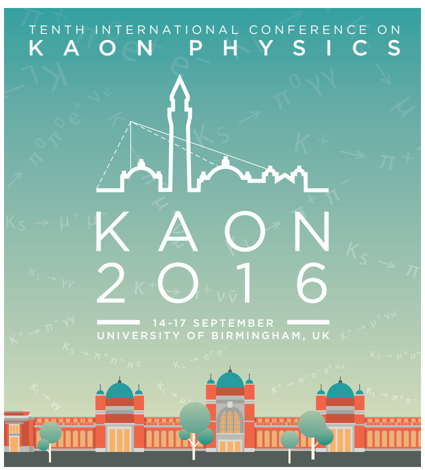
Supersymmetry and Kaon physics



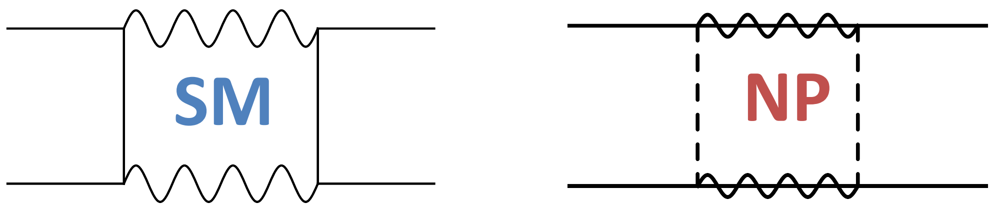
Kei Yamamoto
(KEK IPNS)

KAON2016
Sep. 15th

based on *M. Endo(KEK), S. Mishima(KEK), D. Ueda(Sokendai) and KY, arXiv:1608.01444*
M. Tanimoto(Niigata U.) and KY, arXiv:1603.07960

Why Kaon?

- Indirect searches are important probes of new physics.



$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \frac{1}{\Lambda_{NP}^2}\sum_i C_i \mathcal{O}_i^{\rm dim6}$$

If $|C_{\rm NP}| \sim 1 \;\Rightarrow\; \Lambda_{\rm NP} \sim \begin{cases} \mathcal{O}(10^5\,{\rm TeV}) & : K^0 \\ \mathcal{O}(10^4\,{\rm TeV}) & : D^0 \\ \mathcal{O}(10^3\,{\rm TeV}) & : B_{d,s} \end{cases}$ [G.Isidori, 1507.00867]

- Kaon observables are sensitive to NP at a very high scale, which is not accessible at the LHC.

Kaon observables

	SM	Exp
ϵ_K	$(1.90 \pm 0.26) \times 10^{-3}$ [J.Brod and M.Gorbahn, '10]	$(2.228 \pm 0.011) \times 10^{-3}$ [PDG]

- gives strong constraint on NP

	SM	Exp
$K^+ \to \pi^+ \bar{\nu}\nu$	$(9.11 \pm 0.72) \times 10^{-11}$ [A.J.Buras, M.Gorbahn, S.Jäger and M.Jamin, '15]	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ [E949]
$K_L \to \pi^0 \bar{\nu}\nu$	$(3.00 \pm 0.30) \times 10^{-11}$ [A.J.Buras, M.Gorbahn, S.Jäger and M.Jamin, '15]	$< \ 2.6 \times 10^{-8} (90\% \text{C.L.})$ [E391a]

- theoretically clean (extracted hadronic matrix element from bruncning ratio)
- dominant errors come from CKM elements
- NA62 & KOTO experiments are searching

	SM		Exp
ϵ'/ϵ	$(1.38 \pm 6.90) \times 10^{-4}$ [RBC-UKQCD'15] $(1.9 \pm 4.5) \times 10^{-4}$ [Buras et.al'15] $(0.96 \pm 4.96) \times 10^{-4}$ [Kitahara et.al '16]	2.1-2.9σ discrepancy ⟺	$(16.6 \pm 2.3) \times 10^{-4}$ [NA48, KTeV]

- recently, non-perturbative matrix elements (B6 & B8) have been calculated by RBC-UKQCD lattice collaboration

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ϵ'/ϵ

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2.1-2.9σ discrepancy ⟺

Exp: $(16.6 \pm 2.3) \times 10^{-4}$ [NA48, KTeV]

- recently, non-perturbative matrix elements (B6 & B8) have been calculated by RBC-UKQCD lattice collaboration

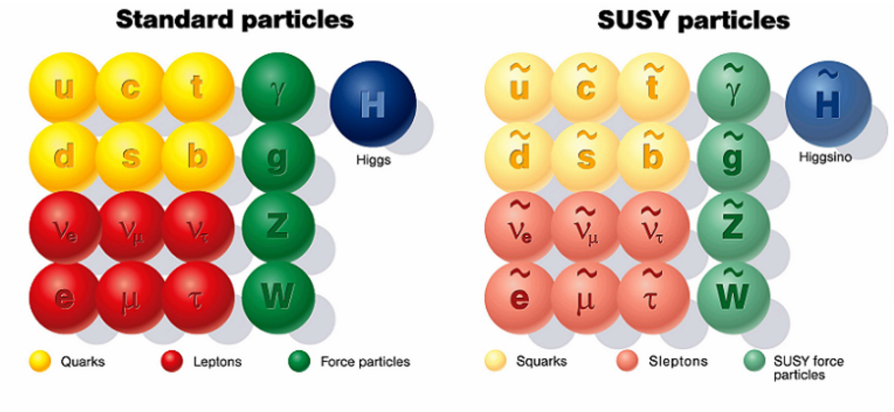
may be suggestion of NP

contents

- Introduction
- Supersymmetry
- Numerical analyses
  - chargino contribution
  - gluino contribution
- Summary

Supersymmetry

- supersymmetry : one of the most attractive candidates of new physics



Squark $\tilde{q}$
Slepton $\tilde{l}$
Gluino $\tilde{g}$
Bino, Wino, Higgsino } Neutralino χ^0, Chargino $\chi^{\pm}$

