Physics with 10^9 and More B Mesons

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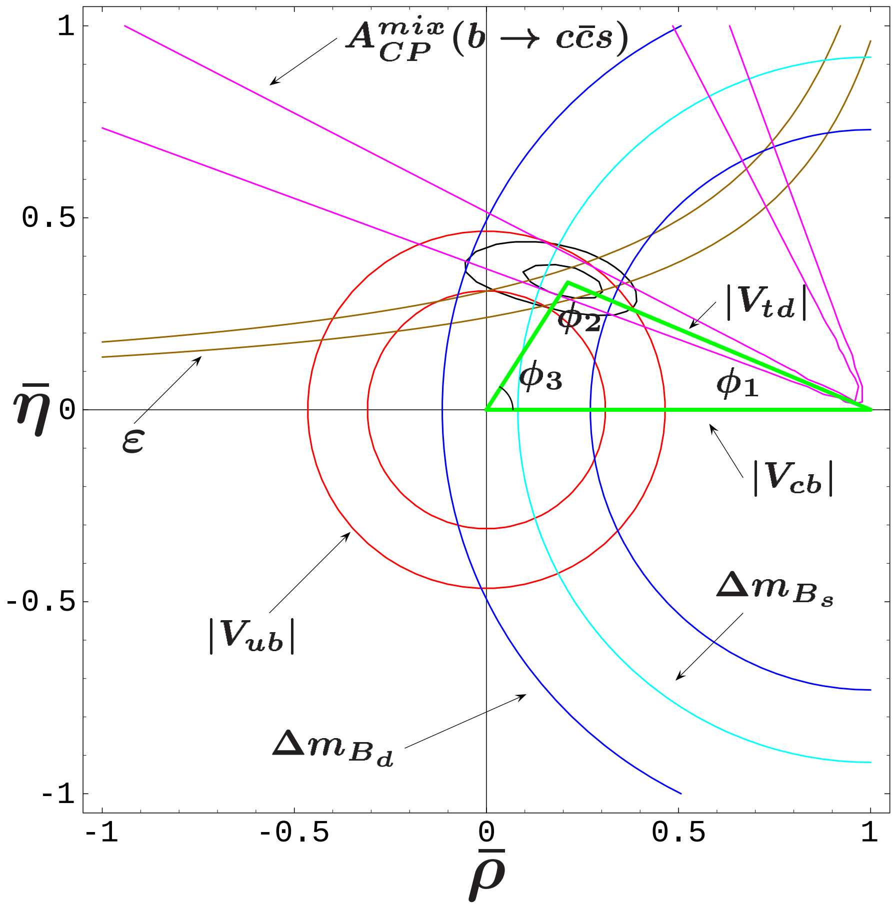
1. Introduction



- 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 $B_d \longrightarrow \psi K_s, \cdots$
  ($A^{mix}_{CP}(b \longrightarrow c\bar{c}s)$)
  $\sin 2\phi_1$

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

Super B factory will unveil these new flavor and CP violation.

Super B factory

KEK

$L \sim 10^{35}\, cm^{-2} s^{-1}$, $1\, ab^{-1}/yr$, $10^9\, B\bar{B}$ pairs$/yr$

SLAC

$L \sim 10^{36}\, cm^{-2} s^{-1}$

PLAN

1. Introduction
2. Flavor structure of soft SUSY breakings
3. SUSY effects in $\boldsymbol{b \longrightarrow s}$ transitions
4. $\boldsymbol{\bar{B} \longrightarrow D\tau\bar{\nu}}$
5. Summary and discussion

2. 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

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

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

The large 2–3 mixing in the ν oscillation

- $B \longrightarrow X_s \gamma$
- $B \longrightarrow X_s l^+ l^-$
- $B \longrightarrow X_s \nu \bar{\nu}$
- $B \longrightarrow \phi K_S$
- $B \longrightarrow \eta' K_S$
- $B \longrightarrow K \pi$
- Δm_{B_s}

  etc.

$B \to \phi K_S$ $(b \to s\bar{s}s)$

- Experiment
  $\mathrm{BR} = (8.4^{+2.5}_{-2.1}) \times 10^{-6}$ (BaBar + Belle)
  $S_{\phi K_S} = -0.39 \pm 0.41$ (BaBar + Belle)
  $-A_{\phi K_s} = C_{\phi K_S} = 0.56 \pm 0.41 \pm 0.12$ (Belle)
- SM prediction
  $\mathrm{BR} \sim 5 \times 10^{-6}$
  $S_{\phi K_S} = S_{\psi K_S} = 0.734 \pm 0.054$ (theoretically clean)
  $C_{\phi K_S} \sim -0.008$
- SUSY contribution to explain $S_{\phi K_s}$
  larger hadronic uncertainty
  $|\mathrm{Im}(\delta^d_{LR})_{23}| \sim 2 \times 10^{-3}$ ($m_{\tilde{g}}/m_b$ enhancement)
  $|\mathrm{Im}(\delta^d_{RL})_{23}| \sim 2 \times 10^{-3}$ ($m_{\tilde{g}}/m_b$ enhancement)
  $|\mathrm{Im}(\delta^d_{LL})_{23}| \sim 0.4$ (controversial)
  $|\mathrm{Im}(\delta^d_{RR})_{23}| \sim 0.4$ (controversial)
  $\Rightarrow$ Correlation with other observables

$B \to \phi K_S$ (cont'd)

