*K*中間子の精密測定で探る物理

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Karlsruhe Institute of Technology (KIT)

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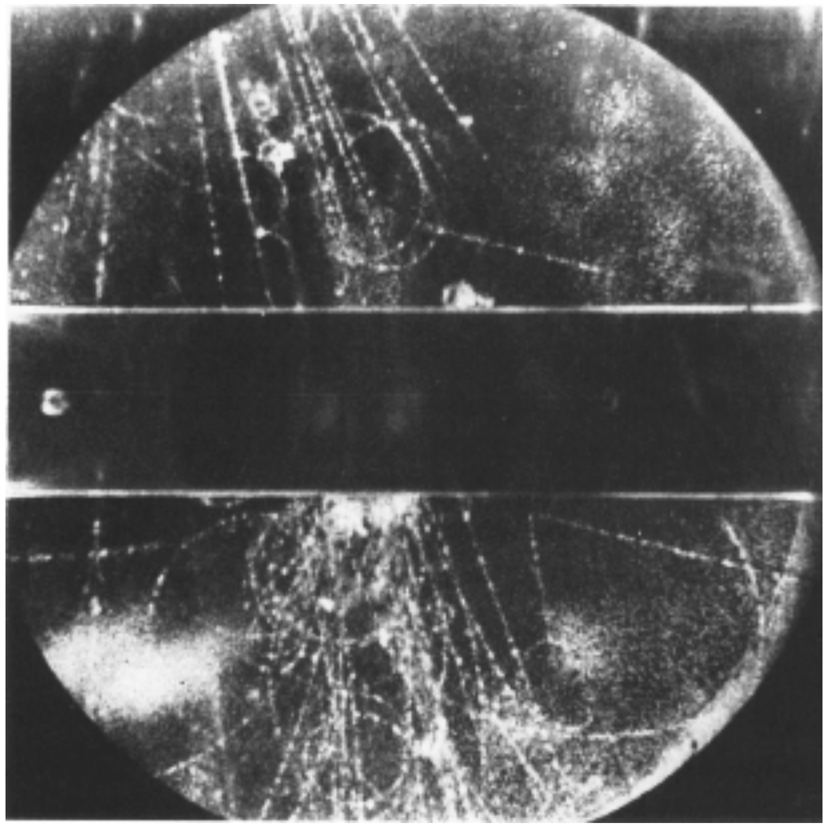
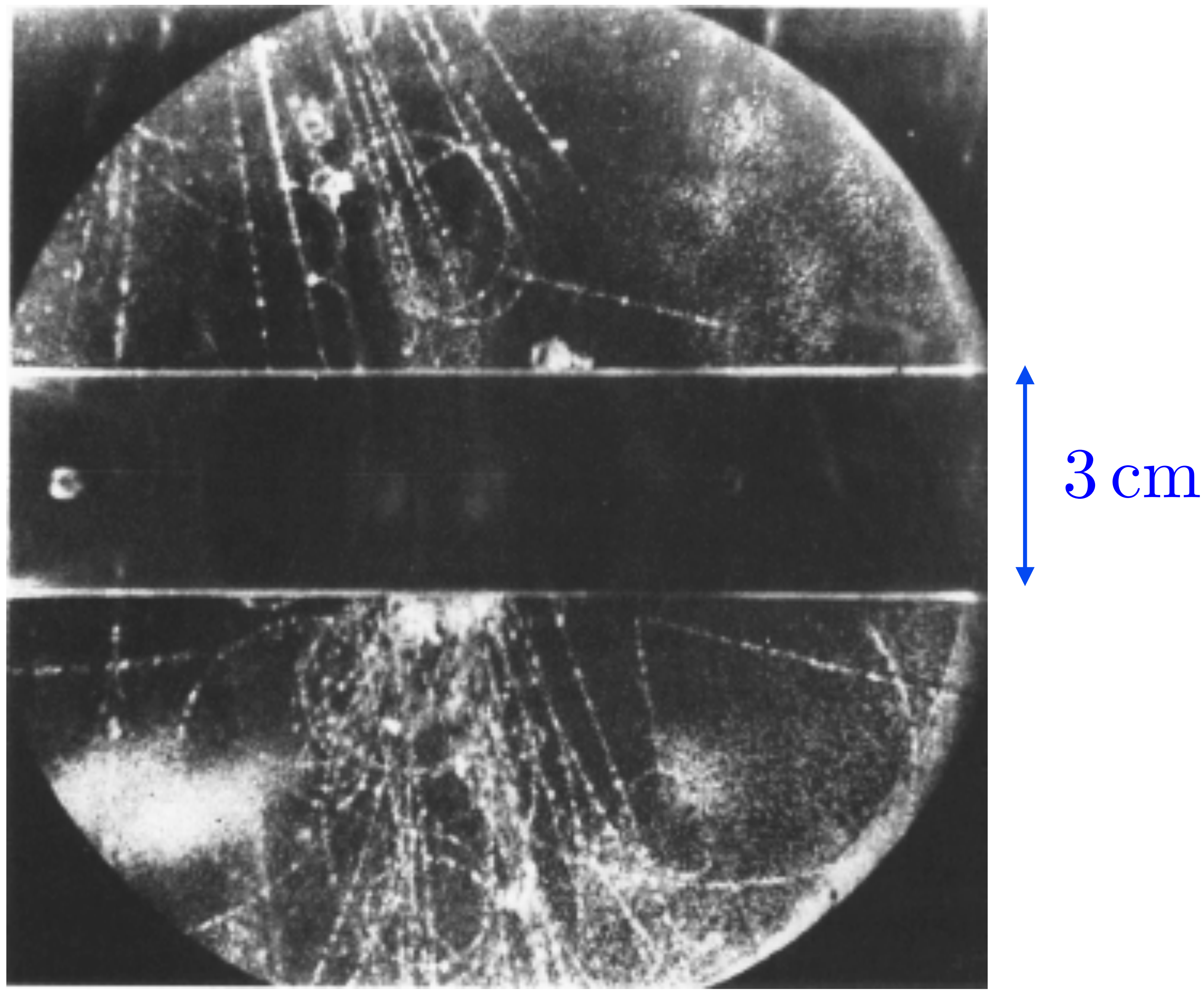


Karlsruhe Institute of Technology

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
Dr. C. C. BUTLER
Physical Laboratories, University, Manchester

NATURE December 20, 1947



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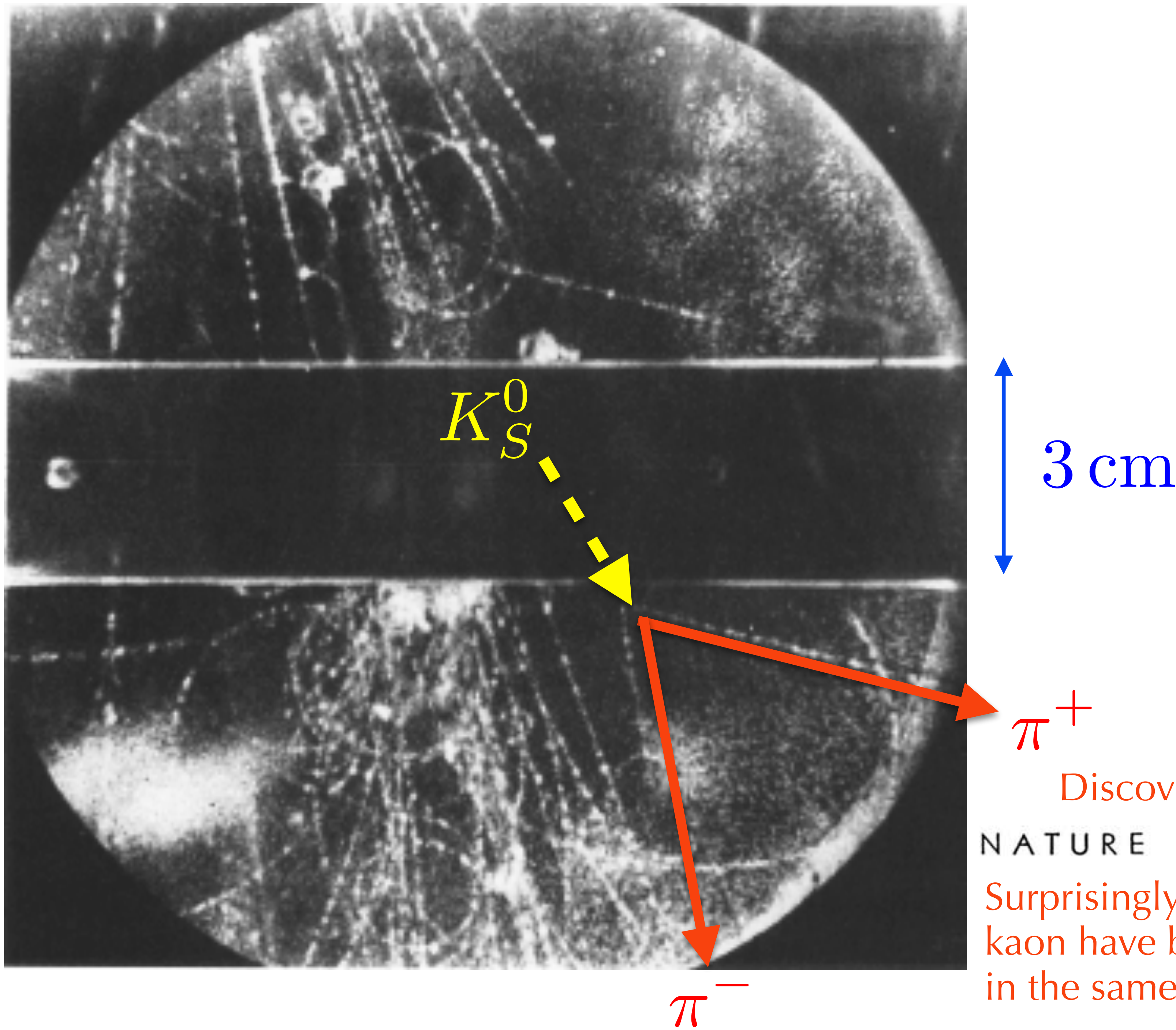
Discovery of Kaon

"V particle"



Discovery of Pion

NATURE January 25, 1947

Surprisingly for me, pion & kaon have been discovered in the same year

KAON

A GOLDEN CHANNEL

- Discovery of CP violation ['64]
- GIM mechanism and prediction of charm ['64-70]
  → November Revolution (J/ψ) ['74]
- CKM matrix and prediction of beauty/truth ['73]

Kaon!

Kaon physics is still an exciting field!

- `Discovery channel` → **Precision physics:** FCNC and *CP* violation can be probed precisely using rare decay channels Br~$\mathcal{O}(10^{-11})$
- There are many promising on-going experiments for kaon precisions; LHCb / NA62 / KOTO / KLOE-2 / TREK
- One can test our understanding of the SM, unitarity of CKM and ChPT, and also probe physics beyond the SM

collider search

could give stronger constraints

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

ε'_K and ε_K discrepancies?

$$K_L \to \pi\pi$$

correlations

B

LFUV

CP-violating FCNC

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

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

reduce Th uncertainty

Understanding of ChPT

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

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

$$K_S \to 4l$$

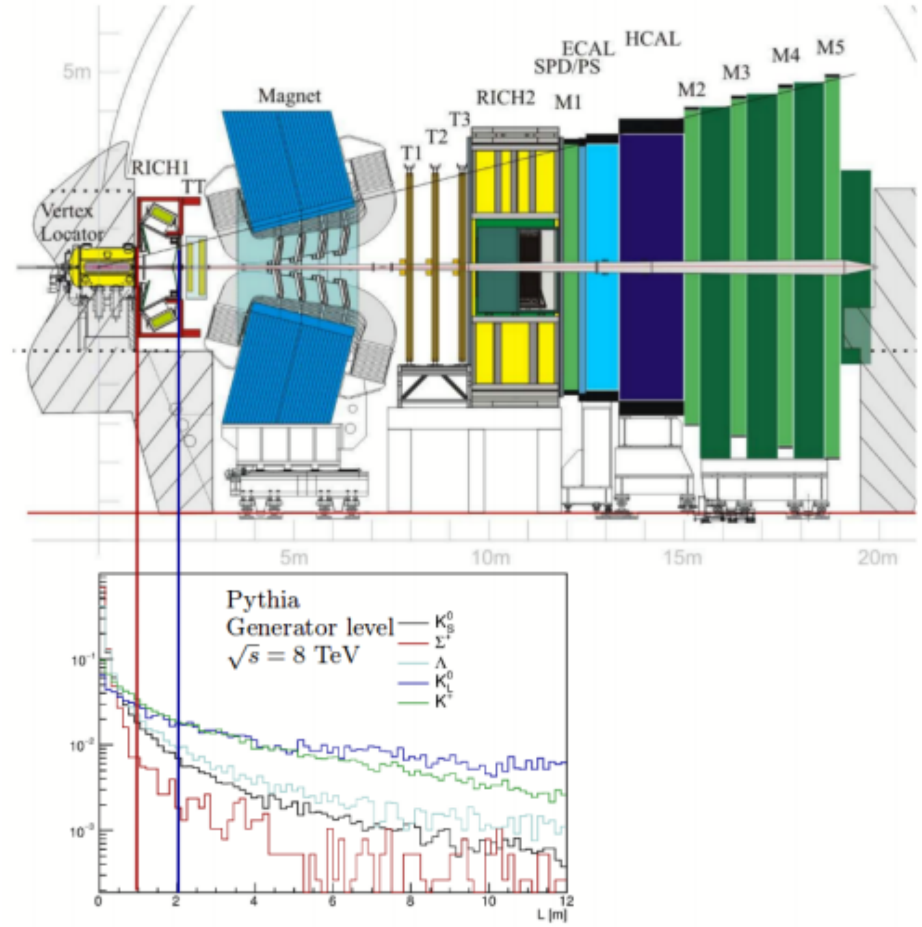
$$K_S \to \pi^+\pi^- e^+e^-$$

reduce Th uncertainty

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

CPV decay
less sensitive because of LD contributions

Kaon in LHCb



- LHCb experiment has been designed for efficient reconstructions of b and c
- Huge production of strangeness [$O(10^{13})$/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~$O(10^{-11})$

Kaon & *CP* violation

- Kaon = bound state of $\bar{s}d$ and *CP* transformation

$$CP|K^0\rangle = |\overline{K}^0\rangle, \qquad CP|\overline{K}^0\rangle = |K^0\rangle,$$

$$CP|K^0_{1,2}\rangle = \pm|K^0_{1,2}\rangle, \qquad \text{where } |K^0_{1,2}\rangle \equiv \frac{1}{\sqrt{2}}\left(|K^0\rangle \pm |\overline{K}^0\rangle\right)$$

- $|K^0_{1,2}\rangle$ are *CP*-eigenstates but are not mass-eigenstates, because nature does not respect the *CP* symmetry

Short-lived mass eigenstate $\quad |K_S\rangle \simeq \dfrac{1}{\sqrt{1+|\epsilon_K|^2}}\left(|K^0_1\rangle + \epsilon_K|K^0_2\rangle\right)$

Long-lived mass eigenstate $\quad |K_L\rangle \simeq \dfrac{1}{\sqrt{1+|\epsilon_K|^2}}\left(|K^0_2\rangle + \epsilon_K|K^0_1\rangle\right)$

