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Sensitivity of High-Scale SUSY in Low Energy Hadronic FCNC

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Contents

1 Introduction

2 SUSY Mass Spectrum

3 FCNC of B mesons

4 CP violation of K meson

5 Summary
1 Introduction

No evidence of SUSY at LHC

SUSY Scale may be high $>> 1$ TeV

Then, we need Indirect Search for SUSY!

We examine the sensitivity of High Scale SUSY in the FCNC of K and B mesons.
How is the present status of New Physics in FCNC of B mesons?

SM explains successfully CP violation of $B^0$ meson.

However,

there is still possibility to find New Physics in the CP violation phenomena in $B^0$, $B_s$ systems!
Constraint to New Physics parameters in $\Delta B=2$ processes

$$M_{12}^q = (M_{12}^q)^{SM} + (M_{12}^q)^{NP}$$

$$= (M_{12}^q)^{SM} \left(1 + \frac{(M_{12}^q)^{NP}}{(M_{12}^q)^{SM}}\right)$$

$$= (M_{12}^q)^{SM} (1 + h_q e^{2i\sigma_q})$$

Off diagonal amplitude of $B-\bar{B}$

Possible NP contribution of 20-30%

NP is expected in the precise measurements of CP violation in $B^0$, $B_s$ mesons at LHCb and Belle-II.
How large is the theoretical predictions of SUSY effect?

Letter Of Intent of Belle@2004

Example: time dependent CP asymmetry @ $m_{\text{SUSY}} \sim 1$ TeV

$m_{\text{SUGRA}}$  $SU(5)+\nu_R$  $U(2)$ FLASY

MFV  Non-MFV  Non-MFV

$B^0 \rightarrow \phi K_s$

$S_{\phi K_s}$

$\Delta S(\phi K_s) = 0.029 \pm 0.009$ (50 ab$^{-1}$)

$0.74^{+0.11}_{-0.13}$
We should take account of recent progress of experiments.

- **Higgs mass**:  
  \[ m_H = 125 \text{ GeV} \]

- **SUSY bound**:  
  \[ m_{\tilde{q}} \gtrsim 1.8 \text{ TeV} \]
  \[ m_{\tilde{g}} \gtrsim 1.4 \text{ TeV} \]

- **B_s decay**:  
  \[ \mathcal{B}(B_s^0 \to \mu^+ \mu^-)_{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9} \]
\[ m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3 m_t^4}{4 \pi^2 v^2} \left( \log \left( \frac{M_S^2}{m_t^2} \right) + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right) \]

Heavy stop or large A term

Patrick Draper,\textsuperscript{1} Patrick Meade,\textsuperscript{2} Matthew Reece,\textsuperscript{3} and David Shih\textsuperscript{4}
$m_A$ vs. $\tan \beta$

[Endo, Moroi, Nojiri (2015)]
2 SUSY Mass Spectrum

We take SUSY particle spectrum, which is consistent with Higgs Discovery, with non-MFV. [M.Tanimoto and KY (2014)]

\[ \Lambda = 10^{17} \text{GeV}, 10^{16} \text{GeV} \]

Taking universal soft parameters at SUSY breaking scale \( \Lambda \)

\[
\begin{align*}
m_{Q_i}^2(\Lambda) &= m_{U_i^c}^2(\Lambda) = m_{D_i^c}^2(\Lambda) = m_{\nu}^2 \quad (i = 1, 2, 3), \\
M_1(\Lambda) &= M_2(\Lambda) = M_3(\Lambda) = m_{1/2}, \\
m_{H_1}^2(\Lambda) &= m_{H_2}^2(\Lambda) = m_0^2, \\
A_U(\Lambda) &= A_0 y_U(\Lambda), \\
A_D(\Lambda) &= A_0 y_D(\Lambda), \\
A_E(\Lambda) &= A_0 y_E(\Lambda).
\end{align*}
\]

Running soft masses in SUSY

\( H_1, H_2 \)

