KLEVER

Outlook and plans

NA62 CSN1 referee meeting

15 September 2020

Matthew Moulson
INFN Frascati

NA62 through LS3

$K^+ \to \pi^+ \nu\nu$ in NA62 Run 1 (2016-2018):

$$\mathrm{BR}(K^+ \to \pi^+ \nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \mathrm{stat}} \pm 0.3_{\mathrm{syst}}) \times 10^{-11}$$

Plans for NA62 Run 2 (from LS2 to LS3):

NA62 to resume data taking in July 2021

Key modifications to reduce background from upstream decays and interactions:

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

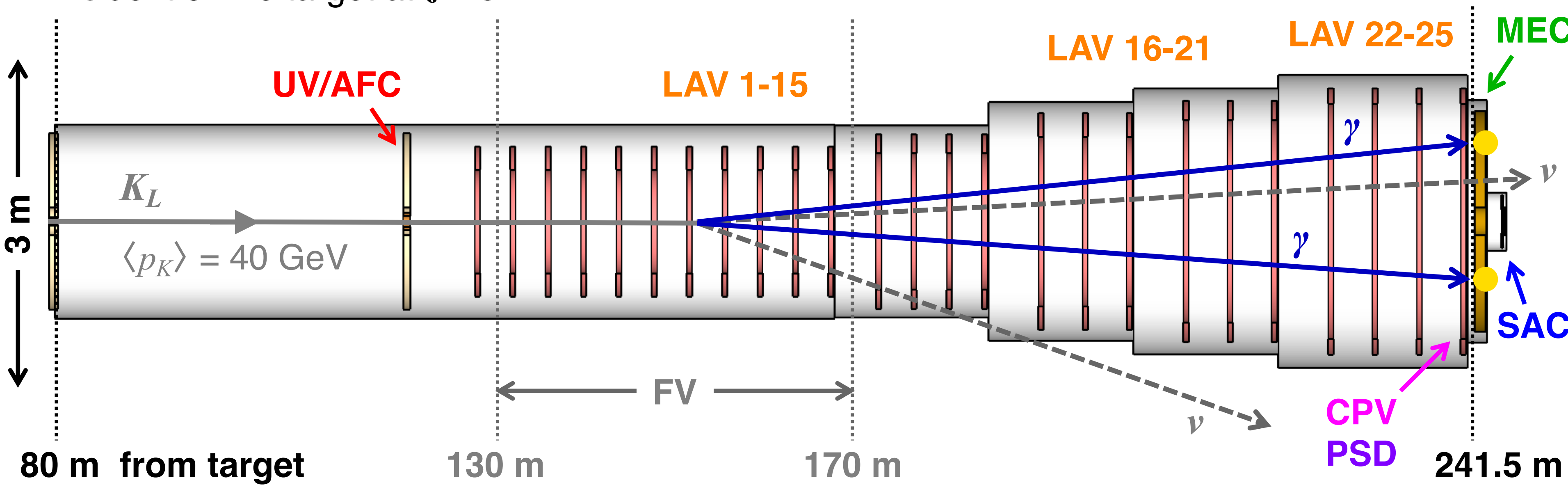
Run at higher beam intensity (70% → 100%)

Expect to measure BR($K^+ \to \pi^+ \nu\nu$) to better than 20%

What happens after LS3 (mid-2027 onwards)?

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

400-GeV SPS proton beam (2 × 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 $K_L \to \pi^0 \nu\nu$

$S/B \sim 1$

δBR/BR($\pi^0\nu\nu$) ~ 20%

Evolution of relationship to NA62

NA62 high-intensity K^+ discussion, Jan 2019:

- **Goal: Measure BR($K^+ \to \pi^+ \nu\nu$) to 5%**
- **4x increase in primary intensity ("NA62x4")**
  Based on feasibility studies for KLEVER beam
- Many technological challenges, esp. beam and spectrometer tracking
  Adopt calorimetry and veto designs from KLEVER
- Significant interest from NA62 collaboration and community
  Harness synergies with KLEVER to ensure success of both projects

Outcome of European Strategy Update:

- Support for intensity frontier physics reaffirmed
  Rare kaon decays explicitly mentioned in supporting document
- Physics Beyond Collider programs generally supported
- SPS beam dump facility judged to be to expensive

