On Yukawa quasi-unification with $\mu < 0$

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Although recent data on the muon anomalous magnetic moment strongly disfavor the constrained minimal supersymmetric standard model with $\mu < 0$, they cannot exclude it because of theoretical ambiguities. We consider this model supplemented by a Yukawa quasi-unification condition which allows an acceptable $b$-quark mass. We find that the cosmological upper bound on the lightest sparticle mass is incompatible with the data on the branching ratio of $b \rightarrow s\gamma$, which is evaluated by including all the next-to-leading order corrections. Thus, this scheme is not viable.

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The constrained minimal supersymmetric standard model (CMSSM), which is a predictive version of the minimal supersymmetric standard model (MSSM) based on universal boundary conditions, can be further restricted by being embedded in a supersymmetric (SUSY) grand unified theory (GUT) with a gauge group containing $SU(4)$ and $SU(2)_R$. This can lead to Yukawa unification [2], i.e., the exact unification of the third generation ‘asymptotic’ Yukawa couplings. However, for both signs of the MSSM parameter $\mu$, the CMSSM supplemented by the assumption of exact Yukawa unification yields unacceptable values of the $b$-quark mass. This is due to the generation of sizeable SUSY corrections to $m_b$ which have the sign of $\mu$. The predicted tree-level $m_b(M_Z)$, which turns out to be close to the upper edge of its 95% confidence level (c.l.) experimental range $2.684 - 3.092$ GeV, receives, for $\mu > 0$ ($\mu < 0$), large positive (negative) corrections which drive it well above (a little below) the allowed range. This range is derived from the 95% c.l. range for $m_b(m_b)$ in the MSS scheme $3.95 - 4.55$ GeV [3] evolved up to $M_Z$ in accord with the analysis of Ref. [4] and with $\alpha_s(M_Z) = 0.1185$.

In Ref. [6], we have built SUSY GUT models based on the Pati-Salam gauge group $SU(4)_c \times SU(2)_L \times SU(2)_R$ which moderately violate Yukawa unification and, thus, can allow an acceptable $b$-quark mass for both signs of $\mu$ even with universal boundary conditions. These models yield a class of ‘asymptotic’ Yukawa quasi-unification conditions (YQUCs) replacing exact Yukawa unification. Suplementing the CMSSM with one of these YQUCs, we achieved [6] for $\mu > 0$, an acceptable $m_b(M_Z)$ in accord with all the phenomenological and cosmological requirements. The corresponding SUSY GUT model leads [5] to a new version of shifted hybrid inflation [8].

Here, we will examine whether the CMSSM with a YQUC can yield an acceptable $m_b(M_Z)$ in accord with all the available constraints for $\mu < 0$ too. In this case, compatibility of the $b$-quark mass with the data requires a deviation from Yukawa unification which is much smaller than the one needed for $\mu > 0$. Consequently, there is no need to extend the simplest SUSY GUT model of Ref. [3], which yields a suppressed violation of Yukawa unification originating from non-renormalizable interactions.

The CMSSM with $\mu < 0$ is now strongly disfavored (but not excluded [9]) by the constraint on the deviation, $\delta a_\mu$, of the measured value of the muon anomalous magnetic moment $a_\mu$ from its predicted value in the standard model (SM) $a_\mu^{SM}$. The recent data [10] on $a_\mu$ confirm the earlier ones [11] but their precision is twice that of the previous data. On the other hand, $a_\mu^{SM}$ is not yet stabilized. This is mainly due to the hadronic vacuum polarization contribution. According to the most updated [12] evaluation of this contribution, there is a considerable discrepancy between the results based on $e^+e^-$ data and on $\tau$ data. Taking into account both results, we obtain the 95% c.l. range $-4.7 \times 10^{-10} \leq \delta a_\mu \leq 56 \times 10^{-10}$, where the negative values are allowed only by the $\tau$-based calculation. Using the formulae of Ref. [13], we calculate $\delta a_\mu$ in the CMSSM and we observe that the result is negative (positive) for $\mu < 0$ ($\mu > 0$) and increases (decreases) as the lightest sparticle (LSP) mass $m_{LSP}$ increases. Consequently, a lower bound on $m_{LSP}$ can be derived from the lower (upper) experimental limit on $\delta a_\mu$ for $\mu < 0$ ($\mu > 0$). Also, we see that $\mu < 0$ is allowed only by the $\tau$-based calculation.

