New Physics Searches at Kaon and Hyperon Factories

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based on community report 2201.07805 (editors: Goudzovski, Redigolo, Tobioka, JZ)

QNP2022, virtual@FSU, Tallahassee, FL, Sep 6 2022,
MAIN MESSAGES

• NA62, KOTO, KLEVER,... are not single purpose experiments
  • flagship decays: $K^+ \rightarrow \pi^+\nu\bar{\nu}, K_L \rightarrow \pi^0\nu\bar{\nu}$
    ⇒ probe heavy NP

• can also search for light NP: $K \rightarrow \pi X_{NP}$
  • ⇒ probe even higher scales
THE CASE FOR LIGHT NEW PHYSICS SEARCHES

- explored only part of the NP parameter space
- light particles: a window to high UV dynamics
THE CASE FOR LIGHT NEW PHYSICS SEARCHES

• explored only part of the NP parameter space
• light particles: a window to high UV dynamics

light mass & small coupling region
THE CASE FOR LIGHT NEW PHYSICS SEARCHES

• explored only part of the NP parameter space
• light particles: a window to high UV dynamics
LIGHT NEW PARTICLES

• how generic are light new particles?
• any spontaneously broken global symmetry
  • ⇒ massless Nambu-Goldstone boson
PORTALS

<table>
<thead>
<tr>
<th>Portal</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Photon, $A'_\mu$</td>
<td>$-\epsilon F'_{\mu\nu} B^{\mu\nu}$</td>
</tr>
<tr>
<td>Dark Higgs, $S$</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>Heavy Neutral Lepton, $N$</td>
<td>$y_N LHN$</td>
</tr>
<tr>
<td>Axion-like pseudo scalar, $a$</td>
<td>$a F\tilde{F}/f_a$, $a G\tilde{G}/f_a$, $(\bar{\psi} \gamma^\mu \gamma_5 \psi) \partial_\mu a/f_a$</td>
</tr>
</tbody>
</table>
**Light New Physics $\Rightarrow$ Probe of High Scales**

- rare decays into a light state, $X$, e.g., $K \rightarrow \pi X$,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops.
  - SM decay width power suppressed: $\Gamma_K \propto m^K_5/m^4_W$
- if through dim 5 op. suppressed by $1/f_a$
  - $\Rightarrow Br(K \rightarrow \pi \phi) \propto (m^2_W/f_a m_K)^2$
  - similar for dim 4
- no such $1/m_K$ enhancement for dim. 6 couplings
  - $Br(K \rightarrow \pi e^- \mu^+) \propto (m_W/\Lambda)^4$
UPSHOT

- searching for \( K \rightarrow \pi X \), with \( X \) light NP, expect to reach very high UV scales
EXAMPLE: FLAVOR VIOLATING QCD AXION

- QCD axion with FV couplings to quarks
  - solves the strong CP problem
  - can be a cold DM candidate
  - effectively massless in FV transitions
- general analysis, allowing for FV couplings as well

\[ \mathcal{L}_{\text{eff}} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G \tilde{G} + \frac{E}{N} \frac{\alpha_{\text{em}}}{8\pi} \frac{a}{f_a} F \tilde{F} + \frac{\partial_{\mu} a}{2 f_a} \bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j} \gamma_5) f_j \]

\[ F^{V,A}_{f_i f_j} \equiv \frac{2 f_a}{C_{f_i f_j}} \]
THE STRONGEST FV CONSTRAINTS

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623
MANY MODES

• many modes/possible NP searches possible at kaon&hyperon factories
### MANY MODES

- many modes/possible NP searches

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<table>
<thead>
<tr>
<th>Decay \ Model</th>
<th>2.1 Higgs portal</th>
<th>2.2 ALP</th>
<th>2.3 Heavy Neutral Lepton</th>
<th>2.4 Dark Photon</th>
<th>2.5 Leptonic Force (X)</th>
<th>2.6 Strongly Int. Neutrino</th>
<th>2.7 GN Violation</th>
<th>2.8 Two dark sector particles</th>
<th>2.9 Dark Baryons</th>
<th>2.10 More exotic</th>
<th>2.11 Heavy New Physics</th>
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<td>$4.1 \ K \to \pi^{+}+\text{inv}$</td>
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<td>$\pi^{0} \to \gamma A'$</td>
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<td>$4.5 \ K \to \pi\gamma\gamma$</td>
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<td>$4.6 \ K \to \pi\ell_{\alpha}\ell_{\alpha}$</td>
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<td>$4.17 LFV$</td>
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<td>$4.18 LNV$</td>
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<td>$4.19$ Rare $K_{S}$ decays</td>
<td>$K_{S} \to \pi(\pi)2\ell$</td>
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<td>$4.20$ Dark Shower</td>
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</table>

**Table 1**

- $B_{1} \to B_{2}\gamma$
- $B_{1} \to B_{2}\ell$
- $B_{1} \to B_{2}A'$

**Table 2**

- $K_{S} \to \pi^{0}$
- $K_{S} \to \gamma$
- $K_{S} \to A^{'\gamma}$
- $K_{S} \to A^{'\pi}$
- $K_{S} \to 4\ell$
- $K_{S} \to 2\gamma^{+}+\text{inv}$
- $K_{S} \to \mu^{+}$

