CP and Flavor Physics

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"New era of CP and Flavor Physics"

- For a long time, the only observed CP violati
  was that in the $K^0-\bar{K}^0$ mixing.
  Now, we have
  - ϵ'/ϵ
  - CP violation in $B \to J/\psi K_S$ decay.
- For a long time, flavor mixing was observ
  only in the quark sector.
  Now, we observe
  - Neutrino Oscillation

Knowledge on Flavor and CP violation is a basis of the Standard Model.

1940's. , μ ; a new lepton.

why another electron?

Non observation of $\mu \to e\gamma$

1960's . two neutrinos

$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$ " generation structure

CP violation in K_L decay

1970's –

3 generation Standard Model

Kobayashi · Maskawa mechanism

(1) CP violation in K decay

(2) Cabibbo - Kobayashi - Maskawa matrix

(3) SUSY and Flavor Physics

(1) CP violation in K decay

CP violation in $K^0-\bar{K}^0$ mixing $(\Delta S = 2)$

$$|K_L\rangle = \overset{\curvearrowright 3\pi}{|K(CP-)\rangle} + \epsilon\, \overset{\curvearrowright 2\pi}{|K(CP+)\rangle}$$

$$|K_S\rangle \simeq |K(CP+)\rangle + \epsilon\, |K(CP-)\rangle$$

$K_L \to \pi\pi$ amplitude

$$\eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = |\eta_{+-}|\, e^{i\phi_{+-}} = \epsilon + \epsilon'$$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = |\eta_{00}|\, e^{i\phi_{00}} = \epsilon - 2\epsilon'$$

CPLEAR98

$$|\eta_{+-}| = (2.264 \pm 0.023 \pm 0.026) \times 10^{-3}$$

$$\varphi_{+-} = 43.19 \pm 0.53^\circ \pm 0.28^\circ$$

Superweak phase

$$\varphi_{SW} = \tan^{-1}\left(\frac{2\Delta m}{\Gamma_S - \Gamma_L}\right) = 43.50^\circ \pm 0.08^\circ$$

Main source of CP violation in the K system is the $K^0-\bar{K}^0$ mixing.

where τ_S is in ps, and has negligible dependence on the value of Δm.

$$A_{+-}(\tau) \simeq \frac{\overline{N}_{\overline{K}^0\to\pi^+\pi^-}(\tau) - N_{K^0\to\pi^+\pi^-}(\tau)}{\overline{N}_{\overline{K}^0\to\pi^+\pi^-}(\tau) + N_{K^0\to\pi^+\pi^-}(\tau)} = -2\frac{|\eta_{+-}| e^{\frac{1}{2}\Delta\Gamma\tau} \cos(\Delta m\tau - \phi_{+-}}{1 + |\eta_{+-}|^2 e^{\Delta\Gamma\tau}}$$

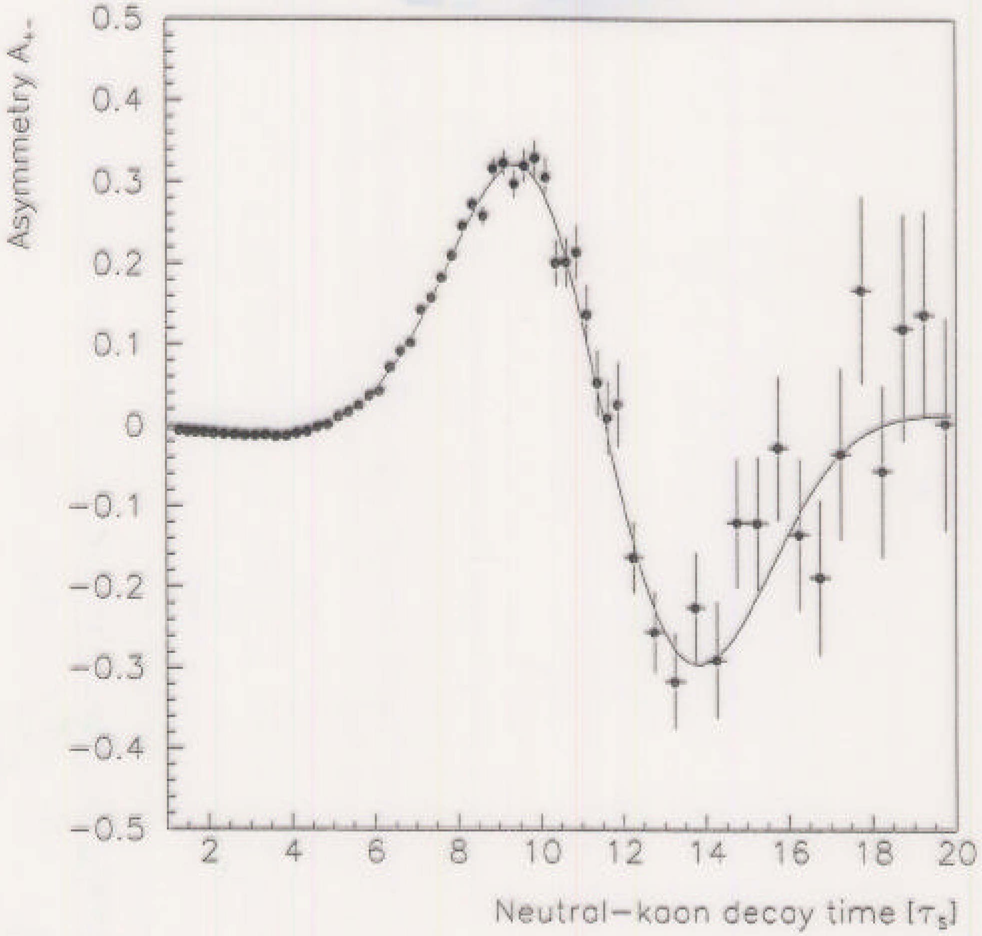


Figure 4: The time-dependent asymmetry A_{+-} vs the neutral-kaon decay time. The solid circles represent the data, including residual background, whereas the solid line is the result of our fit.

Using for $<\Delta m>$ and $<\tau_S>$ the world averages [8], $<\Delta m> = (530.1 \pm 1.4) \times 10^7 \hbar s^{-1}$ and $<\tau_S> = (89.32 \pm 0.08)$ ps, the results of the fit for ϕ_{+-} and $|\eta_{+-}|$ are:

$$\begin{aligned} |\eta_{+-}| &= (2.264 \pm 0.023) \times 10^{-3} \\ \phi_{+-} &= 43.19^\circ \pm 0.53^\circ, \end{aligned}$$

where the errors are purely statistical and $\chi^2/d.o.f. = 1.2$. Table 1 shows the correlation coefficients between ϕ_{+-}, $|\eta_{+-}|$ and α, given by the fit.

	ϕ_{+-}	$\lvert\eta_{+-}\rvert$	α
ϕ_{+-}	1	0.17	0.37
$\lvert\eta_{+-}\rvert$	-	1	0.65
α		-	1

Table 1: Correlation coefficients for the fitted values in the case of fixed Δm

An alternative way of presenting the data is given by the 'reduced asymmetry' $A_{\rm red}(\tau) = A_{+-}(\tau) \times e^{-\frac{1}{2}(\Gamma_S - \Gamma_L)\tau}$, as shown in Fig. 5. The physics content of this plot is identical to that of

Direct CP violation

$$\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 = 1 + 6\,\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (28.0 \pm 4.1)\times 10^{-4} \quad (\text{KTeV})$$

$$(14.0 \pm 4.3)\times 10^{-4} \quad (\text{NA 48})$$

$$(19.3 \pm 2.4)\times 10^{-4} \quad (\text{World Average}$$

In the SM. we can explain

- CP violation in K system is small ($O(10^{-3})$)
- $\Delta S = 2$ is dominant.
  $\Delta S = 1$ is non zero $\quad \frac{\epsilon'}{\epsilon} \sim O(10^{-3})$
- Large CP violation is expected in B system.

