Kaon physics and connection to B anomalies

Teppei Kitahara
Technion / Nagoya University

Workshop on high-energy implications of flavor anomalies

CERN
24 October 2018

הטכניון
מכון טכנולוגי לישראל
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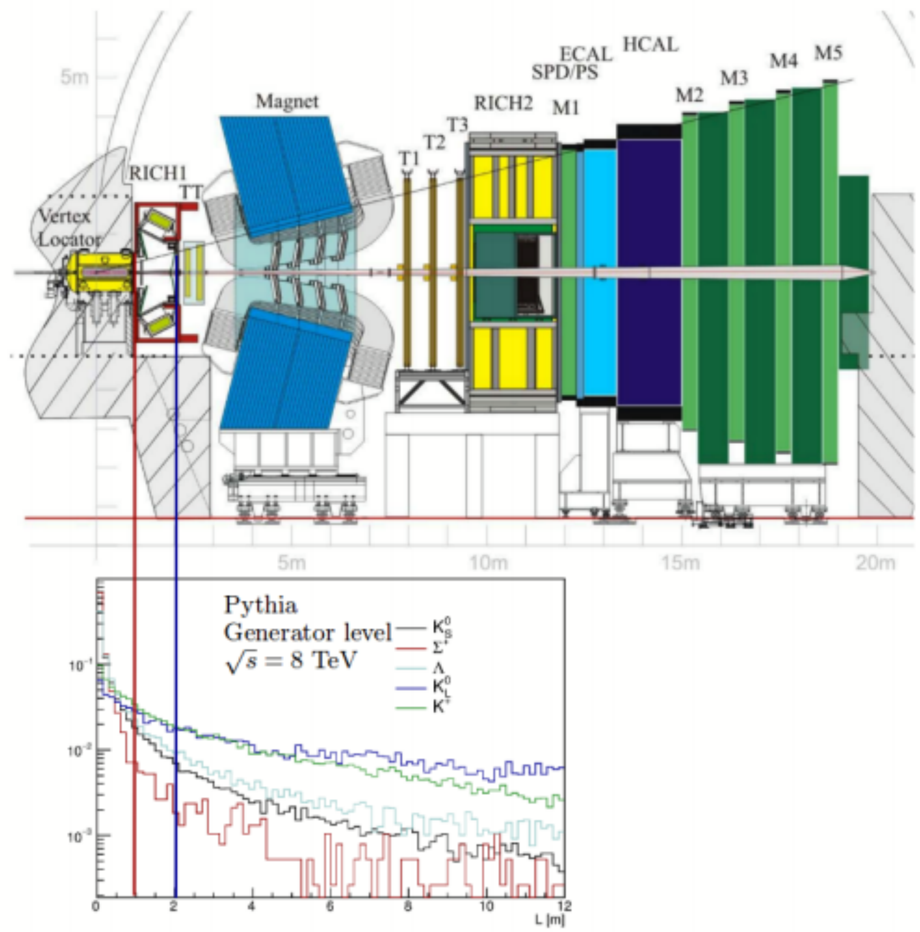
Kaon physics is still an exciting field

- Discovery channel (CPV/ CKM/ Heavy quarks)
  → **Precision physics:** FCNC and *CP* violation; Br~$O(10^{-11})$ can be probed

- There are many promising on-going experiments for kaon precisions;
  LHCb / NA62 / KOTO / KLOE-2 / TREK

- Huge production of strangeness in **LHCb** [$O(10^{13})/\mathrm{fb}^{-1}$ K^0_S] was suppressed by its trigger efficiency [ε~1-2%@LHC Run-I, ε~18%@LHC Run-II]
  → LHCb Upgrade can realize high efficiency for K^0_S[ε~90%@LHC Run-III] [LHCb strangeness group: 1808.03477]



collider
search

could give
stronger constraints

Lattice [RBC-UKQCD]
perturbative calculations
meson effective theory (ChPT/dual QCD)

ε'_K and ε_K discrepancies?

$$K_L \to \pi\pi$$

B

LFUV

CORRELATION

CP-violating
FCNC

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

reduce Th
uncertainty

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

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

$K_S \to 4l$

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

Understanding
of ChPT

$$K_L^{(+)} \to \pi^{0(+)}\nu\bar{\nu}$$

reduce Th
uncertainty

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

CPV decay
less sensitive because of LD contributions

$$K_L \rightarrow \pi^+\pi^-, \pi^0\pi^0$$

$K_L \to \pi\pi$: two types of *CP* violation

- **two types of *CP* violation**: **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]

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

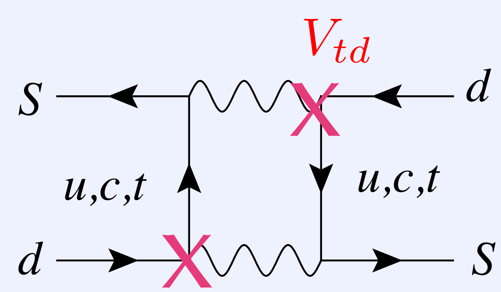
[NA48/CERN and KTeV/FNAL '99]

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

ΔS=2
Indirect *CP* violation
[Kaon mixing]

W box

$$\varepsilon_K \propto \mathrm{Im}\left[(V_{ts}^* V_{td})^2\right]$$

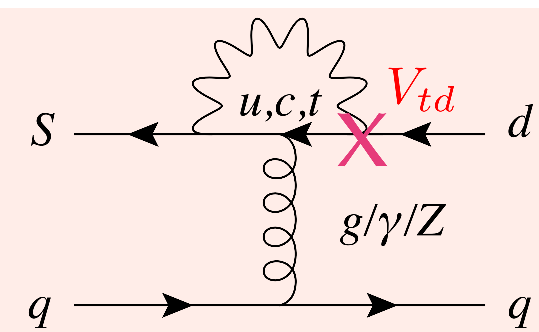


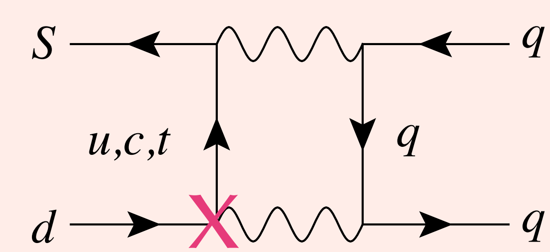
$$K^0 \longleftrightarrow \overline{K}^0$$

ΔS=1
Direct *CP* violation

penguin and W-box

$$\varepsilon'_K \propto \mathrm{Im}\left[V_{ts}^* V_{td}\right]$$





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

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

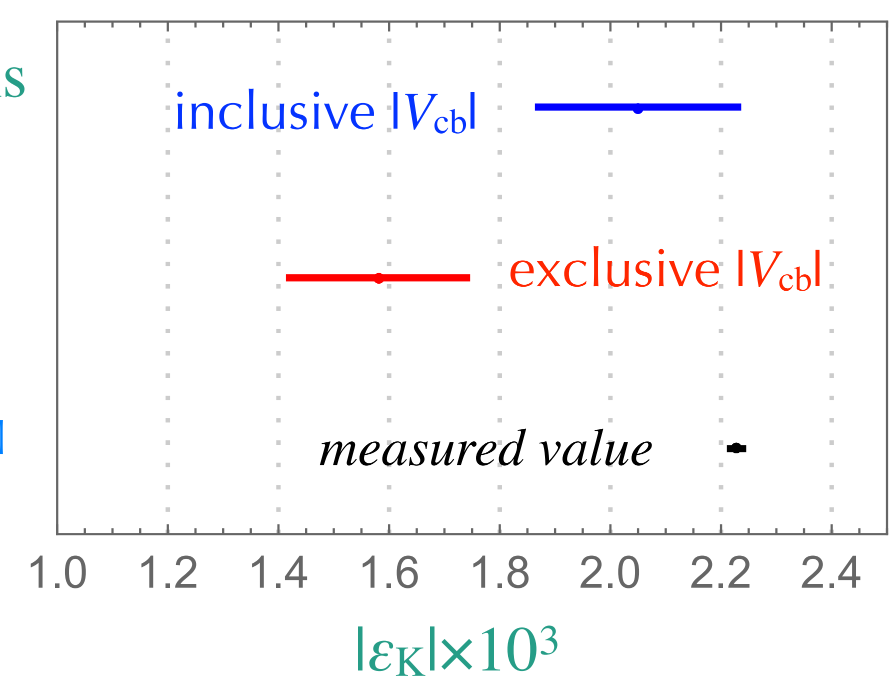
Leading contribution is proportional to $|V_{cb}|^4$

$|\varepsilon_K|$ predictions

($\pm 1\sigma$ error bar)

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

[Brod, Gorbahn '12]



SM prediction with inclusive $|V_{cb}|$ is consistent with data, while there is 4.0σ tension in exclusive $|V_{cb}|$ case

[LANL-SWME, 1710.06614, 1808.09657]
Wolfenstein parameters are determined by the angle-only fit

O(10%) NP contribution is still allowed

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

- Further strong suppression of ε'_K comes from $\Delta I = 1/2$ 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

