Kaon Physics: Theory View

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→ Technion (from Oct.)

Workshop on the physics of HL-LHC,
and perspectives at HE-LHC

Karlsruhe Institute of Technology

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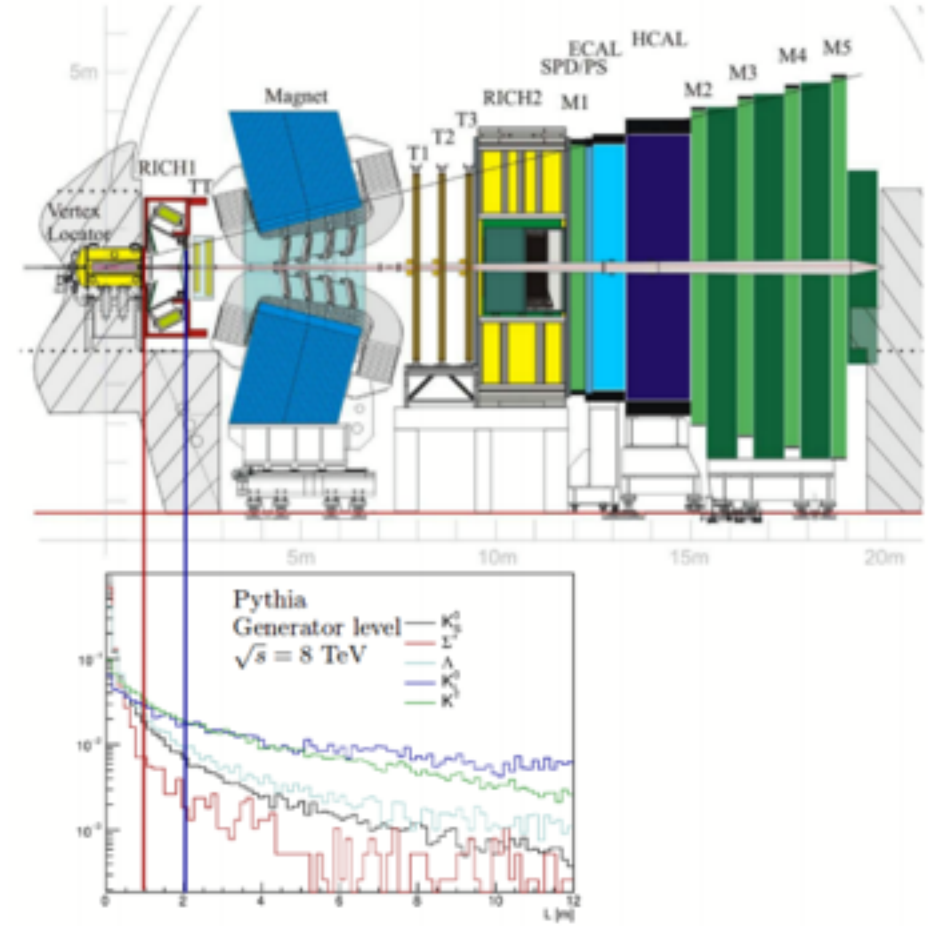
Institute for Theoretical Particle Physics

Kaon in LHCb



- LHCb experiment has been designed for efficient reconstructions of ***b*** and ***c***
- Huge production of strangeness [$O(10^{13})/\text{fb}^{-1}$ K^0_S] is suppressed by its trigger efficiency [ε~1-2%@LHC Run-I, ε~18%@LHC Run-II]
- LHCb Upgrade (LS2=Phase I upgrade, LS4=Phase II upgrade) could realize high efficiency for K^0_S [ε~90%@LHC Run-III] [M. R. Pernas, HL/HE LHC meeting, FNAL, 2018]
- In LHC Run-III and HL-LHC, we could probe the *ultra* rare decay Br~$O(10^{-11\sim-12})$

collider search

could give stronger constraints

Lattice
perturbative calculations
meson effective theory (ChPT)

ε_K and ε'_K discrepancies?

$K_L \to \pi\pi$

B

correlations

CP-violating FCNC

$K_S \to \mu^+\mu^-$

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

Yellow Report

Understanding of ChPT

$K_S \to \pi^0 \mu^+ \mu^-$

$K_S \to \pi^+ \pi^- e^+ e^-$

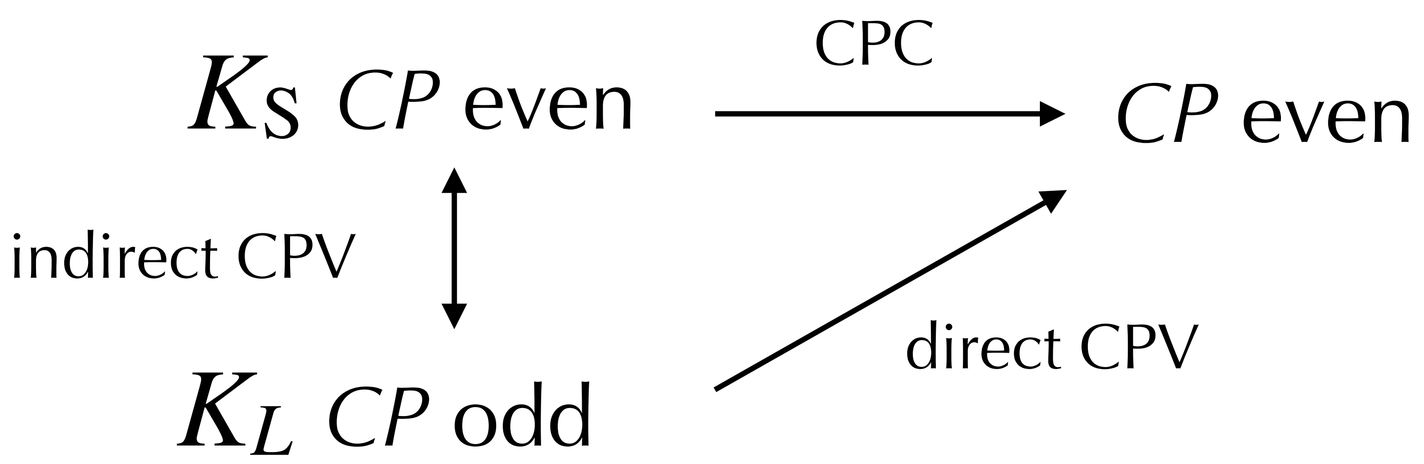
$K_S \to 4l$

reduce th. error →

$K_L \to \pi^0 l^+ l^-$

less sensitive because of LD contributions

$K^0 \to \pi\pi$



$K^0 \to \pi\pi$ systems: two *CP* violations

- Precise measurements for neutral kaon decay into two pions have revealed **two types of *CP* violations**: **indirect CPV ε_K** & **direct CPV ε'_K**:

$$\mathcal{A}\left(K_L \to \pi^+\pi^-\right) \propto \varepsilon_K + \varepsilon'_K \quad \text{with } \varepsilon_K = \mathcal{O}(10^{-3}) \neq 0$$

[Christenson, Cronin, Fitch, Turlay '64 with Nobel prize]

$$\mathcal{A}\left(K_L \to \pi^0\pi^0\right) \propto \varepsilon_K - 2\varepsilon'_K \qquad \varepsilon'_K = \mathcal{O}(10^{-6}) \neq 0$$

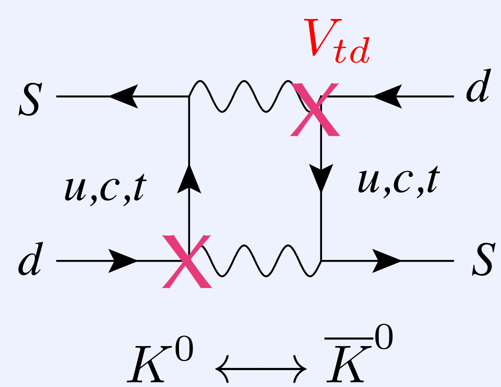
[NA48/CERN and KTeV/FNAL '99]

$$\Longleftrightarrow \quad \mathrm{Re}\left(\frac{\varepsilon'_K}{\varepsilon_K}\right) = \frac{1}{6}\left[1 - \frac{\mathcal{B}(K_L \to \pi^0\pi^0)}{\mathcal{B}(K_S \to \pi^0\pi^0)}\frac{\mathcal{B}(K_S \to \pi^+\pi^-)}{\mathcal{B}(K_L \to \pi^+\pi^-)}\right] = \mathcal{O}(10^{-3})$$

Δ*S*=2
Indirect *CP* violation
[Kaon mixing]

W box

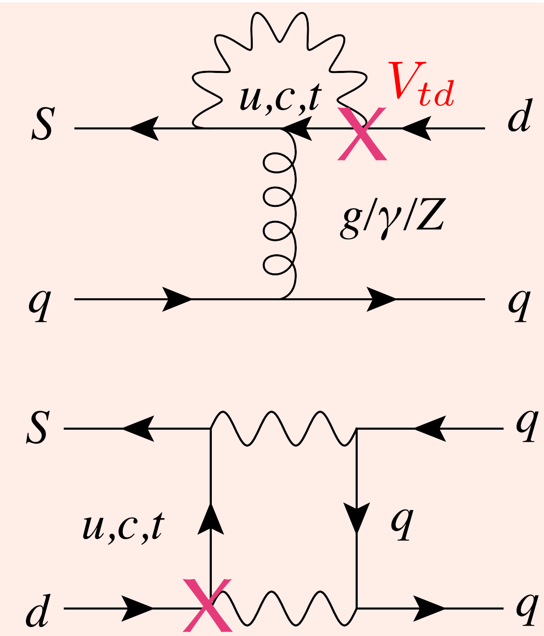
$$\varepsilon_K \propto \mathrm{Im}[(\mathrm{CKM})^2]$$



