BCP4

Ise, 19-23 Feb. 01

SUSY CONTRIBUTIONS TO LOW ENERGY OBSERVABLES

or

THE PRE-LHC SUSY CHALLENGE

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SISSA and INFN TRIESTE

MECHANISMS → FLAVOR STRUCTURE (m_f, CKM, $m_{\tilde{f}}$, ...)

MECHANISMS → SUSY BREAKING

↓

implications if they **are** or **are not** related for FCNC, CP̸, a_μ in the pre-LHC epoch

LOW ENERGY SUSY

WHY
- GAUGE HIERARCHY PROBLEM
- UNIFICATION OF STRONG + ELW. INTER.
- ONLY COMPLETE, PHENOMENOLOGICALLY VIABLE THEORY OF NEW PHYSICS AT $O(\text{TeV})$

SIGNATURE
MOST (but not necessarily all) SUSY PARTICLES HAVE A MASS $\lesssim O(1\text{ TeV})$

↯ doubling of known particles with the same $SU(3)$, $SU(2)$, $U(1)$, flavor, ... numbers

HOW TO FIND IT

DIRECT SEARCHES
production and observation of s-particles

limits: $m_{\text{colored s-part}} > 200\text{-}250$ GeV

$m_{\tilde{\ell},\text{chargini}} > m_Z$

$m_{\text{lightest neutralino LSP}} > 40$ GeV

($m_H \sim 115$ GeV? → favors SUSY)

INDIRECT SEARCHES FCNC, CP̸, g-2

MINIMAL LOW ENERGY SUSY

↙ - minimal amount of superpart. needed to supersymmetrize the SM

- IMPOSING THE (ADDITIONAL) SYMM. R parity
  ⇒ to eliminate B and L ≠ dangereous terms

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

$\mathcal{L}_{N=1\,\text{SUSY SM}}$ ↓

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

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

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

↳ Constrained — minimal SuperGravity

or how to reduce the param. from 124 → 5

MSSM

\+

FLAVOR UNIVERSALITY

$$m^2_{ij} = \delta_{ij}\, m^2_0$$

m^2_0 → common scalar mass term

$$A_{ij} \rightarrow A_0$$

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

(GRAND) UNIFICATION

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

M ← common gaugino mass

m^2_{ij}, 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: $m^2_0,\ \mu,\ B_0,\ A_0,\ M$

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, Thoma

- 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 CMSSM only a very limited area of the parameter sp
is available for baryogenesis ⇒ light $\tilde{t}$, $\tilde{\chi}^{+}$)

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** $\Rightarrow \phi_A, \phi_\mu$ too small because of d_n^e

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

CANCELLATIONS AMONG THE SUSY CONTRIBUTIONS TO d_n^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

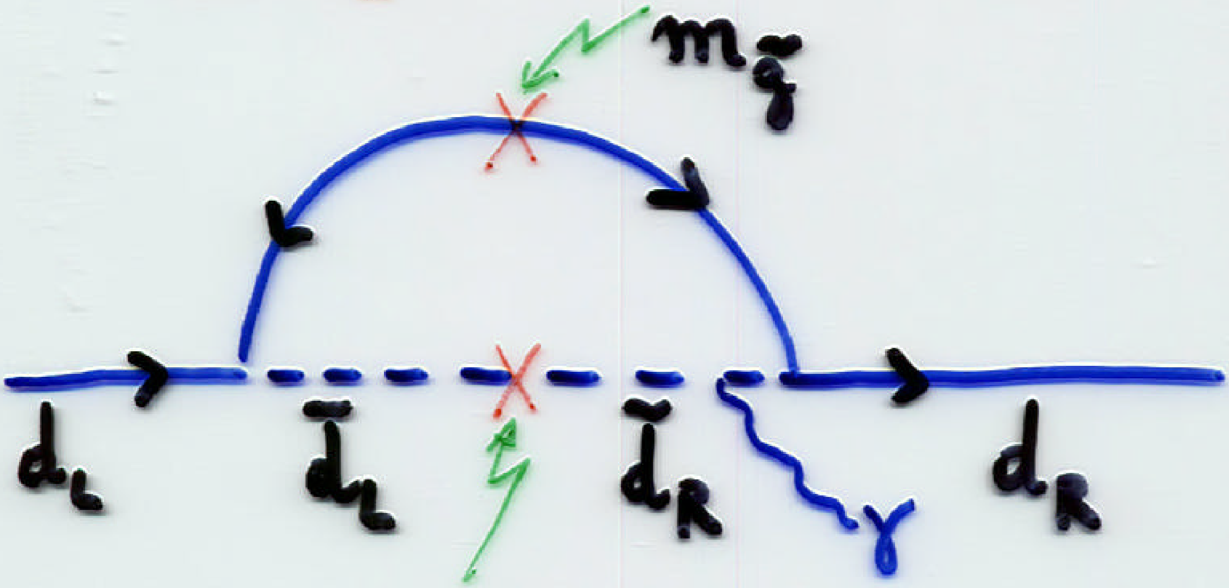
LARGE MASSES OF $\tilde{Q}$ OF THE FIRST TWO GENERATIONS

