HOW TO ACCOUNT FOR FCNC IN $\boxed{\text{GENERAL}}$ SUSY MODELS

$\tilde{g}$ - fermion - sfermion

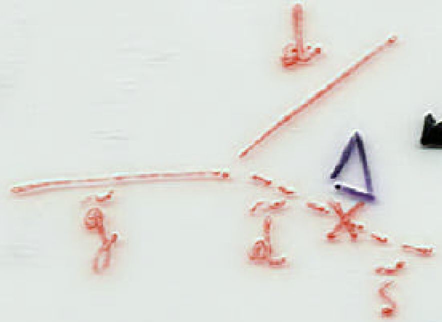
FCNC vertices **without** a detailed knowledge of the sfermion mass matrices:

ex: $M_q \to \begin{array}{ccc} & s & d \\ s & \multicolumn{2}{c}{\multirow{2}{*}{$\begin{pmatrix} a & b \\ c & d \end{pmatrix}$}} \\ d & & \end{array}$ $\qquad M^2_{\tilde{q}} \to \begin{array}{ccc} & \tilde{s} & \tilde{d} \\ \tilde{s} & \multicolumn{2}{c}{\multirow{2}{*}{$\begin{pmatrix} a' & b' \\ c' & d' \end{pmatrix}$}} \\ \tilde{d} & & \end{array}$

$$\Big\downarrow \text{U, V rotations} \qquad\qquad \Big\downarrow \text{U, V rotations}$$

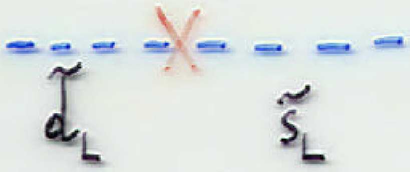
$$M_q^{diag} \Rightarrow \begin{pmatrix} m_s & \\ & m_d \end{pmatrix} \qquad M'^2_{\tilde{q}} = \begin{pmatrix} \tilde{m}^2 & \Delta \\ \Delta & \tilde{m}^2 \end{pmatrix}$$

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

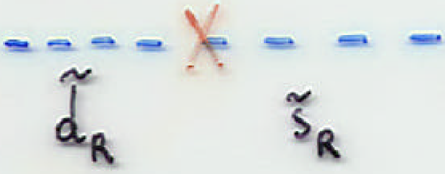


MASS INSERTION APPROXIMATION

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

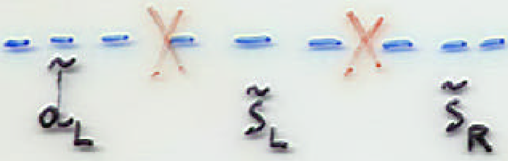


$$\left(\delta^d_{12}\right)_{LL}$$



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

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



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

$$\vdots$$

CP CHALLENGING SUSY

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

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

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

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

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

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

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

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

for $m_{\tilde \ell} = m_{\tilde \gamma} = 100$ GeV (it scales as $(m_{\tilde \ell}/100\,\mathrm{GeV})^2$)

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

WILL SUSY SHOW UP IN CP$\not=$ B DECAYS ?

CP$\not=$ in decay
phase ϕ_D

$\Downarrow$

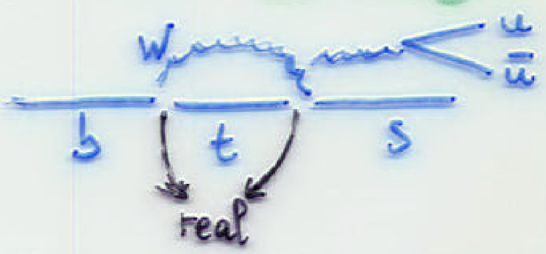
CP$\not=$ in mixing $\Rightarrow$ phase ϕ_M

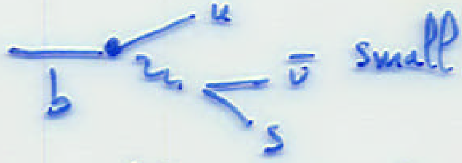
Nir, Quinn ;
Gronau, London ;
Grossman, Nir, Rattazzi

