Sensitivity of High-Scale SUSY in Low Energy Hadronic FCNC

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Contents

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, Bs systems** !

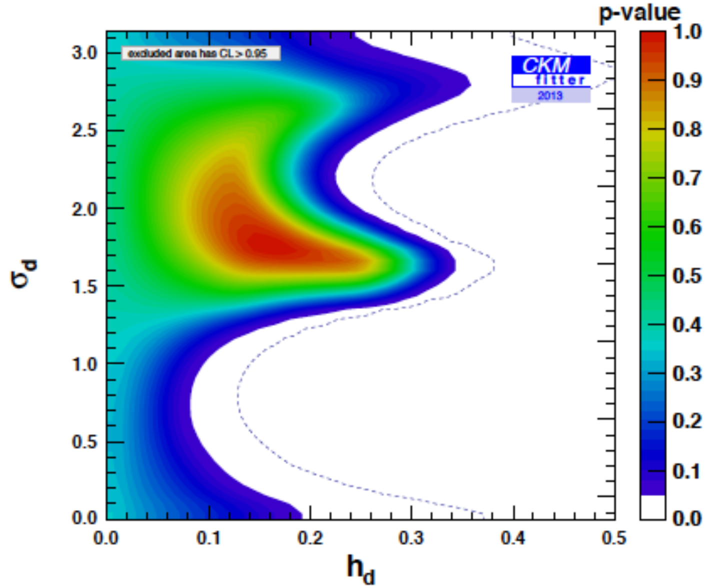
●Constraint to New Physics parameters in ΔB=2 processes

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

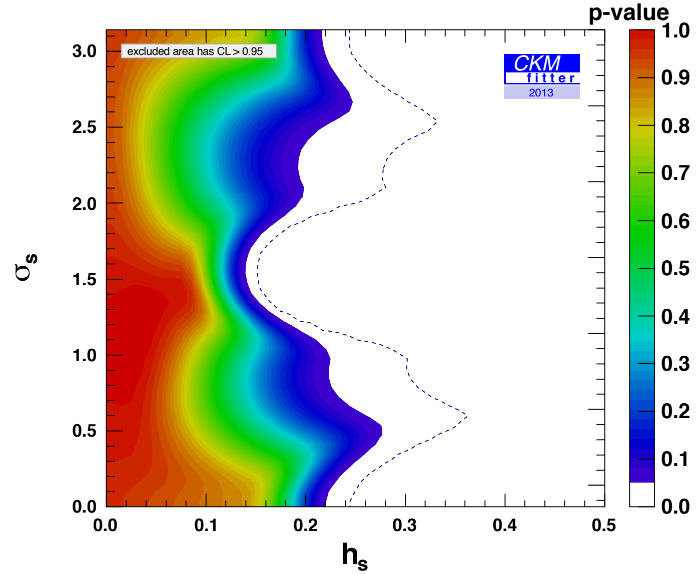
Off diagonal amplitude of B-$\bar{B}$

Possible NP contribution of 20-30%

B⁰



B_s



NP is expected in the precise measurements of CP violation in B⁰, Bs mesons at LHCb and Belle-II.

How large is the theoretical predections of SUSY effect?

Letter Of Intent of Belle@2004

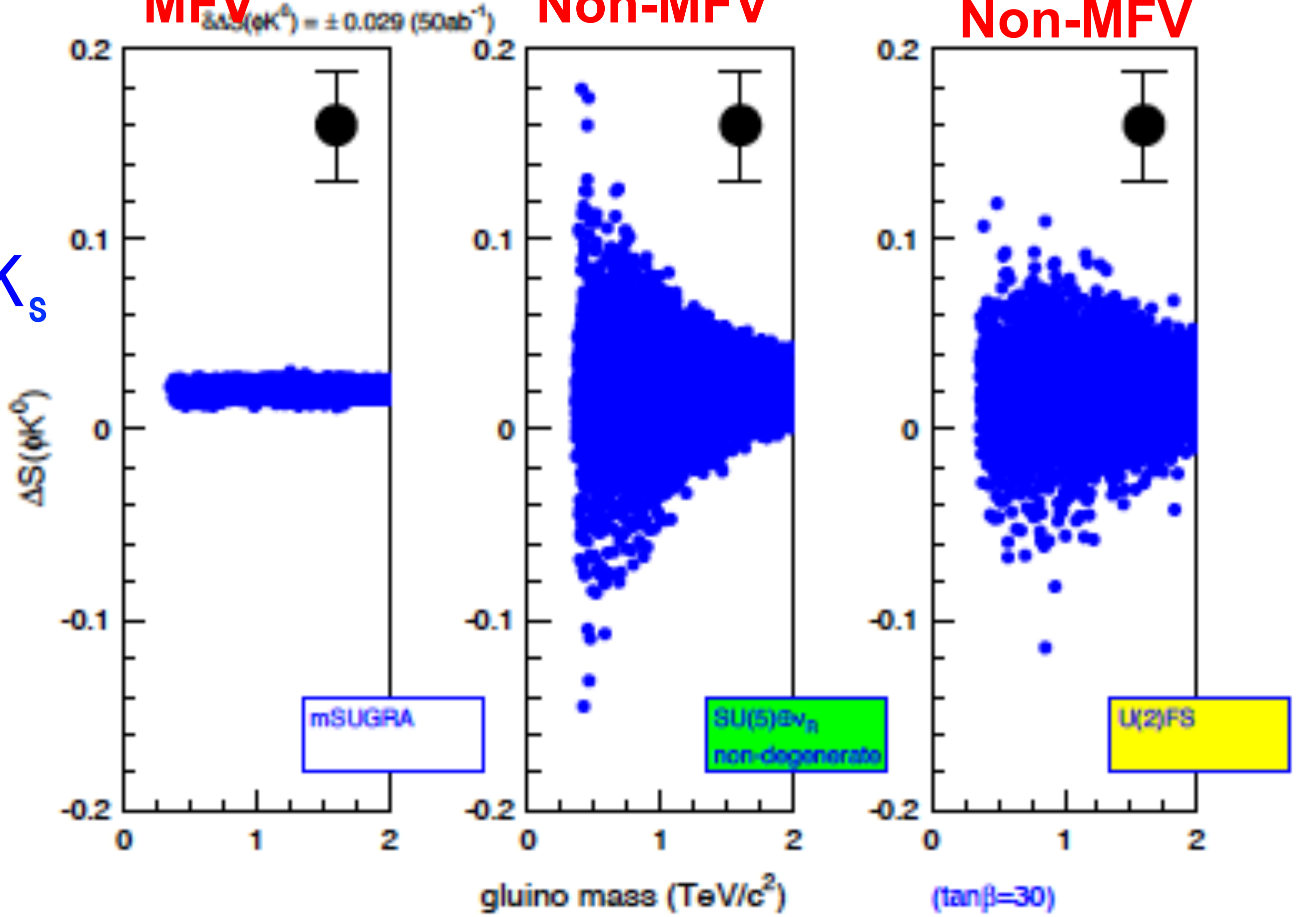
Example: time dependent CP asymmetry @ m_{SUSY} ~1 TeV

$B^0 \rightarrow \phi K_s$

$S_{\phi K_S}$

$0.74^{+0.11}_{-0.13}$

mSUGRA	SU(5)+ν_R	U(2) FLASY
MFV	Non-MFV	Non-MFV



We should take account of recent progress of experiments.

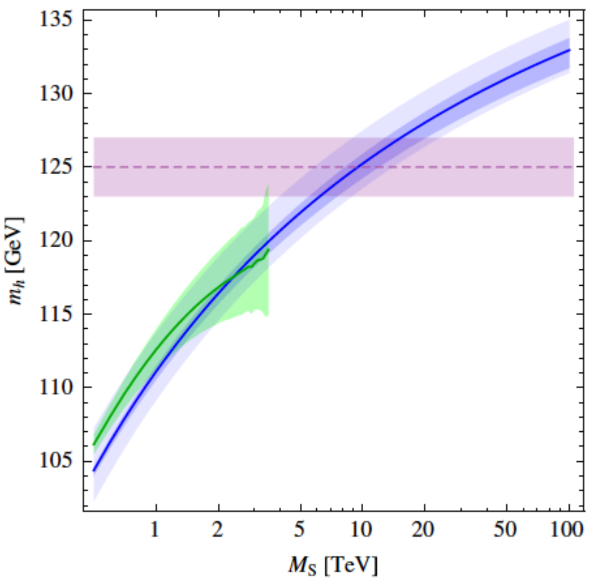
- Higgs mass : $m_H = 125 \text{ GeV}$

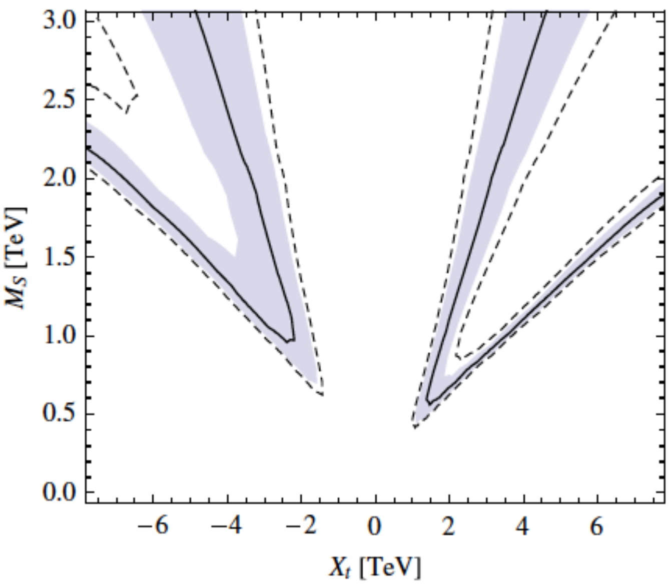
- SUSY bound : $m_{\tilde{q}} \gtrsim 1.8\text{TeV}$
  $m_{\tilde{g}} \gtrsim 1.4\text{TeV}$

