KOTO vs NA62
Dark Sector with Grossman-Nir bound and Beyond

Israel Joint Seminar
Israel (virtual), July 8, 2020

Kohsaku Tobioka
Florida State University
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Outline

• Introduction
  ‣ Rare kaon decay $K \to \pi \nu \nu$
  ‣ Observed events at KOTO, and NA62 result

• Dark Sector with Grossman-Nir bound and Beyond
  ‣ Heavy new physics (EFT)
  ‣ Light new physics with GN bound
  ‣ Light new physics beyond GN bound

• Future prospects [ALP search at Kaon factories]

• Summary

Stefania Gori, Gilad Perez [2005.05170]
Introduction
Very Rare Kaon Decays

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad K_L \rightarrow \pi^0 \nu \bar{\nu} \]
\[ \propto |\mathcal{M}|^2 \quad \propto (\text{Im}\mathcal{M})^2 \]

\[ \mathcal{M} \sim \]

Extremely rare and precise process in SM. [Buras et al., 1503.02693]

\[ \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (9.11 \pm 0.72) \times 10^{-11} \]
\[ \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.00 \pm 0.30) \times 10^{-11} \]

- Br~10^{-11} due to suppressions of 1loop, CKM and GIM
- Unlike LHC physics, a few events are already significant!
Grossman-Nir bound

\[ \mathcal{M} \sim \]

- **Br[K_L]** indirectly bounded by **Br[K^+]**
  \[
  \frac{\Gamma[K_L \rightarrow \pi^0 \nu \bar{\nu}]}{\Gamma[K^+ \rightarrow \pi^+ \nu \bar{\nu}]} = \frac{(\text{Im } M)^2}{|M|^2} \leq 1
  \]
  Isospin relation (\(\Delta I = 1/2\))

  \[
  \frac{\text{BR}[K_L \rightarrow \pi^0 \nu \bar{\nu}]}{\text{BR}[K^+ \rightarrow \pi^+ \nu \bar{\nu}]} \leq 4.3
  \]
  Ratio of total widths +isospin breaking

- **GN bound** can be generalized to new physics case
  \[
  \text{BR}(K_L \rightarrow \pi^0 X) \lesssim 4.3 \text{BR}(K^+ \rightarrow \pi^+ X)
  \]
  saturates, e.g., when \(X\) is CP-even

[H. Leutwyler, M. A. Shifman ('90)]
Experiments for Rare Koan Decays

**JPARC**

- 30 GeV p since 2013 (restart ‘15)
- ~2 GeV $K_L$

**CERN**

- 400 GeV p from SPS physic run since 2015
- 75 GeV $K^+$
- ~150 m

Aim for precision $\text{Br} \sim 10^{-11} \Rightarrow N_K \sim 10^{13} \Rightarrow N_{B\text{-pair,BelleII}} \sim 10^{11}!!

Kohsaku Tobioka (FSU)
Reports at KAON2019
Observed Events at KOTO

Search for the rare decay
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC KOTO experiment

Satoshi Shinohara (Osaka Univ.),
on behalf of the KOTO collaboration

KAON2019
10-13 September 2019 University of Perugia (Italy)

Observed Events at KOTO

- Data until 2018
  Incoming $7 \times 10^{12} K_L$
  $\sim 5 \times 10^{11} K_L$ decays

- Two ECAL hits.
  Reconstruction assumes $\pi^0 \rightarrow \gamma \gamma$.

Reconstructed $\pi^0$ $p_T$ [MeV]

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ MC

Reconstructed decay position

Z : reconstructed decay position
Observed Events at KOTO

Blind analysis

BG: 0.05 ± 0.02,
SM\([K_L \rightarrow \pi^0\nu\nu] 0.05 \pm 0.01\)

Open the box [unblinding]

4 events!
[note: nothing outside SR]

[S. Shinohara, KAON2019]
One event suspected as BG

Even 3 events $\Rightarrow$ SM+BG~0.1.  

