PHASES AND CP VIOLATION IN SUSY

[PN]

SUSY02, DESY, June 19, 2002

Topics

- phases in SUSY models
- edm of quarks & leptons and experimental constraints
- low energy implications of phases

The electro-weak sector of the Standard Model has one CP violating phase in the CKM matrix. An important constraint on the CKM matrix is that of unitarity

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The constraint can be represented by a unitarity triangle whose angles α, β, γ are defined by

$$\alpha = arg(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}), \beta = arg(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}), \gamma = arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$$

<u>Experimental evidence for CP violation</u>

(1) K system: $\epsilon = (2.28 \pm 0.02) \times 10^{-3}$

(2) K system: $\epsilon'/\epsilon = (1.72 \pm 0.18) \times 10^{-3}$

(3) B_d^0 ($\overline{B_d^0}$)$\rightarrow J/\Psi K_s$ decay gives

$$\sin(2\beta) = 0.75 \pm 0.10 \quad BaBar$$

$$\sin(2\beta) = 0.99 \pm 0.15 \quad Belle$$

(4) baryon asymmetry in the universe

$$n_B/n_\gamma = (1.5 - 6.3) \times 10^{-10}$$

(1+2+3) appear to be consistent with the CP violation given by the Standard Model. Specifically (3) is consistent with the indirect constraint on unitarity triangle from ϵ, $|V_{ub}/V_{cb}|$, and the mass difference of neutral B mesons ΔM_{Bd} etc. Breakdown of the unitarity triangle would be one sign of new physics beyond the standard model including susy.

EDMs in SM

Lepton sector: edms arise at the multi loop level and are too small to be observed.

	SM (ecm)	Experiment (ecm)
e	$\leq 10^{-38}$	$< 4.3 \times 10^{-27}$
μ	$\leq 10^{-35}$	$< 1.1 \times 10^{-18}$
τ	$\leq 10^{-34}$	$< 3.1 \times 10^{-16}$

Observation of a lepton EDM would be a clear indication of new physics beyond the Standard Model.

- Quark sector: QCD generates a new CP violation: $\theta_G \frac{\alpha_s}{8\pi} G\tilde{G}$. The effective $\bar{\theta} = \theta_G + arg(det M_u M_d) + ..$ gives a neutron edm $d_n \simeq 1.2 \times 10^{-16} \bar{\theta} ecm$ and the current limit $d_n < 6.5 \times 10^{-26}\ ecm$ implies $\bar{\theta} < 6 \times 10^{-10}$.

  Need to suppress this either by axions, by massless up quark or by symmetry arguments (Barr -Nelson; Dine, Leigh, MacIntire). Some recent analyses include

  - gluino-axino model: Demir, Ma
  - L-R models: Babu, Dutta, Mohapatra
  - suppression by SUSY non-renormalization theorem: Hiller, Schmaltz
  - gauge away the strong CP problem: Aldazabal, Ibanez, Uranga

- Atomic EDMs: $d_{H_g} < 2.1 \times 10^{-28} ecm$

EDM problem of SUSY/String/Brane Models

In a broad class of susy/string/brane models soft susy breaking generates CP violating phases of abitrary size which is problematic for the satisfaction of the EDM constraints. Possible solutions

- Fine tune the phases to be small
- Assume the phases are large but suppress their effects on the edm of the quarks and leptons by making masses of the first two generations in the range of 10 TeV which would suppress the EDMs. This solution is contrary to the spirit of naturalness.
- Arrange so that the phases in the first two generations and the flavor blind phases vanish and the only phases present are in the third generation, and variants of this idea.
- Internal cancellations: If this mechanism holds then one will expect to observe EDMs by a factor of 10 improvement in experiment.

Operators that contribute to the neutron EDM

- electric dipole operator

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

- chromoelectric operator

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

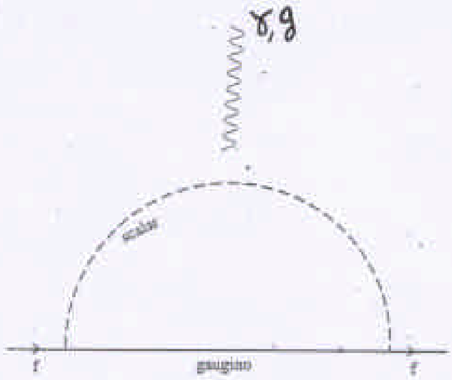
- Weinberg's purely gluonic dim 6 operator

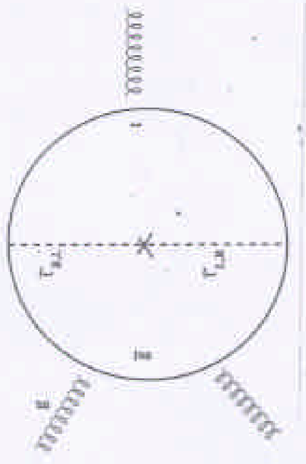
$$-\frac{1}{6}\tilde{d}^G f_{\alpha\beta\gamma}G_{\alpha\mu\rho}G^{\rho}_{\beta\nu}G_{\gamma\lambda\sigma}\epsilon^{\mu\nu\lambda\sigma}$$

