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ELECTRIC DIPOLE MOMENTS FROM SOFT SUSY PHASES And The MUON g - 2

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- Supersymmetry models contain new sources of CP violation phases.

- These phases can contribute to the electric dipole moments of electron, neutron etc. We have strict experimental limits on electron and neutron EDMs:
  $|d_e| < 4.3\times10^{-27}$ ecm and $|d_n| < 6.3\times10^{-26}$ ecm. [The SM contribution is very small.]

- Phase of O(1) size can predict large EDM, which can be larger than the experimental limits.

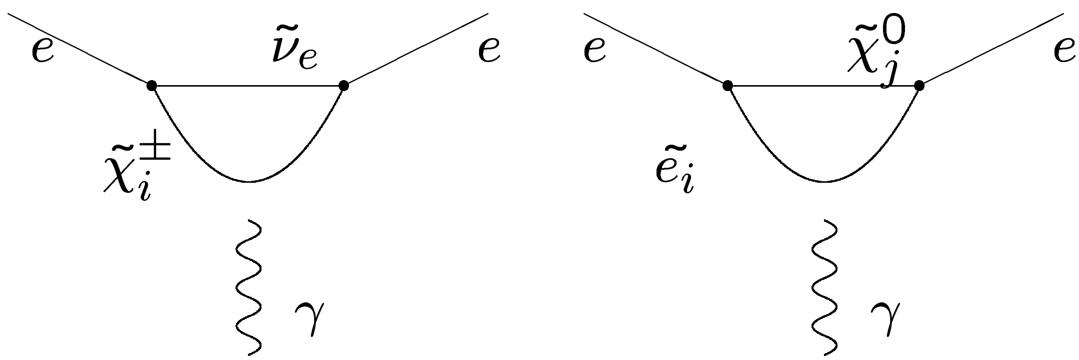
  Conventionally,

- The phases are assumed to be small $O(10^{-2}$–$10^{-3})$.

- The masses are very heavy (several TeV).

Recent proposal:

The EDM constraint can be satisfied by tuning the cancellation among different Feynman diagrams which contribute to the calculation of EDM [Ibrahim, Nath '98, Falk, Olive '98, Brhlik, Good, Kane '99]. For example,
Electron EDM:



- These diagrams can cancel each other and satisfy the EDM constraint.

- We can have large SUSY phases in the theory even in the regions of smaller sparticle masses.

In this talk:

- I will discuss the cancellation mechanism for EDM in the mSUGRA model with a generalized phase structure. I will show that the cancellation is fine tuned at the GUT scale for certain regions of parameter space.

- I will discuss the fine tuning problem in the parameter space allowed by the following constraints:

  (i)The recent result of $a_\mu(\equiv (g-2)/2)$ of muon: This has restricted the SUSY parameter space. The calculation of a_μ^{mSUGRA} and EDM involve the same set of diagrams. The former however is related to the real part.

(ii) Cosmological constraint : The SUSY model, I dicuss, conserves R parity and thus the lightest supersymmetric particle can be a candidate for cold dark matter. The parameter space is restricted by the relic density constraint .

(iii)Recent accelerator and rare decay bounds: The latest bound on Higgs mass and the CLEO bound on $b \to s\gamma$ put important constraint in the model space.

Model Parameters:

Supergravity GUT models with universal soft breaking of supersymmetry, mSUGRA, depend upon five parameters at the GUT scale:

$m_{1/2}$ (the universal gaugino mass),
A_0 (the cubic soft breaking mass),
B_0 (the quadratic soft breaking mass),
μ_0 (the Higgs mixing parameter) and
m_0 (the universal squark and slepton mass).

- Electroweak symmetry is broken radiatively.

- Magnitudes of μ and B are determined from the electroweak symmetry breaking conditions.

We assume a general phase structure at the GUT scale i.e.

- $\tilde{m}_1$, $\tilde{m}_2$, $\tilde{m}_3$, A_0, B_0 and μ are complex at the GUT scale.

- Among these phases, we rotate away one of the gaugino phases.

- Finally, we have the following phases at the GUT scale:

- $|\tilde{m}_1|e^{i\phi_1}$, $|\tilde{m}_3|e^{i\phi_3}$, $|A_0|e^{i\phi_{0A}}$, $|B_0|e^{i\theta_{0B}}$, $|\mu_0|e^{i\theta_\mu}$.

- The RGEs relate these GUT scale parameters to the weak scale values.

  For example:

$$\tilde{m}_i = \frac{\alpha_i}{\alpha_G}\tilde{m}_{1/2}$$

  In the low and intermediate tanβ region, we can solve the RGEs to obtain:

$$A_t(t) = D_0 A_0 + \sum \Phi_i |m_{1/2i}| e^{i\phi_i}$$

  the Φ_i are real and $O(1)$, $D_0 \simeq 0.25$,

$$B = B_0 - \frac{1}{2}(1 - D_0)A_0 - \sum \Phi'_i |m_{1/2i}| e^{i\phi_i}$$

  [Accomando,Arnowitt, Dutta'99]

- Superpartner masses: The chargino and the neutralino mass matrices are:

$$M_{\chi^\pm} = \begin{pmatrix} \tilde{m}_2 & \sqrt{2}M_W sin\beta \\ \sqrt{2}M_W cos\beta & |\mu|e^{i\theta} \end{pmatrix}$$

$$M_{\chi^0} = \begin{pmatrix} |\tilde{m}_1|e^{i\phi_1} & 0 & a & b \\ 0 & \tilde{m}_2 & c & d \\ a & c & 0 & -|\mu|e^{i\theta} \\ b & d & -|\mu|e^{i\theta} & 0 \end{pmatrix}$$

where $a = -M_Z sin\theta_W cos\beta$, $b = M_Z sin\theta_W sin\beta$, $c = -cot\theta_W a$, $d = -cot\theta_W b$, $tan\beta = v_2/v_1$ ($v_{1,2} =|< H_{1,2} >|$) and θ_W is the weak mixing angle.

