# Reconciling large CP-violating phases with bounds on the electric dipole moments in the MSSM

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*Based on a upcoming paper by: Y. A , Yasaman. Farzan*

M31X

For this reason, studying EDMs of the elementary particles is of prime importance as it can teach us about CP-violation which is closely related to the creation of the baryon asymmetry of the universe.

Elementary particles can possess **EDMs**, only if the CP-symmetry is violated.

SM of elementary particles allows for CP-violation:

1. $\theta$-term in QCD
2. CKM matrix in quark sector

***In fact in the Kaon and B-meson sector, CP symmetry has been observed to be violated in accordance with the prediction of the Standard Model***

The maximum possible values of EDMs in the context of SM are extremely small

So far no electric dipole moment for the electron or neutron has been detected but strong bounds on these quantities have been obtained.

$$d_e \sim 10^{-38}\ e\ \mathrm{cm}$$
$$d_n \sim 10^{-31}\ e\ \mathrm{cm\ to\ } 10^{-33}$$

$<$

$$|d_e| < 1.4 \times 10^{-27}\ e\ \mathrm{cm}$$
$$|d_n| < 3.0 \times 10^{-26}\ e\ \mathrm{cm}.$$

***Values of EDMs much larger than the SM prediction would indicate new sources of CP-violation with origin in physics beyond the SM.***

***The Minimal Supersymmetric Standard Model (MSSM) is the most popular model beyond the SM. The general MSSM introduces 44 sources of CP-violation. Mainly for the sake of simplicity, studies in the literature are concentrated on the mSUGRA model.***

In the constrained MSSM the number of independent CP-violating phases are reduced to two which are usually attributed to the phases of $a_0$ and the $\mu$-term.

In the context of MSSM one finds that the EDMs of the electron, neutron and mercury exceed the experimental bounds by several orders of magnitude. In principle, to suppress the EDMs to below their experimental bounds, three possibilities exist:

1. The first generation slepton and the first two generation squarks are very heavy. This assumption is disfavor because of:

- the production and study of these particles at LHC and ILC will be difficult.
- with large sfermion masses the annihilation rate of the Lightest Supersymmetric Particle (LSP) will be too low and the relic density of the LSP be larger than expected from the cosmological observations.

2. $\theta_{\mu}$ and $\theta_{a0}$ are both zero or very small which means that there will not be any interesting display of CP-violation in colliders. Moreover, electroweak baryogenesis cannot happen in this case.

3.The contributions of the phases of $a_0$ and $\mu$ cancel each other. From the phenomenological point of view, this is the most interesting solution because it has non-trivial CP-violating as well as CP-conserving phenomena to be discovered.

The third possibility has been extensively studied in the literature and unfortunately it seems that cancellation scenario works only if the phase of $\mu$ is $O(10^{-2})$ or less which is too small to result in detectable CP-violating effects in colliders.

This is due to two reasons:

1. The severe upper bounds on EDMs of mercury and neutron have to be simultaneously satisfied that is while there are only two CP-violating phases.
2. In the large $\tan\beta$ regime ( which is favored by LEPII data) the contribution of $\theta_\mu$ to the EDMs of the electron as well as the down quark is enhanced such that it cannot be canceled by the effect of the phase of $a_0$,unless the phase of $\mu$ itself is small.

## Model Building

***In this paper, we consider the minimal Supersymmetric Standard Model with superpotential:***

$$W_{MSSM} = Y_u \widehat{u^c}\, \widehat{Q} \cdot \widehat{H_u} - Y_d \widehat{d^c}\, \widehat{Q} \cdot \widehat{H_d} - Y_e \widehat{e^c}\, \widehat{L} \cdot \widehat{H_d} - \mu\, \widehat{H_u} \cdot \widehat{H_d}$$

