b → s Transitions in SUSY: Left-Handed vs. Right-Handed

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3rd International conference on Flavor Physics @ NCU, Taiwan

Oct. 6, 2005
1. Introduction: Why $b \to s$ Penguins?

$b \to c$: tree level in Standard Model (SM)
- Good place to test SM

$b \to s$: SM contribution at loop level
- More chance to probe new physics

$b \to s$ is now being explored at B factories.
- Hints on anomalies !!?

Theoretical Prejudice: Mixing between $2^{nd}$ and $3^{rd}$ generations may be large $\leftrightarrow$ atmospheric neutrino
Here I want to talk about new physics contributions to $b \to s$ penguin processes in the context of supersymmetry.

Special Focus on chiral structure in SUSY flavor violation

Combining more than one mode will enable one to identify new physics contributions at effective operator level. Identification of origin of flavor mixing in SUSY

– Some part of the idea may apply to other extensions of SM.
Talk Plan

1. Introduction: Why \( b \rightarrow s \) Penguins?
2. Soft SUSY breaking masses and \( b \rightarrow s \) flavor violation
3. \( B \rightarrow \phi K^0 \) and \( B \rightarrow \eta'K^0 \): Left-handed vs. Right-handed
4. Summary
2. Soft SUSY breaking masses and $b \rightarrow s$ flavor violation
Structure of Squark (sdown) Masses

\[ L \supset [Q^+_L Z_L Q_L + D^+_R Z_R D_R]_{\theta^2 \bar{\theta}^2} + [D^+_R Y_D H_D Q_L]_{\theta^2} + H.c \]

- \( Q_L \): SU(2) doublet quark supermultiplets (3 generations)
- \( D_R \): SU(2) singlet quark supermultiplets (3 generations)
- \( Y \): Yukawa coupling matrix (3 x 3 matrix)
- \( Z_L \): Wave functions for QL (3 x 3 matrix)
- \( Z_R \): Wave functions for DR (3 x 3 matrix)

Consider the case where SUSY breaking comes from wave function (Kaeher Potential)

\[
Z_L = I + \theta^2 A_L + \bar{\theta}^2 A_L^\dagger - \theta^2 \bar{\theta}^2 \tilde{m}_L^2
\]
\[
Z_R = I + \theta^2 A_R + \bar{\theta}^2 A_R^\dagger - \theta^2 \bar{\theta}^2 \tilde{m}_R^2
\]
\[
Y_D = y_D
\]
• SUSY breaking part of scalar potential

\[
\tilde{d}^C_R ( - A_R m_D - m_D A_L ) \tilde{q}_L + H.c. \\
+ \tilde{q}^*_L ( \tilde{m}_L^2 - A_L^\dagger A_L ) \tilde{q}_L + \tilde{d}^C_R ( \tilde{m}_R^2 - A_R^\dagger A_R ) \tilde{d}^C_R
\]

• Squark Mass\(^2\) Matrix (for sdown sector)

\[
( \tilde{d}^\dagger_L \tilde{d}^\dagger_R ) \begin{pmatrix}
  m_{dLL}^2 & m_{dLR}^2 \\
  m_{dRL}^2 & m_{dRR}^2
\end{pmatrix}
\begin{pmatrix}
  \tilde{d}_L \\
  \tilde{d}_R
\end{pmatrix}
\]

each entry: 3 x 3 matrix

\[
m_{dLL}^2 = \tilde{m}_L^2 - A_L^\dagger A_L + m_D^\dagger m_D \\
m_{dRR}^2 = \tilde{m}_R^2 - A_R^\dagger A_R + m_D m_D^\dagger \\
m_{dRL}^2 = - A_R m_D - m_D A_L + m_D \mu \tan \beta \\
m_{dLR}^2 = m_{dRL}^2
\]
Simplification in LR mixing entry

– Approximation:

Only $m_b$ is taken non-zero. Ignore $m_s$ and $m_d$

\[
(m^2_{dLR})_{23} = -(A^*_L)_{23} m_b
\]
\[
(m^2_{dRL})_{23} = -(A_R)_{23} m_b
\]

Classification of 2-3 mixing sdown masses

\[
(m^2_{dLL})_{23}, (m^2_{dLR})_{23} \quad \leftarrow \text{left-handed sdown sector}
\]
\[
(m^2_{dRR})_{23}, (m^2_{dRL})_{23} \quad \leftarrow \text{right-handed sdown sector}
\]
RH vs LH in “SDOWN” sector

