B Physics at Hadron Colliders

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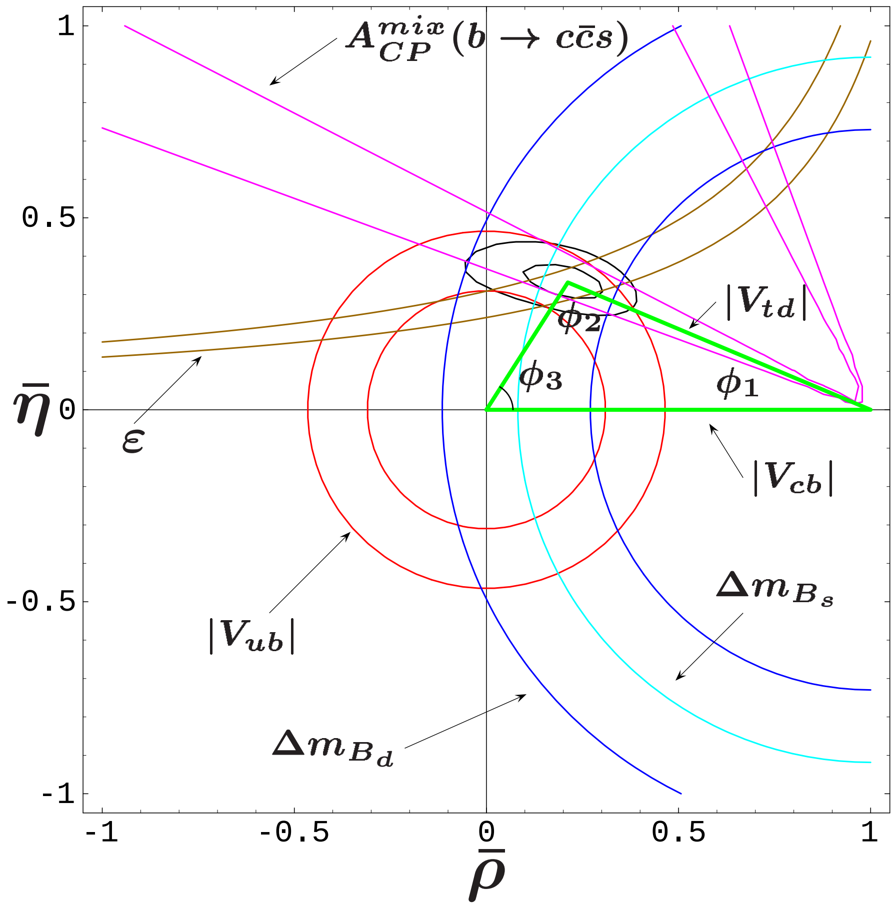
1. Introduction



- CPV in $K \longrightarrow \pi\pi$
  ε parameter
- $b \longrightarrow c, u$ transition
  $|V_{cb}|$, $|V_{ub}|$
- B_d–$\bar{B}_d$ mixing (Δm_{B_d})
  $|V_{td}|$
- B_s–$\bar{B}_s$ mixing (Δm_{B_s})
  $|V_{td}|$ (upper bound)
- CPA in $B_d \longrightarrow \psi K_s, \cdots$
  $(A_{CP}^{mix}(b \longrightarrow c\bar{c}s))$
  $\sin 2\phi_1$

The unitarity triangle looks closed.
But, this is not the whole story. We want to go further.
$\Rightarrow$ Precision test of the standard model
$\Rightarrow$ New physics search

Supersymmetry

The most attractive candidate of new physics

- Hierarchy problem: Why $M_{\text{weak}} \ll M_{\text{GUT}}$?
  SUSY protects this hierarchy against radiative corrections
  For this mechanism to work, $M_{\text{SUSY}} \sim M_{\text{weak}}$
- SUSY must be broken.
  No degenerate SUSY pair of a fermion and a boson.
- SUSY breaking must be soft.
  Cancellation of the second order divergence is required.
  Allowed soft breakings: gaugino masses, scalar masses, trilinear scalar couplings, etc.
  $\Rightarrow$ New sources of flavor and CP violation

B experiments will unveil these new flavor and CP violation.

