Looking for New Physics via the Flavor observables

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KMI Topics

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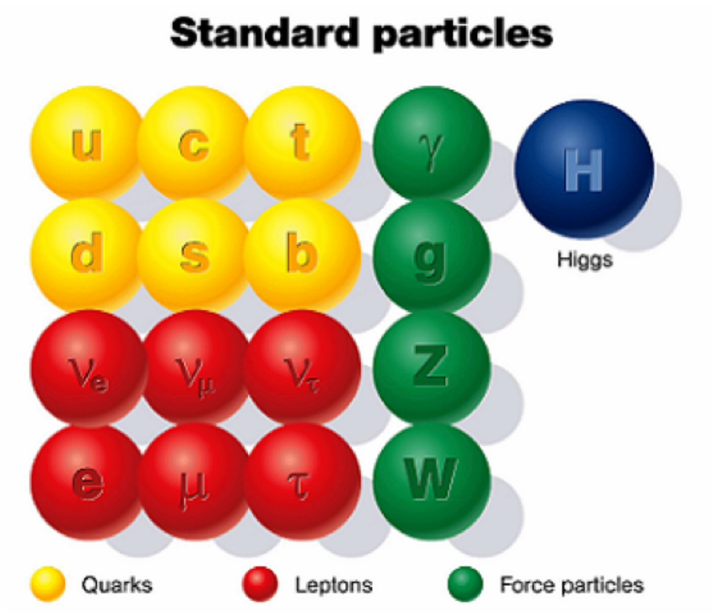
Physics beyond the Standard model (SM)

The SM of particle physics is the successful theory which explain many experimental results and phenomena



- Structure of matter
  Quarks and **Leptons** :
  fundamental constituents of matter
- Mechanism of force propagation
  Force particles : carry forces
- Mechanism of getting mass
  Higgs boson : gives mass to matter

On 4 July 2012, the Higgs boson (=last missing peace of the SM) has been found at LHC (Large Hadron Collider) experiment at CERN

Physics beyond the Standard model (SM)

However, the SM is not satisfactory:

- Neutrino mass
- Cosmological problems (Dark matter, Dark energy, Baryon asymmetry,,,)
- Hierarchy problem
- Origin of the flavor structure

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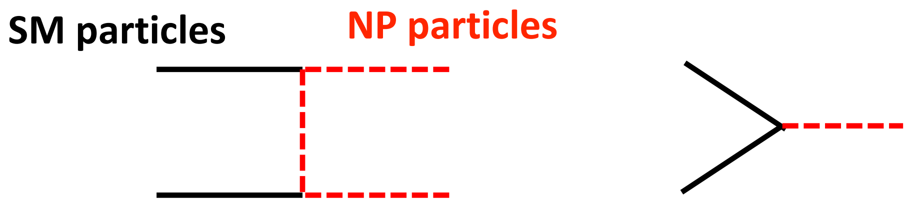
We need to search for New physics beyond the SM

How to search for new physics

Direct search High energy frontier ATLAS/CMS (LHC)

Generate new particles directly with high energy collider



Indirect search High luminosity frontier e.g.) Belle/Belle II

Search for NP through the virtual effects of new particles

How to search for new physics

Direct search | **High energy frontier** | ATLAS/CMS (LHC)

Generate new particles directly with high energy collider

SM particles | NP particles

New particles have not been observed yet (~1TeV)

The NP scale might be higher than the TeV scale

Indirect search | **High luminosity frontier** | e.g.) Belle/Belle II

Search for NP through the virtual effects of new particles

Indirect searches for NP can explore above TeV scale

⇒ Flavor physics

Flavor physics

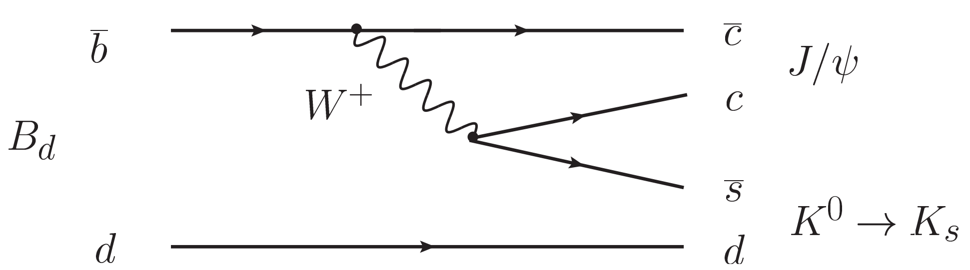
Flavor physics: flavor (type of quarks (leptons)) transition processes

Typical example)

Decay processes and CP asymmetries in Kaon and B mesons

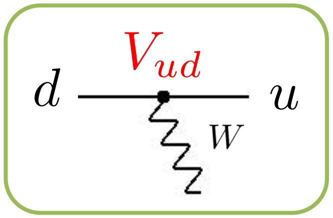
Mesons :	Kaon	$K^0(\bar{s}d)$	$\bar{K}^0(s\bar{d})$
	Bd meson	$B^0(\bar{b}d)$	$\bar{B}^0(b\bar{d})$
	Bs meson	$B_s(\bar{b}s)$	$\bar{B}_s(b\bar{s})$

e.g.) $B_d^0 \to J/\psi K_s$



Flavor physics

In the SM, flavor transition processes are governed by Cabibbo-Kobayashi-Maskawa (CKM) matrix

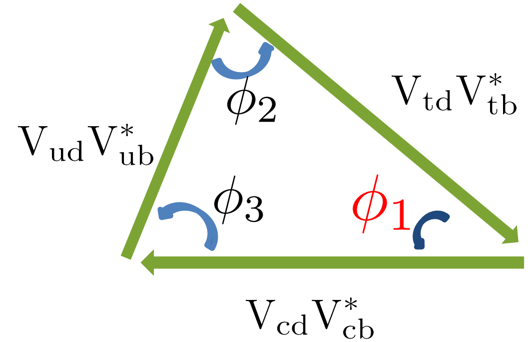


$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

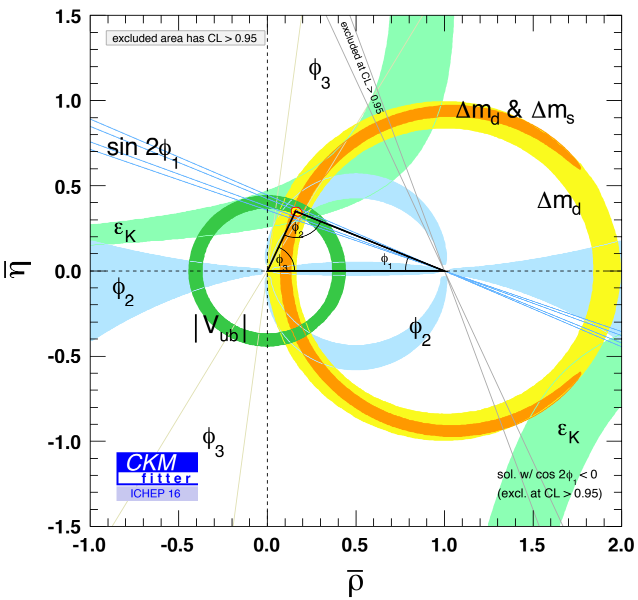
Unitarity :