$p$-value$\sim 10^{-4}$

Corresponding BR

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{KOTO}} = 2.1^{+2.0 (+4.1)}_{-1.1 (-1.7)} \times 10^{-9}$$

[Kitahara, Okui, Perez, Soreq, KT (1909.11111)]
New Result on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ from the NA62 Experiment

Giuseppe Ruggiero (Lancaster University)

KAON 2019
Perugia, 10/09/2019

On behalf of the NA62 Collaboration

• Slightly inconsistent $K^+$ result reported in the same conference via GN bound
2016+2017 Result

- 2016 and 2017 data uncorrelated

<table>
<thead>
<tr>
<th>Events observed</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single event sensitivity</td>
<td>$(0.346 \pm 0.017) \times 10^{-10}$</td>
</tr>
<tr>
<td>Expected background</td>
<td>$1.65 \pm 0.31$</td>
</tr>
</tbody>
</table>

- Upper limits (CLs method)

<table>
<thead>
<tr>
<th>Observed</th>
<th>Expected (background only)</th>
<th>CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) &lt; 1.85 \times 10^{-10}$</td>
<td>$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) &lt; 1.32 \times 10^{-10}$</td>
<td>90%</td>
</tr>
<tr>
<td>$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) &lt; 2.44 \times 10^{-10}$</td>
<td>$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) &lt; 1.62 \times 10^{-10}$</td>
<td>95%</td>
</tr>
</tbody>
</table>

- Two-sided 68% band: $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.47^{+0.72}_{-0.47}) \times 10^{-10}$

KOTO data indicates

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\text{KOTO}} = 2.1^{+2.0}_{-1.1} (^{+4.1}_{-1.7}) \times 10^{-9}$

Inconsistent with GN bound!

$$\frac{\text{BR}[K_L \to \pi^0 \nu\bar{\nu}]}{\text{BR}[K^+ \to \pi^+ \nu\bar{\nu}]} \leq 4.3$$
• SM point, inconsistent \(3+\sigma\)

• IF GN bound saturates [1D]

\[
\frac{\text{BR}[K_L \rightarrow \pi^0 \nu \bar{\nu}]}{\text{BR}[K^+ \rightarrow \pi^+ \nu \bar{\nu}]} = 4.3
\]

still tension of \(2.1 \sigma\)

• Violation of GN bound in \(K \rightarrow \pi \nu \nu\) is very difficult.

If this is NP, a new light state is favored.
Dark Sector
with Grossman-Nir bound and Beyond
Dark Sector with Grossman-Nir bound and Beyond

Heavy new physics

- EFT: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
- Leptoquark: R. Mandal, A. Pich [1908.11155]
- $Z'$: Calibbi, Crivellin, Kirk, Manzari, and Vernazza [1910.00014], Aebischer, Buras, Kumar [2006.01138]
- Generic neutrino interactions: Li, Ma, and Schmidt [1912.10433]

Light new state with GN bound

- General analysis: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
- Light dark fermions (do not work): Fabbrichesi and Gabrielli (1911.03755)

Light new states violating GN bound

- M. Pospelov. Status and phenomenology of light bsm. talk Jan 20, 2019

Exotic (not in this talk)

- Fixed target production: Kitahara, Okui, Perez, Soreq, KT [1909.11111]
- Pionium($K \rightarrow \pi^0 A_{13}$): P. Lichard [arXiv:2006.02969]
Heavy New Physics

Conventional solution: SM higher dim. operator due to heavy state

\[ \mathcal{O}_{BSM}(\psi_{SM}) \supset \sum_i C_i \mathcal{O}_i \] to enhance \( K \to \pi \nu \nu \)

\[ \mathcal{O}_S = \bar{L} \bar{\sigma}^\mu L \bar{Q}_2 \bar{\sigma}^\mu Q_1 \]

\[ \mathcal{O}_T = \bar{L} \tau^a \bar{\sigma}^\mu L \bar{Q}_2 \tau^a \bar{\sigma}^\mu Q_1 \]

\[ \mathcal{O}_R = \bar{L} \bar{\sigma}^\mu L \ s^c \bar{\sigma}^\mu \bar{d}^c \]

Best Fit

\[ C_{S,R} - C_T \sim e^{-\frac{3}{4} \pi i} /(75 \text{ TeV})^2 \]

Lepton Universality
leads to charged lepton channels

\[ K_L \to \pi^0 \ell^+ \ell^- \ (\ell = e, \mu) \]

\[ K_S \to \mu^+ \mu^- \]

Prescriptions

(1) neutrino is only \( \nu_\tau \)

(2) Impose \( C_R = C_S \)