- B_s decay : $\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\text{exp}} = (2.9 \pm 0.7) \times 10^{-9}$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

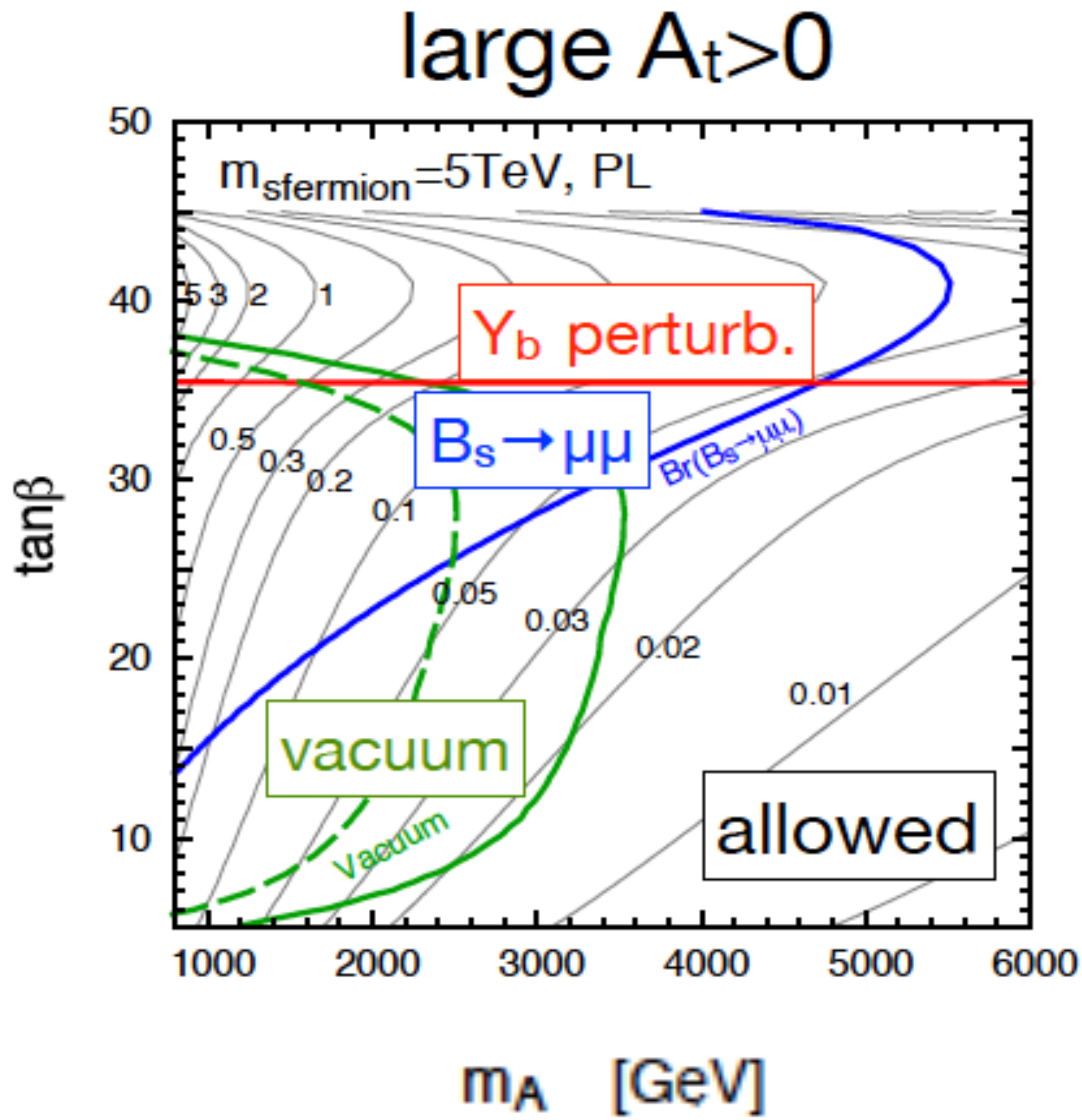
Heavy stop or large A term





Patrick Draper,[1] Patrick Meade,[2] Matthew Reece,[3] and David Shih[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)]

Λ — **SUSY breaking scale $\Lambda = 10^{17}$GeV,10^{16}GeV**

Taking **universal soft parameters** at SUSY breaking scale Λ

$$m^2_{\tilde{Q}_i}(\Lambda) = m^2_{\tilde{U}^c_i}(\Lambda) = m^2_{\tilde{D}^c_i}(\Lambda) = m_0^2 \ (i = 1, 2, 3) \ ,$$
$$M_1(\Lambda) = M_2(\Lambda) = M_3(\Lambda) = m_{1/2}, \ ,$$
$$m^2_{H_1}(\Lambda) = m^2_{H_2}(\Lambda) = m_0^2 \ ,$$
$$A_U(\Lambda) = A_0 y_U(\Lambda), \quad A_D(\Lambda) = A_0 y_D(\Lambda), \quad A_E(\Lambda) = A_0 y_E(\Lambda).$$

Running soft masses in SUSY

H_1, H_2

Q_0 — **SM-SUSY matching scale Q_0 =10-1000 TeV**

Running Higgs coupling in SM λ, m^2

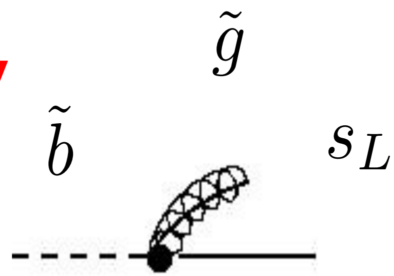
H_{SM}

m_H — **SM scale $m_{H,}$ 125 GeV**

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

[Delgado, Garcia, Quiros, PRD90(2014)015016]

Squark flavor mixing non−MFV



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

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

We work in the basis of mass eigenstate.

Parameters
s13L, s23L
s13R, s23R

$$m^2_{\tilde{q}} = \Gamma^{(q)}_G M^2_{\tilde{q}} \Gamma^{(q)\dagger}_G$$

Mixing matrix

$$\Gamma^{(q)}_{GL} = \begin{pmatrix} c^{qL}_{13} & 0 & s^{qL}_{13}\, e^{-i\phi^{qL}_{13}}\, c_{\theta^q} & 0 & 0 & -s^{qL}_{13}\, e^{-i\phi^{qL}_{13}}\, s_{\theta^q}\, e^{i\phi^q} \\ -s^{qL}_{23}\, s^{qL}_{13}\, e^{i(\phi^{qL}_{13}-\phi^{qL}_{23})} & c^{qL}_{23} & s^{qL}_{23}\, c^{qL}_{13}\, e^{-i\phi^{qL}_{23}}\, c_{\theta^q} & 0 & 0 & -s^{qL}_{23}\, c^{qL}_{13}\, e^{-i\phi^{qL}_{23}}\, s_{\theta^q}\, e^{i\phi^q} \\ -s^{qL}_{13}\, c^{qL}_{23}\, e^{i\phi^{qL}_{13}} & -s^{qL}_{23}\, e^{i\phi^{qL}_{23}} & c^{qL}_{13}\, c^{qL}_{23}\, c_{\theta^q} & 0 & 0 & -c^{qL}_{13}\, c^{qL}_{23}\, s_{\theta^q}\, e^{i\phi^q} \end{pmatrix} \begin{matrix} d_L \\ s_L \\ b_L \end{matrix}$$

$$\Gamma^{(q)}_{GR} = \begin{pmatrix} 0 & 0 & s^{qR}_{13}\, s_{\theta^q} e^{-i\phi^{qR}_{13}}\, e^{-i\phi} & c^{qR}_{13} & 0 & s^{qR}_{13}\, e^{-i\phi^{qR}_{13}}\, c_{\theta^q} \\ 0 & 0 & s^{qR}_{23}\, c^{qR}_{13}\, s_{\theta^q} e^{-i\phi^{qR}_{23}}\, e^{-i\phi^q} & -s^{qR}_{13}\, s^{qR}_{23}\, e^{i(\phi^{qR}_{13}-\phi^{qR}_{23})} & c^{qR}_{23} & s^{qR}_{23}\, c^{qR}_{13}\, e^{-i\phi^{qR}_{23}}\, c_{\theta^q} \\ 0 & 0 & c^{qR}_{13}\, c^{qR}_{23}\, s_{\theta^q} e^{-i\phi^q} & -s^{qR}_{13}\, c^{qR}_{23}\, e^{i\phi^{qR}_{13}} & -s^{qR}_{23}\, e^{i\phi^{qR}_{23}} & c^{qR}_{13}\, c^{qR}_{23}\, c_{\theta^q} \end{pmatrix} \begin{matrix} d_R \\ s_R \\ b_R \end{matrix}$$

$$\tilde{d}_1 \quad \tilde{s}_1 \quad \tilde{b}_1 \quad \tilde{d}_2 \quad \tilde{s}_2 \quad \tilde{b}_2$$

Θ is the Left-Right mixing angle which is fixed in our scheme.