PLAN

1. Introduction
2. Hadron colliders and e^+e^- colliders
3. SUSY effects in $b \longrightarrow s$ transitions
4. Summary

2. Hadron colliders and e^+e^- colliders

	hadron				e^+e^-		
	Tevatron ($p\bar{p}$)		LHC (pp)		KEKB PEP II	Super KEKB Super PEP II	LC
	CDF D0	BTeV	ATLAS CMS	LHCb	Belle Babar	Super Belle Super Babar	GigaZ
$\sqrt{s}$	2 TeV		14 TeV		10.6 GeV		91.2 GeV
L	$2 \cdot 10^{32}$		10^{33-34}	$2 \cdot 10^{32}$	10^{34}	10^{35-36}	10^{34}
$\sigma_{b\bar{b}}$	0.1 mb		0.5 mb		1.1 nb		6.6 nb
σ_{total}	75 mb		100 mb				
pileup	1.6		2–20	0.53			
	B_s				two missings ($\nu\bar{\nu}$)		Λ_b polarization

Physics reach: CKM

CKM Reach
super B factories & hadron facilities

	BTeV 10^7 s	LHC-b 10^7 s	BABAR BELLE (2005)	10^{35} 10^7 s	10^{36} 10^7 s	
sin2β	0.011	0.02	0.037	0.026	0.008	Equal
Sin2"α"	0.05	0.05	0.14	0.1	0.032	Equal
γ $B_s(D_sK)$	~7^0					Had
γ B(DK)	~2^o		~20^0		1-2.5^o	Equal
Sin2χ	0.023	0.04	--	--	--	Had
Br($B \rightarrow \pi^0 \pi^0$)	--	--	~20%	14%	6%	e+e-
Vub	--	--	~2.3%	~1% (sys)	~1% (sys)	e+e-

SBF numbers based on BABAR experience need simulations to estimate signal efficiencies & bkgds so that the comparison to BTeV/LHC-b is on an equal footing

Burdman/Butler/Shipsey/Yamamoto (Table compiled by SBF E2 subgroup & E2 convenors) 45

$$\text{Belle } \sin 2\phi_1 = 0.719 \pm 0.074 \pm 0.035$$

$$\text{BaBar } \sin 2\beta = 0.741 \pm 0.067 \pm 0.033$$

Physics reach: rare decays

Rare B decay Reach
super B fac. & hadron facilities

All numbers are per year except current B factories (cumulative Through 2005)

Best measurement ●

Greater reach?
Hadronic: B→μμ
e+e-: sνν, τυ, γγ,K*γ

Including additional rare Λb and Bs modes not in Table
10^{35} reach < BTeV/LHCb
10^{36} reach ~ BTeV/LHCb

(Table compiled by SBF E2 subgroup & E2 convenors)
Burdman/Butler/Shipsey/Yamamoto

