Probing SUSY in Kaon physics

Kei Yamamoto
(KEK IPNS)

World Research Unit for Heavy Flavor Particle Physics
Symposium 2016
“Interplay between LHC and Flavor Physics”
Nagoya, Japan, 14-15 March, 2016

Interplay between LHC and Flavor Physics @Nagoya
Mar. 14 2016

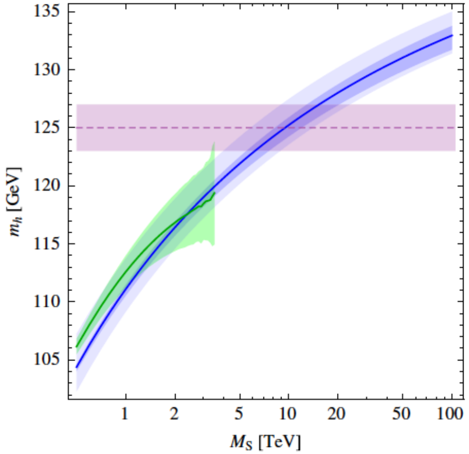
LHC Run1 results

- Discovery of Higgs

Mass $m = 125.7 \pm 0.4$ GeV

In supersymmetry, heavy stop can push up higgs mass

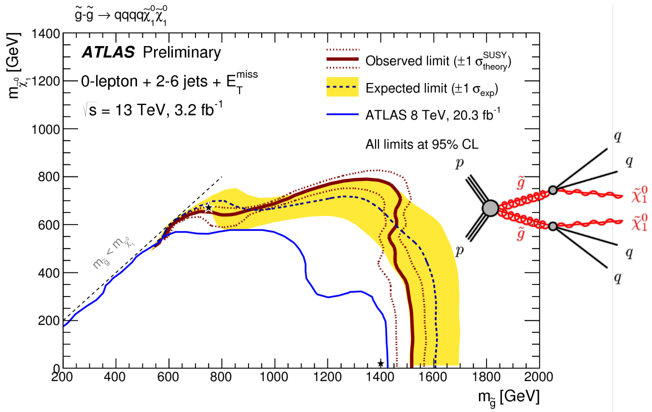
$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$



[Draper, Meade, Reece, Shih 2011]

- No signals of new physics

Gluino mass > 1.4 TeV
Squark mass > 1.0 TeV

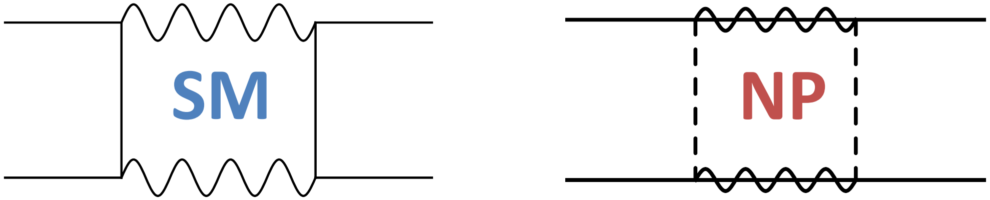


Suggestion of high scale New Physics

NP scale >> SM scale

Why Kaon ?

- Kaon is powerful probe to search for high scale NP effect



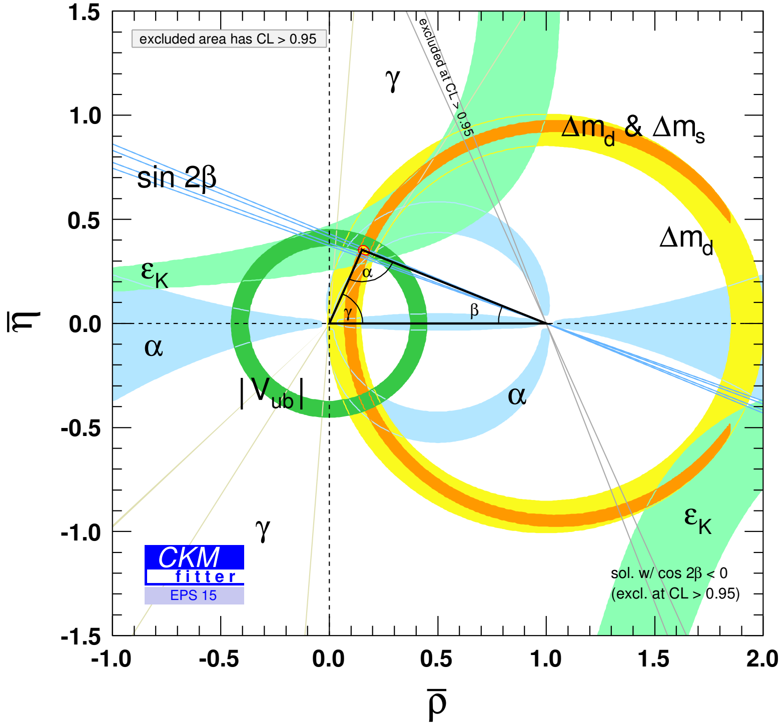
$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \frac{1}{\Lambda_{NP}^2} \sum_i C_i \mathcal{O}_i^{\text{dim6}}$$

$$|C_{\text{NP}}| \sim 1 \quad \Rightarrow \quad \Lambda_{\text{NP}} \sim \begin{cases} 500\ \text{TeV} & : \quad B_s \\ 2000\ \text{TeV} & : \quad B_d \\ 10^4 - 10^5\ \text{TeV} & : \quad K^0 \end{cases}$$

