K_LEVER

R&D activity and plans

CSN1 referee meeting, 24 September 2019

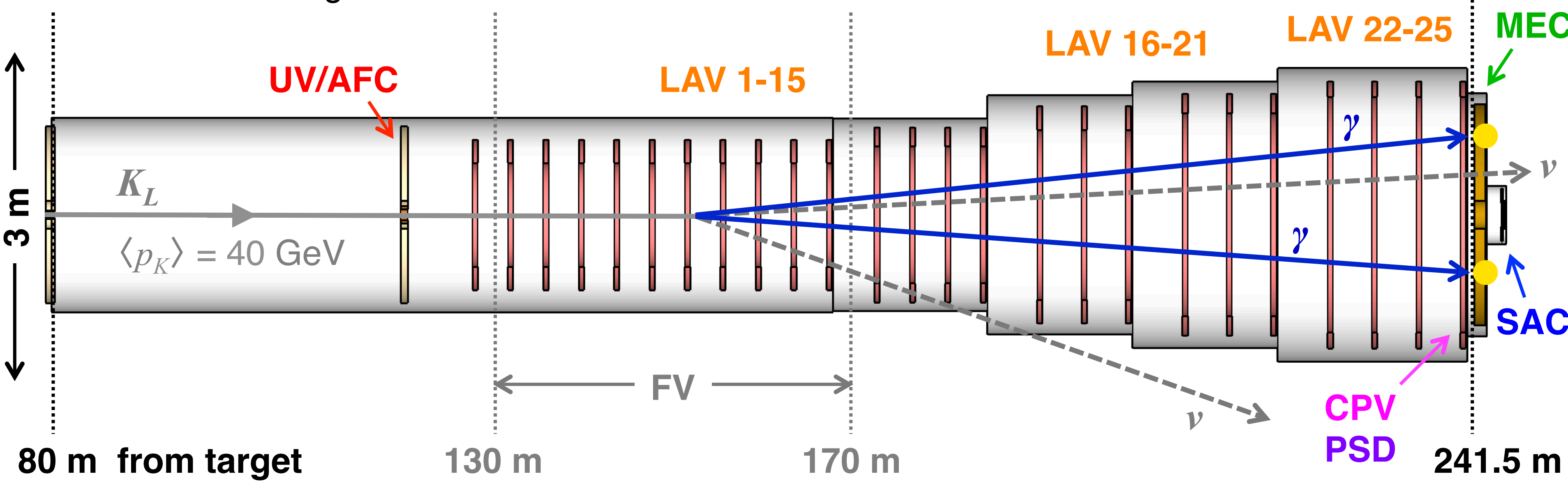
Matthew Moulson
INFN Frascati

A $K_L \to \pi^0 \nu \bar{\nu}$ experiment at the SPS

KLEVER

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

See also: KLEVER at KAON 2019 (link)



KLEVER target sensitivity:

