UNIVERSITY OF BIRMINGHAM

High Intensity Kaon Experiments at CERN SPS

Angela Romano, University of Birmingham

High Intensity Kaon Experiments

 a.romano@bham.ac.uk

High Intensity Kaon Experiments (HIKE):

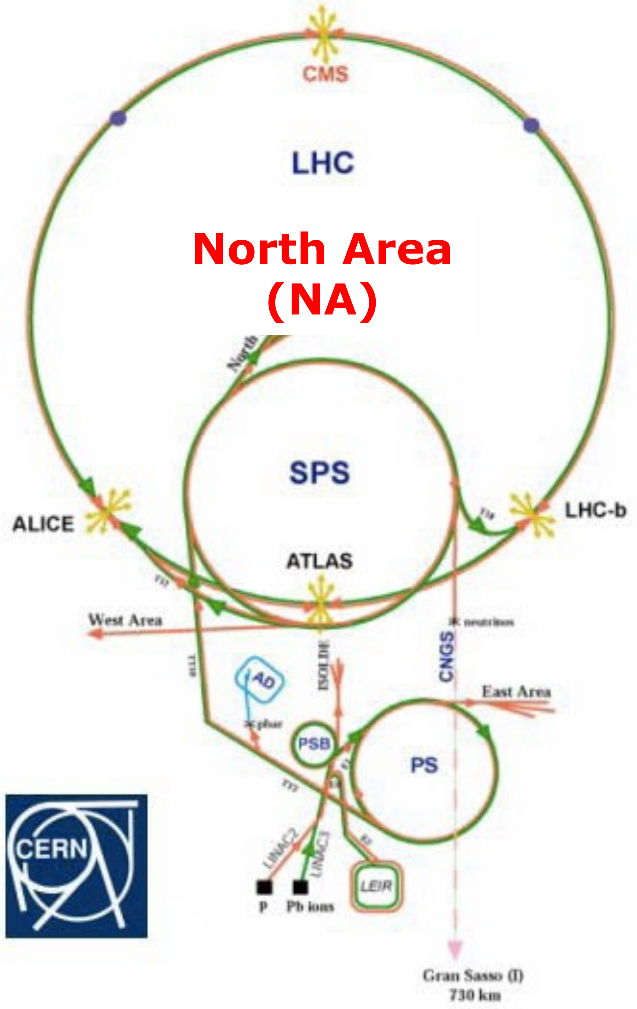
- Physics goals and sensitivity
- Experimental layouts (Phase1, Phase2, Dump)
- Detector technologies and R&D

HIKE Phase 1 & 2 proposal: 195 collaborators, 42 institutions [**CERN-SPSC-2023-031; SPSC-P-368**]

Ancona, Birmingham, Bratislava, Bristol, Bucharest, Cagliari, CERN, Como, Edinburgh, Fairfax, Ferrara, Florence, Frascati, Glasgow, Groningen, Kazakhstan, Lancaster, Lausanne, Liverpool, Louvain-la-Neuve, Lyon, Mainz, Manchester, Marseille, Milano, München, Naples, Oxford, Padova, Perugia, Pisa, Prague, Rome I, Rome II, San Luis Potosi, Santiago de Compostela, Syracuse, Sussex, TRIUMF, Turin, Vancouver (UBC), Warwick.

A history of Kaons at the CERN SPS

Kaons have been fundamental to the development of the Standard Model flavour sector



Fixed-target Kaon experiments at the CERN SPS

NA31	1982-1993:	First-generation experiment to measure $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48	1992-2000:	Next generation measurement of $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48/1	2000-2002:	Rare K_S decays, e.g., $K_S \rightarrow \pi^0\ell^+\ell^-$
NA48/2	2003-2007:	Direct CPV in $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$
NA62	2007-2008:	$R_K = \Gamma(K \rightarrow e\nu)/\Gamma(K \rightarrow \mu\nu)$ with NA48 detector
	2005-2015:	Design, construction, installation, commissioning
	2016-2018:	$\mathrm{BR}(K^+\rightarrow \pi^+\nu\bar{\nu}) = (10^{+4.0}_{-3.4}\vert_{stat} \pm 0.9_{syst})\times 10^{-11}$
	2021-LS3:	Aim at 15% precision on $\mathrm{BR}(K^+\rightarrow \pi^+\nu\bar{\nu})$

More than 40 years of precision measurements and discoveries shaping the SM

A history of Kaons at the CERN SPS

Kaons have been fundamental to the development of the Standard Model flavour sector

Present: NA62 beam line & detector in ECN3

North Area of Super Proton Synchroton (SPS)

Fixed-target Kaon experiments at the CERN SPS

NA31	1982-1993:	First-generation experiment to measure $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48	1992-2000:	Next generation measurement of $\mathrm{Re}\,\varepsilon'/\varepsilon$
NA48/1	2000-2002:	Rare K_S decays, e.g., $K_S \to \pi^0\ell^+\ell^-$
NA48/2	2003-2007:	Direct CPV in $K^\pm \to \pi^+\pi^-\pi^\pm$
NA62	2007-2008:	$R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ with NA48 detector
	2005-2015:	Design, construction, installation, commissioning
	2016-2018:	BR$(K^+ \to \pi^+\nu\bar{\nu}) = (10^{+4.0}_{-3.4}\vert_{stat} \pm 0.9_{syst})\times 10^{-11}$
	2021-LS3:	Aim at 15% precision on BR$(K^+ \to \pi^+\nu\bar{\nu})$

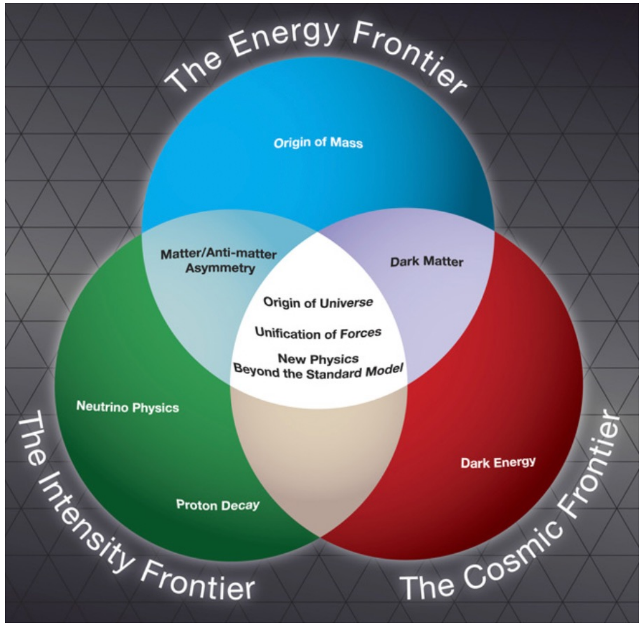
More than 40 years of precision measurements and discoveries shaping the SM

HIKE: a multi-purpose physics approach

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

HIKE will profit from a beam intensity increase by 4x 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

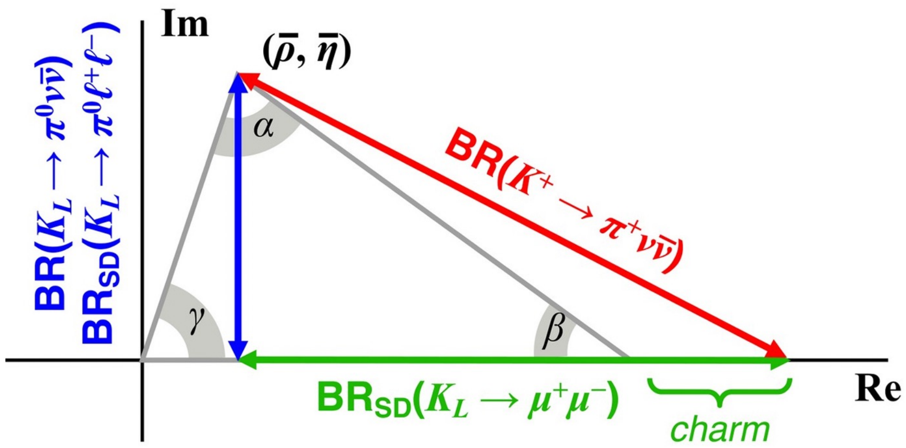
HIKE

- **HIKE-K**: Kaon beam
  - Flavour Physics
    - 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
  - Hidden Sector
- **HIKE-dump**: Proton beam
  - Hidden Sector
    - 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), Axion-Like Particle (ALP)..

Rare Kaon Decays

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 200	KOTO	2023
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	$10.6^{+4.0}_{-3.6} \pm 0.9$	NA62	2021
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	<38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

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



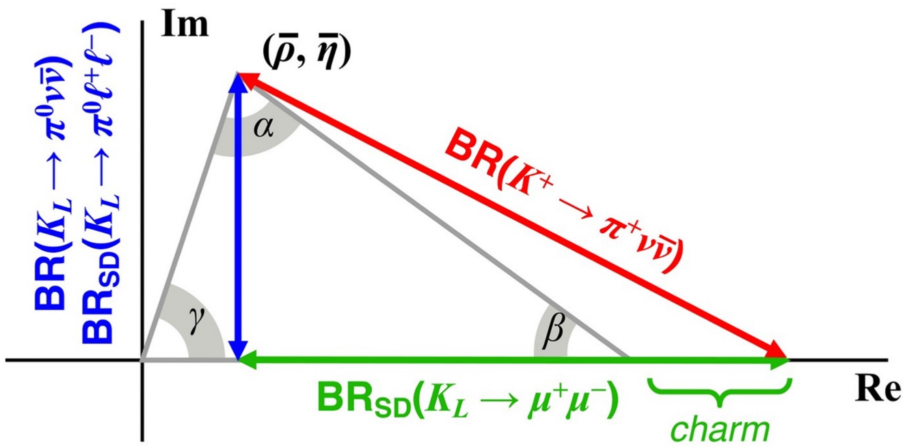
- FCNC processes dominated
- by short-distance amplitude
- SM rates related to V_{CKM},
- with minimal non-parametric theory uncertainty
- BRs overconstrain CKM matrix

- FCNC processes forbidden at tree level: 1-loop contributions as leading order
- Highest CKM suppression ($BR \sim |V_{ts}^* V_{td}|^2 \sim \lambda^{10}$)
- High sensitivity to New Physics

Rare Kaon Decays

	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%	2%	3.4 ± 0.6	< 200	KOTO	2023
Phase1 ➡	$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	90%	4%	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

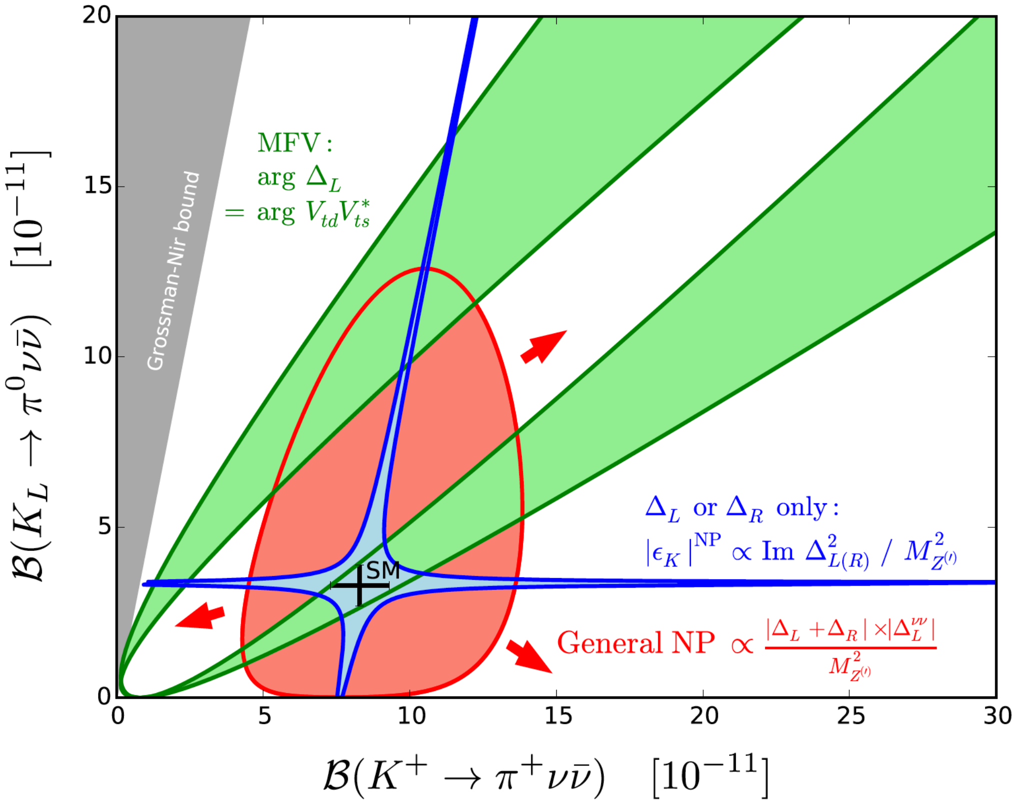
Phase 2:
- Measure $BR(K_L \rightarrow \pi^0 l^+ l^-)$ at 20% precision

$K \to \pi\nu\bar{\nu}$: New Physics Scenarios

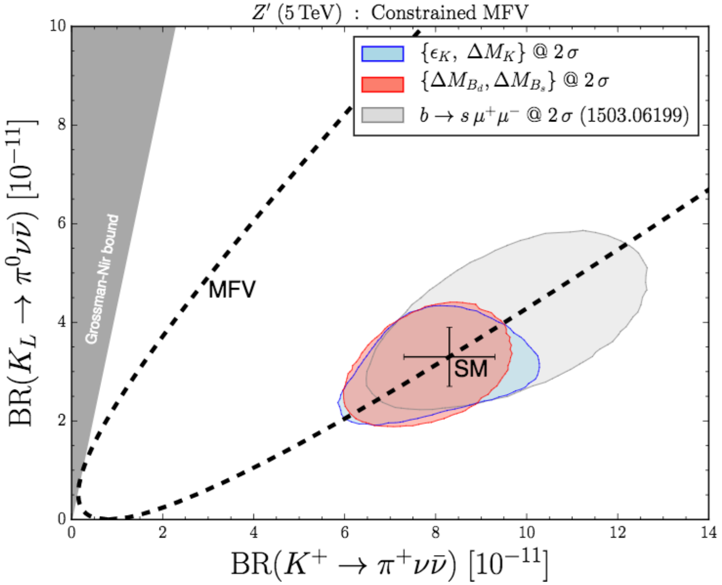
Indirect searches of New Physics with high precision studies of rare K decays

Measurement of $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ modes can **discriminate among NP scenarios**

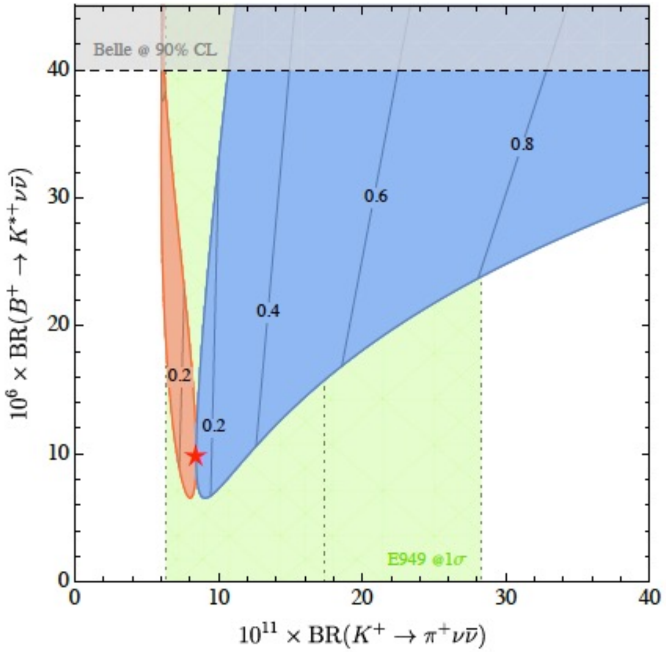
[Buras, Buttazzo, Knegjens, JHEP1511 (2015) 166]



Z'(5 TeV in Constrained MFV)



LFU violation



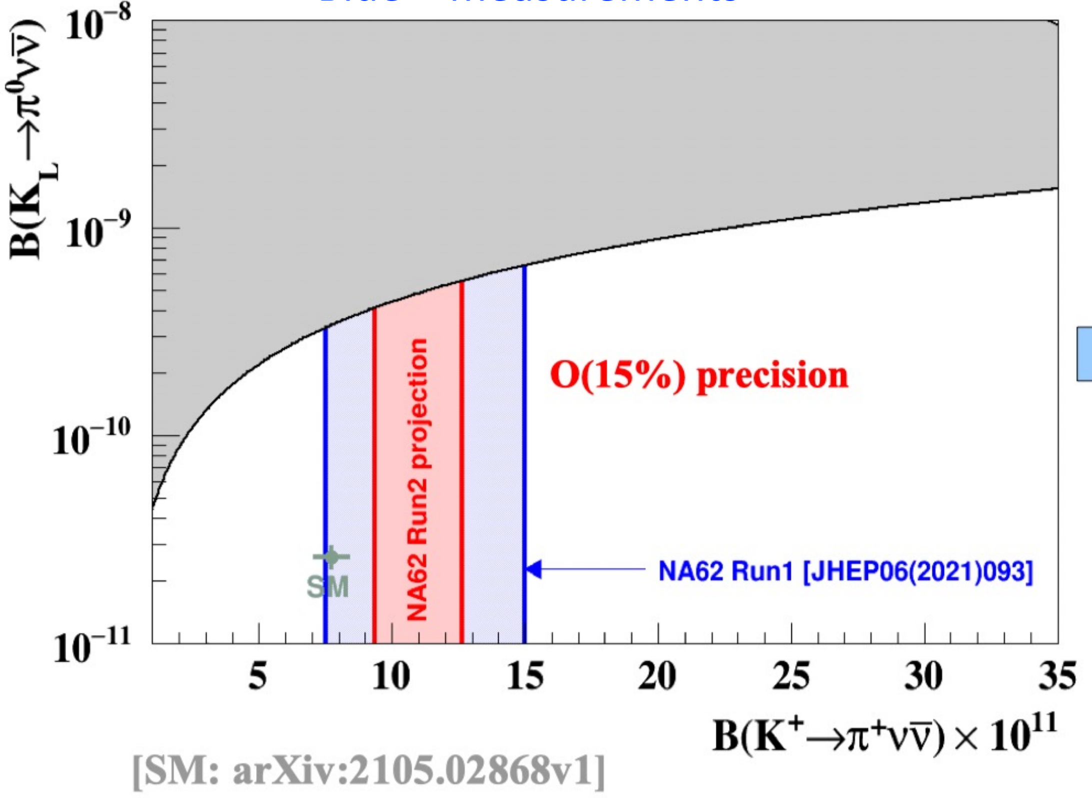
[Isidori et al., Eur. Phys. J. C(2017)77: 618]

Correlations significantly change for different classes of NP models [EPJ C76 (2016) no.4 182]

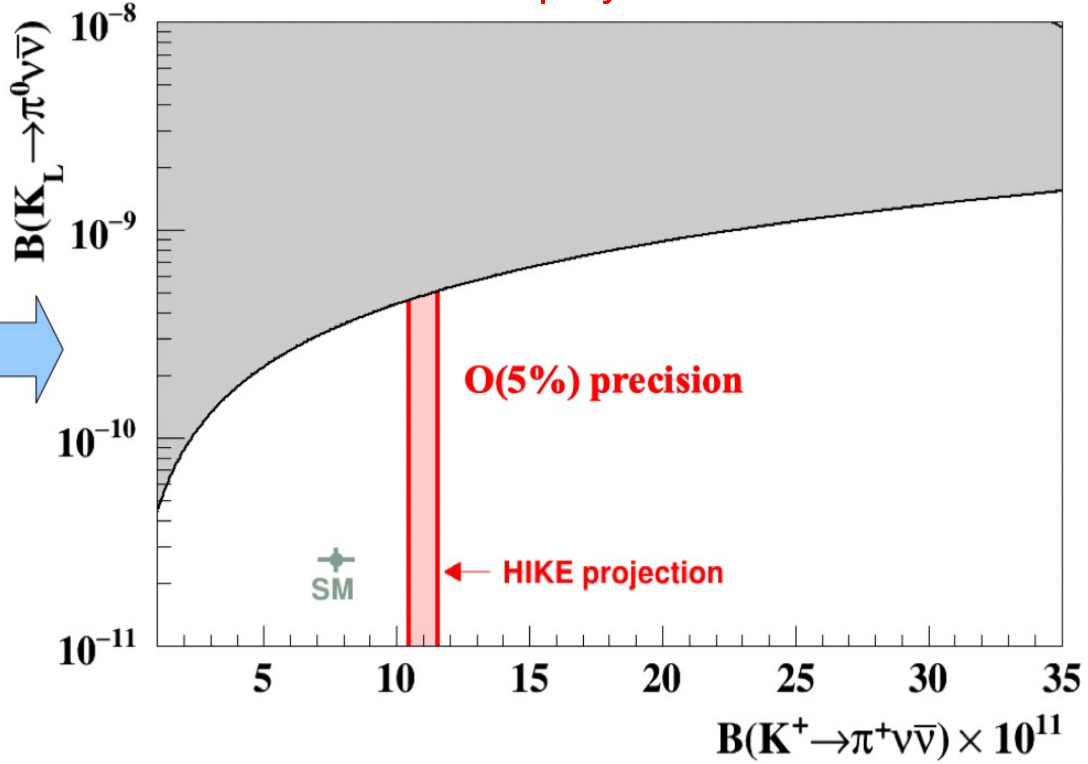
$K^+ \to \pi^+\nu\bar{\nu}$ at HIKE: physics reach

Measure BR($K^+ \to \pi^+\nu\bar{\nu}$): stringent precision test of the Standard Model
Model-independent standard candle constraining many BSM scenarios, present or future

Blue = measurements



Red = projections



From NA62 to HIKE (Phase 1): Precision on BR($K^+ \to \pi^+\nu\bar{\nu}$) improved by a factor of 3

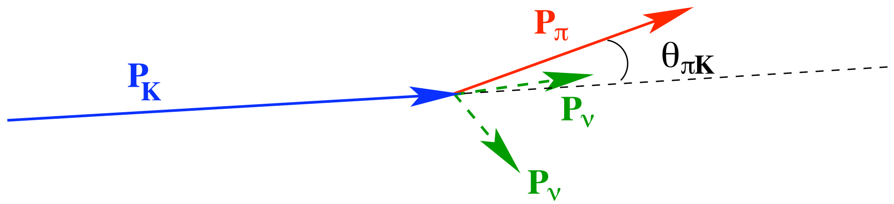
$K^+ \to \pi^+\nu\bar{\nu}$ at HIKE: experimental strategy

High Intensity Kaon Experiments

The NA62 kaon decay-in-flight technique is well established!

