Recent developments on direct CP violation in the Kaon system and connection to $K \rightarrow \pi \nu \nu$ measurements

Teppei Kitahara
Karlsruhe Institute of Technology (KIT)

Heavy Quarks and Leptons 2018
Yamagata Terrsa, Yamagata
May 30, 2018
Kaon physics is still an exciting field!

- FCNC and its CP violation can be probed precisely by race decays: \( \text{Br} \sim O(10^{-11}) \)
- Non-perturbative QCD parts are calculable by ChPT and 2+1 flavour lattice
- One can test understanding of the SM, ChPT, unitarity of CKM… and BSM
- There are many promising on-going experiments; NA62 / KOTO / LHCb / KLOE-2 / TREK
Precise measurements for Kaon decay into two pions have discovered the **two types of CP violations**: indirect CPV $\epsilon_K$ & direct CPV $\epsilon'_K$:

\[
\mathcal{A}(K_L \to \pi^+\pi^-) \propto \epsilon_K + \epsilon'_K \quad \text{with} \quad \epsilon_K = \mathcal{O}(10^{-3}) \neq 0 \quad \text{[Christenson, Cronin, Fitch, Turlay, '64 with Nobel prize]}
\]

\[
\mathcal{A}(K_L \to \pi^0\pi^0) \propto \epsilon_K - 2\epsilon'_K \quad \text{with} \quad \epsilon'_K = \mathcal{O}(10^{-6}) \neq 0 \quad \text{[NA48/CERN and KTeV/FNAL '99]}
\]

### $\Delta S=2$

**Indirect CP violation**

[Kaon mixing]

*W box*

\[
\epsilon_K \propto \text{Im}[(\text{CKM})^2]
\]

### $\Delta S=1$

**Direct CP violation**

*W-box and penguin*

\[
\epsilon'_K \propto \text{Im}[(\text{CKM})]
\]

---

**Main topic of this talk**

Recent developments on direct CP violation in the kaon system and connection to $K \to \pi\pi\nu$ measurements

Teppei Kitahara: Karlsruhe Institute of Technology (KIT), HQL2018, Yamagata, May 30, 2018
Direct CPV in $K \to \pi \pi$

- **The strong suppression** of $\epsilon'_K$ comes from the smallness of the $\Delta I-3/2$ amplitude ($\Delta I = 1/2$ rule) and an accidental cancellation between the SM contributions

$$A(K^0 \to (\pi\pi)_I) \equiv A_I e^{i\delta_I}$$

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

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

$\delta_I$: strong phase

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

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

accidental cancellation

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

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

$~ \text{Im [ QCD penguin ]}$

$~ \text{Im [ EW penguin ]}$
Accidental cancellation

Composition of $\epsilon'_K / \epsilon_K$ with respect to the operator basis

$[TK, \text{Nierste, Tremper, JHEP '16}]$

$\times 10^{-4}$

Here, the hadronic matrix elements obtained from lattice result are used

First lattice result $[\text{RBC-UKQCD, PRL '15}]$

Recent developments on direct CP violation in the kaon system and connection to $K \to \pi \nu \nu$ measurements

Teppei Kitahara: Karlsruhe Institute of Technology (KIT), HQL2018, Yamagata, May 30, 2018
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']

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

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

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

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

- Singularity-free 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 $\alpha_s^2/\alpha_s^2$ is also included for the first time and we find it is numerically irrelevant in the SM $\rightarrow$ good perturbation
Recent developments on direct CP violation in the kaon system and connection to $K \to \pi \nu \nu$ measurements

Current situation of $\epsilon'_K / \epsilon_K$

\[ \propto \text{Im} A_0 - \left( \frac{\text{Re} A_0}{\text{Re} A_2} \right) \text{Im} A_2 \propto B^{(1/2)}_6 \]

\[ \propto B^{(3/2)}_8 \]

\[ B^{(1/2)}_6 \sim 1.6, \quad B^{(3/2)}_8 \sim 0.9 \]
\[ B^{(1/2)}_6 \sim 1.6, \quad B^{(3/2)}_8 \sim 0.9 \]
\[ B^{(1/2)}_6 \approx 3, \quad B^{(3/2)}_8 \approx 3.5 \]
\[ B^{(1/2)}_6 \leq B^{(3/2)}_8 \leq 1 \]
\[ B^{(1/2)}_6 \leq B^{(3/2)}_8 \leq 0.76 \]

