Chargino and neutralino contributions to $(g_\mu - 2)$

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Abstract

Analytical formulae for the chargino and neutralino contributions to the muon anomalous magnetic moment in the framework of MSSM are presented in the basis of physical chargino and neutralino states. They are derived for arbitrary values of supeparticles masses and $\tan\beta$. The analytical formulae for corresponding anomalous magnetic moment type loop integrals are derived.

1 Introduction

The muon anomalous magnetic moment (AMM), $a_\mu \equiv \frac{1}{2}(g-2)_\mu$, measured with the great accuracy presents the test for the standard model (SM). The SM deviation δa_μ from the experimental result for a_μ (Table 1) can testify a new physics beyond SM manifestation such as the supersymmetry (SUSY), the muon or W gauge boson substructure [1, 2].

Table 1: a_μ^{SM} theoretical prediction deviation δa_μ from the experimental result a_μ^{exp} (all values in the units of 10^{-10}).

Quantity	Value $\times 10^{10}$	*References*	*Commentary*
a_μ^{exp}	11 659 203(15)	[3, 4]	1999 data, rel. mist. 1.3 ppm
a_μ^{SM}	11 659 176.7(6.7)	[4, 5]	theory (SM) 0.6 ppm
$\delta a_\mu \equiv a_\mu^{exp} - a_\mu^{SM}$	26(16)	[4, 5]	average deviation 1.6σ
a_μ^{new} range	[− 6 ; 58]	[6]	2σ region

The value of deviation δa_μ have changed during year the 2001 from 2.6σ [1] (February) to average 1.6σ (December). The last value is 1.7 larger than the SM electroweak contribution to a_μ. The decrease of δa_μ stems mainly from the changing sign [7] (November) of the pion pole part of the light-by-light contribution [8, 9] (June), and it has been confirmed in articles [10, 11, 12] and in recent revisited reviews [13, 14] (December).

The accuracy of the Brookhaven E821 experiment is of the order of the $W^\pm$- and Z-boson loop contribution (Table 2). Furthermore, the new experiment is supposed to reduce the error to 4×10^{-10} which is smaller than the present one by a factor almost 4. Also this supposed error is less than half of the hadron light-by-light contribution and than the uncertainty of the theoretical result. The major part of the uncertainties come from hadrons in the photon vacuum polarization diagram and also from hadrons in the light-by-light scatering diagram. However, before making any conclusions, it is necessary to have a more precise theoretical result than the experimental planned one.

Table 2: The SM contributions to a_μ

Quantity	Value $\times 10^{10}$ December, 2001	*References*	*Comments*
a_μ^{QED}	11 658 470.6(0.3)	[15]	$\mathcal{O}(\alpha^5)$ estimation
a_μ^{Had} (vacuum polar.)	684.9(6.4)	[14, 13]	3-loop estimation
a_μ^{EW}	15.1(0.4)	[16, 17] [18, 19, 20]	2-loop, $M_H \approx 150$ GeV
a_μ^{Had} (light-by-light)	8.6(3.2)	[14, 12, 7] [21, 10, 11]	$\mathcal{O}(\alpha^3)$

The new level of accuracy had changed the physical meaning of result radically. The theoretical calculations of the muon AMM value in the SM frames have estimated the error to be less than 1 ppm. At the same time some interactions beyond SM give relative contributions to the muon AMM of the order 1 ppm. And this opens the posibility of their analysis. One of the main motivations for experiment on the muon AMM was to confront the SM, and to search for possible contributions from non-standard model physics [2].

One of the possible reasons for the decreased SM theoretical value of a_μ may be the additional contribution in the supersymmetry models framewoks via the neutralino-smuon and chargino-sneitrino loops [22, 23, 1]:

$$a_\mu^{SUSY} = a_\mu(\tilde{\chi}^\pm) + a_\mu(\tilde{\chi}^0). \tag{1}$$

Even if we do not have high energy colliders, we can constrain SUSY models by using precision measurements in low energy experiments. This is because superparticles contribute to low energy physics through radiative corrections.

