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HINTS FOR NEW PHYSICS IN FLAVOR PHYSICS: HOW AND WHERE?

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Out of the three main motivations for

NEW PHYSICS BEYOND THE SM:

- UNIF. OF FUNDAMENTAL INTERACTIONS INCLUDING ALSO GRAVITY IN THE GAME
- GAUGE HIERARCHY PROBLEM
- FLAVOR PROBLEM (fermion masses and mixings as free param.)

the FLAVOR PROBLEM IS THAT WHICH HAS REGISTERED LESS PROGRESS IN UNDERSTANDING AND LESS TRULY INNOVATIVE IDEAS. In particular admitting that there exists new physics at the ELW scale (SUSY?)

FLAVOR BLINDNESS

NEW FLAVOR STRUCTURES

ELW NEW PHYSICS IS FLAVOR BLIND

ex: new contributions to FCNC ⇒ addition of the new particles carrying flavor in the FCNC loops, but always with the same CKM flavor structure

ELW NEW PHYSICS POSSESSES NEW FLAVOR STRUCTURES (different from CKM) in the sector of the new particles carrying flavor

ex: SUSY models without flavor universality

MINIMAL LOW ENERGY SUSY

- minimal amount of superpart. needed to supersymmetrize the SM
- IMPOSING THE (ADDITIONAL) SYMM. R parity
  ⇒ to eliminate $\not{B}$ and $L \neq$ dangerous terms

$$\mathcal{L} = \mathcal{L}_{N=1\,SUSY\,SM} + \mathcal{L}_{\substack{soft\,SUSY\\ breaking}}$$

$\mathcal{L}_{N=1\,SUSY\,SM}$ ↓

$$\ldots h_{U_{ij}} Q_i H_U U_j + h_{D_{ij}} Q_i H_D D_j + h_{L_{ij}} L_i H_D E_j + \mu H_U H_D$$

$\mathcal{L}_{soft\,SUSY\,breaking}$ ↓

trilinear and bilinear scalar terms + gaugino masses

↓

$$m^2_{ij}\varphi_i\varphi_j^* \quad \mu B H_U H_D \quad A_{U_{ij}}\tilde{Q}_i H_U \tilde{U}_j$$

$$A_{D_{ij}}\tilde{Q}_i H_D \tilde{D}_j \quad A_{L_{ij}}\tilde{L}_i H_D \tilde{E}_j \quad M_k \lambda_k \lambda_k$$

(k ↳ SU(3), SU(2), U(1))

⟹ 124 PARAM.

CMSSM or mSUGRA

C → Constrained   mSUGRA → minimal SuperGravity

or how to reduce the param. from 124 → 5

MSSM
+

FLAVOR UNIVERSALITY ⇓

$$m_{ij}^2 = \delta_{ij}\, m_0^2$$

m_0^2 → common scaler mass term

$$A_{ij} \to A_0$$

A_0 → common scaler trilinear coeff. multiplying the Yukawa coupl.

(GRAND) UNIFICATION ⇓

$$M_1 = M_2 = M_3 \equiv M$$

M → common gaugino mass

m_{ij}^2, A_{ij}, M_i → "running" quantities : specify the energy scale where the above equalities hold

⇒ **BOUNDARY CONDITIONS AT THE LARGE SCALE WHERE SUPERGRAVITY IS BROKEN** M_X

at M_X : m_0^2 (real), μ (complex), B_0 (complex), A_0 (complex), M (complex)

NEW CP≠ in SUSY

unconstrained MSSM ⇒ ~ 40 phases

mSUGRA ⇒ μ M A B 4 phases
but only 2 combinations are physical

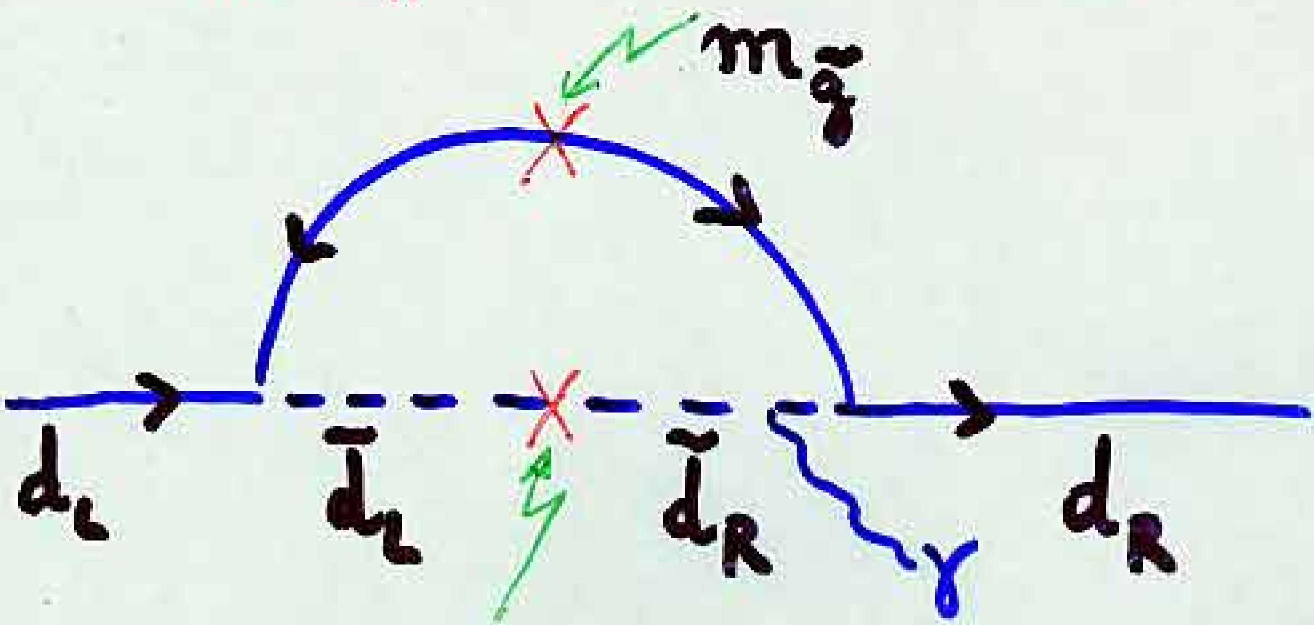
Dugan, Grinstein, Hall ;
Dimopoulos, Thomas

* THE PRESENCE OF LOW ENERGY SUSY
* ENTAILS THE PRESENCE OF (AT LEAST TWO)
* NEW CP≠ PHASES IN ADDITION TO
* THE CKM PHASE

THE PRESENCE OF NEW SOURCES OF CP≠ IS NEEDED TO HAVE AN EFFICIENT BARYOGENESIS

(in SM no significant baryogenesis is possible;
in MSSM only a very limited area of the parameter space is available for baryogenesis ⇒ light $\tilde{t}$, $\tilde{\chi}^{+}$)

THE d_N SUSY PROBLEM



$$A\, m_d + m_d\, \mu \tan\beta \qquad \tan\beta = \frac{v_u}{v_d}$$

$$d_d = \frac{m_d}{\tilde{m}^4} \frac{e\,\alpha_s}{18\pi} \left(|A m_{\tilde{g}}| \sin\phi_A + \tan\beta\, |\mu m_{\tilde{g}}| \sin\phi_B \right)$$

taking $m^2_{\tilde{d}_L} \sim m^2_{\tilde{d}_R} \sim m^2_{\tilde{g}} \sim \tilde{m}^2$

$$d_N \sim 2 \left(\frac{100\ \mathrm{GeV}}{\tilde{m}} \right)^2 \sin\phi_{A,B} \times 10^{-23}\ e\,\mathrm{cm}.$$

Buchmuller, Wyler
Polchinski, Wise
Fischler, Paban, Thomas

exp: $d_N < 1.1 \times 10^{-25}\ e\,\mathrm{cm}$

$\tilde{m} > O(1\ \mathrm{TeV})$

$\phi_{A,B} < O(10^{-2})$

CMSSM WITH $\phi_A, \phi_\mu \neq 0$

'83 Frère and Gavela : is it possible to put $\delta_{CKM} = 0$ and explain ε only as a SUSY effect?

Dugan, Grinstein, Hall : **NO** ⇒ ϕ_A, ϕ_μ too small because of d_n^e

NEW DEVELOPMENTS ON THE THEME LARGE SUSY CP≠ PHASES WHILE TAMING THE d_n^e

VERY DIFFICULT TO SIMULTANEOUSLY CANCEL d_n^e, d_e^e, d_{Hg}^e (Abel et al.)

CANCELLATIONS AMONG THE SUSY CONTRIBUTIONS TO d_n^e (d_e^e d_{Hg}^e ?)

Ibrahim, Nath;
Brhlik, Good, Kane;
Brhlik, Everett, Kane, Lykken;
Accomando, Arnowitt, Dutta

need for non-universal gaugino masses ⇒ SUGRAGUT disfavored, D-branes within Type I strings favored

LARGE MASSES OF $\tilde{q}$ OF THE FIRST TWO GENERATIONS

Dimopoulos, Giudice;
Pomarol, Tommasini;
Dine, Kagan, Samuel;
Dine, Kagan, Leigh;
Carena et al.;
D.E. Kaplan et al

NON-UNIVERS. OF THE A-TERMS

Abel, Frere;
Khalil, A.M. Kobayashi;
Khalil, Kobayashi, Vives

3 QUESTIONS TACKLED IN THIS TALK

- SUSY WITH LOW ENERGY FLAVOR BLINDNESS

(i.e. also the running from the scale of SUSY breaking down to M_W does not introduce new significant flavor structures)

$\Rightarrow$ is it possible to get hints of the SUSY presence looking at departures from the SM predictions in FCNC and CP$\not$ phenomena?