Δ*S*=1
Direct *CP* violation

penguin and W-box

$$\varepsilon'_K \propto \mathrm{Im}[\mathrm{CKM}]$$



ε_K discrepancy

- SM prediction of the indirect CP violation ε_K is sensitive to $|V_{cb}|$

$$\varepsilon_K = \varepsilon_K(\mathrm{SD}) + \varepsilon_K(\mathrm{LD})$$

⟵ $\varepsilon_K(\mathrm{LD}) = -3.6(2.0)\% \times \varepsilon_K(\mathrm{SD})_{\mathrm{SM}}$ [Buras,Guadagnoli, Isidori '10]

$$\varepsilon_K(\mathrm{SD}) \propto \mathrm{Im}\lambda_t \left[-\mathrm{Re}\lambda_t \eta_{tt} S_0(x_t) + (\mathrm{Re}\lambda_t - \mathrm{Re}\lambda_c)\,\eta_{ct} S_0(x_c, x_t) + \mathrm{Re}\lambda_c \eta_{cc} S_0(x_c)\right]$$

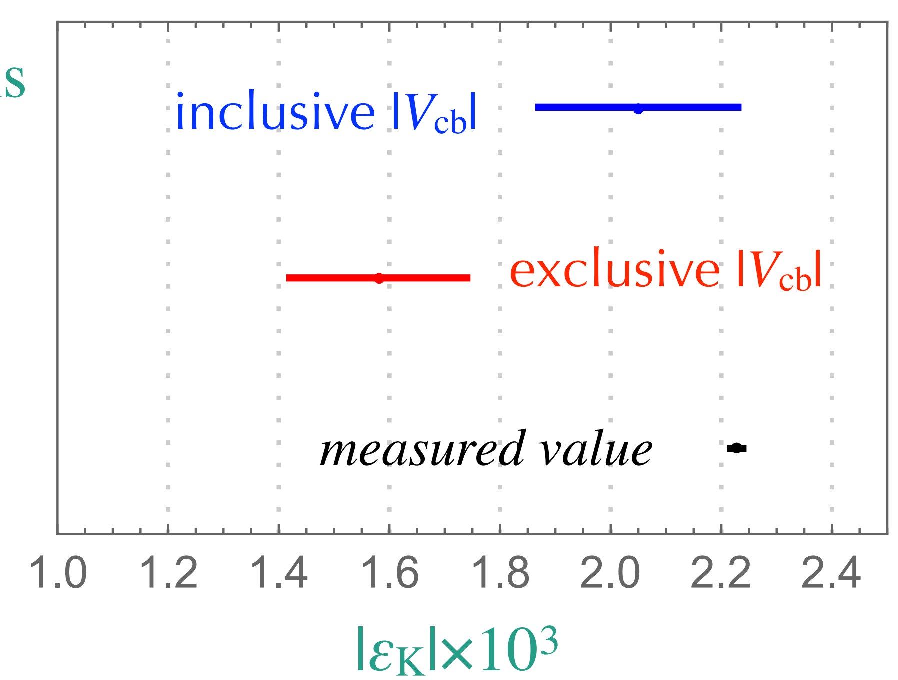
Wolfenstein parametrization →

$$\simeq \bar{\eta}\lambda^2 |V_{cb}|^2 \left[|V_{cb}|^2 (1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} S_0(x_c)\right]$$

Leading contribution is proportional to $|V_{cb}|^4$

$|\varepsilon_K|$ predictions
($\pm 1\sigma$ error bar)

errors are dominated by $|V_{cb}|$, $\bar{\eta}$, η_{ct}, η_{cc}

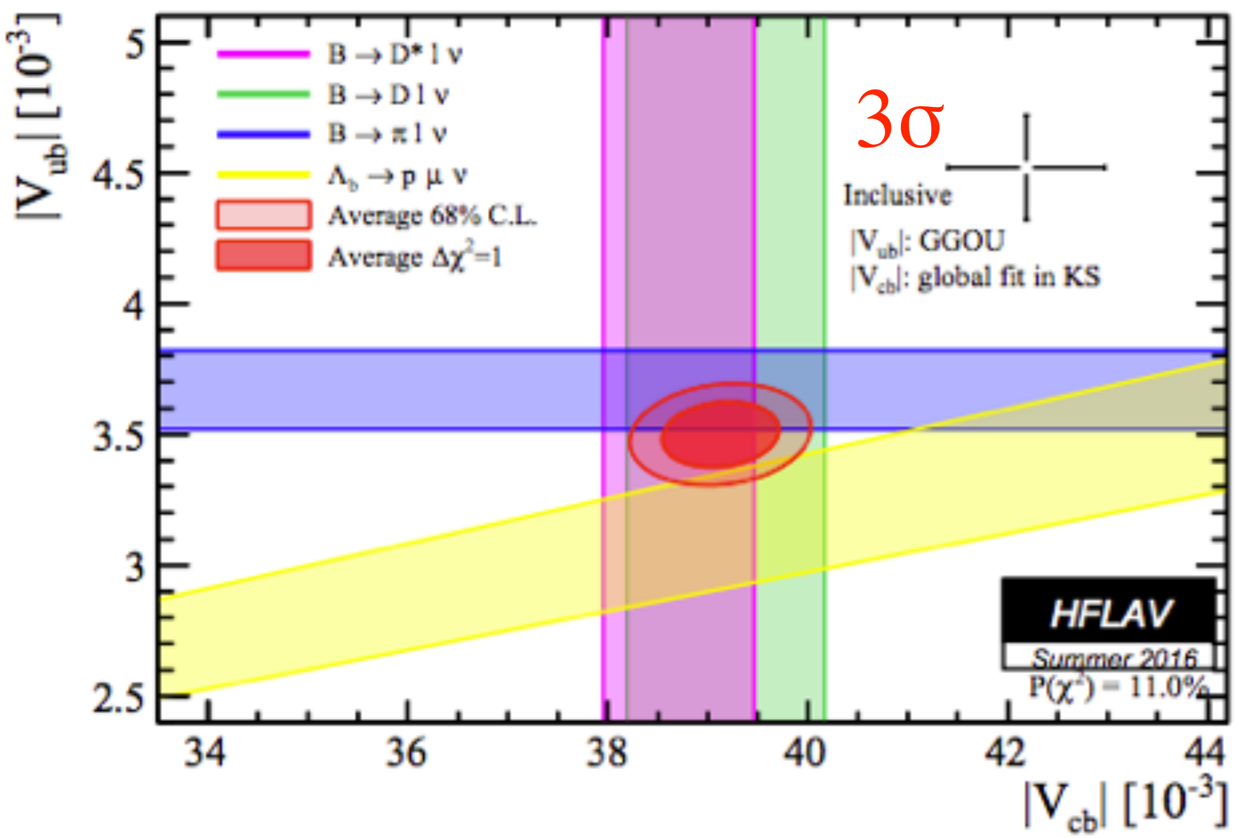


Theoretical prediction of ε_K with inclusive $|V_{cb}|$ is consistent with the measured value, while there is 4.0σ tension in exclusive $|V_{cb}|$ case

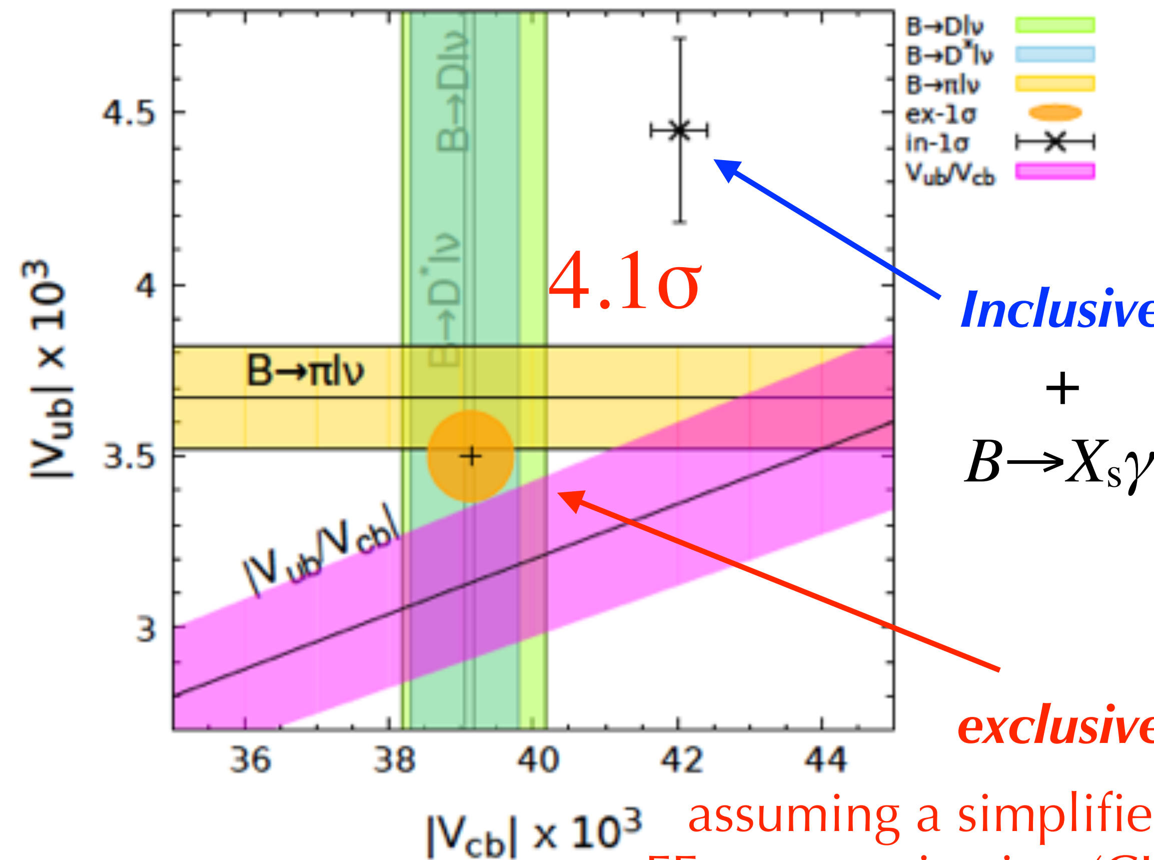
[LANL-SWME, 1710.06614]
Wolfenstein parameters are determined by the angle-only fit

ε_K discrepancy ~ $|V_{cb}|$ discrepancy

[HFLAV average, 1612.07233]



[LANL-SWME, 1710.06614]



assuming a simplified FF parametrization (CLN)

- Recent progress on exclusive $|V_{cb}|$ in $B \to D^*$ transition

$B \to D^* \ell \bar{\nu}$ [Belle, 1702.01521]

