KLEVER

Status and discussion

NA62 Italia

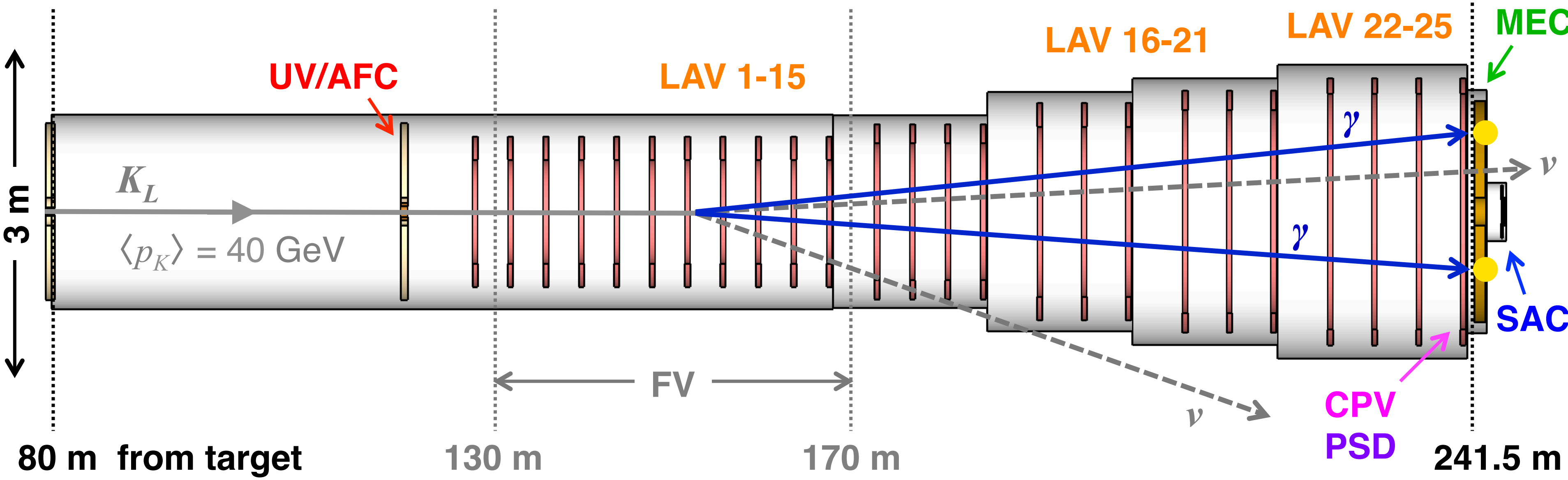
Napoli, 17 April 2019

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**



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

Expression of Interest: dates

EoI is needed in order to provide detail and documentation for discussions about the future of NA62

- **2-3 Apr: SPSC meeting**
  - Original goal was to submit by 11 Mar
- **13-16 May: ESPP Open Symposium, Granada**
  - Real (although approximate) deadline for the EoI if we want it to be available to the Physics Preparatory Group to summarize for the European Strategy Group
- **13-14 June: SPSC meeting**
- **15-16 October: SPSC meeting**
- **5-6 Nov: General Physics Beyond Colliders WG meeting**

  "The meeting will have a similar format as that of the June 2018 WG meeting. Its main goal will be to review the status of the projects' preparation close to the EPPSU drafting session of January 2020. Please freeze the date in your agendas and take this milestone as a target to converge on the short term open issues."

Items in progress for EoI

Beamline (Maarten)

- Extend studies of detector/veto rates to lower particle energies
- Rates are an important feasibility item and need study in further detail

Neutron background (Maarten + other volunteers?)

- Neutron halo in beam
- Beam-gas interaction probability and background rates

H2 test beam analysis (Valerio + Giovanni + Ferrara + Matt)

- Raw data reprocessing and calorimeter calibration
  Valerio and Giovanni working on producing a final data set: almost done
- Geometry and cuts
  Brief look at data at Ferrara: essentially waiting for calibrations
- Implementation of coherent interaction in W in simulation
  Work being done at Ferrara: status?

Items in progress for EoI

IRC/SAC placement, geometry tuning (Matt + volunteers?)

- Particularly important because of backsplash
- Any design changes may require real simulation to validate (e.g. Maarten)

Sensitivity estimate

- Requires IRC/SAC tuning
- MVA for signal/background discrimination (Silvia, see presentation 5 Apr)
  - Optimize selection for signal/$\pi^0\pi^0$/$\Lambda \to n\pi^0$ samples
- Efficiency weights for zOptical (Matt, basically done)

Introductory, physics & writing (Matt + ?)

- Flesh out connection between LFU in B decays/expectations for PNN
- Need to correspond with theory community

Items in progress for EoI

We probably have enough for the EoI for the following items

We do need to add depth to the initial studies for the proposal including start on R&D, prototyping, and tests

- **AFC** (Matteo + Matt)
- **Shashlyk** (Sergey + ?)
  - Write-up of substantial progress made so far
  - Plans for further testing
- **LAV** (Matt)
  - Detailed simulation for efficiencies
  - Incorporate changes to Geant4 photonuclear interaction from LDMX
- **CPV** (?)
- **PSD** (?)
- **Hadronic calormeters (MUV1/2)** (?)
- **Readout** (Dario, Riccardo, Marco, Gianluca, Tor Vergata)

Next steps for R&D

KLEVER

Expression of Interest and related studies

Funding and resource opportunities:

- For Italian groups, request internal funding from INFN (CSN1) for small scale R&D projects as part of NA62
- Submit project for CSN5 call?
- For other groups, explore similar possibilities in host countries
- European Research Commission funding:
    - One project, one institution, one investigator
    - Advanced Grant, deadline 29 Aug 2019
    - No calls for Starting or Consolidator grants until Horizon Europe (2021?)
    - Marie Curie applications for interested individuals!

Other funding possibilities?

