New physics implication from Kaon physics

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Why Kaon? & What’s new?

- Kaon observables are sensitive to NP at a very high scale, which is not accessible at the LHC

- FCNC and CP violation in Kaon system are suppressed in the SM

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

If \( |C_{NP}| \sim 1 \)

\[ \Lambda_{NP} \sim \begin{cases} \mathcal{O}(10^5 \text{TeV}) & : K^0 \\ \mathcal{O}(10^4 \text{TeV}) & : D^0 \\ \mathcal{O}(10^3 \text{TeV}) & : B_{d,s} \end{cases} \]

- Several on-going experiments for Kaon observables (KOTO/NA62...)

🌟 Using recent result of lattice calculation, there is discrepancy in \( \varepsilon'/\varepsilon \) between SM value and data
$\varepsilon$ and $\varepsilon'$

1964 $K_L \rightarrow 2\pi$ was observed

*Discovery of CP violation*

\[ |K_L\rangle = |K_2\rangle + \varepsilon |K_1\rangle \]

**Direct CPV (decay)** $\varepsilon'$

\[ \eta_{00} = \frac{A(K_L \rightarrow \pi^0\pi^0)}{A(K_S \rightarrow \pi^0\pi^0)} \equiv \varepsilon - 2\varepsilon' \]

**Indirect CPV (mixing)** $\varepsilon$

\[ \frac{\eta_{00}}{\eta_{+-}} \simeq 1 - 6\text{Re} \left( \frac{\varepsilon'}{\varepsilon} \right) \]

**Direct CPV (decay)** $\varepsilon'$

\[ \eta_{+-} = \frac{A(K_L \rightarrow \pi^+\pi^-)}{A(K_S \rightarrow \pi^+\pi^-)} \equiv \varepsilon + \varepsilon' \]

\[ \varepsilon = \mathcal{O}(10^{-3}) \quad \text{Re} \left( \frac{\varepsilon'}{\varepsilon} \right) = \mathcal{O}(10^{-3}) \quad \varepsilon' = \mathcal{O}(10^{-6}) \]

*Highly suppressed and sensitive to NP*
\( \varepsilon'/\varepsilon \)

\[
\frac{\varepsilon'}{\varepsilon} = -\frac{\omega}{\sqrt{2}} |\varepsilon|_{\text{exp}} \text{Re} A_0
\]

\[
A(K^0 \rightarrow (\pi\pi)_{I=0,2}) = A_{0,2}e^{i\delta_{0,2}}
\]

\[
\left( \frac{\text{Im} A_0}{\text{Im} A_2} - \frac{1}{\omega} \right)
\]

QCD penguin operator

EW penguin operator

\[
\frac{\text{Re} A_0}{\text{Re} A_2} \equiv \frac{1}{\omega} = 22.46 \quad (\text{exp.})
\]

In the SM, there is accidental cancellation between \( \text{Im} A_0 \) and \( \text{Im} A_2 \) due to the enhancement factor \( 1/\omega \)

EW penguin is comparable to QCD penguin due to the enhancement factor

\( 4/19 \)
\[\langle (\pi\pi)_I | \mathcal{H} | K^0 \rangle = \sum_n C_n \langle (\pi\pi)_I | \mathcal{O}_n | K^0 \rangle\]

**Short distance**
- NLO result has been available since early 90’s
- NNLO QCD calculation is in progress

**Long distance (Matrix elements)**
- First lattice result by RBC-UKQCD in 2015

From the lattice result, \(\varepsilon'/\varepsilon\) has been calculated in SM using data for ReA_{0,2}.

\[
\begin{align*}
\left(\frac{\varepsilon'}{\varepsilon}\right)_{\text{SM}} &= (1.06 \pm 5.07) \times 10^{-4} \\
\left(\frac{\varepsilon'}{\varepsilon}\right)_{\text{Exp}} &= (16.6 \pm 2.3) \times 10^{-4}
\end{align*}
\]

