Fully SUSY $\cancel{CP}$ in the Kaon System

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(hep-ph/9907572)

1. Introduction to ϵ_K & ϵ'/ϵ_K
2. SM predictions
3. SUSY $\cancel{CP}$: folklore
4. SUSY $\cancel{CP}$: our model
5. Conclusions

*. Talk at ICHEP2K, Osaka, Japan (July 29, 2000)

1. Introduction to ϵ_K & ϵ'/ϵ_K.

$$K_L \propto K_2^{CP-} + \bar{\varepsilon}\, K_1^{CP+}$$

direct ε'

indirect ε

2π (CP even)

$$2M_K M_{12}^{*} \equiv \langle \bar{K}^0 | \mathcal{H}_{eff}(\Delta S=2) | K^0 \rangle$$

$$\bar{\varepsilon} = \frac{i}{1+i}\frac{\mathrm{Im}\, M_{12}}{\Delta M_K} + \frac{\xi}{1+i} \qquad \left(\xi \equiv \frac{\mathrm{Im}\, A_0}{\mathrm{Re}\, A_0}\right)$$

$$\varepsilon \equiv \frac{A(K_L \to (2\pi)_{I=0})}{A(K_S \to (2\pi)_{I=0})} = \bar{\varepsilon} + i\xi$$

$$= \frac{e^{i\pi/4}}{\sqrt{2}\,\Delta M_K}\left[\mathrm{Im}\, M_{12} + 2\xi\, \mathrm{Re}\, M_{12}\right] \longleftarrow \text{Key Eq.}$$

$$\varepsilon' = \frac{1}{\sqrt{2}}\,\mathrm{Im}\left(\frac{A_2}{A_0}\right) e^{i\left(\frac{\pi}{2}+\delta_2-\delta_0\right)}$$

$$= -\frac{\omega}{\sqrt{2}}\,\xi(1-\Omega)\, e^{i\left(\frac{\pi}{2}+\delta_2-\delta_0\right)} \longleftarrow \text{Key Eq.}$$

w/ $\omega = \dfrac{\mathrm{Re}\, A_2}{\mathrm{Re}\, A_0}$, $\Omega = \overset{\simeq 22}{\dfrac{1}{\omega}}\,\dfrac{\mathrm{Im}\, A_2}{\mathrm{Im}\, A_0}$

& $A_I e^{i\delta_I} = \langle (\pi\pi)_I | \mathcal{H}(\Delta S=1) | K^0 \rangle$.

Data :

① $\varepsilon_K = (2.280 \pm 0.013) \times 10^{-3}\, e^{i\frac{\pi}{4}}$

② $\mathrm{Re}(\epsilon'/\epsilon_K) \cong \frac{1}{6}\left[\dfrac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right]$

$= \begin{cases} (23 \pm 7) \times 10^{-4} \\ (28 \pm 4) \times 10^{-4} \end{cases}$

NA31 (CERN) (93)

KTeV (99)

cf. $(7.4 \pm 5.9) \times 10^{-4}$ FermiLab E731 (93)

Average : $(21.7 \pm 3.0) \times 10^{-4}$ (A. Alavi-Harati et al. PRL 83 (99) 22-27.)

Assume

$$|K_L^0\rangle \simeq |K_2^0\rangle + \varepsilon\, |K_1^0\rangle \quad \text{CP admixture}$$

$$\downarrow 3\pi \qquad \downarrow 2\pi$$

Call it $\not{CP}$ in K^0–$\overline{K^0}$ mixing. ($\Delta S = 2$)

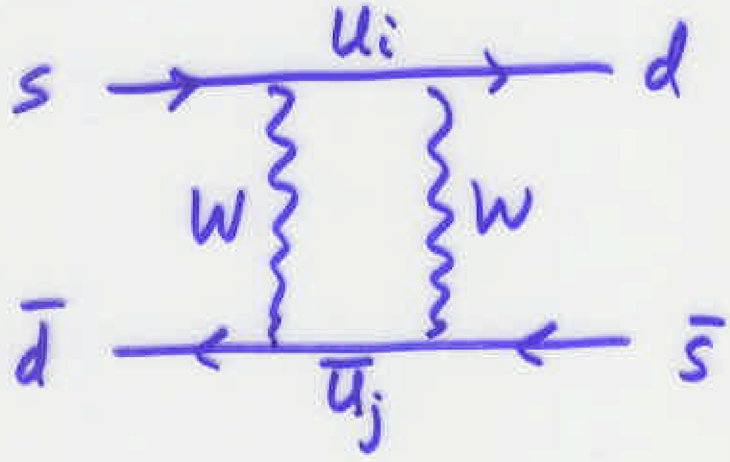
Also, $\mathcal{M}(K_2^0 \to 2\pi) \neq 0$ may be possible, and we call it "Direct CP Violation, or $\not{CP}$ in the decay amplitude" ($\sim \varepsilon'$) ($\Delta S = 1$)

What's the origin of $\not{CP}$?

- SM : KM phase in the CKM mixing matrix
- Superweak, SUSY, 4-th generation, ...
- Any case, need some "complex" couplings.