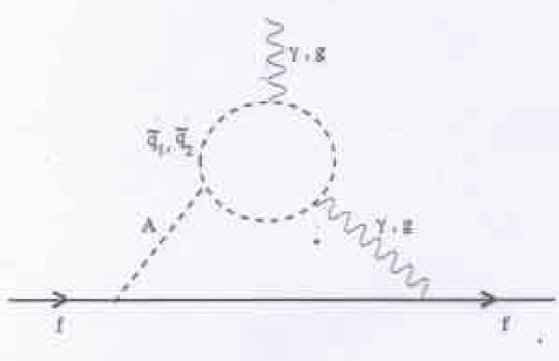
Naive dimensional analysis

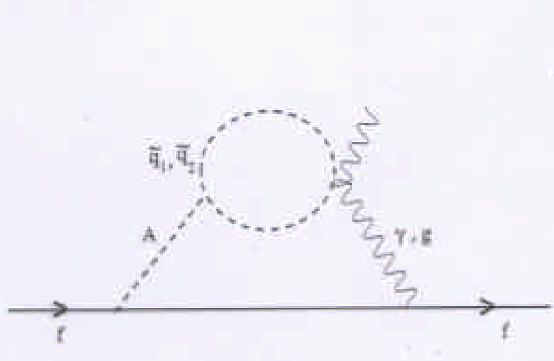
$$d_q^C = \frac{e}{4\pi}\tilde{d}_q^C\eta^C, \quad d^G = \frac{eM}{4\pi}\tilde{d}^G\eta^G$$

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


γ,g
scalar
f
gaugino
f




γ, g
$\tilde{q}_1, \tilde{q}_2$
A
γ, g
f
f


$\tilde{q}_1, \tilde{q}_2$
A
γ, g
f
f

References on Suppression of Phases

Mass suppression

PN; Kizukuri, Oshimo; Giudice, Dimopoulos, ..

Constrained phases

Chang, Keung, Pilaftsis; Babu, Datta, Mohapatra; Khalil, ..

Internal Cancellations

Ibrahim, PN
Falk, Olive
Brhlik, Good, Kane
Bartl, Gajdosik, Porod, Stockinger, Stremnitzer
Pokorski, Rosiek, Savoy
Accomando, Arnowitt, Dutta
Brhlik, Everett, Kane, Lykken
Olive, Pospelov, Roiban
Abel, Khalil, Lebedev, ..

CP violation as probe of flavor structure

CP violation can act as a probe of the flavor structure of susy theories. This can happen if the size of the SUSY CP violation in K and B physics is significant. There are three scenarios

- Negligible contribution from the SUSY phases: All of the CP violation in K and B physics has standard model origin, i.e., arises from δ_{CKM}. No new flavor structure beyond what is present in the Yukawas is necessary.
- Sizable contribution from SUSY phases: Here in addition to the large SUSY CP phases, a new flavor structure is needed. For example, one needs flavor off diagonal mass insertions $(\delta_{ij})_{LR}(d) = (m^2_{LR}(d))_{ij}/\tilde{m}^2_q$ to get a significant contribution to ϵ'/ϵ.

  (Masiero, Murayama; Dine, Kramer, Nir, Shadmi,..)
- All of the CP phenomena in K and B system arises from SUSY phases.

  (Frere, Gavela, Abel, Brhlik, Everett, Kane, King, Lebedev,..)

In the last two scenarios CP violation can act as a probe of the flavor structure of the theory.

Origins of CP violation

(1) Compactification (hard CP violation)
(2) Spontaneous symmetry breaking
(soft CP violation)

- δ_{CKM} is formed at the string scale and SUSY breaking does not play any role. Thus δ_{CKM} is essentially a probe of string compactification.

- SUSY CP phases have origin in spontaneous symmetry breaking as they arise from moduli fields achieving complex VEV's. In SUGRA/ heterotic string models the scale where VEV formation appears is the Planck /string scale.

- Additionally, there is the possibility that new sources of CP violation can occur from spontaneous symmetry breaking at the EW scale, e.g., in extensions of MSSM with the addition of two Higgs singlets. (Ham, Oh, Son)

If SUSY contributions to K and B physics turn out to be small, then one has a rather clean bifurcation, i.e., the CP violations in K and B physics are probe of string compactification, and baryogenesis and other CP phenomena that may be seen in sparticle decays etc become a probe of spontaneous symmetry breaking.

CKM phase vs SUSY phases

The trilinear soft susy breaking term in SUGRA/string models is

$$A_{\alpha\beta\gamma} = F^i \partial_i ln Y_{\alpha\beta\gamma} + ..$$

Could large phases in Yukawas lead to large phases in the trilinear couplings? May be, but there is no rigid relationship. Large phases can be manufactured even when the CKM phase is vanishing, and conversely the SUSY phases can be zero even when the CKM phase is maximal. For example, in some models $A_0 = 0$ and so there is no communication on phases between the Yukawas and the soft breaking sector.

However, in a broad class of SUSY/string/brane models large CP phases do occur. In mSUGRA, θ_μ and α_{A_0} can be large and similarly in non-minimal sugra models, in heterotic string and brane models the phases in general would be large.

CP phases affect low energy phenomena

- Sparticle masses, decay branching ratios and cross-sections

  (Dudas, Moretti, Bartl, Gajdosik, Majerotto, Choi, Kalinowski, Moortgat-pick, Zerwas,..)

- Higgs boson decays

  (Choi, Drees, Lee, song,...)

- Neutralino relic density and detection rates in dark matter detectors

  (Olive, Srednicki, Ibrahim, PN, Freese, Gondolo, Khalil,..)

- g-2 (Ibrahim, PN, Arnowitt, Dutta)

- CP even -CP odd mixing in neutral Higgs system

  (Pilaftsis, Wagner, Demir, Drees, Ibrahim, PN, Ellis, Carena,..)

- FCNC $b \rightarrow s + \gamma$ (Goto, Keum,Nihei, Okada, Shimizu, Demir, Olive,..)

- Trileptonic signal (Choi, Song & Song, ..)

- ϵ'/ϵ (Masiero, Murayama; Brhlik, Everette, Kane, King, Lebedev,..)

- CP effects on e^+e^- collider phenomenology

  (Barger, Falk, Han, Jiang, Li, Plehn; Choi, Djouadi, Guchait, Kalinowski, Zerwas, .)