- The phase θ is given by

$$\theta = \epsilon_1 + \epsilon_2 + \theta_\mu$$

where at the electroweak scale, $< H_{1,2} >= v_{1,2}e^{i\epsilon_{1,2}}$, and $\mu = |\mu|e^{i\theta_\mu}$.

- $\tan\beta$ is a free parameter.

- The slepton mass matrix can be written as

$$\tilde{m}_l^2 = \begin{pmatrix} m^2_{l_{LL}} & m^2_{l_{LR}} \\ m^{2\,*}_{l_{RL}} & m^2_{l_{RR}} \end{pmatrix}$$

$$m^2_{l_{LR}} = m_l(A_l e^{-i\phi_{A_l}} - |\mu| e^{i\theta} \tan\beta)$$

where m_l is the lepton mass.

$$m^2_{l_{LL}} = m^2_L + m^2_l - 1/2(2cos^2\theta_W - 1)M^2_Z cos2\beta$$

$$m^2_{l_{RR}} = m^2_R + m^2_l - sin^2\theta_W M^2_Z cos2\beta$$

Electroweak symmetry breaking and relation among phases:

- The condition for electroweak symmetry breaking is obtained by minimizing the effective potential V_{eff} with respect to v_1, ϵ_1, v_2 and ϵ_2. The Higgs sector of V_{eff} is

$$V_{eff} = m_1^2 v_1^2 + m_2^2 v_2^2 - 2|B\mu| cos(\theta + \theta_B) v_1 v_2$$

$$+\frac{g_2^2}{8}(v_1^2 + v_2^2)^2 + \frac{{g_1}^2}{8}(v_2^2 - v_1^2)^2 + V_1$$

where V_1 is the one loop contribution, $m_i^2 = \mu^2 + m_{H_i}^2$ and $m_{H_{1,2}}^2$ are the $H_{1,2}$ running masses.

We now minimize V_{eff} in order to determine the Higgs VEVs i.e. v_1, v_2, ϵ_1, ϵ_2.

- In the tree approximation, the extrema equations
  $\partial V_{eff}/\partial \epsilon_i = 0$ yield $2|B\mu| sin(\theta + \theta_B) = 0$.
  Hence the minimum of V_{eff} requires

$$\theta = -\theta_B$$

  At the one loop level, one gets a correction of the form

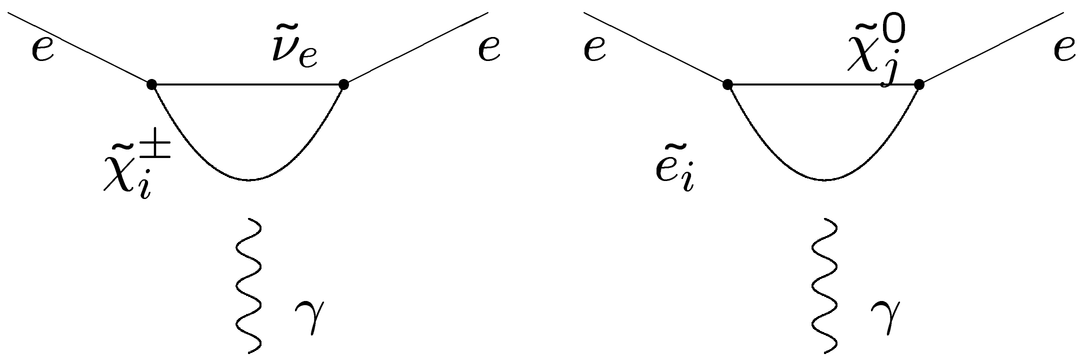
$$\theta = -\theta_B + f_1(-\theta_B + \phi_{A_q}, -\theta_B + \phi_{A_l})$$

  where f_1 is the one loop correction with θ approximated by its tree value [Demir'99, Pilaftsis, Wagner'99].

- This correction can become significant for large tanβ.

  In our analysis we use $\theta = \theta_\mu$.

EDM calculation:



$\propto \sin \theta_\mu$

$\propto \sin(\theta_\mu + \phi_1)$

$\propto \sin(\phi_A + \phi_1)$

$\propto \sin(\theta_\mu + \phi_A)$

- The above diagrams cancel with each other and hence large phases can be allowed.

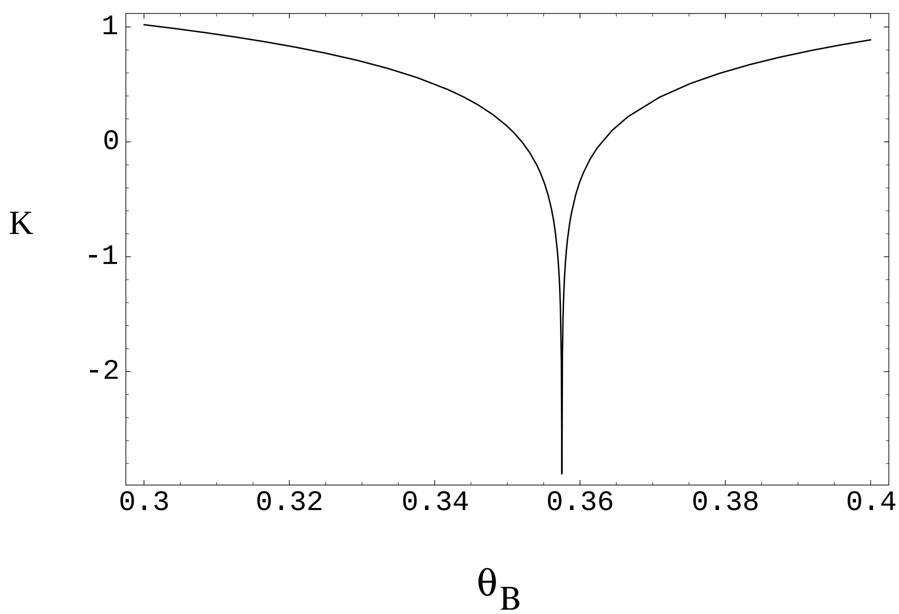
- The condition we get (assuming $\phi_A = 0$):

