Probe of SUSY and Extra Dimensions by the Brookhaven g-2 Experiment

[PN]

LaThuile, March 4-10, 2001

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Topics

- **SUSY electro-weak effects on** $g_\mu - 2$
- **Kaluza-Klein effects**
- **CP violation effects**
- **Implications of Precise BNL** $g_\mu - 2$ **result**

See also talks at this meeting by R. Arnowitt, G. Kane and B. Khazin which have overlap with some of the topics discussed in this talk.

THE STANDARD MODEL a_μ^{EW}

$$a_\mu^{SM} = a_\mu^{qed} + a_\mu^{had} + a_\mu^{EW}$$

$$a_\mu^{qed} : O(\alpha^5) \quad (Kinoshita\ etal)$$

$$a_\mu^{had} : O(\alpha^2) + O(\alpha^3)$$

$$a_\mu^{EW}(SM) = a_\mu^W + a_\mu^Z \quad (Fujikawa\ etal)$$

$$a_\mu^W = \frac{5m_\mu^2 G_F}{12\pi^2\sqrt{2}}$$

$$a_\mu^Z = \frac{m_\mu^2 G_F}{2\sqrt{2}\pi^2}(-\frac{5}{12} + \frac{4}{3}(\sin^2\theta_W - \frac{1}{4})^2)$$

There are important two loop corrections to $a_\mu^{EW}(SM)$ (Czarnecki & Marciano)

$$a_\mu^{EW}(SM) = 15.1(0.4) \times 10^{-10} \quad (1 + 2\ loop)$$

$$a_\mu^{had} = 673.9(6.7) \times 10^{-10} \quad (Davier\ \&\ Hocker)$$

$$a_\mu^{SM} = 11659159.7(6.7) \times 10^{-10}$$

$$a_\mu^{exp} - a_\mu^{SM} = 43(16) \times 10^{-10} \quad (BNL)$$

Nature of new physics

Some of the possibilities for the nature of new physics consist of

- SUSY
- **Compact extra dimensions**
- **Muon compositeness**
- **Anomalous W couplings**
- **New gauge bosons**
- **Lepto-quarks**
- **Radiative muon masses**
- **...**

SUSY

- **Exact SUSY Limit: (Ferrara-Remiddi)**

$$a_\mu = \frac{g_\mu - 2}{2} = 0$$

- **Broken SUSY**

$$a_\mu = a_\mu^{SM} + a_\mu^{SUSY} \neq 0$$

a_μ^{SUSY} **is sensitive to the nature of new physics.**

- **SUGRA unification: SUSY breaking is mediated by gravity. Assumption of a Flat Kahler potential gives**

mSUGRA : m_0,$m_{\frac{1}{2}}$, A_0, $\tan\beta$, $sign(\mu)$

- **Gauge mediated breaking of SUSY (GMBS)**
- **Anomaly mediated breaking of SUSY (AMBS)**

The SUSY contribution to a_μ at one loop

(Yuan, Arnowitt, Chamseddine, P.N.; Kosower, Krauss, Sakai, 1983-84)

$$a_\mu^{SUSY} = a_\mu^{\tilde{W}} + a_\mu^{\tilde{Z}}$$

$$a_\mu^{\tilde{W}} = \frac{m_\mu^2}{48\pi^2}\frac{{A_R^{(a)}}^2}{m_{\tilde{W}_a}^2}F_1(\left(\frac{m_{\tilde{\nu}}}{m_{\tilde{W}_a}}\right)^2) + \frac{m_\mu}{8\pi^2}\frac{A_R^{(a)}A_L^{(a)}}{m_{\tilde{W}_a}}F_2(\left(\frac{m_{\tilde{\nu}}}{m_{\tilde{W}_a}}\right)^2)$$