S. Bertolini
hep-ph/0101212

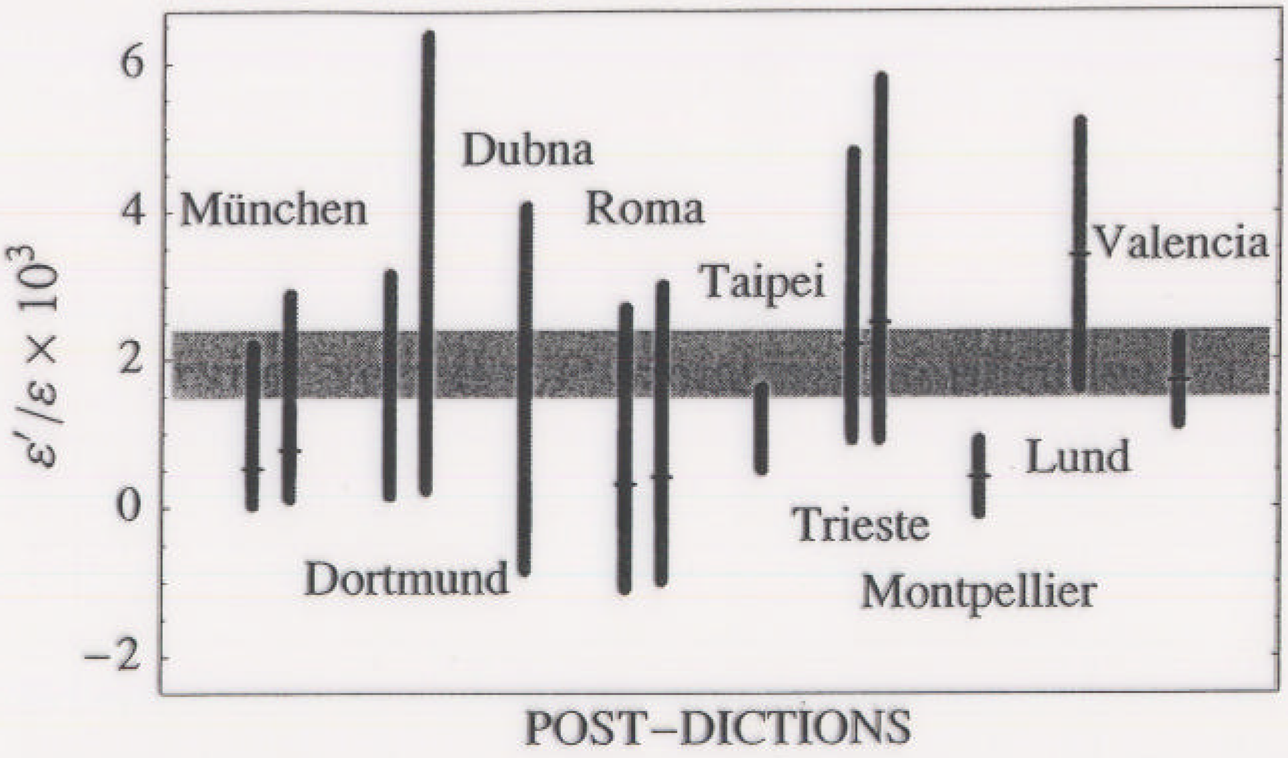


Figure 2: The latest theoretical calculations of ε'/ε are compared with the combined 1-σ average of the NA31, E731, KTeV and NA48 results ($\varepsilon'/\varepsilon = 19.2 \pm 4.6 \times 10^{-4}$), depicted by the gray horizontal band (the error is inflated according to the Particle Data Group procedure when averaging over data with substantially different central values).

(2) Cabibbo - Kobayashi - Maskawa Matrix

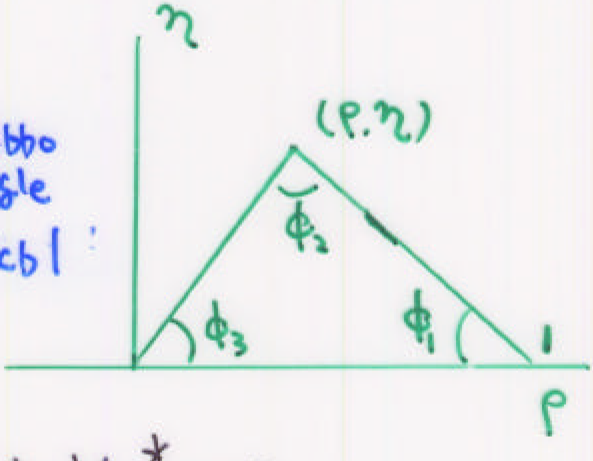
$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{u}_{iL} \gamma^{\mu} (V)_{ij} d_{jL} W^{+}_{\mu} + \text{c.c}$$

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$$\simeq \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$\lambda \sim 0.22$ cabibbo angle

$A \sim 0.8$ $|V_{cb}|$



Unitarity triangle

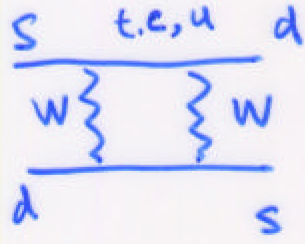
$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

$\phi_1 = \beta$

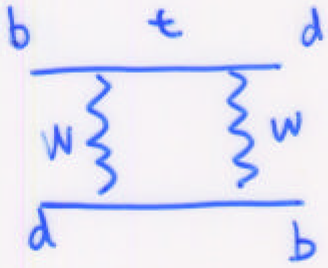
$\phi_2 = \alpha$

$\phi = \gamma$

Constraints on (ρ, η) space

① $\epsilon = \mathrm{Im}\ \langle K^0|$  $|\bar{K}^0\rangle$

② $|V_{ub}| \propto \sqrt{\rho^2+\eta^2}$

③ $\Delta M_{Bd} = \Big|\langle B^0|$  $|\bar{B}^0\rangle\Big|$

$$\propto f_{Bd}^2 B_d \left((1-\rho)^2 + \eta^2\right)$$

④ $$\frac{\Delta M_{Bs}}{\Delta M_{Bd}} \propto \frac{f_{Bs}^2 B_{Bs}}{f_{Bd}^2 B_{Bd}} \frac{1}{(1-\rho)^2+\eta^2}$$

The ratio of $f_{Bs}^2 B_s$ and $f_{Bd}^2 B_d$ is better determined by lattice gauge theory than $f_{Bd}^2 B_d$ itself.

$\Delta M_{Bs} > 14.9\,\mathrm{ps}^{-1}$ (95%CL)

ICHEP 2000

⇒ Tevatron Run II.

⑤ CP asymmetry of $B \to J/\psi K_S$ and related modes

Time dependent asymmetry of $B \to J/\psi K_S$ decay provides a direct measurement of $\sin 2\phi_1$

$$\frac{\Gamma(B^0(t) \to J/\psi K_S) - \Gamma(\bar{B}(t) \to J/\psi K_S)}{\Gamma(B^0(t) \to J/\psi K_S) + \Gamma(\bar{B}(t) \to J/\psi K_S)}$$

$$= - \sin 2\phi_1 \cdot \sin \Delta m\, t$$

$$\begin{tikzcd}
B^0 \arrow[rr] \arrow[dr, swap, "{M_{12} = \langle B^0 | \Delta H_W | \bar{B}^0 \rangle \propto e^{+2i\phi_1} |M_{12}|}"] & & J/\psi K_S \\
& \bar{B}^0 \arrow[ur] &
\end{tikzcd}$$