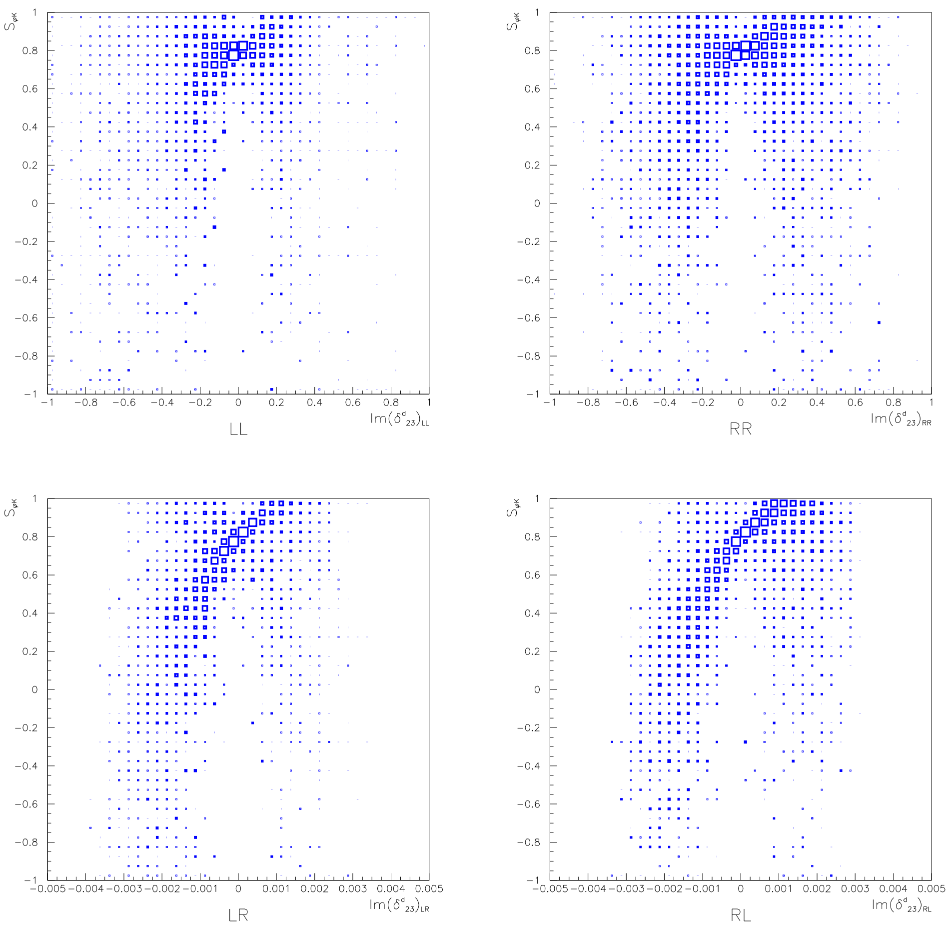


Figure 5: Correlations between $S_{\phi K}$ and $\mathrm{Im}(\delta_{23}^d)_{AB}$ for $m_{\tilde{q}} = m_{\tilde{g}} = 350$ GeV and $AB = (LL, RR, LR, RL)$. Constraints from $BR(B \to X_s\gamma)$, $A_{CP}(B \to X_s\gamma)$, $BR(B \to X_s l^+ l^-)$ and the lower bound on ΔM_s have been used.

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$S_{\phi K_S}$

Ciuchini et al
hep-ph/0212397

$B \to X_s\gamma$

- Experiment
  $\mathrm{BR} = (3.29 \pm 0.34) \times 10^{-4}$, $A_{CP} = -0.02 \pm 0.04$
- SM prediction
  $\mathrm{BR} = (3.60 \pm 0.30) \times 10^{-4}$
  $|A_{CP}| \lesssim 0.5\%$, $|A_{CP}^{\mathrm{mix}}| \sim 1\%$
- SUSY contribution
  - ⋆ $|(\delta^d_{LR})_{23}| \sim 0.002$, $b_R \to s_L$ as the SM
    $\Rightarrow$ Interference with the SM part, $|A_{CP}| \lesssim 15\%$
  - ⋆ $|(\delta^d_{RL})_{23}| \sim 0.002$, $b_L \to s_R$
    $\Rightarrow |A_{CP}^{\mathrm{mix}}| \sim O(0.1)$ or larger?
  - ⋆ $|(\delta^d_{LL})_{23}| \sim 0.4$, $b_R \to s_L$ as the SM
    $\Rightarrow |A_{CP}| \lesssim 15\%$
  - ⋆ $|(\delta^d_{RR})_{23}| \sim 0.4$, $b_L \to s_R$
    $\Rightarrow |A_{CP}^{\mathrm{mix}}| \sim O(0.1)$ or larger?