In fact, there were several works in which the muon AMM is calculated in the framework of SUSY models depending on the fundamental parameters: the higgsino μ (characterizes Higgs mixing) and $SU(2)$ gaugino M_2 mass parameters and the ratio of the Higgs vacuum expectation values $\tan\beta \equiv v_2/v_1$ (β is the mixing angle in the Higgs CP-odd and charged sectors, $0 \leq \beta \leq \frac{\pi}{2}$). The common formulae were obtained in works [24, 25]. In [26, 27] the estimation of the supersymmetric quantum contributions to the muon AMM in the framework of the CP-invariant minimal supersymmetric standard model (MSSM) for limit ranges of μ M_2: $\mu >> M_2$, $\mu << M_2$, $\mu \approx M_2$ was presented. It was shown that taking into account mixing parameter of light chargino leads to the increase in the MSSM contribution. In ref. [28] maximum values of contributions were obtained in frames of the MSSM for large and small $\tan\beta$.

In this article, the chargino and neutralino a_μ contributions depending on parameters of MSSM are presented. Analytical formulae for the chargino and neutralino contributions to the muon AMM in the framework of MSSM obtained in the basis of chargino and neutralino states. They are derived for arbitrary values of supeparticles masses and $\tan\beta$, without using the large loop masses and $\tan\beta$ approximations for loop integration. The analytical formulae for anomalous magnetic moment type loop integrals are derived.

2 Analytical formulae

The lagrangian, describing the interaction between chargino $\tilde{\chi}_j^+$ ($j=1,2$), muon μ and muon (left or right) sneutrino $\tilde{\nu}_{\mu L}$, $\tilde{\nu}_{\mu R}$, for chargino mass eigenstates in the $\{\tilde{\nu}_{\mu L}, \tilde{\nu}_{\mu R}\}$ basis is following [29, 30, 31]:

$$\mathcal{L}_{\mu\tilde{\nu}_\mu\tilde{\chi}^+} = \bar{\mu}(L_{Lj}P_R + L_{Rj}P_L)\tilde{\chi}_j^{+C}\tilde{\nu}_{\mu L} + \bar{\mu}(R_{Lj}P_R)\tilde{\chi}_j^{+C}\tilde{\nu}_{\mu R} +$$

$$+\bar{\tilde{\chi}}_j^{+C}(L_{Lj}P_L + L_{Rj}P_R)\mu\tilde{\nu}^*_{\mu L} + \bar{\tilde{\chi}}_j^{+C}(R_{Lj}P_L)\mu\tilde{\nu}^*_{\mu R}\,, \tag{2}$$

$$L_{Lj} \equiv -gV_{j1}\,, \quad L_{Rj} \equiv gY_\mu U_{j2}\,, \quad R_{Lj} \equiv gY_{\nu_\mu}U_{j2}\,, \quad R_{Rj} \equiv 0\,. \tag{3}$$

Y_μ and Y_{ν_μ} – Yukawa couplings, g – $SU(2)$ gauge constant:

$$g = \frac{\sqrt{4\pi\alpha}}{\sin\theta_W}\,, \quad Y_\mu = \frac{m}{\sqrt{2}m_W\cos\beta}\,, \quad Y_{\nu_\mu} = \frac{m_{\nu_\mu}}{\sqrt{2}m_W\sin\beta}\,. \tag{4}$$

Here and below m – the muon mass, $P_L \equiv \frac{1}{2}(\hat{1}-\gamma_5)$ and $P_R \equiv \frac{1}{2}(\hat{1}+\gamma_5)$ – operators of the projection on spirality, U and V – matrices of the transformation for chargino with elements [31]

$$U_{12} = U_{21} = \frac{\theta_1}{\sqrt{2}}\sqrt{1 + \frac{M_2^2 - \mu^2 - 2m_W^2\cos 2\beta}{W}}\,, \tag{5}$$

$$U_{22} = -U_{11} = \frac{\theta_2}{\sqrt{2}}\sqrt{1 - \frac{M_2^2 - \mu^2 - 2m_W^2\cos 2\beta}{W}}\,, \tag{6}$$

$$V_{21} = -U_{12} = \frac{\theta_3}{\sqrt{2}}\sqrt{1 + \frac{M_2^2 - \mu^2 + 2m_W^2\cos 2\beta}{W}}\,, \tag{7}$$

$$V_{22} = V_{11} = \frac{\theta_4}{\sqrt{2}}\sqrt{1 - \frac{M_2^2 - \mu^2 + 2m_W^2\cos 2\beta}{W}}\,, \tag{8}$$

where

$$W = \sqrt{(M_2^2 + \mu^2 + 2m_W^2)^2 - 4(M_2\mu - m_W^2\sin 2\beta)^2}\,, \tag{9}$$

$$\{\theta_1, \theta_2, \theta_3, \theta_4\} = \{1, \varepsilon_B, \varepsilon_A, 1\} \qquad \text{for} \quad tg\beta > 1, \tag{10}$$

$$\varepsilon_A = sign(M_2\sin\beta + \mu\cos\beta), \quad \varepsilon_B = sign(M_2\cos\beta + \mu\sin\beta). \tag{11}$$

