]. However, we find that both $\Delta S_Z$ and $\Delta T_Z$ can remain small in the presence of a light chargino, if the ratio of the higgsino mass $\mu$ and the SU(2)$_L$ gaugino mass $M_2$ is order unity \[13\]. Let us recall that $S_Z$ is the sum of $S$- and $R$-parameters, while $T_Z$ is the sum of $T$- and $R$-parameters. The $S$- and $T$-parameters are associated with the SU(2)$_L \times U(1)_Y$ gauge symmetry breaking while the $R$-parameter is negative as long as a light chargino of mass $\sim 100 \text{ GeV}$ exists. The contributions of the ino-particles to the $S$- and $T$-parameters are essentially zero when the lighter chargino is almost pure wino or pure higgsino, whereas they both become positive when their mixing is large because the mixing occurs through the gauge symmetry breaking. As a consequence, the negative $R$
contributions from a light chargino can be compensated by the positive $S$ and $T$ contributions to the parameters $S_Z$ and $T_Z$, if the light-chargino has a mixed character ($|\mu/M_2| \sim 1$). The parameter $\Delta m_{W}$ is increased by the lightino-sector contribution when $\mu/M_2 \sim 1$, and hence the fit is slightly improved. This is largely because of the positive $T$ contribution due to the symmetry breaking. The overall fit, therefore, can be improved in the MSSM if a light chargino with the mixed wino-higgsino character ($|\mu/M_2| \sim 1$) exists and all sfermions are heavy. We find no sensitivity to the sign of the ratio $\mu/M_2$ in the fit to the electroweak data.

Now we examine the effects of vertex and box corrections. Since we find that the light chargino can improve the fit slightly through the oblique corrections, we set the chargino mass to be $m_{\tilde{\chi}_{1}^{\pm}} = 100$ GeV, as a representative number in our analysis. Our task is to look for the possibility of further improving the fit through the vertex and box corrections when squarks and sleptons are also light. We find that sizable $Zff$ vertex corrections via the loop diagrams mediated by the

1All our numerical results are obtained under the constraint $M_2/\alpha_2 = M_1/\alpha_1$, although our results are insensitive to the magnitude of $M_1$.

2Our results are not significantly altered as long as the mass of the lighter chargino is smaller than about 150 GeV.
left-handed squarks or the Higgs bosons make the fit worse always \[13\]. On the other hand, the fit is found to be improved slightly by the slepton contributions to the $Z\ell\ell$ vertices ($\Delta g^\ell_{\ell}$) and the muon lifetime ($\Delta\delta G_{\mu}$), when the left-handed slepton mass is around $200 \sim 500$ GeV. We show the total $\chi^2$ as a function of the left-handed smuon mass $m_{\tilde{\mu}_L}$ in Fig. 1. The $\tan\beta$ dependence is shown for $\tan\beta = 50$ (a) and $\tan\beta = 3$ (b), and the character of the 100 GeV lighter chargino is shown by $\mu/M_2 = 1.0$ (solid), 0.1 (dotted) and 10 (dashed). For simplicity, we assume that the universality of the slepton mass parameters in the flavor space. We find no sensitivity to the right-handed slepton mass, and $m_{\tilde{\mu}_R}$ is fixed at 100 GeV. The masses of all the squarks and the CP-odd Higgs-boson mass are set at 1 TeV. The improvement of the fit is maximum at around $m_{\tilde{\mu}_L} \simeq 300$ GeV for $\tan\beta = 50$ (a) and $\simeq 200$ GeV for $\tan\beta = 3$ (b) for $\mu/M_2 = 1.0$, where the total $\chi^2$ value is smaller than those of the decoupling limits, which are shown by the dot-dashed horizontal lines, by about 1.4 and 1.9, respectively.

The origin of the improvement at those points is found to come from the vertex corrections to the hadronic peak cross section on the $Z$-pole, which more than compensate the disfavored negative contributions to the oblique parameter $S_Z$ from the light left-handed sleptons \[7\]. The hadronic peak cross section $\sigma^0_h$ is given by

$$\sigma^0_h = \frac{12\pi \Gamma_e \Gamma_h}{m_Z^2 \Gamma_Z^2},$$

(6)