2. SM predictions (see Buras et al. hep-ph/9904408, Rev. Mod. Phys.)
Also, Bertolini (Sissa) et al.
Paschos (Dortmund) ..
⋮

① ε_K



+ (crossed)

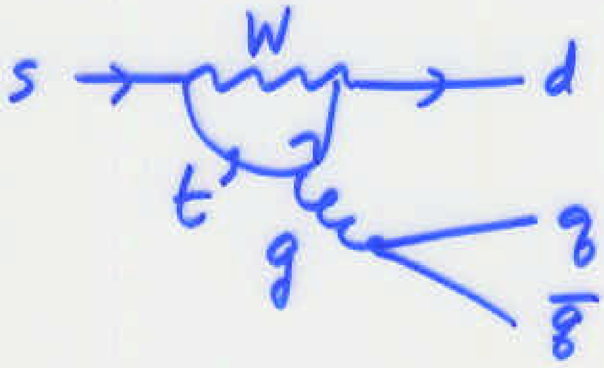
$$\varepsilon_K = \frac{G_F^2 F_K^2 M_K M_W^2}{6\sqrt{2}\pi^2 \Delta M_K} \hat{B}_K (\mathrm{Im}\,\lambda_t)$$

$$\times \left\{ \mathrm{Re}\,\lambda_c \left[\eta_1 S_0(x_c) - \eta_3 S_0(x_c, x_t) \right] - \mathrm{Re}\,\lambda_t\, \eta_2 S_0(x_t) \right\} e^{i\pi/4}$$

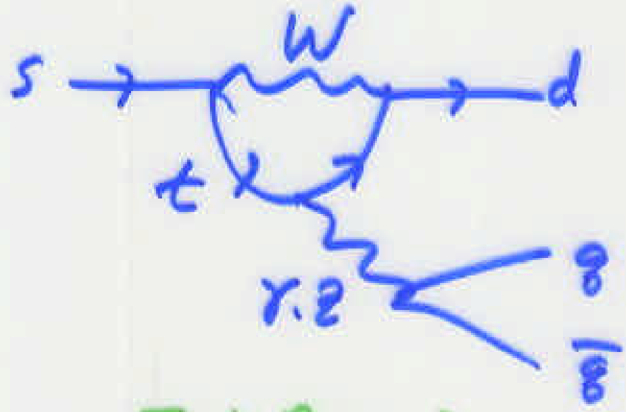
w/ $\lambda_i = V_{is}^* V_{id}$

Setting $\varepsilon = \varepsilon_{exp}$, we get constraint on δ_{KM} of CKM matrix elements.

① $\varepsilon'/\varepsilon_K$



QCD Penguin



EW Penguin

+ (Box Diagrams)

$$\mathrm{Re}(\varepsilon'/\varepsilon_K) = \begin{cases} (1 \sim 28) \times 10^{-4} & \text{(NDR)} \\ (0.26 \sim 22) \times 10^{-4} & \text{(HV)} \end{cases}$$

Both centered around $\begin{pmatrix} 7.7 \\ 5.2 \end{pmatrix}$.

Lower side compared to NA 31 & KTeV Data ..

Is this a signal for "New Physics"?

(cf. uncertainties in $\langle (\pi\pi)_I | Q_i | K^0 \rangle$ & m_s)

(Buras et al., hep-ph/9904408)

• $(\varepsilon'/\varepsilon)_{SM}$ by other groups

$$\begin{cases} \text{Ciucchini et al}: & (4.4 \pm 3.0 \pm 0.4)\, 10^{-4} \\ \text{Bertolini et al}: & (17 \pm ^{14}_{10})\, 10^{-4} \end{cases}$$

see also talks by (ICHEP 2K)

{ J. Prades, E. Pallante,
H.Y. Cheng, G. Golowich,
G.E. Valencia, ...

Some theoretical uncertainties
in $\mathrm{Re}(\epsilon'/\epsilon_K)$!

Still, worthwhile to consider
New Physics contributions to
ϵ_K & ϵ'/ϵ_K .

→ SUSY

3. SUSY $\not{CP}$: folklore.

$\exists$. many new sources of $\not{CP}$ in MSSM.

$\begin{cases} \text{Flavor Preserving (FP): } A_t, \mu, \cdots & \leftarrow \text{EDM} \\ \text{Flavor Changing (FC): } m^2_{\tilde{Q}}, A_{ij}, \cdots & \leftarrow \varepsilon_K \end{cases}$

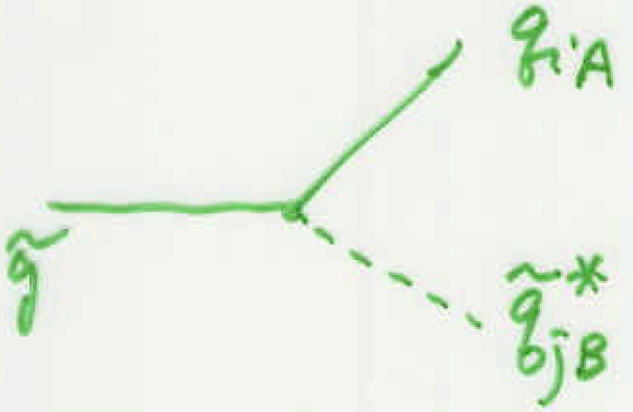
- A_t, μ phases cannot generate enough ε_K or New phase shift in $B^0-\overline{B^0}$ mixing.

- Still, they can generate Direct $\not{CP}$ asym. in $B \to X_s \gamma$ up to $\sim \pm 16\%$.