$B \to \phi K_S$ and $B \to X_s\gamma$

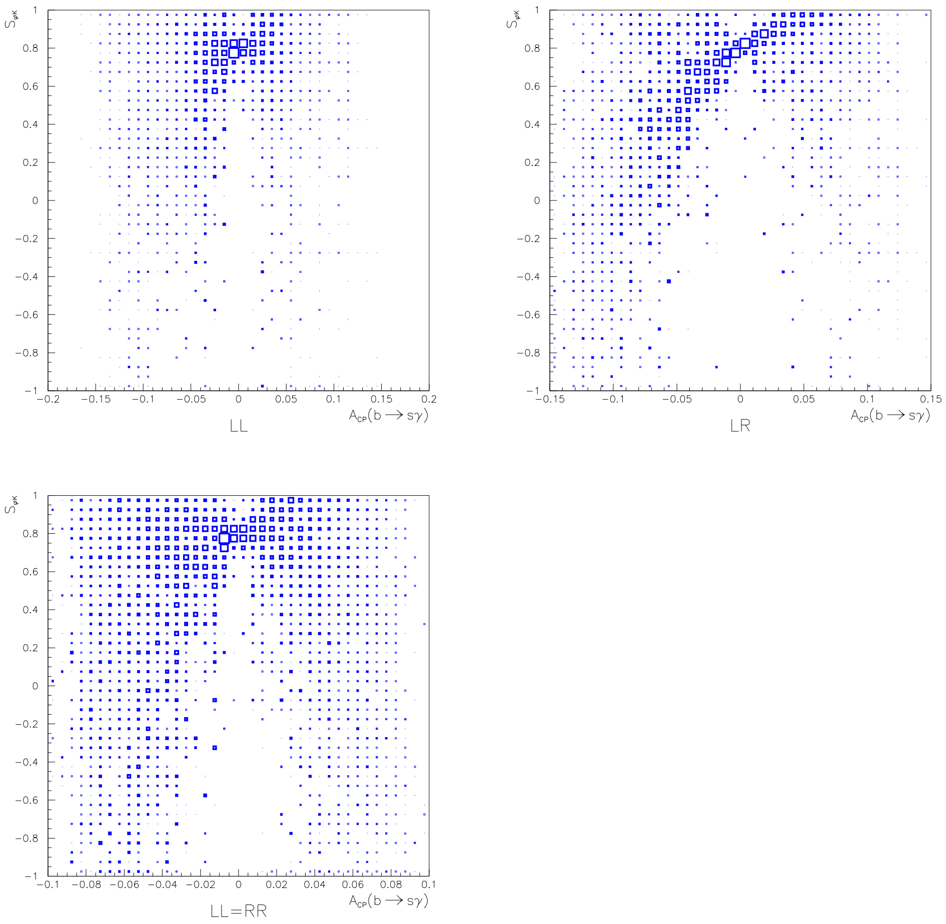

Figure 7: Correlation between $S_{\phi K}$ and $A_{CP}(b \to s\gamma)$ for various SUSY mass insertions $(\delta^d_{23})_{AB}$ with $AB = (LL, LR, LLRR)$. Constraints from $BR(B \to X_s\gamma)$, $A_{CP}(B \to X_s\gamma)$, $BR(B \to X_s l^+ l^-)$ and the lower bound on ΔM_s have been used.

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$A_{\mathrm{CP}}(b \to s\gamma)$–$S_{\phi K_S}$

Ciuchini et al
hep-ph/0212397

$B \to \eta^{(\prime)} K_S, K\pi, \ldots$ $(b \to s\bar{q}q)$

- Experiment
  $S_{\eta' K_S} = 0.73 \pm 0.36^{+0.05}_{0.06} (\simeq S_{\psi K_S})$ (Belle)
  $A_{\eta' K_S} = 0.26 \pm 0.22 \pm 0.03$ (Belle)
- SUSY contribution
  Similar as ϕK_S at the quark level, but different parity
  $\mathcal{P}(\bar{B}^0) = -1, \mathcal{P}(VP) = -1, \mathcal{P}(PP) = +1$

  $\langle VP|\mathcal{O}_+|\bar{B}^0\rangle$, $\mathcal{O}_+ = (\bar{s}s)_V(\bar{s}b)_V, (\bar{s}s)_A(\bar{s}b)_A$
  $\langle PP|\mathcal{O}_-|\bar{B}^0\rangle$, $\mathcal{O}_- = (\bar{s}s)_A(\bar{s}b)_V, (\bar{s}s)_V(\bar{s}b)_A$

  $VV(AA) \propto RR + LL \pm (LR + RL) \propto$
  $(\delta^d_{RR})_{23} + (\delta^d_{LL})_{23}$
  $VA(AV) \propto RR - LL \pm (LR - RL) \propto$
  $(\delta^d_{RR})_{23} - (\delta^d_{LL})_{23}$

  $\Rightarrow$ SUSY contributions to VP and PP are different.

Δm_{B_s}

- Experiment
  $\Delta m_{B_s} > 14.4\,\mathrm{ps}^{-1}$ (95% CL)
- SM prediction
  $\Delta m_{B_s} = 17.3^{+1.5}_{-0.7}\,\mathrm{ps}^{-1}$
- SUSY contribution
  Could be larger (beyond Tevatron reach $\sim 41\,\mathrm{ps}^{-1}$)
  $(\delta^q_{LL}) \sim 0.5 \Rightarrow \Delta m_{B_s} \sim 30\,\mathrm{ps}^{-1}$

Δm_{B_s} (cont'd)