- CP effects on $b\bar{b}$ system (Demir, Voloshin,..)

- Baryogenesis

  (Carena, Quiros, Wagner, Moreno, Seco,..)

- Proton decay

  (Ibrahim and PN)

CP Phases: What can experiment measure?

Dependence on CP violating phases of SUSY phenomena

SUSY Quantity	Combinations of CP violating phases
$m_{\tilde{W}}$ (m_{χ_i})	$\xi_2 + \theta_\mu$ $(\xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu)$
$b \to s + \gamma$	$\alpha_{A_t} + \theta_\mu,\ \xi_2 + \theta_\mu,\ \xi_3 + \theta_\mu,\ \xi_1 + \theta_\mu$
$\tilde{W} \to q_1\bar{q}_2 + \chi_1,..$	$\xi_2 + \theta_\mu,\ \alpha_{A_{q1}} + \theta_\mu, \alpha_{A_{q2}} + \theta_\mu,\ \xi_1 + \theta_\mu,.$
$\tilde{g} \to q\bar{q} + \chi_1,..$	$\xi_2 + \theta_\mu,\ \alpha_{A_q} + \theta_\mu,\ \xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu,.$
$g_\mu - 2$	$\xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu,\ \alpha_{A_\mu} + \theta_\mu$
m_{H_i}(small $\tan\beta$)	$\alpha_{A_t} + \theta_\mu$
m_{H_i}(large $\tan\beta$)	$\alpha_{A_t} + \theta_\mu,\ \alpha_{A_b} + \theta_\mu,\ \xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu$
$Z^* \to Z + H_i$	$\alpha_{A_t} + \theta_\mu,\ \alpha_{A_b} + \theta_\mu,\ \xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu$
d_e (d_μ)	$\xi_2 + \theta_\mu,\ \xi_1 + \theta_\mu,\ \alpha_{A_e} + \theta_\mu(\alpha_{A_e} + \theta_\mu\ )$
d_n	$\xi_i + \theta_\mu$ (i=1,2.3), $\alpha_{A_u} + \theta_\mu, \alpha_{A_d} + \theta_\mu$

θ_μ: μ phase
ξ_i: Phase of gaugino mass $\tilde{m}_i$ (i=1,2,3)
α_{A_q}: Phase of trilinear coupling A_q

- Measurement of several SUSY quantities will be needed to determine the phases.

Effects of CP violation in the Higgs Sector

Pilaftsis, Wagner, Demir, Choi, Drees, Lee, Carena, Ellis,..: $t-\tilde{t}$ exchange

Ibrahim & PN: $W, H^+, \tilde{W}, Z, A, H^0, \chi^0$ exchange

The Higgs VEVs develop an induced phase

$$(H_1) = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 + \phi_1 + i\psi_1 \\ H_1^- \end{pmatrix}$$

$$(H_2) = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} = \frac{e^{i\theta_H}}{\sqrt{2}} \begin{pmatrix} H_2^+ \\ v_2 + \phi_2 + i\psi_2 \end{pmatrix}$$

In the basis $\{\phi_1, \phi_2, \psi_{1D}, \psi_{2D}\}$

$$\psi_{1D} = \sin\beta\psi_1 + \cos\beta\psi_2$$
$$\psi_{2D} = -\cos\beta\psi_1 + \sin\beta\psi_2$$

ψ_{2D} decouples. The remaining 3×3 matrix is

$$M^2_{Higgs} = \begin{pmatrix} M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 + \Delta_{11} & -(M_Z^2 + M_A^2) s_\beta c_\beta + \Delta_{12} & \Delta_{13} \\ -(M_Z^2 + M_A^2) s_\beta c_\beta + \Delta_{12} & M_Z^2 s_\beta^2 + M_A^2 c_\beta^2 + \Delta_{22} & \Delta_{23} \\ \Delta_{13} & \Delta_{23} & (M_A^2 + \Delta_{33}) \end{pmatrix}$$

- Analysis of $t-\tilde{t}$ and $W, H^+, \tilde{W}$ exchanges is straightforward and can be carried out analytically since diagonalization of only 2×2 matrices are involved.
- Analysis of Z, A, H^0, χ^0 exchange is more involved. Requires calculus of eigenvalues.

CP violation effects on neutralino exchange correction: Ibrahim, PN: hep-ph/0204092

Similar analysis for 4×4 squark matrix by Carena, Ellis, Pilaftsis, Wagner, hep-ph/0003180

and by Ham, Oh,Yoo, Kim, Son, hep-ph/0205244

$$\Delta M^2_{ab} = \frac{1}{32\pi^2}\sum_i\left(\frac{\partial\lambda_i^2}{\partial\Phi_a}\frac{\partial\lambda_i^2}{\partial\Phi_b}log\frac{\lambda_i^2}{Q^2} + \lambda_i^2\frac{\partial^2\lambda_i^2}{\partial\Phi_a\partial\Phi_b}log\frac{\lambda_i^2}{eQ^2}\right)_0$$

Consider an nth order eigen value equation

$$F(\lambda) = Det(M^\dagger M - \lambda I) = \lambda^n + c^{(n-1)}\lambda^{n-1} + c^{(n-2)}\lambda^{n-2} + .. + c^{(1)}\lambda + c^{(0)} = 0$$

The co-efficients are explicit functions of the background fields which depend on fields $\Phi_\alpha = \{\phi_1, \phi_2, \psi_1, \psi_2\}$. The eigen values are implicit functions of the background fields through the satisfaction of the eigen value equation. One can now establish that

$$\frac{\partial\lambda_i}{\partial\Phi_\alpha} = -\left(\frac{D_\alpha F}{D_\lambda F}\right)_{\lambda=\lambda_i}$$