*The soft supersymmetry breaking at the electroweak scale*

$$\begin{aligned} \mathrm{L}^{\mathrm{MSSM}}_{\mathrm{soft}} \;=\; & -1/2\left(M_3 \tilde{g}\tilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \mathrm{H.c.}\right) \\ & - \left(A_{ui} Y_{uii} \widetilde{u_i^c}\, \widetilde{Q_i} \cdot H_u - A_{di} Y_{dii} \widetilde{d_i^c}\, \widetilde{Q_i} \cdot H_d - A_{ei} Y_{eii} \widetilde{e_i^c}\, \widetilde{L_i} \cdot H_u + \mathrm{H.c.}\right) \\ & - \widetilde{Q_i}^\dagger\, m^2_{\tilde{Q}ii} \widetilde{Q_i} - \widetilde{L_i}^\dagger\, m^2_{\tilde{L}ii} \widetilde{L_i} - \left(\widetilde{u_i^c}\right)^\dagger m^2_{\tilde{u}ii} \widetilde{u_i^c} - \left(\widetilde{d_i^c}\right)^\dagger m^2_{\tilde{d}ii} \widetilde{d_i^c} - \widetilde{e_i^c}^\dagger\, m^2_{\tilde{e}ii} \widetilde{e_i^c} \\ & - m^2_{H_u}\, H_u^\dagger\, H_u - m^2_{H_d}\, H_d^\dagger\, H_d - (\, b\, H_u \cdot H_d + \mathrm{H.c.}\,), \end{aligned}$$

- **Notice that here we have relaxed the universality assumption.**
- **There is no off-diagonal terms in the flavor basis.**
- **In this paper, we focus on $|A_s|$, $|A_d| > 1$ TeV and show that, for large values of $|A_i|$ cancellation scenario is revived even for intermediate values of *$\tan\beta$*.**

For large values of A-terms, one of course has to check CCB bounds.
In the following, we consider that by relaxing the condition of universality at the GUT scale, we can have values of $A_e$ and $A_d$ as large as a few TeV while keeping the parameters relevant for neutralino annihilation at cosmologically desirable values without encountering Color or Charge Breaking (CCB) vacua.

For positive $m^2_{Hd}$ as discussed in [J. F. Gunion, Nucl.Phys. B306 (1988)] to guarantee that no CCB occurs, it is sufficient to have:

$$\boxed{\begin{aligned} A_e^2 &< 3(m^2_{H_d} + m^2_{\tilde{e}_L} + m^2_{\tilde{e}_R}) \\ A_d^2 &< 3(m^2_{H_d} + m^2_{\tilde{d}_L} + m^2_{\tilde{d}_R}) \end{aligned}}$$

# ***Numerical result***

- **In this section, we study the electric dipole moments of the electron, mercury and neutron to find the range of phases for which cancellation is possible.**

  First we discuss the constraints on the input parameters from various observations and the uncertainty in calculations. We then analyze the possibility of cancellation in the following cases that are phenomenologically interesting:

- close to the benchmark SPS1a' [J.Aguilar-Saavedra, hep-ph/0511344]

*constraints on the input parameters*:

1. In the present model, it is possible to tune the (co) annihilation rate of neutralino to a value that explains the data of WMAP.
2. The other major constraint on the MSSM parameters comes from the radiative correction to Br $(b \rightarrow s\gamma)$.

To calculate the EDMs and CEDMs of the elementary particles, we use the formalism developed in [T. Ibrahim, P. Nath, hep-ph/9708456]. In the literature, there are various different formulae for the EDM of mercury:

- according to [T. Falk et all., hep-ph/9904393 ]:

$$\boxed{d_{Hg} = -(\tilde{d}_d - \tilde{d}_u - 0.012\tilde{d}_s) \times 3.2 \cdot 10^{-2} e}$$

That is while according to[J. Hisano et all.,hep-ph/0407169]:

$$\boxed{d_{Hg} = 8.7 \times 10^{-3} \times e(\tilde{d}_d - \tilde{d}_u - 0.0051\tilde{d}_s)}$$

To calculate the EDM of neutron various theoretical approaches have been taken which give different and even conflicting results. For example:

$$\boxed{d_n = (1 \pm 0.5)\frac{|\langle \bar{q}q \rangle|}{(225\ \mathrm{MeV})^3} \times \left[0.55e(\tilde{d}_d + 0.5\tilde{d}_u) + 0.7(d_d - 0.25d_u)\right.}$$