- SUSY with NEW FLAVOR STRUCTURES AT THE ELW SCALE: HOW SEVERE IS THE FCNC THREAT ($\Rightarrow$ degree of tuning to prevent too large FCNC and/or CP$\not$ contributions)

- IF THESE NEW FLAVOR STRUCTURES ARE PRESENT WHERE TO LOOK FOR SIGNIFICANT "VIRTUAL" SUSY MANIFESTATIONS (in particular in the pre-LHC era)

Bartl, Gajdosik, Lunghi, A.M., Porod, Stockinger, Stremnitzer, Vives: mSUGRA and minimal SU(5) (with 2-loop RGE for running $M_{GUT} \to M_W$)

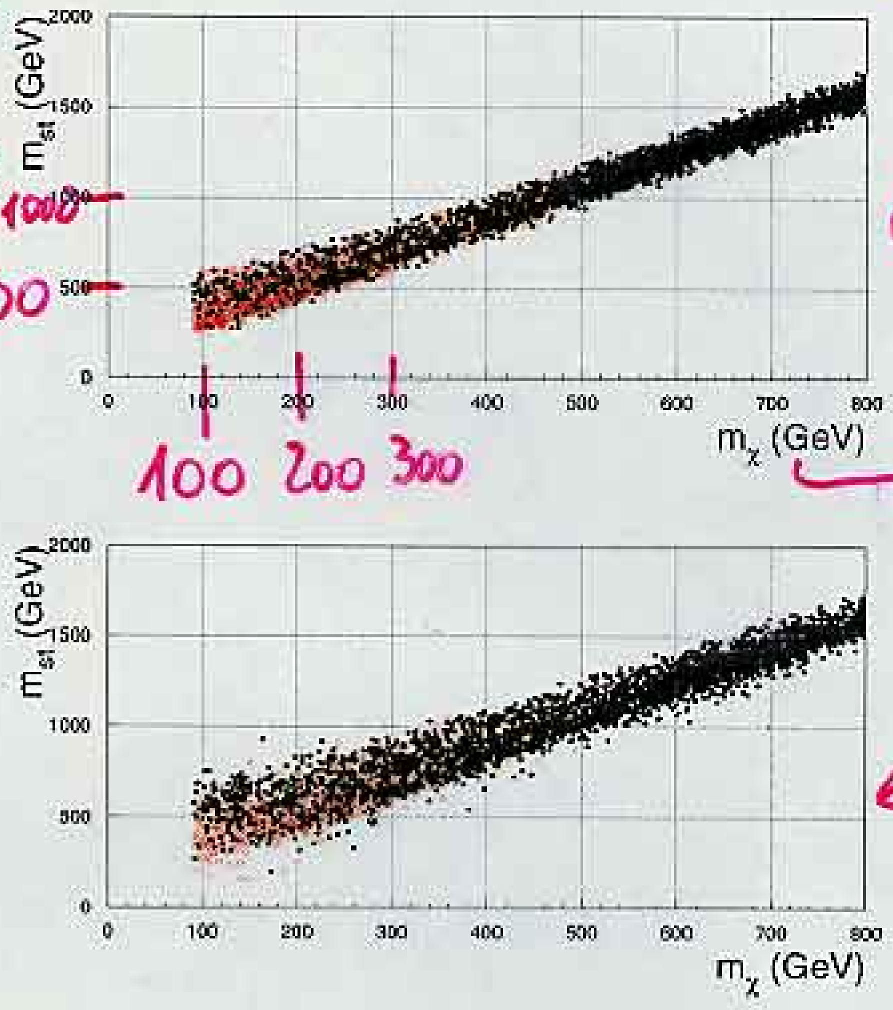


Figure 1: Chargino mass versus lightest stop mass as for the parameter space described in the text in the CMSSM and SU(5) cases.

for $m_\chi = 100$ GeV $\Rightarrow$ 240 GeV $< m_{\tilde{t}_1} <$ 660 GeV (in mSUGRA)

with 10^2 GeV $< m_0 <$ 1 TeV

Bartl et al

Heaviness of H^+

mSUGRA

SusySU(5)

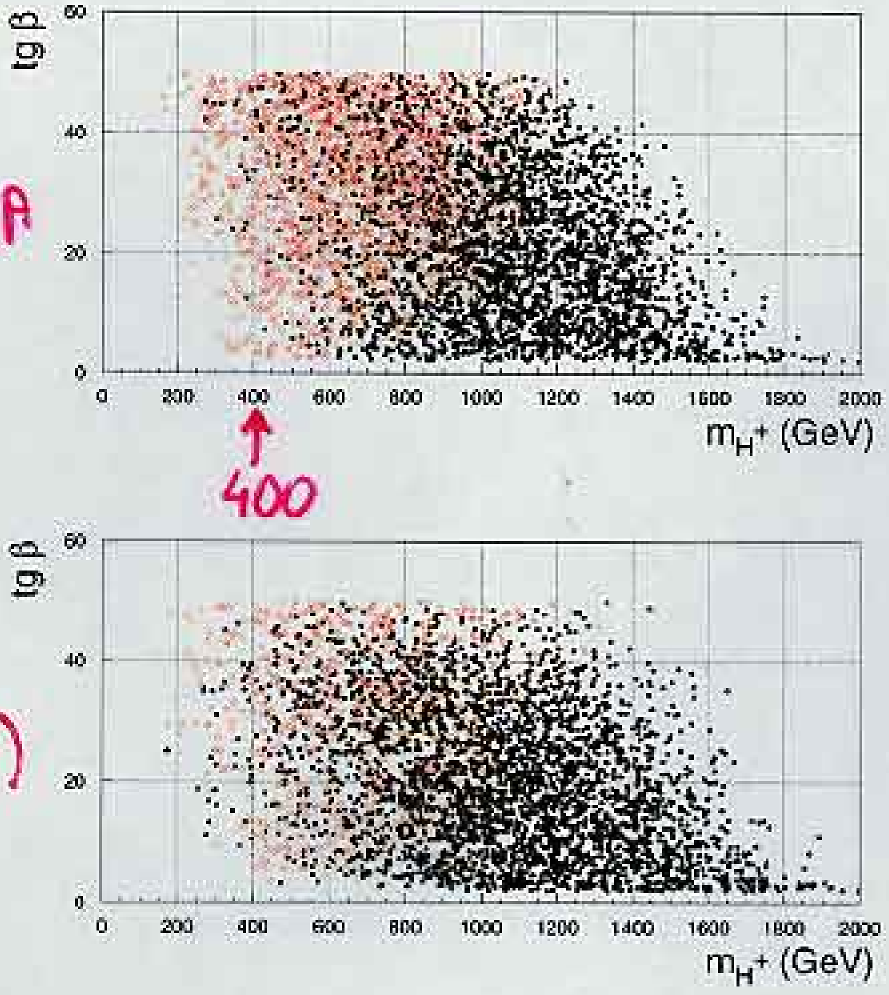


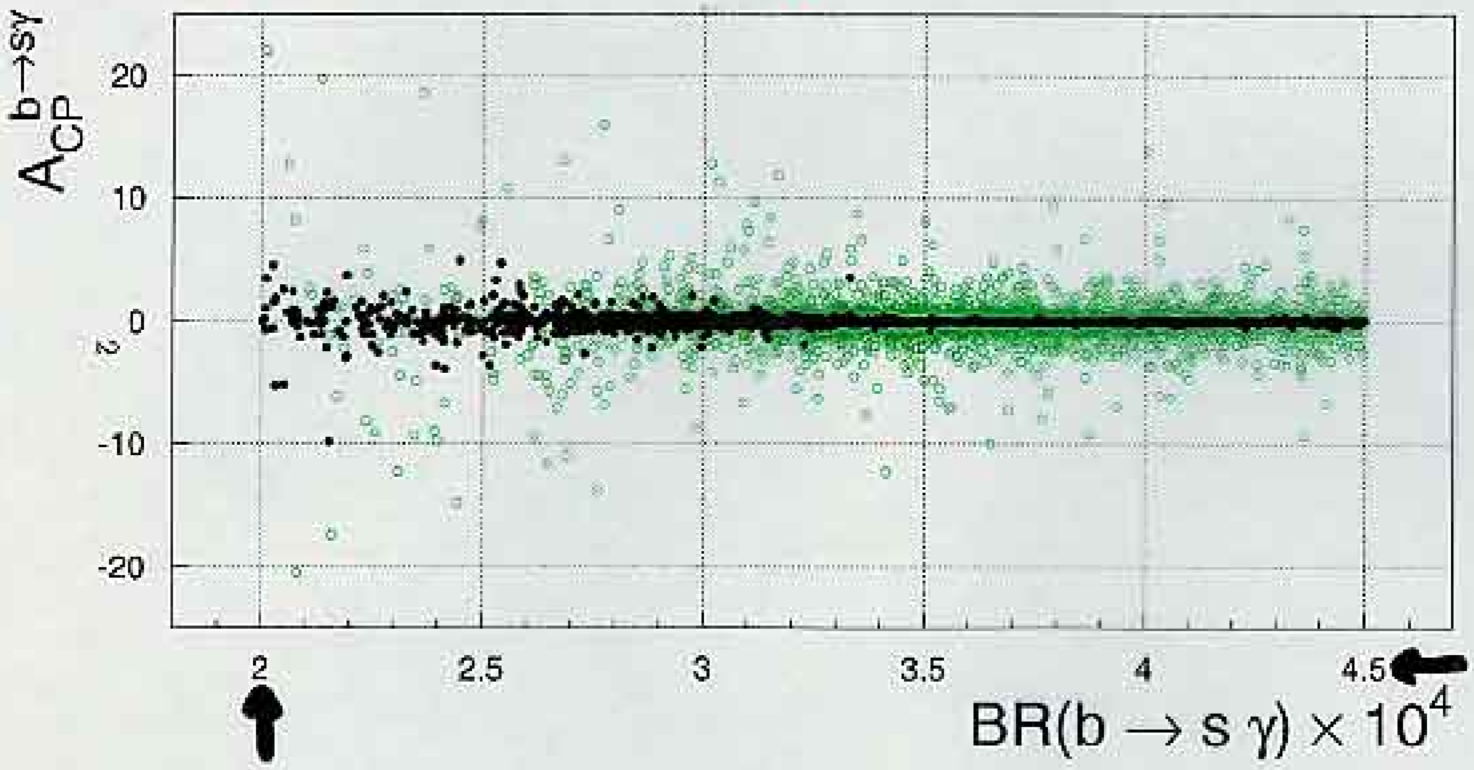
Figure 2: Charged Higgs mass as a function of $\tan\beta$ for the parameter space described in the text in the CMSSM and SU(5) cases.