- Model independent form factors parametrization [Boyd-Grinstein-Lebed (BGL) '97]
- $|V_{cb}|^{\rm excl.}_{\rm BGL} = (40.6^{+1.2}_{-1.3}) \times 10^{-3}$ [Bigi, Gambino, Schacht '17] — error will be reduced by future lattice result
- + Similar recent progress [Grinstein, Kobach '17, Bernlochner, Ligeti, Papucci, Robinson '17]

Direct *CP* violation in $K^0 \to \pi\pi$

- Further strong suppression of ε'_K comes from the smallness of the ΔI=3/2 amplitude (i.e. ΔI =1/2 rule) and an accidental cancellation between the SM penguins

$$\mathcal{A}(K^0 \to (\pi\pi)_I) \equiv A_I e^{i\delta_I}$$
$$\mathcal{A}(\overline{K}^0 \to (\pi\pi)_I) \equiv \bar{A}_I e^{i\delta_I} = A_I^* e^{i\delta_I}$$

I : two-pion isospin=0,2 pion = isospin triplet

δ_I: strong phase

$$\frac{\varepsilon'_K}{\varepsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|\mathrm{Re}A_0} \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}\left(-\mathrm{Im}A_0 + \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\mathrm{Im}A_2\right)$$

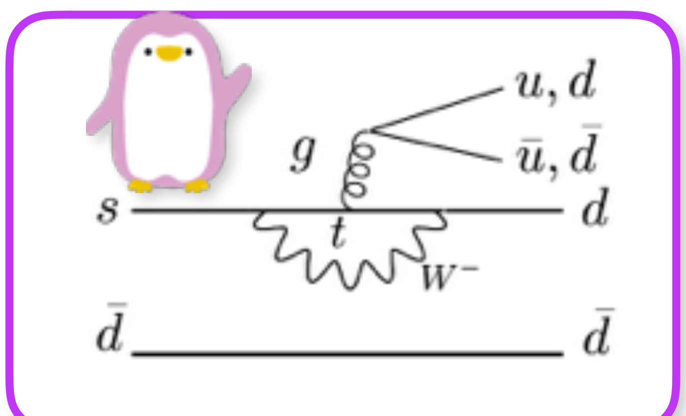
ΔI =1/2 rule: factor = 0.04

Accidental cancellation

$$\mathcal{O}(\alpha_s) \overset{!}{\sim} \frac{1}{\omega}\mathcal{O}(\alpha)$$

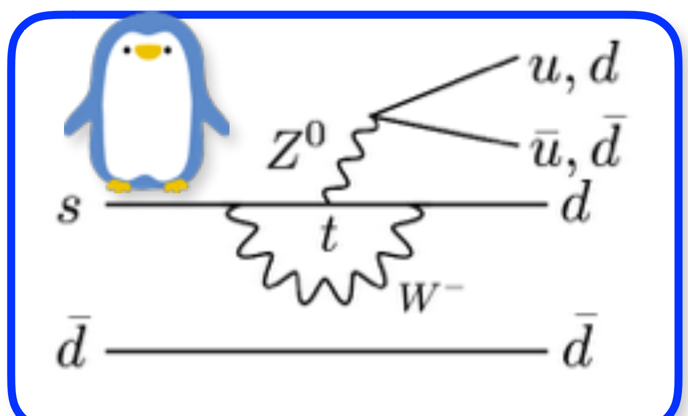
where $\frac{1}{\omega} \equiv \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.46$ (exp.)

~ Im [QCD penguin]



sensitive

~ Im [EW penguin]



Progress on RG evolution

- Analytic solution of f=3 QCD-NLO RG evolution has a unphysical singularity [Ciuchini,Franco,Martinelli,Reina '93, '94, Buras,Jamin,Lautenbacher '93]

$$\hat{J}_s - \left[\hat{J}_s, \frac{\hat{\gamma}_s^{(0)T}}{2\beta_0}\right] = \frac{\beta_1}{\beta_0}\frac{\hat{\gamma}_s^{(0)T}}{2\beta_0} - \frac{\hat{\gamma}_s^{(1)T}}{2\beta_0}, \quad \Leftrightarrow \quad \left(\hat{V}^{-1}\hat{J}_s\,\hat{V}\right)_{ij} = \frac{\cdots}{2\beta_0 \mp \left((\hat{\gamma}_{s,D}^{(0)T})_{jj} - (\hat{\gamma}_{s,D}^{(0)T})_{ii}\right)}.$$

10x10 matrix $\hat{J}_s$ is a solution of the f=3 QCD-NLO RG evolution

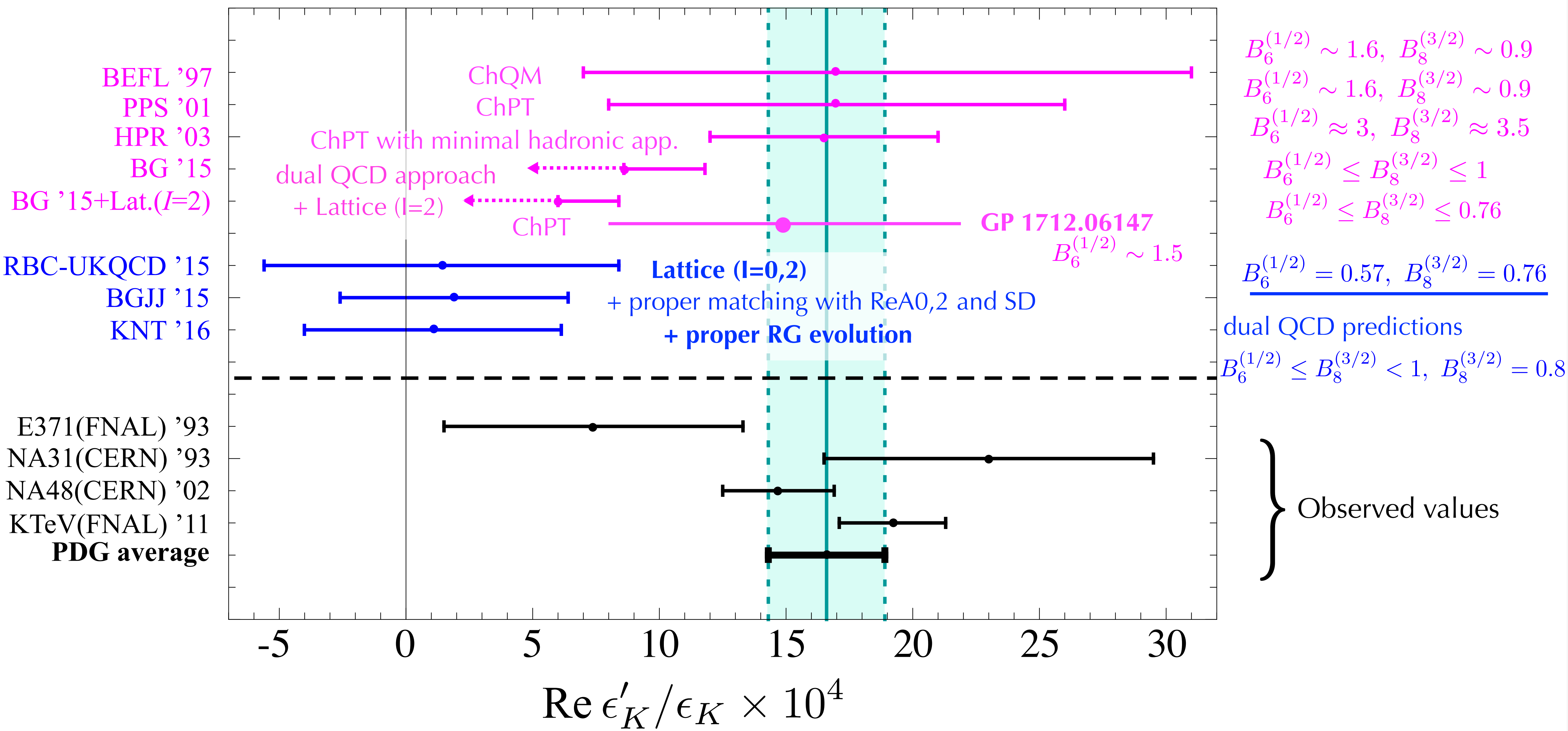
$2\beta_0 = 18,\ \hat{\gamma}_{s,D}^{(0)T} \supset +2, -16$ leads to singularity, which requires a regulator in ADM $\hat{\gamma}_s^{(0)}$

- Similar singularities exist in QED-NLO and QCD-QED-NLO RG evolutions

- Singularity-free analytic solutions are obtained using more generalized ansatz for the NLO evolution matrices [TK, Nierste, Tremper, JHEP '16]
  - $\ln \alpha_s(\mu_2)/\alpha_s(\mu_1)$ terms are added compared to the previous solution
  - Contribution of order α^2/α_s^2 is also included for the first time and we find it is numerically irrelevant in the SM → good perturbation

Current situation of $\varepsilon'_K/\varepsilon_K$

$$\propto \underbrace{\mathrm{Im}A_0}_{\propto B_6^{(1/2)}} - \left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right) \underbrace{\mathrm{Im}A_2}_{\propto B_8^{(3/2)}}$$



$\Delta I = 1/2$ rule $\left(\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\right)$	Exp.	ChPT	dual QCD	Lattice
	22.45 ± 0.05	~ 14	16.0 ± 1.5	31.0 ± 11.1

$\varepsilon'_K/\varepsilon_K$ discrepancy

- Lattice result with recent progress on the short-distance physics predicts $\varepsilon'_K/\varepsilon_K = O(10^{-4})$ which is below the experimental average **at 2.8-2.9σ level**

  NNLO QCD in progress [Cerdà-Sevilla, Gorbahn, Jäger, Kokulu]

- A large-N_c analysis (dual QCD method) including final-state interaction (FSI) is consistent with lattice results [Buras, Gerard, '15, '17]

- ChPT including FSI predicts $\varepsilon'_K/\varepsilon_K = O(10^{-3})$ with large error which is consistent with measured values [Gisbert, Pich 1712.06147]

- Main difference comes from $B_6^{(1/2)} = 0.6$ (lattice) vs 1.5 (ChPT)