- Bounds from direct searches have been pushed up beyond 1 TeV.

$$m_{\tilde{g}},\ m_{\tilde{q}} \gtrsim 1\mathrm{TeV}$$

- Higgs mass can be realized due to heavy stop. → suggestion of high scale susy

Supersymmetry

- soft SUSY breaking terms

$$-\mathcal{L}_{\rm soft} \supset (m^2_{\tilde{Q}})_{ij}\tilde{q}_i^\dagger \tilde{q}_j + (m^2_{D})_{ij}\tilde{d}_i^\dagger \tilde{d}_j + (m^2_{U})_{ij}\tilde{u}_i^\dagger \tilde{u}_j$$

Scalar mass terms

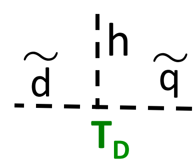
$$+ \left(T_U^{ij}\tilde{u}_i^\dagger \tilde{q}_j h_2 + T_D^{ij}\tilde{d}_i^\dagger \tilde{q}_j h_1 + \mathrm{h.c.} \right)$$

Trilinear scalar terms

EW breaking

$$\frac{v_2}{\sqrt{2}} T_U^{ij}\tilde{u}_i^\dagger \tilde{q}_j$$

$T_{D,U}$: Trilinear scalar coupling

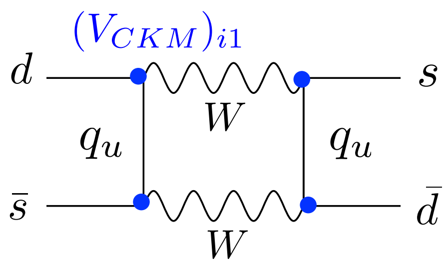


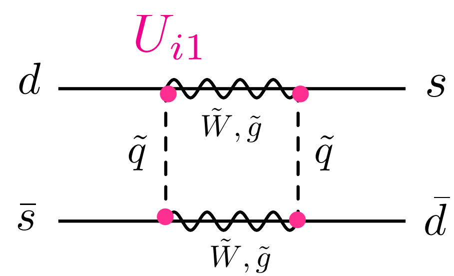
Supersymmetry

- **squark mass matrix** EW symmetry breaking + SUSY breaking
  - quark & squark mass matrices cannot be diagonalized simultaneously

$$\mathcal{M}_{\tilde u}^2 = \begin{pmatrix} m_{\tilde Q}^2 + m_u^2 + \cos 2\beta\, m_Z^2 \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W\right) & \frac{v_2}{\sqrt{2}} T_U^* - \mu m_u \cot\beta \\ \frac{v_2}{\sqrt{2}} T_U^T - \mu^* m_u \cot\beta & m_{\tilde U}^{2T} + m_u^2 + \frac{2}{3}\cos 2\beta\, m_Z^2 \sin^2\theta_W \end{pmatrix}$$

  - squark interactions depend on mixing matrix which is different from V_{CKM}



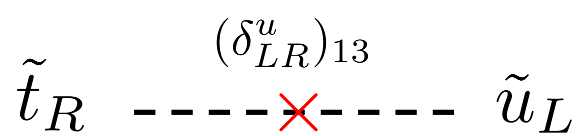


  - after diagonalizing quark mass matrix, off diagonal elements of squark mass matrix give flavor violating effects

LR mixing

$$\mathcal{M}_{\tilde u}^2 = \mathrm{diag}(m_{\tilde q}^2) + m_{\tilde q}^2 \begin{pmatrix} \delta_{LL}^u & \delta_{LR}^u \\ \delta_{RL}^u & \delta_{RR}^u \end{pmatrix}$$

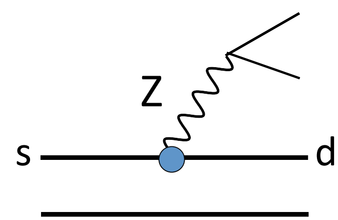
$$(\delta_{LR}^u)_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)_{ij}^*}{m_{\tilde q}^2}$$



we consider Z penguin contribution

$K^+ \to \pi^+ \bar{\nu}\nu$

$K_L \to \pi^0 \bar{\nu}\nu$

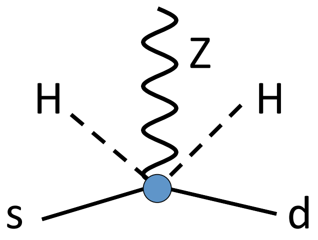


ϵ'/ϵ

because if we allow large trilinear couplings, this contribution does not decouple even if susy particle masses are heavy

Z coupling

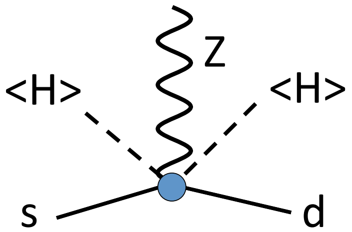
[A.J.Buras, A.Romanino, L.Silvestrini, ‘98]



