An experiment to measure $\text{BR}(K_L \rightarrow \pi^0\nu\bar{\nu})$ at the CERN SPS

International Conference on Kaon Physics
Perugia, 13 September 2019

Matthew Moulson – INFN Frascati
For the KLEVER project
\( K \rightarrow \pi \nu \bar{\nu} \) in the Standard Model

FCNC processes dominated by \( Z \)-penguin and box amplitudes:

- Hard GIM mechanism + pattern of CKM suppression \((V_{ts}^*V_{td})\)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from \( \text{BR}(K_{e3}) \) via isospin rotation

Extremely rare decays with rates very precisely predicted in SM:
- Hard GIM mechanism + pattern of CKM suppression \((V_{ts}^*V_{td})\)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from \( \text{BR}(K_{e3}) \) via isospin rotation

### SM predicted rates

<table>
<thead>
<tr>
<th>Decay</th>
<th>Predicted Rate</th>
<th>Experimental status</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \rightarrow \pi^+ \nu \bar{\nu} )</td>
<td>( (8.4 \pm 1.0) \times 10^{-11} )</td>
<td>( \text{BR} = (17.3^{+11.5}_{-10.5}) \times 10^{-11} )</td>
</tr>
<tr>
<td>( K_L \rightarrow \pi^0 \nu \bar{\nu} )</td>
<td>( (3.4 \pm 0.6) \times 10^{-11} )</td>
<td>( \text{BR} &lt; 300 \times 10^{-11} ) 90%CL</td>
</tr>
</tbody>
</table>

* Tree-level determinations of CKM matrix elements

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KLEVER: An experiment to measure \( \text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \) at the CERN SPS – M. Moulson – KAON 2019 – Perugia, 13 Sep 2019
\[ K \rightarrow \pi^+ \pi^- \text{ and the unitarity triangle} \]

**Dominant uncertainties for SM BRs are from CKM matrix elements**

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

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

**Intrinsic theory uncertainties \sim \text{few percent}**

Measuring both \( K^+ \) and \( K_L \) BRs can determine the CKM unitarity triangle independently from \( B \) inputs

- Overconstrain CKM matrix \( \rightarrow \) reveal NP?

**Hypothetical CKM fit to \( K \rightarrow \pi^+ \pi^- \nu\bar{\nu} \)**

10% mmts for \( K^+ \) and \( K_L \)

**Prospective study on rare Kaons**

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KLEVER: An experiment to measure BR(\( K_L \rightarrow \pi^0 \nu\bar{\nu} \)) at the CERN SPS – M. Moulson – KAON 2019 – Perugia, 13 Sep 2019
New physics affects BRs differently for $K^+$ and $K_L$ channels
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
The NA62 experiment at the CERN SPS
BR($K^+ \rightarrow \pi^+ \nu\nu$) from 2017 data

- High-rate, precision tracking
- Redundant PID and muon vetoes
- Hermetic photon vetoes
- High-performance EM calorimeter

Preliminary from 2016 + 2017 data

$2 \times 10^{12}$ $K^+$ decays total

SES = $(3.46 \pm 0.17) \times 10^{-11}$

Expected signal $2.43 \pm 0.31$

Expected bkgd $1.65 \pm 0.31$

3 events observed in R2

BR($K^+ \rightarrow \pi^+ \nu\nu$) < $16.2 \times 10^{-11}$ (95%CL)
< $13.2 \times 10^{-11}$ (90%CL)

$= 4.7^{+7.2}_{-4.7} \times 10^{-11}$ (68% CL)
Analysis of NA62 data from 2018 data in progress
Solid extrapolation to ultimate sensitivity achievable after LS2

Intention to continue data taking with NA62
- Measure BR($K^+ \rightarrow \pi^+\nu\nu$) with ultimate sensitivity
- Search for hidden particles in beam-dump mode

Turn focus to measurement of BR($K_L \rightarrow \pi^0\nu\nu$)

1902.00260
$K_L \rightarrow \pi^0 \nu \bar{\nu}$: 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>$K_L \rightarrow \pi^0 \nu (\gamma)$</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>$n + \text{gas} \rightarrow X \pi^0$</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 ($2 \times 10^{13}$ pot/16.8 s) incident 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
$K_L \rightarrow \pi^0\nu\bar{\nu}$: Discovery potential