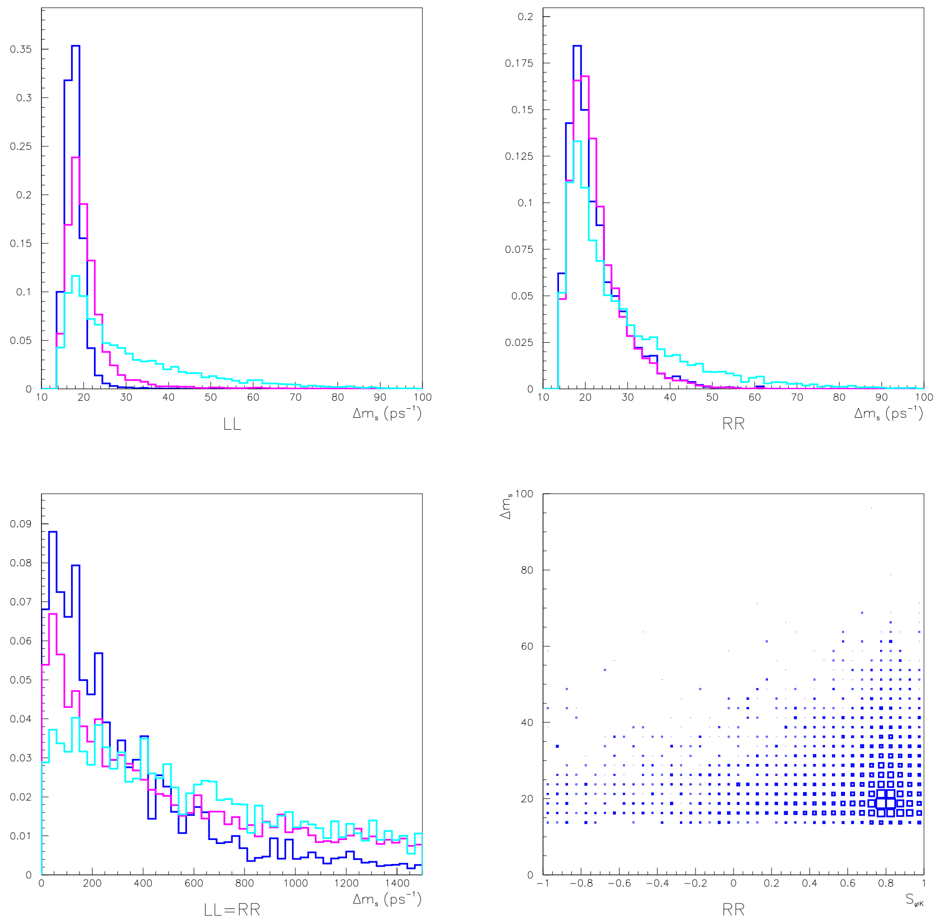

Figure 8: Distributions of ΔM_s for various SUSY mass insertions $(\delta^d_{23})_{AB}$ with $AB = (LL, RR, LLRR)$. Different curves correspond to the inclusion of constraints from $B \to X_s\gamma$ only (magenta), $B \to X_s l^+ l^-$ only (cyan) and all together (blue). Lower right: correlation between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

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Δm_{B_s}

Ciuchini et al
hep-ph/0212397

$B \to X_s l^+ l^-$ $(b \to s l^+ l^-)$

- Experiment
  $\mathrm{BR} = (6.1 \pm 1.4^{+1.3}_{-1.1}) \times 10^{-6}$ (Belle)
- SM prediction Ali et al., PRD66,034002, 2002
  $\mathrm{BR}(e^+e^-) = (6.89 \pm 1.01) \times 10^{-6}$
  $\mathrm{BR}(\mu^+\mu^-) = (4.15 \pm 0.70) \times 10^{-6}$
  $A_{\mathrm{FB}} \simeq 23\%,\ A'_{\mathrm{FB}}(\mu) \simeq 11\%$
- SUSY contribution
  $(\delta^q_{LL})_{23}, (\delta^q_{LR})_{23}$ are most relevant.