gauge invariant operator

$$(H^\dagger D_\mu H)(\bar{s}\gamma_\mu d)$$

EW breaking



two SU(2) breakings

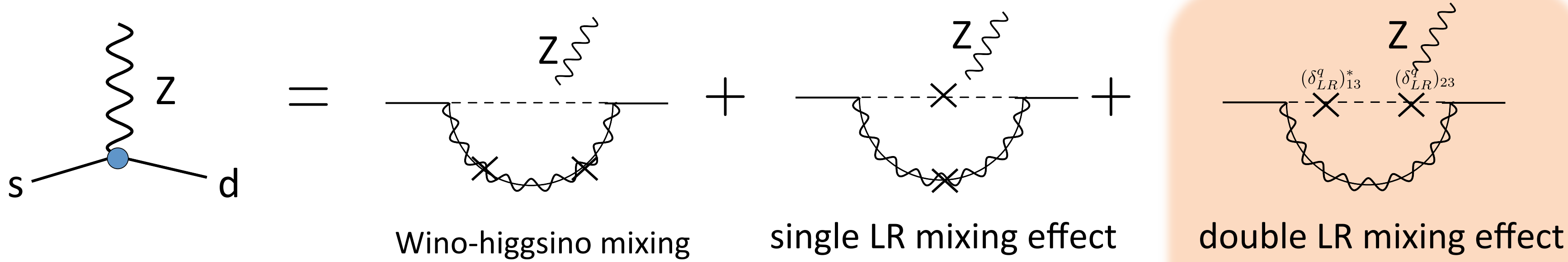
SU(2) breakings in SUSY

- LR mixing of quark
- LR mixing of squark
- Wino-higgsino mixing

Z coupling in MSSM

SU(2) breaking
- LR mixing of quark
- LR mixing of squark
- Wino-higgsino mixing

How to derive two SU(2) breaking



[A.J.Buras, A.Romanino, L.Silvestrini, '98]

[G.Collangero, G.Isidori, '98]

- double LR mixing effect

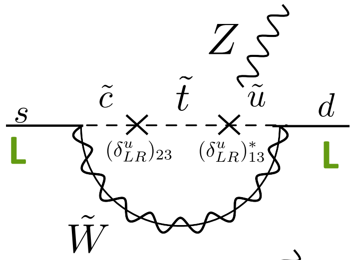
$$Z_{sd}^{(\mathrm{SUSY})} \propto (\delta^q_{LR})^*_{13}(\delta^q_{LR})_{23}$$

- They do not decouple even if SUSY particles are heavy as long as a product of the mass insertion (MI) parameters $(\delta_{LR}{}^q)^*$ $(\delta_{LR}{}^q)$ is fixed.

not assume trilinear coupling $\propto$ yukawa
large trilinear coupling -> large contribution

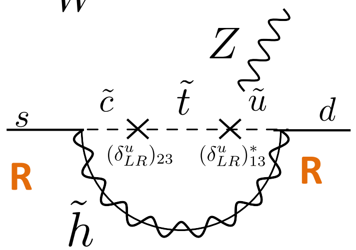
Z coupling in MSSM

Chargino Z penguin



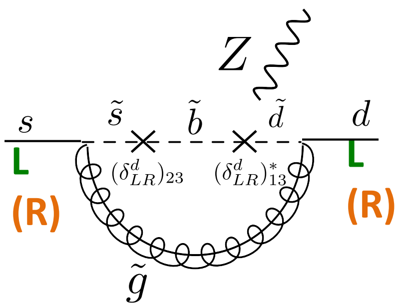
▶ L-L-Wino coupling : $(\delta^u_{LR})^*_{13}(\delta^u_{LR})_{23}$

large trilinear couplings bring large contribution



(▶ R-R-higgsino coupling : get 1st & 2nd yukawa $\Rightarrow$ insensitive)

Gluino Z penguin



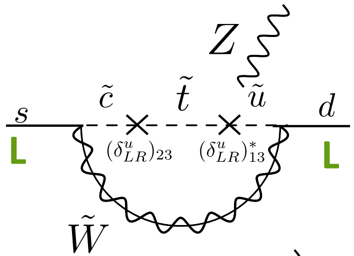
▶ L-L-gluino coupling + R-R-gluino coupling : $(\delta^d_{LR})^*_{13}(\delta^d_{LR})_{23}$

large trilinear term gives large contribution

(Neutralino Z penguin through U(1) gauge coupling $\Rightarrow$ insensitive)

Z coupling in MSSM

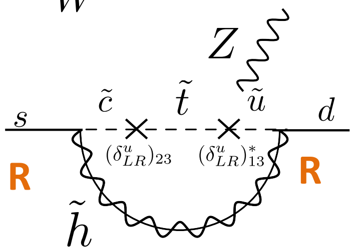
Chargino Z penguin



- L-L-Wino coupling : $(\delta^u_{LR})^*_{13}(\delta^u_{LR})_{23}$

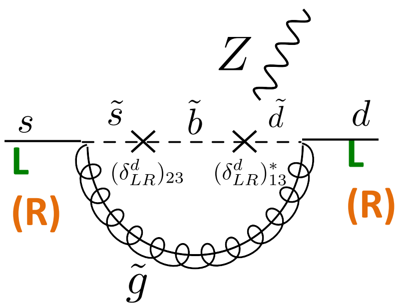
  large trilinear couplings bring large contribution

  $\Rightarrow$ vacuum stability



(R-R-higgsino coupling : get 1^{st} & 2^{nd} yukawa $\Rightarrow$ insensitive)

Gluino Z penguin



- L-L-gluino coupling + R-R-gluino coupling : $(\delta^d_{LR})^*_{13}(\delta^d_{LR})_{23}$

  large trilinear term gives large contribution

(Neutralino Z penguin through U(1) gauge coupling $\Rightarrow$ insensitive)

chargino contribution

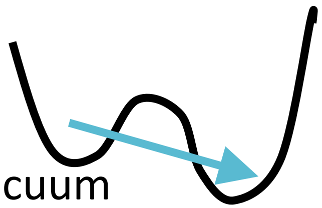
M. Endo, S. Mishima, D. Ueda and KY, arXiv:1608.01444

Vacuum stability

- large trilinear couplings make the vacuum unstable

scalar potential : $V \supset (T_U) h_u \tilde{t}_L \tilde{t}_R$

- The chargino Z-penguin contributions are constrained by requiring the meta stability of the electroweak (EW) vacuum