$K^+ \to \pi^+\nu\bar{\nu}$ signature:

Kaon track + Pion track + nothing else

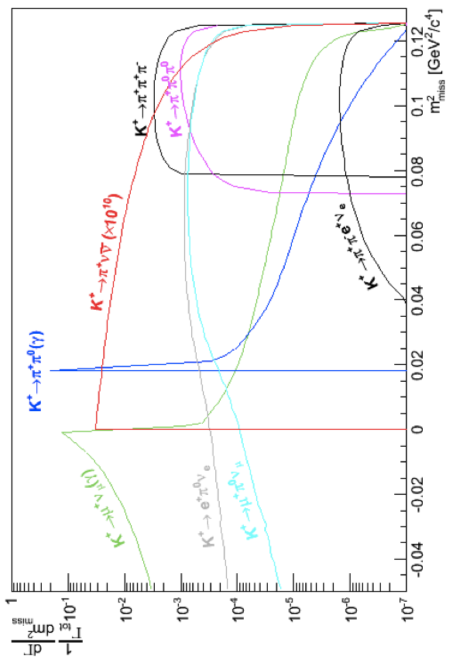


Main kaon decay backgrounds

Process	Branching ratio
$K^+ \to \mu^+\nu_\mu(\gamma)$	63.5%
$K^+ \to \pi^+\pi^0\,(\gamma)$	20.7%

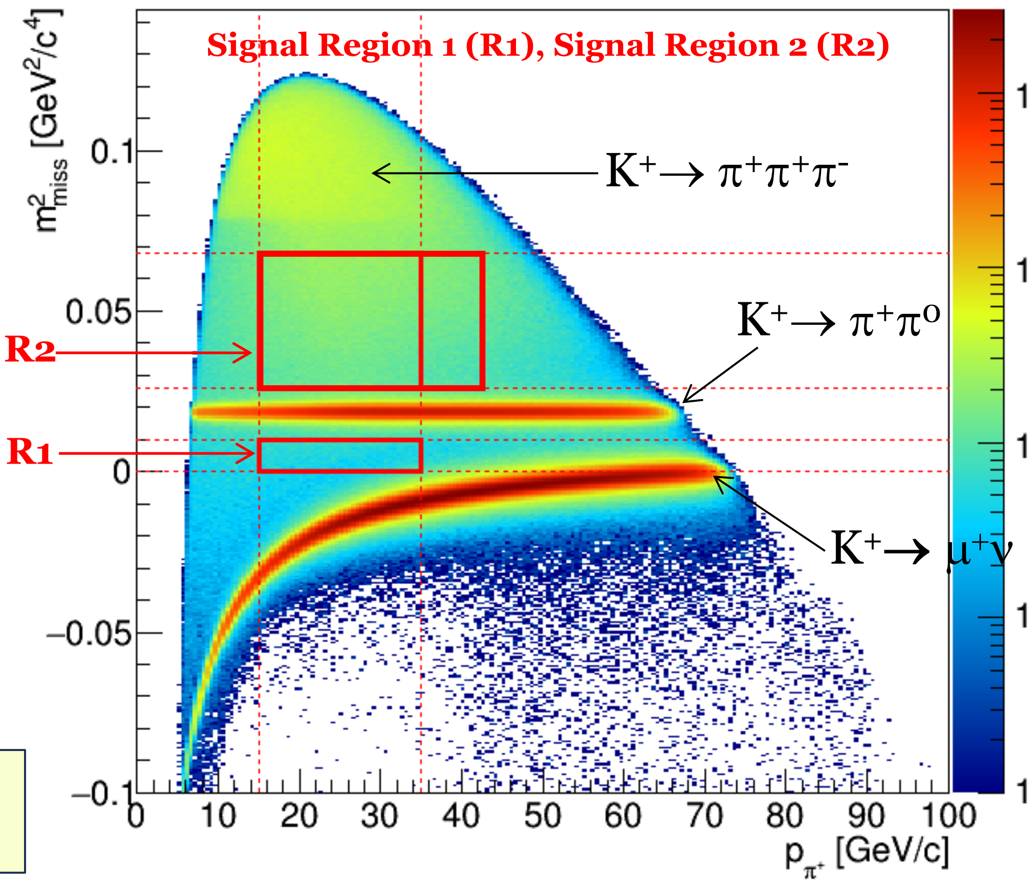
NA62/HIKE-Phase1 keystones:

- precise tracking
- PID (in particular π/μ)
- photon veto
- precise timing



$$m^2_{miss} \approx m^2_K\left(1-\frac{|p_\pi|}{|p_K|}\right)+m^2_\pi\left(1-\frac{|p_K|}{|p_\pi|}\right)-|p_K||p_\pi|\theta^2_{\pi K}$$

$m^2_{miss} = (P_K - P_\pi)^2$; m_π mass hypothesis

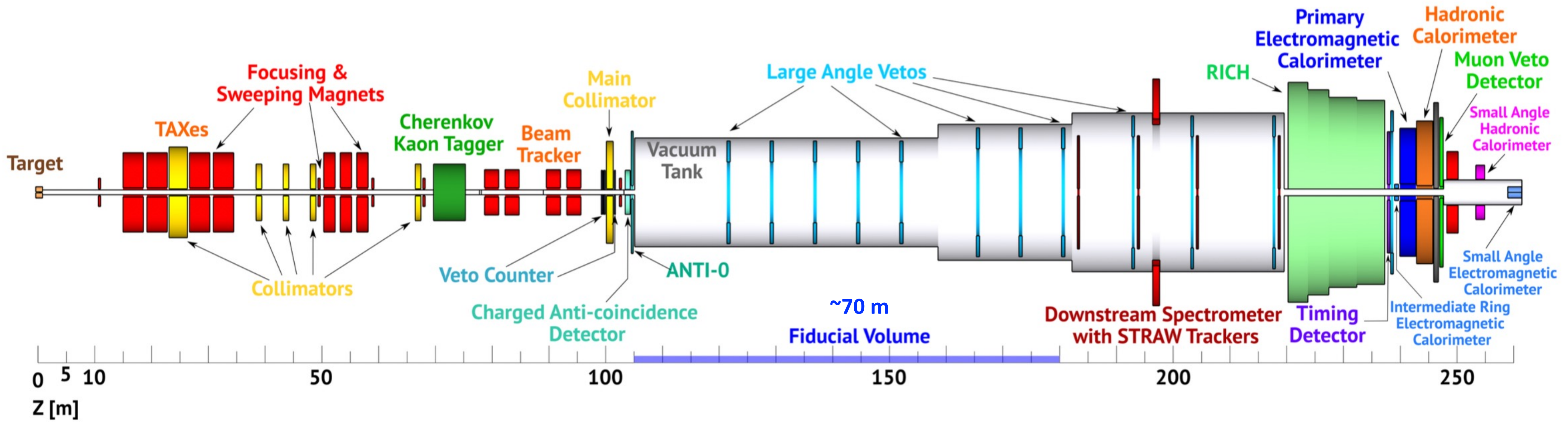


Background rejection at ~10^{11} level:
Kinematics (m^2_{miss}), **PID**, **Hermetic Veto**

HIKE-Phase1 Experimental Layout

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

Max possible beam intensity in HIKE-Phase1 (after major beamline upgrades):
1.2×10^{13} POT / spill = 4x NA62 max beam intensity
Statistical power: 2×10^{13} Kaon decays in decay volume per year (7×10^{18} POT / year)



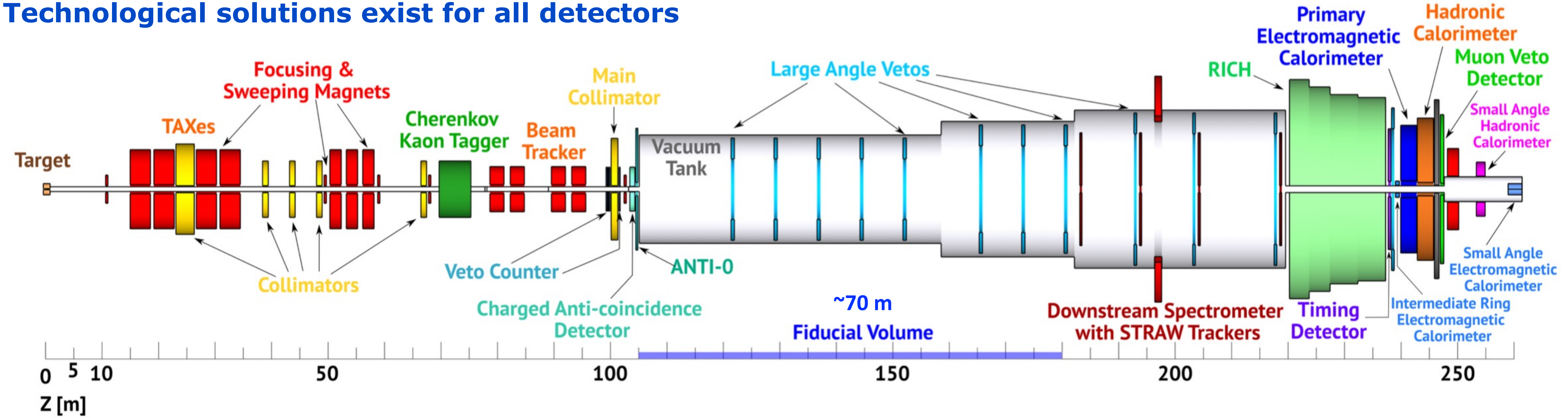
NA62-like design of experiment will work at high intensity

HIKE-Phase1 Experimental Layout

HIKE-Phase1 improvements wrt NA62:

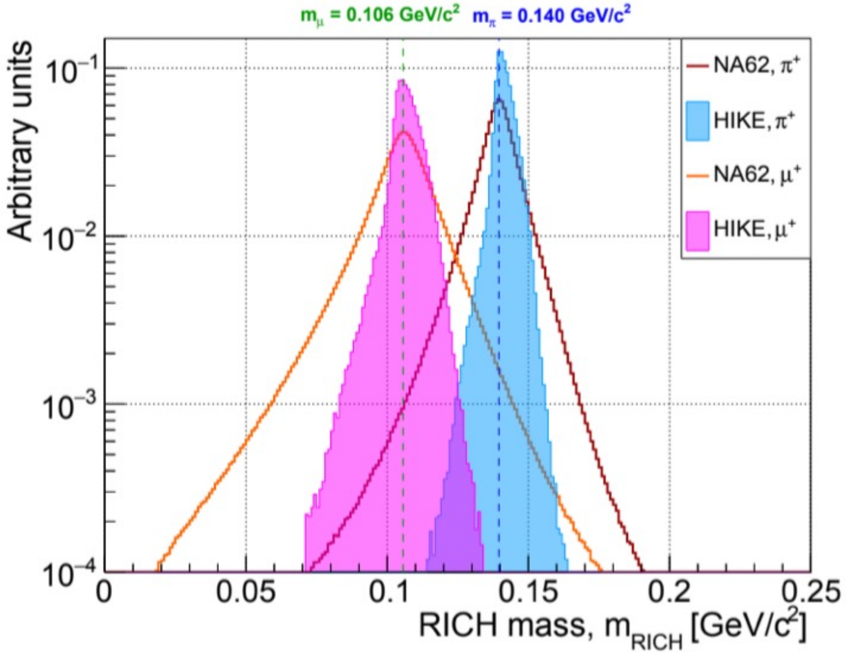
- **improved timing and double pulse resolution are crucial elements** to withstand the beam intensity increase
- **equal or better key performance** at high-rate to achieve background rejection at ~10^{11} level
- up to x2 **increase in signal acceptance** (improved detector performance, software trigger)
- improved **suppression of background** from upstream K^+ decays

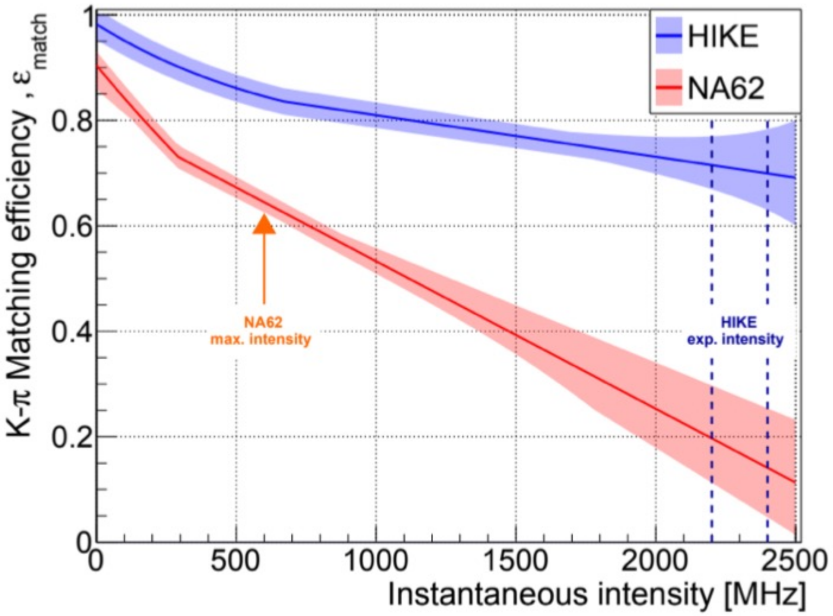
Technological solutions exist for all detectors



Challenges: 20-40 ps time resolution for key detectors, while maintaining all other NA62 specs
Technology challenges aligned with HL-LHC projects and future flavour/dark matter experiments

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ at HIKE: K/π ID





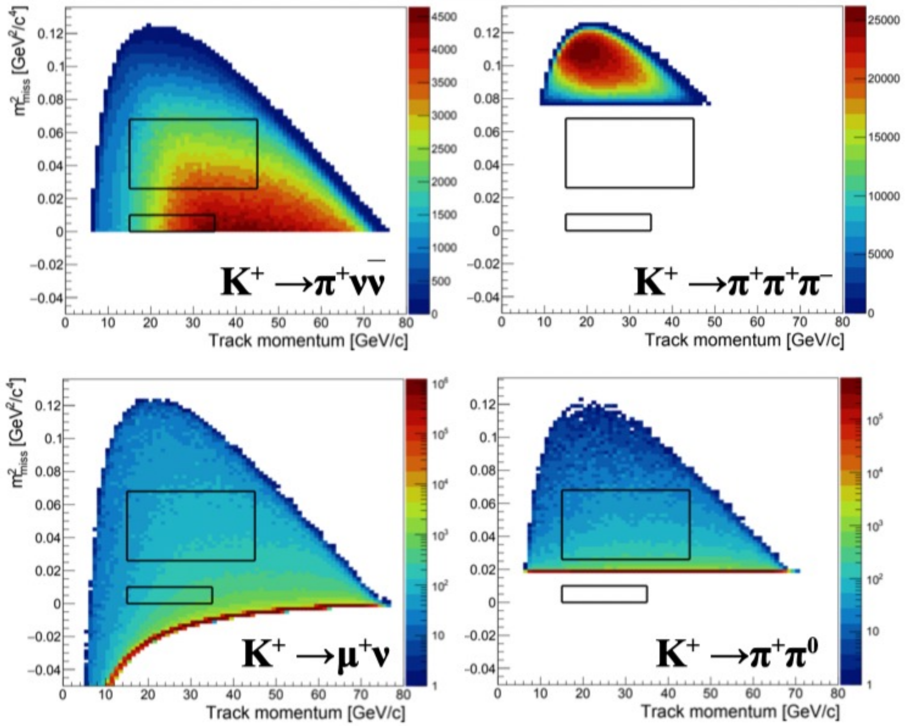
RICH PID for π with 15 < p < 45 GeV/*c*.
RICH granularity increased
+ better photodetectors (x2 Quantum Efficiency, time resolution: 300→100ps)
→ Improved photon yield and time resolution

K-π matching: x4 better timing, x3 smaller pixel size in beam tracker, 40% lower material budget in STRAW

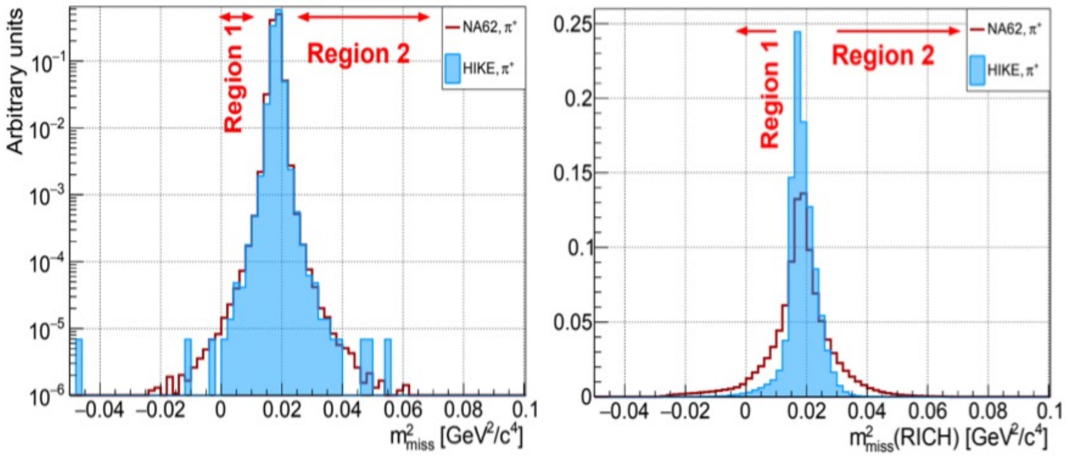
HIKE:
- π ID efficiency: > 10% higher than NA62, keeping same μ/π misID probability.
- K–π efficiency: ~ 10% higher than NA62. K-π misID probability ~2%, similar to NA62.

$K^+ \to \pi^+ \nu\bar{\nu}$ at HIKE: Kinematics

Simulated m^2_{miss} distribution vs momentum



m^2_{miss} distribution for $K^+ \to \pi^+ \pi^0$



NA62 MC extensively validated with data.

Main kaon decay modes enter the signal regions via resolution tails in the reconstructed value of m^2_{miss}

- Signal regions determined by resolution
- Slightly better m^2_{miss} resolution at HIKE wrt NA62

(40% less material budget in STRAW spectrometer)

- Missing mass with RICH much improved

HIKE signal regions can be optimised:
signal acceptance 10% higher than NA62, keeping same level of kinematic rejection

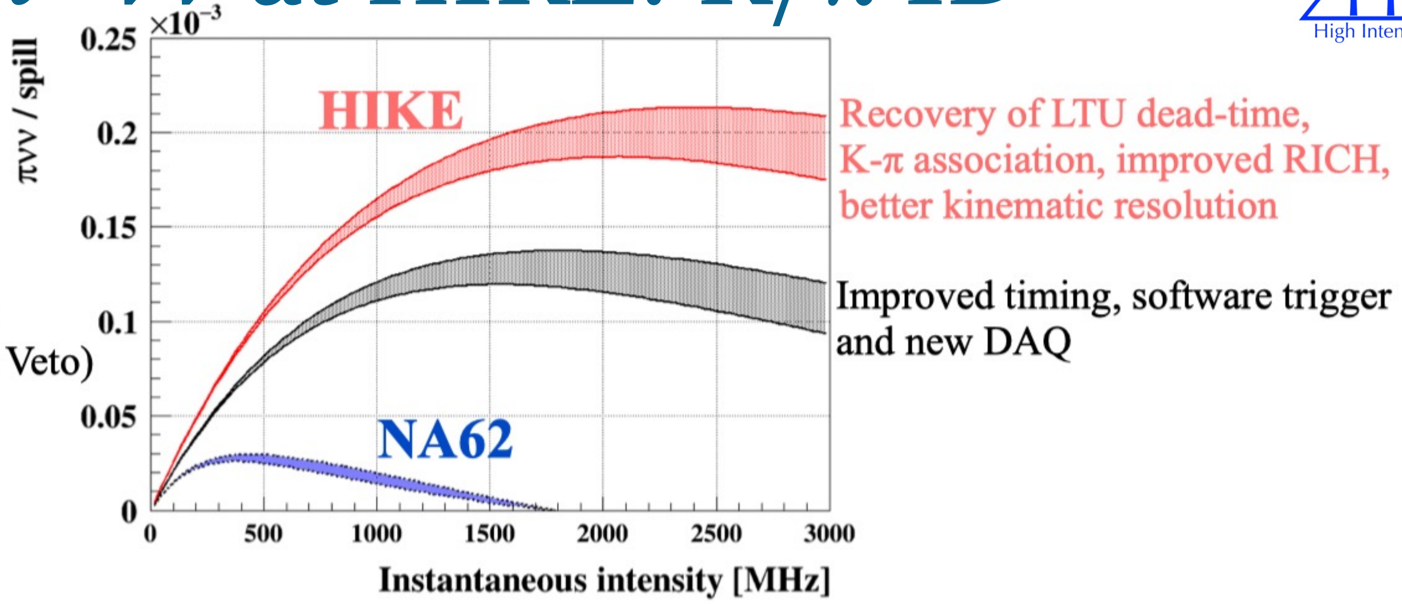
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ at HIKE: K/π ID

Signal intensity dependence:

Dead-time-equivalent paralyzable model accounting for intensity dependence of the trigger, DAQ, and all selection criteria (except Random Veto)

×

Polynomial description of the random veto efficiency



Background from K decays to remain the same fraction of signal

Improved coverage and design of upstream background veto
→ Upstream background reduced to same level as K background

Maintain or improve the same random-veto efficiency
→ time resolution for veto detectors improved by at least x4

Number of spills	2.4×10^6
Protons on target	3.2×10^{19}
K^+ decays in FV	8.0×10^{13}
Expected SM $K^+ \rightarrow \pi^+\nu\bar{\nu}$	480
Background from K^+ decays	115
Upstream/accidental background	85–240
Expected statistical precision $\sigma(\mathcal{B})/\mathcal{B}$	5.4%–6.1%

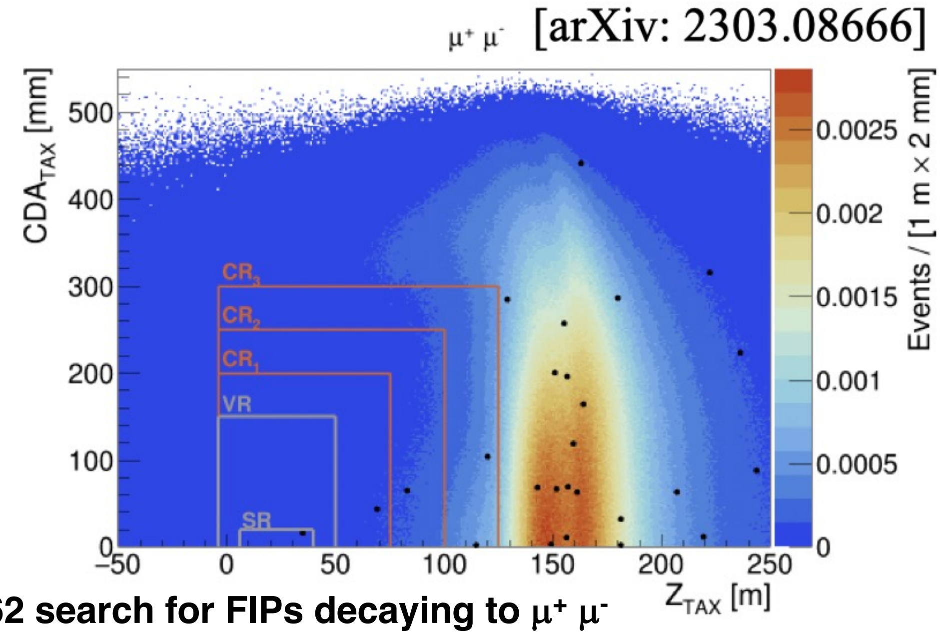
With background contamination and systematic uncertainty under control, measurement of **BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) at O(5%) precision in 4 years** of data-taking

Feebly-Interacting Particles (FIPs) at HIKE

HIKE fixed-target configuration, long decay volume: suitable to **search for FIPs, in kaon and beam-dump.** Exploring regions below 1 GeV, with unprecedented sensitivity. Detector low rate allows for high beam intensity.

Search for FIP production in **kaon mode**: $K^+ \to l^+ N$, $K^+ \to \pi^+ X$, ...

Dump mode: most sensitive to forward processes, complementary to off-axis experiment SHADOWS.
An ad-hoc setting of the dipoles allows a substantial reduction of the rate of muons emitted by pion decays in the proton-induced hadronic showers in the TAX.



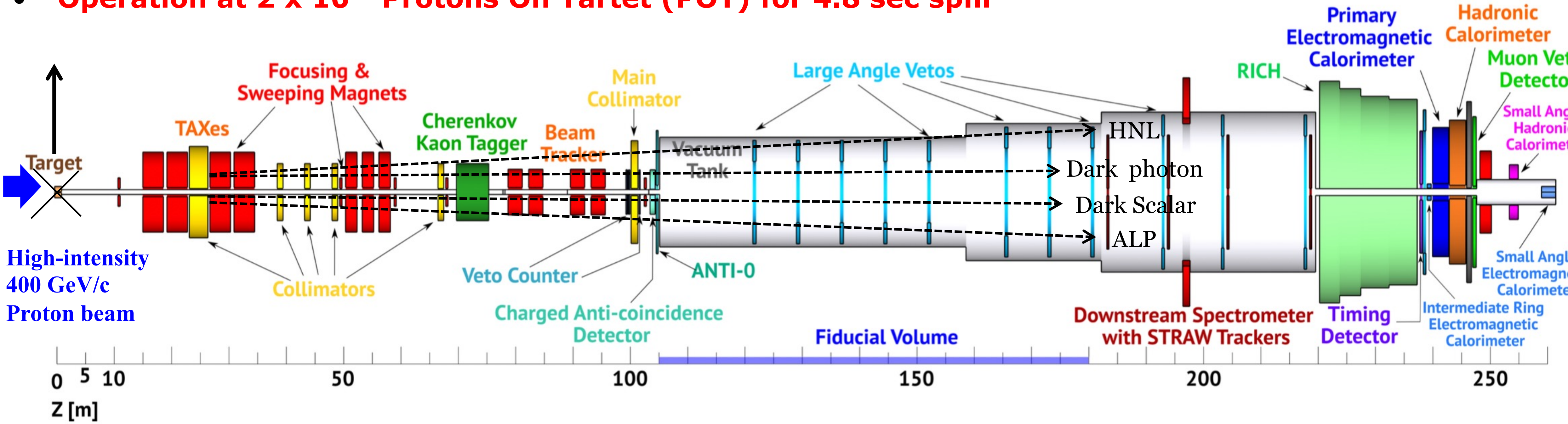
NA62 search for FIPs decaying to $\mu^+\mu^-$

Expected background in HIKE-dump (5×10^{19} POT)
based on extrapolation from 1.4×10^{17} POT collected by NA62 in 2021 in beam-dump mode

Final state	Expected background
$\mu^+\mu^-$	< 0.02
e^+e^-	< 0.9
$\pi^+\pi^-(\gamma)$	< 0.09
$\mu^\pm\pi^\mp$, $e^\pm\pi^\mp$	< 0.1
$\gamma\gamma$	work in progress

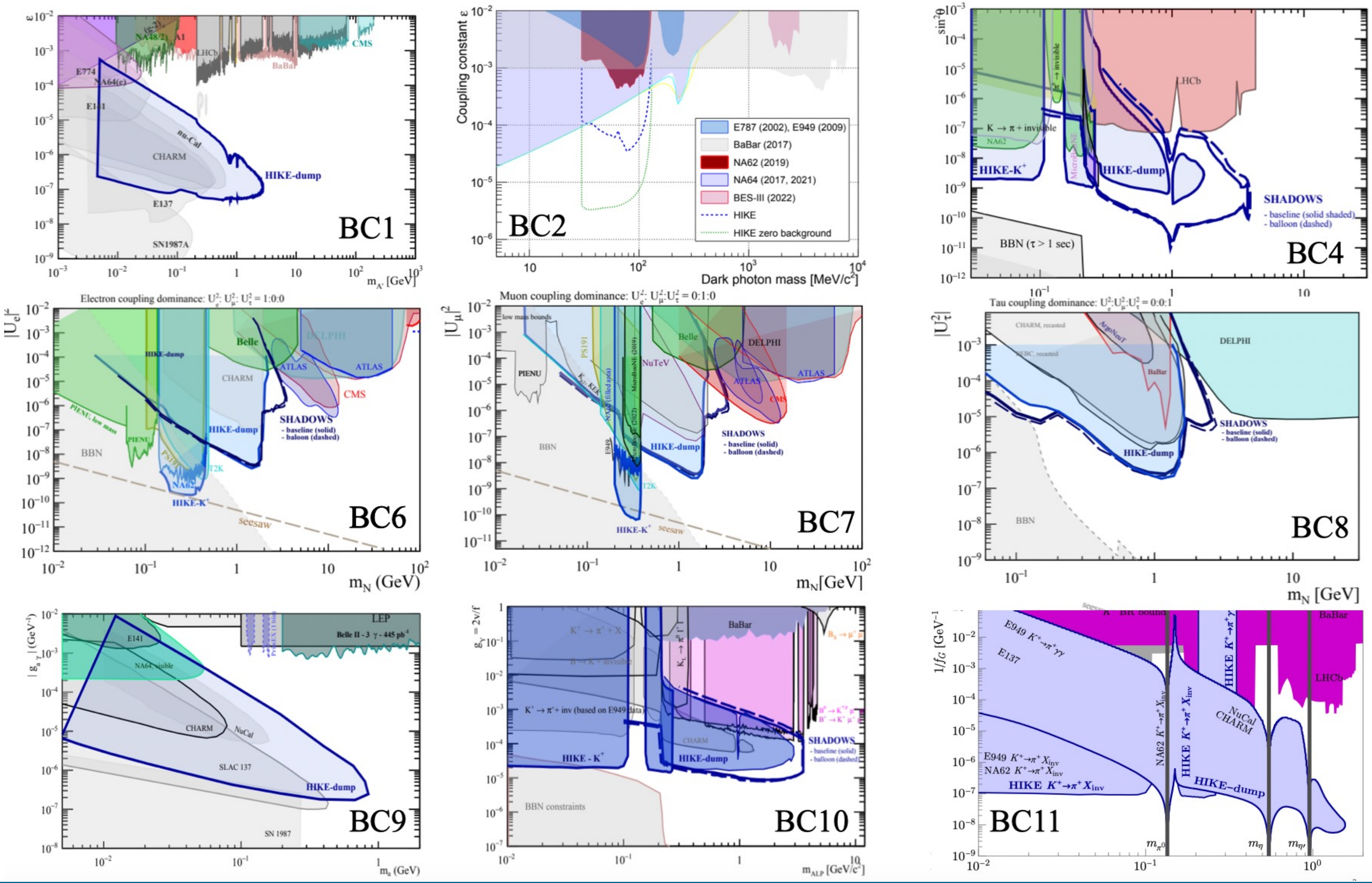
HIKE-Dump Experimental Layout

- Target can be moved out of beam
- **Proton beam impinges on TAXes, which act as a beam "dump"**
- New TAX complex to withstand much higher proton intensity and comply with modern radiation facility standards
- Additional heavy shielding around TAX due to higher radiation (under study within the NA consolidation project)
- Production of HNL, DP, DS and ALP from charm, beauty and γ produced in proton interaction with the dump
- **Operation at 2 x 10^{13} Protons On Tartet (POT) for 4.8 sec spill**



HIKE Phase1 kaon or proton "dump" modes are easily switchable in proposed setup

HIKE Phase 1: FIPs Sensitivity



Assume 5 x 10^{19} POT taken in 4 years concurrently with SHADOWS operation

HIKE sensitive to Physics Beyond Collider benchmark scenarios.

