The search for new physics with rare kaon decays at the CERN SPS

University of Michigan
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for the NA62 Collaboration
Precision physics and rare decays

How can we extend the search for new physics to high effective scales?

<table>
<thead>
<tr>
<th>Energy frontier</th>
<th>Intensity frontier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct search</td>
<td>Indirect investigation</td>
</tr>
<tr>
<td>Create new degrees of freedom in lab</td>
<td>Evidence of new degrees of freedom as alteration of SM rates</td>
</tr>
<tr>
<td>Explore spectroscopy of new d.o.f.</td>
<td>Explore symmetry properties of new d.o.f</td>
</tr>
<tr>
<td>$\Delta \sim 1-10$ TeV</td>
<td>$\Delta \sim 1-1000$ TeV</td>
</tr>
</tbody>
</table>

A rare decay is useful as an NP probe if:

- Process is (strongly) suppressed in the SM
- Parameter to be measured precisely calculated in SM
- There are specific predictions for NP contributions

Examples of what may be studied with rare decays:

- Explicit violations of the SM (e.g., lepton flavor violation)
- Tests of fundamental symmetries such as $CP$ and $CPT$
- Search for new d.o.f. in the flavor sector, e.g., in FCNC processes
- Strong interaction dynamics at low energy using exclusive processes
What have kaons taught us?

Strangeness, concept of flavor quark model
\(\tau-\theta\) puzzle: hint of \(P\) violation, confirmation of weak \(V-A\) structure
\(CP\) violation in mixing of neutral kaons
Suppression of \(K_L \rightarrow \mu^+\mu^-\): GIM mechanism and the charm quark
Direct CP violation in \(K \rightarrow \pi\pi\) and the CKM paradigm
Quiet successes of confirmation: conservation of lepton flavor, \(V_{us}\), etc.

Kaons have been fundamental in the development of the SM flavor sector
A history of kaons at the SPS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Years</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA31</td>
<td>1982-1993</td>
<td>$1^{st}$ generation experiment to measure $\text{Re } \epsilon'/\epsilon$</td>
</tr>
<tr>
<td>NA48</td>
<td>1992-2000</td>
<td>Next generation measurement of $\text{Re } \epsilon'/\epsilon$</td>
</tr>
<tr>
<td>NA48/1</td>
<td>2000-2002</td>
<td>Rare $K_S$ decays, e.g., $K_S \rightarrow \pi^0 \ell^+ \ell^-$</td>
</tr>
<tr>
<td>NA48/2</td>
<td>2003-2007</td>
<td>Direct CPV in $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$</td>
</tr>
<tr>
<td>NA62</td>
<td>2007-2008</td>
<td>Measurement of $R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$ with NA48</td>
</tr>
<tr>
<td></td>
<td>2007-2013</td>
<td>Design, construction, installation</td>
</tr>
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<td>From 2014</td>
<td>Measurement of $K^\pm \rightarrow \pi^\pm \nu\nu$</td>
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</tbody>
</table>
Rare kaon decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\Gamma_{SD}/\Gamma$</th>
<th>Theory err.*</th>
<th>SM BR $\times 10^{11}$</th>
<th>Exp. BR $\times 10^{11}$ (Sep 2019)</th>
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<tr>
<td>$K_L \to \mu^+\mu^-$</td>
<td>10%</td>
<td>30%</td>
<td>79 ± 12 (SD)</td>
<td>684 ± 11</td>
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<td>&gt;99%</td>
<td>2%</td>
<td>3.4 ± 0.6</td>
<td>&lt; 300†</td>
</tr>
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*Approx. error on LD-subtracted rate excluding parametric contributions  †90% CL

FCNC processes dominated by Z-penguin and box diagrams

Highly suppressed in Standard Model

Rates related to $V_{CKM}$ with minimal non-parametric uncertainty
Rare kaon decays

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Rates for FCNC decays are suppressed by GIM mechanism:

$$V^\dagger V = 1 \quad V_{us}^* V_{ud} L(x_u) + V_{cs}^* V_{cd} L(x_c) + V_{ts}^* V_{td} L(x_t) \approx 0$$

$$x_q = m_q^2/m_W^2$$

$L(x_q) \sim x_q \ln x_q \quad (x_q \to 0)$
Rare kaon decays

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No LD contributions from states with intermediate $\gamma$s for $K \rightarrow \pi \nu \bar{\nu}$
$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model

The branching ratio in the Standard Model is given by

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ \left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) + \frac{\text{Re} \lambda_c}{\lambda} P_c(X) \right)^2 \right]$$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = \kappa_L \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2$$
$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model

Loop functions favor top contribution

\[ \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+ \]
\[ \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = \kappa_L \]

\[ \left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) + \frac{\text{Re} \lambda_c}{\lambda} P_c(X) \right)^2 \right] \]
$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model

Loop functions favor top contribution

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \kappa_+$$
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$$\left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \frac{\text{Re} \lambda_c}{\lambda} P_c(X) \right]^2$$

QCD corrections for charm diagrams contribute to uncertainty

$$\lambda = V_{us}$$
$$\lambda_c = V_{cs}^* V_{cd}$$
$$\lambda_t = V_{ts}^* V_{td}$$
$$x_q \equiv m_q^2 / m_W^2$$
$K \to \pi \nu \bar{\nu}$ in the Standard Model

Hadronic matrix element obtained from $\text{BR}(K_{e3})$ via isospin rotation

Loop functions favor top contribution

QCD corrections for charm diagrams contribute to uncertainty

\[
\text{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = \kappa_+ \left[ \left( \frac{\text{Im} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \left( \frac{\text{Re} \lambda_t}{\lambda^5} X(x_t) \right)^2 + \frac{\text{Re} \lambda_c}{\lambda} P_c(X) \right]^2
\]

$\kappa_+ = r_{K^+} \frac{3 \alpha^2 \text{BR}(K^+ \to \pi^0 e^+ \nu)}{2 \pi^2 \sin^4 \theta_W} \lambda^8$

\[
\lambda_c = V_{cs}^* V_{cd}
\]

\[
\lambda_t = V_{ts}^* V_{td}
\]