$B \to X_s l^+ l^-$ *FB asymmetry*

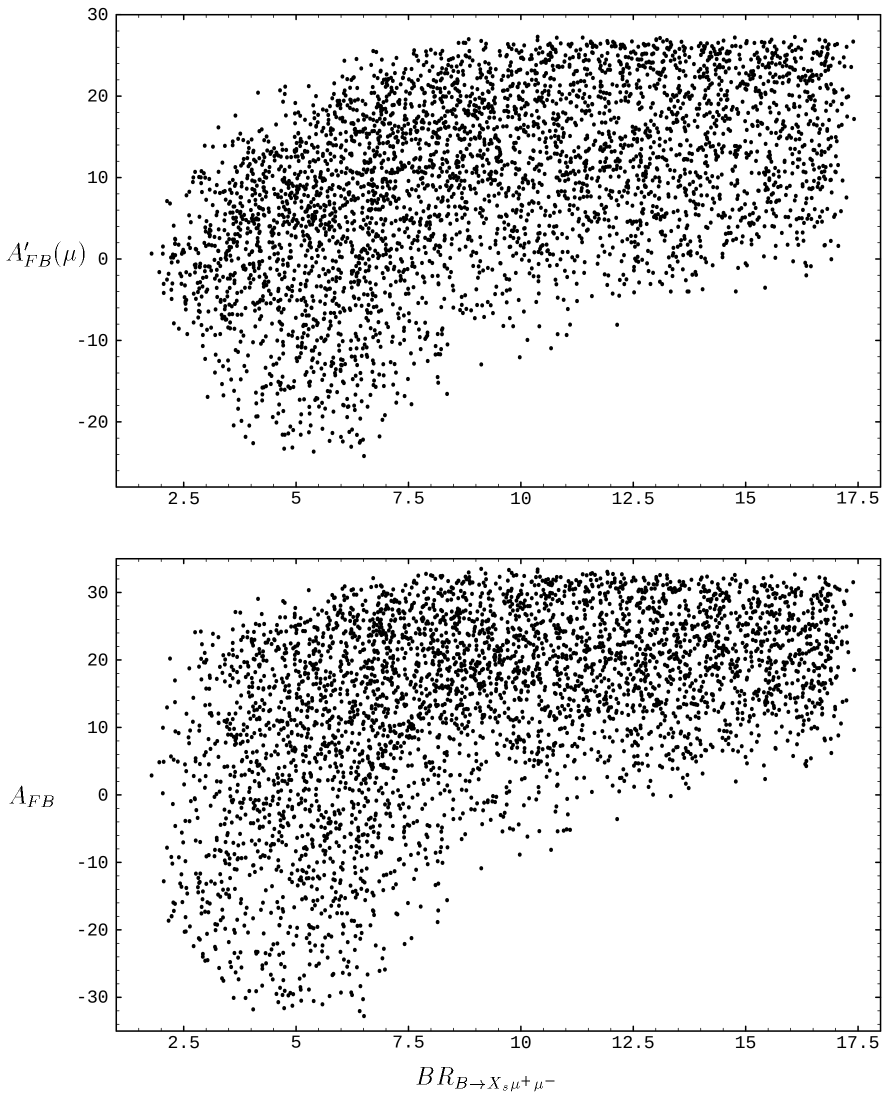

Figure 1: Inclusive decay $B \to X_s \mu^+ \mu^-$. Scatter plots of the Integrated F–B asymmetries (A_{FB} and A'_{FB}) versus the BR (in units of 10^{-6}). Scenario **A**.

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FB asym.

Lunghi, Scimemi
NP574, 43, 2000

$B \to X_s l^+ l^-$ CP asymmetry

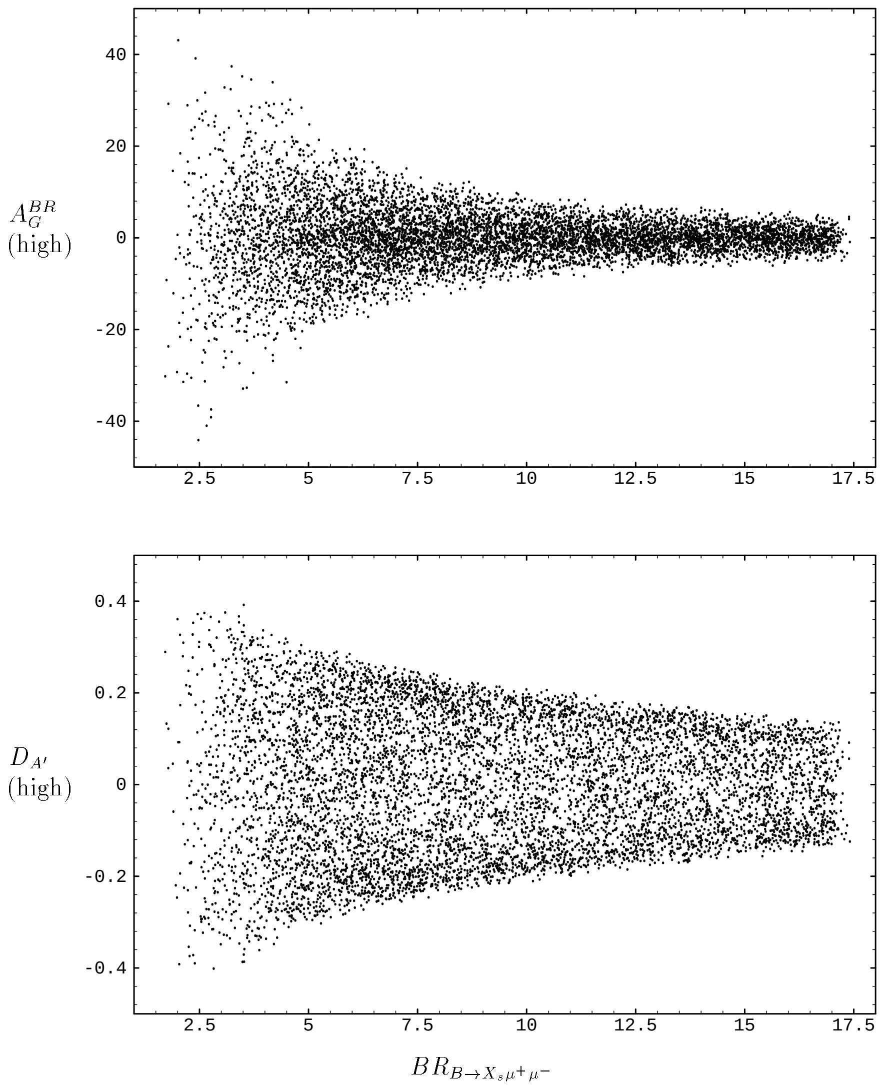

Figure 7: Inclusive decay $B \to X_s \ell^+\ell^-$. Scatter plots of A_G^{BR} and $D_{A'}$ versus the integrated BR (in units of 10^{-6}) in the high–s region. Scenario **A**.

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CP asym.
High s region
$(\mathbf{14 - 23 GeV^2})$

Lunghi, Scimemi
NP574, 43, 2000

$B \to X_s \nu\bar{\nu}$ $(b \to s\bar{\nu}\bar{\nu})$

Less theoretical uncertainty.

- Experiment
  $\mathrm{BR} < 7.7 \times 10^{-4}$ (ALEPH)
- SM prediction
  $\mathrm{BR} = (3.5 \pm 0.7) \times 10^{-5}$
- SUSY contribution
  $(\delta^u_{LL})_{23}, (\delta^u_{LR})_{23}$

4. $\bar{B} \to D\tau\bar{\nu}$

The best probe into the MSSM Higgs sector at B factories. Some recent theoretical results were reported by T. Miura in HLBF3.