K. Agashe, R. Contino, L. Da Rold, and A. Pomarol, [hep-ph/0605341]

Lepton Universality leads to charged lepton channels

 bounds are \( \text{BR} \sim 10^{-10} \)
Heavy New Physics

Conventional solution: SM higher dim. operator due to heavy state

\[ \mathcal{O}_{\text{BSM}}(\psi_{\text{SM}}) \supset \sum C_i \mathcal{O}_i \] to enhance \( K \to \pi \nu \nu \)

\[ \begin{align*}
\mathcal{O}_S &= \bar{L} \sigma^\mu L \bar{Q}_2 \sigma_\mu Q_1 \\
\mathcal{O}_T &= \bar{L} \tau^a \sigma^\mu L \bar{Q}_2 \tau^a \sigma_\mu Q_1 \\
\mathcal{O}_R &= \bar{L} \sigma^\mu L \ s^c \sigma_\mu d^c
\end{align*} \]

GN bound tension

Best Fit

\[ C_{S,R} - C_T \sim e^{-\frac{3}{4} \pi i} / (75 \ \text{TeV})^2 \]

\[ \text{still } 2.1\sigma \text{ tension} \]

*Operator violating GN bound starts dimension 9(\( \Delta l=3/2 \)) w/ \( \Lambda \sim 10 \text{GeV} \)

He, Ma, and Valencia [2002.05467]

\[ \text{BR}[K_L] < 4.3 \times \text{BR}[K^+ \to \pi^+ \nu \bar{\nu}] \]

\[ \text{BR}[K^+] \to 17 \times \text{BR}[K^+] \]
Heavy New Physics

Conventional solution: SM higher dim. operator due to heavy state

\[ \mathcal{O}_{\text{BSM}}(\psi_{\text{SM}}) \supset \sum C_i \mathcal{O}_i \] to enhance \( K \rightarrow \pi \nu \nu \)

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\[ C_{S,R} - C_T \sim e^{-\frac{3}{4} \pi i}/(75 \text{ TeV})^2 \]

still 2.1\( \sigma \) tension

*Operator violating GN bound starts dimension 9(\( \Delta l = 3/2 \)) w/ \( \Lambda \sim 10\text{GeV} \)

He, Ma, and Valencia [2002.05467]

\[ \text{BR}[K_L]<4.3\text{BR}[K^+] \rightarrow 17\text{BR}[K^+] \]
New Light State
Single light particle couples to SM.

\[ \mathcal{O}_{SM} X \]

X: SM gauge singlet
\[ m_X < 350 \text{MeV} \]
\[ \mathcal{O}_{SM} \supset \bar{s}d \]

Respects GN bound \( \rightarrow \) **How to accommodate** \( K^+ \) results

\[ \text{BR}(K_L \rightarrow \pi^0 X) \lesssim 4.3 \text{BR}(K^+ \rightarrow \pi^+ X) \]
Single light particle couples to SM.

\[ \mathcal{O}_{\text{SM}}X \]

X: SM gauge singlet
\[ m_X < 350 \text{MeV} \]
\[ \mathcal{O}_{\text{SM}} \supset \bar{s}d \]

\[ K_L \rightarrow \pi^0 X \]
\[ K^+ \rightarrow \pi^+ X \]

For KOTO events,

- Observed events are aligned.
  Prefer \( K_L \rightarrow \pi^0 X \) to \( K_L \rightarrow \pi^0 \nu \nu \).

Remaining events of 50k \( K_L \rightarrow \pi^0 X \) after kinematic cuts
Light New Physics with GN bound

Single light particle couples to SM.

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X: SM gauge singlet
\[ m_X < 350 \text{ MeV} \]
\[ \mathcal{O}_{\text{SM}} \supset \bar{s}d \]

\[ K_L \to \pi^0 X \]
\[ K^+ \to \pi^+ X \]

For KOTO events,

- Observed events are aligned. Prefer \( K_L \to \pi^0 X \) to \( K_L \to \pi^0 \nu \nu \).
- Large \( m_X \to \) less \( p_{T,\text{max}}^{\pi^0} \).
  \( \text{BR} \sim 10^{-9} \) and \( m_X < 180 \text{ MeV} \)
  to accommodate 3 events.