5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$

S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

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

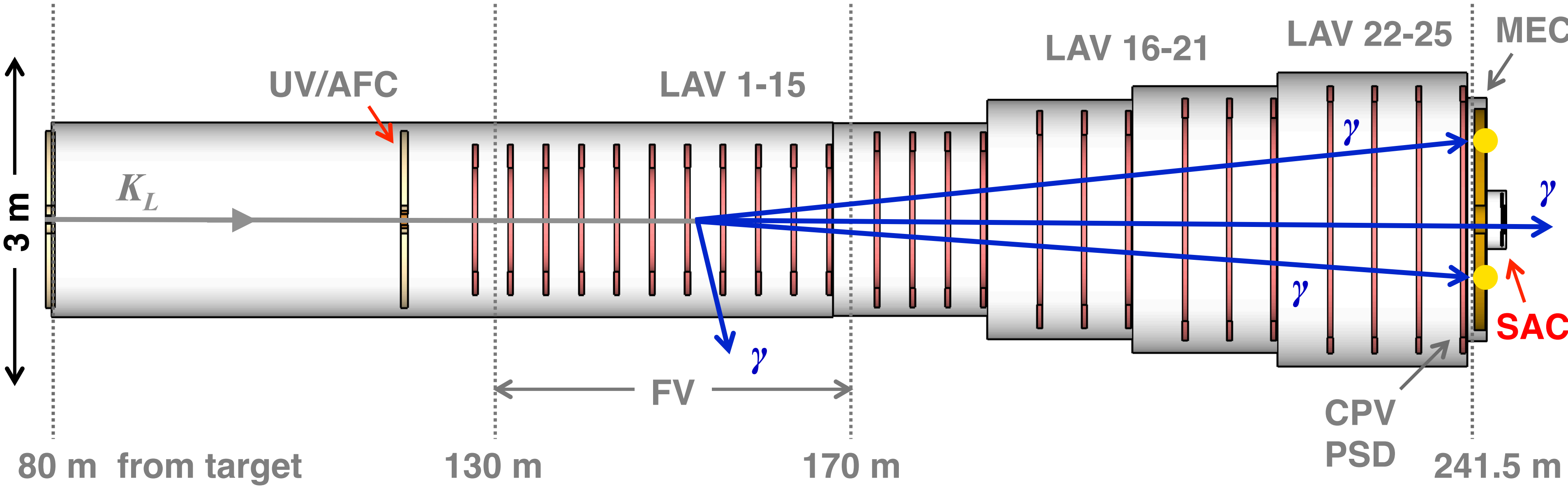
Status and timeline

KLEVER

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 Q3	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**

Small-angle photon veto



Small-angle photon calorimeter system (SAC)

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

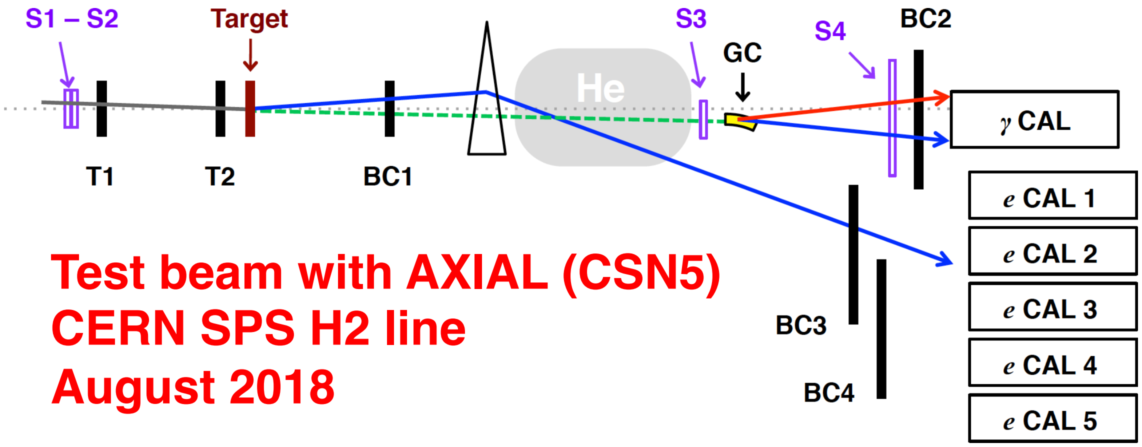
Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

Baseline solution:

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

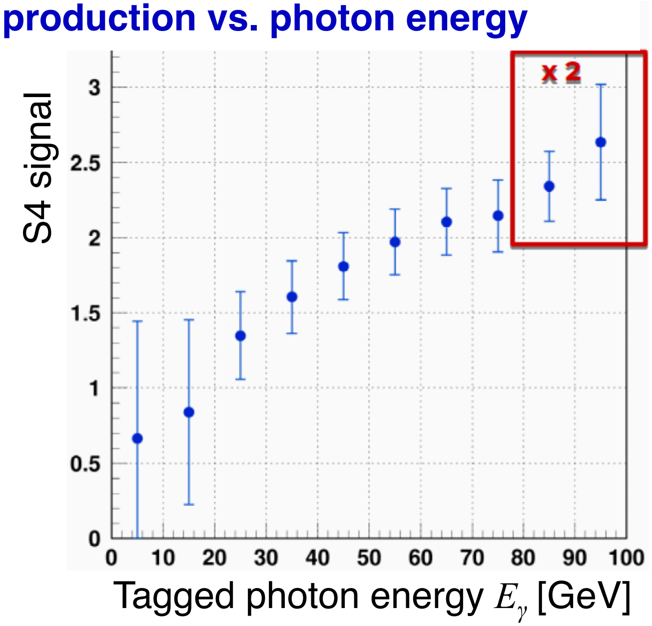
Alternate solution: Ultra-fast heavy Cerenkov calorimeter (e.g. PADME, g-2)

Test beam analysis

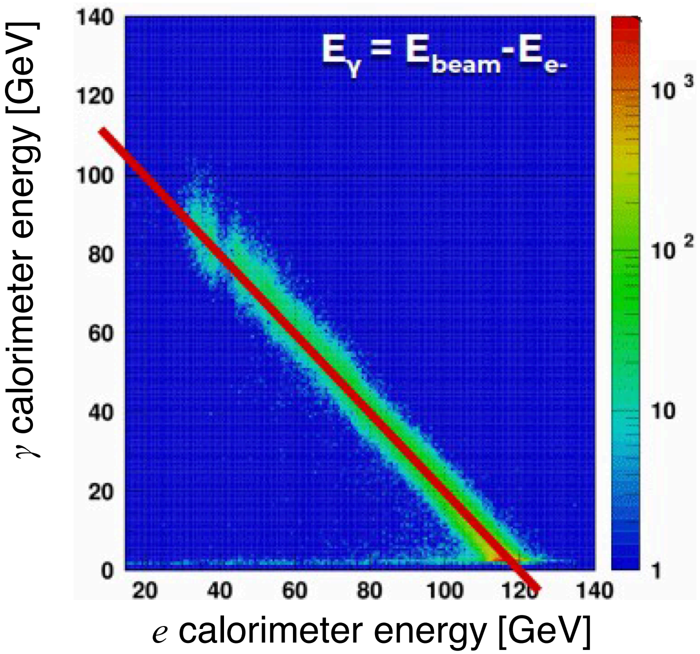


Test beam with AXIAL (CSN5)
CERN SPS H2 line
August 2018

Enhancement in charged particle production vs. photon energy



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)

Cerenkov small-angle calorimeter

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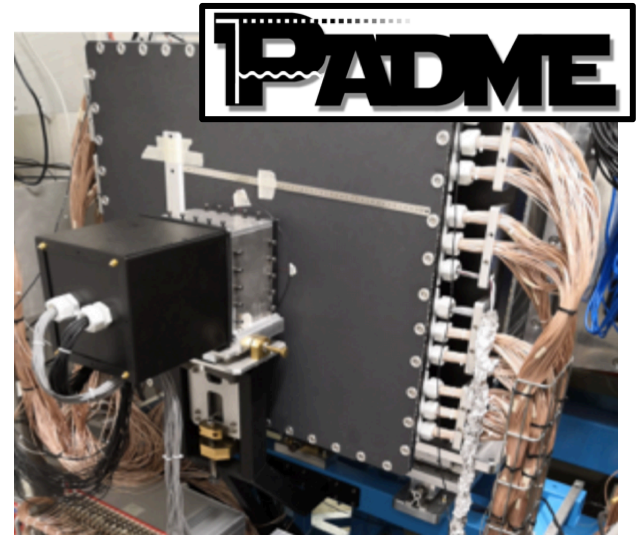
PADME SAC = In-beam PbF_2 Cerenkov calorimeter