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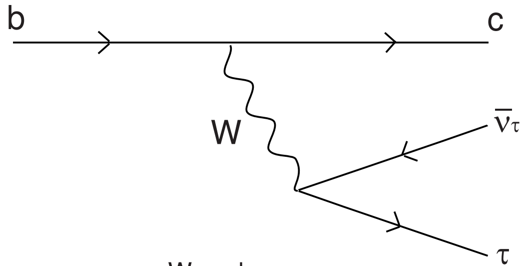
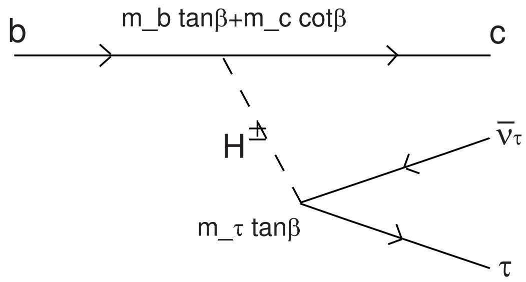
Feynman diagram of $\overline{B} \to D\tau\overline{\nu}_\tau$



W exchange



charged Higgs exchange

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Why $\bar{B} \to D\tau\bar{\nu}_\tau$?

- Tree level process
  Less dependent on the other sectors of the model
  (Radiative correction is important when $\tan\beta \gg 1$)
- Charged Higgs couplings to fermions: $\propto m_f$

$$\begin{aligned} \text{Amp}(\bar{K} \to \pi\mu\bar{\nu}) &\sim m_s m_\mu \\ &\quad\ \Downarrow \quad \sim\text{500 times} \\ \text{Amp}(\bar{B} \to D\tau\bar{\nu}) &\sim m_b m_\tau \end{aligned}$$

- B factories

# of B		$\text{BR}(b \to c\tau\bar{\nu}_\tau)$	
$\sim 10^8$	$\times$	~ 0.01	$\sim O(10^6)$ events !

Super B factories $\Rightarrow$ More events. BR, Distributions.

D vs D^*

$\bar{B} \to$	DW^*	DH^*	$D^*_L W^*$	$D^*_L H^*$
$L=0$	H^s_s	H^s_s	H^0_0	
$L=1$	H^s_0		H^0_s	H^0_s

$$H^s_0,\ H^0_s \quad \propto \quad \sqrt{(m_B - m_M)^2 - q^2}$$

$$\longrightarrow \ 0 \qquad \text{as} \quad q^2 \to q^2_{max} = (m_B - m_M)^2$$

$\boxed{D \text{ is more sensitive than } D^*_L.}$

Branching ratio

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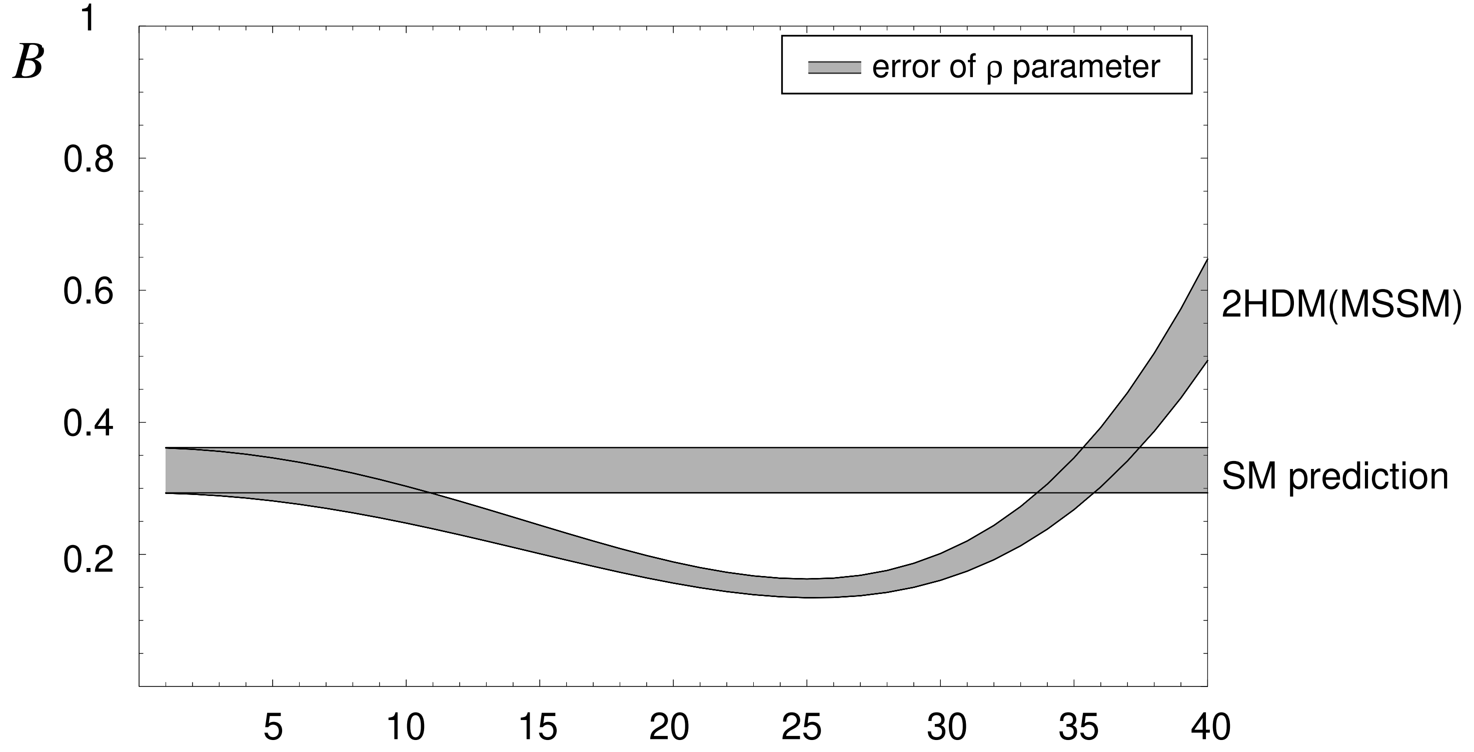
$\Lambda_{\overline{MS}} = 0.25(\mathrm{GeV})$