BARTL et al.

No RESTRICTION ON $\phi_A, \phi_\mu \Rightarrow A_{CP}^{b\to s\gamma}$ up to ~ 5-10%

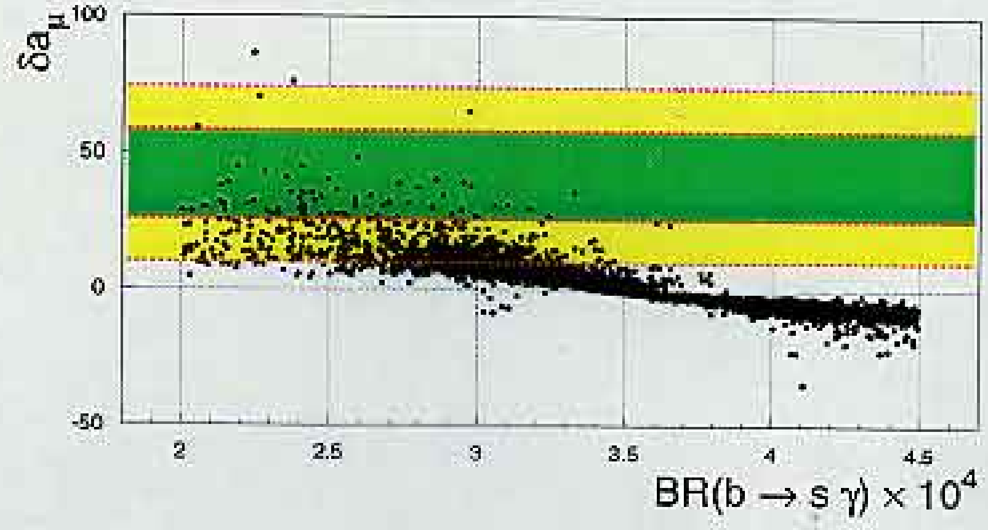
ϕ_A, ϕ_μ RESTRICTED BY EDM's $\Rightarrow A_{CP}^{b\to s\gamma} \leq 1\%$, but up to 5% for small $BR(b\to s\gamma)$

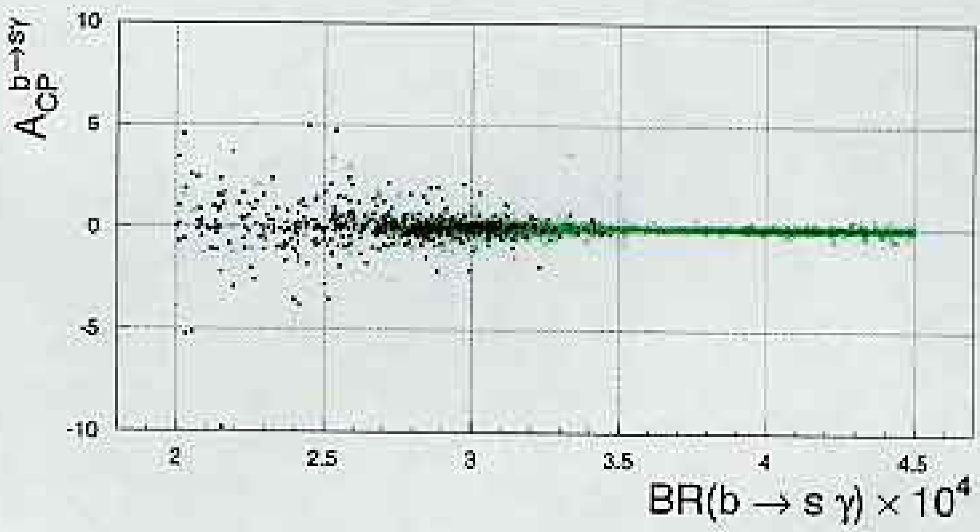
$2\times 10^{-4} \leq BR(b\to s\gamma) \leq 4.5\times 10^{-4}$ at 95% C.L.



- black dots : satisfy the EDM's constraints
  green dots : no restrictions on phases

BARTL et al


δa_μ
100
50
0
-50
2
2.5
3
3.5
4
4.5
BR(b → s γ) × 10^4


A_CP^{b→sγ}
10
5
0
-5
-10
2
2.5
3
3.5
4
4.5
BR(b → s γ) × 10^4

IF LOW ENERGY SUSY is

FLAVOR BLIND

(i.e.: SUSY breaking sector possesses FLAVOR UNIVERSALITY at the (large) energy scale where SUSY is broken + the running from such scale down to M_W does not produce any new relevant flavor structure in the s-fermion sector ⇒ only CKM structure)

⇒ SUSY with MINIMAL FLAVOR VIOLATION

(not necessarily mSUGRA or CMSSM)

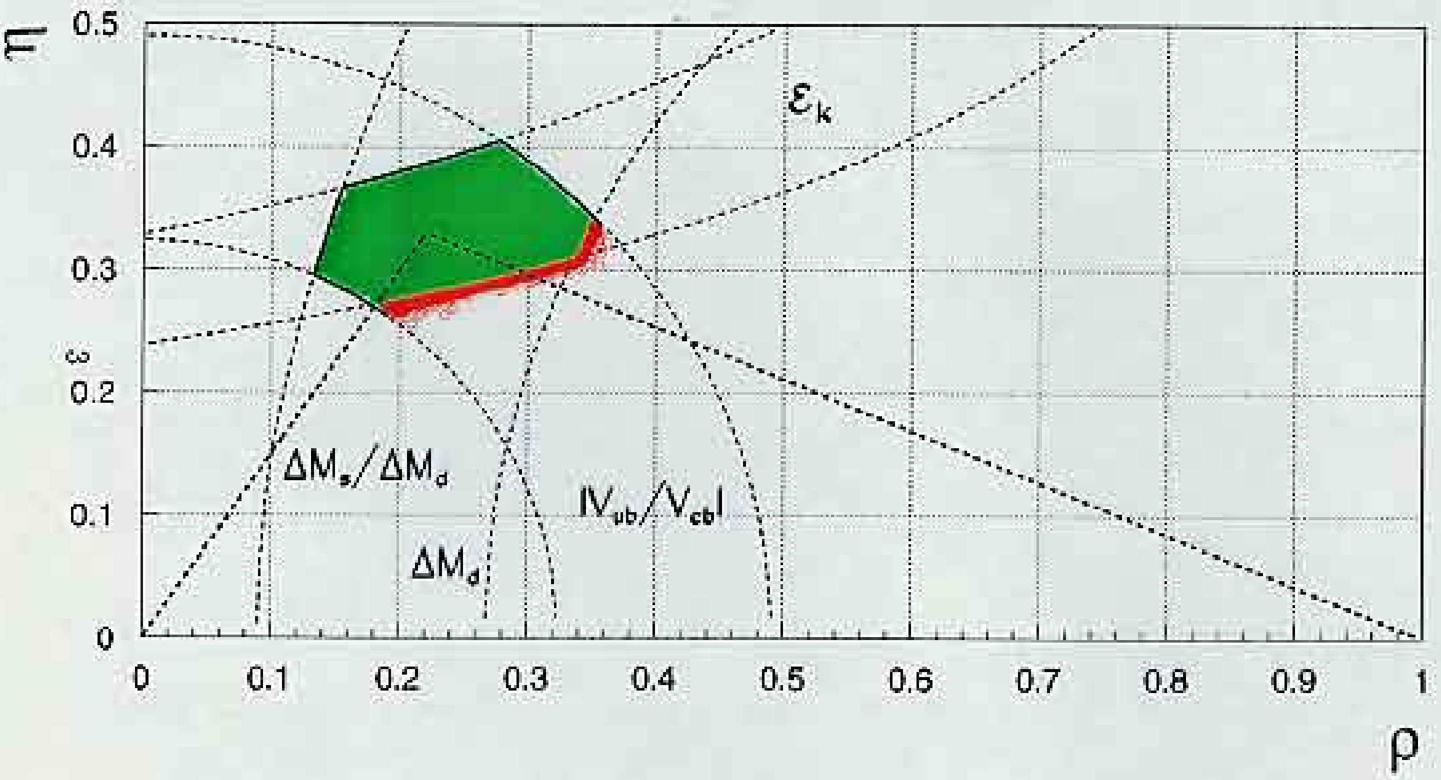
↗ FCNC contributions from the exchange of SUSY particles (in particular of the possibly light stop and chargino)

↘ SUSY CP≠ phases ⟹ ELECTRIC DIPOLE MOMENTS

↓ + FC conserving SM suppressed quantities: $(g-2)_\mu$

BARTL et al.

- red dots: departure from SM due to the exchange of mSUGRA particles



DIFFICULT TO GET LARGE SUSY CONTRIBUTIONS TO FCNC in MINIMAL FLAVOR MODELS because

- the exp. lower bounds on SUSY masses keep going up ($m_{\tilde{q}}, m_{\tilde{g}} > 200$ GeV $m_{\tilde{t}}, m_{\chi^+} > m_Z, \ldots$)
- strong constraints from measured FCNC processes, in particular $b \to s + \gamma$ (Besmer, Greub, Hurth)

POTENTIALLY MORE INTERESTING PROCESSES TO REVEAL "VIRTUAL" SUSY IN THE FLAVOR BLINDNESS CASE:

→ FLAVOR CONSERVING CP̸ (EDM's)

→ FLAVOR CONSERVING PRECISION TESTS OF THE SM: ex. $(g-2)_\mu$

$$\Delta M_d = \Delta M_d^{SM}\left[1 + \Delta^{SUSY}\right]$$

$$\Delta M_s = \Delta M_s^{SM}\left[1 + \Delta^{SUSY}\right]$$

$$|\varepsilon_K| = \frac{G_F^2 f_K^2 M_K M_W^2}{6\sqrt{2}\pi^2 \Delta M_K} \hat{B}_K (A^2\lambda^6\bar{\eta})\Big(y_c\{\hat{\eta}_{ct} f_3(y_c, y_t) - \hat{\eta}_{cc}\}$$

$$+ \hat{\eta}_{tt} f_2(y_t)\left[1 + \Delta^{SUSY}\right] A^2\lambda^4(1-\bar{\rho})\Big)$$