- Lifetime difference is so large and mass difference is small (opposite from B^0)

$$\tau_S = 0.89 \times 10^{-10}\,\text{sec.} \qquad c\tau_S = 2.6\,\text{cm}$$

$$\tau_L = 511 \times 10^{-10}\,\text{sec.} \qquad c\tau_L = 15\,\text{m}$$

$$\Delta M_K = 3.4 \times 10^{-12}\,\text{MeV}$$

Kaon & *CP* violation

- $K^0 \to \pi\pi$

$$J(K^0) = J(2\pi) = S(2\pi) + L(2\pi) \qquad \to L = 0$$

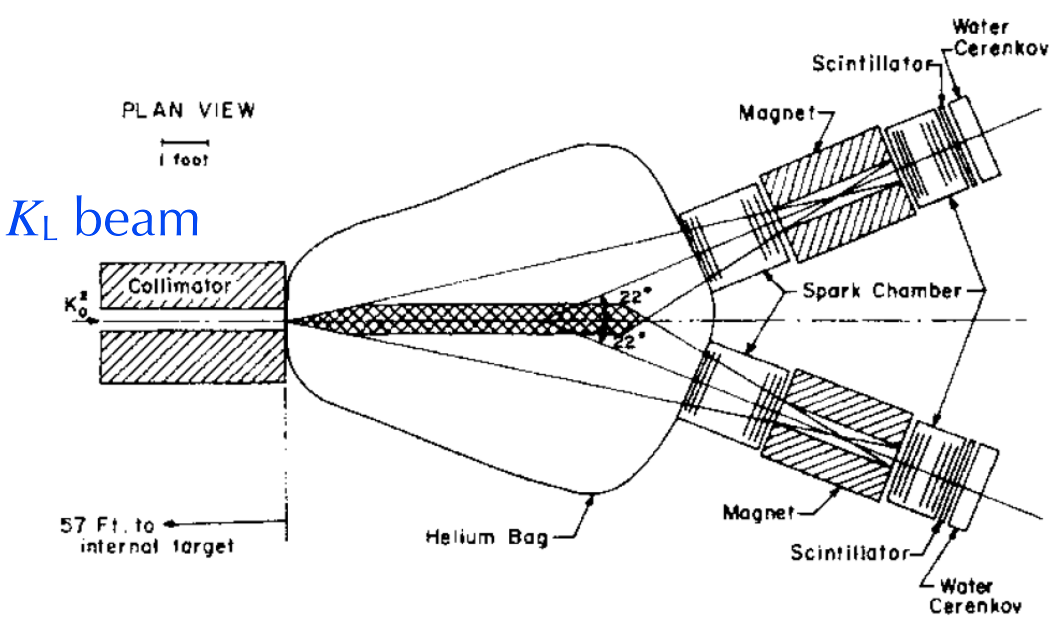
=0   =0 2π state can not carry angular momentum

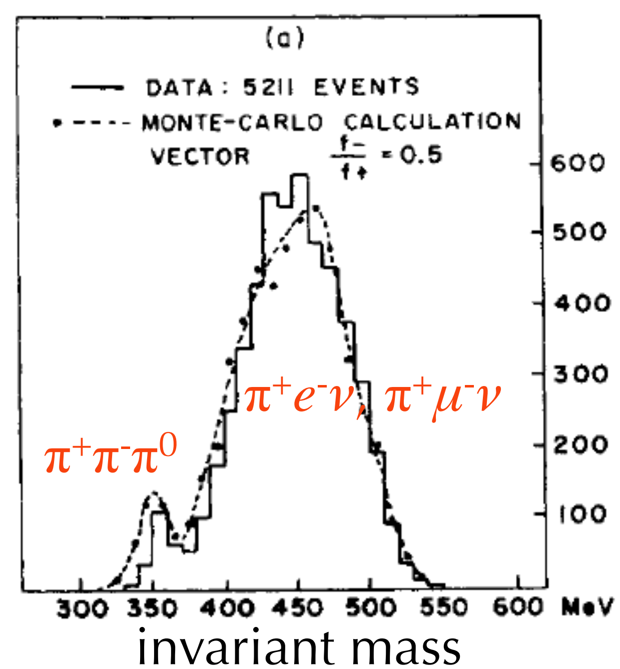
$$P = (-1)^L = +1, C = (-1)^L = +1 \quad \to CP(2\pi) = +1 = CP \text{ even}$$

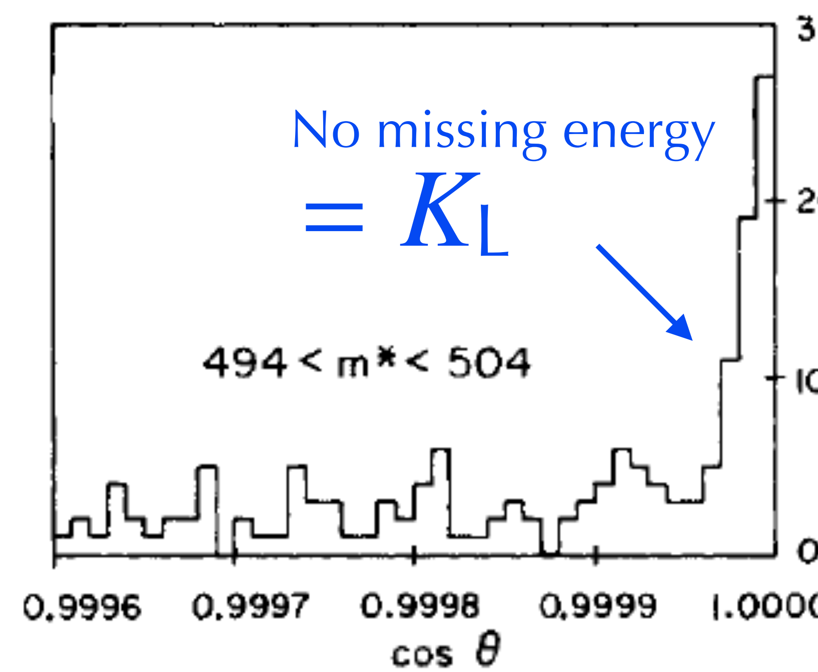
- The *CP* violation was measured by

$$\mathcal{A}(K_L\ (\text{almost } CP \text{ odd}) \to \pi^+\pi^-\ (CP \text{ even})) \propto \varepsilon_K = \mathcal{O}(10^{-3}) \neq 0$$

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







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

$K^0 \to \pi\pi$: 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]

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

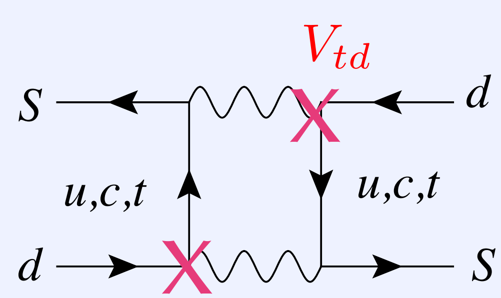
[NA48/CERN and KTeV/FNAL '99]

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

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

W box

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

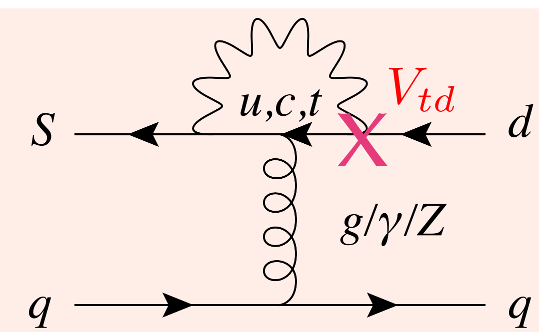


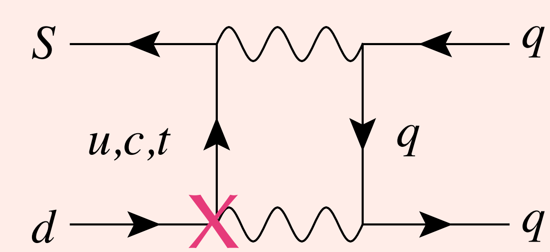
$$K^0 \longleftrightarrow \overline{K}^0$$

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 $|V_{cb}|$

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

$\longleftarrow$ $\varepsilon_K(\mathrm{LD}) = -3.6(2.0)\% \times \varepsilon_K(\mathrm{SD})_{\mathrm{SM}}$ [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

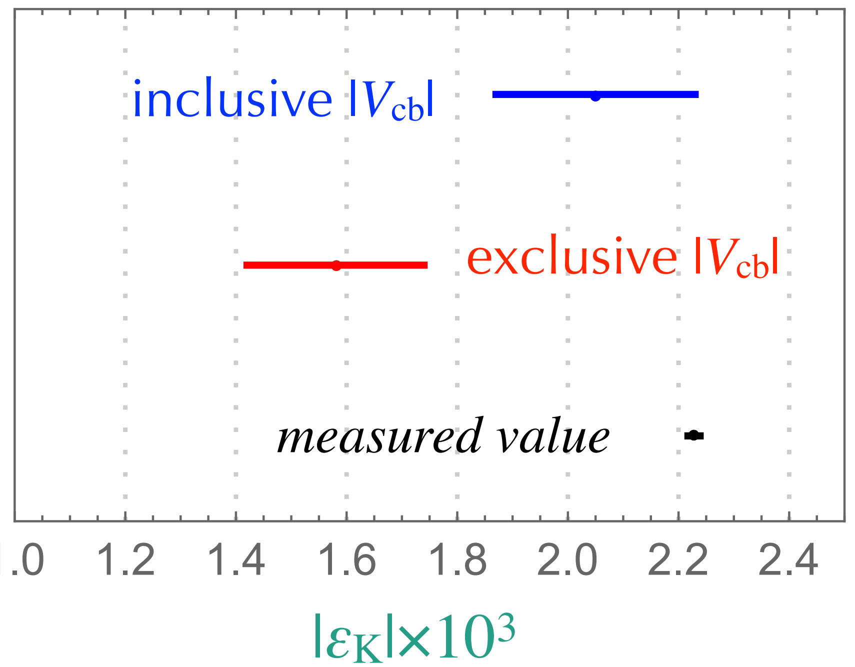
$$\simeq \bar{\eta}\lambda^2 |V_{cb}|^2 \left[|V_{cb}|^2 (1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} S_0(x_c)\right]$$

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

$|\varepsilon_K|$ predictions

($\pm 1\sigma$ error bar)

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

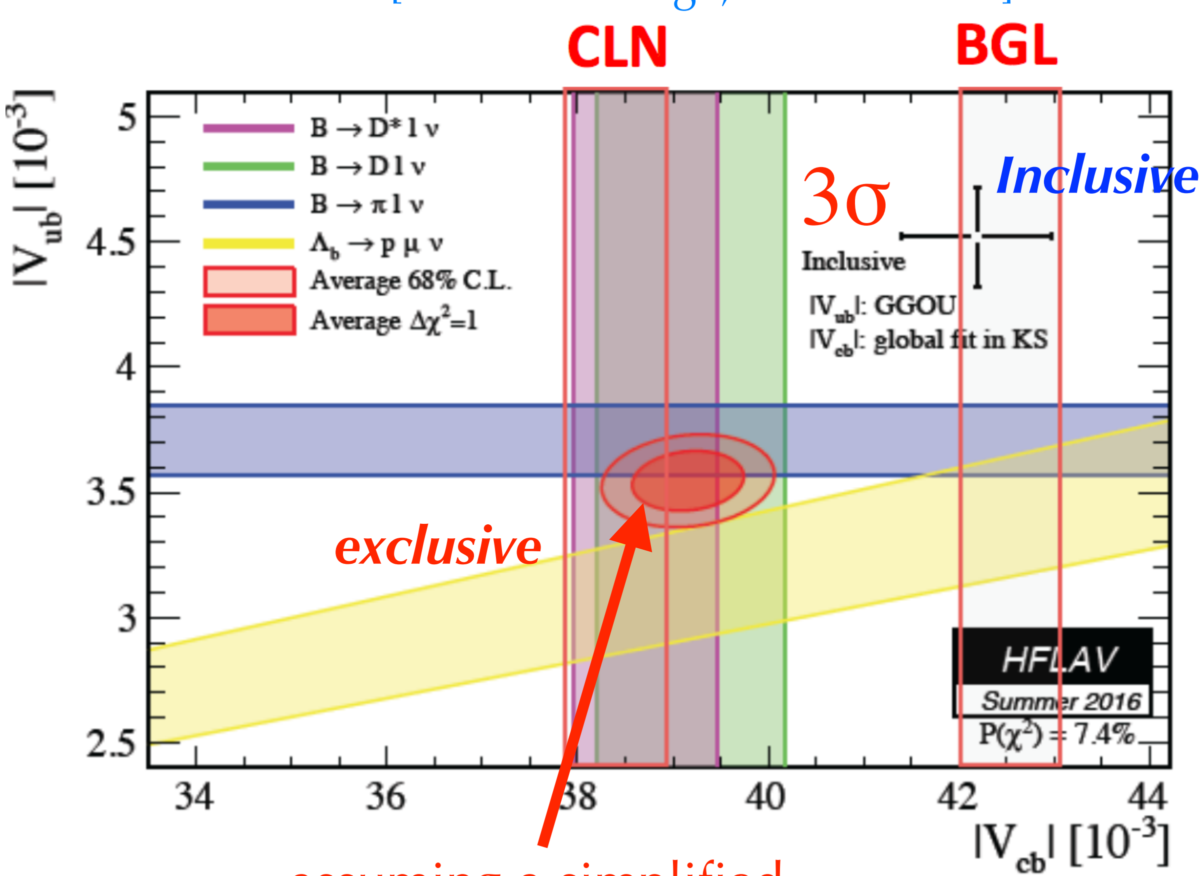


Theoretical prediction of ε_K with inclusive $|V_{cb}|$ is consistent with the measured value, while there is 4.0σ tension in exclusive $|V_{cb}|$ case

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

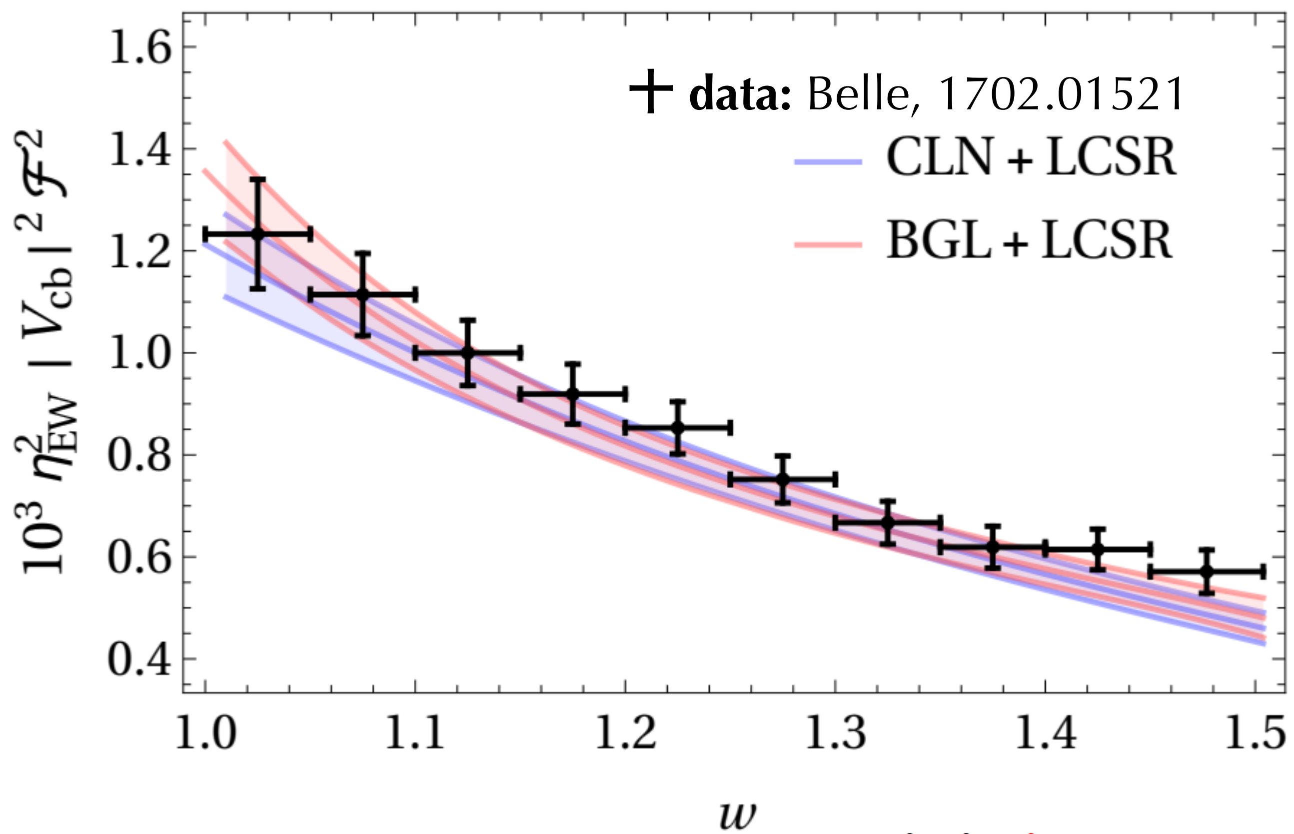
ε_K discrepancy ~ $|V_{cb}|$ discrepancy

[HFLAV average, 1612.07233]



assuming a simplified FF parametrization (**CLN**)

[Bigi, Gambino, Schacht '17]



$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$, $q^2 = (p_B - p_{D^*})^2$