$$B(R) = \frac{\Gamma(\bar{B} \to D\tau\bar{\nu}_\tau)}{\Gamma(\bar{B} \to D\mu\bar{\nu}_\mu)_{SM}} \text{ (including error of } \rho \text{ parameter)}$$



$$R = \frac{m_W}{m_H}\tan\beta$$

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Branching ratio (cont'd)

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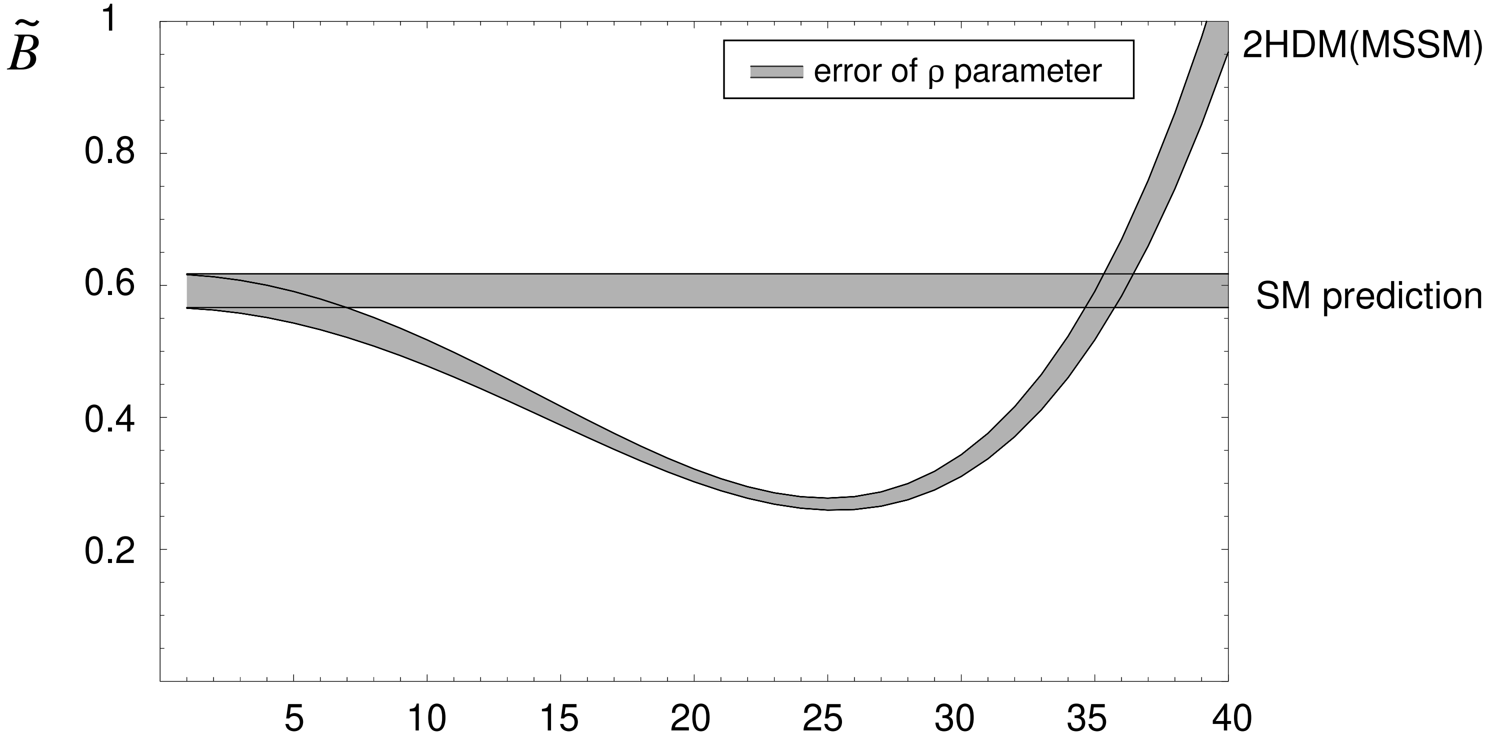
$\Lambda_{\overline{MS}} = 0.25(\mathrm{GeV})$

$$\tilde{B}(R) = \frac{\Gamma\left(\bar{B} \to D\tau\bar{\nu}_\tau\right)}{\tilde{\Gamma}\left(\bar{B} \to D\mu\bar{\nu}_\mu\right)_{SM}} \text{ (including error of } \rho \text{ parameter)}$$