**KLEVER** target sensitivity:
- 5 years starting Run 4

**60 SM** $K_L \rightarrow \pi^0\nu\nu$
- $S/B \sim 1$

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

60 $K_L \rightarrow \pi^0\nu\nu$ events at SM BR
- 60 background events

Signif. $\approx \frac{S_{\text{obs}} - S_{\text{SM}}}{\sqrt{S_{\text{obs}} + B_{\text{obs}}}}$

If $BR(K_L \rightarrow \pi^0\nu\nu)$ is:
- Suppressed to 0.25 $BR_{\text{SM}} \Rightarrow 5\sigma$
- Enhanced to 2 $BR_{\text{SM}} \Rightarrow 5\sigma$
- Suppressed to 0.5 $BR_{\text{SM}} \Rightarrow 3\sigma$

**NP effects on $K \rightarrow \pi\nu\nu$ BRs with constraints from Re $\epsilon'/\epsilon$, $\epsilon_K$, $\Delta m_K$, $K_L \rightarrow \mu\mu$**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Lambda$ [GeV]</th>
<th>Effect on BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$)</th>
<th>Effect on BR($K_L \rightarrow \pi^0\nu\bar{\nu}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptoquarks, most models</td>
<td>1-20</td>
<td>Very large enhancements; mainly ruled out</td>
<td></td>
</tr>
<tr>
<td>Leptoquarks, $U_1$</td>
<td>1-20</td>
<td>+10% to +60%</td>
<td>+100% to +800%</td>
</tr>
<tr>
<td>Vector-like quarks</td>
<td>1-10</td>
<td>-90% to +60%</td>
<td>-100% to +30%</td>
</tr>
<tr>
<td>Vector-like quarks + $Z'$</td>
<td>10</td>
<td>-80% to +400%</td>
<td>-100% to 0%</td>
</tr>
<tr>
<td>Simplified modified $Z$, no tuning</td>
<td>1</td>
<td>-100% to +80%</td>
<td>-100% to -50%</td>
</tr>
<tr>
<td>General modified $Z$, cancellation to 20%</td>
<td>1</td>
<td>-100% to +400%</td>
<td>-100% to +500%</td>
</tr>
<tr>
<td>SUSY, chargino $Z$ penguin</td>
<td>4-6 TeV</td>
<td>-100% to -40%</td>
<td></td>
</tr>
<tr>
<td>SUSY, gluino $Z$ penguin</td>
<td>3-5.5 TeV</td>
<td>0% to +60%</td>
<td>-20% to +60%</td>
</tr>
<tr>
<td>SUSY, gluino $Z$ penguin</td>
<td>10</td>
<td>Small effect</td>
<td>0% to +300%</td>
</tr>
<tr>
<td>SUSY, gluino box, tuning to 10%</td>
<td>1.5-3</td>
<td>$\pm 10%$</td>
<td>$\pm 20%$</td>
</tr>
<tr>
<td>LHT</td>
<td>1</td>
<td>$\pm 20%$</td>
<td>$-10%$ to $-100%$</td>
</tr>
</tbody>
</table>
A $K_L \rightarrow \pi^0\nu\bar{\nu}$ experiment at the SPS

400-GeV SPS proton beam ($2 \times 10^{13}$ pot/16.8 s) incident on Be target at $z = 0$ m

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

**KLEVER** target sensitivity:
- 5 years starting Run 4
- 60 SM $K_L \rightarrow \pi^0\nu\nu$
- $S/B \sim 1$
- $\delta BR/BR(\pi^0\nu\nu) \sim 20\%$
Beam and intensity requirements

\[ K_L \text{ and } \Lambda \text{ fluxes, } \theta = 8.0 \text{ mrad} \]

Parameterized from FLUKA simulation

- 400 GeV \( p \) on 400 mm Be target
- Production at \( \theta = 8.0 \text{ mrad} \):
  - As much \( K_L \) production as possible
  - Low ratio of \( n/K_L \) in beam \( \sim 3 \)
  - Reduce \( \Lambda \) production and soften momentum spectrum
- Solid angle \( \Delta \theta = 0.4 \text{ mrad} \):
  - Large \( \Delta \theta \) = high \( K_L \) flux
  - Maintain tight beam collimation to improves \( p_\perp \) constraint for background rejection
- \( 2.1 \times 10^{-5} \) \( K_L \) in beam/pot
- Probability for decay inside FV \( \sim 4\% \)
- Acceptance for \( K_L \to \pi^0 \nu \nu \) decays occurring in FV \( \sim 5\% \)

\[ \begin{align*}
\langle p \rangle & = 40 \text{ GeV} \\
\langle p \rangle & = 90 \text{ GeV} \\
\langle p \rangle & = 27 \text{ GeV} \\
\langle p \rangle & = 255 \text{ GeV} \\
\langle p \rangle & = 90 \text{ GeV} \\
\langle p \rangle & = 27 \text{ GeV} \\
\langle p \rangle & = 255 \text{ GeV}
\end{align*} \]