$x_q \equiv m_q^2/m_W^2$
$K \rightarrow \pi \nu \bar{\nu}$ and the unitarity triangle

BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) = $(8.39 \pm 0.30) \times 10^{-11} \cdot \left( \frac{|V_{cb}|}{0.0407} \right)^{2.8} \cdot \left( \frac{\gamma}{73.2^\circ} \right)^{0.74}

BR($K_L \rightarrow \pi^0 \nu \bar{\nu}$) = $(3.36 \pm 0.05) \times 10^{-11} \cdot \left( \frac{|V_{ub}|}{3.88 \times 10^{-3}} \right)^2 \cdot \left( \frac{|V_{cb}|}{0.0407} \right)^2 \cdot \left( \frac{\sin \gamma}{\sin 73.2^\circ} \right)^2

Dominant uncertainties for SM BRs are from CKM matrix elements

Intrinsic theory uncertainties 1.5-3.5%

Measuring BRs for both $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ can determine the CKM unitarity triangle independently from $B$ inputs:

- Over-constrain CKM matrix → reveal NP effects
- Sensitivity complementary to $B$ decays

Buras et al., JHEP 1511

Excluded area has CL > 0.95

Prospective study on rare Kaons
The search for new physics with rare kaon decays

$K \rightarrow \pi \nu \bar{\nu}$ and new physics

New physics affects $K^+$ and $K_L$ BRs differently
Measurements of both can discriminate among NP scenarios

- Models with CKM-like flavor structure
  - Models with MFV

- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - $Z/Z'$ models with pure LH/RH couplings
  - Littlest Higgs with $T$ parity

- Models without above constraints
  - Randall-Sundrum

- Grossman-Nir bound
  Model-independent relation

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \times 10^{11}$$

$$\Delta_L \text{ or } \Delta_R \text{ only: } |\epsilon_K|_{NP} \propto \text{Im} \frac{\Delta_{L(R)}^2}{M_{Z'}^2}$$

Buras, Buttazzo, Knechtens
JHEP 1511

$\text{BR}(K_L \rightarrow \pi^+ \nu \bar{\nu}) \times 10^{11}$

$\Delta_L \text{ or } \Delta_R \text{ only: } |\epsilon_K|_{NP} \propto \text{Im} \frac{\Delta_{L(R)}^2}{M_{Z'}^2}$
The NA62 experiment at the CERN SPS
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with decay in flight

**Signal:**
$\text{BR} = (8.4 \pm 1.0) \times 10^{-11}$

- $K$ track in
- $\pi$ track out
- No other particles in final state
- $M^2_{\text{miss}} = (p_K - p_{\pi})^2$

**Main backgrounds:**
- $K^+ \rightarrow \mu^+ \nu(\gamma)$
  $\text{BR} = 63.5\%$
- $K^+ \rightarrow \pi^+ \pi^0(\gamma)$
  $\text{BR} = 20.7\%$

**Selection criteria:**
- $K^+$ beam identification
- Single track in final state
- $\pi^+$ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- $\gamma$ rejection ($\varepsilon_{\pi^0} \sim 3 \times 10^{-8}$)
K12 high-intensity $K^+$ beamline

Primary SPS proton beam:
- $p = 400$ GeV protons
- Nominal intensity: $3.3 \times 10^{12}$ protons/pulse (ppp)
- Typical duty cycle: 4.8 s/16.8 s
  - Flat-top: 3 eff. s

High-intensity, unseparated secondary beam
- $p = 75$ GeV with $\Delta p/p \sim 1$

Total rate:
- $525$ MHz $\pi$
- $170$ MHz $p$
- $45$ MHz $K$

Decay volume:
- 60 m long, starting at $z = 102$ m from target
- 10% of $K^+$ decay in FV ($\beta\gamma\tau = 560$ m)

Up to $5 \times 10^{12} K^+$ decays/yr
The search for new physics with rare kaon decays

- High-rate, precision tracking
- Redundant particle ID & $\mu$ vetoes
- Hermetic photon vetoes
- High-performance EM calorimeter

400 GeV primary $p$ from SPS
75 GeV positive secondary beam
- 750 MHz total rate
- 45 MHz $K^+$ in beam

The NA62 experiment at the SPS

- Beam tracking
  Si pixels, 3 stations

- KTAG
  Differential Cerenkov for $K^+$ ID in beam

- CHANTI
  Charged veto

- Dipole spectrometer
  4 straw-tracker stations

- LAV
  Large angle photon vetoes
  OPAL lead glass

- RICH
  RICH $\mu/\pi$ ID
  1 atm Ne

- MUV
  $\mu$ veto
  Fe/scint

- GIGATRACKER

- 5 MHz $K^+$ decays

- Fiducial volume ~60m
  $10^{-6}$ mbar

- $400$ GeV primary $p$ from SPS
- $75$ GeV positive secondary beam

- 750 MHz total rate
- 45 MHz $K^+$ in beam

- Beam tracking
  Si pixels, 3 stations

- KTAG
  Differential Cerenkov for $K^+$ ID in beam

- CHANTI
  Charged veto
High-rate beam tracking

Gigatracker (GTK) beam spectrometer:
3 stations of hybrid silicon pixel detectors installed in beamline achromat

- $\sigma_t = 100$ ps
- $\sigma_p = 0.15$ GeV
- $\sigma_\theta = 16$ mrad

62 × 27 mm² sensor area
300 × 300 $\mu$m² pixels

Thickness in active area 510 $\mu$m:
- Sensor 200 $\mu$m + readout chip 100 $\mu$m
- Cooling plate 210 $\mu$m
Beam particle identification

- Must identify 45 MHz of $K^+$ in 750 MHz beam
- Good time resolution ($\sigma_t < 100$ ps) needed to determine event $t_0$
- **KTAG: Differential Cerenkov detector** based on CEDAR-W with new light collection system
  \[ \sigma_t = 70 \text{ ps} \]
  \[ \varepsilon_K > 95\% \quad (N_C \geq 5) \]
  \[ \varepsilon_\pi < 10^{-4} \]