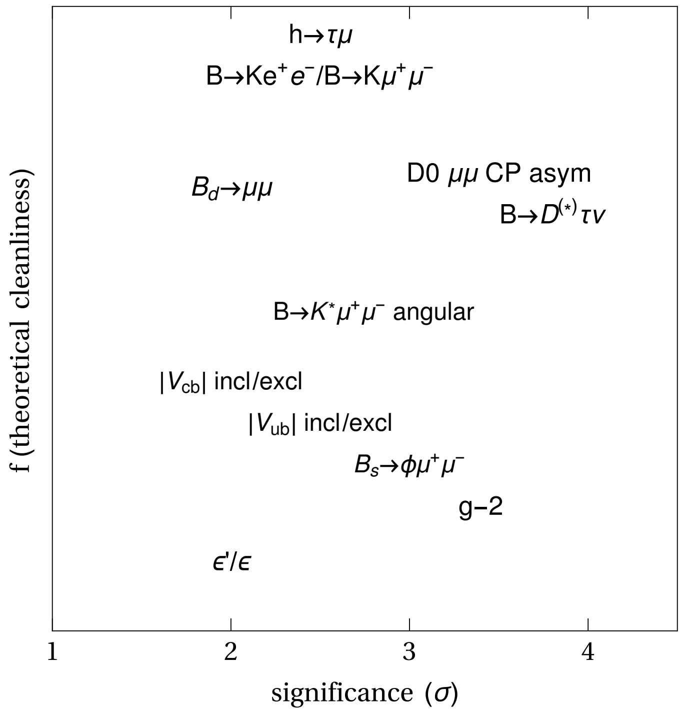
[CKMfitter, 1309.2293]

Current status of Flavor physics

- **Unitarity triangle**



- **Flavor anomaly**



Contents

CP violation in Kaon

$$\begin{tikzcd} K_S \arrow[r] & 2\pi \\ K_L \arrow[r] \arrow[ur, "!"] & 3\pi \end{tikzcd}$$

CP even

CP odd

π : pseudo scalar (0^{-+})

$\Rightarrow$ CP odd

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

mixing

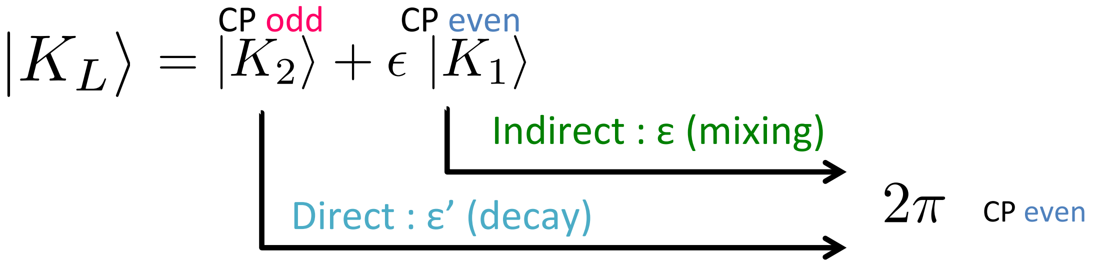
$$= \frac{1}{\sqrt{2}}\left[(1+\epsilon)|K^0\rangle + (1-\epsilon)|\bar{K}^0\rangle\right]$$

$$= \underbrace{|K_2\rangle}_{\text{CP odd}} + \epsilon \underbrace{|K_1\rangle}_{\text{even}}$$

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

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

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



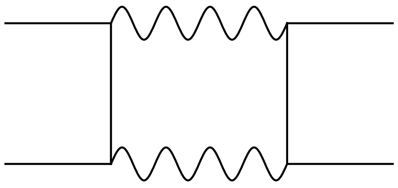
$$|K_L\rangle = \overset{\text{CP odd}}{|K_2\rangle} + \epsilon \overset{\text{CP even}}{|K_1\rangle}$$

Indirect : ε (mixing)

Direct : ε' (decay)

2π CP even

Indirect CPV (KK mixing) : ε_K



K-Kbar mixing

- formulation

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

- measurement

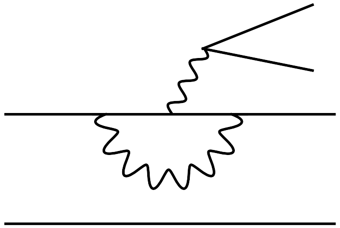
$$\epsilon_K = \frac{\mathcal{A}\left(K_L \to (\pi\pi)_{I=0}\right)}{\mathcal{A}\left(K_S \to (\pi\pi)_{I=0}\right)}$$

★**SM** $$|\epsilon_K|_{\mathrm{SM}} = (1.90 \pm 0.26) \times 10^{-3}$$

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

- Very precise measurement (~0.5%)
- strong constraint on NP

Direct CPV (K->ππ decay) : ε'



K->ππ decay

- measurement

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

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

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

- Formulation

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

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

QCD penguin EW penguin

- In SM, there is accidental cancellation between ImA0 and ImA2 due to the enhancement factor 1/ω

ΔI=1/2 rule $$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \equiv \frac{1}{\omega} = 22.46$$

SM prediction for ε’/ε

- Recently, RBC-UKQCD collaboration give a first lattice results of ε’/ε

B6, B8 : Non-perturbative parameter

$$B_6^{(1/2)}(m_c) = 0.57 \pm 0.15 \qquad B_8^{(3/2)}(m_c) = 0.76 \pm 0.05$$

★**SM**

[RBC-UKQCD’15]

$$(\epsilon'/\epsilon)_{\rm SM} = (1.4 \pm 7.0) \times 10^{-4}$$

[Buras et.al‘15]

$$(\varepsilon'/\varepsilon)_{\rm SM} = (1.9 \pm 4.5) \times 10^{-4}$$

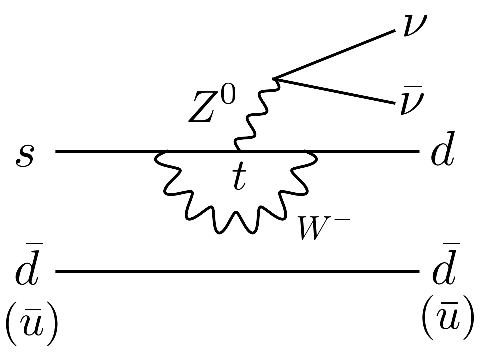
quantity	error on ε'/ε
$B_6^{(1/2)}$	4.1
NNLO	1.6
$\hat{\Omega}_{\rm eff}$	0.7
p_3	0.6
$B_8^{(3/2)}$	0.5