- 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]

$$|V_{cb}|^{\mathrm{excl.}}_{\mathrm{BGL}} = \left(40.6^{+1.2}_{-1.3}\right) \times 10^{-3}$$ [Bigi, Gambino, Schacht '17]

Error will be reduced by future lattice result

+ Similar recent progress [Grinstein, Kobach '17, Bernlochner, Ligeti, Papucci, Robinson '17]

Formulae of *CP* violating decay

- Precise definitions of $K \to \pi\pi$ system

time-dependence of K_L-K_S interference

$$\eta_{00} \equiv \frac{\mathcal{A}(K_L \to \pi^0\pi^0)}{\mathcal{A}(K_S \to \pi^0\pi^0)} \overset{exp.}{=} \left(2.220 \cdot 10^{-3}\right) \cdot e^{43.52^\circ i} \qquad \epsilon_K \equiv \frac{2\eta_{+-} + \eta_{00}}{3} \quad \in \mathbb{C}$$

$$\eta_{+-} \equiv \frac{\mathcal{A}(K_L \to \pi^+\pi^-)}{\mathcal{A}(K_S \to \pi^+\pi^-)} \overset{exp.}{=} \left(2.232 \cdot 10^{-3}\right) \cdot e^{43.51^\circ i} \qquad \epsilon'_K \equiv \frac{\eta_{+-} - \eta_{00}}{3} \quad \in \mathbb{C}$$

- Pion isospin decomposition of the physical states

$$|\pi^0\pi^0\rangle = \sqrt{\frac{1}{3}}|\pi\pi\rangle_{I=0} - \sqrt{\frac{2}{3}}|\pi\pi\rangle_{I=2}$$

$$|\pi^+\pi^-\rangle = \sqrt{\frac{2}{3}}|\pi\pi\rangle_{I=0} + \sqrt{\frac{1}{3}}|\pi\pi\rangle_{I=2}$$

Two pions (I=1) can decompose into I=0,2 states with CG coefficients

$$\epsilon_0 \equiv \frac{\mathcal{A}(K_L \to (\pi\pi)_0)}{\mathcal{A}(K_S \to (\pi\pi)_0)} \qquad \epsilon_2 \equiv \frac{1}{\sqrt{2}}\frac{\mathcal{A}(K_L \to (\pi\pi)_2)}{\mathcal{A}(K_S \to (\pi\pi)_0)} \ll \epsilon_0 \qquad \omega \equiv \frac{\mathcal{A}(K_S \to (\pi\pi)_2)}{\mathcal{A}(K_S \to (\pi\pi)_0)} \ll \epsilon_0$$

then $\quad \epsilon_K = \epsilon_0 - \sqrt{2}\epsilon_2\omega + \mathcal{O}(\epsilon_0\omega^2) \qquad \epsilon'_K = \epsilon_2 + \frac{\omega}{\sqrt{2}}(\epsilon_2 - \epsilon_0) + \mathcal{O}(\epsilon_0\omega^2)$

Formulae of *CP* violating decay cont.

- Then,

$$\frac{\epsilon'_K}{\epsilon_K} = \left(\epsilon_2 + \frac{\omega}{\sqrt{2}}(\epsilon_2 - \epsilon_0)\right)\left(\epsilon_0 - \sqrt{2}\epsilon_2\omega\right)^{-1} + \mathcal{O}(\omega^2)$$
$$= \frac{1}{\sqrt{2}}\left[\frac{\mathcal{A}(K_L \to (\pi\pi)_2)}{\mathcal{A}(K_L \to (\pi\pi)_0)} - \frac{\mathcal{A}(K_S \to (\pi\pi)_2)}{\mathcal{A}(K_S \to (\pi\pi)_0)}\right] + \mathcal{O}(\omega^2)$$

- K_L and K_S also can be decomposed into isospin eigenstates (K^0, $\overline{K}^0$)

$$|K_S\rangle \equiv \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\delta_\epsilon|^2}}\left((1+\delta_\epsilon)|K^0\rangle + (1-\delta_\epsilon)|\overline{K}^0\rangle\right)$$
$$|K_L\rangle \equiv \frac{1}{\sqrt{2}}\frac{1}{\sqrt{1+|\delta_\epsilon|^2}}\left((1+\delta_\epsilon)|K^0\rangle - (1-\delta_\epsilon)|\overline{K}^0\rangle\right)$$

- Let us define *isospin amplitudes*

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

δ_I is a strong phase, which comes from the final pion state re-scattering

then

$$\frac{\mathcal{A}(K_L \to (\pi\pi)_2)}{\mathcal{A}(K_L \to (\pi\pi)_0)} = e^{i(\delta_2-\delta_0)}\frac{i\mathrm{Im}(A_2) + \delta_\epsilon \mathrm{Re}(A_2)}{i\mathrm{Im}(A_0) + \delta_\epsilon \mathrm{Re}(A_0)}$$

$$\frac{\mathcal{A}(K_S \to (\pi\pi)_2)}{\mathcal{A}(K_S \to (\pi\pi)_0)} = e^{i(\delta_2-\delta_0)}\frac{\mathrm{Re}(A_2) + i\delta_\epsilon \mathrm{Im}(A_2)}{\mathrm{Re}(A_0) + i\delta_\epsilon \mathrm{Im}(A_0)}$$

Formulae of *CP* violating decay cont.

- Using $\epsilon_K = |\epsilon_K| e^{i\phi_\epsilon} = \epsilon_0 - \sqrt{2}\epsilon_2\omega + \mathcal{O}(\epsilon_0\omega^2) \simeq \dfrac{i\mathrm{Im}(A_0) + \delta_\epsilon \mathrm{Re}(A_0)}{\mathrm{Re}(A_0) + i\delta_\epsilon \mathrm{Im}(A_0)}$

$$\frac{\epsilon'_K}{\epsilon_K} = \frac{i}{\sqrt{2}|\epsilon_K|} e^{i(\delta_2-\delta_0-\phi_\epsilon)} \frac{\mathrm{Re}(A_2)}{\mathrm{Re}(A_0)} \left(\frac{\mathrm{Im}(A_2)}{\mathrm{Re}(A_2)} - \frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)} \right) + \mathcal{O}((\delta_\epsilon, \omega) \cdot \text{1st term})$$

- The total phase is excellently real

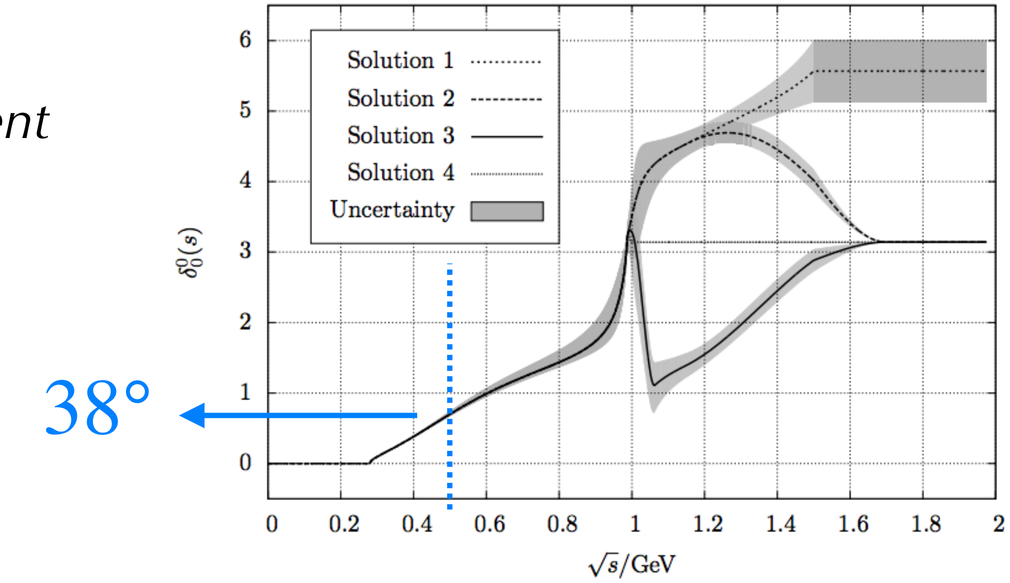
$$\phi_\epsilon = \tan^{-1} \frac{2\Delta M_K}{\Delta\Gamma}$$

$$\begin{aligned} ie^{i(\delta_2-\delta_0-\phi_\epsilon)} &= 0.9990 + 0.04i \left[\delta_0 = (38.3 \pm 1.3)^\circ,\ \delta_2 \approx -7^\circ,\ \phi_\epsilon = (43.52 \pm 0.05)^\circ\ \ (\text{exp.})\right] \\ &= 0.98 + 0.19i\ (\delta_0 = (23.8 \pm 5.0)^\circ,\ \delta_2 = (-11.6 \pm 2.8)^\circ\ (\mathit{Lattice})) \end{aligned}$$

$$\simeq 1$$

In my knowledge, this is accidental incident

dispersive treatment from $K^+ \to \pi^+\pi^- l^+\nu$



[Colangelo, Passemar, Stoffer '15]

Formulae of *CP* violating decay cont.

For theorists

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

- General remarks
  - This formula is modified by $m_u \neq m_d$ [Cirigliano,Pich,Ecker,Neufeld,PRL 03′]
  - Theoretical value of $\varepsilon'_K/\varepsilon_K$ is almost real number
  - $|\epsilon_K|,\ \mathrm{Re}A_0,\ \text{and } \mathrm{Re}A_2$ have been measured by experiments very precisely
  - Theorist calculates $\mathrm{Im}A_0,\ \text{and } \mathrm{Im}A_2$ for $\varepsilon'_K/\varepsilon_K$
  - Experiments can precisely probe $\varepsilon'_K/\varepsilon_K$ by the following combination

For experimentalists

$$\mathrm{Re}\left[\frac{\epsilon'_K}{\epsilon_K}\right] \simeq \frac{1}{6}\frac{|\eta_{+-}|^2 - |\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{1}{6}\left(1 - \frac{\frac{\mathrm{Br}(K_L\to\pi^0\pi^0)}{\mathrm{Br}(K_S\to\pi^0\pi^0)}}{\frac{\mathrm{Br}(K_L\to\pi^+\pi^-)}{\mathrm{Br}(K_S\to\pi^+\pi^-)}}\right)$$

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

δ_I: strong phase

pion = isospin triplet

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

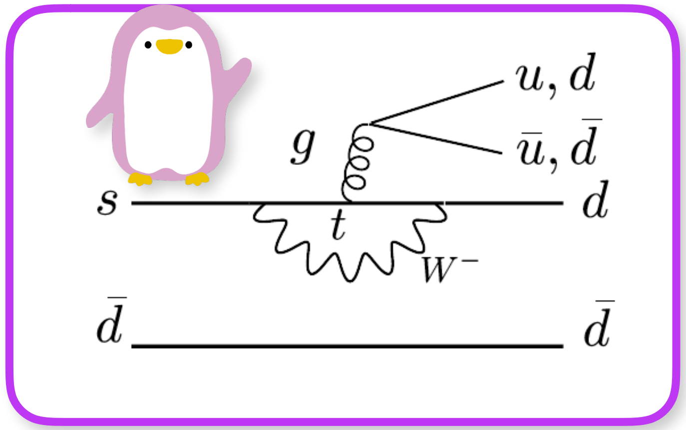
ΔI =1/2 rule: factor = 0.04

Accidental cancellation

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

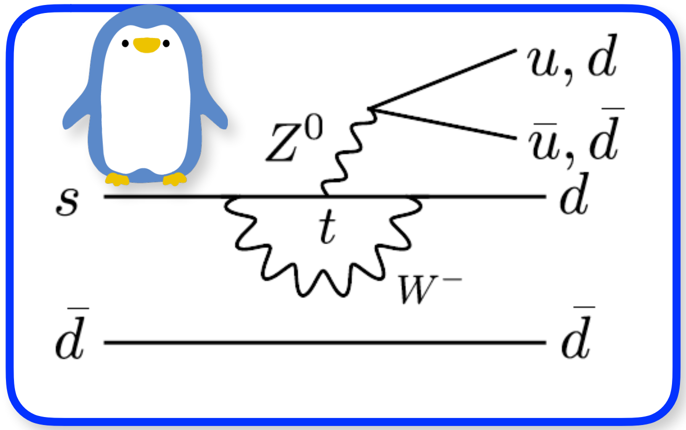
$$\text{where}\quad \frac{1}{\omega} \equiv \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.46\ (\text{exp.})$$

~ Im [QCD penguin]



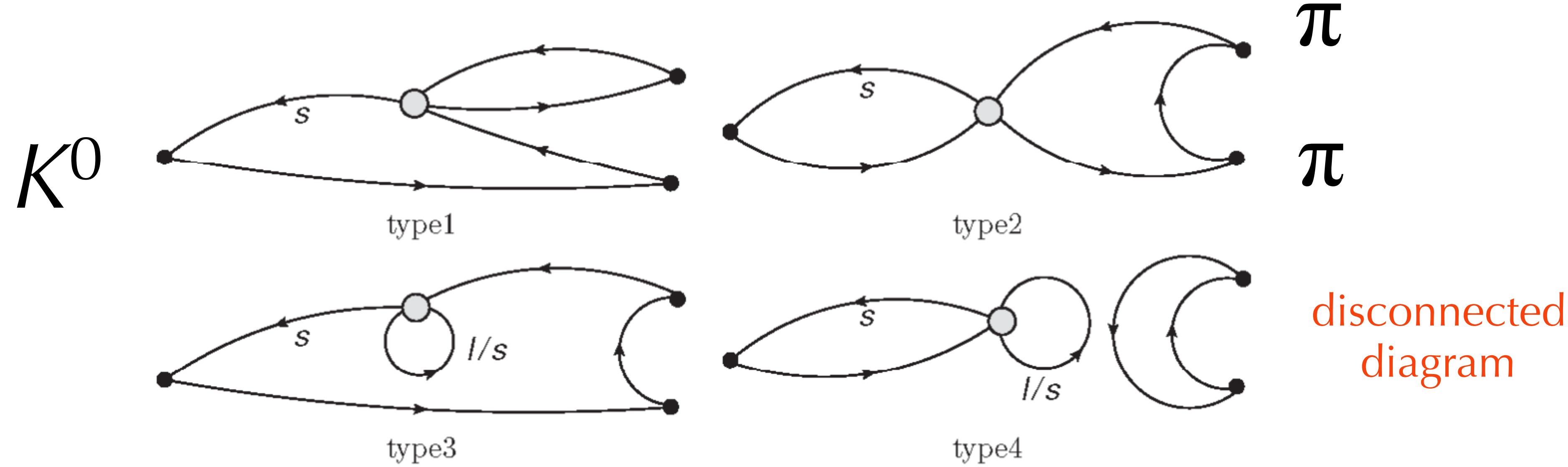
sensitive

~ Im [EW penguin]