10\(^{19}\) pot/year (\( = 100 \text{ eff. days} \))

E.g.: \( 2 \times 10^{13} \) ppp/16.8 s \( \times 5 \text{ years} \)

\[ 60 \] \( K_L \to \pi^0 \nu \nu \) events
Neutral beamline layout

- 400 GeV/c protons from SPS incident at 8 mrad on beryllium target
- Vertical bending magnet to dump proton beam on collimator
- Photon absorber in dump collimator
- 4 collimation stages to minimize neutron halo, including beam scattered from absorber
- Horizontal sweeping magnet after each collimator
- Active final collimator in LYSO
High-intensity neutral beam study

Conclusions from PBC Conventional Beams working group

<table>
<thead>
<tr>
<th>Issue</th>
<th>Approach</th>
</tr>
</thead>
</table>
| **Proton availability**      | SHiP supercycle = $4 \times 10^{19}$ pot/yr with $1 \times 10^{13}$ ppp for users  
KLEVER requires $1 \times 10^{19}$ pot/yr (25% of SHiP) |
| **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 $\rightarrow$ 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 $\rightarrow$ 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 dump collimator
- Identify 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
- Muons: Additional shielding around 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
Neutral beam simulation

$K_L$ in beam: 140 MHz
35% scattered by converter

- Before photon absorber
- After photon absorber
- After dump collimator
- After defining collimator
- After cleaning collimator
- After final collimator
- Passing into SAC

FLUKA simulation of beamline
32-mm tungsten converter ($9X_0$)

Detail of target and dump collimator:

Neutrons in beam
$E > 1$ GeV: 440 MHz

Photons in beam
$E > 5$ GeV: 50 MHz
$E > 30$ GeV: 2.5 MHz

Effect of $\gamma$ converter
NA48 LKr calorimeter as MEC?

Quasi-homogeneous ionization calorimeter, $27X_0$ of LKr

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \quad \sigma_t = \frac{2.5 \text{ ns}}{\sqrt{E}}$$

Photon detection efficiency probably adequate

- NA48-era studies for NA62: $1 - \varepsilon < 10^{-5}$ for $E_\gamma > 10$ GeV
- High-energy efficiency confirmed with NA62 data

Other concerns about LKr:

Time resolution

- $\sigma_t \sim 500$ ps for $\pi^0$ with $E_\gamma > 20$ GeV
- Would require improvement: SAC may have $\sim 100$ MHz accidental rate

Long-term reliability ($1996 \rightarrow 2018 \rightarrow 2030$?)

LKr cold bore $r = 80$ mm and start of sensitive volume $r = 120$ mm limits beam solid angle to $\Delta \theta < 0.3$ mrad $\rightarrow 40\%$ less $K_L$ flux

Baseline design calls for NA48 LKr to be replaced by new MEC
Shashlyk calorimeter with spy tiles

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

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

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

1st prototype assembled and tested at Protvino
OKA beamline, April 2018
Vetoes for upstream $K_L \rightarrow \pi^0\pi^0$

Upstream veto (UV):
- $10 \text{ cm} < r < 1 \text{ m}$:
- Shashlyk calorimeter modules à la PANDA/KOPIO, like MEC

Active final collimator:
- $4.2 < r < 10 \text{ cm}$
- LYSO collar counter
- 80 cm long
- Internal collimating surfaces
  - Intercepts halo particles from scattering on upstream collimators or $\gamma$ absorber
  - Rejects $\pi^0$s from inelastic interactions
  - Rejects $K_L \rightarrow \pi^0\pi^0$ in transit through collimator
25 new large-angle photon veto stations (LAV)

- 5 sizes, sensitive radius 0.85 to 1.5 m, at intervals of 4 to 5 m
- Hermetic coverage out to 100 mrad
  Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)
- Baseline technology: Lead/scintillator tile with WLS readout
  Based on design of CKM VVS
  Assumed efficiency based on E949 and CKM VVS experience
Large-angle photon vetoes