Kitahara, Nierste and Tremper, 1607.06727
C.f. RBC-UKQCD / Buras, Gorbahn, Jager and Jamin 1507.06345

average of NA48 and KTeV

**2.8σ difference**  NP in \(\varepsilon'/\varepsilon\)?
**ε'/ε discrepancy**

- O₆ & O₈ have dominant effects on ε'/ε due to chiral enhancement

\[
\begin{align*}
\langle (\pi\pi)_0 | \mathcal{O}_6 | K \rangle & \propto B_6^{(1/2)} \\
\langle (\pi\pi)_2 | \mathcal{O}_8 | K \rangle & \propto B_8^{(3/2)}
\end{align*}
\]

- Values extracted from the lattice result

\[ B_6^{(1/2)} = 0.57 \pm 0.19 \quad B_8^{(3/2)} = 0.76 \pm 0.05 \]

- Error for ε'/ε is dominated by \( B_6^{(1/2)} \)

- Two ways of analytic approaches

|-----------------------------------|-----------------------------|-----------|---------------------------------------------|
| \( B_6^{(1/2)} \leq B_8^{(3/2)} < 1 \) | \( \left( \frac{\epsilon'}{\epsilon} \right)_{\text{SM}} < (6.0 \pm 2.4) \times 10^{-4} \) | \( B_6^{(1/2)} \sim 1.5 \) \( B_8^{(3/2)} \sim 0.9 \) | \( \left( \frac{\epsilon'}{\epsilon} \right)_{\text{SM}} = (15 \pm 7) \times 10^{-4} \)

Result in DQCD approach gives support to lattice result. On the other hand, result in ChPT is consistent with data.

- Wait for improved lattice results
\( \varepsilon' / \varepsilon \) at Lattice study

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Exp. data</th>
<th>Lattice QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReA_0 [10^{-7} \text{ GeV}]</td>
<td>3.322 \pm 0.001 [1]</td>
<td>4.66 \pm 1.00 \pm 1.26 [2]</td>
</tr>
<tr>
<td>ImA_0 [10^{-11} \text{ GeV}]</td>
<td>---</td>
<td>-1.90 \pm 1.23 \pm 1.08 [2]</td>
</tr>
<tr>
<td>ReA_2 [10^{-8} \text{ GeV}]</td>
<td>1.479 \pm 0.003 [1]</td>
<td>1.50 \pm 0.04 \pm 0.14 [3]</td>
</tr>
<tr>
<td>ImA_2 [10^{-13} \text{ GeV}]</td>
<td>---</td>
<td>-6.99 \pm 0.20 \pm 0.84 [3]</td>
</tr>
</tbody>
</table>

- ReA_0, ReA_2 are consistent with exp. Data \( \rightarrow \Delta l = 1/2 \) rule is confirmed

- Calculated \( l=0 \) \( \pi \pi \) scattering phase shift of was smaller than measured value

\[
\delta_0 = 23.8(4.9)(1.2)^\circ \quad 2015 \quad (\delta_0)_{\text{exp}} = 38.3(1.3)^\circ
\]

\( \rightarrow \) New preliminary result \( \text{RBC-UKQCD preliminary, 2018} \)

\[
\delta_0 = 30.9(1.5)(3.0)^\circ \quad \text{“Puzzle is resolved“}
\]

- Lattice update with higher statistics will appear soon
Motivated by $\varepsilon'/\varepsilon$ discrepancy, several new physics models have been studied:

- **Little Higgs Model with T-parity**
  - Blanke, Buras and Recksiegel 1507.06316
- **Modified Z scenario**
  - Buras, Buttazzo and Knegjens 1507.08672/Buras, 1601.00005
  - Endo, Kitahara, Mishima and KY 1612.08839/Bobeth, Buras, Celis and Jung 1703.04753
- **Z’ models**
  - Buras, Buttazzo, Knegjens 1507.08672 /Buras 1601.00005
  - Endo, Kitahara, Mishima and KY 1608.01444
- **331 model**
  - Buras and De Fazio 1512.02869/1604.02344
- **MSSM Chargino Z penguin**
  - Endo, Mishima, Ueda and KY 1603.07960
  - Endo, Goto, Kitahara, Mishima, Ueda and KY 1712.04959
- **Gluino Z penguin**
  - Tanimoto and KY 1603.07960
  - Endo, Goto, Kitahara, Mishima, Ueda and KY 1712.04959
- **Gluino Box**
  - Kitahara, Nierste and Tremper 1604.07400, 1703.05786
  - Crivellin, D’Ambrosio, Kitahara, Nierste 1712.04959
  - Chobanova, D’Ambrosio, Kitahara, Martínez, Santos, Fernández and KY 1711.11030
- **Vector-like quarks**
  - Bobeth, Buras, Celis and Jung 1609.04783
- **Right handed current**
  - Cirigliano, Dekens, Vries and Mereghetti 1612.03914
  - Alioli, Cirigliano, Dekens, de Vries and Mereghetti 1703.04751
- **Leptoquark**
  - Bobeth and Buras 1712.01295
- **LR symmetric model**
  - Haba, Umeeda and Yamada 1802.09903/1806.0342
- **Type-III 2HDM**
  - Chen and Nomura 1804.06017/1805.07522
  - Matsuzaki, Nishiwaki and KY 1806.02312
- **Flavorful composite vectors**
  - Chen and Nomura 1808.04097
  - Matsuzaki, Nishiwaki and KY 1806.02312
- **Diquark model**
  - Chen and Nomura 1808.04097
- **3HDM**
  - Marzola and Raidal 1901.08290
- **General 2HDM**
  - Iguro and Omura, 1905.11778
**ε’/ε beyond the SM**

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

- CPV effect
- ImA2 is enhanced by enhancement factor 1/ω
- SM effect is small due to this accidental cancellation

- NP in ImA0 or (and) ImA2

ImA2 ... have enhancement factor 1/ω

ImA0 ... likely to result in huge contribution to $\epsilon_K$

→ NP in ImA2 is likely
**ε’/ε beyond the SM**

- **Master formulae for ε’/ε**
  - Aebischer, Bobeth, Buras, Gérard and Straub 1807.02520

  Master formula including BSM operators is derived with DQCD

  \[
  \left( \frac{\varepsilon'}{\varepsilon} \right)_{BSM} = \sum_{i} P_{i}(\mu_{W}) \text{Im} \left[ C_{i}(\mu_{W}) - C'_{i}(\mu_{W}) \right]
  \]

  \( P_{i} \): Hadronic matrix elements + RG effects

- Most efficient operators explaining ε’/ε anomaly

  \[
  \begin{align*}
  O^{u}_{VLR} &= (\bar{s}^{\alpha}\gamma_{\mu}P_{L}d^{\alpha})(\bar{u}^{\beta}\gamma^{\mu}P_{R}d^{\beta}) \\
  \tilde{O}^{u}_{VLR} &= (\bar{s}^{\alpha}\gamma_{\mu}P_{L}d^{\alpha})(\bar{u}^{\beta}\gamma^{\mu}P_{R}d^{\alpha}) \\
  O^{d}_{VLR} &= (\bar{s}^{\alpha}\gamma_{\mu}P_{L}d^{\alpha})(\bar{d}^{\beta}\gamma^{\mu}P_{R}d^{\beta}) \\
  \tilde{O}^{d}_{VLR} &= (\bar{s}^{\alpha}\gamma_{\mu}P_{L}d^{\alpha})(\bar{d}^{\beta}\gamma^{\mu}P_{R}d^{\alpha})
  \end{align*}
  \]

  - SM type operators
    - HME calculated by Lattice & DQCD
    - Generate O6(ImA0) & O8(ImA2)

  \[
  \begin{align*}
  O^{u}_{TLL} &= (\bar{s}^{\alpha}\sigma_{\mu\nu}P_{L}d^{\alpha})(\bar{u}^{\beta}\sigma^{\mu\nu}P_{L}d^{\beta}) \\
  \tilde{O}^{u}_{TLL} &= (\bar{s}^{\alpha}\sigma_{\mu\nu}P_{L}d^{\alpha})(\bar{u}^{\beta}\sigma^{\mu\nu}P_{L}d^{\alpha}) \\
  O^{d}_{TLL} &= (\bar{s}^{\alpha}\sigma_{\mu\nu}P_{L}d^{\alpha})(\bar{d}^{\beta}\sigma^{\mu\nu}P_{L}d^{\beta}) \\
  \tilde{O}^{d}_{TLL} &= (\bar{s}^{\alpha}\sigma_{\mu\nu}P_{L}d^{\alpha})(\bar{d}^{\beta}\sigma^{\mu\nu}P_{L}d^{\beta}) \\
  O^{u}_{SLR} &= (\bar{s}^{\alpha}P_{L}d^{\alpha})(\bar{u}^{\beta}P_{R}u^{\beta})
  \end{align*}
  \]

  - New scalar & tensor Operators
    - HME calculated by only DQCD

- **NP scenario**
  - New heavy vectors
  - Modified Z penguin
    (MSSM, VLQ, LHT, ...)