• RH:
  – Large 2-3 RH sdown mixing in SUSY GUT see-saw models (Moroi 01)
    • Atmospheric neutrino implies large 2-3 mixing in neutrino Yukawa
    • SUSY GUTs → large 2-3 mixing in RH sdown sector
    • Large contribution to $B \rightarrow \phi K$

• LH:
  – Renormalization Group Flow: does not give significant flavor mixing with new CP phase
  – May be imprinted at Ultra-High Energy Scale
    • Flavor symmetry!?
  – Large 2-3 neutrino mixing may also give large 2-3 mixing in LH squark sector.
$\Delta B = 1$ Effective Hamiltonian

$$H_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \left[ \sum_{q'=u,c} V_{q'b} V_{q's}^* \sum_{i=1,2} C_i O_i^{(q')} - V_{tb} V_{ts}^* \sum_{i=3,6,7,8G} \left( C_i O_i + \tilde{C}_i \tilde{O}_i \right) \right] + \text{h.c.,}$$

$$O_1^{(q')} = (\bar{s}_i \gamma_\mu P_L q_j^i)(\bar{q}_j^i \gamma^\mu P_L b_i) , \quad O_2^{(q')} = (\bar{s}_i \gamma_\mu P_L q_i^j)(\bar{q}_j^i \gamma^\mu P_L b_j) ,$$

$$O_3 = (\bar{s}_i \gamma_\mu P_L b_i) \sum_q (\bar{q}_j^i \gamma^\mu P_L q_j) , \quad O_4 = (\bar{s}_i \gamma_\mu P_L b_j) \sum_q (\bar{q}_j^i \gamma^\mu P_L q_i)$$

$$O_5 = (\bar{s}_i \gamma_\mu P_L b_i) \sum_q (\bar{q}_j^i \gamma^\mu P_R q_j) , \quad O_6 = (\bar{s}_i \gamma_\mu P_L b_j) \sum_q (\bar{q}_j^i \gamma^\mu P_R q_i)$$

$$O_{7\gamma} = \frac{e}{16\pi^2 m_b \bar{s}_i \sigma^{\mu\nu} P_R b_i F_{\mu\nu}} , \quad O_{8G} = \frac{g_s}{16\pi^2 m_b \bar{s}_i \sigma^{\mu\nu} P_R T_{ij}^a b_j G_{\mu\nu}^a}$$

$O_i$ --- left-handed operators (s in final state is left-handed)

$\tilde{O}_i$ --- right-handed operators (s in final state is right-hande)

(L $\rightarrow$ R, R $\rightarrow$ L)
SUSY contributions to Effective Hamiltonian

Gluino-Squark Loops → Effective Operators
Chromo-Dipole Type Diagrams
(a) LR23 mixing (RL23 mixing)
(b) LL mixing (RR mixing) + double mass insertion
$\rightarrow$ LH operator $O_{8G}$ (RH op) is generated

Box Diagrams with LL mixing (RR mixnig)
$\rightarrow$ LH op. $O_{3,4,5,6}$ (RH ops.) are generated

LH (RH) Mixings in SUSY Masses
$\rightarrow$ LH (RH) Operators in Effective Hamiltonian
Summary of this section

Origin of Flavor Violation in SUSY Sector

Left-handed Squarks: \((Z_L)_{ij}\)

\[ Z_R = I + \theta^2 A_R + \bar{\theta}^2 A_R^\dagger - \theta^2 \bar{\theta}^2 \bar{m}_R^2 \]

\[ (m_{d_{LL}}^2)_{23}, (m_{d_{LR}}^2)_{23} \]

Left-handed operators

\[ O_{3,4,5,6}, O_{7\gamma}, O_{8G} \]

Right-handed Squarks: \((Z_R)_{ij}\)

\[ Z_L = I + \theta^2 A_L + \bar{\theta}^2 A_L^\dagger - \theta^2 \bar{\theta}^2 \bar{m}_L^2 \]

\[ (m_{d_{RR}}^2)_{23}, (m_{d_{RL}}^2)_{23} \]

Right-handed operators

\[ \tilde{O}_{3,4,5,6}, \tilde{O}_{7\gamma}, \tilde{O}_{8G} \]

Q. How to distinguish LH/RH operators experimentally?
A. Look at more than one modes

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3. $B \rightarrow \phi K \ & \ B \rightarrow \eta' K$: Left-handed vs. Right-handed
Sign of Contributions: Final-state Parity

- **Effective Hamiltonian** \( H_{\text{eff}} \sim C_i O_i + (\tilde{C}, \tilde{O} : R \leftrightarrow L) \)

\[
\begin{align*}
O_i & \quad \text{(even)} \\
\tilde{O}_i & \quad \text{(odd)}
\end{align*}
\]

