The muon $(g-2)$ in MSSM: precision corrections and novel phenomenological scenario

Hyejung Stöckinger-Kim

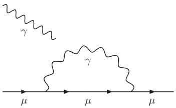
TU Dresden

with

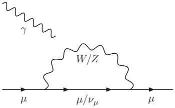
M. Bach, H. Fargnoli, C. Gnendiger, J. Park, S. Paßehr, D. Stöckinger

HEPKIT Karlsruhe, 6. Oct. 2015

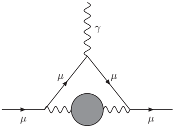
a_μ^{SM}



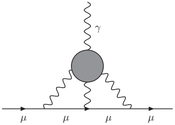
a_μ^{QED}



a_μ^{EW}



$a_\mu^{\mathrm{Had.VP}}$



$a_\mu^{\mathrm{Had.lbl}}$

- QED 5-loop calculation completed. [Kinoshita et al '12]
- Convergence of hadronic contributions.
- New BESIII results [1507:08188]
- Precision improvement in a_μ^{EW} : uncertainty caused by M_{H} eliminated $\Rightarrow$ $a_\mu^{\mathrm{EW}} = (154 \pm 1 \pm 2) \times 10^{-11}$ [Czarnecki, Krause, Marciano]
  $a_\mu^{\mathrm{EW}} = (153.6 \pm 1.0) \times 10^{-11}$ [Gnendiger, Stöckinger, S-K '13]
  with $M_{\mathrm{H}} = 125.6 \pm 1.5\,\mathrm{GeV}$

$a_\mu^{\rm Exp}$

- The latest result from BNL [Bennett et al. '06]
  $a_\mu^{\rm E821} = (11659208.9 \pm 6.3) \times 10^{-10}$
- New experiment at Fermilab E989:
  0.54 $\to$ 0.14 ppm.
  Current uncertainty in $a_\mu^{\rm SM}$: 0.42 ppm

Current status of $a_\mu^{\rm Exp} - a_\mu^{\rm SM}$

$$\Delta a_\mu(\mathrm{E821} - \mathrm{SM}) = \begin{cases} (28.7 \pm 8.0) \times 10^{-10} & \text{[Davier et al.]} \\ (26.1 \pm 8.0) \times 10^{-10} & \text{[Hagiwara et al.]} \end{cases}$$

$\sim 3...4\,\sigma$

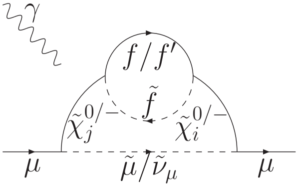
- This deviation motivates New Physics: SUSY can explain it.
- a_μ is an important constraint on SUSY
- Still, large contributions possible, e.g. if sleptons $<<$ squarks (non-traditional models)

[Endo, Hamaguchi, Iwamoto, Yanagida, D.P. Roy, et al]

a_μ in MSSM

1. MSSM loop corrections:

$f\tilde{f}$ two-loop



2. Radiative muon mass generation:

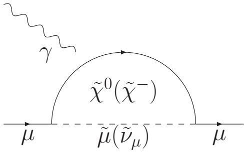
$$\tan\beta \equiv \frac{v_u}{v_d}\Big|_{v_d=0} \to \infty$$

MSSM loop corrections

MSSM loop corrections

1. MSSM one-loop corrections

- Parameter dependence:
  $\mu, M_1, M_2, M_L, M_E, \tan\beta$
- For the equal mass case:

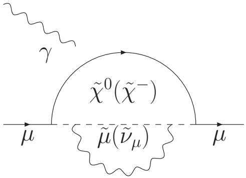


$$a_\mu^{\rm SUSY,1L} \approx 13 \times 10^{-10}\, {\rm sgn}(\mu) \tan\beta \left(\frac{100\,{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

2. MSSM photonic two-loop corrections

[v.Weitershausen, Schäfer, Stöckinger, S-K '10]

