Magnetic moment \((g - 2)_\mu\) and beyond the Standard Model physics

Dominik Stöckinger

TU Dresden

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Discrepancy

SM prediction too low by \((28.7 \pm 8.0) \times 10^{-10}\)

Note: discrepancy twice as large as \(a_{\mu}^{\text{SM, weak}}\)

but we expect: \(a_{\mu}^{\text{NP}} \sim a_{\mu}^{\text{SM, weak}} \times \left( \frac{M_W}{M_{NP}} \right)^2 \times \text{couplings} \)
Outline

1. Impact on New Physics in general
   - Complementary
   - Model dependent

2. Dark photon

3. SUSY
   - Can explain the deviation — tension with LHC data?
   - details, new results
   - Complementarity
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Why is $a_\mu$ special?

**CP- and Flavour-conserving, chirality-flipping, loop-induced**

compare: EDMs, $B \to \tau \nu$

$\mu \to e\gamma$

EWPO
Why is $a_\mu$ special?

**CP- and Flavour-conserving, chirality-flipping, loop-induced**

Compare: EDMs, $B \to \tau \nu$, $\mu \to e\gamma$

Note relation to $m_\mu$
Very different contributions to $a_\mu$

generally:  
\[ C = \frac{\delta m_\mu (N.P.)}{m_\mu}, \quad \delta a_\mu (N.P.) = O(C) \left( \frac{m_\mu}{M} \right)^2 \]

classify new physics: $C$ very model-dependent

Very useful constraints on new physics
Very different contributions to $a_\mu$

generally:

$$C = \frac{\delta m_\mu (N.P.)}{m_\mu}, \quad \delta a_\mu (N.P.) = \mathcal{O}(C) \left( \frac{m_\mu}{M} \right)^2$$

classify new physics: $C$ very model-dependent

Very useful constraints on new physics

\[ O(1) \]

\[ O\left( \frac{\alpha}{4\pi} \ldots \right) \]

\[ O\left( \frac{\alpha}{4\pi} \right) \]

$Z'$, $W'$, UED, Littlest Higgs (LHT)...
generic analysis $\rightarrow$ talk S. Westhoff
Very different contributions to \( a_\mu \)

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C = \frac{\delta m_\mu(N.P.)}{m_\mu}, \quad \delta a_\mu(N.P.) = \mathcal{O}(C) \left( \frac{m_\mu}{M} \right)^2
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classify new physics: \( C \) very model-dependent

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supersymmetry (\( \tan \beta \)), unparticles

extra dim. (ADD/RS) (\( n_c \))...

\[ [\text{Cheung, Keung, Yuan '07}] \]

\[ [\text{Davioudasl, Hewett, Rizzo '00}] \]

\[ [\text{Graesser,'00, Park et al '01, Kim et al '01}] \]

\[ Z', W', UED, \text{ Littlest Higgs (LHT)} \ldots \]

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radiative muon mass generation . . .

[Czarnecki, Marciano '01]

[Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]

\[ O(\frac{\alpha}{4\pi} \ldots) \]

supersymmetry ($\tan \beta$), unparticles

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extra dim. (ADD/RS) ($n_c$) . . .

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\[ \mathcal{O}\left( \frac{\alpha}{4\pi} \right) \quad Z', \; W', \; \text{UED, Littlest Higgs (LHT)} \ldots \]

generic analysis $\rightarrow$ talk S. Westhoff

dark photon \ldots
Complementarity

Checking models with large $a_\mu$ contributions

- electroweak scale models
  - generic collider signals [Freitas, Lykken, Westhoff '14]

- SUSY
  - specific LHC signals depending on scenario [Endo, Hamaguchi, Iwamoto, Yoshinaga'13]
  - correlation to $\mu \to e\gamma$, ...

- dark photons
  - low-energy signals

Different types of new physics lead to very different $\delta a_\mu (\text{N.P.})$

- very useful, complementary constraints on N.P.
- $28.7 \times 10^{-10}$ only possible if $M_{\text{NP}} < 2\text{TeV}$ (for $C \leq 1$)
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What if the LHC does not find new physics?