Decay Mode (Br. Ratio)	HADRONIC EXP. CDF /D0 (2 fb^{-1})	BTeV /LHC-b (10^7 s)	ATLAS /CMS (1 Year)	B-FACTORY BABAR /BELLE (0.5 ab^{-1})	10^{35} (1 ab^{-1})	10^{36} (10 ab^{-1})
$B \to X_s\gamma$ $(3.29 \pm .21 \pm .21) \times 10^{-4}$				11K	22K ●	220K ●
With B Tags				1.7K	3.4K	34K
$B \to K^*\gamma$ $(3-8) \times 10^{-5}$	170/–	27K/24K		6K	12K	120K ●
$\delta(A_{CP})$		0.01		0.02	0.01	< 0.01
$B \to X_s\nu\bar{\nu}$ $(4.1 \pm 0.9) \times 10^{-5}$				8	16	160 ●
$B \to K^*\nu\bar{\nu}$ (5×10^{-6})				1.5	3	30
$B \to X_s\mu^+\mu^-$ $(6.0 \pm 1.5) \times 10^{-6}$		7.2K/- ●		300	600	6K ●
$B \to X_s e^+e^-$				350	700	7K
$B \to K^*\mu^+\mu^-$ $(2 \pm 1) \times 10^{-6}$	61/60-150	4.4 k /4.5k ●	665/4.2K ●	120	240	2.4K ●
$B \to K^*e^+e^-$				150	300	3K
$B_d^0 \to \tau^+\tau^-$ (10^{-7})				$< 10^{-5}$	$< 5 \times 10^{-6}$ ●	$< 10^{-6}$ ●
$B^0 \to \mu^+\mu^-$ $B_s(10^{-9})$	5/1.5-6	10/11 ●	9/7 ●			
$B_d(8 \times 10^{-11})$	0/0	2/2	0.7/20	$< 10^{-8}$	$< 5 \times 10^{-9}$	$< 10^{-9}$
$B_d^0 \to e^+e^-$ (10^{-14})				$< 10^{-8}$	$< 5 \times 10^{-9}$ ●	$< 10^{-9}$ ●
$B \to \tau\nu$ (5×10^{-5})				17	34	350 ●
$B \to \mu\nu$ (1.6×10^{-7})				8	16	150 ●
$B^0 \to \gamma\gamma$ (10^{-8})				0.4	0.8	8 ●

3. SUSY effects in $b \longrightarrow s$ transitions

The large 2–3 mixing in the ν oscillation

- $B \longrightarrow X_s\gamma$, $B \longrightarrow K^*\gamma$
- $B \longrightarrow X_s l^+ l^-$, $B \longrightarrow K^{(*)} l^+ l^-$
- $B \longrightarrow X_s \nu\bar{\nu}$, $B \longrightarrow K^{(*)} \nu\bar{\nu}$
- $B \longrightarrow \phi K_S$
- $B \longrightarrow \eta' K_S$
- $B \longrightarrow K\pi$
- B_s mixing (Δm_{B_s}, $\Delta\Gamma_{B_s}$)
- $B_s \longrightarrow \mu^+\mu^-$

  etc.

Soft SUSY breakings

Scalar masses, scalar trilinear couplings
$\Rightarrow$ New sources of flavor and CP violation

- Squark mass matrix (6×6)

$$\tilde{M}_q^2 = \begin{pmatrix} \tilde{M}^2_{q,LL} & \tilde{M}^2_{q,LR} \\ \tilde{M}^{2\dagger}_{q,LR} & \tilde{M}^2_{q,RR} \end{pmatrix}, \quad (q = u, d)$$

- Quark mass matrix (3×3)

$$V_L^q M_q V_R^{q\dagger} = \hat{M}_q \text{ (diagonal)}$$

FV is caused by off-diagonal

$$(\delta^q_{MN})_{ij} \equiv \frac{(V_M^q \tilde{M}^2_{q,MN} V_N^{q\dagger})_{ij}}{\tilde{m}^2}$$

Typical constraints

Nir and Seiberg, hep-ph/9304307

- K–$\bar{K}$ mixing
  $\sqrt{(\delta^d_{LL})_{12}(\delta^d_{RR})_{12}} < 0.006,\ (\delta^d_{MM})_{12} < 0.05$
  $\sqrt{(\delta^u_{LL})_{12}(\delta^u_{RR})_{12}} < 0.04,\ (\delta^u_{MM})_{12} < 0.1$
- B–$\bar{B}$ mixing
  $\sqrt{(\delta^d_{LL})_{13}(\delta^d_{RR})_{13}} < 0.04,\ (\delta^d_{MM})_{13} < 0.1$
- $b \longrightarrow s\gamma$
  $(\delta^d_{LR})_{23} < 0.03\ (\tilde{m} \sim 400\mathrm{GeV})$ Kane et al., hep-ph/0212092

$\Rightarrow (\delta^q_{MN})_{ij} < 0.01 \sim 0.1\ \ (\tilde{m} \sim 1\mathrm{TeV})$
We need some mechanism to suppress δ's.