Nominal $N_2$ gas pressure = 1.75 bar
Precision downstream tracking

Low-mass, precision tracking: 4 straw chambers in vacuum

- 4 views per chamber \((xy, uv)\)
- 4 staggered layers of straws per view
- 2.1 m long, 9.6 mm Ø mylar tubes
- Central gap in each view for beam
- Gas mixture 70% Ar + 30% CO₂
- 1.8% \(X_0\) total
- \(\sigma \leq 130\, \mu\text{m} \) (1 view)
- \(\sigma_p/p \sim 0.3\text{-}0.4\%\)
- 99% hit eff
- \(\sigma_\theta \sim 20\text{-}60\, \mu\text{rad}\)
Redundant downstream PID

Ring-imaging Cerenkov (RICH)

Mirror mosaic
\( f = 17 \text{ m} \)

17-m vessel: Ne at 1 atm
\( n - 1 = 6.7 \times 10^{-5} \)

Hadronic calorimeters and muon vetoes

- **MUV1**: Iron/scintillator 4.1 \( \lambda_{\text{int}} \)
- **MUV2**: Iron/scintillator 3.7 \( \lambda_{\text{int}} \)
- **Muon filter**: 80 cm iron 4.8 \( \lambda_{\text{int}} \)
- **MUV3**: Scintillator tiles –

Overall \( \mu \) rejection from LKr + MUV1-2 ~ \( 10^{-6} \)
MUV3 provides low-level trigger veto

E\( \pi \) > 75%
E\( \mu \) ~ \( 10^{-3} \)
\( \sigma_\ell = 100 \text{ ps} \)
**Hermetic photon veto**

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\theta$ [mrad]</th>
<th>Max. $1 - \varepsilon$</th>
</tr>
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<tbody>
<tr>
<td>LAV</td>
<td>8.5 - 50</td>
<td>$10^{-4}$ at 200 MeV</td>
</tr>
<tr>
<td>LKr</td>
<td>1 - 8.5</td>
<td>$10^{-3}$ at 1 GeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$10^{-5}$ at 10 GeV</td>
</tr>
<tr>
<td>IRC &amp; SAC</td>
<td>&lt; 1</td>
<td>$10^{-4}$ at 5 GeV</td>
</tr>
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$K^+ \rightarrow \pi^+\pi^0$  
BR = 21%  
Cut $p_{\pi^+} < 35$ GeV gives $2\gamma$ with 40 GeV  
Rejection from kinematics $10^{-4}$

**Large-Angle Vetoes (LAV)**

Energy resolution $\sim 10\%$ at 1 GeV  
Time resolution $\sim 1$ ns  
Operation in vacuum $10^{-6}$ mbar

12 stations of different size
NA48 liquid krypton calorimeter

**Forward veto** ($1 < \theta < 8.5$ mrad)
Need $1 - \varepsilon < 10^{-5}$ for $E_\gamma > 5$ GeV

Quasi-homogeneous ionization calorimeter
13248 channels
Readout towers 2x2 cm$^2$
Depth 127 cm = 27 $X_0$

$$\frac{\sigma_E}{E} = 3.2\% \oplus \frac{9\%}{\sqrt{E}} \oplus 0.42\%$$

$$\sigma_x = \sigma_y = \frac{4.2 \text{ mm}}{\sqrt{E}} \oplus 0.06 \text{ mm}$$

$$\sigma_t = \frac{2.5 \text{ ns}}{\sqrt{E}}$$

NA62 readout electronics:
14-bit 40 MHz FADCs with large buffers to handle 1 MHz L0 rate
After commissioning in 2014-2015, NA62 Run 1 from 2016-2018 (until LS2)  
2.2 \times 10^{18} \text{ protons on target in total} - \text{three rounds of } K^+ \rightarrow \pi^+ \nu \nu \text{ analysis}

\begin{itemize}
  \item **2016**
    \begin{itemize}
      \item 40\% of nominal intensity
      \item $0.12 \times 10^{12} K^+$ decays in FV
      \item PLB 791 (2019) 156-166
    \end{itemize}
  \item **2017**
    \begin{itemize}
      \item 60\% of nominal intensity
      \item $1.5 \times 10^{12} K^+$ decays in FV
      \item JHEP 11 (2020) 042
    \end{itemize}
  \item **2018**
    \begin{itemize}
      \item 60-70\% of nominal intensity
      \item $2.6 \times 10^{12} K^+$ decays in FV
      \item JHEP 06 (2021) 093
    \end{itemize}
\end{itemize}

Nominal intensity = $3.3 \times 10^{12} \text{ pot}/3 \text{ eff sec}$

Instantaneous beam intensity can vary by up to a factor of 2
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ analysis scheme

**PNN trigger: 1 track + missing energy**

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<th>Level 1</th>
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<td>FPGAs in TEL62 acquisition boards</td>
<td>Fast online reconstruction</td>
</tr>
<tr>
<td>RICH signal (provides time reference)</td>
<td>$K^+$ identification from KTAG</td>
</tr>
<tr>
<td>1-4 CHOD hits, not in opposite quadrants</td>
<td>$\leq 2$ LAV hits in time</td>
</tr>
<tr>
<td>$E(LKr) &lt; 30$ GeV and $\leq 1$ LKr clusters</td>
<td>1 positive track with $p &lt; 50$ GeV</td>
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<tr>
<td>No MUV3 hits</td>
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**Offline selection:**

1. Reconstruct vertex between beam and secondary tracks
2. Kinematic selection
3. $\pi$ identification/µ rejection (RICH + LKr/MUV1-2 + MUV3)
4. Veto any extra activity (LAV, LKr, IRC-SAC, multiplicity conditions, etc.)