[M. Pospelov, A. Ritz, hep-ph/0010037]

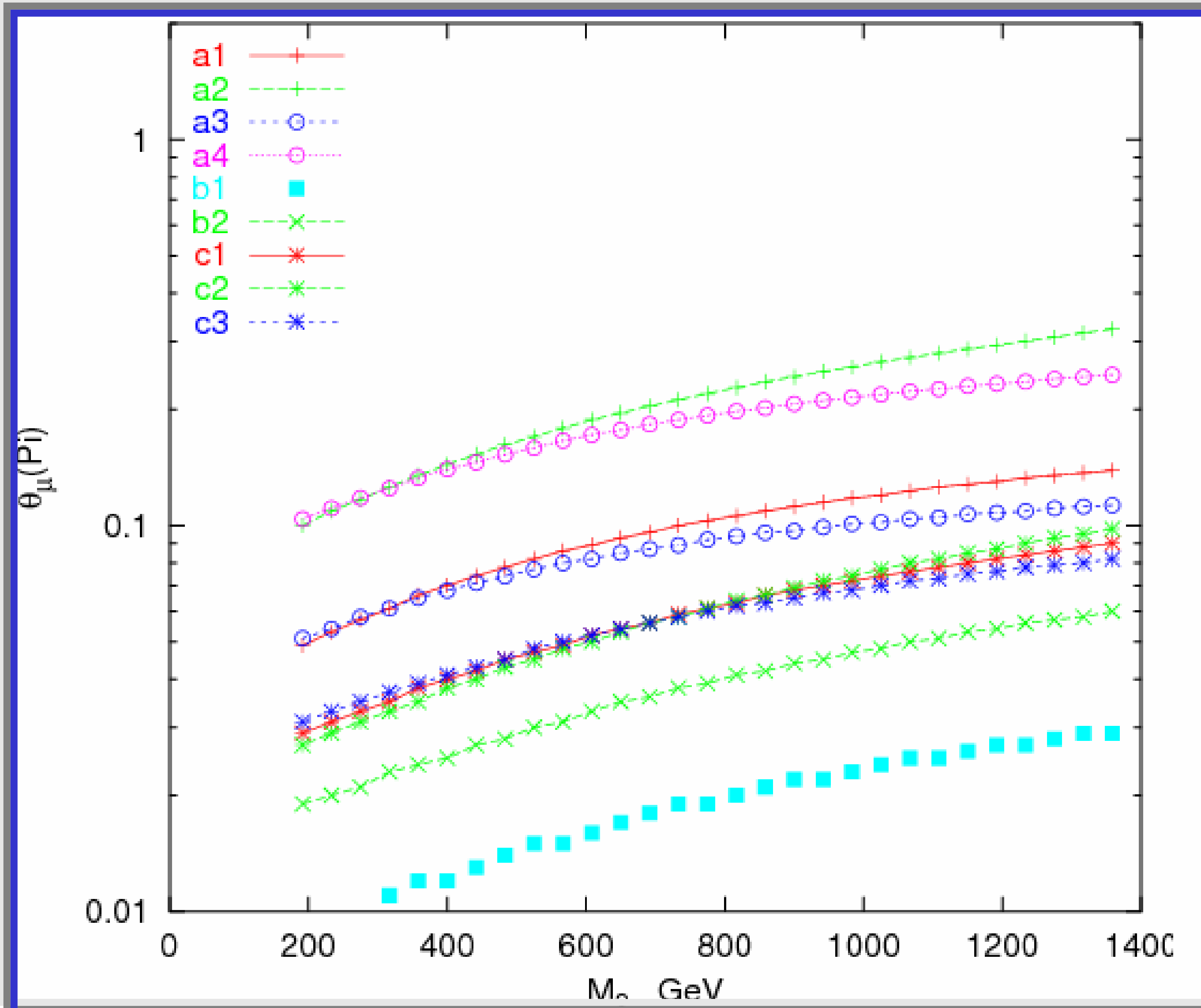
$$\boxed{d_n = (1.6 \times \tilde{d}_u + 1.3 \times \tilde{d}_d + 0.26 \times \tilde{d}_s) \quad \text{e cm.}}$$