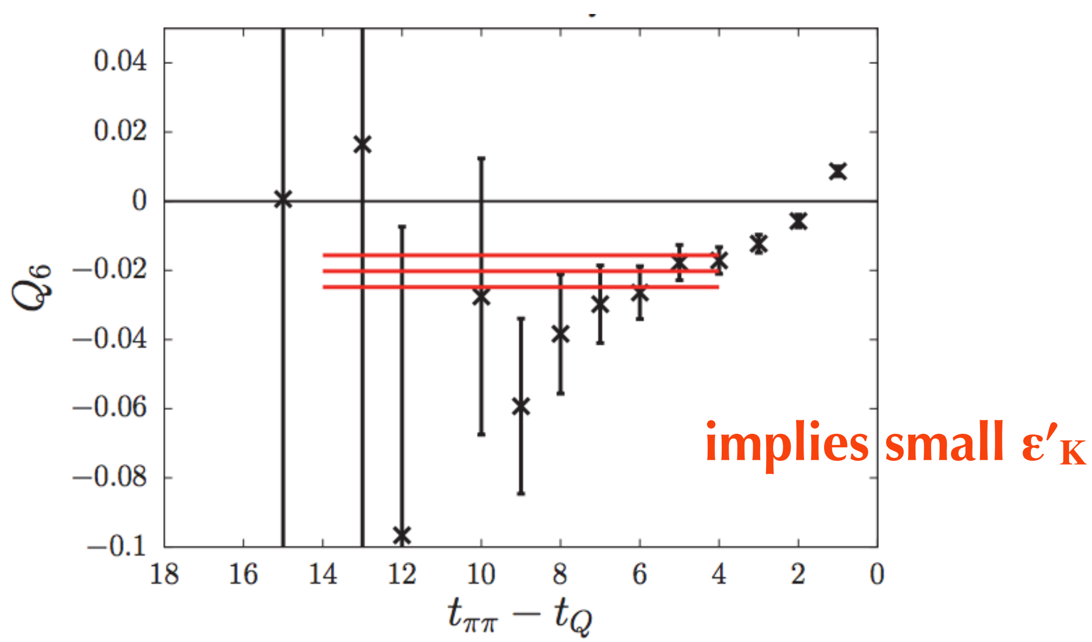


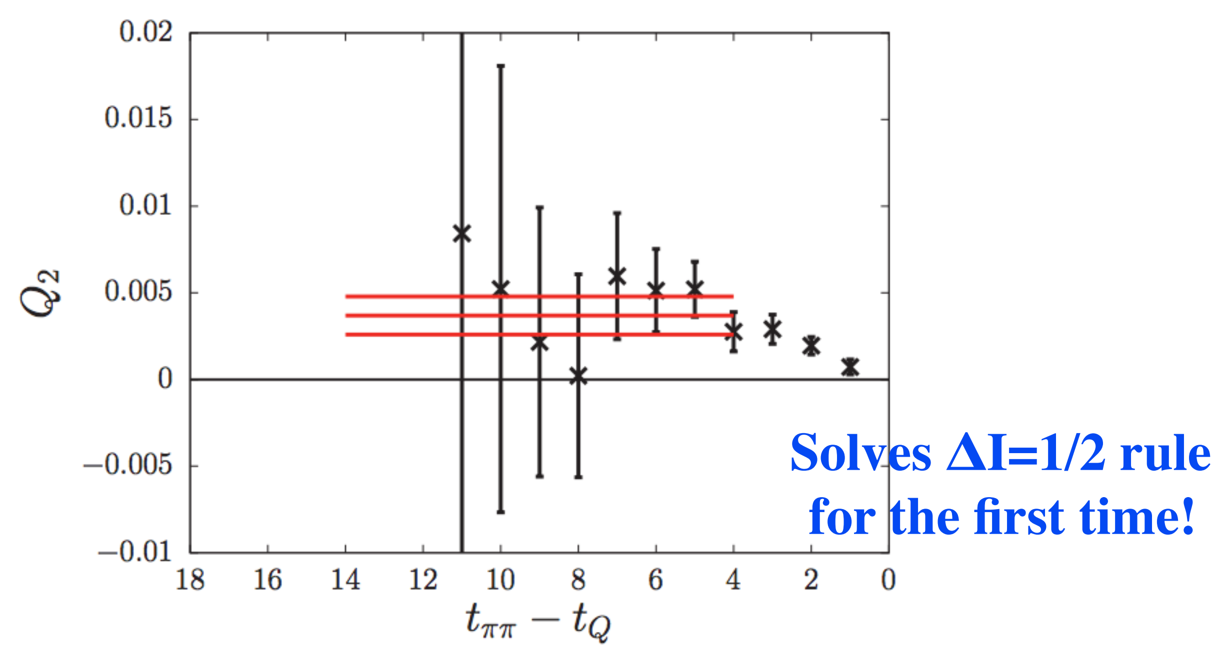
Lattice result

- Serious noise comes from disconnected diagrams in lattice simulation



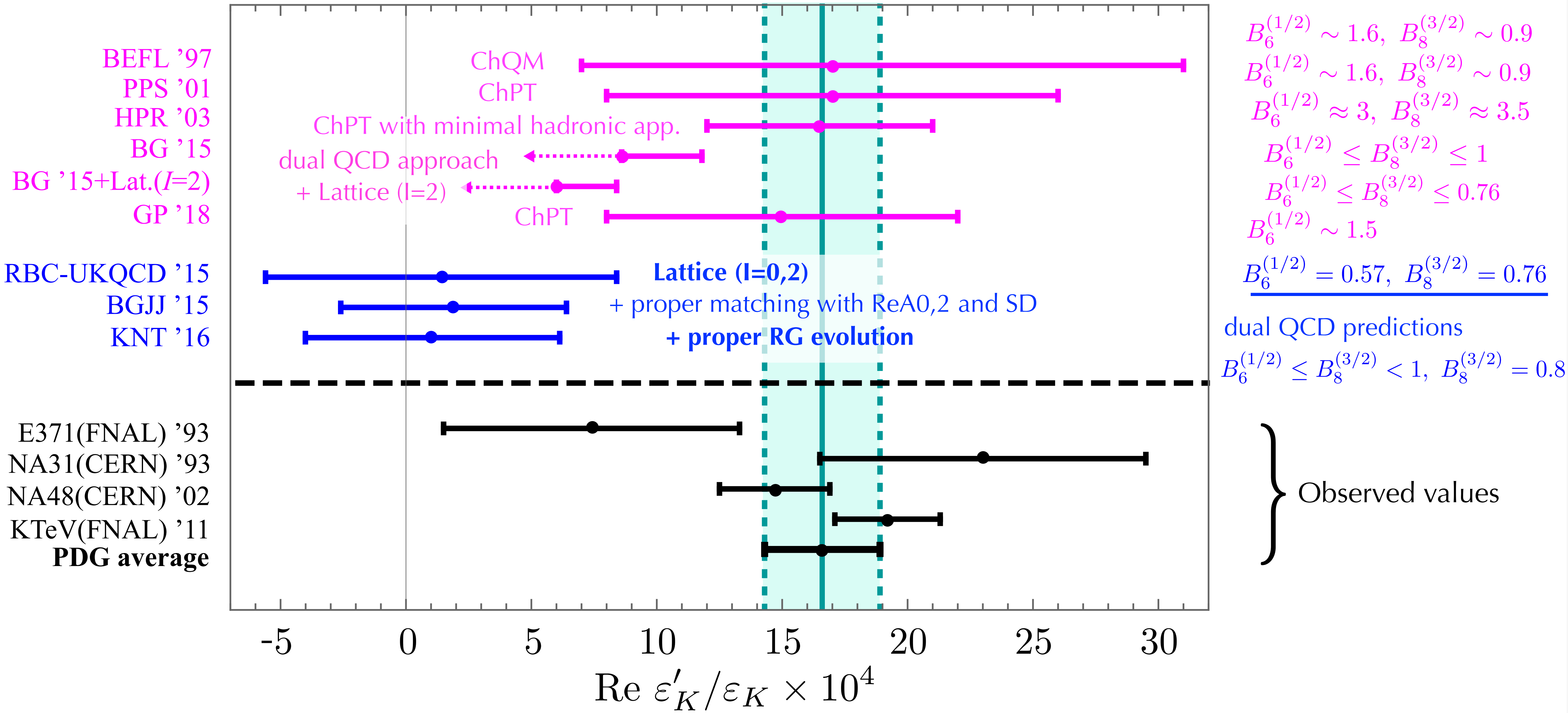
- RBC-UKQCD group achieved calculations of **all SM hadronic matrix elements (HMEs)** at 2015 [RBC-UKQCD, PRD '15, PRL '15]





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, 1611.08276]

- A large-N_c analyses (dual QCD method) including final-state interaction (FSI) are 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 '18]

- 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 2.8σ level**

  [Colangelo, Gasser, Leutwyler '01, Colangelo, Passemar, Stoffer '15]

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

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

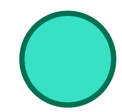
Lattice simulation with improved methods and higher statistics is on-going [1711.05648]

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

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

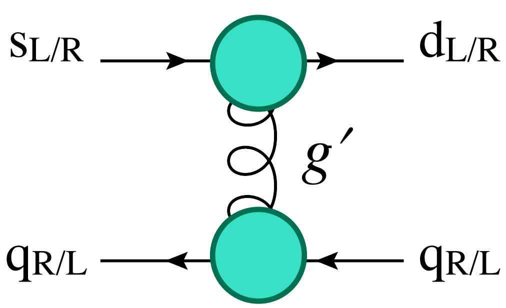
$$\frac{\varepsilon'_K}{\varepsilon_K} = \frac{1}{\sqrt{2}|\epsilon_K|\mathrm{Re}A_0}\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}\left(-\mathrm{Im}A_0 + \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}\mathrm{Im}A_2\right)$$

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


: BSM vertex (must include *CPV* phase)

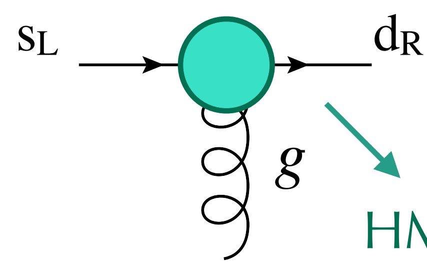
$\mathrm{Im}A_0$

g' scenario



RS model 1404.3824
chiral-flavorful vector 1806.02312

chromomagnetic scenario

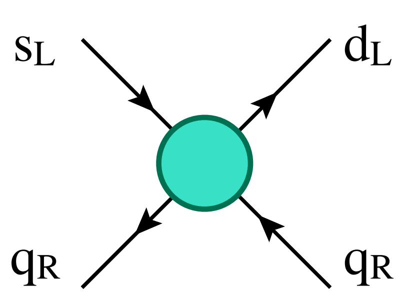


HME would be suppressed [1712.09824, 1803.08052]

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

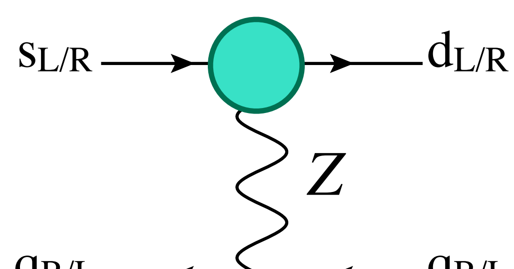
$\mathrm{Im}A_2$

Box scenario



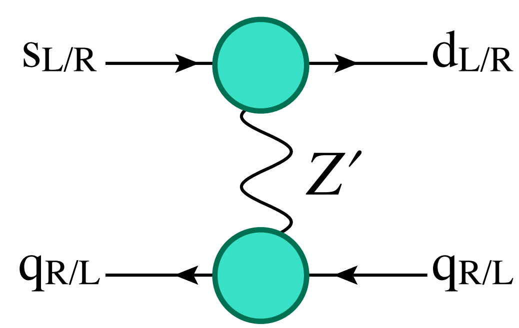
SUSY
1604.07400,...

Z scenario



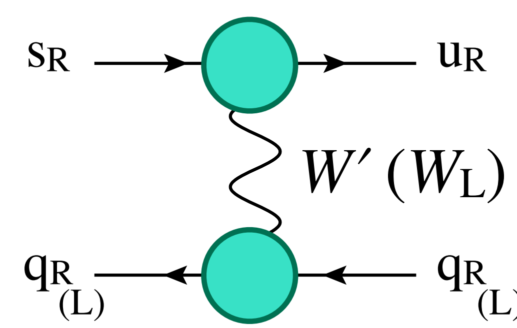
SUSY 1608.01444,...
VLQ 1609.04783,...
LHT 1507.06316

Z' scenario



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

W_R scenario



LR model
1612.03914, 1802.09903

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

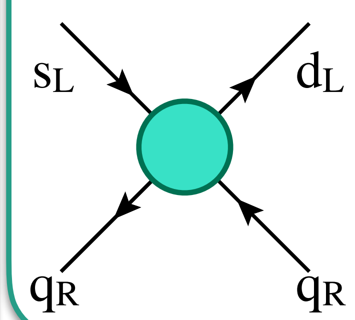
- Recently, HMEs of **general four-quark operators** and **a chromomagnetic operator** contributing to $\varepsilon'_K/\varepsilon_K$ have been calculated by dual QCD approach [Aebischer, Buras, Gérard, 1807.01709]
  - HMEs of SM four-quark operators are consistent with lattice [RBC-UKQCD, PRD '15, PRL '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, DOI: 10.5281/zenodo.1326349]

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

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

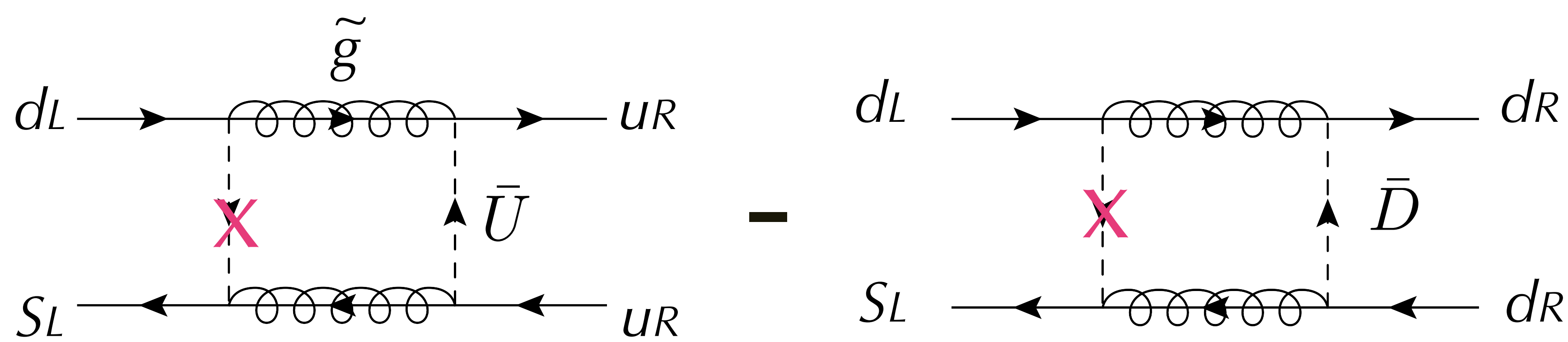
Gluino-box contribution

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

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

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

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

- We take all SUSY masses equal to M_S, except for the gaugino masses (M_3) and the right-handed up-type squark mass ($m_{\bar{U}}$)

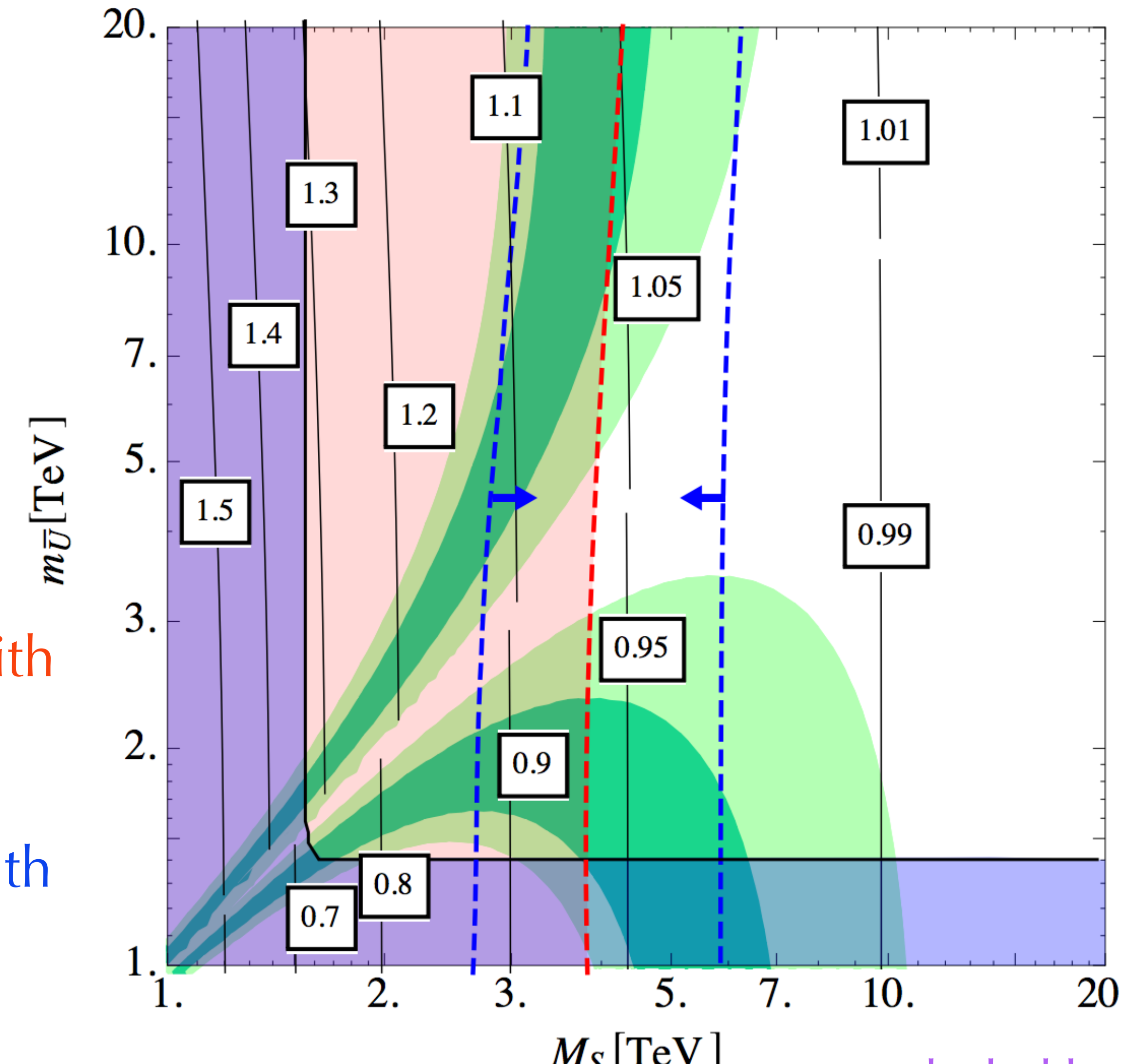
contour of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})/\mathcal{B}^{\rm SM}(K_L \to \pi^0 \nu\bar{\nu})$