Note: no constraint on $(\delta^d_{LL,RR})_{23}$

Possible mechanisms

Several ideas in the market

- Universal soft breakings
  Gravity mediation of SUSY breaking (SUGRA),
  Gauge mediation
  Phenomenology depends on the scale of SUSY breaking and extra interaction below it (GUT, ν Yukawa).
- Flavor symmetry
  Must explain the fermion masses and mixings.
  Depends on the breaking sector.
- Alignment
- Effective SUSY

$\boxed{\text{SUSY breaking mechanism} \Longleftrightarrow \delta' s \Longleftrightarrow \text{B physics}}$

B_s–$\bar{B}_s$ mixing: $|V_{td}|$

$\Delta m_{B_s} = 2|M_{12}(B_s)|$: box diagram

- Hadronic uncertainty

  $f_{B_s}\sqrt{B_{B_s}} = 276 \pm 38\,\mathrm{MeV}$ (lattice)

  Taking a ratio $\Delta m_{B_s}/\Delta m_{B_d}$ reduces the hadronic uncertainty.$\Leftarrow$ SU(3) symmetry.

  $f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}} = 1.18 \pm 0.04^{+0.12}_{-0}$ (lattice)

  But, the SU(3) breaking may be larger.

- Possible new physics contribution

  $$M_{12}(B_s) = M_{12}(B_s)|_{\mathrm{SM}} + M_{12}(B_s)|_{\mathrm{NP}}$$

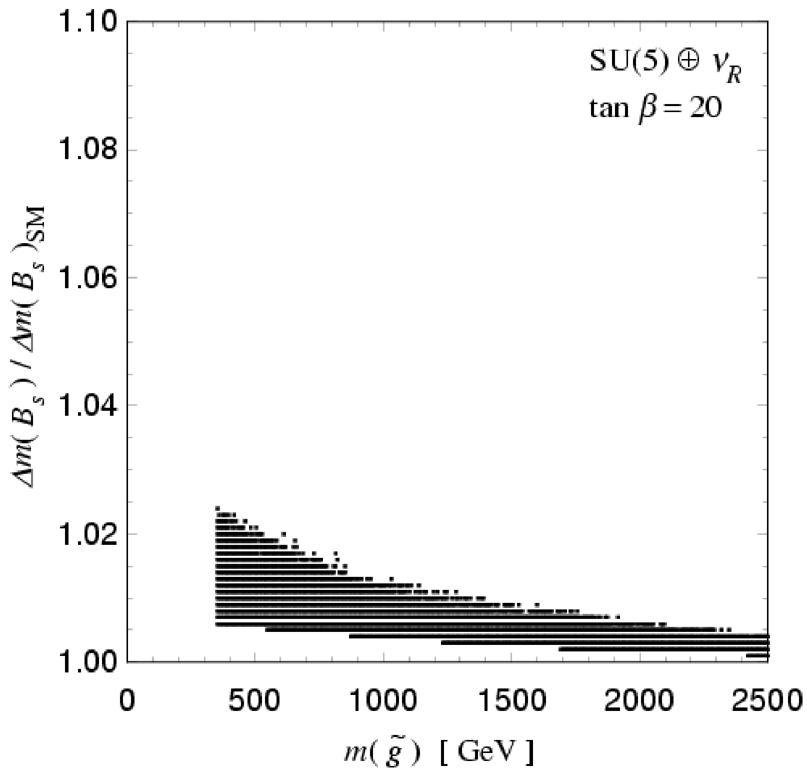
  The effect might be large.
  cf. large 2–3 mixing in the ν sector

