Rare kaon decays

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Outline:
1) The NA62 experiment at CERN.
2) Hidden sector mediator & other BSM searches.
3) Rare kaon decay measurements.
4) Summary.

K→πνν decays are reviewed by Yu-Chen Tung in this session

CKM 2021 conference
25 November 2021
NA62 experiment at CERN
Main **NA62** goal: $K^+ \rightarrow \pi^+ \nu \nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~**300** participants from **31** institutions.
Unseparated hadron (p/π+/K+) beam. SPS protons: 400 GeV, nominally $3.3 \times 10^{12}$/spill. K+: 75 GeV/c ($\pm 1\%$), divergence $< 100 \, \mu$rad. Nominal beam rate: 750 MHz, K+ rate: 45 MHz; ~5 MHz K+ decays in fiducial volume.

- KTAG: Cherenkov kaon tagger, $\sigma_\tau = 70$ ps
- GTK: beam tracker
- Anti-counters
- Decay Region
- LAV: large-angle photon veto (12 stations)

- Hadronic Calorimeter (HAC)
- Muon detector (MUV)
- RICH
- LKr EM calorimeter
- Spectrometer: STRAW chambers

- In 2018: 1 year of operation $\approx 10^{18}$ protons on target; $4 \times 10^{12}$ K+ decays.
- Single event sensitivities for K+ decays: down to $\text{BR}\sim 10^{-12}$.
- Kinematic rejection factors: $1 \times 10^{-3}$ for $K^+ \rightarrow \pi^+\pi^0$, $3 \times 10^{-4}$ for $K \rightarrow \mu^+\nu$.
- Hermetic photon veto: $\pi^0 \rightarrow \gamma\gamma$ decay suppression (for $E_{\pi^0} > 40$ GeV) $\sim 10^{-8}$.
- Particle ID (RICH+LKr+HAC+MUV): $\sim 10^{-8}$ muon suppression.
v Commissioning run 2015: minimum bias data (\(\sim 3 \times 10^{10}\) protons/pulse).

v Physics run 2016 (30 days, \(\sim 1.3 \times 10^{12}\) ppp): \(2 \times 10^{11}\) useful \(K^+\) decays.

v Physics run 2017 (160 days, \(\sim 1.9 \times 10^{12}\) ppp): \(2 \times 10^{12}\) useful \(K^+\) decays.

v Physics run 2018 (217 days, \(\sim 2.3 \times 10^{12}\) ppp): \(4 \times 10^{12}\) useful \(K^+\) decays.

v Run 2 in progress: June 2021 till LS3 (\(\sim 3 \times 10^{12}\) ppp).
Recent NA62 results

Searches:
- $K^+ \rightarrow \pi^+ X$: JHEP 06 (2021) 93; JHEP 03 (2021) 58.
- $\pi^0 \rightarrow$ invisible: JHEP 02 (2021) 201.
- HNL production: PLB 807 (2020) 135599; PLB 816 (2021) 136259.
- LFV/LNV: PLB 797 (2019) 134794; PRL 127 (2021) 131802; new results.

Rare decay measurements:
- SM decays (to be published soon): $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, $K^+ \rightarrow \pi^0 e^+ \nu \gamma$. 
Hidden-sector with $K^+ \to \pi^+ \nu \nu$

- Signal regions $R1, R2$: search for $K^+ \to \pi^+ X$ ($X$=invisible), $0 \leq m_X \leq 110 \text{ MeV/c}^2$ and $154 \leq m_X \leq 260 \text{ MeV/c}^2$.
  - Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - Main background: $K^+ \to \pi^+ \pi^0$.

- The $\pi^+ \pi^0$ region: search for $\pi^0 \to \text{invisible}$.
  - SM rate: $\text{BR}(\pi^0 \to \nu \nu) \sim 10^{-24}$.
  - Observation = BSM physics.
  - Reduction of $\pi^0 \to \gamma \gamma$ background: optimised $\pi^+$ momentum range.
  - Interpretation as $K^+ \to \pi^+ X$, with $m_X$ between $R1$ and $R2$. 