$\varepsilon'_K/\varepsilon_K$ 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

$M_3 = 1.5 M_S$

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

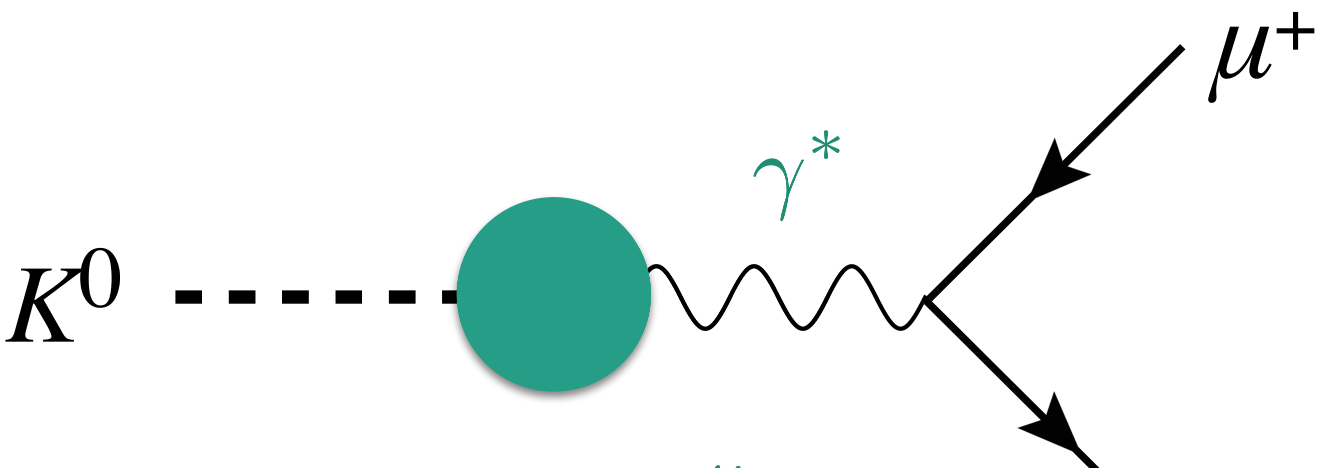
amplifies $\varepsilon'_K/\varepsilon_K$

suppresses ε_K

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

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

- There is no single photon exchange in $P \to l^+l^-$



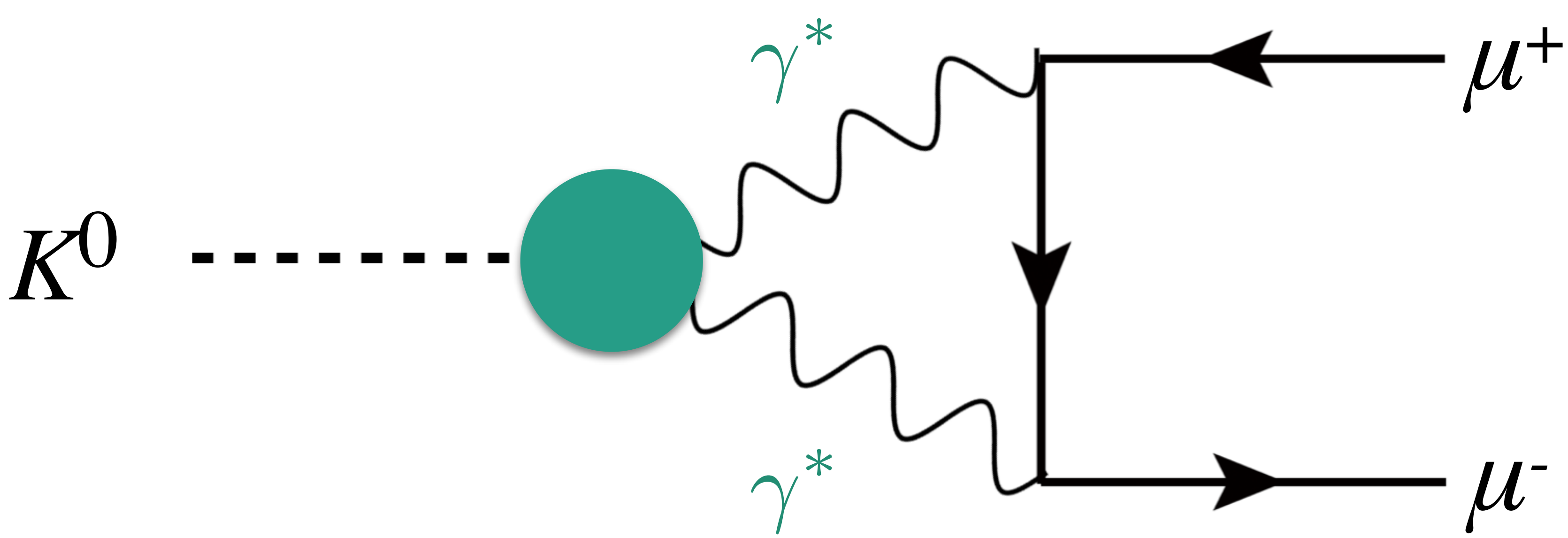
$$\propto p^\mu_{K^0}\left(\bar{\ell}\gamma_\mu \ell\right)$$
$$= (p+q)^\mu \left(\overline{u}(p)\gamma_\mu v(q)\right) = 0$$

Hadronic matrix element $\propto p^\mu_{K^0}$

No contribution from single photon diagrams

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

- There is no single photon exchange in $P \to l^+ l^-$
- Two photons exchange give dominant contributions in $K^0 \to \mu^+\mu^-$



K_L almost CP-odd $\longrightarrow$ $\bar{\ell}\gamma_5\ell$ = CP-odd

$CP|K_L\rangle \sim CP|K_2^0\rangle = -|K_2^0\rangle$ S-wave (L=0, S=0, J=0) $CP|\bar{\ell}\gamma_5\ell\rangle \to -|\bar{\ell}\gamma_5\ell\rangle$

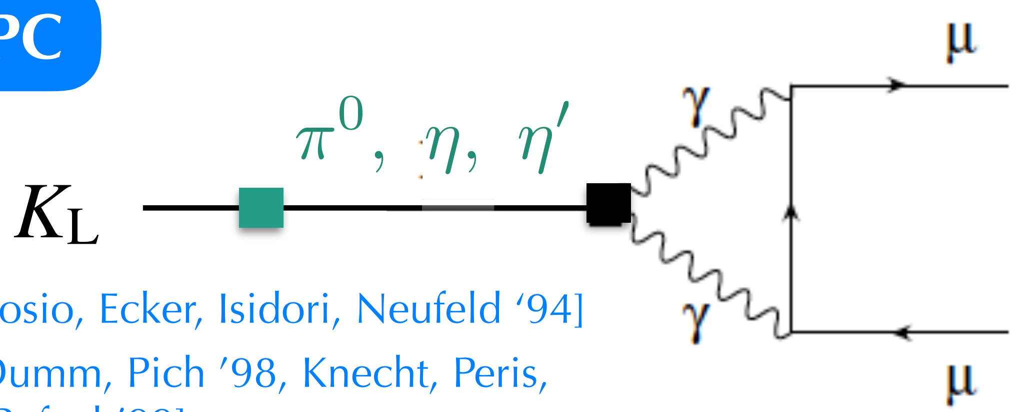
K_S almost CP-even $\longrightarrow$ $\bar{\ell}\ell$ = CP-even

$CP|K_S\rangle \sim CP|K_1^0\rangle = |K_1^0\rangle$ P-wave (L=1, S=1, J=0) $CP|\bar{\ell}\ell\rangle \to |\bar{\ell}\ell\rangle$

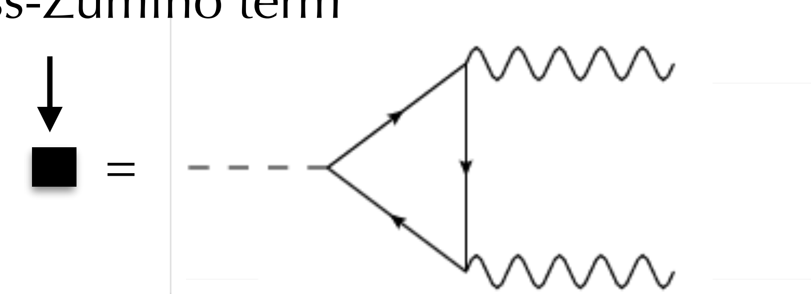
$K_L \to \mu^+\mu^-$

- $K_L \to \mu^+\mu^- = |\text{S-wave}|^2 + |\text{P-wave}|^2$ P-wave is significantly suppressed in the SM

LD CPC



Wess-Zumino term



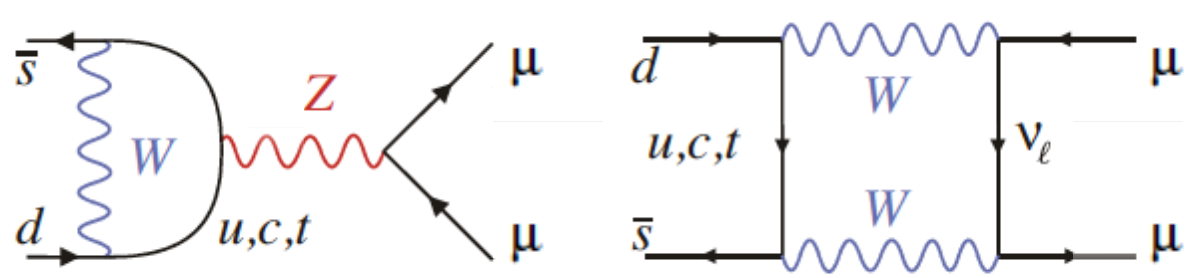
chiral anomaly

[D'Amborosio, Ecker, Isidori, Neufeld '94]
[Gomez Dumm, Pich '98, Knecht, Peris, Perrottet, Rafael '99]

- $[K_L \to \pi \to \gamma\gamma] + [K_L \to \eta \to \gamma\gamma] = 0$ (by Gell-Mann—Okubo formula)
- Higher chiral orders spoil this cancellation.
  exact mass relation in SU(3)F with its breaking $\frac{\left(\frac{K^- + \bar{K}^0}{2}\right)^2 + \left(\frac{K^+ + K^0}{2}\right)^2}{2} = \frac{3\eta^2 + \pi^2}{4}$
- Only abs. of the amplitude can be determined from $B(K_L \to \gamma\gamma)_{exp}$

→ **sign ambiguity of $A(K_L \to \gamma\gamma)$**

SD CPC



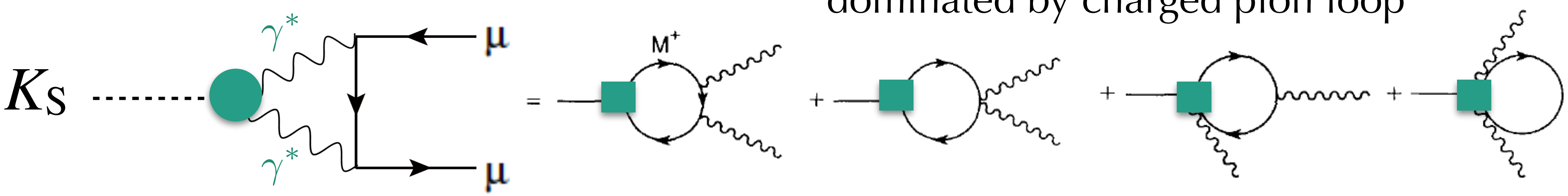
$\propto \mathrm{Re}\left[V_{ts}^* V_{td}\right]$

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

- $K_S \to \mu^+\mu^- =$ |S-wave|^2 + |P-wave|^2 ←no interference if μ polarizations are not measured

LD CPC [Ecker, Pich '91]

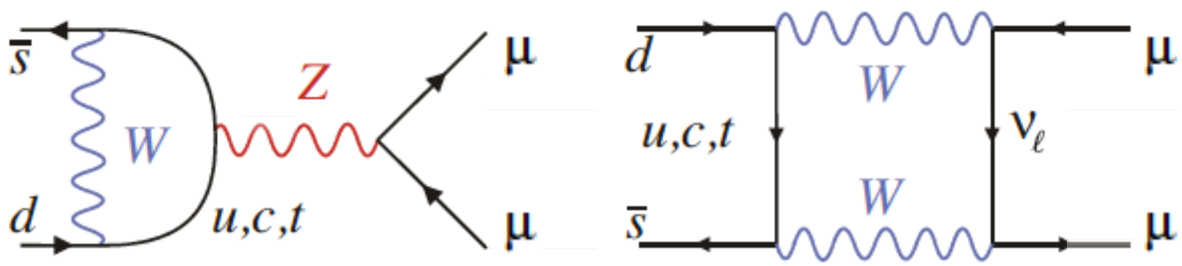
dominated by charged pion loop



- Abs. of the amplitude can be determined from $B(K_S \to \gamma\gamma)_{exp}$, which includes 17% enhancement from a final state interaction (FSI) of pions
- Since two photons are off-shell states, the FSI is debatable and large uncertainty is considered (which will be sharpened by a dispersive treatment of $K_S \to \gamma\gamma$, $K_S \to \gamma\mu\mu$, $K_S \to \mu\mu\mu\mu$ and $K_S \to \mu\mu ee$ measured by KLOE-2, LHCb Upgrade)

[Colangelo, Stucki, Tunstall '16]

SD CPV



$$\propto \mathrm{Im}\,[V_{ts}^* V_{td}]$$

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

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

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

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

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

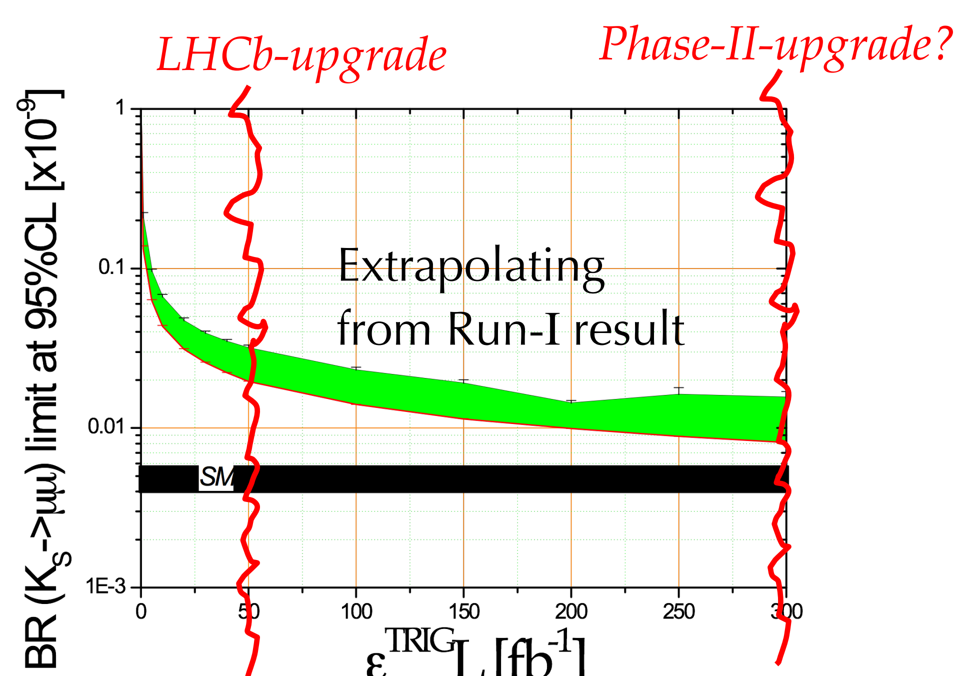
- Both of $K_L \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-$ are dominated **by the *CP*-conserving long-distance contributions (two photon exchanges)**