New results from Belle and BaBar

$$\sin 2\phi_1 = 0.58^{+0.32}_{-0.34}{}^{+0.09}_{-0.10} \quad \left(\begin{array}{l}\text{Belle} \\ \text{hep-ex/0102018}\end{array}\right)$$

$$0.34 \pm 0.20 \pm 0.05 \quad \left(\begin{array}{l}\text{BaBar} \\ \text{hep-ex/0102030}\end{array}\right)$$

$$0.79^{+0.41}_{-0.44} \quad (\text{CDF } 98)$$

⑥ $K^+ \to \pi^+ \nu \bar{\nu}$, $K_L \to \pi^0 \nu \bar{\nu}$

Theoretically clean processes

Little hadronic ambiguitiy

Form factor is determined from $K^+ \to \pi^0 e^+ \nu$

QCD corrections are under control (A. Buras et

5% unbiguity for $K^+ \to \pi^+ \nu \bar{\nu}$

o(1)% 〃 for $K_L \to \pi^0 \nu \bar{\nu}$

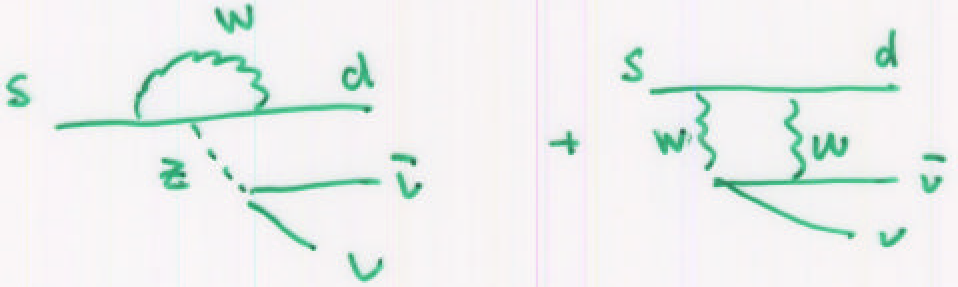
In the SM

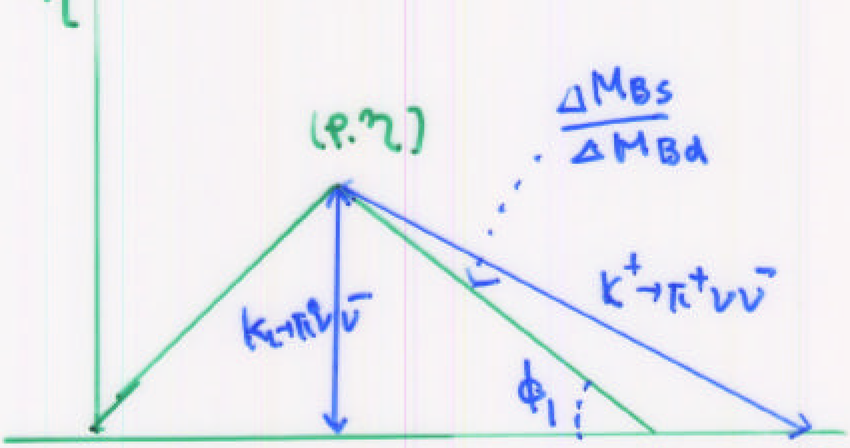
$1.5^{+3.4}_{-1.2} \times 10^{-1}$

(B

$$B(K^+ \to \pi^+ \nu \bar{\nu}) \sim 4.2 \times 10^{-11} (\eta^2 + (1.4 - \rho)^2)$$

$$B(K_L \to \pi^0 \nu \bar{\nu}) \sim 1.8 \times 10^{-10} \eta^2$$





Determination of $B(K \to \pi \nu \bar{\nu})$ at 10% level is useful to test the consistency of the Unitarity triangle

(3) SUSY and Flavor Physics

Supersymmetry (SUSY)

- A very attractive candidate of physics beyond the S
  - Solve hierarchy problem in the SM
  - Gauge coupling unification in SUSY GUT.

- Tevatron and LHC experiments will provide (almost) definitive answer on existence of SUSY.
  - Super particle's mass reach $\lesssim 2$ TeV at LHC
  - Light Higgs boson ($m_h \lesssim 130$ GeV for MSSM)

- If we are lucky, we may be able to obtain some hint on SUSY from flavor physics before the start of LHC.

When some of SUSY particles are discovered, flavor physics becomes very important.