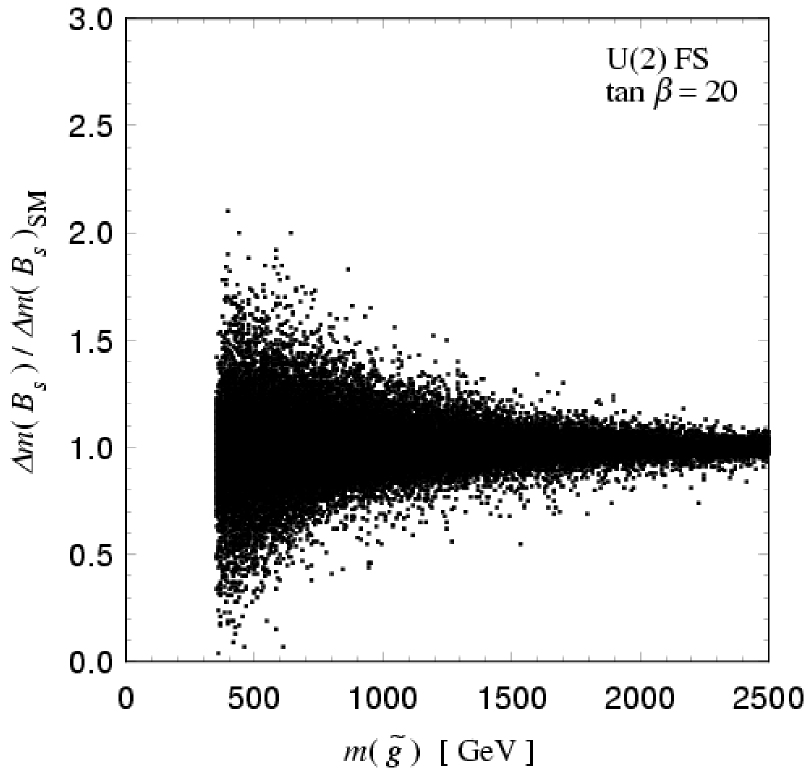
Δm_{B_s}

- Experiment
  $\Delta m_{B_s} > 14.9\,\mathrm{ps}^{-1}$ (95% CL)
  cf. $\Delta m_{B_d} = 0.489 \pm 0.008\,\mathrm{ps}^{-1}$
- SM prediction
  $\Delta m_{B_s} = 17.3^{+1.5}_{-0.7}\,\mathrm{ps}^{-1}$
- SUSY contribution
  Could be large.
  $(\delta^q_{LL}) \sim 0.5 \Rightarrow \Delta m_{B_s} \sim 30\,\mathrm{ps}^{-1}$
- Experimental reach
  CDF $38 \sim 48\,\mathrm{ps}^{-1}$, BTeV $\sim 49\,\mathrm{ps}^{-1}$
  ATLAS $30\,\mathrm{ps}^{-1}$, CMS $26\,\mathrm{ps}^{-1}$, LHCb $48\,\mathrm{ps}^{-1}$

