$(G-2)_\mu$ and Supersymmetric Extensions of the Standard Model

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Prologue: $(G-2)_\mu$ and New Physics

- BNL experiment vs. SM estimates [Davier *et al.*,2011]:

$$a_\mu^{exp.} - a_\mu^{SM} = (28.7 \pm 8.0) \cdot 10^{-10}\,(3.6\,\sigma,\ e^+e^-)\ \ ;\ \ (19.5 \pm 8.3) \cdot 10^{-10}\,(2.4\,\sigma,\ \tau)$$

- Compare with EW contribution in the SM [*Czarnecki et al. (2003,2006)*]:

$$a_\mu^{EW/SM} = (15.4 \pm 0.2) \times 10^{-10}$$

$\rightarrow$ *generate a New-Physics effect of the same order!*

- Sensitivity of $(G-2)_\mu$ to heavy states of mass M, typical coupling g_M:

$$\left(\delta a_\mu\right)_M \sim \frac{\alpha}{2\pi}\left(\frac{g_M}{g_{EW}}\right)^2\left(\frac{m_\mu}{M}\right)^2$$

$\Rightarrow$ *New Physics close to the EW scale?*

Outline

Supersymmetry (SUSY) in a nutshell

… A Symmetry!

- *The* symmetry algebra generalizing the Poincaré group to anticommutators:

$$\left\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\right\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu \quad ; \quad (N = 1 \text{ SUSY} \rightarrow \text{chirality})$$

- To define a SUSY model, work with Supermultiplets (Superfields).

… Relating Fermions and Bosons:

For model building, use $N = 1$ Supermultiplets:

- Chiral Supermultiplets (“matter”) → 1 Complex Scalar Field (A) + 1 Weyl Spinor (ψ):

$$\hat{\Phi} \supset \begin{pmatrix} A \\ \psi \end{pmatrix} \quad ; \quad \hat{\Phi}^+ \supset \begin{pmatrix} A^+ \\ \bar{\psi} \end{pmatrix}$$

- Vector Supermultiplets (“gauge”) → 1 Weyl spinor (λ) + 1 Vector Field (A^μ):

$$\hat{V} \supset \begin{pmatrix} \lambda \\ A^\mu \end{pmatrix}$$

- (…)

Why are SUSY models so interesting?

Supersymmetry has unique properties with respect to renormalization

- **"Non-renormalization" theorems**:
  For $N = 1$ SUSY, the superpotential receives no quantum corrections;
  $\Rightarrow$ Only Wave-function renormalization;
  $\Rightarrow$ Radiative corrections at most logarithmic (under certain conditions).
- At the diagrammatic level:
  Cancellations between scalar/pseudoscalar + among superpartner contributions.

In particular: No quadratic divergences for scalar squared masses!

Hierarchy problem of the SM:

- SM as an effective field theory: Higgs mass^2 quadratically sensitive to heavy new masses $M \gg M_Z$: $(m_H^2)^{SM} \sim (m_H^2)^{SM+M} + C \cdot M^2$
  $\rightarrow (m_H^2)^{SM} \sim M_Z^2 \;\Rightarrow\; (m_H^2)^{SM+M} \sim -C \cdot M^2$: *"Technically unnatural"!*
- SUSY as a solution: no quadratic corrections in SUSY
  $\Rightarrow$ Stabilization of $(m_H^2)^{SM} \sim M_Z^2$ w.r.t. GUT/Planck scales.

$\Rightarrow$ *Propose a SUSY version of the SM*

Supersymmetric Extensions of the SM

Minimal Supersymmetric Standard Model (MSSM)

- Global SUSY (N=1) + R-Parity + Gauge Group $SU(3)_c \times SU(2)_L \times U(1)_Y$;
- Minimal Supersymmetric matter content for SM particles:
  1. **Three Families of Lepton/Quark Superfields**:
     $$\hat{L}_L,\ \hat{E}^c_R = \text{(leptons+sleptons)}, \quad \hat{Q}_L\,,\ \hat{U}^c_R\,,\ \hat{D}^c_R = \text{(quarks+squarks)}.$$
  2. **Two (Higgs+higgsinos) Doublets**: $\hat{H}_u\,,\ \hat{H}_d$
     coupling respectively to u-like fields and d-like fields;
     Electroweak Symmetry Breaking $\Rightarrow$ v.e.v.'s v_u, v_d $\rightarrow$ parameter $\tan\beta \equiv \frac{v_u}{v_d}$.
  3. **(Vector+gaugino) fields** for all the gauge groups: $\hat{B}\,,\ \hat{W}^a\,,\ \hat{A}^c$.
- Superpotential: $W = \mu\hat{H}_u.\hat{H}_d + Y_u\hat{Q}_L.\hat{H}_u\hat{U}^c_R - Y_d\hat{Q}_L.\hat{H}_d\hat{D}^c_R - Y_e\hat{L}_L.\hat{H}_d\hat{E}^c_R$
- Soft SUSY Breaking terms…

BONUS:

* **Dark matter** (natural WIMP candidate)

* One-step **Gauge-Unification**

μ-problem: a Naturalness Problem of the MSSM

- μ : SUSY parameter → Natural Scale: $O(M_{\text{Planck, GUT,}\dots})\dots$ or Zero!
- LEP Constraints on Chargino masses: $\mu \gtrsim 100\,\text{GeV}$
- Electroweak Symmetry Breaking needs: $\mu \lesssim O(TeV)$

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- Additional Gauge-Singlet superfield $\hat{S}$ *[Fayet (1975)]*
- Superpotential ($\mathbb{Z}_3$ symmetry: scale invariant):

$$W = \frac{\kappa}{3}\hat{S}^3 + \lambda\hat{S}\hat{H}_u.\hat{H}_d + Y_u\hat{Q}_L.\hat{H}_u\hat{U}^c_R - Y_d\hat{Q}_L.\hat{H}_d\hat{D}^c_R - Y_e\hat{L}_L.\hat{H}_d\hat{E}^c_R$$

- v.e.v. $\langle S\rangle = s \quad \Rightarrow \quad \mu_{eff} = \lambda s$
- + Soft terms…
- Richer Higgs/Dark matter phenomenology:
  * additional contributions to the tree-level Higgs mass;
  * light Higgs scalar circumventing detection at colliders;
  * ~ 10 GeV-like pseudoscalars intervening in cascade-Higgs decays and/or Dark matter annihilation;
  * singlino Dark Matter…

+ Extensions with additional $U(1)$-gauge-symmetry;

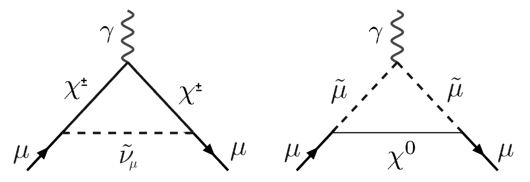
+ …

Outline

One-Loop Contributions in the MSSM [*Martin, Wells (2001)*]

Chargino / Sneutrino Loop:

- Dominant contribution;
- Linear dependance on $\tan\beta$;
- Same sign as the SUSY parameter μ: $\mu > 0$ favoured;
- Light chargino/Sneutrino required.



Neutralino / Smuon Loop:

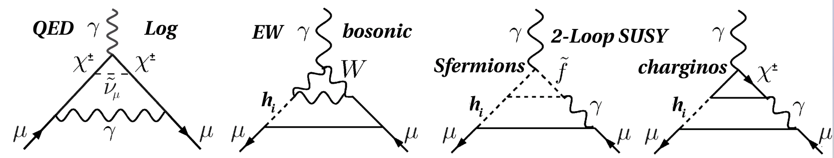
Can be large enough even for low values of $\tan\beta$ when there is a light neutralino ~ bino.

$$\left(\delta a_\mu\right)^{MSSM}_{1L} \sim \frac{\alpha}{2\pi}\left(\frac{m_\mu}{M_{SUSY}}\right)^2 \tan\beta\,\mathrm{sign}(\mu M_2)$$

Two-Loop Contributions in the MSSM

Large QED Logarithms: [*Degrassi, Giudice (1998)*]

$$a_\mu^{SUSY} = a_\mu^{SUSY\,1L}\left(1 - \frac{4\alpha}{\pi}\ln\frac{M_{SUSY}}{m_\mu}\right)$$



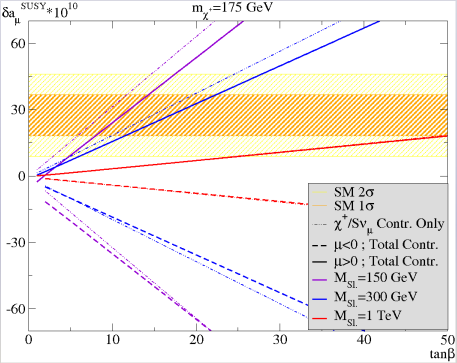
SM-like 2L Diagrams: [*Heinemeyer et al. (2004)*]

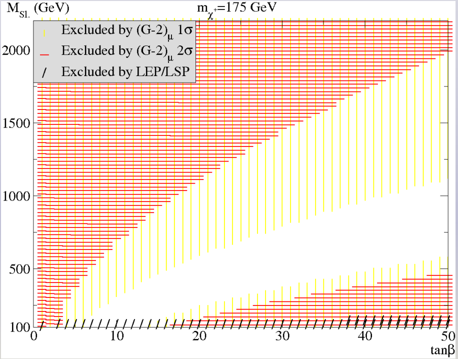
2-loop Bosonic Electroweak Diagrams: reproduce the SM value.

Diagrams with a closed SUSY Loop: [*Arhrib, Baek (2002), Heinemeyer et al. (2004), Stöckinger (2006)*]

Sfermion; chargino diagrams.

Constraints on the MSSM parameter space





- Chargino/Slepton loop tends to be dominant;
- Effect $\propto Y_\mu \propto \tan\beta$;
- $\mu > 0$ required;
- Light binos can also have significant effect.