**Normalize to $K^+ \rightarrow \pi\pi^0(\gamma)$ events collected with minimum-bias trigger**

- Similar selection criteria as for $\pi^+\nu\nu$ but no photon veto
$K \rightarrow \pi$ vertex selection

- Track in GTK in time with KTAG signal
- Single positive track in downstream detectors (straw, RICH)
- Upstream-downstream timing cuts ($\sigma_t \sim 100$ ps)
- Vertex reconstruction:
  Closest approach < 4 mm
  110 m < $z_{reco}$ < 165 m
- Kinematic cuts to define:
  Signal regions
  Background control regions
  Control samples
- Signal and background control regions blinded

$m^2_{\text{miss}} = (P_K - P_\pi)^2$ with $m_\pi$ hypothesis

$\sigma(m^2_{\text{miss}}) \sim 10^{-3}$ GeV$^2$

R1: $0 < m^2_{\text{miss}} < 0.10$ GeV$^2$ \hspace{1cm} $15 < p < 35$ GeV
R2: $0.26 < m^2_{\text{miss}} < 0.68$ GeV$^2$ \hspace{1cm} $15 < p < 35$ GeV (45 GeV for 2018)
Track-driven likelihood discriminant:
- Direction from spectrometer track
- Estimate ring radius for $\mu/\pi/e$
- Obtain likelihood from ring fit
- Additional cuts on $m_{track}$ from free ring fit and straw momentum measurement

Veto activity in MUV3

BDT classifier with 13 variables:
- Electromagnetic calorimeter (LKr),
- Hadronic calorimeters (MUV1-2)
- Energy, energy sharing, cluster shape
Photon veto efficiency

Evaluate $\pi^0$ rejection with $K \to \pi\pi^0$ decays, $0.15 < m_{\text{miss}}^2 < 0.21 \text{ GeV}^2$

Single-photon efficiencies from tag-and-probe study:

- Selection and trigger stream same as for $K^+ \to \pi^+\nu\nu$ (1/3 of data set)
- Reconstruct $K^+$ and one $\gamma$ from $\pi^0$
- Predict location of second $\gamma$
- Cuts to eliminate $\pi^+\pi^0\gamma$ events

Inefficiency includes $\gamma$ losses from interaction with material

Obtain correction for method bias by comparing MC results with MC truth

Fold single-particle efficiencies with MC kinematics for $\pi^+\pi^0(\gamma)$

$$
\varepsilon_{\pi^0} = 2.7^{+1.5}_{-1.9} \times 10^{-8}
$$

$$
15 \text{ GeV} < p_{\pi^+} < 35 \text{ GeV}
$$

Derive limit on $\text{BR}(\pi^0 \to \text{invisible})$

$$
\text{BR} < 4.4 \times 10^{-9} \ (90\% \ CL)
$$

JHEP 02 (2021) 201
Single event sensitivity (SES)

\[ \text{SES} = \frac{\text{BR}^{\text{exp}}(K^+ \rightarrow \pi^+ \pi^0)}{N_{\pi\pi}^{\text{exp}}} = \frac{1}{N_K^{\text{obs}} \epsilon_{\pi\nu\nu}} \]

- \( N_{\pi\nu\nu}^{\text{exp}} \): Expected (SM) \( \pi\nu\nu \) decays
- \( N_K^{\text{obs}} \): Total \( K^+ \) flux
- \( \epsilon_{\pi\nu\nu} \): Overall acceptance for observing \( \pi\nu\nu \)

- \( N_{\pi\pi}^{\text{obs}} \): Observed \( \pi\pi \) decays
- \( \epsilon_{\pi\pi} \): Overall acceptance for observing \( \pi\pi \)

Acceptances obtained with MC

Cancellation of systematic effects (e.g., \( K^+ \), \( \pi^+ \) selection efficiencies) in ratio

- \( \epsilon_{\pi\pi} \sim 0.08 \)
- \( \epsilon_{\pi\nu\nu} \sim 0.03 - 0.06 \), depending on period

- \( \epsilon_{\text{MinBi}} \): Minimum bias trigger efficiency \( \sim 1 \)
- \( D \): Minimum bias scaledown (400)
- \( \epsilon_{\text{PNN}} \): PNN trigger efficiency \( \sim 0.9 \)
Control and signal regions initially blinded:
Control regions are unblinded to validate background estimates before signal regions are unblinded.
Background rejection for $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- $\pi^+\pi^0, \mu^+\nu, \pi^+\pi^-\pi^+$ backgrounds estimated from tails of $m_{\text{miss}}^2$ distribution in control samples
- Upstream background estimated by inverting $K^+ \rightarrow \pi^+$ matching cuts

$K^+ \rightarrow \mu^+\nu$

Control sample:
- Reconstruct $\pi^0$
- Impose 2-body kinematics with nominal $K^+$ momentum

$\epsilon_{\pi^0} = 1.3 \times 10^{-8}$

Control sample does not include $K^+ \rightarrow \pi^+\pi^0\gamma$!
- Overlaps signal region
- Photon veto more efficient
- Confirm MC with single-$\gamma$ analysis

Control sample: like $\pi^+\nu\nu$ selection but $\mu$ instead of $\pi$ ID required
Background from upstream activity

Accidental matching of $K^+$ and $\pi^+$ tracks can occur when $K^+$ decays or beam particle interacts upstream of GTK3

Example:
- $K^+$ decays between GTK2 and GTK3
- Decay $\pi^+$ misreconstructed due to scattering in first straw chamber
- Accidental $\pi^+$ leaves track in GTK

Upstream background rejected with cuts on DCA and timing between KTAG-GTK-RICH

Track projection to final collimator with \textit{inverted} cuts:

"Box cut" effective but incurs 40% loss of $\pi\nu\nu$ efficiency
Background from upstream activity

**Background model:**
MC model validated with control data with $\Delta t$ (GTK – KTAG) cut inverted

Final estimate of upstream background validated by comparison with 7 different subsamples defined by different inversions of background suppression cuts
- box cuts, GTK veto, near-beam charged veto, $m^2_{\text{miss}}$

![Graph showing normalized entries vs. CDA](image1)
![Heatmap showing $\Delta T(GTK - KTAG)$ vs. $\Delta T$](image2)
New final collimator installed shortly after start of 2018 run:

“Box cut” eliminated $\rightarrow +60$-$70\% \pi\nu\nu$ acceptance with $S/B$ unchanged
## Expected signal and background

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected evts 2017 data</th>
<th>Expected evts 2018 data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\nu\nu$ (SM)</td>
<td>$2.16 \pm 0.13 \pm 0.26_{\text{ext}}$</td>
<td>$7.58 \pm 0.40 \pm 0.75_{\text{ext}}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0(\gamma)$</td>
<td>$0.29 \pm 0.04$</td>
<td>$0.75 \pm 0.40$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu(\gamma)$</td>
<td>$0.15 \pm 0.04$</td>
<td>$0.49 \pm 0.05$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^-e^+\nu$</td>
<td>$0.12 \pm 0.08$</td>
<td>$0.50 \pm 0.11$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+\pi^-$</td>
<td>$0.008 \pm 0.008$</td>
<td>$0.24 \pm 0.08$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\gamma\gamma$</td>
<td>$0.005 \pm 0.005$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0\ell^+\nu$</td>
<td>$&lt; 0.001$</td>
<td>$&lt; 0.001$</td>
</tr>
<tr>
<td>Upstream background</td>
<td>$0.89 \pm 0.31$</td>
<td>$3.30^{+0.98}_{-0.73}$</td>
</tr>
<tr>
<td><strong>Total background</strong></td>
<td><strong>$1.46 \pm 0.33$</strong></td>
<td><strong>$5.28^{+0.99}_{-0.74}$</strong></td>
</tr>
</tbody>
</table>

2x acceptance increase from 2016 → 2018:

New collimator and other analysis optimizations ($p_{\text{max}} 35 \rightarrow 45$ GeV for R2)
Background validation, 2018 data

Verify good agreement between expected and observed counts in each background control region
Final results: 2016-2018

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon decays in FV</td>
<td>$0.12 \times 10^{12}$</td>
<td>$1.5 \times 10^{12}$</td>
<td>$2.6 \times 10^{12}$</td>
</tr>
<tr>
<td>Expected signal</td>
<td>$0.26$</td>
<td>$2.16 \pm 0.29$</td>
<td>$7.58 \pm 0.85$</td>
</tr>
<tr>
<td>Expected background</td>
<td>$0.15 \pm 0.09$</td>
<td>$1.46 \pm 0.33$</td>
<td>$5.28^{+0.99}_{-0.74}$</td>
</tr>
<tr>
<td>Observed</td>
<td>1</td>
<td>2</td>
<td>17</td>
</tr>
</tbody>
</table>
NA62 through LS3


- Expected signal (SM): 10 events
- Expected background: 7 events
- Total observed: 20 events

\[ \text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = (10.6 \pm 4.0_{-3.4}^{+0.0} \text{ stat} \pm 0.9 \text{ syst}) \times 10^{-11} \]

- 3.4\sigma signal significance
- Most precise measurement to date

Plans for NA62 Run 2 (from LS2 to LS3, 2021-2024):

NA62 resumed data taking in July 2021!

Key modifications to reduce background from upstream decays and interactions:

- Rearrangement of beamline elements around GTK achromat
- 4th station added to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Running at higher beam intensity (70\% \rightarrow 100\%)

Expect to measure \text{BR}(K^+ \rightarrow \pi^+ \nu \nu) to O(10\%) by LS3
NA62 resumed data taking in July 2021!

Key modifications to reduce background from upstream decays and interactions:

- Rearrangement of beamline elements around GTK achromat
- 4th station added to GTK beam tracker
- New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe

Running at higher beam intensity (70% → 100%)

Expect to measure $\text{BR}(K^+ \rightarrow \pi^+\nu\nu)$ to $O(10\%)$ by LS3
There is an opportunity at the SPS for an **integrated program** to pin down new physics in kaon decays

Measurement of all rare kaon decay modes—**charged and neutral**—to give clear insight into the flavor structure of new physics
Physics opportunities with kaons

Precision measurements of $K \to \pi \nu \nu$ BRs can provide model-independent tests for new physics at mass scales of up to $O(100 \text{ TeV})$

- $\text{BR}(K^+ \to \pi^+ \nu \nu) = \text{BR}_{\text{SM}}$ with $\delta \text{BR} = 5\%$
- $\text{BR}(K_L \to \pi^0 \nu \nu) = \text{BR}_{\text{SM}}$ with $\delta \text{BR} = 20\%$
- $\text{BR}(K^+ \to \pi^+ \nu \nu) = 1.33 \text{BR}_{\text{SM}}$ with $\delta \text{BR} = 5\%$
- $\text{BR}(K_L \to \pi^0 \nu \nu) = 1.50 \text{BR}_{\text{SM}}$ with $\delta \text{BR} = 20\%$
Ultra-high-intensity kaon beams

Operational scenarios and limits on the intensity deliverable to the North Area targets were studied in context of the BDF proposal as part of Physics Beyond Colliders

Experiments to measure $K \rightarrow \pi \nu \nu$ BRs at the SPS would require:

- $K^+ \rightarrow \pi^+ \nu \nu$
  $6 \times 10^{18}$ pot/year
  4x increase

- $K_L \rightarrow \pi^0 \nu \nu$
  $1 \times 10^{19}$ pot/year
  6x increase

increases with respect to present primary intensity

A kaon experiment at 6x present intensity is compatible with a diverse North Area program
## Conclusions from PBC Conventional Beams working group

