UNIVERSITY OF BIRMINGHAM

NA62

High Intensity Kaon Experiments

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HIKE
High Intensity Kaon Experiments

HIKE Phase 1 & 2 proposal: 195 collaborators from 42 institutions
10 UK institutes

[Proposal: CERN-SPSC-2023-031; SPSC-P-368]

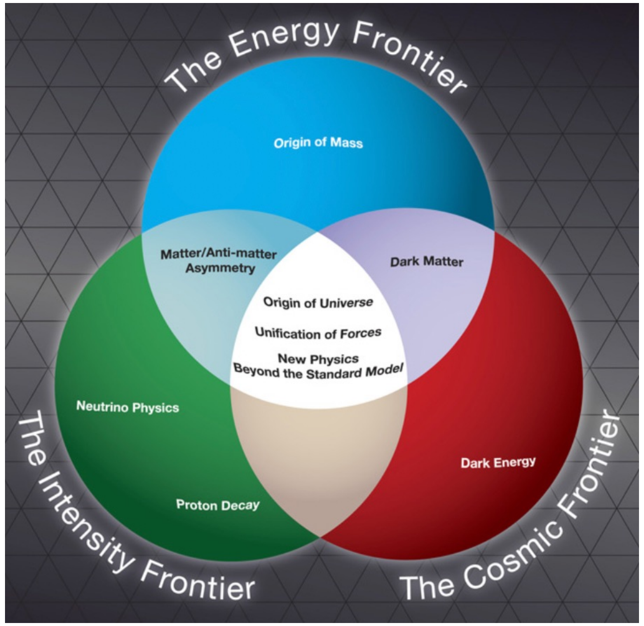
HIKE: a multi-purpose physics approach

High Intensity Kaon Experiments

HIKE is a timely, broad and long-term Particle Physics programme at the intensity frontier

HIKE will profit from a beam intensity increase by 4-6x wrt nominal intensity in NA62 (ECN3 upgrade)

HIKE project: high-intensity beams and kaon decay measurements at a new level of precision



https:/science.osti.gov/hep/About/Vision-for-HEP

HIKE

HIKE-K

HIKE-dump

Kaon beam

Proton beam

Flavour Physics

Hidden Sector

Search for **NP at the EW scale** with sizeable coupling to SM particles via **indirect effects in loops:**

→ Rare Kaon decays

Precise tests of **Lepton Flavour Universality** and searches for **lepton flavour and number violation**

→ LFU, LFV/LNV

Search **for NP below the EW scale** (MeV-GeV range) **feebly-coupled to SM** particles via direct detection of long-lived particles:

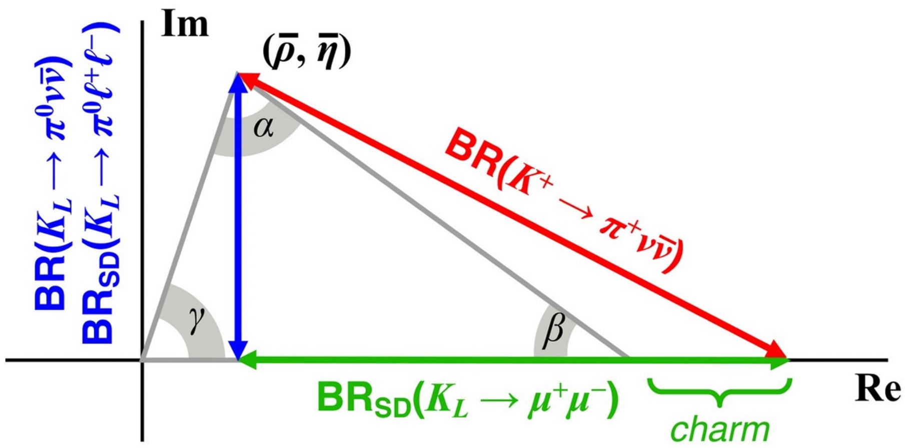
→ Heavy Neutral Lepton (HNL)
Dark Photon (DP), ALP..

Rare Kaon Decays

HIKE
High Intensity Kaon Experiments

	Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
	$K_L \rightarrow \pi^0\nu\bar{\nu}$	>99%	3%	3.4 ± 0.6	< 200	KOTO	2023
Phase1 ➡	$K^+ \rightarrow \pi^+\nu\bar{\nu}$	90%	4-5%	8.4 ± 1.0	$10.6\ ^{+4.0}_{-3.6} \pm 0.9$	NA62	2021
Phase2	$K_L \rightarrow \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
Phase2	$K_L \rightarrow \pi^0\mu^+\mu^-$	30%	15%	1.5 ± 0.3	<38	KTeV	2000
	$K_L \rightarrow \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

(*) approximate error on LD-subtracted rate excluding parametric contributions



Principal HIKE Physics goals:

Phase 1:
- ➢ Measure BR$(K^+ \rightarrow \pi^+\nu\bar{\nu})$ at 5% precision

Phase 2:
- ➢ Measure $(K_L \rightarrow \pi^0 l^+ l^-)$ at 20% precision

HIKE sensitivity to flavour observables

HIKE: measurements of rare K^+ and K_L decays to an unprecedented level of precision

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi \mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$)	% – ‰	Chiral parameters (LECs)
$K_L \to \pi^0 \ell^+ \ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+\mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	% – ‰	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0\ell^+\ell^-$ rates
Search for FIPs	Sensitivity O(10^{-5}) - O(10^{-10})	BC1,2,4,5,6,7,8,9,10,11