[Kitahara, Okui, Perez, Soreq, KT (1909.11111)]
Two regions compatible with $K^+$[NA62, E949]

- GN bound saturated [best case, $X$: CP even]. Require 3 events at KOTO.

$$\mathcal{B}(K_L \to \pi^0 X) = 4.3 \mathcal{B}(K^+ \to \pi^+ X)$$

\begin{align*}
&\{ \\
&\quad \text{E949 bound [0903.0030]} \\
&\quad \text{NA62 } \mathcal{B}(K^+ \to \pi^+ X)_{\text{NA62}}^{95\% \text{CL}} = 1.6 \times 10^{-10} \\
\end{align*}

Two experimental loopholes

1. $m_X \sim m_{\pi^0}$ loophole
   - Large $K^+ \to \pi^+ \pi^0$ BG
   - Fuyuto, Hou, Kohda [1412.4397]

2. Finite lifetime of $X$
   - Exploit detector size.

KOTO signal and $K^+ \to \pi^+ X$ Bounds
Two regions compatible with $K^+[\text{NA62, E949}]$

1. $m_X \sim m_{\pi 0}$ loophole
   - Large $K^+ \to \pi^+\pi^0$ BG
   - Fuyuto, Hou, Kohda [1412.4397]
   - Minimal Higgs portal works.
     A little tension with CHARM.
     Egana-Ugrinovic, Homiller, Meade [1911.10203]

2. Finite lifetime of $X$

   If $X$ is unstable ($\tau_X \sim \text{nsec}$),
   Some $X$ does not decay at KOTO while all decay to $\gamma\gamma$ at NA62(E949)

   $$\mathcal{B}(K \to \pi X; \text{detector}) = \mathcal{B}(K \to \pi X)e^{-\frac{L}{\rho} \frac{m_X}{c\tau_X}}$$

   Effective Br in each experiment as “invisible $X$”

   see also F. Kling, S. Trojanowski [2006.10630]

   Decay factor of $X$
   $$\frac{L_{\text{NA62}}/p_{\text{NA62}}}{L_{\text{KOTO}}/p_{\text{KOTO}}}$$
   NA62 is effectively larger
Dark Sector
beyond GN bound
Light New Physics violating GN (I)

With more than 2 dark sector particles, **GN bound violated**.

\[ \mathcal{O}_{\text{SM}} X_1 X_2 \]

\( X_{1,2}: \text{SM singlet} \)

\[ \mathcal{O}_{\text{SM}} \supset \bar{s}d \]

\[ K_L \rightarrow X_i X_j \]

\[ K^+ \rightarrow \pi^+ X_i X_j \]

- **Neutral particle (e.g., \( K^0, B^0 \)) decays directly to dark sector.**
- **Charged particle decays with extra SM particle (\( \pi^+ \)) \( \rightarrow 1/16 \pi^2 \) or forbidden.**


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- **Neutral particle (e.g., K^0, B^0) decays directly to dark sector.**
- Charged particle decays with extra SM particle \((\pi^+) \to 1/16\pi^2 \text{ or forbidden.} \)

(A) E.g. \(\phi\) carries 1/2 strange (or 2nd generation) charge [\(\phi: \text{stable}\)] [2005.05170]

\[ y_1 H \bar{Q}_1 s \phi^2 / \Lambda^2 \quad y_2 H \bar{Q}_2 d \phi^2 / \Lambda^2 \]

Small breaking induces \(\chi = \text{Im}[\phi]\) decays to \(\gamma\gamma\)

\[ \mathcal{L}_\chi \supset \frac{\chi}{\Lambda_\chi} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Another realization w/Higgs portal&Z’ in [2005.07102]
Light New Physics violating GN (I)

With more than 2 dark sector particles, **GN bound violated.**

\[ \mathcal{O}_{SM} X_1 X_2 \]

- \( X_{1,2}: \) SM singlet
- \( \mathcal{O}_{SM} \supset \bar{s}d \)

\[ K_L \rightarrow X_i X_j \]

\[ K^+ \rightarrow \pi^+ X_i X_j \]

non-trivial acceptance \([\pi^0 \rightarrow \gamma\gamma \text{ is wrong assumption}]\)

To explain KOTO events

\( m_\phi(\sigma, \chi) \sim [80 \text{GeV}, 140 \text{GeV}] \)

\( \Lambda \sim 10^7 \text{GeV} \quad (B[K_L \rightarrow \gamma\gamma + \text{inv}] \sim 10^{-9}) \)

\( \Lambda_\chi \sim 50 \text{TeV} \) (prompt decay)
Light New Physics violating GN (II)

With more than 2 dark sector particles, **GN bound violated.**

\[
\mathcal{O}_{\text{SM}} X_2 + \lambda m_X X_1 X_2^2, \lambda' X_1^2 X_2^2
\]

\[
\mathcal{O}_{\text{SM}} \supset g_{sd} \bar{s}d, \ g_{dd} \bar{d}d
\]


**Mixing** among neutral particles: \(K_L, \pi^0\), and new scalar \(X_2\).

\(m_{X_2} > m_K\) but has to be light, since \(\text{BR}[K_L \rightarrow \pi^0 X_1(X_1)] \sim (1/m_{X_2})^8\).