$VV^{\dagger} = 1$

The unitarity triangle



Φ1 : CP asymmetry in $B_d^0 \to J/\psi K_s$ decay
Measured by B factory

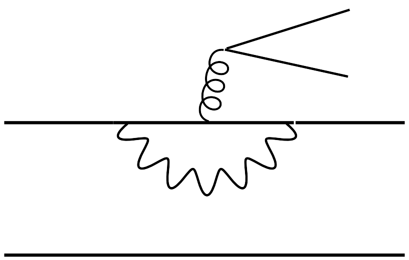


Kobayashi and Maskawa won the 2008 Nobel prize!

Flavor Changing Neutral Current

FCNC is strongly suppressed in the SM $\Rightarrow$ high sensitivity to NP

- Loop factors
- GIM mechanism (CKM unitarity)
- CKM hierarchy :



$$V_{ts}^* V_{td} \sim 5 \cdot 10^{-4} \ll V_{tb}^* V_{td} \sim 10^{-2} < V_{tb}^* V_{ts} \sim 4 \cdot 10^{-2}$$

K system *Bd system* *Bs system*

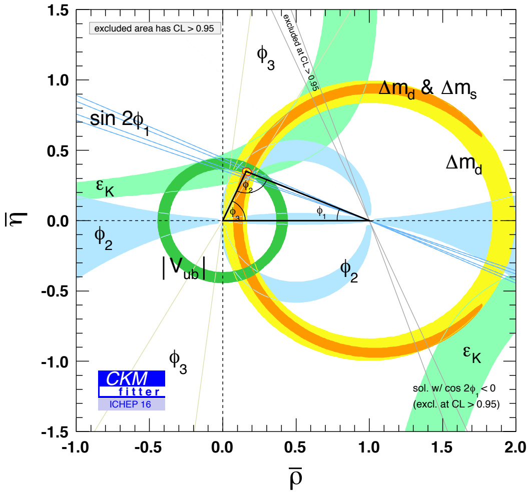
Sensitive to high scale NP beyond the energy range accessible at the LHC

$$\Lambda_{\mathrm{NP}} \sim \left(\begin{array}{ll} \mathcal{O}(10^5 \mathrm{TeV}) & : K^0 \\ \mathcal{O}(10^3 \mathrm{TeV}) & : B_{d,s} \end{array} \right.$$

[G.Isidori, 1507.00867]

Current status of flavor physics

SM works very well



there is still room for NP

e.g.) O(10-20%) NP contributions to B-Bbar mixing are still allowed

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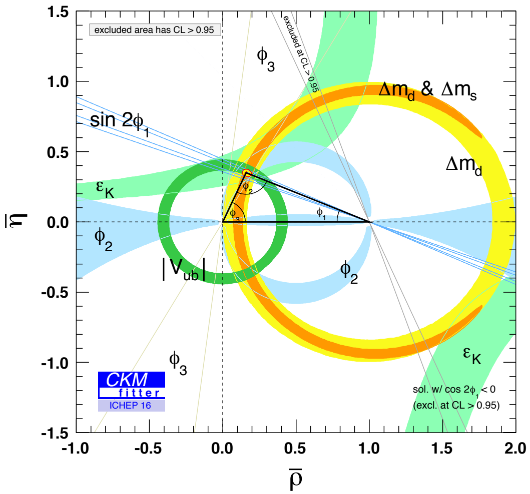

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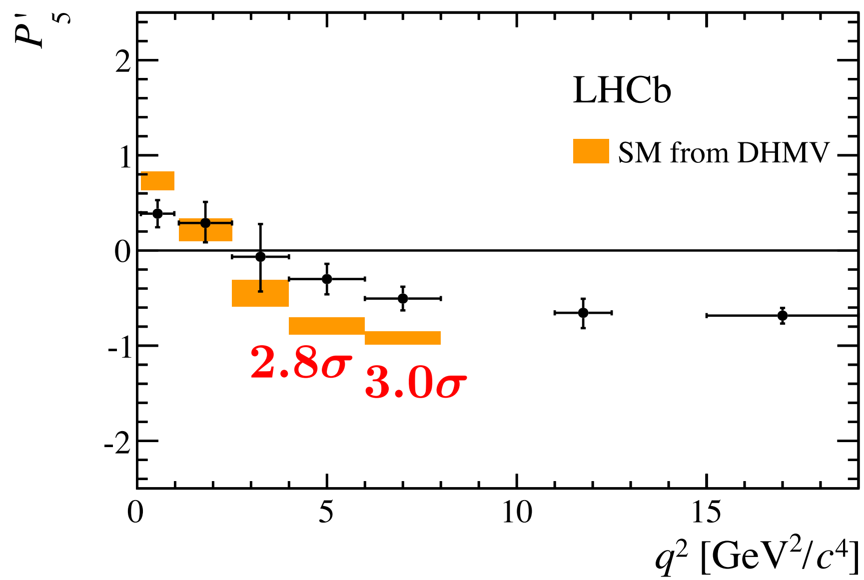
Some discrepancies from the SM are reported

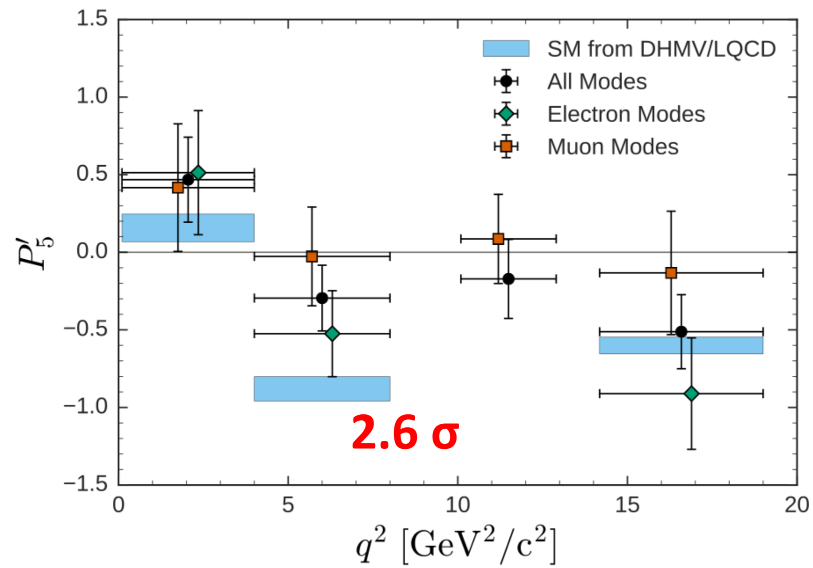
- angular distributions in $BR(B \to K^* \mu\mu)$: P_5' ~3σ
- lepton flavor non-universality : $R_K \equiv \frac{BR(B^+ \to K^+ \ell\ell)}{BR(B^+ \to K^+ ee)}$ ~2.6σ
- leptonic decay rates : $BR(B \to D^* \tau\nu)$ ~3.9σ
- Direct CP violation in Kaon : ϵ'/ϵ ~2.9σ