The CMSSM with $\mu < 0$ is, also, severely restricted by the recent experimental results [14] on the inclusive branching ratio $BR(b \rightarrow s\gamma)$. We compute this branching ratio by using an updated version of the relevant calculation in the micrOMEGAs code [12]. Comparing carefully this version with our calculation of $BR(b \rightarrow s\gamma)$ in Ref. [6], we concluded that this improved version is complete and reliable. The SM contribution is calculated by using the formalism of Ref. [15] and incorporating the improvements of Ref. [16]. The charged Higgs boson $(H^\pm)$ contribution is evaluated by including the next-to-
leading order (NLO) QCD corrections from Ref. 18 and the \( \tan \beta \) enhanced contributions from Ref. 19. The dominant SUSY contribution includes resummed NLO SUSY QCD corrections from Ref. 13, which hold for large \( \tan \beta \). The \( H^\pm \) contribution interferes constructively with the SM contribution, while the SUSY one interferes constructively (destructively) with the other two contributions when \( \mu < 0 \) \((\mu > 0)\). The SM plus \( H^\pm \) and the SUSY contributions decrease as \( m_{\text{LSP}} \) increases and so, for \( \mu < 0 \), an additional lower bound on \( m_{\text{LSP}} \) can be derived \( 20 \) from the upper experimental limit on this branching ratio. At 95% c.l., the experimental range of \( BR(b \to s\gamma) \) is estimated \( 6 \) by combining appropriately the various experimental and theoretical errors involved. The result is \( 1.9 \times 10^{-4} \lesssim BR(b \to s\gamma) \lesssim 4.6 \times 10^{-4} \). We find that the NLO corrections reduce \( BR(b \to s\gamma) \) by 10 – 15%. In Ref. 21 (which adopts the opposite sign convention for \( \mu \)), where the \( \tan \beta \) enhanced and NLO SUSY QCD corrections were ignored, the reduction was considerably higher yielding a less stringent restriction.

The LSP mass is bounded above by the requirement that the LSP relic abundance \( \Omega_{\text{LSP}}h^2 \) in the universe does not exceed the upper limit on the cold dark matter (CDM) abundance derived from observations. Recent results \( 22 \) suggest that, at 95% c.l., \( \Omega_{\text{LSP}}h^2 \lesssim 0.22 \). In general, \( \Omega_{\text{LSP}}h^2 \) increases with \( m_{\text{LSP}} \). So, its value is expected to be quite large due to the large \( m_{\text{LSP}} \)’s required by the constraints from \( \delta m_\mu \) and, especially, \( b \to s\gamma \). The \( \Omega_{\text{LSP}}h^2 \) is calculated by using micrOMEGAs \( 17 \), which is the most complete code available at present. It includes accurately thermally averaged exact tree-level cross sections of all possible (co)annihilation processes and treats pole effects properly with one-loop QCD corrected decay widths. In the model which we will consider, the LSP is an almost pure bino \( (\tilde{\chi}) \) and the next-to-LSP (NLSP) \((\tilde{\chi}) \) is the lightest stau \( (\tilde{\tau}_2) \). Important annihilation channels are not only the ones with fermions \( ff \) in the final state, but also the ones with \( HZ, W^\pm H^\mp, hA \) \( 23 \) \((h, H \) are the CP-even neutral Higgs bosons and \( A \) the CP-odd neutral Higgs boson). On the other hand, as we can observe from the particle spectrum of the model \( (\text{see Fig. 1}) \), \( m_A \) is much smaller than \( 2m_{\text{LSP}} \). So, the LSP annihilation via the s-channel exchange of an \( A \)-boson is not enhanced as in the \( \mu > 0 \) case \( 6, 24 \). As a consequence, the only available mechanism for reducing \( \Omega_{\text{LSP}}h^2 \) is bino-stau coannihilation \( 6, 21, 22, 26 \) \( (\text{for an updated analysis, see Ref. 27}) \), which is activated when \( \Delta_\tau = (m_{\tilde{\tau}_2} - m_{\text{LSP}})/m_{\text{LSP}} \), is reduced below about 0.25. For fixed \( m_{\text{LSP}} \), \( \Omega_{\text{LSP}}h^2 \) decreases with \( \Delta_\tau \), since coannihilation becomes more efficient. So the CDM bound yields an upper limit on \( \Delta_\tau \).