Possible R&D projects

AFC

- Test single crystals with different SiPMs
- Efficiency, time resolution for test assemblies with photons (Frascati)
- Preliminary module design considerations

Shashlyk with spy tiles (MEC and UV)

- Continue simulation work
- Optimize and test Protvino prototype in beam:
  - Efficiency, time resolution with photons (Frascati)
  - EM/hadron discrimination (Protvino)
- Preliminary module and/or system design considerations

Large-angle vetoes

- Basic mechanical design for module
- Prototype construction
- Efficiency and time resolution with electrons and photons (Frascati)

Possible R&D projects

SAC/Crystal studies (possible CSN5 application)

- Beam test properties of Mateck crystals (Ferrara)
- Continued research into crystal candidates for converter and SAC, including XRD and beam test characterization
- SAC design studies
- Procurement and characterization of photon absorber crystal
- Elaboration of possible strategy for realization of converter and SAC prototypes and beam test with neutral hadrons in ECN3 at end of Run 3

CPV

- Test scintillator tiles with SiPM configurations: efficiency, time resolution (Frascati)

PSD

- Obtain MPGDs on loan (e.g. ATLAS or RD51 prototypes)
  - Gain experience with technology
- Validation of basic PSD concept using tagged photon beam (Frascati)

Possible R&D projects

Common readout platform (possible CSN5 application)

- Interface with work on simulations (hit rates, signal selection)
  - Evaluate necessity of FADCs and determine frequency
  - Evaluate cost/complexity of triggerless readout including SAC
- Conceptually develop common elements of readout system:
  - Analog front-end stage
  - Digital front-end stage for digitization and zero suppresion
  - Digital readout/data transmission board
  - Fully pipelined MEC trigger if needed to handle SAC dataflow
  - Networking and online computing architecture with model for dataflow from readout boards to permanent storage

Beam test possibilities for R&D

Frascati BTF

- 200-550 MeV electrons, tagged photons
- May help to commission tagged photon line – adds significant value to any R&D proposal!

MAMI

- 1600 MeV electrons and tagged photons
- Experience with tagged photon measurements

DESY II

- 1-6 GeV electrons with possibility of tagged photon beam
- Also used by Ferrara group for studies of crystal quality

Protvino

- OKA beamline: 5 GeV electrons; 12.5, 17.7 GeV hadrons

$K^+ \to \pi^+ \nu\nu$ and KLEVER

KLEVER

NA62 run at 4x intensity in Run 4 or beyond = “NA62x4”

- **In early 2012 (first KLEVER PRIN proposal), it seemed certain that NA62 would have ~100 $K^+ \to \pi^+ \nu\nu$ events by now**
  - 2026 KLEVER start date seemed natural even allowing for a Run 3 high-statistics NA62 phase in Run 3
- **KOTO will not reach SES for SM $K_L \to \pi^0 \nu\nu$ decay until ~2024**
- **Can NA62 and/or KOTO results make NA62x4 more attractive than KLEVER in the short term?**
  - Significant effect in K^+ would generate curiosity about K_L
  - Marginal or no observed effect in K^+ would call for better statistics
- **NA62x4 no less of a technological challenge than KLEVER**
- **No realistic way for NA62/K^+ and KLEVER/K_L to run concurrently**
  - $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ at CERN must be envisioned as two parts of the same program
- **Seek a unitary design:**
  - If K^+ program first, begin work on key KLEVER detectors and put to good use
  - Modular layout, to ensure detectors can be reused for K_L

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

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

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%

NA62x4 physics sensitivity

KLEVER

NA62x4 target sensitivity:

500 SM $K^+ \to \pi^+ \nu\nu$
S/B ~ 0.25

δBR/BR($\pi^0\nu\nu$) ~ 5%

500 $K^+ \to \pi^+ \nu\nu$ events at SM BR
125 background events

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

If BR($K^+ \to \pi^+ \nu\nu$) is:

- BR_{SM} **–25%** or **+30%** ➡ **5σ**
- BR_{SM} **±15%** ➡ **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($K_L \to \pi^0 \nu\bar{\nu}$)
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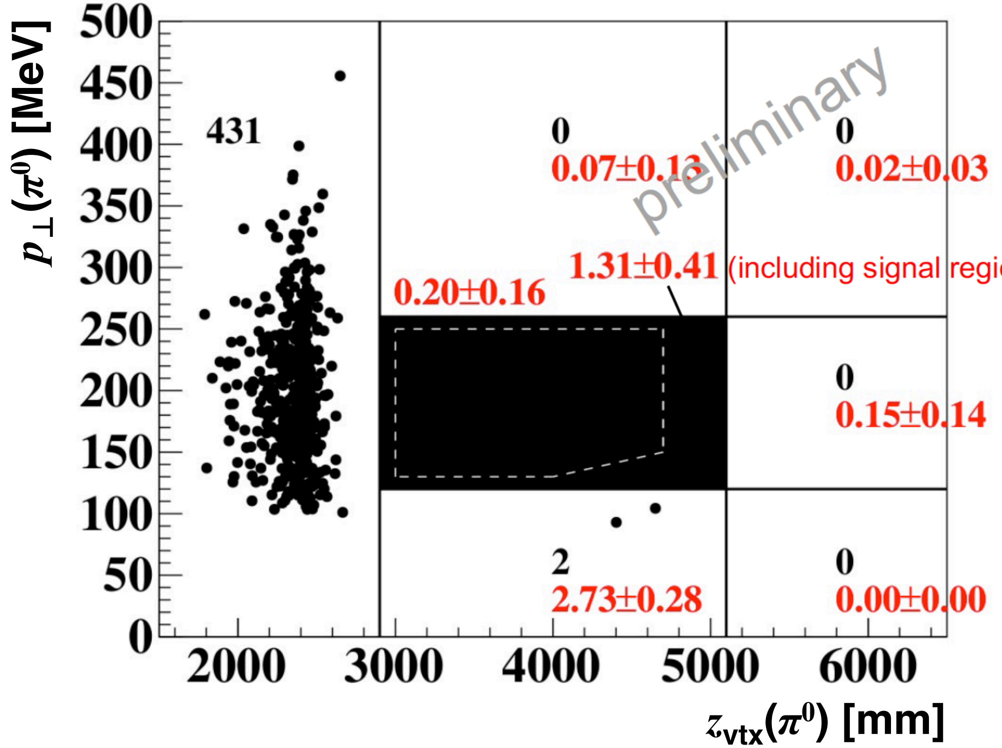
Sensitivity for 2016-2018 data