The amplitude for the photon-muon-muon coupling can be written as

$$i\mathcal{M} = -ie\tilde{A}_\mu^{Cl}(q)\bar{u}(p')\Gamma^\mu u(p). \tag{12}$$

The vertex operator Γ^μ in the oneloop approximation is equal $\gamma^\mu + \Lambda^\mu$. The contribution in the oneloop correction Λ^μ, due to the interaction muon with supersymmetric chargino and sneutrino (left and right), is determined by the Feynman rules from kinetic, mass terms of the lagrangian and interaction $\mathcal{L}_{\mu\tilde{\nu}_\mu\tilde{\chi}^+}$

$$\Lambda^\mu(\tilde{\chi}^\pm) = \sum_{j=1}^{2}\int\frac{d^4q}{(2\pi)^4}\times \tag{13}$$

$$\times \left\{ \frac{(iL_{Lj}P_R + iL_{Rj}P_L)i[\hat{p}' - \hat{k} + m_{\tilde{\chi}_j^+}]i\gamma^\mu i[\hat{p} - \hat{k} + m_{\tilde{\chi}_j^+}](iL_{Lj}P_L + iL_{Rj}P_R)}{[(p'-k)^2 - m^2_{\tilde{\chi}_j^+}][k^2 - M^2_{\tilde{\nu}_{\mu L}}][(p-k)^2 - m^2_{\tilde{\chi}_j^+}]} + \right.$$

$$\left. + \frac{(iR_{Lj}P_R)i[\hat{p}' - \hat{k} + m_{\tilde{\chi}_j^+}]i\gamma^\mu i[\hat{p} - \hat{k} + m_{\tilde{\chi}_j^+}](iR_{Lj}P_L)}{[(p'-k)^2 - m^2_{\tilde{\chi}_j^+}][k^2 - M^2_{\tilde{\nu}_{\mu R}}][(p-k)^2 - m^2_{\tilde{\chi}_j^+}]} \right\}.$$

Chargino masses $m_{\tilde{\chi}_j^+}$ [31]:

$$m_{\tilde{\chi}_1^+} = \frac{1}{2}\left|\sqrt{M_2 - \mu)^2 + 2m_W^2(1 + \sin 2\beta)} - \sqrt{M_2 + \mu)^2 + 2m_W^2(1 - \sin 2\beta)}\right|, \quad (14)$$

$$m_{\tilde{\chi}_2^+} = \frac{1}{2}\sqrt{M_2 - \mu)^2 + 2m_W^2(1 + \sin 2\beta)} + \sqrt{M_2 + \mu)^2 + 2m_W^2(1 - \sin 2\beta)}. \quad (15)$$

Standing out in the numerator of Λ^μ terms, determing the contribution in AMM, using the Feynman parametrization, leaving only convergent part and integrating over 4-momentum, we obtain the expression for vertex operator of the magnetic transmission amplitude (magnetic moment type operator) in lowest order. The coefficient at $(p + p')_\mu/(-2m)$ determines AMM a_μ. Thus, supposing $M^2_{\tilde{\nu}_{\mu R}} \approx M^2_{\tilde{\nu}_{\mu L}} = M_L^2 + \frac{1}{2}m_Z^2 \cos 2\beta \equiv M^2_{\tilde{\nu}_\mu}$.

$$a_\mu(\tilde{\chi}^\pm) = \frac{2}{16\pi^2}\times \quad (16)$$

$$\times \sum_{j=1}^{2} \left\{ (E_1 + E_2)_j \lambda_2(b_j, a) - \left[(E_1 + E_2)_j + (E_1 - E_2)_j \frac{m_{\tilde{\chi}_j}}{m} \right] \lambda_1(b_j, a) \right\} \times$$

$$\times \left(1 - \frac{2\alpha}{\pi} \ln \frac{M_{\tilde{\nu}_\mu} m_{\tilde{\chi}_j}}{m^2} \right),$$

where

$$b_j = a + \frac{m^2 - m^2_{\tilde{\chi}_j}}{2m^2}, \qquad a = \frac{M^2_{\tilde{\nu}_\mu}}{2m^2}. \quad (17)$$