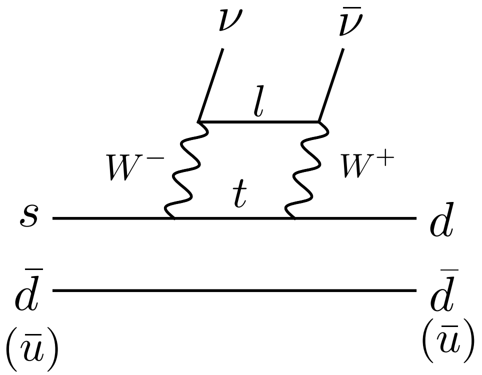
★**Exp** [NA48, KTeV]

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

2.9σ difference

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





- Features of K → πνν decay

  - Rare decay : BR_{SM} ∼10^{-11}
  - Theoretically clean : hadronic matrix element can be removed

    Isospin symmetry $\langle \pi^0 | \left(\bar{d}_L \gamma^\mu s_L \right) | \bar{K}^0 \rangle = \langle \pi^0 | \left(\bar{s}_L \gamma^\mu u_L \right) | K^+ \rangle$

    ← $BR(K^+ \to \pi^0 e^+ \bar{\nu})_{\rm exp} = (5.07 \pm 0.04) \times 10^{-2}$

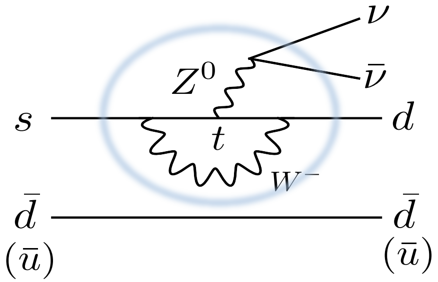
  - Experiments are in progress

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

$BR(K^+ \to \pi^+ \nu \bar{\nu})_{\rm exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ ←NA62 experiment @CERN

K → πνν and Unitarity triangle

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



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

$K_L \rightarrow \pi^0 \nu\nu$

CP - CP +

Direct CPV

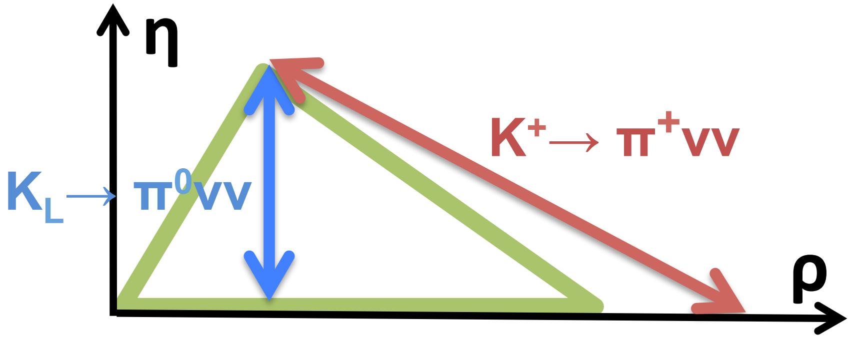
$$\begin{aligned} A(K_L \to \pi^0 \nu\bar{\nu}) &\propto A(K^0 \to \pi^0 \nu\bar{\nu}) - A(\bar{K}^0 \to \pi^0 \nu\bar{\nu}) \\ &\propto F - F^* \\ &\propto \text{Im} F \\ &\propto \eta \end{aligned}$$

$K^+ \rightarrow \pi^+ \nu\nu$

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

K → πνν and Unitarity triangle

- Determination of CPV phase (η) directly



$K_L \rightarrow \pi^0 \nu\nu$

CP – CP +

Direct CPV

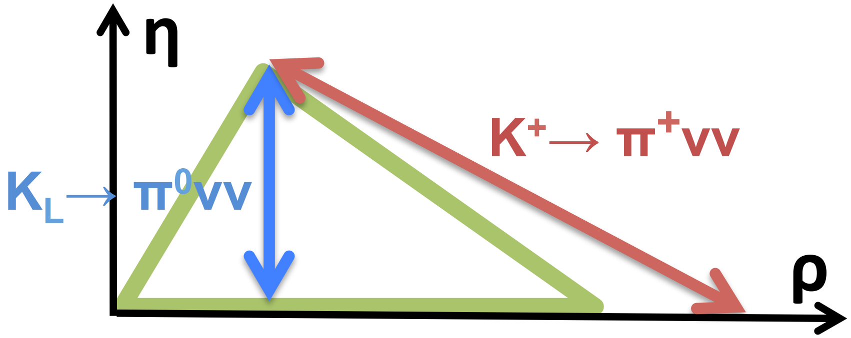
$$A(K_L \rightarrow \pi^0 \nu\bar{\nu}) \propto A(K^0 \rightarrow \pi^0 \nu\bar{\nu}) - A(\bar{K}^0 \rightarrow \pi^0 \nu\bar{\nu})$$
$$\propto F - F^*$$
$$\propto \mathrm{Im} F$$
$$\propto \eta$$