$a_\mu^{SUSY} \sim a_\mu^{SM}$ predicted in sugra models (1984)

$$A_R^{(1)} = -\frac{e}{\sqrt{2}\sin\theta_W}\cos\gamma_1; \quad A_L^{(1)} = (-1)^\theta\frac{em_\mu\cos\gamma_2}{2M_W\sin\theta_W\cos\beta}$$

$$A_R^{(2)} = -\frac{e}{\sqrt{2}\sin\theta_W}\sin\gamma_1; \quad A_L^{(2)} = -\frac{em_\mu\sin\gamma_2}{2M_W\sin\theta_W\cos\beta}$$

SUSY limit to check absolute signs (Ibrahim & P.N.)

$$a_\mu^{\tilde{W}} = -\frac{5m_\mu^2 G_F}{12\pi^2\sqrt{2}}$$

$$a_\mu^{\chi^0} = -\frac{\alpha_{em}}{2\pi} - \frac{m_\mu^2 G_F}{2\sqrt{2}\pi^2}(\frac{4}{3}\sin^4\theta_W - \frac{2}{3}\sin^2\theta_W - \frac{1}{3})$$

$$a_\mu^W + a_\mu^{\tilde{W}} = 0, \quad a_\mu^\gamma + a_\mu^Z + a_\mu^{\chi^0} = 0$$

Features of SUSY contributions

- *Couplings* $\sim 1/\cos\beta$. Thus a_μ increases linearly with $\tan\beta$ for large $\tan\beta$.

  (Yuan, Arnowitt, Chamseddine, PN; Lopez, Nanopoulos, Wang: Chattopadhyay & PN)

- Correlation of chargino eigen values with μ

  $$\lambda_{1,2} = \frac{1}{2}\left(\left[2M_W^2 + (\mu - \tilde{m}_2)^2 - 2M_W^2 sin2\beta\right]^{\frac{1}{2}} \mp \left[2M_W^2 + (\mu + \tilde{m}_2)^2 + 2M_W^2 sin2\beta\right]^{\frac{1}{2}}\right)$$

  Since $\sin 2\beta$ is negligible unless $\tan\beta \sim 1$, one finds $\lambda_1 < 0 (> 0)$ for $\mu > 0 (< 0)$

- The chiral interference term $A_L A_R$ arising from the light chargino has a front factor of $(-1)^\theta$ where

  $$\theta = 0(1), \quad \lambda_1 > 0(< 0)$$

  λ_1 is the smaller eigenvalue of the chargino mass matrix.

- Because of the above one finds that generally (Chattopadhyay & PN)

  $$a_\mu^{SUSY} > 0, \mu > 0$$
  $$a_\mu^{SUSY} < 0, \mu < 0$$

  except when $\tan\beta \sim 1$.

g-2 SUSY papers pre and post BNL Data

Pre BNL data papers

1980-1990

• SUGRA unification 1983-84

D.Kosower, L.M. Krauss, N. Sakai

T.C. Yuan, R. Arnowitt, A. Chamseddine, P. Nath

1990-2001

J.L. Lopez, D.V. Nanopoulos, X.Wang (1994)

U. Chattopadhyay and P. Nath (1995)

T. Moroi (1996)

M. Carena, M. Guidice, and C. Wagner (1997)

P. Nath & M. Yamaguchi (2000)

M.L. Graesser (2000)

T. Ibrahim & P. Nath (2000)

2001- Post BNL data papers

A. Czarnecki & W. Marciano

L. Everett, G.L. Kane, S. Rigolin & L.T. Wang

J. Feng & K.T. Matchev

U. Chattopadhyay & P. Nath

S. Komine, T. Moroi and M. Yamaguchi

T. Ibrahim, U. Chattopadhyay, & P. Nath

J.Ellis, D.V. Nanopoulos, K. Olive

Arnowitt, Dutta, Hu & Santoso

...