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

KOTO preliminary 2016-2018 data, Moriond 2019

SES = 8.2 × 10^{-10}

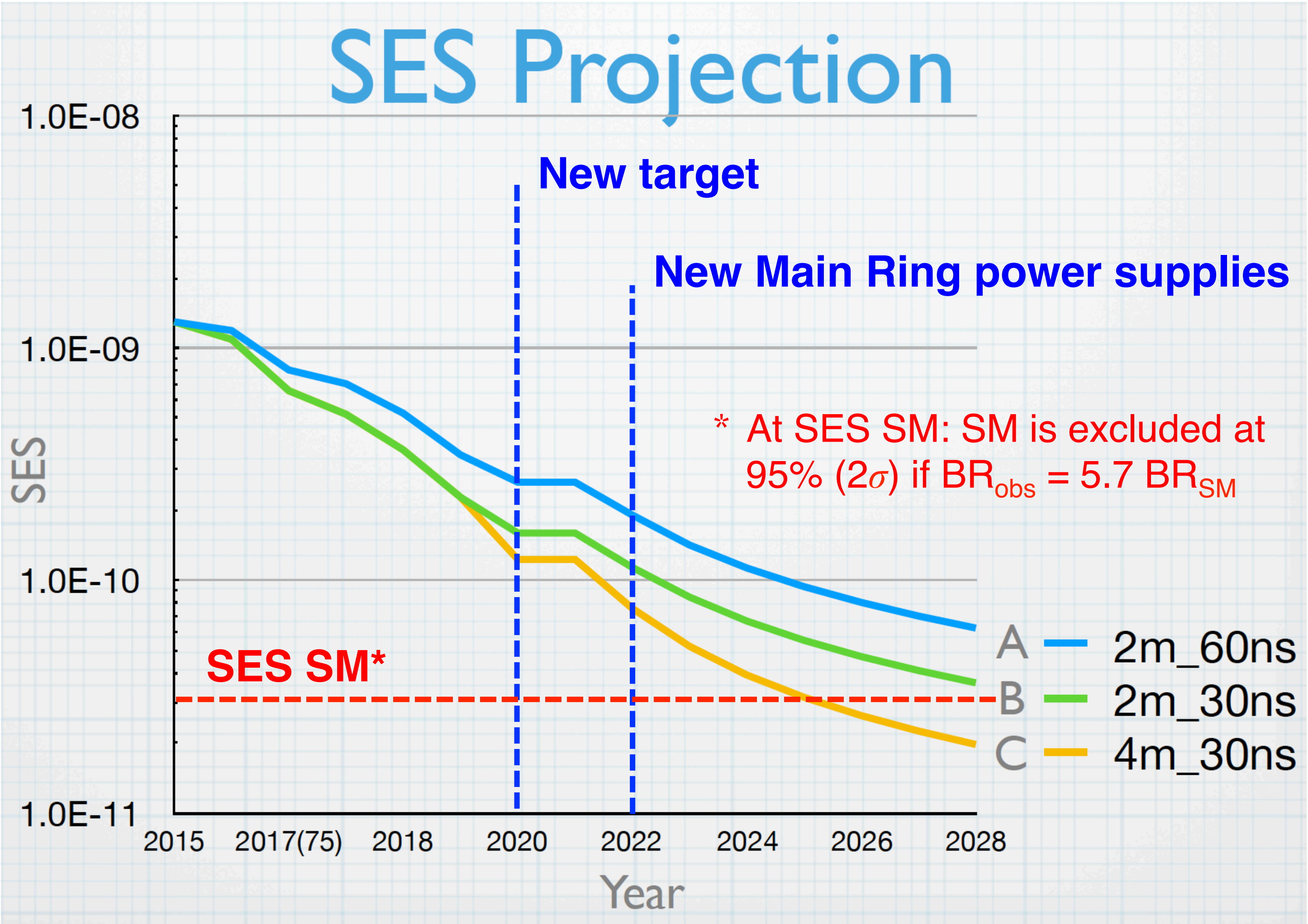
Background	Expected counts
$K_L \to 2\pi^0$	0.09 ± 0.09
$K_L \to \pi^+\pi^-\pi^0$	0.02 ± 0.02
Hadron cluster	0.07 ± 0.13
π^0 from NCC	< 0.19
η from CV	0.02 ± 0.01
Total	**0.20 ± 0.16**



Combined with 2015 result SES ~ 5 × 10^{-10}

New results expected summer 2019!

KOTO projected sensitivity (step 1)



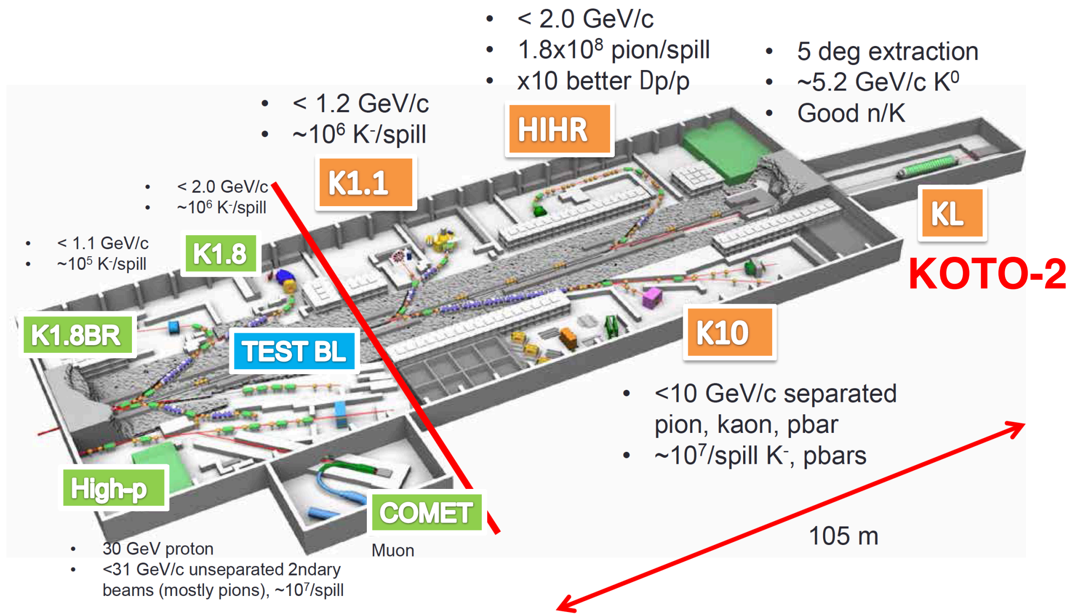
T. Yamanaka, J-PARC PAC, 18 Jul 18, https://kds.kek.jp/indico/event/28286/