We will consider here the CMSSM with \( \mu < 0 \) which results from the simplest SUSY GUT model constructed in Ref. 6 without the extra Higgs superfields \( \phi, \phi, 0, \phi' \). To reduce the number of free parameters, we will further assume that the non-renormalizable \( SU(2)_R \) triplet coupling of Ref. 6 which leads to violation of Yukawa unification is suppressed. The violation is then achieved predominantly via the non-renormalizable \( SU(2)_R \) singlet coupling of Ref. 6 and, thus, \( \alpha_1 = \alpha_2 \) in Eq. (15) of this reference, with \( \alpha_1, \alpha_2 \) of order 0.1 or smaller. Note that the other alternative with the triplet coupling dominating, which was studied in Ref. 6 with \( \mu > 0 \), is not viable for \( \mu < 0 \) since it leads to a charged LSP. Under the above assumptions, the YQUC takes the form:

\[
\left| h_1 \right| : \left| h_2 \right| : \left| h_\tau \right| = |1 - c| : |1 - c| : |1 + 3c|, \tag{1}
\]

where \( c \) is a complex parameter of order 0.1 or smaller. We will take \( c < 0 \), where the maximal splitting between \( h_1, h_\tau \) and, thus, the largest enhancement of \( m_6(M_Z) \) is achieved for fixed \( |c| \neq 0 \). For \(-1/3 < c < 0 \), this splitting is \(-\delta h \equiv (h_1 - h_\tau)/h_0 = -4c/(1 - c) \). We see that the tau Yukawa coupling becomes smaller than the top and bottom Yukawa couplings which remain unified, in contrast to the \( \mu > 0 \) case of Ref. 6, where the tau and bottom Yukawa couplings split from the top Yukawa coupling by the same amount. The SUSY GUT model used leads \( 8 \) to successful shifted hybrid inflation.

Below the GUT scale \( M_{\text{GUT}} \), this SUSY GUT model reduces to the CMSSM with universal soft SUSY breaking scalar masses \( m_0 \), gaugino masses \( M_{1/2} \), and trilinear scalar couplings \( A_0 \) at \( M_{\text{GUT}} \). It also applies the YQUC in Eq. (11). We closely follow the renormalization group and radiative electroweak breaking analysis of Ref. 6. The conditions for electroweak breaking are imposed on an optimized scale \( M_{\text{SUSY}} = (m_{\tilde{t}_1}m_{\tilde{t}_2})^{1/2} \) \( (\tilde{t}_{1,2} \) are the stop mass eigenstates), where the particle spectrum is also evaluated. We incorporate the two-loop corrections to the CP-even neutral Higgs boson mass matrix by using FeynHiggsFast \( 28 \) and the SUSY corrections to \( m_6(M_{\text{SUSY}}) \) and \( m_6(M_{\text{SUSY}}) \) from Ref. 29. The corrections to \( m_6(M_{\text{SUSY}}) \) lead \( 21 \) to a small enhancement of \( \tan \beta \). For \( m_6(M_{1}) = 166 \text{ GeV} \), \( m_6(M_Z) = 1.746 \text{ GeV} \), and any given \( m_6(M_Z) \) in its 95% c.l. range \((2.684 - 3.092 \text{ GeV}) \), we can determine the parameters \( c \) and \( \tan \beta \) at \( M_{\text{SUSY}} \) so that the YQUC in

![Figure 1](image-url)
Eq. (1) is satisfied. We are then left with only three free input parameters \(m_0\), \(M_{1/2}\) and \(A_0\). The first two can be replaced \([21]\) by \(m_{\text{SP}}\) and \(\Delta \tau_2\). In Fig. 1 we present the values of \(m_A\), \(m_0\), \(M_{1/2}\) and \(M_{\text{USY}}\) versus \(m_{\text{LSP}}\) for \(A_0 = 0\), \(\Delta \tau_2 = 0\), \(m_b(M_Z) = 2.888\) GeV. These values are affected very little by varying \(m_b(M_Z)\). Our scheme, unlike the \(\mu > 0\) model of Ref. [6], yields \(2m_{\text{LSP}} \gg m_A\).