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

if only one decay amplitude
$\Rightarrow$ CP$\not=$ asymmetry depends on $\phi_M + \phi_D$

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

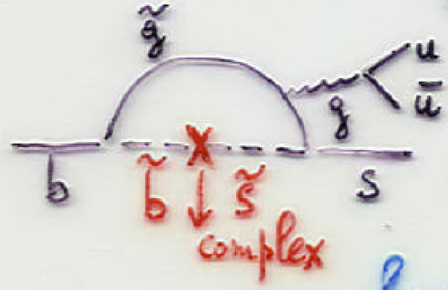




small

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

SUSY :



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

for SUSY masses ~ 250 GeV and maximal

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

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

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

$\Rightarrow$ in SM all the above decays

$B_d \to \pi^0 K_S$; $B_d \to \phi K_S$;

$B_d \to J/\psi K_S$; $B_d \to D^0 \pi^0$

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

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 $70\%)$

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

Lunghi, A.M., Scimemi, Silvestrini

Cho – Misiak – Wyler
Goto – Okada – Shimizu – Tanaka
Ali – Giudice – Mannel
Gronau – London

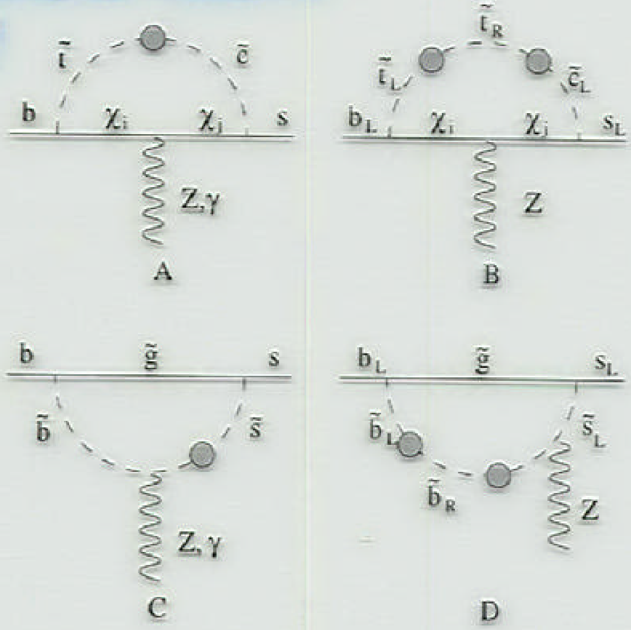


Figure 5: *Some of the relevant penguin diagrams for semileptonic B-decays. Bubbles indicate Mass Insertions. Diagrams A,B are based on chargino interaction. Diagrams C,D consider gluino interactions.*

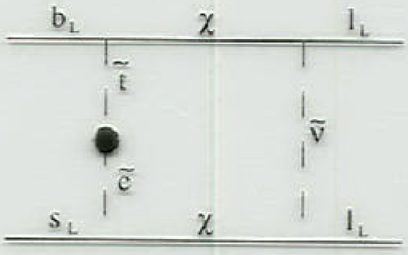


Figure 6: *Relevant box diagram for semileptonic B-decays. Bubble indicates Mass Insertion.*