KOTO will not reach SES SM until 2024 at earliest without step-2 upgrade

Long-term upgrade plans

KOTO Step-2 upgrade:

- Increase beam power to >100 kW
- New neutral beamline at 5°
  $\langle p(K_L) \rangle$ = 5.2 GeV
- Increase FV from 2 m to 11 m
  Complete rebuild of detector
- Requires extension of hadron hall

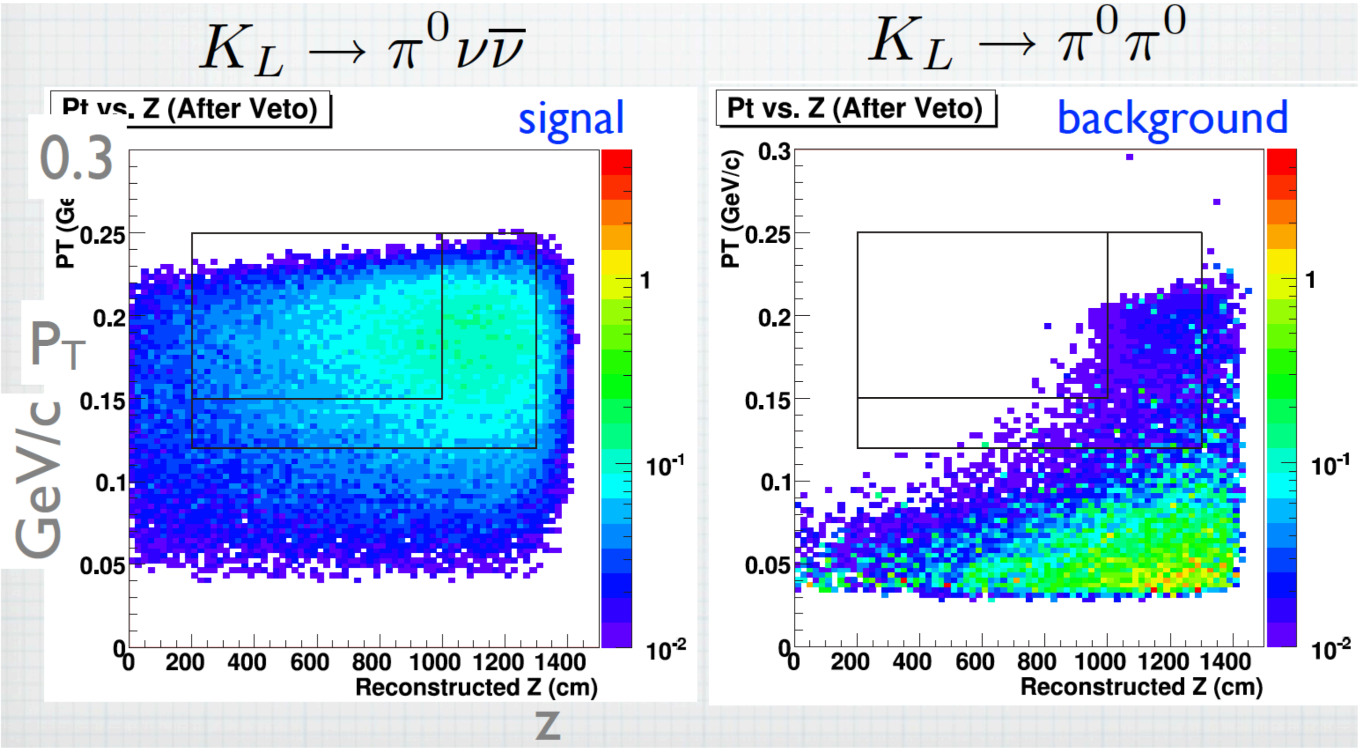


Strong intention to upgrade to 10-100 event sensitivity over long term:

- No official Step 2 proposal yet (plan outlined in 2006 KOTO proposal)
- Scaling KOTO performance for smaller beam angle & larger detector:
  ~10 SM evts/year (10^7 s) at 100 kW beam power?
- Exploring possibilities for machine & detector upgrades to further increase sensitivity

KOTO Step2 —Sensitivity—

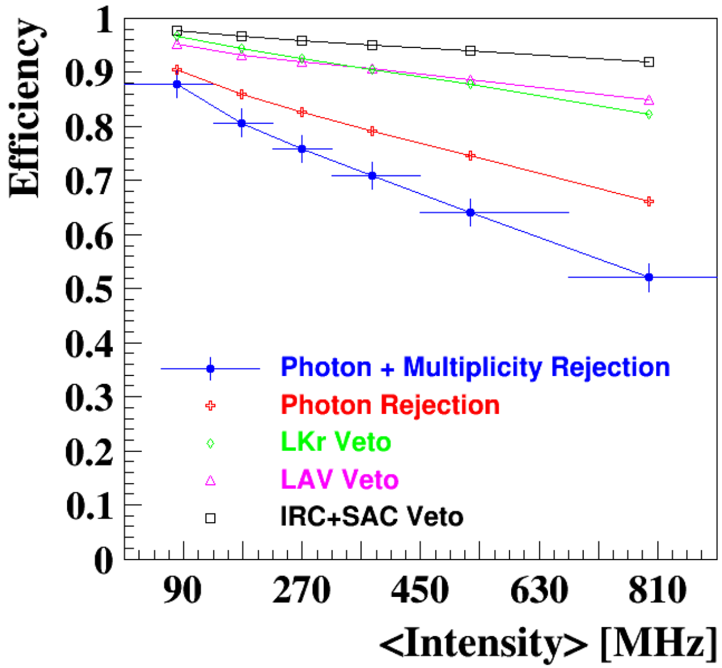
- 30 SM events with 100kW beam × 3e7 sec
  - Measurement of BR with ~20% stat. error.
- S/N(K decay) = 4.8