- Dark sector
  
  still possible and appealing:

  \[
  \mathcal{L} = \ldots \frac{\epsilon}{2} F^\mu_{d\nu} F_{\mu\nu} \xrightarrow{\text{diag.}} \mathcal{L}_{\text{int}} = \ldots (A_\mu + \epsilon A'_\mu) J^\mu_{\text{e.m.}}
  \]

  two parameters: coupling \( \epsilon \), mass \( m_{A'} \)

- is generic if there is new U(1) gauge boson (GUT, strings,\ldots)

- window to possibly many new, SM-neutral particles

- **Motivation:** dark matter, \((g - 2)_\mu\)
  
  (assume specific coupling/mass range)
Dark photon and $a_\mu$

\[ A' = \epsilon^2 \frac{\alpha}{4\pi} F \left( \frac{m_\mu}{m_{A'}} \right) \]

explain $a_\mu$ without messing up $a_e$: $M_{A'} \gg 1$MeV

- constrained by $(g - 2)_e$, $\Upsilon$, $K$, $\phi$, $\pi$ meson decays, …
beam dump: dark bremsstrahlung (works for specific coupling range)
electron fixed target (APEX,A1)
Babar, KLOE, WASA: meson decays
often assumed: $A' \rightarrow e^+ e^-$ dominant
if not: $K \rightarrow \pi A'$, $A' \rightarrow$invisible and $e^+ e^- \rightarrow \gamma+$invisible lead to bounds
[Davidılması,Lee,Marcião’14][Izaguirre et al ’13]
generalization: also mass mixing “dark Z” with more general couplings, also strongly constrained
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SUSY and the MSSM

\[ a_\mu^{\text{SUSY}} \approx 12 \times 10^{-10} \tan \beta \, \text{sign}(\mu) \left( \frac{100 \text{GeV}}{M_{\text{SUSY}}} \right)^2 \]

SUSY could be the origin of the observed \((28 \pm 8) \times 10^{-10}\) deviation!
SUSY and the MSSM

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SUSY could be the origin of the observed \((28 \pm 8) \times 10^{-10}\) deviation!

But has the LHC ruled out SUSY? No!

- Motivation: natural Higgs and EWSB, dark matter, GUT

- free parameters: \(\tilde{p}\) masses and mixings, \(\mu\) and \(\tan \beta\)
**LHC-data! The tension is increasing . . .**

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LHC:

$L_{\mu} > \sim 1$ TeV

$m_{\tilde{\mu}, \chi} < \sim 700$ GeV

$m_{h} = 126$ GeV

$m_{\tilde{t}} > \sim 1$ TeV

$m_{\tilde{t}}, \mu$ small

Distinguish SUSY from concrete models/scenarios

- Constrained MSSM links $m_{\tilde{q}} - m_{\tilde{\mu}} - m_{h} \rightarrow$ cannot explain $a_{\mu}$

Tension motivates non-traditional models:

- sleptons $\ll$ squarks [1303.4256, 1210.3122]
- 2nd gen $\ll$ 3rd gen [1303.6995]
- new extra matter or U(1)' (e.g. $\sim M_{2} \ll \mu$) [1108.3071, 1112.6412]
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Note: SUSY does not require $\phi_{CPV}, \delta_{LFV} \neq 0$

$\rightarrow a_\mu$ decoupled from LFV, EDMs
LHC-data! The tension is increasing . . .

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$m_h = 126$ GeV

$m_{\tilde{\tau}} > \sim 1$TeV

finetuning

$m_{\tilde{\tau}}, \mu$ small

Distinguish SUSY from concrete models/scenarios

- Constrained MSSM links $m_{\tilde{q}} - m_{\tilde{\mu}} - m_h \rightarrow$ cannot explain $a_\mu$

Tension motivates non-traditional models: [Endo, Hamaguchi, Ibe, Yanagida, D.P. Roy, et al]

- sleptons $\ll$ squarks [1303.4256, 1210.3122]
- 2nd gen $\ll$ 3rd gen [1303.6995]
- new extra matter or U(1)' (e.g. $\sim \rightarrow M_2 \ll \mu$) [1108.3071, 1112.6412]

$\Rightarrow$ split/hierarchical spectra
It is worthwhile to look at the details
\[ g - 2 \text{ in the MSSM: chirality flips, } \lambda_\mu, \text{ and } H_u \]

\[ \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad \mu = H_u - H_d \text{ transition} \]

some terms

\[ \propto \lambda_\mu \langle H_u \rangle \mu = m_\mu \tan \beta \mu \quad \rightarrow a_\mu^{\text{SUSY}} \propto \tan \beta \text{ sign}(\mu) \frac{m_\mu^2}{M_{\text{SUSY}}^2} \]

potential enhancement \( \propto \tan \beta = 1 \ldots 50 \) (and \( \propto \text{sign}(\mu) \))
Physics of subleading contributions (examples)

\[
\begin{align*}
\tilde{H}_d^+ & \rightarrow \tilde{H}_u^+ & \tilde{W}^+ \\
\mu_R & \rightarrow \nu_{\mu_L} & \mu_L
\end{align*}
\]