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

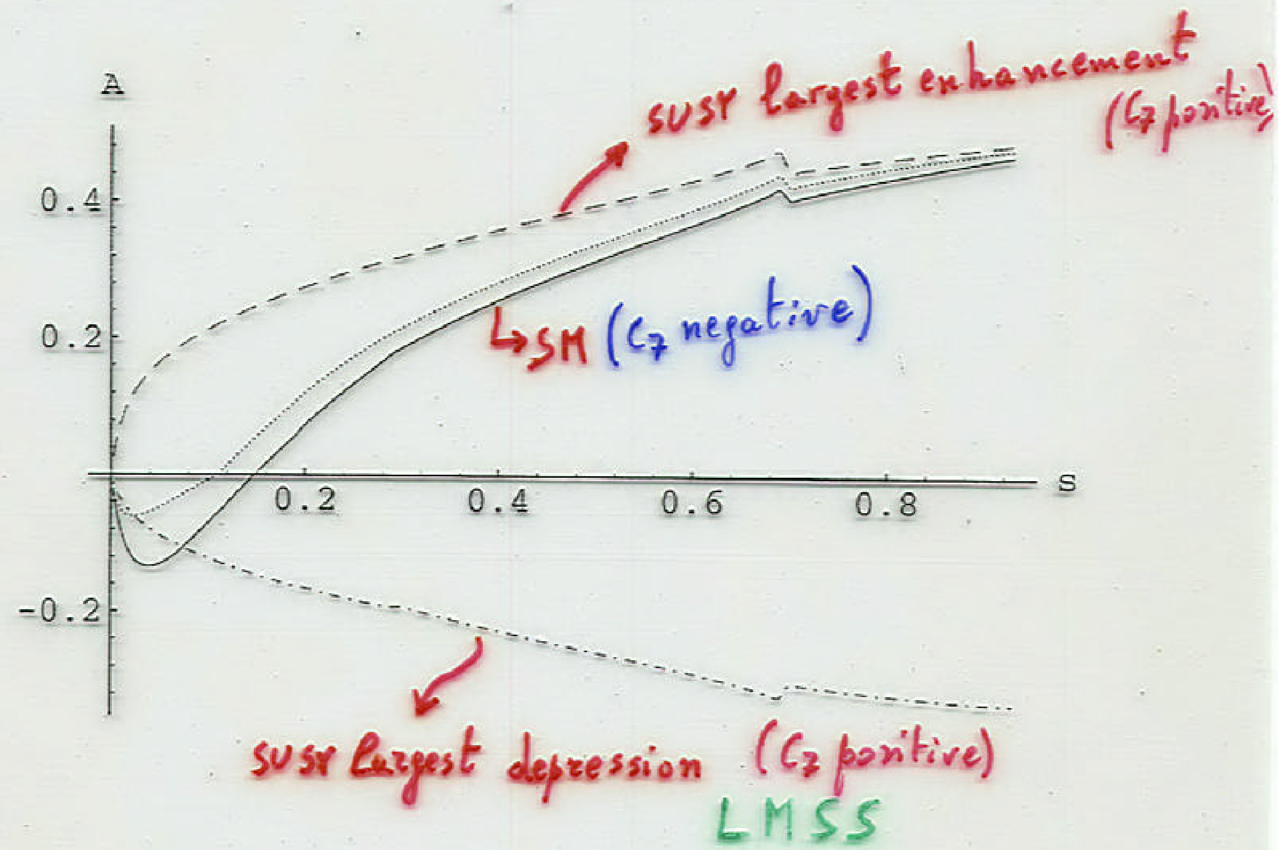


Figure 6: *Forward–Backward asymmetry (A_{FB}) for the decay $B \to X_s\ell^+\ell^-$. The solid line corresponds to the SM expectation; the dashed and dotted-dashed line corresponds to the SUSY best enhancement ($C_7^{eff} = 0.445, C_9^{MI} = 1.2, C_{10}^{MI} = -2.1$) and depression ($C_7^{eff} = .250,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

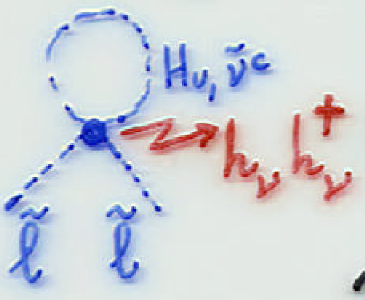
LEPTON FLAVOR $\neq$

Ex: SUSY SEE-SAW MECHANISM

Borzumati, A.M. ; Leontaris, Tamvakis, Vergados ;

