KLEVER

Status report
Physics Beyond Colliders
Beyond Standard Model Working Group
05 November 2019

Matthew Moulson
For the KLEVER project
**$K \to \pi^0\nu\bar{\nu}$: an overview**

Extremely rare decays with rates very precisely predicted in SM:

<table>
<thead>
<tr>
<th>$K^+ \to \pi^+\nu\bar{\nu}$</th>
<th>$K_L \to \pi^0\nu\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR = $(8.4 \pm 1.0) \times 10^{-11}$</td>
<td>BR = $(3.4 \pm 0.6) \times 10^{-11}$</td>
</tr>
</tbody>
</table>

**SM predicted rates**

**Experimental status**

- 7 evts from BNL787, **3 evts from NA62**
- NA62 goal: BR to < 20% by end of Run 3
- Only limits at present
- **KOTO** (J-PARC): few SM evts by mid 2020s

Buras et al, JHEP 1511*

**New physics affects $K^+$ and $K_L$ differently**

- Measurements of both can discriminate among NP scenarios
- Excellent sensitivity at multi-TeV mass scales
  - Higher mass scale reach than for $B$ decays in many scenarios
  - Independent information from $B$ decays

**Well-grounded predictions for BSM effects**

Sensitive to models proposed to explain LFU anomalies in $B$ system ($R_K$, $P_5'$, etc.)

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*Min. flavor viol.  
Z/Z', LHT  
Randall-Sundrum*

Buras, Buttazzo, Knegjens - JHEP 1511
A $K_L \rightarrow \pi^0\nu\bar{\nu}$ experiment at the SPS

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

If BR($K_L \rightarrow \pi^0\nu\nu$) is:

- Suppressed to 0.25 BR$_{SM} \Rightarrow 5\sigma$
- Enhanced to 2 BR$_{SM} \Rightarrow 5\sigma$
- Suppressed to 0.5 BR$_{SM} \Rightarrow 3\sigma$

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

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Lambda$ [TeV]</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></td>
<td>−100% to −40%</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>±10%</td>
<td>±20%</td>
</tr>
<tr>
<td>LHT</td>
<td>1</td>
<td>±20%</td>
<td>−10% to −100%</td>
</tr>
</tbody>
</table>
Status update for 2016-2018 data

1.4x more data than for 2015 collected in 2016-2018
Several important detector upgrades and analysis improvements

KOTO preliminary 2016-2018 data, KAON 2019

SES = $6.9 \times 10^{-10}$ (20x SM)

<table>
<thead>
<tr>
<th>Background</th>
<th>Expected counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0$</td>
<td>$&lt; 0.18$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0\pi^0\pi^0$</td>
<td>$&lt; 0.04$</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^+\pi^-\pi^0$</td>
<td>$&lt; 0.09$</td>
</tr>
<tr>
<td>$K_L \rightarrow \gamma\gamma$</td>
<td>$0.00 \pm 0.00$</td>
</tr>
<tr>
<td>Hadron cluster</td>
<td>$0.02 \pm 0.00$</td>
</tr>
<tr>
<td>$\pi^0$ from NCC</td>
<td>$0.00 \pm 0.00$</td>
</tr>
<tr>
<td>$\pi^0$ from CV</td>
<td>$&lt; 0.10$</td>
</tr>
<tr>
<td>$\eta$ from CV</td>
<td>$0.03 \pm 0.01$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.05 \pm 0.02$</td>
</tr>
</tbody>
</table>

One candidate event looks like pileup in NCC
Re-examination of background esp. from overlapped signals in progress
Projected sensitivity

**SES Projection**

- **New target**
- **New Main Ring power supplies**

*At SES SM: SM is excluded at 95% (2\(\sigma\)) if \(BR_{\text{obs}} = 5.7\)

\(BR_{\text{SM}}\)


**KOTO will not reach SES SM until mid 2020s without Step-2 upgrade**
Long-term upgrade plans

KOTO Step-2 upgrade:

- 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 11 m
  Complete rebuild of detector
- Requires extension of hadron hall

Strong intention to upgrade to 10-100 event sensitivity over long term:

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- **New sensitivity studies** for smaller beam angle & larger detector:
  - $\sim 60$ SM evts with $S/B \sim 1$ at 100 kW beam power $(3 \times 10^7$ s)
- Exploring possibilities for machine & detector upgrades to further increase sensitivity
Cooperation efforts

KLEVER and KOTO Step 2 have similar sensitivity and timescale
- KLEVER target schedule is more immediate but both experiments are dependent on current programs

Experimental approaches are quite different: low vs. high energy

Each group can contribute valuable insight to the other
- KOTO has more direct experience with $K_L \rightarrow \pi^0 \nu \bar{\nu}$
- NA62 has solid roots in NA48 experiments with $K_L$