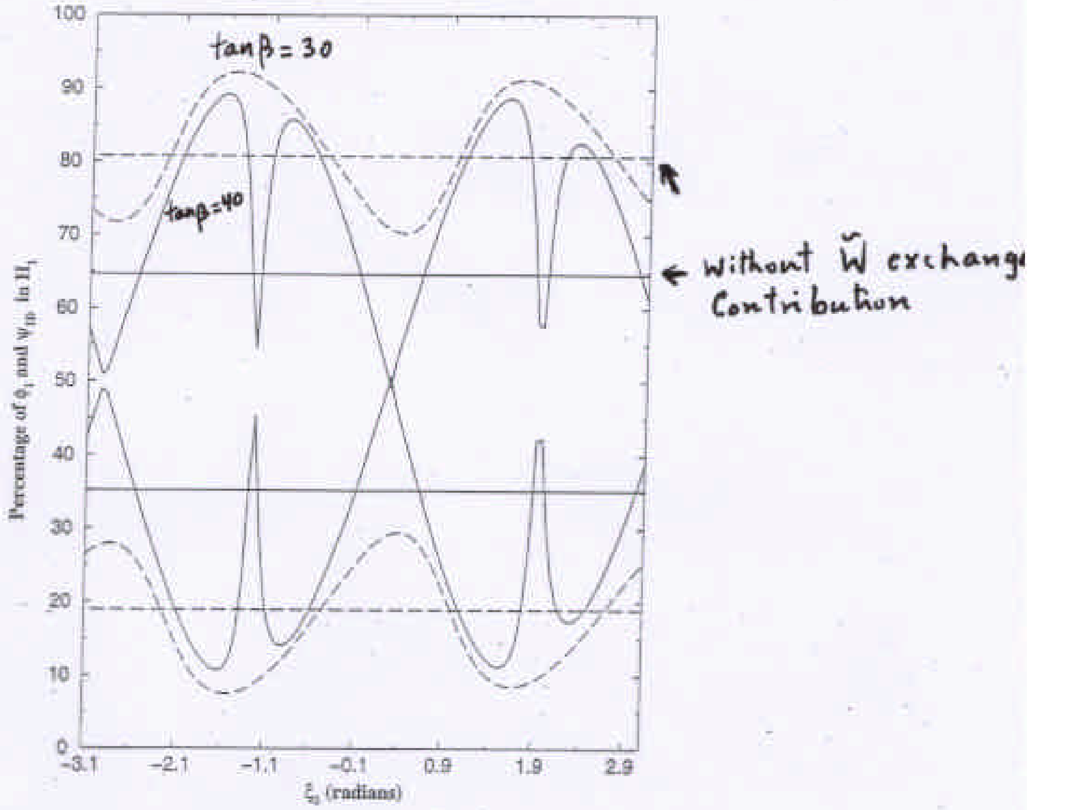
$$\frac{\partial^2\lambda_i}{\partial\Phi_\alpha\partial\Phi_\beta} = \left[-\frac{D_\alpha F D_\beta F D_\lambda^2 F}{(D_\lambda F)^3} + \frac{D_\alpha F D_\beta D_\lambda F + D_\beta F D_\alpha D_\lambda F}{(D_\lambda F)^2} - \frac{D_\alpha D_\beta F}{D_\lambda F}\right]_{\lambda=\lambda_i}$$

D_λ differentiates the λ dependence in F, $D_\lambda F(\lambda) = dF/d\lambda$ and D_α differentiates only the co-efficients, i.e.,

$$D_\alpha F = c_\alpha^{(n-1)}\lambda^{(n-1)} + c_\alpha^{(n-2)}\lambda^{(n-2)} + .. + c_\alpha^{(1)}\lambda + c_\alpha^{(0)}$$

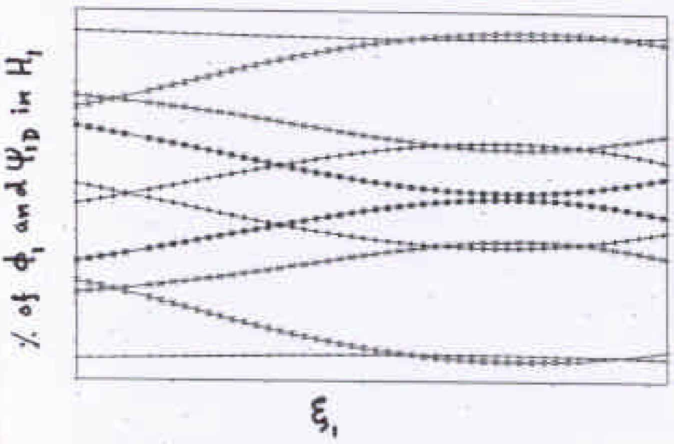
$$[D_\alpha, D_\lambda] = 0$$

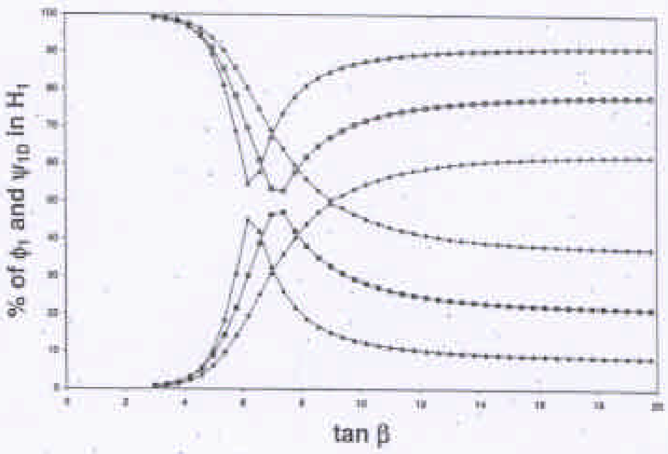
These equations provide us with a technique of analyzing cases where the analytic solutions to the eigen values are not available.