Observed values

\[ B^{(1/2)}_6 = 0.57, \quad B^{(3/2)}_8 = 0.76 \]

dual QCD predictions

\[ B^{(1/2)}_6 \leq B^{(3/2)}_8 < 1, \quad B^{(3/2)}_8 = 0.8 \]

\[ \Delta I = 1/2 \text{ rule} \quad \left( \frac{\text{Re} A_0}{\text{Re} A_2} \right) \]

\[ \text{Exp.} \quad 22.45 \pm 0.05 \quad \text{ChPT} \quad \sim 14 \quad \text{dual QCD} \quad 16.0 \pm 1.5 \quad \text{Lattice (I=0,2)} \quad 31.0 \pm 11.1 \]
Anomaly?

- Lattice result with recent progress on the short-distance physics predicts $\varepsilon'/\varepsilon = O(10^{-4})$ which is below the experimental average at $2.8$-$2.9\sigma$ level.
  
  NNLO QCD in progress [Cerdà-Sevilla, Gorbahn, Jäger, Kokulu]

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

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

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

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

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

**Lattice result of I=0 with further statistics would shed light on the above discrepancies.**

Lattice simulation with improved methods and higher statistics is on-going [1711.05648]
Recent developments on direct CP violation in the kaon system and connection to $K \to \pi \nu \nu$ measurements

Several types of BSM can explain $\epsilon'_K / \epsilon_K$ discrepancy

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

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

---

**$\Im A_0$**

- **$g'$ scenario**
  - RS model
    - 1404.3824
  - SUSY
    - Type-III 2HDM
      - 1805.07522
  - Box scenario

- **Chromomagnetic scenario**
  - SUSY
    - 1711.11030,…

**$\Im A_2$**

- **$Z$ scenario**
  - SUSY
    - 1604.07400,…
    - 1608.01444,…
  - VLQ
    - 1609.04783,…
  - LHT
    - 1507.06316

- **$Z'$ scenario**
  - SUSY
    - 1608.01444,…
    - 1609.04783,…

- **$W_R$ scenario**
  - SUSY
    - 1802.09903
  - LR model
    - 1512.02869
    - 331 model
      - 1512.02869,…
    - 1612.03914, 1802.09903

---

HME would be suppressed [1712.09824, 1803.08052]
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu \nu$ measurements

Gluino-box contribution

- In the supersymmetric models, the gluino box can significantly contribute to $\epsilon'_K / \epsilon_K$

- In spite of QCD correction, gluino box can break isospin symmetry through mass difference between right-handed up and down squarks, which contributes $\text{Im} A_2$

$\text{Im} A_2$ is generated at the low energy scale with HMEs, contributing to $\epsilon'_K$ can be solved.
Recent developments on direct CP violation in the kaon system and connection to $K \to \pi \nu \nu$ measurements

**SUSY contributions to $\epsilon_K'/\epsilon_K$**

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

$\epsilon_K'/\epsilon_K$ discrepancy can be solved at

$1\sigma$ $2\sigma$

- $\epsilon_K$ excluded by $\epsilon_K$ with inclusive $|V_{cb}|$
- $\epsilon_K'$ preferred by $\epsilon_K$ with exclusive $|V_{cb}|$

$M_3 = 1.5M_S$

for suppressed $\epsilon_K$

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

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

maximum CPV phase for $\epsilon_K$

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

amplifies $\epsilon_K'/\epsilon_K$

suppresses $\epsilon_K$

excluded by LHC

---

**Recent developments on direct CP violation in the kaon system and connection to $K \to \pi \nu \nu$ measurements**

**Tepppei Kitahara**: Karlsruhe Institute of Technology (KIT), HQL2018, Yamagata, May 30, 2018
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu \bar{\nu}$ measurements