[J. Hisano,Y. Shimizu, hep-ph/0406091]

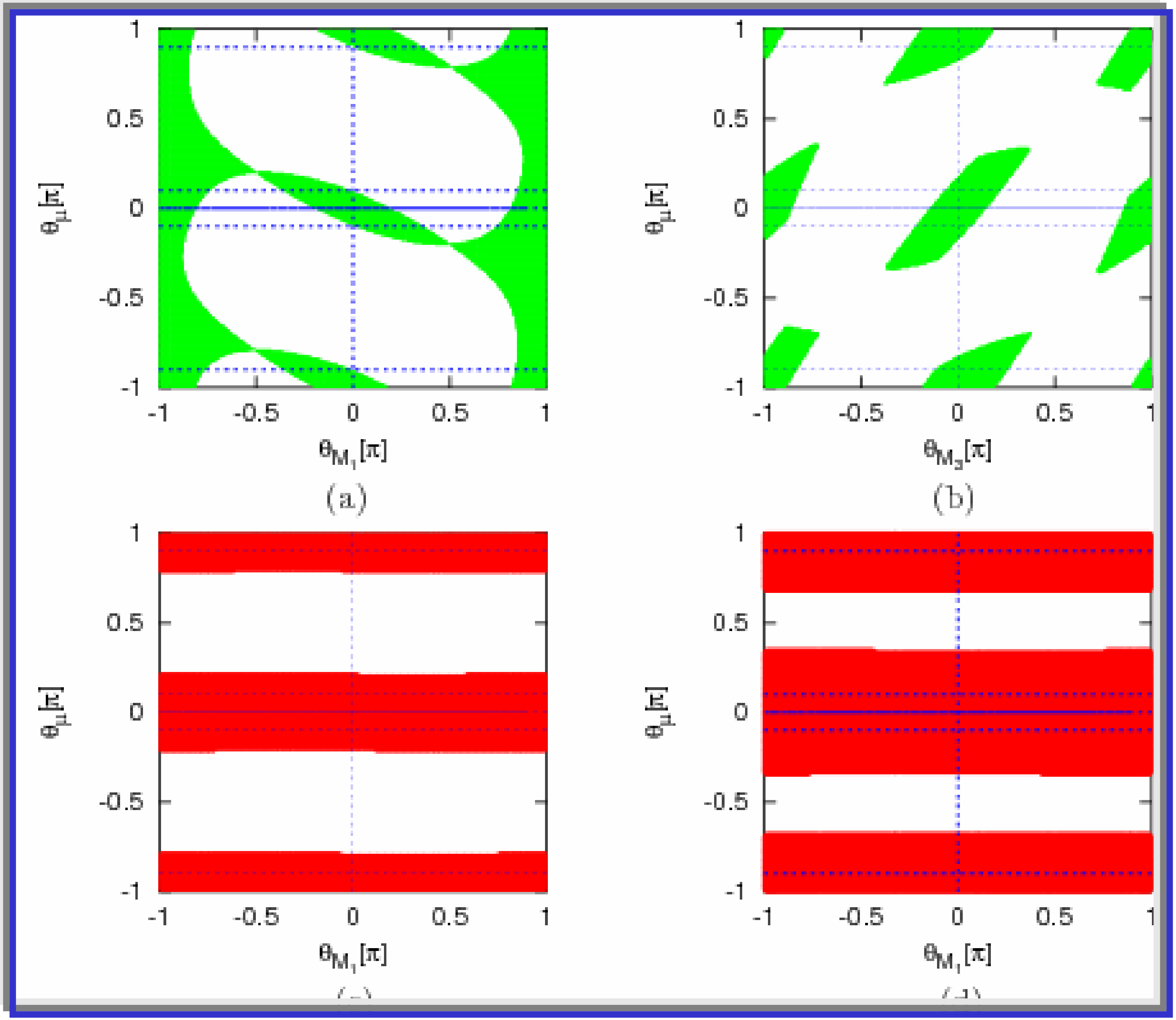
$$\boxed{\tilde{d}_s/\tilde{d}_d \sim m_s/m_d \simeq 19}$$

Because of theoretical uncertainties, we do not put much emphasis on the bounds from neutron EDM.