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

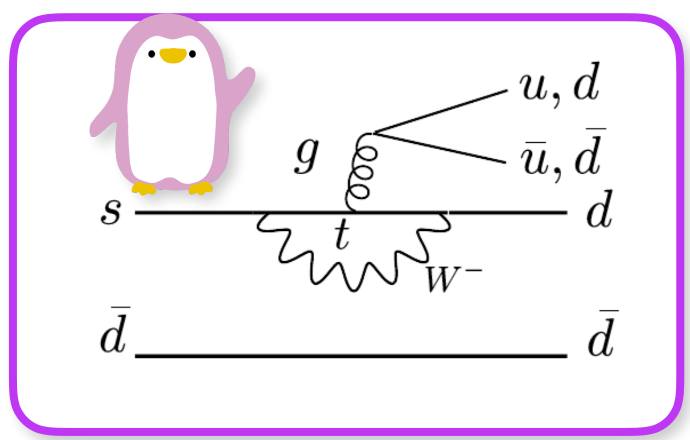
$\Delta I = 1/2$ rule: factor = 0.04

Accidental cancellation

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

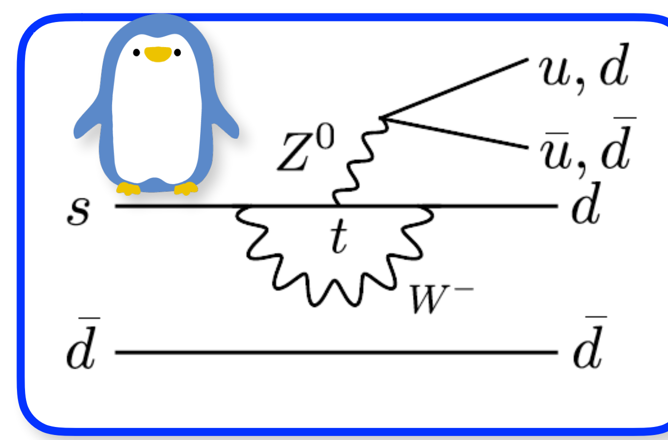
where $\frac{1}{\omega} \equiv \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.46$ (exp.)

~ Im [QCD penguin]



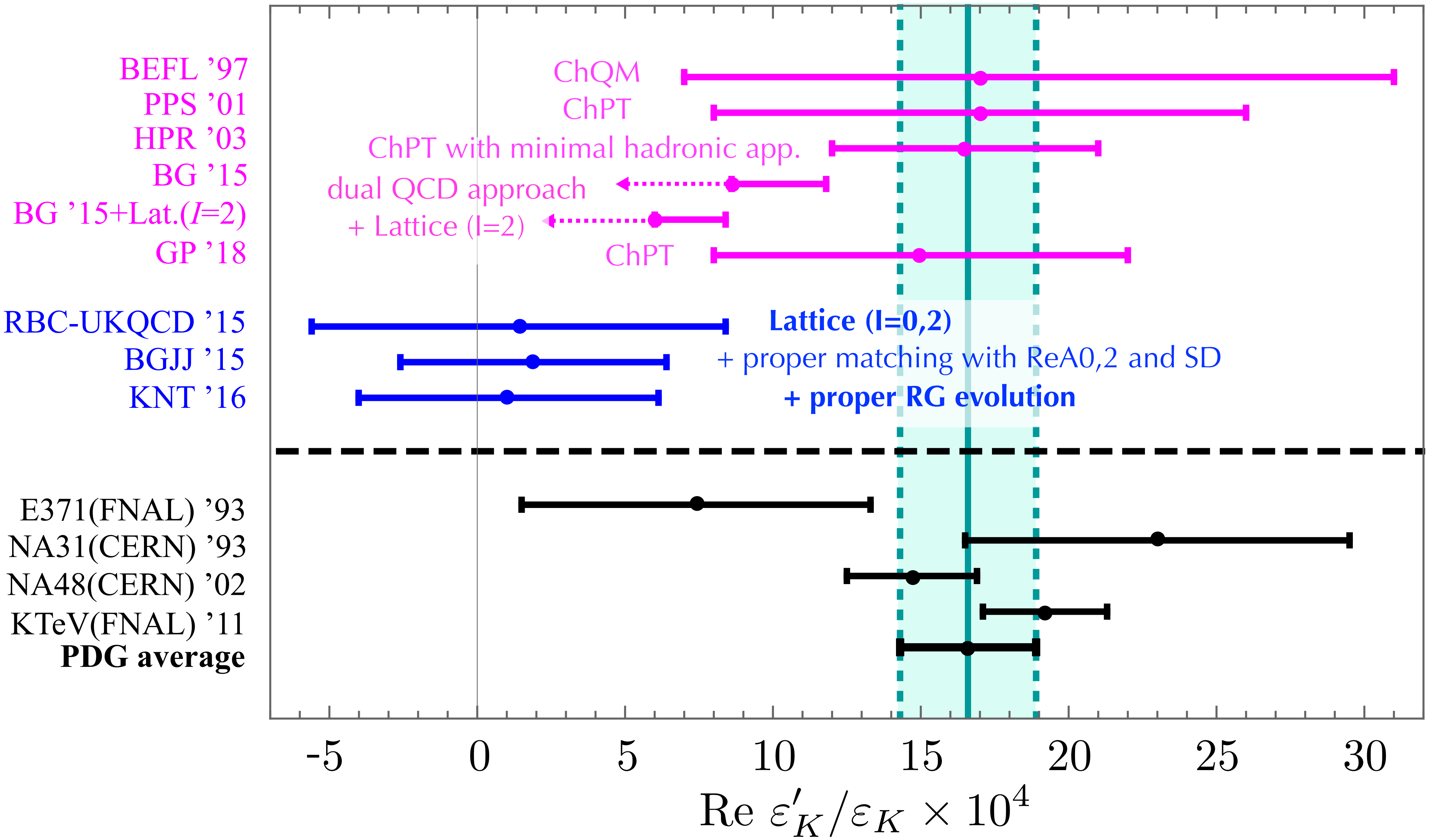
sensitive

~ Im [EW penguin]



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

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



$B_6^{(1/2)} \sim 1.6,\ B_8^{(3/2)} \sim 0.9$

$B_6^{(1/2)} \sim 1.6,\ B_8^{(3/2)} \sim 0.9$

$B_6^{(1/2)} \approx 3,\ B_8^{(3/2)} \approx 3.5$

$B_6^{(1/2)} \leq B_8^{(3/2)} \leq 1$

$B_6^{(1/2)} \leq B_8^{(3/2)} \leq 0.76$

$B_6^{(1/2)} \sim 1.5$

$B_6^{(1/2)} = 0.57,\ B_8^{(3/2)} = 0.76$

dual QCD predictions

$B_6^{(1/2)} \leq B_8^{(3/2)} < 1,\ B_8^{(3/2)} = 0.8$

Observed values

$\Delta I = 1/2$ 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

→ Soni's talk

- Lattice result with recent progress on the short-distance physics predicts $\varepsilon'_K/\varepsilon_K = O(10^{-4})$: **2.8-2.9σ discrepancy** [Buras, Gorbahn, Jäger, Jamin '15, TK, Nierste, Tremper '16]

  NNLO QCD in progress [Cerdà-Sevilla, Gorbahn, Jäger, Kokulu, 1611.08276]

- 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 data [Gisbert, Pich '18]

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

- The lattice simulation includes FSI and can explain ΔI=1/2 rule for the first time. However, the strong phase shift of I=0 is inconsistent with the expectation **at 2.8σ level** [Colangelo, Gasser, Leutwyler '01, Colangelo, Passemar, Stoffer '15]

  → **0.9σ** [RBC-UKQCD group preliminary, C.Kelly, CKM2018]

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

  [e.g., hep-ph/0201071, 1807.10837]

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

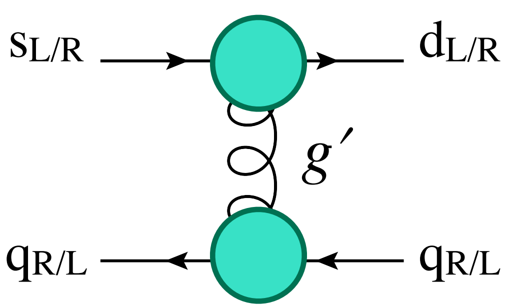
- Several types of BSM can explain $\varepsilon'_K/\varepsilon_K$ discrepancy

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

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

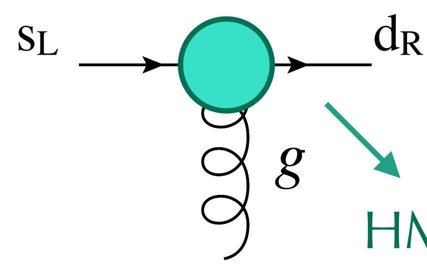
$\mathrm{Im}A_0$

g' scenario



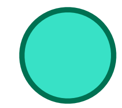
RS model 1404.3824
chiral-flavorful vector 1806.02312

chromomagnetic scenario



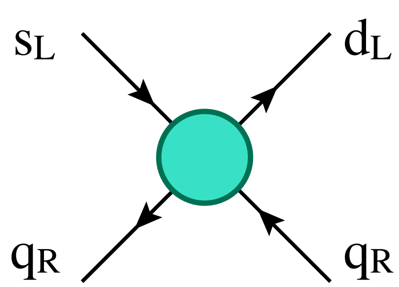
SUSY 1711.11030,...
Type-III 2HDM 1805.07522

HME would be suppressed [1712.09824, 1803.08052]

 : BSM vertex (must include *CPV* phase)

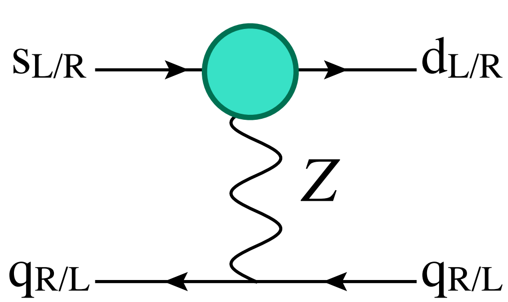
$\mathrm{Im}A_2$

Box scenario



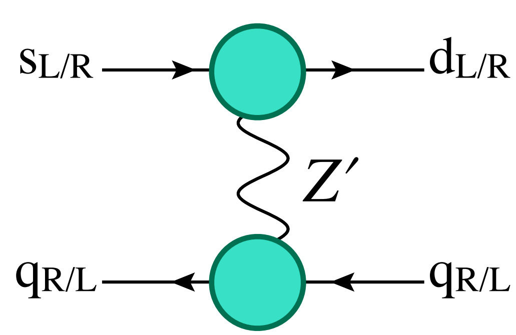
SUSY 1604.07400,...