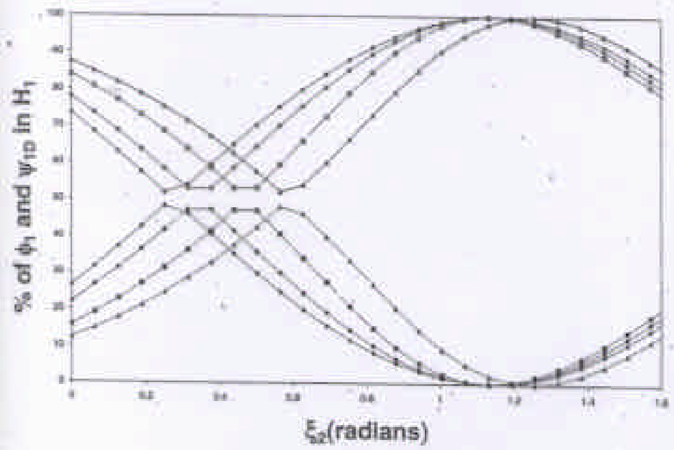
tan β = 30
tan β = 40
← without W̃ exchange Contribution
100
90
80
70
60
50
40
30
20
10
0
−3.1
−2.1
−1.1
−0.1
0.9
1.9
2.9
ξ_2 (radians)

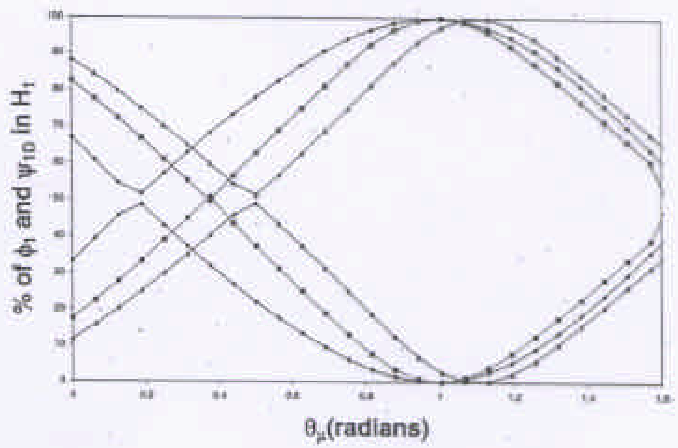
Ibrahim & PN





| tan β = 5, θ_μ = .4
× tan β = 6, θ_μ = .6
✱ tan β = 8, θ_μ = .8
■ tan β = 10, θ_μ = .2
◆ tan β = 15, θ_μ = .3





◇ tan β = 15, ξ_1 = 1.5
□ tan β = 8, ξ_1 = 1.5
△ tan β = 8, ξ_1 = .5
○ tan β = 10, ξ_1 = 1.5

Ibrahim & PN

Observable Effects of Mixing

- The CP even -CP odd mixing in the neutral higgs sector can be seen directly at colliders, e.g., three peaks in the process $e^+e^-, q\bar{q} \to Z^* \to Z + H_i$, and via modified rates of $h \to b\bar{b}, c\bar{c}$ etc.

- If a mixing effect is observed experimentally then among the three possibilities, i.e., the fine tuning, the heavy sparticle spectrum, and the cancellation mechanism, it is only the cancellation mechanism that can survive under the naturalness constraint.

Table 1: EDMs and CP structure of H_1

$\tan\beta$, m_0, $m_{\frac{1}{2}}$, $\lvert A_0$, m_A ξ_1, ξ_2, ξ_3, θ_μ, α_{A_0},	d_e, d_n	$CP-even$, $CP-odd$
(1)2, 500, 400, 2, 500 all phases $= 10^{-2}$	-7.4×10^{-28}, -3.1×10^{-26}	99.999%, .001%
(2)30, 500, 400, 2, 500, all phases $= 10^{-3}$	-1.3×10^{-27}, -4.0×10^{-26}	99.999%, .001%
(3)5, 4000, 1200, 2, 500, all phases $= 10^{-1}$	-6.2×10^{-28}, -3.8×10^{-26}	99.996%, .004%
(4)5, 5000, 2240, 2, 500, $-2.$, $-.3$, .5, $-.4$, .4	1.1×10^{-27}, 2.7×10^{-26}	99.86%, .14%
(5)30, 5000, 2240, 2, 500, all phases $= 10^{-2}$	-2.2×10^{-28}, -9.5×10^{-27}	99.996%, .004%
(6)30, 9500, 3600, 2, 500, $-2.$, $-.3$, .5, $-.4$, .4	2.2×10^{-27}, 6.2×10^{-26}	93.7%, 6.3%
m_A, $\tan\beta$, m_0, $m_{\frac{1}{2}}$, $\lvert A_0\rvert$, ξ_1, ξ_2, ξ_3, θ_μ, α_{A_0},	d_e, d_n	$CP-even$, $CP-odd$
(1)300, 30, 500, 400, 2, -2, $-.24$, $-.43$, .3, $-.4$	1.1×10^{-27}, 2.4×10^{-26}	88.4%, 11.6%
(2)400, 40, 400, 490, 2, -1.2, .57, $-.09$, $-.4$, .6	2.1×10^{-27}, -2.1×10^{-26}	68.8%, 31.2%
(3)300, 45, 600, 600, 2, .1, $-.45$, $-.28$, .4, .5	-3.2×10^{-27}, 2.7×10^{-26}	56.4%, 43.6%
(4)300, 40, 500, 400, 2, -2, $-.24$, $-.43$, .3, $-.4$	2.3×10^{-27}, -1.8×10^{-26}	79.3%, 20.7%
(5)300, 35, 650, 400, 1, -1.5, 1.2, 1.22, 1.95, .7	2.9×10^{-27}, -1.8×10^{-26}	99.94%, .06%

Ibrahim PRD 64, 035009

CP violation in the muon system

- a_μ^{SUSY} is a sensitive function of the phases and shows a rapid variation with the μ phase and the SU(2) phase ξ_2. As a consequence of the phases the chargino contribution need not be much larger than the neutralino contribution to a_μ^{SUSY} as is usually the case. If an $a_\mu^{SUSY} \geq 10^{-10}$ emerges at BNL then this limit will significantly constrain CP phases. Further, it is possible to generate models with low sparticle spectra satisfying BNL and EDM constraints.