SM-SUSY matching scale \( Q_0 = 10-1000 \text{ TeV} \)

Running Higgs coupling in SM \( \lambda, m^2 \)

\( H_{SM} \)

SM scale \( m_H, 125 \text{ GeV} \)

\[ V_{SM} = -m^2 |H|^2 + \frac{\lambda}{2} |H|^4 \]

[Delgado, Garcia, Quiros, PRD90(2014)015016]
Squark flavor mixing non-MFV

1\textsuperscript{st} and 2\textsuperscript{nd} family squarks are degenerate: \( s_{12} = 0 \)

\[
\mathcal{L}_{\text{int}}(\tilde{g} q \tilde{q}) = -i \sqrt{2} g_s \sum \tilde{q}_i^* (T^a) \tilde{G}^a \left[ (\Gamma_{GL}^{(q)})_{ij} L + (\Gamma_{GR}^{(q)})_{ij} R \right] q_j + \text{h.c.}
\]

We work in the basis of mass eigenstate.

\[
m^2_{\tilde{q}} = \Gamma_{GL}^{(q)} M^2_{\tilde{q}} \Gamma_{GL}^{(q)\dagger}
\]

Mixing matrix

\[
\Gamma_{GL}^{(q)} = \begin{pmatrix}
    s_{13}^L & 0 & s_{13}^L e^{-i\phi_{13}^L} c_{\theta_q} & 0 & 0 & -s_{13}^L e^{-i\phi_{13}^L} s_{\theta_q} e^{i\phi_q} \\
    -s_{23}^L s_{13}^L e^{i(\phi_{13}^L - \phi_{23}^L)} & c_{23}^L & 0 & 0 & -s_{13}^L e^{-i\phi_{13}^L} s_{\theta_q} e^{i\phi_q} \\
    -s_{13}^L c_{23}^L e^{i\phi_{13}^L} & -s_{23}^L e^{i\phi_{23}^L} & c_{13}^L c_{23}^L c_{\theta_q} & 0 & 0 & -c_{13}^L c_{23}^L s_{\theta_q} e^{i\phi_q} \\
\end{pmatrix}
\]

\[
\Gamma_{GR}^{(q)} = \begin{pmatrix}
    0 & 0 & s_{13}^R s_{\theta_q} e^{-i\phi_{13}^R} e^{-i\phi} & c_{13}^R & 0 & s_{13}^R e^{-i\phi_{13}^R} c_{\theta_q} \\
    0 & 0 & s_{23}^R s_{\theta_q} e^{-i\phi_{23}^R} e^{-i\phi} & c_{23}^R & 0 & s_{23}^R e^{-i\phi_{23}^R} c_{\theta_q} \\
    0 & 0 & c_{13}^R c_{23}^R s_{\theta_q} e^{-i\phi} & -s_{13}^R c_{13}^R e^{i(\phi_{13}^R - \phi_{23}^R)} & 0 & s_{13}^R c_{13}^R e^{-i\phi_{13}^R} c_{\theta_q} \\
\end{pmatrix}
\]

\( \Theta \) is the Left-Right mixing angle which is fixed in our scheme.
# Mass and Mixing Parameters

- **Squark and Gaunino Masses**

| Parameter | $Q_0 = 10 \text{TeV}$ | $Q_0 = 50 \text{TeV}$ |
|-----------|-----------------------|------------------------|
| $m_{\tilde{b}_L} = m_{\tilde{t}_L}$ | 12.2 TeV | 100.9 TeV |
| $m_{\tilde{b}_R}$ | 14.1 TeV | 104.0 TeV |
| $m_{\tilde{t}_R}$ | 8.4 TeV | 83.2 TeV |
| $m_{\tilde{B}}$ | 2.9 TeV | 33.45 TeV |
| $m_{\tilde{W}}$ | 5.2 TeV | 55.4 TeV |
| $m_{\tilde{g}}$ | 12.8 TeV | 115.6 TeV |