25 new LAV detectors providing hermetic coverage out to 100 mrad
Need good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)

Baseline technology: CKM VVS
Scintillating tile with WLS readout

Good efficiency assumptions based on E949 and CKM VVS experience

E949 barrel veto efficiencies
Same construction as CKM

Tests for NA62 at Frascati BTF

Parameterization:
- 1-129 MeV: KOPIO (E949 barrel)
- 203-483 MeV: CKM VVS

Tests at JLAB for CKM:
- $1 - \varepsilon \sim 3 \times 10^{-6}$ at 1200 MeV

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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

Baseline solution:
- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice

<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>
Efficient $\gamma$ conversion with crystals

Coherent effects in crystals enhance pair-conversion probability

Use coherent effects to obtain a converter with large effective $\lambda_{\text{int}}/X_0$:

1. **Beam photon converter in dump collimator**
   
   Effective at converting beam $\gamma$s while relatively transparent to $K_L$

2. **Absorber material for small-angle calorimeter (SAC)**
   
   Must be insensitive as possible to high flux of beam neutrons while efficiently vetoing high-energy $\gamma$s from $K_L$ decays

![Graph showing coherent effects in crystals](image-url)
Beam test of $\gamma \rightarrow e^+e^-$ in crystals

AXIAL group is collaborating with KLEVER on test beam measurement of pair-production enhancement in crystals

Test beam setup for tagged photons from 120 GeV $e^-$:

Test goals:
1. Observe $\gamma \rightarrow e^+e^-$ enhancement with a commercially available tungsten crystal
2. Measure spectrum of transmitted $\gamma$ energy for a thick (~10 mm) crystal
3. Measure pair conversion vs. $E_\gamma$, $\theta_{inc}$
4. Obtain information to assist MC development for beam photon converter and SAC

- Nearly all detectors and DAQ system made available by AXIAL
- 1 week of H2 beam: 8-15 August 2018
First look at test beam data

Enhancement of mean charged multiplicity (S4), axial/amorphous

Charged multiplicity enhanced ~ 2x for $E_\gamma \sim 60$ GeV

- 1 extra shower generation in 10 mm $\rightarrow X_0$ reduced by 33%
- Enhancement seen for incidence ± few mrad around crystal axis
- No sign of saturation up to $E_\gamma \sim 80$ GeV
Charged particle rejection

Most dangerous mode: $K_{e3}$
- BR = 40%
- Easy to mistake $e \leftrightarrow \gamma$ in LKr
- Acceptance $\pi^0\nu\nu/K_{e3} = 30$

→ Need $10^{-9}$ suppression!

Charged particle veto (CPV)
- Scintillating tiles, just upstream of MEC

Calorimetric ID for $\mu$ and $\pi$
- Shower profile in MEC
- Re-use NA62 hadronic calorimeters MUV1/2 (not shown), downstream of MEC
Mispaired $K_L \rightarrow \pi^0\pi^0$ events

Distance from FV to LKr significantly helps for rejection of “odd” background

- Most $K_L \rightarrow \pi^0\pi^0$ decays with lost photons occur just upstream of the MEC
- “$\pi^0$s” from mispaired $\gamma$s are mainly reconstructed upstream of true position

Preshower detector (PSD) is particularly effective against downstream decays

$K_L \rightarrow \pi^0\pi^0$ odd
2$\gamma$ on LKr only

- True decay $z$
- Reconstructed $z$
Mispaired $K_L \rightarrow \pi^0\pi^0$ events

Distance from FV to LKr significantly helps for rejection of “odd” background

- Most $K_L \rightarrow \pi^0\pi^0$ decays with lost photons occur just upstream of the MEC
- “$\pi^0$s” from mispaired $\gamma$s are mainly reconstructed upstream of true position

Preshower detector (PSD) is particularly effective against downstream decays
Preshower background rejection

Preshower vertex $z_{\text{pre}}$ vs. LKr vertex $z_{\text{rec}}$

$z_{\text{rec}}$ reconstructed by imposing $M(\gamma\gamma) = m_{\pi^0}$

- $K_L \rightarrow \pi^0\pi^0$, 1 year equivalent
- No cuts on FV, $p_\perp, r_{\text{min}}$