CERN-ESU-014
June 2020

Many of the proposals for new experiments at CERN are on a scale such that they could be considered for approval in the usual manner by the scientific committees and the Research Board. Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

European Strategy Update

Support for diverse program of high-impact measurements, including flavor physics

CERN-ESU-013
June 2020

4. Other essential scientific activities for particle physics

a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. *Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.*

Supported flavor physics program includes rare kaon decays

CERN-ESU-014
June 2020

Studying the flavour puzzle may indicate the way to new physics with sensitivity far beyond what is reachable in direct searches, e.g. the evidence for the existence of the top quark that followed from the study of B-meson mixing. In addition, flavour physics and CP violation, which play a vital role in determining the parameters of the Standard Model, are explored by a wide spectrum of experiments all over the world. These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC, in particular with the LHCb experiment. New results are expected in the near future from the Belle II experiment at KEK in Japan and from LHCb (currently undergoing an upgrade) at CERN.

- **KLEVER had a direct role in generating support for kaon physics in ESPP**
- **KLEVER was the only kaon physics experiment represented in PBC study and the only kaon project to provide an input document**
- **Still, KLEVER input to ESPP should be considered to be *prototypical***

NA62/KLEVER integrated plan

KLEVER

High-intensity kaon facility at SPS with three experimental phases:

1. "NA62x4": $K^+ \to \pi^+ \nu\nu$
2. KLEVER: $K_L \to \pi^0 \nu\nu$
3. Intermediate stage: K_L beam + charged-particle tracking/PID
   $K_L \to \pi^0 \ell^+ \ell^-$; LFV and radiative K_L decays

Common features:

- Same primary beamline based on PBC studies for KLEVER
  - 4x NA62 intensity for NA62x4; 6x NA62 intensity for KLEVER
- Interchangeable detectors
  - Calorimetry (incl. LKr replacement) and vetoes from KLEVER studies
  - New Gigatracker, straw tracking, and PID detectors for NA62x4

Order of running not yet determined

- KLEVER may be more feasible in the short term
  - Project more mature; relies mainly on tried and true technologies
- However, intermediate stage should run before KLEVER:
  - Critical information on K_L, Λ, n fluxes and halo

NA62/KLEVER Snowmass EoI

KLEVER

On the combined NA62x4/KLEVER long-term program:

Following upon NA62's successful application of the in-flight technique to measure BR($K^+ \to \pi^+ \nu \bar{\nu}$), we envision a comprehensive program for the study of the rare decay modes of both K^+ and K_L mesons, to be carried out with high-intensity kaon beams from the CERN SPS in multiple phases, including both an experiment to measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) at the 5% level and an experiment to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) at the 20% level, which together with the KOTO measurement will push the precision below 15%. The detectors could also be reconfigured to allow measurements of K_L decays with charged particles, such as $K_L \to \pi^0 \ell^+ \ell^-$.

On KLEVER:

The baseline design for the K_L experiment is the KLEVER project [31], presented as part of the Physics Beyond Colliders initiative [32]. The KLEVER goal is to measure BR($K_L \to \pi^0 \nu \bar{\nu}$) to within 20%. The measurement technique is complementary to that for KOTO: the boost from the high-energy neutral beam facilitates the rejection of background channels such as $K_L \to \pi^0 \pi^0$ by detection of the additional photons in the final state. Background from $\Lambda \to n \pi^0$ decays in fiducial volume must be kept under control, and recent work has focused on the possibility of a beamline extension and other adaptations of the experiment to ensure sufficient rejection of this channel. The layout poses challenges for the design of the small-angle vetoes, which must reject photons from K_L decays escaping through the beam exit amidst an intense background from soft photons and neutrons in the beam. A notable feature of KLEVER is the exploitation of coherent interaction effects in oriented crystals [33, 34, 35] to remove high-energy photons from the neutral beam and, possibly, for the construction of small-angle photon vetoes with high conversion efficiency for photons but good transparency to beam neutrons.