  $d_{\tilde{\chi}_1^0} \sin(\theta_\mu + \phi_1) + d_{\tilde{\chi}_1^0 + \tilde{\chi}_1^\pm} \sin(\theta_\mu) = 0$

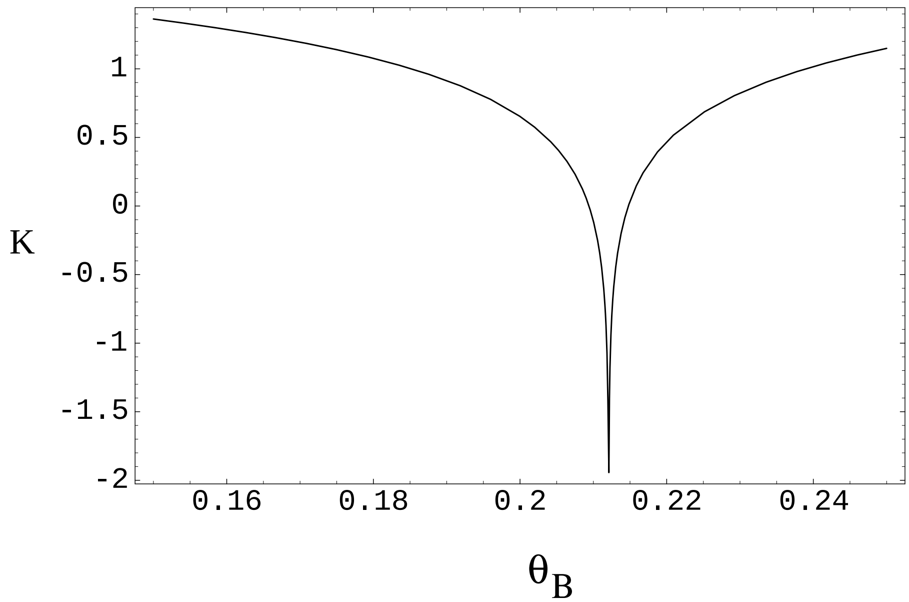
  $\Rightarrow \tan \theta_B = \frac{\epsilon \sin \phi_1}{1 + \epsilon \cos \phi_1}$

  where $\epsilon = \frac{d_{\tilde{\chi}_1^0}}{d_{\tilde{\chi}_1^0 + \tilde{\chi}_1^\pm}}$.
  $d_{\tilde{\chi}_1^0 + \tilde{\chi}_1^\pm}$ contains diagrams involving chargino and neutralino and $d_{\tilde{\chi}_1^0}$ contains diagrams involving neutralino only. Typically $\epsilon \simeq 0.3$.

- This is the situation where we have exact cancellation and electron EDM is 0. But the experimental upper bound generates a spread of θ_B which depends on the experimental bound on EDM.



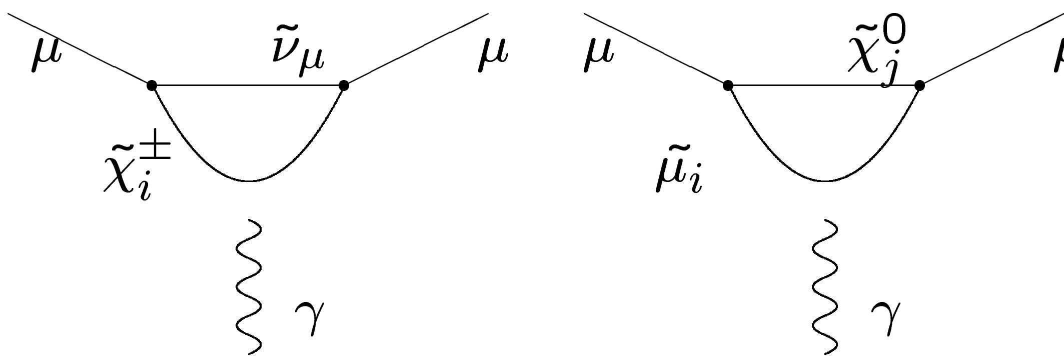
$K = log_{10} \mid \frac{d_e}{(d_e)_{exp}} \mid$ vs θ_B for $\tan\beta = 15$, $m_0 = 100$ GeV, $m_{1/2} = 400$ GeV, $\phi_1 = 0.9$ and $A_0 = 0$.



$K = log_{10} \mid \frac{d_e}{(d_e)_{exp}} \mid$ vs θ_B for $\tan\beta = 40$, $m_0 = 210$ GeV, $m_{1/2} = 400$ GeV, $\phi_1 = 0.9$ and $A_0 = 0$.

- The magnitude of m_0 being different compared to $\tan\beta = 15$ case is because of dark matter constraint.

Calculation of a_μ:



- The real part of the diagrams contribute in this case.

- BNL 821 experiment gives a 2.6σ deviation from standard model[Brown, hep-ex/0102017]

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

- This deviation can be explained in the framework of SUGRA GUT model. [Kosower, Krauss, Sakai'83, Yuan, Arnowitt, Chamseddine, Nath '84]

- In mSUGRA model, the dominant contribution is given by:

  $$a_\mu \simeq \frac{\alpha}{4\pi}\frac{\tan\beta}{\sin^2\theta_W}\frac{m_\mu^2}{|\tilde{m}_2||\mu|}A[\cos\theta_\mu+\epsilon\cos(\theta_\mu+\phi_1)]$$

  A is expressed in terms of the ratio of masses and is O(1).

- Using $\tan\theta_B = \frac{\epsilon\sin\phi_1}{1+\epsilon\cos\phi_1}$ (where EDM is 0), we find

  $$a_\mu \simeq \frac{\alpha}{4\pi}\frac{\tan\beta}{\sin^2\theta_W}\frac{m_\mu^2}{|\tilde{m}_2||\mu|}A\sqrt{(1+2\epsilon\cos\phi_1+\epsilon^2)}$$

  for $\phi_1 = 0$, we have $a_\mu \propto (1+\epsilon)$,

  for $\phi_1 = \pi$, we have $a_\mu \propto (1-\epsilon)$.