Teppei Kitahara: Karlsruhe Institute of Technology (KIT), HQL2018, Yamagata, May 30, 2018

When BSM contribution to FCNC ($s d Z$) coupling is the same magnitude as the SM, $\epsilon'_K$ discrepancy be explained

$\epsilon'_K / \epsilon_K \times 10^{-4}$

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

$[- \text{Im} s_L d_L] \sim \text{Im} s_{L/R} d_{L/R}$

Positive contribution

SM Z-penguin gives the biggest negative contribution

$\epsilon'_K$ can be solved

$O(1)$ contribution to $B(K \rightarrow \pi \nu \bar{\nu})$
Modified Z-coupling scenario cont.

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

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{c_L}{\Lambda^2} i (H^\dagger \bar{D}_\mu H)(\bar{Q}_L \gamma^\mu Q'_L) + \frac{c_R}{\Lambda^2} i (H^\dagger \bar{D}_\mu H)(\bar{d}_R \gamma^\mu d'_R),
\]

\[
= \mathcal{L}_{\text{SM}} - \frac{\sqrt{2} v M_Z}{\Lambda^2} (c_L s_R \gamma^\mu Z_\mu P_L d + c_R \bar{s}_R \gamma^\mu Z_\mu P_R d) + \ldots
\]

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

- Constraint comes from $\Delta S=2$ process : $\epsilon_K$

\[
(H^\dagger i \bar{D}_\mu H)(\bar{s}_R \gamma^\mu d_R) \quad @\text{high scale}
\]

\[
\Delta S = 1
\]

\[
(\bar{s}_L \gamma^\mu d_L)(\bar{s}_R \gamma^\mu d_R) \quad @\text{low scale}
\]

\[
\Delta S = 2
\]

Interference terms

They can be significant in a certain case
Other rare kaon decays

CP violation + FCNC decays of kaon $K \to \pi \pi$, $K \to \pi \nu \bar{\nu}$, $K \to \mu^+ \mu^-$ are sensitive to NP and can probe virtual effects from particles with masses far above the reach of LHC

They should be correlated with each other

\[ \epsilon'_K \text{ discrepancy (} K_L \to \pi \pi) \rightarrow \text{deviations of the other rare kaon decays} \]

$K \to \pi \nu \bar{\nu}$ $K_L$ is CPV, and clean BG. The experiments are on-going

- **NA62** experiment at CERN $K^+ \to \pi^+ \nu \bar{\nu}$, target: 10% precision compared with SM (2018)
- **KOTO** experiment at J-PARC $K_L \to \pi^0 \nu \bar{\nu}$, target: 100% (step1), 10% (step2)

$K_S \to \mu^+ \mu^-$ : CPC(dom.) + CPV. Br is amplified in a certain case: $\tan^3 \beta / M_A^2$

  : In **LHCb**, Direct CP asymmetry could be probed, which is sensitive to CPV FCNC

$K_L \to \pi^0 \ell^+ \ell^-$ : CPV(dom.) + CPC. The theoretical uncertainty can be reduced by precise measurement of $K_S \to \pi^0 \ell^+ \ell^-$  $\rightarrow$ LHCb

  : Direct detection of $K_L \to \pi^0 \ell^+ \ell^-$ is necessary.
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu \nu$ measurements

B($K \rightarrow \pi \nu \nu$) in box scenario [Crivellin, D’Ambrosio, TK, Nierste, ’17]

$m_{\tilde{q}_1} = 1.5$ TeV, $m_L = 300$ GeV

\begin{align*}
\frac{m_{\bar{U}}}{m_{\bar{D}}} &= 2 \\
\frac{m_{\bar{U}}}{m_{\bar{D}}} &= 0.5
\end{align*}

1σ 2σ

$\epsilon'_K$ discrepancy can be solved at 1σ (10%) level is required in light of a constraint from $\epsilon_K$

parameter tuning at 1-10% level is required for a fine-tuning at the 1(10)% level