(Baek & Ko, PRL (99)), S. Pokorski et al. (99))
" (PLB (99))

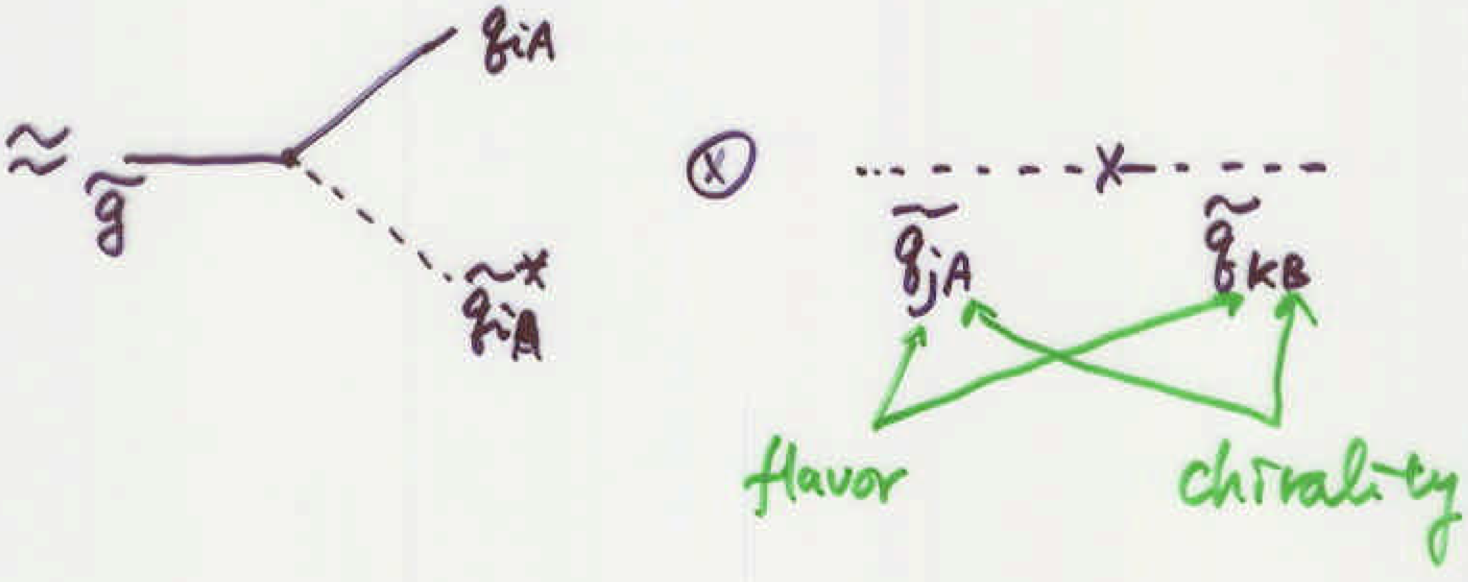
- However, FC $\not{CP}$ can change the story. Most notorious is the $q_i - \tilde{q}_j - \tilde{g}$ vertex.

Misalignment of quark & squark mass matrices in the flavor space leads to <u>FCNC</u> interactions mediated by $\tilde{g}$ (strong interactions).

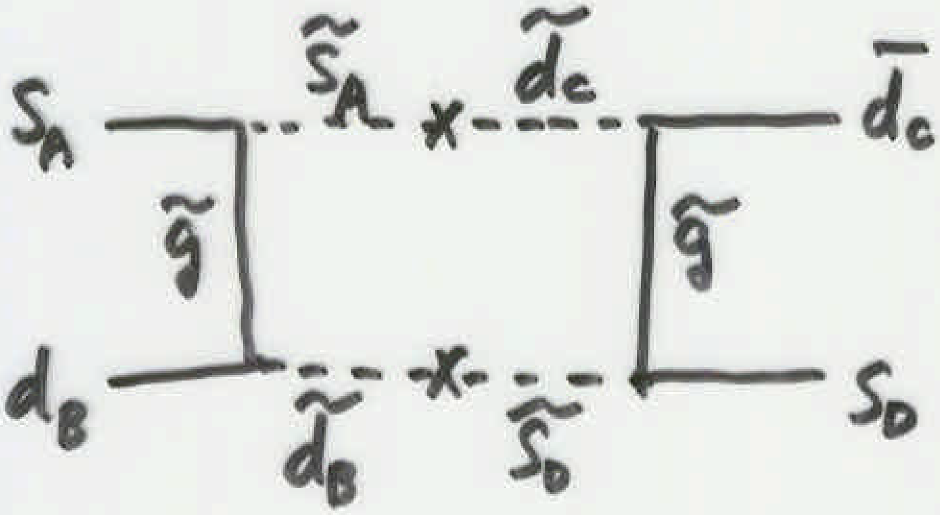


($i \neq j$, in general).