$\mathit{SUSY\ effect\ in}\ \Delta m_{B_s}$

mSUGAR $\sim O(0.01)$, SU(5) $\sim O(0.01)$, U(2) $\sim O(1)$



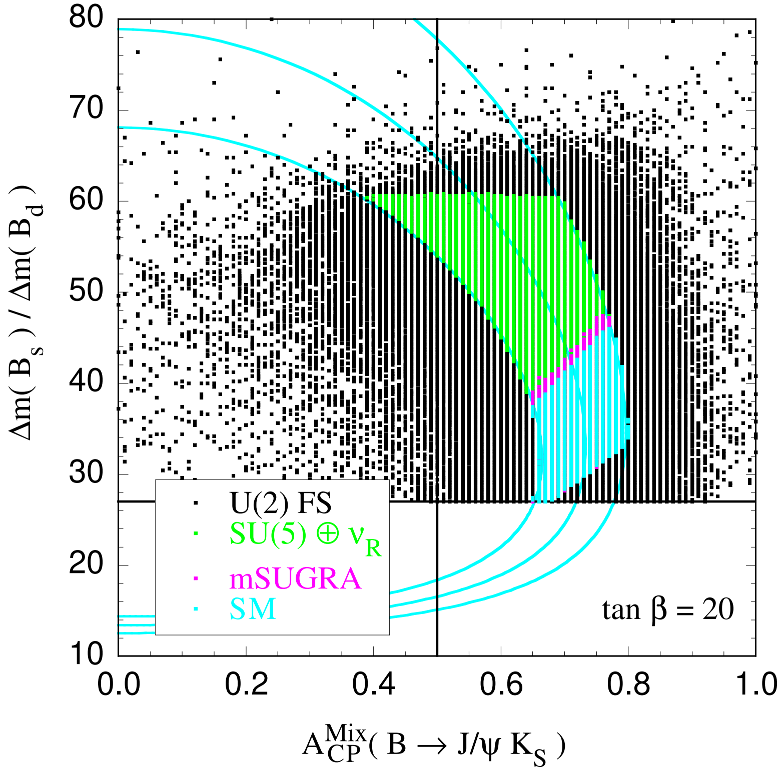


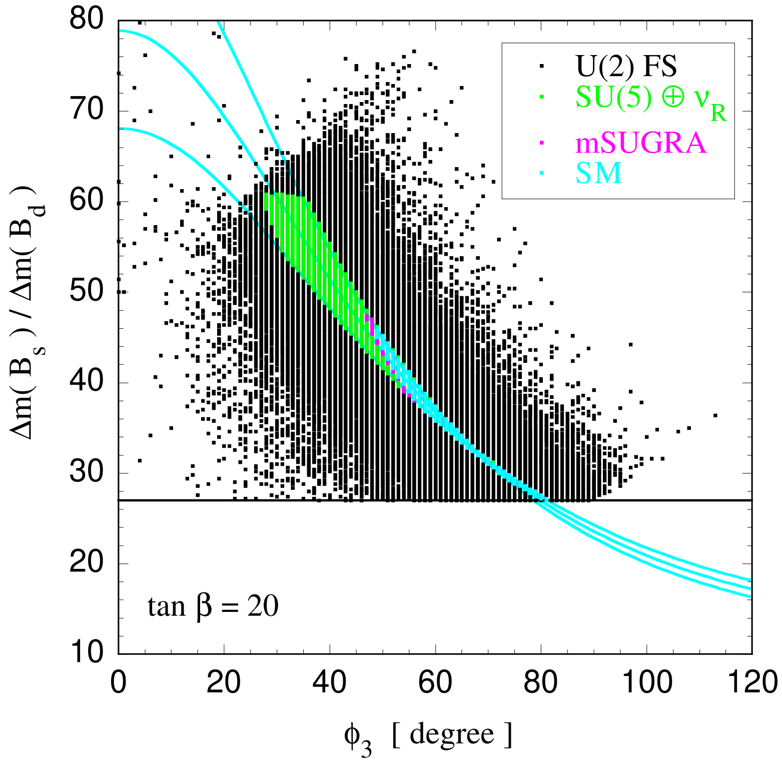
T. Goto, Y. Okada, Y. Shimizu, T. Shindou, M.T.

Phys. Rev. D 66, 035009 (2002)

Correlations

$\Delta m_{B_s}/\Delta m_{B_d}$, $A^{\rm mix}_{\rm CP}(B \to \psi K_S)$, and ϕ_3





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SUSY effect in Δm_{B_s} (cont'd)