$\Delta^{SUSY} > 0 \Rightarrow$ SUSY contributions add CONSTRUCTIVELY to the SM contribution in the entire allowed SUSY parameter space

$\Delta = 0 \longrightarrow$	$14.6 \leq \Delta M_s \leq 31.2$ (ps^{-1})	SM
$\Delta = 0.2 \longrightarrow$	$14.6 \leq \Delta M_s \leq 35.5$	mSUGRA
$\Delta = 0.4 \longrightarrow$	$14.9 \leq \Delta M_s \leq 39.4$	non-minimal SUGRA
$\Delta = 0.75 \longrightarrow$	$15.1 \leq \Delta M_s \leq 48.6$	non-SUGRA

ALI-LONDON

$\Downarrow$ SUSY theories with MINIMAL FLAVOR VIOLATION (no new flavor structure)

exp: $\Delta M_s > 14.9\ ps^{-1}$ (at 95% C.L.)

local minimum in the log-likelihood function $\Delta M_s = 17.7 ps^{-1}$ (2.5σ away from 0)

Ex :

$B_s - \overline{B_s}$ mixing

$$\Delta m_{B_s} \simeq (28 \pm 5) \frac{\Delta m_{B_d}}{\left[(1-\rho)^2 + \eta^2\right]}$$

Branco, Cho, Kizukuri, Oshimo ;
Branco, Grimus, Lavoura ;
Brignole, Feruglio, Zwirner ;
Misiak, Pokorski, Rosiek ; Chankowski, Pokorski: can be smaller than in SM

new MSSM contributions to Δm_{B_d} and ε_K

Ali-London: effects up to 60% of the SM contribution

CP ≠ in $B \to X_s + \gamma$

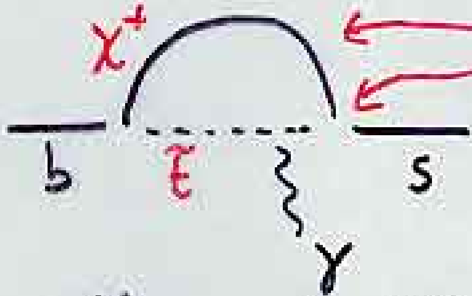
$A_{CP}^{b \to s\gamma}$ in SM is very small < 1 %

(because of a combination of CKM and GIM suppression)

Soares ; Kagan, Neubert ; Ali, Asatrian, Greub

in Constrained MSSM:

Kagan, Neubert



φ_A, φ_μ SUSY CP≠ phases

if $\varphi_\mu = 0$ (to avoid severe problems with d_e^n)

$\Rightarrow$ $A_{CP}^{b \to s\gamma}$ can still grow up to few (4 or 5) %

Aoki, Cho, Oshimo

if both $\varphi_A, \varphi_\mu \neq 0$ ➡ $A_{CP}^{b \to s\gamma}$ can reach 10 %

Chua, He, Hou

Baek, Ko

MSSM without new flavor structure but with new, large CP ≠ phases

(d_n^e tamed by cancellations among different contributions)

Ibrahim, Nath; Brhlik, Good, Kane; Brhlik, Everett, Kane, Lykken; Accomando, Arnowitt, Dutta

⇒ GENERAL MSSM with $\delta_{CKM} = 0$

WITH ALL POSSIBLE PHASES IN THE SOFT BREAKING TERMS

$$\left(A_u e^{i\varphi_{A_u}},\ A_D e^{i\varphi_{A_D}},\ A_E e^{i\varphi_{A_E}},\ m_{\tilde{g}} e^{i\varphi_3},\ m_{\tilde{W}} e^{i\varphi_2},\ m_{\tilde{B}} e^{i\varphi_1},\ \mu = |\mu| e^{i\varphi_\mu} \right)$$

BUT **NO NEW FLAVOR STRUCTURE** in addition to the usual Yukawa matrices

DEMIR, A.M., VIVES

IT IS NOT POSSIBLE TO GIVE SIZABLE CONTRIBUTIONS TO ε, ε'/ε, HADRONIC B^0 CP ASYMMETRIES

(only $A_{CP}^{b\to s\gamma}$, isospin violation in $B \to \rho\gamma$ Ali, Handoko London

if some new flavor structure is present (even if phase, flavor indep.)

⇒ possibly large effects Brhlik, Everett, Kane, King, Lebedev

HOW TO ACCOUNT FOR FCNC IN GENERAL SUSY MODELS

$\tilde{g}$ - fermion - sfermion

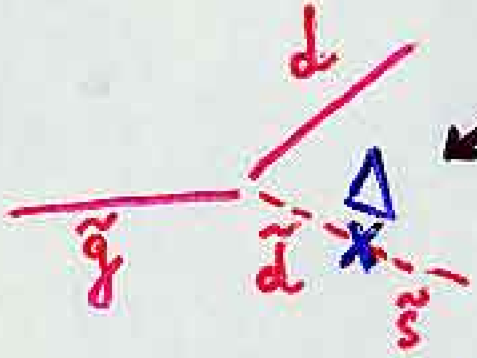
FCNC vertices **without** a detailed knowledge of the sfermion mass matrices:

ex: $M_q \to \begin{matrix} & s & d \\ s & a & b \\ d & c & d \end{matrix}$ $\qquad M^2_{\tilde{q}} \to \begin{matrix} & \tilde{s} & \tilde{d} \\ \tilde{s} & a' & b' \\ \tilde{d} & c' & d' \end{matrix}$

U, V rotations $\qquad$ U, V rotations

$M^{diag}_q \to \begin{pmatrix} m_s & \\ & m_d \end{pmatrix}$ $\qquad M'^2_{\tilde{q}} = \begin{pmatrix} \tilde{m}^2 & \Delta \\ \Delta & \tilde{m}^2 \end{pmatrix}$

$\Delta \ll \tilde{m}^2$

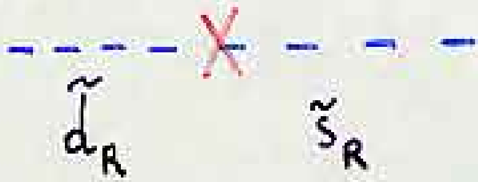


MASS INSERTION APPROXIMATION

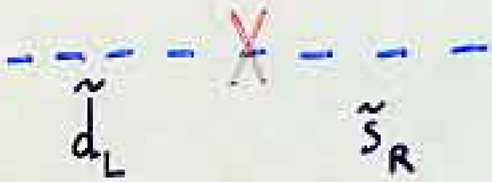
amount FCNC $\dfrac{\Delta}{\tilde{m}^2} \equiv \delta$

Hall, Raby, Kostelecki

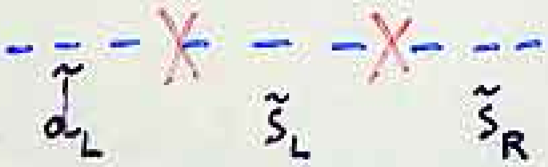
$$\left(\delta^d_{12}\right)_{LL}$$



$$\left(\delta^d_{12}\right)_{RR}$$



$$\left(\delta^d_{12}\right)_{LR}$$



$$\left(\delta^d_{12}\right)_{LL} \cdot \left(\delta^d_{22}\right)_{LR}$$

$$\vdots$$

CONSTRAINTS on δ's

FROM $\tilde{g}$ or $\tilde{\gamma}$ EXCHANGE (CP conserving processes)

Δm_K	$(\delta^d_{12})_{LL} < 4\cdot 10^{-2}$	$(\delta^d_{12})_{LR} < 4\cdot 10^{-3}$
Δm_{B_d}	$(\delta^d_{13})_{LL} < 10^{-1}$	$(\delta^d_{13})_{LR} < 3\cdot 10^{-2}$
Δm_D	$(\delta^u_{12})_{LL} < 10^{-1}$	$(\delta^u_{12})_{LR} < 3\cdot 10^{-2}$
$b \to s\gamma$	$(\delta^d_{23})_{LL}$ NO BOUND	$(\delta^d_{23})_{LR} < 10^{-2}$
$\mu \to e\gamma$	$(\delta^\ell_{12})_{LL} < 8\cdot 10^{-3}$	$(\delta^\ell_{12})_{LR} < 2\cdot 10^{-6}$
$\tau \to \mu\gamma$	$(\delta_{23})_{LL}$ NO BOUND	$(\delta^\ell_{23})_{LR} < 2\cdot 10^{-2}$

for $m_{\tilde{q}} = 500$ GeV, $m_{\tilde{\ell}} = 100$ GeV,

$$m_{\tilde{g}}/m_{\tilde{q}} = m_{\tilde{\gamma}}/m_{\tilde{\ell}} = 1$$

bounds scale with $(m_{\tilde{q}}(\mathrm{GeV})/500)$ for $\Delta m_K, \Delta m_B, \Delta m_D$ and with $(m_{\tilde{q}}(\mathrm{GeV})/500)^2$ or $(m_{\tilde{\ell}}(\mathrm{GeV})/100)^2$ for $b\to s\gamma$, $\mu\to e\gamma$, $\tau\to\mu\gamma$

Gabbiani; A.M.; Hagelin et al.; Gabbiani, Gabrielli, A.M., Silvestrini; Bagger, Matchev, Zang; Ciuchini et al.