- $\sim \frac{\alpha}{4\pi} \log \frac{m_\mu}{m_{\tilde{\mu}}(m_{\tilde{\nu}_\mu})} \times a_\mu^{\rm SUSY,1L\chi^0(\chi^-)}$
- $-(7\ldots9)$ % for SUSY masses between 100 - 1000 GeV

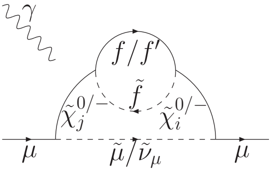


MSSM loop corrections

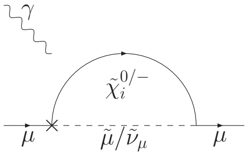
3. MSSM $f\tilde{f}$ two-loop corrections

[Fargnoli, Gnendiger, Paßehr, Stöckinger, S-K '13]

- Maximum complexity:
  5 heavy scales + 2 light scales
- Additional parameter dependence:
  $M_{Q_i}, M_{U_i}, M_{D_i}, M_{L_i}, M_{E_i}$, $i \in \{1,2,3\}$
- solve the one-loop ambiguity caused by α ⇒
- Non-decoupling behaviour ⇒



α ambiguity solved



$$= a_\mu^{\rm 1L} \times \left(\frac{\delta(e^2/s_W^2)}{e^2/s_W^2} + \ldots \right)$$
$$= a_\mu^{\rm 1L} \times \left(\Delta\alpha_{f,\tilde{f}} - \frac{c_W^2}{s_W^2} \Delta\rho_{f,\tilde{f}} + \ldots \right)$$

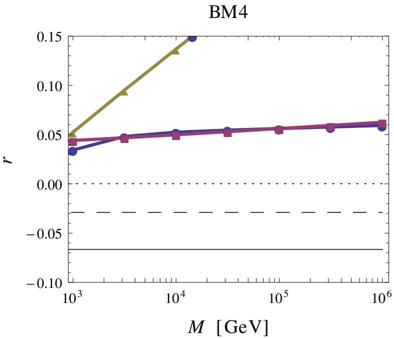
1-loop ambiguity — fixed by full 2-L $f\tilde{f}$

$$a_\mu^{\rm 1L}|\alpha(0) = 29.4 \times 10^{-10}$$
$$a_\mu^{\rm 1L}|\alpha(M_Z) = 31.6 \times 10^{-10}$$
$$a_\mu^{\rm 1L}|\alpha(G_F) = 30.5 \times 10^{-10}$$

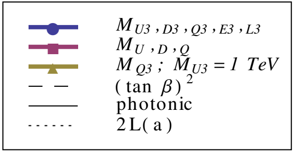
$$\Longrightarrow a_\mu^{\rm 1L+2Lf\tilde{f}} = 32.2 \times 10^{-10}$$

Difference from $\Delta\alpha$ and $\Delta\rho$: 2-loop $f\tilde{f}$ terms.

$f\tilde{f}$-loop corrections: Non-decoupling behaviour



- $M_2, m_{\tilde{\mu}_L} >> M_1, m_{\tilde{\mu}_R}$
- $M_1 = 140\mathrm{GeV}$
- $m_{\tilde{\mu}_R} = 200\mathrm{GeV}$
- $M_2 = m_{\tilde{\mu}_L} = 2000\mathrm{GeV}$
- $\mu = -160$, $\tan\beta = 40$
- $\mathcal{O}(10...30\%)$



Leading logarithmic approximation

[http://iktp.tu-dresden.de/index.php?id=theory-software]

$$a_\mu^{\rm 1LSUSY,M.I.} = a_\mu^{\rm 1L}(\tilde{W}\text{–}\tilde{H}, \tilde{\nu}_\mu) + a_\mu^{\rm 1L}(\tilde{W}\text{–}\tilde{H}, \tilde{\mu}_L) + a_\mu^{\rm 1L}(\tilde{B}\text{–}\tilde{H}, \tilde{\mu}_L) + a_\mu^{\rm 1L}(\tilde{B}\text{–}\tilde{H}, \tilde{\mu}_R) + a_\mu^{\rm 1L}(\tilde{B}, \tilde{\mu}_L\text{–}\tilde{\mu}_R)$$