Squared missing mass (2018 data)

![Graph showing signal regions and backgrounds]

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Search for $K^+ \rightarrow \pi^+ X$ (Run 1 data)

- Mass resolution improves with $m_X$ and is $\delta m_X \sim 40$ MeV/c$^2$ at $m_X=0$.
- Upper limits of $\text{BR}(K^+ \rightarrow \pi^+ X)$ established depending on $X$ mass and lifetime.
- Improvement on BNL-E949 over most of $m_X$ range. [PRD79 (2009) 092004]
- Interpretation within the minimal dark scalar model (decays to visible SM particles only). [PBC Model BC4, J Phys G47 (2020) 010501]
- Note the KOTO result based on 2015 data. [PRL122 (2019) 021802]
Search for $\pi^0 \to$ invisible (2017 data)

- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: simulation based on single-photon efficiency measured with $K^+ \to \pi^+\pi^0$ decays.
- Rejection of $\pi^0 \to \gamma\gamma$ decays for $K^+ \to \pi^+\nu\nu$ analysis: $\varepsilon \approx 10^{-8}$.
- For $\pi^0 \to$ invisible search ($25 < p_{\pi} < 40$ GeV/c): $\varepsilon = (2.8^{+5.0}_{-2.1}) \times 10^{-9}$

Search for $\pi^0 \to$ invisible: (1/3 of the 2017 data set).

- $K_{\pi\nu\nu}$ trigger and selection used, with $0.015 < m^2_{\text{miss}} < 0.021$ GeV$^2$/c$^4$.
- Expected $\pi^0 \to \gamma\gamma$ events: $10^{+22}_{-8}$, events observed: 12.

UL at 90% CL on BR($K^+ \to \pi^+X$) vs $m_X$
HNL production search: data sample

- Triggers used: $K_{\pi\nu\nu}$ for $K^+\to e^+N$; Control/400 for $K^+\to \mu^+N$.
- Numbers of $K^+$ decays in fiducial volume:
  - $N_K=(3.52\pm0.02)\times10^{12}$ in positron case; $N_K=(4.29\pm0.02)\times10^9$ in muon case.
- Squared missing mass: $m_{\text{miss}}^2=(P_K-P_\ell)^2$, using STRAW and GTK trackers.
- HNL production signal: a spike above continuous missing mass spectrum.

### Squared missing mass: $(P_K-P_\ell)^2$

**$K^+\to e^+\nu$**
- BR: $1.6\times10^{-5}$
- 3.5M candidates

**$K^+\to \mu^+\nu$**
- BR: 64%
- 2.2G candidates

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HNL production search: results

- Full Run 1 dataset analysed.
- Improvement over earlier production searches by up to two orders of magnitude in terms of $|U_{\ell 4}|^2$.
- For $|U_{e4}|^2$, the BBN-allowed range excluded up to 350 MeV. [NPB 590 (2000) 562]
- For $|U_{\mu 4}|^2$, reached BNL-E949 sensitivity, and extended the HNL mass range to 384 MeV.
- New upper limit at 90% CL: $\text{BR}(K^+ \rightarrow \mu^+ \nu \nu \nu) < 1.0 \times 10^{-6}$. Similar limits on $\text{BR}(K^+ \rightarrow \mu^+ \nu X)$, with $X=\text{invisible}$. [Theory: PRL 124 (2020) 041802]
Candidates observed: 8357
Background: 0.07%
BR($K^+ \rightarrow \pi^+\mu^+\mu^-$) = $(0.962 \pm 0.025) \times 10^{-7}$
$K^+$ decays in FV: $(7.94 \pm 0.23) \times 10^{11}$