- The lattice simulation includes FSI as the Lellouch-Lüscher finite-volume correction and explained ΔI=1/2 rule for the first time. But, the strong phase of I=0 is smaller than a phenomenological expectation **at 2.7σ level**

  [Colangelo, Passemar, Stoffer '15]

- For I=2 decay, lattice/dual QCD/ChPT give well consistent results

Lattice simulation with improved methods and higher statistics is on-going [1711.05648]

$\varepsilon'_K/\varepsilon_K$ in the BSM

- Several types of BSM can explain $\varepsilon'_K/\varepsilon_K$ discrepancy

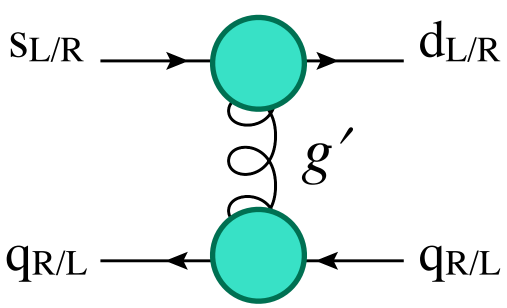
$$\frac{\varepsilon'_K}{\varepsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|\mathrm{Re}A_0}\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}\left(-\mathrm{Im}A_0 + \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\mathrm{Im}A_2\right)$$

$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.46\ (\mathrm{exp.})$$

: BSM vertex (must include CPV phase)

$\mathrm{Im}A_0$

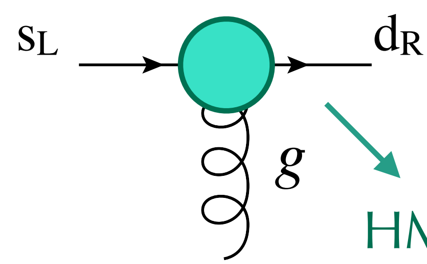
g' scenario



RS model 1404.3824

chiral-flavorful vector 1806.02312

chromomagnetic scenario



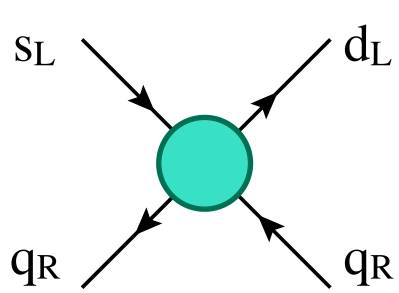
HME would be suppressed [1712.09824, 1803.08052]

SUSY 1711.11030,...

Type-III 2HDM 1805.07522

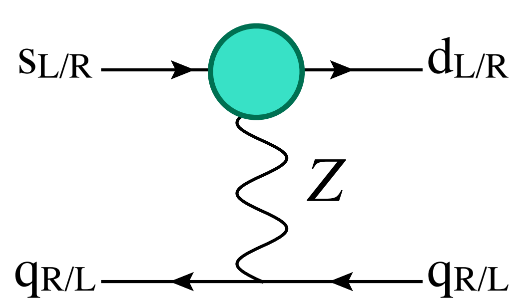
$\mathrm{Im}A_2$

Box scenario



SUSY 1604.07400,...

Z scenario

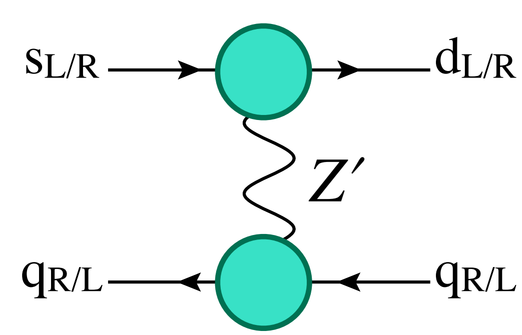


SUSY 1608.01444,...

VLQ 1609.04783,...

LHT 1507.06316

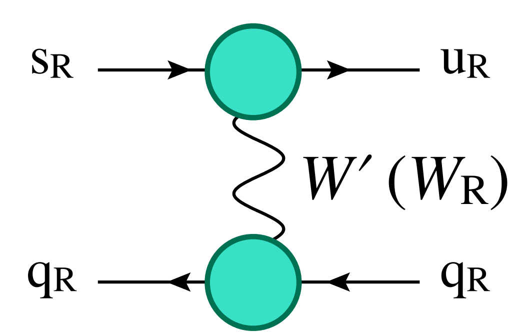
Z' scenario



VLQ 1609.04783,...

331 model 1512.02869,...

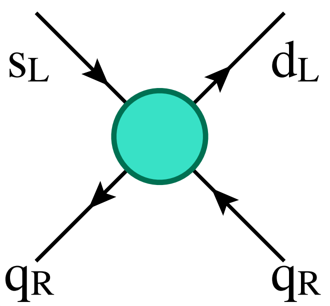
W_R scenario



LR model 1612.03914, 1802.09903

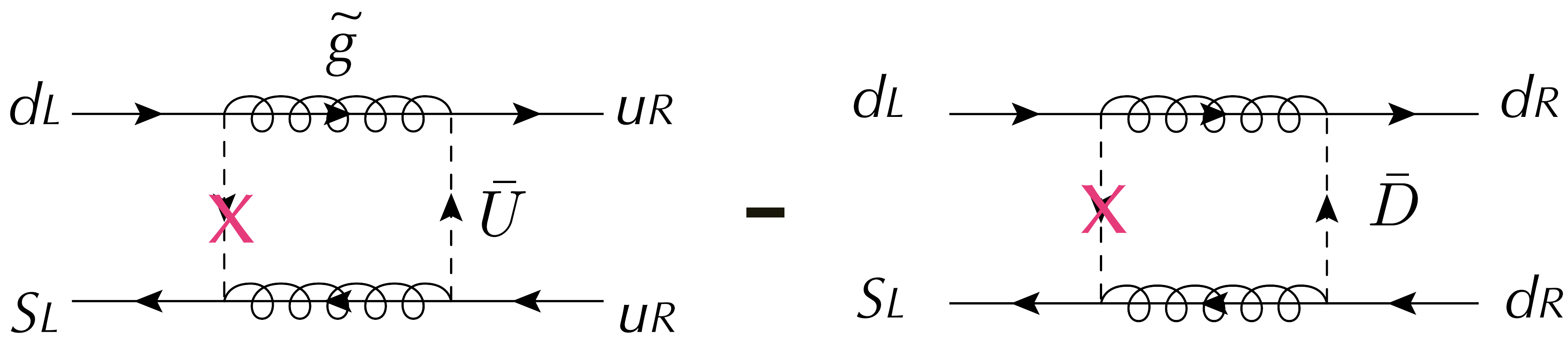
Gluino-box contribution

Box scenario



[Kagan, Neubert, PRL '99, Grossman, Kagan, Neubert, JHEP '99, TK, Nierste, Tremper, PRL '16]

- In the supersymmetric models, the gluino box can significantly contribute to $\varepsilon'_K/\varepsilon_K$
- In spite of QCD correction, gluino box **can** break isospin symmetry through mass difference between right-handed up and down squarks, which contributes **ImA_2**



$m_{\bar{U}} \neq m_{\bar{D}}$ $\xrightarrow{\text{RGE}}$ EW penguin operator Q_8 is generated at the low energy scale

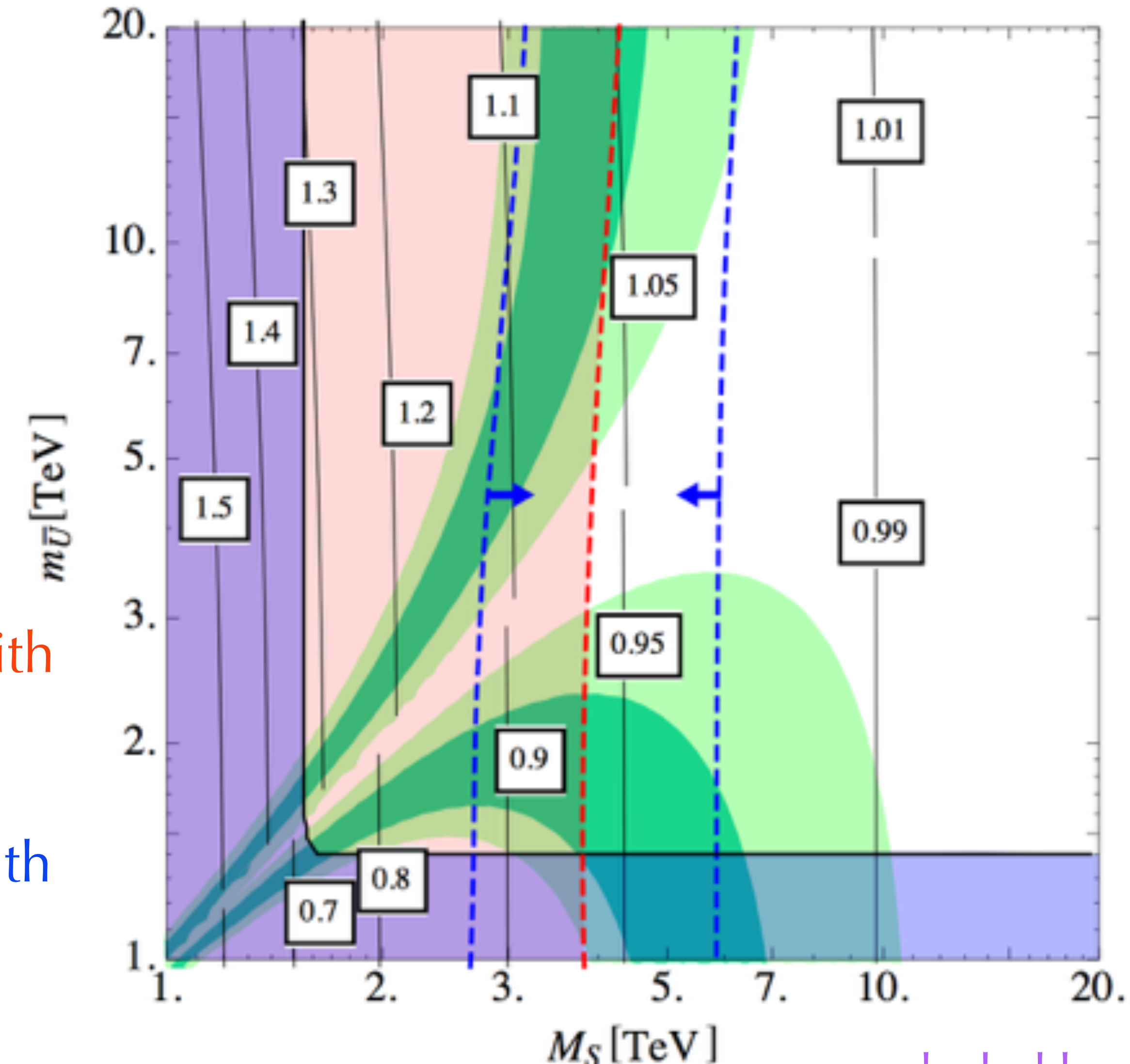
$\xrightarrow{\text{with HMEs}}$ contribute to **ImA2** ⟶ **$\varepsilon'_K/\varepsilon_K$ can be solved**