Mass and Mixing Parameters

- **squark and gaunino masses**

	$Q_0 = 10\mathrm{TeV}$	$Q_0 = 50\mathrm{TeV}$
$m_{\tilde{b}_L} = m_{\tilde{t}_L}$	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

※ $m_{\tilde{q}_1} \simeq m_{\tilde{q}_2}$

- **mixing parameters** ：free parameter

$s^L_{23},\ s^R_{23},\ s^L_{13},\ s^R_{13}$ For simplicity, $s^L_{ij} = s^R_{ij}$

$\phi^L_{23},\ \phi^R_{23},\ \phi^L_{13},\ \phi^R_{13}$ random

$s_{12} = 0$

Input at Λ 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, $m_{\mathcal{H}} = 13.7$ 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, $m_{\mathcal{H}} = 83.1$ 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 !

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

Third family

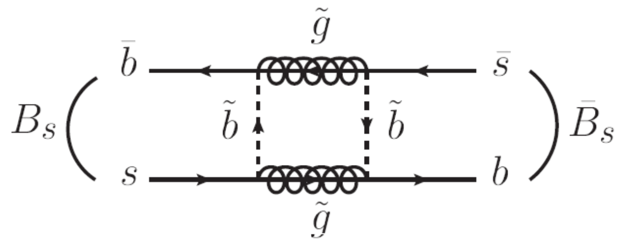
$$\tan 2\theta = \frac{2m_b(A_b - \mu\tan\beta)}{m_{\tilde{d}_L}^2 - m_{\tilde{d}_R}^2}$$

$\Theta = 0.56^\circ$ for 10TeV, $\tan\beta = 10$

3 FCNC of B and D mesons

How large contributions of Squark flavor mixing in B mesons ?

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



$$\Delta M_d = 2\left|M_{12}^d\right| \qquad \epsilon_K \propto {\rm Im}(M_{12}^K)$$

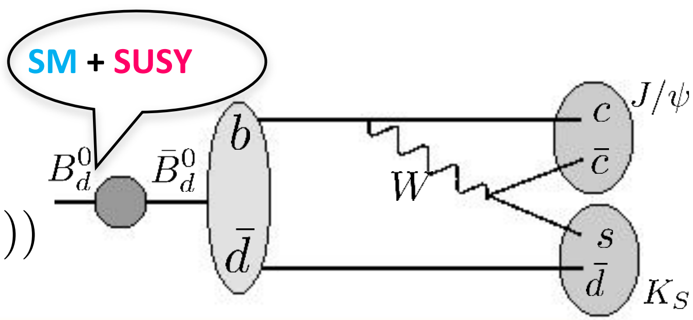
SUSY contribution

$$\left|\epsilon_K\right| \propto s_{13}s_{23} \qquad \Delta M_d \propto s_{13} \qquad \Delta M_s \propto s_{23}$$

Time dependent CP asymmetry : B^0 $S_{J/\psi K_S}$ Bs $S_{J/\psi\phi}$

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

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



SUSY contribution

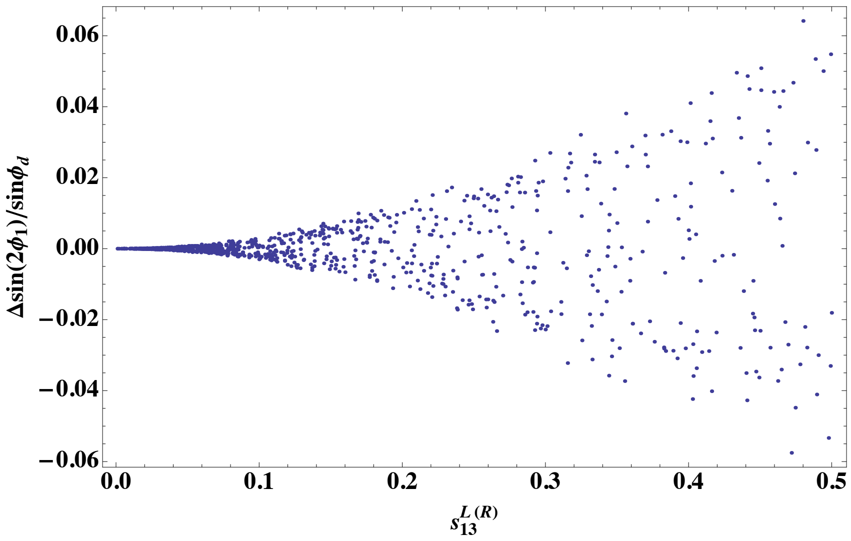
$$S_{J/\psi K_S} \propto s_{13} \qquad S_{J/\psi\phi} \propto s_{23}$$

We have scanned susy mixing parameters $s_{13}=s_{23}=0\sim0.5$.

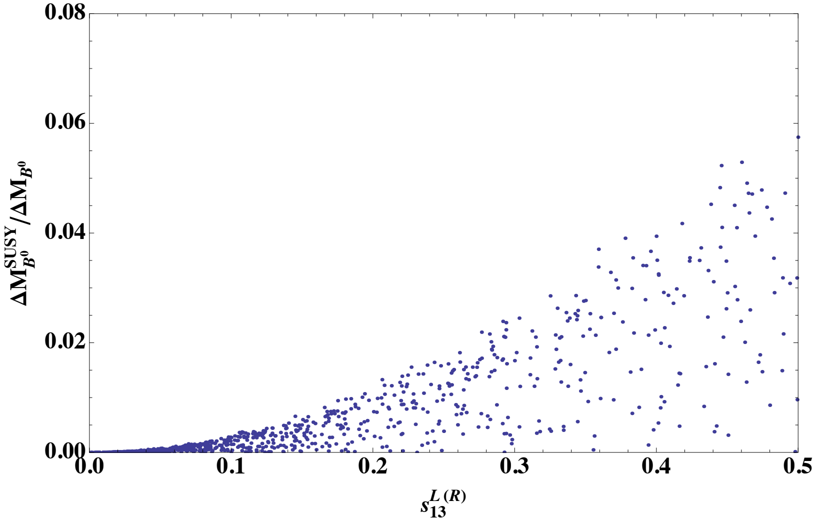
	(a) $Q_0 = 10$ TeV	(b) $Q_0 = 50$ TeV
$\lvert\epsilon_K\rvert$	40%	35%
$S_{J/\psi K_S}$	6%	0.1%
$S_{J/\psi\phi}$	8%	0.1%
ΔM_{B^0}	6%	0.1%
ΔM_{B_s}	0.4%	0.005%
$\lvert S_{\phi K_S}/S_{\eta' K^0}\rvert - 1$	0.2%	0.001%
$\mathrm{BR}(b \to s\gamma)$	0.3%	0.001%
$\lvert a^d_{sl}\rvert$	$\leq 1 \times 10^{-3}$	$\leq 8 \times 10^{-4}$
$\lvert a^s_{sl}\rvert$	$\leq 5 \times 10^{-5}$	$\leq 4 \times 10^{-5}$
$\lvert d^C_s\rvert$	$\leq 4 \times 10^{-25}$cm	$\leq 1 \times 10^{-27}$cm