$K^+ \rightarrow \pi^+ \nu\nu$

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

$K \to \pi\nu\nu$ and Unitarity triangle

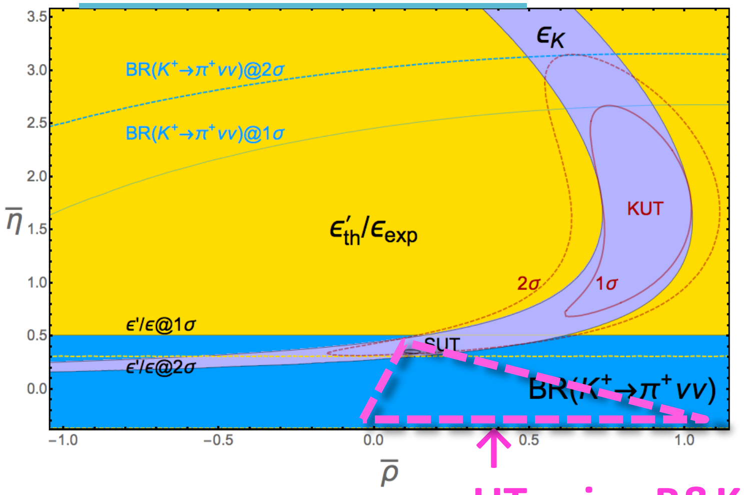
- Determination of CPV phase (η) directly



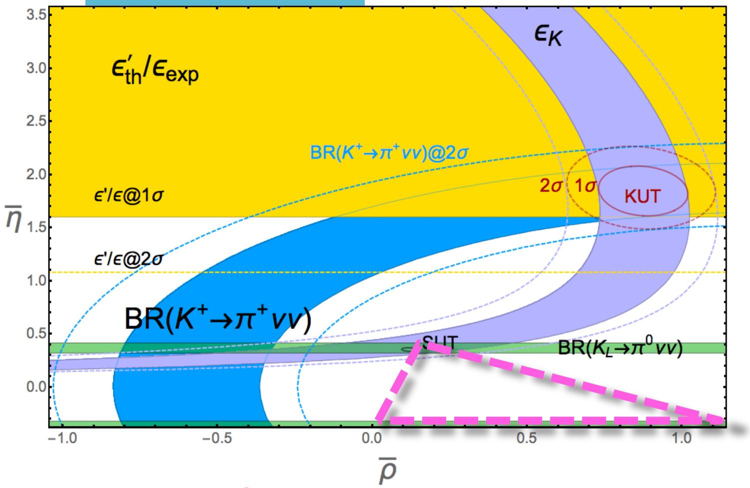
- **Unitarity triangle fit independently of B physics**

[Lehnera, Lunghi, Soni 1508.01801]

Current status



Prospect



UT using B&K physics measurements

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

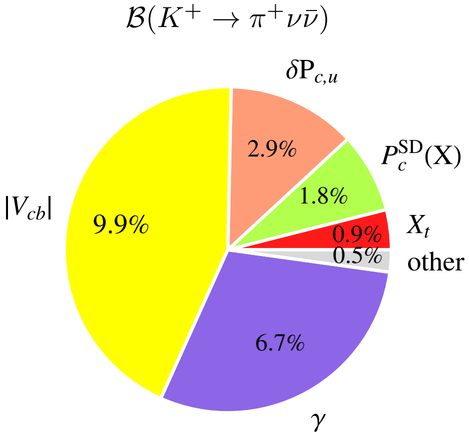
★SM [Buras et al, 1503.02693]

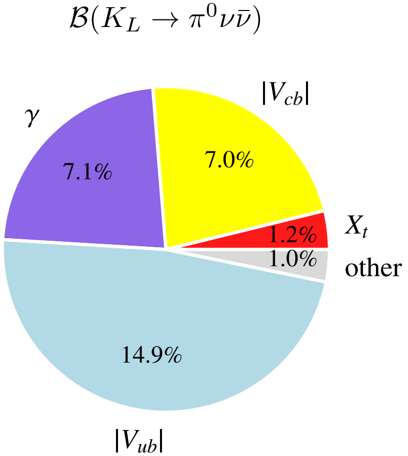
$$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11}$$

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

NLO QCD corrections to the top quark contributions
NNLO QCD corrections to the charm contribution in K+ → π+νν¯
NLO electroweak corrections

- CKM error dominant





Vub and Vcb
Inclusive / exclusive puzzle

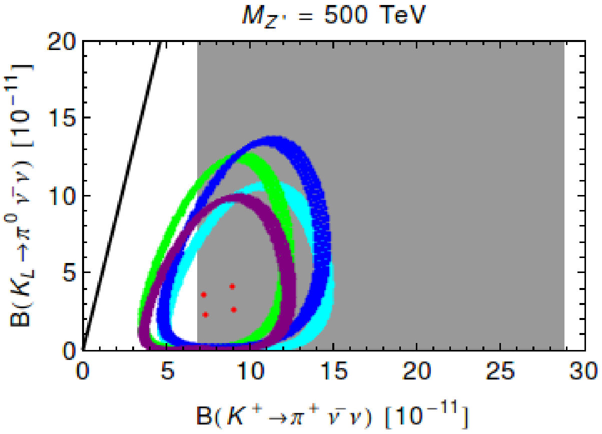
Sensitivity of $K \to \pi\nu\nu$

- K → πνν is sensitive to high scale NP

e.g.)Tree level flavor changing Z' model

K → πνν is sensitive to high scale up to 2000 TeV

[Buras et al '14]



- Can $K \to \pi\nu\nu$ be enhanced even in the high scale SUSY?