T. Goto. Y. Okada. Y. Shimizu
hep-ph/9908499

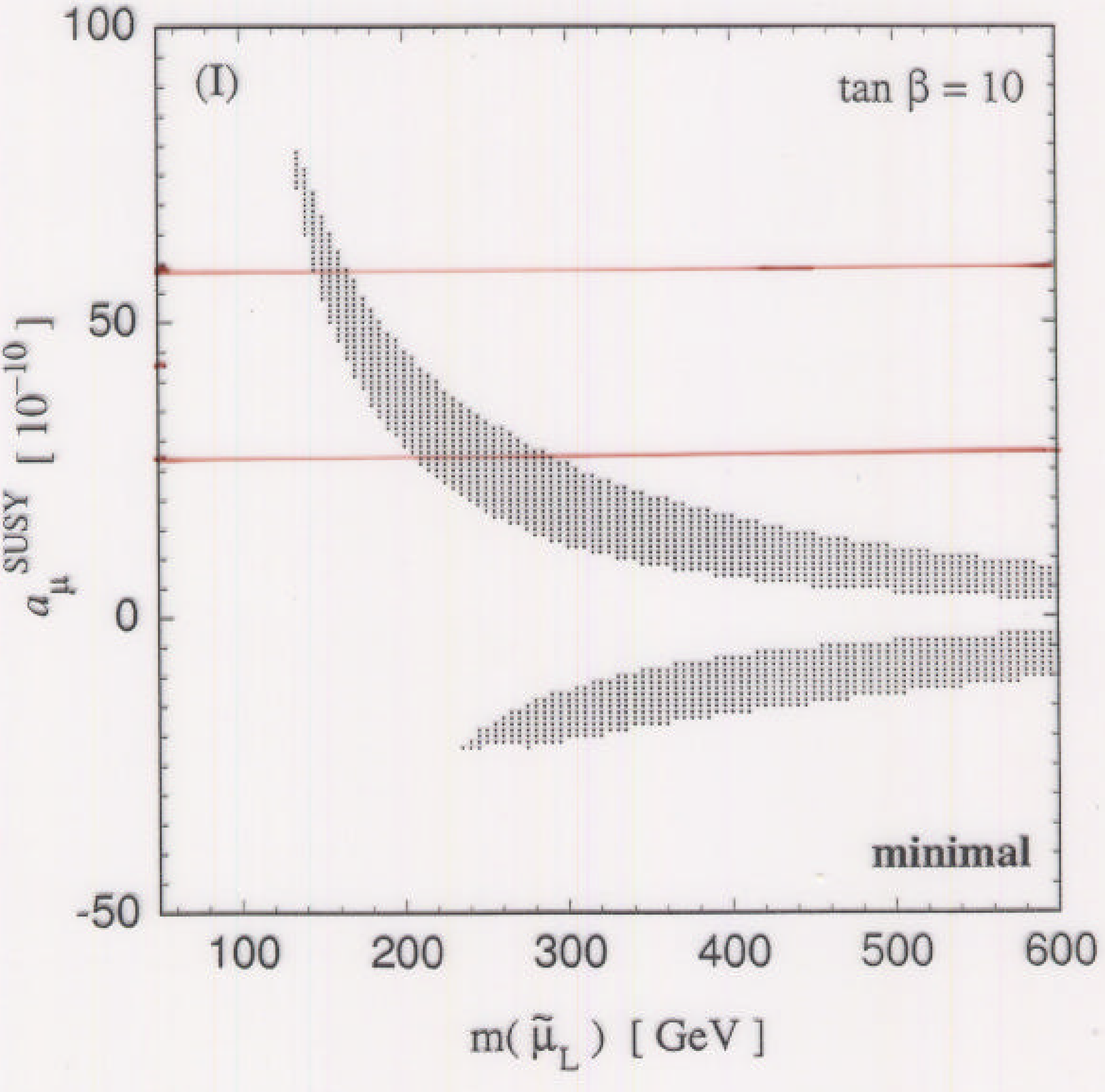
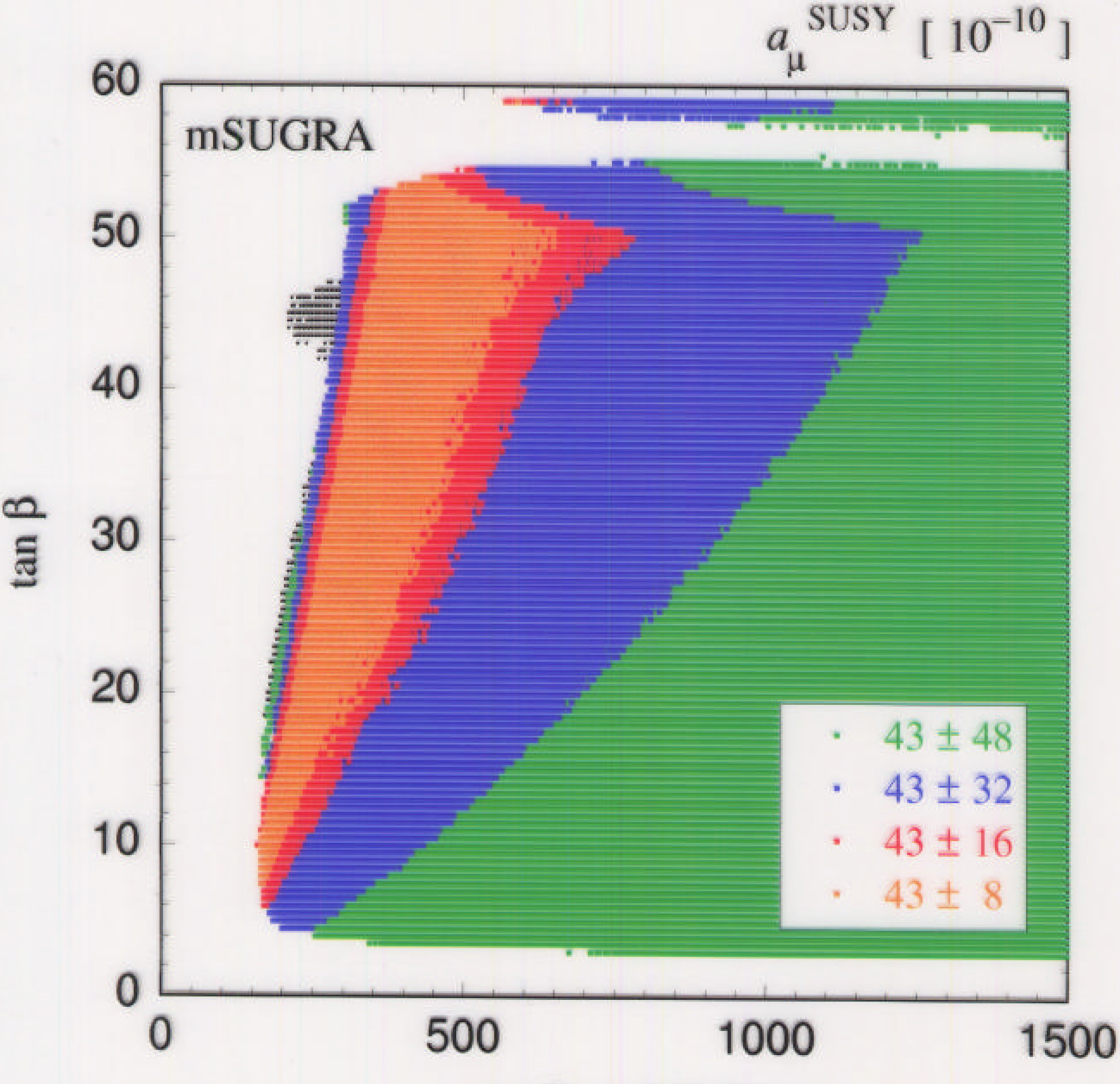


Fig. 10(b)

minimal supergravity
model

T. Goto - Y.



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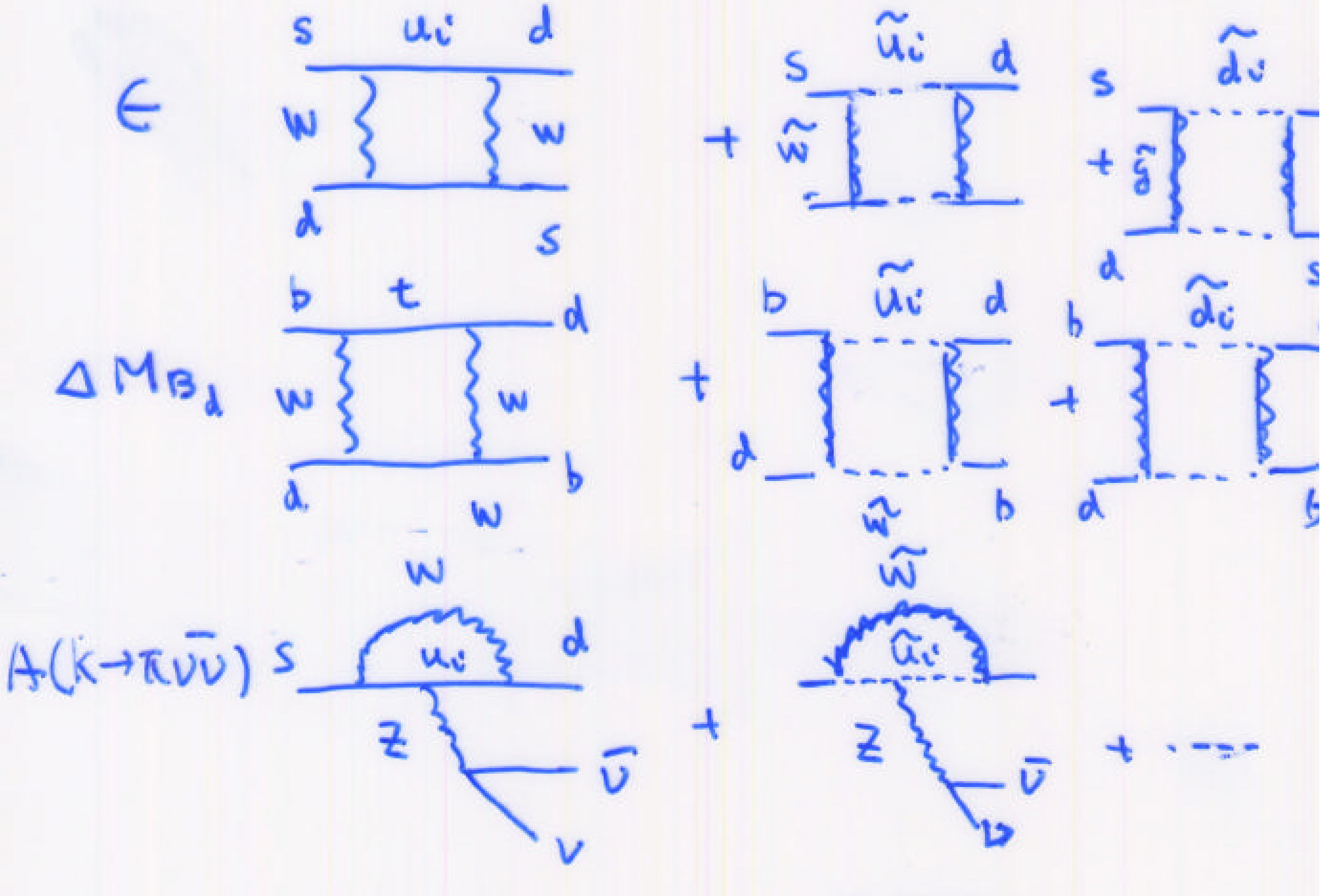
② minimal supergravity model

A unique source of the squark flavor mixing is the quark Yukawa coupling constant.