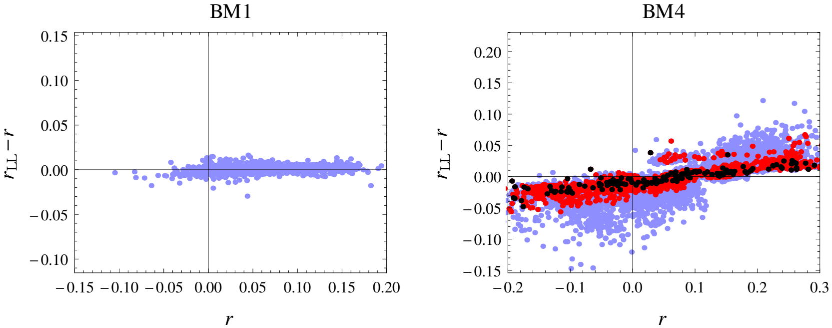
$$a_\mu^{\rm 1L}(\tilde{W}/\tilde{B}, \ldots) \propto g_{2/1}^2 \mu \tan\beta$$

$$\begin{aligned} a_\mu^{2{\rm L}, f\tilde{f}{\rm LL}} &= a_\mu^{\rm 1L}(\tilde{W}\text{–}\tilde{H}, \tilde{\nu}_\mu)\left(\Delta_{g_2} + \Delta_{\tilde{H}} + \Delta_{\tilde{W}\tilde{H}} + \Delta_{t_\beta} + 0.015\right), \\ &+ a_\mu^{\rm 1L}(\tilde{W}\text{–}\tilde{H}, \tilde{\mu}_L)\left(\Delta_{g_2} + \Delta_{\tilde{H}} + \Delta_{\tilde{W}\tilde{H}} + \Delta_{t_\beta} + 0.015\right), \\ &+ a_\mu^{\rm 1L}(\tilde{B}\text{–}\tilde{H}, \tilde{\mu}_L)\left(\Delta_{g_1} + \Delta_{\tilde{H}} + \Delta_{\tilde{B}\tilde{H}} + \Delta_{t_\beta} + 0.015\right), \\ &+ a_\mu^{\rm 1L}(\tilde{B}\text{–}\tilde{H}, \tilde{\mu}_R)\left(\Delta_{g_1} + \Delta_{\tilde{H}} + \Delta_{\tilde{B}\tilde{H}} + \Delta_{t_\beta} + 0.04\right), \\ &+ a_\mu^{\rm 1L}(\tilde{B}, \tilde{\mu}_L\text{–}\tilde{\mu}_R)\left(\Delta_{g_1} + \Delta_{t_\beta} + 0.03\right) \end{aligned}$$

$$\Delta_{\tilde{H}} = \frac{1}{16\pi^2}\frac{1}{2}\left(3y_t^2 \log\frac{M_{U3}}{m_{\rm SUSY}} + 3y_b^2 \log\frac{M_{D3}}{m_{\rm SUSY}} + 3(y_t^2 + y_b^2)\log\frac{M_{Q3}}{m_{\rm SUSY}} + y_\tau^2 \log\frac{M_{E3}}{m_{\rm SUSY}} + y_\tau^2 \log\frac{M_{L3}}{m_{\rm SUSY}}\right)$$

Leading logarithmic approximation

[PLB 726 (2013)][arXiv:1309.0980][Fargnoli, Gnendiger, Paßehr, Stöckinger, S-K '13]



[GeV]	BM1	BM4
μ	[100,200]	[-200,-100]
M_1	[100,200]	[100,200]
M_2	[200,400]	[1000,3000]
M_E	[200,500]	[100,300]
M_L	[200,500]	[1000,3000]