$B(K_L \rightarrow \pi^0 \nu \bar{\nu})/SM \lesssim 2 (1.2)$

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})/SM \lesssim 1.4 (1.1)$

determines a position of the green bands

Positive $\epsilon'_K$ predicts a strict correlation

$sgn \left[ B(K_L \rightarrow \pi^0 \nu \bar{\nu}) - B^{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \right]$

$= sgn \left[ m_{\bar{U}} - m_{\bar{D}} \right]$

$sgn \left[ m_{\bar{U}} - m_{\bar{D}} \right] \xrightarrow{\epsilon'_K} \arg \left[ m_{Q12}^2 \right]$

$sgn \left[ B(K_L \rightarrow \pi^0 \nu \bar{\nu}) - B^{SM}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \right]$
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu \nu$ measurements

**B(K→πνν) in Z scenario**

**Result of simplified cases**

Constraint comes from $\epsilon_K$, $\Delta M_K$, $B(K_L \rightarrow \mu^+ \mu^-)$

- $\mu_{\text{NP}} = 1 \text{ TeV}$
- $\epsilon_K'$ discrepancy can be explained at 1σ
- $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$ is smaller than the SM prediction
- $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$ can be enhanced by overshothing $\epsilon_K'$ from $C_R$ with destructive $\epsilon_K'$ from $C_L$
- Parameter tuning is required
- → study in concrete models in next slide

\[
\frac{c_L}{\Lambda^2} i(H^\dagger \tilde{D}_\mu H)(\overline{Q}_L \gamma^\mu Q'_L)
\]

\[
\frac{c_R}{\Lambda^2} i(H^\dagger \tilde{D}_\mu H)(\overline{d}_R \gamma^\mu d'_R)
\]

[Endo, TK, Mishima, Yamamoto, '16]
**B(K→πνν) in Z scenario (MSSM)**

**chargino Z-penguin in the MSSM**

[Endo, Mishima, Ueda, Yamamoto, ’16]

\[
\begin{array}{c}
\begin{aligned}
\text{Z model (LH)} & \quad \text{Z model (RH + LH)} \\
\end{aligned}
\end{array}
\]

**Upper bounds under the constraints:**

Vacuum, \( \varepsilon_K, \Delta M_K, K_L \rightarrow \mu\mu \)

**gluino Z-penguin in the MSSM**

[Tanimoto, Yamamoto, ’16]

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

\[
\begin{array}{c}
\begin{aligned}
\text{Z model (LH)} & \quad \text{Z model (RH + LH)} \\
\end{aligned}
\end{array}
\]

**Upper bounds under the constraints:**

Vacuum, \( \varepsilon_K, \Delta M_K, K_L \rightarrow \mu\mu, b \rightarrow s(d)\gamma \)

\[
\begin{array}{c}
\begin{aligned}
\text{with } & \quad B(K^+ \rightarrow \pi^+\nu\bar{\nu})/SM \lesssim 1.5 \\
\end{aligned}
\end{array}
\]

Recent developments on direct CP violation in the kaon system and connection to \( K \rightarrow \pi\nu\nu \) measurements

**Teppei Kitahara:** Karlsruhe Institute of Technology (KIT), HQL2018, Yamagata, May 30, 2018
Direct CP asymmetry in $K_S \rightarrow \mu\mu$

- $K_S \rightarrow \mu\mu$ (almost CPC) can be probed by an upgrade of the LHCb at the SM accuracy. [$K_L \rightarrow \mu\mu$ (CPC) has been observed precisely by BNL E871] [BNL E871, PRL '00]

- An interference contribution between $K_L$ and $K_S$ emerges from a genuine direct CP violation (indirect CPV is negligible) [TK, D’Ambrosio, PRL '17]

- Interference contribution is comparable size to CPC of $K_S \rightarrow \mu\mu$ thanks to the large absorptive part of long-distance contributions to $K_L \rightarrow \mu\mu$