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

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 $m^2_{\tilde d_L} \sim m^2_{\tilde d_R} \sim m^2_{\tilde g} \sim \tilde m^2$

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

Buchmuller, Wyler
Polchinski, Wise
Fischler, Paban, Thomas

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

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

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

ORIGIN OF FLAVOR

⇕

SUSY BREAKING

NO RELATION

SUSY BREAKING IS FLAVOR BLIND

(ex.: MSSM with FLAVOR UNIVERSALITY $\tilde{m}$, A ; GMSB)

↓

- still room for NEW SOURCES OF CP$\not$ (at least 2 new CP$\not$ phases - unrelated to the flavor structure)
- SUSY FCNC contributions ($\chi^{\pm}$-$\tilde{t}_R$)

SUSY BREAKING KNOWS FLAVOR

↓

SUSY breaking terms introduce a NEW FLAVOR STRUCTURE in addition to the Yukawa flavor structure of the SM

$A \Rightarrow A_{ij} \not\propto h_{ij}$

$\tilde{m} \Rightarrow \tilde{m}^2_{ij} \neq \delta_{ij}\, \tilde{m}^2$

$a_\mu \equiv (g_\mu - 2)/2$: CANDIDATE FOR

SUSY { (Severe) CONSTRAINTS
MANIFESTATION }

even if { SUSY BREAKING IS FLAVOR BLIND
NO SUSY CP$\not$ ARE PRESENT }

a_μ^{exp}(Average) = $116\,592023\,(151) \times 10^{-11}$ (Cern '77 + BNL '98, '99)

⇒ ultimate goal E821 $\pm 40 \times 10^{-11}$
↯ (final scheduled run with μ^- during 2001)

⇒ inclusion of data from the 2000 run expected to lead to $\pm 80 \times 1$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{EW} = 116591597\,(67) \times 10^{-11}$$

(Czarnecki, Marciano)

a_μ^{Had}(vac. pol.) = $6924\,(62) \times 10^{-11}$ (Davier + Höcker)

(but a_μ^{Had}(vac pol) = $6988\,(111) \times 10^{-11}$ (Jegerlehner 2000, preliminary))

$a_\mu^{exp} - a_\mu^{SM} = 426 \pm 165 \times 10^{-11}$ (2.6σ)

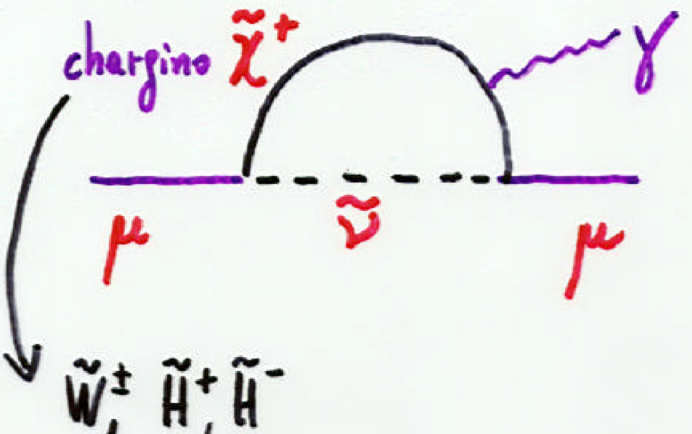
$$215 \times 10^{-11} \leq a_\mu(\text{New Physics}) \leq 637 \times 10^{-11}$$