Cooperation efforts

KLEVER and KOTO Step 2 have similar sensitivity and timescale

- **Experimental approaches are quite different:** low vs. high energy
- **Each group can contribute valuable insight to the other**
  - KOTO has more direct experience with $K_L \to \pi^0 \nu\bar{\nu}$
  - NA62 has solid roots in NA48 experiments with K_L

Model for cooperation discussed at KAON 2019:

- Periodic, structured discussions
  - 2 meetings since KAON 2019; next meeting October 2020
  - Status updates, future plans, detector ideas
  - MC and event generators: model benchmarking, common standards
    E.g. neutral hadron production in primary and secondary interactions

Applying for cooperation funds in Italy (MAECI) and Japan

- KOTO-KLEVER-NA62 workshops, building on above meetings
- Joint R&D: Calorimeters with photon vectoring; small-angle vetoes
- Exchange of students and early-career researchers

Recent progress on KLEVER

Layout and beamline design:

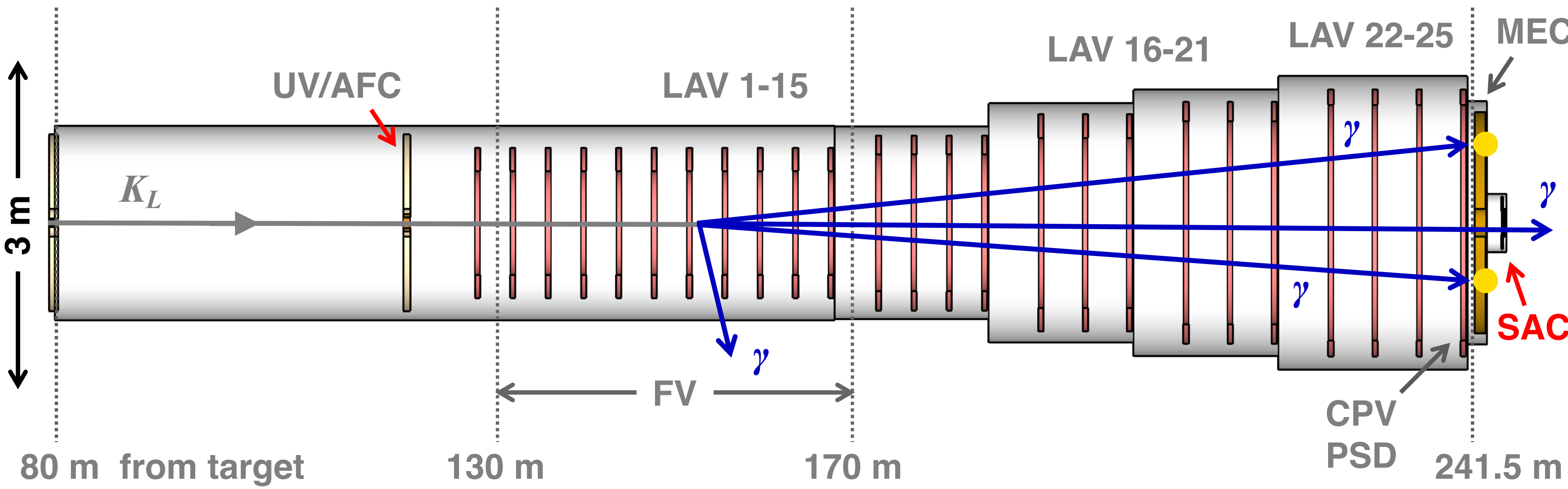
- Mature beamline design with 8 mrad production angle, including shielding, RP, rate, and halo studies
- New layouts at larger angle and/or with longer baseline
  - Error in event generator used to study $\Lambda \to n\pi^0$ background
  - $\Lambda \to n\pi^0$ background was always a bit critical found to be unacceptable
  - Long-baseline designs more expensive but more robust

Recent focus on sensitivity and detector design/simulation:

- Shashlyk calorimeter as replacement for NA48 LKr
- Small-angle calorimeter using oriented crystals
- Preshower detector for photon tracking
- KLMC: Geant4-based MC
  - Code update, inclusion of new detectors, fast simulation
  - MC production on INFN Tier1 with intention to move to grid

Small-angle photon veto

KLEVER



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γs from $K_L \to \pi^0\pi^0$ 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:

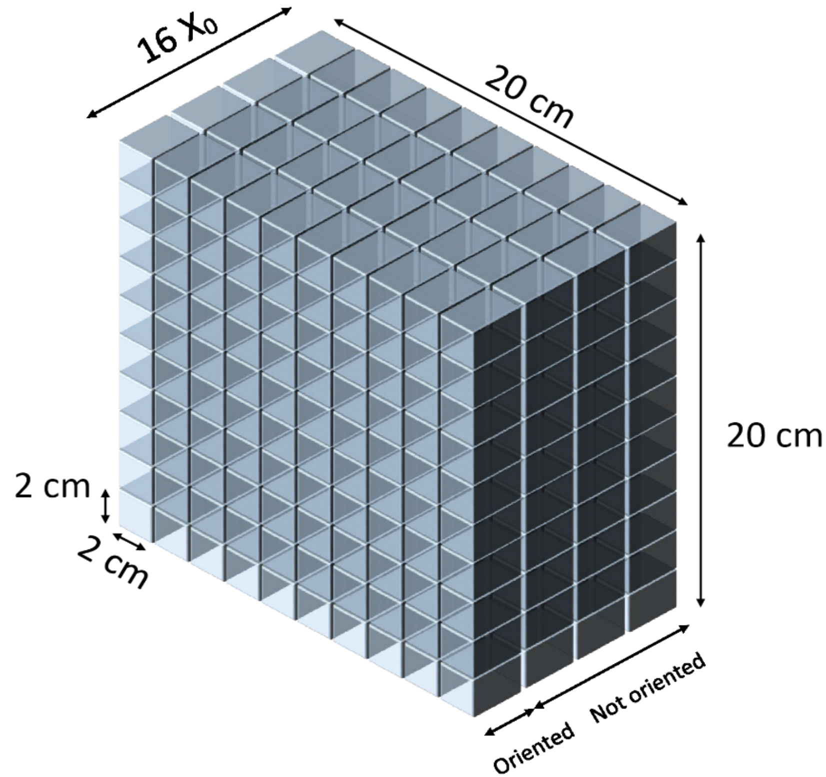
- Tungsten/silicon-pad sampling calorimeter with crystal metal absorber to exploit enhancement of photon conversion by coherent interaction with lattice

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

A Cerenkov SAC for KLEVER?

PADME SAC = PbF2 Cerenkov calorimeter

- **σ_t < 100 ps**
- **2 pulse separation at ~ 1 ns**

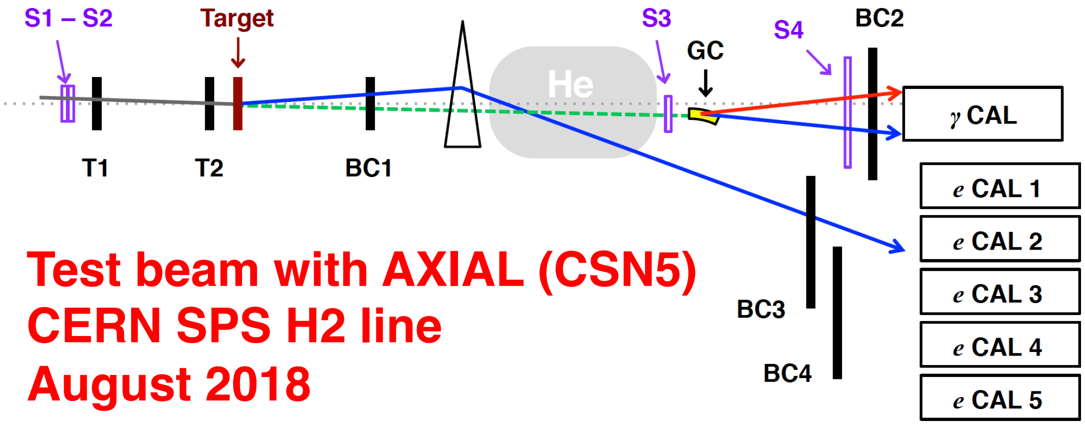


Questions:

- Use of PbF_2 needs validation at continuous high rates and high radiation doses
  - Eliminate afterglow from fluorescence?
  - Verify radiation-hardness (including possibilities for in-situ recovery) or identify alternative crystal candidates
    - 10^{14} n/cm^2 and 10^5-10^6 Gy
- Optimization of choice of photodetectors
  - Excellent time resolution
  - Radiation hardness
- Study response to neutral hadrons
- Possibilities for γ/n discrimination: multilayer structure/longitudinal segmentation
  - Compact light readout multilayer structure
- Align crystal axis with beam to exploit effect of coherent interactions with lattice?