EW vacuum

charge-color breaking (CCB) vacua

$$\Gamma / V = A \exp(-S_E)$$

Γ : vacuum decay rate
V : volume
SE : bounce action
A : typical energy scale

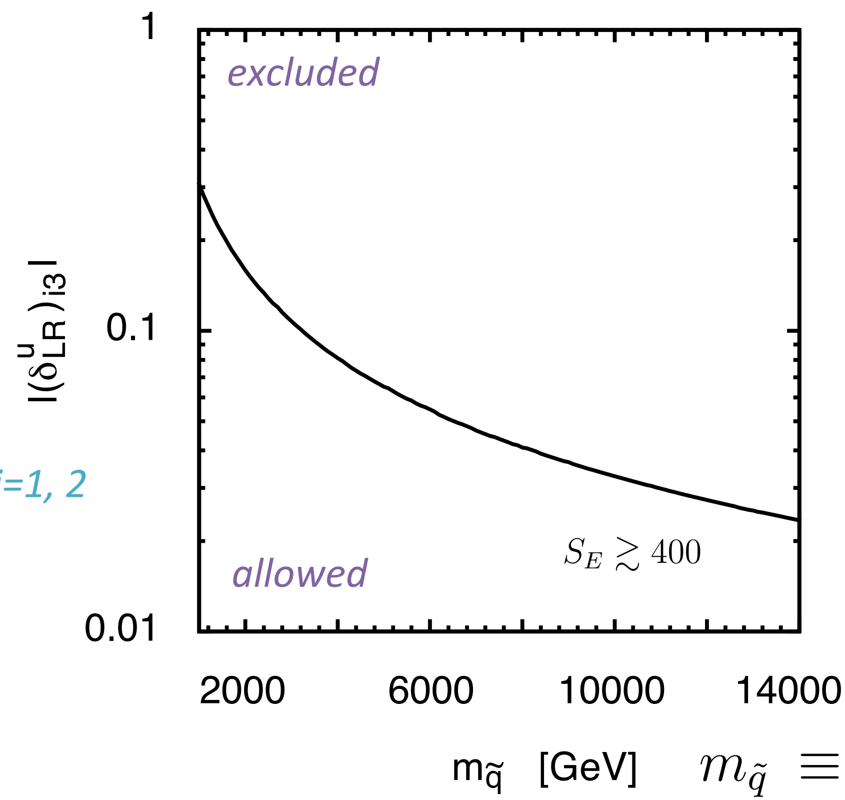
$A \sim (100\,\mathrm{GeV})^4$ or $(10\,\mathrm{TeV})^4$

The lifetime of the EW vacuum is longer than the age of the universe if the bounce action satisfies

$$S_E \gtrsim 400$$

Vacuum stability

M. Endo, S. Mishima, D. Ueda and KY, '16



i=1, 2

$$m_{\tilde{q}} \equiv m_{\tilde{Q}_i} = m_{\tilde{U}_3}$$

$$(\delta^u_{LR})_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)^*_{ij}}{m^2_{\tilde{q}}}$$

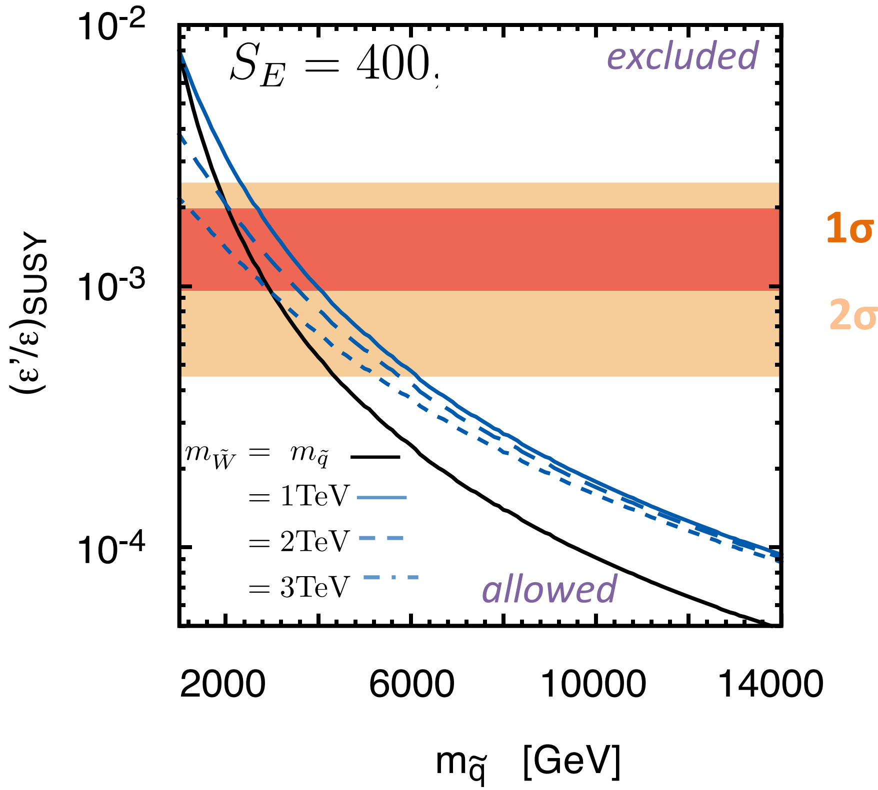
- $m_{squark} \sim 5$ TeV $\Leftrightarrow$ $(\delta_{LR}{}^u)_{i3} < 0.07$