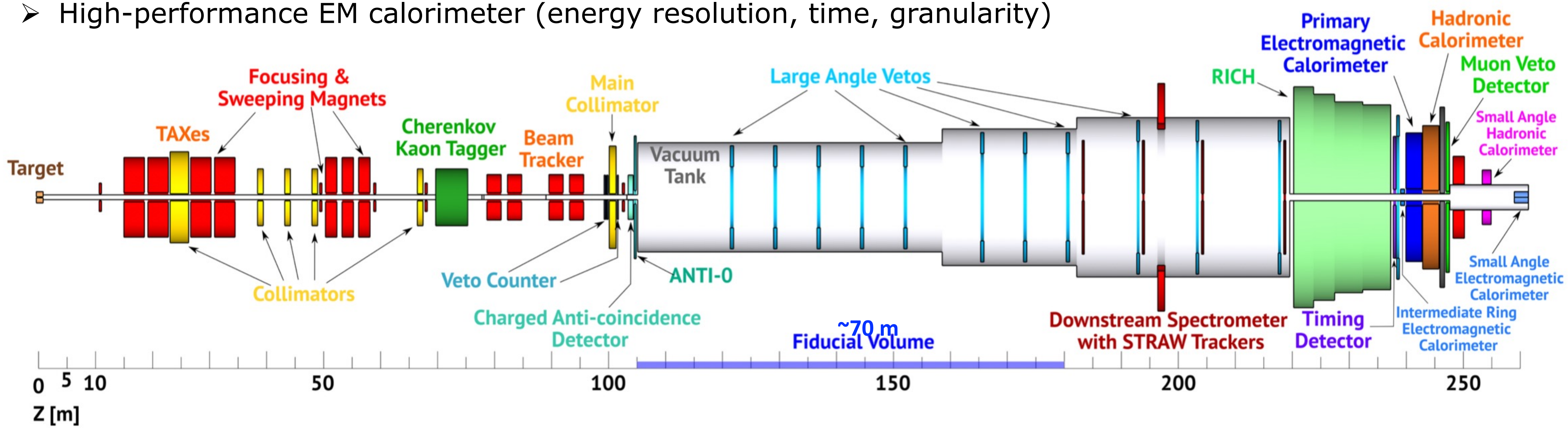
Only place worldwide where this programme is addressed experimentally

HIKE-Phase1 Experimental Layout

High Intensity Kaon Experiments

- Full tracking of ~3GHz beam with ~40 ps time resolution and tagging of 200 MHz of K^+
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

Max beam intensity after ECN3 Upgrade: 1.2×10^{13} POT / 4.8s



HIKE-Phase1 detector optimized for the measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) at 5% precision

Main challenges: 20-40 ps time resolution for key detectors

HIKE-Phase2 Experimental Layout

120 m long neutral (NA48-like) beam line:

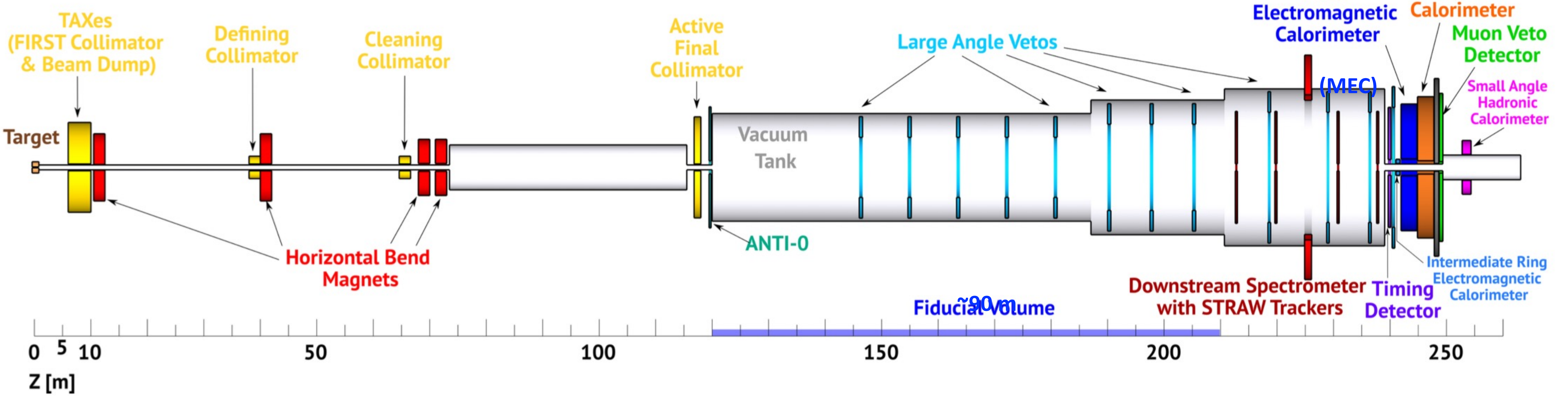
- Secondary beam opening angle = 0.4 mrad; 2.4 mrad production angle
- Mean momentum of decaying K_L mesons = 46 GeV/c

Reconfigured HIKE-Phase1 detector:

- Kaon tagger, beam spectrometer, RICH removed
- STRAW spectrometer shortened and chambers realigned

High Intensity Kaon Experiments

Max beam intensity after ECN3 Upgrade: 2×10^{13} POT / 4.8s



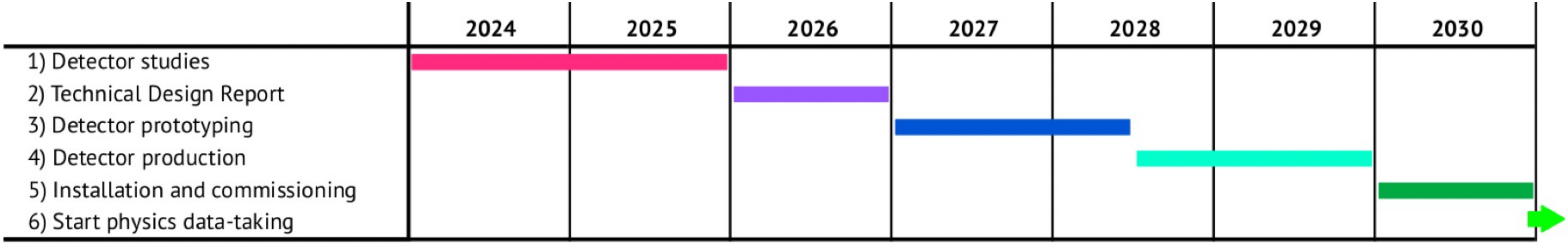
HIKE-Phase2 detector optimized for the measurement of BR($K_L \to \pi^0 l^+ l^-$) at 20% precision

Challenges: 90m long instrumented decay volume, 100ps time resolution for π^0 of few GeV energies

R&Ds on Calorimetry (innovative scintillator materials, longitudinal segmentation techniques, etc.)