- **Heavy scalars**

- **Chrome magnetic operator <O_{8g}>** (calculated by Lattice & DQCD)
  - would be suppressed
ε'/ε beyond the SM

- Model independent approach  

The constraints from $K^0$ and $D^0$ mixing as well as EDM are potentially important

- Z penguin scenario

$\Delta S=1$ operators generate $\Delta S=2$ contributions, through top-Yukawa enhanced RG evolution

\[
\begin{align*}
(H^\dagger i \bar{D}_\mu H) (\bar{s}_R \gamma^\mu d_R) & \quad \xrightarrow{\text{RG evolution}} \quad (\bar{s}_R \gamma^\mu d_R) Z_\mu \\
\Delta F=2 \text{ operator} \quad & \quad (\bar{s}_L \gamma^\mu d_L)(\bar{s}_R \gamma^\mu d_R)
\end{align*}
\]
\[ \varepsilon' / \varepsilon \text{ beyond the SM} \]

- NP in \( \varepsilon' / \varepsilon \) also affect other observables

- \( \Delta S=2 \) process \( \varepsilon_K \) and \( \Delta M_K \) give severe constraint
  
  Some model need tuning to avoid this constraint

- Kaon rare decay \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) and \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) could be good probe
  
  Pure imaginary. Strong correlation with \( \varepsilon' / \varepsilon \)

- B observables have correlation (and become constraint) in some models

- Other observables (EDM)

- Different implications (correlations & predictions) for other observables appear depending on models \( \Rightarrow \) Possibility of model discriminations

\[ \star K \rightarrow \pi \nu \bar{\nu} \]

\[ \star \text{Correlation with B anomalies} \]
\( K_L \rightarrow \pi^0 \nu \bar{\nu} \) and \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

- Highly suppressed in SM: \( \text{BR}_{\text{SM}} \approx 10^{-11} \)
- Theoretically clean (Hadronic matrix element can be estimated using isospin sym.)
- \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) is purely CP violating mode

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

**NA62@CERN**

- NA62 at CERN observed one event in 2016 data
  
  \[
  \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (9.11 \pm 0.72) \times 10^{-11} 
  \]
  
  \[
  \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} = (1.73^{+1.15}_{-1.05}) \times 10^{-10} 
  \]
  
  \(< 14 \times 10^{-10} (95\% \text{C.L.}) \quad \text{BNL 949/E787} \quad \text{New 2018}\)

- Expected about 20 SM events from the 2017-2018 data sample

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]

**KOTO@J-PARC**

- KOTO at J-PARC reported result from the 2015 data last summer
  
  \[
  \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}} = (3.00 \pm 0.30) \times 10^{-11} 
  \]
  
  \[
  \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{exp}} < 2.6 \times 10^{-8} (90\% \text{C.L.}) 
  \]
  
  \(< 3.0 \times 10^{-9}(90\% \text{C.L.}) \quad \text{E391a} \quad \text{New 2018}\)

- KOTO-phase2 aims to measure at 10% accuracy
There are interesting correlations between Kaon observables depending on the chiral structure of coupling (LH and/or RH)

\[ \text{Re} \left( \frac{\epsilon'}{\epsilon} \right) \propto -\text{Im} \Delta_{L}^{sd} - 3 \text{Im} \Delta_{R}^{sd} + \cdots \]

\[ \text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) \propto |X| + \cdots \]

\[ \text{BR}(K_L \to \pi^0 \nu \bar{\nu}) \propto (\text{Im } X)^2 \]

\[ |\epsilon_K| \propto \text{Im} \left[ (\Delta_{L}^{sd})^2 + (\Delta_{R}^{sd})^2 - 240 \Delta_{L}^{sd} \Delta_{R}^{sd} \right] \]

\[ \Delta_{L}^{sd} (Z) = 0 \]

\[ \Delta_{R}^{sd} (Z) = -0.5 \Delta_{L}^{sd} (Z) \]