$S_{J/\psi K_S}$

$\Delta M_B{}^0$

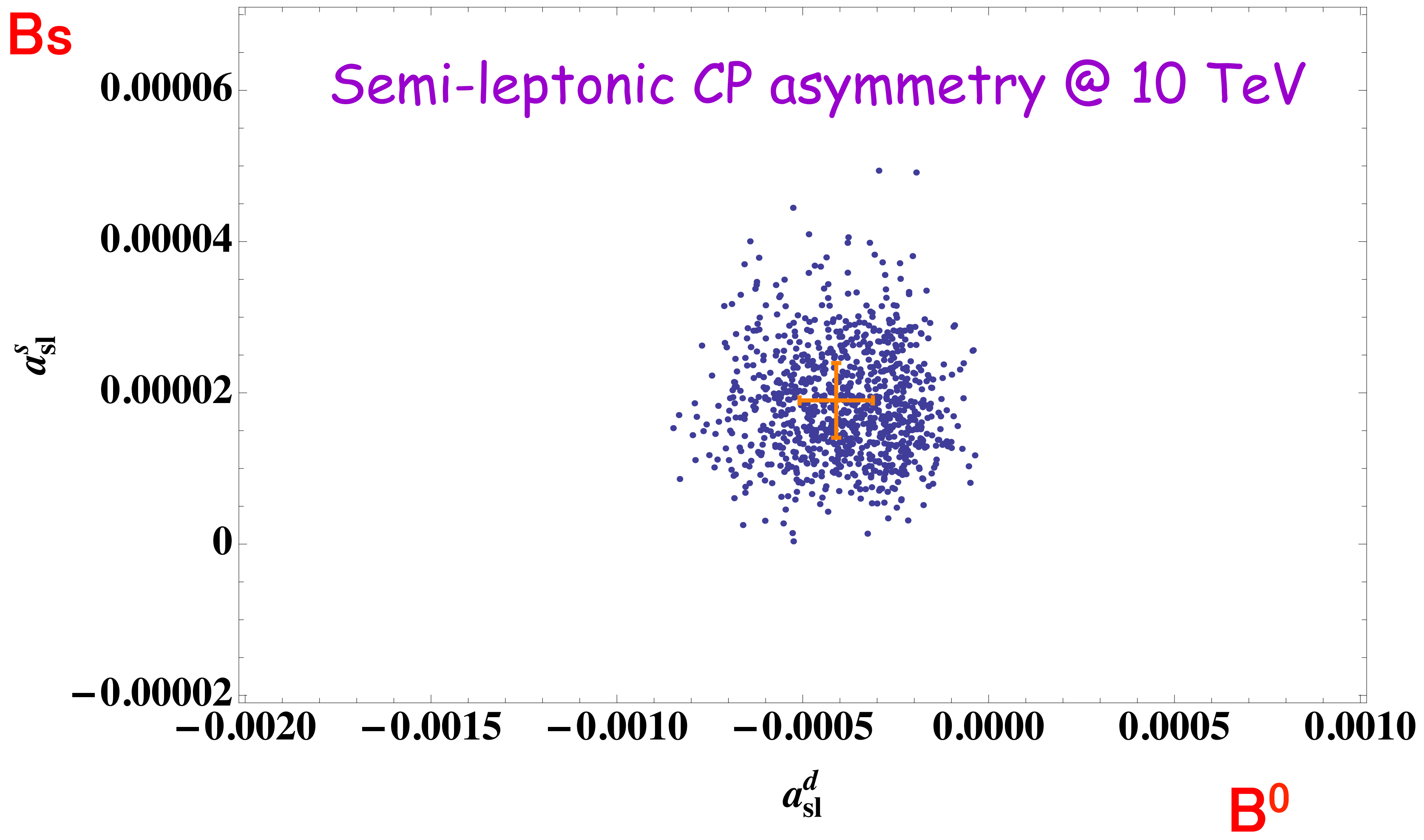


The deviation of $\sin\phi_d$ from $\sin 2\phi_1$ versus $s_{13}^{L(R)}$.



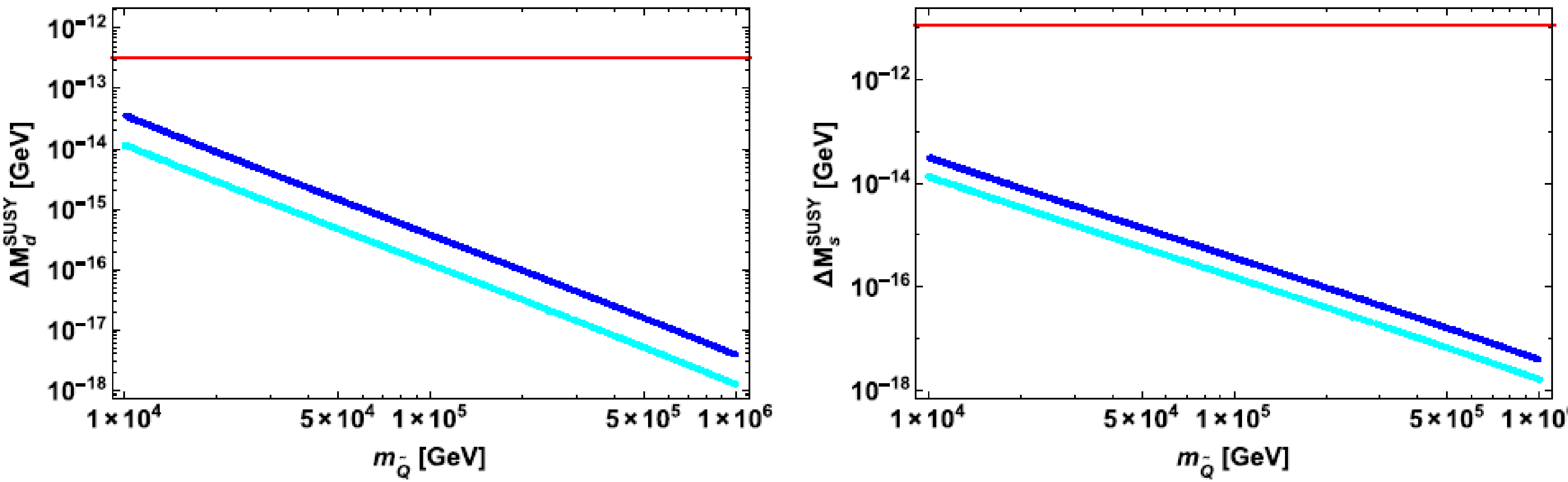
The SUSY contribution to ΔM_{B^0} versus $s_{13}^{L(R)}$.

SUSY contribution to B^0 system @ 10 TeV



$$a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33) \times 10^{-2}, \qquad a^d_{sl} = (-0.3 \pm 2.1) \times 10^{-3}.$$

B^0 **Bs**

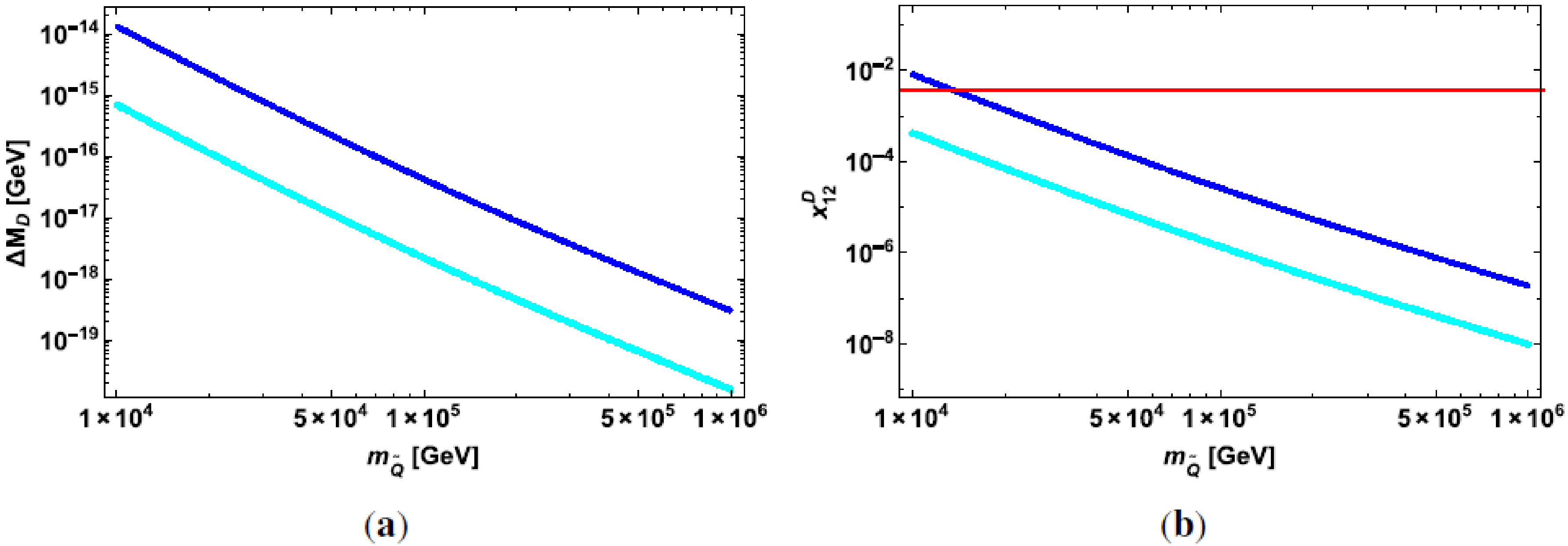


(**a**) (**b**)

The SUSY components of (**a**) ΔM_{B^0} and (**b**) ΔM_{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

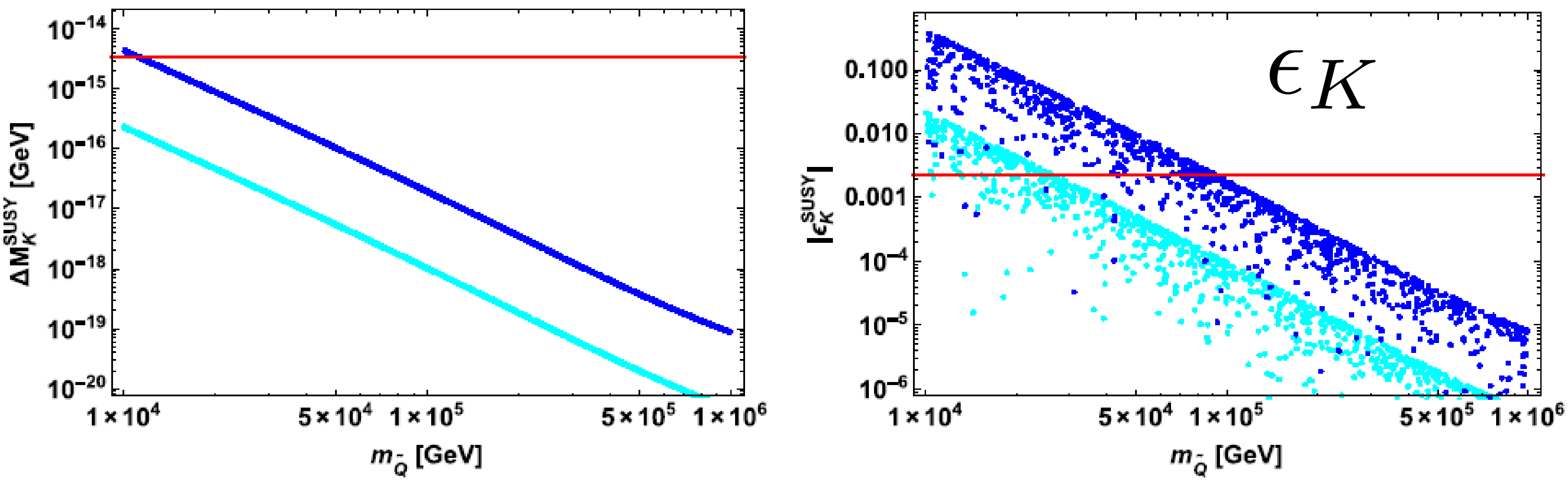
$$x_D = \frac{\Delta M_D}{\Gamma_D} = (3.6 \pm 1.6) \times 10^{-3}$$