- PMT readout: Hamamatsu R13478UV (25 ch)
- FADC sampling: 2.5 GS/s, 1024 samples
- Time resolution σ_t < 100 ps
- 2-pulse separation at ~ 1 ns



Questions for future development

- PbF_2 needs validation for use at continuous high rates and high radiation doses
  - Verify radiation-hardness or identify alternatives (e.g. PWO)
- Optimization of design with SiPMs:
  - Time resolution
  - Radiation hardness
- Study suitability of design for $K_L \to \pi^0 \nu\nu$
  - Response to neutral hadrons
  - Possibilities for γ/n discrimination: multilayer structure/longitudinal segmentation?

AIDA++ projects:

- Instrument R&D
- Calorimeter readout

Exploit coherent interactions in *oriented* Cerenkov crystals to enhance pair conversion?

- ERC Starting Grant proposal in development (L. Banidera)

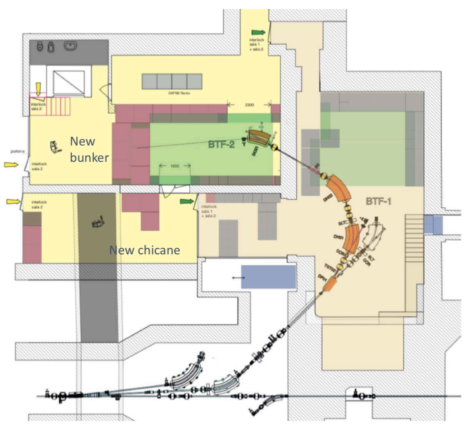
Beam tests with tagged photons

Measurements with tagged photons essential for development of rare-decay experiments with photon veto ($K_L \to \pi^0 \nu\nu$, 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

Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

Fine-sampling shashlyk based on PANDA forward EM calorimeter produced at Protvino

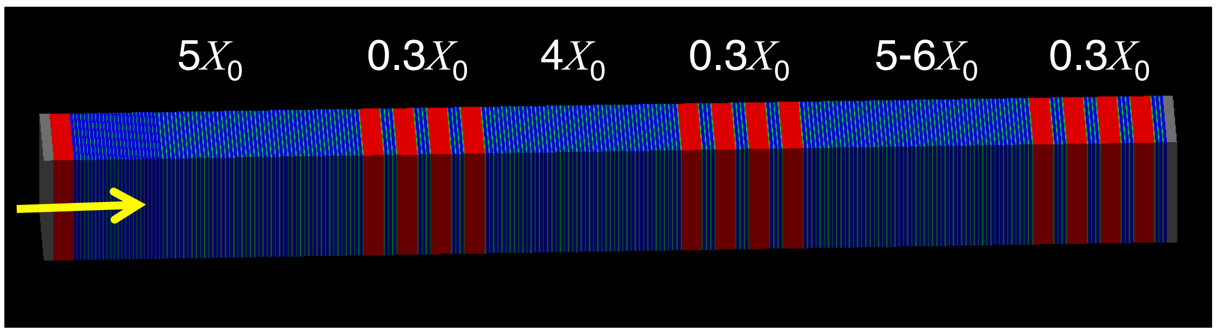
0.275 mm Pb + 1.5 mm scintillator

PANDA/KOPIO prototypes:

- $\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)
- σ_t **~ 72 ps** $/\sqrt{E}$ (GeV)
- σ_x **~ 13 mm** $/\sqrt{E}$ (GeV)