Squark mixing ≃ quark mixing (CKM matrix)



- SUSY contribution is $\overset{\text{SUSY loop}}{\lesssim}$ 10 – 30%
- Correlations
  - ϵ. ΔM_d enhanced
  - $B(K\to\pi\nu\nu)$ suppressed
  - $\frac{\Delta M_{Bs}}{\Delta M_{Bd}}$ $A_{cp}(B\to J/\psi K_S)$ unchanged

T.Goto. Y.Okada. Y.Shimizu
hep-ph/9908499

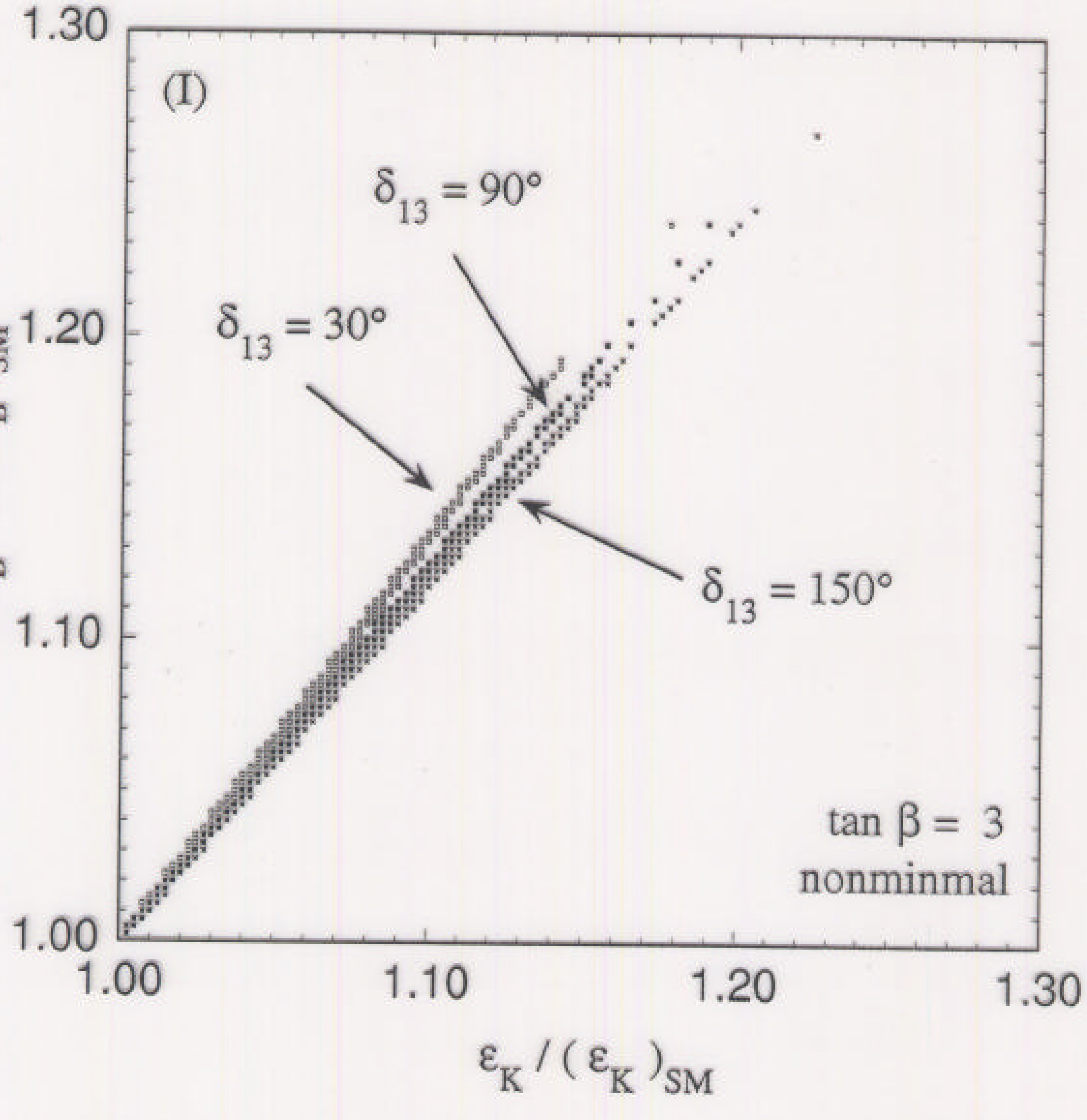


Fig. 6

T.Goto. Y.Okada. Y.Shimiz
hep-ph/9908499

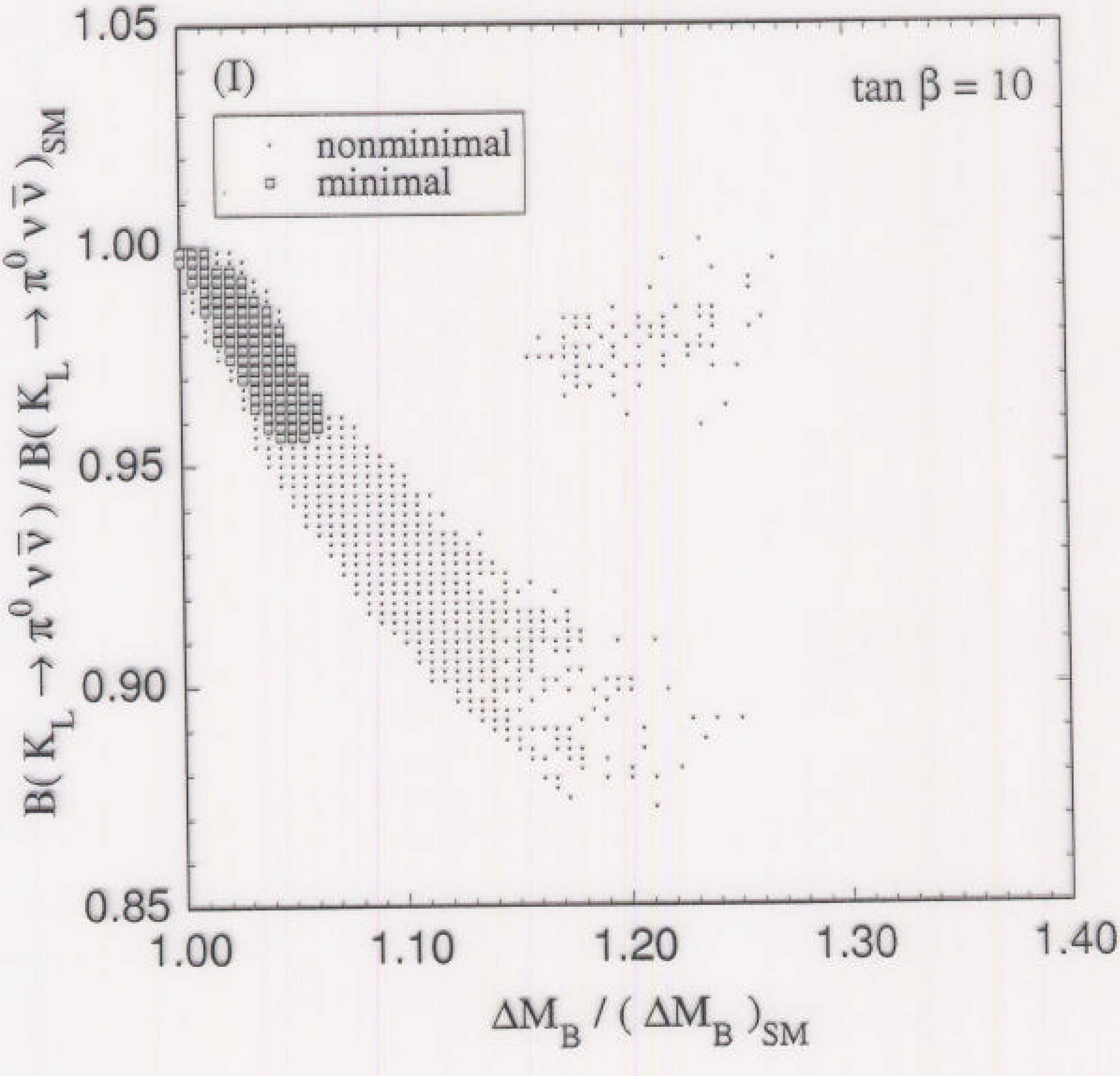
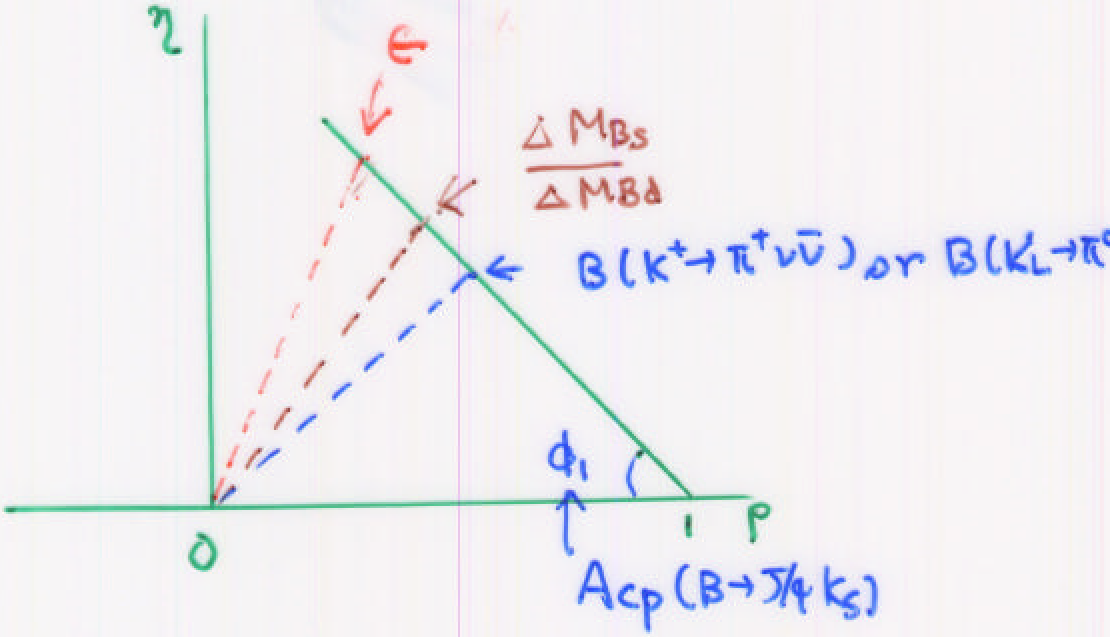