- Nonzero dilution factor ($D$) can be obtained by an accompanying charged kaon tagging and a charged pion tagging

\[ pp \rightarrow K^0 K^- X \]

\[ pp \rightarrow K^{*+} X \rightarrow K^0 \pi^+ X \]

with $K^* \rightarrow \{K_S, K_L\} \rightarrow \mu^+ \mu^-$

\[ D = \frac{K^0 - \bar{K}^0}{K^0 + \bar{K}^0} \]
Summary

- RBC-UKQCD lattice group and perturbative calculations of $\epsilon_K'/\epsilon_K$ have revealed that the SM expected value deviates from measured value (2.8-2.9σ).
- Several types of BSM can explain $\epsilon_K'/\epsilon_K$ discrepancy.
- Correlations with the other rare decays are crucial for discrimination of BSM.

- NA62 experiment $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ with 10% precision (2018) could probe whether modified Z-coupling scenario is realized or not.
- KOTO experiment $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ with 10% precision can probe both box and modified-Z coupling scenarios.
- The upgrade of LHCb experiment can probe $\mathcal{B}(K_S \to \mu^+\mu^-)$ at the SM accuracy, which can also probe CP-violating FCNC.
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu\nu$ measurements.
Overview of effective models

- Chiral perturbation theory ($\Delta S=1$)
  - Effective theory of the QCD Goldstone bosons: $\Phi = \begin{pmatrix} \sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{2}} \eta & \pi^- & K^+ \\ \pi^- & -\sqrt{\frac{1}{2}} \pi^0 + \sqrt{\frac{1}{2}} \eta & K^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}} \eta \end{pmatrix}$
  
  $$\mathcal{L} = -\frac{G_F}{\sqrt{2}} V_{ud} V_{us}^* \left( g_8 f^4 \text{tr} (\lambda L_\mu L^\mu) + g_{27} f^4 \left( L_{\mu 23} L^\mu_{11} + \frac{2}{3} L_{\mu 21} L^\mu_{13} \right) + \mathcal{O}(g_E W) \right)$$

  with $L_\mu = -i U^\dagger D_\mu U$ and $U = \exp \left( \frac{i \sqrt{2} \Phi}{f} \right)$

- Dual QCD method [Bardeen, Buras, Gerard, '87, '14]

- Effective theory of the truncated pseudo-scalar and vector mesons:
  $$\mathcal{L} = \frac{f^2}{4} \text{tr} (\partial_\mu U \partial^\mu U^\dagger) - \frac{1}{4} \text{tr} (V_{\mu \nu} V^{\mu \nu}) - \frac{f^2}{2} \text{tr} (\partial_\mu \xi^\dagger \xi + \partial_\mu \xi \xi^\dagger - 2ig V_\mu)^2$$
  with $U = \xi \xi$

- Chiral quark model
  - Mean-field approximation of the full extended NJL model
    $$\mathcal{L} = \mathcal{L}_{QCD} - M \left( \bar{q}_R U q_L + \bar{q}_L U^\dagger q_R \right)$$
Box scenario in the MSSM

- In the supersymmetric model (MSSM), the following parameter region is interesting for $\epsilon'_K$ discrepancy:

$$M_3 \gtrsim 1.5M_S, \ m_{Q,12}^2 \neq 0, \text{ and } m_{U}/m_{D} \neq 1$$

ΔS=1

- can explain $\epsilon'_K$ discrepancy

TK, Nierste, Tremper, '16

ΔS=2

- can suppress ΔS=2 process

Crivellin, Davidkov, '10

ΔS=1

- can contribute to $K \rightarrow \pi \nu\bar{\nu}$ correlating with above two physics

Crivellin, D'Ambrosio, TK, Nierste, '17
Recent developments on direct CP violation in the kaon system and connection to $K \rightarrow \pi \nu \bar{\nu}$ measurements

- NA62 experiment $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ with 10% precision (2018) could probe whether modified Z-coupling scenario is realized or not.

- KOTO experiment $B(K_L \rightarrow \pi^0 \nu \bar{\nu})$ with 10% precision can probe both box and modified-Z coupling scenarios.