The HIKE Detectors

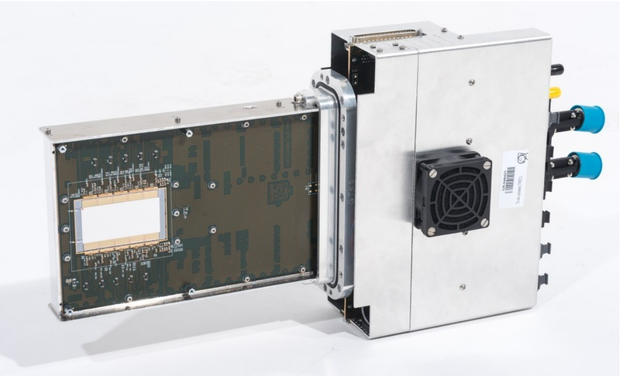
Detector	Phase 1	Phase 2	Comment	Preliminary group interests
Cherenkov K^+ tagger	upgraded	removed	faster photo-detectors	UK
Beam tracker	replaced	removed	3D-trenched silicon sensor	Italy,CERN,UK,Belgium,Canada,France
Upstream veto detectors	replaced	kept	SciFi	Switzerland
Large-angle vetos	replaced	kept	lead/scintillator tiles	UK
Downstream spectrometer	replaced	kept	STRAW (ultra-thin straws)	CERN,Kazakhstan,Slovakia,Czech Republic
Pion identification (RICH)	upgraded	removed	faster photo-detectors	Italy,Mexico
Main EM calorimeter	replaced	kept	fine-sampling shashlyk	Italy
Timing detector	upgraded	kept	higher granularity	Belgium
Hadronic calorimeter	replaced	kept	high-granularity sampling	Germany
Muon detector	upgraded	kept	higher granularity	Germany
Small-angle calorimeters	replaced	kept	oriented high-Z crystals	Italy
HASC	upgraded	kept	larger coverage	Romania



New Beam Tracker for HIKE

NA62 GigaTracker design:
- Material budget: 0.5% X_0 per layer
- Use minimum number of planes, time mmts to constrain event reconstruction
- 200 μm planar silicon sensors
- TDCPix readout chips
- Cooled with silicon microchannel plates

NA62 GigaTracker performance:
- ✓ track time resolution of O(100 ps)
- ✓ angular resolution ~16 μrad
- ✓ momentum resolution ~0.2%



For HIKE @ 4x intensity:
- **Smaller pixels**
  Reduce occupancy
- **Better time resolution**
- **Better heat dissipation**
  Power consumption will increase
- **Reduced material budget**

New Beam Tracker for HIKE

High Intensity Kaon Experiments

NA62 GigaTracker design:

- Material budget: 0.5% X_0 per layer
- Use minimum number of planes, time mmts to constrain event reconstruction
- 200 μm planar silicon sensors
- TDCPix readout chips
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for 4x intensity

	NA62 GigaTracker	New beam tracker
Single hit time resolution	< 200 ps	< 50 ps
Track time resolution	< 100 ps	< 25 ps
Peak hit rate	2 MHz/mm^2	8 MHz/mm^2
Pixel efficiency	> 99%	> 99%
Peak fluence / 1 year [10^{14} 1 MeV n_{eq}/cm^2]	4	16

NA62 GigaTracker performance:

- ✓ track time resolution of O(100 ps)
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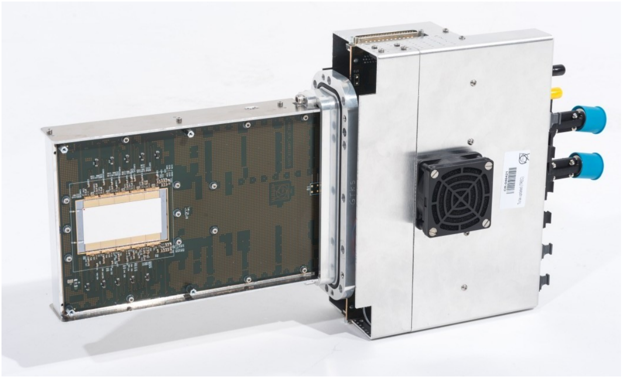
- ✓ momentum resolution ~0.2%



Requirements for next generation of upgrades

(LHCb Run5, CMS-PPS & ATLAS-AFP Run4 FCC-hh)

- $\sigma_s \approx 10$ μm (→ pixel pitch ≈ 40-60 μm)
- $\sigma_t \leq 50$ ps on full chain ($\sigma_t = \sigma_{sensor} \oplus \sigma_{FE} \oplus \sigma_{TDC}$)
- Radiation hardness to $\Phi = 10^{16} \div 10^{17}$ 1 MeV n_{eq}/cm^2
- Detection efficiency >99% per layer
- Material budget < 1÷0.5% X_0 per layer

Silicon detectors with fast timing information capable to operate in a high-radiation environment → shared interest with HL-LHC experiments

Kaon Identification System

Goal: excellent PID performances, crucial for HIKE-Phase1 physics exploitation

K^+ ID requirements: tagging efficiency >95% and time resolution $\sigma_t(K)$ = 15-20 ps

HIKE working conditions: high-intensity hadron **beam ~3GHz, K^+ rate ~200 MHz**

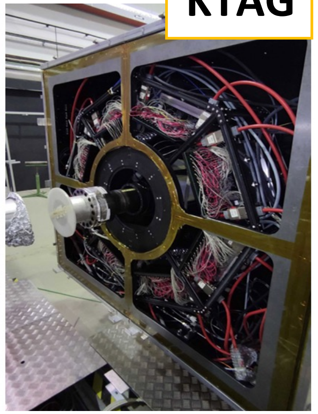
HIKE Kaon tagging detector concept (KTAG):

- Cherenkov detector from NA62, refurbished readout
- >20 detected photons per Kaon: **hit rate ~8 MHz/cm^2**
- Photo-detector (PD) with high granularity
- High radiation tolerance
- Single-photon detection capability and **$\sigma_t(\gamma)$ ~50 ps**

Kaon tagging detector in NA62

CEDAR

KTAG

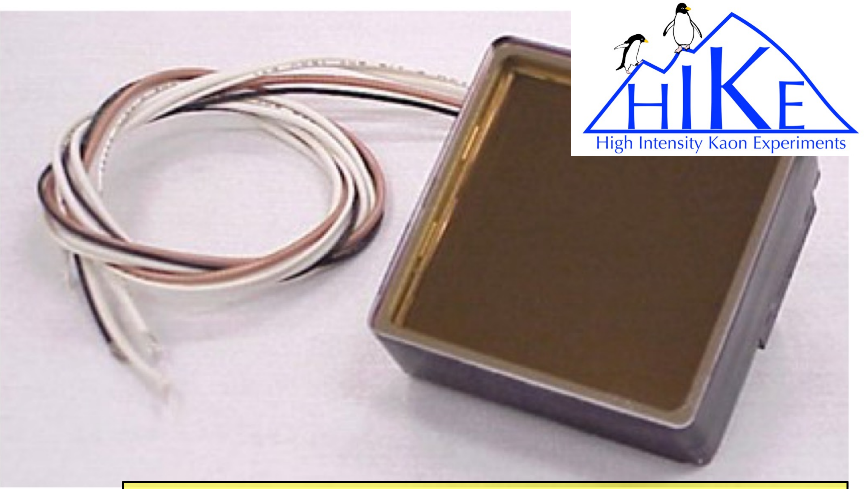


KTAG photo-detector R&D:

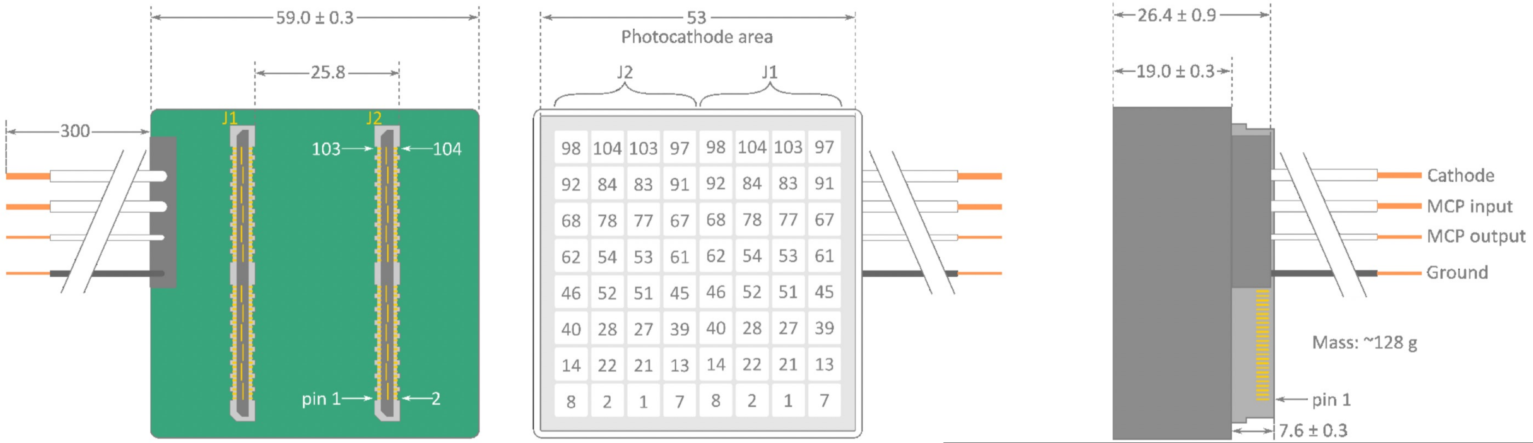
- ultra-fast timing single-photon detection capability with extended lifetime
- **unexplored cutting-edge application of existing PD technology**
- synergy with requirements of next-generation experiments at HL-LHC

MCP-PMT Prototype for KTAG

Photonis Planacon XP85112-S-BA MCP-PMT with specs similar to the model in production for PANDA DIRC. 2-ALD coating to maximise PC lifetime and low MCP resistance (~10MΩ) to improve rate capability.
<u>Prototype will be characterised in lab (QE, Gain, Lifetime, Time resolution)</u>



Planacon MCP-PMT and HV divider



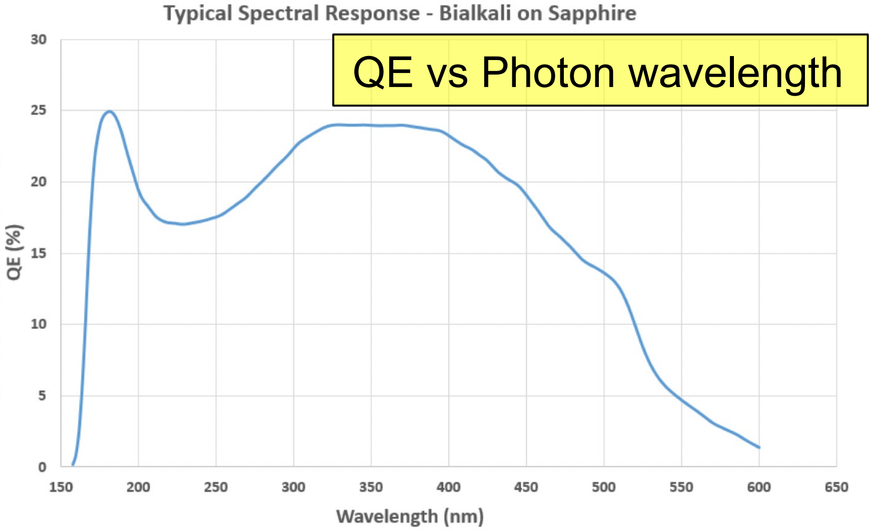
Investigate Photek, Hamamatzu, and SiPMs

Table of Planacon MCP-PMT specs

Configuration	
Input window	Al_2O_3 (Sapphire)
Photocathode type	Bi-alkali
MCP	double, chevron, 10μm pore size, 60:1 L:D, Hi-CE, Long life Time
Anode	multi anode structure, 8x8 array, 5.9 / 6.5 mm (size / pitch)