Flavor physics ⇔ High scale SUSY

$K \to \pi\nu\nu$

$m_{\tilde{q}} = 10$ TeV

Rare and (theoretically) clean process

suggestion from LHC result

⇒ this talk

Mass spectra

- We consider split family supersymmetric model

3rd family of squark is heavy. $\mathcal{O}(10)\mathrm{TeV}$
1st & 2nd family of squark are relatively light. $\mathcal{O}(1)\mathrm{TeV}$

Motivated by

- ★ The Nambu-Goldstone fermion hypothesis for quarks and leptons in the first two generations [Mandal, Nojiri, Sudano and Yanagida '11]
- ★ Muon g-2 with light SUSY spectrum [Ibe, Yanagida and Yokozaki '13]
- ★ Like-sign di-muon anomaly by the D0 [Endo, Shirai, Yanagida '10]
- ★ Higgs mass suggests heavy stop, O(10)TeV

- mass spectra :

$m_{\tilde{q}1}$	2 TeV	$m_{q4}{}^{\sim}$	2 TeV	M_1	0.5 TeV	tanβ	10
$m_{\tilde{q}2}$	2 TeV	$m_{q4^{\sim}}$	2 TeV	M_2	1 TeV		
$m_{\tilde{q}3}$	10 TeV	$m_{\tilde{q}6}$	11 TeV	M_3	3 TeV		

Chargino Z penguin

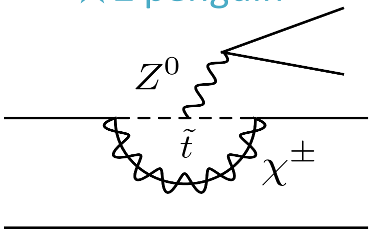
- In K → πνν decay, the dominant contribution to Z-penguin comes from chargino mediated one, and the effects of gluino and neutralino are suppressed.

  This is because the Z-q_i–q_j effective coupling is always proportional to SU(2)L breaking.

★ focus on chargino Z penguin

$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\, X_{\mathrm{eff}}}{\lambda^5} \right)^2$$

★Z penguin



Chargino Z penguin

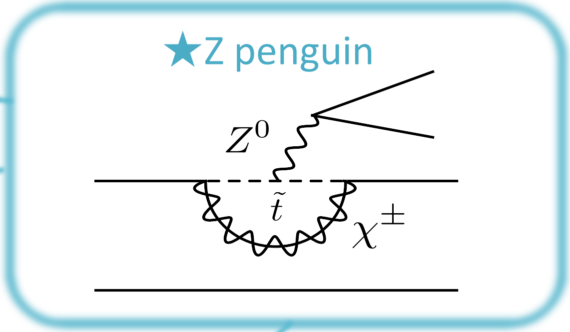
- In K → πνν decay, the dominant contribution to Z-penguin comes from chargino mediated one, and the effects of gluino and neutralino are suppressed.

  This is because the Z-q_i–q_j effective coupling is always proportional to SU(2)L breaking.

★ focus on chargino Z penguin

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \cdot \left(\frac{\mathrm{Im}\, X_{\mathrm{eff}}}{\lambda^5}\right)^2$$

$$\frac{\varepsilon'}{\varepsilon} = a\, \mathrm{Im}\lambda_{\mathrm{t}} \cdot \left[\, (1-\Omega_{\mathrm{eff}})\, P^{(1/2)} - P^{(3/2)} \,\right]$$



$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto \left(\left| \frac{m_{B_s}}{2} C_S \right|^2 \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) + \left| \frac{m_{B_s}}{2} C_P + m_\mu (C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{NP}} - C'_{10}) \right|^2 \right)$$

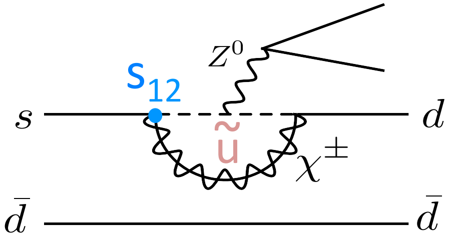
- Chargino Z penguin contributes not only K->πνν but also ε'/ε and Bq ->μμ

  -> correlate to each other

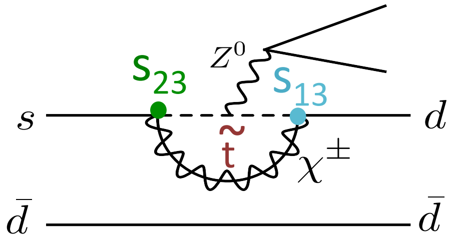
Mixing dependence

- Z penguin (K_L→πνν & ε') :

s_{12} , 1st&2nd squark



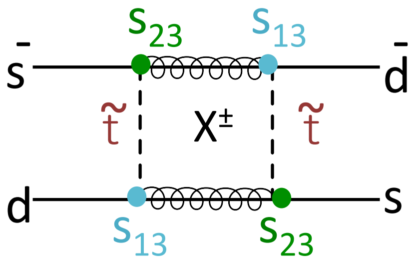
s_{13}×s_{23}, 3rd squark



↑single mixing effect is minor

[Colangelo and Isidori '98] ⇒ neglect S12

- ΔF=2 (ε_K and ΔM_K): s_{13}×s_{23}, 3rd squark

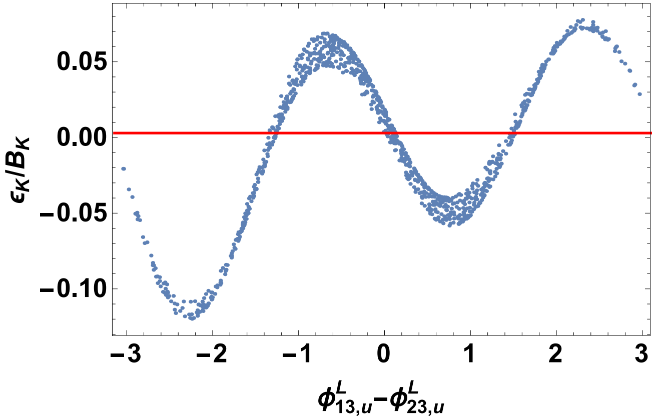


★ neglect s12 mixing and only consider s23 and s13
⇒ combination s23*s13 brings s->d transition