$r \equiv a_\mu^{2\mathrm{L},f\tilde{f}}/a_\mu^{1\mathrm{L}}$, $r_{\mathrm{LL}} \equiv a_\mu^{2\mathrm{L},f\tilde{f},\mathrm{LL}}/a_\mu^{1\mathrm{L}}$,
red/black min(M_{SUSY}) $> 150/180 GeV$

invalid when tan β or M_{SUSY} is very small,

$M_{SUSY} > 200\mathrm{GeV}$

MSSM: Radiative muon mass generation

$$\tan\beta \to \infty$$

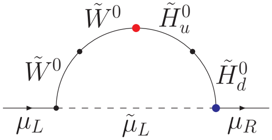
Novel phenomenological approach

Radiative muon mass generation: $\tan\beta \to \infty$

$$m_\mu^{\rm tree} = y_\mu v_d \quad \Rightarrow \quad 0$$

- $v_d \to 0$, $\tan\beta \equiv \frac{v_u}{v_d} \to \infty$,
  m_μ generated via coupling to v_u

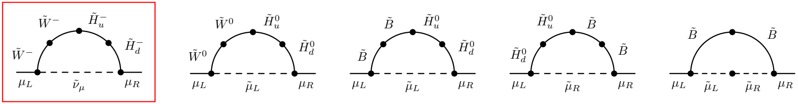
  [Dobrescu, Fox '10][Altmannshofer, Straub '10]
- $m_\mu \equiv \cancel{y_\mu v_d} + y_\mu v_u \Delta_\mu^{\rm red}$:
  y_μ obtained from one-loop self energy.
- $a_\mu^{\rm SUSY} = \frac{y_\mu v_u}{m_\mu} a_\mu^{\rm red}$
- $a_\mu^{\rm SUSY} \propto y_\mu$ and $m_\mu \propto y_\mu$



$$\Rightarrow \quad a_\mu^{\rm SUSY} = \frac{a_\mu^{\rm red}}{\Delta_\mu^{\rm red}}$$

[1504.05500][Bach, Park, Stöckinger,S-K]

The limit of $\tan\beta \to \infty$



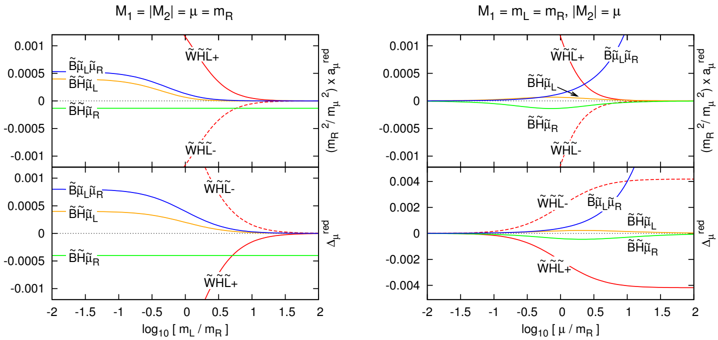
$$a_\mu^{\rm red} = a_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu}) + a_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\mu}_L) + a_\mu^{\rm red}(\tilde{B}\tilde{H}\tilde{\mu}_L) + a_\mu^{\rm red}(\tilde{B}\tilde{H}\tilde{\mu}_R) + a_\mu^{\rm red}(\tilde{B}\tilde{\mu}_L\tilde{\mu}_R)$$
$$\Delta_\mu^{\rm red} = \Delta_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu}) + \Delta_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\mu}_L) + \Delta_\mu^{\rm red}(\tilde{B}\tilde{H}\tilde{\mu}_L) + \Delta_\mu^{\rm red}(\tilde{B}\tilde{H}\tilde{\mu}_R) + \Delta_\mu^{\rm red}(\tilde{B}\tilde{\mu}_L\tilde{\mu}_R)$$