- **Decay Amplitude** \( \langle f | \tilde{O}_i | B_d \rangle = -(-1)^{P_f} \langle f | O_i | B_d \rangle \)

\[
A \sim \left[ C_i - (-1)^{P_f} \tilde{C}_i \right] \langle f | O_i | B_d \rangle
\]

Kagan; Khalil&Kou

\[
\begin{align*}
A_{i}^{\text{NP}}(\phi K) & \propto \left[ C_i^{\text{SM}} + C_i^{\text{NP}} + \tilde{C}_i^{\text{NP}} \right] \langle \phi K | O_i | B_d \rangle \quad \text{(odd)} \\
A_{i}^{\text{NP}}(\eta' K) & \propto \left[ C_i^{\text{SM}} + C_i^{\text{NP}} - \tilde{C}_i^{\text{NP}} \right] \langle \eta' K | O_i | B_d \rangle \quad \text{(even)}
\end{align*}
\]

LH

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Schematic View of SUSY contributions

$S_{\eta'K}$

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<th>LH</th>
<th>SM</th>
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$S_{\phi K}$

2004 (summer) | 2005 (summer)

| All charmonium         | $0.726 \pm 0.037$ | $0.687 \pm 0.032$
|------------------------|-------------------|-------------------|
| $\varphi K^0$          | $0.34 \pm 0.20$   | $0.41 \pm 0.11$
| $\eta'K^0$             | $0.47 \pm 0.19$   | $0.50 \pm 0.09$

Central values of Experimental Data:
May prefer LH.

Endo, Mishima & MY 04

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Numerical Evaluation in MSSM

The current data prefers LH dominant case!

Here we consider the case only LL/RR operators are dominant and Ignore LR/RL mixings. Inclusion of LR/RL mixings does not change our results.
Numerical Evaluation in MSSM

Endo, Mishima & MY 04

favored by current data from B-factories (1σ)

The current data prefers LH dominant case!

Caution: deviation less than 2 sigmas.

Premature to conclude

\[ (\delta^d_{LL,RR})_{23} = (m^2_{d_{L,R}})_{23}/m^2_q \]

\[ m_{soft} = 500 \text{ GeV, } \tan \beta = 10 \]

GF: \[ q^2 = m_b^2/2 \]
Lesson from this analysis

Future confirmation of the s-penguin anomalies will tell us
– not only the existence of NP
– but also the pattern of chiral structure (and hopefully more structure) of the NP.

Determination of Wilson coefficients
Usage of more than one mode is crucial!
Future Prospects

More Data on $b \to s$ penguins: wait and watch!

Correlation with other B decay processes

e.g. $B_s - \bar{B}_s$ mixing: $\Delta m_s \geq 20 - 100 \, \text{ps}^{-1}$ (Endo&Mishima 04)

$$\text{Br}(B \to \mu^+ \mu^-) \text{ can be } 10^{-7} > > 10^{-9} \text{ (SM)}$$

Correlation with Lepton Flavor Violation

$$\tau \to \mu \gamma, \tau \to \mu \eta \text{ etc}$$

$$\mu \to e \gamma \text{ etc}$$
4. Conclusions

b → s Penguins: sensitive to new physics
Chiral structure of flavor violation in SUSY → Chiral structure of effective operators

Use of more than one mode (e.g. $B \rightarrow \phi K$, $B \rightarrow \eta' K$) will enable us to distinguish the structure of effective operators, and thus the chiral structure of flavor violation in SUSY.

- Present data prefers LH contributions, but only less than 2 sigmas.

Need more data to say something definite on new physics contributions.
THANK YOU!
Comments on RH/LH

LH interpretation:
OK for generic choice of CP phase

RH interpretation:
may marginally work for special choice of CP phase and $r \sim 1$
(danger of $b \to s$ gamma etc)

Larson, Murayama & Perez 04

$\mathcal{A}(B^0 \to \phi, \eta') = A_{\phi, \eta'}^{SM} \left(1 \pm r_{\phi, \eta'} e^{i\sigma_s}\right)$

$\leftarrow$ detailed study
(Endo, Mishima & MY, in preparation)
• This requires large SUSY contributions comparable to SM.
  – Generically excluded by $b \to s$ gamma

• Ways to escape $b \to s$ gamma
  – Suppression of $C7/C8$
    1) Light gluino, heavy squarks $\to$ clear signal at LHC
    2) Cancellation between RL and RR in C7