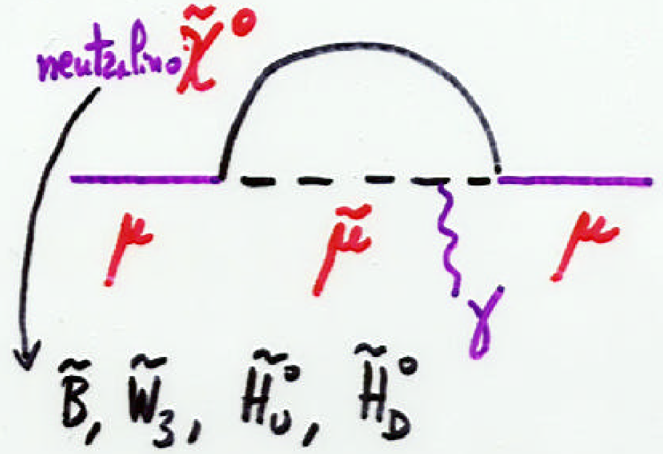
(Incomplete) bibliography on a_μ in SUSY

Fayet '80 ; Grifols, Mendez '82 ;
Ellis, Hagelin, Nanopoulos '82 ;
Barbieri, Maiani '82 ;
Romao, Barroso, Bento, Branco '85 ;
Kosover, Krauss, Sakai '83 ;
Yuan, Arnowitt, Chamseddine, Nath '84 ;
Vendramin '89 ; Grifols, Sola, Mendez '86 ;
Morris '88 ; Frank, Kalman '88 ;

Lopez, Nanopoulos, Wang '94 → $\tan\beta$
Moroi '96 ;
Cho, Hagiwara, Hayakawa '00 ;
Ibrahim, Nath '00 ;
Carena, Giudice, Wagner '97 GMSB
Brignole, Perazzi, Zwirner '99
Mahantappa, Oh '00
Chattopadhyay, Nath '96
Goto, Okada, Shimizu '99 ; Blazek '99
Chattopadhyay, Ghosh, Roy '00

SUSY CONTRIBUTION TO a_μ





(generally) dominant contribution

for large $\tan\beta$:

$$|a_\mu^{SUSY}| \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \left(1 - \frac{4\alpha}{\pi} \ln \frac{\tilde{m}}{m_\mu}\right)$$

↳ $\tilde{m}$ average SUSY mass in the loop
→ $\tilde{\chi}^+, \tilde{\nu}$ taken to be degenerate

Czarnecki, Marciano

$$|a_\mu^{SUSY}| \simeq 130 \times 10^{-11} \left(\frac{100\,\text{GeV}}{\tilde{m}}\right)^2 \tan\beta$$

for sizeable SUSY contrib.

$$\tilde{m} \simeq (55\,\text{GeV}) \sqrt{\tan\beta}$$

rough relation valid only if $m_{\tilde{\chi}} = m_{\tilde{\nu}}$, ...

FCNC and CP $\neq$

WHEN SUSY BREAKING IS

FLAVOR BLIND

⇓

STILL LARGE CONTRIBUTIONS FROM THE EXCHANGE OF SUSY PARTICLES ARE POSSIBLE IN SOME FCNC processes (most relevant case: $b \to s + \gamma$), in particular if LIGHT STOP AND CHARGIN are present, or in Flavor conserving and Flavor changing CP$\neq$ (d_n^e, d_e^e *, $A_{CP}^{b \to s\gamma}$) (see figs)

* d_n^e, d_e^e ➡ ϕ_A, ϕ_μ even in CMSSM: close to the exp. bound for $m_{\tilde{q}, \tilde{g}} \lesssim 1$ TeV $\phi_\mu \sim 10^{-1} - 10^{-2}$

* LIGHT STOP ($\tilde{t}_R$) and CHARGINO (exp. bounds $m_{\tilde{t}_R}, m_\chi >$

Bartl, Gajdosik, Lunghi, A.M., Porod, Stockinger, Strzemnitzer, Vives (in preparation)