<u>Time Capability</u>

		MIN	MAX	
Timing precision RMS		120		ps
TTS, sigma		30	50	ps



QE vs Photon wavelength

KTAG Photon Detector Design for HIKE

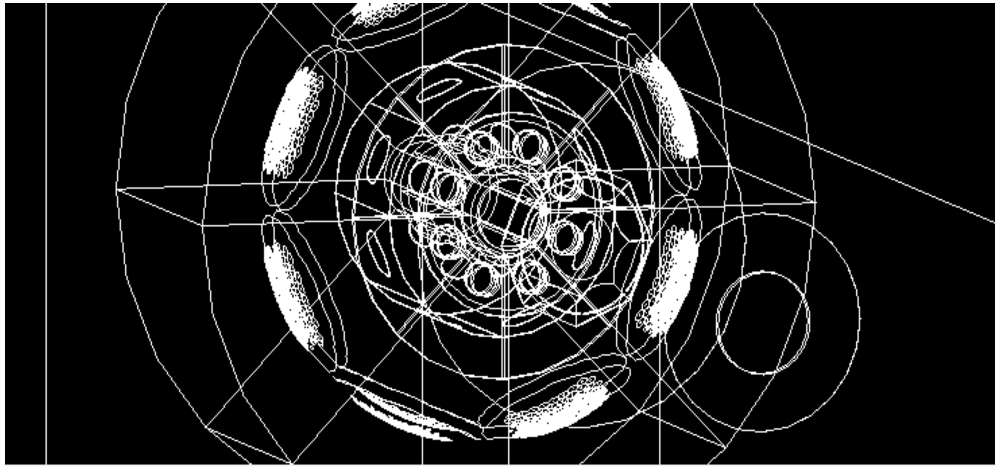
High Intensity Kaon Experiments

Replacement of existing PMTs and light guides

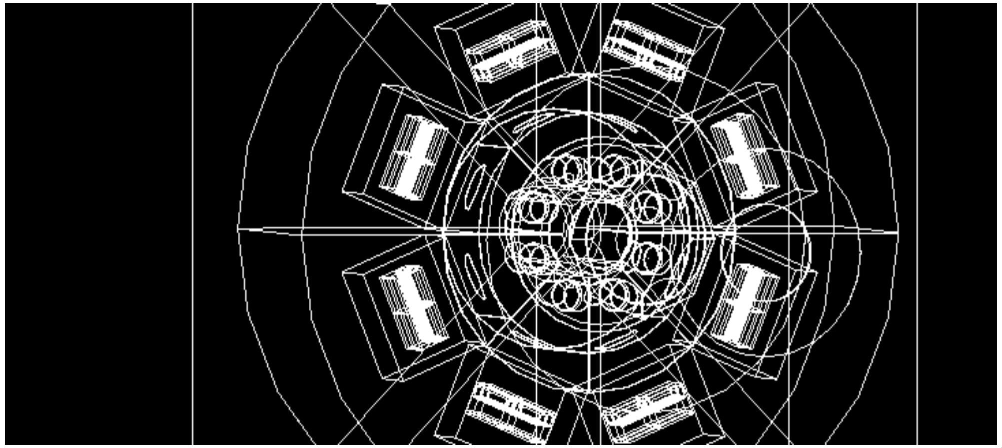
- Instrumented KTAG area/octant ~ 10cm*15cm
- Use a matrix of 4 MCP-PMTs/octant
- Expected MCP-PMT pixel/anode rate ~2-3MHz
- Total number of channels: 2048

Simulations with filling factor ~75% and collection efficiency ~60% show that K^+ tagging efficiency >95% and time resolution of 15-20ps are achievable

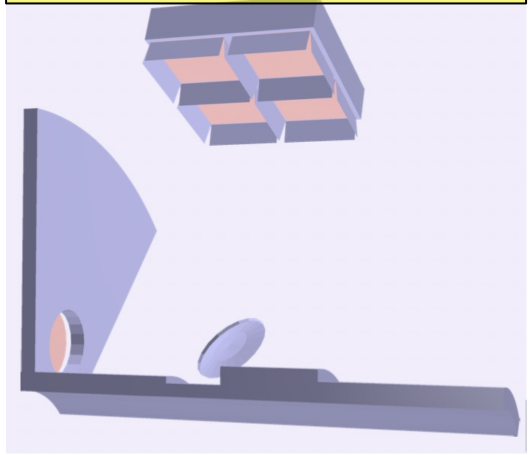
KTAG with PMTs in NA62



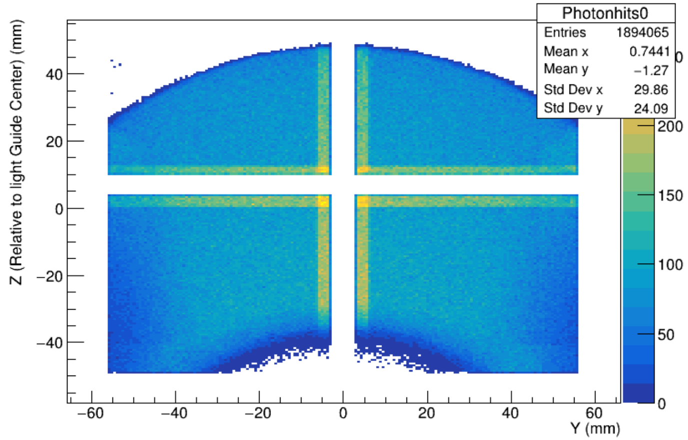
KTAG with MCP-PMTs in HIKE



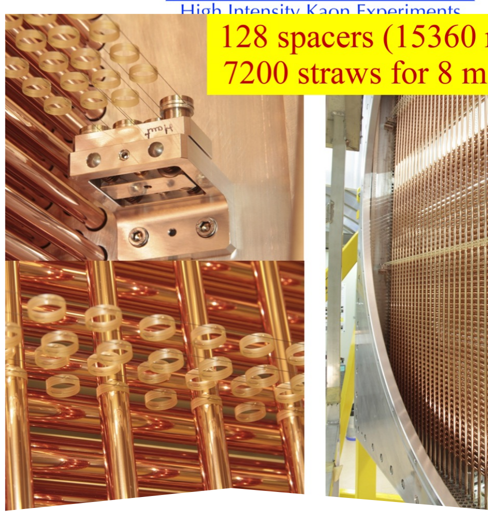
MCP Geant4 Simulation



Photon distribution at MCP-PMT plane



The HIKE STRAW Spectrometer



Same detector configuration as NA62 STRAW: 4 chambers + dipole magnet, in vacuum

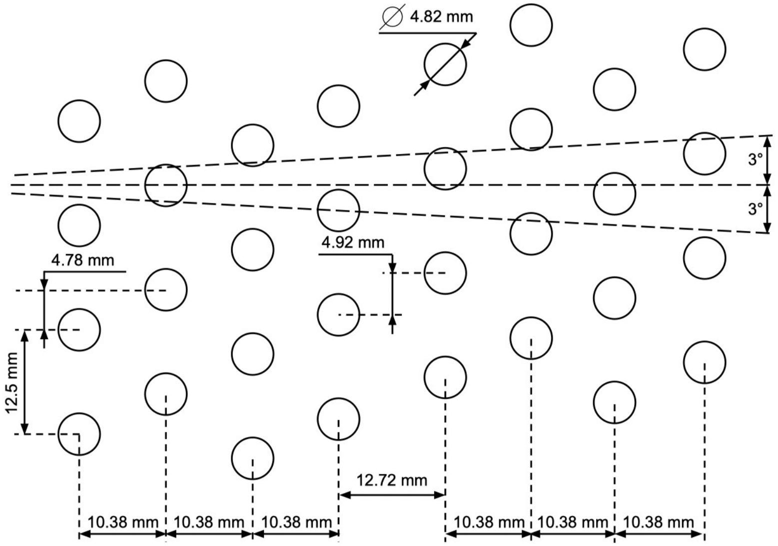
New STRAW design for HIKE @ 4x intensity:
- ❖ **Increased rate capability** (reduced straw diameter, use fast shaping)
- ❖ Improved momentum resolution (material budget, position resolution)