<table>
<thead>
<tr>
<th>Issue</th>
<th>Approach</th>
</tr>
</thead>
</table>
| Extraction losses             | Good results on ZS losses and spill quality from SPS Losses & Activation WG (SLAWG) workshop, 9-11 November 2017:  
                                 | [https://indico.cern.ch/event/639766/](https://indico.cern.ch/event/639766/)                                                    |
| Beam loss on T4               | Vertical by-pass to increase T4 → T10 transmission to 80%                                                                                                                         |
| Equipment protection          | Interlock to stop SPS extraction during P0Survey reaction time                                                                                                                     |
| Ventilation in ECN3           | Preliminary measurements indicate good air containment  
                                 | Comprehensive ventilation system upgrade not needed                                                                         |
| ECN3 beam dump                | Significantly improved for NA62  
                                 | Need to better understand current safety margin                                                                               |
| T10 target & collimator       | Thermal load on T10 too high → Use CNGS-like target?  
                                 | Dump collimator will require modification/additional cooling                                                                 |
| Radiation dose at surface above ECN3 | 8 mrad vertical targeting angle should help to mitigate  
                                 | Preliminary results from FLUKA simulations  
                                 | Proposed target shielding scheme appears to be adequate  
                                 | Mixed mitigation strategy may be needed for forward muons                                                                  |
Beam and target simulations

Thermal simulations of target and TAX dump collimator
- Identified upgrades needed for high-intensity beam
- Target: CNGS-like design: carbon-carbon supports, pressurized air cooling
- TAX: Cooling elements nearer to center of collimator, like for SPS beam dump

Neutral beam and prompt surface dose
- **Neutrons**: Shielding adequate to reduce surface dose; need access shaft airlock
- **Muons**: Additional shielding at target and/or at downstream end of ECN3

Complete evaluation of random veto and trigger rates with full FLUKA beamline simulation for all particles down to 100 MeV
- Random veto rate = 140 MHz
$K^+ \rightarrow \pi^+\nu\nu$ at high-statistics

The NA62 decay-in-flight technique is now well established!

- Background estimates validated by in-depth study with data and MC
- Lessons learned in 2016-2018 will be put in action in 2021-2024

Possible next step:

An experiment at the SPS to measure $\text{BR}(K^+ \rightarrow \pi^+\nu\nu)$ to within $\sim$5%!

Requires 4x increase in intensity → matches present limit with charged secondary beam (after major upgrades)

Basic design of experiment will work at high intensity

Key challenges:

- Require much improved time resolution to keep random veto rate under control
- Must maintain other key performance specifications at high-rate:
  - Space-time reconstruction, low material budget, single photon efficiencies, control of non-gaussian tails, etc.

Synergies to be explored:

- Challenges often aligned with (sometimes more stringent than) High Luminosity LHC projects and next generation flavor/dark matter experiments
Experimental challenges: STRAW

NA62 straw chambers

- Straw diameter: 9.8 mm
- Hit trailing-time resolution: ~30 ns
- Maximum drift time: ~150 ns
- Mylar straws: 36 wall μm thickness
- Material budget: 1.7% $X_0$

Straw chambers for 4x intensity

- Main feature: Straw diameter ~5 mm
- Improved trailing-time resolution: ~6 ns (per straw)
- Smaller maximum drift time: ~80 ns
- Rate capability increased 6-8x
- Layout: 4 chambers, ~21000 straws
- Decreased straw wall thickness: ~20 μm, with copper and gold plating
- Material budget: 1.4% $X_0$

Design studies in progress at CERN and Dubna
Experimental challenges: GTK

GTK for 4x intensity

- Time resolution < 50 ps per plane, no non-gaussian tails!
- Pixel size: $< 300 \times 300 \, \mu m^2$
- Efficiency: > 99% (incl. fill factor)
- Material budget: 0.3-0.5% $X_0$
- Beam intensity: 3 GHz over ~ 3x6 cm$^2$
- Maximum local intensity: 8 MHz/mm$^2$
- Radiation resistance: $2.3 \times 10^{15} \, n \, eq/cm^2/yr$

Continue to improve planar sensors while monitoring progress on new technologies

Possible synergies with ongoing development efforts:

LGAD: Low Gain Avalanche Detectors

TimeSPOT: time-stamping 3D sensors
$K_L \rightarrow \pi^0 \nu \bar{\nu}$: Experimental issues

Essential signature: 2$\gamma$ with unbalanced $p_\perp$ + nothing else!

All other $K_L$ decays have $\geq 2$ extra $\gamma$s or $\geq 2$ tracks to veto

Exception: $K_L \rightarrow \gamma\gamma$, but not a big problem since $p_\perp = 0$

$K_L$ momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint

Generally used to reconstruct vertex position

Main backgrounds:

<table>
<thead>
<tr>
<th>Mode</th>
<th>BR</th>
<th>Methods to suppress/reject</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0$</td>
<td>$8.64 \times 10^{-4}$</td>
<td>$\gamma$ vetoes, $\pi^0$ vertex, $p_\perp$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0\pi^0$</td>
<td>19.52%</td>
<td>$\gamma$ vetoes, $\pi^0$ vertex, $p_\perp$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi\nu\bar{\nu}(\gamma)$</td>
<td>40.55%</td>
<td>Charged particle vetoes, $\pi$ ID, $\gamma$ vetoes</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^0 n$</td>
<td></td>
<td>Beamline length, $p_\perp$</td>
</tr>
<tr>
<td>$n + A \rightarrow X\pi^0$</td>
<td></td>
<td>High vacuum decay region</td>
</tr>
</tbody>
</table>
A $K_L \rightarrow \pi^0\nu\bar{\nu}$ experiment at the SPS?

400-GeV SPS proton beam on Be target at $z = 0$ m

- High-energy experiment: Complementary to KOTO
- Photons from $K_L$ decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

$K_{L\text{EVER}}$ target sensitivity:
- 5 years starting Run 4
- ~ 60 SM $K_L \rightarrow \pi^0\nu\nu$
- $S/B \sim 1$
- $\delta BR/BR(\pi^0\nu\nu) \sim 20\%$
A $K_L \rightarrow \pi^0 \nu\bar{\nu}$ experiment at the SPS

400-GeV SPS proton beam on Be target at $z = 0$ m

$\langle p_K \rangle = 40$ GeV

Main detector/veto systems:
- **UV/AFC**: Upstream veto/Active final collimator
- **LAV1-25**: Large-angle vetoes (25 stations)
- **MEC**: Main electromagnetic calorimeter
- **SAC**: Small-angle vetoes
- **CPV**: Charged particle veto
- **PSD**: Pre-shower detector

