Muon $g - 2$ and BSM physics

General remarks and three $a_\mu$-motivated BSM scenarios

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Motivation

**Big questions... point to (TeV scale) new physics**

EWSB, Higgs

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Dark Matter?

Baryon Asymmetry?

**There are also some experimental hints!** (but even more null results)

- dark matter, B-anomalies, \((g - 2)_\mu\), \((g - 2)_e\)?

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Motivation 2: Current $a_{\mu}$ and $a_{e}$ — prepare for new data

\[
a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} \approx (30 \pm 8) \times 10^{-10}
\]

\[
a_{e}^{\text{Exp}} - a_{e}^{\text{SM}} = (-8.8 \pm 3.6) \times 10^{-13}
\]

\[
a_{\mu}^{\text{EW}} \approx 15 \times 10^{-10}
\]

\[
a_{e}^{\text{EW}} \approx 0.3 \times 10^{-13}
\]

Largest SUSY ($\tan \beta \to \infty$)

[Bach,Park,DS,Stöckinger-Kim '15]

Largest THDM

[Cherchiglia,DS,Stöckinger-Kim '17]
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In this talk:
- Relation between $g - 2$ and other observables
- Which models/scenarios can explain $a_\mu^{\text{Exp} - \text{SM}}$?
- How can these be tested/excluded?

Outcome: interesting scenarios, correlated observables, tests

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Largest THDM  
[Cherchiglia, DS, Stöckinger-Kim '17]
Complementarity: $g - 2$, DM, LFV/EDMs, B-physics

CP- and Flavor-conserving, chirality-flipping, loop-induced

- $a^\text{NP}_\mu$ related to $\Delta m^\text{NP}_\mu$: at most $a_\mu = \mathcal{O}(1) \times \frac{m^2_\mu}{M^2_{\text{NP}}} \Rightarrow M_{\text{NP}} \lesssim 2$ TeV
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**CP- and Flavor-conserving, chirality-flipping, loop-induced**

- $a^\text{NP}_\mu$ related to $\Delta m^\text{NP}_\mu$: at most $a_\mu = \mathcal{O}(1) \times \frac{m^2_\mu}{M^2_NP} \Rightarrow M_NP < \sim 2$ TeV

- Dark matter, e.g. if SUSY WIMP:
  - preferred parameter space well compatible with $a_\mu$

- LFV/EDMs $\mu \rightarrow e\gamma$, $d_e$ . . . :
  - high mass reach, $a_\mu |\delta_{12}|$, $a_\mu |\sin \phi_{CP}| \Rightarrow |\delta_{12}, \phi_{CP}| \ll 1$

- B-anomalies $R^{D(*)}[b \rightarrow c\tau\nu], R^{K(*)}[b \rightarrow s\mu\mu]$:
  - need tree-level TeV-exchange, must not violate $\tau \rightarrow \mu\gamma$, . . .
  - $\Rightarrow$ very restricted models, unusual flavour structure

  only possible: LQ [Sumensari'18] $\sim$ no MFV [Bansal,Capdevilla,Kolda'18],
  - incompatible with $a_\mu$ [Crivellin,Müller,Ota'17], vector LQ might work [Crivellin,Calibbi,Li'17]
Typical behaviour: \(\sim\) chirality flip (\(\sim\) Higgs!) and masses

- **EWSM:** \(\alpha \frac{m_\mu^2}{M_W^2}\)

- **SUSY:** \(\alpha \frac{m_\mu^2 \tan \beta}{M_{\text{SUSY}}^2}\)

- **LQ:** \(g_L g_R \frac{m_\mu m_t}{M_{\text{LQ}}^2}\)
Typical behaviour: $\sim$ chirality flip ($\sim Higgs!$) and masses

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  Well-motivated theory. Also possible: dark matter

- **LQ:** $g_L g_R \frac{m_{\mu} m_t}{M_{LQ}^2}$
Typical behaviour: $\sim$ chirality flip ($\sim Higgs!$) and masses

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Can also involve Higgs couplings to $b$, $c$ or new particles. Also possible, although difficult: B-physics.

Beware: $\Delta m_{\mu} / m_{\mu} \sim g_L g_R m_t / m_{\mu}$ restricts couplings
Typical behaviour: \( \sim \) chirality flip (\( \sim \) Higgs!) and masses

- **EWSM:** \( \alpha \frac{m^2_{\mu}}{M^2_W} \)

- **2HDM:** \( \alpha^2 \tan^2 \beta \frac{m^2_{\mu}}{M^2_H} \)

  Also possible: \( B \rightarrow D_{\tau} \nu \) [Crivellin, Heeck, Stoffer’16...]