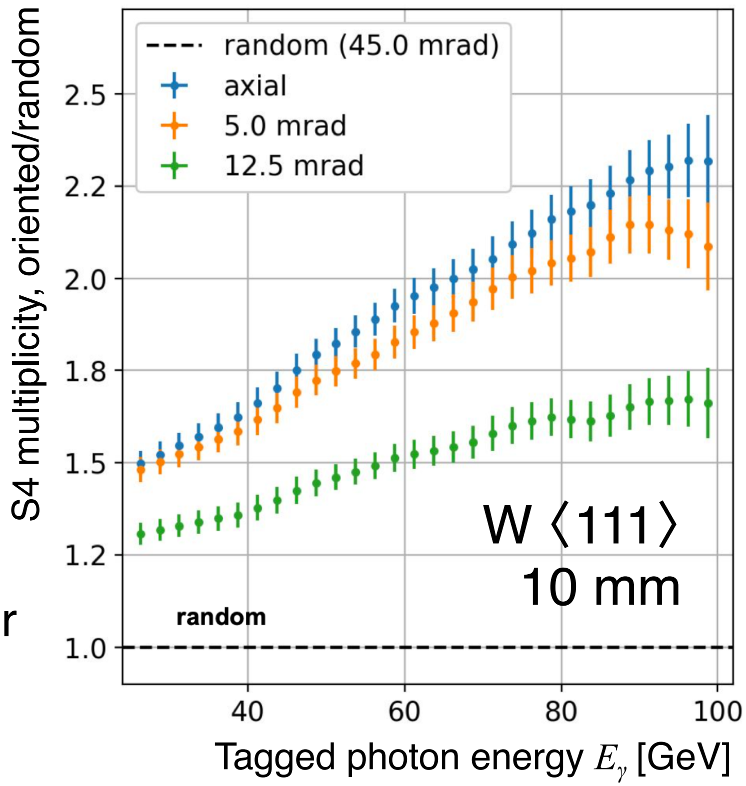
Test beam with oriented crystals

KLEVER



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

Tungsten samples tested:
1-2 mm tiles → sampling calorimetry
10 mm cube (commercial) → beam photon converter



<u>Recent progress:</u>

1. Data preparation, time-dependent calorimeter calibration

   M. Soldani, Ferrara, spring 2020

2. Publication in preparation
3. Continued development of simulation including coherent interactions (Ferrara)

Next step:
Investigation of coherent interactions in optical crystals

AIDA++ project for Cerenkov SAC

EoI 36: Development of compact, ultra-fast Cerenkov calorimeters
KLEVER-PADME: INFN Ferrara/Frascati/Roma/Napoli/Torino

Deliverables

1. **Validate detector components**
   - Identify a SiPM with excellent timing and good radiation resistance
   - Characterization of PbF_2 crystals and alternatives
   - Participation in test → irradiation → test cycle for SiPMs and crystals
     - Irradiation of components: IRRAD (CERN PS T8) or Frascati Neutron Generator (ENEA)
     - Test-bench and BTF measurements (100-550 MeV e^- and tagged γ)
2. **Test prototype with single e^- and tagged γ at the Frascati BTF**
   - Measure energy and time resolution and detection efficiency
3. **Demonstrate feasibility of Cerenkov calorimeter with oriented crystals to exploit enhanced conversion efficiency from coherent interactions.**
   - Test beam program at DESY and/or the CERN North Area from 2021 onwards to measure enhancement in bremsstrahlung and pair-production in Cerenkov crystals and to determine crystal axes
   - Construction and test of a small prototype with an oriented crystal

AIDAinnova project organization

KLEVER

AIDAinnova WP8.3.1
Fast, radiation-hard crystals

"LNF group" = LNF + TO + RM1 + NA + FE

- 10 kE for LNF group
- 10 kE for PG group (Cecchi et al.)

Project funds should be sufficient if approved

Possible requests for ME/MI for meetings before project funds become available

AIDAinnova approval expected Oct/Nov 2020

MI + ME: 1 kE (LNF)

- Missions for NA, TO, RM1 from metabolism etc.