The restrictions on the \(m_{\text{LSP}} - \Delta \tau_2\) plane for \(A_0 = 0\) and any \(m_b(M_Z)\) in its 95\% c.l. range are given in Fig. 2. The lower bound on \(m_{\text{LSP}}\) from \(\delta \alpha_\mu \gtrsim -4.7 \times 10^{-10}\) corresponds to \(m_b(M_Z) \approx 3.092\) GeV and is represented by a solid line. The maximal \(\Delta \tau_2\) on this line is about 0.0105 and yields \(\Omega_{\text{LSP}} h^2 \approx 0.22\) for the same value of \(m_b(M_Z)\). As \(m_b(M_Z)\) decreases, the maximal \(\Delta \tau_2\) from \(\Omega_{\text{LSP}} h^2 \leq 0.22\) increases along the double dot-dashed line and reaches its overall maximal value \(\Delta \tau_2 \approx 0.0142\) at \(m_b(M_Z) \approx 2.684\) GeV. The upper bound on \(m_{\text{LSP}}\) from \(\Omega_{\text{LSP}} h^2 \leq 0.22\) is achieved at \(m_b(M_Z) \approx 2.684\) GeV and corresponds to the dashed line. In the lightly shaded region allowed by \(\delta \alpha_\mu\) and CDM considerations, \(612.4\) GeV \(\lesssim m_{\text{LSP}} \lesssim 873.4\) GeV. The maximal \(m_{\text{LSP}}\) is achieved at \(\Delta \tau_2 = 0\) yielding \(\text{BR}(b \rightarrow s\gamma) \approx 5.26 \times 10^{-4}\). The lower bound on \(m_{\text{LSP}}\) (dot-dashed line) from \(\text{BR}(b \rightarrow s\gamma) \lesssim 4.6 \times 10^{-4}\) corresponds to \(m_b(M_Z) \approx 3.092\) GeV. In the corresponding allowed (dark shaded) area, \(m_{\text{LSP}} \approx 1305.04\) GeV with the minimal \(m_{\text{LSP}}\) achieved at \(\Delta \tau_2 = 0\) and yielding \(\Omega_{\text{LSP}} h^2 \approx 0.65\). So, for \(A_0 = 0\), there is no region where all the restrictions are satisfied. Note that the constraints \(\text{BR}(b \rightarrow s\gamma) \gtrsim 1.9 \times 10^{-4}\) and \(\delta \alpha_\mu \gtrsim 56 \times 10^{-10}\) always hold for the CMSSM with \(\mu < 0\). Also, \(m_b \gtrsim 114.4\) GeV \([30]\) is valid due to the heavy SUSY spectrum.

Departure from the \(A_0 = 0\) case does not change our conclusion as we can see from Fig. 3 where the restrictions on the \(m_{\text{LSP}} - A_0/M_{1/2}\) plane are presented for any \(\Delta \tau_2\) and any allowed \(m_b(M_Z)\). Actually, we can just take \(\Delta \tau_2 = 0\), where all the constraints happen to become as less restrictive as possible for any given \(A_0\) (see Fig. 2). We follow the same notation for the various lines and areas as in Fig. 2. For \(\sim 1.84 \lesssim A_0/M_{1/2} \lesssim 1.21\) \((-1.67 \lesssim A_0/M_{1/2} \lesssim 1.03\) the solid (dashed) line corresponds to \(\delta \alpha_\mu \approx -4.7 \times 10^{-10}\) \((\Omega_{\text{LSP}} h^2 \approx 0.22\) with \(m_b(M_Z) \approx 3.092\) GeV \((2.684\) GeV). As \(|A_0|\) increases, \(m_A\) decreases and reaches its lowest allowed value \((\approx 100\) GeV for the \(\tan \beta\)'s encountered here \([31]\)) on the boundaries of the lightly shaded regions for fixed \(A_0\). Allowing \(m_b(M_Z)\) to increase from its lower value, we then obtain the upper and lower inclined parts of the dashed line corresponding to \(m_A \approx 100\) GeV. Their end points lie at \(A_0/M_{1/2} \approx 1.21, -1.84\), where \(m_b(M_Z)\) is maximized. At the maximal (minimal) \(m_{\text{LSP}}\) on the dotted line (inclined parts of the solid line), \(\Omega_{\text{LSP}} h^2 \lesssim 0.22\) \((\delta \alpha_\mu \gtrsim -4.7 \times 10^{-10}\) is not saturated, due to the combined requirements \(m_A \gtrsim 100\) GeV and \(m_{\tau_2} \gtrsim m_\tau\).