If squarks are almost degenerate, convenient to use Mass Insertion Approx.
(Hall et al. (85), <u>Gabbiani et al. (96)</u>. ----)



• $\Delta S = 2 \longrightarrow \epsilon_K$

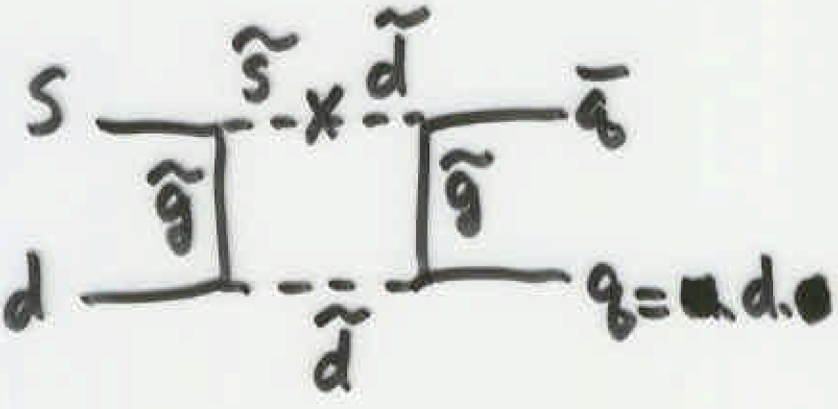


$+ (\text{SM})$

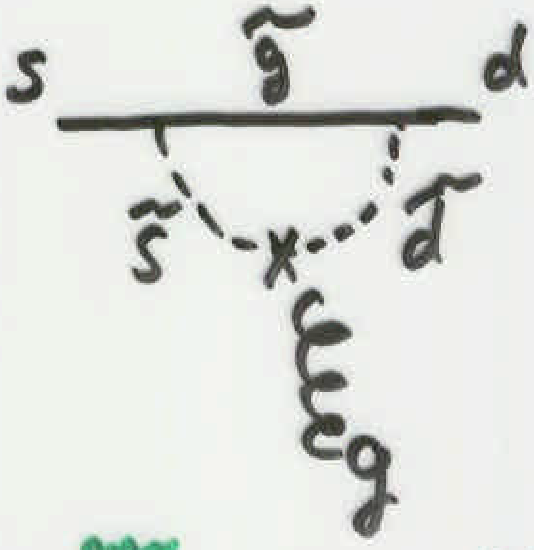
$$(\delta^d_{12})_{AC} \equiv \frac{\Delta \tilde{m}^2_{\tilde{q}}}{\tilde{m}^2}$$

common squark mass.

• $\Delta S = 1 \longrightarrow \epsilon'$



$+$



$\left(\dfrac{m_{\tilde{g}}}{m_s} \text{ enhance!} \right)$

The results are

$$\begin{cases} \epsilon_K^{SUSY} \sim \mathrm{Im}(\delta_{12}^d)_{LL}^2 \; f_{loop}(x) & \left(x \equiv \dfrac{m_{\tilde{g}}^2}{\tilde{m}^2}\right) \\[2em] \epsilon' \sim \mathrm{Im}(\delta_{12}^d)_{LL} \; \tilde{f}_{loop}(x) & \end{cases}$$

where $\overset{(\sim)}{f}_{loop} \sim O(0.1 \sim 1)$

So $\epsilon_K^{SUSY} = \epsilon_{K,exp} \rightarrow \underline{\epsilon'/\epsilon_K = ?}$

Δm_K	x	$\lvert Re(\delta^d_{12})^2_{LL} \rvert^{1/2}$	$\lvert Re(\delta^d_{12})^2_{LR} \rvert^{1/2}$
	0.3	0.019	0.0078
	1.0	0.040	0.0044
	4.0	0.092	0.0053

ε	x	$\lvert Im(\delta^d_{12})^2_{LL} \rvert^{1/2}$	$\lvert Im(\delta^d_{12})^2_{LR} \rvert^{1/2}$
	0.3	0.0015	0.00063
	1.0	0.0032	0.00035
	4.0	0.0075	0.00042

ϵ'/ϵ	x	$\lvert Im(\delta^d_{12})_{LL} \rvert$	$\lvert Im(\delta^d_{12})_{LR} \rvert$
$= 28 \times 10^{-4}$	0.3	0.10	0.000011
	1.0	0.50	0.000021
	4.0	0.27	0.000065

$\tilde{m} = 500$ GeV , $x \equiv m_{\tilde{g}}^2 / \tilde{m}^2$

Folklore:

If (Δm_K &) ϵ are saturated by $(\delta_{12}^d)_{LL}$, ϵ'/ϵ : too small.

$$\because \left|(\delta_{12}^d)_{LL}\right| = \left[\mathrm{Re}(\delta_{12}^d)_{LL}^2 + \mathrm{Im}(\delta_{12}^d)_{LL}^2\right]^{1/4}$$

$$\lesssim 0.019 - 0.092$$

$$\ll \left|\mathrm{Im}(\delta_{12}^d)_{LL}\right|_{\substack{\text{saturation}\\ \text{for } \epsilon'/\epsilon}} (0.10 \sim 0.27)$$

Masiero & Murayama (PRL(99)).

$$(\delta_{12}^d)_{LR} \sim \frac{m_{3/2} M_{12}^d}{m_{\tilde{q}}^2},$$

$$\sim \frac{m_{3/2}\, m_s\, V_{us}}{m_{\tilde{q}}^2}$$

$$\sim 2\times 10^{-5}\left(\frac{m_s(M_{pl})}{50\,\mathrm{MeV}}\right)\left(\frac{m_{3/2}}{m_{\tilde{q}}}\right)\left(\frac{500\,\mathrm{GeV}}{m_{\tilde{q}}}\right)$$

$(\delta_{11}^d)_{LR} \sim \frac{m_{3/2}\, m_d}{\tilde{m}^2} \sim 3\times 10^{-6} \rightarrow$ close to EDM limit.