Calculational details:

- We use the Higgs mass constraint : $m_h > 111$ GeV.
  This bound puts constraint on $m_{1/2}$ e.g. for $\tan\beta = 10$, $m_{1/2} > 300$ GeV.

- We use the $b \to s\gamma$ constraint.
  We use NLO contributions to SUSY and charged Higgs diagrams[Degrassi etal.'00, Ciuchini etal.'00]

- We use SUSY one loop correction to b-mass. This correction is important for large tanβ. [Rattazzi, Sarid' 94; Carena, Wagner, Pokorski'94].
  We do not demand $b - \tau$ unification

- In our calculation $m_{\tilde{\chi}^0_1}$ is the lightest SUSY particle. We use the dark matter constraint in the parameter space, i.e. $0.02 < \Omega_{\tilde{\chi}^0_1} h^2 < 0.25$

Dark matter constraint (in detail)

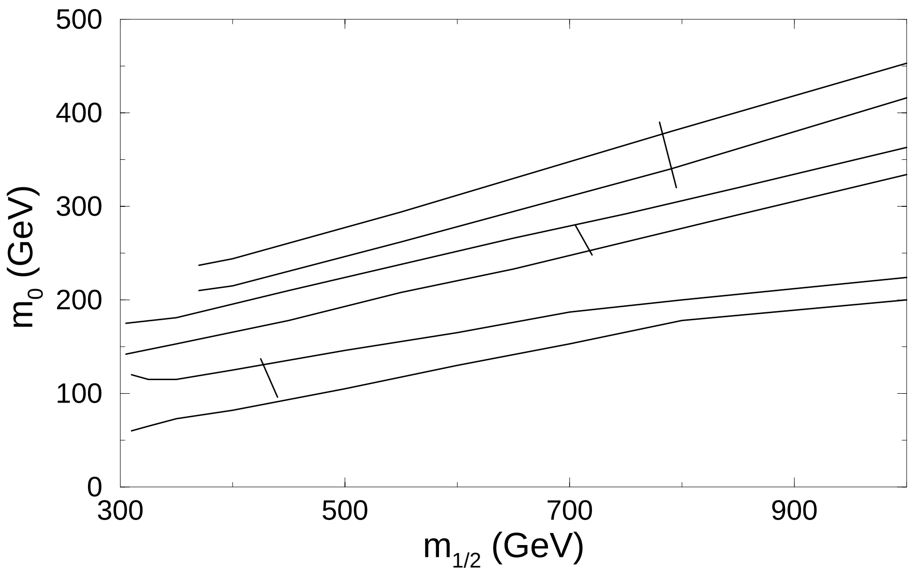
- $\Omega_{\chi_1^0} h^2 \propto \frac{1}{<\sigma v>}$

- As m_0 and $m_{1/2}$ increase σ decreases and $\Omega_{\chi_1^0} h^2$ increases. The new LEP limit on the Higgs mass and the $b \to s\gamma$ constraint require larger values of $m_{1/2}$.

- However, it is possible to decrease $\Omega_{\chi_1^0} h^2$ by choosing the mass of one of the scalar particles to be close to the neutralino and thereby giving rise to coannihilation in the early universe.

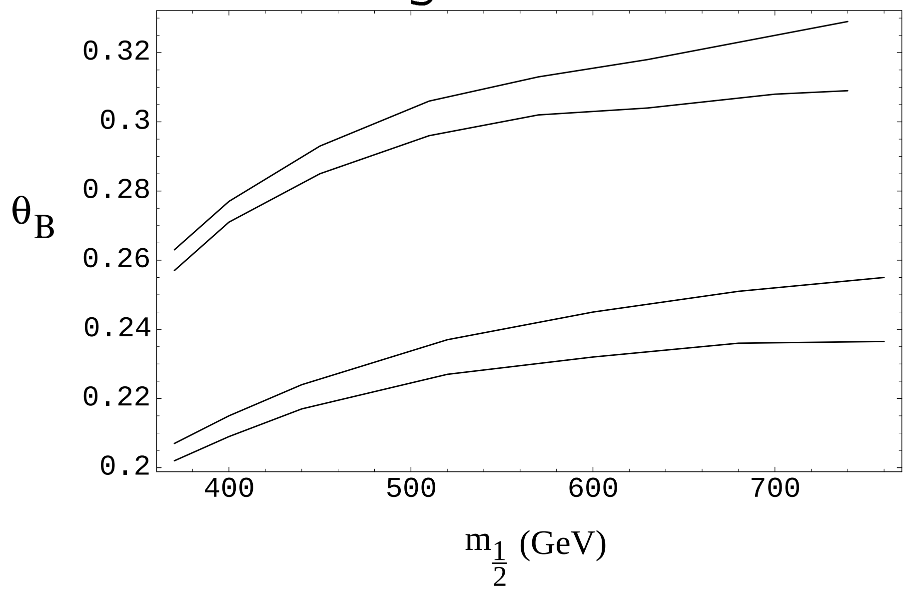
- In mSUGRA model the lighter stau mass comes close to the neutralino mass naturally. When this happens we find the relic density in the desired range. [Arnowitt, Dutta, Santoso'01; Falk, Ellis, Olive, Srednicki'01]

- In the coannihilation corridors m_0 gets fixed within a narrow window for a given value of $m_{1/2}$.



Corridors in the $m_0 - m_{1/2}$ plane allowed by the relic density constraint for $\tan\beta = 10$, 30 and 40 (from bottom to top), $m_h > 111$ GeV, $\mu > 0$ for $A_0 = 0$. The slanted lines indicate the bound from a_μ.