The maximal \(m_{\text{LSP}}\) in the lightly shaded area of Fig. 3, which is allowed by \(\delta \alpha_\mu\) and CDM considerations, and for \(A_0/M_{1/2} > 0\) \((< 0)\) is \(m_{\text{LSP}} \approx 868\) GeV \((967.3\) GeV) and is achieved at \(A_0/M_{1/2} \approx 1.03\) \((-1.67\) This corresponds to the upper (lower) corner of the dashed line, where \(\text{BR}(b \rightarrow s\gamma) \approx 5.58 \times 10^{-4}\) \((5.45 \times 10^{-4}\). Note that, for \(A_0/M_{1/2} < 0\), the processes \(t_2 \rightarrow W^\pm H^\mp, Z\) become more efficient. Their total contribution to the effective cross section is \(3 - 6.5\%\) as \(A_0/M_{1/2}\) decreases from 0 to \(-1.67\). So, coannihilation is strengthened and bigger \(m_{\text{LSP}}\)'s are allowed than for \(A_0/M_{1/2} > 0\). The minimal \(m_{\text{LSP}}\) in the dark shaded area, allowed by \(b \rightarrow s\gamma\), is \(m_{\text{LSP}} \approx 1295\) GeV and is achieved at \(A_0/M_{1/2} \approx -0.2\), where \(\Omega_{\text{LSP}} h^2 \approx 0.62\). Thus, even for \(A_0 \neq 0\), there is no range of parameters allowed by all the constraints.

In the lightly shaded area of Fig. 3 \(\tan \beta\)'s \((c)\) ranges between about \(44.1\) \((-0.09)\) and \(51.5\) \((-0.007)\). These values are achieved at the lowest corner of this area \((A_0/M_{1/2} \approx -1.89\), \(m_b(M_Z) \approx 3.092\) GeV) and the
upper corner of the dashed line ($A_0/M_{1/2} \simeq 1.03$, $m_0(M_Z) \geq 2.684$ GeV) respectively. Consequently, the splitting $-\delta h$ ranges from about 0.33 to 0.028. However, fixing $m_0(M_Z)$ to its central value, the range of $-\delta h$ is reduced to 0.13–0.09 corresponding to 47.6 $\lesssim \tan \beta \lesssim 49$ and $-0.038 \lesssim \delta \lesssim -0.024$.

The present investigation is an improved version of our analysis in Ref. [21] (the sign of $\mu$ there is opposite to the one adopted here). The main improvements are the replacement of Yukawa unification by the YQUC of Eq. (11) in connection with the more stringent present bounds on $m_b$, the consideration of the $\delta \alpha_\mu$ constraint [12], the inclusion of the NLO SUSY QCD and $\tan \beta$ enhanced corrections [14] in BR($b \to s\gamma$), and the evaluation of $\Omega_{\text{LSP}} h^2$ by the updated code of Ref. [15]. These improvements turn out to be of crucial importance overruling our previous conclusion. Our results are essentially unaffected by allowing $\alpha_s(M_Z)$ to vary in its 95% c.l. range, which slightly enlarges the range of $m_0(M_Z)$. This is due to the fact that, here, the LSP annihilation to $b\bar{b}$ via an $A$-pole exchange is subdominant in $\Omega_{\text{LSP}} h^2$.

In summary, we studied the CMSSM with $\mu < 0$ and a YQUC from the simplest SUSY GUT of Ref. [22]. We imposed the constraints from $m_b$, $\delta \alpha_\mu$, $b \to s\gamma$ and CDM. Although the NLO corrections to $b \to s\gamma$ (coanniliations) drastically reduce (enhance) the lower (upper) bound on $m_{\text{LSP}}$, the $b \to s\gamma$ and CDM requirements remain incompatible. Thus, despite the fact that, with the $\tau$-based calculation of $\alpha_\mu^\text{SM}$, the $\delta \alpha_\mu$ and CDM criteria can be simultaneously valid, this model is excluded.

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