- ✓ **straw diameter reduced to ~5mm** → shorter drift time, better trailing edge time resolution
- ✓ geometric rearrangement of 8 layers per view → recover acceptance
- ✓ **Mylar thickness reduced to ~12-19um** → minimise material budget

for 4x intensity

	Current NA62 spectrometer	New straw spectrometer
Straw diameter	9.82 mm	4.82 mm
Straw length	2100 mm	2100 mm
Planes per view	4	8
Straws per plane	112	~160
Straws per chamber	1792	~5200
Mylar thickness	36 μm	(12 or 19) μm
Anode wire diameter	30 μm	(20 or 30) μm
Total material budget	1.7% X_0	(1.0 – 1.5)% X_0
Maximum drift time	~150 ns	~80 ns
Hit leading time resolution	(3 – 4) ns	(1 – 4) ns
Hit trailing time resolution	~30 ns	~6 ns
Average number of hits hits per view	2.2	3.1

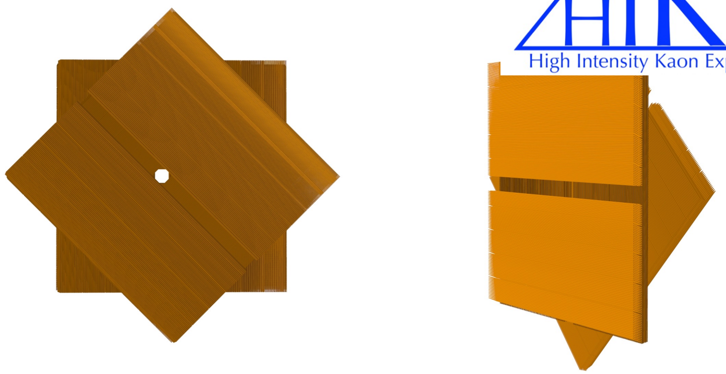
Optimised layout of straw tubes with 4.82 mm diameter in a single view



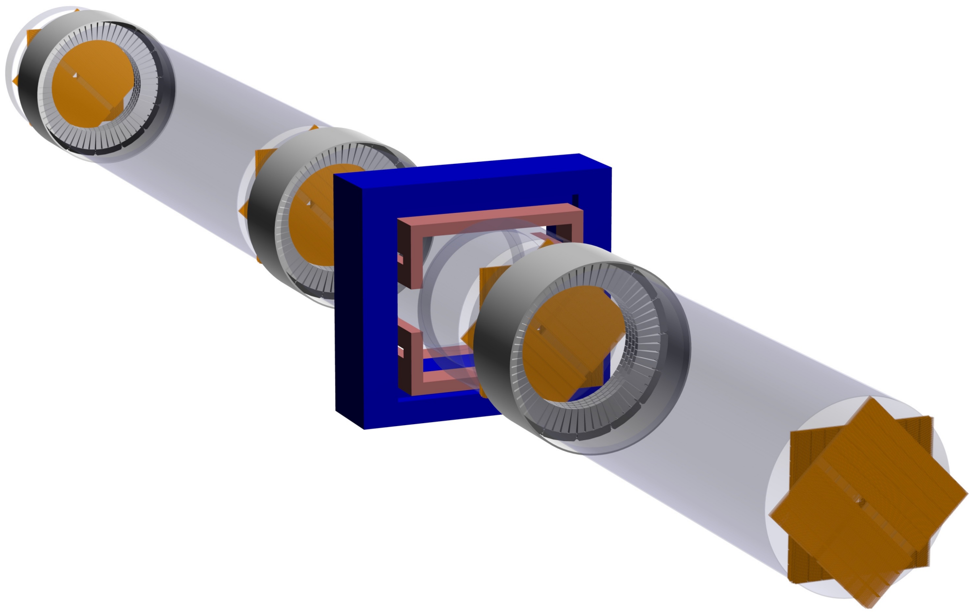
The HIKE STRAW Spectrometer

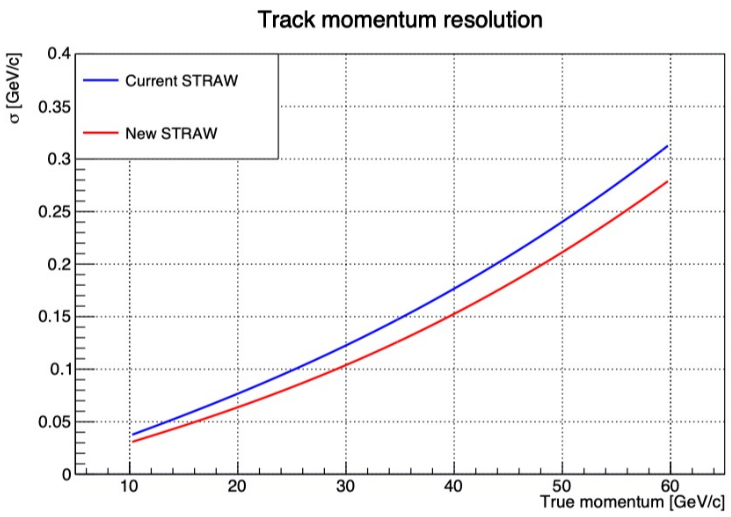
Geant4 visualization of the new STRAW spectrometer

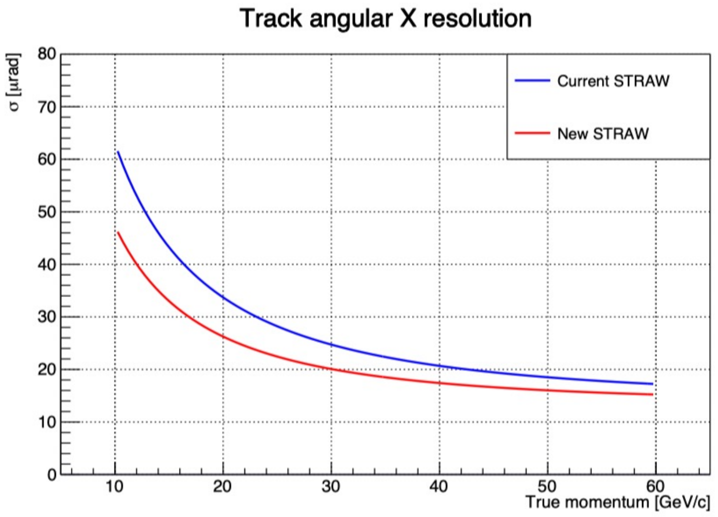
Same assumptions as in current NA62 layout:
- ✓ dimensions and positions of STRAW chambers
- ✓ number and orientation of views per chamber
- ✓ gas composition (Ar + CO_2 with 70:30 ratio)
- ✓ properties of dipole magnets