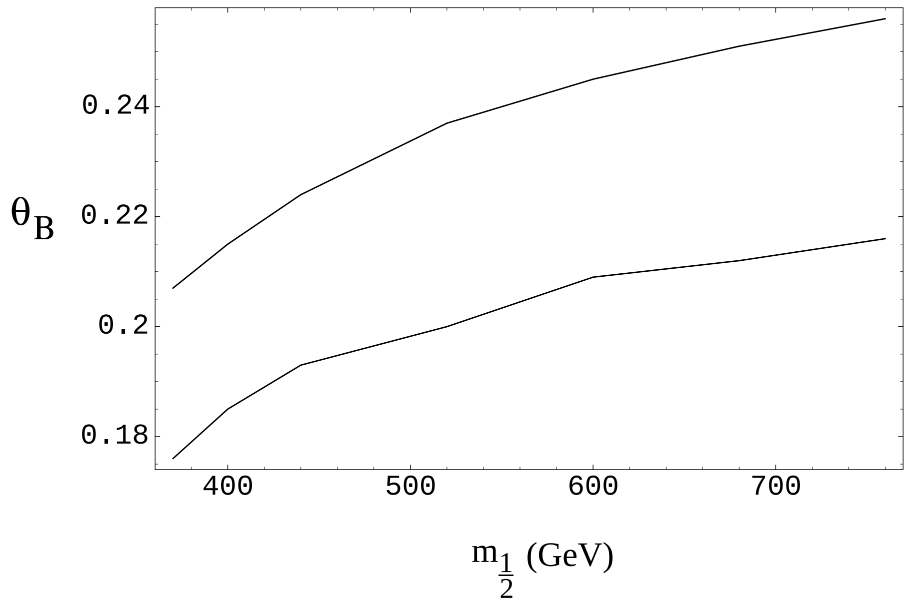
Numerical results using different constraints



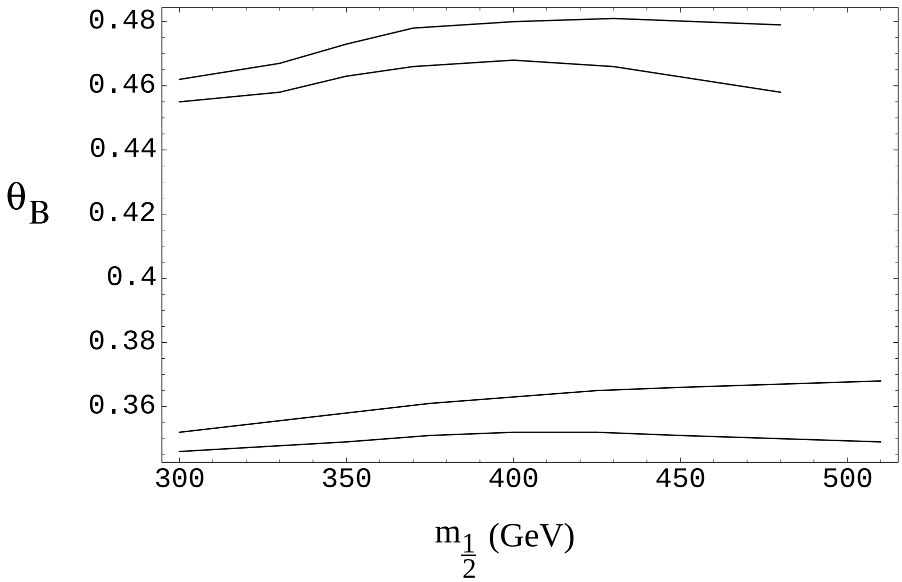
θ_B vs $m_{1/2}$ for $\tan\beta = 40$ and $A_0 = 0$. The upper region is for $\phi_1 = 1.2$ and the lower region is for $\phi_1 = 0.9$. The corridors appear due to the EDM constraint.

- Since we are in the coannihilation region, roughly $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \leq 25$ GeV. We choose m_0 for a fixed $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ value.

- The regions terminate at low $m_{1/2}$ is due to $b \to s\gamma$ bound and the termination at high $m_{1/2}$ is due to the lower bound on a_μ.



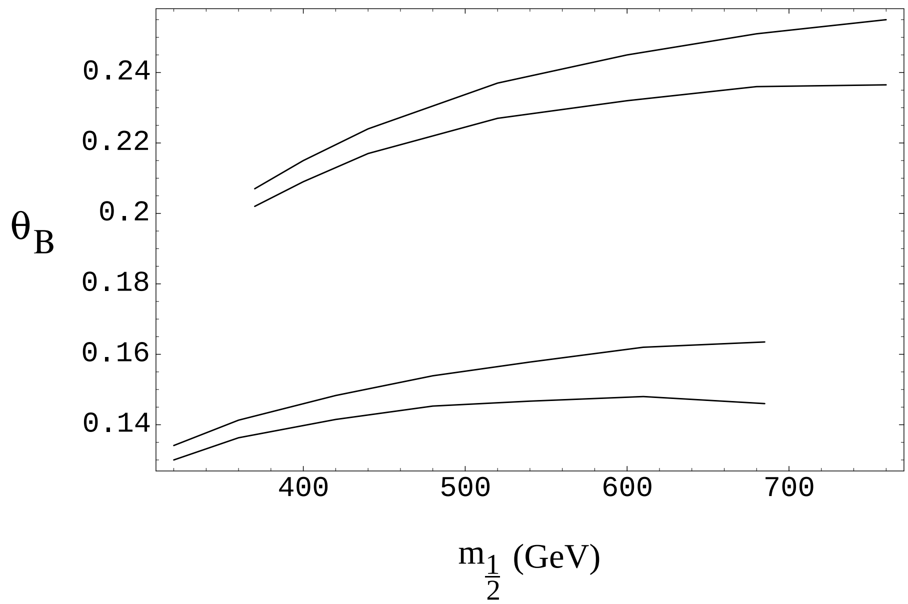
θ_B vs $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$ and $\phi_1 = 0.9$. The maximum and the minimum values of phases correspond to the entire range of $\Omega_{\tilde{\chi}_1^0} h^2$ i.e. $0.02 - 0.25$.