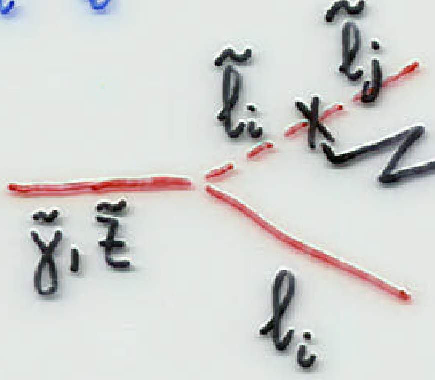
in SUSY SU(5) Barbieri, Hall; Barbieri, Hall, Strumia ;
Hisano, Nomura, Yanagida ; Hisano, Moroi, Tobe, Yamaguchi

$$W = h_L L H_d e^c + h_\nu L H_u \nu^c + M \nu^c \nu^c$$



$$\Rightarrow M_{\tilde{\ell}_L \tilde{\ell}_L^+} = \tilde{m}^2 \mathbb{1} + m_\ell m_\ell^+ + c\, m_\nu^D m_\nu^{D+}$$

$$m_\nu^D = h_\nu \langle H_u \rangle$$



$$\Delta^\ell_{ij} = c \left(\underbrace{U}_{\text{diagonalizes } m_\ell m_\ell^+} m_\nu^D m_\nu^{D+} U^+ \right)_{ij}$$

for $m_\nu^D \sim 10\text{–}20$ GeV and $U \sim K_{CKM}$

$$BR(\mu \to e\gamma) \sim 10^{-12} \div 10^{-13}$$

and also μ–e conversion in nuclei close to the exp. bound

WHAT CAN WE "REASONABLY" EXPECT FROM SUSY IN FCNC and CP$\neq$

- MINIMAL PARTICLE CONTENT
- SOFT BREAKING TERMS OF THE ORDER OF A SINGLE SCALE $m_{3/2}$
- TRILINEAR TERMS ORIGINATE FROM YUKAWA COUPLINGS

$$Y^A_{ij} = A_{ij} \cdot Y_{ij} \quad \text{with all } A_{ij} \simeq O(m_{3/2})$$

↳ Yukawa couplings

- $M_1 = M_2 = M_3$ at M_{GUT}

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

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

$\Downarrow$ in MSSM with flavor universality:

$$- - \tilde{s}_R - - \underset{A m_s \tilde{m}}{\times} - - \tilde{s}_L - - \underset{\left(K \left(m_\nu^{\mathrm{diag}}\right)^2 K^+\right)_{12}}{\times} - - \tilde{d}_L - - \longrightarrow \text{completely negligible}$$

Gabrielli, Giudice

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

($\rightarrow$ MSSM WITH FLAVOR UNIV. $CP\!\!\!/$ OF SUPERWEAK KIND)

THIS STATEMENT DOES **NOT** APPLY TO

"REASONABLE" SUSY MODELS WITH NEW FLAVOR STRUCTURE

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

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

A. M., Murayama

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

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

a, b, c constants of $O(1)$ $\Longrightarrow$ unless

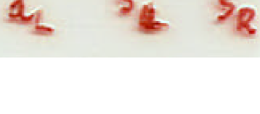
$a = b = c$ exactly, M_d and $M^2_{\tilde d_L \tilde d_R}$ are

NOT SIMULTANEOUSLY DIAGONALIZABLE

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

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

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

possibility of achieving it through double mass insertion 

Back. Ko

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 $\mu \to e\gamma$ very constraining

  $\mu \to e\gamma$ 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 $V_{\nu_e \mu} \sim \sqrt{\dfrac{m_e}{m_\mu}}$ (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

$\mathrm{Im}\left(\delta^{d}_{12}\right)_{LL} \sim \lambda \left(\frac{m_{\tilde{q}}}{500\,\mathrm{GeV}}\right)^2$ ⇒ violates the $\Delta m_K, \varepsilon_K$ constraints

⇒ exception Kagan-Neubert mechanism

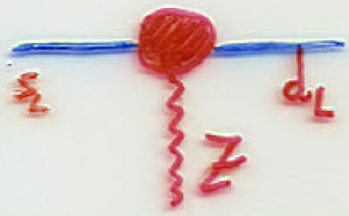
$\mathrm{Im}\left(\delta^{d}_{12}\right)_{LR} \sim \lambda^7 \left(\frac{m_{\tilde{q}}}{500\,\mathrm{GeV}}\right)$ ⇒ possible with $A \not\parallel M_q$