**Even pairs** (2 $\gamma$ from same $\pi^0$)
1 $\gamma$ converts in preshower

**Odd pairs** (2 $\gamma$s from different $\pi^0$)
1 $\gamma$ converts in preshower

977771 evts total
4591 evts sel

8161448 evts total
281 evts sel
Basic signal selection

No hits in UV, AFC, LAV, SAC + fiducial volume (FV) and $p_{\perp}$ cuts

$K_L \rightarrow \pi^0\nu\nu$

$K_L \rightarrow \pi^0\pi^0$ ($\gamma\gamma$ from same $\pi^0$)

$K_L \rightarrow \pi^0\pi^0$ ($\gamma\gamma$ from different $\pi^0$'s)

$K_L \rightarrow \pi^0\pi^0$ (overlapped clusters)
Additional background rejection

Cluster radius $r_{\text{MEC}} > 35$ cm – Require $z_{\text{PSD}}$ in FV if PSD hit available

$K_L \rightarrow \pi^0\nu\nu$

$K_L \rightarrow \pi^0\pi^0$ ($\gamma\gamma$ from same $\pi^0$)

$K_L \rightarrow \pi^0\pi^0$ ($\gamma\gamma$ from different $\pi^0$s)

$K_L \rightarrow \pi^0\pi^0$ (overlapped clusters)
Status and timeline

Project timeline – target dates:

2017-2018  Project consolidation
  • Participation in Physics Beyond Colliders
  • Beam test of crystal pair enhancement
  • Input to European Strategy for Particle Physics

2019 Q3    Expression of Interest to CERN SPSC (in preparation)

2020 Q2    Conclusion of European Strategy update
            KLEVER proposal

2019-2021  Detector R&D

2021-2025  Detector construction
  • Possible K12 beam test if compatible with NA62

2025       Installation during LS3

2026-      Data taking beginning Run 4

Most groups participating in NA62 have expressed interest in KLEVER
We are actively seeking new collaborators!
Summary and outlook

\( K \rightarrow \pi \nu \nu \) is a uniquely sensitive indirect probe for high mass scales

- Need precision measurements of both \( K^+ \) and \( K_L \) decays

NA62 will improve on current knowledge of \( \text{BR}(K^+ \rightarrow \pi^+ \nu \nu) \) in short term, ultimately reaching ~100 event sensitivity

KOTO is making significant progress in background reduction and will reach SM sensitivity to \( \text{BR}(K_L \rightarrow \pi^0 \nu \nu) \) by mid-2020s

Design studies indicate that an experiment to measure \( \text{BR}(K_L \rightarrow \pi^0 \nu \nu) \) can be performed at the SPS in Run 4 (2026)

- Many issues still to be addressed!
- Expected sensitivity: \( \sim 60 \) SM events with \( S/B \sim 1 \)
- KLEVER is preparing Expression of Interest to CERN SPSC and is actively seeking new collaborators
Additional information

International Conference on Kaon Physics
Perugia, 13 September 2019

Matthew Moulson – INFN Frascati
For the KLEVERER project
Active final collimator

- Intercepts halo particles from scattering on upstream collimators or $\gamma$ absorber
  - Rejects $\pi^0$s from inelastic interactions
- Rejects $K_L \to \pi^0\pi^0$ in transit through collimator

Design in progress:

LYSO collar counter with internal collimating surfaces
- Fast (40 ns), bright ($\sim$ NaI), radiation hard ($>10^6$ Gy)

Crystals read out on back side with APDs
- Good coupling with LYSO and high quantum efficiency
- Simple signal and HV management
- E.g. RMD S1315 (13x13 mm$^2$)

Expected light yield $> 4000$ p.e./MeV

- 60 mm $< r < 100$ mm
- 80 cm long (3-4 consecutive rings)
- 20-24 crystals per ring
Large-angle vetoes

Time resolution for current LAVs ~ 1 ns
- Cerenkov light is directional
- Complicated paths to PMT with multiple reflections

CKM Vacuum Veto System (VVS)
- Pb/scintillating tile
- 1 mm Pb + 5 mm scint $f_{em} \sim 36\%$
- WLS fiber readout

Light read out with PMTs in original design
- $Y \sim 20$ p.e./MeV
  - cf NA62 $\sim 0.3$ p.e./MeV

Modify design to use SiPM arrays
**CKM VVS prototype: time resolution**

Measurements at Frascati BTF, Jul 2007

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$</th>
<th>$\sigma_t$ tag</th>
<th>$\sigma_t$ CKM</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 MeV</td>
<td>201</td>
<td>155</td>
</tr>
<tr>
<td>483 MeV</td>
<td>205</td>
<td>250</td>
</tr>
</tbody>
</table>