θ_B vs $m_{1/2}$ for $\tan\beta = 15$ and $A_0 = 0$. The upper region is for $\phi_1 = 1.2$ and the lower region is for $\phi_1 = 0.9$.

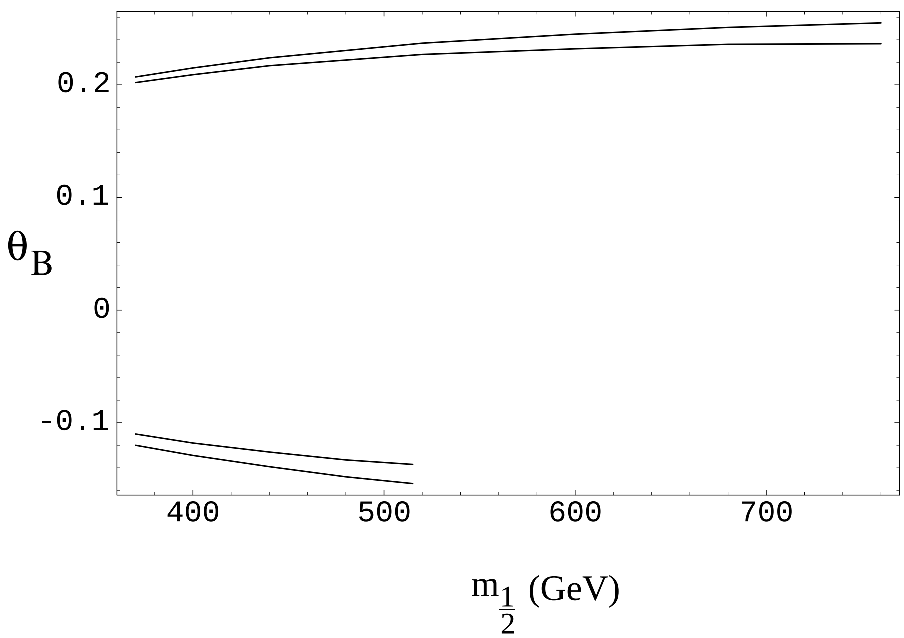
- The regions terminate at low $m_{1/2}$ is due to the Higgs mass constraint.

- θ_B is larger in this case compared to the $\tan\beta = 40$ case.



θ_B vs $m_{1/2}$ for $\tan\beta = 40$.
The upper region is for $A_0 = 0$ and the lower region is for $A_0 = 2m_{1/2}$ and $\phi_{0A} = 0.5$.

- $A_0 = 2m_{1/2}$ region requires larger m_0 to satisfy the dark matter constraint.



θ_B vs $m_{1/2}$ for $\tan\beta = 40$ and $A_0 = 0$. The upper region is for $\phi_1 = 0.9$ and the lower region is for $\phi_1 = 3.4$.

Fine tuning of phases at the GUT scale:

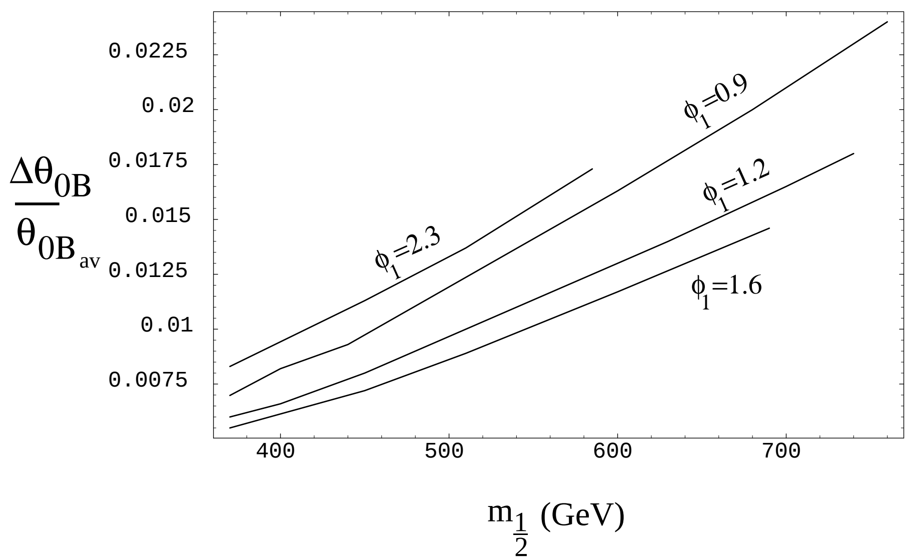
- $\frac{\Delta\theta_\mu}{\theta_{\mu_{av}}} > 1\%$ for most of the parameter space. [where $\Delta\theta_\mu$ is the regions allowed in the pervious figures by EDM]

- However, $\frac{\Delta\theta_{0B}}{\theta_{0Bav}} < 1\%$ for larger values of ϕ_1 and lower values of $m_{1/2}$.

  $\Delta\theta_{0B}$ is the allowed range of θ_{0B} at the GUT scale and is smaller compared to the $\Delta\theta_B$.