Z scenario



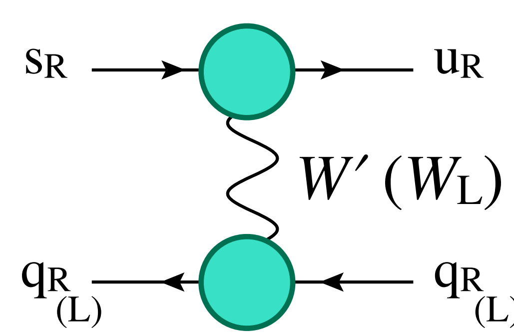
SUSY 1608.01444,...
VLQ 1609.04783,...
LHT 1507.06316

Z' scenario



VLQ 1609.04783,...
331 model 1512.02869,...

W_R scenario



LR model 1612.03914, 1802.09903

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

- HMEs of **general four-quark operators** and **a chromomagnetic operator** contributing to $\varepsilon'_K/\varepsilon_K$ have been calculated by dual QCD approach [Aebischer, Buras, Gérard, 1807.01709]
  - HMEs of SM four-quark operators are consistent with lattice [RBC-UKQCD, PRD '15, PRL '15]
  - HME of the chromomagnetic operator is consistent with lattice ($K \to \pi$) [ETM collaboration, '18]
  - $\Delta S=2$ (ε_K) HMEs B_1 [Buras, Gérard, Bardeen, '14] and B_2-B_5 [Buras, Gérard, 1804.02401] are consistent with lattices [ETM, SWME and RBC-UKQCD]
- Based on dual QCD results, master formula for $\varepsilon'_K/\varepsilon_K$ in the SM effective field theory **(SMEFT)** is derived [Aebischer, Bobeth, Buras, Gérard, Straub, 1807.02520, 1808.00466] and are implemented in the open source code ***flavio*** [Straub et al '18]

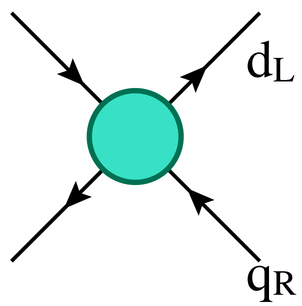
$$\boxed{\left(\frac{\varepsilon'}{\varepsilon}\right)_{\rm BSM} = \sum_i P_i(\mu_{\rm ew})\ {\rm Im}\left[C_i(\mu_{\rm ew}) - C_i'(\mu_{\rm ew})\right]}$$

some tensor four-quark operators are sensitive to $\varepsilon'_K/\varepsilon_K$

Gluino-box contributions to $\varepsilon'_K/\varepsilon_K$

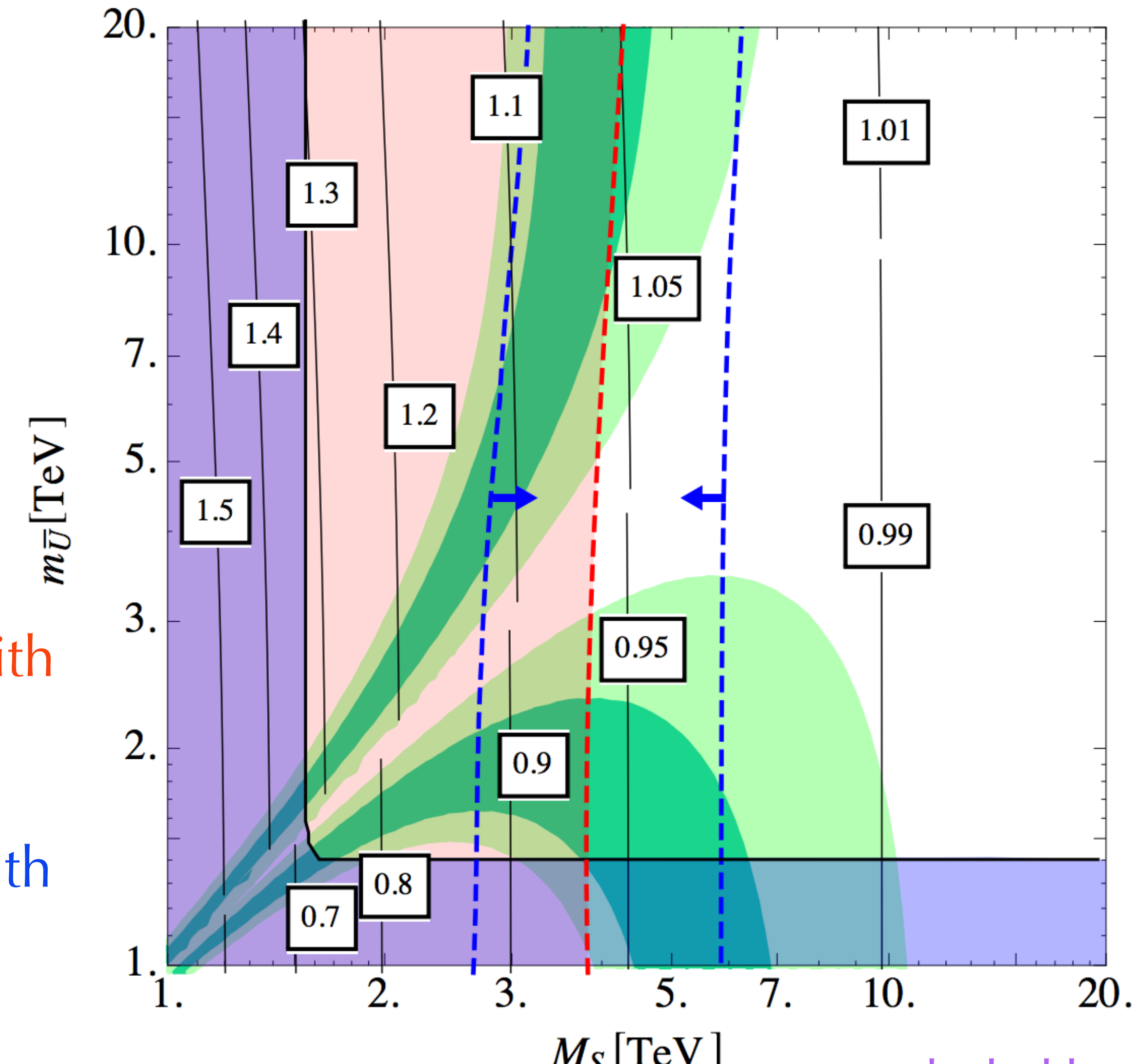
[TK, Nierste, Tremper, PRL '16, Crivellin, D'Ambrosio, TK, Nierste '17]

Box scenario



- Mass difference of right-handed up and down squarks gives a significant contribution to $\varepsilon'_K/\varepsilon_K$

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



excluded by LHC

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

1σ	2σ

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

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

$$M_3 = 1.5 M_S$$

to suppress 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

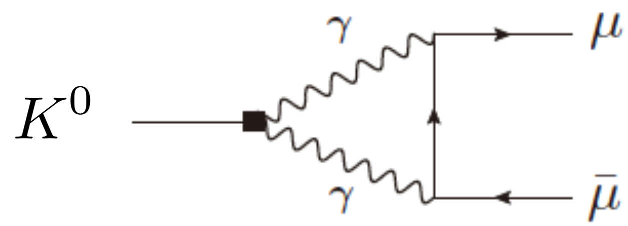
when $i\pi/4 \to i\pi/2$

amplifies $\varepsilon'_K/\varepsilon_K$

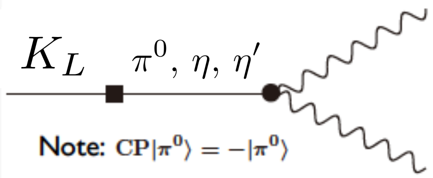
suppresses ε_K

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

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



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

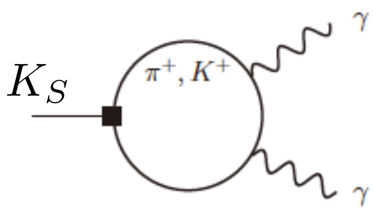


$$\mathcal{B}(K_L \to \mu^+\mu^-)_{\rm SM} = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} (+) \\ (8.11 \pm \underbrace{1.49}_{\text{LD}} \pm \underbrace{0.13}_{\text{other}}) \times 10^{-9} (-) \end{cases}$$