Conclusion: The 3σ deviation can be reproduced provided SUSY particles are sufficiently light / $\tan\beta$ is large.

Consequences of a ~ 125 GeV Higgs?

In a Constrained Model

CMSSM/NUHM: Universality conditions at the GUT scale for the SUSY-breaking terms.

- $(G-2)_\mu$: light SUSY particles;
- $m_H \sim 125$ GeV: heavy SUSY particles;

  ⇒ Tensions…

  [Buchmuller et al., 2011]

Model	Minimum χ^2/d.o.f.	Fit Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM						
pre-Higgs	28.8/22	15%	780	450	−1110	41
$M_h \simeq 125$ GeV, $(g-2)_\mu$	30.6/23	13%	1800	1080	860	48
$M_h \simeq 125$ GeV, no $(g-2)_\mu$	21.0/22	52%	2000	1050	430	46
$M_h \simeq 119$ GeV	28.8/23	19%	780	450	−1110	41
NUHM1						
pre-Higgs	26.9/21	17%	730	150	−910	41
$M_h \simeq 125$ GeV, $(g-2)_\mu$	29.7/22	13%	830	290	660	33
$M_h \simeq 125$ GeV, no $(g-2)_\mu$	20.6/21	48%	2000	1400	2560	47
$M_h \simeq 119$ GeV	26.9/22	22%	730	150	−910	41

Table 1

Comparison of the best-fit points found in the CMSSM and NUHM1 pre-Higgs [3] and for the two potential LHC Higgs mass measurements discussed in the text: $M_h \simeq 119$ and 125 GeV. In the latter case, we also quote results if the $(g-2)_\mu$ constraint is dropped.

In the general case

- $(G-2)_\mu$: essentially sensitive to 2nd generation sleptons $(\tilde{\nu}_\mu, \tilde{\mu})$;
- Higgs mass: essentially sensitive to 3rd generation squarks $(\tilde{T}, \tilde{B})$;

⇒ Both constraints are no longer mutually exclusive.

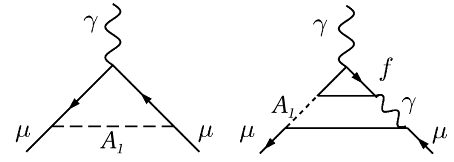
Outline

Specific NMSSM Contributions: Light Pseudoscalar

Light Pseudoscalars in the NMSSM:

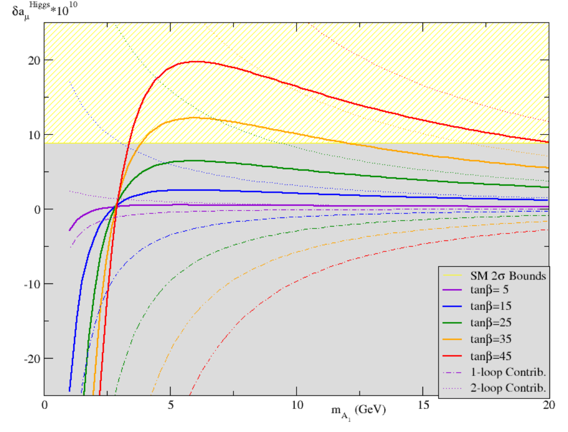
- Higgs Effects negligible in the SM and the MSSM: $m_H \geq 115\,\text{GeV} \;\; \Rightarrow \;\; a_\mu^H \leq 5.10^{-14}$;
- NMSSM: Pseudoscalars A_1 can be very light ($\sim$ a few GeV) without violating LEP constraints;
- B-constraints ($B_s \to \mu^+\mu^-$, $B \to X_s\mu^+\mu^-$, $\Upsilon \to \gamma\tau^+\tau^-, \ldots$) can be avoided too.

Light Pseudoscalars can lead to a non-negligible effect on a_μ, specific to the NMSSM.



Light Pseudoscalar contribution to a_μ [*Krawczyk (2002), Gunion et al. (2006)*]

- 1-loop contribution negative / 2-loop contribution positive;
- When $m_{A_1} \geq 3\,GeV$, 2-loop contribution dominates;
- Proportional to $\tan^2\beta$;
- Proportional to A_1 coupling to the Standard sector (doublet component).



Effect of the A_1 contribution:

- Proportional to $\tan^2\beta$;
- 1-loop contribution negative / 2-loop contribution positive;
- When $m_{A_1} \geq 3\,GeV$, 2-loop contribution dominates.

Can reach the 2σ level by itself.

$\Rightarrow$ Alleviates the requirements on the slepton/chargino masses.

Outline

Conclusion

- Hint for Physics beyond the SM in $(G-2)_\mu$ favours New Physics close to the EW scale.
- Interestingly, SUSY-inspired models seem able to generate an effect of the correct order of magnitude...

  ... provided sufficiently-light SUSY particles / $\tan\beta$-enhancement.

  $\Rightarrow$ *Significant constraints on their parameter spaces!*
- New effects beyond MSSM can be relevant.