- **rad.** \( m_{\mu} \sim \frac{m^2_{\mu}}{M^2_{NP}} \)
Typical behaviour: $\sim$ chirality flip ($\sim\sim$ Higgs!) and masses

- **EWSM:** $\alpha \frac{m_\mu^2}{M_W^2}$

- **2HDM:** $\alpha^2 \tan^2 \beta \frac{m_\mu^2}{M_H^2}$

- **rad. $m_\mu:** $\sim \frac{m_\mu^2}{M_{NP}^2}$
Is standard SUSY already excluded?

Not in general, but CMSSM cannot accommodate $a_\mu$ anymore

- Constrained MSSM:
  - excluded by $a_\mu \perp M_H$
  - or by $a_\mu \perp$ LHC-limits
    (if $\Delta a_\mu$ confirmed)
    (because all scalars must be heavy)

⇒ can we also exclude other models?
Motivation:

- more than one Higgs well motivated $\leadsto$ simplest model
- $a_\mu$ not very promising since 2-loop
$a_\mu$ in the 2-Higgs doublet model? [Cherchiglia, DS, Stöckinger-Kim ’17]

- 2-Higgs doublet model with light $A_0$, large couplings to $\tau$ (and top)
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$a_\mu$ from:

$\tau$- or top-loop need large $\mu$, $\tau$- and possibly top-Yukawa
\( a_\mu \) in the 2-Higgs doublet model? [Cherchiglia,DS,Stöckinger-Kim ’17]

- 2-Higgs doublet model with light \( A_0 \), large couplings to \( \tau \) (and top)

\( a_\mu \) from:

- \( \tau \)- or top-loop

Constraints:

\[ Z \to \tau \tau, \ \tau \text{-decay}, \ LEP-4\tau \text{-search}; \]
\[ b \to s\gamma \ \text{and} \ B_s \to \mu\mu, \ LHC \ gg \to A, \ H \to \tau\tau \]

Results: \( a_\mu \) explained in tightly constrained parameter space; testable by many observables: \( Z \to \tau\tau, \ \tau \)- and \( b \)-decays, LHC \( gg \to A, \ H \to \tau\tau \), future ILC?
$a_\mu$ in R-symmetric SUSY?

Motivation:

- MRSSM: beautiful alternative realization of SUSY: $U(1)$ R-symmetry, $N = 2$ SUSY gauge sectors, Dirac gauginos/Higgsinos, protection from FCNC [Kribs, Poppitz, Weiner]
- successful phenomenology (Higgs, dark matter, LHC bounds, EWPO, many light states possible) [Diessner, Kalinowski, Kotlarski, DS’14–’17]
Motivation:

- MRSSM: beautiful alternative realization of SUSY: $U(1)$ R-symmetry, $N = 2$ SUSY gauge sectors, Dirac gauginos/Higgsinos, protection from FCNC [Kribs, Poppitz, Weiner]
- successful phenomenology (Higgs, dark matter, LHC bounds, EWPO, many light states possible) [Diessner, Kalinowski, Kotlarski, DS’14-'17]
- However, $a_\mu$ NOT tan $\beta$-enhanced! Small unless $m_{\text{SUSY}}$ very small
$a_\mu$ in R-symmetric SUSY?

R-symmetry forbids $\mu$-term but allows new Yukawa couplings $\Lambda_i$ for Dirac gauginos/Higgsinos

\[
\mu_R \xrightarrow{\tilde{H}_u^+} \tilde{H}_d^+ \rightleftarrows \tilde{\nu}_\mu \tilde{W}^+ \xrightarrow{\tilde{R}_d^+} \tilde{T}^+ \rightleftarrows \tilde{\nu}_\mu \tilde{W}^+ \\
\mu_L \\

\text{MSSM} \propto v_u y_\mu \propto \tan \beta \\
\text{MRSSM} \propto \Lambda_d / g_2 \]
$a_\mu$ in R-symmetric SUSY?