Model for cooperation discussed at KAON 2019:
- Periodic, structured discussions
- MC and event generators: model benchmarking, common standards
  E.g. neutral hadron production in primary and secondary interactions
- Joint R&D: Calorimeters with photon vectoring; small-angle vetoes
- Exchange of students and early-career researchers

Applying for cooperation funds in Italy and Japan
Beamline optimization and hit rates

High rates on UV from $\gamma$'s leaking through magnets and avoiding collimators

Place fixed collimators (TCX, 10 cm dia) in front of defining and cleaning collimators

Rate on UV decreased from 94 $\rightarrow$ 10 MHz

Complete evaluation of random veto and trigger rates

- Full FLUKA beamline simulation for all particles down to 100 MeV
- Random veto rate = 140 MHz
  
  Including offline $\gamma/n$ discrimination in SAC (95%)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Hit rate [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC</td>
<td>2.9</td>
</tr>
<tr>
<td>UV</td>
<td>10</td>
</tr>
<tr>
<td>LAV</td>
<td>21</td>
</tr>
<tr>
<td>MEC</td>
<td>24</td>
</tr>
<tr>
<td>IRC</td>
<td>47</td>
</tr>
<tr>
<td>SAC</td>
<td>101</td>
</tr>
</tbody>
</table>

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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 & prompt surface dose

- Neutrons: Shielding adequate to reduce surface dose
- Muons: Significant dose rate at end of earthen barrier (~70 μSv/h)
  - Changes to muon sweeping
  - Add shielding in target region
  - Zone exclusion
Beam-gas studies with FLUKA

- Construct interaction probability and fold with beam composition and momentum distributions
- Distribute along vacuum volume
- Simulated 10x interactions expected in 5 yrs at residual pressure $10^{-6}$ mbar

Inelastic events/GeV, 5 yrs

Require: Exactly $2\gamma$s from same $\pi^0$ on MEC
No hits on other detectors

Both $\gamma$ with $r < 35$ cm
$p_\perp > 0.15$ GeV
$130$ m $< z < 170$ m

Expect 16.7 evts
Small-angle photon veto

- 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

### Small-angle photon calorimeter system (SAC)

<table>
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<tr>
<th>Beam comp.</th>
<th>Rate (MHz)</th>
<th>Req. $1 - \epsilon$</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>
Test beam data analysis

Test beam with AXIAL (CSN5)
CERN SPS H2 line
August 2018

Calorimeter energy calibration

Recent progress:
1. Data preparation, calorimeter calibration, preliminary analysis (Como)
   G. Ballerini, Laurea, Univ. Insubria, March 2019
2. Data analysis in progress with full calibrations (CERN summer student, Frascati, Ferrara)
3. Continued development of simulation including coherent interactions (Ferrara)
Alternative design for SAC

PADME SAC: Ultra-fast PbF$_2$ Cerenkov calorimeter
- $\sigma_t < 100$ ps
- 2-pulse separation at $\sim 1$ ns

Questions for use in KLEVER:
- Use of PbF$_2$ needs validation for use at continuous high rates and high radiation doses
  - Eliminate afterglow from fluorescence?
  - Verify radiation-hardness or identify alternative crystal candidates?
- Optimization of choice of photodetectors
  - Excellent time resolution
  - Radiation hardness
- Study suitability of design at higher energies (e.g. adaptations to $K_L \rightarrow \pi^0 \nu \nu$)
- Study response to neutral hadrons
- Possibilities for $\gamma/n$ discrimination: multilayer structure/longitudinal segmentation
R&D projects for SAC

Development of fast Cerenkov calorimeter by participation in R&D initiatives with broader focus

Synergy with PADME: SAC upgrade for future running with continuous beam

AIDA++ work package on highly granular calorimeters

Participation in development tasks as associated project

Task 2.1: Crystal detectors

Task 3.1: Innovative SiPMs

Feasibility studies for SAC with oriented crystals

Forward photons from FV arrive with $\theta < 2$ mrad

Crystals may be aligned to exploit coherent interactions

ERC Starting Grant project (COMPACTOR) – L. Bandiera, INFN Ferrara

KLEVER an ideal application for calorimetry with oriented crystals

Development of free-running, fully digitizing readout system

- 100 MHz hit rate digitized at 1 GHz $\rightarrow$ 100 GB/s
- Development of flexible, fast digitizers with possible applications in NA62
- Data reconstruction and filtering in front end with ML algorithms:
  Use case for INFN APEIRON project

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**MEC R&D at the Frascati BTF**

**Beam test of shashlyk calorimeter with spy tiles (MEC)**

Fine-sampling: 0.275 mm Pb + 1.5 mm scintillator

Spy tiles measure longitudinal shower development:
- Identification of $\mu$, $\pi$, $n$ interactions
- Improved time resolution for EM showers

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

- 100-550 MeV single $e^+/e^-$ from DAΦNE linac, with photon-tagging systems
- Ideal for measurement of low-energy efficiencies
  - Recently upgraded with installation of new BTF-2 beamline
  - Photon-tagging systems upgraded