PBC BC classification from arXiv:1901.09966

Vector Portal
- 9.1.1 Minimal Dark Photon model (BC1)
- 9.1.2 Dark Photon decaying to invisible final states (BC2)
- 9.1.3 Milli-charged particles (BC3)

Scalar Portal
- 9.2.1 Dark scalar mixing with the Higgs (BC4 and BC5)

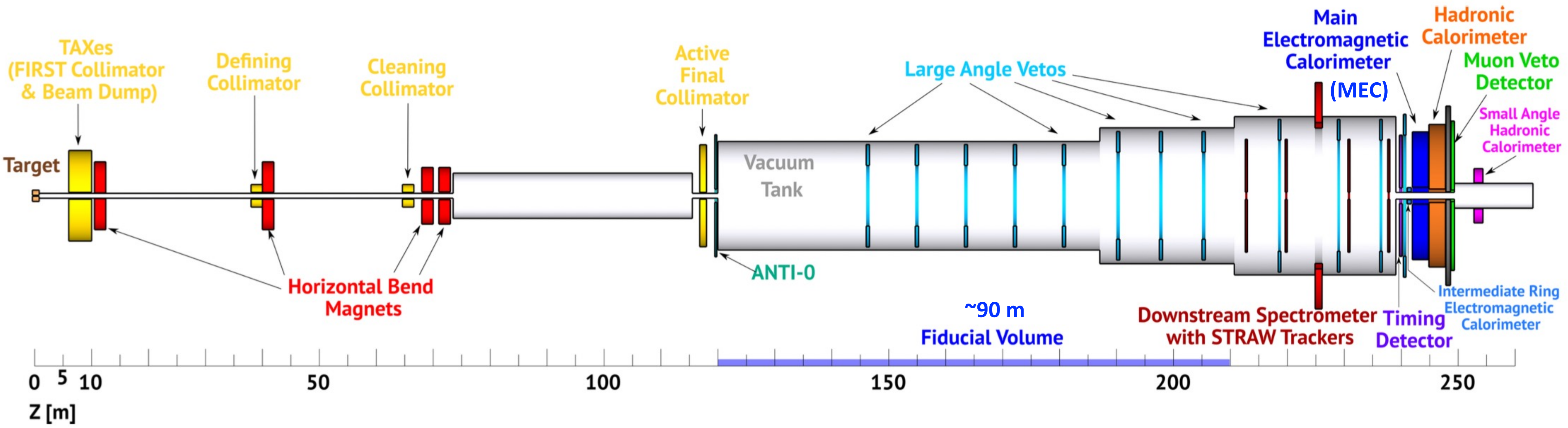
Neutrino Portal
- 9.3.1 Neutrino portal with electron-flavor dominance (BC6)
- 9.3.2 Neutrino portal with muon-flavor dominance (BC7)
- 9.3.3 Neutrino portal with tau-flavor dominance (BC8)

Axion Portal
- 9.4.1 Axion portal with photon-coupling (BC9)
- 9.4.2 Axion portal with fermion-coupling (BC10)
- 9.4.3 Axion portal with gluon-coupling (BC11)

HIKE-Phase2 Experimental Layout

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

Max possible intensity in HIKE-Phase2 (upgraded NA48 neutral beamline): 2 $\times 10^{13}$ POT / spill
Statistical power: 3.8×10^{13} Kaon decays in decay volume per year (1.2×10^{19} POT / year)



NA48 neutral beam-like design of experiment will work at high intensity

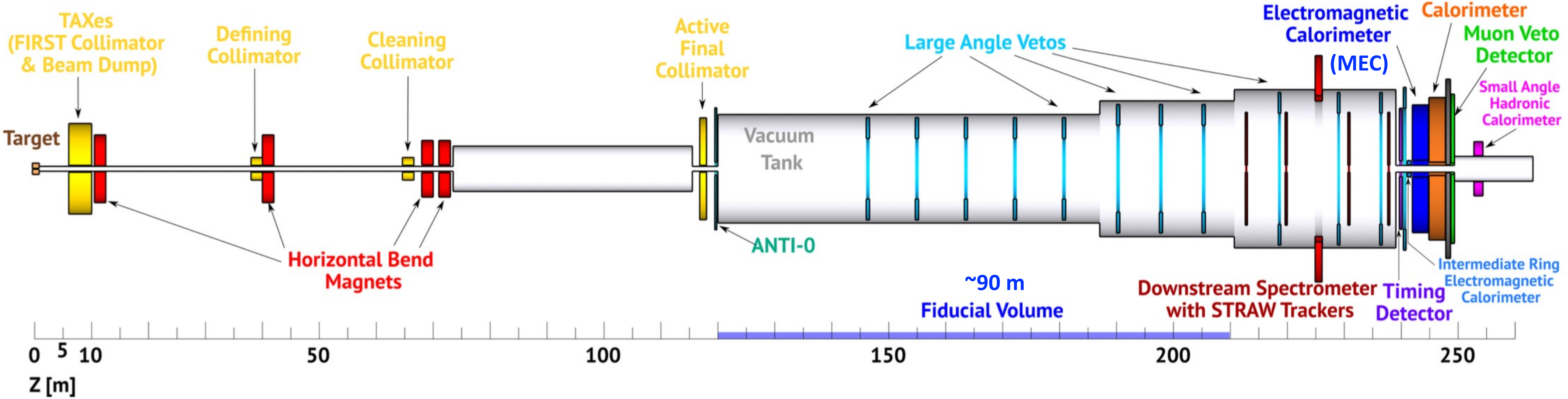
HIKE-Phase2 Experimental Layout

<u>A 120 m long neutral (NA48-like) beam line:</u>

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

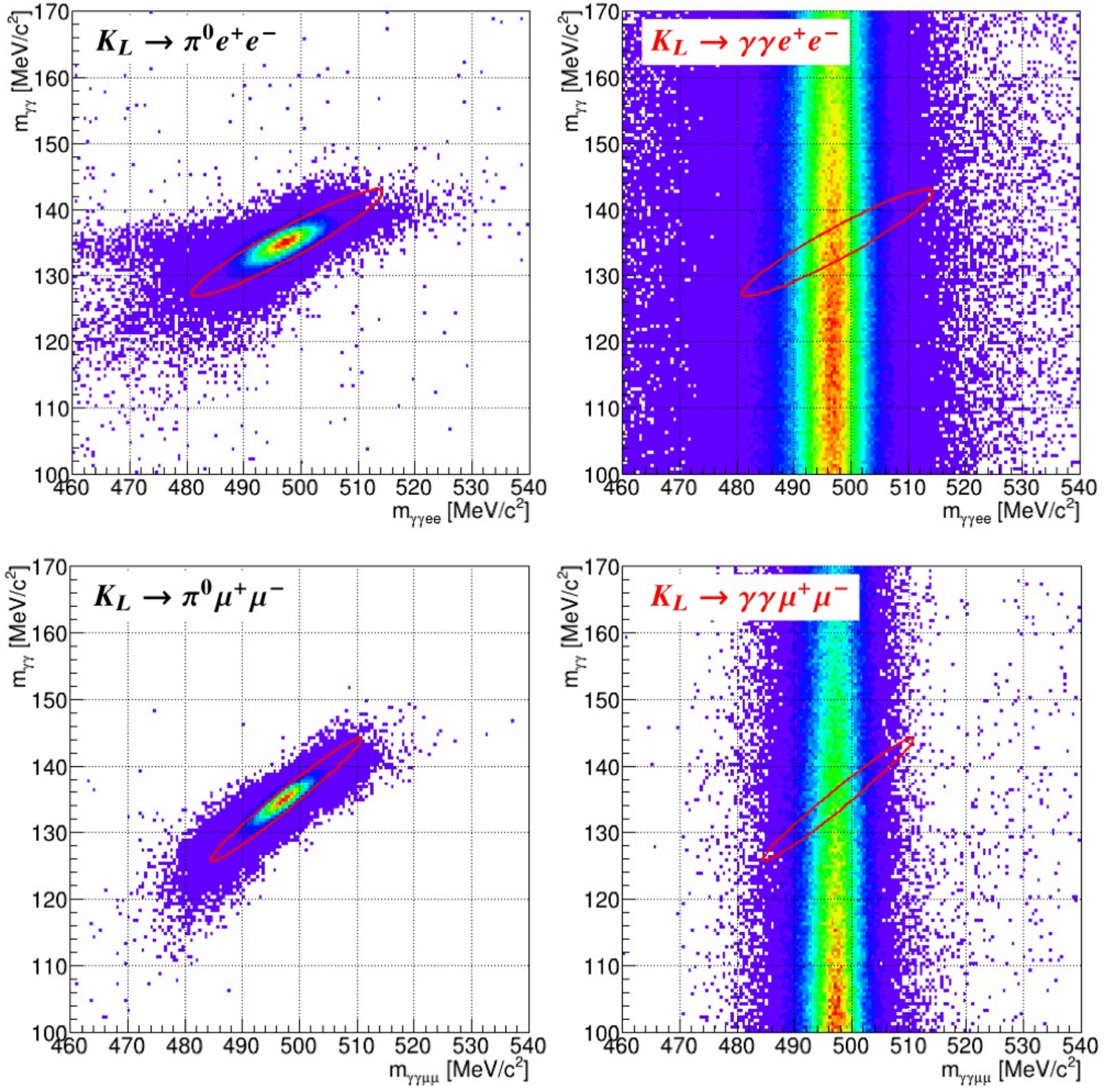
<u>Reconfigured HIKE-Phase1 detector:</u>

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



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, oriented crystals)

HIKE Phase-2: Signal & Background



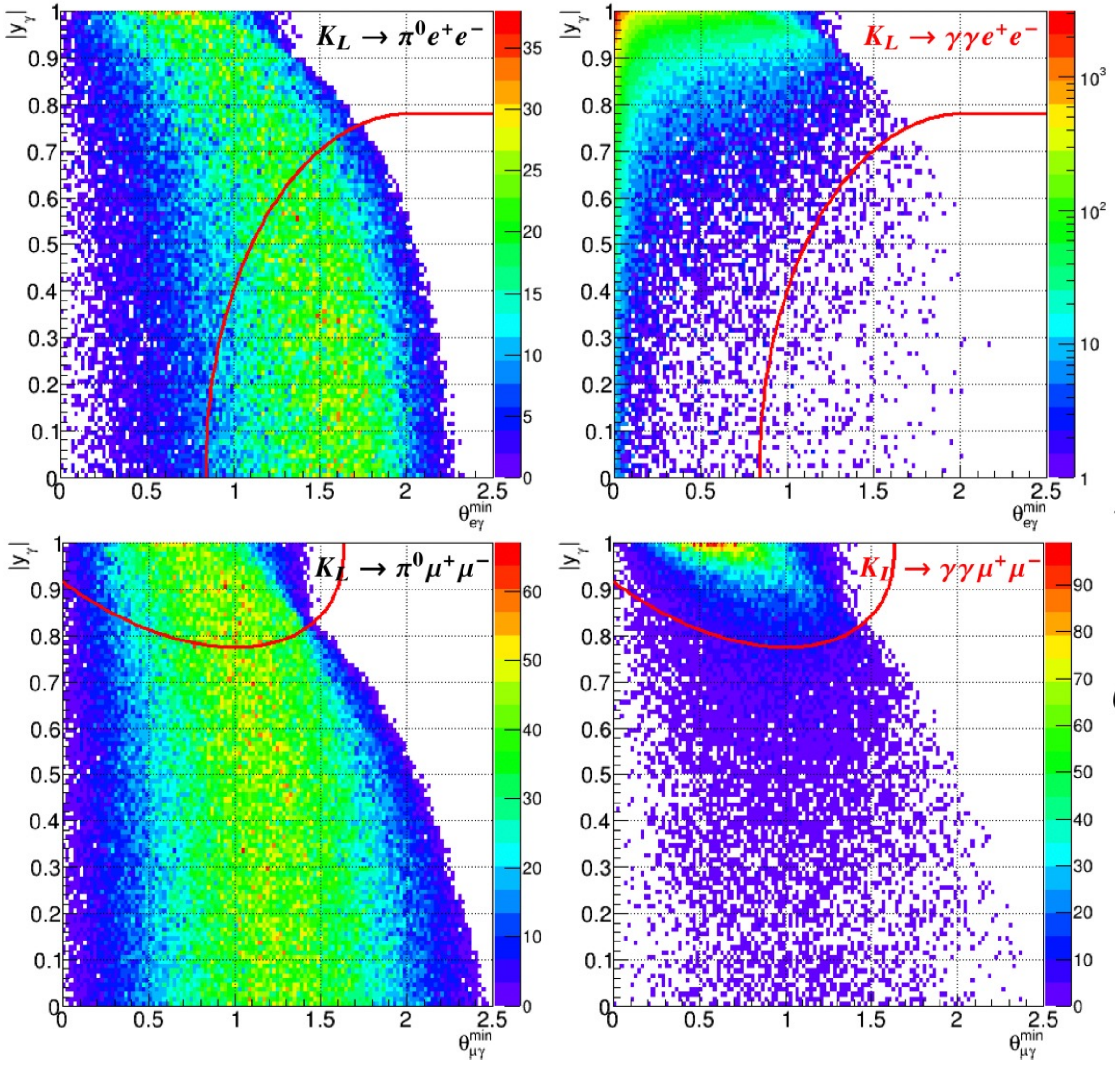
Main background: $K_L \to \gamma\gamma l^+ l^-$ [Greenlee, PDR42(1990)]

Mode	Phase space region	Branching ratio
$K_L \to \gamma\gamma e^+ e^-$	$x = (m_{ee}/m_K)^2 > 0.05$, $x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.55 \pm 0.05) \times 10^{-7}$
$K_L \to \gamma\gamma \mu^+ \mu^-$	$x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.49 \pm 0.28) \times 10^{-9}$

$K_L \to \pi^+\pi^-\pi^0$ decay with $\pi^\pm$ decaying in flight is sub-dominant

Suppression of the $K_L \to \gamma\gamma\, l^+ l^-$ background: rely on **excellent photon energy resolution** provided by the HIKE EM calorimeter.

HIKE Phase-2: Background Estimate



The kinematic selection is based on two reconstructed variables:

$$y_\gamma = \frac{2P \cdot (k_1 - k_2)}{m_K^2 \cdot \lambda^{1/2}(1, x, x_\gamma)}$$

P = kaon four-momentum $\qquad x = (m_{ee}/m_K)^2$

k = photon four-momenta $\qquad x_\gamma = (m_{\gamma\gamma}/m_K)^2$

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ac)$$

$\theta^{min}_{l\gamma}$ = smallest angle between any of the photons and any of the leptons in the kaon frame

HIKE Phase-2: Physics Sensitivity

Expected SM signal and background events collected in 5 years of HIKE operation:

Number of spills			3×10^6	
Protons on target			6×10^{19}	
K_L decays in FV			1.9×10^{14}	
Mode	N_S	N_B	$N_S/\sqrt{N_S+N_B}$	$\delta\mathcal{B}/\mathcal{B}$
$K_L \to \pi^0 e^+ e^-$	70	83	5.7	18%
$K_L \to \pi^0 \mu^+ \mu^-$	100	53	8.1	12%

HIKE will make the first observation at >5σ significance and measurement of both ultra-rare decay modes

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 e^+ e^-) = \left(15.7|a_S|^2 \pm 6.2|a_S|\left(\frac{\text{Im}\,\lambda_t}{10^{-4}}\right) + 2.4\left(\frac{\text{Im}\,\lambda_t}{10^{-4}}\right)^2\right) \times 10^{-12}$$

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 \mu^+ \mu^-) = \left(3.7|a_S|^2 \pm 1.6|a_S|\left(\frac{\text{Im}\,\lambda_t}{10^{-4}}\right) + 1.0\left(\frac{\text{Im}\,\lambda_t}{10^{-4}}\right)^2 + 5.2\right) \times 10^{-12}$$

LHCb Phase-I upgrade expected to measure $|a_S|$ to 5% relative precision from the $K_S \to \pi^0 \mu^+ \mu^-$ decay

Assuming constructive interference, determine the CKM parameter $\lambda_t = V_{ts}^* V_{td}$:

$$\left.\frac{\delta(\text{Im}\,\lambda_t)}{\text{Im}\,\lambda_t}\right|_{K_L\to\pi^0 e^+ e^-} = 0.33, \qquad \left.\frac{\delta(\text{Im}\,\lambda_t)}{\text{Im}\,\lambda_t}\right|_{K_L\to\pi^0 \mu^+ \mu^-} = 0.28$$

20% precision on CKM parameter λ_t

HIKE: Kaon Global Fit

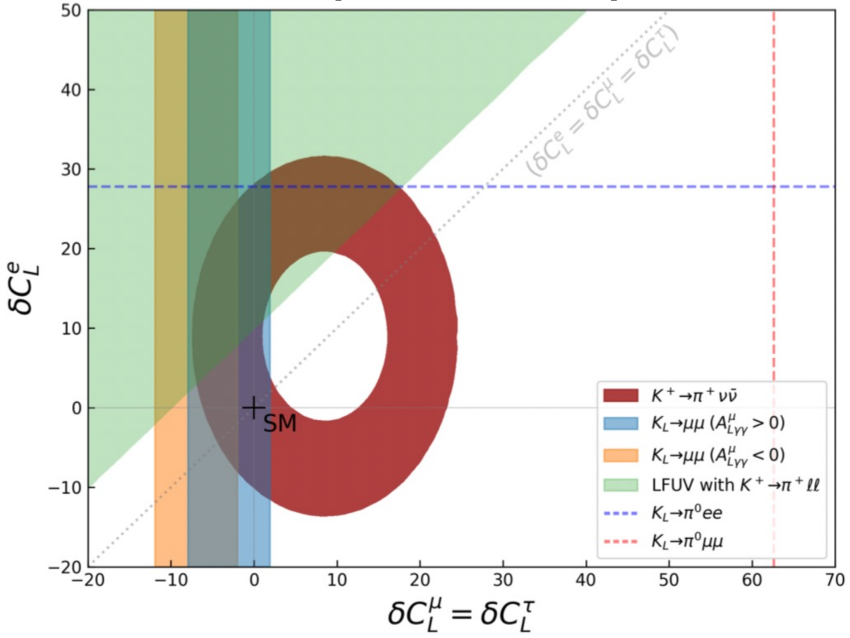
Global fits to set of kaon measurements, in the framework of lepton universality.
Effect on Wilson coefficients for NP scenarios with only left-handed quark currents.

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

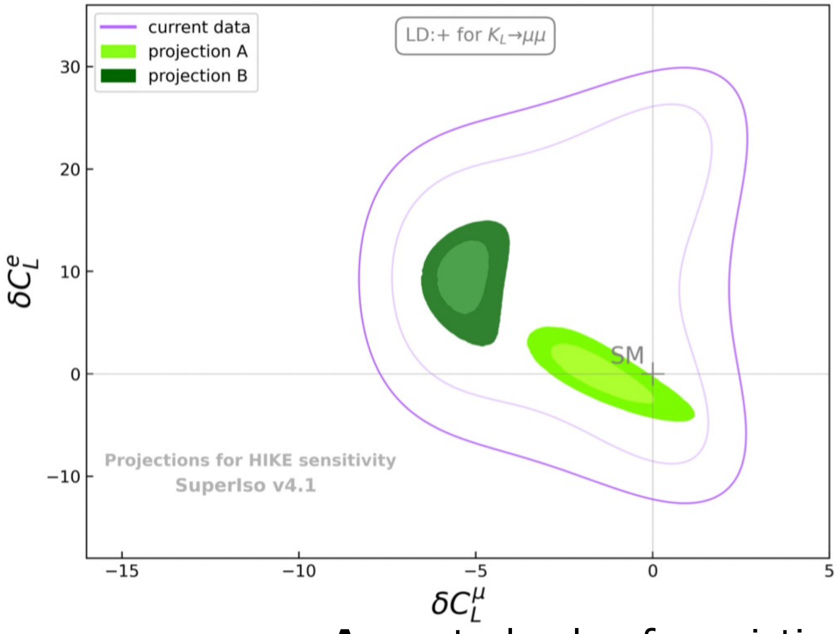
$$C_k^\ell = C_{k,\rm SM}^\ell + \delta C_k^\ell$$
$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

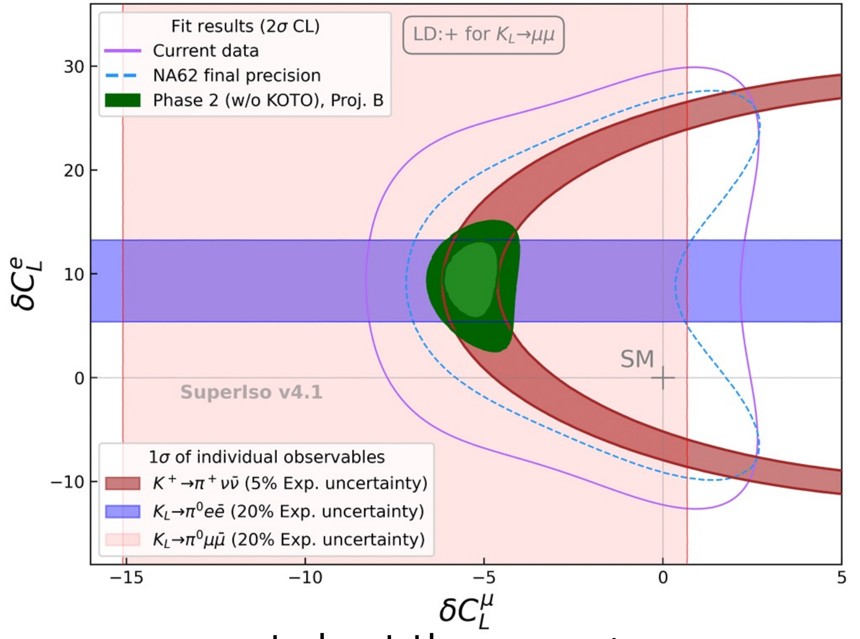
[arXiv:2206.14748]



[arXiv:2207.04956]



[arXiv:2311.04878]



Bounds from individual observables.
Colored regions are 68% CL measurements
Dashed lines are 90% CL upper limits

A: central value for existing measurements kept the same + SM expectation used for measurement with upper bounds
B: central value of all observables is projected to the best-fit points obtained from fits to existing data

HIKE Kaon Physics Programme

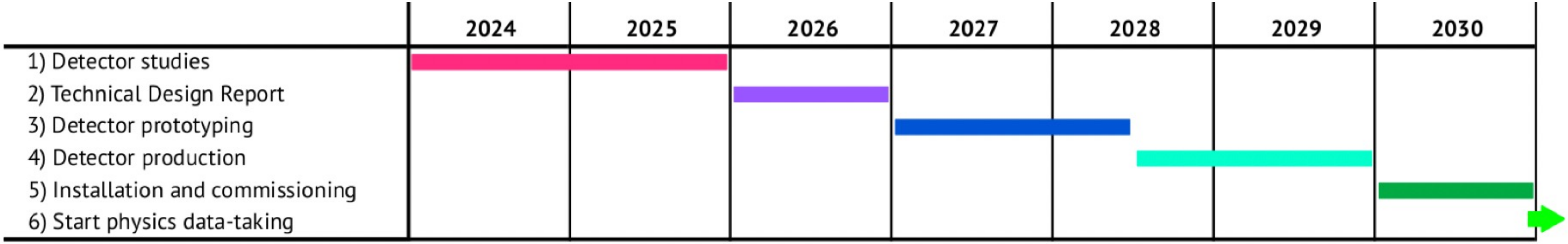
HIGH Intensity Kaon Experiments

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

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:

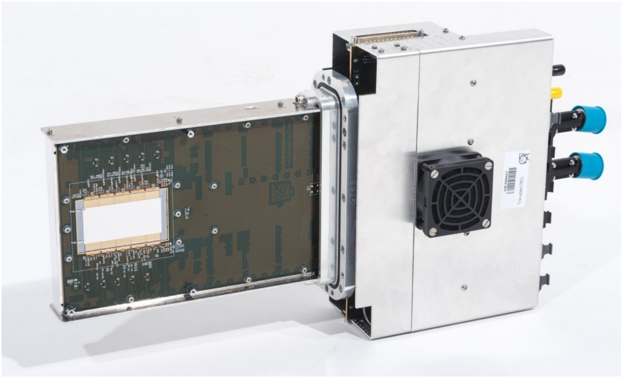
- Material budget: 0.5% X_0 per layer
- Use minimum number of planes, time mmts to constrain event reconstruction
- 200 µm planar silicon sensors
- TDCPix readout chips
- Cooled with silicon microchannel plates

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)
- ✓ angular resolution ~16 µrad
- ✓ momentum resolution ~0.2%



Requirements for next generation of upgrades

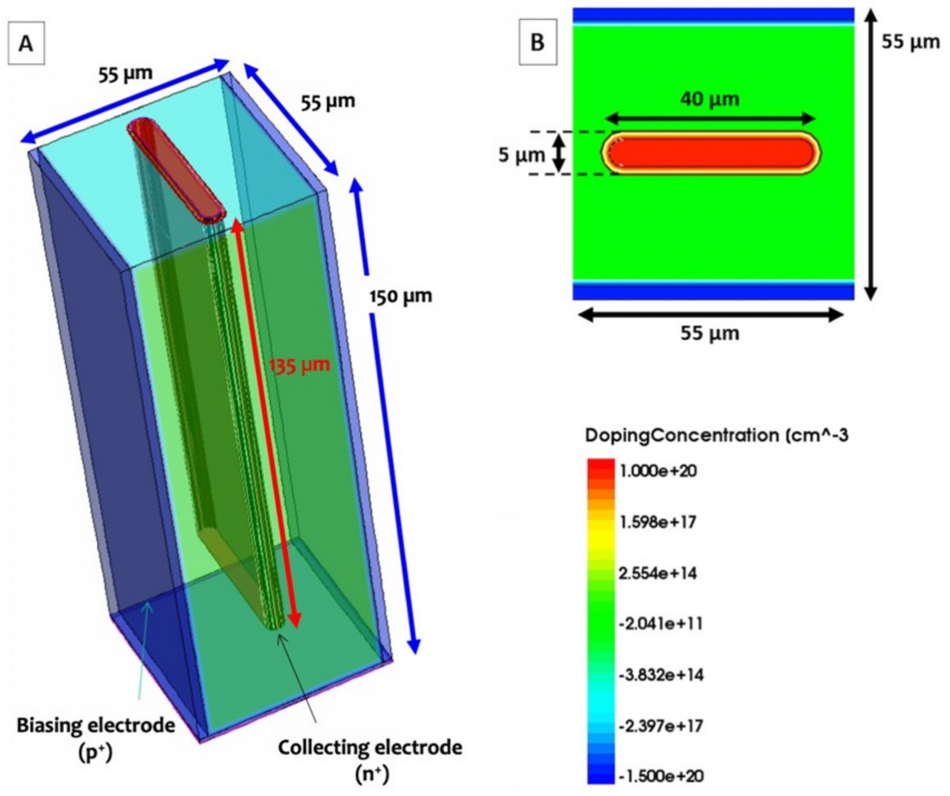
(LHCb Run5, CMS-PPS & ATLAS-AFP Run4 FCC-hh)

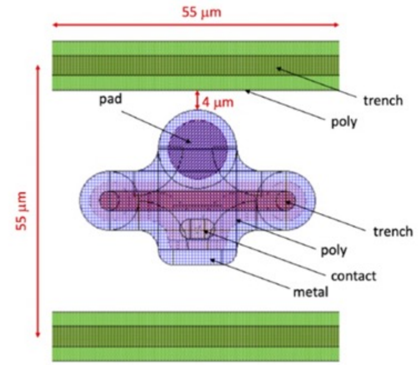
- $\sigma_s \approx 10$ µm (→ pixel pitch ≈ 40-60 µm)
- $\sigma_t \leq 50$ ps on full chain ($\sigma_t = \sigma_{sensor} \oplus \sigma_{FE} \oplus \sigma_{TDC}$)
- Radiation hardness to $\Phi = 10^{16} \div 10^{17}$ 1 MeV n_{eq}/cm^2
- Detection efficiency >99% per layer
- Material budget < 1÷0.5% X_0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

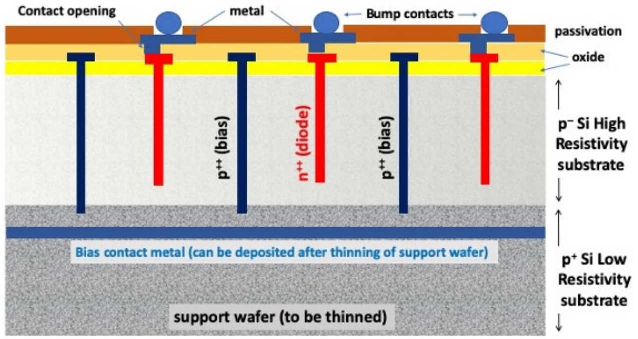
Silicon detectors with fast timing information capable to operate in a high-radiation environment → shared interest with HL-LHC experiments

The trench-type TimeSPOT 3D pixels

A strong option that can satisfy all requirements for the HIKE beam tracker







Trench geometry improves
charge collection time uniformity

Hybrid 3D-trenched technology:

- ✓ electrode geometry optimised for timing performance
- ✓ able to withstand very large irradiation
- ✓ excellent detection efficiency
- ✓ Spatial resolution O(10μm)
- ✓ Data throughput > 1 TB/s

Associated 28nm ASIC: first prototype

Sensor size 2×2 cm^2 can be produced and technical solution like stitching are being explored to produce larger devices

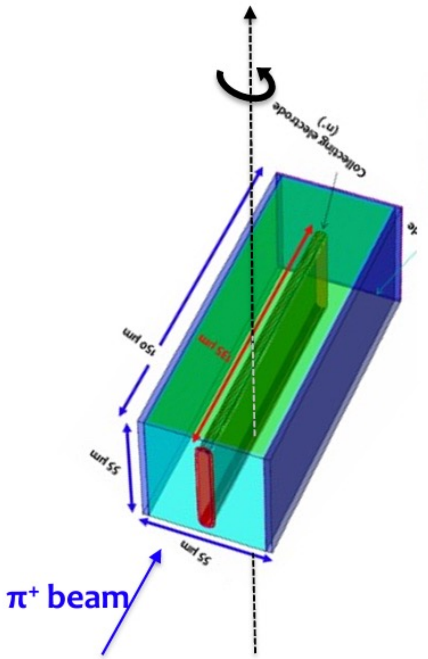
F. Borgato et al. Frontiers in Physics 11 (2023) 1117575

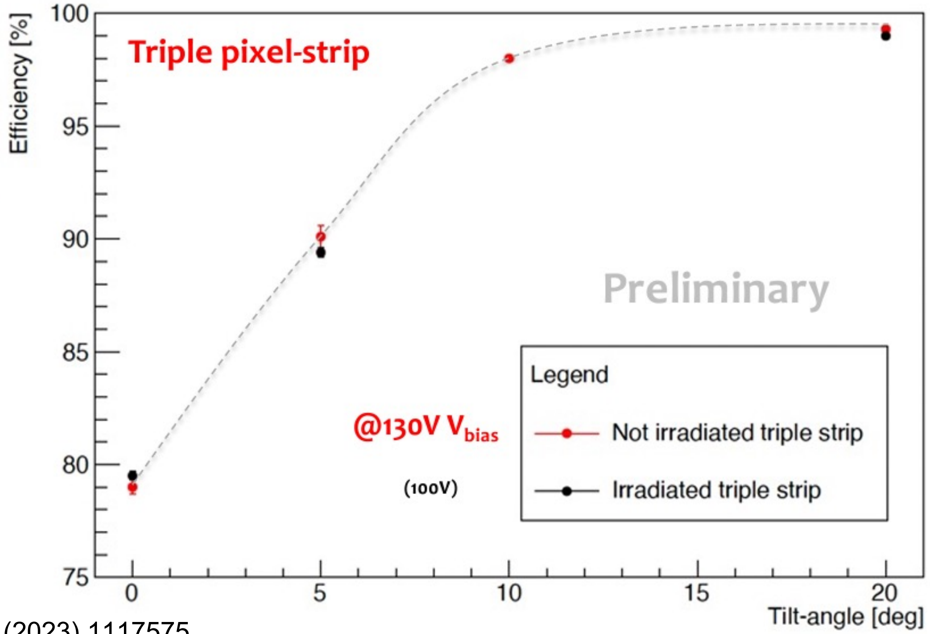
The trench-type TimeSPOT 3D pixels

Detection Efficiency ~99.1% tilting the sensor around the trench axis at angles of 20°
Irradiated sensor shows same efficiency as unirradiated sensor

Time performance ~ 10 ps up to a fluence of 2.5×10^{16}MeV n_{eq}/cm^2
Exceeding a bias of 100 V **irradiated pixel has the same time resolution of an unirradiated pixel**
Tilted sensor → excellent time performance (same as for non-tilted sensor)

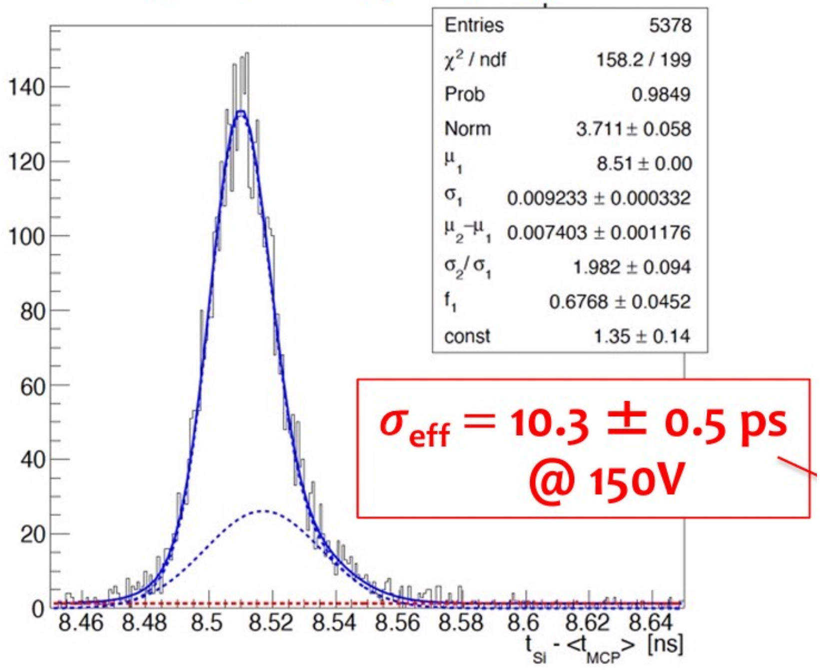
TimeSPOT collaboration planning to extend tests up to fluences of 1×10^{17} 1 MeV n_{eq}/cm^2





F. Borgato et al. Frontiers in Physics 11 (2023) 1117575

Irradiated @ 2.5 10^{16} n_{eq}/cm^2 , $\alpha_{tilt} = 0°$



To be compared with 11 ps @ 100 V of the not-irradiated case

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/cm²**
- Photo-detector (PD) with high granularity
- High radiation tolerance
- Single-photon detection capability and **$\sigma_t(\gamma)$ ~50 ps**

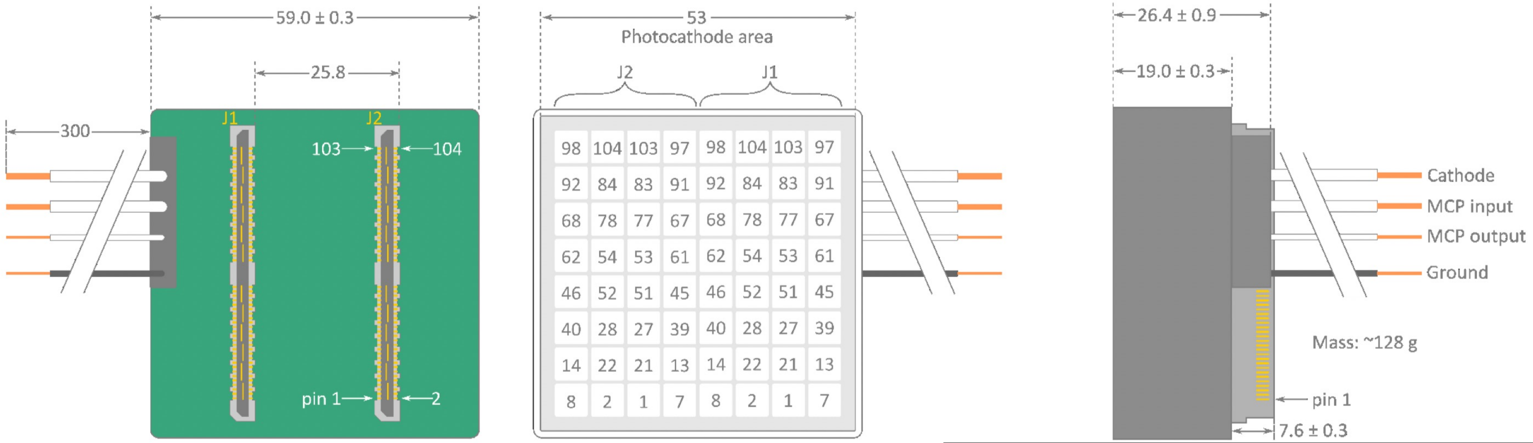
Kaon tagging detector in NA62

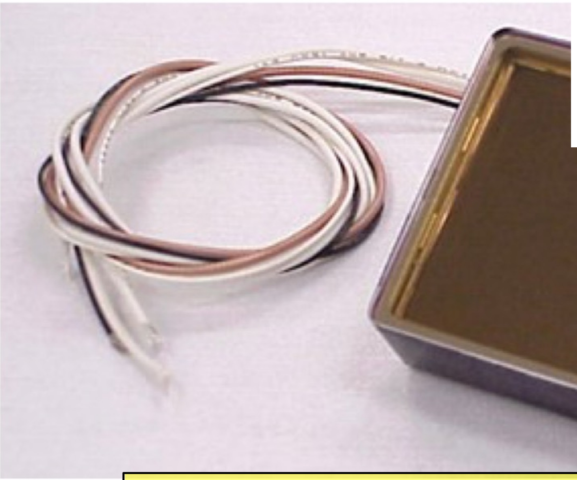
KTAG photo-detector R&D (to be started in Birmingham)**:**

- 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

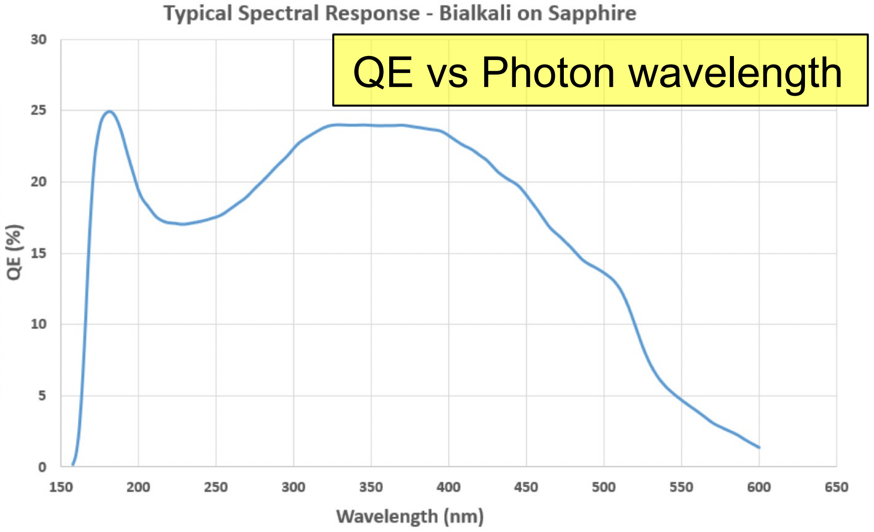
MCP-PMT Prototype for KTAG

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



QE vs Photon wavelength

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)

Time Capability

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

KTAG Photon Detector Design for HIKE

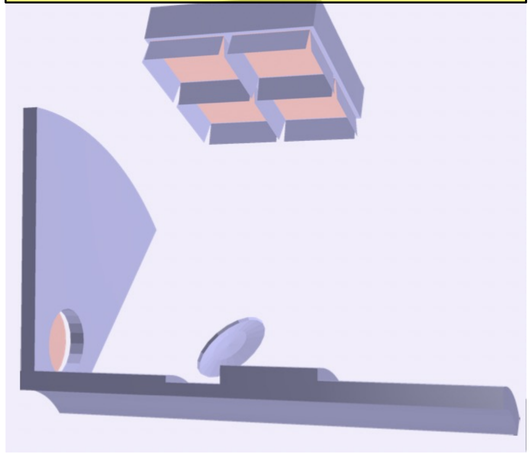
High Intensity Kaon Experiments

Replacement of existing PMTs and light guides

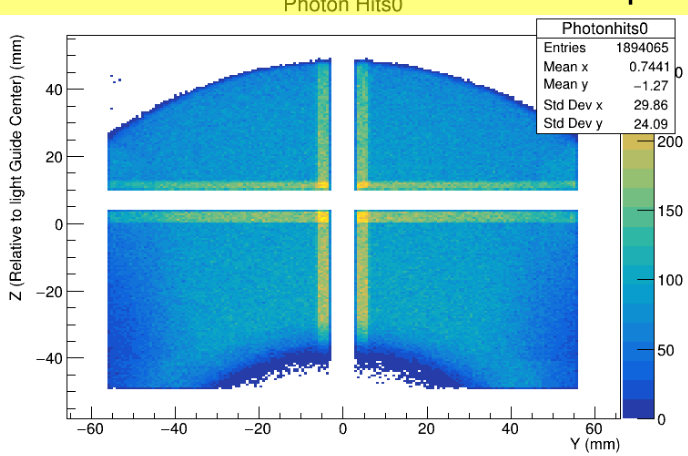
- Instrumented KTAG area/octant ~ 10cm*15cm
- Use a matrix of 4 MCP-PMTs/octant
- Expected MCP-PMT pixel/anode rate ~2-3MHz
- Total number of channels: 2048

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

MCP Geant4 Simulation

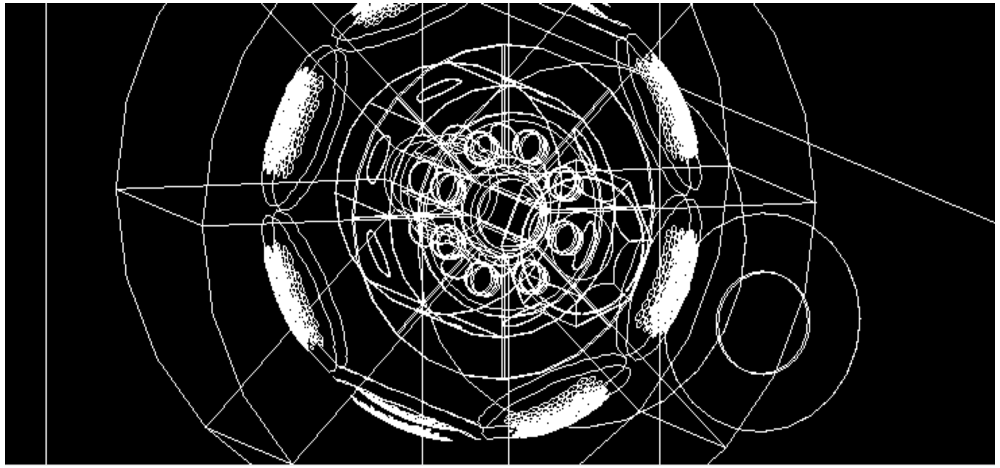


Photon distribution at MCP-PMT plane

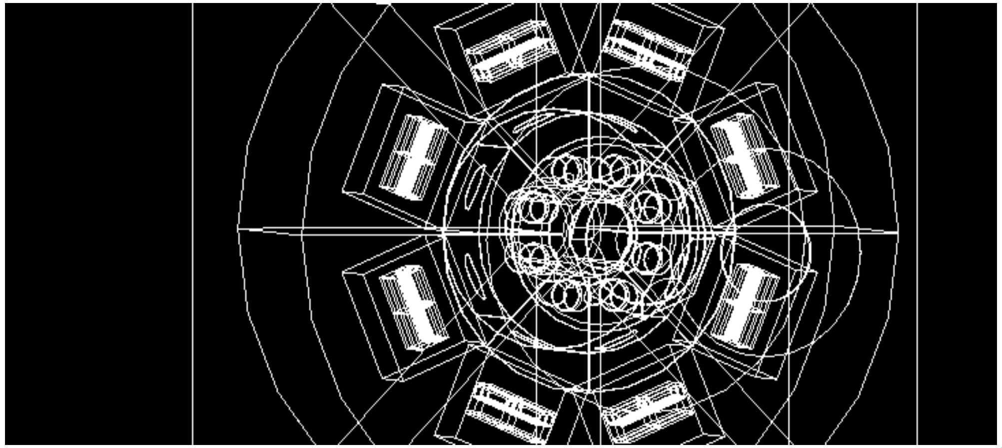


Simulations developed in Birmingham:

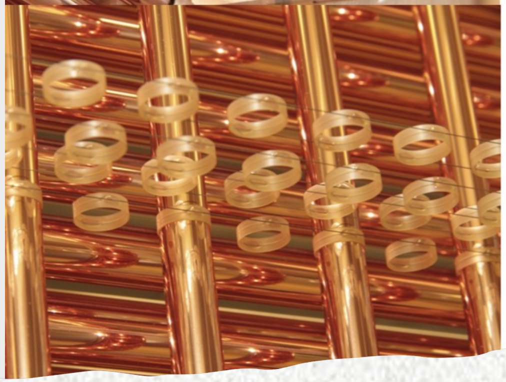
KTAG with PMTs for NA62



KTAG with MCP-PMTs for HIKE







The NA62 STRAW Spectrometer in ECN3

NA62 has developed techniques for making **state-of-the-art straws by ultrasonic welding**

High-precision measurements of track parameters with **36 straws per track**

The HIKE STRAW Spectrometer

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

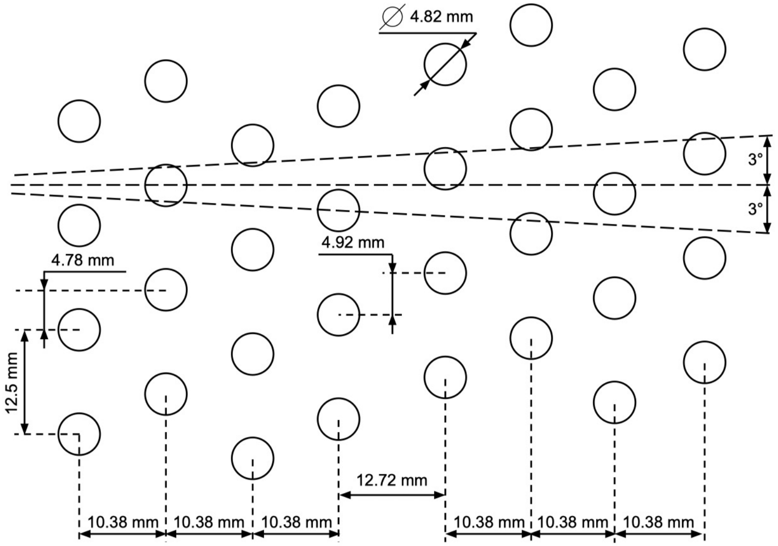
New STRAW design for HIKE @ 4x intensity:

- ❖ **Increased rate capability** (reduced straw diameter, use fast shaping)
- ❖ Improved momentum resolution (reduced material budget, improve position resolution)

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

	Current NA62 spectrometer	New straw spectrometer **for 4x intensity**
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

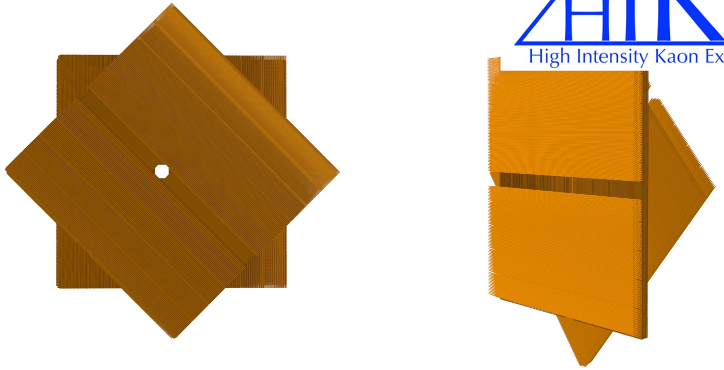
Optimised layout of straw tubes with 4.82 mm diameter in a single view