$$\left(\tilde{\Gamma} \to m_\tau^2 \le q^2 \le (m_B - m_D)^2\right)$$



$$R = \frac{m_W}{m_H} \tan\beta$$

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Distribution

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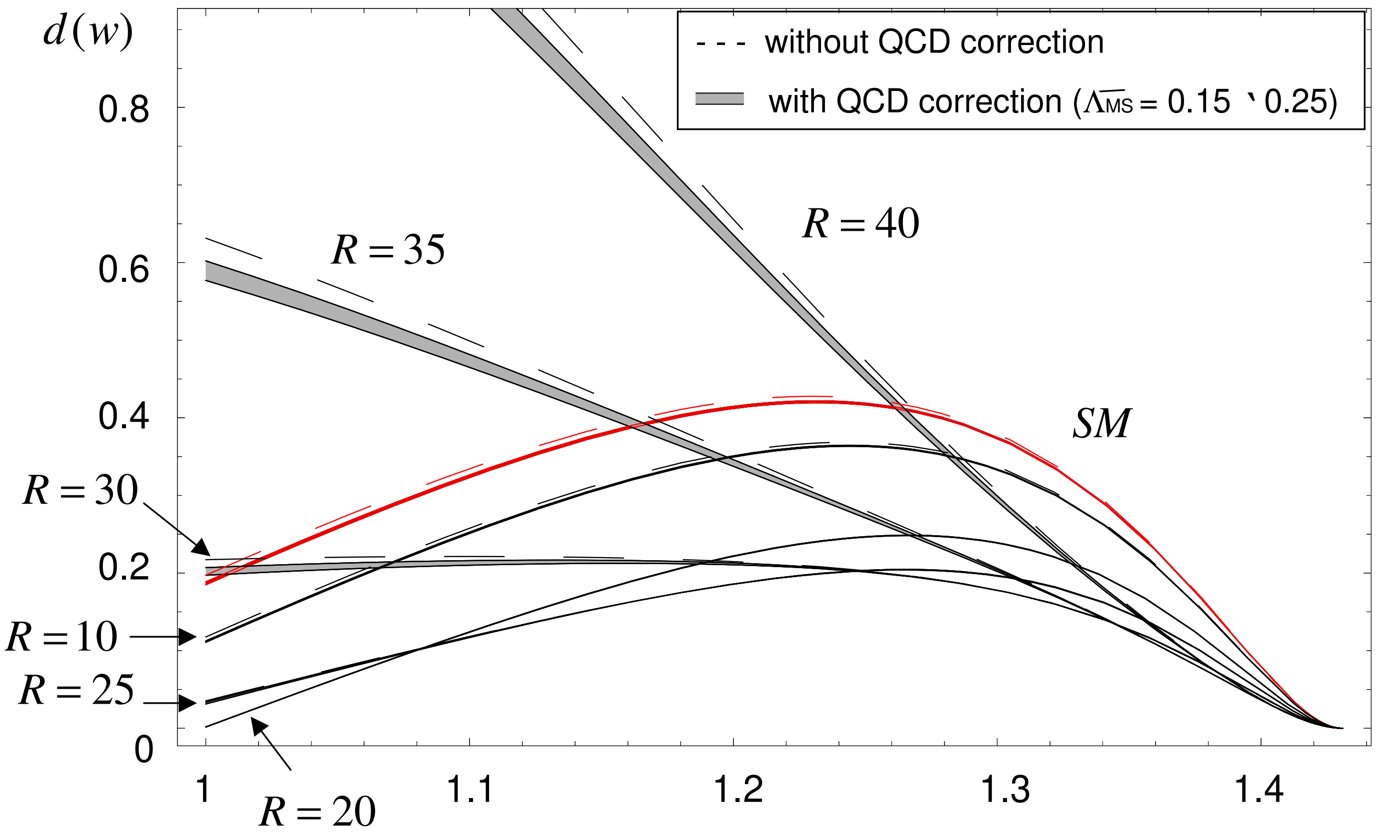
$$d(w) = (w^2 - 1)\frac{\Gamma\left(\overline{B} \to D\tau\overline{\nu}_\tau\right)/dw}{\Gamma\left(\overline{B} \to D\mu\overline{\nu}_\mu\right)_{SM}/dw}$$

$$\boxed{R = \frac{m_W}{m_H}\tan\beta}$$



$$w \equiv v \cdot v' = (m_B^2 + m_D^2 - q^2)/2m_B m_D$$

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5. Summary and discussion

- SUSY effects could be found in the $b \to s$ transitions.
  Correlation among several observables would tell us about the SUSY breaking.
  Hadronic uncertainty should be studied in detail.
  Expected experimental precision of CP and FB asymmetries?

- The charged Higgs in the MSSM affects BR and the decay distribution of $\bar{B} \to D\tau\bar{\nu}$.
  The deviation would be seen only in B factories (not in hadron machines).
  The hadronic uncertainty is understood well and can be reduced by data from B factories.
  SUSY radiative correction is significant for large $\tan\beta$ and may enhance the deviation.
  Can the distribution be measured? How precisely?
  (Nozaki's talk)

Summary and discussion (cont'd)

Subjects not discussed

- What about $b \to d$ transitions?
  $B \to X_d\gamma, X_d l^+ l^-, X_d \nu\bar{\nu}, \pi\pi, \rho\pi$, etc.
  Δm_{B_d} gives a constraint,
  $|M_{12}(\mathrm{SUSY})| \lesssim |M_{12}(\mathrm{SM})|$.

  The isospin analysis in $\pi\pi$ and $\rho\pi$ is important.
  SUSY penguin contributes to the $\Delta I = 1/2$ part.
  Further study is necessary.
- Model-independent ϕ_3 measurement
  Use tree processes like $B \to DK$.
  ϕ_3 can differ from the value of the CKM fitting in the SM.
  (Okada's talk)
- Hadron machines