- $a_\mu$ NOT $\tan \beta$-enhanced! Small unless $m_{\text{SUSY}}$ very small and $\Lambda_i \gg g_i$ (non-$N=2$ SUSY)

- In this parameter region $\Rightarrow$ strong correlation $\mu \to e/\mu \to e\gamma$

Result: $a_\mu$ explained for $M_{\text{SUSY}} \sim 100\text{GeV}$, compressed spectra; testable by LHC/ILC, $\mu \to e/\mu \to e\gamma$
and radiative muon mass: MSSM for $\tan \beta \to \infty$

[Bach, JH Park, DS, Stöckinger-Kim, '15]

Idea: $\nu_d = 0 \leadsto m_{\mu}^{\text{tree}} = y_{\mu} \nu_d = 0$
$a_\mu$ and radiative muon mass: MSSM for $\tan \beta \rightarrow \infty$

[Bach, JH Park, DS, Stöckinger-Kim, '15]

Idea: $v_d = 0 \sim m_\mu^{\text{tree}} = y_\mu v_d = 0$

\[
\begin{align*}
    a_\mu^{\text{SUSY}} &\approx y_\mu v_u \times \text{loop} \\
    m_\mu^{\text{pole}} &\approx y_\mu v_d + y_\mu v_u \times \text{loop}
\end{align*}
\]

usual approx. \hspace{1cm} now important

\[
\frac{a_\mu^{\text{SUSY}}}{\text{loop}} \rightarrow \frac{\text{loop}}{\text{loop}}
\]
$a_\mu$ and radiative muon mass: MSSM for $\tan \beta \rightarrow \infty$

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$a_{\mu}^{\text{SUSY}} \approx y_\mu v_u \times \text{loop}$

$m_\mu^{\text{pole}} \approx y_\mu v_d + y_\mu v_u \times \text{loop}$

\[ a_{\mu} \rightarrow \frac{\text{loop}}{\text{loop}} \]

New features for $\tan \beta \rightarrow \infty$:

- simpler behaviour, larger results

\[ a_{\mu}(M_{\text{SUSY}}) \approx -70 \times 10^{-10} \left( \frac{1 \text{TeV}}{M_{\text{SUSY}}} \right)^2 \]

\[ a_{\mu}(m_L \rightarrow \infty) \approx +36 \times 10^{-10} \left( \frac{1 \text{TeV}}{M_{\text{SUSY}}} \right)^2 \]
$a_\mu$ and radiative muon mass: MSSM for $\tan \beta \rightarrow \infty$

[Bach, JH Park, DS, Stöckinger-Kim, '15]

Idea: $v_d = 0 \rightsquigarrow m^\text{tree}_\mu = y_\mu v_d = 0$

\[
a^\text{SUSY}_\mu \approx y_\mu \times \text{loop}
\]

\[
m^\text{pole}_\mu \approx y_\mu v_d + y_\mu v_u \times \text{loop}
\]

Results: $a_\mu$ explained even if $M_{\text{LSP}} > 1$ TeV $\rightsquigarrow$ largest $a^\text{SUSY}_\mu$

tests: 1TeV chargino searches, Higgs-physics/couplings, . . .
Radiative muon/electron mass fits well to $a_\mu$ and $a_e$!

\begin{align*}
  a^{\text{Exp-SM}}_\mu &\approx 30 \times 10^{-10} \\
  a^{\text{Exp-SM}}_e &= -8.8(3.6) \times 10^{-13}
\end{align*}

Impossible in 2HDM, MRSSM, barely in MSSM/\(t_\beta = 50\) (\(M_{\text{SUSY}} < 150\) GeV)

Idea: either very light NP \cite{Davoudiasl,Marciano'18} or . . .

Radiative \(m_e, m_\mu, \tan \beta \to \infty\):

\begin{align*}
  M_{\text{SUSY}} &= \ldots = m_{\tilde{e}_R} = 500\text{ GeV}, \text{ and } m_{\tilde{\mu}_R} = (7\ldots 10) \times M_{\text{SUSY}} \\
  \Rightarrow a_e &= -7 \times 10^{-13} \text{ and } \Rightarrow a_\mu \approx 30 \times 10^{-10}
\end{align*}

\(\tan \beta \to \infty\): perfect fit to \(a_\mu\) and \(a_e\)!
Conclusions

- $(g - 2)_\mu$: Intriguing hint for new physics
  - many potential explanations, $M_{NP} \lesssim 2$ TeV
  - LFV, EDMs imply special flavour structure $\left| \delta_{12}, \phi_{CP} \right| \ll 1$
  - difficult to reconcile with B-anomalies

- 2HDM and $a_\mu$: light $A_0$, large $\tau, t$ Yukawas
  - strongly constrained and
  - (future) LHC, $B$-physics, $a_\mu$ could exclude 2HDM!

- R-symmetric SUSY: $a_\mu$ different from MSSM
  - small $a_\mu$, no $\tan \beta$ enhancement
  - test: ILC; interplay $a_\mu/\mu \rightarrow e\gamma/\mu \rightarrow e$

- Radiative $m_\mu$, MSSM $\tan \beta \rightarrow \infty$
  - can explain $a_\mu$ for $M_{SUSY} = 1$ TeV or $a_e$ and $a_\mu$
  - tests: future colliders; Higgs couplings?