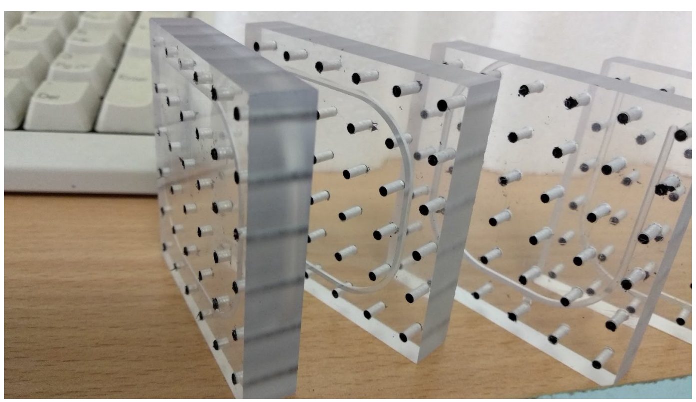
New for KLEVER: Longitudinal shower information from spy tiles

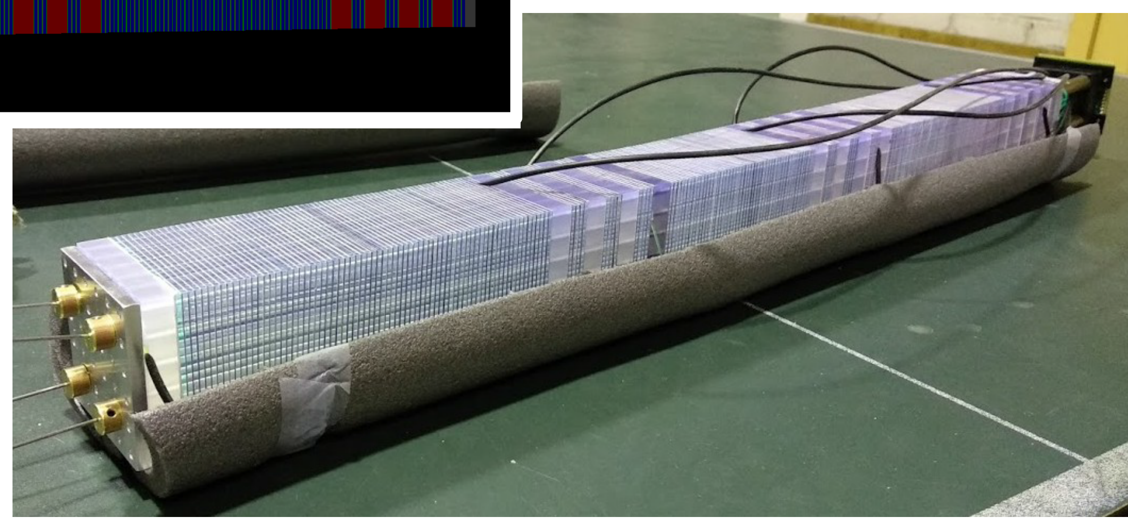
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



1st prototype assembled and tested at Protvino

OKA beamline, April 2018





Beam tests at Frascati

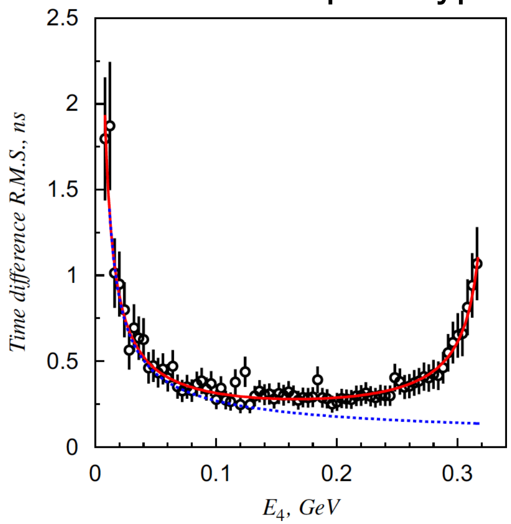
Start with basic studies: validate with single electron beam