AIDAinnova WP8.3.1 project organization

M1-M24	Investigation of different materials	CERN, MIB, FZU, Vilnius, Minsk
M6-M48	Characterisation of optical, timing properties, radiation damage	CERN, MIB, FZU, Vilnius, Minsk, **PG**
M6-M36	Simulation	Minsk, ICCUB, CERN, **PG, LNF**
M18-M48	Production techniques	GlassToPower, Crytur
M18-M42	Prototype construction	**PG, LNF,** CERN, Minsk, ICCUB
M30-M48	Beam tests	**PG, LNF**, CERN, Minsk, ICCUB

Shashlyk calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

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

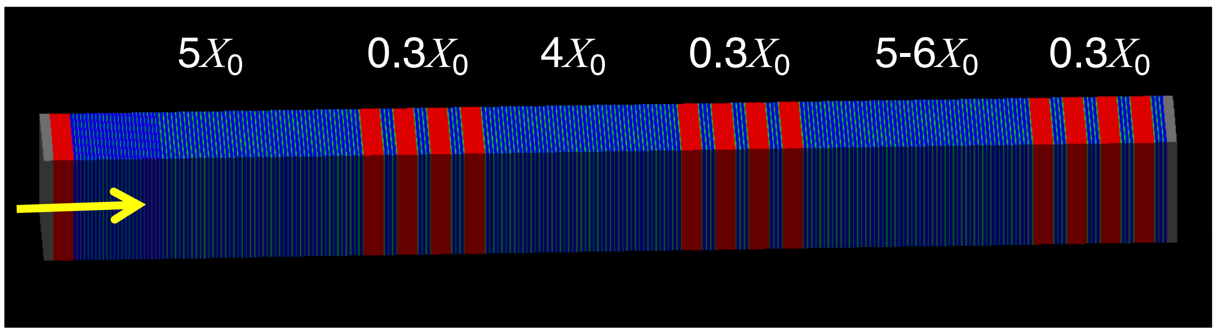
0.275 mm Pb + 1.5 mm scintillator

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)

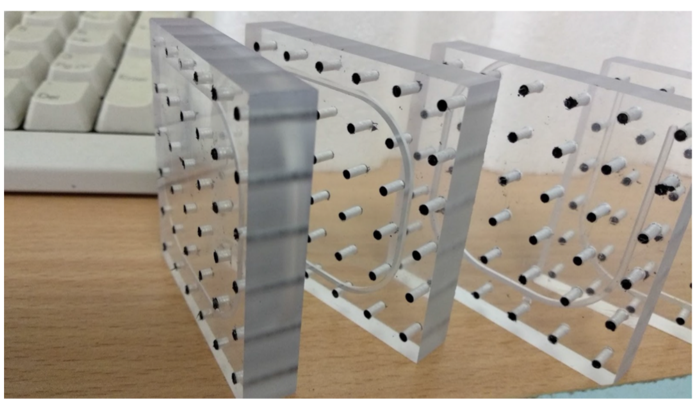
New for KLEVER: Longitudinal shower information from spy tiles

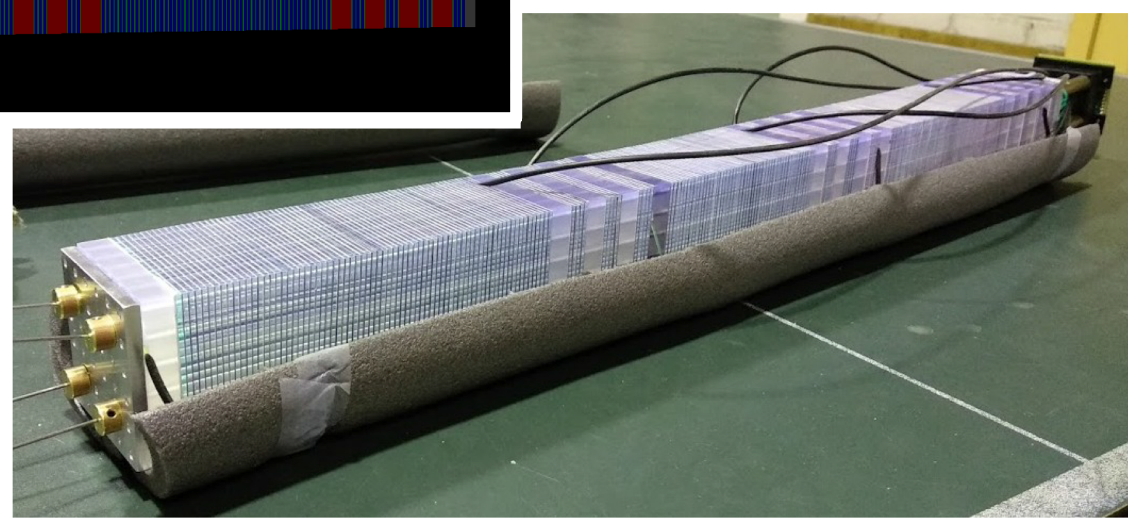
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