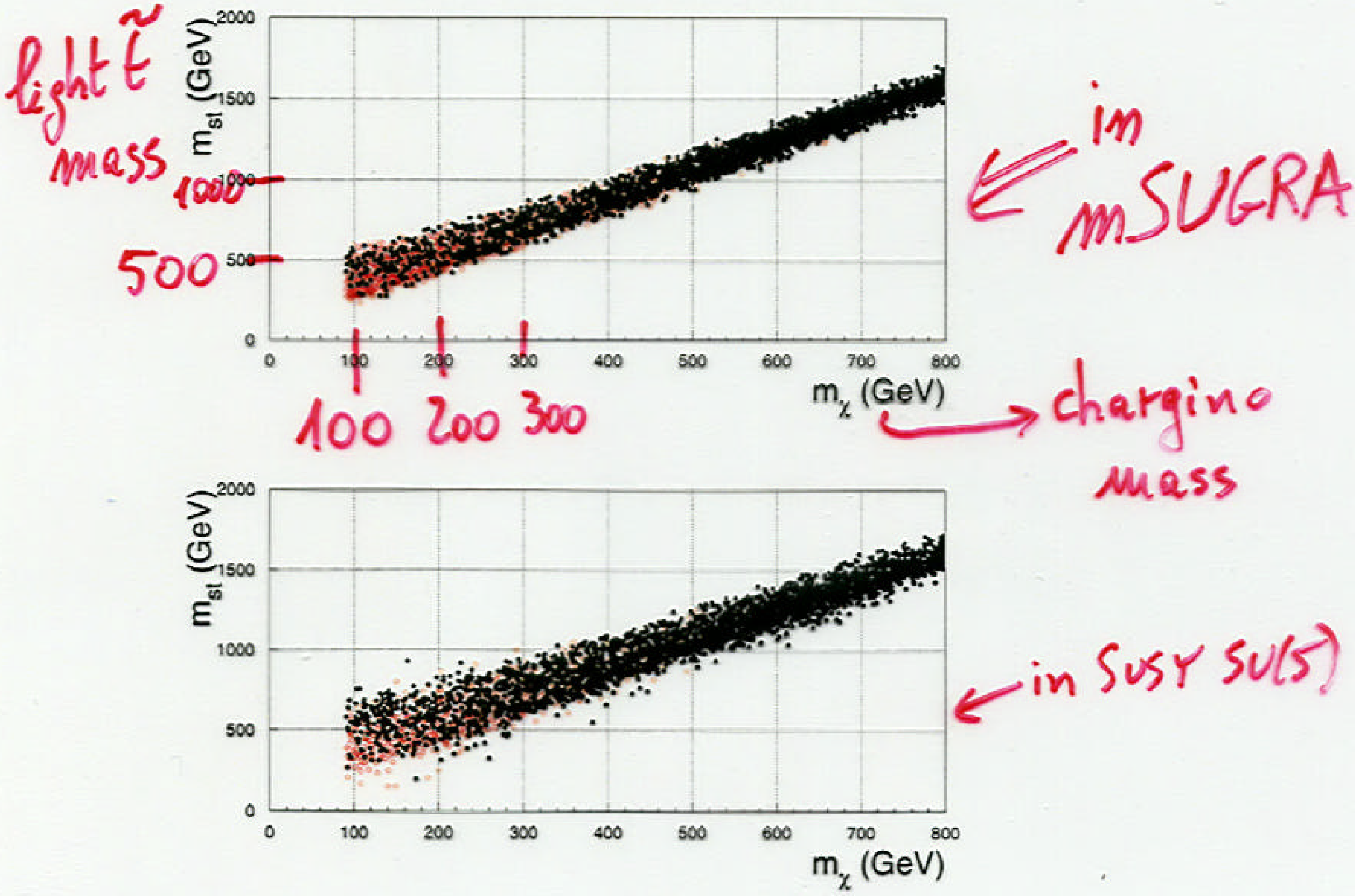


Figure 1: Chargino mass versus lightest stop mass as for the parameter space described in the text in the CMSSM and SU(5) cases.