The SUSY component of (**a**) ΔM_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

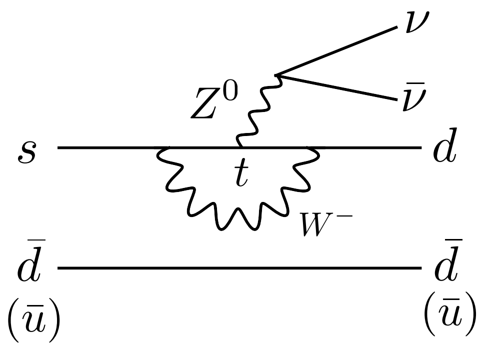
SUSY contributions to ΔM_K and ε_K

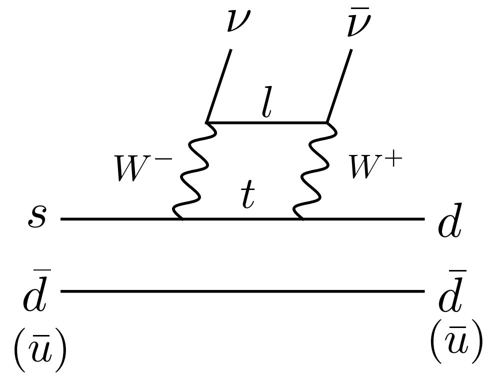


(a) (b)

The SUSY components of (**a**) ΔM_{K^0} and (**b**) $|\epsilon_K|$ *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.

$K_L \to \pi^0\nu\nu$ and $K^+ \to \pi^+\nu\nu$





- Rare decay : $BR_{SM} \sim 10^{-11}$

SM

$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11}$$

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11}$$

- Clean theoretically : theoretical uncertainty $\sim 2\%$ [Buras et all, 2006]

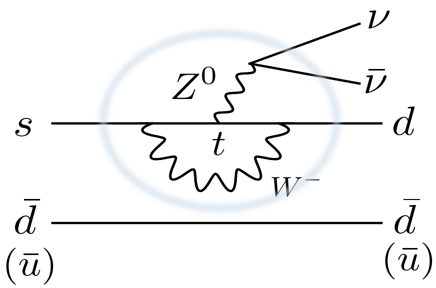
⇒ Sensitive to New Physics

$$BR(K_L \to \pi^0\nu\bar{\nu})_{\mathrm{exp}} < 2.6 \times 10^{-8} \ (90\%\mathrm{C.L.})$$ ←KOTO experiment

$$BR(K^+ \to \pi^+\nu\bar{\nu})_{\mathrm{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$ @J-PARC

K → πνν in SM

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



$$F = V_{cs}^* V_{cd} X_c + V_{ts}^* V_{td} X_t$$

$K_L \to \pi^0 \nu\nu$

CP - CP +

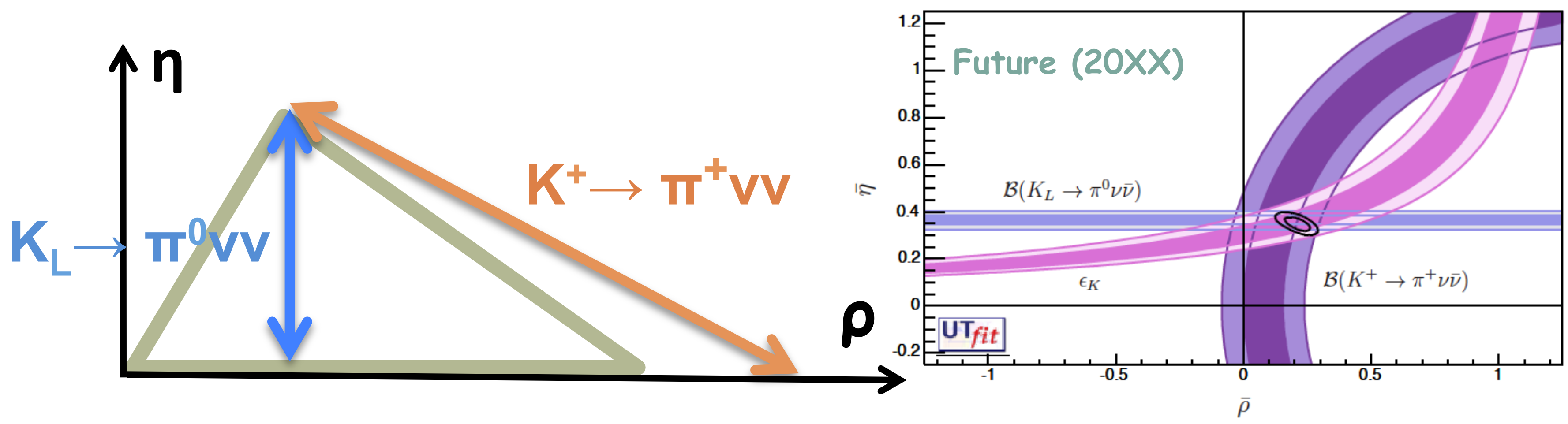
Direct CPV

$$A(K_L \to \pi^0 \nu\bar{\nu}) \propto A(K^0 \to \pi^0 \nu\bar{\nu}) - A(\bar{K}^0 \to \pi^0 \nu\bar{\nu})$$
$$\propto F - F^*$$
$$\propto \text{Im}F$$
$$\propto \eta$$

$K^+ \to \pi^+ \nu\nu$

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) \propto |F|^2$$
$$\propto \left[(\text{Re}F)^2 + (\text{Im}F)^2\right]$$
$$\propto \left[\left(\bar{\rho} - \rho^0\right)^2 + \bar{\eta}^2\right]$$

$K \to \pi\nu\nu$ in SM



$K_L \to \pi^0\nu\nu$

CP − CP +

Direct CPV

$$A(K_L \to \pi^0\nu\bar{\nu}) \propto A(K^0 \to \pi^0\nu\bar{\nu}) - A(\bar{K}^0 \to \pi^0\nu\bar{\nu})$$
$$\propto F - F^*$$
$$\propto \mathrm{Im}F$$
$$\propto \eta$$

$K^+ \to \pi^+\nu\nu$

$$BR(K^+ \to \pi^+\nu\bar{\nu}) \propto |F|^2$$
$$\propto [(\mathrm{Re}F)^2 + (\mathrm{Im}F)^2]$$
$$\propto \left[\left(\bar{\rho} - \rho^0\right)^2 + \bar{\eta}^2\right]$$

SUSY contribution to K → πνν

Chargino Penguin dominance

It is known there are no large enhancement in K → πνν 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

$$\frac{BR(K_L \to \pi^0 \nu \bar{\nu})}{BR(K_L \to \pi^0 \nu \bar{\nu})_{\rm SM}} \leq 1.02$$

- with non-MFV [A.J.Buras,et al (2005)]