Summary

- Physics of $K \to \pi \nu \nu$
- KOTO improving sensitivity with upgrades
  - SES=1.3×10^{-9} for 2015 data (PRL.122 021802)
  - $\to 5\times10^{-10}$ for combining 2015-18 data
  - Successful upgrade of calorimeter
  - Explore NP with BR of $O(10^{-11})$ ~2024
    - Calorimeter upgrade + Accelerator upgrade
- Other analysis topics
  - Dark photon search, $K_L \to 3\gamma$, $K_L \to \pi^0 \gamma \gamma$
- Let's discuss future kaon experiments.
    - J-PARC KOTO step2(KL)
    - CERN SPS: NA62(K+)→KLEVER(KL)
  - Now is good time to start. Join us!

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

Large-angle vetoes

Time resolution for current LAVs ~ 1 ns

- Cerenkov light is directional
- Complicated paths to PMT with multiple reflections
- Coincidence windows ±3 ns perhaps a bit tight
  Need more detailed study of LAV efficiency vs time

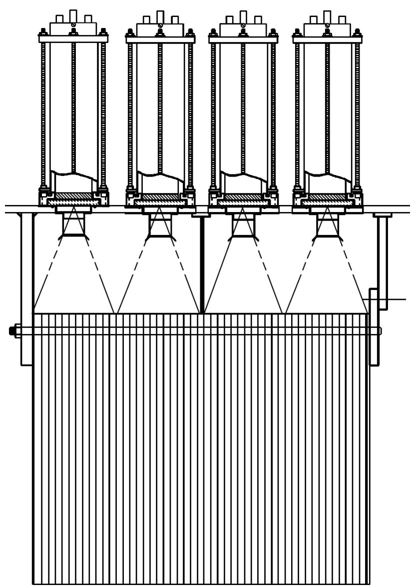
CKM Vacuum Veto System (VVS)

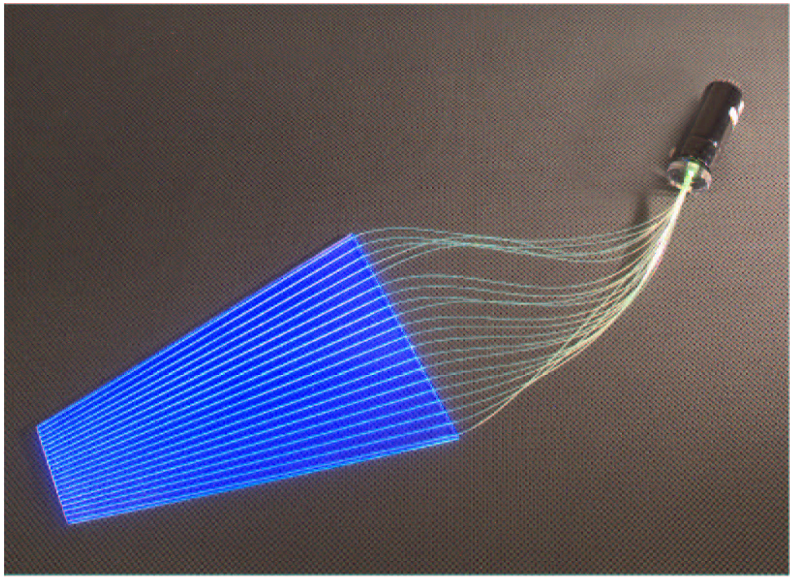
- Pb/scintillating tile
- 1 mm Pb + 5 mm scint
  f_{em} ~ 36%
- WLS fiber readout