$\times m_{\tilde{q}_1} \approx m_{\tilde{q}_2}$

- **Mixing Parameters**

For simplicity, $s_{ij}^L = s_{ij}^R$

$s_{12} = 0$
| Input at \( \Lambda \) and \( Q_0 \) | Output at \( Q_0 \) |
|----------------------------------|--------------------------|
| at \( \Lambda = 10^{17} \) GeV, \( m_0 = 10 \) TeV, \( m_{1/2} = 6.2 \) TeV, \( A_0 = 25.803 \) TeV; at \( Q_0 = 10 \) TeV, \( \mu = 10 \) TeV, \( \tan \beta = 10 \) | \( m_\tilde{g} = 12.8 \) TeV, \( m_\tilde{W} = 5.2 \) TeV, \( m_\tilde{B} = 2.9 \) TeV \( m_{\tilde{b}_L} = m_{\tilde{t}_L} = 12.2 \) TeV \( m_{\tilde{b}_R} = 14.1 \) TeV, \( m_{\tilde{t}_R} = 8.4 \) TeV \( m_{\tilde{s}_L,\tilde{d}_L} = m_{\tilde{c}_L,\tilde{u}_L} = 15.1 \) TeV \( m_{\tilde{s}_R,\tilde{d}_R} \simeq m_{\tilde{c}_R,\tilde{u}_R} = 14.6 \) TeV, \( m_\tilde{H} = 13.7 \) TeV \( m_{\tilde{\tau}_L} = m_{\tilde{\nu}_{\tau-L}} = 10.4 \) TeV, \( m_{\tilde{\tau}_R} = 9.3 \) TeV \( m_{\tilde{\mu}_L,\tilde{e}_L} = m_{\tilde{\nu}_{\mu-L},\tilde{\nu}_{e-L}} = 10.8 \) TeV, \( m_{\tilde{\mu}_R,\tilde{e}_R} = 10.3 \) TeV \( X_t = -0.22, \quad \lambda_H = 0.126 \) |
| at \( \Lambda = 10^{16} \) GeV, \( m_0 = 50 \) TeV, \( m_{1/2} = 63.5 \) TeV, \( A_0 = 109.993 \) TeV; at \( Q_0 = 50 \) TeV, \( \mu = 50 \) TeV, \( \tan \beta = 4 \) | \( m_\tilde{g} = 115.6 \) TeV, \( m_\tilde{W} = 55.4 \) TeV, \( m_\tilde{B} = 33.45 \) TeV \( m_{\tilde{b}_L} = m_{\tilde{t}_L} = 100.9 \) TeV \( m_{\tilde{b}_R} = 104.0 \) TeV, \( m_{\tilde{t}_R} = 83.2 \) TeV \( m_{\tilde{s}_L,\tilde{d}_L} = m_{\tilde{c}_L,\tilde{u}_L} = 110.7 \) TeV, \( m_{\tilde{s}_R,\tilde{d}_R} = 110.7 \) TeV \( m_{\tilde{c}_R,\tilde{u}_R} = 105.0 \) TeV, \( m_\tilde{H} = 83.1 \) TeV \( m_{\tilde{\tau}_L} = m_{\tilde{\nu}_{\tau-L}} = 63.6 \) TeV, \( m_{\tilde{\tau}_R} = 54.6 \) TeV \( m_{\tilde{\mu}_L,\tilde{e}_L} = m_{\tilde{\nu}_{\mu-L},\tilde{\nu}_{e-L}} = 63.8 \) TeV, \( m_{\tilde{\mu}_R,\tilde{e}_R} = 55.0 \) TeV \( X_t = -0.65, \quad \lambda_H = 0.1007 \) |
Remark

Left-Right Mixing angle is very small!