New straw chamber:
(left) front view; (right) tilted back view







Improved resolution for reconstructed track angles and momenta by 10–20% wrt NA62 spectrometer while maintaining the high track reconstruction efficiency

Pion Identification with RICH

Remain the same as NA62 RICH detector:
- ✓ Radiator: neon at atmospheric pressure as the radiator
- ✓ Mechanical structure (vessel, mirror support, end-caps)

Changes for HIKE:
- ✓ Cherenkov light sensors and flanges hosting them
- → Improvement of geometrical acceptance for negative particles also considered

Region to be instrumented with new photo-sensors

Sensor type	Layout	Sensor size	$N_{Channels}$	σ_{Hit}	σ_{Radius}
Hamamatsu R7400U-03 (NA62 RICH)		$R_{Winston}$=18 mm R_{PMT}=7.5 mm	1952	4.7 mm	1.5 mm
SiPM		3x3 mm²	62K	2.3 mm	0.66 mm
		6x6 mm²	16K	2.8 mm	0.78 mm
		9x9 mm²	7K	3.4 mm	0.95 mm

9 × 9 mm² SiPM satisfies HIKE requirements and provides reasonable number of channels

for 4x intensity

	NA62 RICH	HIKE RICH
Sensor type	PMT	SiPM
Sensor time resolution	240 ps	100 ps
Sensor quantum efficiency	20%	40%
Number of hit for π^+ at 15 GeV/c	7	14
Number of hit for π^+ at 45 GeV/c	12	24
Time resolution for π^+ at 15 GeV/c	90 ps	27 ps
Time resolution for π^+ at 45 GeV/c	70 ps	20 ps

The Main Electromagnetic Calorimeter (MEC)

Excellent efficiency and time resolution (~100ps), good two-cluster separation, good energy resolution

Quasi-homogeneous ionization calorimeter, $27X_0$ of LKr @ NA62

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

$1 - \varepsilon < 10^{-5}$ for $E_\gamma > 10$ GeV

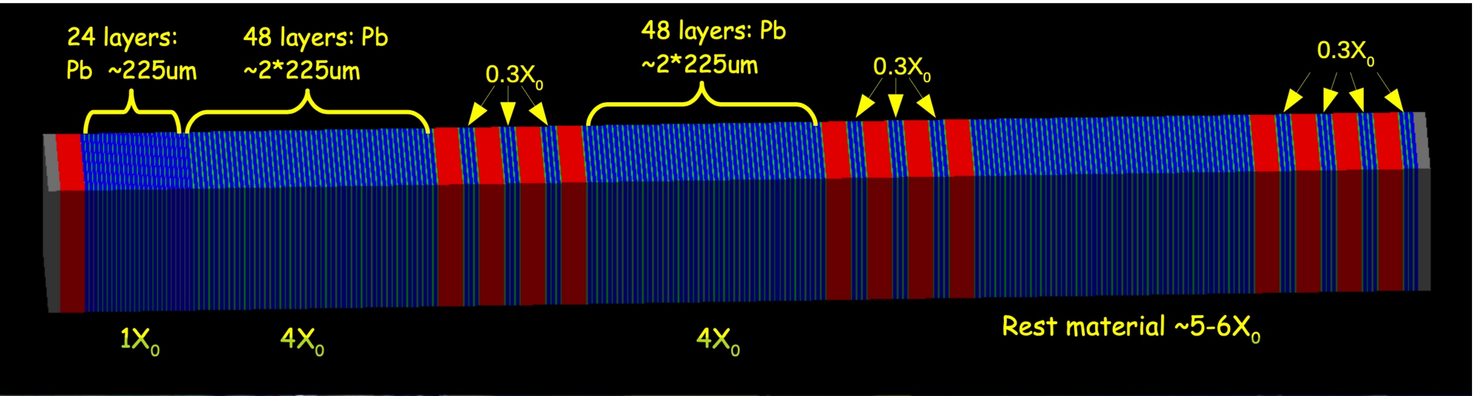
$\sigma_t \sim 500$ ps for π^0 with $E_{\gamma\gamma} > 20$ GeV

Efficiency/energy resolution same as HIKE
Time resolution: 4x improvement for HIKE

Fine-sampling shashlyk based on PANDA forward EM calorimeter

PANDA prototypes:

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



New for Phase2: Longitudinal shower information from spy tiles

- PID additional information for γ/n separation
- Provides 5-10x improvement in neutron rejection
- Overall neutron rejection at level of 10^3

Full-depth prototype (25 X_0) of baseline solution in 2024

Photon Veto

Current NA62 LAVs: Lead glass
- Time resolution ~ 1 ns
- Cerenkov light is directional
- Complicated paths to PMT with multiple reflections

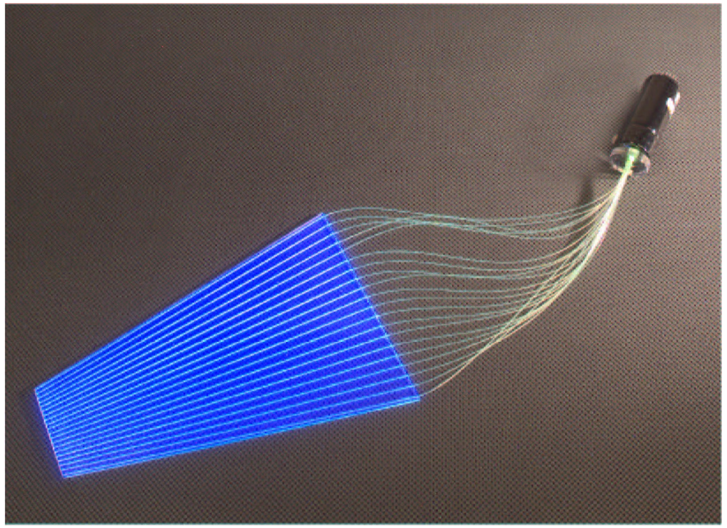
NA62 Large-angle veto station

New large-angle photon veto stations (LAV)