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

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

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

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

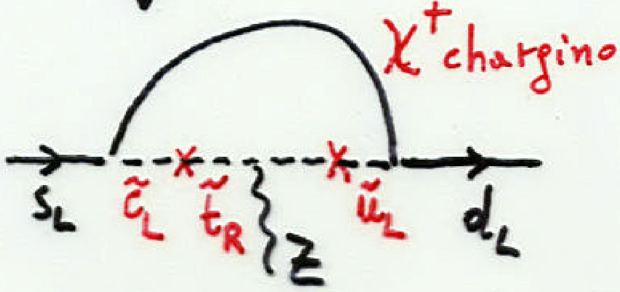
$\Longrightarrow$ gluino box $\Delta S = 1$ contributions in the exact isospin symmetry in the $\tilde{q}$ sector induce only $\Delta I = 1/2$ operators, but if $m_{\tilde{u}_R} \neq m_{\tilde{d}_R}$ then they generate also large $\Delta I = 3/2$ components.

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

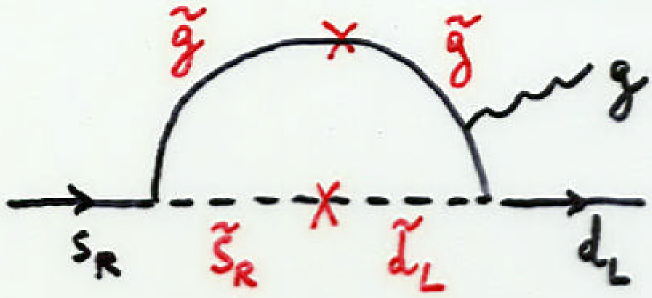
need $$\frac{m_{\tilde{u}_R} - m_{\tilde{d}_R}}{m_{\tilde{d}_R}} > 0.1$$

ε'/ε and RARE K DECAYS

BURAS, COLANGELO, ISIDORI, ROMANINO, SILVESTRI



s-d-Z



s-d-g

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

assuming the usual determination of the CKM para

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

SM

$BR(K_L \to \pi^0 e^+ e^-)_{dir} \lesssim 2 \cdot 10^{-11}$ (7·10

$BR(K_L \to \pi^0 \nu \bar{\nu}) \lesssim 1.2 \cdot 10^{-10}$ (4·10

$BR(K^+ \to \pi^+ \nu \bar{\nu}) \lesssim 1.7 \cdot 10^{-10}$ (1.1·1

(larger values possible but rather unlikely)

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

On "REASONABLE" EXPECTATIONS in B PHYSICS

- GLUINO EXCHANGE: $(\delta^d_{i3})_{A,B}$ $i=1,2$ $A,B=L,R$

color + charge breaking $\longrightarrow$ $(\delta^d_{LR})_{i3} \lesssim \sqrt{3}\,\frac{m_b}{m_{\tilde{q}}}$

$\simeq 0.01\left(\frac{500\,GeV}{m_{\tilde{q}}}\right)$

if mixings in the $\tilde{q}$ sector have a pattern similar to CKM $\longrightarrow$ δ_{i3} TOO SMALL TO PROVIDE SIZABLE CONTRIBUTIONS TO $B-\bar{B}$ MIXING OR $CP\!\!\!/$ B DECAYS

- CHARGINO EXCHANGE: δ^u_{i3} again sizeable departures of the $\tilde{q}$ mixings from the CKM is needed to have large SUSY contributions to $B-\bar{B}$, B decays

A.M., VIVES

$\Longrightarrow$ K PHYSICS MORE SENSITIVE TO "REASONABLE" SUSY MODELS WITH $\tilde{Q}$ FLAVOR PATTERN NOT TOO FAR FROM Q FLAVOR PATTERN

B PHYSICS LARGE DEVIATIONS FROM SM IF THE SUSY FLAVOR STRUCTURE IS QUITE DIFFERENT FROM CKM

$CP\!\!\!\!/$ in K and B physics

$\Downarrow$

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 $\longrightarrow$ $a_{J/\psi}$?