Fig. 8(b)

Inconsistency in determination of the Unitarity triangle



③ SU(5) SUSY GUT + right-handed neutrino

Neutrino Oscillation

⇐ Flavor mixing in the neutrino sector.

See-Saw model

Introduce heavy ($10^{10}-10^{14}$ GeV) right-handed neutrino and the neutrino Yukawa coupling consta

$$\mathcal{L} = y_\nu H^\dagger \bar{\nu}_R l_L - \frac{1}{2} \bar{\nu}_R M_R \nu_R^c + h.c.$$

$$m_\nu \sim (y_\nu v)^T \frac{1}{M_R} y_\nu v$$

small neutrino mass

The neutrino Yukawa coupling constants become a new source of flavor mixing.

$y_\nu \xrightarrow{\text{SUSY}}$ flavor mixing in the slepton sector

⇒ Lepton Flavor Violation (LF

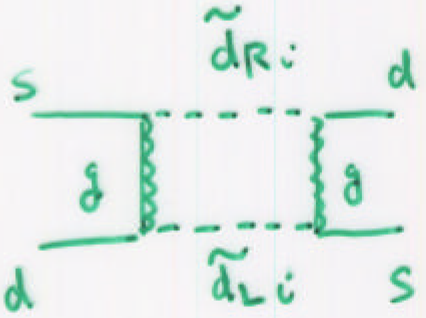
$y_\nu \xrightarrow{\text{GUT}}$ flavor mixing in the the squark sector

⇒ Flavor Changing neutral Current (FCNC) in B &

Atmospheric ν $\Longleftrightarrow$ Large mixing in $2 \leftrightarrow 3$

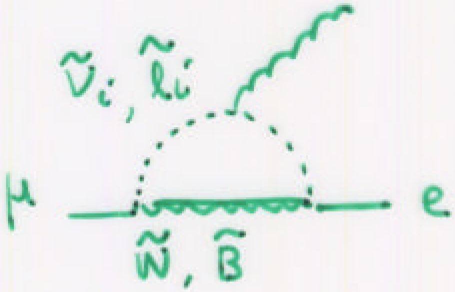
Solar ν $\Longleftrightarrow$ Large mixing in $1 \leftrightarrow 2$

SUSY contributions to ϵ and $B(\mu \to e\gamma)$ are large.