Implications of Precise BNL Data

(Chattopadhyay & PN)

- **BNL measurement**

$$a_\mu^{exp} - a_\mu^{SM} = 43(16) \times 10^{-10}$$

- **Assuming CP conservation and setting** $a_\mu^{SUSY} = a_\mu^{exp} - a_\mu^{SM}$ **BNL data determines**

$$sign(\mu) = +1$$

- **Using the 2σ error corridor one finds that the data implies upper bounds on the sparticle masses. Within mSUGRA one finds** (Chattopadhyay & PN)

$$m_{\tilde{W}} \leq 600GeV, m_{\tilde{\nu}} \leq 1.1TeV$$

$$m_{1/2} \leq 750GeV, m_0 \leq 1.1TeV$$

- **Sparticles should become visible at the LHC and perhaps even at RUNII of the Tevatron.**
- $b \to s + \gamma$ **constraint favors** $\mu > 0$ **which is favorable for dark matter. The fact that with CP conservation the BNL data implies** $\mu > 0$ **is very encouraging for dark matter analyses:**

(Arnowitt & PN; Borzumati, Drees & Nojiri)

Physics of Extra Dimensions

Antoniadis, Quiros,Pomeral,Masip..; PN & Yamaguchi

- **Consider a class of models with one large extra dimension compactified on S^1/Z_2 with compactification radius R ($M_R = 1/R = O(TeV)$).**
- **After compactification the resulting spectrum contains massless modes with N=1 supersymmetry in 4D, which precisely form the spectrum of MSSM in 4D.**
- **The massive Kaluza-Klein modes form N=2 multiplets in 4D.**
- **In $4D$ a rescaling of couplings**

$$g_i^{(5)}/\sqrt{\pi R} = g_i$$

The zero mode and KK interactions

$$L_{int} = g_i j^\mu (A_{\mu i} + \sqrt{2} \sum_{n=1}^{\infty} A_{\mu i}^n)$$

- **G_F is corrected** (PN & Yamaguchi)

$$G_F = G_F^{SM}(1 + \frac{\pi^2}{3}\frac{M_W^2}{M_R^2})$$

- **With current error corridor on G_F^{SM} one finds $M_R \geq 3$TeV ($M_* \geq 3.5$TeV from new gravity experiment).**

Effects Of Large Extra Dimensions on a_μ

(PN & Yamaguchi)

- **Large extra dimensions affect the value of a_μ from contributions via the excitations of W, Z, γ.**
- **KK corrections**

$$a_\mu^{KK} = a_\mu^{W-ZKK} + a_\mu^{\gamma KK}$$

$$(\Delta a)_\mu^{W-ZKK} = \frac{G_F m_\mu^2}{6\sqrt{2}}(-\frac{5}{12}+\frac{4}{3}(sin^2\theta_W-\frac{1}{4})^2)(\frac{M_Z^2 - M_W^2}{M_R^2})$$

The minus sign occurs because the Fermi constant must be normalized to take account of the KK corrections.

$$(\Delta a)_\mu^{\gamma KK} = \alpha\frac{\pi}{9}\frac{m_\mu^2}{M_R^2}$$

- **Numerically the effects of the KK states is small. So extra dimensions do not create a strong background to SUSY.**

$$a_\mu^{extra}/a_\mu^{SUSY} \le O(10^{-2})$$

Soft SUSY breaking parameters are in general complex with phases O(1).

- **CP phases affect low energy physics**
- **Phases O(1) create a severe EDM problem giving $d_n \sim 10^{-24}$ ecm while experimentally**

$$d_n < 6.5 \times 10^{-26} ecm \quad (experiment)$$

$$d_e < 4.3 \times 10^{-27} ecm \quad (experiment)$$

Possible solutions

- **small phases O(10^{-2})**
  Ellis, Ferrara, Nanopoulos; Polchinski and Wise;
  Weinberg; Arnowitt, Duff, Lopez, Nanopoulos, Stelle,..
- **heavy SUSY spectrum with masses O(several) TeV**
  P.N.; Kizukuri, Oshimo
- **internal cancellations**
  Ibrahim, P.N.; Falk, Olive; Brhlik, Good, Kane; Bartel etal, Pokorski, Rosiek, Savoy; Accomando,
  Arnowitt, Dutta.