- $a_\mu^{\rm SUSY}$ sign depends on the mass ratios.
- ${\rm sgn}(\mu)$ and $\tan\beta$ dependence disappears.
- $a_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu})$ and $\Delta_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu})$ have opposite signs.
- For the equal mass case, $a_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu})$ and $\Delta_\mu^{\rm red}(\tilde{W}\tilde{H}\tilde{\nu})$ dominate $\Longrightarrow$ negative $a_\mu^{\rm SUSY}$

$$a_\mu^{\rm SUSY} = \frac{a_\mu^{\rm red}}{\Delta_\mu^{\rm red}}$$

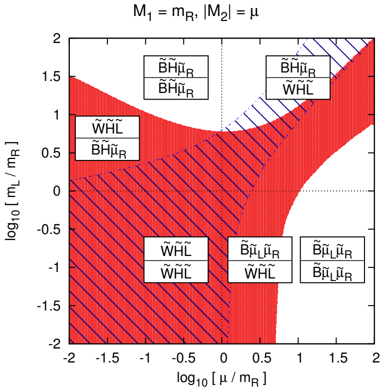
$$a_\mu^{\rm SUSY} \approx -72 \times 10^{-10} \left(\frac{1{\rm TeV}}{M_{\rm SUSY}}\right)^2$$

However! $a_\mu^{\rm SUSY}$ can be positive,
if any of $\tilde{B}\tilde{H}\tilde{\mu}_L$, $\tilde{B}\tilde{H}\tilde{\mu}_R$, and $\tilde{B}\tilde{\mu}_L\tilde{\mu}_R$ dominates.



“μ_R-dominance” “large μ-limit”

The sign of $a_\mu^{\rm SUSY}$



At the equal mass limit,

$$a_\mu^{\rm SUSY} \approx -72 \times 10^{-10} \left(\frac{1\,{\rm TeV}}{M_{\rm SUSY}}\right)^2$$

Generally,

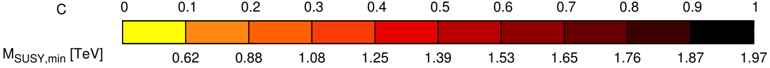
$$a_\mu^{\rm NP} = C_{\rm NP}\frac{m_\mu^2}{M_{\rm NP}^2},$$

$$C_{\rm NP} = \mathcal{O}(\delta m_\mu^{\rm NP}/m_\mu)$$

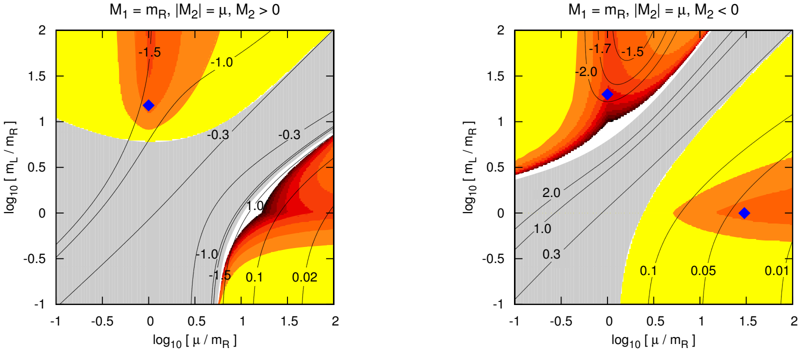
(model dependent)

What can be the C-value/$a_\mu^{\rm SUSY}$ for the given parameter ratio space?