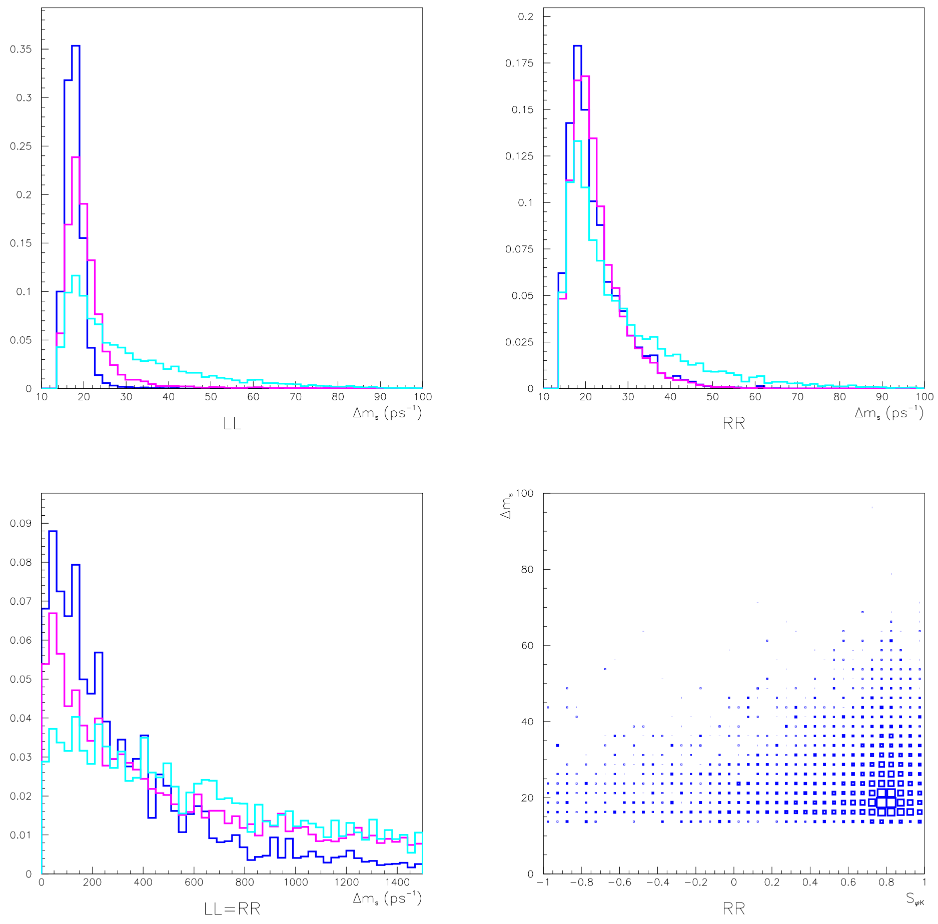

Figure 8: Distributions of ΔM_s for various SUSY mass insertions $(\delta^d_{23})_{AB}$ with $AB = (LL, RR, LLRR)$. Different curves correspond to the inclusion of constraints from $B \to X_s\gamma$ only (magenta), $B \to X_s l^+ l^-$ only (cyan) and all together (blue). Lower right: correlation between ΔM_s and $S_{\phi K}$ in the RR case.

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Δm_{B_s}

$B \to \phi K_S$ implied.

Ciuchini et al.
hep-ph/0212397

$B_s \to l^+l^- \ (b \to sl^+l^-)$

- Experiment
  $\mathrm{BR}(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6}$ (CDF, 95% CL)
- SM prediction
  $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.1 \pm 1.4) \times 10^{-9}$
- Experimental reach
  CDF $\sim 1 \times 10^{-8}$
  ATLAS, CMS (3yrs) $\sim$ SM
  LHCb (1yr) $\sim$ SM

$B_S \to l^+ l^-$ (cont'd)