Constrains from K-Kbar oscillation\((g_{sd})\), SN1987, beam dump \((g_{dd})\)
Prospects

KOTO is investigating all the events

Current events confirmed.
GN violation indicates light new state(s)!
*Search @beam dump*[e^+e^-], K^+ → π^+γγ, KLEVER

Mild excess remains.
Heavy NP scenarios revive. Need more precision.

All the KOTO events are new BG.
SM wins. Wait for new data (a few events are exciting!)

talk in Jan 2020, still preliminary.

Search for Axion-like-particles via Kaon

- Consider an ALP with \( \frac{\alpha_s}{8\pi F_a} a G \tilde{G} \) for the strong CP problem

- PQ quality problem:
  Global symmetry is not robust. The ALP potential ruined even by gravity.

- Large \( m_a \) and small \( f_a \) are favored

\[
V(a) = m_a^2 F_a^2 \left\{ 1 - \cos \left( \frac{a}{F_a} \right) \right\} + \frac{F_a^2}{\Lambda_{UV}^{D-4}} \cos \left( \frac{a}{F_a} + \Delta \right)
\]

\[
\delta \bar{\theta} = \frac{\delta a_{\text{min}}}{F_a} \sim \frac{F_a^{D-2}}{m_a^2 \Lambda_{UV}^{D-4}}.
\]

**Big picture & status**
for Axion-like-particles via Kaon

Big picture & status

Kohsaku Tobioka (Fermilab, T2K)

Search for Axion-like-particles via Kaon

F_a = \frac{\Lambda}{32\pi^2c_g}

10^{-2}

10^{-3}

10^{-4}

D. Aloni, Y. Soreq, M. Williams [1811.03474, 1903.03586]

Astro, Cosmology

Beam dump

K + K_L

[visible]

K + K_L

[invisible]

X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala, KT [1810.09452]+[1710.01743]
\[
\frac{\alpha_s}{8\pi F_a} a G \tilde{G} \]

induces axion mixing with mesons

\[
\begin{pmatrix} a \\ \pi \\ \eta \end{pmatrix} \approx \begin{pmatrix} 1 & -\frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & -\frac{K_\eta M_\eta^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} \\ \frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & 1 & 0 \\ \frac{K_\eta M_\eta^2 + \delta M_{\eta a}}{M_\eta^2 - M_a^2} & 0 & 1 \end{pmatrix} \begin{pmatrix} a_{\text{phys}} \\ \pi_{\text{phys}} \\ \eta_{\text{phys}} \end{pmatrix}
\]

\[K_\pi = -\frac{F_\pi}{2F_a} (\kappa_u - \kappa_d), \quad K_\eta = -\frac{F_\eta}{\sqrt{6}F_a} (\kappa_u + \kappa_d - \kappa_s),\]

\[
\delta M_{\eta a} = \sqrt{\frac{1}{3} F_\pi} \frac{m_u m_d m_s}{(m_u + m_d)(m_u m_d + m_d m_s + m_s m_u)} m_{\pi a}^2
\]

\[\text{• Naively the production rate}
\]

\[
\text{BR}(K^+ \rightarrow \pi^+ a)_{\text{naive}} \approx \text{BR}(K^+ \rightarrow \pi^+ \pi^0) \theta^2_{\pi a} \frac{|\vec{P}_a|}{|\vec{P}_{\pi^0}|} \rightarrow \text{not leading}
\]

\[\text{“}\Delta l=1/2 \text{ rule”} \quad \Delta l=1/2 (\text{octet, } 8_L) \gg \Delta l=3/2 (27\text{plet, } 27_L)
\]

\[\text{• } \Delta l=1/2 (\text{octet}) \text{ contribution is important, e.g. through } \eta^{(')*}
\]

Weinberg(’78); Bardeen, Tye(’78); Antoniadis, Truong(’82); Bardeen, Peccei, Yanagida(’87)

\[
\text{Br}(K^+ \rightarrow \pi^+ a)_{\text{octet enh.}} \approx \theta^2_{\pi a \kappa_u d} \frac{\Gamma_{K^0}}{\Gamma_{K^+}} 2 \frac{\Gamma_{K^0}}{\Gamma_{K^+}} \text{Br}(K^0_{s} \rightarrow \pi^+ \pi^-) \frac{|\vec{P}_a|}{|\vec{P}_\pi|} D^2_{\pi\pi}
\]