\[
M_{\tilde{q}}^2 = \begin{pmatrix}
  m_{\tilde{d}_L}^2 & m_b(A_b - \mu \tan \beta) \\
  m_b(A_b - \mu \tan \beta) & m_{\tilde{d}_R}^2
\end{pmatrix}
\]

\[
\tan 2\theta = \frac{2m_b(A_b - \mu \tan \beta)}{m_{\tilde{d}_L}^2 - m_{\tilde{d}_R}^2}
\]

\[
\Theta = 0.56^\circ \quad \text{for } 10\text{TeV, } \tan \beta = 10
\]
3 FCNC of B and D mesons

How large contributions of Squark flavor mixing in B mesons?

\[ M_{12}^q = \langle B_q | H_{\text{eff}} | \bar{B}_q \rangle = M_{12}^{q, \text{SM}} + M_{12}^{q, \text{SUSY}} \]

\[ \Delta M_d = 2 |M_{12}^d| \epsilon_K \propto \text{Im}(M_{12}^K) \]

SUSY contribution

|\epsilon_K| \propto s_{13} s_{23} \quad \Delta M_d \propto s_{13} \quad \Delta M_s \propto s_{23}

Time dependent CP asymmetry:

B0 \quad S_{J/\psi K_S} \quad Bs \quad S_{J/\psi}\phi

\[ S_{J/\psi K_S} \rightarrow \sin(2\beta_{SM} + \text{Arg}(1 + \left| \frac{M_{12}^{SM}}{M_{12}^{SUSY}} \right| e^{2i\sigma})) \]

\[ S_{J/\psi}\phi \rightarrow \sin(-2\beta_{s,SM} + \text{Arg}(1 + \left| \frac{M_{s,12}^{SM}}{M_{s,12}^{SUSY}} \right| e^{2i\sigma})) \]

SUSY contribution

\[ S_{J/\psi K_S} \propto s_{13} \quad S_{J/\psi}\phi \propto s_{23} \]
We have scanned susy mixing parameters $s_{13}=s_{23}=0\sim0.5$.

| | (a) $Q_0 = 10$ TeV | (b) $Q_0 = 50$ TeV |
|---|---|---|
| $|\epsilon_K|$ | 40% | 35% |
| $S_{J/\psi K_S}$ | 6% | 0.1% |
| $S_{J/\psi\phi}$ | 8% | 0.1% |
| $\Delta M_{B^0}$ | 6% | 0.1% |
| $\Delta M_{B_s}$ | 0.4% | 0.005% |
| $|S_{\phi K_S}/S_{\eta' K^0} - 1|$ | 0.2% | 0.001% |
| $\text{BR}(b \to s\gamma)$ | 0.3% | 0.001% |
| $|a_{d_{sL}}|^d$ | $\leq 1 \times 10^{-3}$ | $\leq 8 \times 10^{-4}$ |
| $|a_{s_{sL}}|$ | $\leq 5 \times 10^{-5}$ | $\leq 4 \times 10^{-5}$ |
| $|d_{s}|$ | $\leq 4 \times 10^{-25}\text{cm}$ | $\leq 1 \times 10^{-27}\text{cm}$ |
where we define the SUSY scale is 10 TeV.

Figure 4: The deviation of $\sin^2 \phi / \Delta(1 - \phi^2)$ left-right mixing could be also 6% in the mass di.

mass di. The deviation of $\sin \phi_3$ from $\sin 2\phi_1$ versus $s_{13}^{L(R)}$.

$S_{J/\psi K_S}$

$\Delta M_{B^0}$

The deviation of $\sin \phi_d$ from $\sin 2\phi_1$ versus $s_{13}^{L(R)}$.

The SUSY contribution to $\Delta M_{B^0}$ versus $s_{13}^{L(R)}$.