ϵ

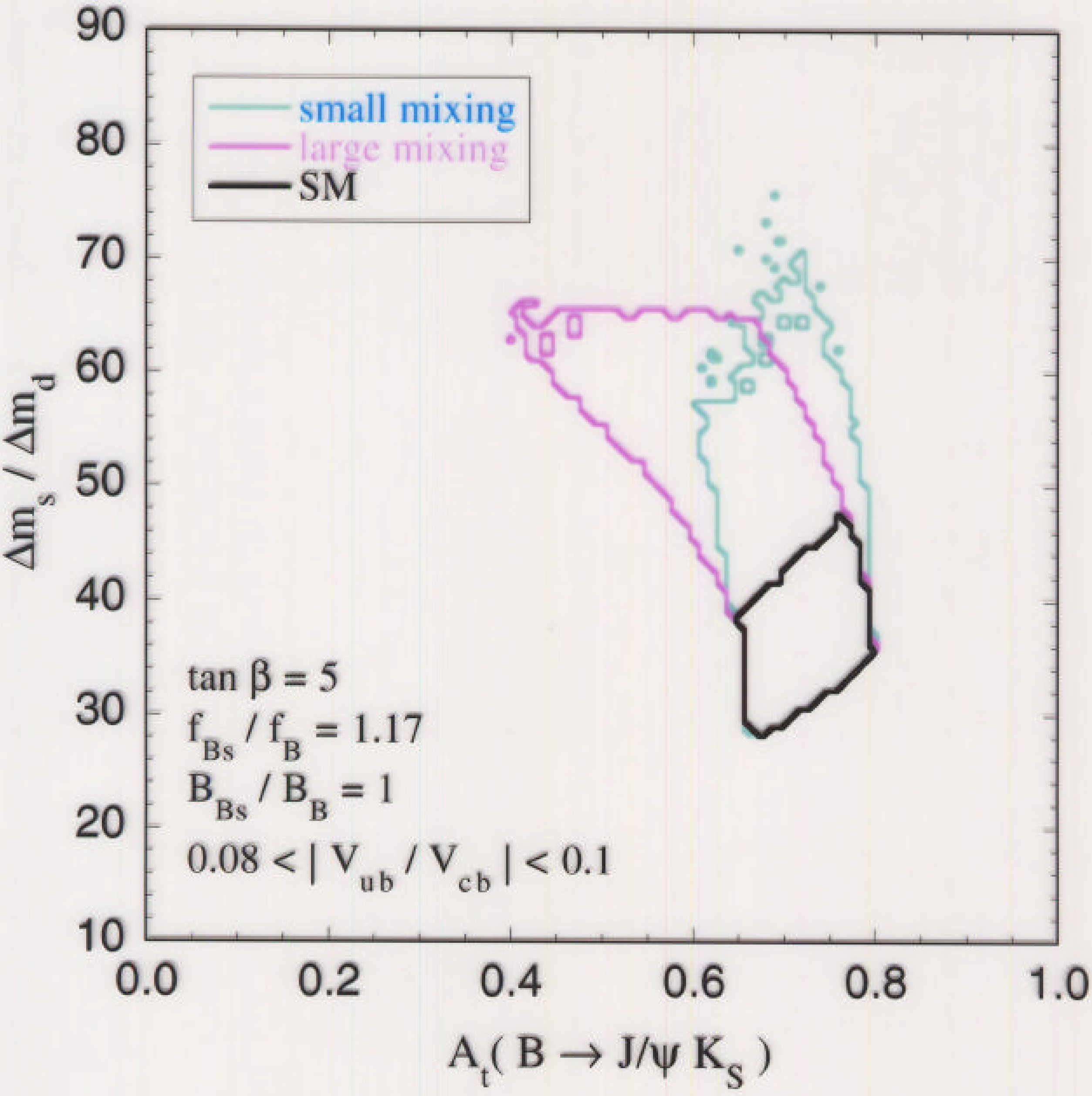
,



$B(\mu \to e\gamma)$

- Allowed region in $\frac{\Delta M_{Bs}}{\Delta M_{Bd}}$, $A_{cp}(B \to J/\psi K_s)$ is different from the SM case

- $B(\mu \to e\gamma)$ can be close to the current experimental bound.



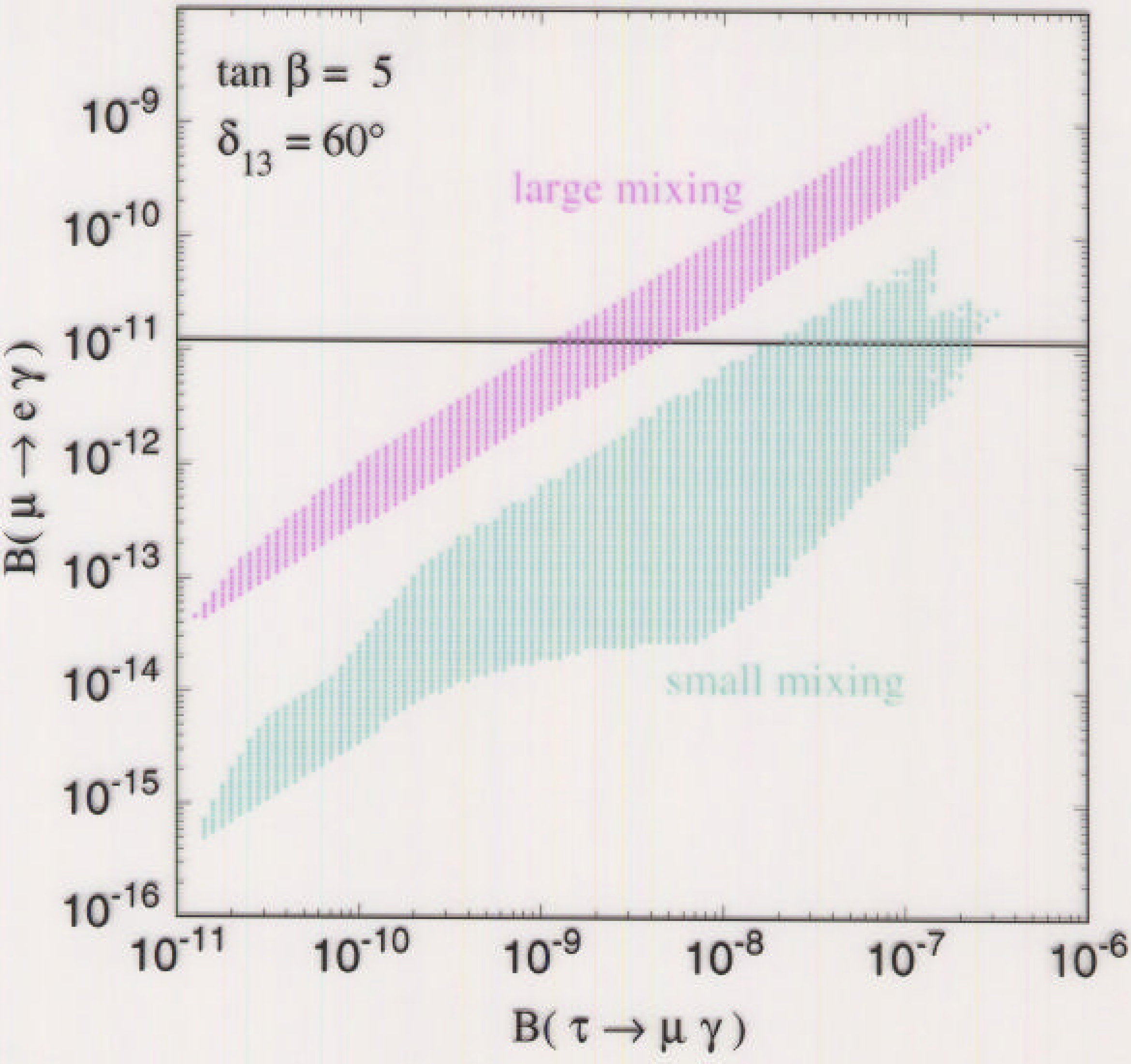
small mixing
large mixing
SM
tan β = 5
$f_{Bs} / f_B = 1.17$
$B_{Bs} / B_B = 1$
$0.08 < | V_{ub} / V_{cb} | < 0.1$
$\Delta m_s / \Delta m_d$
$A_t(B \rightarrow J/\psi K_S)$
90
80
70
60
50
40
30
20
10
0.0
0.2
0.4
0.6
0.8
1.0

SU(5) SUSY GUT with Right-handed Neutrino

large mixing : MSW large mixing angle solution

small mixing : MSW small mixing angle solution with $(V_{MNS})_{13} = 0$

$(M_R)_{ij} = (4 \times 10^{14}\ \text{GeV})\delta_{ij}$, $m_0 < 1$ TeV, $M_{1/2} < 1$ TeV, $|\frac{A_0}{m_0}| < 5$