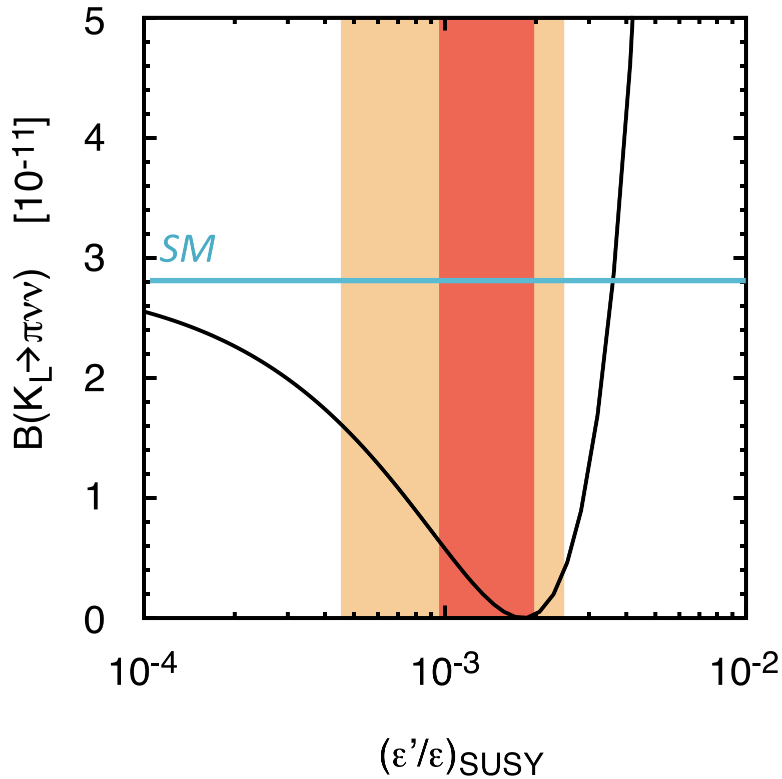
Vacuum stability

M. Endo, S. Mishima, D. Ueda and KY, '16

$|(T_U)_{13}| = |(T_U)_{23}| \quad m_{\tilde{q}} \equiv m_{\tilde{Q}_i} = m_{\tilde{U}_3} \quad \tan\beta = 50$

※The CP-violating phase of Zsd coupling is taken to be maximal





- The current discrepancy of ε′/ε can be explained; the SUSY scale can be as large as 4–6 TeV, depending on the choice of wino mass.
- The current discrepancy implies that B(KL → π0νν̄) is predicted to be less than 60% of the SM prediction.

gluino contribution

M. Tanimoto and KY, arXiv:1603.07960

Setup

- Squark mass matrix

M. Tanimoto and KY, '16

$$M_{\tilde{q}}^2 = \Gamma^{(q)\dagger}\,\mathrm{diag}(m_{\tilde{q}}^2)\,\Gamma^{(q)}$$

mass ⇔ SCKM

$$\Gamma_L^{(q)} = \begin{pmatrix} c_{13}^{qL} & 0 & s_{13}^{qL} e^{-i\phi_{13}^{qL}} c_{\theta_{LR}^q} & 0 & 0 & -s_{13}^{qL} e^{-i\phi_{13}^{qL}} s_{\theta_{LR}^q} e^{i\phi_{LR}^q} \\ -s_{23}^{qL} s_{13}^{qL} e^{i(\phi_{13}^{qL}-\phi_{23}^{qL})} & c_{23}^{qL} & s_{23}^{qL} c_{13}^{qL} e^{-i\phi_{23}^{qL}} c_{\theta_{LR}^q} & 0 & 0 & -s_{23}^{qL} c_{13}^{qL} e^{-i\phi_{23}^{qL}} s_{\theta_{LR}^q} e^{i\phi_{LR}^q} \\ -s_{13}^{qL} c_{23}^{qL} e^{i\phi_{13}^{qL}} & -s_{23}^{qL} e^{i\phi_{23}^{qL}} & c_{13}^{qL} c_{23}^{qL} c_{\theta_{LR}^q} & 0 & 0 & -c_{13}^{qL} c_{23}^{qL} s_{\theta_{LR}^q} e^{i\phi_{LR}^q} \end{pmatrix}^T,$$

$$\Gamma_R^{(q)} = \begin{pmatrix} 0 & 0 & s_{13}^{qR} s_{\theta_{LR}^q} e^{-i\phi_{13}^{qR}} e^{-i\phi_{LR}^q} & c_{13}^{qR} & 0 & s_{13}^{qR} e^{-i\phi_{13}^{qR}} c_{\theta_{LR}^q} \\ 0 & 0 & s_{23}^{qR} c_{13}^{qR} s_{\theta_{LR}^q} e^{-i\phi_{23}^{qR}} e^{-i\phi_{LR}^q} & -s_{13}^{qR} s_{23}^{qR} e^{i(\phi_{13}^{qR}-\phi_{23}^{qR})} & c_{23}^{qR} & s_{23}^{qR} c_{13}^{qR} e^{-i\phi_{23}^{qR}} c_{\theta_{LR}^q} \\ 0 & 0 & c_{13}^{qR} c_{23}^{qR} s_{\theta_{LR}^q} e^{-i\phi_{LR}^q} & -s_{13}^{qR} c_{23}^{qR} e^{i\phi_{13}^{qR}} & -s_{23}^{qR} e^{i\phi_{23}^{qR}} & c_{13}^{qR} c_{23}^{qR} c_{\theta_{LR}^q} \end{pmatrix}^T,$$

LR mixing

$$\theta_{LR}^b \simeq \frac{m_b\left((T_D)_{33}^* - \mu\tan\beta\right)}{m_{\tilde{b}_L}^2 - m_{\tilde{b}_R}^2}$$

- Input parameters

$$m_{\tilde{b}_1} = 10\ \mathrm{TeV}$$
$$m_{\tilde{b}_2} = 15\ \mathrm{TeV}$$

$$\text{gluino mass} = 10\mathrm{TeV}$$
$$\text{wino mass} = 3.3\mathrm{TeV}$$
$$\text{bino mass} = 1.6\mathrm{TeV}$$

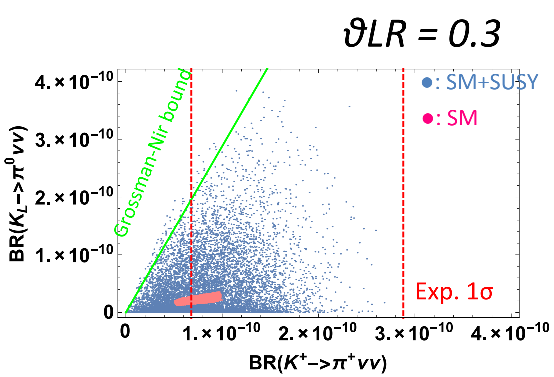
$$\mu = 10\ \mathrm{TeV}$$
$$\tan\beta = 3$$