**Time resolution 150-250 ps**
Extra jitter at 483 MeV not understood

---

$\sigma_t = 290$ ps

$\sigma_t = 320$ ps

$\sigma_t = 327$ ps
Performance of KOPIO shaslyk

**KLEVER requirement**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>1 - $\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>1</td>
</tr>
<tr>
<td>1 → 5.5</td>
<td>$10^{-3}$ → $10^{-4}$</td>
</tr>
<tr>
<td>5.5 → 7.5</td>
<td>$10^{-4}$ → $5 \times 10^{-5}$</td>
</tr>
<tr>
<td>7.5 → 10</td>
<td>$5 \times 10^{-5}$ → $10^{-5}$</td>
</tr>
<tr>
<td>10 → 15</td>
<td>$8 \times 10^{-6}$</td>
</tr>
<tr>
<td>&gt; 15</td>
<td>$4 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

**KOPIO performance**

- Spec: $\leq 10^{-4}$, 50-1000 MeV
- Ach: $\sim 5 \times 10^{-5}$, 250 MeV
- Dominated by punch through
- Photonuclear not included

**Photon eff.** $1 - \varepsilon_{\gamma}$

- Energy res.: $\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} (\text{GeV}) \oplus \frac{9\%}{E} \oplus 0.42\%$
- $\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} (\text{GeV}) \oplus 2\%$

**Time res.**

- $\sigma_t < 150 \text{ ps}$
- $\sigma_t \sim 72 \text{ ps}/\sqrt{E} (\text{GeV})$

**2-cluster sep.**

- Clust. resolved if $d < 6 \text{ cm}$
- LKr Molière radius = 6 cm
- LKr cell size = 2 cm
- Molière radius = 6 cm
- Cell size = 5.5 cm
Beam tests with tagged photons

Measurements with tagged photons essential for development of rare-decay experiments with photon veto ($K_L \rightarrow \pi^0 \nu \nu$, dark photons, etc.)

- Challenging to obtain single-photon tag of sufficient quality to measure very small ($< 10^{-3}$) inefficiencies!

**Frascati Beam-Test Facility (BTF):**

- 550 MeV single $e^+/e^-$ from DAΦNE linac: ideal for measurement of low-energy efficiencies:
  - Recently upgraded with installation of new BTF-2 beamline (AIDA2020 T15.4)
  - Photon-tagging systems upgraded (AIDA2020 D15.5)
    - New readout with zero-suppression and self-trigger
    - Not yet installed and commissioned
  - PADME and KLEVER ideal test cases for further development and possibility of enabling measurements of very small inefficiencies

Develop sensitive photon tagging techniques to be used at higher energy:

- **MAMI** 1600 MeV electrons and tagged photons; experience with tagged photon measurements
- **DESY II** 1-6 GeV electrons with possibility of tagged photon beam
Charged particle veto

\[ K_L \rightarrow \pi e \nu \text{ can emulate signal when both } \pi \text{ and } e \text{ deposit energy in MEC} \]

- Fake \( \pi^0 \) vertexes from \( \pi e \) all reconstructed downstream of true decay
  - \( \pi^+ \) deposits only a fraction of its energy
- \( K_{e3} \) decays with "\( \pi^0 \)" reconstructed in FV have \( z_{\text{rec}} < 200 \text{ m} \)
  - All within the acceptance of the CPV

Baseline CPV design

Square scintillator tiles, 5-mm thick, supported on carbon fiber membrane

- 2 planes \( \rightarrow \) 3% \( X_0 \)

Tile geometry: 4x4 cm\(^2\) or 8x8 cm\(^2\)

- Smaller tiles near beam line
- Cracks staggered between planes
- 4 chamfered corners (45°) for direct SiPM coupling
Charged particle rejection

$K_L \to \pi e \nu$ can emulate signal when both $\pi$ and $e$ deposit energy in LKr

Use cluster RMS in LKr to identify and reject $\pi$ interactions
- Geant4 confirmed by preliminary analysis of $\pi \pi^0$ events in NA62 data:
  \begin{align*}
  \epsilon_\gamma &= 0.95 \\
  \epsilon_\pi &= 0.05
  \end{align*}

If LKr replaced by shashlyk, longitudinal shower profile information also available