Constraints from ε_K & ΔM_K

- εK

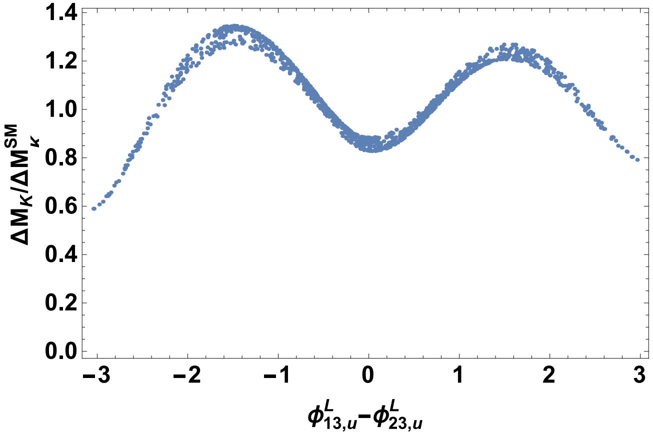
chargino Z penguin's phase dependence



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

★ need phase tuning

- ΔM_K



$$0.75 \leq \frac{\Delta M_K}{(\Delta M_K)_{\rm SM}} \leq 1.25$$

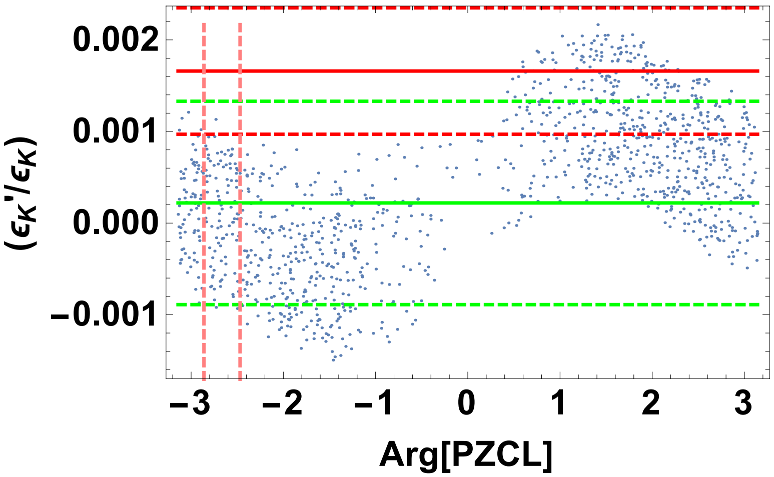
[Buras et al, 1306.3775]

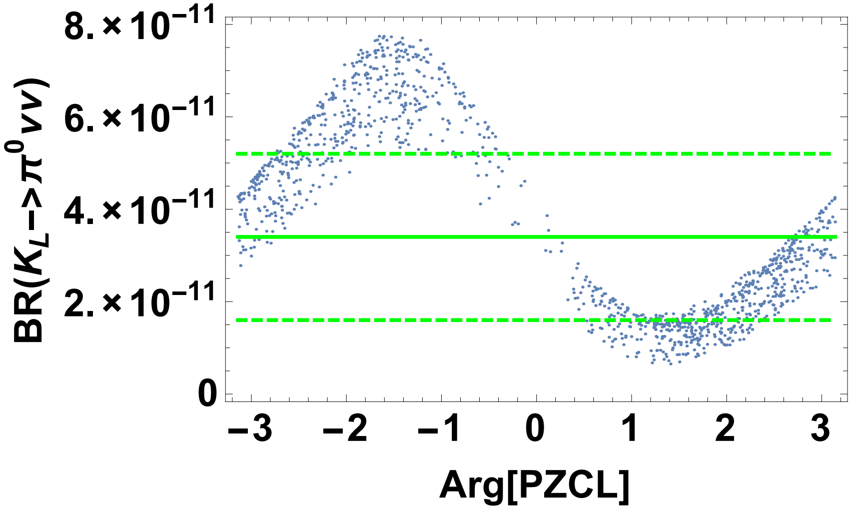
★ to avoid ΔMK constraint
s23, s13 < 0.3