4. SUSY $\not{CP}$: Our model.

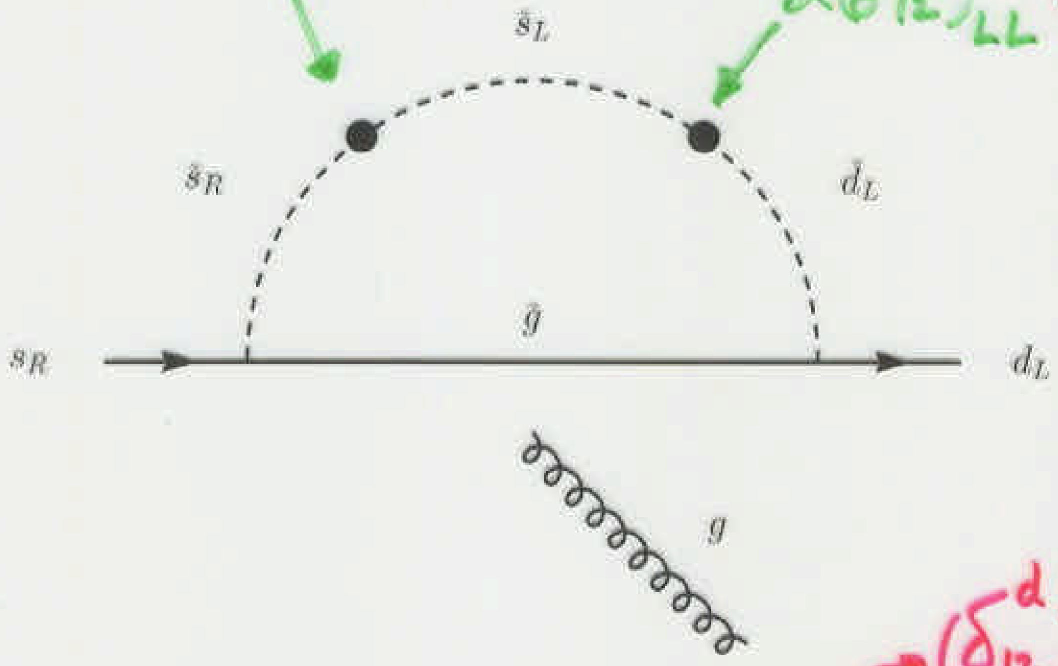
- Consider <u>double mass insertion.</u>

flavor preserving

$$\propto (\delta^d_{22})_{LR} \equiv \frac{m_s(A_s^* - \mu \tan\beta)}{\tilde{m}^2}$$

flavor ~~??~~ changing

$$\propto (\delta^d_{12})_{LL}$$



$\to (\delta^d_{12})^{\text{induced}}_{LR}$

$$\to C_8^{(2)} \sim \frac{\alpha_s}{\tilde{m}^2} \frac{m_{\tilde{g}}}{m_s} \boxed{(\delta^d_{12})_{LL} \times (\delta^d_{22})_{LR}}$$

$$\otimes \underbrace{\left[\text{fct. of } x \equiv \frac{m_{\tilde{g}}^2}{\tilde{m}^2} \right]}_{\sim \mathcal{O}(0.1) \times (\text{a few})}$$

Our point is that

$(\delta^d_{12})_{LL} \sim \mathcal{O}(10^{-3} \sim 10^{-2})$ w/ $\mathcal{O}(1)$ phase

can saturate ϵ_K, &

$$(\delta^d_{12})^{\text{induced}}_{LR} \equiv (\delta^d_{12})_{LL} \times \underbrace{(\delta^d_{22})_{LR}}_{\frac{m_s(A_s^* - \mu \tan\beta)}{\tilde{m}^2}}$$

$\sim \mathcal{O}(10^{-5})$ w/ $\mathcal{O}(1)$ phase

can saturate ϵ'/ϵ_K, if $(\delta^d_{22})_{LR} \sim \mathcal{O}(10^{-2})$.