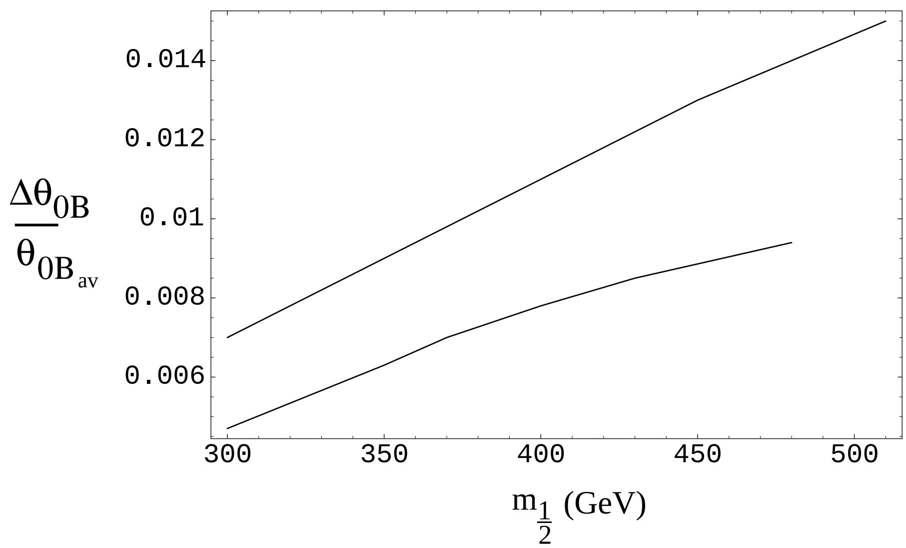
  This is because $\Delta\theta_{0B} \simeq \frac{|B|}{|B_0|}\Delta\theta_B$ and $|B_0| > |B|$.

- $\frac{\Delta\theta_{\phi_1}}{\phi_{1av}} > 1\%$ for most of the parameter space.



$\frac{\Delta\theta_{0B}}{\theta_{0Bav}}$ vs $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$.

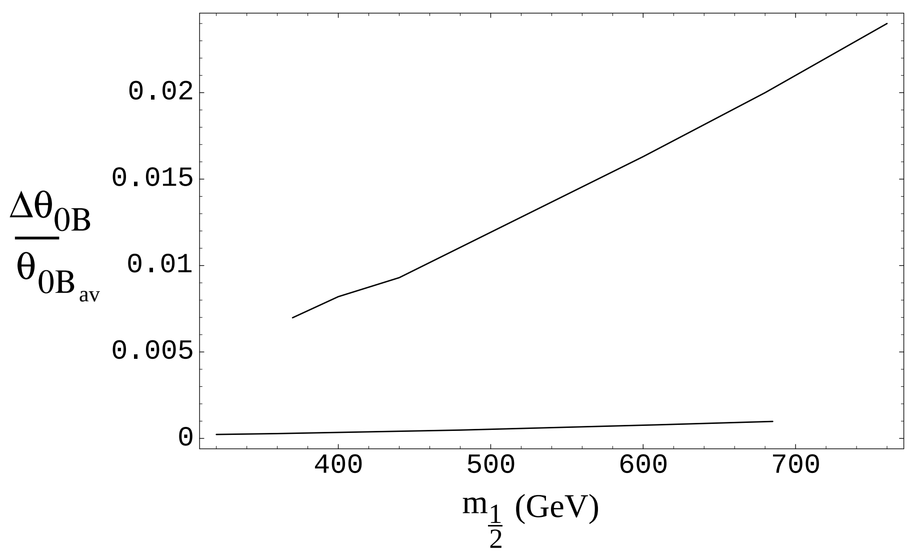
- If we require $\frac{\Delta\theta_{0B}}{\theta_{0Bav}} > 1\%$, the lower values of $m_{1/2}$ are disfavored.



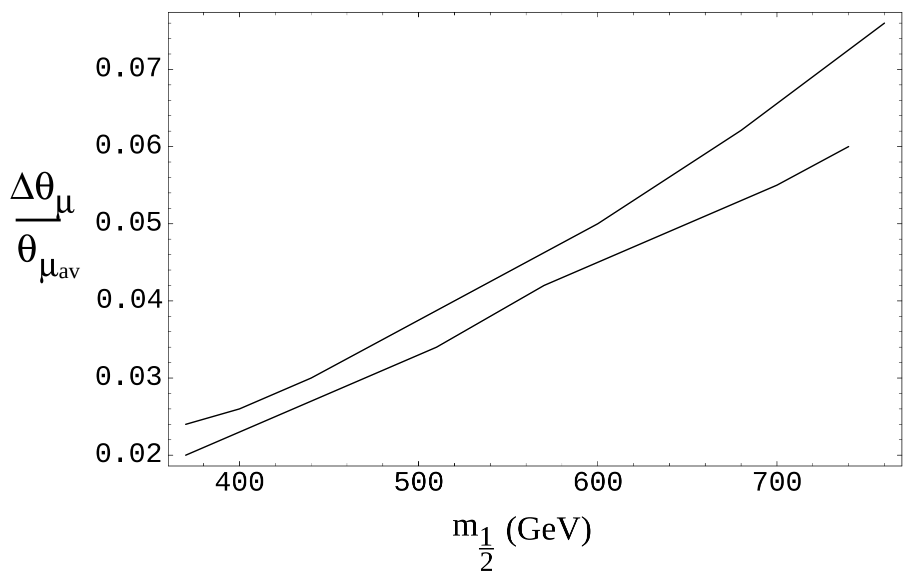
$\frac{\Delta\theta_{0B}}{\theta_{0Bav}}$ vs $m_{1/2}$ for $\tan\beta = 15$, $A_0 = 0$.

The upper line is for $\phi_1 = 0.9$ and the lower line is for $\phi_1 = 1.2$.

- If we require $\frac{\Delta\theta_{0B}}{\theta_{0Bav}} > 1\%$, $\phi_1 > 1.2$ is dis-favored .