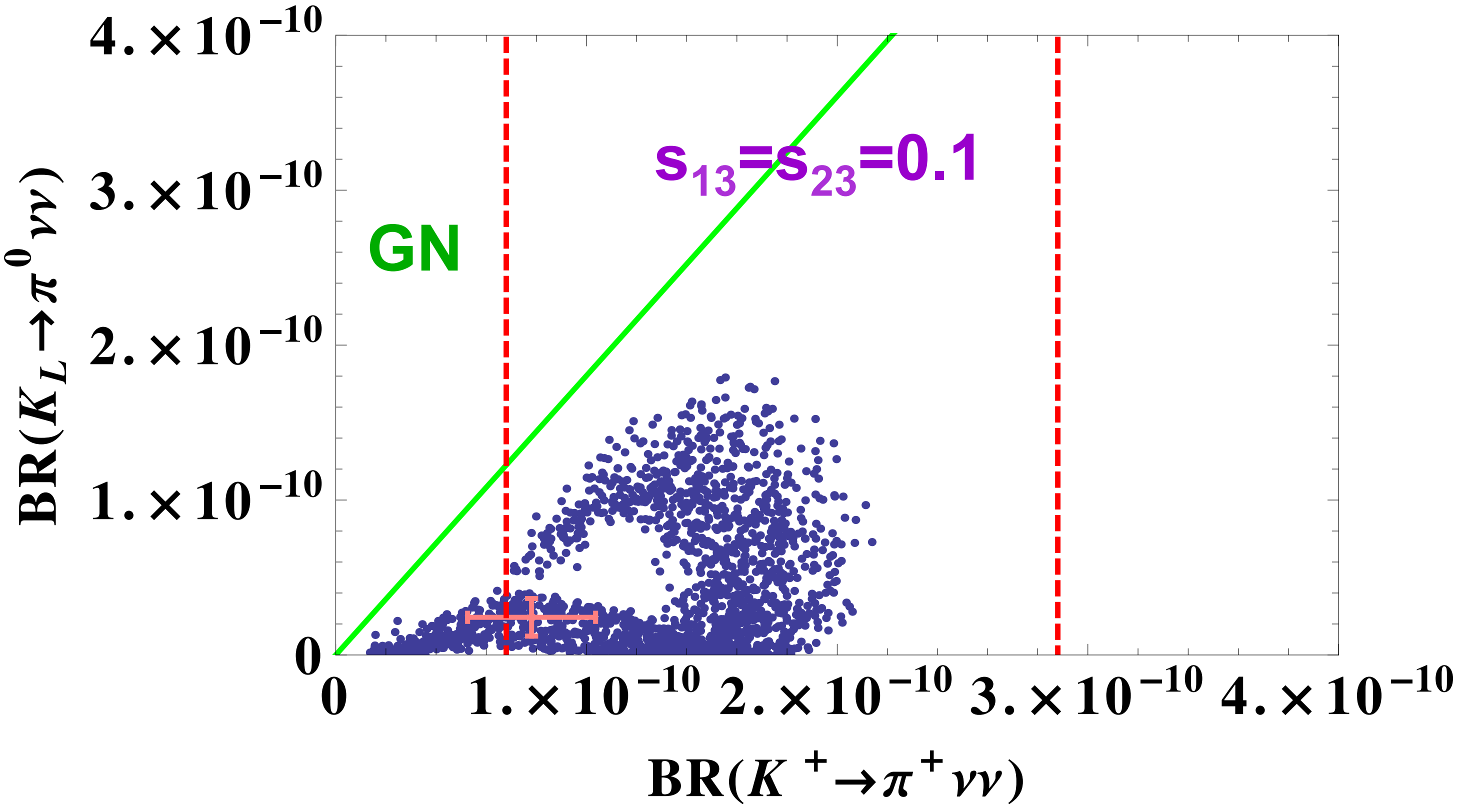
@ Squark mass = 600 GeV, Gluino mass = 1 TeV
$$BR(K_L \to \pi^0 \nu \bar{\nu}) \leq 4.3 \times 10^{-10}$$

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

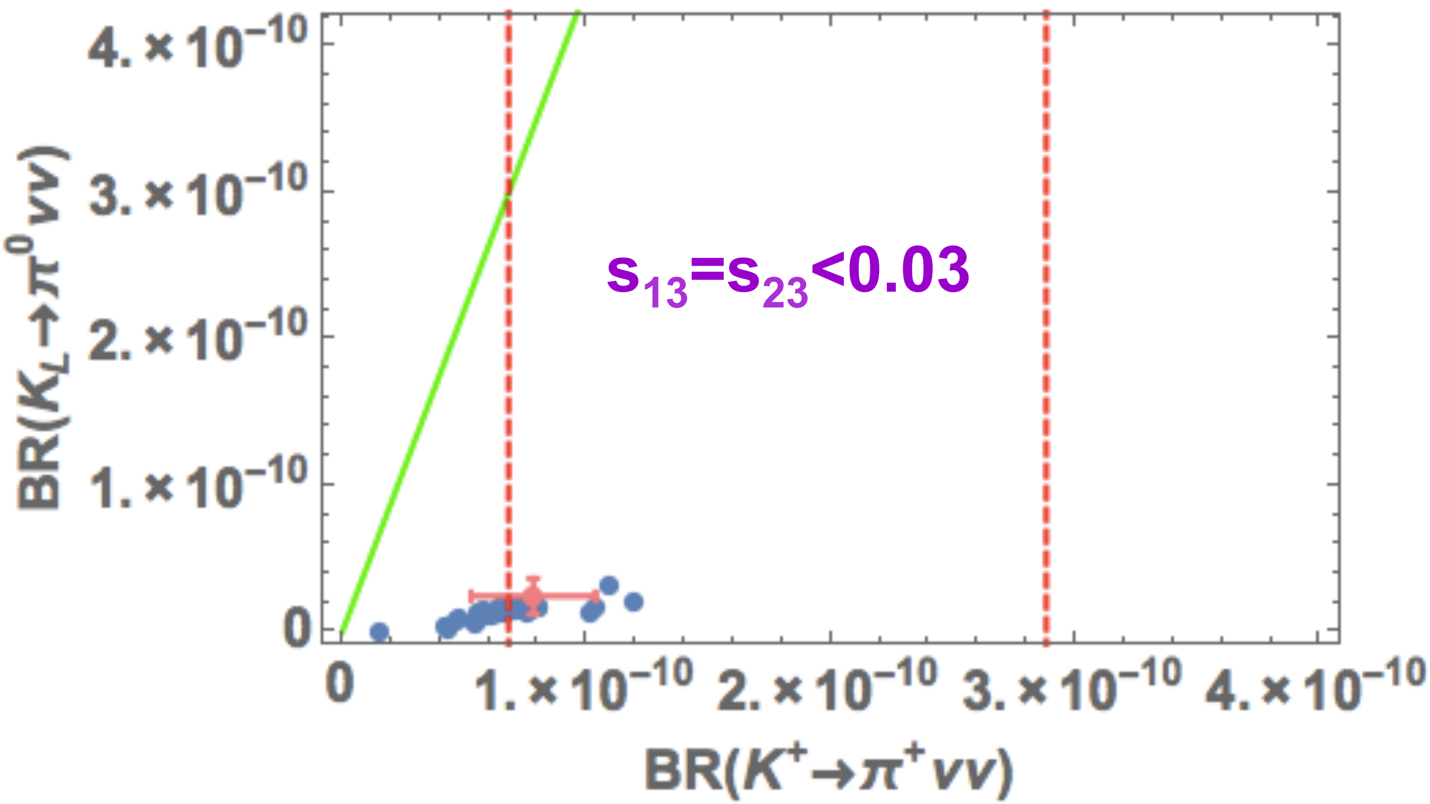
- LR mixing is suppressed due to heavy masses of SUSY.
- LL Chargino contribution is dominant.
- LL is not constrained by Exp. Data.