In following Fig display the maximum values of $\theta_\mu$ for which cancellation between the contributions of the phases of $A_e$ and $\mu$ is possible.



a1
a2
a3
a4
b1
b2
c1
c2
c3
1
0.1
0.01
$\theta_\mu$(Pi)
0
200
400
600
800
1000
1200
1400



θμ[π]
θM1[π]
(a)
θμ[π]
θM3[π]
(b)
θμ[π]
θM1[π]
θμ[π]
θM1[π]
1
0.5
0
-0.5
-1

# EDM bounds and electroweak Baryogenesis

The most important manifestation of CP-violation is its role in the creation of the baryon asymmetry of the Universe.

In the context of MSSM, all three Sakharov's famous conditions can be fulfilled through a mechanism known as electroweak baryogenesis.

***Requirements:***

1. Light s-top,
2. Neutralino must be lighter than top quark.
3. Large CP-violating phases,

However, V. Cirigliano *et. al.* showed that even for values of $Sin\ \theta_\mu \approx 10^{-2}$ successful electroweak baryogenesis can be possible if:

1. We are at the resonance region ($|\mu| \approx |M1|$ or $|\mu| \approx |M2|$) [M. Carena *et al.*, hep-ph/0011055]

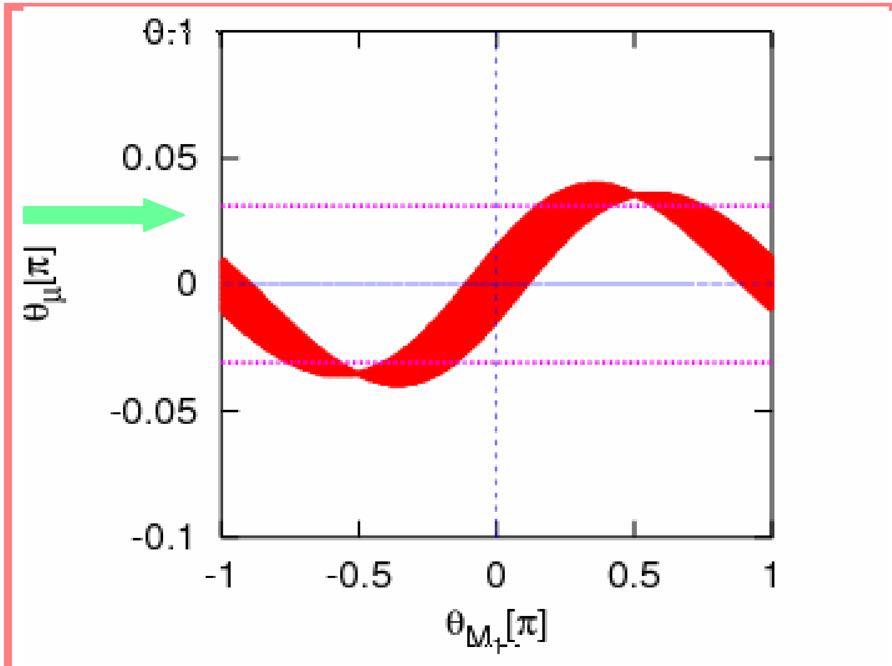
2. The mass of the CP-odd Higgs boson is relatively low. $m_{A0}$ < TeV

Notice that if the masses of selectron and sneutrino are below the TeV scale, even values of $Sin\ \theta_\mu$ as low as $10^{-2}$ will not be compatible with the bounds on the electric dipole moment of electron, unless the cancellation scenario is at work.