In (16) we take into acount the leading logarithmic suppresion factor

$$1 - \frac{2\alpha}{\pi} \ln \frac{M_{\tilde{\nu}_\mu} m_{\tilde{\chi}_j}}{m}, \quad (18)$$

obtained in [19, 17]. It is due [1, 17] with leading 2-loop electroweak effects. E_{1j} and E_{2j} are determined by constants of the interaction:

$$E_{1j} = \left(i\frac{L_{Rj} + L_{Lj}}{2} \right)^2 + \left(i\frac{R_{Lj}}{2} \right)^2, \quad E_{2j} = \left(i\frac{L_{Rj} - L_{Lj}}{2} \right)^2 + \left(i\frac{R_{Lj}}{2} \right)^2. \quad (19)$$

Dimensionless λ_1, λ_2 and $\lambda_{\hat{1}}$, λ_0 (will arise in the neutralino contribution) are determined by integrals contributing in AMM:

$$\lambda_{\{0;1;\hat{1};2\}}\, \bar{u}(p')\, \frac{i}{16\pi^2} \left(-\frac{(p+p')^\mu}{2m} \right) u(p) \;= \quad (20)$$

$$= \int \frac{d^4q}{(2\pi)^4} \frac{\bar{u}(p')\left\{m(p+p')^\mu; mk^\mu; (p+p')^\mu \hat{k}; \hat{k}k^\mu\right\} u(p)}{[(p'-k)^2 - m^2_{\tilde{\chi}^+_j}][k^2 - M^2_{\tilde{\nu}_\mu}][(p-k)^2 - m^2_{\tilde{\chi}^+_j}]}\,.$$

The integration leads to the following analytical results:

$$\lambda_0 = \ln\left|\frac{1-2b+2a}{2a}\right| + 2bL(b,a), \tag{21}$$

$$\lambda_1 = 1 + b\ln\left|\frac{1-2b+2a}{2a}\right| + 2(b^2-a)L(b,a), \qquad \lambda_{\hat{1}} = 2\lambda_1, \tag{22}$$

$$\lambda_2 = \frac{1}{2} + 2b + (2b^2-a)\ln\left|\frac{1-2b+2a}{2a}\right| + 2(2b^3-3ab)L(b,a), \tag{23}$$

where $L(b,a)$ – the continuous function $(a>0)$

$$L(b,a) = \begin{cases} \frac{1}{2K(b,a)}\ln\left|\frac{-b+2a+K(b,a)}{-b+2a-K(b,a)}\right|, & b^2 > 2a, \qquad K(b,a) = \sqrt{|b^2-2a|}, \\ \frac{1}{2a-b}\,, & b^2 = 2a, \\ \frac{1}{K(b,a)}\left(\arctan\frac{1-b}{K(b,a)} + \arctan\frac{b}{K(b,a)}\right), & b^2 < 2a. \end{cases} \tag{24}$$

As the check the above expressions for the integrals were calculate the oneloop SM electroweak contributions in AMM. In particular, for inner muons in the loop $b=a$, formulae for λ_i become

$$\lambda_1 = 1 - a\ln(2a) + 2a(a-1)L(a), \tag{25}$$

$$\lambda_2 = \frac{1}{2} + 2a - a(2a-1)\ln(2a) + 2(2a^3-3a^2)L(a), \tag{26}$$

$$L(a) = \begin{cases} \frac{1}{2K(a)}\ln(a+K(a)-1), & a>2, \\ \frac{1}{2}\,, & a=2, \\ \frac{1}{K(a)}\arctan\left(\frac{K(a)}{a}\right), & 0<a<2, \end{cases} \qquad K(a) = \sqrt{a|2-a|}. \tag{27}$$