Current status of flavor physics

LHCb(3 fb^-1) 1512.04442



Belle 1612.05014



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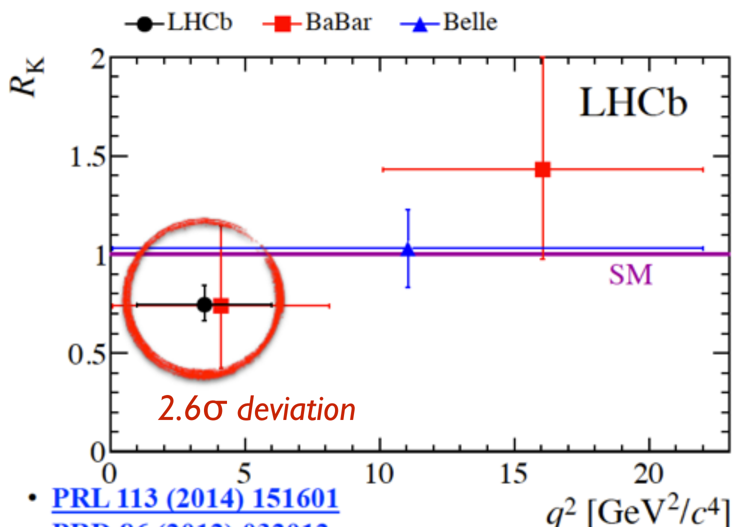
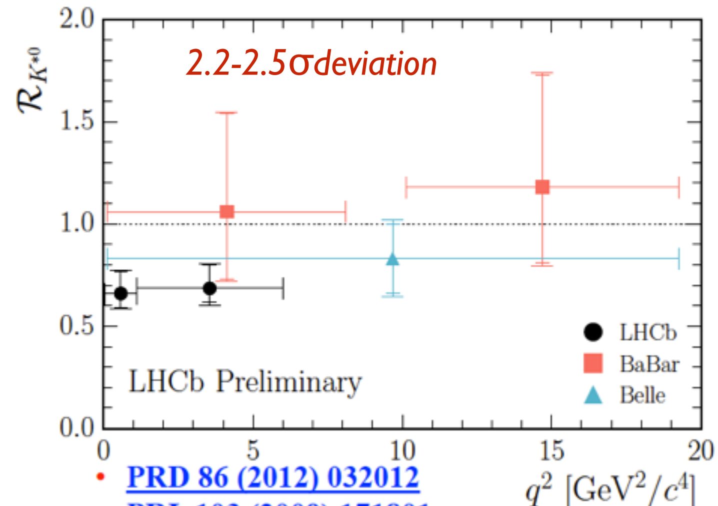


- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801



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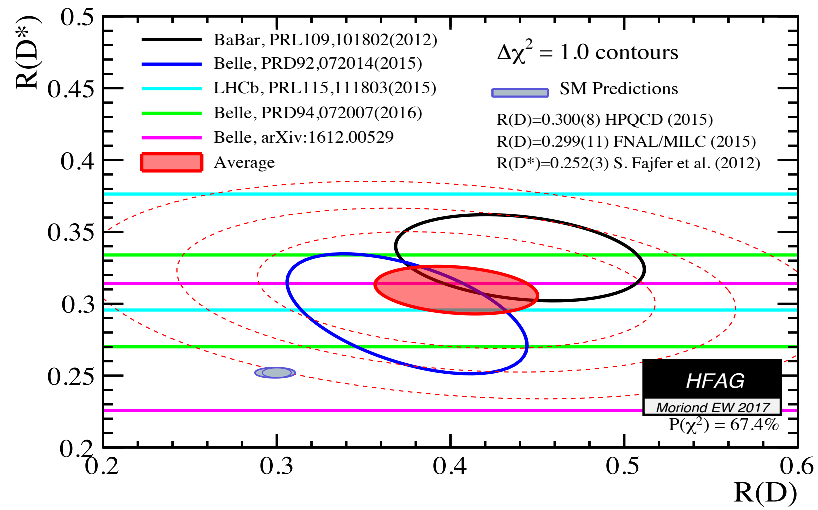
Current status of flavor physics

SM works very well

$$R(D^*) = \frac{BR(B^0 \to D^* \tau \nu)}{BR(B^0 \to D^* \ell \nu)}$$



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Current status of flavor physics

SM works very well

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-> discuss later in detail

Current status of flavor physics

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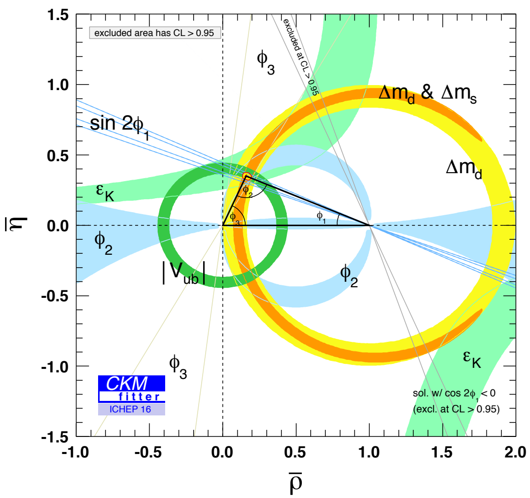

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- ☆ Direct CP violation in Kaon : ϵ' / ϵ ~2.9σ

It may be a hint of new physics beyond the SM

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- What is ε'/ε anomaly ?
  - CP violation in Kaon
  - Current status of ε'/ε
- New physics implications
  - Correlations with other observables: $K \to \pi\nu\nu$
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- Summary

Contents

CP violation in Kaon

$K_S \longrightarrow 2\pi$ CP even

! ($K_L \nearrow 2\pi$)

$K_L \longrightarrow 3\pi$ CP odd

π : pseudo scalar (0^{-+})

$\Rightarrow$ CP odd

$$|K_L\rangle \neq \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\bar{K}^0\rangle\right]$$

$$\mathrm{CP}|K^0\rangle = -|\bar{K}^0\rangle$$

CPV parameter

$$= \frac{1}{\sqrt{2}}\left[(1+\epsilon)|K^0\rangle + (1-\epsilon)|\bar{K}^0\rangle\right]$$