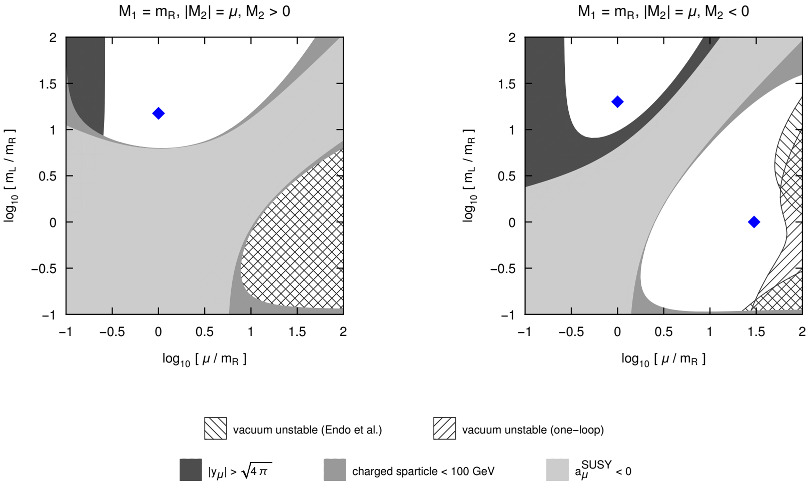
$\tan\beta \to \infty$: C-value and y_μ



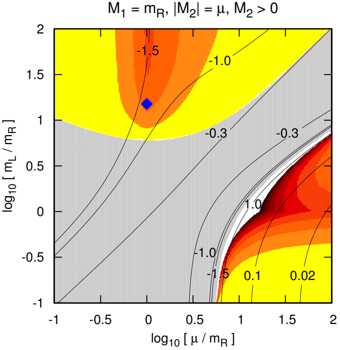
$M_{\rm SUSY,min}$ evaluated using $a_\mu^{\rm SUSY} = 28.7 \times 10^{-10}$.

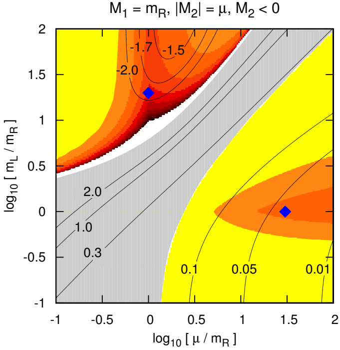


Further constraints



$\tan\beta \to \infty$: Benchmark points





[TeV]	μ	M_1	M_2	m_L	m_R	$a_\mu/10^{-10}$
	1	1	1	15	1	26.4
	1.3	1.3	-1.3	26	1.3	29.0
	30	1	-30	1	1	28.0

$a_\mu^{\rm SUSY}$ simple approximation

MSSM one-loop approximation with finite $\tan\beta$:

$$a_\mu^{\rm SUSY,1L} \approx 13 \times 10^{-10} {\rm sgn}(\mu) \tan\beta \left(\frac{100\,{\rm GeV}}{M_{\rm SUSY}}\right)^2$$

MSSM in the limit of $\tan\beta \to \infty$:

1. The equal mass case,

$$a_\mu^{\rm SUSY} \approx -72 \times 10^{-10} \left(\frac{1\,{\rm TeV}}{M_{\rm SUSY}}\right)^2$$

2. $|\mu| \gg |M_1| = m_L = m_R \equiv M_{\rm SUSY}$, $m_L \gg |\mu| = |M_1| = m_R \equiv M_{\rm SUSY}$

$$a_\mu^{\rm SUSY} \approx 37 \times 10^{-10} \left(\frac{1\,{\rm TeV}}{M_{\rm SUSY}}\right)^2$$

GM2Calc

all known 2-loop results taken into account

[https://gm2calc.hepforge.org/]

- Home
- Downloads
- Documentation
- Online
- ChangeLog
- Bugs
- Development
- Contact

GM2Calc

This is the home page of the GM2Calc project. GM2Calc is a C++ program which calculates the anomalous magnetic moment of the muon in the MSSM at 1-loop and leading 2-loop order.

Current version

The current release is **0.2.16** (released 05 October 2015).
Download: GM2Calc-0.2.16.tar.gz

Authors

- Peter Athron
- Markus Bach
- Helvecio Fargnoli
- Christoph Gnendiger
- Robert Greifenhagen
- Jae-hyeon Park
- Sebastian Passehr
- Dominik Stöckinger
- Hyejung Stöckinger-Kim
- Alexander Voigt

References

Summary

- 3σ deviation in a_μ motivates New Physics.
- MSSM $f\tilde{f}$ two-loop corrections solve the α ambiguity in one-loop result and show non-decoupling behaviour $\mathcal{O}(10\ldots30\%)$.
- Radiative muon mass generation in the limit of $\tan\beta \to \infty$
  - Relevant parameter regions different from the usual MSSM
  - TeV-scale SUSY masses can explain a_μ.
  - "large μ-limit" and "μ_R-dominance" regions:

$$a_\mu^{\mathrm{SUSY}} \approx 37 \times 10^{-10} \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

- https://gm2calc.hepforge.org/

$a_\mu^{\mathrm{THDM,2L}}$ coming soon!