WHAT a "SMALL" $a_{J/\psi}$ WOULD IMPLY

NIR, EYAL, PEREZ

no NEW PHYSICS intervention

↓

"stretching" of the SM parameters

⇒ hadronic uncertainties in the SM prediction of $a_{J/\psi}$

$R_u \equiv \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right|$;

$\Delta m_{B_d} \Rightarrow \sqrt{B_{B_d}}\, f_{B_d}$

$\varepsilon_K \Rightarrow B_K$

* hard to have $a_{J/\psi} < 0.5$ *

for instance $\left|\frac{V_{ub}}{V_{cb}}\right| < 0.06$

NEW PHYSICS PLAYS A RELEVANT ROLE IN AT LEAST SOME OBSERVABLES ENTERING THE FIT

SUSY WITHOUT NEW FLAVOR STRUCTURE (but providing relevant contributions to the amplitudes entering the analysis)

SUSY WITH NEW FLAVOR STRUCTURE

LOWER BOUND ON $\sin 2\beta$ in

MINIMAL FLAVOR VIOLATION MODELS (i.e. models which do not have new operators beyond those present in the SM and without new flavor structure or new CP$\neq$ phases)

A. BURAS,
R. BURAS

performing a scanning over the ranges of the param. involved in the hadronic uncertainties leads to

$$\sin 2\beta > 0.34$$

ALI, LONDON

$\sin 2\beta$ 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., Piai, Romanino, Silvestrini:

FIGURES

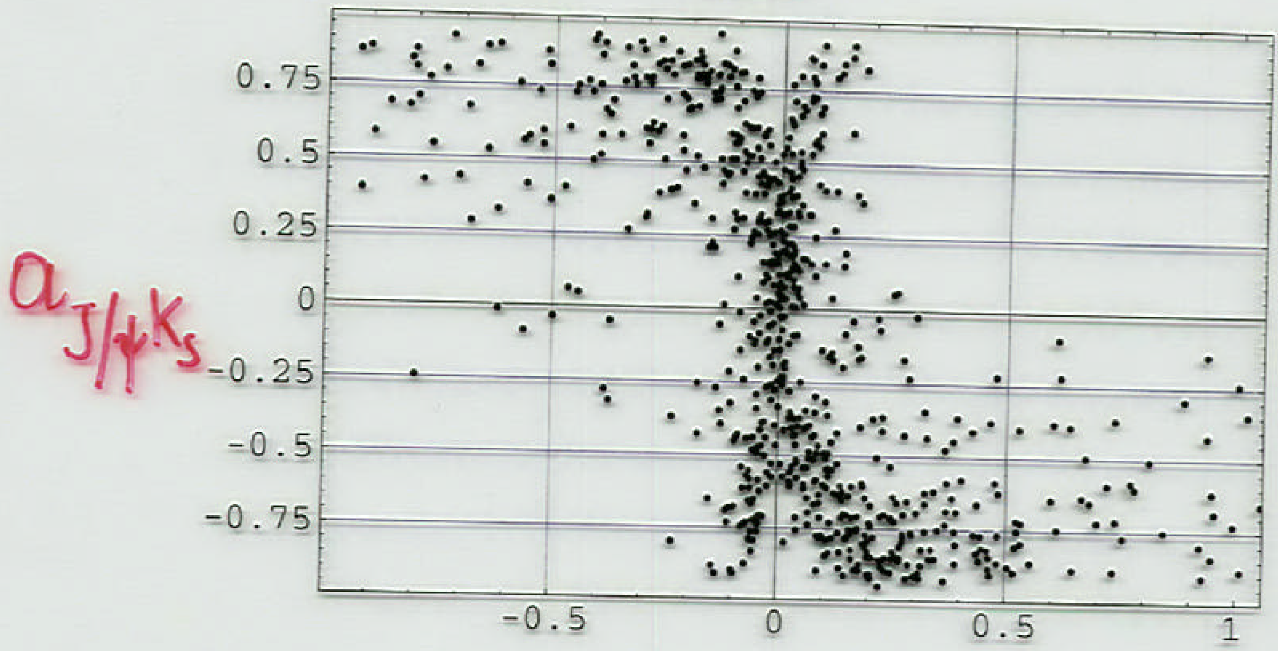


FIG. 1. Prediction for $a_{J/\psi K_S}$: dependence on $Arg(\beta')$.