Relation between ε’/ε and K→πνν

- Large enhancement ε’/ε implies suppressed K_L->$\pi^0\nu\nu$

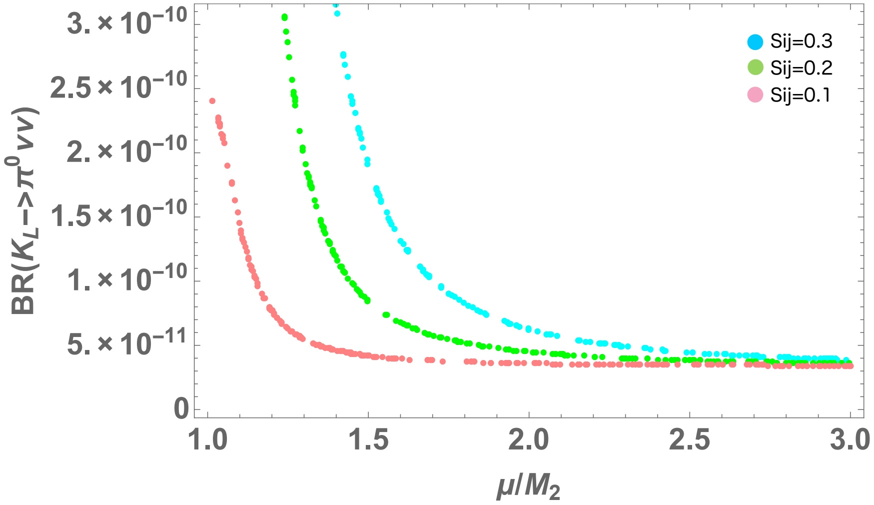
chargino Z penguin’s phase dependence





Other parameters

- μ/M2 dependence



★ K->πνν increase in the region of sizable mixing wino and higgsino

μ/M2 = 1.5 ～2.5

- LR mixing

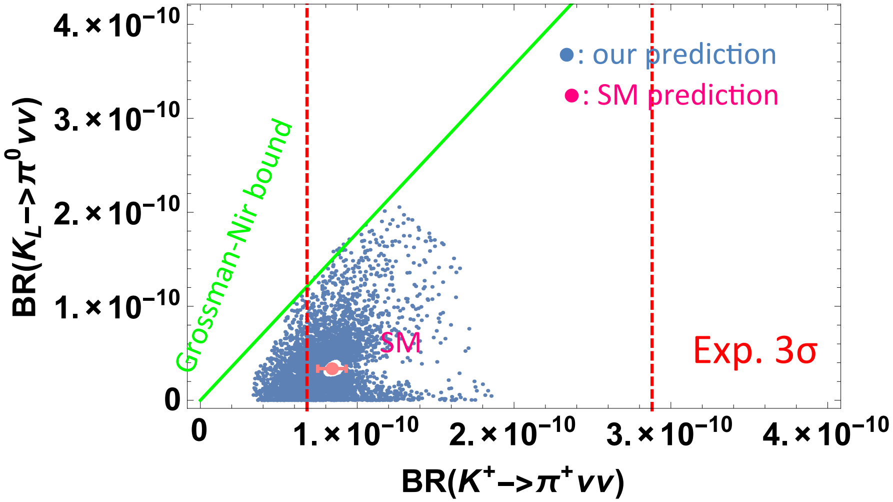
$$\theta^t_{LR} \simeq \frac{m_t(A_0 - \mu \cot\beta)}{m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R}}$$

★ $\theta_{LR,\,u}$=0.3

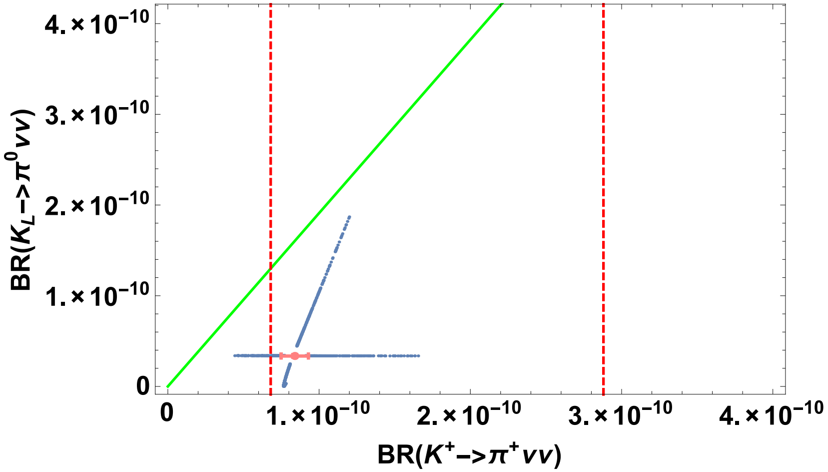
Work in progress

Numerical results 1 ; $K_L \rightarrow \pi^0 \nu\nu$ vs $K^+ \rightarrow \pi^+ \nu\nu$

[M Tanimoto, KY,1603.XXXX]



↓ with constraint from εK



- Input parameter :

Mixing parameters

$s^u_{L,\,12}=s^u_{R,\,12}=0$

$s^u_{L,\,13}=0.3$, $s^u_{R,\,13}=0$

$s^u_{L,\,23}=0.3$, $s^u_{R,\,23}=0$

LR mixing

$\theta_{LR,\,u}=0.3$

μ /M2= 1.5 ∼ 2.5

CKM input : best fit value

B6 & B8 : 3σ

- Predicted region :

$BR(K_L\text{->}\pi\nu\nu) < 2\times 10^{-10}$

$BR(K^+\text{->}\pi\nu\nu) < 2\times 10^{-10}$

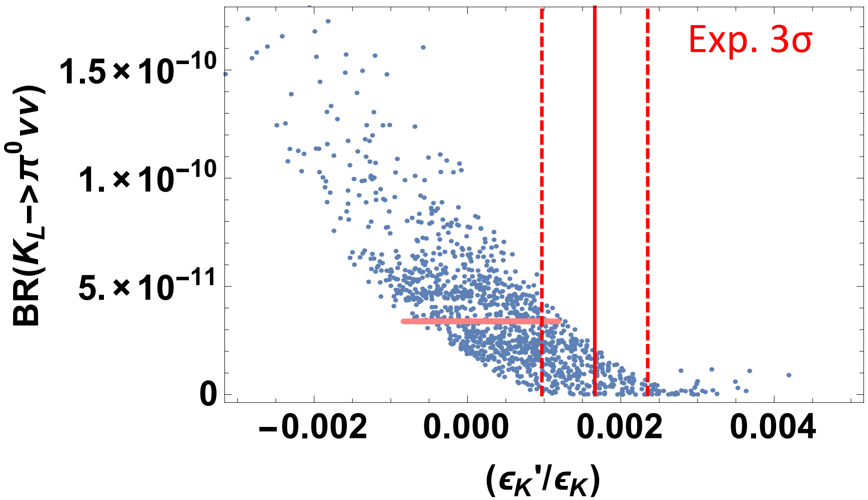
Work in progress

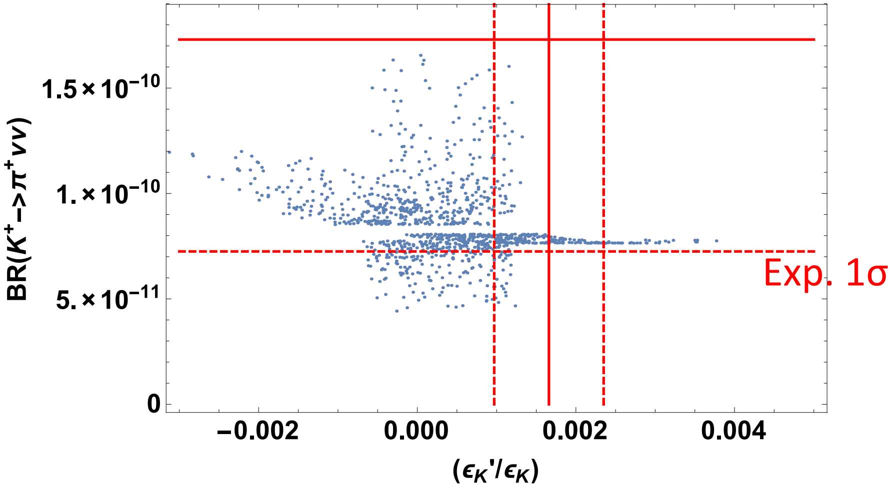
Numerical results 2 ; $K \rightarrow \pi\nu\nu$ vs ε'/ε