CP phases affect: sparticle masses, decay branching ratios, the trileptonic signal, $b \to s\gamma$, $g_\mu - 2$, ϵ'/ϵ, baryon asymmetry,..

Prediction: d_e, d_n must be seen with O(10) improvement in experiment.

Operators that contribute to the neutron edm

- **electric dipole operator**

$$\mathcal{L}_I = -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

- **chromoelectric operator**

$$\mathcal{L}_I = -\frac{i}{2} \tilde{d}^C \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{\mu\nu a}$$

- **dimension 6 purely gluonic operator**

$$\mathcal{L}_I = -\frac{1}{6} d^G f_{\alpha\beta\gamma} G_{\alpha\mu\rho} G^{\rho}_{\beta\nu} G_{\gamma\lambda\sigma} \epsilon^{\mu\nu\lambda\sigma}$$

Naive dimensional analysis (Georgi-Manohar)

$$d_q^C = \frac{e}{4\pi} \tilde{d}_q^C \eta^C, \quad d_n^G = \frac{eM}{4\pi} d^G \eta^G$$

where $\eta^C \approx \eta^G \sim 3.4$ and M =1.19 GeV is the chiral symmetry breaking scale.

Effects of Large CP Phases on $g_\mu - 2$

Ibrahim & PN

- **Chargino mass matrix**

$$M_C = \begin{pmatrix} |\tilde{m}_2|e^{i\xi_2} & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & |\mu|e^{i\theta_\mu} \end{pmatrix}$$

- **Chargino exchange contribution**

$$a_\mu^{\chi^-} = a_\mu^{1\chi^-} + a_\mu^{2\chi^-}$$

$$a_\mu^{1\chi^-} = \frac{m_\mu \alpha_{EM}}{4\pi \sin^2\theta_W} \sum_{i=1}^{2} \frac{1}{M_{\chi_i^+}} Re(\kappa_\mu U_{i2}^* V_{i1}^*) F_3(\frac{M_{\tilde{\nu}}^2}{M_{\chi_i^+}^2})$$

$$a_\mu^{2\chi^-} = \frac{m_\mu^2 \alpha_{EM}}{24\pi \sin^2\theta_W} \sum_{i=1}^{2} \frac{1}{M_{\chi_i^+}^2} (|\kappa_\mu U_{i2}^*|^2 + |V_{i1}|^2) F_4(\frac{M_{\tilde{\nu}}^2}{M_{\chi_i^+}^2})$$

$$U^* M_C V^{-1} = diag(\tilde{m}_{\chi_1^+}, \tilde{m}_{\chi_2^+})$$

- **The chargino exchange contribution depends only on** $\theta_\mu + \xi_2$
- **The neutralino contribution depends on several phases and is a function of both**

$$\theta_\mu, \xi_2$$

- **The BNL data constrains the CP phases and as much as 60-90% of the parameter space in $\theta_\mu - \xi_2$ plane is eliminated by the BNL constraint.** Ibrahim, Chattopadhyay, PN

Conclusion

- **SUSY provides the most natural explanation of the difference $a_\mu^{exp} - a_\mu^{SM}$ seen at BNL.**
- **The effect was already predicted in the realistic SUGRA model that the supersymmetric correction could be as large or larger. Similar size effects also in other models.**
- **A detailed analysis of the effect in mSUGRA shows that the BNL effect implies the existence of sparticles most of which should become visible at the LHC with a good chance for some to become visible at RUNII of the Tevatron.**
- **Extra dims do not pose a strong background to SUSY.**
- **The BNL data imposes impressive constraints on CP phases θ_μ and ξ_2 eliminating up to 60-90% of the parameter space.**
- **There is 4 times more data and the result will tighten in the near future. What the further data may show will shed significant new light on SUSY physics.**