SUSY contribution to $B^0$ system @ 10 TeV
\[ a_{sl}^s = \left( -0.24 \pm 0.54 \pm 0.33 \right) \times 10^{-2}, \quad a_{sl}^d = \left( -0.3 \pm 2.1 \right) \times 10^{-3}. \]
The SUSY components of (a) $\Delta M_{B^0}$ and (b) $\Delta M_{B_s}$ versus $m_{\tilde{Q}}$ for $s_{13} = s_{23} = 0.22$ (cyan) and 0.5 (blue). The horizontal red line denotes the experimental central value.
D mesons

\[ x_D = \frac{\Delta M_D}{\Gamma_D} = (3.6 \pm 1.6) \times 10^{-3} \]

The SUSY component of (a) \( \Delta M_D \) and (b) \( x_D \) versus \( m_{\tilde{Q}} \) for \( s_{13} = s_{23} = 0.22 \) (cyan) and 0.5 (blue). The horizontal red line denotes the experimental central value.
4 CP violation of K meson

SUSY contributions to $\Delta M_K$ and $\varepsilon_K$

The SUSY components of (a) $\Delta M_{K^0}$ and (b) $|\varepsilon_K|$ versus $m_{\tilde{Q}}$ for $s_{13} = s_{23} = 0.22$ (cyan) and 0.5 (blue). The horizontal red line denotes the experimental central value.
$K_L \rightarrow \pi^0\nu\bar{\nu}$ and $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- Rare decay: $\text{BR}_{\text{SM}} \sim 10^{-11}$

\[
\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11}
\]
\[
\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}
\]

- Clean theoretically: theoretical uncertainty $\sim 2\%$ \[\text{[Buras et al, 2006]}\]

$\Rightarrow$ Sensitive to New Physics

$BR(K_L \rightarrow \pi^0\nu\bar{\nu})_{\text{exp}} < 2.6 \times 10^{-8}$ (90$\%$C.L.)

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu})_{\text{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

$\rightarrow$ KOTO experiment

@J–PARC
$K \rightarrow \pi \nu \nu$ in SM

\[ \mathcal{H}_{\text{eff}}^{\text{SM}} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \theta_W} \sum_{i=e,\mu,\tau} \left[ V_{cs}^* V_{cd} X_c + V_{ts}^* V_{td} X_t \right] (\bar{s}_L \gamma^\mu d_L) (\bar{\nu}_L^i \gamma_\mu \nu^i_L) + \text{H.c.} \]

\[ F = V_{cs}^* V_{cd} X_c + V_{ts}^* V_{td} X_t \]

$K_L \rightarrow \pi^0 \nu \nu$

$\text{CP}^- \quad \text{CP}^+$

Direct CPV

$A(K_L \rightarrow \pi^0 \nu \bar{\nu}) \propto A(K^0 \rightarrow \pi^0 \nu \bar{\nu}) - A(\bar{K}^0 \rightarrow \pi^0 \nu \bar{\nu})$

$\propto F - F^*$

$\propto \text{Im} F$

$\propto \eta$

$K^+ \rightarrow \pi^+ \nu \nu$

$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \propto |F|^2$

$\propto [(\text{Re} F)^2 + (\text{Im} F)^2]$

$\propto \left[ (\bar{\rho} - \rho^0)^2 + \bar{\eta}^2 \right]$
$K \rightarrow \pi \nu\nu$ in SM

$K_L \rightarrow \pi^0\nu\nu$

$CP^- \rightarrow CP^+$

Direct CPV

$K^+ \rightarrow \pi^+\nu\nu$

$A(K_L \rightarrow \pi^0\nu\bar{\nu}) \propto A(K^0 \rightarrow \pi^0\nu\bar{\nu}) - A(\bar{K}^0 \rightarrow \pi^0\nu\bar{\nu})$

$\propto F - F^*$

$\propto \text{Im}F$

$\propto \eta$

$BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) \propto |F|^2$

$\propto [(\text{Re}F)^2 + (\text{Im}F)^2]$
**SUSY contribution to K \rightarrow \pi\nu\nu**

**Chargino Penguin dominance**

It is known there are no large enhancement in K \rightarrow \pi\nu\nu decay in the Minimal flavor violation(MFV) scheme