[M Tanimoto, KY,1603.XXXX]

●: our prediction

●: SM prediction





- Input parameter :

Mixing parameters

$s^u_{L,12}=s^u_{R,12}=0$

$s^u_{L,13}=0.3$, $s^u_{R,13}=0$

$s^u_{L,23}=0.3$, $s^u_{R,23}=0$

LR mixing

$\theta_{LR,u}=0.3$

μ /M2= 1.5 ～ 2.5

CKM input : best fit value

B6 & B8 : 3σ

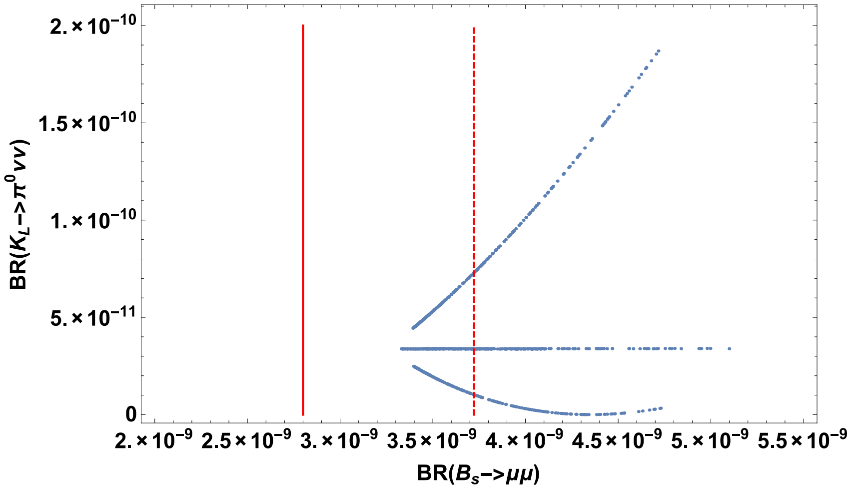
- Predicted region :

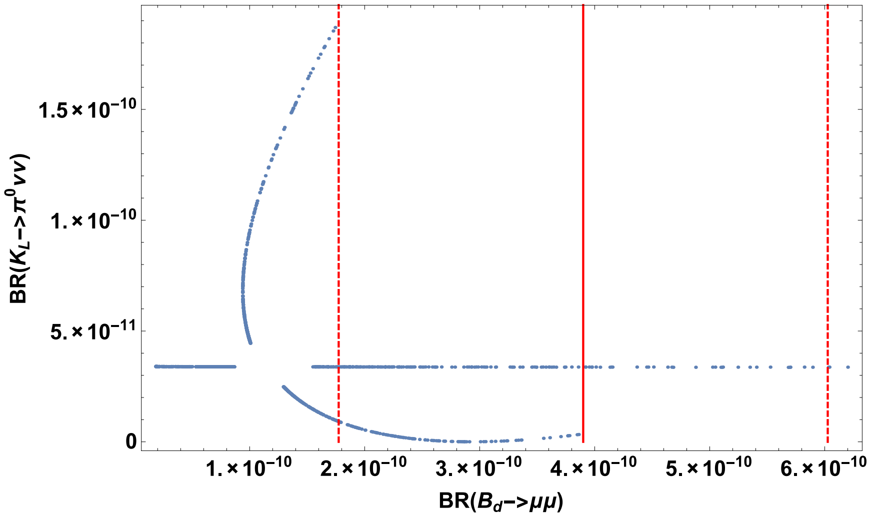
$BR(K_L\text{->}\pi\nu\nu) < 3\times10^{-11}$ ⇔ ε'/ε

Work in progress

Numerical results 3 ; $K_L \rightarrow \pi^0\nu\nu$ vs $Bq \rightarrow \mu\mu$

[M Tanimoto, KY,1603.XXXX]


Exp. 1σ


Exp. 1σ

- Input parameter :

Mixing parameters

$s^u_{L,\,12}=s^u_{R,\,12}=0$

$s^u_{L,\,13}=0.3,\ s^u_{R,\,13}=0$

$s^u_{L,\,23}=0.3,\ s^u_{R,\,23}=0$

LR mixing

$\theta_{LR,\,u}=0.3$

μ /M2= 1.5 ～ 2.5

CKM input : best fit value

B6 & B8 : 3σ

	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
★SM	$(3.65 \pm 0.23) \times 10^{-9}$	$(1.06 \pm 0.09) \times 10^{-10}$
★Exp	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$	$(3.9^{+1.6}_{-1.4}) \times 10^{-10}$

Summary

- Kaon physics offers a powerful probe of NP beyond the SM.
- Rare Kaon decays K → πνν are theoretically very clean and sensitive to NP at a very high scale, which is not accessible at the LHC.
- We have presented correlations between K->πνν , ε'/ε and Bq ->μμ in a split-family supersymmetric model.
  K->πνν can be enhanced even in the high scale SUSY, 10 TeV.

Belle-II, LHCb, KOTO and NA62 results coming soon : exiting future awaits !