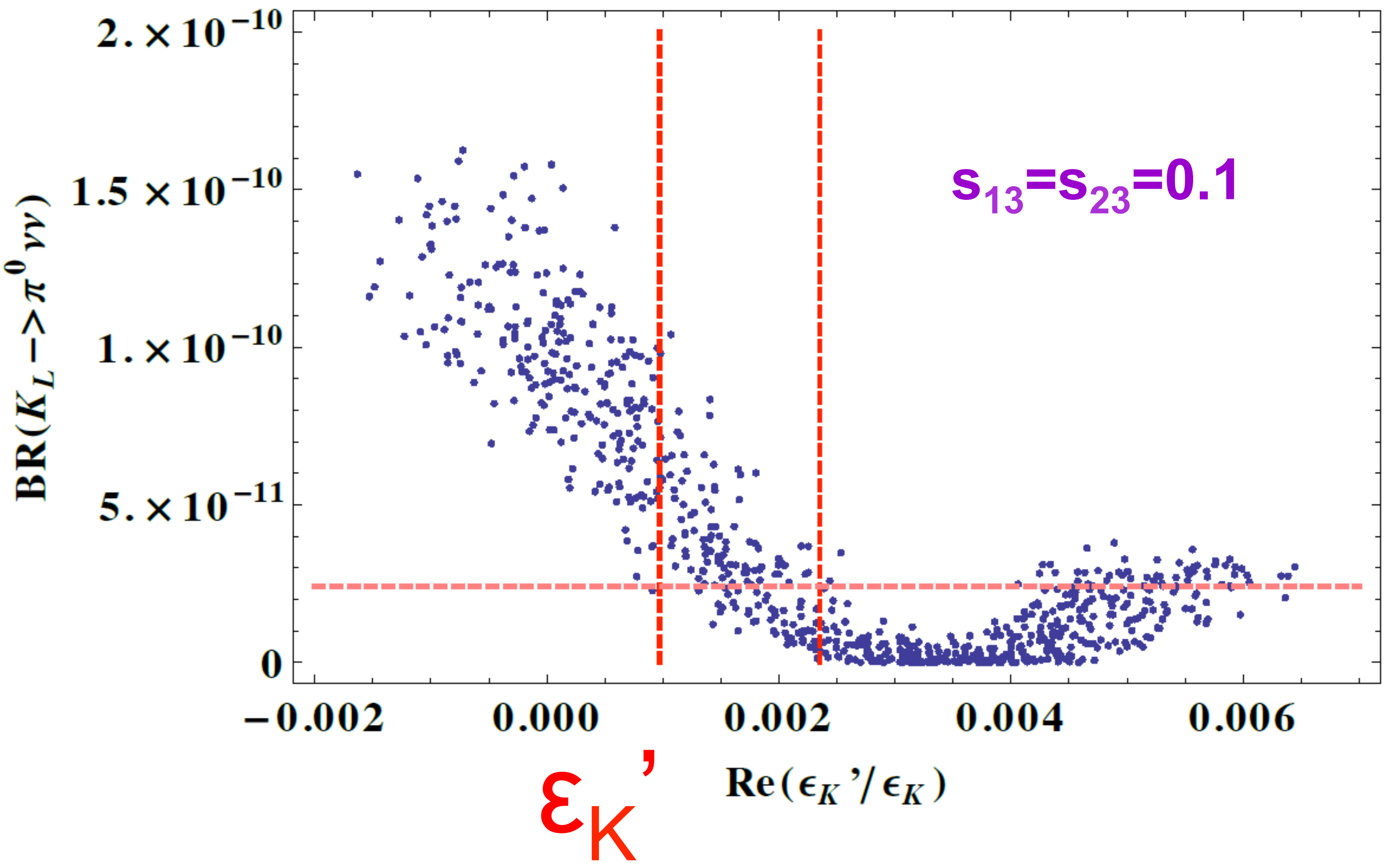
ε_K & $\Delta M_{d,s}$ & sin2β & b->sγ



LL contribution of Chargino Penguin @1TeV

With epsilonK & ΔMd,s & sin2β & b->sγ cut





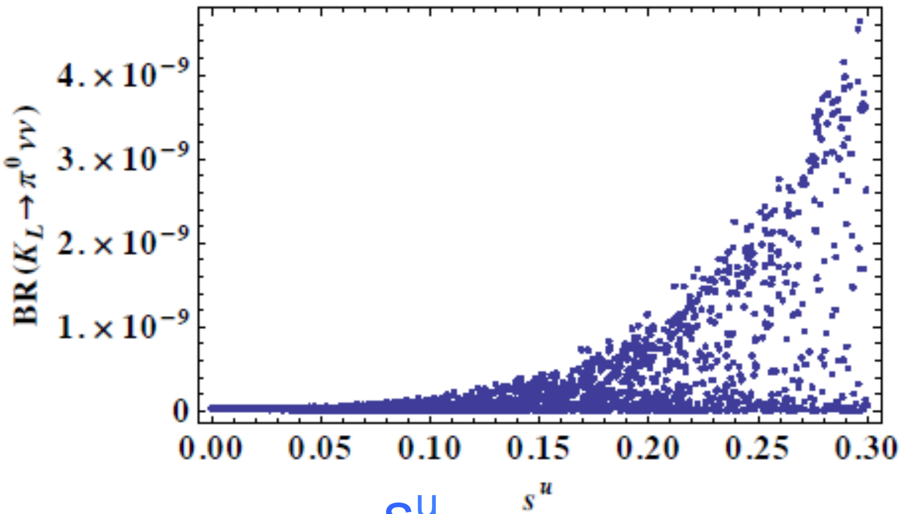
Hadronic Matrix elements:

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

Numerical analysis results @ Q_0=10 TeV

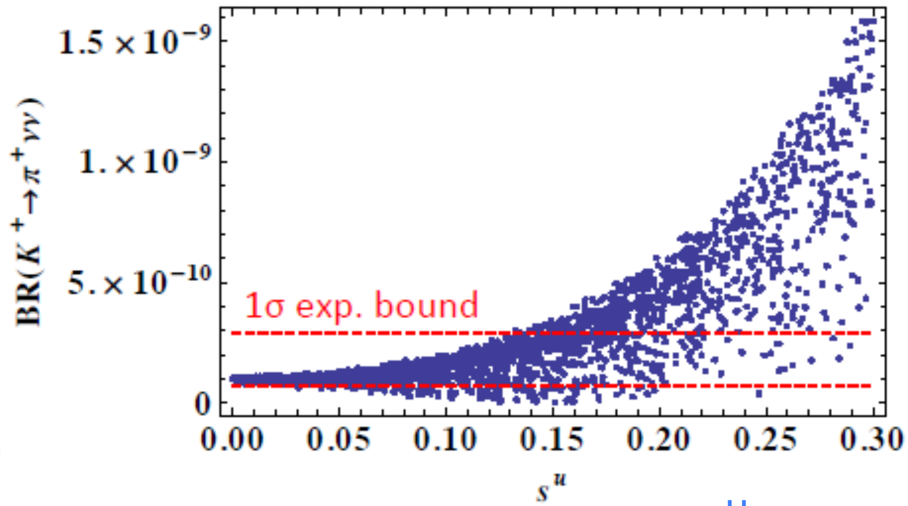
- s^d & s^u dependense

$\sim 100 \times SM$



s^u

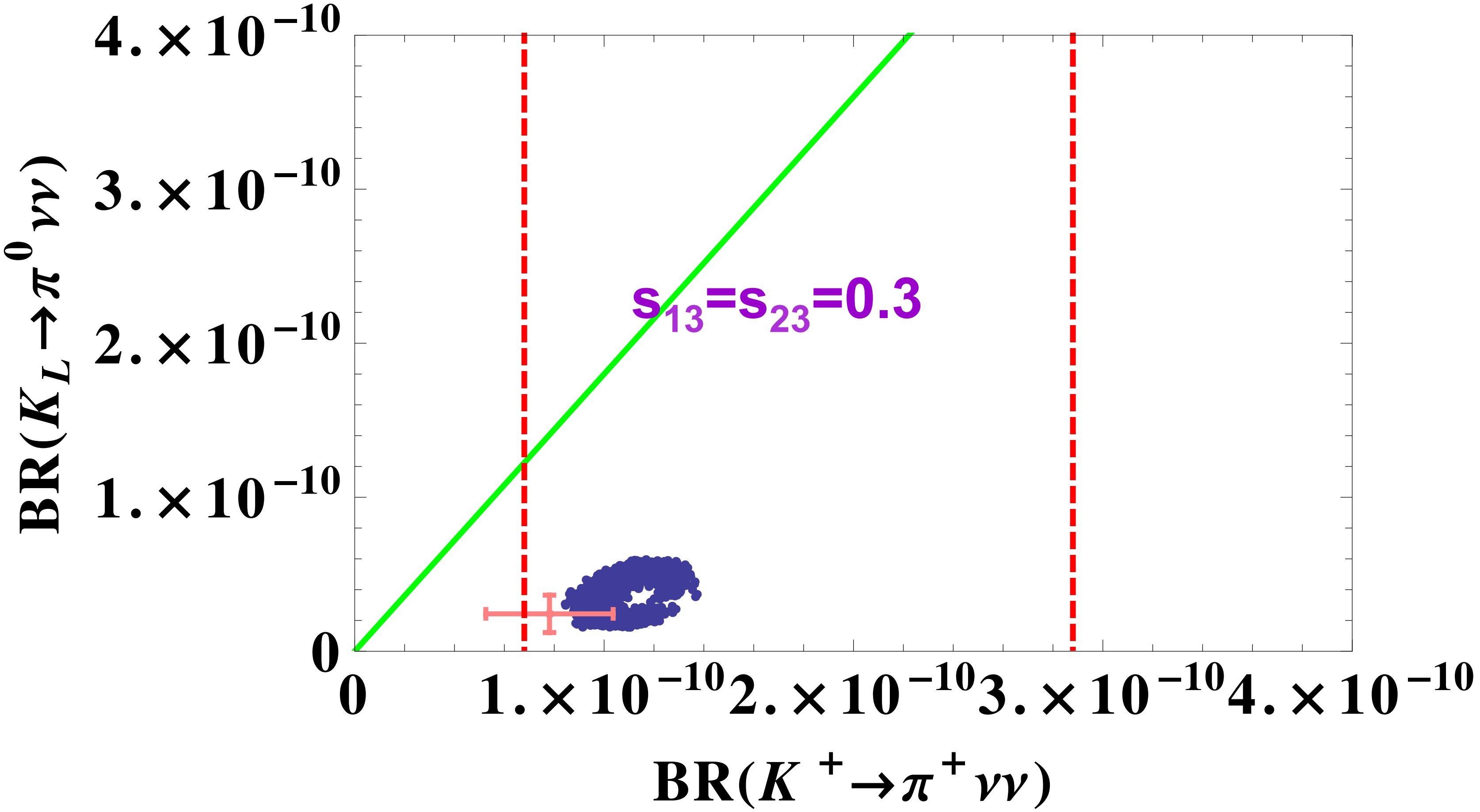
$\sim 20 \times SM$

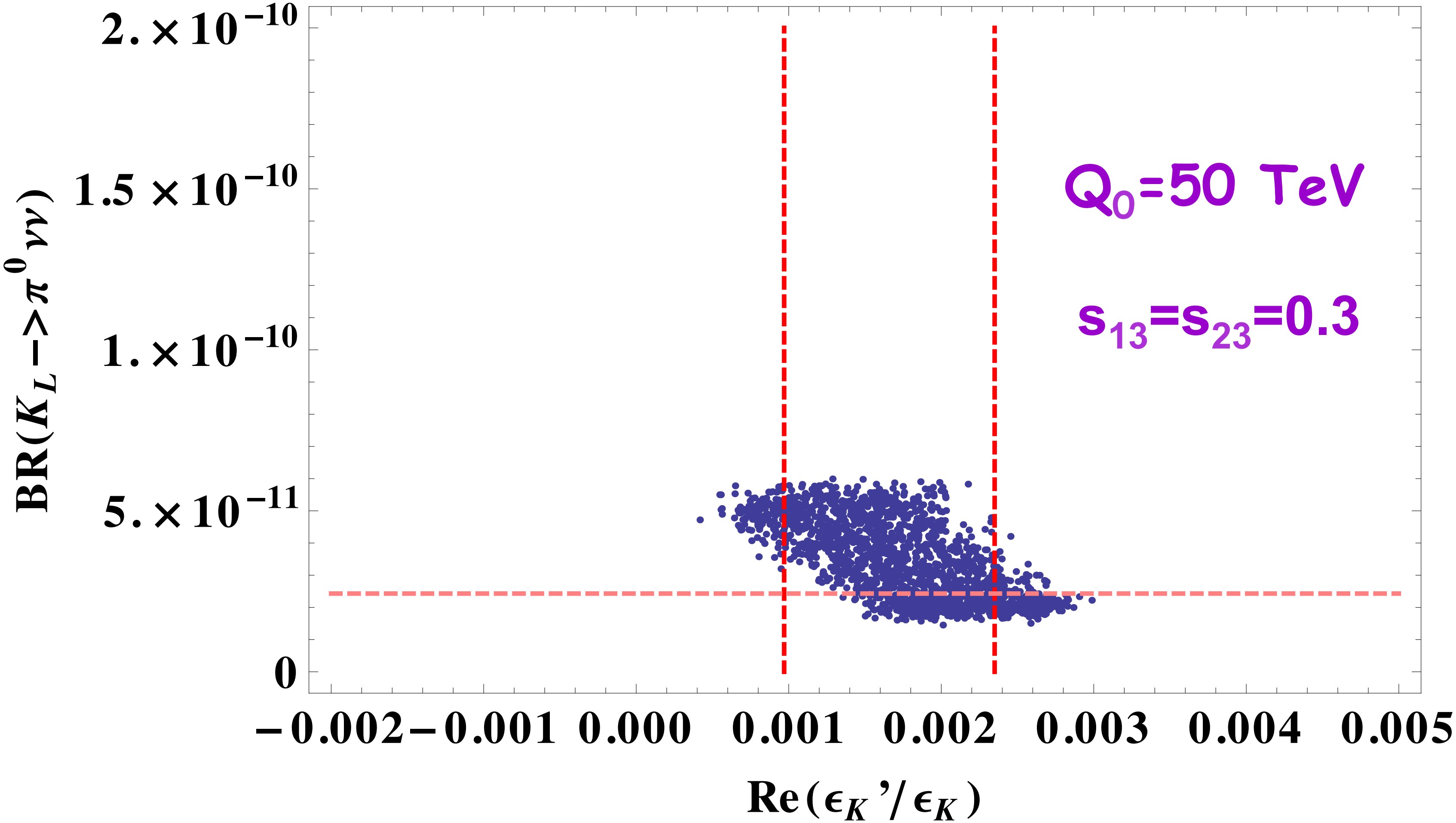


s^u

$s^u \equiv s^u{}_{13} = s^u{}_{23}$

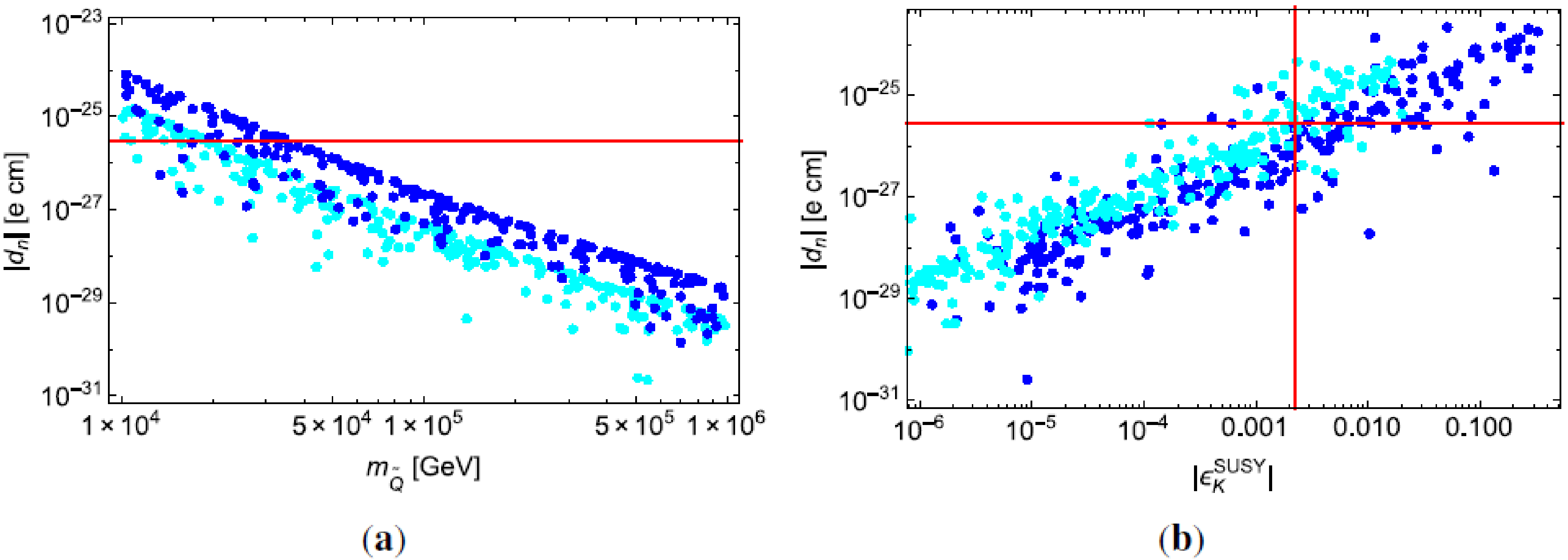
Numerical analysis results @ Q_0=50 TeV





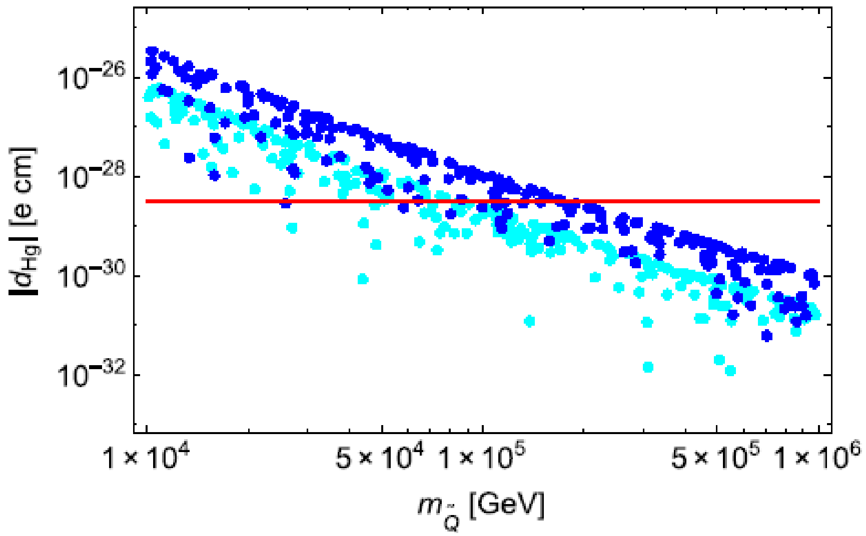
$\varepsilon_K{}'$

Neutron EDM

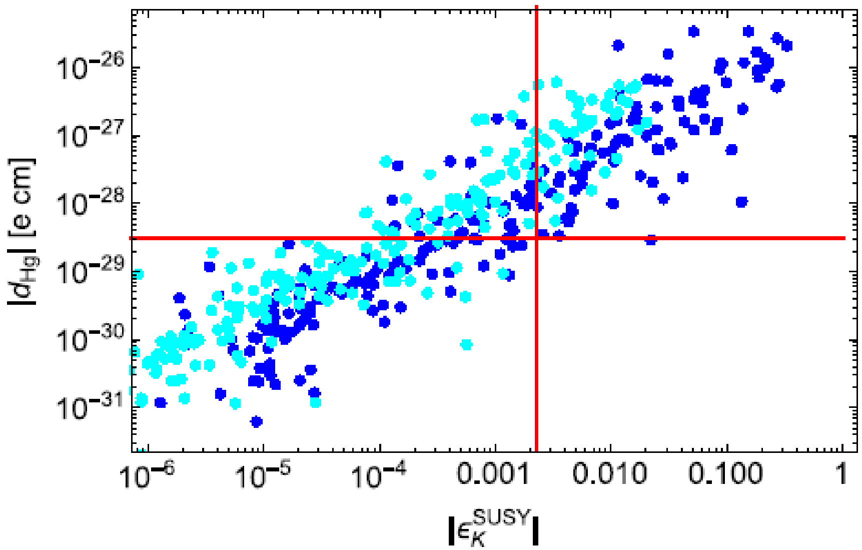


The the neutron EDM *versus* (**a**) $m_{\tilde{Q}}$ and (**b**) *versus* $|\epsilon_K^{\rm SUSY}|$ for $s_{13} = s_{23} = 0.22$ (cyan) and 0.5 (blue) for the case of the QCDsum rule. The horizontal red line denotes the experimental upper bound of $|d_n|$, and the vertical one is the experimental central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

Hg EDM



(a)



(b)

The the mercury EDM *versus* (**a**) $m_{\tilde{Q}}$ and (**b**) *versus* $|\epsilon_K^{\rm SUSY}|$ 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 $|\epsilon_K|$.

5 Summary

- SUSY contribution to FCNC of B mesons is at most 8%.

- ε_K and ε_K' have sensitivity of squark flavor mixing on the present experimental data even if SUSY scale is 100 TeV.

-

	$Q_0 = 10\text{TeV}$	$Q_0 = 50\text{TeV}$
	@s^d=s^u=0.1	@s^d=s^u=0.3
$BR(K_L \to \pi^0 \nu\bar{\nu})$	∼ 8 × SM	∼ 2 × SM
$BR(K^+ \to \pi^+ \nu\bar{\nu})$	∼ 3 × SM	∼ 2 × 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 !