**$K_{LEVER}$** target sensitivity:
- 5 years starting Run 4
- $\sim 60$ SM $K_L \rightarrow \pi^0 \nu\nu$
- $S/B \sim 1$
- $\delta BR/BR(\pi^0 \nu\nu) \sim 20\%$

The search for new physics with rare kaon decays – M. Moulson (Frascati) – University of Michigan, 25 Oct 2021
Neutral beam and beamline

- 400 GeV $p$ on 400 mm Be target
- Production angle $\theta = 8.0$ mrad
- Solid angle $\Delta \theta = 0.4$ mrad
- $2.1 \times 10^{-5} K_L/$pot in beam
- $\langle p(K_L) \rangle = 40$ GeV
- Probability for decay inside FV $\sim 4\%$
- Acceptance for $K_L \rightarrow \pi^0 \nu \nu$ decays occurring in FV $\sim 5\%$

- **4 collimation stages** to minimize neutron halo, including beam scattered from absorber
- **Photon absorber** in dump collimator

NB: Choice of higher production angle under study to decrease rate of $\Lambda \rightarrow n\pi^0$ decays in detector:
Possible changes to beamline configuration and experimental layout
Long beamline to suppress $\Lambda \rightarrow n\pi^0$

Maintain $\theta = 8\text{ mrad}$ and increase length of beamline

E.g.: Move T10 from TCC8 to start of TDC85 (120 m $\rightarrow$ 270 m from T10 to UV)

- Maintain $K_L$ momentum
  Fewer design changes for KLEVER
- Preserve $K_L$ flux per solid angle
  Still lose 2x in $K_L$ flux due to tighter beam collimation
- Infrastructure work needed
- RP issues for area downstream of TDC85 to be investigated
- Alternatively, ECN3 extension would solve problem
Shashlyk calorimeter with spy tiles

Requirements for main electromagnetic calorimeter (MEC):
Excellent efficiency, time resolution ~ 100ps, good 2-cluster separation

LKr calorimeter from NA62:
Photon detection efficiency probably adequate
Time resolution ~ 500 ps for $\pi^0$ with $E_{\gamma\gamma} > 20$ GeV → requires improvement

Main electromagnetic calorimeter (MEC):
Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino
0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:
$\sigma_E/\sqrt{E} \sim 3\%/\sqrt{E}$ (GeV)
$\sigma_t \sim 72$ ps $/\sqrt{E}$ (GeV)
$\sigma_x \sim 13$ mm $/\sqrt{E}$ (GeV)

Longitudinal shower information from spy tiles
• PID information: identification of $\mu$, $\pi$, $n$ interactions
• Shower depth information: improved time resolution for EM showers

The search for new physics with rare kaon decays – M. Moulson (Frascati) – University of Michigan, 25 Oct 2021
Small-angle photon veto

Small-angle photon calorimeter system (SAC)

- Rejects high-energy $\gamma$s from $K_L \rightarrow \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Possible solutions:
- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice
- Compact Cerenkov calorimeter with oriented crystals

<table>
<thead>
<tr>
<th>Beam comp.</th>
<th>Rate (MHz)</th>
<th>Req. 1 – $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma, E &gt; 5$ GeV</td>
<td>50</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>$\gamma, E &gt; 30$ GeV</td>
<td>2.5</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>$n$</td>
<td>430</td>
<td>–</td>
</tr>
</tbody>
</table>
What about $K_L \rightarrow \pi^0 \ell^+ \ell^-$?

$K_L \rightarrow \pi^0 \ell^+ \ell^-$ vs $K \rightarrow \pi \nu \nu$:

- Somewhat larger theoretical uncertainties from long-distance physics
  - SD CPV amplitude: $\gamma/Z$ exchange
  - LD CPC amplitude from $2\gamma$ exchange
  - LD indirect CPV amplitude: $K_L \rightarrow K_S$
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays

Experimental status:

\[
\begin{align*}
\text{BR}(K_L \rightarrow \pi^0 e^+ e^-) &< 28 \times 10^{-11} \\
\text{BR}(K_L \rightarrow \pi^0 \mu^+ \mu^-) &< 38 \times 10^{-11}
\end{align*}
\]


Main background: $K_L \rightarrow \ell^+ \ell^- \gamma \gamma$

- Like $K_L \rightarrow \ell^+ \ell^- \gamma$ with hard bremsstrahlung

\[
\begin{align*}
\text{BR}(K_L \rightarrow e^+ e^- \gamma \gamma) &= (6.0 \pm 0.3) \times 10^{-7} & E_{\gamma}^* &> 5 \text{ MeV} \\
\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) &= 10^{+8 \cdot 6} \times 10^{-9} & m_{\gamma \gamma} &> 1 \text{ MeV}
\end{align*}
\]
Integrated program with $K^+$ and $K_L$ beams

Availability of high-intensity $K^+$ and $K_L$ beams at the SPS:
Important physics measurements at boundary of NA62 and KLEVER!

Example: Experiment for rare $K_L$ decays with charged particles
- $K_L$ beamline, as in KLEVER
- Tracking and PID for secondary particles, as in NA62

Physics objectives:
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$
  Excellent $\pi^0$ mass resolution – look for signal peak over Greenlee background
- Lepton-flavor violation in $K_L$ decays
- Radiative $K_L$ decays and precision measurements
- $K_L$ decays to exotic particles

Will provide valuable information to characterize neutral beam
- Example: Measurement of $K_L$, $n$, and $\Lambda$ fluxes and halo
- Experience from KOTO and studies for KLEVER show this to be critical!

Just getting started!
Summary and outlook

$K \to \pi\nu\nu$ and other rare kaon decays are uniquely sensitive indirect probes for new physics at high mass scales

Need precision measurements of both rare $K^+$ and $K_L$ decays!