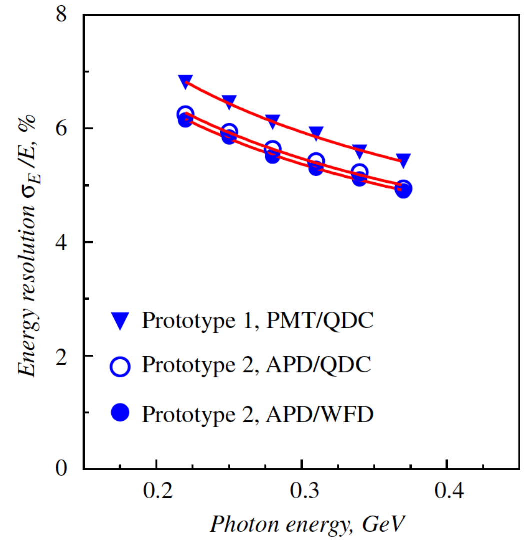
- Energy resolution
- Time resolution
- Efficiency

Further directions:

- Optimization of depth and longitudinal separation
- Measure efficiency with tagged photon beam

KOPIO prototype: NIM A 584 (2008) 291





Previous time resolution measurements:

Mainly used to obtain statistical contribution

Constant term not measured

Beam test program:

- Single electron beam (50 Hz)
- 550 MeV → 200 MeV (or lower)
- Request 1 week at BTF after PADME (March 2020?)

Requests:

Consumables: 5 kE (LNF)

- Construction of tagger
  - 2 Cerenkov fingers, $\sigma_t < 100$ ps
  - Light mechanics for positioning
- Mechanics for prototype support

MI: 2 kE (NA, sj beam time approval)

- Participation in beam test

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Additional information

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$K \to \pi\nu\bar{\nu}$: an overview

KLEVER

Extremely rare decays with rates very precisely predicted in SM:

	SM predicted rates*	Experimental status
$K^+ \to \pi^+\nu\bar{\nu}$	**BR = (8.4 ± 1.0) × 10^{-11}**	7 evts from BNL787, 1 evt from **NA62** Goal: BR to 10% from **NA62** by end of Run 3
$K_L \to \pi^0\nu\bar{\nu}$	**BR = (3.4 ± 0.6) × 10^{-11}**	Only limits at present **KOTO** (JPARC): ~few SM events by 2021