## Our proposal:

Suppose all conditions are close to requirement for a successful electroweak baryogenesis.

Now, suppose that the masses of sfermions be at the scale of a few hundreds of GeV. Next Fig try to address this question by studying the possibility of cancellation between different contributions to $d_e$.




The range of phases of $\mu$ and $M_1$ for which total cancelation among the contributions of the phases $\mu$, $M_1$ and $A_e$ to $d_e$ is possible. We have taken $m_{\tilde{e}_L} = 392$ GeV, $m_{\tilde{e}_R} = 220$ GeV, $m_{\tilde{\nu}_L} = 385$ GeV, $A_e = 700$ GeV, $M_1 = 200$ GeV and $M_2 = 415$ GeV and $\tan\beta = 10$. We have set $|\mu| = 200$ GeV$= M_2$ which corresponds to the neutralino-driven resonance condition of electroweak baryogenesis. The purple dotted horizontal lines depict $\sin\theta_\mu = \pm 0.1$.

***In the next few years LHC will reveal what are the masses of sfermions***

## *Implication of cancellation scenario for CP-violation searches in the collider*

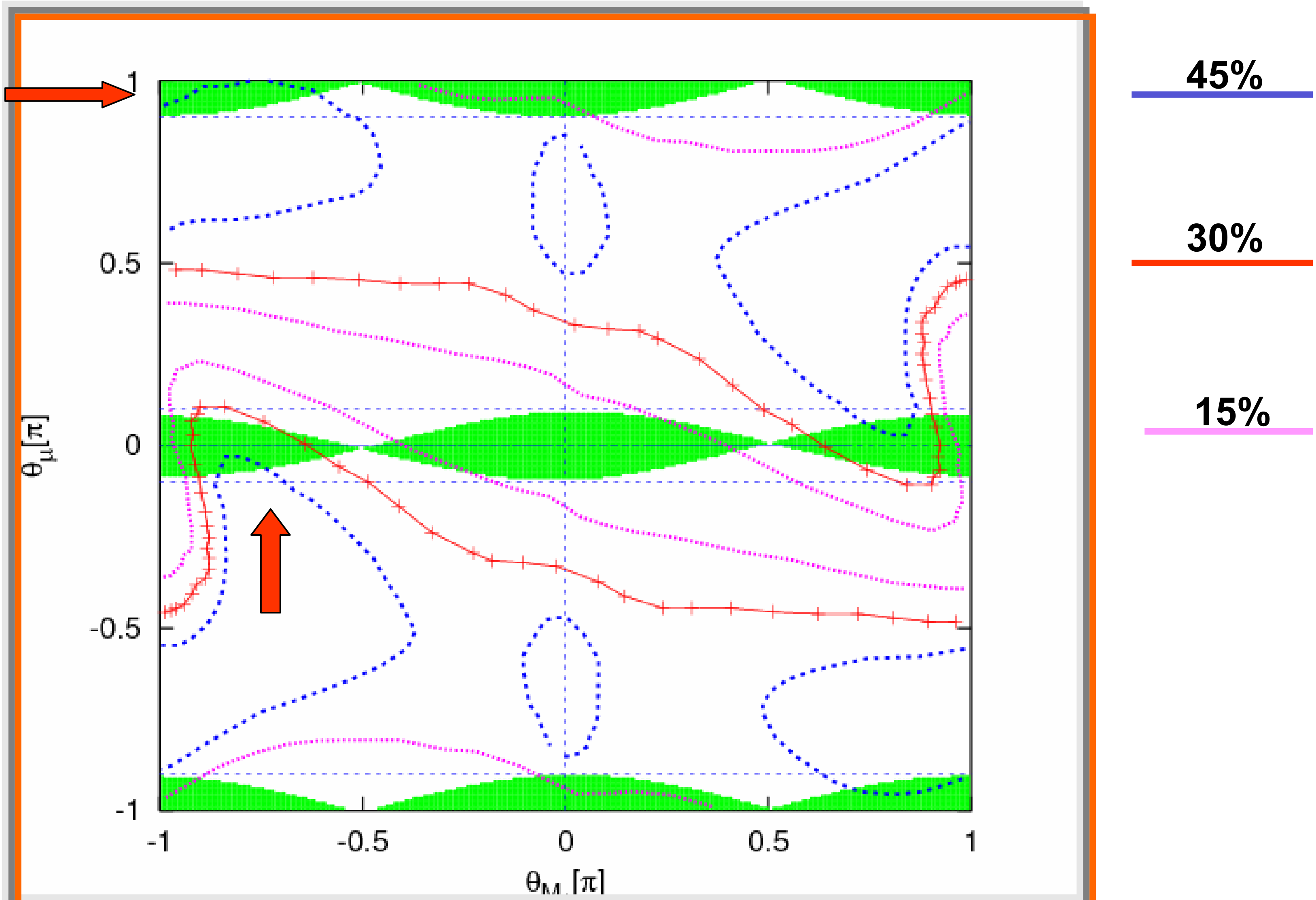
The CP-violating phases can appear by CP-even and CP-odd quantities in LHC and ILC. It is shown [O. Kittel, hep-ph/054183] that even small values of CP-violating can result in an asymmetry between $e^+e^- \rightarrow \tilde{\chi}^o_1 \tilde{\tau}^+_1 \tau^-$ and $e^+e^- \rightarrow \tilde{\chi}^o_1 \tilde{\tau}^-_1 \tau^+$ .