An unknown sign ambiguity

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

changes the relative sign between LD and SD



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

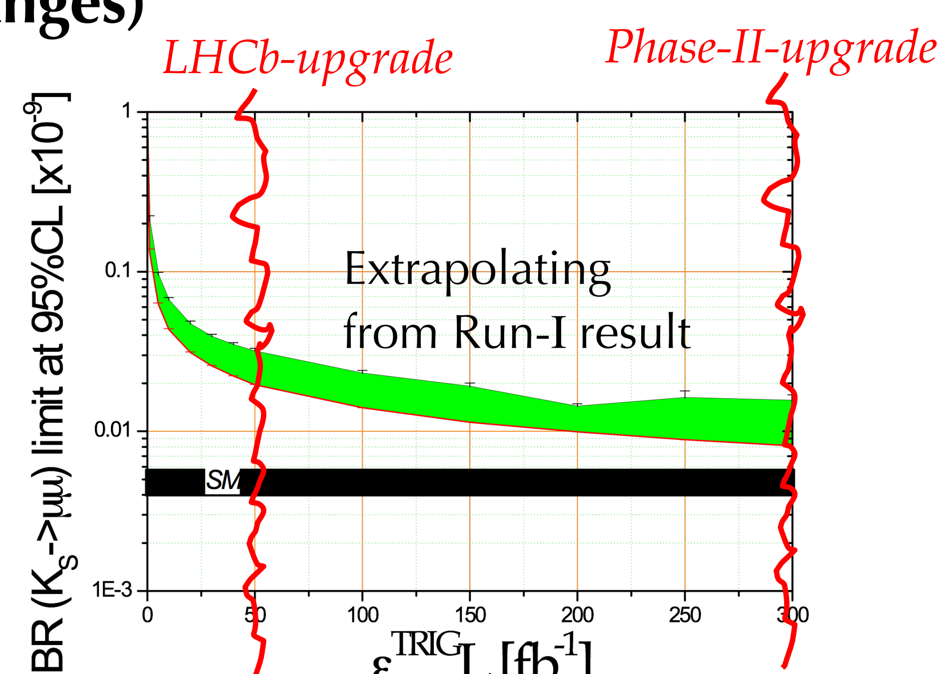
- Both of $K_L \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-$ are dominated **by the *CP*-conserving long-distance contributions (two photon exchanges)**

- 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 full data '17]

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



[LHCb strangeness group: 1808.03477]

Interference between K_S and K_L

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

$$I(t) = \frac{N(K^0)}{N(K^0)+N(\overline{K}^0)}\left|\langle f|\mathcal{H}_{eff}|K^0(t)\rangle\right|^2 + \frac{N(\overline{K}^0)}{N(K^0)+N(\overline{K}^0)}\left|\langle f|\mathcal{H}_{eff}|\overline{K}^0(t)\rangle\right|^2$$
$$= \frac{1}{2}|\mathcal{A}(K_S)|^2 e^{-\Gamma_S t} + \frac{1}{2}|\mathcal{A}(K_L)|^2 e^{-\Gamma_L t} + D\ \mathrm{Re}\left[e^{-i\Delta M_K t}\mathcal{A}(K_S)^*\mathcal{A}(K_L)\right]e^{-\frac{\Gamma_S+\Gamma_L}{2}t} + \mathcal{O}(\bar{\epsilon})$$

$$\boxed{D \equiv \frac{N(K^0)-N(\overline{K}^0)}{N(K^0)+N(\overline{K}^0)}}$$

time dependence

Interference

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

$\tau \sim 2\tau_S$

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

$$\sum_{\rm spin}\mathcal{A}(K_1 \to \mu^+\mu^-)^*\mathcal{A}(K_2 \to \mu^+\mu^-)$$
$$= \frac{16 i G_F^4 M_W^4 F_K^2 M_K^2 m_\mu^2 \sin^2\theta_W}{\pi^3}\mathrm{Im}[\lambda_t] y'_{7A}\{A^\mu_{L\gamma\gamma} - 2\pi\sin^2\theta_W(\mathrm{Re}[\lambda_t]y'_{7A} + \mathrm{Re}[\lambda_c]y_c)\}$$

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

- 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 $\bar{\epsilon}$

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

top loop — $\gamma\gamma$ loop — sign ambiguity

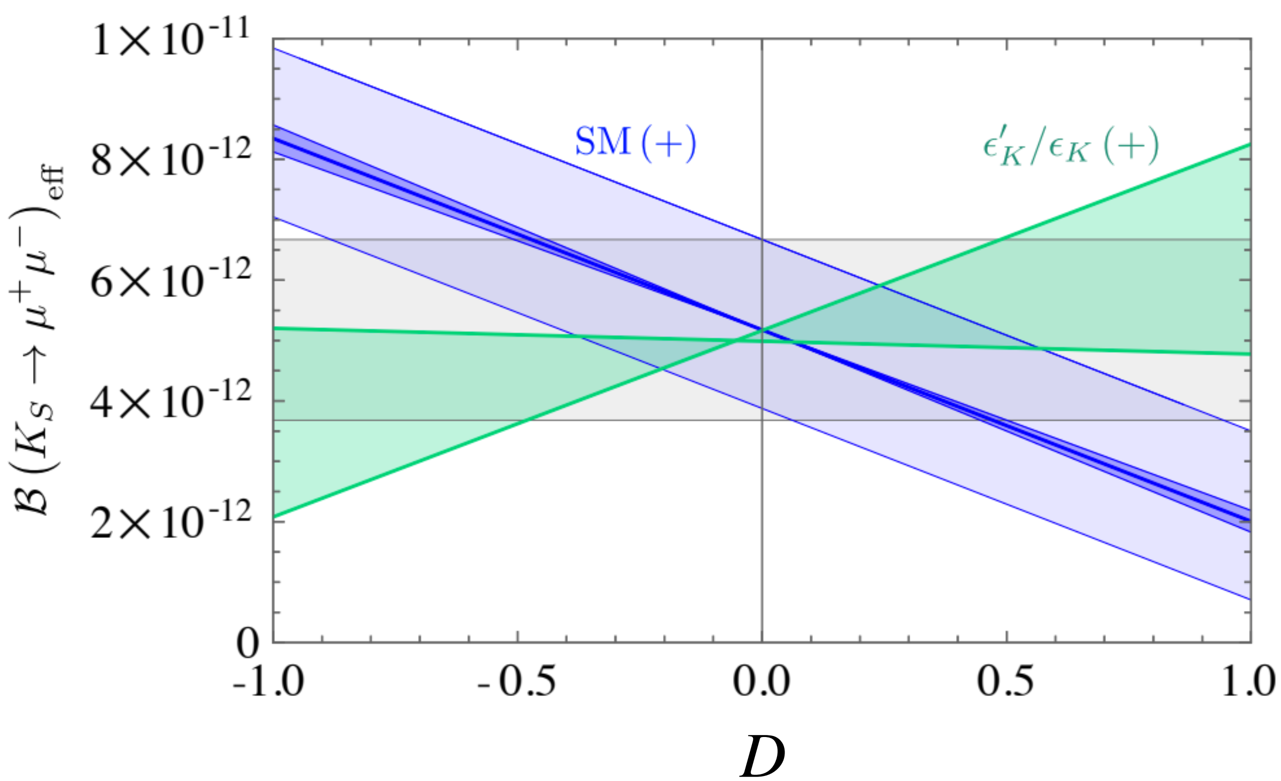
Direct *CP* asymmetry in $K_S \to \mu\mu$

[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, which reduces theoretical uncertainty of $K_L \to \mu\mu$
- Nonzero dilution factor (D) can be achieved by an accompanying charged kaon tagging and a charged pion tagging

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

Dilution factor: $D = \dfrac{K^0 - \overline{K}^0}{K^0 + \overline{K}^0}$



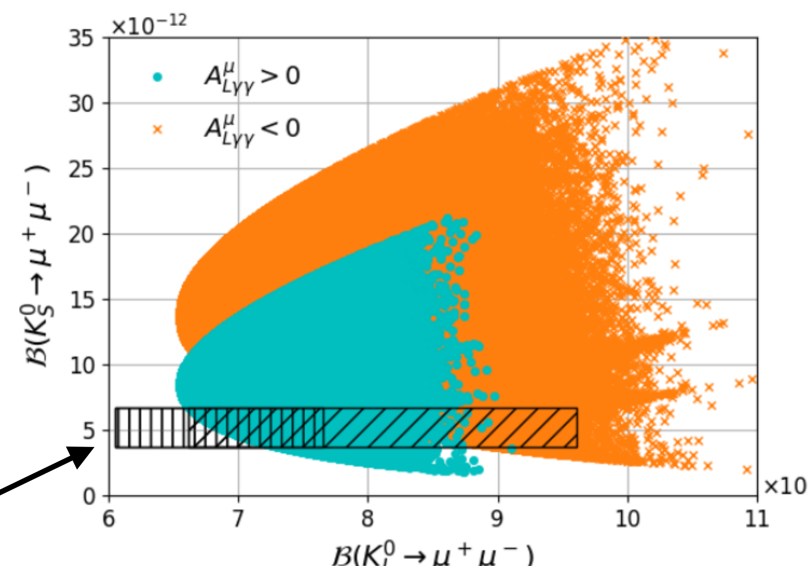
gray: $K_S \to \mu\mu$ (CPC) in the SM
Blue: $K_S \to \mu\mu$ with the interference in the SM
Green: Z scenario (LH) with ε'_K anomaly