The lagrangian, describing the interaction between neutralino, muon and smuon for the neutralino eigenstates $\tilde{\chi}^0_j$ $(j=1,2,3,4)$ in $\{\tilde{\mu}_L, \tilde{\mu}_R\}$ basis, is presented by the following [29, 32]:

$$\begin{aligned} \mathcal{L}_{\mu\tilde{\mu}\tilde{\chi}^0} &= \bar{\mu}(L^0_{Lj}P_R + L^0_{Rj}P_L)\tilde{\chi}^0_j\tilde{\mu}_L + \bar{\mu}(R^0_{Lj}P_R + R^0_{Rj}P_L)\tilde{\chi}^0_j\tilde{\mu}_R + \\ &+ \bar{\tilde{\chi}}^0_j(L^0_{Lj}P_L + L^0_{Rj}P_R)\mu\tilde{\mu}^*_L + \bar{\tilde{\chi}}^0_j(R^0_{Lj}P_L + R^0_{Rj}P_R)\mu\tilde{\mu}^*_R, \end{aligned} \tag{28}$$

$$L^0_{Lj} \equiv -g\sqrt{2}\left(\sin\theta_W Z'_{j1} - \frac{\frac{1}{2}+\sin^2\theta_W}{\cos\theta_W}Z'_{j2}\right), \quad L^0_{Rj} = R^0_{Lj} \equiv -g\frac{m}{\sqrt{2}M_W\cos\beta}Z_{j3}, \tag{29}$$

$$R^0_{Rj} \equiv g\sqrt{2}\left(\sin\theta_W Z'_{j1} + \frac{\sin^2\theta_W}{\cos\theta_W}Z'_{j2}\right). \tag{30}$$

$$\Lambda^\mu(\tilde{\chi}^0) = \sum_{j=1}^{4}\int\frac{d^4q}{(2\pi)^4}\times \tag{31}$$

$$\times\left\{\frac{(iL^0_{Lj}P_R+iL^0_{Rj}P_L)ii[\hat{k}+M_{\tilde{\chi}^0_j}]i(iL^0_{Lj}P_L+iL^0_{Rj}P_R)(p+p'-2k)^\mu]}{[(p'-k)^2-m^2_{\tilde{\mu}L}][k^2-M^2_{\tilde{\chi}^0_j}][(p-k)^2-m^2_{\tilde{\mu}L}]}+\right.$$

$$\left.+\frac{(iR^0_{Lj}P_R+iR^0_{Rj}P_L)ii[\hat{k}+M_{\tilde{\chi}^0_j}]i(iR^0_{Lj}P_L+iR^0_{Rj}P_R)(p+p'-2k)^\mu]}{[(p'-k)^2-m^2_{\tilde{\mu}R}][k^2-M^2_{\tilde{\chi}^0_j}][(p-k)^2-m^2_{\tilde{\mu}R}]}\right\}.$$

In the case of the neutralinos, the four-dimensional neutralino mass matrix depends on the same three parameters $\tan\beta$, μ and M_2, if the grand unified theory (GUT) relation $M_1=\frac{5}{3}\tan^2\theta_W M_2$ [29] is used. Mass matrix can be diagonalized analytically [33] by a single real matrix Z. Corresponding analytical expressions can be found in [33, 34, 35].

$$a_\mu(\tilde{\chi}^0)=\frac{1}{16\pi^2}\times \tag{32}$$

$$\times\sum_{j=1}^{4}\left\{2C_{1j}[\lambda_1(b^0,a^0_j)-\lambda_2(b^0,a^0_j)]+\frac{M_{\tilde{\chi}^0_j}}{m}C_{2j}[\lambda_0(b^0,a^0_j)-2\lambda_1(b^0,a^0_j)]\right\}\times$$

$$\times\left(1-\frac{2\alpha}{\pi}\ln\frac{M_{\tilde{\chi}^0_j}m_{\tilde{\mu}}}{m^2}\right),$$

where

$$b^0=a+\frac{m^2-m^2_{\tilde{\mu}}}{2m^2},\qquad a^0_j=\frac{M^2_{\tilde{\chi}^0_j}}{2m^2}. \tag{33}$$

3 Conclusion

Analytical formulae for the chargino and neutralino contributions to the muon anomalous magnetic moment $(g_\mu-2)$ in the framework of MSSM are derived for arbitrary values of supeparticle masses and $\tan\beta$ in the basis of the physical states of the chargino and neutralino. The dependence of the result from the model parameters $\tan\beta$, μ and M_2 can be analysed using these symbolic representations.

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