[1710.03764] D. Alves, N. Weiner

\[\text{→ still not enough}
\]
**K→πa calculation update by χPT**

- **Naively the production rate**

  \[ BR(K^+ \rightarrow \pi^+ a)_{\text{naive}} \approx BR(K^+ \rightarrow \pi^+ \pi^0) \theta_a^2 \frac{|\vec{p}_a|}{|\vec{p}_{\pi^0}|} \]

- **K→πη*(ΔI=1/2) contribution**

  \[ Br(K^+ \rightarrow \pi^+ a)|_{\text{octet enh.}} \approx \theta_{a\eta_{ud}}^2 \frac{2 \Gamma_K}{\Gamma_{K^+}} Br(K_s^0 \rightarrow \pi^+ \pi^-) \frac{|\vec{p}_a|}{|\vec{p}_\pi|} D_{\pi\pi}^2 \]

- **Update by χLagrangian, found octet & π-a mixing**

  \[ \mathcal{L}_{\Delta S=1} = G_8 F_\pi^4 \text{Tr}[\lambda_{sd} D^\mu \Sigma^i D_\mu \Sigma] + G_27 F_\pi^4 \left( L_{\mu 23} L_{11}^\mu + \frac{2}{3} L_{\mu 21} L_{13}^\mu \right) + \text{h.c.} \]

  \[-iG_27 F_\pi K^0 \pi^0 a \left( - \frac{1}{\sqrt{2}} [2m_{K^0}^2 - m_{\pi^0}^2 - m_a^2] \theta_{\pi a} + \frac{1}{\sqrt{6}} [m_{K^0}^2 - 2m_a^2 + m_{\pi^0}^2] \theta_{\eta a} \right) + \text{h.c.} \]

  \[-iG_8 F_\pi K^+ \pi^- a \left( - [m_{\pi^+}^2 - m_a^2] \theta_{\pi a} + \frac{2}{\sqrt{3}} [m_{K^+}^2 - m_a^2] \theta_{\eta a} \right) \]

  \[ G_{8(\Delta I=1/2) \sim 20 x G_{27(\Delta I=3/2)} \text{ accidental cancelation!}} \]

  + we updated experimental constraints
Another interesting program [ALPs]

Many new bounds and projection in S. Gori, G. Perez, **KT** [2005.05170]

• Updated calculation $K^+ \to \pi^+ a$ finds uncertainty [two “octet” enhancements cancel]

See Yotam’s talk
Another interesting program [ALPs]

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Bounds

\[ \frac{\alpha_s}{8\pi F_a} a G \tilde{G} \]

E949\([K^+]\]

NA62\([K^+]\]

NA62+482\([K^+]\]

KTEV\([K_L]\)

LEP

F[GeV]

\(m_a[\text{MeV}]\)

10

50

100

150

200

250

300

350

400

Bounds

\(F_a[\text{GeV}]\)

0.1

1

10

10^2

10^3

10^4

10^5

1

10

100

1000

10000

\(m_a[\text{MeV}]\)

See Yotam’s talk

\[ K_L \rightarrow \pi^0 a \] is more stable, can be enhanced by two-loop without \(\epsilon_K\)

Full result, \(\text{BR}(\theta_{\pi\eta})\)

\(\text{BR}(\theta_{\pi\eta}=0)\)

\(\text{BR}(\theta_{\pi\eta})\)

\(\text{BR}(K_L \rightarrow e^+e^-)[2\delta_a(p_a/p_\pi)]\)

\(\text{BR}(K_L \rightarrow e^+e^-)[2\delta_a(p_a/p_\pi)]\)

- Updated calculation \(K^+ \rightarrow \pi^+ a\) finds uncertainty [two “octet” enhancements cancel]
Another interesting program [ALPs]

Many new bounds and projection in S. Gori, G. Perez, KT [2005.05170]

See Yotam’s talk
Summary

(1) 3-4 events in $K_L \rightarrow \pi^0 a @ KOTO$. It is more than 3σ, but still preliminary.

(2) GN bound + NA62 favors new light particle over heavy new physics.

(3) New class of models beyond GN bound. Signals from neutral mesons.

(4) Event if consistent with SM, this exercise shows how to nail down a new light state from precision measurements.

(5) KOTO & NA62 have great potential as discovery machine for $m_X < m_K$.