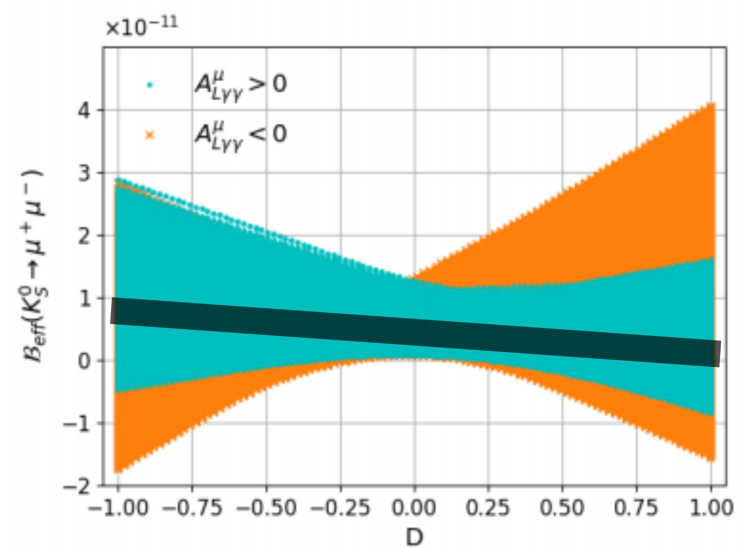
SUSY contributions to $K^0 \to \mu^+\mu^-$

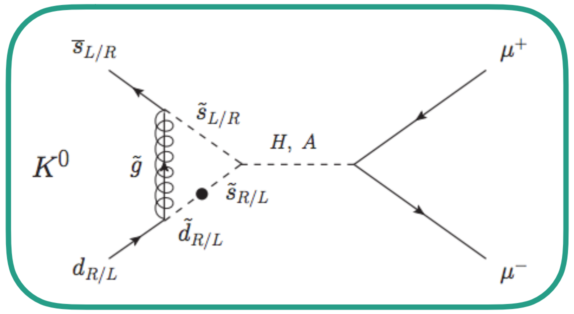
One of the MSSM scenario from Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18

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

No inter-ference plot (D=0)





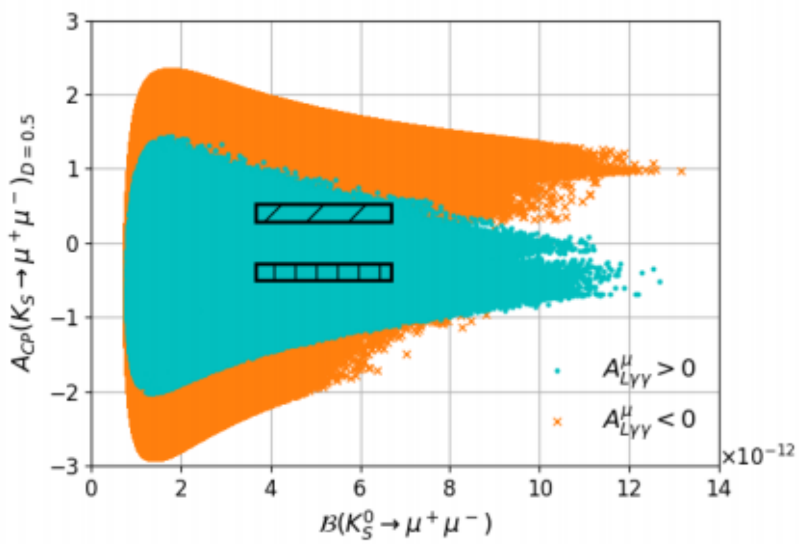


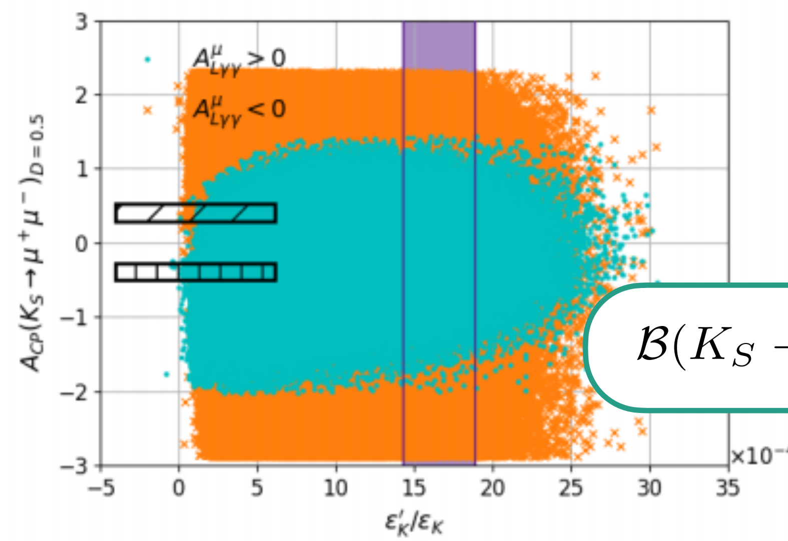
SM prediction [$\mathrm{sgn}(A^\mu_{L\gamma\gamma}) > 0$]

SM prediction

measured $\varepsilon'_K/\varepsilon_K$

D=0.5





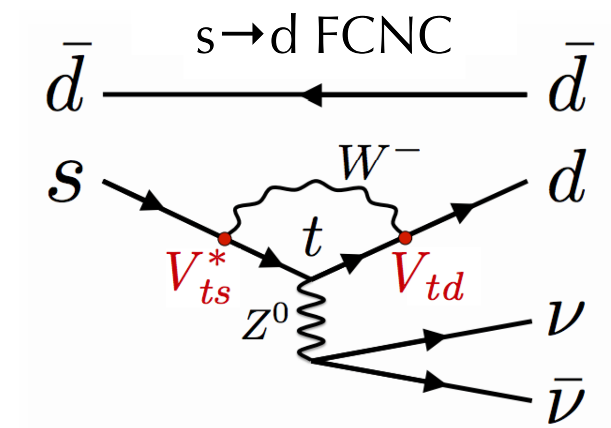
Large deviations from SM predictions are possible in the MSSM

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

See also Leptoquark study: $B(K_S \to \mu\mu)$~O(10^{-10}) is possible [Bobeth, Buras '18]

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

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

- Previous results:

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = 17.3^{+11.5}_{-10.5} \times 10^{-11} \quad \text{[E949, BNL '08]}$$
$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} \leq 2.6 \times 10^{-8} \quad \text{[E391a, J-PARC '10]}$$

- On-going experiments:

NA62 @CERN

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10} (95\%\text{C.L.})$ [NA62, 2016data, FPCP2018]

  - ~20 SM events are expected before LS2

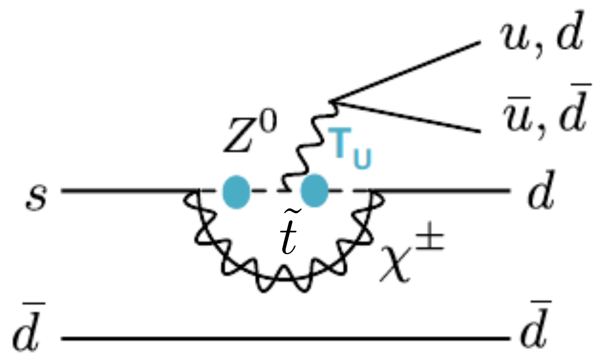
KOTO @J-PARC

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 3.0 \times 10^{-9} (90\%\text{C.L.})$ [KOTO, 2015data, FPCP2018]

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

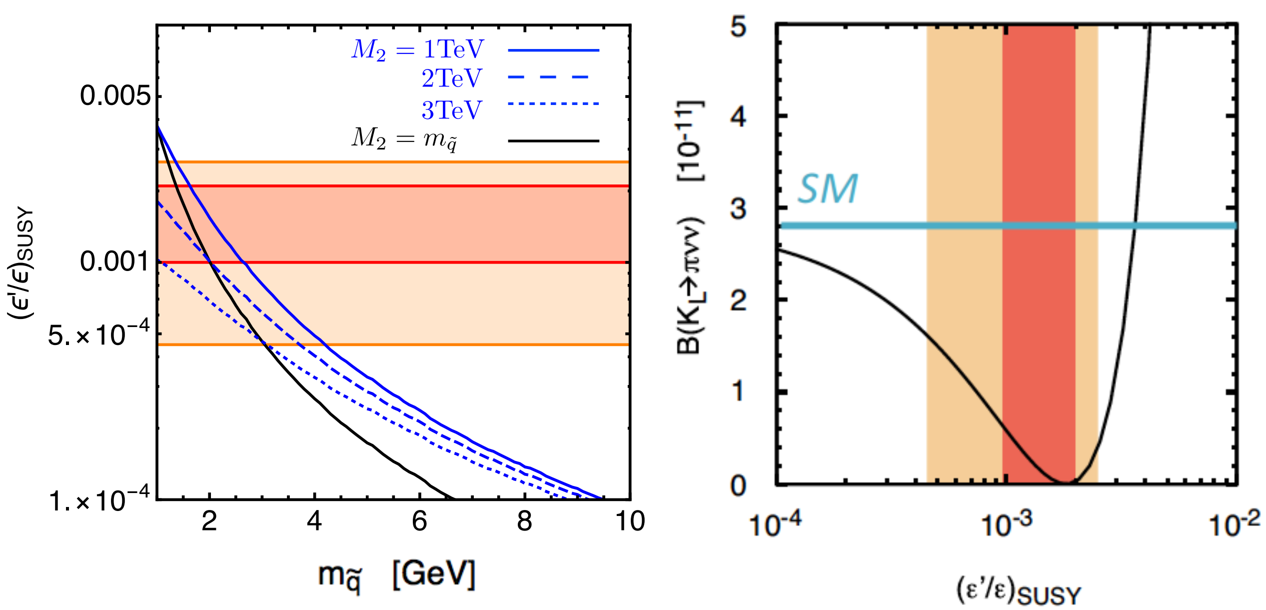
$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ in Z scenario (MSSM)

chargino Z-penguin in the MSSM
[Endo, Mishima, Ueda, Yamamoto, '16]