Bartl et al

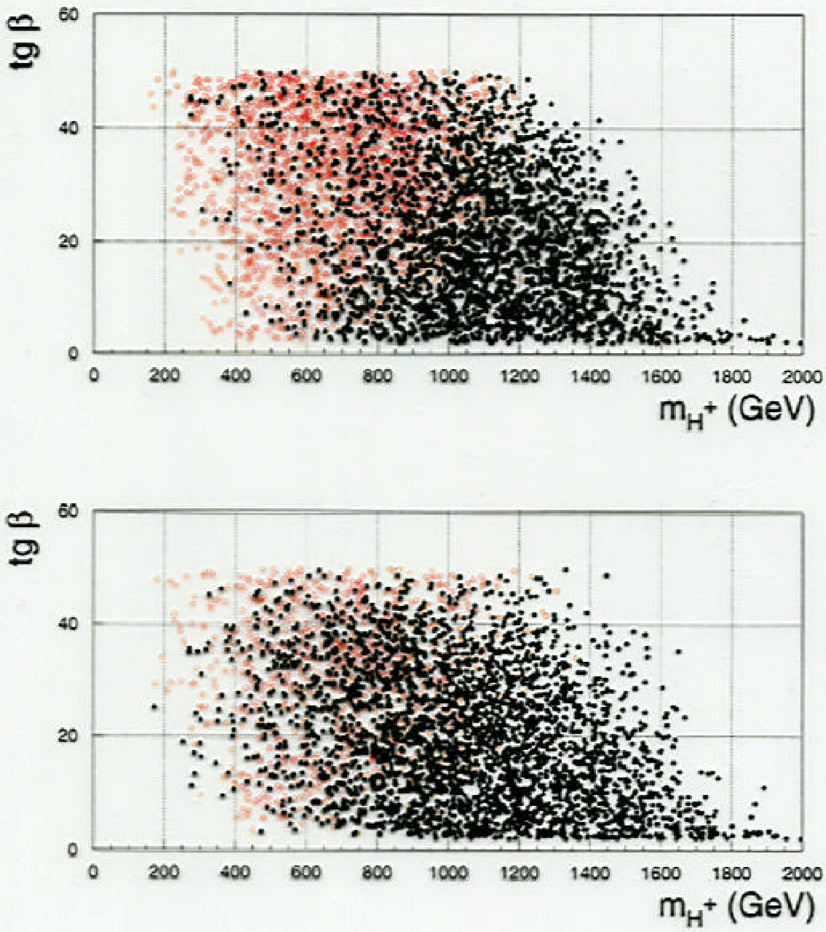


Figure 2: Charged Higgs mass as a function of $\tan\beta$ for the parameter space described in the text in the CMSSM and SU(5) cases.

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

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

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

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

$\Delta^{SUSY} > 0 \Rightarrow$ 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 :

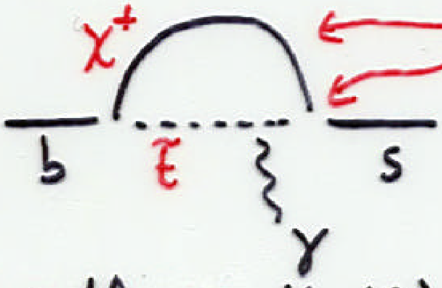
- $B_s - \bar{B}_{\bar{s}}$ mixing $\Delta m_{B_s} \simeq (28 \pm 5) \dfrac{\Delta m_{B_d}}{[(1-\rho)^2 + \eta^2]}$

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)
⇒ $A_{CP}^{b\to s\gamma}$ 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 contribution

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

$(A_u e^{i\varphi_{A_u}}, \; A_D e^{i\varphi_{A_D}}, \; A_E e^{i\varphi_{A_E}},$

$m_{\tilde{g}} e^{i\varphi_3}, \; m_{\tilde{W}} e^{i\varphi_2}, \; m_{\tilde{B}} e^{i\varphi_1}, \; \mu = |\mu| e^{i\varphi_\mu})$

BUT NO NEW FLAVOR

DEMIR, A.M., VIVES STRUCTURE in addition

to the usual Yukawa matrices

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, Hando
London

if some new flavor structure is present (even if phase, flavor ind

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

IF SUSY BREAKING IS NOT FLAVOR BLIND

HOW SEVERE ARE THE CONSTRAINTS ON THE NEW FLAVOR and CP≠ SUSY STRUCTURE ?

- constraint on the underlying theory (bottom-up approach)
- hints for flavor symmetries

HOW LARGE CAN THE SUSY CONTRIBUTIONS TO FCNC and CP≠ BE ?

what is the "maximal hope" we have to observe deviations from the SM predictions in FCNC and CP≠ phenomena

WHAT CAN WE "REASONABLY" EXPECT TO SEE IN FCNC and CP≠ as SUSY deviations from SM

i.e. taking SUSY models with new flavor structures which do not "violently" deviate from the SM flavor pattern