New physics affects K^+ and K_L differently

Measurements of both can discriminate among NP scenarios

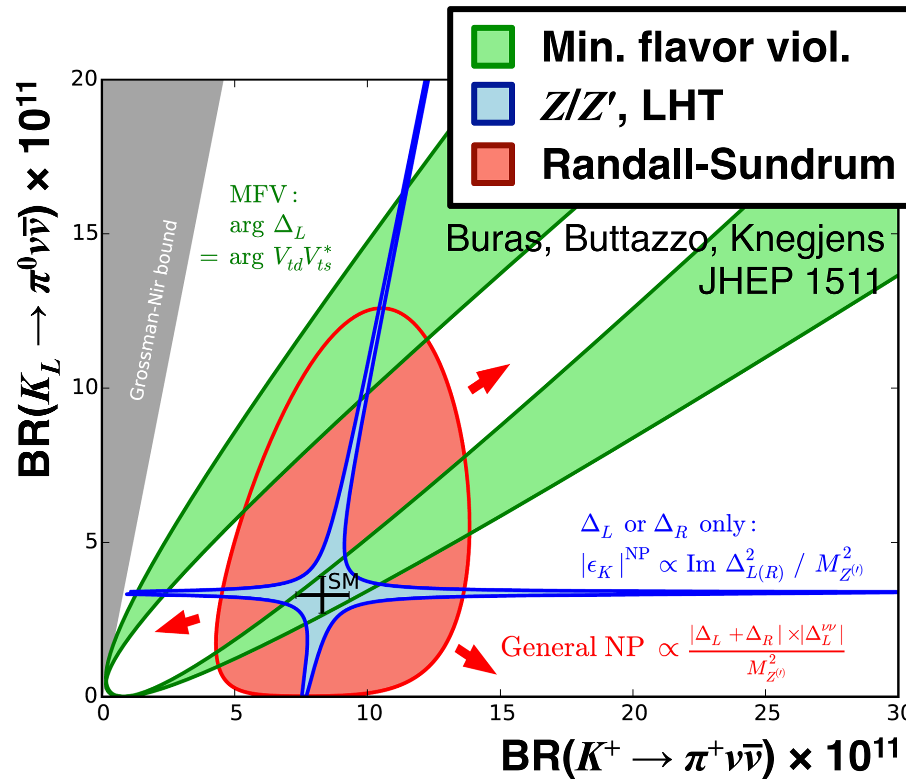
KLEVER target sensitivity

5 years starting Run 4 (2026)

60 SM $K_L \to \pi^0\nu\bar{\nu}$ events

S/B ~ 1

δBR($K_L \to \pi^0\nu\bar{\nu}$) ~ 20%



Buras et al, JHEP 1511*

Physics sensitivity

KLEVER

KLEVER target sensitivity:
5 years starting Run 4

60 SM $K_L \to \pi^0 \nu\nu$
$S/B \sim 1$

δBR/BR($\pi^0\nu\nu$) ~ 20%

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

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

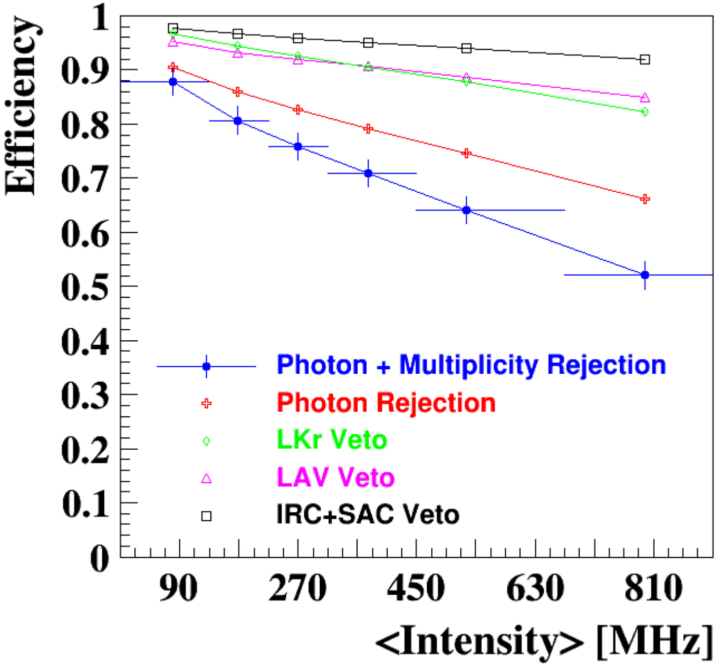
If BR($K_L \to \pi^0 \nu\nu$) is:

- Suppressed to 0.25 BR_{SM} ➡ **5σ**
- Enhanced to 2 BR_{SM} ➡ **5σ**
- Suppressed to 0.5 BR_{SM} ➡ **3σ**

Effects on $K \to \pi\nu\nu$ BRs with constraints from Re ε'/ε, ε_K, Δm_K, $K_L \to \mu\mu$

Model	Λ [TeV]	Effect on BR($K^+ \to \pi^+ \nu\bar{\nu}$)	Effect on BR($K_L \to \pi^0 \nu\bar{\nu}$)
Leptoquarks, most models	1–20	Very large enhancements; mainly ruled out	
Leptoquarks, U_1	1–20	+10% to +60%	+100% to +800%
Vector-like quarks	1–10	−90% to +60%	−100% to +30%
Vector-like quarks + Z'	10	−80% to +400%	−100% to 0%
Simplified modified Z, no tuning	1	−100% to +80%	−100% to −50%
General modified Z, cancellation to 20%	1	−100% to +400%	−100% to +500%
SUSY, chargino Z penguin	4–6 TeV		−100% to −40%
SUSY, gluino Z penguin	3–5.5 TeV	0% to +60%	−20% to +60%
SUSY, gluino Z penguin	10	Small effect	0% to +300%
SUSY, gluino box, tuning to 10%	1.5–3	±10%	±20%
LHT	1	±20%	−10% to −100%