- 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]

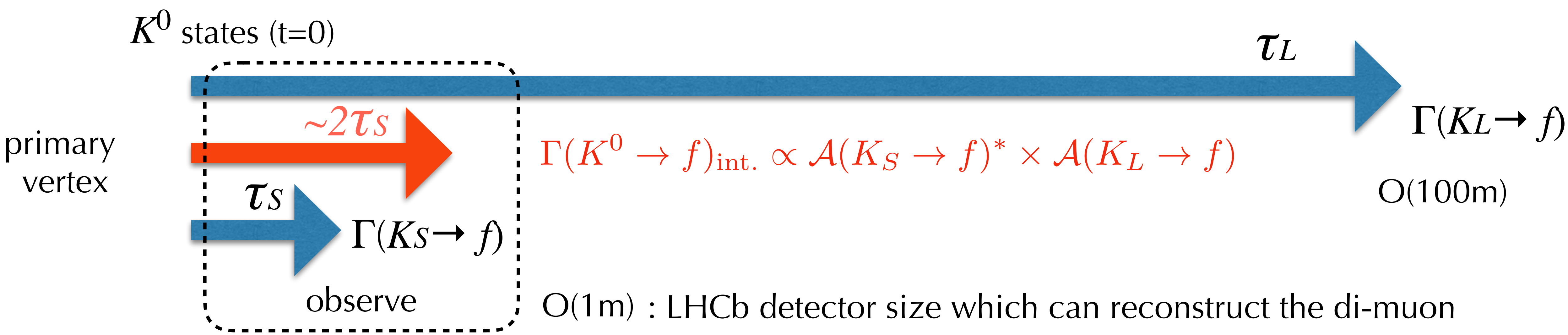
- LHCb Upgrade is aiming to reach the SM sensitivity of $K_S \to \mu\mu$ [D. M. Santos, HQL2018]




Interference

Interference between K_L and K_S

- When the same final states exist in K_L and K_S decays, the interference between K_L and K_S initial states gives a contribution

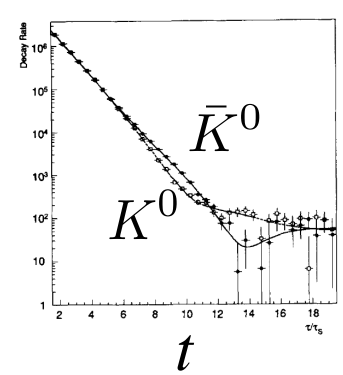


O(1m) : LHCb detector size which can reconstruct the di-muon [boosted K]

- Such an interference is discussed from '67 (Sehgal and Wolfenstein), and has been observed and utilized in many processes: e.g., $K^0 \to \pi\pi$, $K^0 \to 3\pi^0$, $K^0 \to \pi^+\pi^-\pi^0$, and $K^0 \to \pi^0 e^+ e^-$

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_L and K_S
[CPLEAR collaboration '95]

Interference between K_S and K_L

- Neutral kaon state (t=0) evolves into a mixture of K_1(t)(CP-even) ad K_2(t) (CP-odd) states

CP impurity $\bar{\epsilon} \simeq \epsilon_K \simeq \mathcal{O}(10^{-3})$

$$|\overset{(-)}{K^0}(t)\rangle = \frac{1}{\sqrt{2}(1\pm\bar{\epsilon})}\left[e^{-iH_S t}\,(\underbrace{|K_1\rangle + \bar{\epsilon}|K_2\rangle}_{K_S}) \pm e^{-iH_L t}\,(\underbrace{|K_2\rangle + \bar{\epsilon}|K_1\rangle}_{K_L})\right],$$

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

$$\begin{aligned}
I(K\to f)(t) &= \frac{1+D}{2}\left|\langle f| - \mathcal{H}_{\mathrm{eff}}^{|\Delta S|=1}|K^0(t)\rangle\right|^2 + \frac{1-D}{2}\left|\langle f| - \mathcal{H}_{\mathrm{eff}}^{|\Delta S|=1}|\overline{K}^0(t)\rangle\right|^2 \\
&= \frac{1}{2}\Big[\left\{(1-2D\mathrm{Re}[\bar{\epsilon}])\,|\mathcal{A}(K_1)|^2 + 2\mathrm{Re}\left[\bar{\epsilon}\mathcal{A}(K_1)^*\mathcal{A}(K_2)\right]\right\}e^{-\Gamma_S t} \qquad \longleftarrow \quad |\mathcal{A}(K_S\to f)|^2 \\
&\quad + \left\{(1-2D\mathrm{Re}[\bar{\epsilon}])\,|\mathcal{A}(K_2)|^2 + 2\mathrm{Re}\left[\bar{\epsilon}\mathcal{A}(K_1)\mathcal{A}(K_2)^*\right]\right\}e^{-\Gamma_L t} \qquad \longleftarrow \quad |\mathcal{A}(K_L\to f)|^2 \\
&\quad + \Big\{2D\mathrm{Re}\left[e^{-i\Delta M_K t}\left(\mathcal{A}(K_1)^*\mathcal{A}(K_2) + \bar{\epsilon}|\mathcal{A}(K_1)|^2 + \bar{\epsilon}^*|\mathcal{A}(K_2)|^2\right)\right] \\
&\quad -4\mathrm{Re}[\bar{\epsilon}]\mathrm{Re}\left[e^{-i\Delta M_K t}\mathcal{A}(K_1)^*\mathcal{A}(K_2)\right]\Big\}\,e^{-\frac{\Gamma_S+\Gamma_L}{2}t}\Big] \\
&\quad + \mathcal{O}(\bar{\epsilon}^2),
\end{aligned}$$

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

time dependence

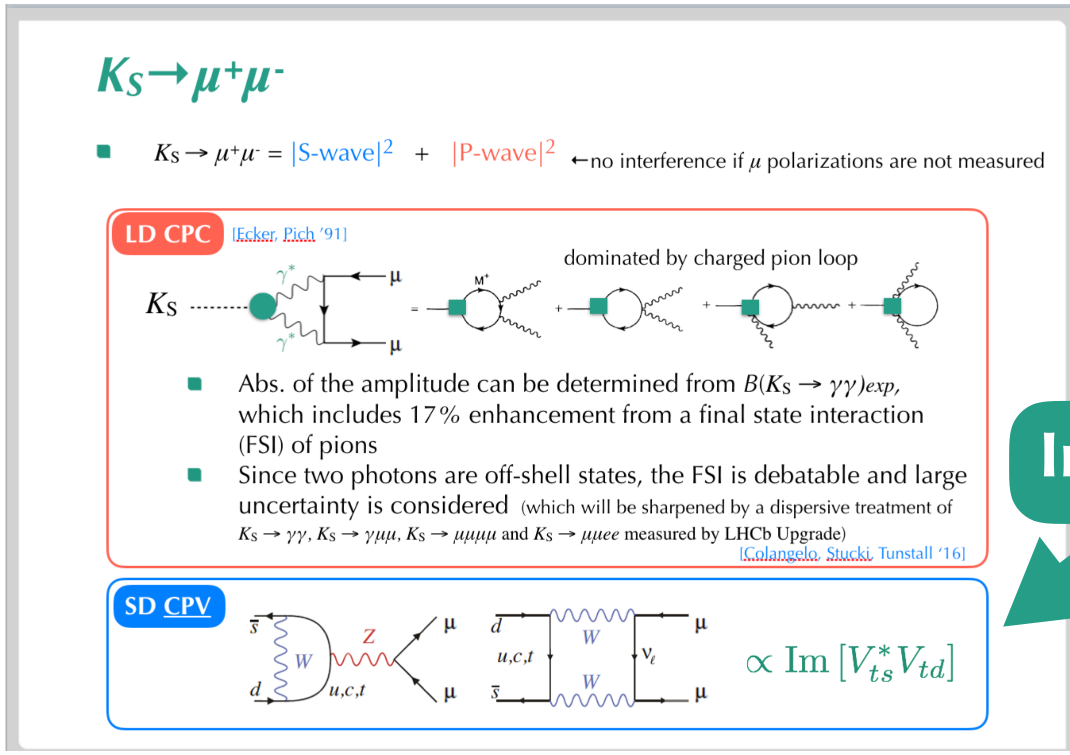
$\tau \sim 2\tau_S$

$\longleftarrow \; |\mathcal{A}(K_L\to K_S\to f)|^2$

- A dilution factor D is a measure of the initial (t=0) asymmetry

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

Interference between K_L and K_S



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

- $K_S \to \mu^+\mu^-$ = |S-wave|^2 + |P-wave|^2 ←no interference if μ polarizations are not measured

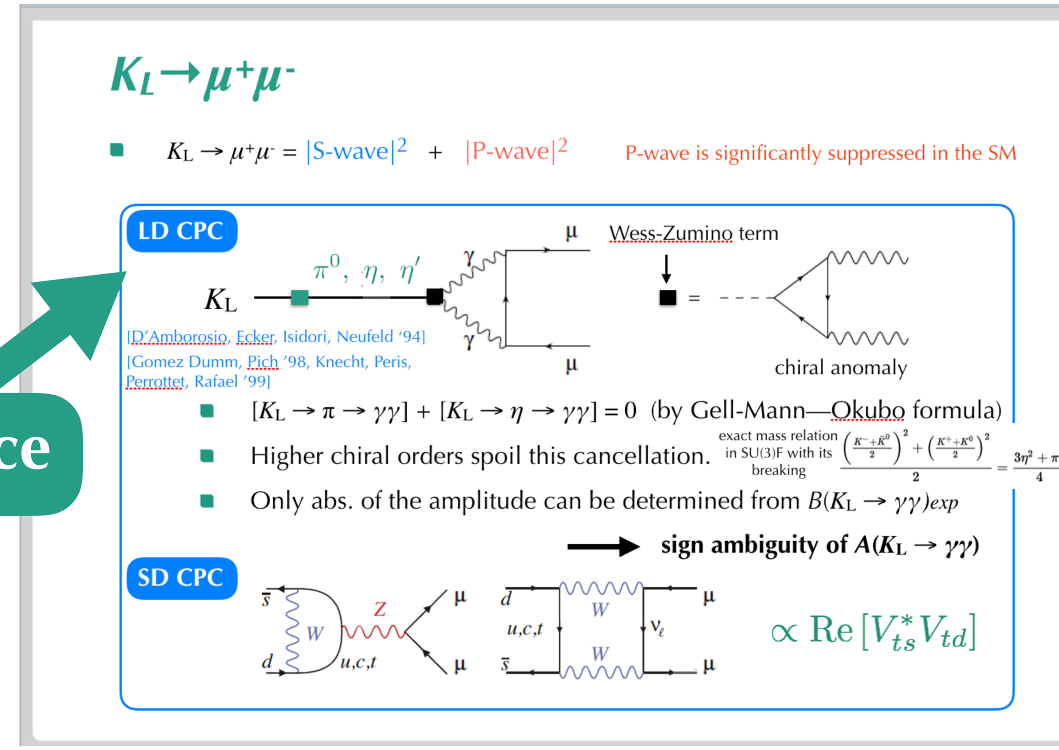
LD CPC [Ecker, Pich '91]

- Abs. of the amplitude can be determined from $B(K_S \to \gamma\gamma)exp$, which includes 17% enhancement from a final state interaction (FSI) of pions
- Since two photons are off-shell states, the FSI is debatable and large uncertainty is considered (which will be sharpened by a dispersive treatment of $K_S \to \gamma\gamma$, $K_S \to \gamma\mu\mu$, $K_S \to \mu\mu\mu\mu$ and $K_S \to \mu\mu ee$ measured by LHCb Upgrade) [Colangelo, Stucki, Tunstall '16]

SD CPV

$\propto \mathrm{Im}\,[V_{ts}^* V_{td}]$

Interference



$K_L \to \mu^+\mu^-$

- $K_L \to \mu^+\mu^-$ = |S-wave|^2 + |P-wave|^2 P-wave is significantly suppressed in the SM

LD CPC

[D'Amborosio, Ecker, Isidori, Neufeld '94] [Gomez Dumm, Pich '98, Knecht, Peris, Perrottet, Rafael '99]

- $[K_L \to \pi \to \gamma\gamma] + [K_L \to \eta \to \gamma\gamma] = 0$ (by Gell-Mann—Okubo formula)
- Higher chiral orders spoil this cancellation. exact mass relation in SU(3)F with its breaking $\frac{\left(\frac{K^- + \bar{K}^0}{2}\right)^2 + \left(\frac{K^+ + K^0}{2}\right)^2}{2} = \frac{3\eta^2 + \pi^2}{4}$
- Only abs. of the amplitude can be determined from $B(K_L \to \gamma\gamma)exp$

→ **sign ambiguity of $A(K_L \to \gamma\gamma)$**

SD CPC

$\propto \mathrm{Re}\,[V_{ts}^* V_{td}]$

- Dominant interference term [TK, D'Ambrosio, PRL '17]

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

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

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

- 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 $\bar{\epsilon}$

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

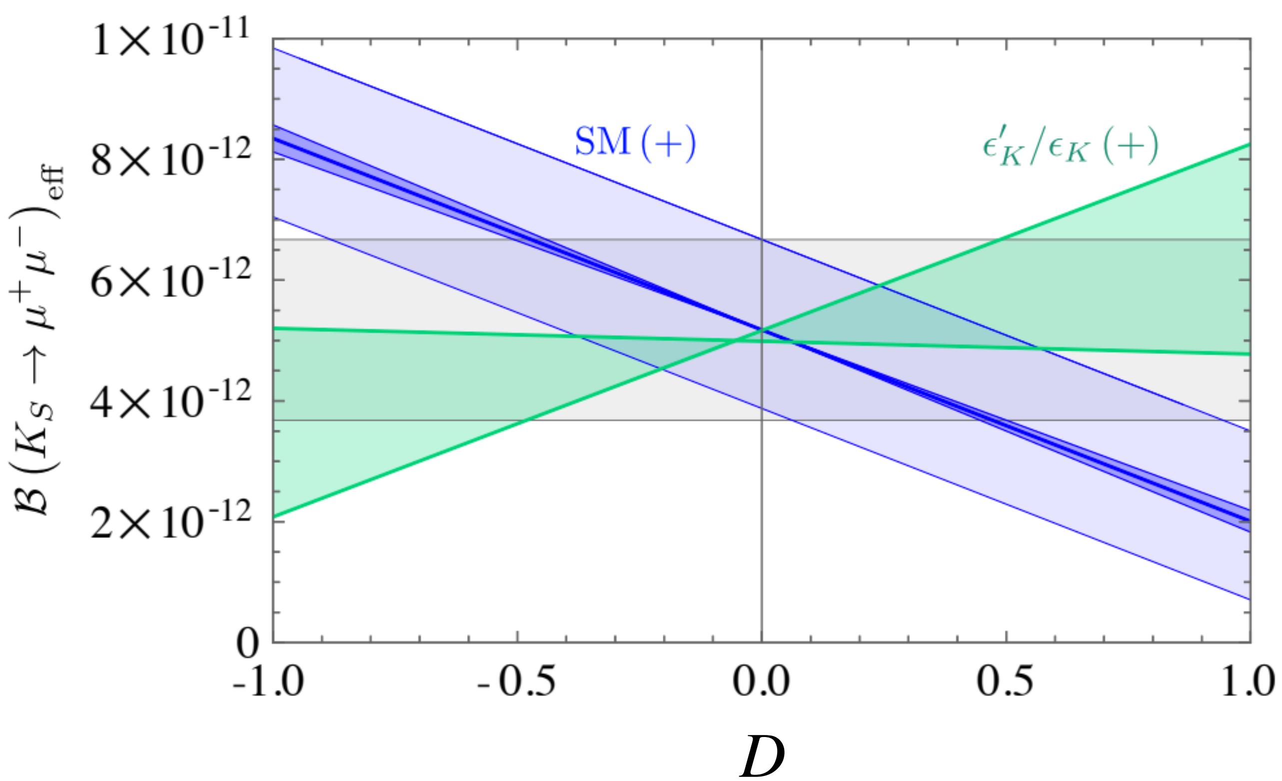
Direct *CP* asymmetry in $K_S \to \mu\mu$