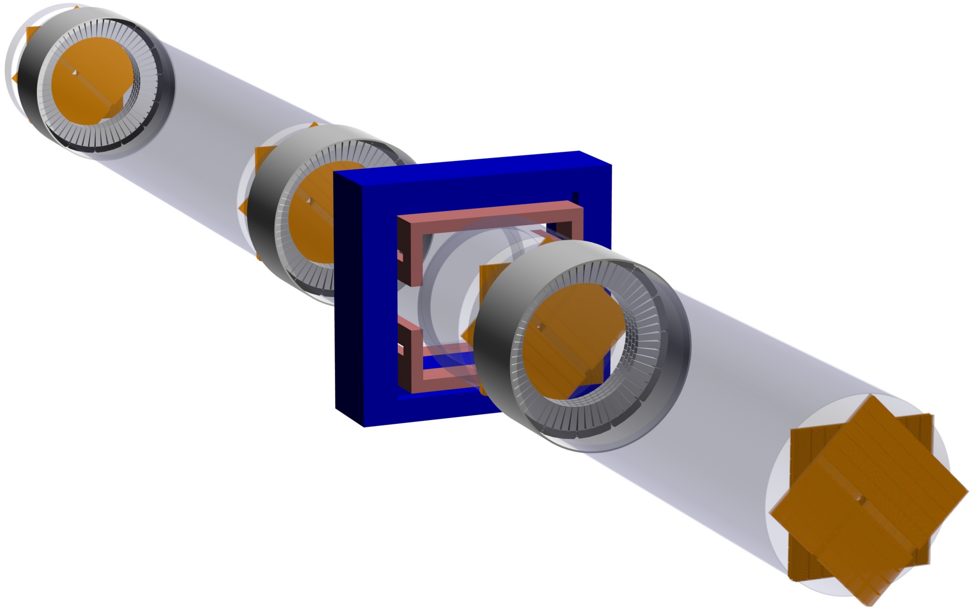
The HIKE STRAW Spectrometer

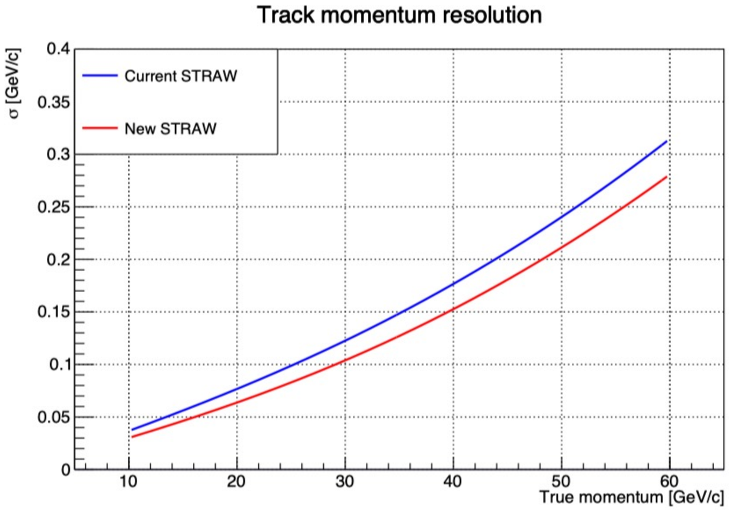
Geant4 visualization of the new STRAW spectrometer

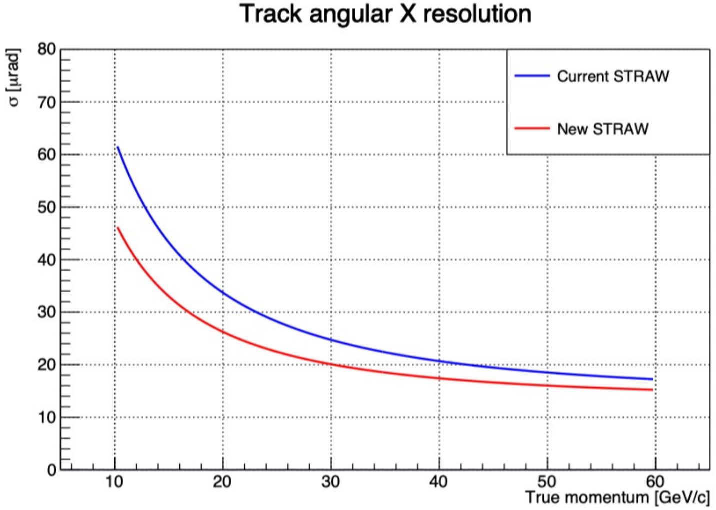
Same assumptions as in current NA62 layout:
- ✓ dimensions and positions of STRAW chambers
- ✓ number and orientation of views per chamber
- ✓ gas composition (Ar + CO_2 with 70:30 ratio)
- ✓ properties of dipole magnets



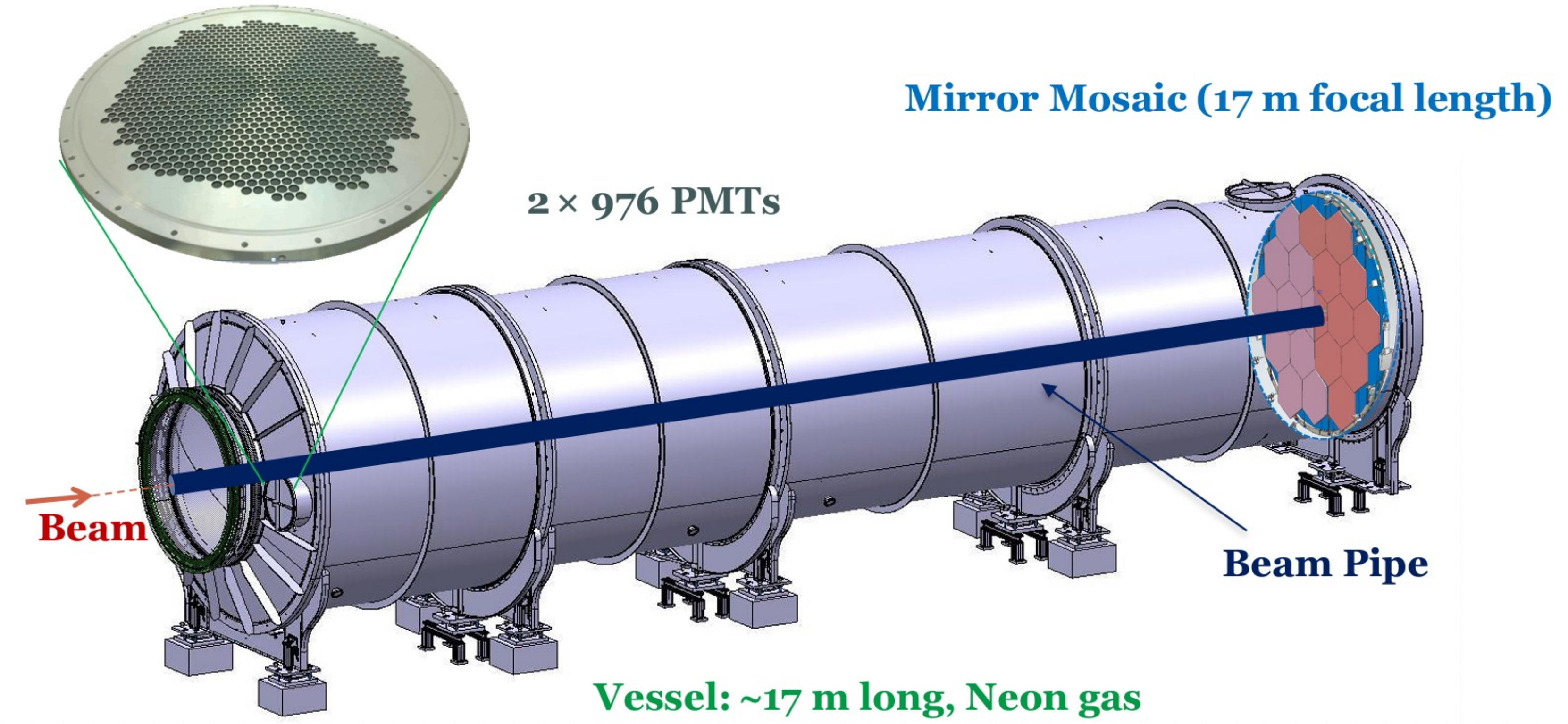
New straw chamber:
(left) front view; (right) tilted back view







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



The NA62 RICH in ECN3

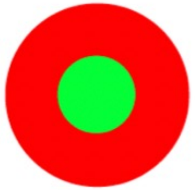
Pion identification with time resolution < 100 ps
Muon contamination< 1% in pion sample 15<p<35 GeV/c
Trigger signal for charged particles

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 HIKE Electromagnetic Calorimeter

Principal photon veto for $\boldsymbol{K^+} \rightarrow \boldsymbol{\pi^+ \nu \bar{\nu}}$ (Phase1); $\boldsymbol{\pi^0}$ reconstruction, PID, extra photon veto for $\boldsymbol{K_L} \rightarrow \boldsymbol{\pi^0 l^+ l^-}$ (Phase2)

Technical challenge: fast (~100ps) ECAL with excellent energy resolution and detection efficiency

NA62 Liquid Krypton calorimeter (from NA48):
quasi-homogeneous ionization calorimeter, $27X_0$ of LKr

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \qquad \sigma_t = \frac{2.5\ \text{ns}}{\sqrt{E}}$$

Photon detection efficiency: $1\text{-}\varepsilon < 10^{-5}$ for $E\gamma > 10$GeV
Time resolution $\sigma_t \sim 500$ ps for π^0 with $E_{\gamma\gamma} > 20$ GeV

HIKE @ 4x intensity (Phase1, Phase2):
- ✓ LKr energy resolution and detection efficiency could work
- ✓ Time & double pulse resolution needs improvement
- ✓ LKr infrastructure needs consolidation

NA62 LKr efficiency/energy resolution meet HIKE requirements, time/double pulse resolution needs to be 4x better

LKr cold bore r = 80 mm and start of sensitive volume r = 120 mm limits beam solid angle to $\Delta\theta < 0.3$ mrad → 40% less K_L flux (Phase2)

Baseline design calls for LKr to be replaced by new ECAL

The Main Electromagnetic Calorimeter (MEC)

Baseline option: Fine-sampling shashlyk based on PANDA forward EM calorimeter

Sampling: 0.275 mm Pb + 1.5 mm scintillator. Transverse module size: 55 x 55 mm^2

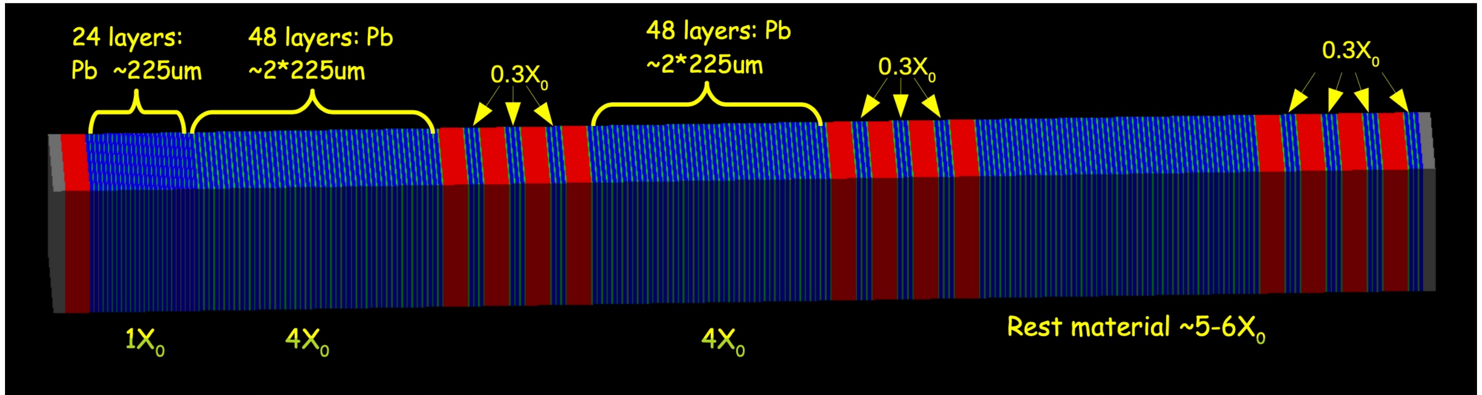
Composition: Moliere radius ~59mm, X_0 ~3.80 cm, sampling fraction ~39%

PANDA/KOPIO (16 X_0) prototypes:

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

HIKE: design and construct full-depth prototype (~25 X_0) for test beam in 2024

Same energy resolution as LKr, meet time resolution requirements for HIKE



New for Phase2: Longitudinal shower information from spy tiles

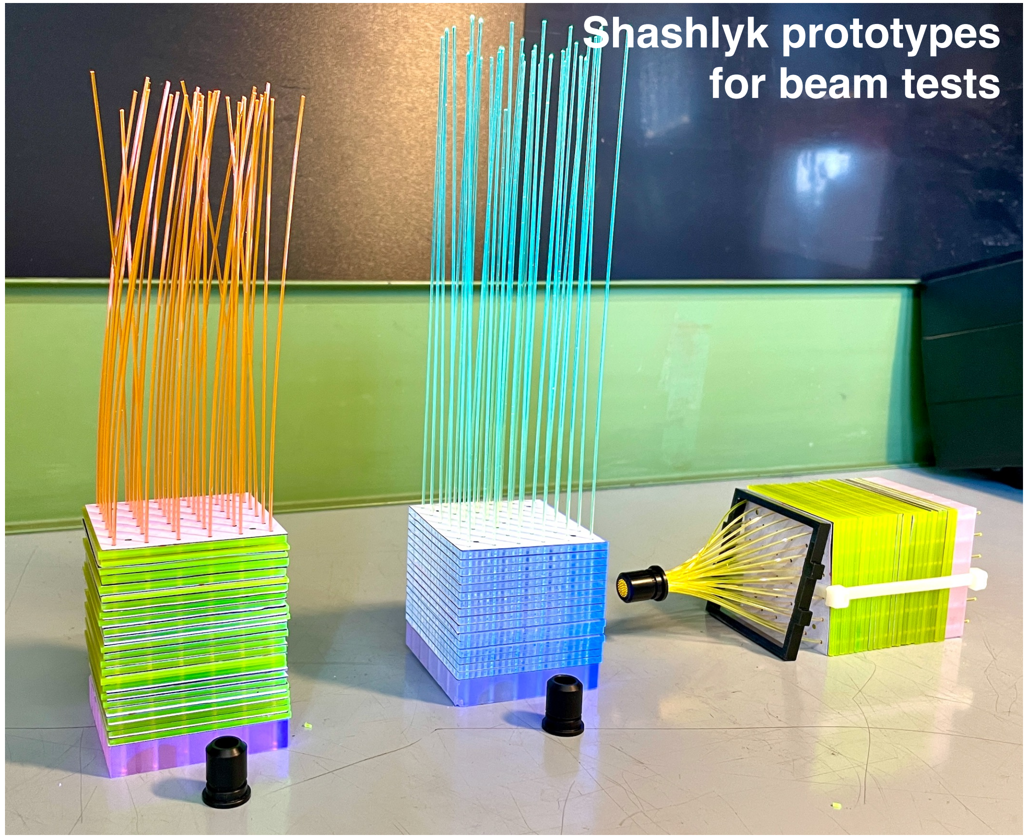
- PID additional info for γ/n separation
- 5-10x improvement in neutron rejection
- Overall neutron rejection at level of 10^3

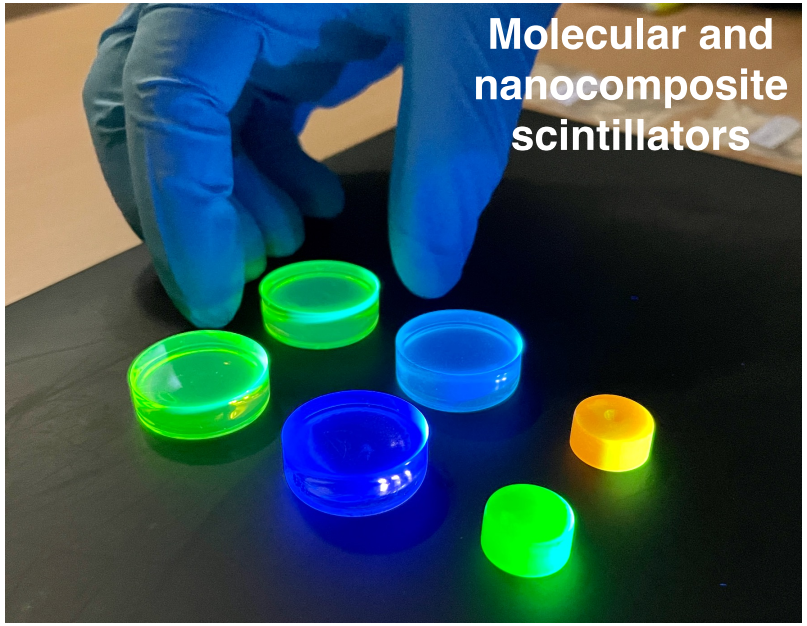
HIKE R&D on innovative scintillators

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)





Excellent candidates for HIKE shashlyk!

Potential applications for LAVs, 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

The HIKE Small Angle Calorimeter (SAC)

Veto of photons emitted at polar angle down to zero. Sensitive to photons escaping the detector through the downstream beam pipe. Hermetic small-angle photon veto for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (Phase1)

Technical challenge with HIKE neutral beam: particularly relevant for future phase with $K_L \rightarrow \pi^0 \nu\bar{\nu}$

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

HIKE neutral beam with production angle of 8mrad

Beam component	Rate (MHz)	Required 1 – ε
γ, E > 5 GeV	50	10^{-2}
γ, E > 30 GeV	2.5	10^{-4}
n	430	–

Requirements for HIKE SAC detector:

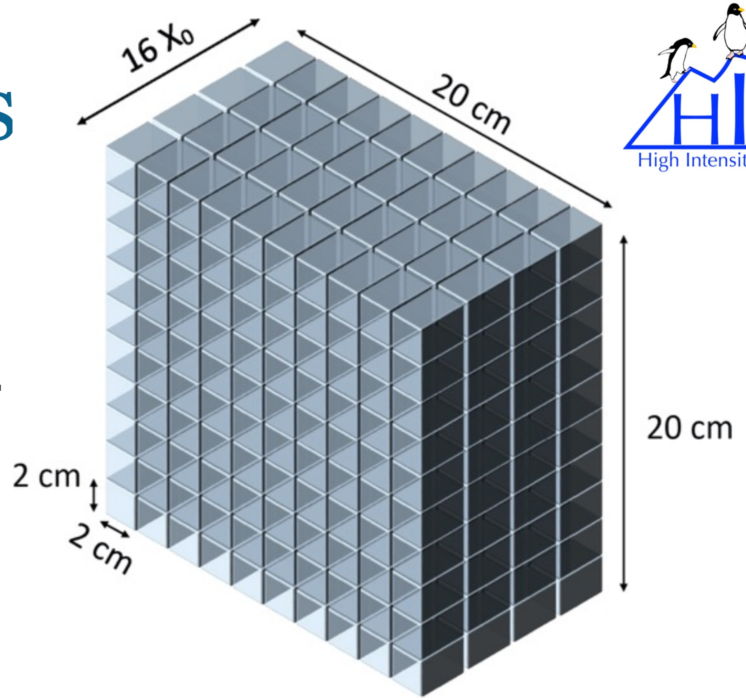
- ✓ nuclear interaction length much greater than radiation length ($\lambda_{int} >> X_0$)
- ✓ good transverse segmentation to provide γ/n discrimination
- ✓ additional information for offline γ/n (longitudinal segmentation, pulse-shape analysis,..)
- ✓ time resolution ~100 ps or less
- ✓ double-pulse resolution capability at the level of a few ns
- ✓ radiation tolerant (exp. exposure in 5 years of operation: 10^{14} 1MeV n_{eq}/cm^2 + 10^5 - 10^6 Gy from photons)

Small Angle Calorimeter with crystals

Proposed solution:

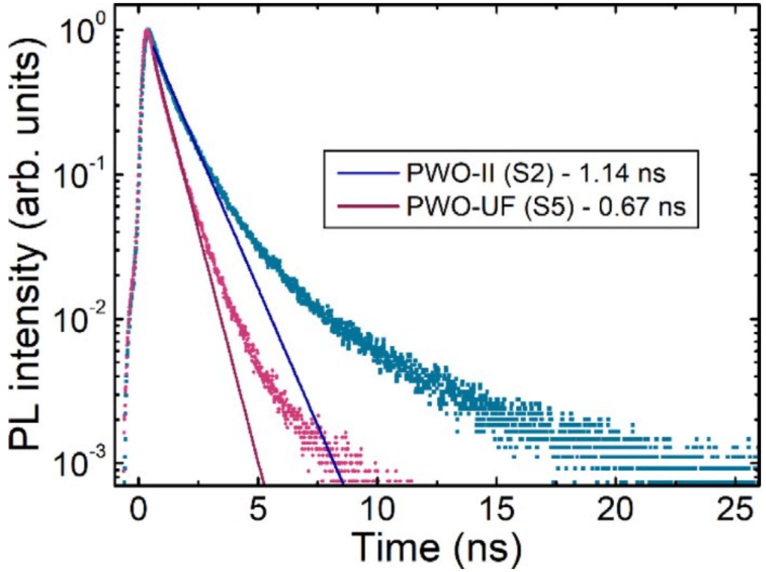
Ultra-fast, high-*Z* crystal calorimeter

- Cerenkov radiator like PbF_2 or ultra-fast scintillator such as **PWO-UF**
- Transverse and longitudinal segmentation for *γ/n* discrimination
- Exploit coherent interactions in crystals to reduce thickness

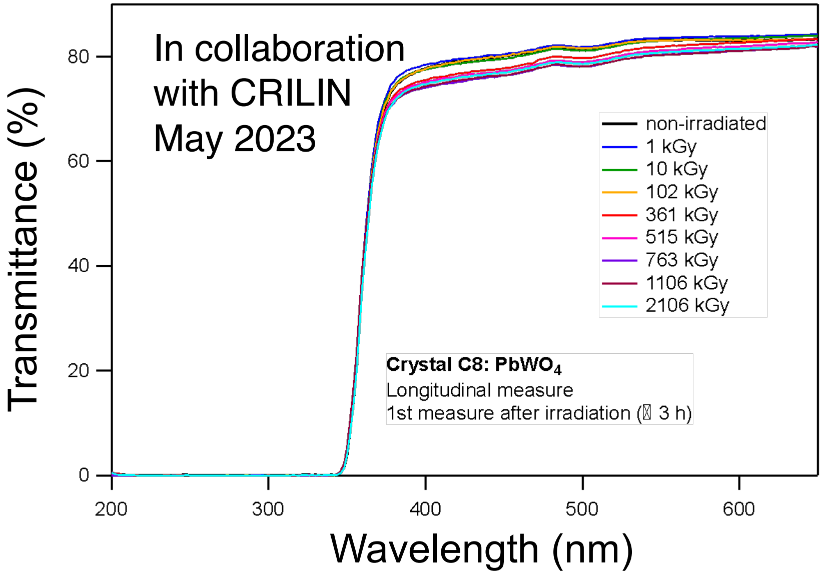


PWO-UF (ultra-fast): Dominant emission with $\tau < 0.7$ ns

M. Korzhik et al., NIMA 1034 (2022) 166781



Tests with ^{60}Co γ at Calliope (ENEA Casaccia)

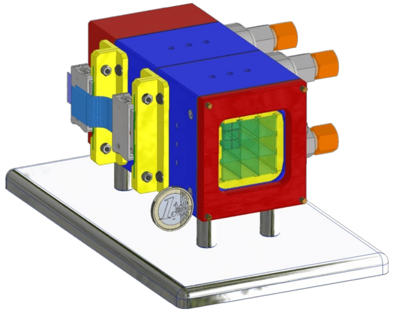


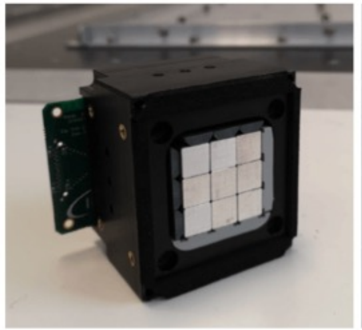
PWO-UF undamaged to 2106 kGy!