  (Ibrahim, Chattopadhyay & PN hep-ph/0102324)

- There is a recent proposal to probe d_μ with a sensitivity of $d_\mu \sim O(10^{-24})ecm$ [Y.K. Semertzidiz et.al., "Sensitive search for permanent muon dipole moment", hep-ph/0012087] . In most theoretical models the charge lepton edms scale, i.e.,

$$\frac{d_\mu}{d_e} \simeq \frac{m_\mu}{m_e}$$

  $d_e < 4.3 \times 10^{-27} ecm$ implies $d_\mu < 10^{-24} ecm$ below sensitivity of the proposed BNL experiment. Large muon edms can be gotten only by the breakdown of scaling, e.g., in

  - With non-universalities in the slepton sector: $\alpha_{A_\mu} \neq \alpha_{A_e}$, $|A_\mu| \neq |A_e|$
    (Ibrahim & PN; Feng, Matchev, Shadmi)
  - Left-Right models
    (Babu, Dutta, Mohapatra, Barr, dosner, ..)

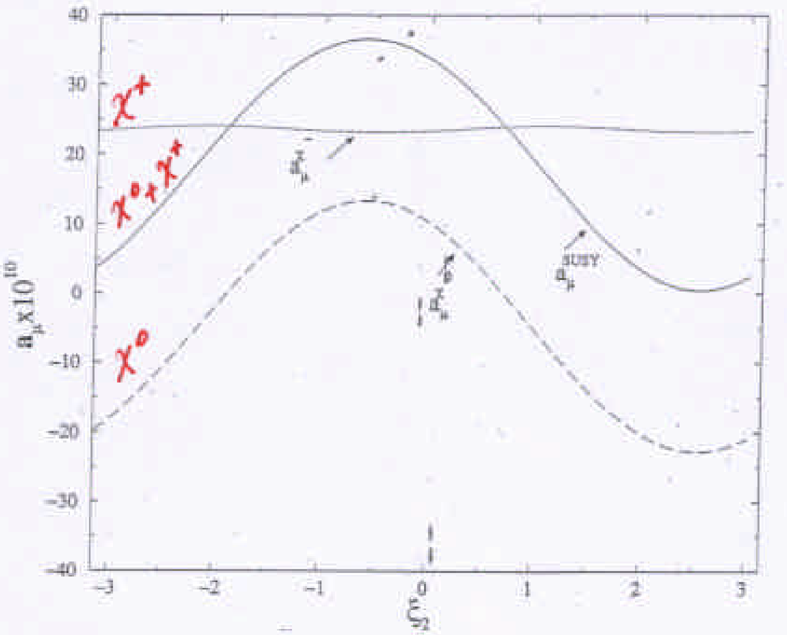


Figure 2: A plot of the chargino contribution $a_\mu^{\chi^-}$ (dotted line), neutralino contribution $a_\mu^{\chi^0}$ (dashed line) and the total a_μ^{SUSY} (solid line) as a function of ξ_2 in the range $-\pi \leq \xi_2 \leq \pi$ when $\theta_\mu + \xi_2 = -1$, $m_0 = 100$, $m_{\frac{1}{2}} = 246$, $\tan\beta = 20$, $A_0 = 1$, $\xi_1 = .4$, $\alpha_{A_0} = .5$, where all masses are in GeV. The small fluctuation of the chargino contribution from exact constancy is due to small rounding off errors in the numerical integration program.