Light read out with PMTs in original design

Y ~ 20 p.e./MeV
cf NA62 ~ 0.3 p.e./MeV

Modify design to use SiPM arrays

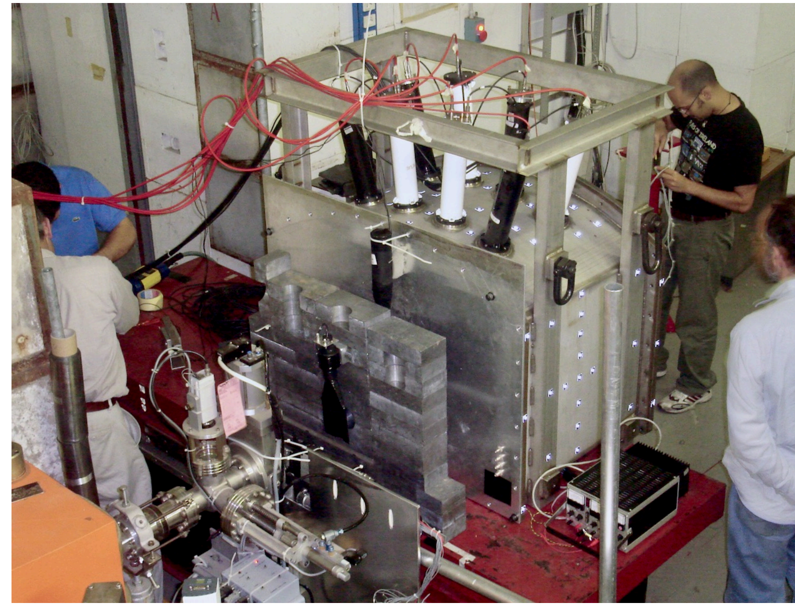




CKM VVS prototype: time resolution

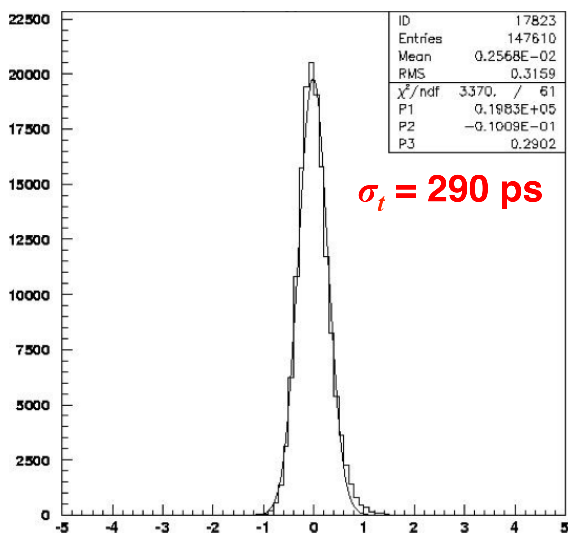
Measurements at Frascati BTF, Jul 2007

E_{beam}	σ_t tag	σ_t CKM
350 MeV	201	155
483 MeV	205	250

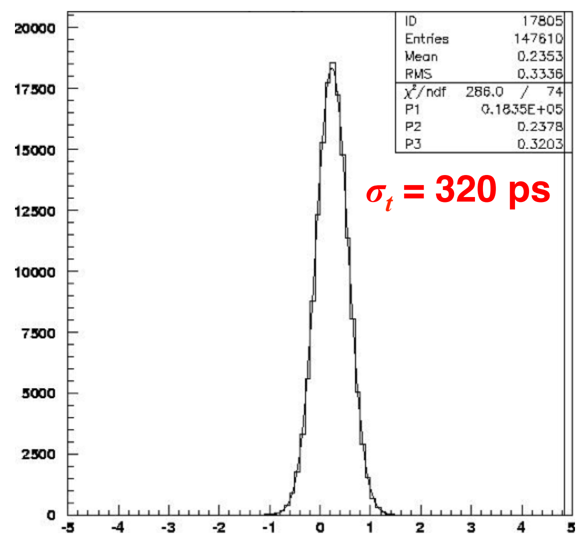


Time resolution 150-250 ps

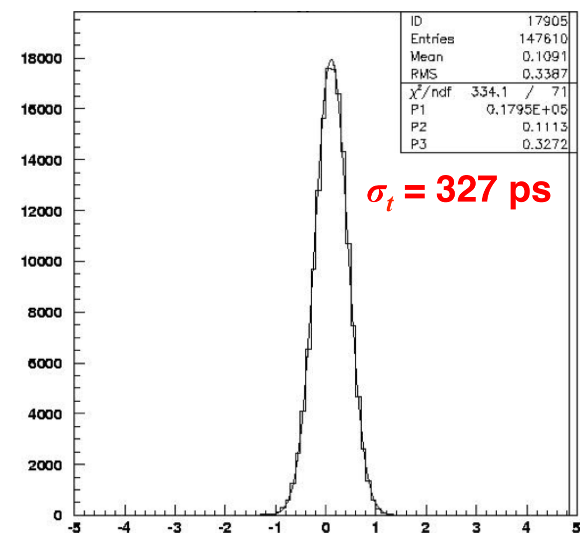
Extra jitter at 483 MeV not understood



tag 1 – tag 2 [ns]



CKM 1 – tag 1 [ns]

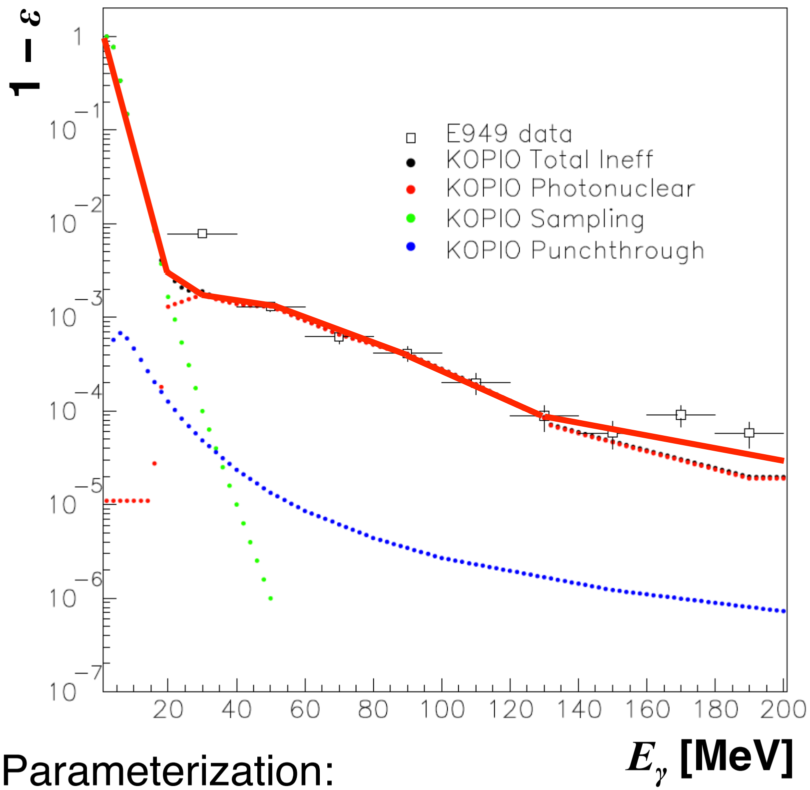


CKM 1 – CKM 2 [ns]

CKM VVS photon efficiency

Need good detection efficiency at low energy (1 – ε ~ 0.5% at 20 MeV)