CP CHALLENGING SUSY

$$\varepsilon \Rightarrow \begin{cases} \sqrt{\mathrm{Im}\,(\delta^d_{12})^2_{LL}} < 3\cdot 10^{-3} \\ \sqrt{\mathrm{Im}\,(\delta^d_{12})^2_{LR}} < 3\cdot 10^{-4} \end{cases}$$

$$\varepsilon' \Rightarrow \begin{cases} \left|\mathrm{Im}\,(\delta^d_{12})_{LL}\right| < 5\cdot 10^{-1} \\ \left|\mathrm{Im}\,(\delta^d_{12})_{LR}\right| < 2\cdot 10^{-5} \end{cases}$$

(bounds scale as $(m_{\tilde{q}}(\mathrm{GeV})/500))^2$

$$d^e_n \Rightarrow \mathrm{Im}\,(\delta^d_{11})_{LR} < 10^{-6}$$

scales as $(m_{\tilde{q}}(\mathrm{GeV})/500)^2$

for $m_{\tilde{q}} = m_{\tilde{g}} = 500$ GeV

Gabbiani, A.M; Hagelin et al.; Nir, Seiberg; Gabbiani, Gabrielli, A.M., Silvestrini; Bagger, Matchev, Zhang; Ciuchini et al.

$$d^e_e \Rightarrow \mathrm{Im}\,(\delta^\ell_{11})_{LR} < 10^{-7}$$

for $m_{\tilde{\ell}} = m_{\tilde{\gamma}} = 100$ GeV (it scales as $(m_{\tilde{\ell}}/100\,\mathrm{GeV})$

STEPS TOWARDS A FULL NLO ANALYSIS OF FCNC AND CP̸ IN A GENERAL MSSM

- **1996 GGMS** constraints on δ's
  - without QCD corrections
  - in the Vacuum Insertion Approximation (VIA)
  - only gluino exchange

(for previous works: '89 Gabbiani, A.M. ; '94 Hagelin, Kelley, Tanaka)

- **1997 Bagger, Matchev, Zang**
  - inclusion of the LO QCD corrections in the $K-\bar{K}$ mixing computation

- **1998 Ciuchini et al.** $\Delta S = 2$
  - Δm_K and ε_K : inclusion of the NLO anomalous dimensions of the $\Delta S = 2$ effective hamiltonian and replacement of the B-parameters in the VIA with the values obtained in a lattice computation (Allton et al)

2001 BECIREVIC et al $\Delta B = 2$

$$\Delta m_d = 2\,\mathrm{Abs}\left[\langle \bar{B}_d | \mathcal{H}_{eff}^{\Delta B=2} | B_d \rangle \right]$$

$$a_{J/\psi K_S} = \sin 2\beta_{eff} \; \sin \Delta m_d t$$

$$2\beta_{eff} = \mathrm{Arg}\left[\langle \bar{B}_d | \mathcal{H}_{eff}^{\Delta B=2} | B_d \rangle \right]$$

most general Hamiltonian for $\Delta B = 2$ processes

- NLO QCD corrections in the evolution from the scale of new physics down to low energy
- hadronic matrix elements from lattice QCD for operators renormalized consistently with the Wilson coeff. at the NLO

this general result is particularized for the MSSM

$\Rightarrow \tilde{g}$ exchange, mass insertion approximation

exp. $\sin 2\beta \Longrightarrow$ new stringent constraints on $\mathrm{Im}\,\delta_{13}^{d}$

still lacking the full NLO computation: $O(\alpha_s)$ corrections to the matching conditions at the SUSY scale $M_S \sim (m_{\tilde{g}} + m_{\tilde{q}})/2$ which determine the Wilson coeff.

(maybe they are small being of $O(\alpha_s(M_W))$)

Quantitatively the variation of the constraints on the δ's involved in $\Delta S = 2$ and $\Delta B = 2$ processes when going from the '96 GGMS analysis to the present works (with NLO + lattice B's) is nonnegligible:

ex.:

	NLO, LATTICE B:	GGMS
$\mathrm{Re}\,(\delta^d_{12})_{LL}$	$< 4.6 \times 10^{-2}$	3×10^{-2}
$\mathrm{Re}\,(\delta^d_{12})_{LR}$	$< 2.8 \times 10^{-2}$	3.4×10^{-2}
$\mathrm{Im}\,(\delta^d_{12})_{LL}$	$< 6.1 \times 10^{-3}$	3.9×10^{-3}
$\mathrm{Im}\,(\delta^d_{12})_{LR}$	$< 3.7 \times 10^{-4}$	4.1×10^{-4}
$\mathrm{Re}\,(\delta^d_{13})_{LL}$	$< 2.1 \times 10^{-2}$	3.4×10^{-2}
$\mathrm{Re}\,(\delta^d_{13})_{LR}$	$< 1.2 \times 10^{-2}$	8.3×10^{-2}
$\mathrm{Im}\,(\delta^d_{13})_{LL}$	$< 9 \times 10^{-3}$	1.5×10^{-2}
$\mathrm{Im}\,(\delta^d_{13})_{LR}$	$< 2.3 \times 10^{-2}$	3.6×10^{-2}

HOW TO JUSTIFY THE SMALLNESS OF δ's

MECHANISMS TO SUPPRESS FCNC in SUSY

➡ "PRESET UNIVERSALITY" : mechanism of SUSY breaking leads to universality (ex: pure dilaton breaking)

➡ "ALIGNMENT" : $M_{\tilde{f}} \underset{\text{aligned}}{\propto} M_f$

U(1) symm. + additional scalar fields

⇒ FLAVOR SYMMETRY ⇐

➡ NON-ABELIAN (HORIZONTAL) SYMM.

⇒ ex.: $SU(2)_{Hor}$ for the first two families

➡ HEAVY SQUARK MODELS ($m_{\tilde{q}}$ for the first two generations ~ 5 ÷ 20 TeV

$\tilde{t}, \tilde{b}$, gauginos light ⇒ no problem for gauge hierarchy)

GIVEN THE ABOVE CONSTRAINTS on the δ's

WHERE (in FCNC and CP$\not$) TO LOOK FOR SUSY SIGNALS ?

(maximally allowed FCNC and CP$\not$ SUSY contributions, not typical SUSY predictions)

KAON PHYSICS

ε_K, ε'/ε

↳ large SUSY contributions

enhancement of rare K decays

$K_L \to \pi^0 \nu \bar{\nu}$, $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \mu^+ \mu^-$

B PHYSICS

$b \to s \ell^+ \ell^-$

$b \to d \gamma$ ($B \to \rho \gamma$)

CP$\not$ B decays

LEPTON PHYSICS

$\mu \to e \gamma$

$\mu \to e e \bar{e}$

μ-e conversion in nuclei

$$M_d \propto \begin{pmatrix} m_d & m_s \sin\theta_c \\ & m_s \end{pmatrix}$$

$(\delta_{12})_{LR}$

$$M^2_{\tilde{d}_L \tilde{d}_R} \propto \begin{pmatrix} a\, m_d & b\, m_s \sin\theta_c \\ & c\, m_s \end{pmatrix}$$

a, b, c constants of $O(1)$ ⟹ unless $a = b = c$ exactly, M_d and $M^2_{\tilde{d}_L \tilde{d}_R}$ are

NOT SIMULTANEOUSLY DIAGONALIZABLE

$\tilde{d}_L$ --- ✕ --- $\tilde{s}_R$

$$\left(\delta^d_{12}\right)_{LR} \simeq \frac{\tilde{m}\, m_s \sin\theta_c}{m^2_{\tilde{q}}} \quad (\tilde{m} \leftarrow \langle F_T \rangle) =$$

$$= 2\times 10^{-5} \left(\frac{m_s(M_{PE})}{50\,\text{MeV}}\right)\left(\frac{\tilde{m}}{m_{\tilde{q}}}\right)\left(\frac{500\,\text{GeV}}{m_{\tilde{q}}}\right)$$

A.M., Murayama; Babu, Dutta, Mohapatra
Khalil, Kobayashi, Vives

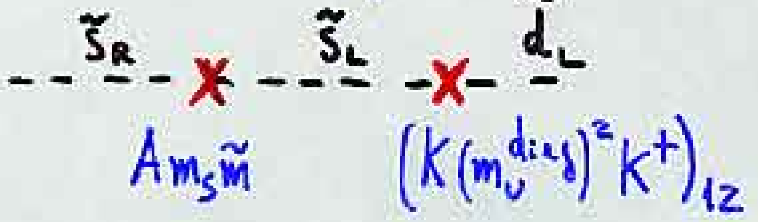
possibility of achieving it through double mass insertion $\tilde{d}_L$ -- ✕ -- $\tilde{s}_L$ -- ✕ -- $\tilde{s}_R$

Back, Ko

ε'/ε $\quad\longrightarrow\quad$ $\mathrm{Im}\,(\delta^d_{12})_{LR} \sim 10^{-5}$

ε $\quad\longrightarrow\quad$ $\mathrm{Im}\,(\delta^d_{12})_{LL} \sim 3\cdot 10^{-3}$ $\Rightarrow$ easy to obtain with SUSY phases of $O(10^{-1})$

in MSSM with flavor universality:



$\longrightarrow$ completely negligible

Gabrielli, Giudice

$\hookrightarrow$ SUSY CONTRIBUTION TO ε'/ε IS VERY TINY

($\rightarrow$ MSSM WITH FLAVOR UNIV. CP̸ OF SUPERWEAK KIND)

THIS STATEMENT DOES **NOT** APPLY TO

"REASONABLE" SUSY MODELS WITH NEW FLAVOR STRUCTURE

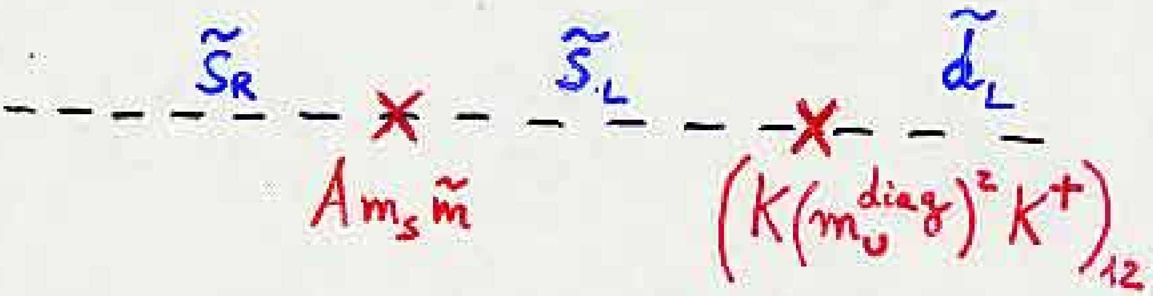
Ex: $\quad W \supset Y_D^{ij}(T)\, Q^i D^j H_D$ (T moduli fields)