Random veto considerations



Linear extrapolation of random veto probability from 2016 analysis

	Random veto efficiency	
	750 MHz	3000 MHz
LAV	85%	55%
LKr	83%	38%
IRC+SAC	92%	75%
Photon veto	**64%**	**15%**

Time resolution for all photon vetoes would have to be improved beyond capabilities of current detectors for NA62x4

- Coincidence windows of < 2 ns
- Coincidence time resolution of ~200 ps (±5σ for full efficiency)
- Photon veto time resolution < 200 ps

These characteristics are necessary for KLEVER too

Thoughts about LKr calorimeter

Concerns about LKr:

Time resolution

- σ_t = 0.56 ns + 1.53/E − 0.233/√E → **640 ps for E ~ 10 GeV**
- **Non-gaussian tails**
  - ±15σ coincidence windows for 2 < E < 15 GeV (35 → 18 ns)
  - ±70σ coincidence windows for E > 15 GeV

Rates of 20 MHz on LKr in NA62x4?

- Naively need 4x better σ_t
- **Faster shaping, faster digitizers (cf Riccardo's talk) necessary**
  - Will they be enough?

Long-term reliability (1996 → 2018 → 2030?)

For KLEVER, LKr central bore is not big enough

- **Limits beam solid angle to $\Delta\theta$ < 0.3 mrad → 40% less K_L flux**

Baseline design for KLEVER calls for NA48 LKr to be replaced

Shashlyk MEC: Items to study

- **Simulation studies:**
  - Sufficiency of effective transverse segmentation; optimization of cell size
  - Optimization of total depth
  - Estimate inefficiency from photonuclear interactions
- **Material studies:**
  - Optimization of scintillator composition: shashlyk tiles, WLS fibers, spy tiles
  - Choice of SiPM: Dimensions of active area, time response, thermal stability, radiation resistance
- **Mechanical design studies:**
  - Readout scheme for SiPM: redundancy (2 SiPM/module, mixed)
  - Mechanical design for spy-tile fiber channeling
- **Effect of channeling through fibers and how to mitigate**
- **Energy/time resolution and detection efficiency measurements with tagged photon beams:**
  - Low energy: Frascati BTF (550 MeV), MAMI (1.6 GeV)
  - Intermediate energy: Protvino (5 GeV), DESY II (6 GeV)
  - High energy: SPS test beam in Run 3

Performance of KOPIO shaslyk

KLEVER

	KLEVER requirement	KOPIO performance
Photon eff. **$1-\varepsilon_\gamma$**	see table below	Spec: ≤ 10^{-4}, 50-1000 MeV Ach: ~ 5×10^{-5}, 250 MeV Dominated by punch through Photonuclear not included
Energy res.	$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E\ (\mathrm{GeV})}} \oplus \frac{9\%}{E} \oplus 0.42\%$	$\frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E\ (\mathrm{GeV})}} \oplus 2\%$
Time res.	$\sigma_t < 150$ ps	$\sigma_t \sim 72\ \mathrm{ps}/\sqrt{E\ (\mathrm{GeV})}$
2-cluster sep.	Clust. resolved if $d < 6$ cm LKr Molière radius = 6 cm LKr cell size = 2 cm	Molière radius = 6 cm Cell size = 5.5 cm

Energy (GeV)	$1-\varepsilon$
< 1	1
$1 \to 5.5$	$10^{-3} \to 10^{-4}$
$5.5 \to 7.5$	$10^{-4} \to 5\times10^{-5}$
$7.5 \to 10$	$5\times10^{-5} \to 10^{-5}$
$10 \to 15$	8×10^{-6}
> 15	4×10^{-6}

Calorimeter readout system

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**