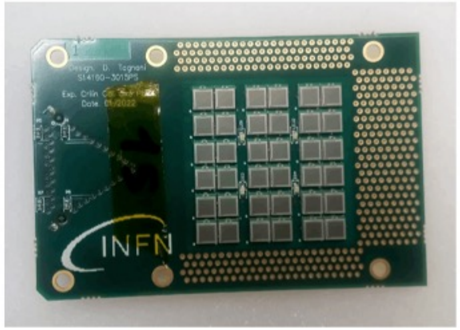
SAC R&D with CRILIN Prototype

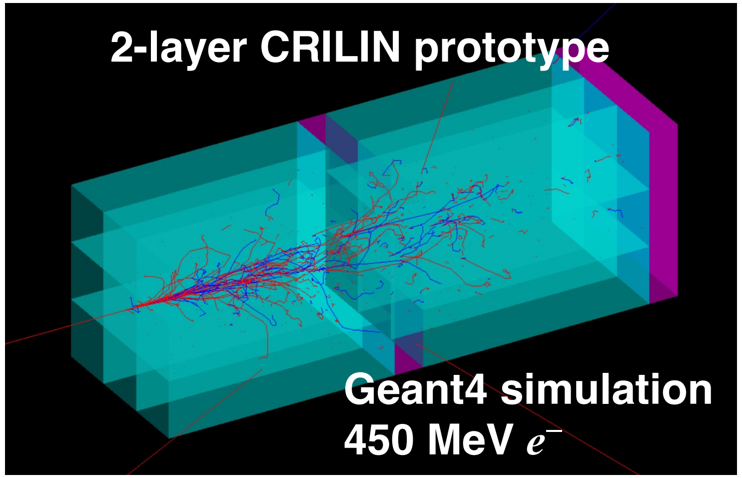
Collaboration with CRILIN to study:

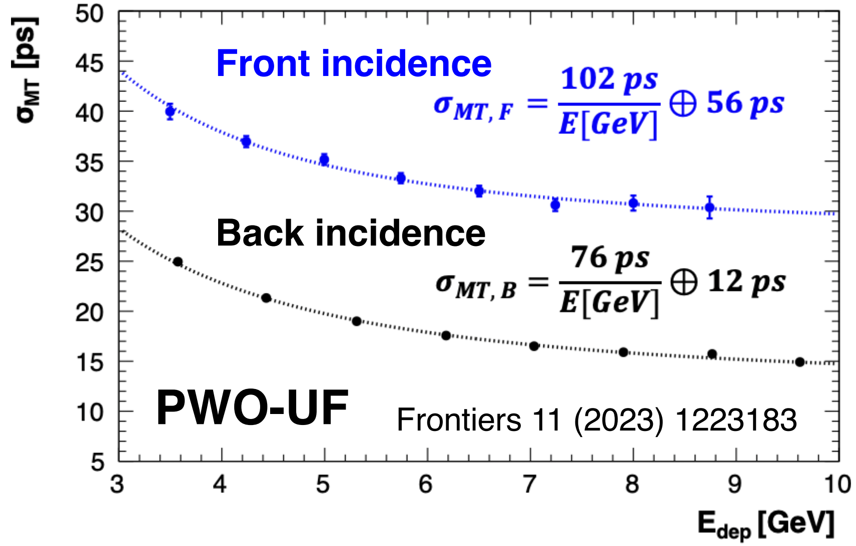
- Materials: PbF_2 vs PWO-UF
- Radiation resistance of crystals
- Photosensors: SiPMs, front-end
- Light collection in small crystals
- Longitudinal segmentation
- Mechanics, cooling, integration



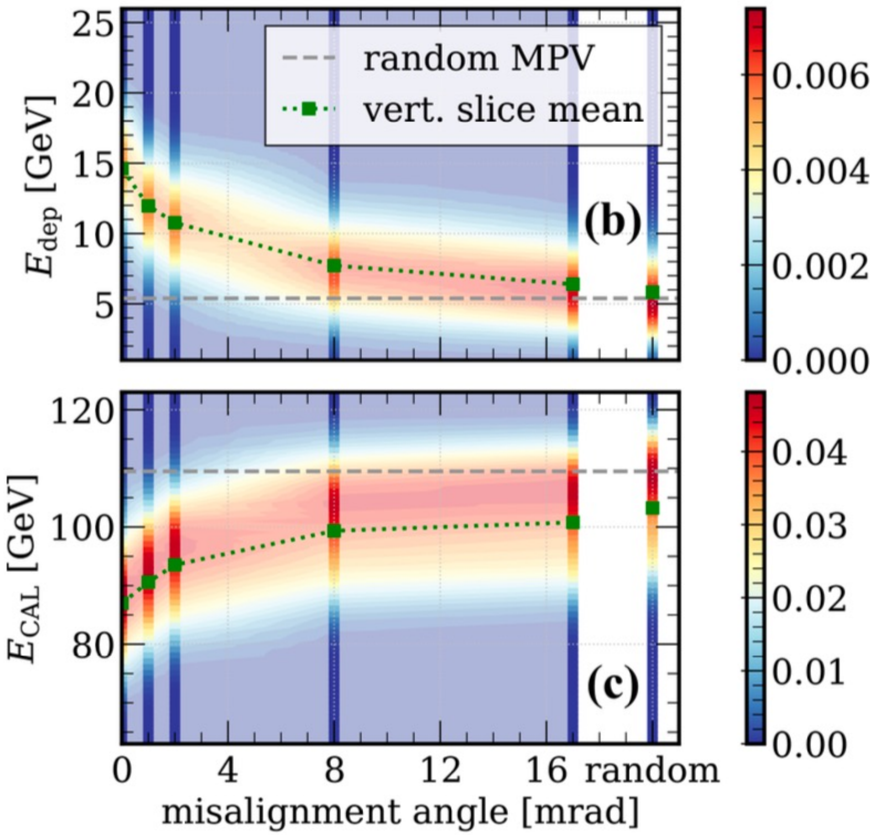








For single crystals of PWO-UF: σ_t **< 20 ps** for $E_{dep} > 5$ GeV!



STORM collab.
In preparation

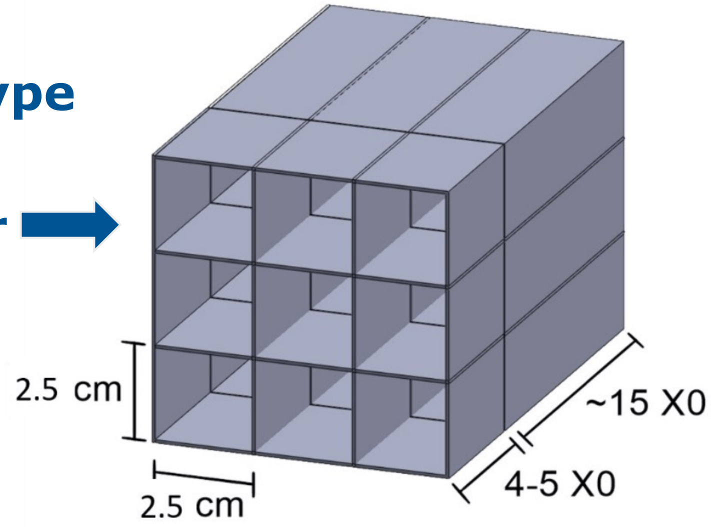
SAC R&D with aligned crystals

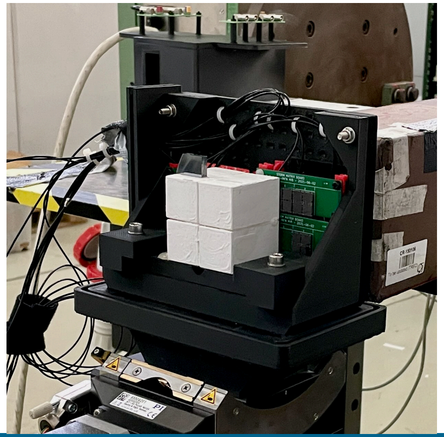
Exploit effects of coherent interactions in crystals to develop a highly compact calorimeter

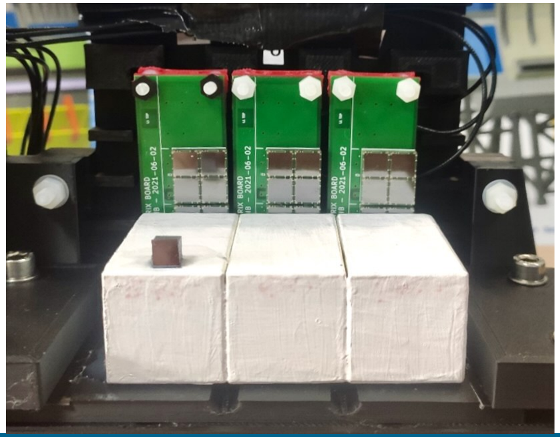
- Excellent response to photons (enhance probability for γ conversion)
- High transparency to neutrons for future phase with $K_L \to \pi^0 \nu \bar{\nu}$

OREO prototype

Aligned layer







OREO project for SAC R&D with aligned PWO-UF crystals:

- Develop techniques for crystal characterization, shaping, alignment and assembly
- Alignment of 1-dim and 2-dim matrices to < 0.5 mrad obtained

HIKE SAC design: combine elements of CRILIN and OREO prototypes, readout with compact PMTs

Summary - HIKE

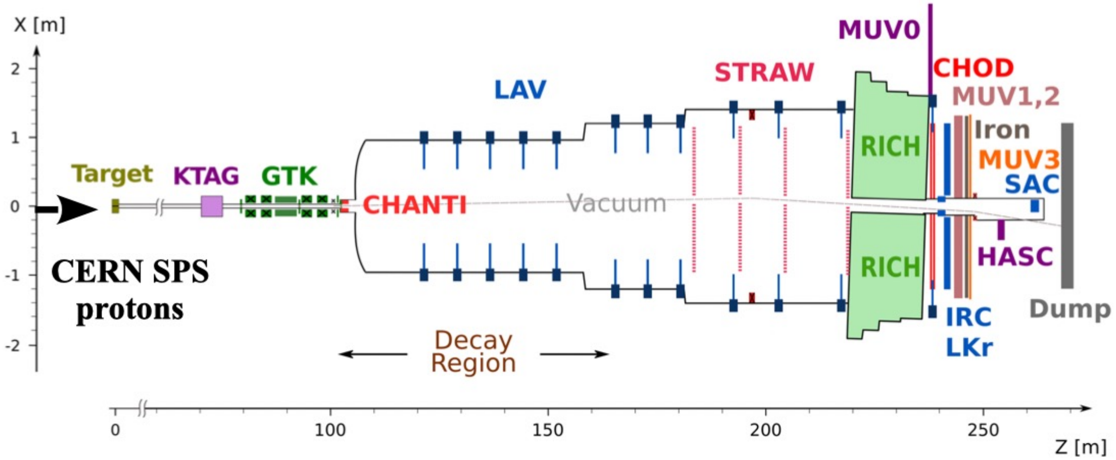
- HIKE propose a timely, broad and long-term HEP programme at the intensity frontier
- **HIKE Phase1 & 2: multi-observables of Flavour Physics at a new level of precision**
  - Main physics goals:
    - Measure BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) at 5% precision
    - Measure BR($K_L \rightarrow \pi^0 l^+ l^-$) at 20% precision
- **HIKE Phase1 & 2: 4x intensity increase wrt NA62 and cutting-edge detector technologies**
  - Build on NA62 experience:
    - Kaon decay-in-flight technique, NA62-like detector + major upgrades
    - Keep same (or better) performances at 4x intensity
- **HIKE Phase1 & 2: innovative R&Ds**
  - High-rate 4D silicon tracker & Super-thin STRAW spectrometer
  - MEC shashlik with innovative scintillators, SAC with oriented crystals

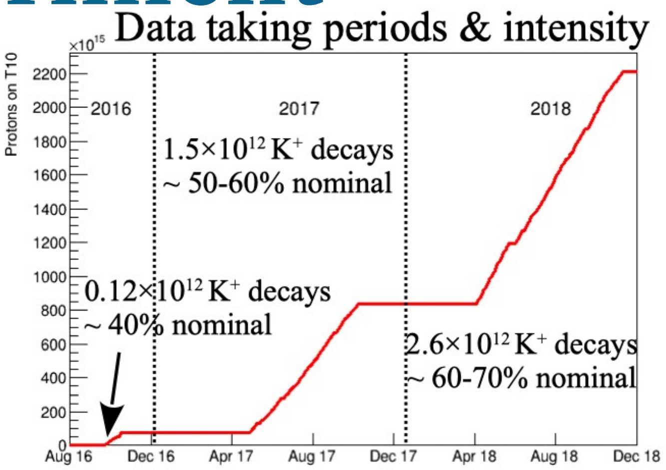
Only place worldwide where this programme is addressed experimentally
Unique and timely opportunity to address a strongly motivated physics case at CERN NA facility

High Intensity Kaon Experiments proposed for the ECN3

SPARES

The NA62 Experiment



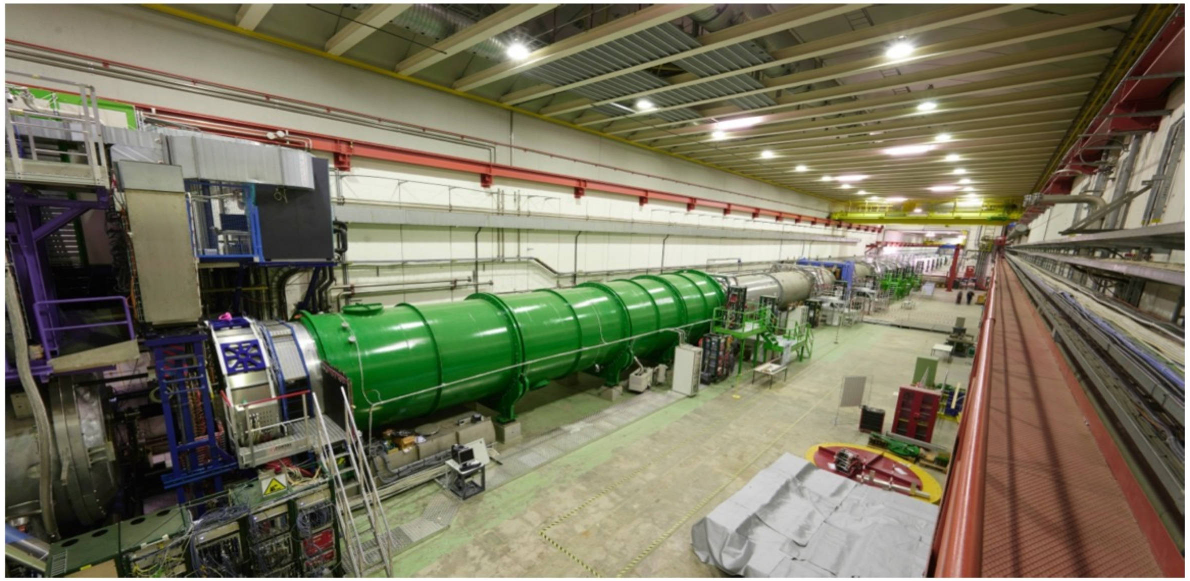


Nominal intensity: $\sim 3 \times 10^{12}$ POT/spill → 750 MHz hadron beam

Primary beam:
- 400 GeV CERN SPS protons

Secondary hadron beam:
- K^+ (6%) / π^+ (70%) / p (24%)
- p = 75 GeV, $\Delta p/p \sim 1\%$
- 60×30 mm^2 transverse size

Decay region:
- 60 m long fiducial volume
- Vacuum ~ $O(10^{-6}$ mbar)
- ~ 5 MHz K^+ decay rate

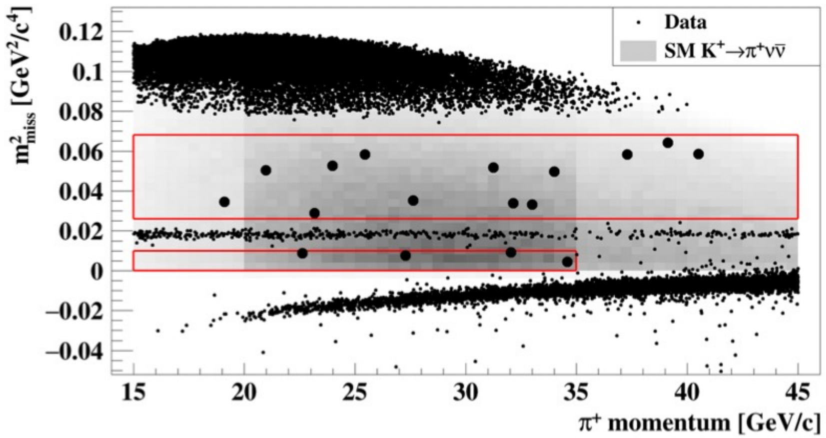


NA62 Run 1 (2016-2018) result

2018 data:

JHEP 06 (2021) 093

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$



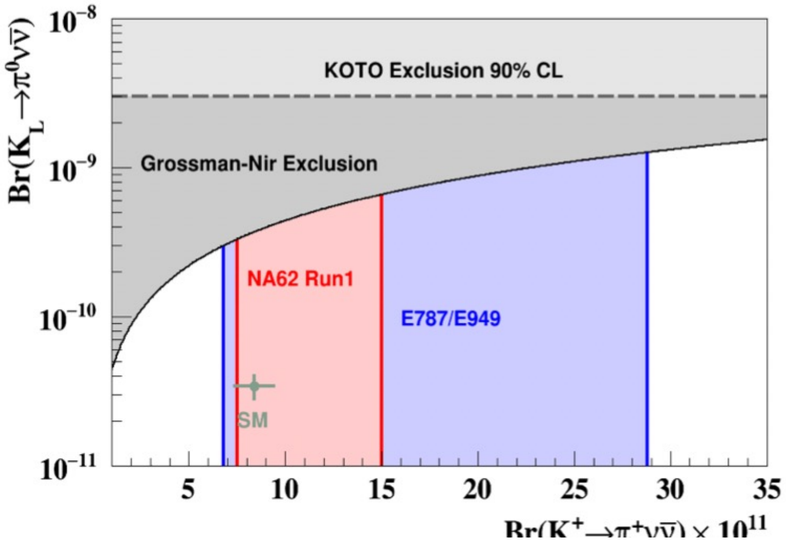
Expected: 7.6 signal + 5.4 background events
Observed: 17 $K^+ \to \pi^+\nu\bar{\nu}$ candidates!

Combined NA62 2016-2018 data

SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
Expected bkg: $7.03^{+1.05}_{-0.82}$
Observed: 20 (1+2+17) events

$BR(K^+\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}\,_{stat} \pm 0.9_{syst}) \times 10^{-11}$

3.4σ significance, most precise measurement to date!



NA62 Run 2 (2021-2025)

NA62 recommended by SPSC and approved by Research Board until LS3

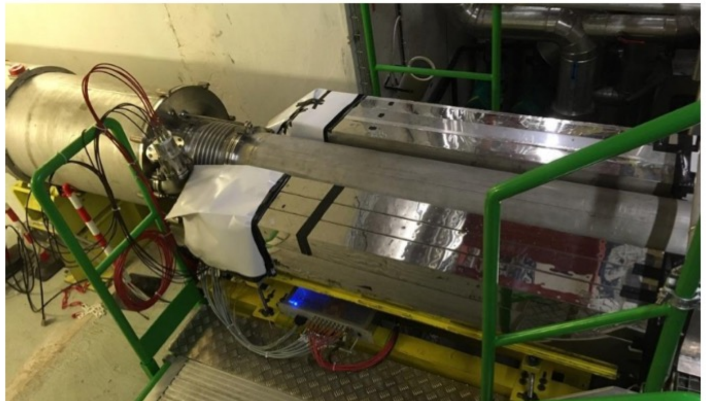
Improvements in NA62 Run2:

- DAQ stability improved: run at higher beam intensity (70% → 100%)
- Rearrangement of beamline elements around GTK achromat
- Added 4th station to GTK beam tracker
- Additional veto counters around beam pipe (both upstream/downstream the FV)
- New veto hodoscope upstream of decay volume (ANTI0)
- New hydrogen-filled Kaon identification detector (CEDAR-H) to reduce material along the beam line (since 2023)

New ANTI0

New upstream veto

New downstream veto



New CEDAR-H

The KOTO Experiment

Study of $K_L \to \pi^0 \nu\bar{\nu}$ @ JPARC 30GeV Main Ring

Goal is to observe few SM events

Primary 30 GeV/c protons on gold target

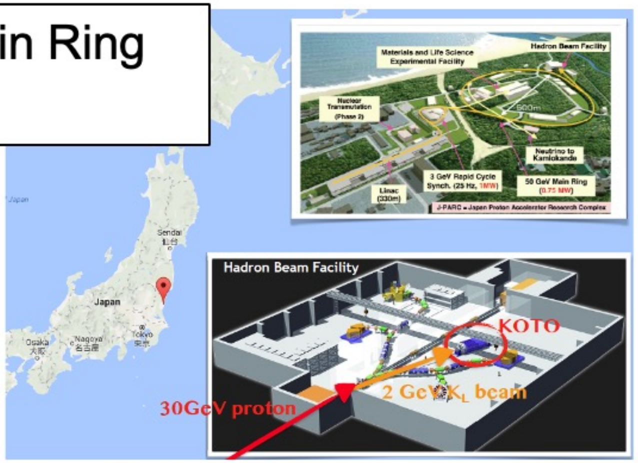
✔ Intensity in 2021: 60 kW = 6.6 x 10^{13} p/5.2 s

Secondary neutral beam (K_L, neutron, photons)

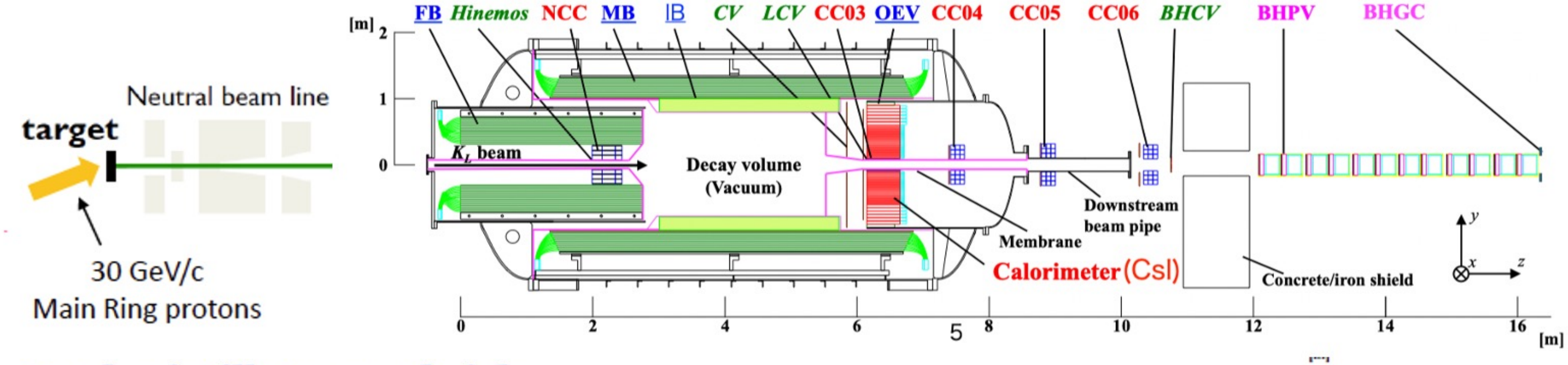
✔ beam angle ~16°, 8 μsr "pencil" beam

✔ <p(K_L)> = 2.1 GeV, 50% in [0.7-2.4] GeV/c range

✔ Fiducial decay region ~3 m



Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

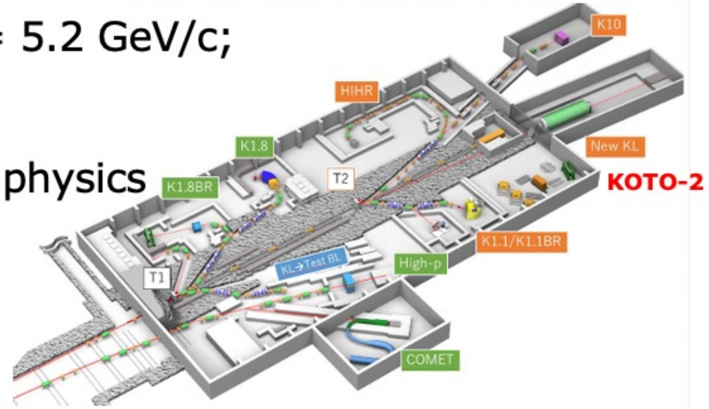


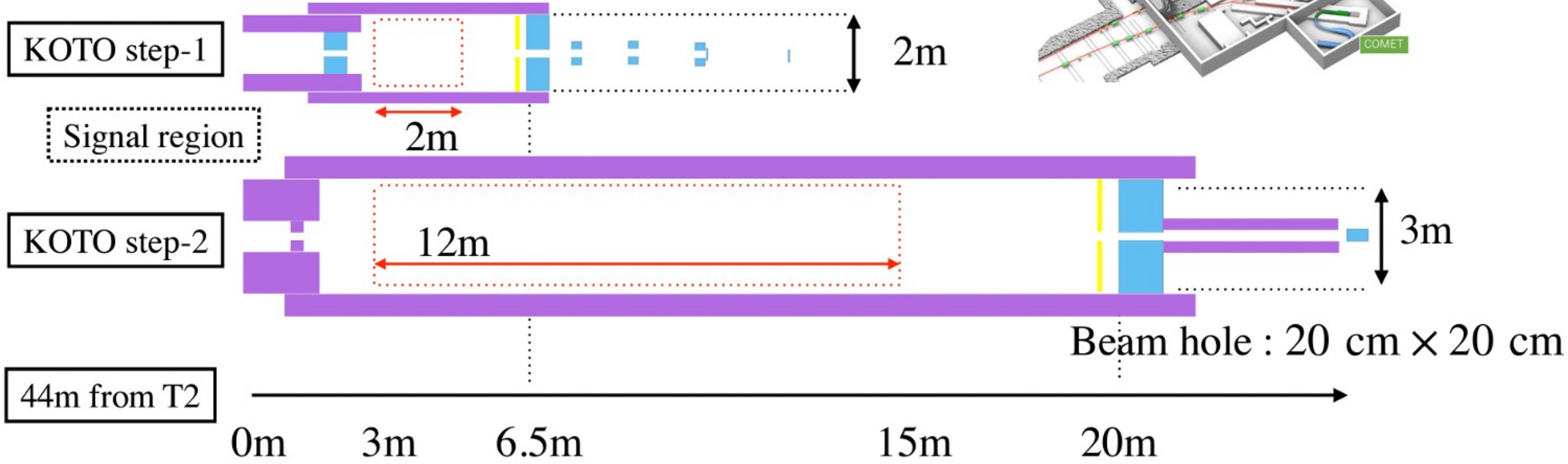
Lead-scintillator sandwich
Plastic scintillator counter
CsI Calorimeter from KTeV

Hermetic Veto Systems → To suppress $K_L \to \pi^0\pi^0$

KOTO Phase-II

- ✓ Upgrade to reach sensitivity $O(10^{-13})$
- ✓ Increase proton beam power → 100 kW;
- ✓ New neutral beamline at 5° → larger K_L yield, <p(KL)> = 5.2 GeV/c;
- ✓ Increase fiducial decay volume from 2m to 12m;
- ✓ Complete rebuild of the detector;
- ✓ Require hadron hall extension: joint project with nuclear physics community;
- ✓ Design work is in progress.