$K_1 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$: CP even

$K_2 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$: CP odd

$$= |K_2\rangle + \epsilon\,|K_1\rangle$$

CP odd even

CP violation in Kaon

CP odd   CP even

$$|K_L\rangle = |K_2\rangle + \epsilon\,|K_1\rangle$$

Indirect : ε (mixing)

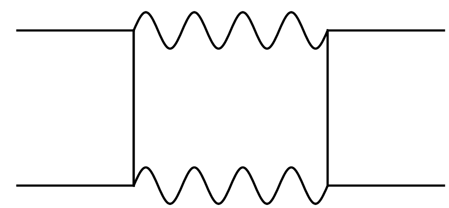
Direct : ε' (decay)

2π CP even

- Indirect : ε (mixing)

$$\epsilon_K \simeq \frac{\mathrm{Im} M_{12}^K}{\Delta M^K}$$

$$(\epsilon_K)_{\mathrm{exp}} = (2.228 \pm 0.011) \times 10^{-3}$$



K-Kbar mixing

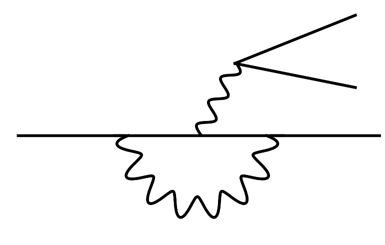
- Direct : ε' (decay)

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

$$\eta_{00} = \frac{A(K_\mathrm{L} \to \pi^0\pi^0)}{A(K_\mathrm{S} \to \pi^0\pi^0)}$$

$$\eta_{+-} = \frac{A(K_\mathrm{L} \to \pi^+\pi^-)}{A(K_\mathrm{S} \to \pi^+\pi^-)}$$

$$(\epsilon'/\epsilon)_{\mathrm{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$



K->ππ decay

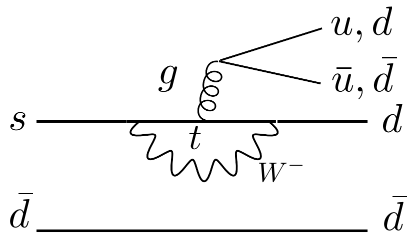
Direct CP violation : ε'/ε

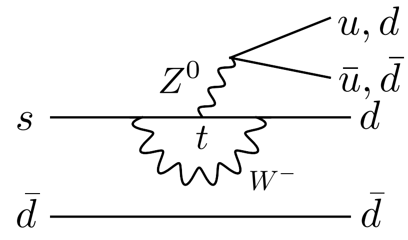
$$A_{0,2} = A(K^0 \to (\pi\pi)_{I=0,2})$$

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\,\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\,\mathrm{Im}A_2\right)$$

Dominated by QCD penguin

EW penguin





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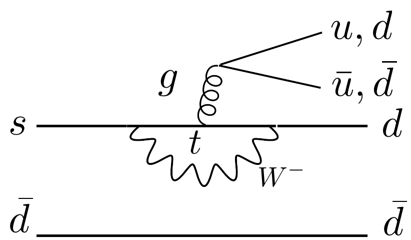
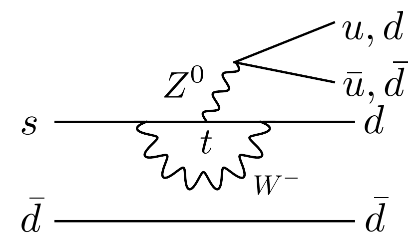




ΔI=1/2 rule

$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \equiv \frac{1}{\omega} = 22.46$$

In SM, there is accidental cancellation between $\mathrm{Im}A_0$ and $\mathrm{Im}A_2$ due to the enhancement factor 1/ω

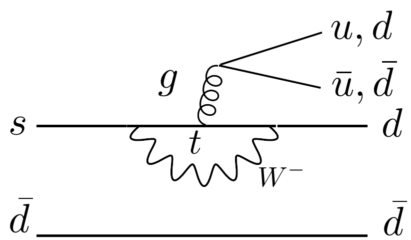
Direct CP violation : ε'/ε

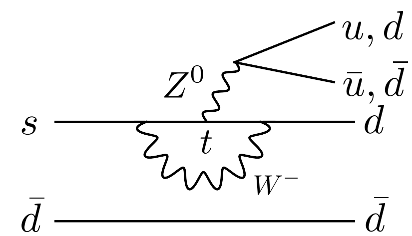
$$A_{0,2} = A(K^0 \to (\pi\pi)_{I=0,2})$$

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\ \mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\,\mathrm{Im}A_2\right)$$

QCD penguin

EW penguin





$$O_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}$$

$$O_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V+A}$$

- <O6> and <O8> have chiral enhancement factor

$$\langle Q_6(\mu)\rangle_0 = -4\left[\frac{m_K^2}{m_s(\mu)+m_d(\mu)}\right]^2 (F_K - F_\pi)\, B_6^{(1/2)}$$

$$\langle Q_8(\mu)\rangle_2 = \sqrt{2}\left[\frac{m_K^2}{m_s(\mu)+m_d(\mu)}\right]^2 F_\pi\, B_8^{(3/2)}.$$

$B_{6,8}$: Non-perturbative parameter

First Lattice result in 2015 !

ε'/ε anomaly

Using the first lattice result, ε'/ ε has been calculated in the SM as

SM $$(\varepsilon'/\varepsilon)_{\rm SM} = (1.9 \pm 4.5) \times 10^{-4}$$ [Buras et.al '15]

Exp $$(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$ [NA48, KTeV]

2.9σ difference

New physics providing enhancement of ε'/ε ?

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ε'/ε beyond SM

- Recall :

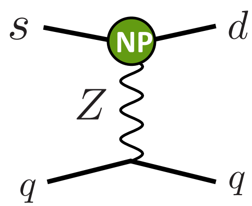
$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\,\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\mathrm{Im}A_2\right)$$

NP in $\mathrm{Im}A_2$ is favored because of ΔI=1/2 enhancement factor : 1/ω ～22

- The type of $(\mathrm{Im}A_2)_{NP}$:

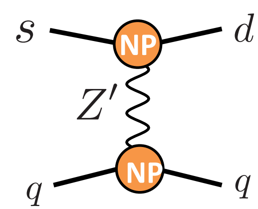
$$(\mathrm{Im}A_2)_{NP} :$$

Z scenario



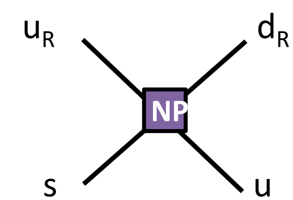
Our work: MSSM
VLQ
LHT

Z' scenario



VLQ
331

Others



RH scenario
Gluino box

ε'/ε beyond SM

- Recall :

$$\frac{\epsilon'_K}{\epsilon_K} = -\frac{\omega}{\sqrt{2}\,|\epsilon_K|_{\exp}\,\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\mathrm{Im}A_2\right)$$