SUSY contributions to $\varepsilon'_K/\varepsilon_K$

[TK, Nierste, Tremper, PRL '16]
[Crivellin, D'Ambrosio, TK, Nierste '17]

- We take universal SUSY mass (M_S) without gaugino masses (M_3) and right-handed up-type squark mass ($m_{\bar{U}}$)

contour of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})/\mathcal{B}^{\rm SM}(K_L \to \pi^0 \nu\bar{\nu})$



$\varepsilon'_K/\varepsilon_K$ discrepancy can be solved at

1σ	2σ

excluded by ε_K with inclusive $|V_{cb}|$

preferred by ε_K with exclusive $|V_{cb}|$

excluded by LHC

$M_3 = 1.5 M_S$

for suppressed ε_K

$m^2_{Q,ij} = \Delta_{Q,ij} M_S^2$

$\Delta_{Q,12} = 0.1 \exp(-i\pi/4)$

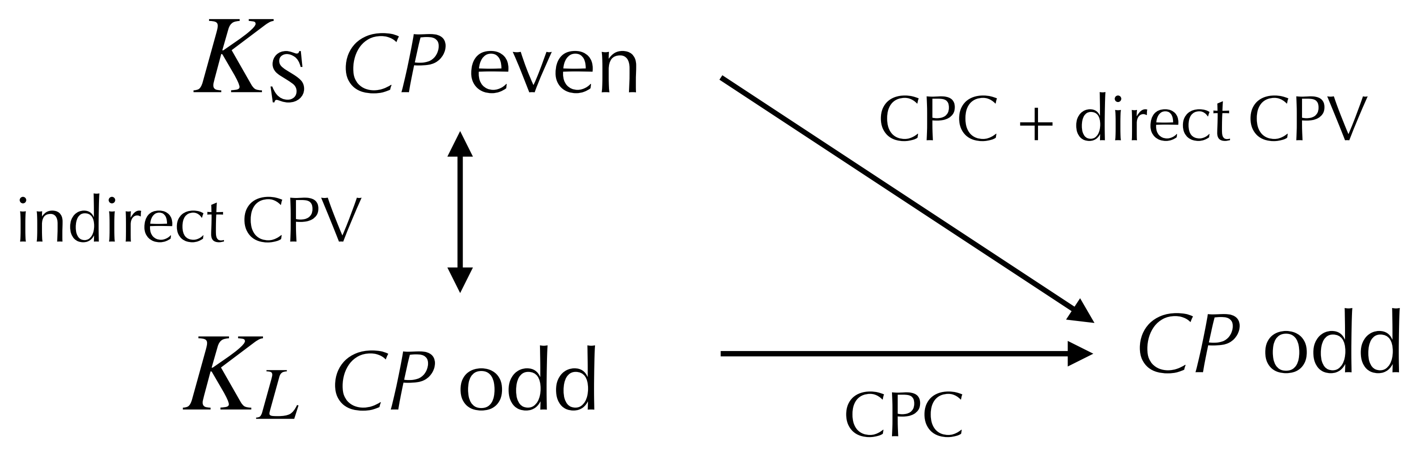
maximum CPV phase for ε_K

when $i\pi/4 \to i\pi/2$

amplifies $\varepsilon'_K/\varepsilon_K$

suppresses ε_K

$K^0 \rightarrow \mu^+\mu^-$



$K^0 \to \mu^+\mu^-$ systems

- SM predictions: [Ecker, Pich '91, Isidori, Unterdorfer '04, TK, D'Ambrosio '17]

$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm SM} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} (+) \\ (8.11 \pm \underset{\rm LD}{1.49} \pm \underset{\rm other}{0.13}) \times 10^{-9} (-) \end{cases}$$

An unknown sign ambiguity

$$\pm = {\rm sgn}\left[\frac{\mathcal{A}(K_L \to \gamma\gamma)}{\mathcal{A}(K_L \to (\pi^0)^* \to \gamma\gamma)}\right]$$

changes the relative sign between LD and SD

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm SM} = [4.99({\rm LD}) + 0.19({\rm SD})] \times 10^{-12}$$
$$= (5.18 \pm \underset{\rm LD}{1.50} \pm \underset{\rm other}{0.02}) \times 10^{-12}$$

- $K_S \to \mu\mu$ is dominated by P-wave *CP*-conserving LD contribution, while S-wave CP-violating SD is subleading

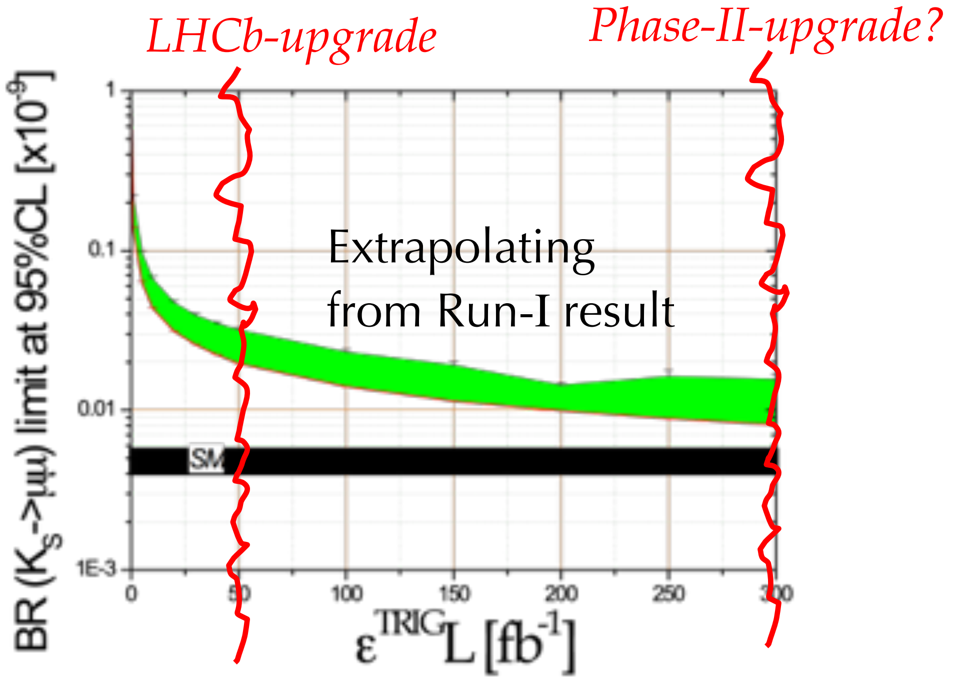
- Current bounds:

$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm exp} = (6.84 \pm 0.11) \times 10^{-9}$$ [BNL E871 '00]

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm exp} < 0.8 \times 10^{-9}$$ [LHCb, Run-I 1706.00758]

- LHCb Upgrade is aiming to reach the SM sensitivity of $K_S \to \mu\mu$

[D. M. Santos,HQL2018]



Interference between K_S and K_L

- Decay intensity of neutral kaon beam into *f states*

$$D = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

$$I(K \to f)(t) = \frac{1+D}{2}\left|\langle f| - \mathcal{H}_{\rm eff}^{|\Delta S|=1}|K^0(t)\rangle\right|^2 + \frac{1-D}{2}\left|\langle f| - \mathcal{H}_{\rm eff}^{|\Delta S|=1}|\overline{K}^0(t)\rangle\right|^2$$

$$= \frac{1}{2}\Big[\left\{(1-2D{\rm Re}[\bar\epsilon])\,|\mathcal{A}(K_1)|^2 + 2{\rm Re}\left[\bar\epsilon\mathcal{A}(K_1)^*\mathcal{A}(K_2)\right]\right\}e^{-\Gamma_S t} \quad \longleftarrow \quad |\mathcal{A}(K_S \to f)|^2$$

$$+\left\{(1-2D{\rm Re}[\bar\epsilon])\,|\mathcal{A}(K_2)|^2 + 2{\rm Re}\left[\bar\epsilon\mathcal{A}(K_1)\mathcal{A}(K_2)^*\right]\right\}e^{-\Gamma_L t} \quad \longleftarrow \quad |\mathcal{A}(K_L \to f)|^2$$

$$+\Big\{2D{\rm Re}\left[e^{-i\Delta M_K t}\left(\mathcal{A}(K_1)^*\mathcal{A}(K_2) + \bar\epsilon|\mathcal{A}(K_1)|^2 + \bar\epsilon^*|\mathcal{A}(K_2)|^2\right)\right]$$

$$-4{\rm Re}[\bar\epsilon]{\rm Re}\left[e^{-i\Delta M_K t}\mathcal{A}(K_1)^*\mathcal{A}(K_2)\right]\Big\}\, e^{-\frac{\Gamma_S+\Gamma_L}{2}t}\Big]$$

$$+\mathcal{O}(\bar\epsilon^2),$$

Interference $\longleftarrow$ $\mathcal{A}(K_S \to f)^*\mathcal{A}(K_L \to f)$

↳ time dependence ↳ $\tau \sim 2\tau_S$

- *f*=$\mu^+\mu^-$ case [TK, D'Ambrosio, PRL '17]

$$\mathcal{H}_{\rm eff}^{|\Delta S|=1} = \frac{G_F\alpha}{\sqrt{2}}\lambda_t y'_{7A}(\bar s\gamma_\mu\gamma_5 d)(\bar\mu\gamma^\mu\gamma_5\mu) + {\rm H.c.}$$

$$\sum_{\rm spin}\mathcal{A}(K_1 \to \mu^+\mu^-)^*\mathcal{A}(K_2 \to \mu^+\mu^-)$$

$$= \frac{16iG_F^4M_W^4F_K^2M_K^2m_\mu^2\sin^2\theta_W}{\pi^3}{\rm Im}[\lambda_t]y'_{7A}\left\{A^\mu_{L\gamma\gamma} - 2\pi\sin^2\theta_W({\rm Re}[\lambda_t]y'_{7A} + {\rm Re}[\lambda_c]y_c)\right\}$$