- SUGRA model with MFV [T.Goto, Y,Okada and Y.Shimizu(1998)]
  
  @ Squark mass < 600 GeV, Gaugino mass < 600 GeV
  \[
  \frac{BR(K_L \rightarrow \pi^0\nu\bar{\nu})}{BR(K_L \rightarrow \pi^0\nu\bar{\nu})_{SM}} \leq 1.02
  \]

- with non-MFV [A.J.Buras, et al (2005)]
  
  @ Squark mass = 600 GeV, Gluino mass = 1 TeV
  \[
  BR(K_L \rightarrow \pi^0\nu\bar{\nu}) \leq 4.3 \times 10^{-10}
  \]

LR with s13*s23 can enhance it.
LL with s13*s23 is constrained to be small by Exp. Data.
Numerical results @ $Q_0=10$ TeV

○ LR mixing is suppressed due to heavy masses of SUSY.
○ LL Chargino contribution is dominant.
○ LL is not constrained by Exp. Data.

$\varepsilon_K \& \Delta M_{d,s} \& \sin 2\beta \& b\rightarrow s\gamma$

- $s_{13}=s_{23}=0.1$
- $s_{13}=s_{23}=0.1$
LL contribution of Chargino Penguin @1TeV

With \( \epsilon_K \), \( \Delta M_{d,s} \), \( \sin 2\beta \), and \( b \rightarrow s \gamma \) cut

\[ s_{13} = s_{23} < 0.03 \]
Hadronic Matrix elements:

Buras, Gambino, Gorbahn, Jager, Silvestrini, Nucl.Phys. B 592 (2001) 55

\[ s_{13} = s_{23} = 0.1 \]
Numerical analysis results @ $Q_0 = 10$ TeV

- $s^d$ & $s^u$ dependence

$S^u \equiv S^u_{13} = S^u_{23}$
Numerical analysis results @ $Q_0 = 50$ TeV

BR($K_L \rightarrow \pi^0 \nu \nu$)

$BR(K^+ \rightarrow \pi^+ \nu \nu)$

$s_{13} = s_{23} = 0.3$
$Q_0 = 50 \text{ TeV}$

$s_{13} = s_{23} = 0.3$
The neutron EDM versus (a) $m_{\tilde{Q}}$ and (b) $|\epsilon_K^{\text{SUSY}}|$ for $s_{13} = s_{23} = 0.22$ (cyan) and 0.5 (blue) for the case of the QCD sum rule. The horizontal red line denotes the experimental upper bound of $|d_n|$, and the vertical one is the experimental central value of $|\epsilon_K|$. 

Neutron EDM
The mercury EDM versus (a) $m_{\tilde{Q}}$ and (b) versus $|\epsilon_K^{\text{SUSY}}|$ for $s_{13} = s_{23} = 0.22$ (cyan) and 0.5 (blue) for the case of the QCD sum rule. The horizontal red line denotes the experimental upper bound of $|d_{Hg}|$, and the vertical one is the experimental central value of $|\epsilon_K|$. 

Hg EDM
5 Summary

- SUSY contribution to FCNC of B mesons is at most 8%.
- $\varepsilon_K$ and $\varepsilon'_K$ have sensitivity of squark flavor mixing on the present experimental data even if SUSY scale is 100 TeV.
- EDM also gives a severe constraint on High-scale SUSY.

\[ Q_0 = 10\text{TeV} \quad \text{and} \quad Q_0 = 50\text{TeV} \]

\[ @s^d=s^u=0.1 \quad @s^d=s^u=0.3 \]

\[ BR(K_L \rightarrow \pi^0 \nu \bar{\nu}) \sim 8 \times \text{SM} \quad \sim 2 \times \text{SM} \]

\[ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \sim 3 \times \text{SM} \quad \sim 2 \times \text{SM} \]

- EDM also gives a severe constraint on High-scale SUSY.

We expect that LHCb, Bell-II and KOTO provide more precise data to search for the SUSY contribution.
Thank you!