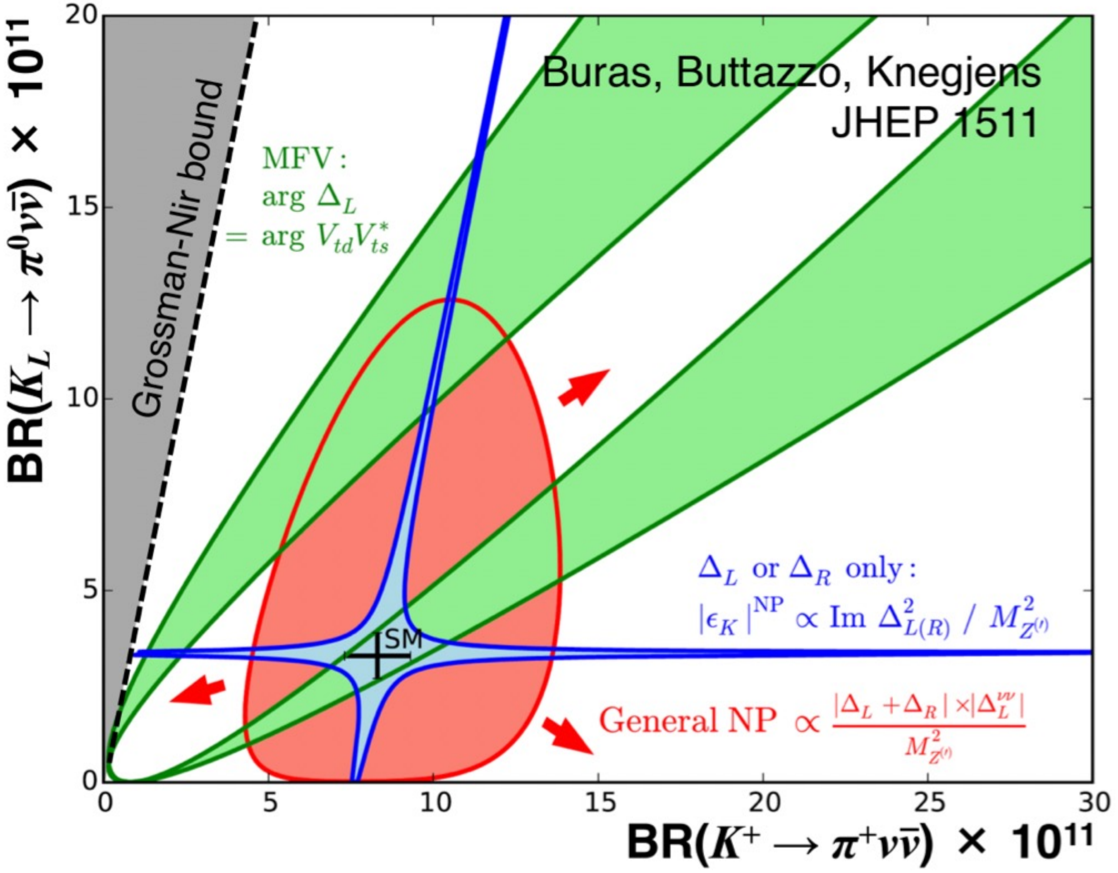
New sensitivity studies for smaller beam angle & larger detector: ~ 60 SM evts with S/B ~ 1 at 100 kW beam power (3×10^7 s)

KOTO Step-2: aim at ~5σ SM $K_L \rightarrow \pi^0 \nu\bar{\nu}$ discovery

$K^+ \to \pi\nu\bar{\nu}$: New Physics Scenarios

High Intensity Kaon Experiments

New physics affects K^+ and K_L BRs differently
Measurements of both can discriminate among NP scenarios



Models with:

- CKM-like flavor structure
  - MFV
- New flavor-violating interactions with dominant LH or RH couplings
  - Z/Z′ with pure LH/RH couplings
  - Littlest Higgs with T parity
- None of the above constraints
  - Randall-Sundrum

Grossman-Nir bound

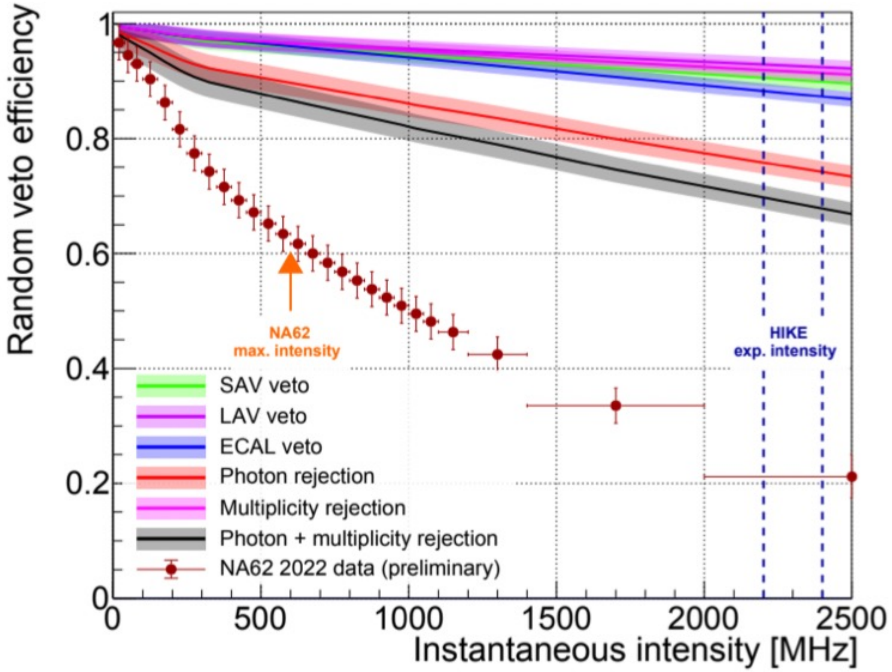
Model-independent relation

$$\frac{BR(K_L \to \pi^0\nu\bar{\nu})}{BR(K^+ \to \pi^+\nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

$K^+ \to \pi^+\nu\bar{\nu}$ at HIKE: Random Veto

Criteria to veto photons and extra activity in-time + pileup = intensity-dependent signal loss
Critical performance indicator: "random veto efficiency", measured on data (with $K^+ \to \mu^+\nu$)

NA62:
- Signal selection efficiency ~ 65% at max beam intensity
- Quasi-linear dependence on the instantaneous beam intensity.
- Limiting factor: timing precision of the detectors (and double pulse resolution).

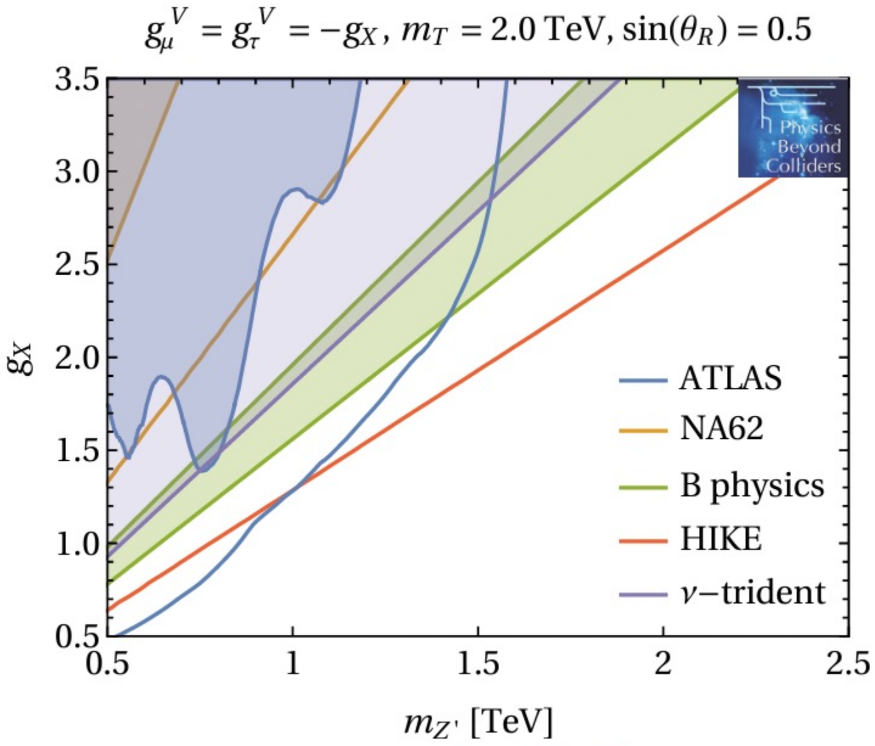


HIKE: Maintain or improve the random-veto efficiency.
→ Requires an improvement in the time resolution for the veto systems at least by the same factor as the intensity increase

$K^+ \to \pi^+ \nu\bar{\nu}$ at HIKE: Specific Models

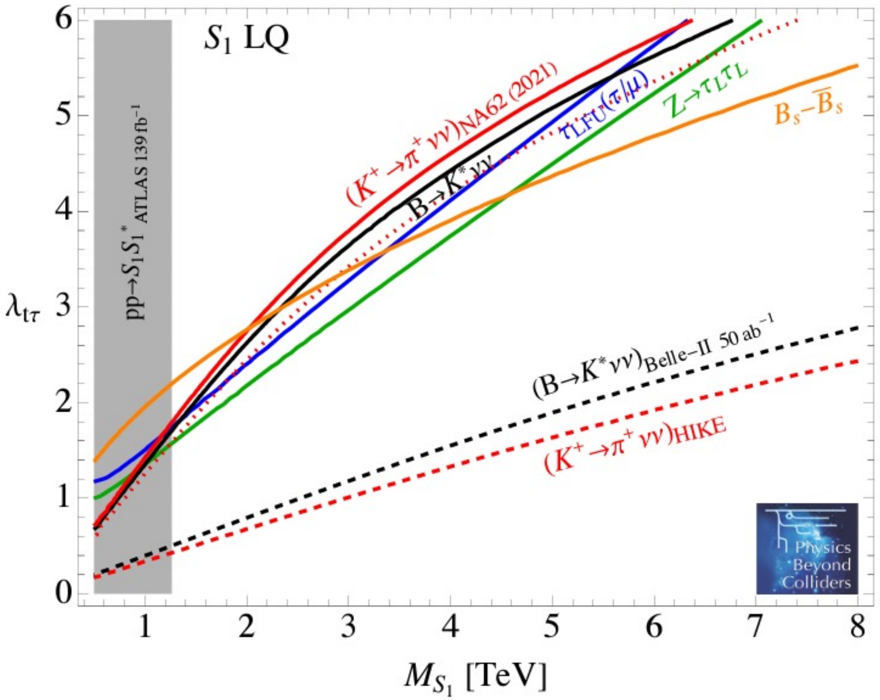
High Intensity Kaon Experiments

arXiv:2310.17726]



Top-philic Z':
(revisited by
F. Kahlhoefer)

Constraints on a top-philic Z', on mass vs gauge coupling, see Refs. [JHEP 03 (2018) 074, Phys. Rev. D 97 (2018) 035002]. Assumed vector couplings to muons and tau leptons, and couplings to top quarks induced via mixing with a vector-like quark with mass 2 TeV and mixing angle 0.5. Lepton couplings are chosen such that various anomalies in b → s transitions can be fitted (green shaded region). Blue shaded regions (blue lines) indicate the current exclusion with 139 fb^{-1} (projection for 3 ab^{-1}) for ATLAS.



Leptoquark model:
(revisited by
D.Marzocca)

Constraints on coupling of S1 leptoquark from flavour and electroweak observables vs leptoquark mass. Region above each line is excluded at 95%CL. Constraints are derived using the complete one-loop matching of this leptoquark to the SMEFT derived in Ref. [JHEP 07 (2020) 225] following the pheno analysis of Refs. [JHEP 01 (2021) 138, Eur. Phys. J. C 82 (2022) 320].

$K^+ \to \pi^+ l^+ l^-$ at HIKE Phase 1

LD dominated, mediated by $K^+ \to \pi^+ \gamma^*$

$$d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

$z = m(l^+ l^-)^2 / M_K^2$ | Form factors (FF) (non pert. QCD) | $K_{3\pi}$ loop term

Long-distance effects are purely universal

$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td} V_{ts}^* (C_9^\mu - C_9^e)\right]$$

[JHEP 02 049 (2019), PRD 93 074038 (2016)]

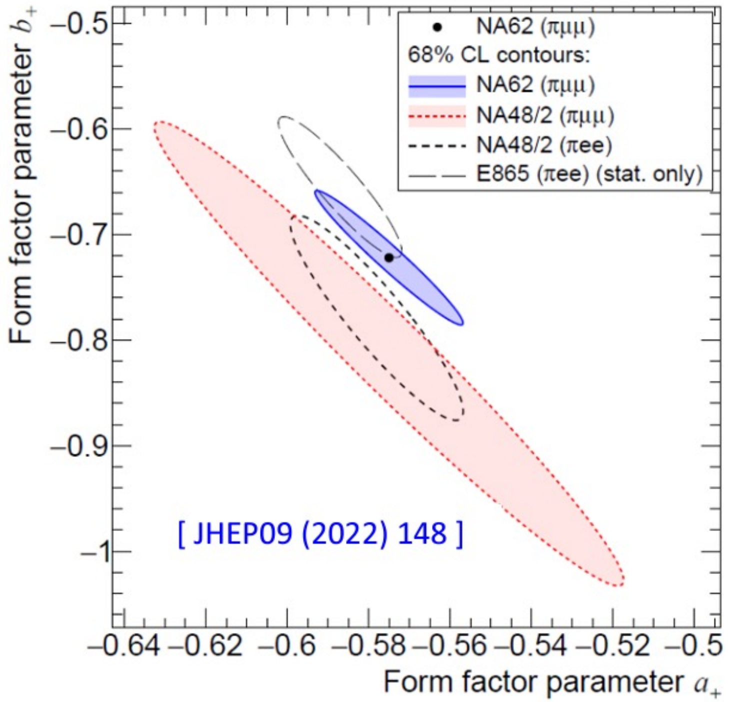
Long-distance contribution to the difference cancels out and is sensitive only to short-distance effects

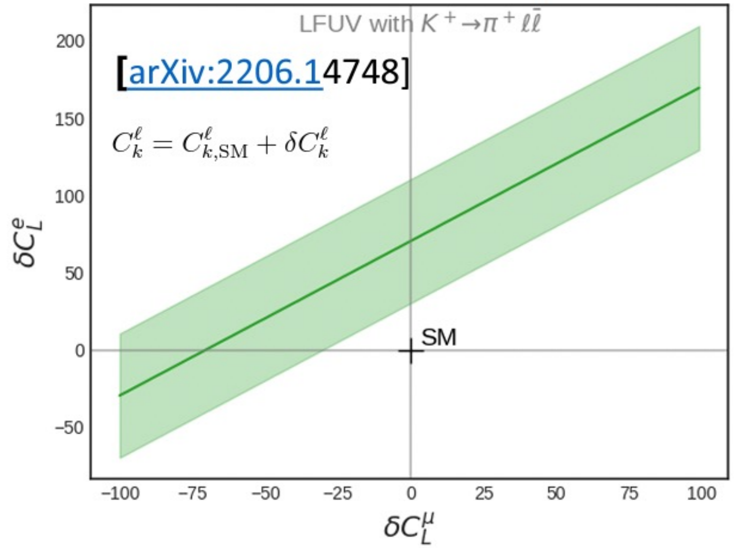
Lepton universitality (LU) predicts same a, b for $l = e, \mu$

HIKE Phase 1: Collect > 5x10⁵ background-free $K^+ \to \pi^+ l^+ l^-$

Measure Δa and Δb to ±0.007 and ±0.015 precision

Sensitivity also to many radiative decays of interest, i.e $K^+ \to \pi^+ \gamma\gamma$ precision of few per mille

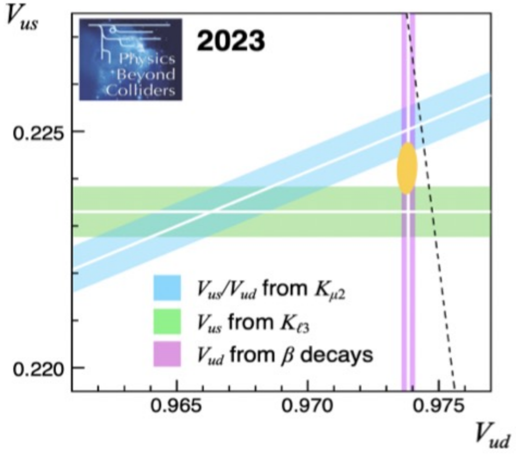


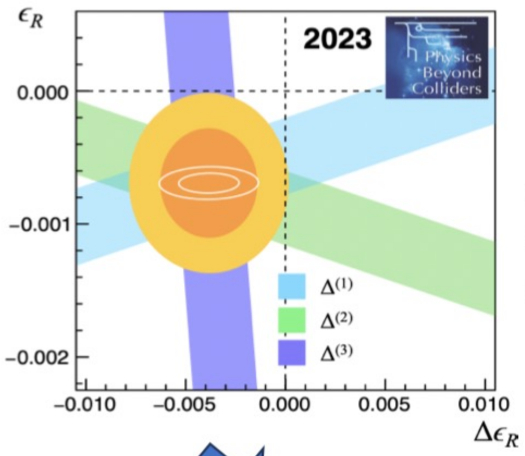


HIKE: Cabibbo Angle Anomaly

Disagreement leads to (apparent?) violation of CKM unitarity:

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$



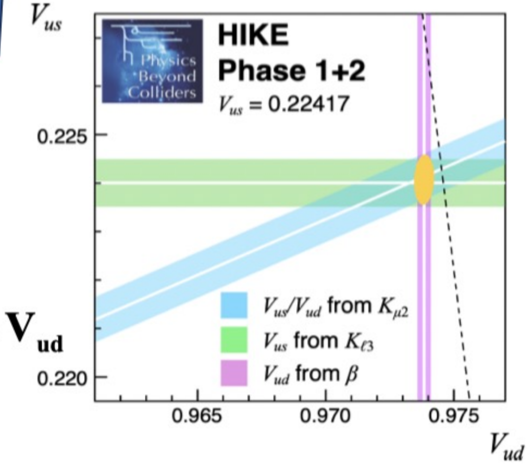


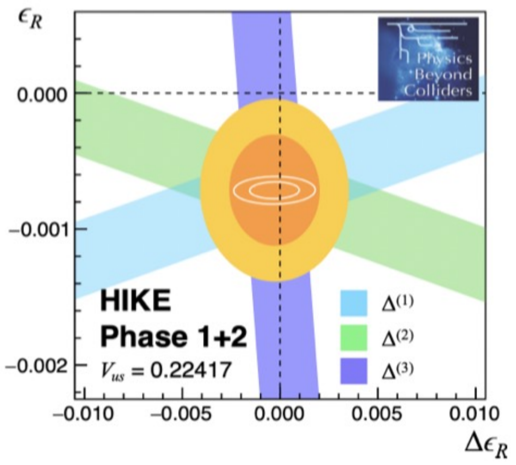
V_{us} from kaon and tau decays,
V_{ud} from super-allowed beta decays

Constraints from CKM unitarity on the contributions to the leptonic and semileptonic kaon decay amplitudes from right-handed quark currents

<u>HIKE can clarify the origin of the Cabibbo angle anomaly</u>

In the scenario illustrated,
HIKE resolves tension between $K_{\mu 2}$ and K_{l3} but confirms anomaly due to V_{ud}

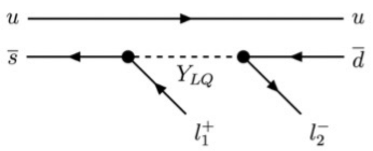




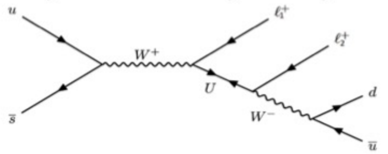
HIKE: LNV/LFV Decays

<u>Lepton Number/Flavor Violation</u>: many decay modes, forbidden in SM

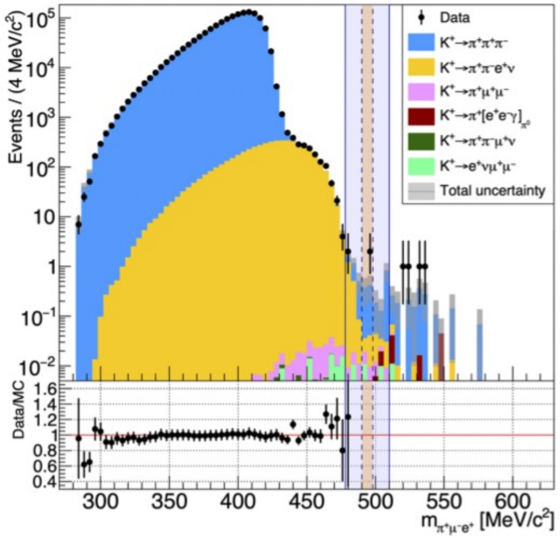
LFV possibly mediated by leptoquark:



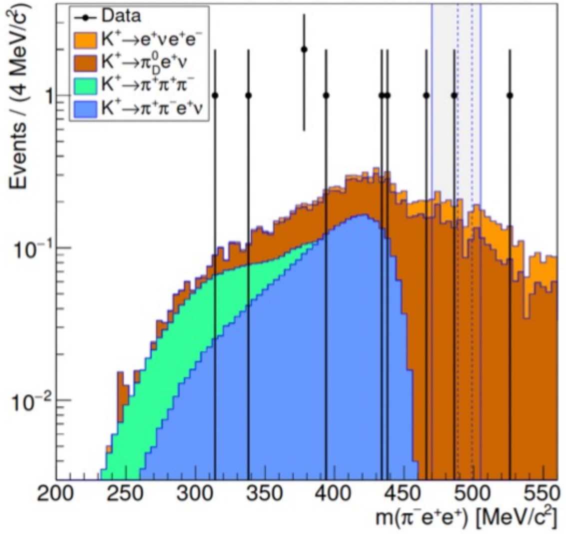
LNV possibly mediated by a Majorana neutrino:



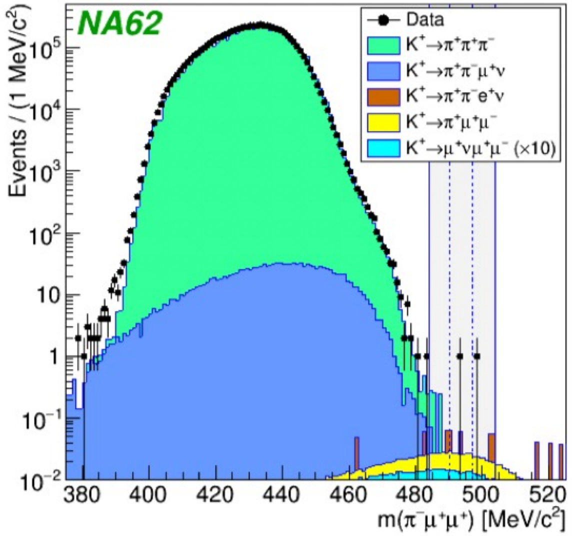
$K^+ \to \pi\mu e$ [PRL127(2021)131802]



$K^+ \to \pi^- e^+ e^+$ [PLB830(2022)137172]



$K^+ \to \pi^- \mu^+ \mu^+$ [PLB797(2019)134794]



NA62: $O(10^{-11})$ limits on BR of LNV/LFV K^+ decays

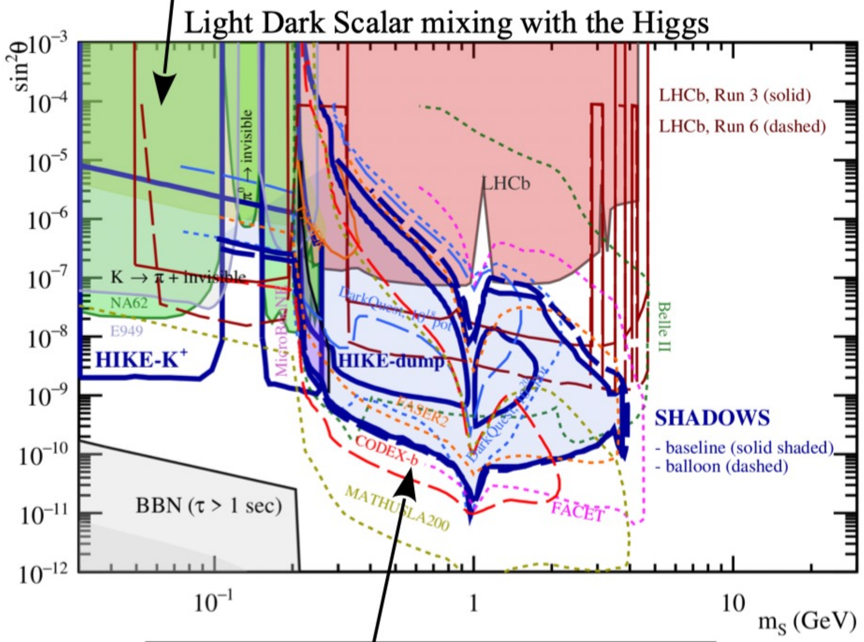
$[K^+ \to \pi^-(\pi^0)\ell_1^+\ell_2^+, K^+ \to \pi\mu e, K^+ \to \pi^-(\pi^0)\ell_1^-\nu\ell_2^+\ell_2^+, \pi^0 \to \mu e, \ldots]$

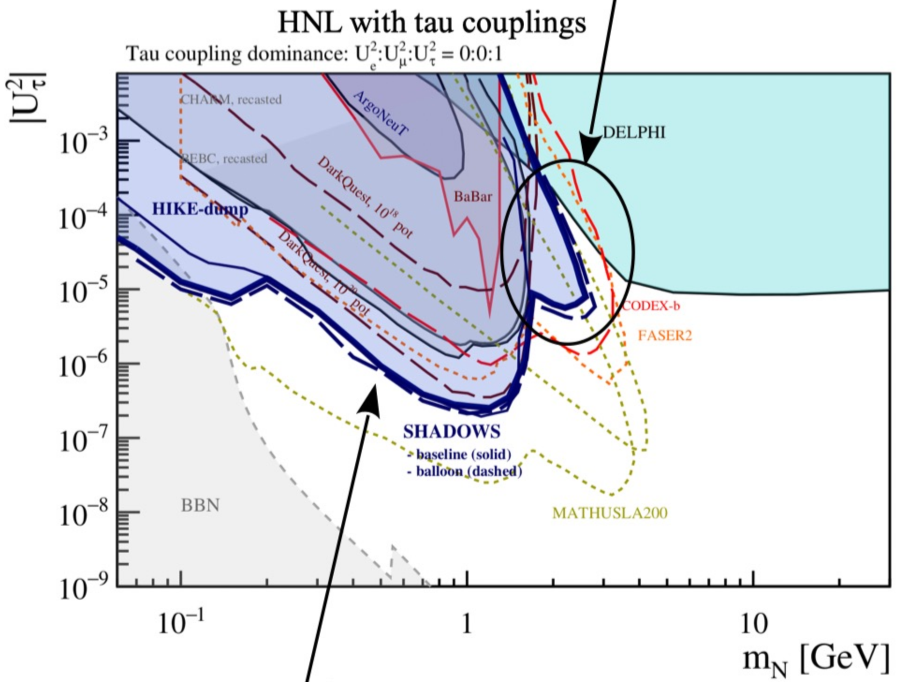
HIKE: $O(10^{-12}$-$10^{-13})$ sensitivity on BR of LNV/LFV K^+ and K_L decays

HIKE + SHADOWS: Dark Sector reach

SHADOWS fully complementary to HIKE-phase 1 (kaon mode), that improves by about one order of magnitude below the kaon mass.