and is almost independent of the oblique corrections \[7, 14\]. The final LEP1 data of $\sigma^0_h$ is larger than the SM best-fit value by about 2-\sigma. Since the squarks and Higgs bosons are taken to be heavy, the partial decay width $\Gamma_e$ is the only quantity which is affected significantly by the vertex corrections. The supersymmetric contribution to $\Gamma_e$ is given by the sleptons and the ino-particles, which constructively interferes with the SM prediction. The fit to the $\sigma^0_h$ data, therefore, improves if the sleptons and ino-particles are both light. The overall fit is found to improve when the left-handed slepton mass is around $200 \sim 500$ GeV, as shown in Fig. 1. If the slepton mass is too light ($m_{\tilde{\mu}_L} \lesssim 200$ GeV for $\tan\beta = 50$, $m_{\tilde{\mu}_L} < 150$ GeV for $\tan\beta = 3$), the total $\chi^2$ increases rapidly because of disfavored contributions to the $S_Z$-parameter and also from the muon lifetime ($\Delta\delta G$). Since, in the large $m_{\tilde{\mu}_L}$ limit, only the oblique corrections from the light chargino and neutralinos remain, the difference of $\chi^2$ between the value at its minimum and that at $m_{\tilde{\mu}_L} \sim 3$ TeV represents the improvement of the fit due to non-oblique corrections. Among the
three cases of $\mu/M_2$ in Fig. 1, only the $\mu/M_2 = 1.0$ case shows a slight improvement of the fit via the non-oblique corrections. This is because the relatively light heavier chargino ($m_{\tilde{\chi}_2^-} \approx 220$ GeV for $\mu/M_2 = 1$) contributes to $\Gamma_e$ but has no other significant effects elsewhere. The improvement of the fit persists for $\mu/M_2 \sim 0.5$ or 2, but the smallest $\chi^2$ is found at $\mu/M_2 = 1.0$. Although we have shown results for $\mu/M_2 > 0$, we found that the electroweak data are insensitive to the sign of $\mu/M_2$.

Now we are ready for the study of the supersymmetric contribution to the muon $g - 2$ in the light of the electroweak precision data. The above study tells us that the electroweak precision data favors the presence of relatively light charginos ($m_{\tilde{\chi}_1^-} \sim 100$ GeV) of mixed wino-higgsino character ($|\mu/M_2| \sim 1$), and that the co-existence of left-handed sleptons can further improve the fit when its mass is in the $200 \sim 500$ GeV range. This is in fact the region of the MSSM parameter space which gives a sizable contributions to the muon $g - 2$ \cite{15, 16, 17}. It is known that the MSSM contribution to $a_\mu$ is most efficient when $|\mu/M_2| \sim 1$ \cite{15, 16}, and the sign of the discrepancy between the data and the SM prediction in eq. (2) favors positive $\mu/M_2$. This may be understood intuitively from the diagram of Fig. 2, where the $\mu_L$-$\mu_R$ transition amplitude is expressed in terms of the electroweak symmetry eigenstates. Since the muon $g - 2$ is given as the coefficient of the magnetic dipole operator, the chirality of the external muon must be flipped at somewhere. In the chargino-sneutrino exchanging diagram, the chirality flip occurs at the internal fermion line. We can tell from the diagram of Fig. 2 that the relevant MSSM contribution to the muon $g - 2$ is proportional to the product $M_2 \mu \tan \beta$. In the wino or higgsino limit, the contribution is suppressed because one of the two charginos is heavy. The chirality flip due to $\tilde{\mu}_L$-$\tilde{\mu}_R$ mixing contributes negligibly to $a_\mu$ even at $\tan \beta = 50$ \cite{16}. In the following analysis, we therefore ignore the
Figure 3: 1-σ allowed region of the \((m_{\tilde{\mu}_L}, \tan \beta)\) plane from the experimental data of muon \(g - 2\) \((2)\) for \(\mu/M_2 = 0.1\) (a), 1.0 (b) and 10 (c). The lighter chargino mass \(m_{\tilde{\chi}_1^-}\) is set at 100 GeV. The region enclosed by the solid lines and dashed lines are obtained for the right-handed smuon mass \(m_{\tilde{\mu}_R} = 100\) GeV and 500 GeV, respectively. In the region of \(m_{\tilde{\mu}_L}\) smaller than the vertical line, the MSSM fit to the electroweak data is worse than the SM \((\Delta \chi^2 \equiv \chi^2_{\text{min}}[\text{MSSM}] - \chi^2_{\text{min}}[\text{SM}] > 0)\).

small \(\tilde{\mu}_L\)-\(\tilde{\mu}_R\) mixing effects.