[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

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

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



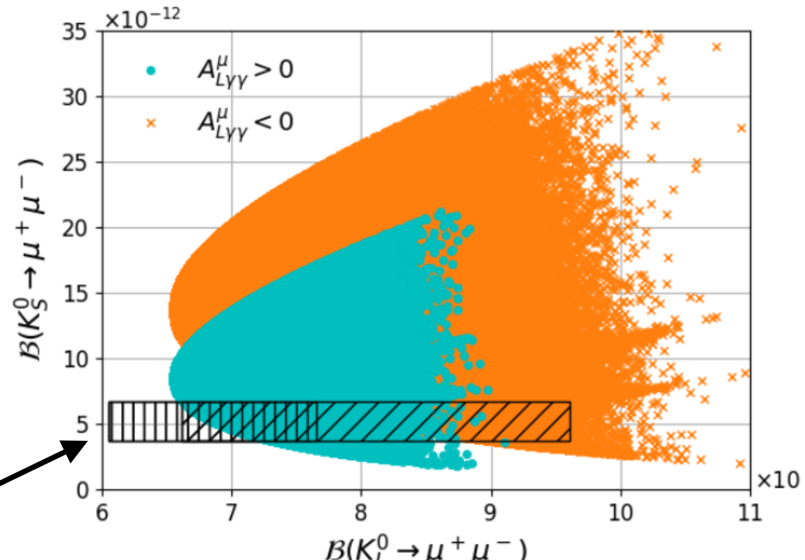
gray: $K_S \to \mu\mu$ (CPC) in the SM
Blue: $K_S \to \mu\mu$ with the interference in the SM
Green: Z scenario (LH) with ε'_K anomaly

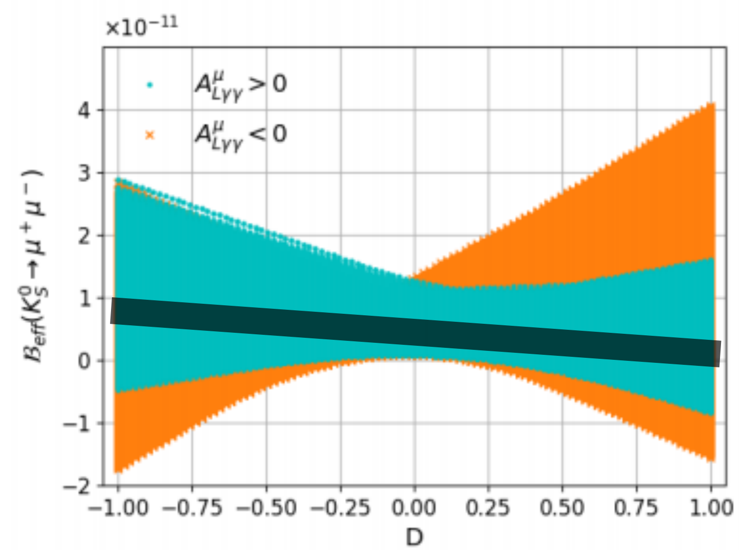
SUSY contributions to $K^0 \to \mu^+\mu^-$

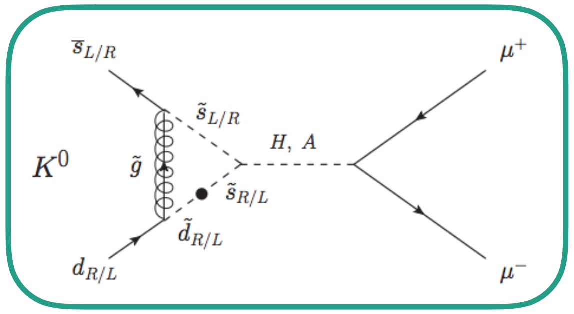
One of the MSSM scenario from Chobanova, D'Ambrosio, TK, Martinez, Santos, Fernandez, Yamamoto '18

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

No inter-ference plot (D=0)





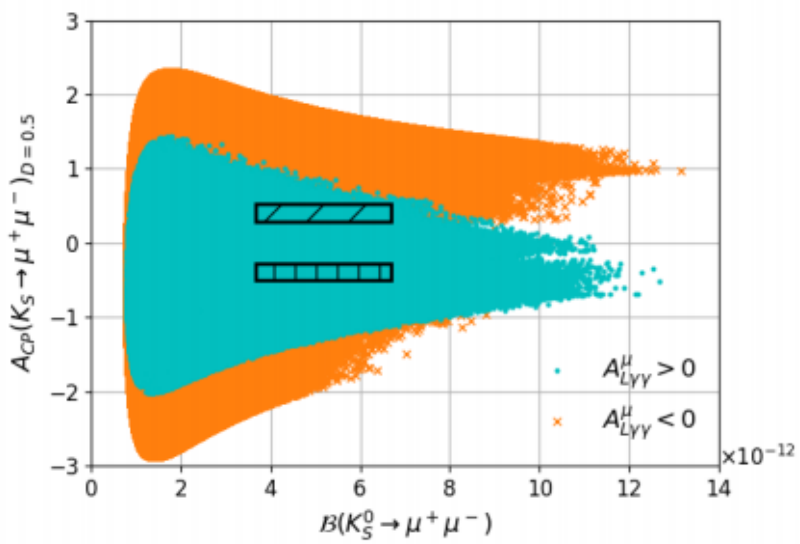


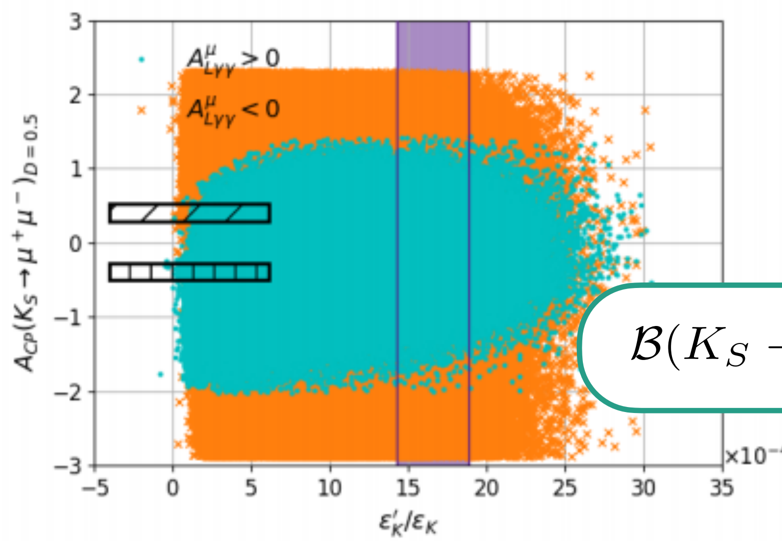
SM prediction [$\mathrm{sgn}(A^\mu_{L\gamma\gamma}) > 0$]

SM prediction

measured $\varepsilon'_K/\varepsilon_K$

D=0.5





Large deviations from SM predictions are possible in the MSSM

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

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

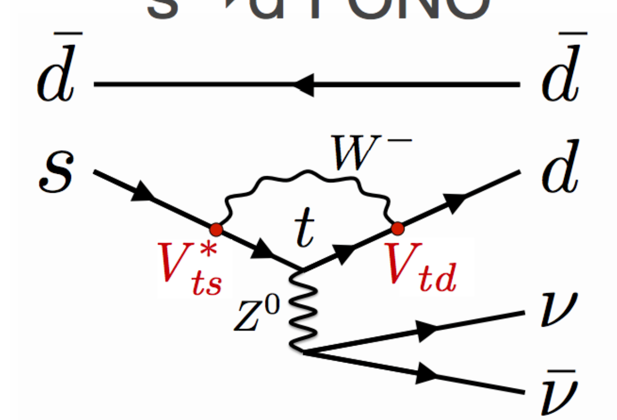
$$K \rightarrow \pi \nu \bar{\nu}$$

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

- Both channels are theoretical clean and very sensitive to short-distance contributions (there is no LD contribution), **especially $K_L \to \pi^0 \nu\nu$ is purely *CPV* decay**

s→d FCNC

almost *CP* odd K_L



π^0 $J^{PC} = 0^{-+} \to CP$=odd

→ *CP* even

vector current →*CP*=odd

- 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:

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

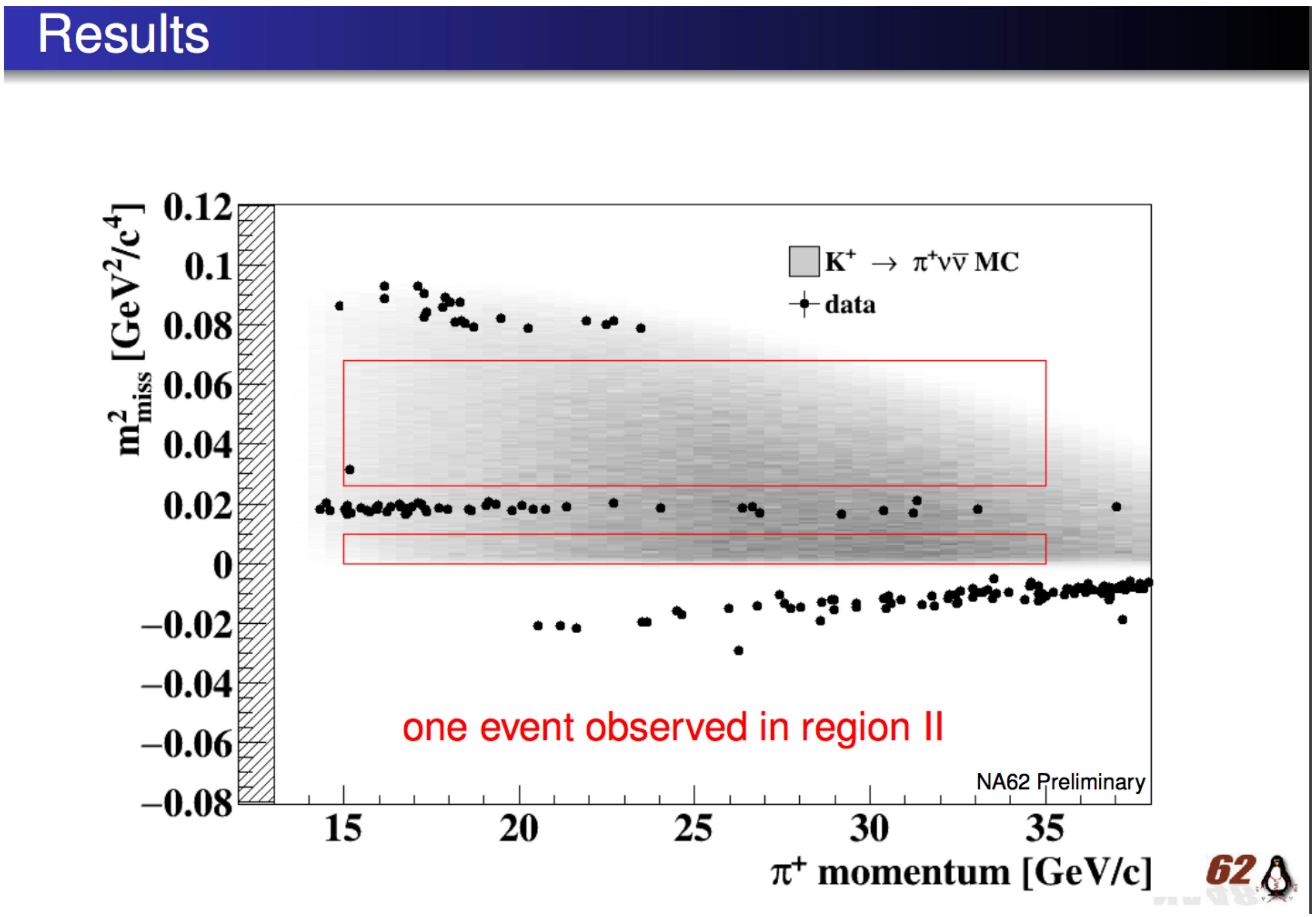
On-going experiments

NA62 @CERN

$$\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10} \ (68\% \ \mathrm{CL})$$

- ~20 SM events are expected before LS2

[NA62, 2016data, FPCP2018]

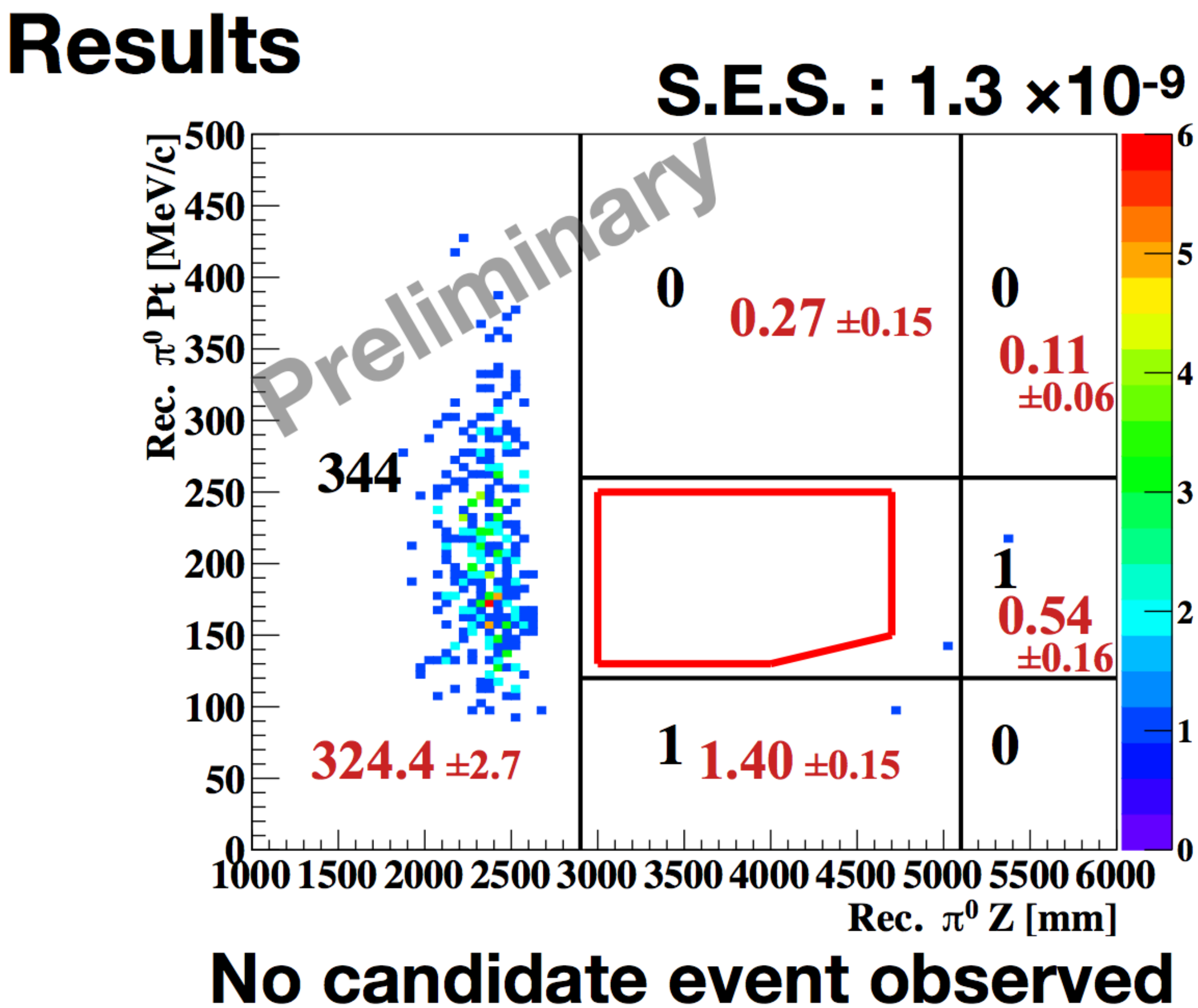


On-going experiments

KOTO @J-PARC

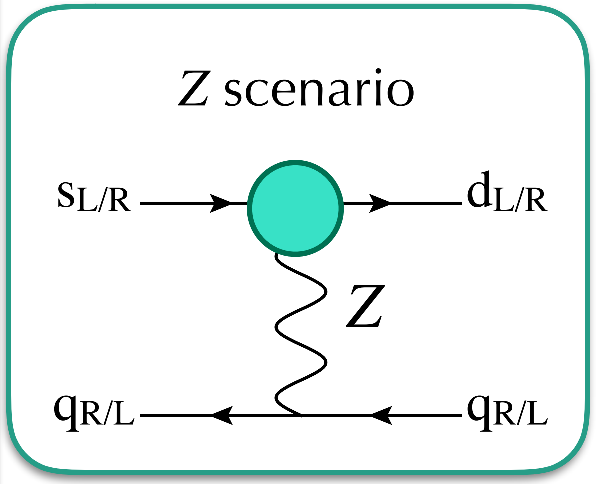
$$\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9} \ (90\% \ \mathrm{CL})$$