During Run 1 (2016-2018), NA62 observed 20 candidate $K^+ \to \pi^+\nu\nu$ events with 10 expected signal events and 7 expected background events

$$\text{BR}(K^+ \to \pi^+\nu\nu) = (10.6 \, ^{+4.0}_{-3.4} \, \text{stat} \, \pm \, 0.9_{\text{syst}}) \times 10^{-11}$$

NA62 will improve on current knowledge of BR($K^+ \to \pi^+\nu\nu$) in short term, ultimately reaching O(10%) precision

Next generation rare kaon experiments with high-intensity beams and cutting-edge detectors will provide a powerful tool to search for physics beyond the Standard Model

An integrated program of $K^+$ and $K_L$ experiments is taking shape at CERN
Additional information

Matthew Moulson, INFN Frascati
for the NA62 Collaboration
The CKM matrix

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

\[V\] is unitary: \(V^\dagger V = 1\)

\[
\sum_i V_{ij} V_{ik}^* = \sum_i V_{ji} V_{ki}^* = \delta_{jk}
\]

### Observables and Measurements

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ \rightarrow \pi^+ \nu \bar{\nu})</td>
<td>(</td>
</tr>
<tr>
<td>(K_L \rightarrow \pi^0 \nu \bar{\nu})</td>
<td>(\text{Im} V_{ts}^* V_{td} \propto \eta)</td>
</tr>
<tr>
<td>(B_d \rightarrow J/\psi K_S)</td>
<td>(\sin 2\beta)</td>
</tr>
<tr>
<td>(\Delta m_{B_d} / \Delta m_{B_s} = \frac{B_d - \bar{B}_d}{B_s - \bar{B}_s})</td>
<td>(</td>
</tr>
</tbody>
</table>

### Unitarity Triangles

- **B unitarity triangle**
  
  \(V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0\)

- **K unitarity triangle**
  
  \(V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0\)
State of the art: BNL 787/949

700 MeV $K^+$ beam stopped in active scintillating-fiber target

Drift chamber ($B = 1$T) to measure $\pi^+$

Range stack:
- 19 layers of 1.9-cm thick scintillator
  - Measures $E$ and $R$ for $\pi^+$
  - Waveform digitizers record $\pi$-$\mu$-$e$ decay chain

$4\pi$ photon vetoes

Main 787 running from 1995-1998
Upgraded to 949 in 2001:
- Expected 10 events in 60 week run

Canceled in 2002 after 12 weeks!
State of the art: BNL 787/949

7 candidate $K^+ \rightarrow \pi^+\pi^0$ events

$$\text{BR} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

$2 \times \text{BR}_{\text{SM}}$ but entirely consistent
$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC

Primary beam: 30 GeV $p$
50 kW = $5.5 \times 10^{13}$ p/5.2 s (2019)
Neutral beam (16°)
$\langle p(K_L) \rangle = 2.1$ GeV
50% of $K_L$ have 0.7-2.4 GeV
8 $\mu$sr “pencil” beam

Au target
Final result: 2016-2018 data

<table>
<thead>
<tr>
<th>Source</th>
<th>Expected (68%CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0\pi^0$</td>
<td>$0.01 \pm 0.01$</td>
</tr>
<tr>
<td>$K_L \rightarrow \gamma\gamma$ halo</td>
<td>$0.26 \pm 0.07$</td>
</tr>
<tr>
<td>Other $K_L$ decays</td>
<td>$0.005 \pm 0.005$</td>
</tr>
<tr>
<td>$K^e_3 + K^\mu_3 + K^\pi_2$</td>
<td>$0.87 \pm 0.25$</td>
</tr>
<tr>
<td>$n$ interaction in CsI</td>
<td>$0.017 \pm 0.002$</td>
</tr>
<tr>
<td>$\eta$ from $n$ in CV</td>
<td>$0.03 \pm 0.01$</td>
</tr>
<tr>
<td>$\pi^0$ from upstream int.</td>
<td>$0.03 \pm 0.03$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.22 \pm 0.26</strong></td>
</tr>
</tbody>
</table>

* Newly evaluated source since KAON 2019

$$BR(K_L \rightarrow \pi^0\nu\nu) < 4.9 \times 10^{-9} \ (90\% CL)$$

30.5 $\times$ 10$^{19}$ pot

 SES = (7.20 $\pm$ 0.05$_{\text{stat}}$ $\pm$ 0.66$_{\text{syst}}$) $\times$ 10$^{-10}$

0.04 signal + 1.22 background events expected

3 events in signal box

**PRL 126 (2021) 121801**
KOTO long-term plans: Step-2

- Plan outlined in 2006 proposal to upgrade to $O(100)$ SM event sensitivity over the long term
- Now beginning design work for a new experiment to achieve this sensitivity

- Increase beam power to $> 100$ kW
- New neutral beamline at $5^\circ$ $\langle p(K_L) \rangle = 5.2$ GeV
- Increase FV from 2 m to 12 m Complete rebuild of detector
- Requires hadron-hall extension

- Hadron-hall extension is a joint project with nuclear physics community KOTO Step-2 is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027
- Focused review conducted in Aug 2021, with KOTO providing Step-2 input
KOTO Step-2 detector

Step-2 beamline setup in hadron-hall extension
- Smaller angle (16° → 5°)
- Longer beamline (20 → 43 m)
- 2 collimators

\( K_L \) spectrum at beam exit
- Peak mom. 3 GeV
- 11 MHz \( K_L \) in beam
  ~ 2.5x Step-1 flux

New sensitivity studies for smaller beam angle & larger detector:
~ 60 SM evts with \( S/B \) ~ 1 at 100 kW beam power (3 × 10^7 s)
Coherent effects in crystals

30 mm tungsten ($9X_0$) beam photon absorber
- reduces $\gamma$ flux in beam 1000x:
- scatters ~35% of $K_L$ in beam
Can it be made thinner?
**Exploit coherent effects in crystals!**

Coherent superposition of Coulomb fields
Electric field $\varepsilon \approx$ approx. const. $\sim 10^{10}$-$10^{12}$ V/cm
Effective field $\varepsilon' = \gamma_{\text{eff}} \quad (\gamma_{\text{eff}} = E/m_ec)$
For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate

Pair production enhanced by coherent effects at small $\theta_\gamma$ and high $E_\gamma$