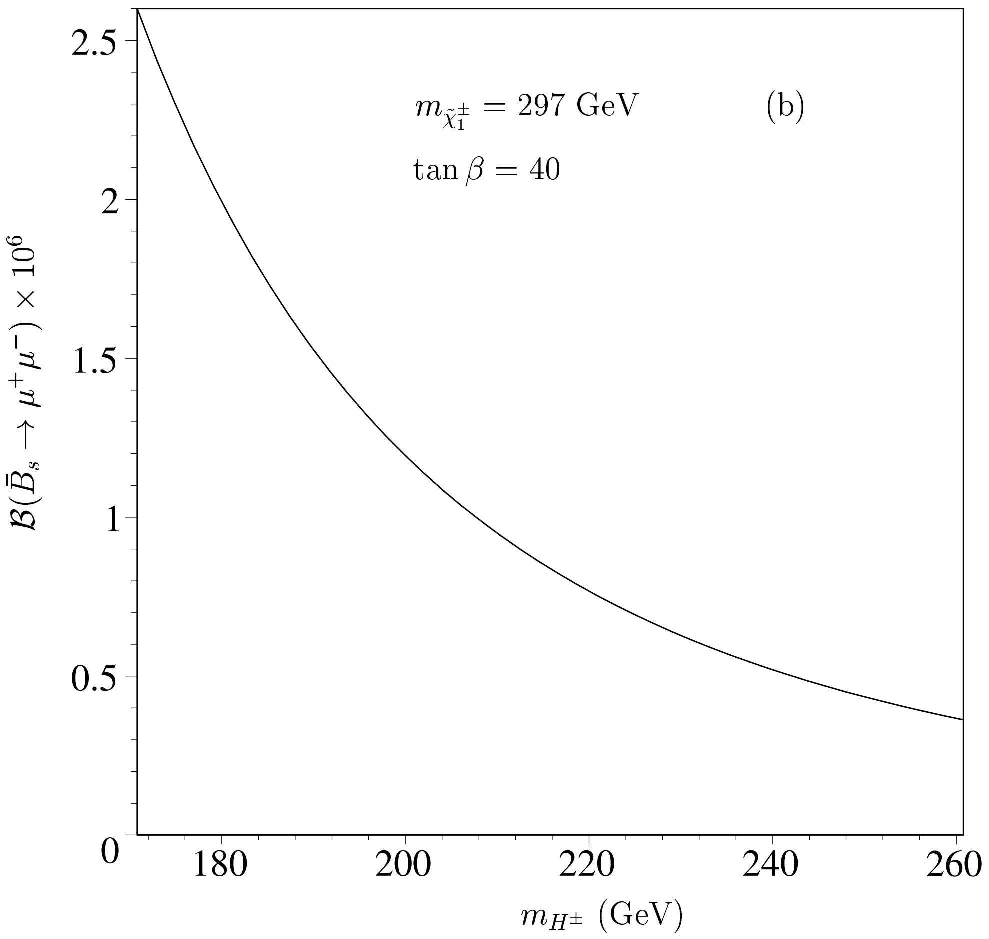
- SUSY contribution
  FCNC via neutral Higgs (h, H and A) exchange

  Huang and Yan, PLB442 209(1998); Huang, Liao and Yan, PRD59 011701(1998); Yan et al., PRD62 094023(2000); Huang et al., PRD63 114021(2001), PRD64 059902(E) (2001); Choudhury and Gaur, PLB451 86 (1999); Babu and Kolda, PRL84(2000); Chankowski and Sławaianowska, PRD63 054012 (2001); Dedes, Dreiner and Nierste, PRL87 251804 (2001); Dedes and Pilaftsis, PRD67 015012 (2003); Bobeth et al., PRD64 074014 (2001), PRD66 074021 (2002); Mizukoshi, Tata and Wang, PRD66 115003 (2002).

$$A(B_s \to \mu^+ \mu^-) \sim \tan^3 \beta \quad \text{as } \tan \beta (= \frac{v_u}{v_d}) \to \infty$$

Does not decouple as $M_{\mathrm{SUSY}} \to \infty$.
Decouples as $m_A \to \infty$.

$B_S \longrightarrow l^+l^-$ (cont'd)



MFV
$m_{\tilde{t}_1} = 120\mathrm{GeV}$
$\theta_{\tilde{t}} \approx -45°$

Bobeth et al.
PRD64 074014
(2001)

4. Summary

- $\boldsymbol{B_s}$ physics is one of the advantages of hadron B experiments.
  $\boldsymbol{B_s}$ mixing measurement by CDF is important.
- Modes with two (or more) missing and modes without charged tracks are difficult for hadron B experiments.
- A dedicated hadron B experiment $\sim$ A $\mathbf{10^{36}}$ B factory
- SUSY effects could be found in the $\boldsymbol{b \longrightarrow s}$ transitions.
- There are lots of other interesting modes,
  $\boldsymbol{B_s \longrightarrow J/\psi\phi}$, $\boldsymbol{B_d \longrightarrow \rho\pi}$, $\boldsymbol{B \longrightarrow DD}$, $\boldsymbol{B \longrightarrow D^{(*)}\pi}$, etc.