This is possible even if $\delta_{KM} = 0$,

and if $\exists$. only one $\cancel{CP}$ parameter

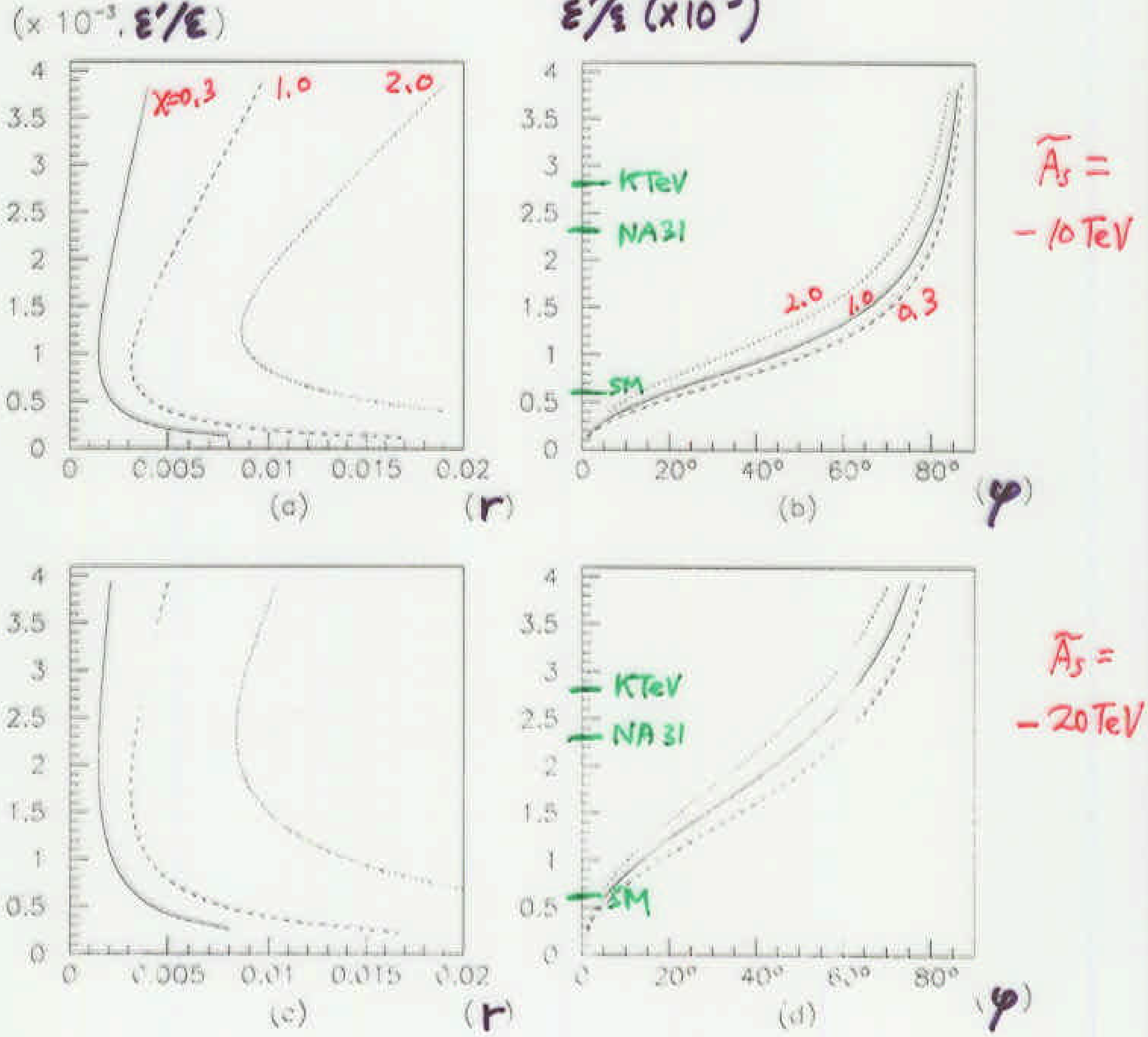
$(\delta^d_{12})_{LL}$.