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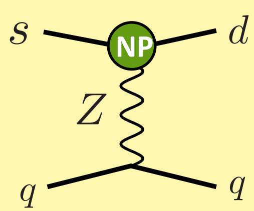

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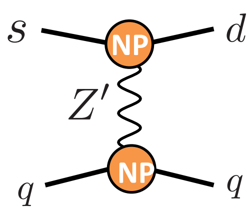
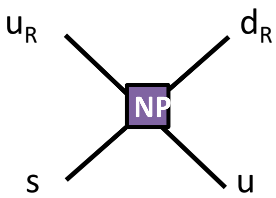


Others



Our work: MSSM
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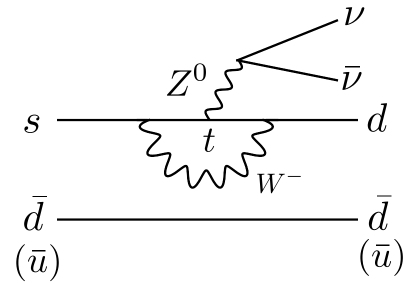
331

RH scenario
Gluino box

Other signal ? ⇒ *K->πνν*

Kaon rare decay : $K_L \to \pi^0\nu\nu$ and $K^+ \to \pi^+\nu\nu$



- Features of $K \to \pi\nu\nu$ decay
  - Rare decay : $BR_{SM} \sim 10^{-11}$
  - Theoretically clean : hadronic matrix element can be removed
  - Experiments are in progress

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

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

KOTO @ J-PARC,
__running__

aim to measure BR($K_L \to \pi^0\nu\nu$) around the SM sensitivity

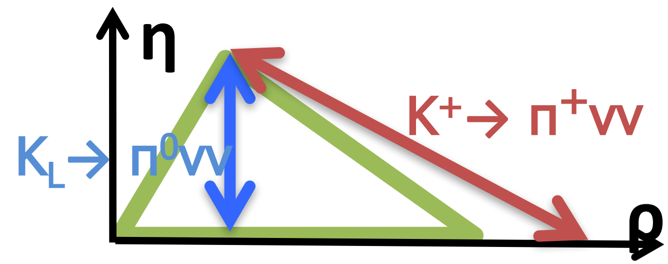
NA62 @ CERN
__running__

aim to measure O(100) events(~10% precision) BR($K^+ \to \pi^+\nu\nu$) by 2018

Kaon rare decay : $K_L \rightarrow \pi^0 \nu\nu$ and $K^+ \rightarrow \pi^+ \nu\nu$

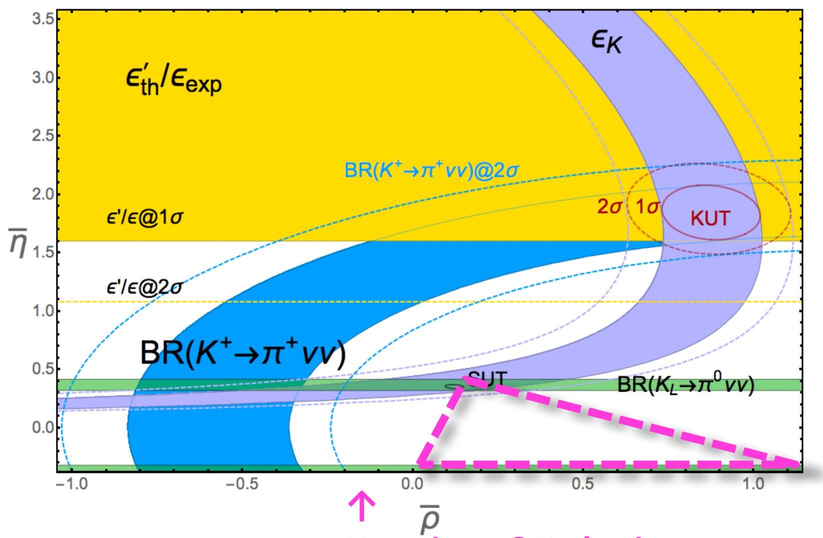
- $K \rightarrow \pi\nu\nu$ and Unitarity triangle

  Determination of CPV phase (η) directly

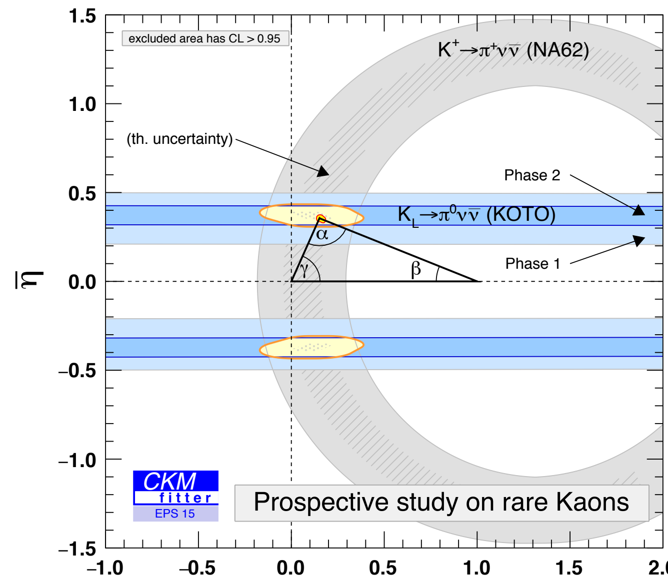


- Unitarity triangle fit independently of B physics

[Lehnera, Lunghi, Soni 1508.01801]



UT using B&K physics measurements



- Prospects :

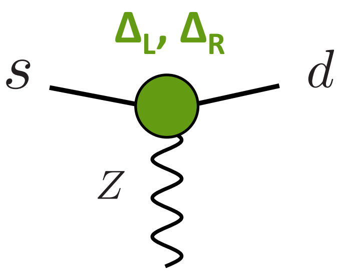
  NA62 : BR($K^+ \rightarrow \pi^+\nu\nu$) at 10% accuracy (End 2018)

  KOTO : Phase 1 : aim to measure BR($K_L \rightarrow \pi^0\nu\nu$) around the SM sensitivity

  Phase 2 : BR($K_L \rightarrow \pi^0\nu\nu$) at 10% accuracy

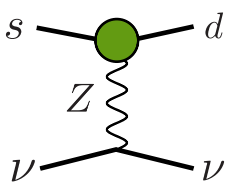
Correlations b/w Kaon observables in Z scenario

[A.J.Buras, D.Buttazzo and R.Knegjens, JHEP1511(2015)166
A.J.Buras, JHEP1604(2016)071
C.Bobeth, A.J.Buras, A.Celis and M.Jung, 1703.04753]