Baseline technology: CKM VVS
Scintillating tile with WLS readout

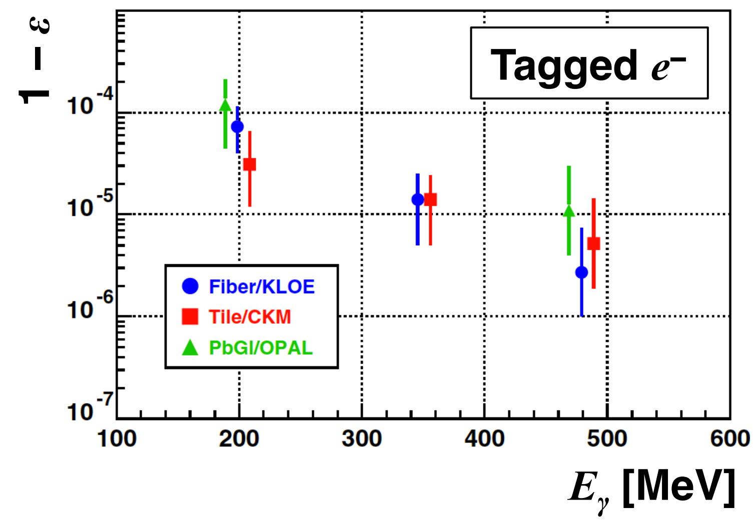


Parameterization:
- 1-129 MeV: KOPIO (E949 barrel)
- 203-483 MeV: CKM VVS

Good efficiency assumptions based on E949 and CKM VVS experience

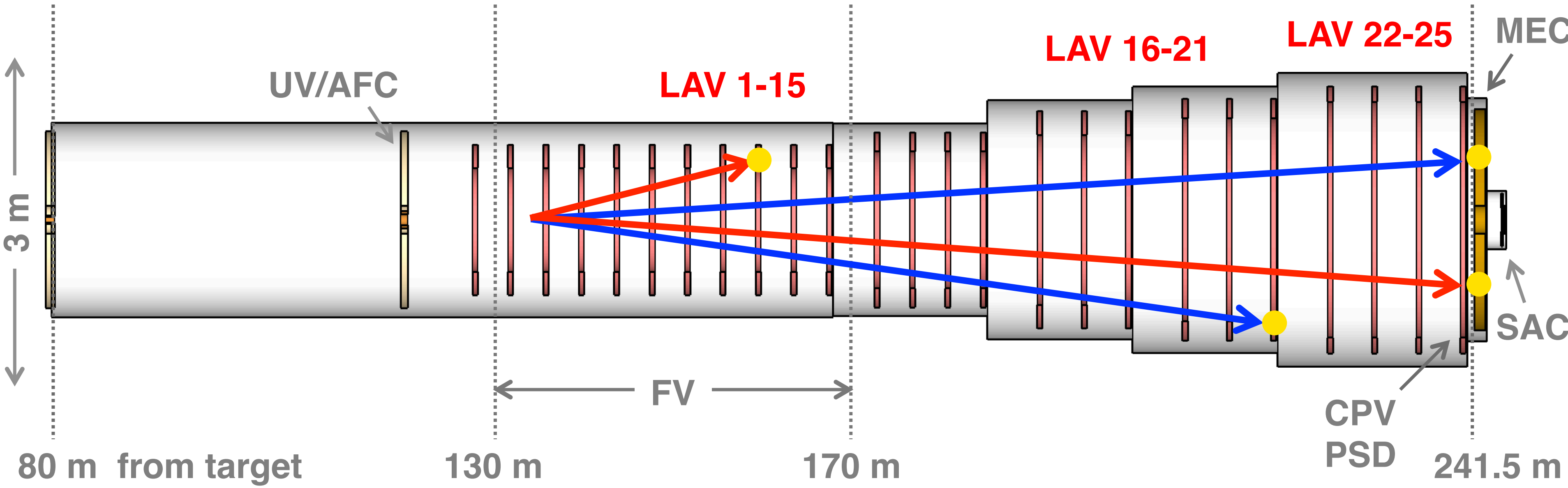
E949 barrel veto efficiencies
Same construction as CKM

Tests for NA62 at Frascati BTF



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

Large-angle photon vetoes



For KLEVER, need 25 new LAV stations based on CKM VVS

- Hermetic coverage out to 100 mrad
- Good detection efficiency at low energy ($1 - \varepsilon \sim 0.5\%$ at 20 MeV)

LAVs	r_{int} (m)	r_{ext} (m)	Sectors	Total ch.	Tot. scint. (kg)
1–11	0.44	0.85	40	3520	9690
12–15	0.58	0.99	48	1536	4290
16–18	0.72	1.23	56	1344	4970
19–21	0.86	1.37	64	1536	5680
22–25	1.00	1.51	72	2304	8525

12 for NA62x4:

→ **5 (LAV1-5)**

→ **3 (LAV 6-8)**

→ **3 (LAV 9-10)**

LAV12 → NA62x4 specific

Large-angle photon vetoes

KLEVER

To handle NA62x4 → KLEVER interface:

- **Need new blue tube from upstream edge to LAV8**
  - Positions of LAVs 1-8 optimized for KLEVER (not same as now in NA62)
  - NA62x4 less stringent – new LAVs have 20% more radial coverage
- **LAVs 9-11 in approx same positions as now in NA62**

Extrapolating from KLEVER LAV cost estimate (€17950k/25 LAVs)

Item	Cost	Notes
Modules	€5160k	17190 kg scint
Mechanics	€1820k	Incl. 12 new blue tube segments
SiPMs	€760k	5056 ch, 500mm2 SiPM array
Front-end	€1260k	12 layers 1 SiPM array, analog sum of outputs
Readout	€1010k	Digitization with 1 GHz FADCs
Total	€10010k	

Intermediate solution may be possible (needs study):

Only replace LAV1-5, LAV12 (use old LAVs 6-11)

Thoughts about LKr calorimeter

Concerns about LKr:

Time resolution

- σ_t = 0.56 ns + 1.53/E − 0.233/$\sqrt{E}$ → **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 calorimeter with spy tiles

Main electromagnetic calorimeter (MEC):