Expected background: $0.91 \pm 0.41$ evt
Candidates observed: 1
BR($K^+ \rightarrow \pi^-\mu^+\mu^+$) < $4.2 \times 10^{-11}$ at 90% CL

[PLB797 (2019) 134794]
Search for $K^+\rightarrow\pi^-e^+e^+$ (Run 1)

SM selection: $m(\pi^+e^+e^-)$

LNV selection: $m(\pi^-e^+e^+)$

Candidates observed: 11041

$\text{BR}(K^+\rightarrow\pi^+e^+e^-) = (3.00\pm0.09)\times10^{-7}$

$K^+$ decays in FV: $(1.015\pm0.032)\times10^{12}$

Expected background: $0.43\pm0.09$ evt

Candidates observed: 0

$\text{BR}(K^+\rightarrow\pi^-e^+e^+)<5.3\times10^{-11}$ at 90% CL

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A new result - first presented today
Search for $K^+ \rightarrow \pi^- \pi^0 e^+ e^+$ (Run 1)

- Normalisation to the SM decay $K^+ \rightarrow \pi^+ e^+ e^-$.  
- The neutral pion is reconstructed in the LKr calorimeter via $\pi^0 \rightarrow \gamma \gamma$ decay.

| Mode | Control region | Signal region |
|------|----------------|---------------|
| $K^+ \rightarrow \pi^+ \pi^0 \pi_D^0$ | 0.16 ± 0.01 | 0.019 |
| $K^+ \rightarrow \pi^+ \pi^0 D \gamma$ | 0.06 ± 0.01 | 0.004 |
| $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ | 0.05 ± 0.02 | – |
| $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$ | 0.01 | 0.001 |
| Pileup | 0.20 ± 0.20 | 0.020 ± 0.020 |
| Total | 0.48 ± 0.20 | 0.044 ± 0.020 |
| Data | 1 | 0 |

Expected background: $0.044 \pm 0.020$ evt

Candidates observed: 0

$\text{BR}(K^+ \rightarrow \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL

First search for this mode.

A new result - first presented today
Search for $K^+\rightarrow\pi\mu e$ decays (Run 1)

**LNV decay: $m(\pi^-\mu^+e^+)$**

- $K^+ \rightarrow \pi^+\pi^-\pi^-$
- $K^+ \rightarrow \pi^+\pi^-e^+\nu$
- $K^+ \rightarrow \pi^+\pi^-\mu^+\mu^-$
- $K^+ \rightarrow \pi^+\pi^-e^+\nu$
- Total uncertainty

| Events / (4 MeV/c²) |
|----------------------|
| 10^6                  |
| 10^5                  |
| 10^4                  |
| 10^3                  |
| 10^2                  |
| 10^1                  |
| 10^0                  |

**LFV decay: $m(\pi^+\mu^-e^+)$**

- $K^+ \rightarrow \pi^+\pi^-e^+\nu$

| Events / (4 MeV/c²) |
|----------------------|
| 10^6                  |
| 10^5                  |
| 10^4                  |
| 10^3                  |
| 10^2                  |
| 10^1                  |
| 10^0                  |

**K^+ decays in FV:** \((1.33 \pm 0.02) \times 10^{12}\)

**Expected background:** \(1.07 \pm 0.20\) evt

**Candidates observed:** 0

**BR($K^+\rightarrow\pi^-\mu^+e^+)<4.2 \times 10^{-11}$ at 90% CL**

**Expected background:** \(0.92 \pm 0.34\) evt

**Candidates observed:** 2

**BR($K^+\rightarrow\pi^+\mu^-e^+)<6.6 \times 10^{-11}$ at 90% CL**

**BR($\pi^0\rightarrow\mu^-e^+)<3.2 \times 10^{-10}$ at 90% CL**
The complete Run 1 sample used.
Candidates observed: 28011.
Ten times larger samples wrt NA48/2.
Expected bkg: $12.5\pm12.5$ events.
Form-factor parameters and model-dependent BR measurement:

|                  | $a$  | $b$  | $\mathcal{B}_{\pi\mu\mu} \times 10^8$ |
|------------------|------|------|----------------------------------------|
| **Best fit**     | -0.592 | -0.699 | **9.27** |
| **Errors**       | $\delta a$ | $\delta b$ | $\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$ |
| **Statistical**  | 0.013 | 0.046 | 0.07 |
| **Systematic**   | 0.005 | 0.026 | 0.06 |
| Reconstruction efficiency | 0.005 | 0.024 | 0.05 |
| Beam & pileup simulation | 0.001 | 0.005 | 0.04 |
| Trigger efficiency | 0.000 | 0.001 | 0.01 |
| Background       | 0.007 | 0.035 | 0.08 |
| **Total systematic** | 0.001 | 0.003 | 0.04 |
| **External**     | 0.015 | 0.058 | 0.11 |

**NA62 Preliminary**

- E865, $K_{\pi ee}$ (1999)
  - 10300 events – statistical error only
- NA48/2, $K_{\pi ee}$ (2009)
  - 7253 events
- NA48/2, $K_{\pi\mu\mu}$ (2011)
  - 3120 events
- NA62, $K_{\pi\mu\mu}$ (2020) – this result
  - 28011 events
\[ R_j = \frac{\mathcal{B}(Ke3\gamma)}{\mathcal{B}(Ke3)} = \frac{\mathcal{B}(K^+\to\pi^0 e^+\nu\gamma \mid E_{\gamma}^j, \theta_{e,\gamma}^j)}{\mathcal{B}(K^+\to\pi^0 e^+\nu(\gamma))} \]

|                | \( E_{\gamma} \) cut (*) | \( \theta_{e,\gamma} \) cut (*) |
|----------------|---------------------------|---------------------------------|
| \( R_1 \times 10^2 \) | \( E_{\gamma} > 10 \text{ MeV} \) | \( \theta_{e,\gamma} > 10^\circ \) |
| \( R_2 \times 10^2 \) | \( E_{\gamma} > 30 \text{ MeV} \) | \( \theta_{e,\gamma} > 20^\circ \) |
| \( R_3 \times 10^2 \) | \( E_{\gamma} > 10 \text{ MeV} \) | \( 0.6 < \cos \theta_{e,\gamma} < 0.9 \) |

T-odd observable \( \xi \) (in the kaon rest frame):
\[
\xi = \frac{\overrightarrow{p}_{\gamma} \cdot (\overrightarrow{p}_e \times \overrightarrow{p}_{\pi})}{m_K^3}; \quad A_\xi = \frac{N_+ - N_-}{N_+ + N_-}
\]

### Missing mass spectrum

**Candidates observed:** 130k
(for \( R_1: E_\gamma > 10 \text{ MeV}, \theta_{e\gamma} > 10^\circ \)).

**Background contamination:** 0.5%.

### NA62 Preliminary

|                | \( O(p^6) \) ChPT  | ISTRA+  | OKA               | NA62 preliminary |
|----------------|---------------------|---------|-------------------|------------------|
| \( R_1 \times 10^2 \) | 1.804 ± 0.021       | 1.81 ± 0.03 ± 0.07 | 1.990 ± 0.017 ± 0.021 | 1.684 ± 0.005 ± 0.010 |
| \( R_2 \times 10^2 \) | 0.640 ± 0.008       | 0.63 ± 0.02 ± 0.03 | 0.587 ± 0.010 ± 0.015 | 0.599 ± 0.003 ± 0.005 |
| \( R_3 \times 10^2 \) | 0.559 ± 0.006       | 0.47 ± 0.02 ± 0.03 | 0.532 ± 0.010 ± 0.012 | 0.523 ± 0.003 ± 0.003 |