- Interference comes from $K_S \to \mu\mu$ S-wave SD times $K_L \to \mu\mu$ S-wave CPC LD; $K_S \to \mu\mu$ P-wave LD is dropped
- **Proportional to direct CPV**
- Insensitive to indirect CPV $\bar\epsilon$

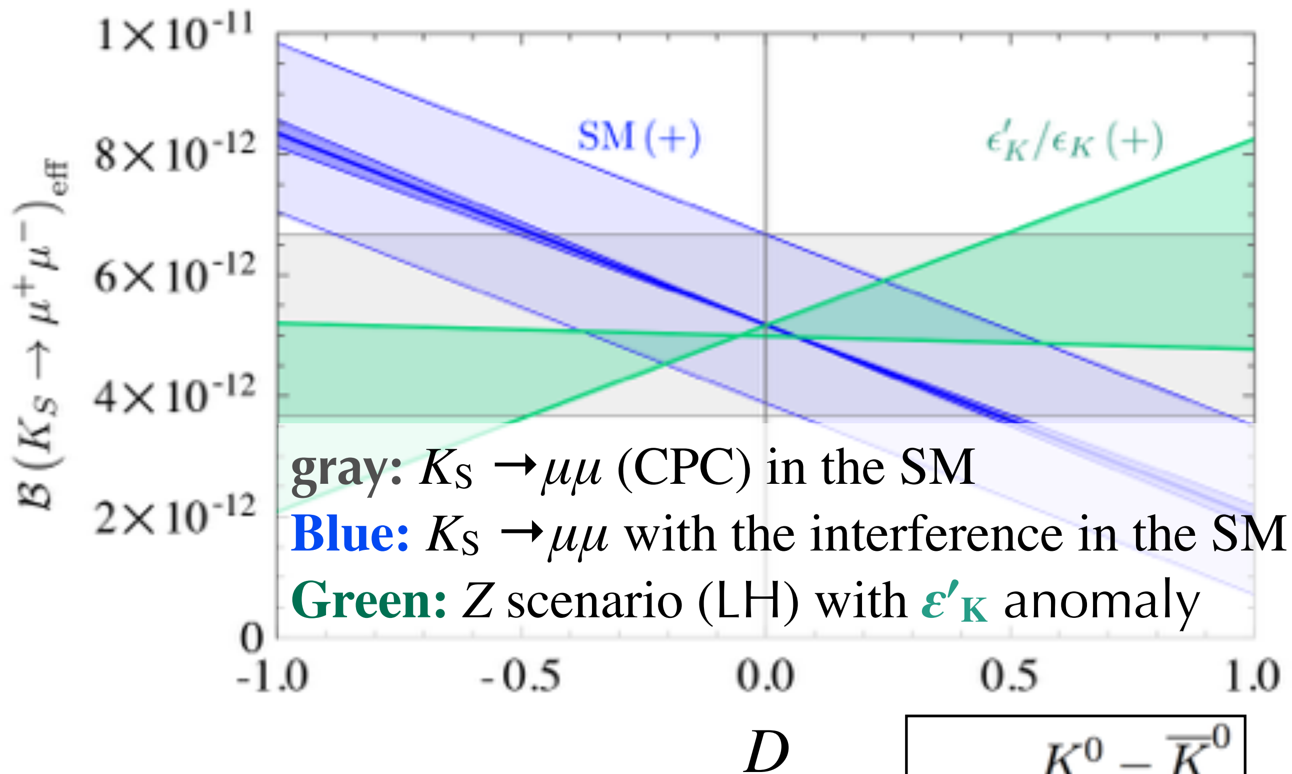
$$y'_{7A} = -0.654(34), \quad A^\mu_{L\gamma\gamma} = \pm 2.01(1)\cdot 10^{-4}\cdot[0.71(101) - i5.21]$$

top loop; $\gamma\gamma$ loop; sign ambiguity

Direct CP asymmetry in $K_S \to \mu\mu$

[TK, D'Ambrosio, PRL '17] [Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18]
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

- Interference contribution is comparable size to CPC of $K_S \to \mu\mu$ thanks to the large absorptive part of long-distance contributions to $K_L \to \mu\mu$
- The unknown sign of $\mathcal{A}(K_L \to \gamma\gamma)$ can be probed
- Nonzero dilution factor (D) can be achieved by an accompanying charged kaon tagging and a charged pion tagging

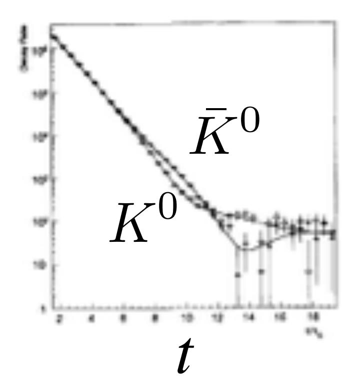


$$D = \frac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$$

$$pp \to K^0 K^- X$$
$$pp \to K^{*+} X \to K^0 \pi^+ X$$
with $K^0 \to \{K_S, K_L\} \to \mu^+\mu^-$

cf. CPLEAR experiment (1990-99@CERN)

$$p\bar{p} \to \left[\begin{array}{l} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{array}\right.$$



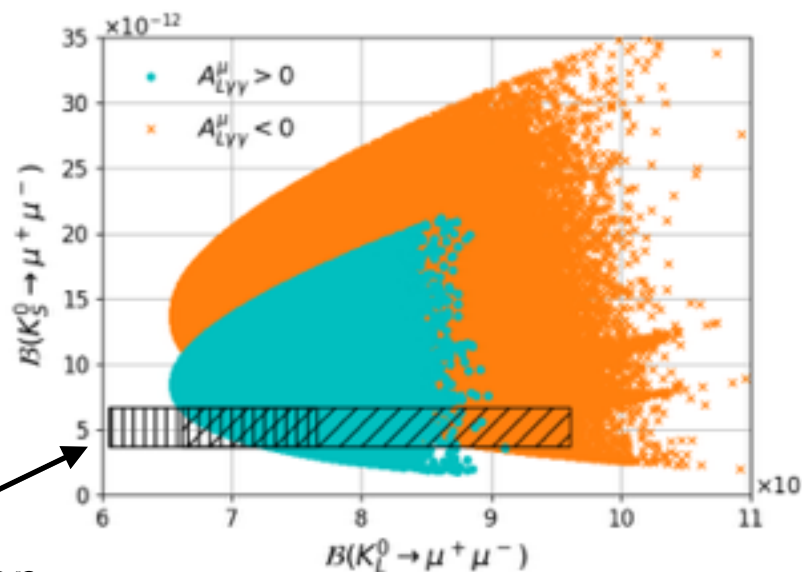
$\{K_S, K_L\} \to \pi^+\pi^-$
measured the interference between K_S and K_L
[CPLEAR collaboration '95]

SUSY contributions to $K^0 \to \mu^+\mu^-$

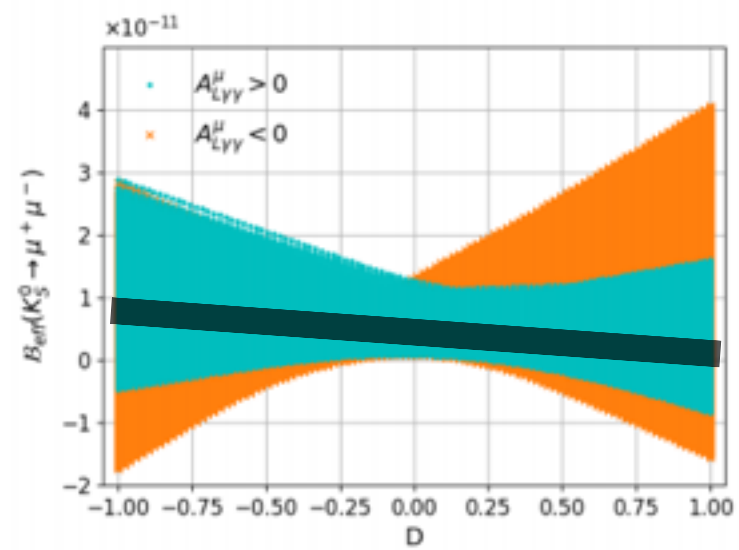
One of the MSSM scenario from Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18

mass difference between right-handed squarks, large tanβ, light M_A~TeV

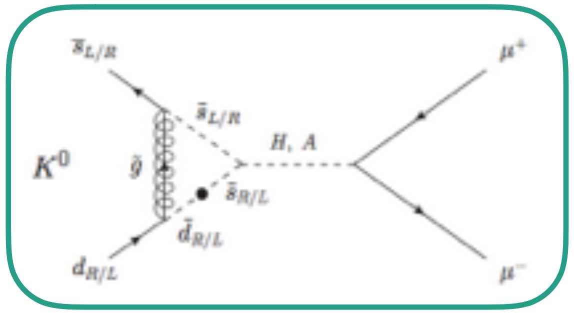
No inter-ference plot (D=0)