“standard”

\[
\begin{align*}
\tilde{W}\tilde{H}\tilde{\mu}_L & \propto \mu \\
\text{for } \mu \rightarrow \infty
\end{align*}
\]

\[
\begin{align*}
\tilde{B}\tilde{\mu}_L\tilde{\mu}_R & \propto \mu \\
\text{1-loop bino}
\end{align*}
\]

\[
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\tilde{B}\tilde{H}\tilde{\mu}_R & \propto \mu \\
\text{1-loop } \tilde{\mu}_R
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\[
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\tilde{H}_u & \rightarrow \tilde{B} & \tilde{B} \\
\mu_L & \rightarrow \tilde{\mu}_L & \tilde{\mu}_R & \mu_R
\end{align*}
\]

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\tilde{H}_d & \rightarrow \tilde{B} & \tilde{B} \\
\mu_L & \rightarrow \tilde{\mu}_L & \tilde{\mu}_R & \mu_R
\end{align*}
\]

note: at least 3 light (<TeV) masses

[Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]
Physics of subleading contributions (examples)

\[ \tilde{H}_u^+ \quad \tilde{W}^+ \]
\[ \tilde{H}_d^- \quad \tilde{\nu}_{\mu_L} \quad \mu_R \]

“standard”

\[ \propto \mu \text{ for } \mu \to \infty \]

\[ \tilde{W} \tilde{H} \tilde{\mu}_L \]

1-loop bino

\[ \tilde{B} \tilde{\mu}_L \tilde{\mu}_R \]

\[ \propto \text{other sign!} \]

\[ \tilde{B} \tilde{H} \tilde{\mu}_R \]

[Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]

small/large \( \mu \)

\[ 7 \times 10^{-9} \quad 6 \times 10^{-9} \quad 5 \times 10^{-9} \quad 4 \times 10^{-9} \quad 3 \times 10^{-9} \quad 2 \times 10^{-9} \quad 1 \times 10^{-9} \]

\[ 500 \quad 1000 \quad 1500 \quad 2000 \]

small/large \( M_{\tilde{\mu}_L} \)

\[ 8 \times 10^{-9} \quad 6 \times 10^{-9} \quad 4 \times 10^{-9} \quad 2 \times 10^{-9} \quad -2 \times 10^{-9} \]

\[ 500 \quad 1000 \quad 1500 \quad 2000 \quad 2500 \]
Physics of subleading contributions (examples)

1-loop bino

$\propto \mu$ for $\mu \to \infty$

1-loop $\tilde{\mu}_R$

$\propto$ other sign!

[Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]

non-decoupling two-loop corrections

$\tilde{W} \tilde{H} \tilde{\mu}_L$

$\tilde{B} \tilde{\mu}_L \tilde{\mu}_R$

$\tilde{B} \tilde{H} \tilde{\mu}_R$

Dominik Stöckinger

$g \rightarrow 2$ and BSM
Complementarity to LHC: $a_\mu$ central for BSM analyses

- $a_\mu$ sharply distinguishes BSM models — here SUSY
- helps measure parameters
Correlation with $\mu \to e\gamma$ [talks by Gouvea, Lim]

- same structure
- additional mixing
  \[ \delta_{LL} = \frac{m^2_{L_{12}}}{\sqrt{m^2_{L_{11}} m^2_{L_{22}}}} \]
- study correlation for fixed $\delta_{LL}$
  - $a_\mu$ measured
  - upper bound $\text{BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ (MEG)
  - e.g. can predict possible range of $\delta_{LL}$ given $a^{\text{SUSY}}_\mu$

[Chacko, Kribs'01; Isidori, Mescia, Paradisi, Temes'07]
Correlation with $\mu \rightarrow e\gamma$

- study correlation for fixed $\delta_{LL} = 2 \times 10^{-5}$
- However: strong correlation of individual diagrams does not imply strong correlation of the sum! Strong correlations for strong parameter constraints or domination of certain diagrams

[Kersten, Park, DS, Velasco-Sevilla '14]