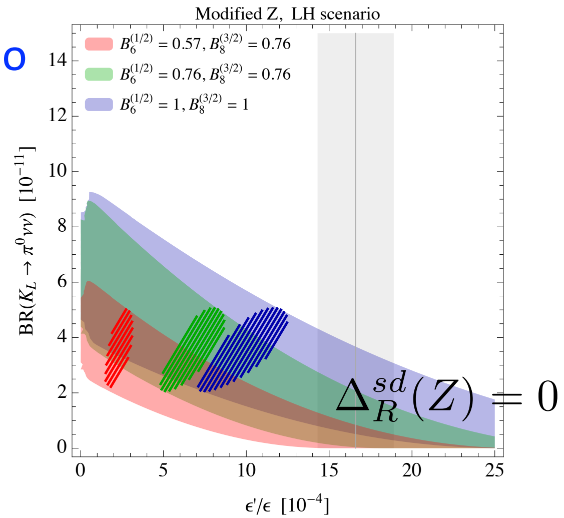
	ε'/ε	ε_K	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$	$K_L \to \mu^+\mu^-$	ΔM_K
ImΔ	*	*	*	*		*
ReΔ		*		*	*	*

$K_L \to \pi^0 \nu\nu$: Direct CPV and depends on only Im part $\Rightarrow$ Strong correlation with ε'/ε

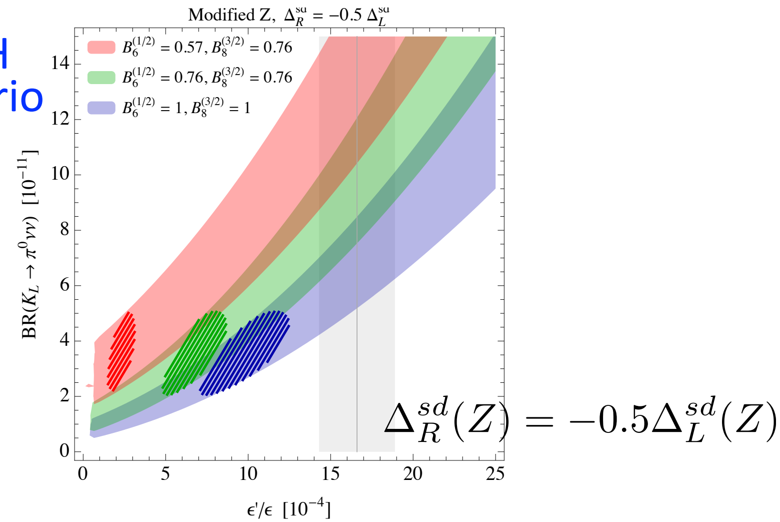


Only RH (or LH) scenario $\Rightarrow$ $K_L \to \pi^0 \nu\nu$ is suppressed
RH + LH scenario $\Rightarrow$ $K_L \to \pi^0 \nu\nu$ can be enhanced

LH scenario

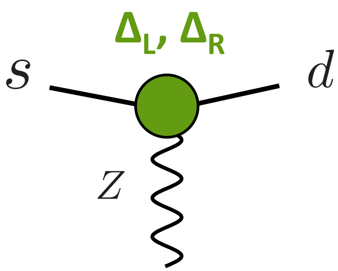


LH+RH scenario



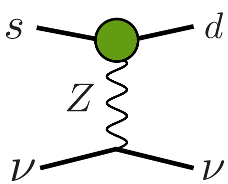
Correlations b/w Kaon observables in Z scenario

[A.J.Buras, D.Buttazzo and R.Knegjens, JHEP1511(2015)166
A.J.Buras, JHEP1604(2016)071
C.Bobeth, A.J.Buras, A.Celis and M.Jung, 1703.04753]



	ε'/ε	ε_K	$K_L \to \pi^0 \nu\bar{\nu}$	$K^+ \to \pi^+ \nu\bar{\nu}$	$K_L \to \mu^+\mu^-$	ΔM_K
$\mathrm{Im}\Delta$	*	*	*			*
$\mathrm{Re}\Delta$		*				

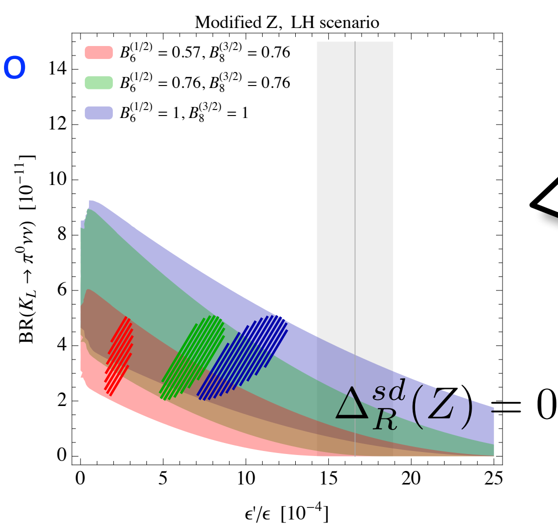
$K_L \to \pi^0 \nu\nu$: Direct CPV and depends on only Im p



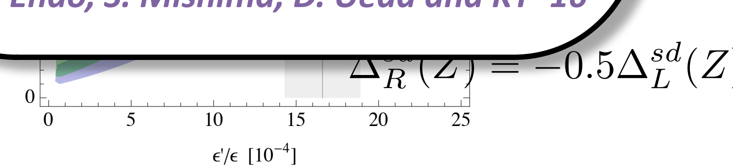
Only RH (or LH) scen

RH + LH scenario

LH scenario



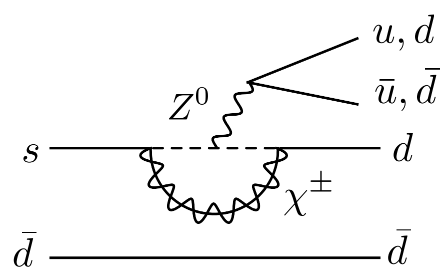
L



our work :

SUSY scenario

Chargino Z penguin

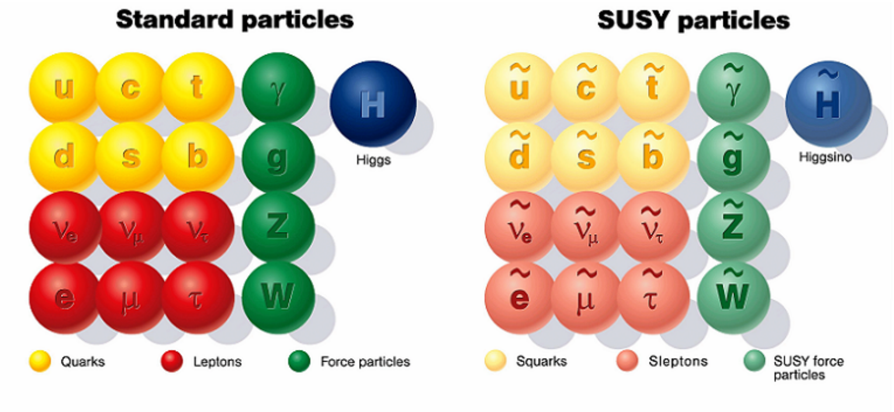


only couples left handed (s)quarks

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

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

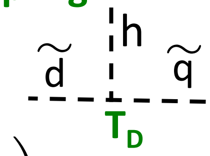
$$m_{\tilde{g}},\ m_{\tilde{q}} \gtrsim 1\mathrm{TeV}$$