**Photon efficiency measurements at BTF will be key for KLEVER R&D**

- Precision efficiency measurement with single $e^+/e^-$
- Development of measurement techniques with tagged photons

**BTF beam requested in 2020 for performance studies with MEC prototype**
Status and timeline

Project timeline – target dates:

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

**2019 Q4**  
Expression of Interest to CERN SPSC

**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

**2024-2026**  
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!
## Status and timeline

### Project timeline – target dates:

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<th>Event</th>
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<td>2026-</td>
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Most groups participating in NA62 have expressed interest in KLEVER. We are actively seeking new collaborators!
We are very grateful for support from Physics Beyond Colliders!
Inclusion in and interest from Beyond Standard Model WG
Substantial contributions from Conventional Beams WG

We would especially like to recognize major, essential contributions from our PBC/CB fellow
M. van Dijk
KLEVER

Additional information
Physics Beyond Colliders
Beyond Standard Model Working Group
05 November 2019

Matthew Moulson
For the KLEVER project
The KLEVER Project


¹University and INFN Naples, Italy
²University and INFN Rome Tor Vergata, Italy
³INFN Frascati National Laboratories, Italy
⁴University of Insubria, Como, Italy
⁵University and INFN Ferrara, Italy
⁶CERN EN-EA-LE, Geneva, Switzerland
⁷University and INFN Turin, Italy
⁸University of Padua and INFN Legnaro National Laboratories, Italy
⁹University and INFN Pisa, Italy
¹⁰Institute for Nuclear Research, Moscow, Russia
¹¹Marconi University and INFN Frascati National Laboratories, Italy
¹²University of Sofia, Bulgaria
¹³Charles University, Prague, Czech Republic
¹⁴Institute for High Energy Physics, Protvino, Russia
¹⁵University and INFN Florence, Italy
¹⁶Scuola Normale Superiore and INFN Pisa, Italy
¹⁷George Mason University, Fairfax VA, USA
¹⁸INFN Milano Bicocca, Italy
¹⁹University of Mainz, Germany
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
- **LAV 1-25** Large-angle vetoes (25 stations)
- **MEC** Main electromagnetic calorimeter
- **SAC** Small-angle vetoes
- **CPV** Charged particle veto
- **PSD** Pre-shower detector

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

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Neutral beamline layout

• 400 GeV/c protons from SPS incident at 8 mrad on beyrllium 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
Neutral beam simulation

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

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

Effect of $\gamma$ converter

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

FLUKA simulation of beamline
32-mm tungsten converter ($9X_0$)
Detail of target and dump collimator:
Beam and intensity requirements

$K_L$ and $\Lambda$ fluxes, $\theta = 8.0$ mrad
Parameterized from FLUKA simulation

- 400 GeV $p$ on 400 mm Be target
- Production at $\theta = 8.0$ 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 $\Delta \theta = 0.4$ mrad
  - Large $\Delta \theta = \text{high } K_L$ 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 $K_L \rightarrow \pi^0\nu\nu$ decays occurring in FV $\sim 5$

10$^{19}$ pot/year ($= 100$ eff. days) $\times$ 5 years $\rightarrow$ 60 $K_L \rightarrow \pi^0\nu\nu$ events

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### High-intensity neutral beam study

**Conclusions from PBC Conventional Beams working group**

<table>
<thead>
<tr>
<th>Issue</th>
<th>Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton availability</strong></td>
<td>SHiP supercycle = $4 \times 10^{19}$ pot/yr with $1 \times 10^{13}$ ppp for users</td>
</tr>
<tr>
<td></td>
<td>KLEVER requires $1 \times 10^{19}$ pot/yr (25% of SHiP)</td>
</tr>
<tr>
<td><strong>Extraction losses</strong></td>
<td>Good results on ZS losses and spill quality from SPS Losses &amp; Activation WG (SLAWG) workshop, 9-11 November 2017: <a href="https://indico.cern.ch/event/639766/">https://indico.cern.ch/event/639766/</a></td>
</tr>
<tr>
<td><strong>Beam loss on T4</strong></td>
<td>Vertical by-pass to increase T4 $\rightarrow$ T10 transmission to 80%</td>
</tr>
<tr>
<td><strong>Equipment protection</strong></td>
<td>Interlock to stop SPS extraction during P0Survey reaction time</td>
</tr>
<tr>
<td><strong>Ventilation in ECN3</strong></td>
<td>Preliminary measurements indicate good air containment</td>
</tr>
<tr>
<td></td>
<td>Comprehensive ventilation system upgrade not needed</td>
</tr>
<tr>
<td><strong>ECN3 beam dump</strong></td>
<td>Significantly improved for NA62</td>
</tr>
<tr>
<td></td>
<td>Need to better understand current safety margin</td>
</tr>
</tbody>
</table>
| **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                                    |
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