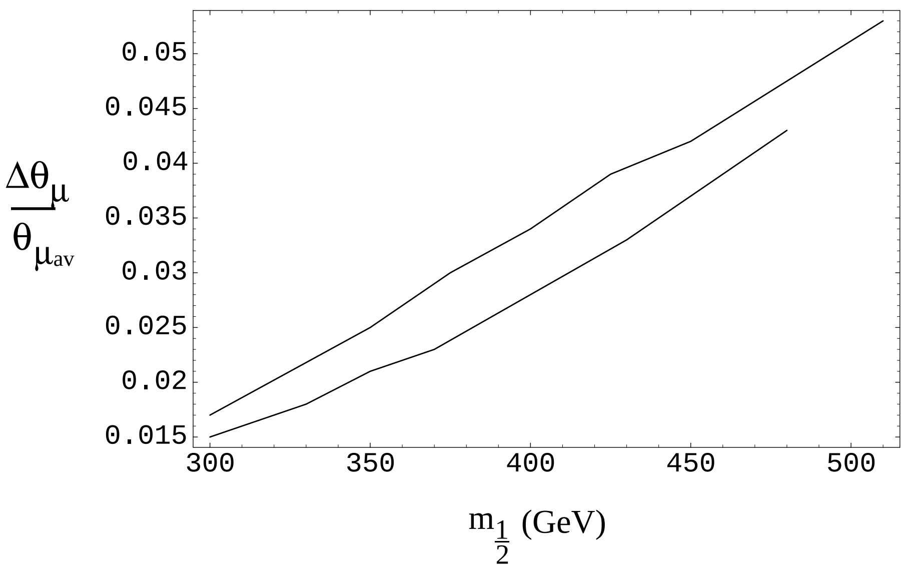


$\frac{\Delta\theta_{0B}}{\theta_{0Bav}}$ vs $m_{1/2}$ for $\tan\beta = 40$ and $\phi_1 = 0.9$. The upper line is for $A_0 = 0$ and the lower line is for $A_0 = 2m_{1/2}$ and $\phi_{0A} = 0.5$.



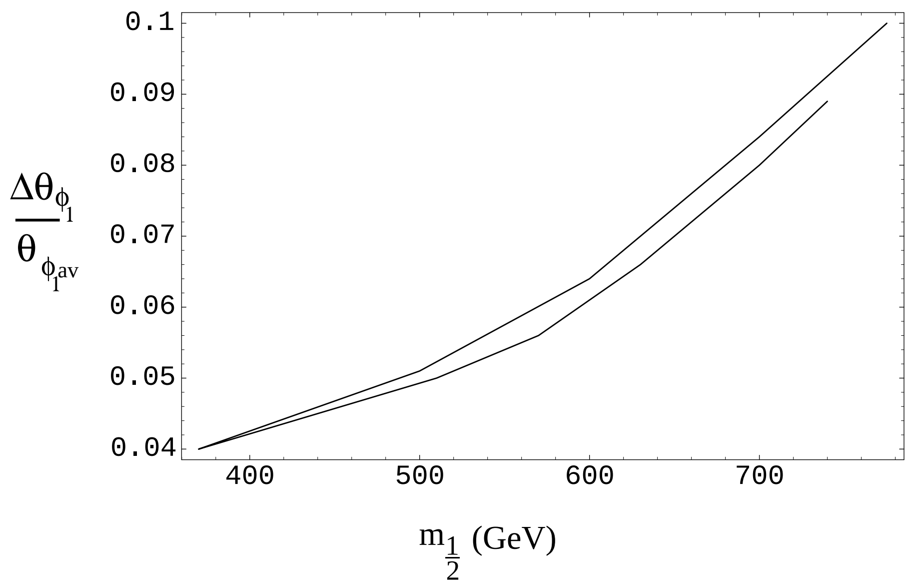
$\frac{\Delta\theta_\mu}{\theta_{\mu_{av}}}$ vs $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$.

The upper line is for $\phi_1 = 0.9$ and the lower line is for $\phi_1 = 1.2$.



$\frac{\Delta\theta_\mu}{\theta_{\mu_{av}}}$ vs $m_{1/2}$ for $\tan\beta = 15$, $A_0 = 0$.

The upper line is for $\phi_1 = 0.9$ and the lower line is for $\phi_1 = 1.2$.



$\frac{\Delta\phi_1}{\phi_{1av}}$vs $m_{1/2}$ for $\tan\beta = 40$, $A_0 = 0$.

The upper line is for $\theta_\mu = 0.2$ and the lower line is for $\theta_\mu = 0.3$.

Conclusion:

- The phases allowed by EDM of electron are not necessarily very small. This happens due to some cancellation among the contributing diagrams.

- This cancellation is necessary for the entire region of the parameter space allowed by a_μ in order to allow large CP violating phases.

- However, the phase of B can become fine tuned at the GUT scale in certain regions of the parameter space.

  If fine tuning less than 1% is excluded then for tan$\beta = 15$, $\phi_1 \leq 1.2$ in the parameter space allowed by a_μ bound.

For the allowed values of ϕ_1, the lower values of $m_{1/2}$ are disfavored. For example, for $\phi_1 = 0.9$, $m_{1/2} < 380$ GeV is disfavored.

The large $\tan\beta$ scenarios are better since a_μ allows higher values of m_0 and $m_{1/2}$. The lower values of $m_{1/2}$ are again disfavored and depend on ϕ_1, for $\phi_1 = 0.9$, $m_{1/2} < 470$ GeV is disfavored.

J.L. Lopez, D.V. Nanopoulos and X. Wang, PRD 49, 366, 1994; U. Chattopadhyay and P. Nath, PRD 53, 1648, 1996; T. Moroi, PRD 53, 6565, 1996; T. Blazek, hep-ph/9912460; T. Ibrahim and P. Nath, Phys.Rev.D6 095008, 2000; PRD 62,015004, 2000; M. Drees, Y. G. Kim, T. Kobayashi and M. Nojiri, hep-ph/0011359.

J. Feng and K. Matchev, Phys.Rev.Lett.86, 3480, 2001; U. Chattopadhyay and P. Nath, hep-ph/0102157; S. Komine, T. Moroi and M. Yamaguchi, Phys.Lett.B506, 93,2001; hep-ph/0103182; T. Ibrahim, U. Chattopadhyay and P. Nath, hep-ph/0102324;J. Ellis, D.V. Nanopoulos, K. A. Olive, hep-ph/0102331; R. Arnowitt, B. Dutta, B. Hu and Y. Santoso, Phys.Lett.B505, 177, 2001; H. Baer, C. Balazs, J. Ferrandis and X. Tata, hep-ph/0103280; F. Richard, hep-ph/0104106