- Higgs mass can be realized due to heavy stop

suggestion of high scale susy

Supersymmetry

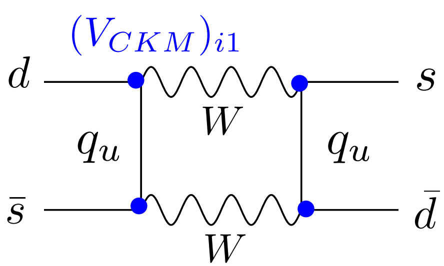
$T_{D,U}$: Trilinear scalar coupling

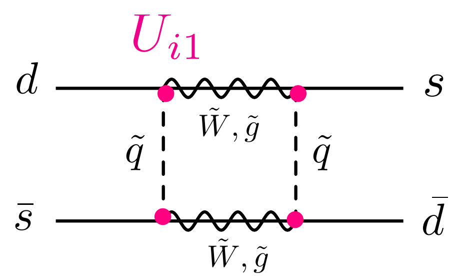


- quark & squark mass matrices cannot be diagonalized simultaneously

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

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



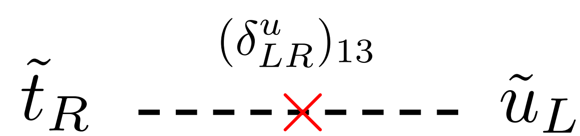


- after diagonalizing quark mass matrix, off diagonal elements of squark mass matrix give flavor violating effects

LR mixing

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

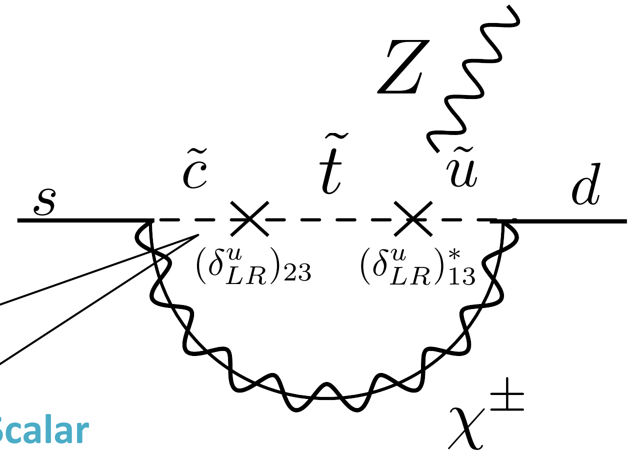
$$(\delta^u_{LR})_{ij} = \frac{\frac{v_2}{\sqrt{2}}(T_U)^*_{ij}}{m^2_{\tilde{q}}}$$



Z penguin in MSSM

Chargino $\chi^{\pm}$ Z penguin

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



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

$(\delta^u_{LR})_{13}$

$\tilde{t}_R$ - - - - ✕ - - - - $\tilde{u}_L$

Scalar trilinear coupling

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

$\Rightarrow$ vacuum stability

Vacuum stability

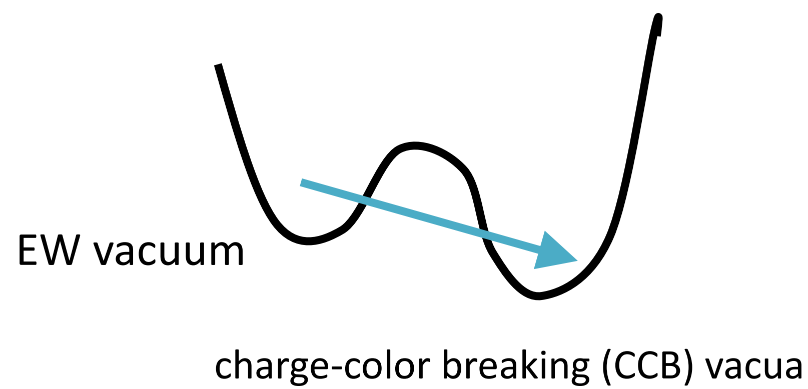
- large trilinear couplings make the vacuum unstable

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

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

scalar potential：

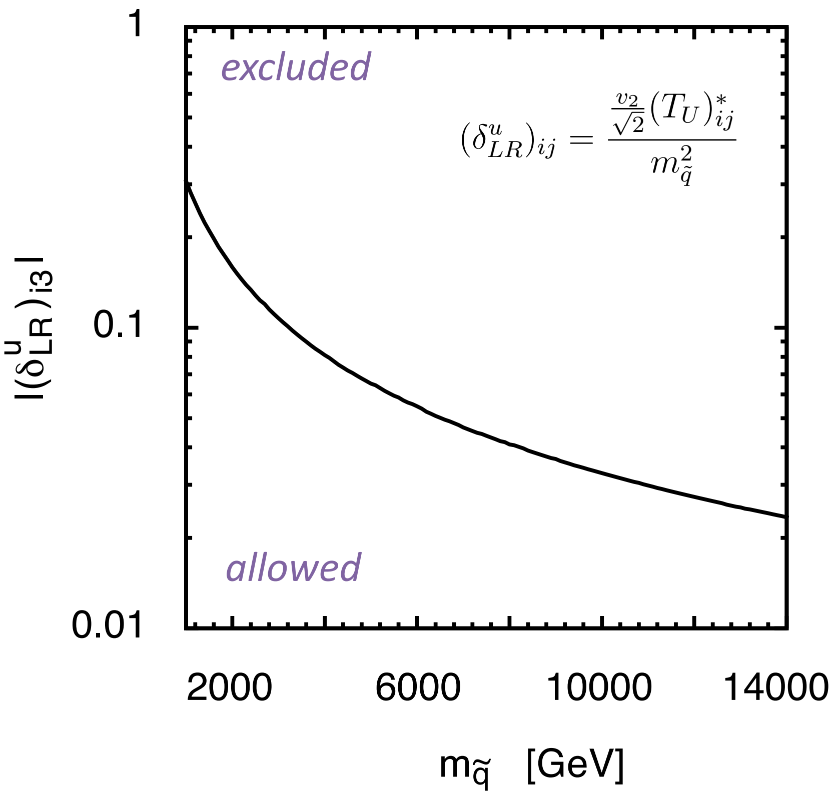
$$V \supset (T_U) h_u \tilde{u}_L \tilde{t}_R$$