1st prototype assembled and tested at Protvino

OKA beamline, April 2018





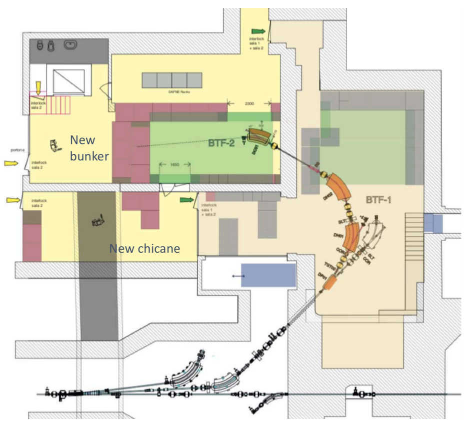
Beam tests with tagged photons

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



- New BTF-2 beamline to be commissioned in 2021
- Photon-tagging systems upgraded
    - 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

Beam tests at Frascati and CERN

Start with basic studies at BTF: validate with single electron beam

- Energy resolution
- Time resolution
- Efficiency

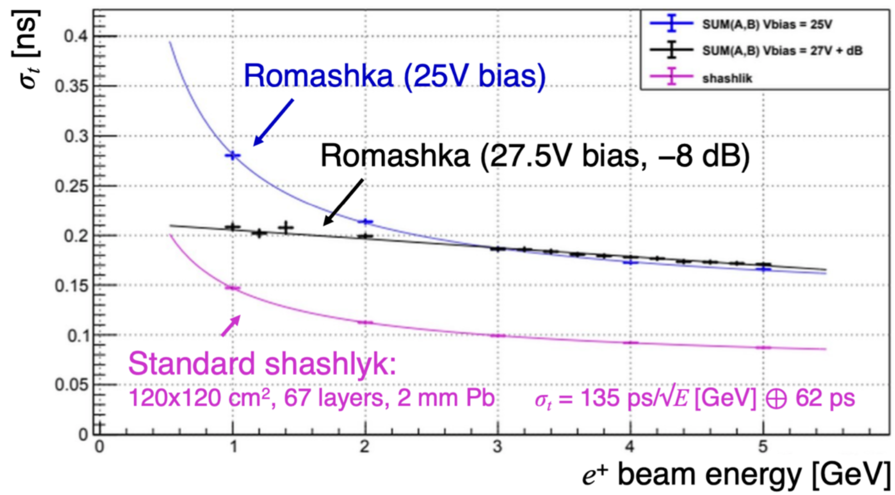
Further directions:

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

Previous time resolution measurements:

Mainly used to obtain statistical contribution

Constant term not measured



Beam time request made in Oct 2019
Delayed due to Be window + Covid-19

Beam time requested:

- 7 days including setup and breakdown
- Single-electron beam, 25-750 MeV
- The energy range is indicative. We plan to study energy and time resolution as a function of incident particle energy. A more restricted range, e.g., 100-500 MeV, would also be acceptable. In particular, the lowest energy used for measurements will depend on the degradation of tagging quality with multiple scattering for the extracted beam.

Scheduling preferences:

- First preference: March 2020
- Second preference: April-July 2020
- Third preference: September-December 2020

DESY test beam, Sep 2019 (1-6 GeV)

- Suspect leakage (longitudinal and transverse) as origin of constant term
- Need points at higher and lower energy for comparison with simulation to confirm

Shashlyk beam test requests

Shashlyk tests at BTF

Validate with single-electron beam:

- Energy resolution
- Time resolution
- Efficiency

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

- Participation in beam test

CONS 1 kE (LNF)

- LNF storeroom and consumables

Shashlyk tests at CERN

Validation with electron beam at SPS H4 instead of BTF

- In combination with FE (STORM), MIB (Prest/Vallazza)
- Possible continuation of studies with crystals in electron beam (Mateck samples, scintillating/Cerenkov crystals)

ME: 6 kE (LNF sj beam time approval)

- Of which 4 kE for MIB personnel (like for FE in 2018)

INV: 3 kE (TO sj beam time approval)

- 4 Hamamatsu R9880U for beam taggers and light readout from crystals

CONS: 1 kE (LNF)

- Crate rental and electronics pool