$\hookrightarrow$ Yukawa couplings: $Y_D^{ij}(\langle T \rangle)$

trilinear scalar couplings: $\tilde{d}_L \tilde{d}_R^* H$: $\langle F_T \rangle$ $\hookrightarrow$ SUSY BREAKING

$$\mathcal{L}_{trilinear} \supset \frac{\partial Y_D^{ij}}{\partial T} \langle F_T \rangle\, \tilde{Q}^i \tilde{D}^j H_D$$

A.M., MURAYAMA



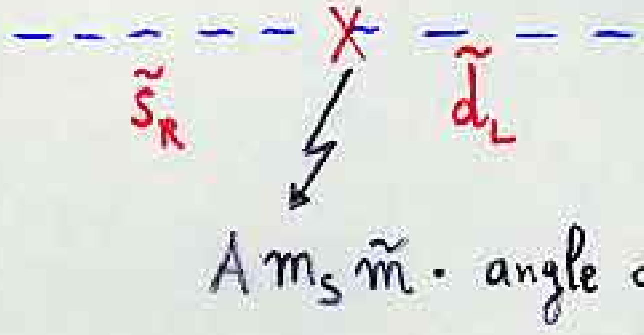
$$(\delta^d_{12})^{MSSM}_{LR} \sim \frac{A m_s \tilde m \; K_{1i} \, (m_u^{diag})^2_{ii} \, K^+_{i2}}{\tilde m^4}$$

$$\simeq m_s \left(V_{cd} V_{cs} m_c^2 + V_{td} V_{ts} m_t^2\right) \left(\frac{1}{\tilde m}\right)^3 \lesssim 10^{-8}$$

completely negligible !

to obtain $(\delta^d_{12})_{LR} \sim 10^{-5}$ (of interest for ε')

need a model where



$\Longrightarrow$ trilinear soft breaking terms $A_{ij} h_{ij} \tilde d_{L_i} H \tilde d^c_{L_j}$ NOT simultaneously diagonalizable with the Yukawa couplings h_{ij}, i.e. NON-UNIVERSAL A_{ij}

It is possible to obtain such large SUSY contributions to ε'/ε even if one has REAL SOFT TERMS provided that

- Yukawa coupl. λ_{ij} complex
- A terms have the form $A_{ij}\lambda_{ij}$ (A_{ij} real and non-universal)
- no negligible entry in the 1,2 sector of the Yukawa matrix

implications:

- d_n^e close to the exp. bound
- if μ real $\rightarrow$ d_e^e not very significant
- simple minded correlation between quarks and leptons makes $\mu \rightarrow e\gamma$ very constraining

$\mu \rightarrow e\gamma$ very close to the exp. bound

Barbieri, Contino, Strumia

IMPLICATIONS FOR $\mu \to e\gamma$, d_e^e

present exp. bounds on $\begin{cases} \mu \to e\gamma \Rightarrow (\delta_{12}^{\ell})_{LR} < (1.3 \div 3.4) \times 10^{-5} \\ d_e^e \Rightarrow \mathrm{Im}(\delta_{11}^{\ell})_{LR} < (2.7 \div 6.3) \times 10^{-6} \end{cases}$

for $0.4 < m_{\tilde{\gamma}}^2 / m_{\tilde{\ell}}^2 < 5.0$, $m_{\tilde{\ell}} = 300\,\mathrm{GeV}$

using the analogue of our previous expression for $(\delta_{12}^{d})_{LR}$ in ε'/ε, we obtain:

$$(\delta_{12}^{\ell})_{LR} \sim \frac{\tilde{m}\; m_\mu V_{\nu_e \mu}}{m_{\tilde{\ell}}^2} \sim 3.3 \times 10^{-4}\, V_{\nu_e \mu}$$

A.M., Murayama

$$(\delta_{11}^{\ell})_{LR} \sim \frac{\tilde{m}\; m_e}{m_{\tilde{\ell}}^2} \sim 1.6 \times 10^{-6}$$

taking $V_{\nu_e \mu} \sim \sqrt{\frac{m_e}{m_\mu}}$ (in the small mixing MSW solution for the solar ν)

$\downarrow$

$V_{\nu_e \mu} \sim 0.05 \Rightarrow$ predicted $(\delta_{12}^{\ell})_{R} \sim 1.6 \times 10^{-5}$

in the ballpark of the range $(1.3 \div 3.4) \times 10^{-5}$

which yields $\mu \to e\gamma$ at a rate close to the present exp. bound

SUSY and ε'/ε

For SUSY to account for ε'/ε at least one of the following conditions should be met: EYAL, A.M., NIR, SILVESTRINI

$\mathrm{Im}\,(\delta^d_{12})_{LL} \sim \lambda \left(\frac{m_{\tilde q}}{500\,\mathrm{GeV}}\right)^2$ ➡ violates the Δm_K, ε_K constraints

➡ exception Kagan-Neubert mechanism

$\mathrm{Im}\,(\delta^d_{12})_{LR} \sim \lambda^7 \left(\frac{m_{\tilde q}}{500\,\mathrm{GeV}}\right)$ ➡ possible with $A \not\parallel M_q$

$\mathrm{Im}\left[(\delta^u_{13})_{LR}\,(\delta^u_{23})_{LR}\right] \sim \lambda^2$ ➡ COLANGELO, ISIDORI

$\mathrm{Im}\left[V_{td}\,(\delta^u_{23})^*_{LR}\right] \sim \lambda^3 \left(\frac{M_2}{M_W}\right)$

$\mathrm{Im}\left[V^*_{ts}\,(\delta^u_{13})_{LR}\right] \sim \lambda^3 \left(\frac{M_2}{M_W}\right)$

} large Z_{ds} effective coupling

BURAS, SILVESTRINI

$\lambda \sim \sin\theta_c \sim 0.2$

- models of heavy $\tilde q$ and approximate CP (i.e. small CP phases) are excluded
- models of alignment and approximate CP are strongly disfavored by ε'/ε
- models of alignment without approximate CP are likely to give a significant SUSY contribution to ε'/ε

Potentially large contributions to ε'/ε from δ_{LL} if there is an isospin violation in the $\tilde{q}_R$ sector: $m_{\tilde{u}_R} \neq m_{\tilde{d}_R}$

KAGAN, NEUBERT

$\Longrightarrow$ gluino box $\Delta S = 1$ contributions in the exact isospin symmetry in the $\tilde{q}$ sector induce only $\Delta I = 1/2$ operators, but if $m_{\tilde{u}_R} \neq m_{\tilde{d}_R}$ then they generate also large $\Delta I = 3/2$ components.

SUSY contributions to the Wilson coeff. of QCD and ELW PENGUIN OPERATORS CAN BE OF THE SAME ORDER

need
$$\frac{m_{\tilde{u}_R} - m_{\tilde{d}_R}}{m_{\tilde{d}_R}} > 0.1$$

ε'/ε from $\overset{\tilde{s}_R}{- - -} \times \overset{\tilde{d}_L}{- - -}$

BURAS, COLANGELO, ISIDORI, ROMANINO, SILVESTRINI

enhancement of $K_L \to \pi^0 e^+ e^-$

$K_L \to \pi^0 \nu \bar{\nu}$ not affected

$BR(K_L \to \pi^0 e^+ e^-)$: SUSY additional contribution is positive and ranges between $(3-4) \times 10^{-12}$ up to 10^{-11}.

$\Downarrow$ indistinguishable from SM expectation

non-universality in the A soft breaking terms in string-inspired SUSY models

Abel, Frère

Khalil, Kobayashi, A.M.

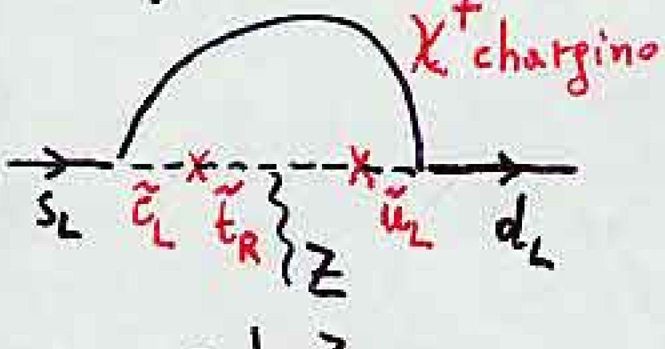
Khalil, Kobayashi, Vives

$\Rightarrow$ compatibility with the $b \to s\gamma$ result (in particular for low $\tan\beta$)

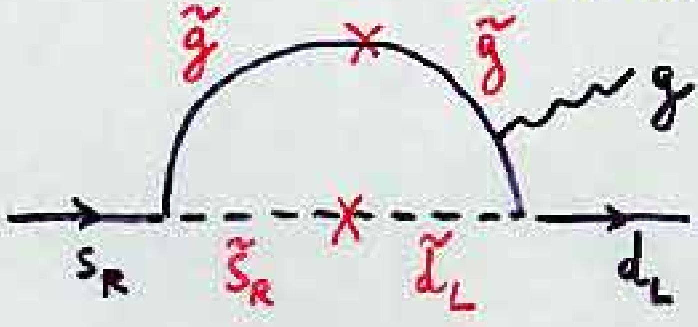
Gabrielli, Khalil, Torrente-Lujan

ε'/ε and RARE K DECAYS

BURAS, COLANGELO, ISIDORI, ROMANINO, SILVESTRINI



s-d-Z



s-d-g

enhancement of $K_L \to \pi^0 e^+e^-$, $K_L \to \pi^0 \nu\bar\nu$, $K^+ \to \pi^+ \nu\bar\nu$

assuming the usual determination of the CKM param.