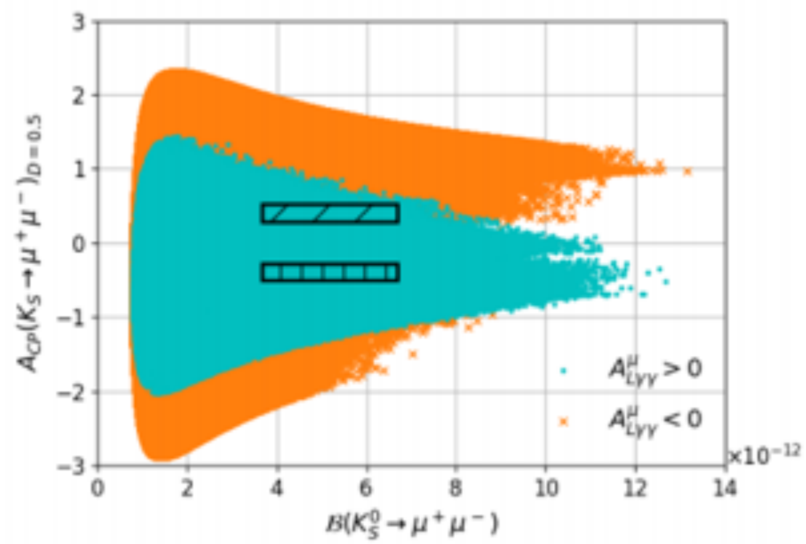
SM prediction

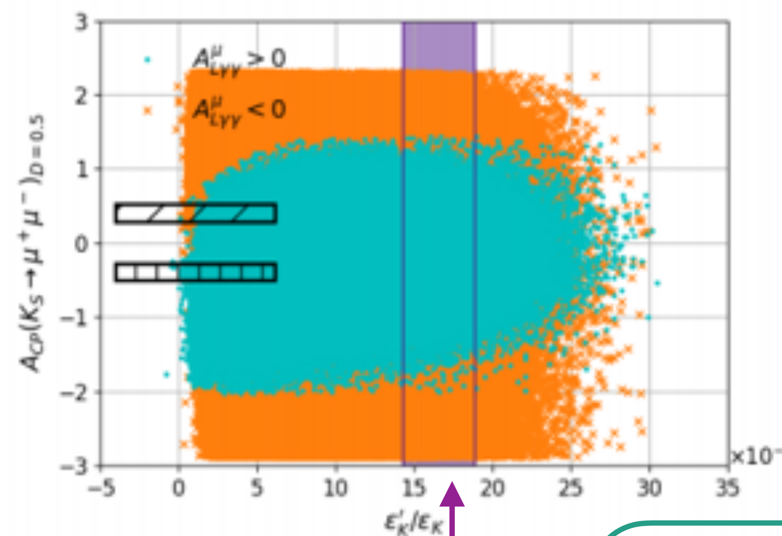


SM prediction [$\mathrm{sgn}(A^{\mu}_{L\gamma\gamma}) > 0$]



D=0.5



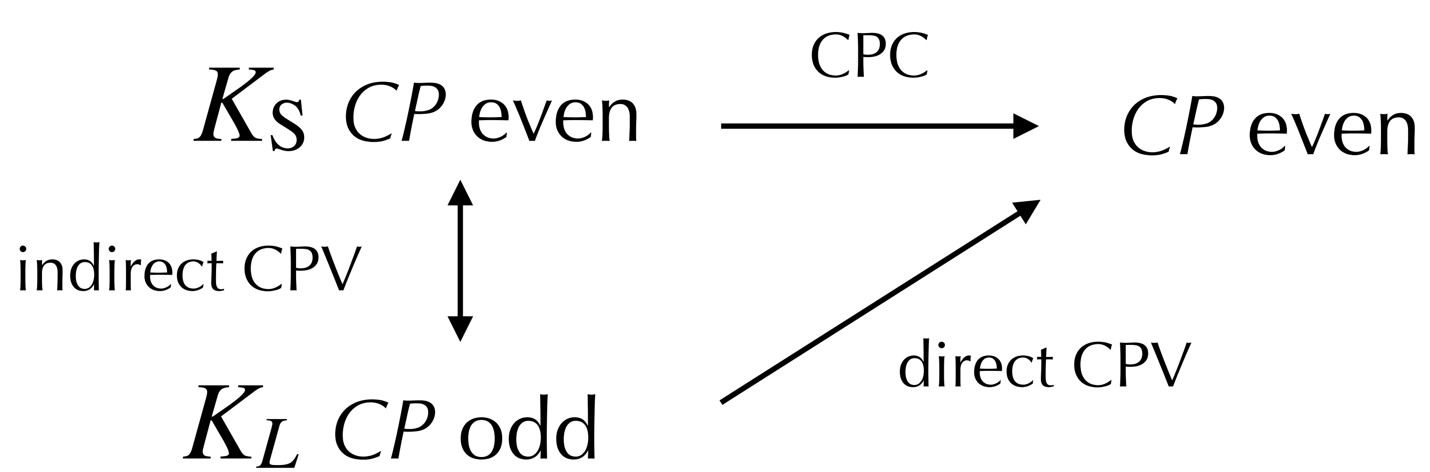


measured $\varepsilon'_K/\varepsilon_K$

Large deviations from SM predictions are possible in the MSSM

$$\mathcal{B}(K_S \to \mu^+\mu^-)|_{\rm MSSM} \sim \mathcal{O}(1) \times 10^{-11}$$

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



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

- Both channels are theoretical clean and very sensitive to short-distance contributions, especially $K_L \to \pi^0 \nu\nu$ is pure direct CPV decay

- SM predictions: [Buras, Buttazzo,Girrbach-Noe, Knegjens '15]

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (8.4 \pm 1.0) \times 10^{-11}\,, \quad (9.11 \pm 0.72) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM} = (3.4 \pm 0.6) \times 10^{-11}\,, \quad (3.00 \pm 0.31) \times 10^{-11}$$

CKM from tree — CKM from tree+loop

- Current bounds:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11}$$ [E949, BNL '08]

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} \leq 2.6 \times 10^{-8}$$ [E391a, J-PARC '10]

- On-going experiments:

NA62 @CERN

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} \ (68\% \ \text{CL})$$ [NA62, 2016data, HQL2018]

  - ~20 SM events are expected before LS2

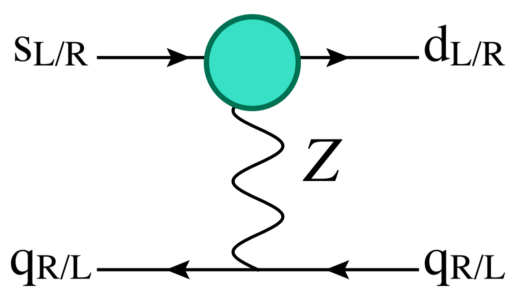
KOTO @J-PARC

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \lesssim \mathcal{O}(10^{-9})$$ [First result will be presented in this summer]

  - detector upgrade in this summer-autumn
  - KOTO-step2 will aim at ~100 SM events

Modified Z-coupling scenario

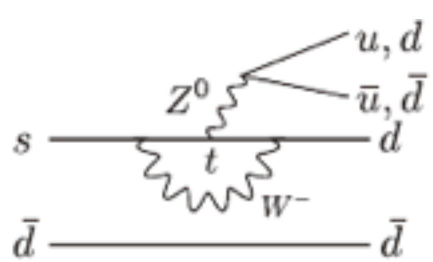
Z scenario



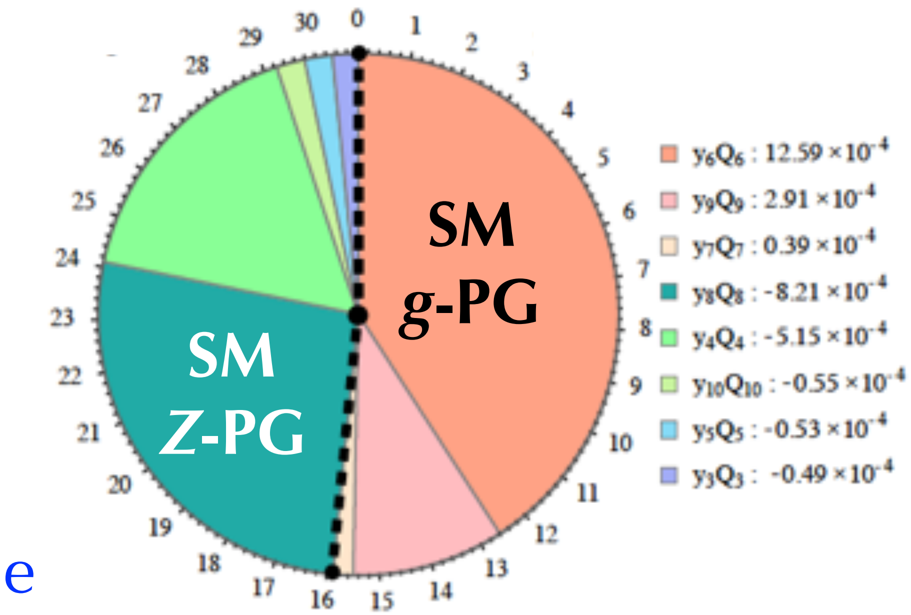
[Buras, De Fazio, Girrbach, '13, '14] [Buras, Buttazzo, Knegjens, '15][Buras, '16]
[Endo, TK, Mishima, Yamamoto, '16] [Bobeth, Buras, Celis, Jung,'17]

- When NP contribution to FCNC (sdZ) coupling is the same magnitude as the SM, $\varepsilon'_K/\varepsilon_K$ discrepancy be explained

Negative contribution

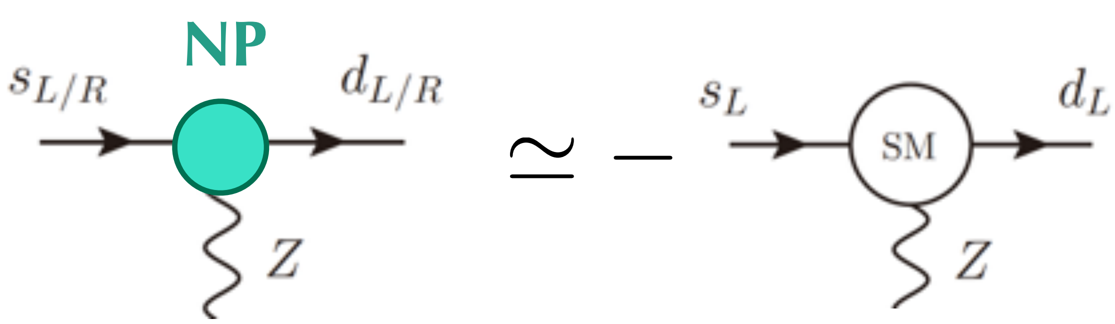


SM Z-penguin gives the biggest negative contribution



$\leftrightarrow \varepsilon'_K/\varepsilon_K$

Positive contribution



→

- **$\varepsilon'_K/\varepsilon_K$ can be solved**
- **O(1) contribution to** $\mathcal{B}(K \to \pi\nu\bar{\nu})$