$\Rightarrow$ $\delta_{LR,RL}$ are constrained by vacuum stability

- The Z-penguin contributions are constrained by requiring the lifetime of the EW vacuum is longer than the age of the universe

Bound from Vacuum stability



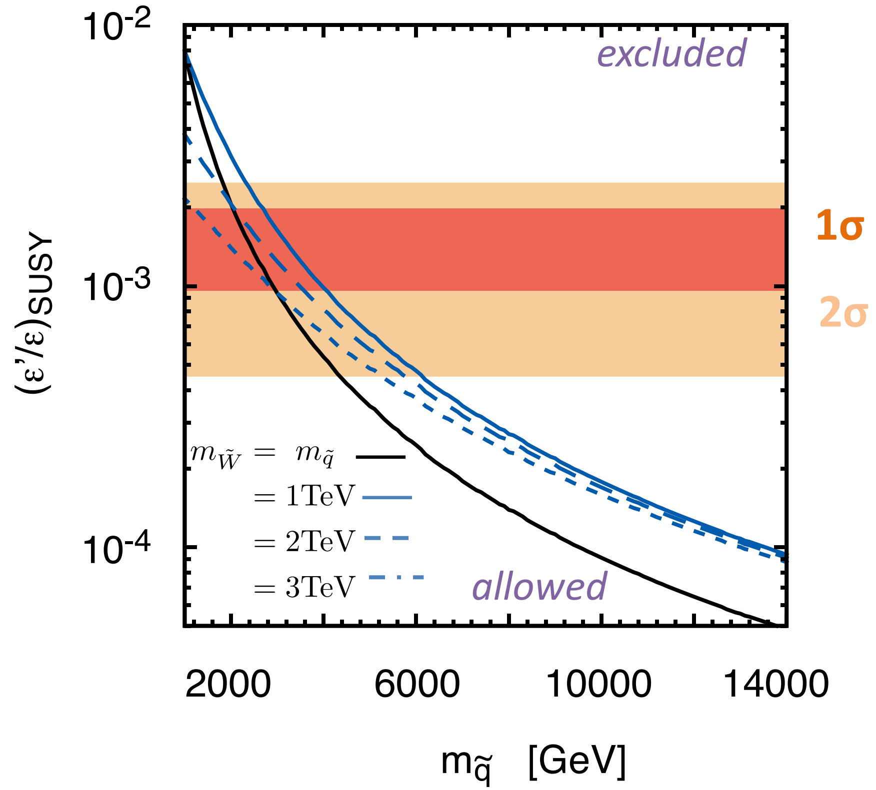
$$m_{\tilde{q}} \equiv m_{\tilde{Q}_i} = m_{\tilde{U}_3}$$

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

ε'/ε

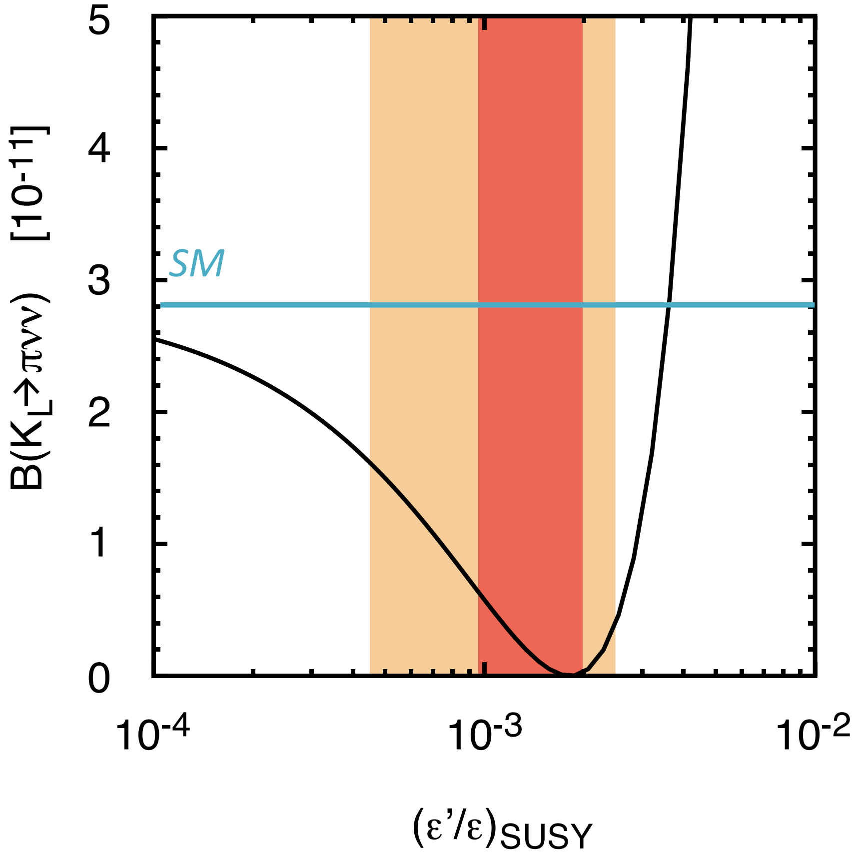
$|(T_U)_{13}| = |(T_U)_{23}| \quad m_{\tilde{q}} \equiv m_{\tilde{Q}_i} = m_{\tilde{U}_3} \quad \tan\beta = 50$

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



ε'/ε can be explained for the SUSY scale < 4–6 TeV

ε'/ε vs. $K_L \to \pi^0 \nu\nu$



Recall :

Chargino is Left handed scenario

$\Rightarrow$ negative correlation

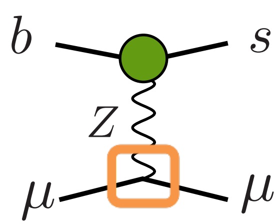
$B(K_L \to \pi^0 \nu\nu)$ is predicted to be less than 60% of the SM prediction

Comments on anomaly in B sector

Z model is not favored by anomalies in b → s transitions (P_5', R(K), R(K*),,,),
which suggest negative C_9^{NP}

$$C_9^{NP} < 0 \qquad O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$

In Z model, it is hard to produce large C_9^{NP} due to smallness of the vector coupling to charged lepton



$(1 - 4\, s_w^2)$

Contents

Summary

- Flavor physics offers a powerful probe of NP beyond the SM
- There is 2.9σ anomaly in direct CP violation in Kaon ε'/ε
- We study SUSY model with large trilinear coupling
  - chargino Z penguin contribution

    $\varepsilon'/\varepsilon \Leftrightarrow$ SUSY scale < 4-6 TeV

    $\Leftrightarrow$ BR($K_L \to \pi\nu\nu$) < 0.6 * SM
- The measurements of $K_L \to \pi^0\nu\nu$ will be important test of this model