+ no cancellations among different SUSY effects in ε'/ε

		SM
$BR(K_L \to \pi^0 e^+e^-)_{dir}$	$\lesssim 2\cdot 10^{-11}$	$(7\cdot 10^{-12})$
$BR(K_L \to \pi^0 \nu\bar\nu)$	$\lesssim 1.2\cdot 10^{-10}$	$(4\cdot 10^{-11})$
$BR(K^+ \to \pi^+ \nu\bar\nu)$	$\lesssim 1.7\cdot 10^{-10}$	$(1.1\cdot 10^{-1}$

(larger values possible but rather unlikely)

correlation "sin 2β" from K and B decays   NIR, WORAH

Lunghi, A.M., Scimemi, Silvestrini

$b \to s l^+ l^-$

Cho - Misiak - Wyler
Goto - Okada - Shimizu - Tanaka
Ali - Giudice - Mannel
Gronau - London
ALI - LUNGHI - GREUB - HILLER

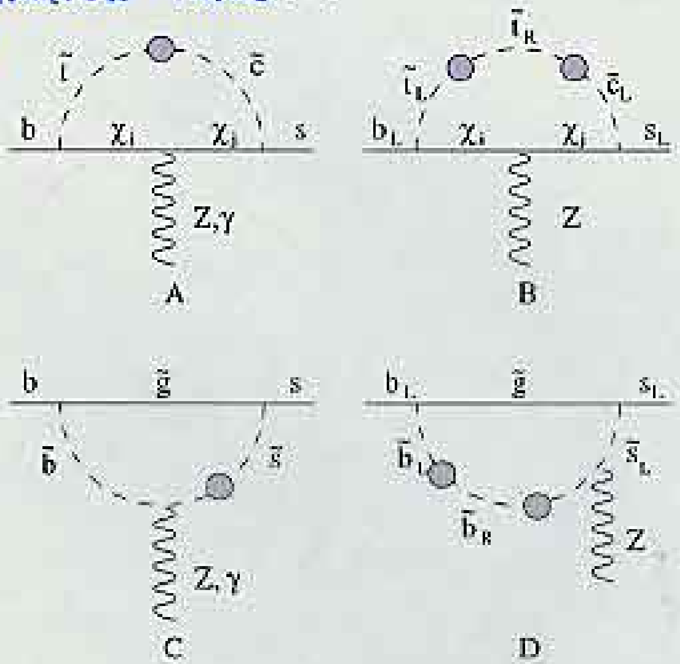


Figure 5: *Some of the relevant penguin diagrams for semileptonic B-decays. Bubbles indicate Mass Insertions. Diagrams A, B are based on chargino interaction. Diagrams C,D consider gluino interactions.*

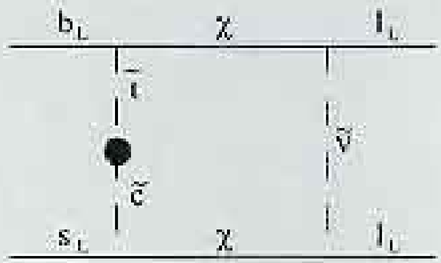


Figure 6: *Relevant box diagram for semileptonic B-decays. Bubble indicates Mass Insertion.*

A_{FB} for $B \to X_s \ell^+ \ell^-$

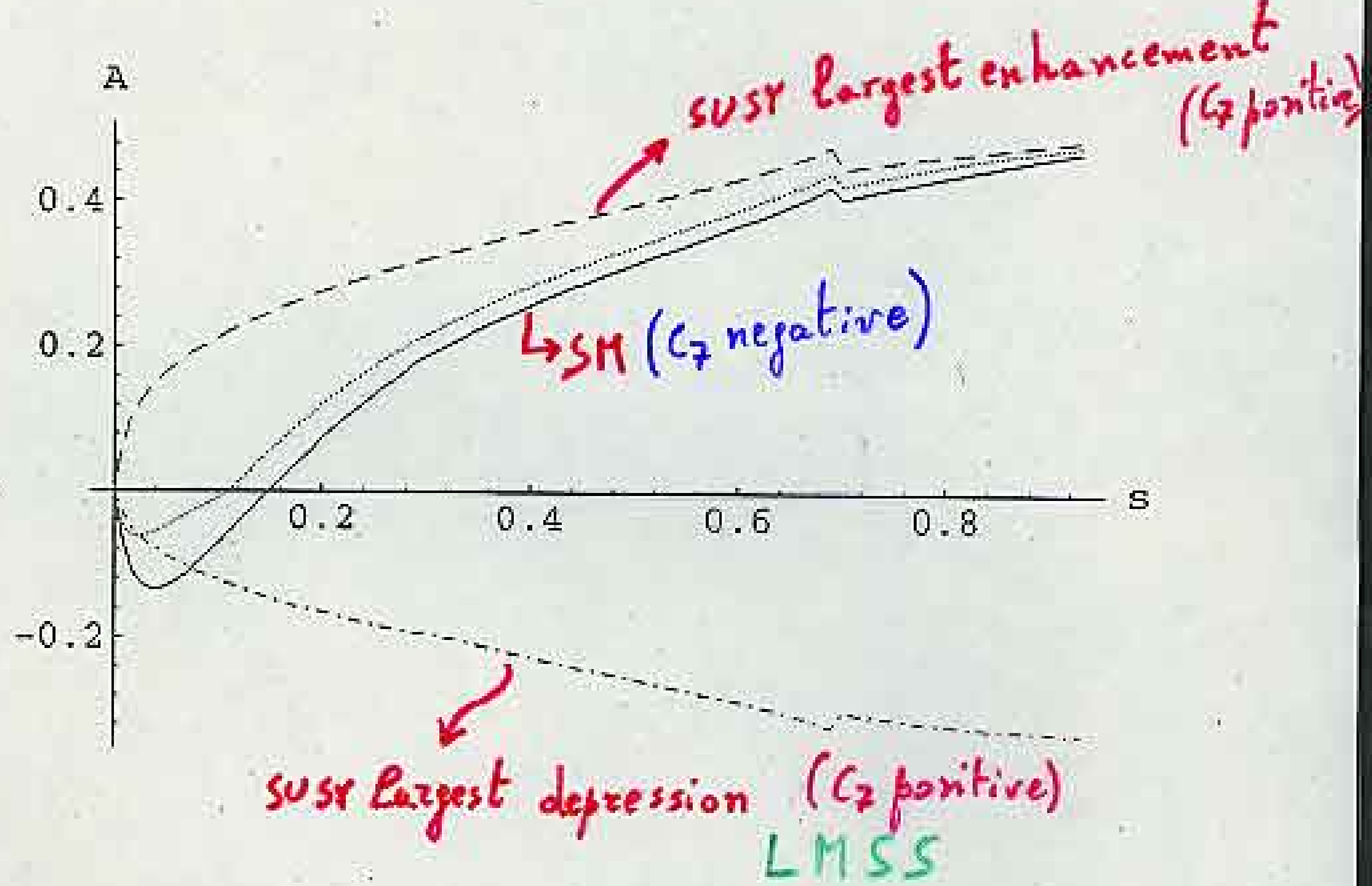
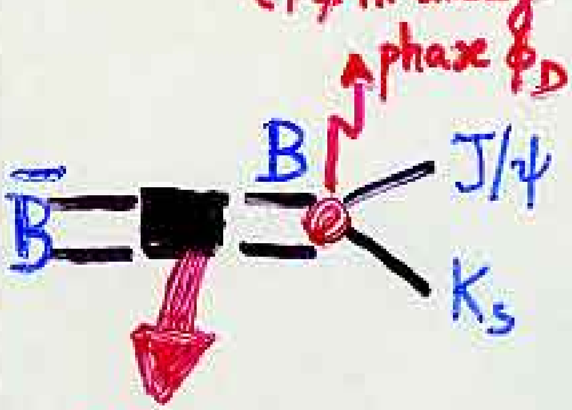


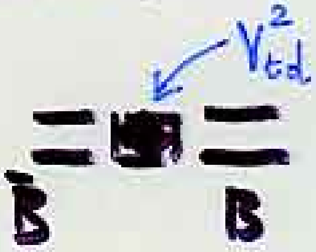
Figure 6: *Forward–Backward asymmetry (A_{FB}) for the decay $B \to X_s \ell^+ \ell^-$. The solid line corresponds to the SM expectation; the dashed and dotted-dashed line corresponds to the SUSY best enhancement ($C_7^{eff} = 0.445, C_9^{MI} = 1.2, C_{10}^{MI} = -2.1$) and depression ($C_7^{eff} = .250, C_9^{MI} = -0.5, C_{10}^{MI} = 6.6$); the dotted line is the maximum enhancement obtained without changing the sign of C_7 ($C_7^{eff} = -0.250, C_9^{MI} = 0.5, C_{10}^{MI} = 1.1$).*

WILL SUSY SHOW UP IN CP≠ B DECAYS ?



CP≠ in mixing → phase ϕ_M

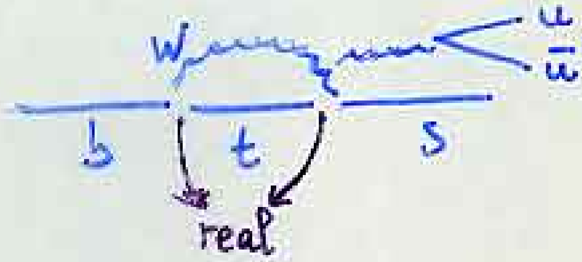
Nir, Quinn ;
Gronau, London ;
Grossman, Nir, Rattazzi

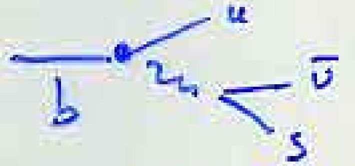


Ciuchini, Franco, Martinelli, A.M. and Silvestrini ;
Grossman and Worah ;
Barbieri and Strumia

if only one decay amplitude
⟹ CP≠ asymmetry depends on $\phi_M + \phi_D$

ex.: $B \to K_S \pi^0$

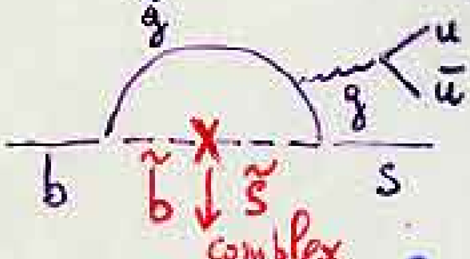




small

$$r_{SM} = \left(\frac{A_{subleading}}{A_{leading}}\right) < 8\%$$

SUSY :



$$r_{susy} = \left(\frac{A_{SUSY}}{A_{SM}}\right) \simeq 0.4 - 0.7$$

for SUSY masses ~ 250 GeV and maximal SUSY phase

$B \to J/\psi\, K_S$ $\quad r_{SUSY} < 0.10 \quad r_{SM} \sim 0$

$B \to \Phi K_S$ $\quad r_{SUSY} \sim 0.4 - 0.7 \quad r_{SM} < 8\%$

$B \to D^0 \pi^0$ $\quad r_{SUSY} \sim 0 \quad r_{SM} < 4\%$

⇒ in SM all the above decays

$B_d \to \pi^0 K_S$; $B_d \to \phi K_S$;
$B_d \to J/\psi K_S$; $B_d \to D^0 \pi^0$
} $\sin 2\beta$

measure the MIXING PHASE $\beta \hookrightarrow V_{td}$

when SUSY is included some decays ($B \to D^0 \pi^0$) are not affected ($\phi = \phi_M \Rightarrow \beta$)

some may be significantly shifted ($B \to J/\psi K_S$) ($\phi = \phi_M + \phi_D \to$ comes from r_{SUSY} up to 10%)

some may be completely different ($B \to \phi K_S$, $B \to \pi^0 K_S$) ($\phi = \phi_M + \phi_D \to$ from r_{SUSY} up to 70%)

CP≠ in K and B physics

⬇

possibility of large SUSY contributions to CP≠ in K $\Rightarrow$ ε would no longer represent a valid constraint for the unitarity triangle $\Rightarrow$ possible to witness (significant ?) departures from SM expectations in CP≠ B decays $\longrightarrow$ $a_{J/\psi}$?