![Graphs showing correlation with $\mu \rightarrow e\gamma$]
Alternative: radiative muon mass in SUSY

\[ m_{\mu}^{\text{tree}} = \lambda_{\mu} v_d \]

1. \( \lambda_{\mu} = 0 \)
   - generate \( m_\mu \) via \( A'_\mu \tilde{\mu}_L \tilde{\mu}_R H_u \) \[\text{[Borzumati et al '99][Crivellin et al '11]}\]

2. \( v_d \rightarrow 0, \tan \beta \rightarrow \infty \)
   - generate \( m_\mu \) via coupling to \( v_u \) \[\text{[Dobrescu, Fox '10][Altmannshofer, Straub '10]}\]
Radiative muon mass: MSSM for $\tan \beta \to \infty$

[Bach, Park, DS, Stöckinger-Kim, soon]

“standard case” (equal masses, 1-loop)

$$a_{\mu}^{\text{SUSY}} \approx 12 \times 10^{-10} \, \tan \beta \, \text{sign}(\mu) \left( \frac{100 \text{GeV}}{M_{\text{SUSY}}} \right)^2$$
Radiative muon mass: MSSM for $\tan \beta \rightarrow \infty$

actually, including higher order effects

$$a_{\mu}^{\text{SUSY}} \approx \frac{12 \times 10^{-10}}{1 - 0.0018 \tan \beta \text{ sign}(\mu)} \frac{\tan \beta \text{ sign}(\mu)}{1 \text{ loop}} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2$$

$$\lambda_{\mu} \approx \frac{m_{\mu}}{v_d + v_u (1\text{-loop})} = \frac{\lambda_{\mu}^{\text{tree}}}{(1 + \sim \mu \tan \beta)}$$
Radiative muon mass: MSSM for $\tan \beta \rightarrow \infty$

[Bach, Park, DS, Stöckinger-Kim, soon]

limit $\tan \beta \rightarrow \infty$

$$a_{\mu}^{\text{SUSY}} \approx -70 \times 10^{-10} \left(\frac{1000\text{GeV}}{M_{\text{SUSY}}}\right)^2$$

tan $\beta$ and sign($\mu$) drop out, large contributions for $M_{\text{SUSY}} \sim \text{TeV}$!
Radiative muon mass: MSSM for $\tan \beta \to \infty$

[Bach, Park, DS, Stöckinger-Kim, soon]

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

$$a_{\mu}^{\text{SUSY}} \approx -70 \times 10^{-10} \left( \frac{1000\text{GeV}}{M_{\text{SUSY}}} \right)^2$$

“standard” case: sign wrong!
Radiative muon mass: MSSM for $\tan \beta \to \infty$

[Bach, Park, DS, Stöckinger-Kim, soon]

limit $\tan \beta \to \infty$

\[
a_{\mu}^{\text{SUSY}} \approx +37 \times 10^{-10} \left( \frac{1000 \text{GeV}}{M_{\text{SUSY}}} \right)^2
\]

sign positive e.g. if $|\mu| \gg M_{\text{SUSY}}$ (then $\tilde{B}_{\mu} \tilde{\mu}_L \tilde{\mu}_R$ dominates)
What is it good for?

Big questions

EWSB, Higgs, mass generation?

hierarchy \( \frac{M_{Pl}}{M_W} \)? Naturalness?

dark matter?

Grand Unification?

... point to the TeV scale... and to new physics
What is it good for?

Big questions

EWSB, Higgs, mass generation? hierarchy $M_{Pl}/M_{W}$? Naturalness?

dark matter?

Grand Unification?

SUSY, extra dimensions, little Higgs, technicolor, . . .
Why new physics?

Big questions also motivate new physics at other scales

dark matter?

Grand Unification?

- Why three generations? Origin of flavor? $m_{\nu}$?
- Baryon asymmetry of the universe?
- Strong CP problem?

dark forces, new CP/flavor violation, seesaw mechanism, axions, . . .
Conclusions

- Many appealing BSM scenarios
  - $a^{\text{BSM}}_\mu$ model-dependent, typically $\mathcal{O}(\pm1\ldots50) \times 10^{-10}$
    - complementary

- models with large $a^{\text{BSM}}_\mu$ for
  - $M_{\text{BSM}} < 1$ GeV (dark photon) $\sim 100$ GeV [talk Westhoff]
  - $\sim 500$ GeV (SUSY) $> 1$ TeV (rad. $m_\mu$)
    - already constrained by data
    - details important