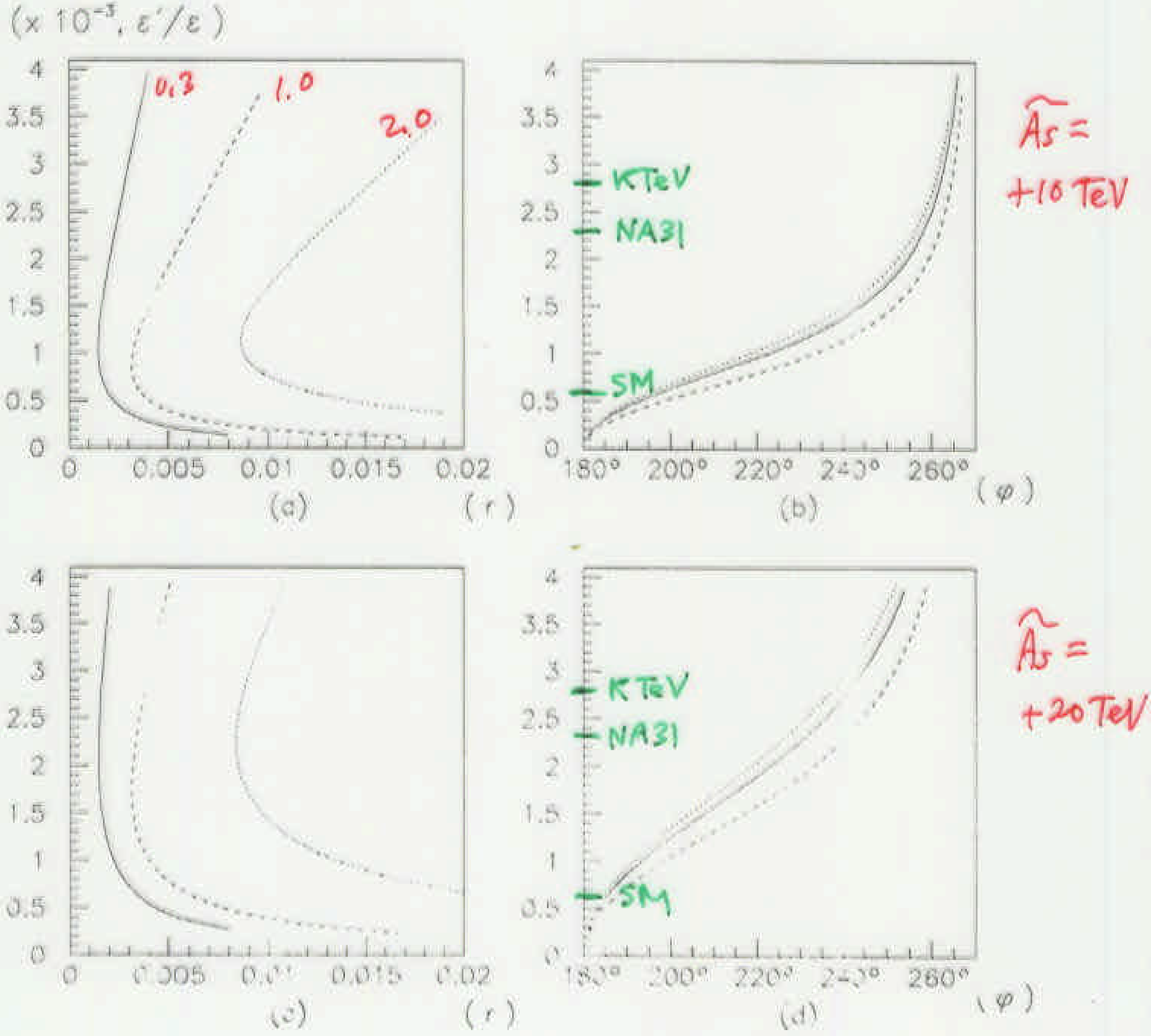
Since m_s is small, we need

relatively large $\mu \tan\beta$. (→ see fig.)

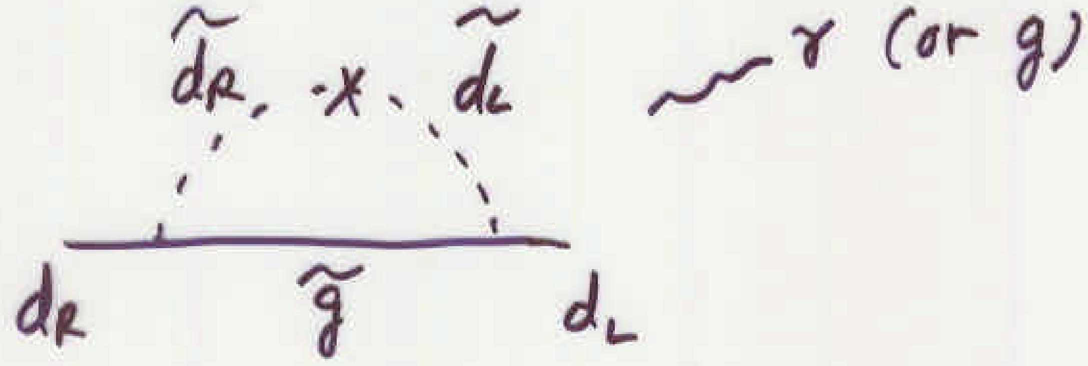
$$\left\{ \begin{array}{l} \boxed{\delta_{LL} \equiv r e^{i\varphi}} \\ x \equiv m_{\tilde{g}}^2 / \tilde{m}^2 \\ \tilde{m} = 500 \text{ GeV} \end{array} \right.$$

$$\tilde{A}_s = A_s^{*} - \mu \tan\beta$$




(x 10⁻³, ε'/ε)
0.3
1.0
2.0
KTeV
NA31
SM
Ãs =
+10 TeV
Ãs =
+20 TeV
(r)
(φ)
(a)
(b)
(c)
(d)
180°
200°
220°
240°
260°
0
0.005
0.01
0.015
0.02

- Neutron edm constraint



$$\mathcal{H}(\text{edm}) = \sum_i C_i^{\text{edm}} \mathcal{O}_i$$

w/ $\begin{cases} \mathcal{O}_1 = -\frac{i}{2} \bar{f} \sigma_{\mu\nu} \gamma_5 f F_{\mu\nu} \\ \mathcal{O}_2 = -\frac{i}{2} \bar{f} \sigma_{\mu\nu} \gamma_5 T^a f G_{\mu\nu}^a \end{cases}$

$$\begin{cases} C_1^{\text{edm}} = -\frac{2}{3} \frac{e\,\alpha_s}{\pi} Q_d \frac{m_{\tilde{g}}}{\tilde{m}^2} \mathrm{Im}(\delta_{11}^d)_{LR}\ \underline{B^{(1)}(x)} \\ C_2^{\text{edm}} = \frac{g_s \alpha_s}{4\pi} \frac{m_{\tilde{g}}}{\tilde{m}^2} \mathrm{Im}(\delta_{11}^d)_{LR}\ \underline{C^{(1)}(x)} \end{cases}$$

Gabbiani et al. NPB (96)

New!