**LH Scenario**  \( \Rightarrow \) negative correlation

**LH+RH Scenario**  \( \Rightarrow \) positive correlation

**Examples**
**Examples**

### Chargino Z penguin

Endo, Mishima, Ueda and KY
1608.01444

Large trilinear couplings bring enhancement of $\varepsilon'/\varepsilon$

LH Z scenario → negative correlation between $\varepsilon'/\varepsilon$ and $K \to \pi 0\nu\nu$

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

- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 0.6$ SM
- $BR(K^+ \to \pi^+ \nu\bar{\nu})$ O(10–100%) effect

### Gluino box

Crivellin, D’Ambrosio, Kitahara and Nierste
1703.05786

Large isospin breaking ($m_U \neq m_D$) gives effect on $\Delta A_2$

- $m_{\tilde{U}} = 1.5$ TeV, $m_L = 300$ GeV

Different correlations between $\varepsilon'/\varepsilon$ and $K \to \pi \nu\nu$ may allow to distinguish among models

- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 0.6$ SM → KOTO
- $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 1.4$ SM → NA62
B anomalies

Lepton flavor universality Violation (LFUV) in semi-leptonic $B$ decays

\[ b \rightarrow c \tau \nu \]

\[ R_{D^{(*)}} = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)} \]

~3σ excess over the SM

\[ b \rightarrow s \ell\ell \]

\[ R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \rightarrow K^{(*)}e^+e^-)} \]

~2.5σ less over the SM

Correlation with $\varepsilon'/\varepsilon$?
**ε'/ε ↔ B anomalies**

Possibility of simultaneous explanation of them are discussed in several models:

- **Z model** is not favored by anomalies in $b \to s$ transitions, which suggest large $C_9^{NP}$ due to smallness of the vector coupling to charged lepton:

  \[
  O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu} \gamma^\mu \mu) (1 - 4s_w^2)
  \]

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

- In **Leptoquark model**, which is one of strong candidate of NP model realizing B anomalies, it is difficult to explain $\varepsilon'/\varepsilon$ because of bounds from rare Kaon decays. \[\text{Christoph and Buras 1712.01295}\]

- **2HDM + νR** can address $R_{K(*)}$ and $\varepsilon'/\varepsilon$. \[\text{Iguro and Omura, 1905.11778}\]

- **3HDM + νR** can access $R_{D(*)}, R_{K(*)}$ and $\varepsilon'/\varepsilon$. \[\text{Marzo, Marzola and Raidal 1901.08290}\]

- **Composite model** can access $R_{K(*)}$ and $\varepsilon'/\varepsilon$. \[\text{Matsuzaki, Nishiwaki and KY 1806.02312}\]
$\varepsilon'/\varepsilon \Leftrightarrow B$ anomalies - Example -

**Flavorful composite vectors**

Matsuzaki, Nishiwaki and KY 1806.02312

New vector particles: $G', Z', W'$, Leptoquark(LQ)

are included as composite vectors

$\varepsilon'/\varepsilon$ (K$\to\pi\pi$)

Flavor texture: Assume pure imaginary
(to avoid $\varepsilon_K$ constraint)

$\varepsilon'/\varepsilon$

$g_{\rho L}^{ij} = \begin{pmatrix} 0 & i g_{\rho L}^{12} & 0 \\ i (g_{\rho L}^{12})^* & 0 & 0 \\ 0 & 0 & g_{\rho L}^{33} \end{pmatrix}$

B anomaly

The correlation b/w $\varepsilon'/\varepsilon$ and B obs. appear in K$\to\pi\nu\nu$

$K\to\pi\nu\nu$

$R(K^*)$ & $\varepsilon'/\varepsilon$ (2σ)

$\Leftrightarrow 1.5 < BR(K^+\to\pi^+\nu\nu)/SM$

$\Leftrightarrow 10 < BR(K_L\to\pi^0\nu\nu)/SM$
Summary

Kaon physics is highly suppressed and sensitive to NP

**2.8σ discrepancy** in direct CPV of Kaon $\varepsilon'/\varepsilon$

Many experiments are on-going, and could allow us to discriminate NP models

**Kaon physics will continue to offer a powerful probe for NP!**