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



[KOTO, 2015data, FPCP2018]

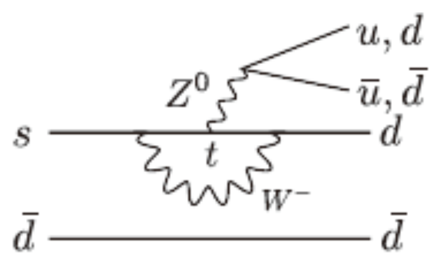
Modified Z-coupling scenario

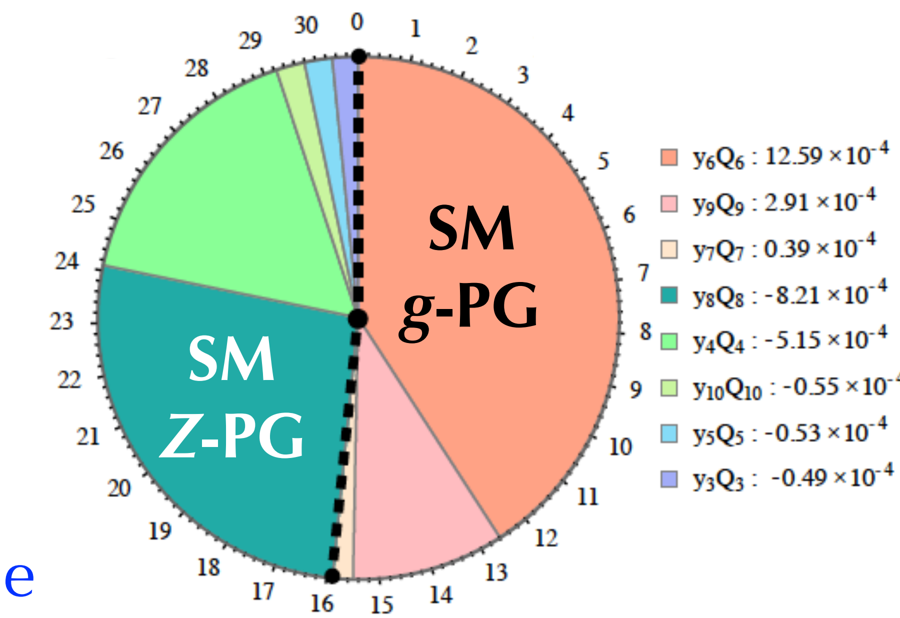


[Buras, De Fazio, Girrbach, '13, '14] [Buras, Buttazzo, Knegjens, '15][Buras, '16]
[Endo, TK, Mishima, Yamamoto, '16] [Bobeth, Buras, Celis, Jung,'17]

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

Negative contribution

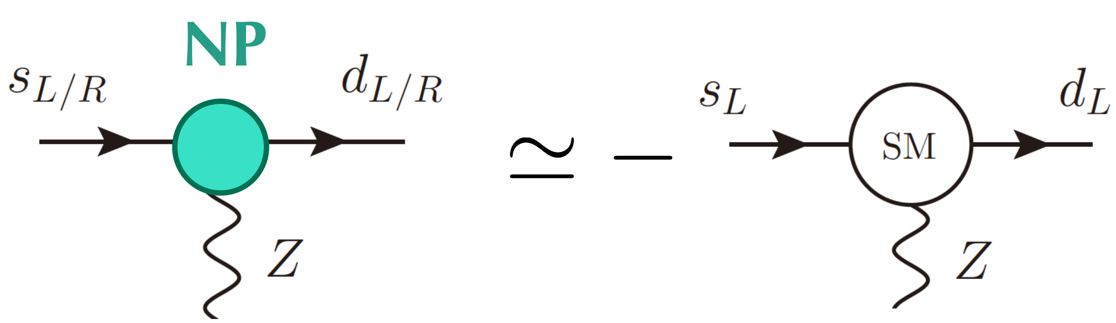




Positive contribution

SM Z-penguin gives the biggest negative contribution

$\Leftrightarrow$ $\varepsilon'_K/\varepsilon_K$



$\varepsilon'_K/\varepsilon_K$ anomaly 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, **SMEFT** should be introduced

[Endo, TK, Mishima, Yamamoto, '16] [Bobeth, Buras, Celis, Jung,'17]
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

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

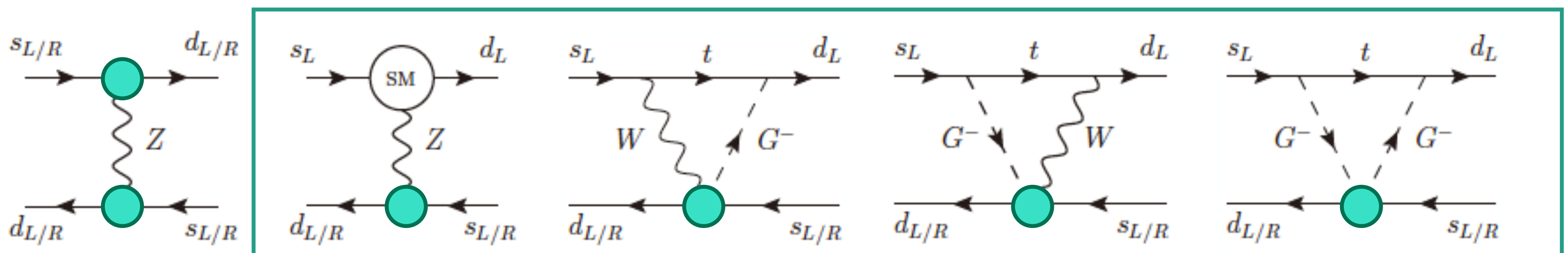
$$= \mathcal{L}_{\rm SM} - \frac{\sqrt{2} v M_Z}{\Lambda^2} (c_L \overline{s} \gamma^\mu Z_\mu P_L d + c_R \overline{s} \gamma^\mu Z_\mu P_R d) + \ldots$$

→ 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 $\xrightarrow{\text{top-Yukawa RG}}$ $(\overline{s}_L \gamma_\mu d_L)(\overline{s}_R \gamma^\mu d_R)$ @low scale

$\Delta S = 1$ $\xleftarrow[\text{constraint}]{}$ $\Delta S = 2$



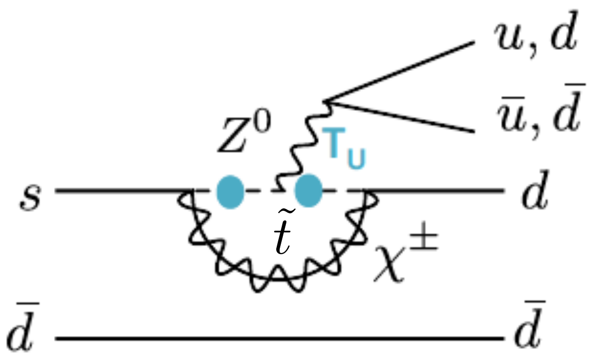
Interference (NP and SM) terms

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

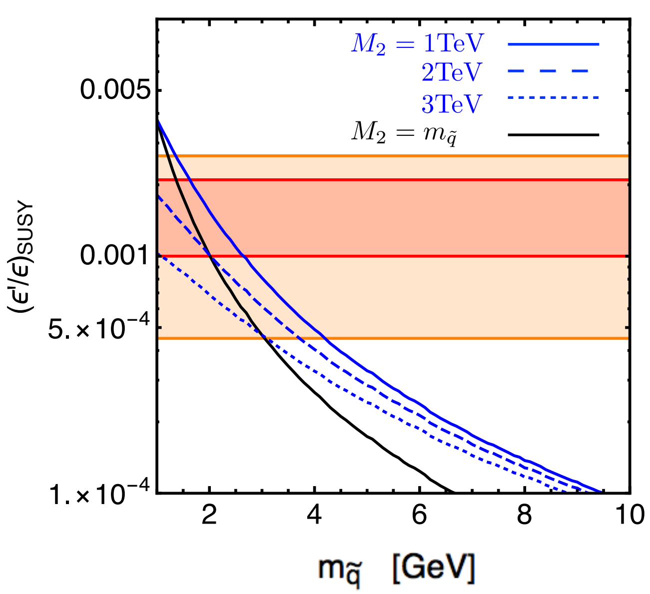
[Endo, Mishima, Ueda, Yamamoto, '16]

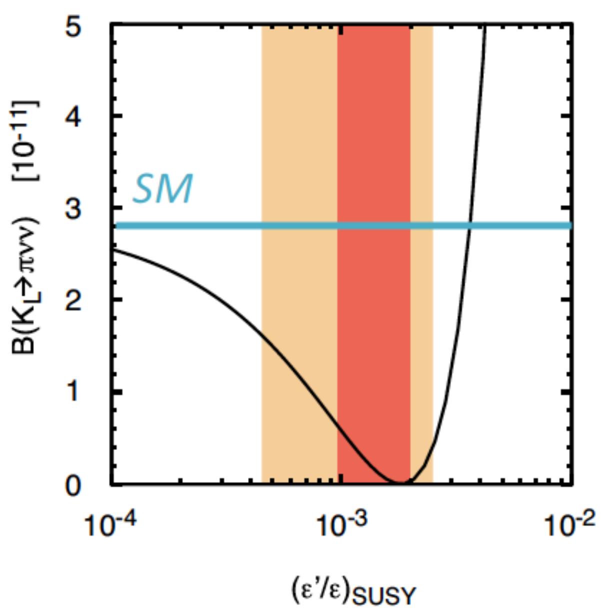


Z model (LH)

Upper bounds under the constraints:

Vacuum, ε_K, ΔM_K, $K_L \to \mu\mu$

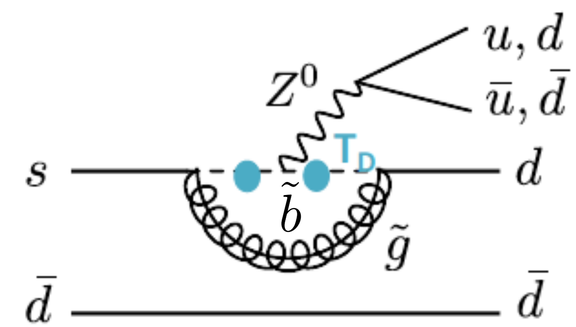




gluino Z-penguin in the MSSM

[Tanimoto, Yamamoto, '16]

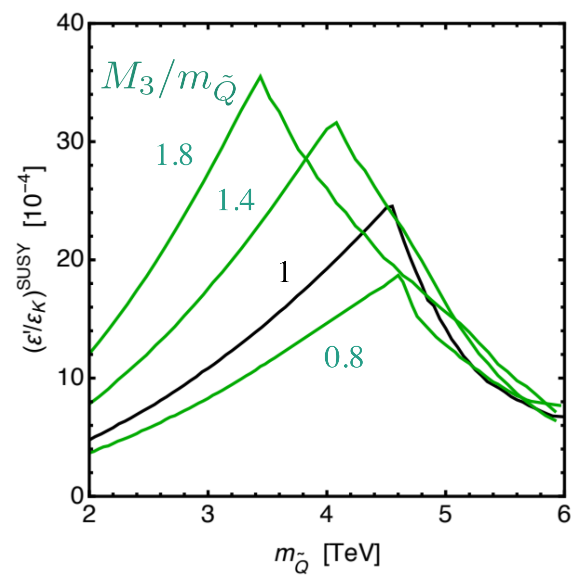
[Endo, Goto, TK, Mishima, Ueda, Yamamoto, '18]

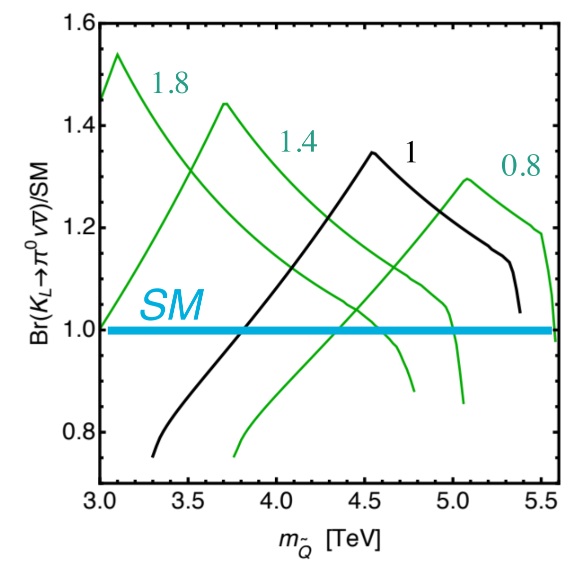


Z model (RH + LH)

Upper bounds under the constraints:

Vacuum, **ε_K**, ΔM_K, $K_L \to \mu\mu$, **$b \to s(d)\gamma$**





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

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**)

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

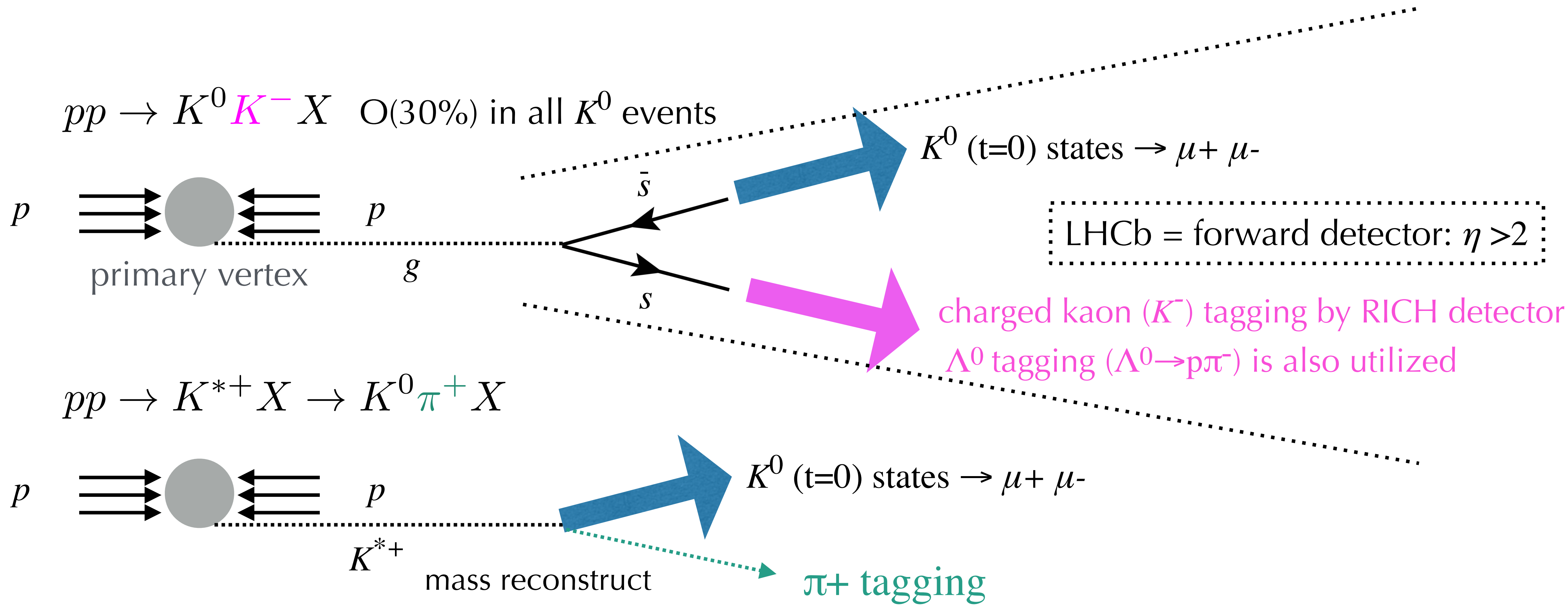

Trojan Penguin
BACKUP

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

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 theory

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]