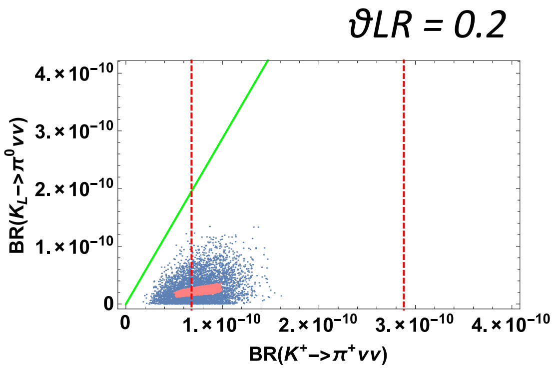
L, R mixings $\quad s_{i3}^{uL}, s_{i3}^{dL} = 0 \sim 0.3\ (i=1,2),\quad s_{i3}^{uR}, s_{d3}^{dR} = 0 \sim 0.3\ (i=1,2)$

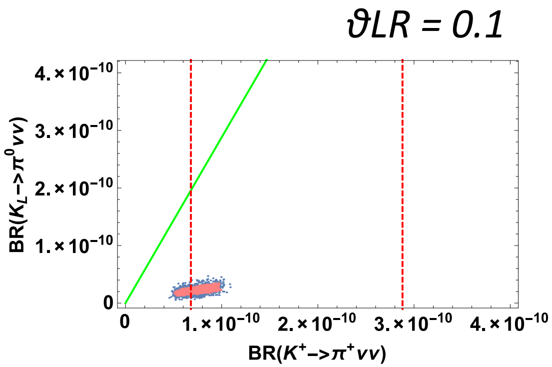
gluino contribution to K → πνν

M. Tanimoto and KY, '16

- Left- Right mixing θLR dependence (without εK constraint)

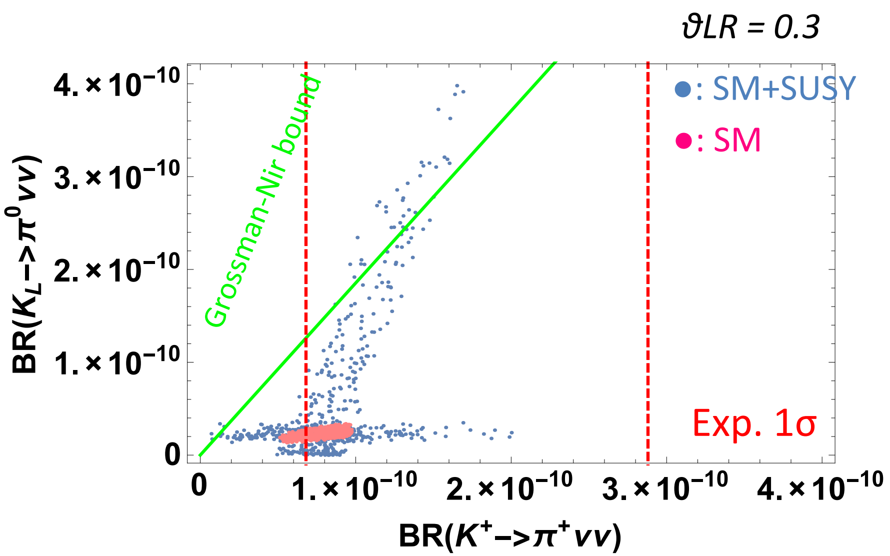






※ *CKM parameters : 3σ*

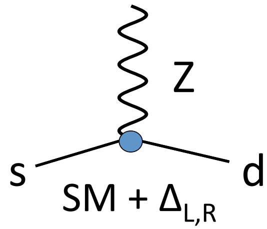
- with imposing εK constraint



BR(KL->πνν) can be enhanced

Can we enhance $K \rightarrow \pi\nu\nu$ with satisfying ε'/ε data?

Correlation between ε'/ε and $K \rightarrow \pi\nu\nu$ in modified Z model *[Buras,Buttazzo,Knegjens'15]*



The correlation between ε' and K -> πνν depends on the relative size of $\mathrm{Im}\Delta_L$ and $\mathrm{Im}\Delta_R$

To get NP contribution with same sign for ε'/ε and K ->πνν, we need both Δ_L and Δ_R, and

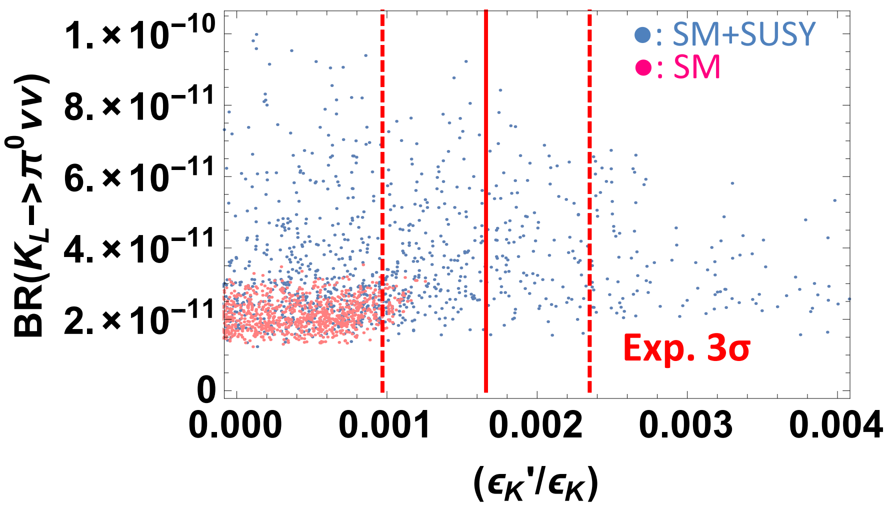
$$|\mathrm{Im}\Delta_R^{sd}(Z)| < \mathrm{Im}\Delta_L^{sd}(Z) < 3|\mathrm{Im}\Delta_R^{sd}(Z)|$$