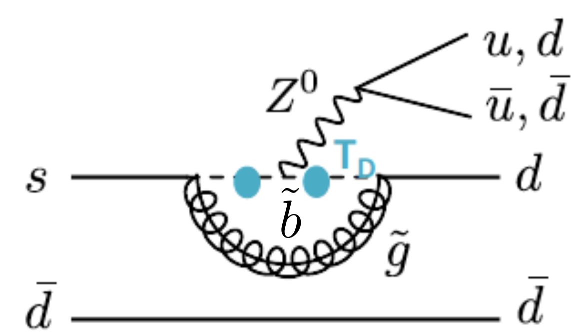


LH FCNC

Upper bounds under the constraints:
Vacuum, ε_K, ΔM_K, $K_L \to \mu\mu$

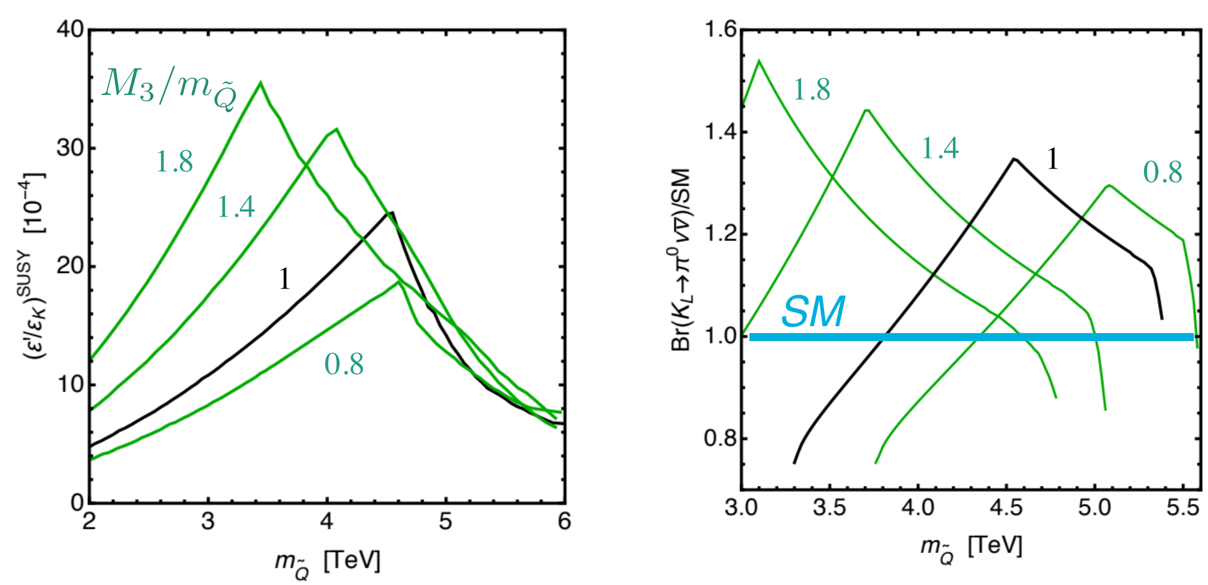


gluino Z-penguin in the MSSM
[Tanimoto, Yamamoto, '16]
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]



RH+LH FCNC

Upper bounds under the constraints:
Vacuum, **ε_K**, ΔM_K, $K_L \to \mu\mu$, **$b \to s(d)\gamma$**

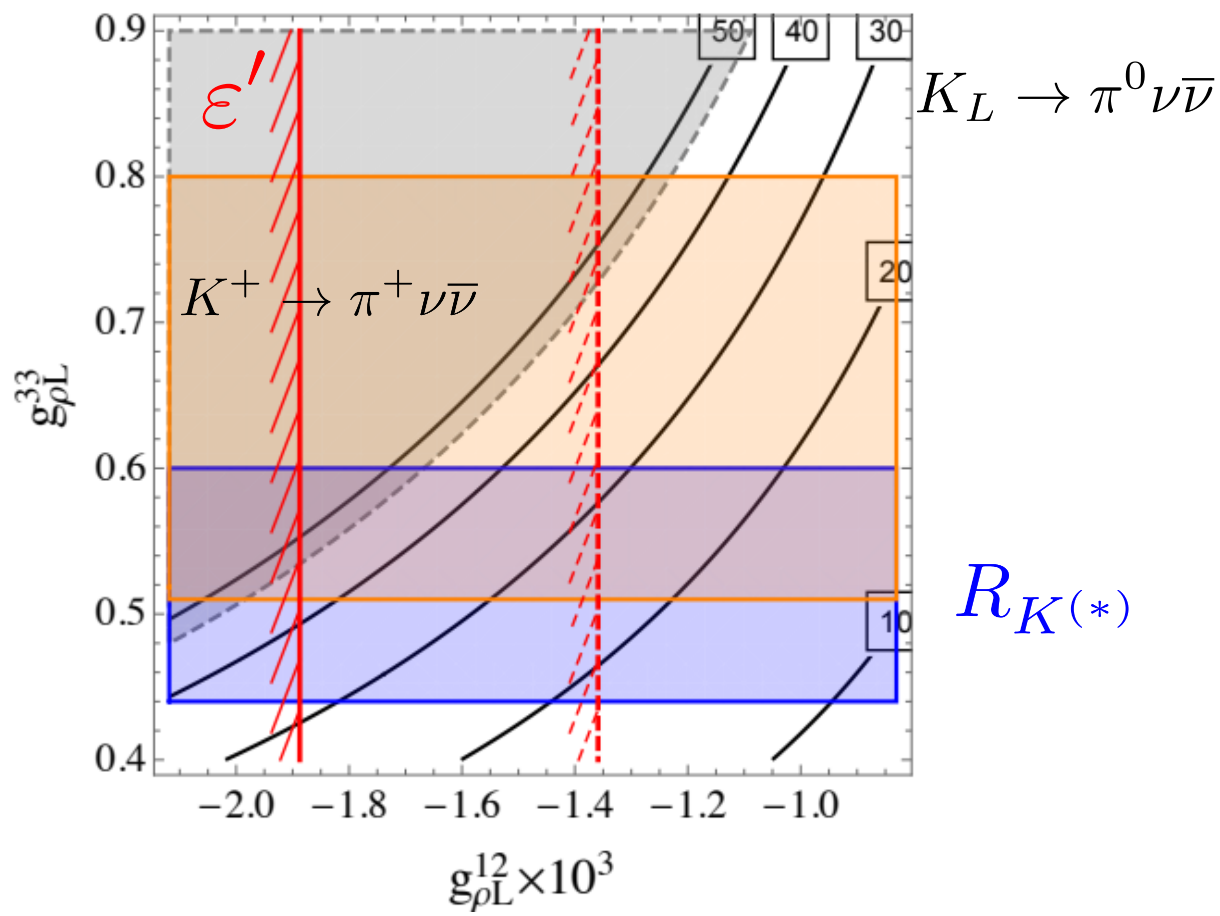


with $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})/\mathrm{SM} \lesssim 1.5$