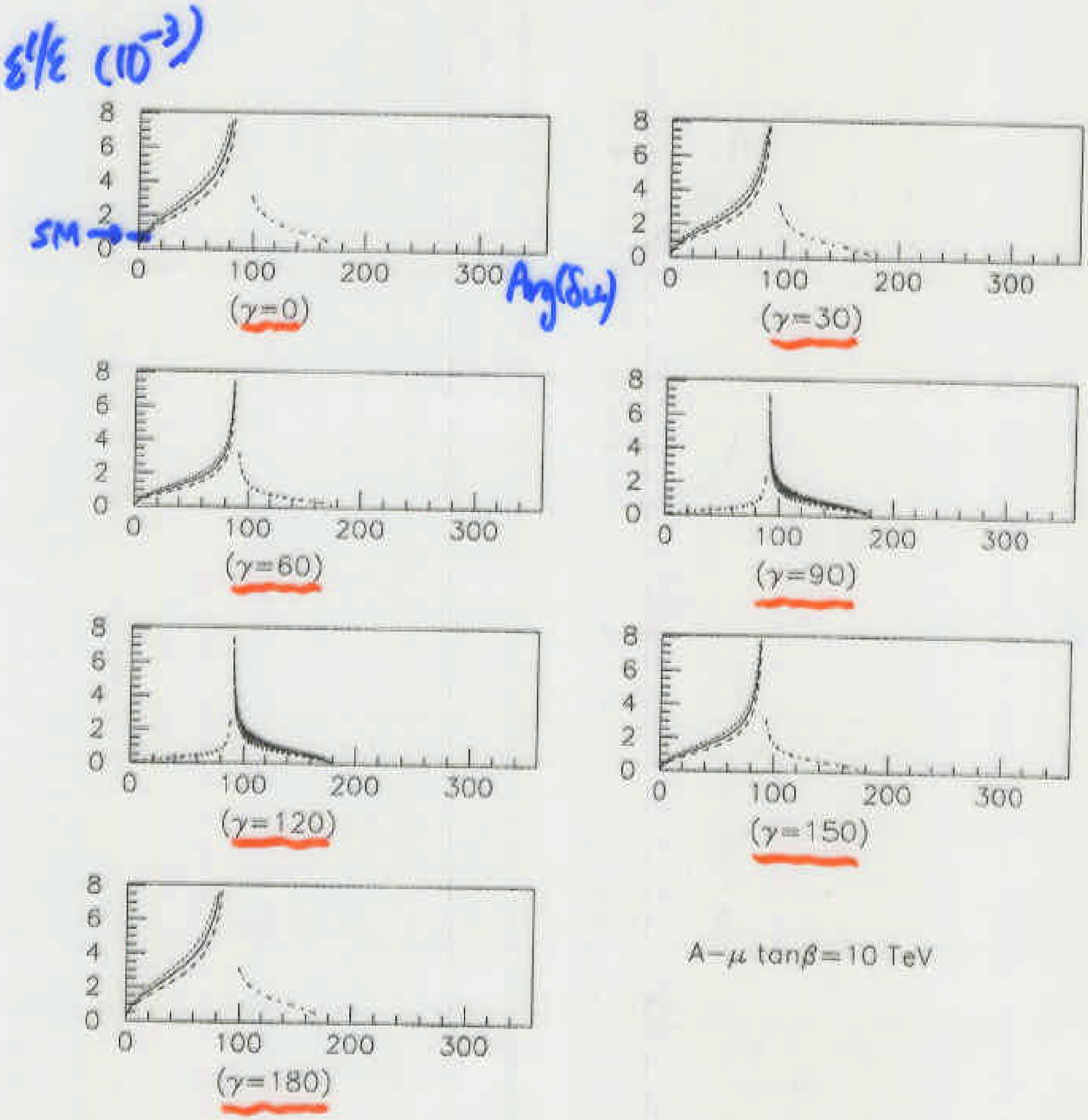
where $C^{(1)}(x),\ B^{(1)}(x) \sim \mathcal{O}(10^{-1})$

$d(n)_{exp} < 6.3 \times 10^{-26}$ e$\cdot$cm

$$\rightarrow\ \delta_{11}^d = \frac{A_d^* - \mu \tan\beta}{\tilde{m}^2} \quad : \underline{\underline{\text{real}}}$$

(indep. of $A_d = A_s$ or not).

$\delta_{KM} \neq 0$ Case



A−μ tanβ=10 TeV

—— : $x=0.3$

- - - : $x=1$

· · · · : $x=2$

—·—· : $x=4$

$\tilde{m} = 500$ GeV

$m_s = 130$ MeV

5. Conclusion.

- A single ~~CP~~ complex #. $(\delta^d_{12})_{LL}$ can generate both

$$\begin{cases} \epsilon_K \ : \ \text{by} \ \underline{(\delta^d_{12})_{LL} \sim O(10^{-3} \sim 10^{-2}) e^{i\varphi(\sim 1)}} \\ \epsilon'/\epsilon_K : \ \text{by} \ (\delta^d_{12})_{LL} \times \underbrace{(\delta^d_{22})_{LR}}_{\text{FP LR transition}} \end{cases}$$

natural in alignment mechanisms (Nir, Seiberg, Pomarol, Hall, et al.)

if $|\mu \tan\beta| \sim O(10 \sim 20)$ TeV.

(This can be lowered in the effective SUSY model by a factor of m_s/m_b.)
(& $(A_b^* - \mu \tan\beta)$ maybe complex → another CP phase)

- Generic effect in any SUSY models
- No fine tuning or contradiction to FCNC & EDM constraints.
- Work in preparation: $\delta_{KM} \neq 0$, δ_{LL} & δ_{RR}. in the effective SUSY models (w/ KM.)

*. SUSY ϵ_K problem implies SUSY ϵ'/ϵ_K problem for relatively large $|\mu \tan\beta| \sim \mathcal{O}(10)$ TeV.

cf. Usual folklore :
SUSY contribution to ϵ'/ϵ_K is small.

"Conclusions"