Ratio of hadronic/total energy effective to identify $\pi$ showers
- Preliminary results based on Geant4:
  \begin{align*}
  \epsilon_\gamma &= 0.99 \\
  \epsilon_\pi &= 0.07
  \end{align*}

Study of HAC (MUV1/2) response in NA62 data in progress
- Parameterization of response for inclusion in fast simulation
### Trigger and veto rate simulations

Detector rates estimated with full FLUKA beamline simulation and idealized detector geometry

<table>
<thead>
<tr>
<th>Event class</th>
<th>Rate [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trigger rates</strong></td>
<td></td>
</tr>
<tr>
<td>Exactly 2 hits on MEC</td>
<td>4.8</td>
</tr>
<tr>
<td>Exactly 2 $\gamma$ on MEC</td>
<td>1.0</td>
</tr>
<tr>
<td>Exactly 2 hits on MEC, no hits on UV or LAVs</td>
<td>3.1</td>
</tr>
<tr>
<td>Exactly 2$\gamma$ on MEC, nothing else</td>
<td>0.007</td>
</tr>
<tr>
<td><strong>Accidental rates</strong></td>
<td></td>
</tr>
<tr>
<td>Single hit</td>
<td>104</td>
</tr>
<tr>
<td>Multi hit</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector</th>
<th>Hit rate [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC</td>
<td>2.3</td>
</tr>
<tr>
<td>UV</td>
<td>7.1</td>
</tr>
<tr>
<td>LAV</td>
<td>14</td>
</tr>
<tr>
<td>MEC</td>
<td>18</td>
</tr>
<tr>
<td>IRC</td>
<td>22</td>
</tr>
<tr>
<td>SAC</td>
<td>95</td>
</tr>
</tbody>
</table>

Simultaneous detector rates

![Simultaneous detector rates](image)
Common readout platform

Development of free-running, fully digitizing readout system for acquisition at 100 MHz, with low-level event selection in front end:

- **Versatile analog front-end stage:**
  - Configurable signal shaping/amplification for different detectors

- **Digital front-end stage:**
  - FADC digitization at up to 1 GHz; zero suppression; time framing
  - Parallel signal processing/data filtering implemented on FPGAs or ASICs
  - Autonomous trigger generation
  - High radiation tolerance (single-event-upset resistant)

- **Readout/data transmission stage**
  - Trigger and clock distribution
  - Merging of channels and trigger information; additional signal processing as needed
  - Data transmission via standard network protocol.

- **Networking and online computing architectures with model for dataflow from readout boards to permanent storage**
Limits on $K_L \rightarrow \pi^0 X$ from $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Assuming:
- $K_L \rightarrow \pi^0 \nu \nu$ according to SM
- 60 expected evts from $K_L \rightarrow \pi^0 \nu \nu$ ($\pm 18\%$)
- 60 expected evts from $K_L \rightarrow \pi^0 \pi^0$ ($\pm 8$ evts)
- 120 observed evts in 5 yrs (no excess)
- For each value of $m_X$ ascribe zero excess to $K_L \rightarrow \pi^0 X$
- 2-body acceptance for $K_L \rightarrow \pi^0 X$ ($\pm$ stat $\oplus 5\%$)
- Derive 90\% Rolke-Lopez UCL

BR$_{UL}(K_L \rightarrow \pi^0 X)$ [90\% CL] vs $m_X$ [GeV]
Limits on $K_L \rightarrow \pi^0 A'$ from $K_L \rightarrow \pi^0 \nu \nu$

For $K_L \rightarrow \pi^0 X$ interpret $X$ as dark photon $A'$ with no decays to SM particles

Obtain limits in $\varepsilon^2$ vs. $m_{A'}$ plane

$\varepsilon^2 = \text{kinetic mixing angle for } A' \text{ and } \gamma$

As per Davoudiasl, Lee, Marciano 2014

Weaker limits obtain if $A'$ also mixed with $Z$

Analogous limits obtained for $X$ interpreted as
- Higgs-mixed scalar
- Axion-like particle
Exclusion potential from $K_L \rightarrow \pi^0 X$

For $K_L \rightarrow \pi^0 X$, interpret $X$ as:

- Invisible dark photon $A'\ (BC2)$
- Higgs-mixed scalar $S\ (BC4)$
- Axion-like particle $a$ with fermion couplings (BC10)

Obtain limits in coupling vs. mass plane for each scenario*.

* Calculation assumes that decaying particles escape the decay volume.