Connection to *B* anomalies

B anomalies vs *K* precisions

$R_{K^{(*)}}$ vs. $K \to \pi\nu\bar{\nu}$



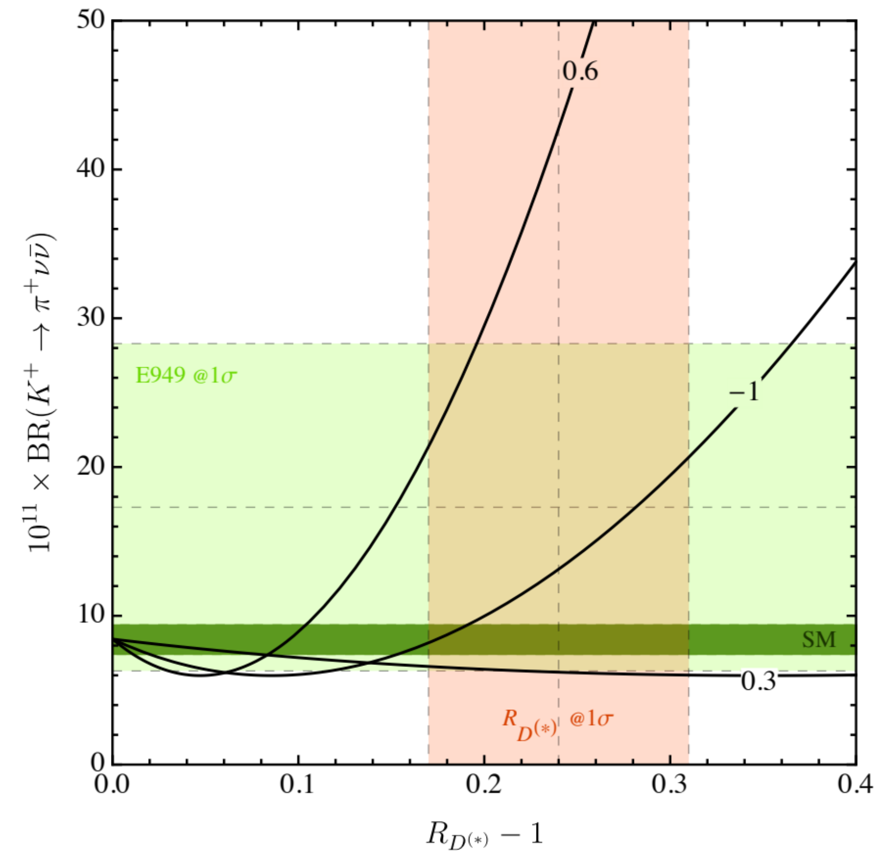
$$\mathcal{L}_{\rho f_L f_L} = \sum_{i,j=1}^{3} g^{ij}_{\rho L} \bar{f}^i_L \gamma^\mu \rho_\mu f^j_L$$

flavorful chiral vector boson

[Matsuzaki, Nishiwaki, Yamamoto 1806.02312]

→ Kei's talk

$R(D^{(*)})$ vs. $K \to \pi\nu\bar{\nu}$



$$\mathcal{L}_{\text{eff}} = -\frac{1}{\Lambda^2}(\bar{q}_{3L}\gamma_\mu\sigma^a q_{3L})(\bar{\ell}_{3L}\gamma^\mu\sigma^a\ell_{3L})$$

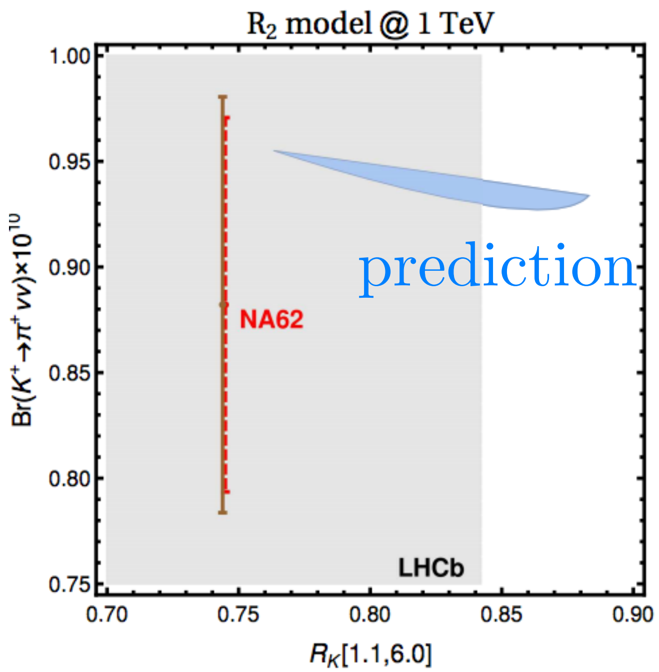
$U(2)_q \times U(2)_\ell$ flavour symmetry

[Bordone, Buttazzo, Isidori, Monnard '17]

→ Isidori's talk

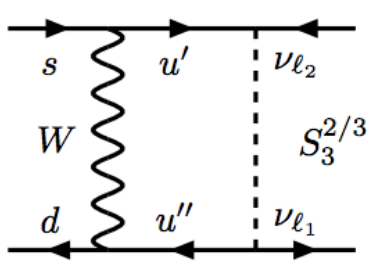
B anomalies vs K precisions

$R_{K^{(*)}}$ vs. $K \to \pi\nu\bar{\nu}$



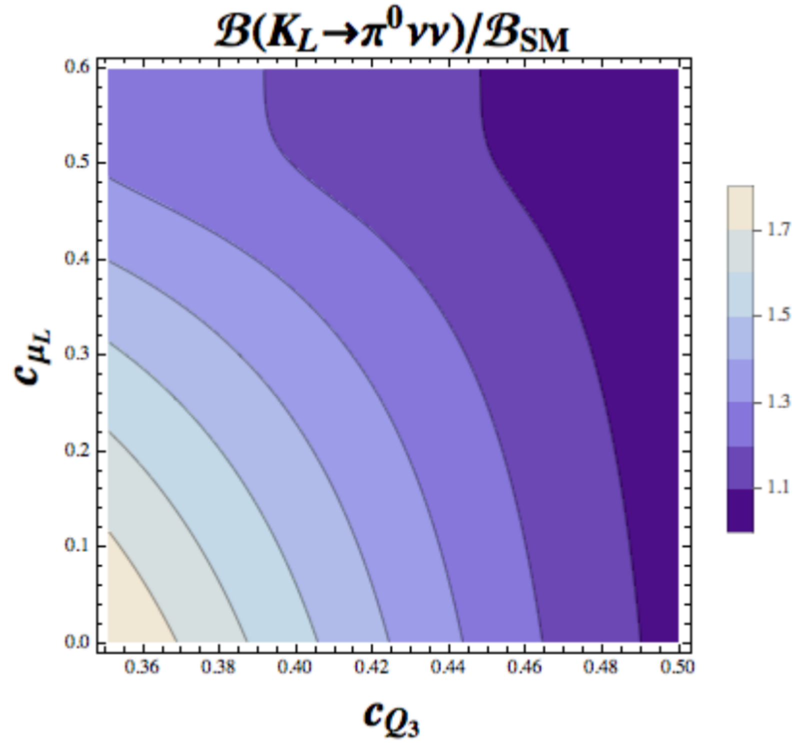
prediction of R_2

LQ-loop



[Fajfer, Kosnik,Silva ’18, Becirevic, Sumensari '17]

$R_{K^{(*)}}$ vs. $K \to \pi\nu\bar{\nu}$



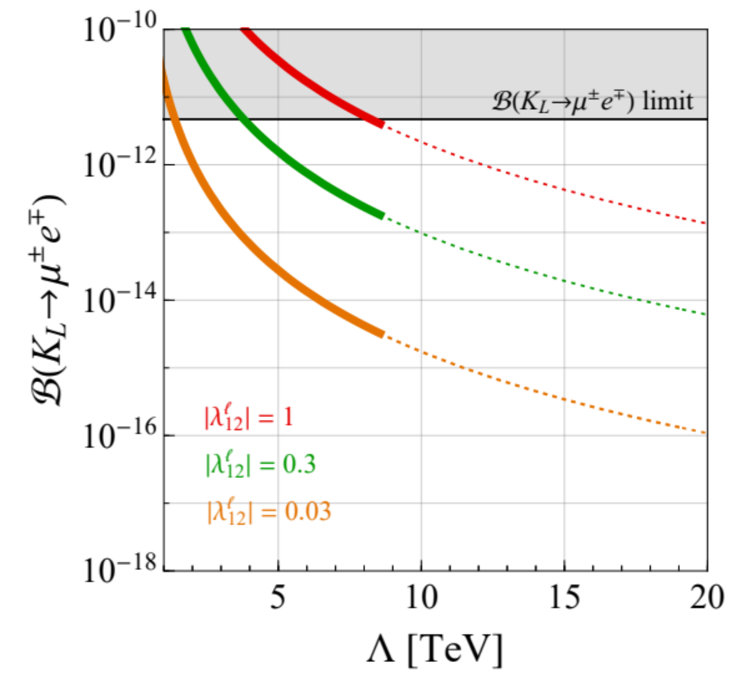
$$\mathcal{L} = \frac{4G_F\alpha}{2\sqrt{2}\pi} V_{ts}^* V_{td} C_{ds,l} \left(\bar{s}_L \gamma_\mu d_L\right)\left(\bar{\nu}_l \gamma^\mu \nu_l\right)$$

by gauge KK in 5D

→ Giancarlo’s talk

[D’Ambrosio, Iyer ’18]