   Axion-like Particles [$K \rightarrow \pi X (\rightarrow \gamma \gamma)$]

   Higgs portal/Relaxion [$K \rightarrow \pi X (\rightarrow \text{inv})$]

Complementary to beam-dump and astrophysics.
Thank you!

Hope see you all in person.
Backup
The naive estimate for the BR(C.4 Octet Enhancement in SM, the ALP (pion). This, however, only captures a small part of the overall NP effects breaking and suppressed by the pion mass splitting (see Eqs. (C.4) and (C.5)). This leads to the interactions reported in Sec. 5.2, and is replaced by the ALP via K → πα transition is dominated by the naïve term while the suppressed term. Moreover,\[ K_\pi = -\frac{F_\pi}{2F_a}(\kappa_u - \kappa_d), \quad K_\eta = -\frac{F_\pi}{\sqrt{6}F_a}(\kappa_u + \kappa_d - \kappa_s), \]
\[ \delta M_{\pi\eta} = \sqrt{\frac{2}{3}}F_\pi m_u m_d m_s \left( m_u m_d + m_d m_s + m_s m_u \right) \]
These terms induce meson mixing with mesons.

The analogous comparison of the BR(C.4 Octet Enhancement in SM, the ALP (eta). This, however, only captures a small part of the overall NP effects breaking and suppressed by the eta mass splitting (see Eqs. (C.4) and (C.5)).

\[
\begin{pmatrix}
a \\
\pi \\
\eta
\end{pmatrix} \approx 
\begin{pmatrix}
1 & -\frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & -\frac{K_\eta M_\eta^2 + \delta M_{\pi\eta}}{M_\eta^2 - M_a^2} \\
\frac{K_\pi M_\pi^2}{M_\pi^2 - M_a^2} & 1 & 0 \\
K_\eta M_\eta^2 + \delta M_{\pi\eta} & 0 & 1
\end{pmatrix}
\begin{pmatrix}
a_{\text{phys}} \\
\pi_{\text{phys}} \\
\eta_{\text{phys}}
\end{pmatrix}
\]

\[ K_\pi = -\frac{F_\pi}{2F_a}(\kappa_u - \kappa_d), \quad K_\eta = -\frac{F_\pi}{\sqrt{6}F_a}(\kappa_u + \kappa_d - \kappa_s), \]
\[ \delta M_{\pi\eta} = \sqrt{\frac{2}{3}}F_\pi m_u m_d m_s \left( m_u m_d + m_d m_s + m_s m_u \right) \]

\[ \frac{\alpha_s}{8\pi F_a} aG\tilde{G} \] induces meson mixing with mesons.

**K → πα calculation updated by χPT**

\[-iG_8 F_\pi K^+ \pi^- a \left( -[m_{\pi+}^2 - m_a^2] \theta_{\pi\alpha} + \frac{2}{\sqrt{3}} [m_{K+}^2 - m_a^2] \theta_{\eta\alpha} \right) \]
\[-iG_2 F_\pi K^0 \pi^0 a \left( -\frac{1}{\sqrt{2}} [2m_{K^0}^2 - m_{\pi^0}^2 - m_a^2] \theta_{\pi\alpha} + \frac{1}{\sqrt{6}} [m_{K^0}^2 - 2m_a^2 + m_{\pi^0}^2] \theta_{\eta\alpha} \right) + h.c. \]
\[-iG_8 F_\pi K^0 \pi^0 a \left( \frac{1}{\sqrt{2}} [2m_{K^0}^2 - m_{\pi^0}^2 - m_a^2] \theta_{\pi\alpha} + \sqrt{\frac{2}{3}} [-m_{K^0}^2 + m_a^2] \theta_{\eta\alpha} \right) \]
\[-iG_2 F_\pi K^+ \pi^- a \left( \frac{1}{3} [5m_{K^+}^2 + 2m_a^2 - 7m_{\pi^+}^2] \theta_{\pi\alpha} + \frac{1}{3\sqrt{3}} [7m_{K^+}^2 - 4m_a^2 - 3m_{\pi^+}^2] \theta_{\eta\alpha} \right) \]
Heavy New Physics (Backup)