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

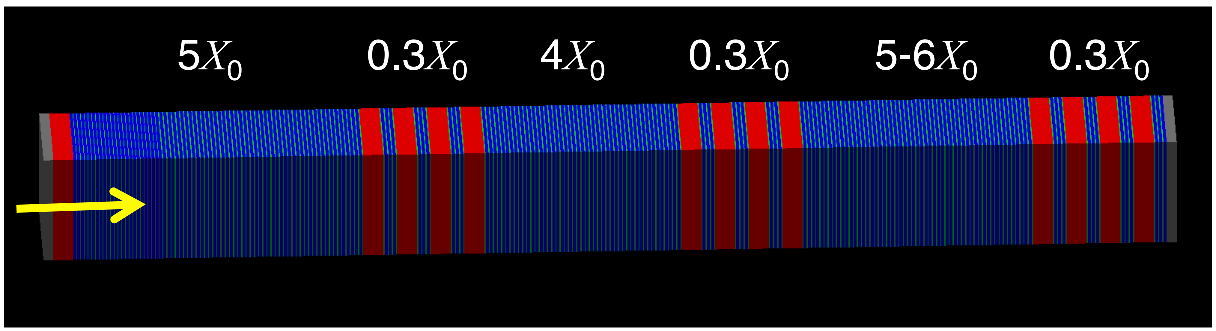
0.275 mm Pb + 1.5 mm scintillator

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)

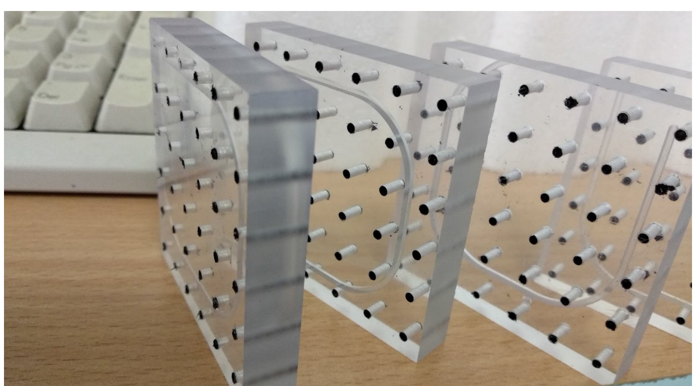
New for KLEVER: Longitudinal shower information from spy tiles

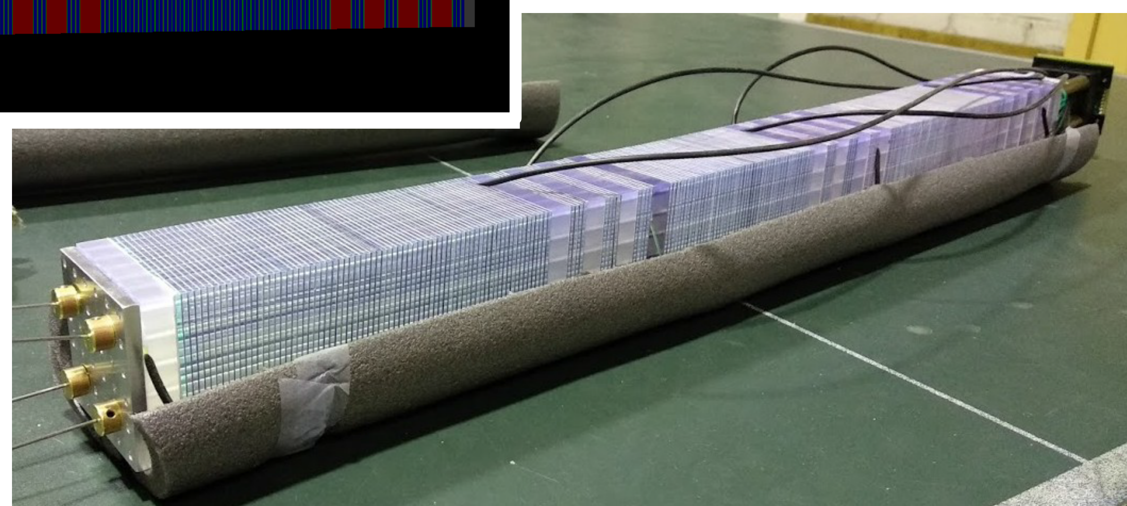
- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers



1[st] prototype assembled and tested at Protvino

OKA beamline, April 2018





Shashlyk calorimeter with spy tiles

KLEVER

Adaptation of KLEVER MEC design to NA62x4:

- **KLEVER MEC has wide bore to accomodate neutral beam: 130 mm**
  - Minimal dead region around beam IRC not necessary
  - IRC-like detector could be used to reduce effective bore diameter
- **Spy tiles**
  - Could save money by not fully instrumenting spy tiles for NA62x4 phase
  - Supplemental PID information perhaps not critical for NA62x4
  - Shower depth information → improved time resolution for EM showers

KLEVER MEC cost estimate

Item	Cost (k€)	Notes
Module construction	1910	1800 modules at € 1060 each
Mechanics	200	
SiPMs	320	10800 channels at € 30 each
Front end	1080	10800 power supply/amplifier channels at € 100 each
Readout	2160	10800 1-GHz FADC channels at € 200 each
MUV1/2 front end	10	264 channels at € 50 each
MUV1/2 readout	50	264 1-GHz FADC channels at € 200 each

Total €5730 including readout (also for MUV1/2)

Readout

KLEVER cost estimates assume "digitizer" = 1 GHz FADC at €200/ch

- Idea was to develop a common, fast CREAM-like readout for KLEVER
- 1 GHz necessary for KLEVER SAC and possibly MEC
- LAVs could likely use 125-250 MHz digitizers in NA62x4

News from Riccardo on new CAEN digitizers:

64 ch x 125 MHz
32 ch x 250 MHz
…
8 ch x 1 GHz

FPGA with integrated CPU (runs Linux)

10 GB Ethernet interface

- Flexible and modular solution adapted well to NA62x4 and KLEVER
- Cost per channel approximately 60% of that for KLEVER estimates

In general, TDAQ solutions very well matched for NA62x4 and KLEVER