$R_{K^{(*)}}$ vs. $K \to (\pi) e^\pm \mu^\mp$



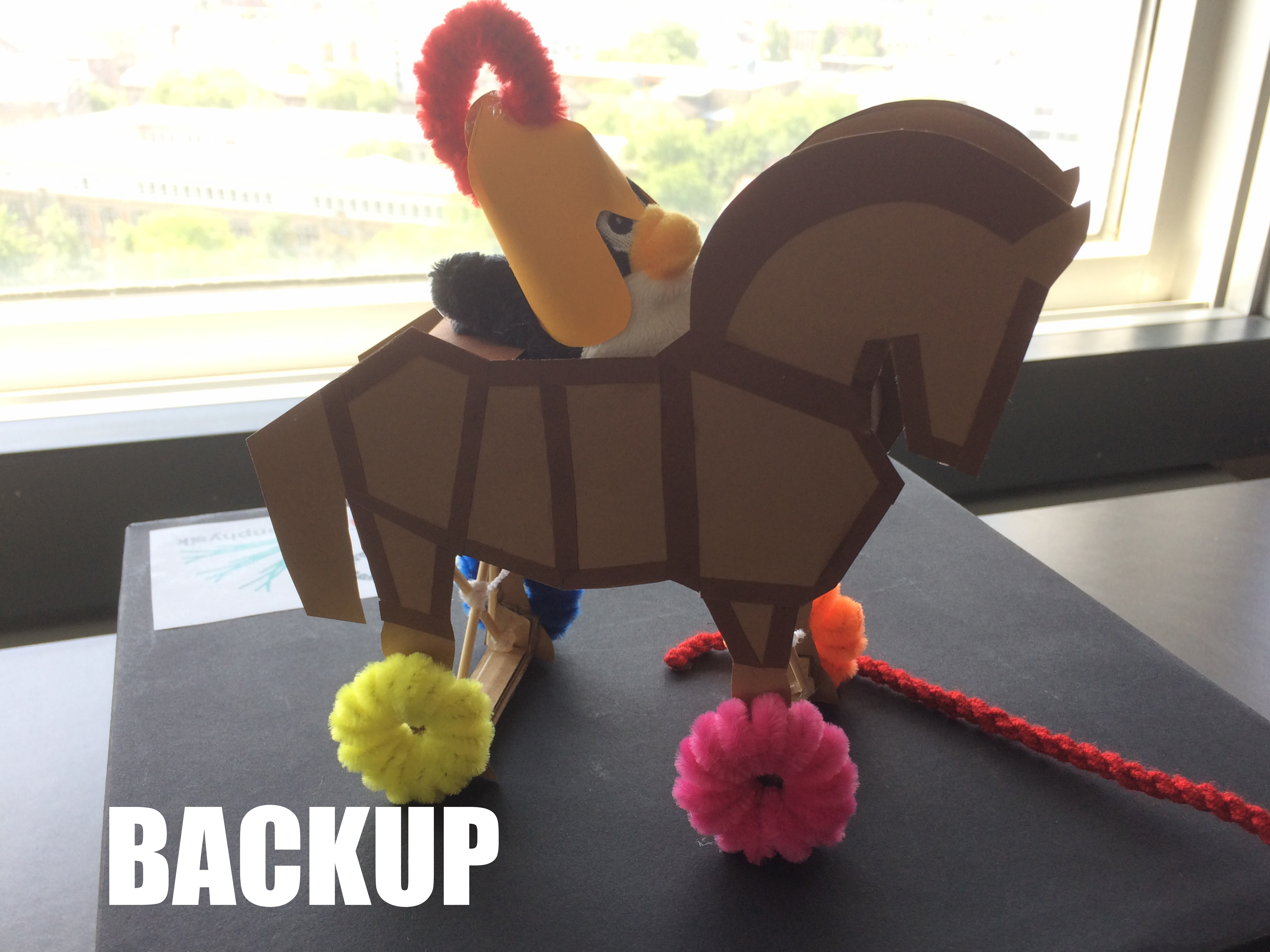
$$\mathcal{H}_{\rm NP} = G\,\lambda^q_{ij}\lambda^\ell_{mn}\,(\bar{d}_i\gamma^\alpha_L d_j)(\bar{\ell}_m\gamma_{L\alpha}\ell_n)$$

$$\lambda^q_{ij} = b_q V^*_{ti} V_{tj}$$

[Borsato, Gligoro, Guadagnoli, Santos, Sumensari 1808.02006]

Conclusions

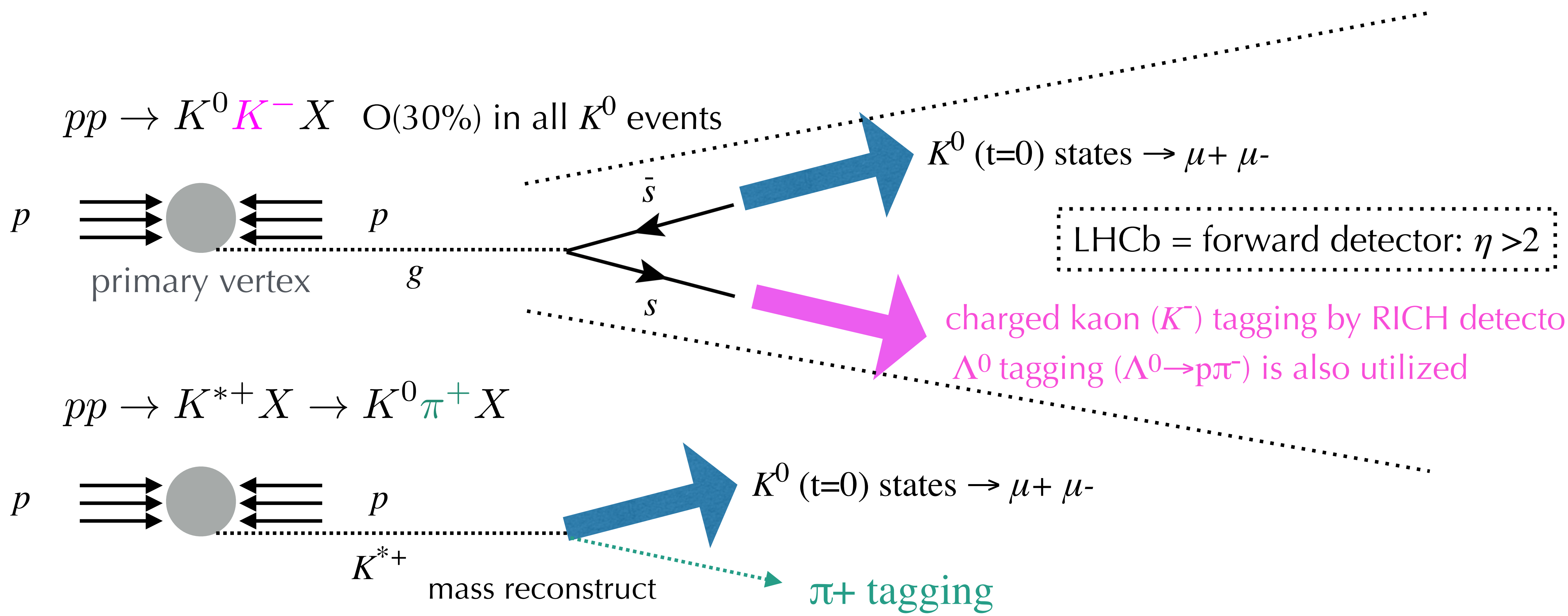
- **Kaon physics can probe *CP*-violating FCNC from various ways**
- First lattice result and theory calculations indicate $\boldsymbol{\varepsilon'_K/\varepsilon_K}$ discrepancy in $\boldsymbol{K^0 \to \pi\pi}$ (**2.8-2.9σ**)
- $\mathcal{B}(K_S \to \mu^+\mu^-)|_{\rm MSSM} \sim \mathcal{O}(1) \times 10^{-11}$ can be probed by **LHCb Upgrade**
- **LHCb Upgrade** could open a short distance window by **the interference effect** in $\boldsymbol{K^0 \to \mu^+\mu^-}$
- **10% precisions** in $\boldsymbol{K_L \to \pi^0 \nu\nu}$ and $\boldsymbol{K^+ \to \pi^+ \nu\nu}$ are crucial
- **Some models for *B* anomalies can be probed by precisions of *K***


BACKUP

Dilution factor D

[D'Amborosio, TK '17]

- Since $f_s(\mu^2) = f_{\bar{s}}(\mu^2)$ (PDF in p), $\sigma(pp \to K^0 X) \simeq \sigma(pp \to \overline{K}^0 X)$ and then $D = 0$ in LHC
- Nonzero dilution factor D could be obtained by an accompanying charged kaon tagging and a charged pion tagging



A similar charged pion tagging for D^0 through $D^{*+} \to D^0 \pi$+(slow) has been achieved in the LHCb

Dual QCD approach

[Bardeen, Buras, Gérard, '86, '87, '14, Aebischer, Buras, Gérard, 1807.01709]

- Effective theory **focusing the meson evolution** which matches the quark-gluon evolution (SD RGE) at the matching scale $\mu = \mathcal{O}(1)\,\mathrm{GeV}$
  - It cannot be achieved in ChPT where a matching to SD physic leads to large uncertainty
- Inclusion of vector meson is crucial for the meson running and the matching

$$\mathcal{L} = \frac{f_\pi^2}{4}\left[\mathrm{Tr}|D^\mu U|^2 + r\mathrm{Tr}(mU^\dagger + \mathrm{h.c.}) - \frac{r}{\Lambda_\chi^2}\mathrm{Tr}(mD^2U^\dagger + \mathrm{h.c.})\right]$$
$$- \frac{1}{4}\mathrm{Tr}{V_{\mu\nu}}^2 - a\frac{f_\pi^2}{4}\mathrm{Tr}\left[\partial_\mu\xi^\dagger\xi + \partial_\mu\xi\xi^\dagger - 2igV_\mu\right]^2$$

with

$$r(\mu) = \frac{2m_K^2}{m_s(\mu) + m_d(\mu)}$$

pseudoscalar octet Π: $U = \exp\left(i\frac{\Pi}{f_\pi}\right) \equiv \xi\xi$

vector-meson nonet V_μ**:** gauge boson of a hidden U(3) local symmetry

[Bando, Kugo, Uehara, Yamawak, Yanagida '85, Bando, Kugo, Yamawaki, '88]

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