**Table 3**

- $B \to \gamma/M+\text{inv}$

**Table 4**

- $B_{1} \to B_{2}A$

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\[QNP2022, Sep 6 2022\]
EXAMPLES

• improved sensitivities expected at next generation of kaon exp.
• $\Rightarrow$ a number of channels and/or models where this translates to a qualitative leap in phenomenology
HIGGS MIXED SCALAR

- for two to three orders of magnitude larger datasets
  - ⇒ could close the gap for Higgs-mixed scalar all the way to the BBN floor
PROMPT ALPS

• searches for prompt ALPs in $K \rightarrow \pi a$
  • either $a \rightarrow \gamma \gamma$ or $a \rightarrow e^+ e^-$
  • close the gap to constraints from beam dump searches
• $\Rightarrow$ either discovery or only $K \rightarrow \pi a_{\text{inv}}$ signature remains
• close the gap to constraints from beam dump searches

• = either discovery or only $K \rightarrow \pi a_{inv}$ signature remains
• close the gap to constraints from beam dump searches

• $\Rightarrow$ either discovery or only $K \rightarrow \pi a_{\text{inv}}$ signature remains
close the gap to constraints from beam dump searches

\[ \Rightarrow \text{either discovery or only } K \rightarrow \pi a_{\text{inv}} \text{ signature remains} \]
• close the gap to constraints from beam dump searches

• \( \Rightarrow \) either discovery or only \( K \to \pi \alpha_{\text{inv}} \) signature remains
HEAVY NEUTRINOS

- two orders improvement in $Br(K^+ \rightarrow \ell^+N)$
  - start probing minimal see-saw neutrino mass models
  - for $O(100 \text{ MeV})$ sterile neutrino masses
• start probing minimal see-saw neutrino mass models

• for $O(100 \text{ MeV})$ sterile neutrino masses
SELF INTERACTING $\nu^I S$

- order of magnitude improvement on $Br(K^+ \rightarrow \mu^+ \nu X_{inv})$
- probe fully self-interacting $\nu_{e,\mu}$ explanation of Hubble tension

J. Zupan  NP in kaon and hyperon...
\( K_L \) DECAYS

- \( K_L \to \pi^0 X_{\text{NP}} \) from \( s \to d X_{\text{NP}} \) less sensitive than 
  \( K^+ \to \pi^+ X_{\text{NP}} \)

- still, many \( K_L \) decays with leading sensitivity to NP
  - \( K_L \to \pi^0 \nu \bar{\nu} \) theoretically the cleanest SM prediction
    - will provide higher sensitivity to heavy NP than 
      \( K^+ \to \pi^+ \nu \bar{\nu} \)

- \( K_L \) decays can probe Grossman-Nir violating models
  - subleading constr. from \( K^+ \) decays

Hostert, Kaneta, Pospelov, 2005.07102
Gori, Perez, Tobioka, 2005.05170
Ziegler, Zupan, Zwicky, 2005.00451

Egana-Ugrinovic, Homiller, Meade, 1911.10203; Kitahara, Okui, Perez, Soreq, Tobioka, 1909.11111;
still, many $K_L$ decays with leading sensitivity to NP

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ theoretically the cleanest SM prediction
  - will provide higher sensitivity to heavy NP than $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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Hostert, Kaneta, Pospelov, 2005.07102
Gori, Perez, Tobioka, 2005.05170
Ziegler, Zupan, Zwicky, 2005.00451
HYPERONS

• exp. limits on rare hyperon decays are less stringent.
• but, hyperons probe different couplings than $K \to \pi$
  • e.g., $B_1 \to B_2 X_{\text{inv}}$ (vs. $K \to \pi X_{\text{inv}}$) probes
    • CP violating (vs. CP conserv.) coupl. of Higgs mixed scalar model ($X_{\text{inv}} = \phi$)
    • axial (vs. vectorial) couplings for ALPs ($X_{\text{inv}} = a$)
• can search for decays kinematically forbidden for kaons
  • example: $B \to \gamma B_{\text{dark}}$ or $B \to MB_{\text{dark}}$ in dark baryon models

Geng et al, 2112.11979
CONCLUSIONS

• rare kaon and hyperon decays: many interesting channels for light NP searches
• a clear set of targets for the next generation of experiments
BACKUP SLIDES
• in neutron star $\Lambda$, $n$, $p$, $e$ are in equilibrium

• $\Lambda \rightarrow na$ decays can cool the proto-neutron star

• $\Lambda$, $n$ have the same Fermi energy
  $\Rightarrow$ at $T=0$ Pauli blocking forbids $\Lambda \rightarrow na$ decays

• at finite temperature volume emission rate (in NR limit)

$$Q \simeq n_n (m_\Lambda - m_n) \Gamma(\Lambda \rightarrow na) \ e^{-\frac{m_\Lambda - m_n}{T}},$$

• assuming this is below neutrino emission rate 1sec after the collapse of SN1987A

  - bounds on $|F^A_{sd}|$ and $|F^V_{sd}|$ in the range $10^9 - 10^{10}$ GeV

see also Camalich et al, 2012.11632