Conventional solution: SM higher dim. operator due to heavy state

\[
\mathcal{O}_{\text{BSM}}(\psi_{\text{SM}}) \supset \sum C_i \mathcal{O}_i \quad \text{to enhance } K \to \pi \nu\nu
\]

\[
\mathcal{O}_S = \bar{L} \sigma^\mu L \bar{Q}_2 \sigma_\mu Q_1 \\
\mathcal{O}_T = \bar{L} \tau^a \sigma^\mu L \bar{Q}_2 \tau^a \sigma_\mu Q_1 \\
\mathcal{O}_R = \bar{L} \sigma^\mu L \bar{s}^c \tau^a \sigma_\mu \bar{d}^c
\]

Lepton Universality
leads to charged lepton channels

\[
K_L \to \pi^0 \ell^+ \ell^- (\ell = e, \mu) \\
K_S \to \mu^+ \mu^-
\]

bounds are BR\sim 10^{-10}

Prescriptions

1. neutrino is only \(\nu_T\)
2. Impose \(C_R = C_S\)

K. Agashe, R. Contino, L. Da Rold, and A. Pomarol, [hep-ph/0605341]

Kohsaku Tobioka (FSU)
GNV scenario

$K_L \rightarrow \sigma \chi$

$K_L \rightarrow \sigma \chi [\text{Future sensitivity}]

$K^\pm \rightarrow \pi^\pm \sigma \chi$

$K_s \rightarrow \chi \chi, \sigma \sigma$

$K_s \rightarrow \pi^0 \sigma \chi$

Expected Branching Ratio

$m_\phi [\text{MeV}]$
III. Exotic Particle from Fixed Target

- They do not “tag” $K_L$ each event

- Two $\gamma$ clusters
- Asymmetry in transverse plane [evidence for $\nu \nu$]

Kohsaku Tobioka (FSU)
III. Exotic Particle from Fixed Target

• Two $\gamma$ may not be from $K_L$

proton

Gold

\[ \sim 20\text{m} \]

Neutral long-lived axion-like particle: $\alpha$

K$^+$ experiment insensitive

\[ \mathcal{L}_{\text{int}} = \frac{\alpha_s}{8\pi f_g} a G_{\mu\nu}^a \tilde{G}_{a\mu\nu} + \frac{\alpha_{\text{EM}}}{8\pi f_\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

• They do not “tag” $K_L$ each event

Very rough estimate

Lifetime: 0.1ns - 1µs

$\text{f}_g \sim \text{TeV}$ if $A^*\text{eff} \sim 10^{-4}$

Need more precise estimates for production and reconstruction (if anomaly is confirmed)
Too striking events for KOTO [30x expected]....

Talk by Nomura Jan 17, 2020

E14/KOTO Status

T. Nomura (KEK/J-PARC)

- Status of 2016-18 data analysis
- Status of 2019 data analysis
- Run plan
Property of Event #1

- Event in Run69
- Overlapped pulse in NCC

Property of Event #2

- Event in Run69
- No hits in veto detectors

Property of Event #3

- Event in Run74
- CV hits in neighboring two strips (each less than the threshold)
- HINEMOS (inner scintillator of NCC) had a hit but the timing was mis-measured.

The on-time hit was lost due to a wrong parameter for peak selection in this run period. (The large deviation existed in this detector and in this run period.)

Property of Event #4

- Event in Run79
- FB hits just outside of the veto window

Official claim is not announced.
Special run in March 2020

$K^\pm \rightarrow \pi^0 e^\pm \nu$ (BR=5.1%)

- $\pi^0$ can have a large $P_T$ ($P^\ast_{\text{max}}=215$ MeV/c)
- If $e^\pm$ goes upstream, its energy becomes low. It could be lost due to interactions with dead materials (lead in sandwich detector, support structure, etc).

The estimated number of BG relies on the $K^\pm$ flux obtained by the simulation. We need to measure it.
**Revised $P_T$-$Z$ plot**

**At KAON 2019**

S.E.S : $6.9 \times 10^{-10}$

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- $462$ 0.07 ± 0.05 0.00 ± 0.00
- $0.05 \pm 0.02$
- $0.33 \pm 0.11$ (whole blinded region)
- $473.1 \pm 4.2$ 0.08 ± 0.06 0.00 ± 0.00

**As of today**

S.E.S : $7.1 \times 10^{-10}$

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- $462$ 0.08 ± 0.04 0.00 ± 0.00
- $0.18 \pm 0.09$
- $1.01 \pm 0.16$ (whole blinded region)
- $473.5 \pm 4.2$ 0.08 ± 0.05 0.00 ± 0.00

* S.E.S. is also updated;
A run-dependent efficiency correction was not applied in the old value.

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Stay Tuned!