### NA62 asymmetry measurements:

|                | \( R_1 \) selection | \( R_2 \) selection | \( R_3 \) selection |
|----------------|----------------------|----------------------|----------------------|
| \( A_\xi \times 10^2 \) | \(-0.1 \pm 0.3_{\text{stat}} \pm 0.2_{\text{MC}}\) | \(-0.3 \pm 0.4_{\text{stat}} \pm 0.3_{\text{MC}}\) | \(-0.9 \pm 0.5_{\text{stat}} \pm 0.4_{\text{MC}}\) |
NA62 Run 1 in 2016–18: $2.2 \times 10^{18}$ POT; $6 \times 10^{12} K^+$ decays in flight. Several dedicated trigger lines: a broad programme of rare decay measurement and hidden-sector searches.

Recent results on hidden-sector mediator production and other BSM physics in kaon decays:

- extension of the $K^+ \rightarrow \pi^+ \nu \nu$ analysis: search for $K^+ \rightarrow \pi^+ X$ and $\pi^0 \rightarrow \text{inv}$;
- searches for $K^+ \rightarrow \ell^+ N$ and $K^+ \rightarrow \mu^+ \nu X$ decays;
- searches for LNV/LFV $K^+$ and $\pi^0$ decays (six modes so far).

Recent results from rare kaon decay measurements, based on world’s largest decay samples:

- $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ analysis based on $28k$ candidates;
- $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ analysis based on $130k$ candidates.
Spares
Short-term plans: NA62 Run 2

KOTO limit (2015 data):
\[ \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9} \]

\[ \text{PRL122 (2019) 021802} \]

2016–18 data also published:
\[ \text{PRL126 (2021) 121801} \]

NA62 Run 2 (up to LS3):
- Higher beam intensity.
- Optimised beamline, new veto detectors.
- Fourth kaon beam tracker station.
- \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \) measurement in low-background, high-acceptance regime, at \( O(10\%) \) precision.
- Collection of \( 10^{18} \) POT in up to 90 days in beam dump mode.

Expected Run 1+2 sensitivity:
\[ \delta \text{BR/BR} \approx 10\% \]
Long-term plans: $K^+\to \pi^+\nu\nu$ at CERN

A possible next step after LS3 (in ~2028): an in-flight $K^+\to \pi^+\nu\nu$ experiment at $\times 4$ beam intensity (present SPS limit), aiming at ~5% precision.

✓ Challenge: 20–40 ps time resolution for key detectors to keep random veto under control, while maintaining other performances.

New pixel beam tracker (GTK):
- time resolution: <50 ps per plane;
- pixel size: $<300 \times 300 \ \mu m^2$;
- efficiency: >99% per plane (incl. fill factor);
- material budget: 0.3–0.5% $X_0$;
- beam intensity: 3 GHz on $30 \times 60 \ mm^2$;
- peak intensity: 8.0 MHz/mm².

New STRAW spectrometer:
- operation in vacuum;
- straw length/diameter: 2.2 m/5 mm;
- trailing time resolution: ~6 ns per straw;
- maximum drift time: ~80 ns;
- layout: ~21000 straws (4 chambers);
- material budget: 1.5%$X_0$.
Long-term plans: $K_L \rightarrow \pi^0 \nu \nu$ at CERN

- **KLEVER**: a high-energy experiment ($10^{19}$ POT/year) complementary to KOTO.
- Photons from $K_L$ decays boosted forward: veto coverage only up to 100 mrad.
- Vacuum tank layout and fiducial volume similar to NA62.
- A possible intermediate NA62/KLEVER step: a $K_L \rightarrow \pi^0 \ell^+ \ell^-$ experiment.

Target sensitivity:
60 SM $K_L \rightarrow \pi^0 \nu \nu$ events with $S/B \sim 1$ in 5 years of running;

$$\delta BR(K_L \rightarrow \pi^0 \nu \nu)/BR(K_L \rightarrow \pi^0 \nu \nu) \sim 20\%.$$