Current bound $B(\tau \to \mu\gamma) < 1.1 \times 10^{-6}$

S.Baek, T.Goto, Y.Okada and K.Okumura hep-ph/0002141

Summary

- CP violation in B decays provide us new insight on the flavor sector of the SM

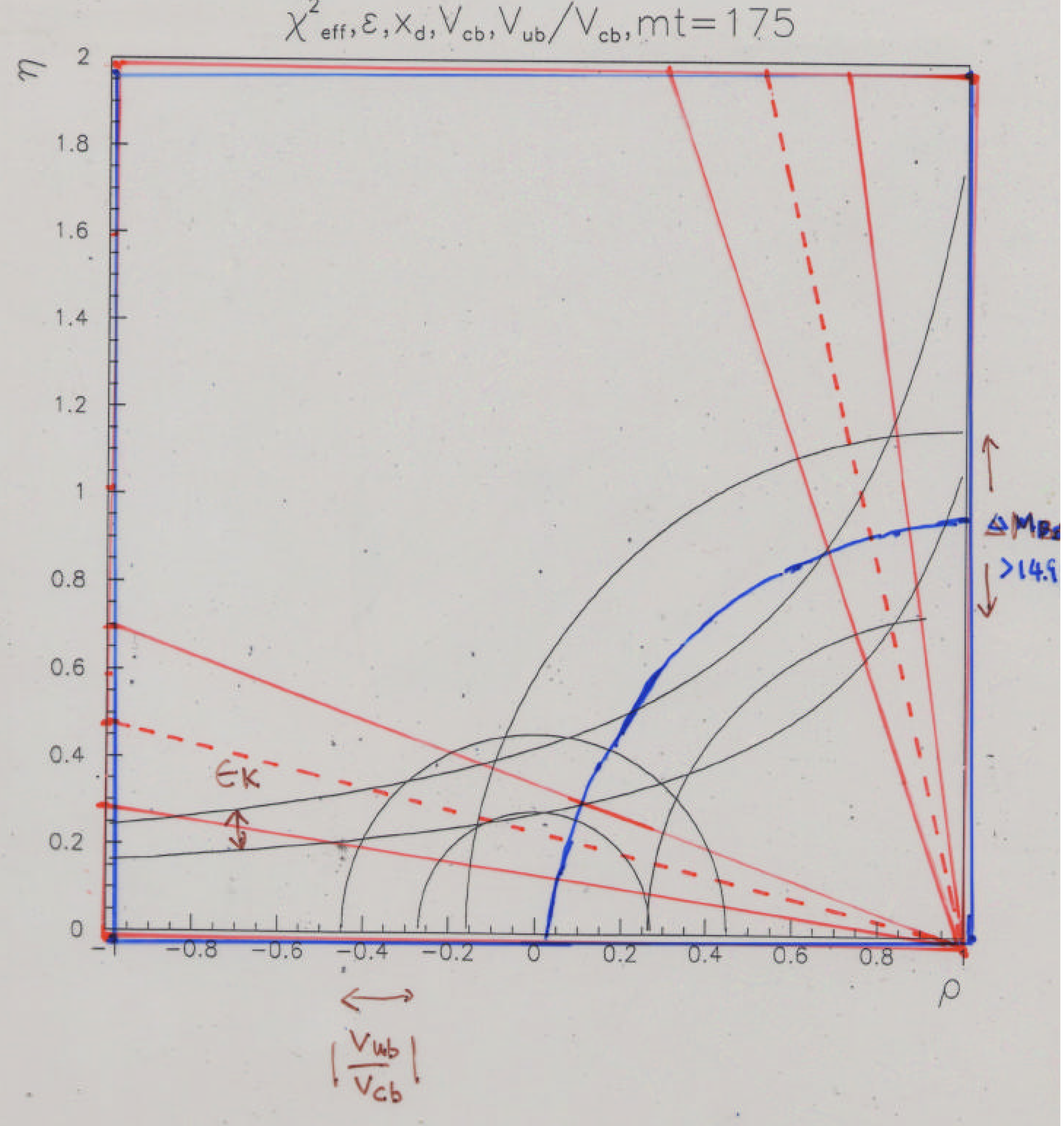
- It is important to pursue B, K, and LFV experiments simultaneously to explore SUSY models because the pattern of the deviations from the SM is a key to understand the flavor structure.

Belle. BaBar . CDF combined

$\sin 2\phi_1 = 0.$

$\sqrt{B_{Bd} f_{Bd}} = 200 \pm 40$ MeV

$B_K = 0.75 \pm 0.15$



New sources of flavor mixings.

= Squark, Slepton mass matrices

$(M_U^2)_{ij}$	up-type squark mass matrix	(6×6)
$(M_D^2)_{ij}$	down-type "	(6×6)
$(M_E^2)_{ij}$	charged slepton "	(6×6)
$(M_N^2)_{ij}$	sneutrino "	(3×3)

- Wheter or not these matrices are related to quark are neutrino mixings is important question

Inorder to answer this question we need B. K. μ decay experiments

- two examples
  ① Minimal Supergravity model $V_{\tilde{q}} \Leftarrow V_{CKM}$
  ② SU(5) SUSY GUT with right-handed neutrino (See Saw model)

$$V_{\tilde{d}_R} \Leftarrow V_{\nu}$$

Langacker 1992

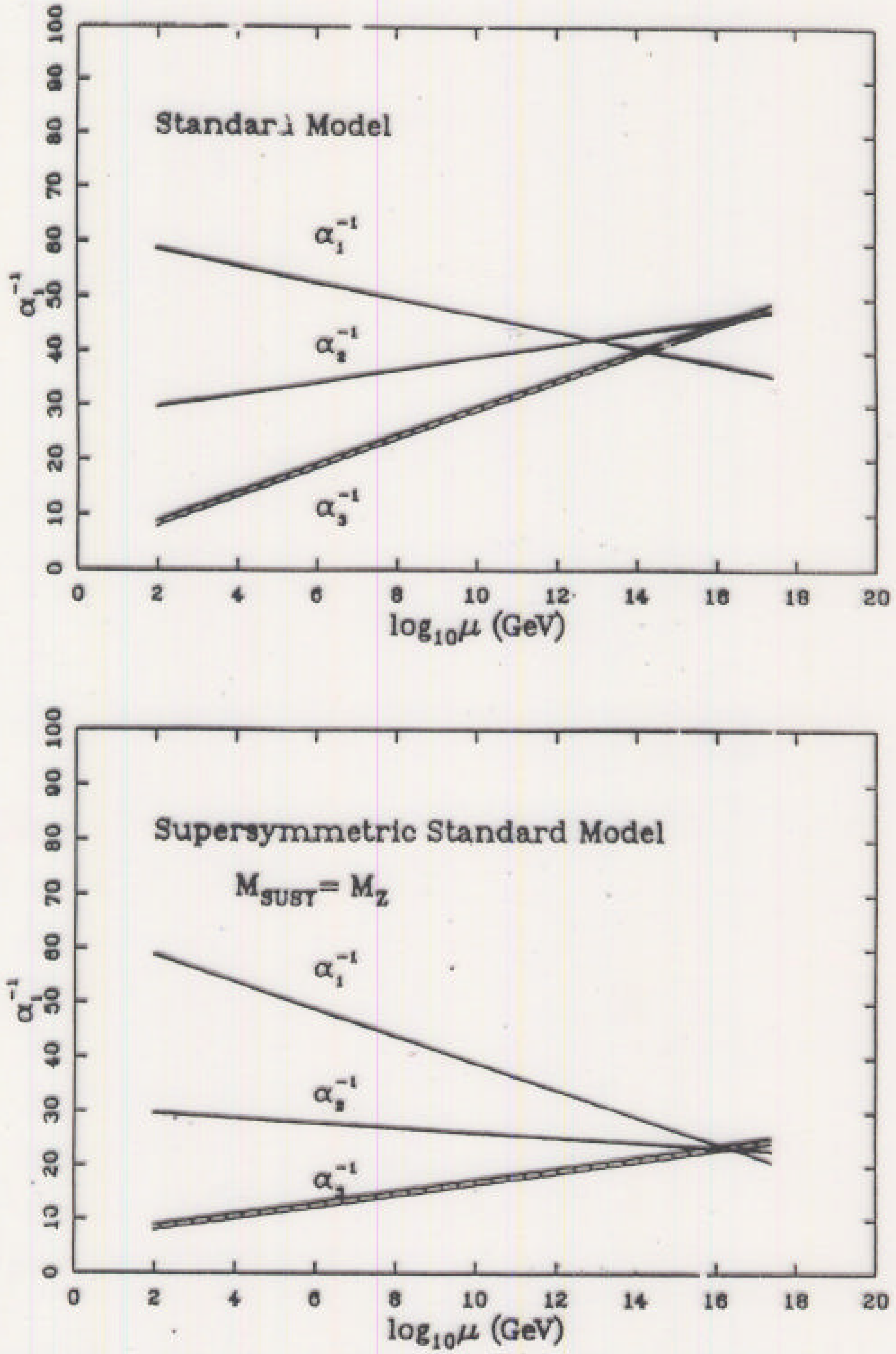


Figure 8: Running coupling in (a) the standard model and (b) in the minimal persymmetric extension of the standard model (MSSM) with two Higgs doublets $M_{SUSY} = M_Z$. The corresponding figure for $M_{SUSY} = 1$ TeV is almost identical is seen that the couplings unify at $\simeq 10^{16}$ GeV in the MSSM.