- Sensitive radius 0.85 to 1.5 m
- **Time resolution <250 ps**
- **Hermetic coverage out to 100 mrad**
- **Need good detection efficiency at low energy**

(1 – ε < few 10^{-4} at at least 100 MeV)

- **Full digitization, segmentation in depth**



Baseline technology:

Lead/scintillator with WLS

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

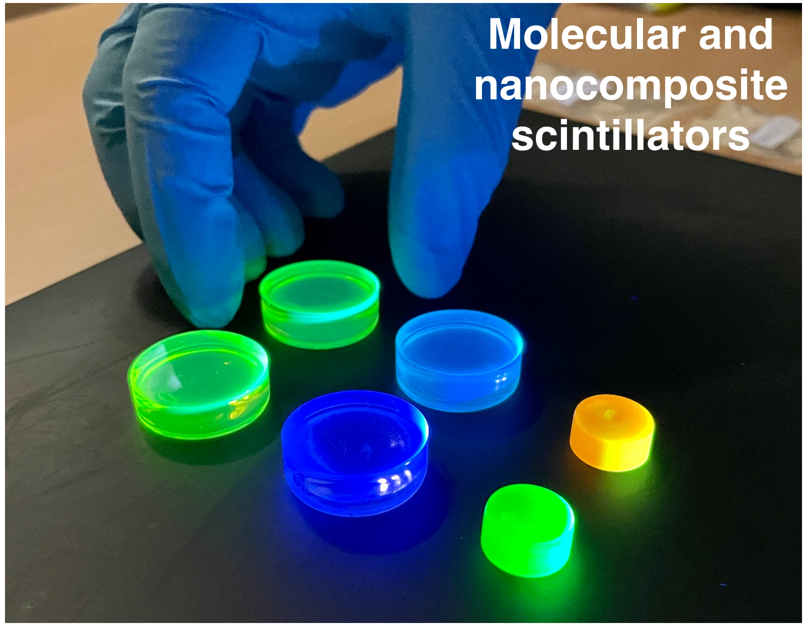
Light read out with
SiPM arrays – see RICH

HIKE R&D on innovative scintillators

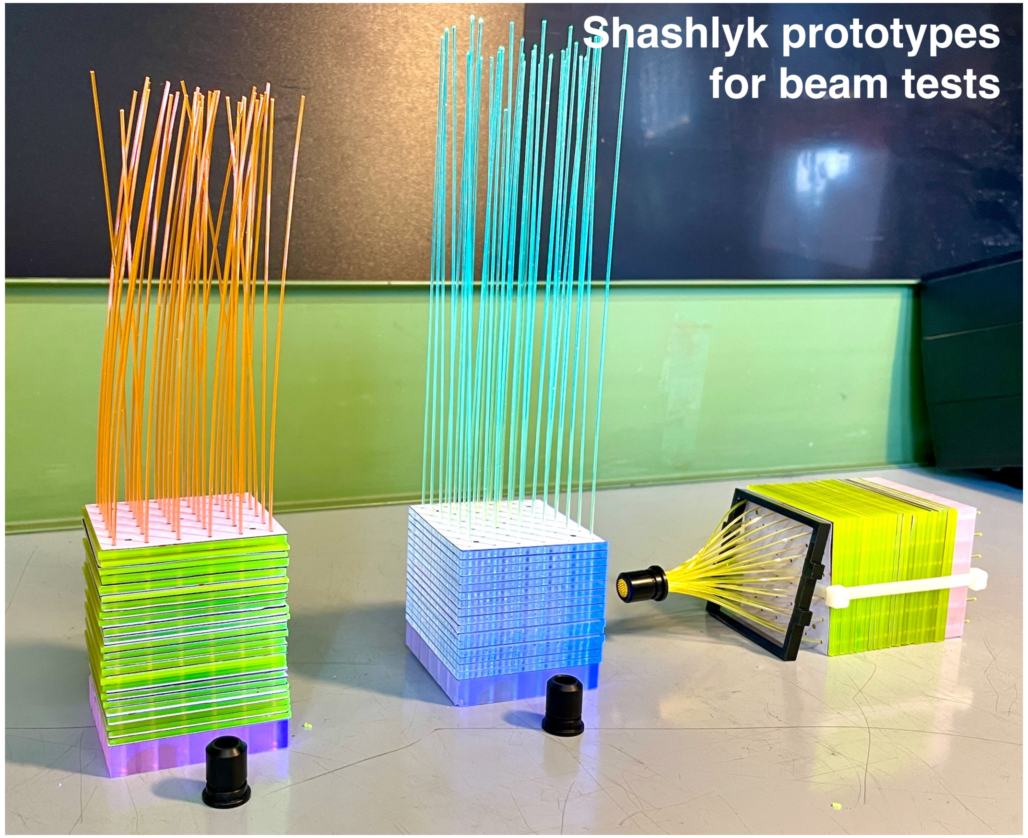
Use of **nanocomposite scintillators** under investigation in collaboration with AIDAinnova project **NanoCal**

Semiconductor nanostructures used as sensitizers/emitters for ultrafast, robust scintillators:

- Perovskite (typically $CsPbX_3$, X = Br, Cl…) nanocrystals cast into polymer matrix
- Decay components << 1 ns
- Radiation hard to O(1 MGy)



Candidates for HIKE calorimeter and photon vetos (and timing planes)



Additionally exploring:

- **New dyes** for optimized molecular scintillators
- Fast, bright **green scintillators** for additional radiation hardness

2022-23: Tests of scintillators/fibers/SiPMs with beams and cosmic rays

2024-25: Construction of full-scale prototype if promising candidate found

Summary - HIKE

- **HIKE Phase1 & 2:** a timely, broad and long-term HEP programme at the intensity frontier
- **Multi-observables of Flavour Physics at a new level of precision**
  - Main physics goals:
    - Measure BR($K^+ \to \pi^+ \nu \bar{\nu}$) at 5% precision
    - Measure BR($K_L \to l^+ l^-$) at 20% precision
- **Innovative R&Ds and cutting-edge detector technologies**
  - Build on NA62 experience:
    - High-rate 4D silicon tracker
    - State-of-the-art photo-detectors (MCP-PMTs and SiPM)
    - Super-thin STRAW spectrometer
    - Electromagnetic Calorimeter with shashlik
    - Innovative scintillators for Vetos and more
    - And more: front-end electronics, cooling solutions