Ibrahim, Chattopadhyay, PN

Models with large phases

Ibrahim, Chattopadhyay & PN hep-ph/0102324

Table 2: Cases where the EDM constraints are satisfied

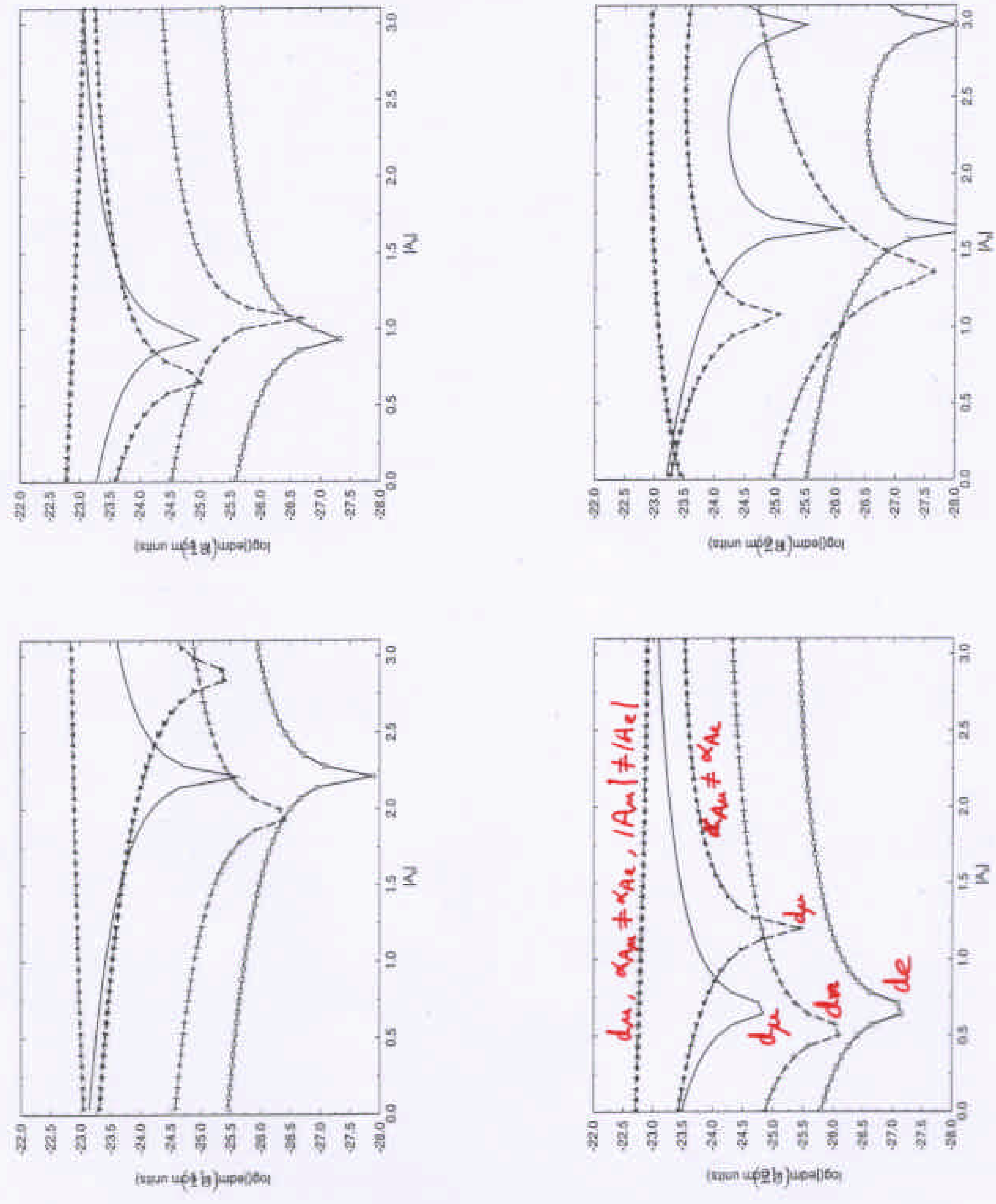
ξ_2, θ_μ, ξ_3	d_e, d_n (ecm)	a_μ^{SUSY}
(a)$-.85$,$.4$,$.37$	4.2×10^{-27}, 4.8×10^{-26}	10.8×10^{-10}
(b)$-.8$,$.2$,1.3	4.0×10^{-27}, 5.4×10^{-26}	12.2×10^{-10}
(c)$-.32$,$.3$,$-.28$	-1.2×10^{-27}, 3.3×10^{-26}	20.1×10^{-10}
(d)$-.5$,$.49$,$-.5$	1.8×10^{-27}, -6.6×10^{-27}	12.7×10^{-10}

Table 3: Sparticle masses (in GeV) for cases (a-d).

	χ_1^0, χ_2^0, χ_3^0, χ_4^0	χ_1^+, χ_2^+	$\tilde{\mu}_1$,$\tilde{\mu}_2$	$\tilde{u}_1$, $\tilde{u}_2$
(a)	97.2, 184.0, 408.3, 426.6	187.0, 426.6	144.6, 209.1	628.6, 647.5
(b)	213.8,421.0, 845.8, 852.2	429.3,853.2	232.0, 397.2	1335.3, 1378.0
(c)	98.1, 186.0, 378.4, 393.4	189.2, 395.3	413.5, 440.3	738.3, 754.4
(d)	98.3,187.1,393.7, 407.3	190.4, 409.3	609.1, 627.6	863.2,877.0

NONUNIVERSALITY AND LARGE MUON EDMS

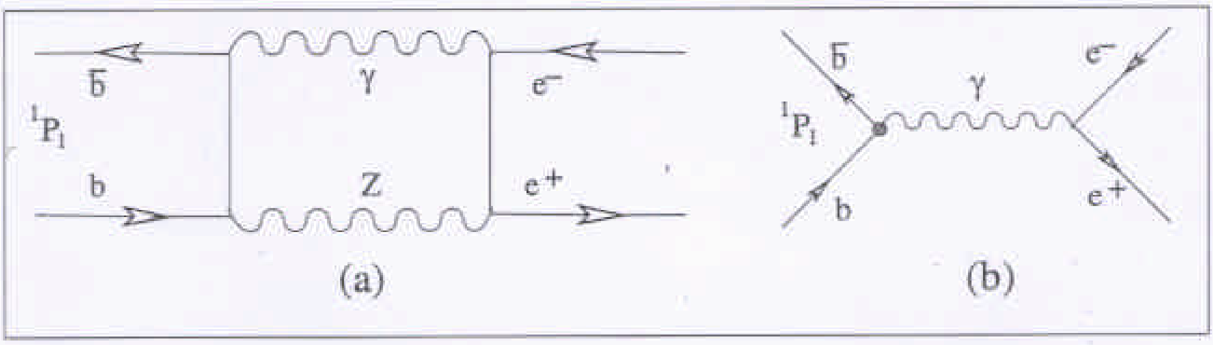
IBRAHIM & PN
hep-ph/0105025



b quark EDM and CP-odd Bottomonium

Demir & Voloshin, PRD 63, 115011

- It is estimated that the CP violating transition amplitude induced by the b-quark EDM in the formation and decay of the CP odd $^1P_1$ bottomonium state $J^{PC} = 1^{\pm}(PC = -1)$ in e^+e^- annihilation is significantly larger than the CP conserving one for large $\tan\beta$.