In this process, $A_{CP}$ is given by:

$$A_{CP} = \frac{1}{2}(P_2 - \overline{P_2})$$

$P_2$ is the polarization of $\tau$ produced in this process $e^+e^- \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_i$ and $\tilde{\chi}^0_i \rightarrow \tau^- \tilde{\tau}^+$.

$$\vec{P} \equiv \frac{\mathrm{Tr}[\rho\vec{\sigma}]}{\mathrm{Tr}[\rho]}$$




Region in the $\theta_\mu - \theta_{M1}$ space for electron EDM where cancellation can be possible. Input data: $A_\tau$=250 Gev, ($Pe^+$ , $Pe^-$)=(-0.8,0.6)

$$|\mu| = 300 \text{ GeV}, \; m_{\tilde{e}_L} = 378 \text{ GeV}, \; m_{\tilde{e}_R} = 211 \text{ GeV}, \; m_{\tilde{\nu}_L} = 370 \text{ GeV}, \; M_1 = 192 \text{ GeV}, \; M_2 = 400 \text{ GeV}, \; A_e = 2000 \text{ GeV and } \tan\beta = 5.$$

- Notice that the input parameters satisfy the the relations that we would have expected In the cMSSM.

- It is remarkable that we can have $A_{CP}$=45% for values $\theta_\mu$ as small as 0.1and $\theta_{M1}=\pi/2$

- The overlap of curves with the shadowed area indicates that even for light sfermion, we still have a hope to observe CP-violating effects in ILC provided that the systematic and statistical errors are under control.

## ***Conclusions***

We have studied the possibility of satisfying the bounds on $d_e$, $d_{Hg}$ and $d_n$ by cancellation scenario, relaxing the universality of parameters at the GUT scale.

***Concluding results:***

1. We have focused on the part of parameter space with intermediate values of $\tan\beta$ and TeV scale A-terms. We find that maximum values of $\theta_\mu$ for which cancellation is possible.
2. We have studied the possibility of cancellation for the region that electroweak baryogenes is enhanced ($|\mu| \approx |M1|$ or $|\mu| \approx M2|$) and find that $|\mathrm{Sin}\ \theta\mu| \approx 0.1$ and $|\mathrm{Sin}\ \theta_{M1}| \approx 1$ even for light sleptons.
3. We show that even for light sfermion, we still have a hope to observe CP-violating effects in ILC provided that the systematic and statistical errors are under control.

CPV in SUSY has almost changed from **ugly duckling . . .**


. . . to a **swan** in the recent years.
[R. M. Godbole, hep-ph/0503088]