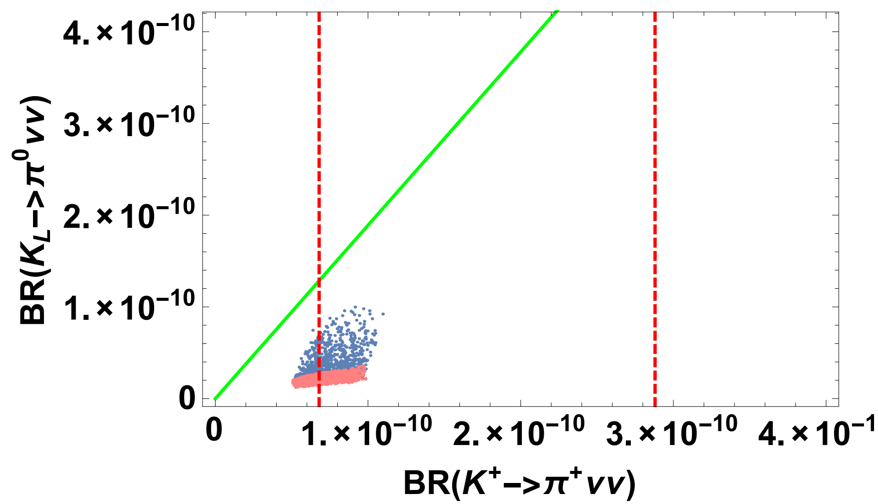
gluino contribution can realize this condition because it has both left & right couplings!

Simultaneous enhancement of K → πνν and ε'/ε in MSSM

M. Tanimoto and KY, '16

regions where Zsd couplings satisfy the condition of $|\mathrm{Im}\Delta_R^{sd}(Z)| < \mathrm{Im}\Delta_L^{sd}(Z) < 3|\mathrm{Im}\Delta_R^{sd}(Z)|$





▶The Z-penguin mediated by the gluino enhances simultaneously ε′/ε and the branching ratio for KL → π0νν̄.

BR(K_L->πνν) < 1×10^{-10} ⇔ ε′/ε

▶The phase of $\mathrm{Im}\Delta^{sd}_L$ and $\mathrm{Im}\Delta^{sd}_R$ becomes opposite, so the enhanced region of BR(KL → π0νν̄) is somewhat reduced by the cancellation between the left-handed coupling of Z and the right-handed one partially.

Summary

- Kaon physics offers a powerful probe of NP beyond the SM.
- Rare Kaon decays $K \to \pi\nu\nu$ and direct CP violation ε'/ε are sensitive to NP at a very high scale, which is not accessible at the LHC.
- We have presented correlations in a high scale supersymmetric model with large trilinear coupling.
  Even if at high scale, large contributions to $K \to \pi\nu\nu$ and ε'/ε are derived.

  - chargino : The chargino Z-penguin contributions are constrained by requiring the meta stability of the electroweak (EW) vacuum.

$$\varepsilon'/\varepsilon \quad \Leftrightarrow \quad \text{SUSY scale} < 4\text{-}6 \text{ TeV}$$

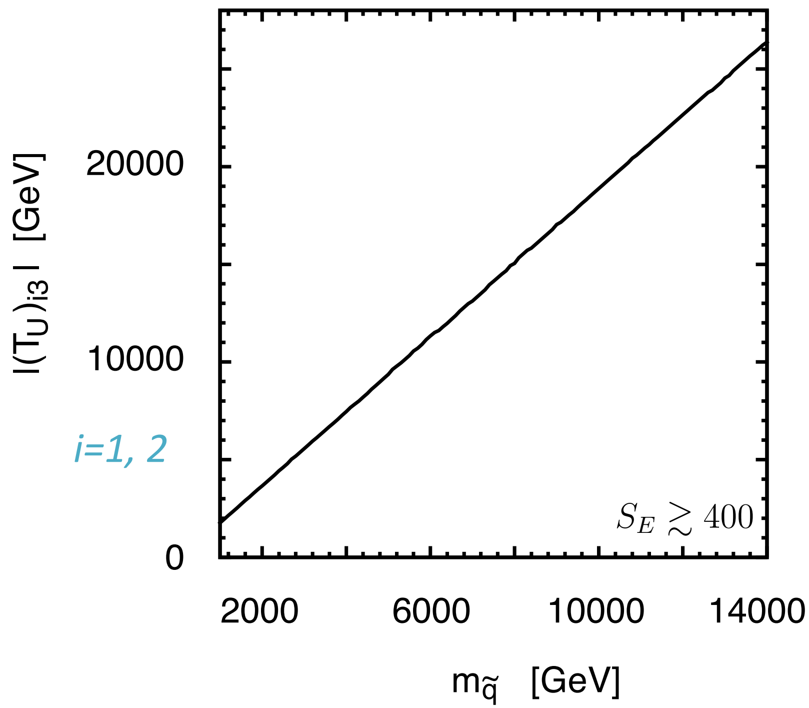
  - gluino : The Z-penguin mediated by the gluino enhances simultaneously ε'/ε and the branching ratio for $K_L \to \pi^0\nu\bar{\nu}$.

$$BR(K_L \to \pi\nu\nu) < 1\times10^{-10} \quad \Leftrightarrow \quad \varepsilon'/\varepsilon$$

- we are studying the vacuum stability for gluino contribution currently.

Vacuum stability

M. Endo, S. Mishima, D. Ueda and KY, '16



i=1, 2

input parameters

- CKM elements *M,Blanke, AJ.Buras, 1602.04020*

$\boldsymbol{S_1}$**:** $\boldsymbol{\Delta M_s}$ **strategy** in which the experimental value of ΔM_s is used to determine $|V_{cb}|$ as a function of $S(v)$, and ε_K is then a derived quantity.