In Fig. 3, we show constraints on the left-handed smuon mass \(m_{\tilde{\mu}_L}\) and \(\tan \beta\) from the experimental data of \(a_\mu\), eq. (4), for \(m_{\tilde{\chi}_1^-} = 100\) GeV and \(\mu/M_2 = 0.1\) (a), 1.0 (b) and 10 (c). The regions enclosed by solid and dashed lines are found for the right-handed smuon mass \(m_{\tilde{\mu}_R} = 100\) GeV and 500 GeV, respectively. In the region of \(m_{\tilde{\mu}_L}\) smaller than the vertical dotted lines, the MSSM fit to the electroweak data is worse than the SM fit \((\chi^2_{\text{min}}[\text{MSSM}] > \chi^2_{\text{min}}[\text{SM}])\). Fig. 3 (b) tells us that if the lighter chargino state has comparable amounts of the wino and higgsino components \((\mu/M_2 = 1.0)\), which is favored from the electroweak data, relatively low values of \(\tan \beta\) is allowed: \(4 \lesssim \tan \beta \lesssim 8\) for \(m_{\tilde{\mu}_L} \approx 110\) GeV. This is the region favored by the electroweak data in Fig. 4. On the other hand, if it is mainly higgsino \((\mu/M_2 = 0.1)\) or wino \((\mu/M_2 = 10)\), low values of \(\tan \beta\) is
Figure 4: Constraints from the muon $g-2$ data (2) on $(M, \tan \beta)$ (a) and on $(\mu/M_2, \tan \beta)$ (b). The mass parameter $M$ is defined as $M \equiv m_{\tilde{\chi}^-_1} = m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R}$. The solid, dot-dashed and dashed lines are corresponding to: (a) $\mu/M_2 = 0.1$, 1.0 and 10, and (b) $M = 100$ GeV, 200 GeV and 400 GeV, respectively.

excluded: $\tan \beta \gtrsim 15$ for $m_{\tilde{\mu}_L} \approx 200$ GeV, where the MSSM fit to the electroweak data is comparable to the SM. In all cases of $\mu/M_2$ in the figure, the right-handed smuon tends to make the bound on $\tan \beta$ lower if its mass is small. It should be noted that the current $g-2$ data can be explained even for larger $m_{\tilde{\mu}_L}$ for appropriately large $\tan \beta$. The electroweak data is insensitive to $m_{\tilde{\mu}_L}$ in this region.

In Fig. 4 we show the 1-σ allowed range from the muon $g-2$ data (2) when all the relevant charged superparticles have the common mass, $m_{\tilde{\chi}^-_1} = m_{\tilde{\mu}_L} = m_{\tilde{\mu}_R} \equiv M$. The constraints on $(M, \tan \beta)$ are given in Fig. 4(a), for three representative cases of $\mu/M_2 = 0.1, 1.0$ and 10. Because the muon $g-2$ decreases if any of the three charged superparticles is heavier than the common value $M$, we can regard the allowed range as an upper mass limit of charged superparticles. We find that, if the lighter chargino is either wino- or higgsino-like, i.e., $\mu/M_2 \gg 1$ or $\mu/M_2 \ll 1$, either the lighter chargino or smuons should be discovered by a lepton collider at $\sqrt{s} = 400$ GeV for any $\tan \beta(\leq 50)$. On the other hand, if no superparticle is found at a 500 GeV lepton collider, then the chargino should have the mixed character and $\tan \beta$ should be bigger than 15. In Fig. 4(b) we show the constraint on $(\mu/M_2, \tan \beta)$ from the $a_\mu$ data (2). We can clearly see from this figure that the lowest value of $\tan \beta$ is allowed at $\mu/M_2 = 1$.

To summarize, we have studied the supersymmetric contributions to the muon
$g - 2$ in the light of its recent measurement at BNL and the finalization of the LEP electroweak data. Although the SM fit to the electroweak data is good, slightly better fit is found in the MSSM when relatively light left-handed sleptons with mass $\sim 200$ GeV and a light chargino of mass $\sim 100$ GeV and of mixed wino-higgsino character ($\mu/M_2 \sim 1$) exist. The improvement is achieved via the light chargino contribution to the oblique parameters and also via the ino-slepton contribution to $\sigma_{\mu}^0$. The improvement of the fit disappears rapidly if the light chargino is higgsino- or wino-like, or if the light chargino mass is heavier ($\gtrsim 200$ GeV), or the sleptons are too light ($\lesssim 180$ GeV for $\tan \beta = 50$ and $\lesssim 120$ GeV for $\tan \beta = 3$). We find that the supersymmetric contribution to the muon $g - 2$ is most efficient for $\mu/M_2 \sim 1$. If $\tan \beta \lesssim 10$, the MSSM parameter space which is favored from the electroweak data is also favored from the muon $g - 2$ data. The wino- or higgsino-dominant chargino contributes significantly to the muon $g - 2$ only for large tan $\beta$ ($\gtrsim 15$), although it does not improve the fit to the electroweak data. The impact on the search for the superparticles at future colliders from the precise measurement of the muon $g - 2$ is also discussed. The present 1-$\sigma$ constraint (2) from the muon $g - 2$ measurement implies that either a chargino or charged sleptons are within the discovery limit of a 500 GeV lepton collider for any $\tan \beta(< 50)$ if the lighter chargino is dominantly wino ($\mu/M_2 \gtrsim 3$) or dominantly higgsino ($0 < \mu/M_2 \lesssim 0.3$).

**Acknowledgements**

The authors thank S. Eidelman, M. Hayakawa and J.H. Kühn for fruitful discussions.

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