New experiments very promising!!
Status of SUSY prediction

1-Loop
\[ \propto \tan \beta \]

2-Loop (SUSY 1L)
\[ \text{e.g. } \propto \log \frac{M_{\text{SUSY}}}{m_{\mu}} \]

2-Loop (SM 1L)
\[ \text{e.g. } \propto \tan \beta \, \mu \, m_t \]

[Fayet '80],... [Kosower et al '83],[Yuan et al '84],... [Lopez et al '94],[Moroi '96]

[Degrassi,Giudice '98] [Marchetti, Mertens, Nierste, DS '08]
[Schäfer, Stöckinger-Kim, v. Weitershausen, DS '10]

[Chen,Geng'01] [Arhib,Baek '02]
[Heinemeyer,DS,Weiglein '03] [Heinemeyer,DS,Weiglein '04]

complete

photonic
\[(\tan \beta)^2\]

aim: full calculation
(65000 diagrams)
The new contributions with $f\tilde{f}$ loops

Motivation:
- Split spectra
- remaining class with dependence on squarks
- maximum complexity: 5 heavy + 2 light scales
Result contains large logs, $\Delta \rho$

1. $\mu \rightarrow a_{\mu}^{1L} \times \Delta \rho$

2. $\mu \rightarrow a_{\mu}^{1L} \times \log(m_{\tilde{f}})$
Result contains large logs, $\Delta \rho$

\[ \rightarrow a^{1L}_\mu \times \Delta \rho \]

1. $\mu \rightarrow \tilde{\mu}_m, \tilde{\nu}_\mu \rightarrow \mu$

2. $\mu \rightarrow \tilde{\chi}_i, \tilde{\nu}_\mu \rightarrow \mu$

Old

\[ \rightarrow a^{1L}_\mu \times \log(m_{\tilde{f}}) \]

3. $\mu \rightarrow \tilde{t}, H, \tilde{z} \rightarrow \mu$

\[ \rightarrow a^{1L}_\mu \times \frac{1}{m^2_{\tilde{t}}} \]
Results for $f \tilde{f}$-loops: Large contributions from heavy squarks [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]

BM4

- non-decoupling
- can be largest 2L contribution $\mathcal{O}(10\% \ldots 30\%)$

$$\mu = -160, \; M_1 = 140, \; m_{\tilde{\mu}_R} = 200, \; M_2 = m_{\tilde{\mu}_L} = 2000 \text{ GeV}, \; \tan \beta = 50$$
Results for $f\tilde{f}$-loops: Large contributions from heavy squarks [Fargnoli, Gnendiger, Passehr, DS, Stöckinger-Kim '13]

BM1

\[ r \sim O(10\% \ldots 30\%) \]

- non-decoupling
- can be largest 2L contribution

\[ \mu = 350, \quad M_2 = 2M_1 = 300, \quad m_{\tilde{\mu}_{R,L}} = 400 \text{ GeV}, \quad \tan \beta = 40 \]
EWSB Models

Large $a_\mu$ possible?

- Randall Sundrum
- Littlest Higgs + T-Parity ("Bosonic SUSY")
- 2-Higgs doublet model + 4th generation
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Randall Sundrum

- KK-gravitons $\rightarrow$ large [Kim, Kim, Song'01]
- However, challenged by electroweak precision data [Hewett et al '00]
  and $\gamma\gamma \rightarrow \gamma\gamma$ unitarity [Kim, Kim, Song '01]
- non-graviton contributions small [Beneke, Dey, Rohrwild '12]
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Tiny $a_\mu$ from $Z_H$, $W_H$ contributions

[Cheng, Low '03]
[Hubisz, Meade, Noble, Perelstein '06]
[Blanke et al '07]
EWSB Models

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[Bar-Shalom, Nandi, Soni '11]

- Large contributions from $\nu' - H^\pm$
- possible
- in agreement with LFV, FCNC constraints
Other types of new physics

What if the LHC does not find new physics?
Hide new particles at colliders $\sim$ large $a_\mu$ possible

- **“Dark force”?** [Pospelov, Ritz...]
  very light, weakly interacting
  $C \propto 10^{-8}$, $M < 1\text{GeV}$

- **Light “Z’” from gauged $L_\mu - L_\tau$**
  [Ma, Roy, Roy '02][Heeck, Rodejohann '11]
  flavour-dependent couplings, hidden at LEP
  $C \sim C_{\text{SM,weak}}$, $M_{Z'} \sim M_Z$