$\sin 2\beta$ in SUSY WITH NEW FLAVOR STRUCTURE

Brhlik, Everett, Kane, King, Lebedev ; Ibrahim, Nath

Ex. : Type-I string inspired low energy SUSY

(I) universal soft scalar masses for doublets,

but non-universal masses for singlets :

$$(m^2_{D^c})_{11} \neq (m^2_{D^c})_{22} \neq (m^2_{D^c})_{33}$$

$$\Downarrow$$

$(\delta^d_{RR})_{12}$ can fully saturate ε_K

but $(\delta^d_{RR})_{13} < 10^{-3}$ leads to a small contribution to M_{13}

$\Rightarrow$ if δ_{CKM} is small (and it can be small given that ε_K is "saturated" by the SUSY contributions)

$a_{J/\psi K_S}$ can be quite small   A.M., PIAI, VIVES

Ex. : Low-energy SUSY with a SU(3) FLAVOR SYMM.

(II) SU(3) broken by a set of heavy scalar SM singlets with hierarchically ordered VEV's :

real CKM (or δ_{CKM} very small) with large SUSY contributions to ε_K and ΔM_d $\Rightarrow$ possible to have a very small $a_{J/\psi K_S}$

A.M., PIAI, ROMANINO, SILVESTRINI

A.M., Pini, Romanino, Silvestrini:

FIGURES

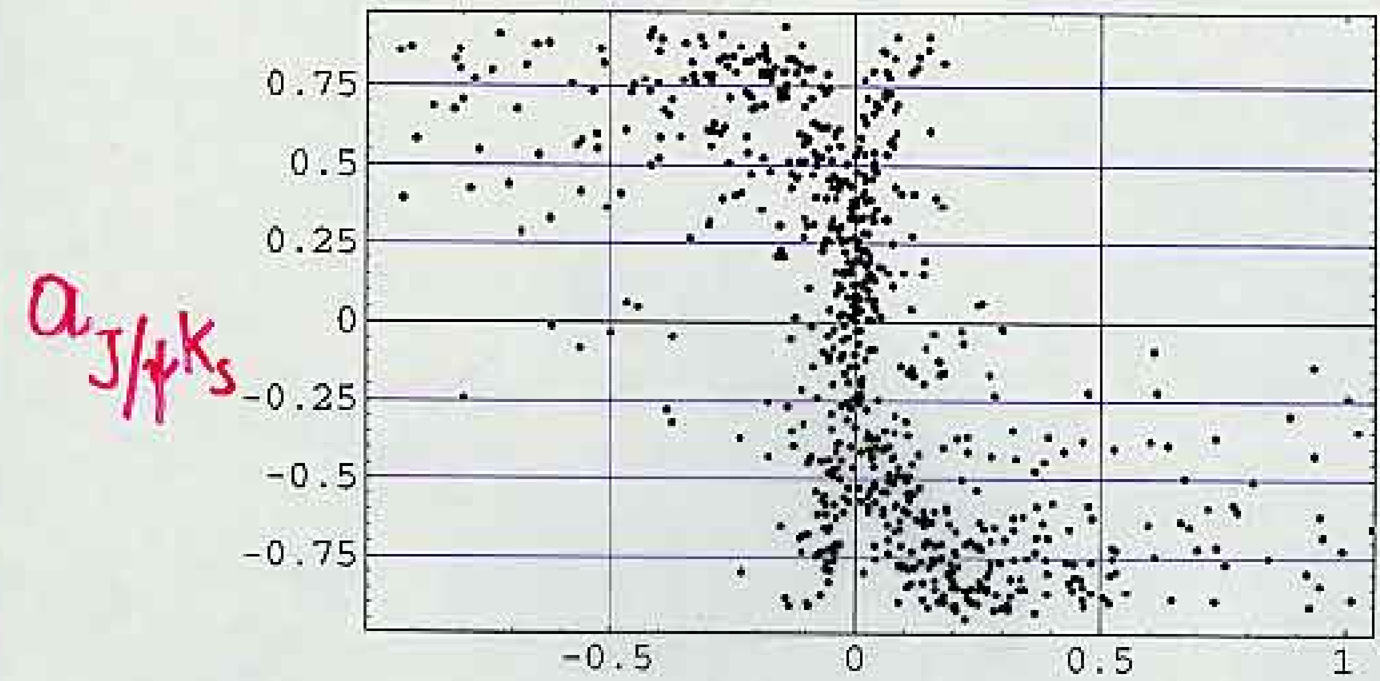


FIG. 1. Prediction for $a_{J/\psi K_S}$: dependence on $Arg(\beta')$.

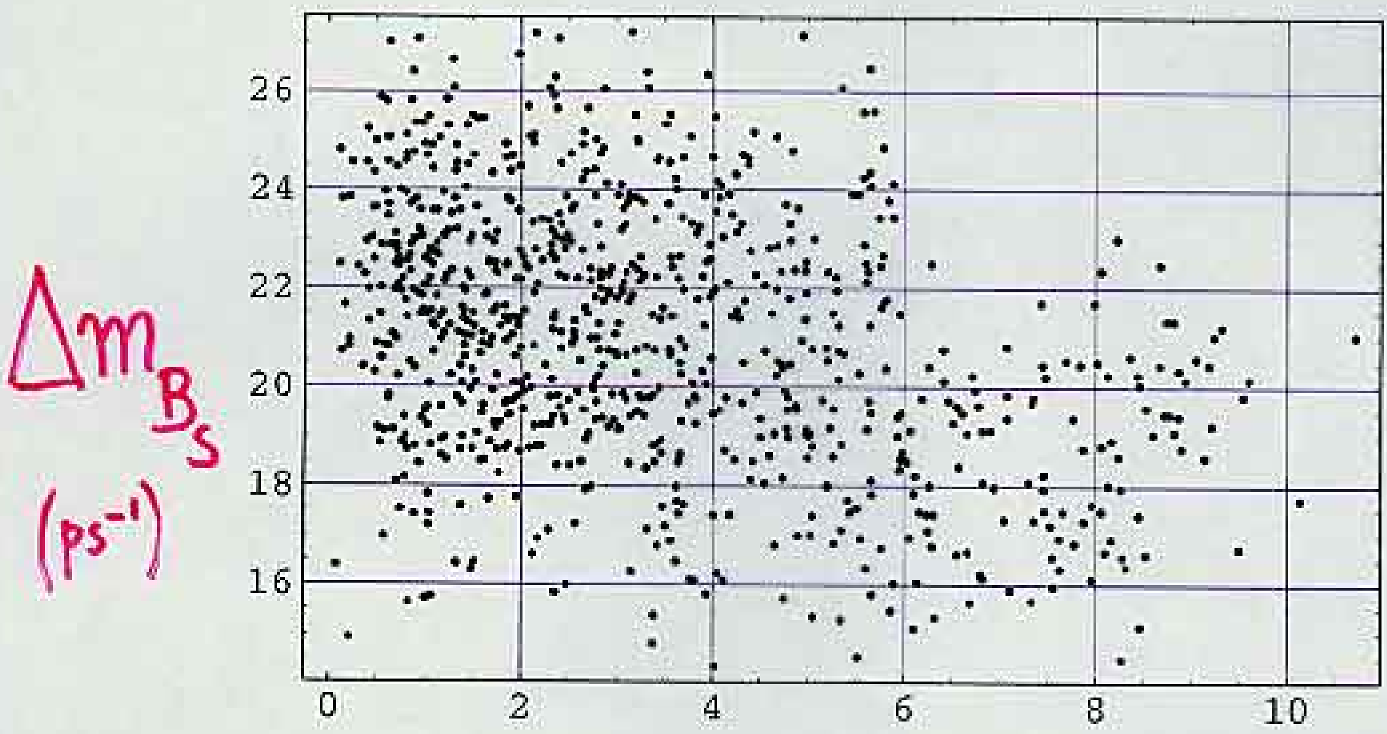


FIG. 2. Prediction for Δm_{B_s}: dependence on $|\beta'|$.

CONCLUSIONS

- FLAVOR BLINDNESS (susy breaking is flavor blind, running does not induce new flavor structures) in LOW ENERGY SUSY
  - best chance : EDM's

- SUSY BREAKING IS FLAVOR BLIND (FLAVOR UNIVERSALITY AT M_S), BUT THE RUNNING INDUCES RELEVANT NEW FLAVOR STRUCTURES ex: SUSY with massive neutrinos through a see-saw mechanism
  - $\mu \to e\gamma$, μ-e conversion in nuclei, $\tau \to \mu\gamma$, ...
  - EDM's
  - CP̸ B decays (SUSYGUT's with a see-saw)

- SUSY BREAKING IS NOT FLAVOR BLIND
  - LFV
  - EDM's
  - RARE K DECAYS
  - RARE AND/or CP̸ B DECAYS

DIRECT vs INDIRECT SUSY SEARCHES : HOPE THERE WILL BE A WINNER !