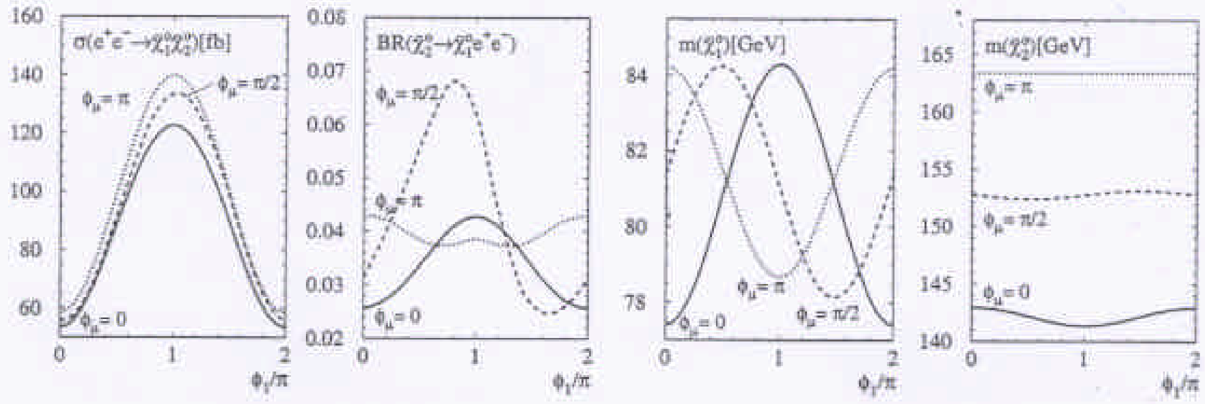


- The decay of $^1P_1$ into neutral charmed mesons $(D\bar{D})$ will proceed mainly via the b quark edm since the CP conserving SUSY contribution to the decay goes like $(\tan\beta)^0$ since the D mesons contain only up-type quarks. Thus an observation of this CP odd resonance could be a direct probe the CP violating phases in SUSY.

Measuring CP phases at Linear Colliders

Barger, Falk, Han, Jiang, Li, Plehn

- Measurement of the chargino and neutralino masses and their pair production cross sections to a high accuracy at linear colliders can allow a determination of the CP violating phases.



- Direct and indirect effects (arising from effect of phases on the neutralino masses) have to be taken account of in extracting the phases. Determination of some of the phases to an accuracy of one tenth of a radian is possible.

CP phases and polarization asymmetries

The decay $H \to \chi_i \chi_j$ is a probe of CP phases in SUSY.

Choi, Drees, Lee, Song, hep-ph/0204200

$$\Gamma(\vec{P}^i, \vec{P}^j) \sim (C_0^{ij}(1 + P_L^i P_L^j) + C_1^{ij}(P_L^i + P_L^j) + P_T^i P_T^j [C_2^{ij} \cos\phi_{ij} + C_3^{ij} \sin\phi_{ij}])$$

$$\mathcal{A}_a^{ij} = \frac{C_a^{ij}}{C_0^{ij}} \sqrt{B(H \to \chi_i \chi_j)}$$

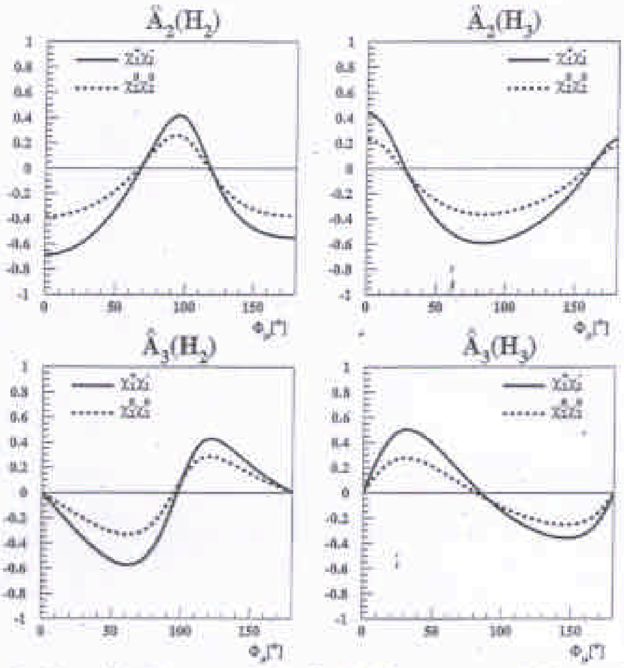
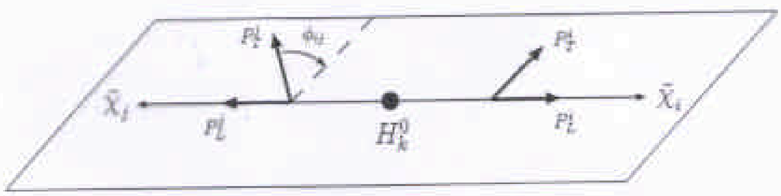


Figure 4: *The polarization asymmetries $\hat{A}_{2,3}$ in the supersymmetric decays of the heavy Higgs bosons, H_2^0 (left frames) and H_3^0 (right frames) with respect to the phase Φ_μ. The phases Φ and Φ_1 are set to 0.*



Conclusions

- CP violation is an important probe of susy/ string/brane models. Most likely there are more than one origin of CP violation: one is string compactification, and another, spontaneous symmetry breaking.
- CP violation could also be a probe of flavor structure of supersymmetric models if SUSY contributions to K and B physics are significant.
- Edms if observed could provide a further probe of flavor structure of supersymmetric theories. The proposed BNL experiment to measure the muon edm at the sensitivity of $10^{-24} ecm$ is important from this viewpoint.
- Collider experiments have the potential to tell a lot about CP violation beyond the K and B systems. This will occur via analyses of sparticle masses and decays, production cross sections, and via possible observation of CP even-CP odd mixing in the neutral Higgs system.