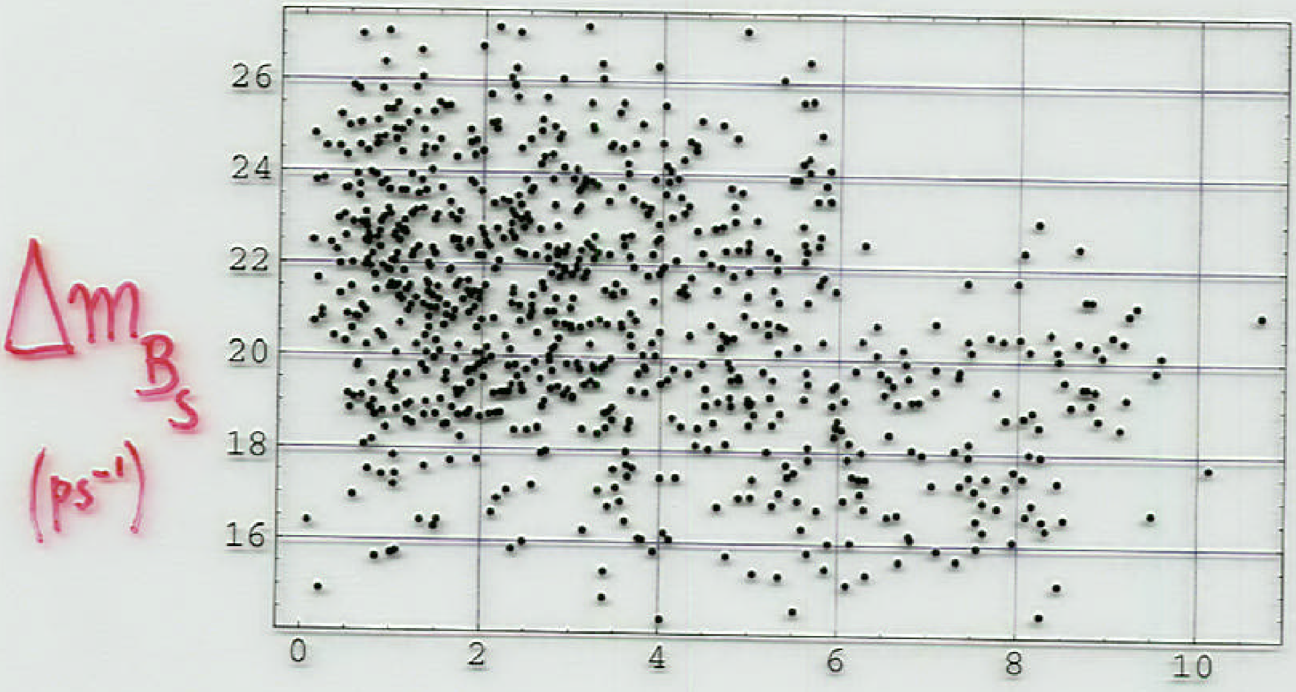


FIG. 2. Prediction for Δm_{B_s}: dependence on $|\beta'|$.

OUTLOOK

CP$\not$ in K

- SUSY WITHOUT NEW FLAV. STRUCTURE ⇒ negligible effects
  (but possibly new CP$\not$ phases)
- SUSY WITH NEW FLAVOR STRUCTURE
  ⇒ possible to have large SUSY contrib. to $\varepsilon, \varepsilon'$
  " " " enhancements in rare K decays

NO NEED FOR "VIOLENTLY" NEW FLAVOR STRUCTURE

CP$\not$ in B

- SUSY WITHOUT NEW FLAVOR STRUCTURE
  (but possibly new CP$\not$ phases)
  ⇒ small chances of "SUSY visibility"
  possibly only in $A_{CP}^{b \to s\gamma}$
- SUSY WITH A NEW "MODERATE" FLAVOR STRUCTURE
  (i.e. mixing angles in the $\tilde{f}$ sector similar to CKM)
  ⇒ still marginal SUSY visibility
- SUSY WITH A "VERY" NEW FLAVOR STRUCTURE
  → sizeable chances of significant departures from SM expectations in CP$\not$ B decays

FLAVOR, CP conserving ⇒ a_μ

FLAVOR CONSERVING CP$\not$ (d_n^e, d_e^e, ...): relevant constraint on any kind of SUSY model with new CP$\not$ phases