Note: Although Z' FCNC scenario can also explain $\varepsilon'_K/\varepsilon_K$, a correlation to $\mathcal{B}(K \to \pi\nu\bar{\nu})$ is **model-dependent**

Modified Z-coupling scenario

- For gauge-invariant predictions, SM + dimension-six effective theory (SMEFT) should be introduced [Endo, TK, Mishima, Yamamoto, '16] [Bobeth, Buras, Celis, Jung,'17] [Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_L}{\Lambda^2} i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{Q}_L \gamma^\mu Q'_L) + \frac{c_R}{\Lambda^2} i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{d}_R \gamma^\mu d'_R),$$

$$= \mathcal{L}_{\rm SM} - \frac{\sqrt{2} v M_Z}{\Lambda^2} (c_L \overline{s} \gamma^\mu Z_\mu P_L d + c_R \overline{s} \gamma^\mu Z_\mu P_R d) + \dots$$

→ After EWSB, in addition to FCNC terms, some NG boson vertices emerge

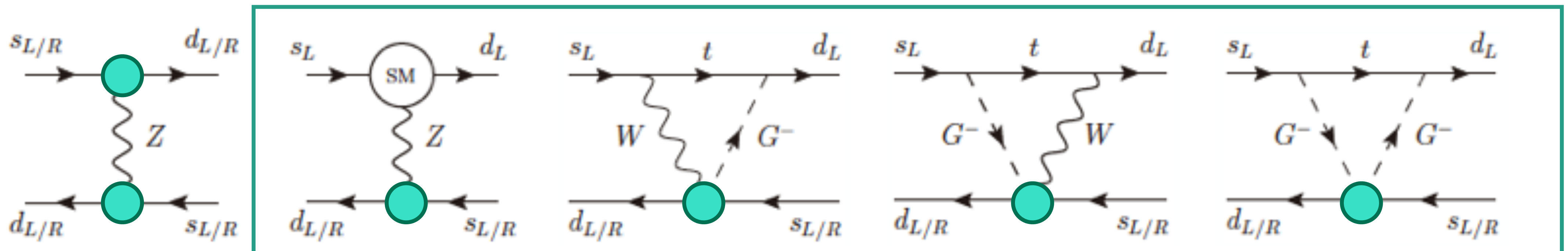
- Constraint comes from ΔS=2 process: ε_K

$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{s}_R \gamma^\mu d_R)$ @high scale $\Delta S = 1$

top-Yukawa RG →

← constraint

$(\overline{s}_L \gamma_\mu d_L)(\overline{s}_R \gamma^\mu d_R)$ @low scale $\Delta S = 2$



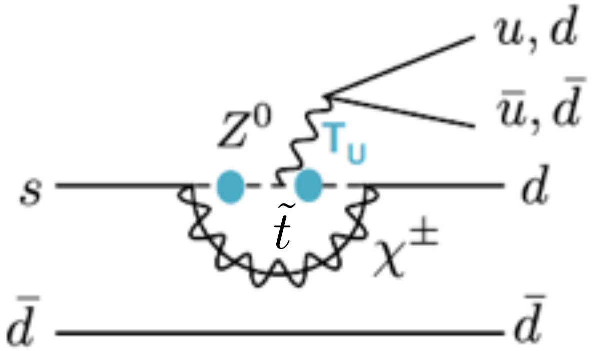
Interference (NP and SM) terms

They can be significant in a certain case

$B(K_L \to \pi^0 \nu\bar{\nu})$ in Z scenario (MSSM)

chargino Z-penguin in the MSSM

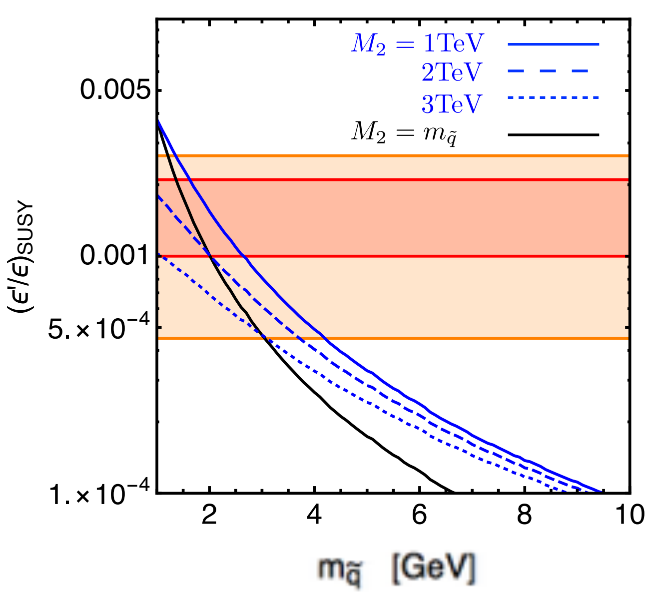
[Endo, Mishima, Ueda, Yamamoto, '16]

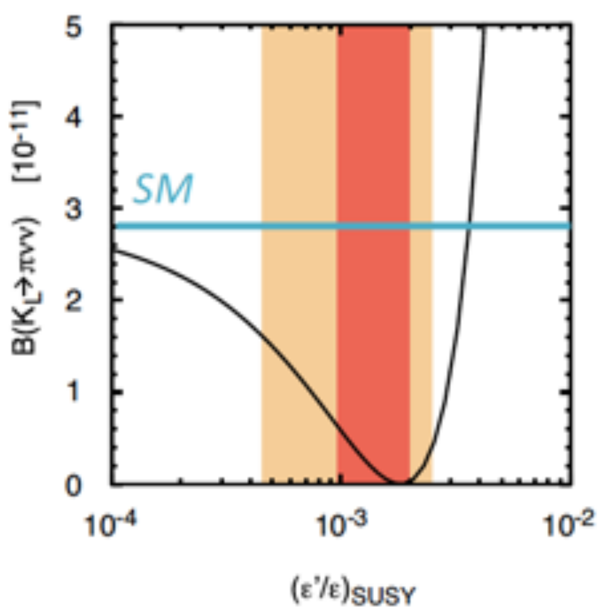


Z model (LH)

Upper bounds under the constraints:

Vacuum, ε_K, ΔM_K, $K_L \to \mu\mu$

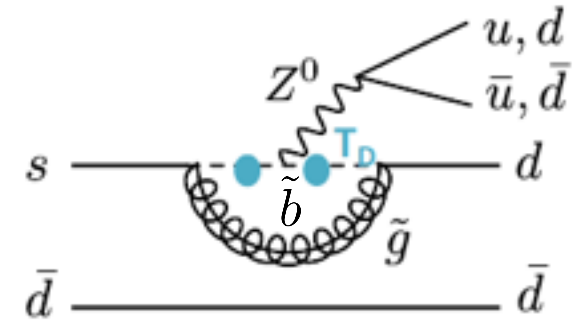




gluino Z-penguin in the MSSM

[Tanimoto, Yamamoto, '16]

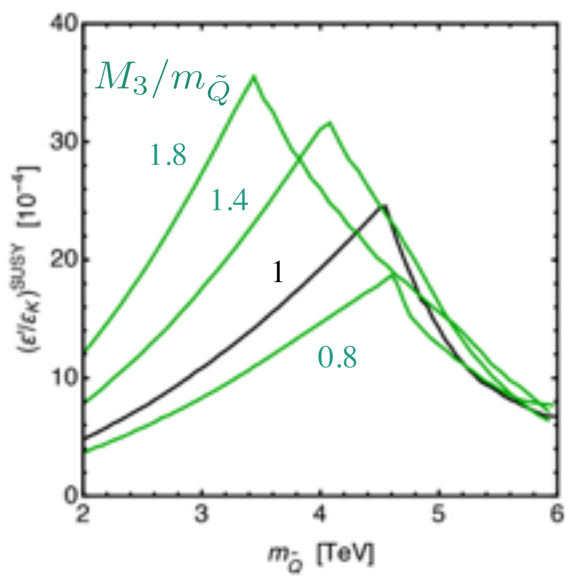
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

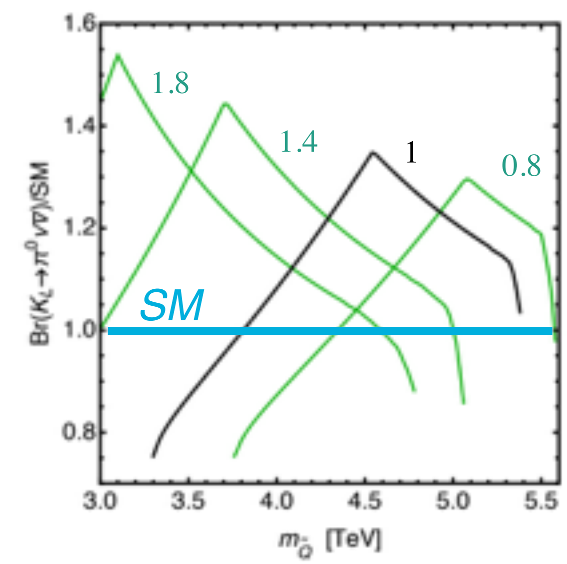


Z model (RH + LH)

Upper bounds under the constraints:

Vacuum, $\underline{\boldsymbol{\varepsilon_K}}$, ΔM_K, $K_L \to \mu\mu$, $\underline{\boldsymbol{b \to s(d)\gamma}}$





with $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})/\mathrm{SM} \lesssim 1.5$

Conclusions

- **Kaon physics can probe *CP*-violating FCNC from various ways**

- First lattice result indicates $\varepsilon'_K/\varepsilon_K$ discrepancy in $K^0 \to \pi\pi$ (**2.8-2.9σ**)
- $\mathcal{B}(K_S \to \mu^+\mu^-)|_{\rm MSSM} \sim \mathcal{O}(1) \times 10^{-11}$ can be probed by **LHCb Upgrade**
- **LHCb Upgrade** could open a short distance window by **the interference effect** in $K^0 \to \mu^+\mu^-$
- **10% precisions** in $K_L \to \pi^0\nu\nu$ and $K^+ \to \pi^+\nu\nu$ are crucial