S_i	$\|V_{ts}\|$	$\|V_{td}\|$	$\|V_{cb}\|$	$\|V_{ub}\|$	$\mathrm{Im}\lambda_t$	$\mathrm{Re}\lambda_t$
S_1	39.0(13)	8.00(29)	39.7(13)	3.43(15)	1.21(8)	−2.88(19)

LR mixing

$$M^2_{LR} = (m^2_{\tilde{q}_{3,1}} - m^2_{\tilde{q}_{3,2}}) \cos\theta^{q_3}_{LR} \sin\theta^{q_3}_{LR} e^{i\phi^q_{LR}}$$

$$\times \begin{pmatrix} s^{qL}_{13} s^{qR}_{13} e^{i(\phi^{qL}_{13} - \phi^{qR}_{13})} & c^{qR}_{13} s^{qL}_{13} s^{qR}_{13} e^{i(\phi^{qL}_{13} - \phi^{qR}_{13})} & c^{qR}_{13} c^{qR}_{23} s^{qL}_{13} e^{i\phi^{qL}_{13}} \\ c^{qL}_{13} s^{qR}_{13} s^{qL}_{23} e^{i(\phi^{qL}_{23} - \phi^{qR}_{13})} & c^{qL}_{13} c^{qR}_{13} s^{qL}_{23} s^{qR}_{23} e^{i(\phi^{qL}_{23} - \phi^{qR}_{23})} & c^{qL}_{13} c^{qR}_{13} s^{qL}_{23} c^{qR}_{23} e^{i\phi^{qL}_{23}} \\ c^{qL}_{13} s^{qR}_{13} c^{qL}_{23} e^{-i\phi^{qR}_{13}} & c^{qL}_{13} c^{qR}_{13} c^{qL}_{23} s^{qR}_{23} e^{-i\phi^{qR}_{23}} & c^{qL}_{13} c^{qR}_{13} c^{qL}_{23} c^{qR}_{23} \end{pmatrix}$$

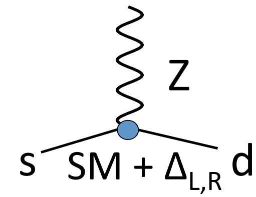
Can we enhance K → πνν with satisfying ε'/ε data?

[Buras,Buttazzo,Knegjens'15]

Correlation between ε'/ε and K → πνν in modified Z model

▶ The correlation between ε' and K -> πνν depends on the relative size of $\mathrm{Im}\Delta_L$ and $\mathrm{Im}\Delta_R$

$$\left(\frac{\epsilon'_K}{\epsilon_K}\right) = \left(\frac{\epsilon'_K}{\epsilon_K}\right)_{\mathrm{SM}} + \left(\frac{\epsilon'_K}{\epsilon_K}\right)^L_Z + \left(\frac{\epsilon'_K}{\epsilon_K}\right)^R_Z$$



$$\left(\frac{\epsilon'_K}{\epsilon_K}\right)^L_Z + \left(\frac{\epsilon'_K}{\epsilon_K}\right)^R_Z = -2.64 \times 10^3 B_8^{(3/2)} \left[\mathrm{Im}\Delta_L^{sd}(Z) + \frac{c_w^2}{s_w^2}\mathrm{Im}\Delta_R^{sd}(Z)\right]$$

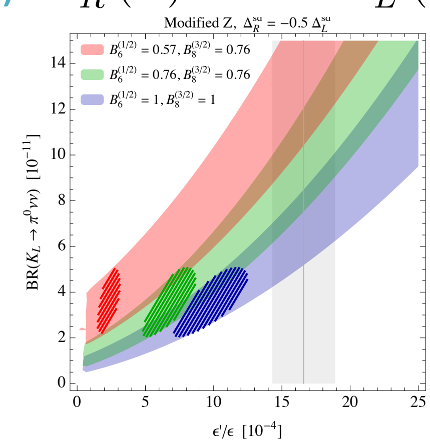
$$A(K_L \to \pi^0 \nu\bar{\nu})_Z \sim \left[\mathrm{Im}\Delta_L^{sd}(Z) + \mathrm{Im}\Delta_R^{sd}(Z)\right]$$

▶ To get same sign for ε'/ε and K ->πνν,

$$|\mathrm{Im}\Delta_R^{sd}(Z)| < \mathrm{Im}\Delta_L^{sd}(Z) < 3|\mathrm{Im}\Delta_R^{sd}(Z)|$$

gluino contribution can realize this condition!

ex.) $\Delta_R^{sd}(Z) = -0.5\Delta_L^{sd}(Z)$



ε'/ε and K → πνν

★ε'/ε

$$(\epsilon'/\epsilon) = (\epsilon'/\epsilon)_{\rm SM} + (\epsilon'/\epsilon)_{\rm SUSY}$$

$$P_X + P_Y + P_Z = 1.52 + 0.12 R_6 - 13.65 R_8$$

$$(\epsilon'/\epsilon)_Z = (P_X + P_Y + P_Z)\,{\rm Im}\,Z_{ds}$$

$$R_6 = B_6^{(1/2)}(m_c)\left[\frac{114.54\,{\rm MeV}}{m_s(m_c)+m_d(m_c)}\right]^2, \quad R_8 = B_8^{(3/2)}(m_c)\left[\frac{114.54\,{\rm MeV}}{m_s(m_c)+m_d(m_c)}\right]^2$$

$$B_6^{(1/2)}(m_c) = 0.57 \pm 0.19, \quad B_8^{(3/2)}(m_c) = 0.76 \pm 0.05$$

★K → πνν

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left[\frac{{\rm Im}\big(\lambda_t X^{({\rm SM})} + Z_{ds}^{({\rm SUSY})}\big)}{\lambda^5}\right]^2$$