Between D and B thresholds SHADOWS improves by two orders of magnitude over the existing experimental bounds (DELPHI)





Between di-muon threshold and ~4 GeV: **SHADOWS can improve by three orders of magnitude over the existing bounds** (mostly LHCb)

From few MeVs up to D threshold: **SHADOWS improves by two-four orders of magnitude over the existing experimental bounds (ArgoNeut & BaBar) and is better than DarkQuest, CODEX-b and FASER2.**

Worldwide landscape from FIPs2022 Proceedings [arXiv:2305.01715, accepted by EPJC]

3×10^{19} POT in kaon mode
5×10^{19} POT in dump mode

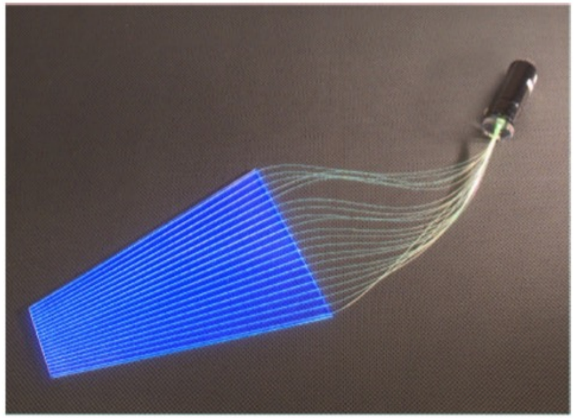
Large-Angle Photon Veto

12 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** (inefficiency < few 10^{-4} for E > 100 MeV)
- **Full digitization, segmentation in depth**

Baseline technology for HIKE:

- Lead/scintillator tile with WLS readout
  1 mm Pb + 5 mm scintillator
- Light read out with SiPM arrays



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

Hadronic Calorimeter

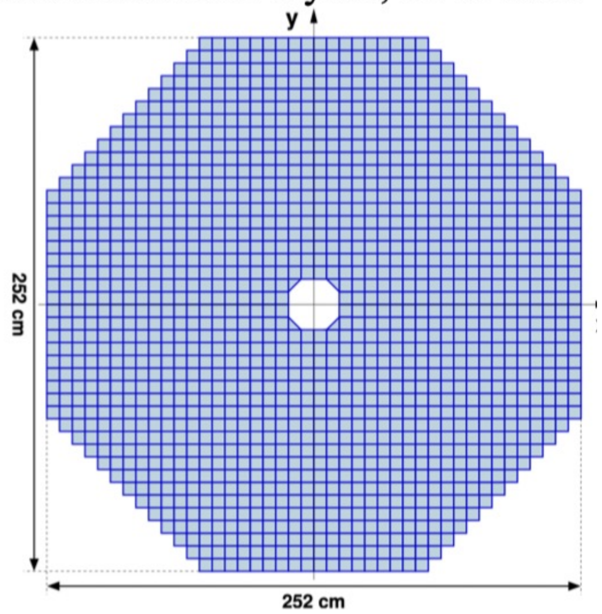
HCAL: main detector for π/μ identification and separation
(including catastrophically interacting muons,
which deposit all or large fraction of their energy in the calorimeter)

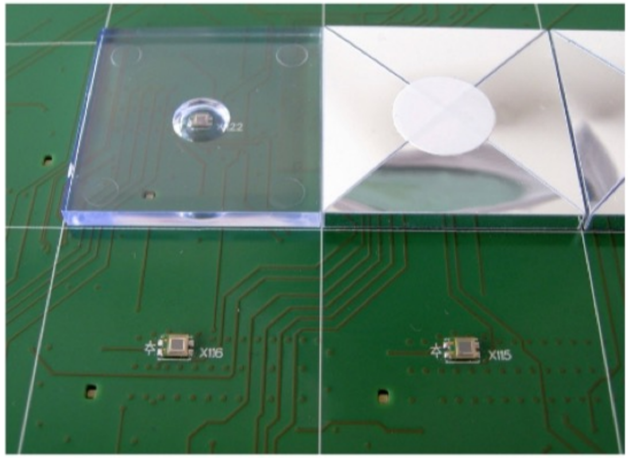
NA62 HAC: Horizontal/Vertical scintillator strips

HIKE HAC: Cellular layout
Reduce rate on each channel & improve time resolution

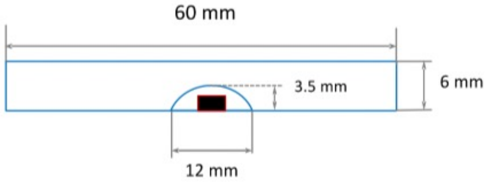
Iron-scintillator sandwich design
active layers built from scintillating tiles readout by SiPMs

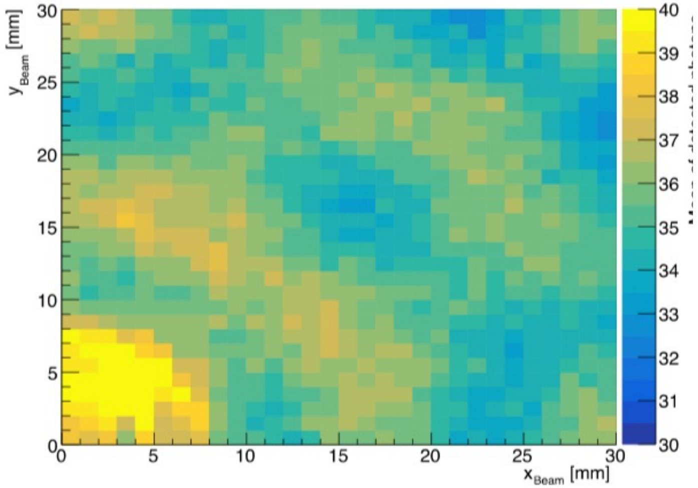
Transverse HCAL layout, 1440 cells



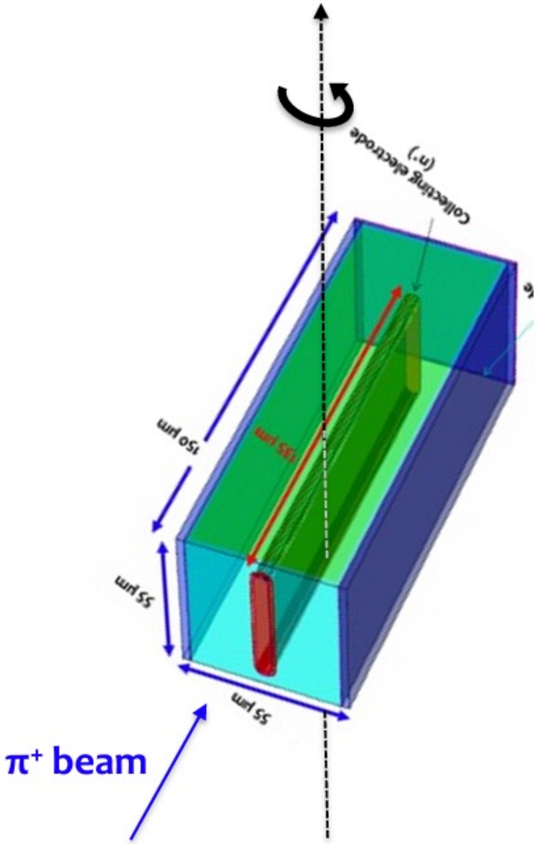


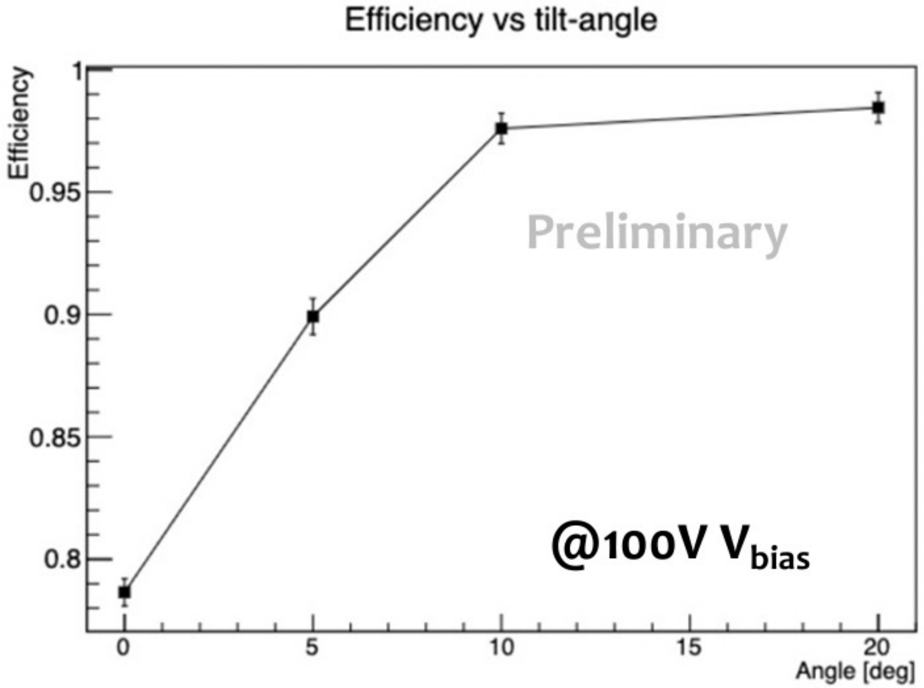
High-Granularity Calorimeter

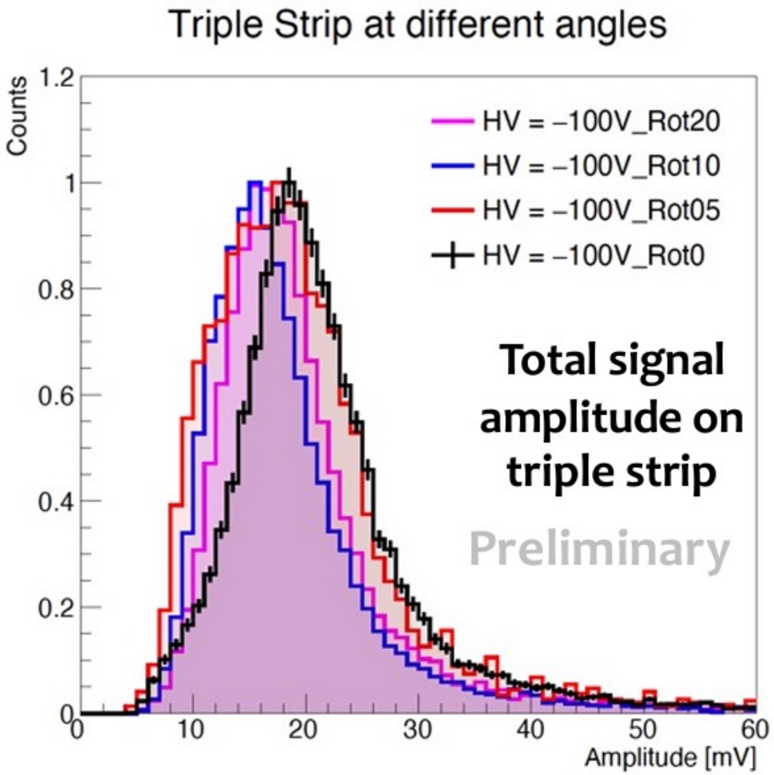




Efficiency: results







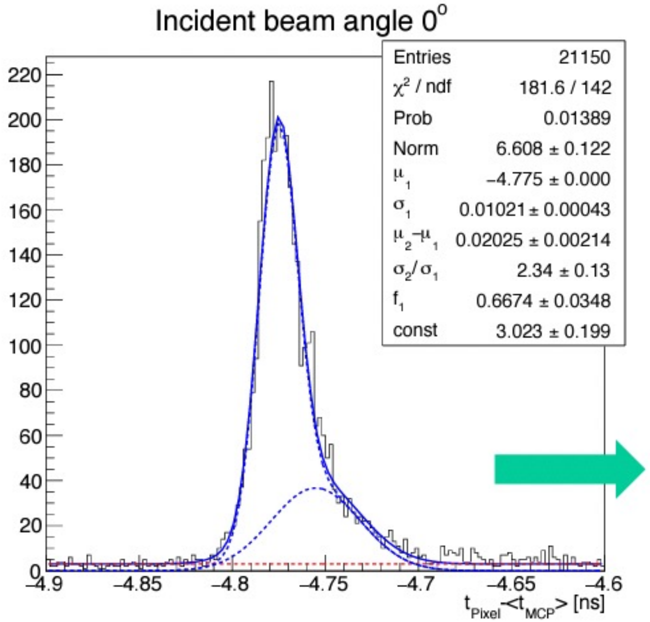
The inefficiency (at normal incidence) due to the 3D pixel dead-area of the trenches is fully recovered by tilting the sensors around the trench axis at angles larger than 10°

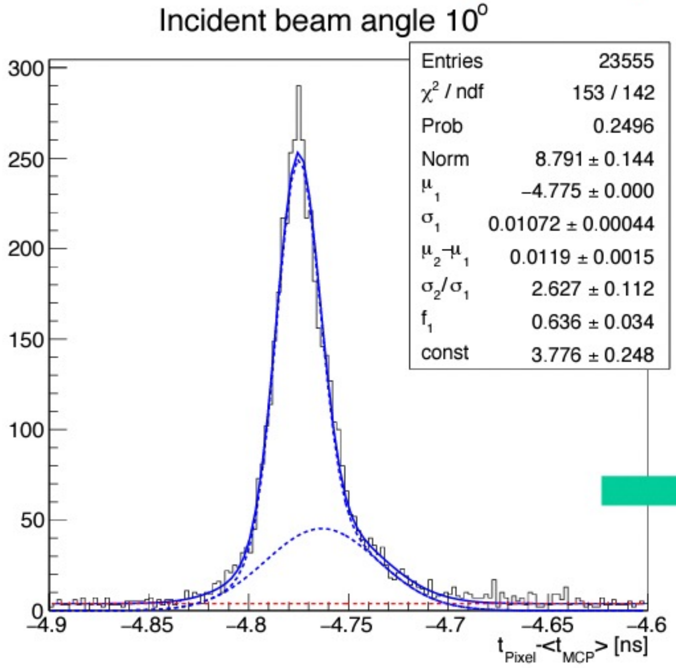
Effect of tilting on distribution shapes

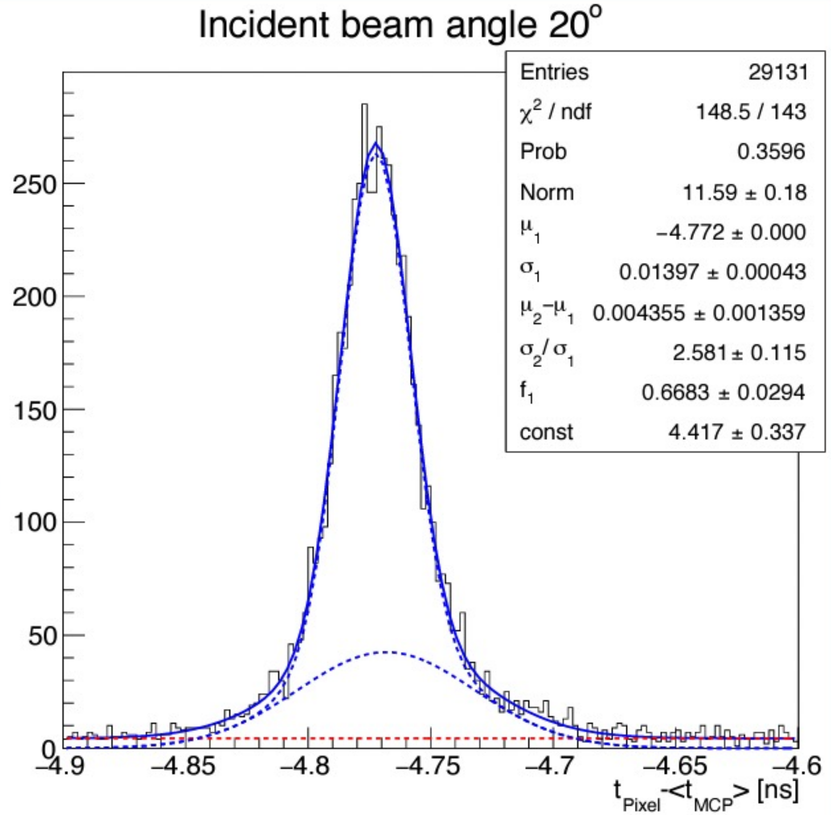
Spline method, SPS/H8 (Nov'21)

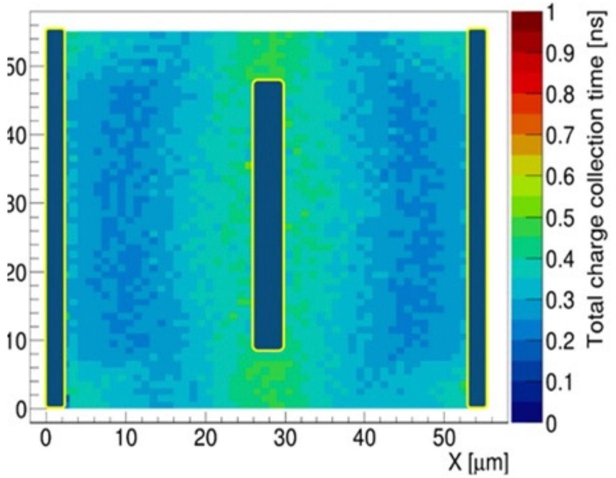
Single Pixel @ 50V

TimeSPOT results – A. Lai – 1st MONOLITH Wshop – UniGeneve, 5-6th September 2022









Simulated CCT map of a single 3D-trench sensor pixel scan (α_{tilt} = 0°)

Tilting has the effect of «mixing up» the fast and less-fast regions of the pixels, thus uniforming the timing response

As a result, the shapes are more Gaussian at increasing α_{tilt}

Notice that, due to detection efficiency, α_{tilt} = 20° is the normal working condition of a 3D in a detecting system

Timespot 1 28 nm CMOS ASIC

- First prototype: 28 nm CMOS pixel read-out ASIC for tracking at high rates
- Pixel matrix of 32×32 elements, with a pixel pitch of 55 μm
- Each pixel contains an analogue, digital circuit and TDC
- Digitised signals sent out via 8 multiplexed output links at 1.28 Gb/s speed

- On-going efforts to scale the size of the ASIC
  → aim: to reach an integrated ASIC of 2 cm^2 by 2026
- ASIC power consumption <1.5 W/cm^2 comparable to GTK
  → GTK cooling system could be reemployed
- Chip and sensor production made by FBK
  → original design by the TimeSPOT project

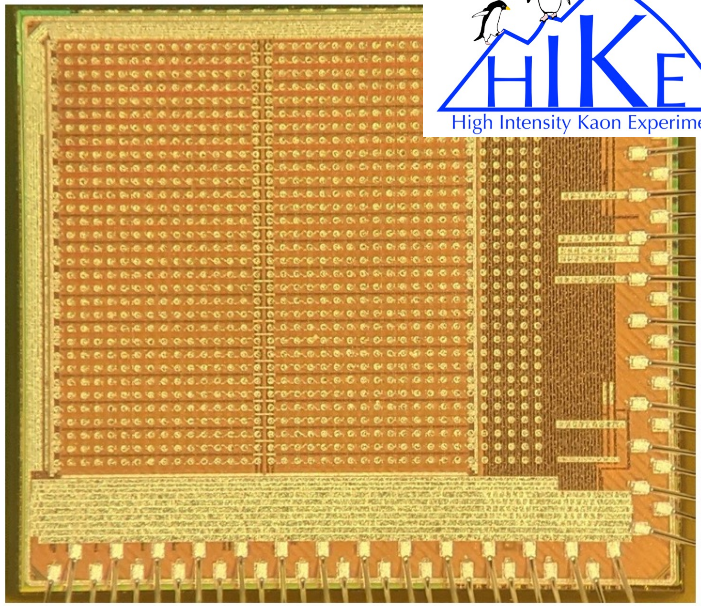
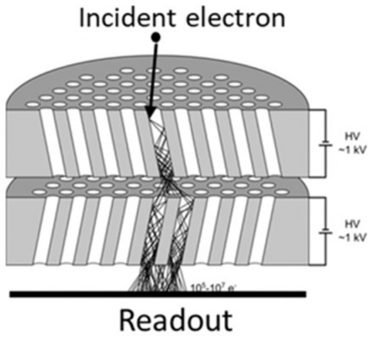


Figure 9. Photograph of the Timespot1 silicon die.

All the above considerations make TimeSPOT with its ASIC Timespot1 a viable option for the HIKE beam tracker

Micro Channel Plate MCP-PMT

Operating principle of MCP electron amplifier



DOI: 10.1109/NSS/MIC42677.2020.9507831

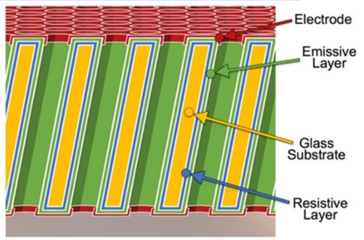
High-speed single photon counting applications <50ps TTS (FWHM)

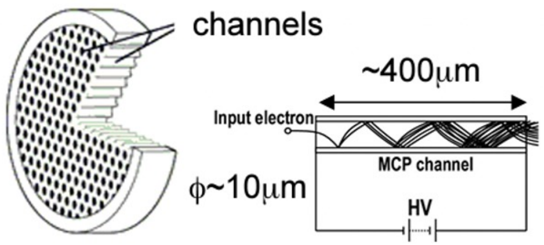
- Similar to PMT → dynode structure replaced by MCP
- MCP is thin glass plate with an array of holes (capillaries) of 3-25μm diameter
- Continuous electron multiplication in thin glass capillaries
- High gain (10^6) even in strong magnetic field (1T)

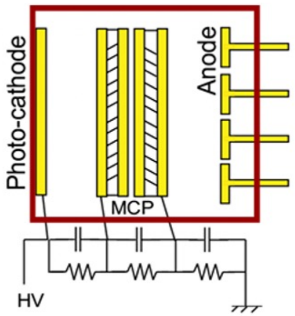
Limitations:

1. Photo Cathode aging (feedback ions)
2. Rate capability (τ=RC)

ALD Coating







Atomic Layer Deposition (ALD) coated MCP

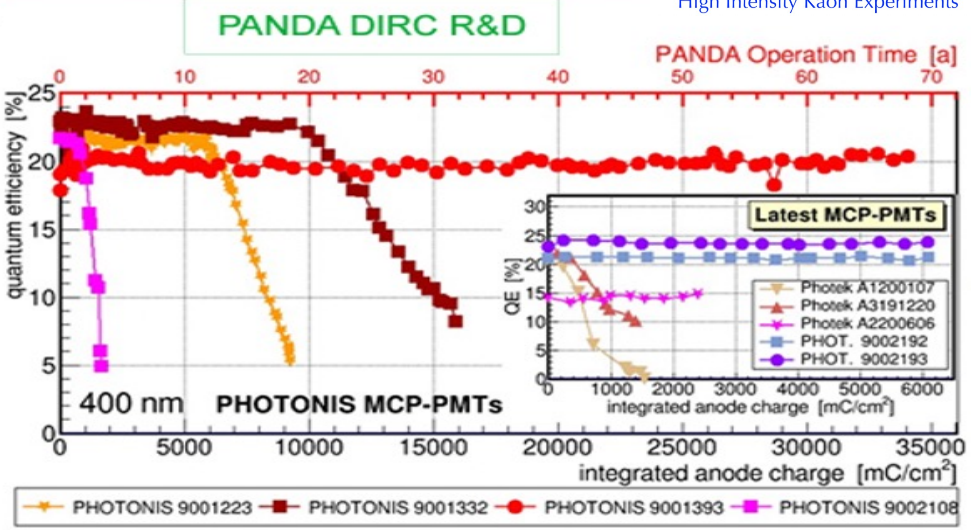
- Ultra-thin films of resistive and emissive layers (MgO, Al_2O_3) applied to glass capillaries
- ALD-coated MCP improved lifetime up to ~10 C/cm² integrated anode charge (IAC)
- Rate capability still marginal (1-10 MHz/cm² depending on PMT size, and MCP resistance)

PMT sizes range from 1x1/2x2 inch² (Hamamatsu, Photonis, Photek)

Micro Channel Plate MCP-PMT

A.Lehmann talk @ RICH2022

Photonis & Photek ALD MCP-PMTs



High-speed single photon application <50ps TTS (FWHM)

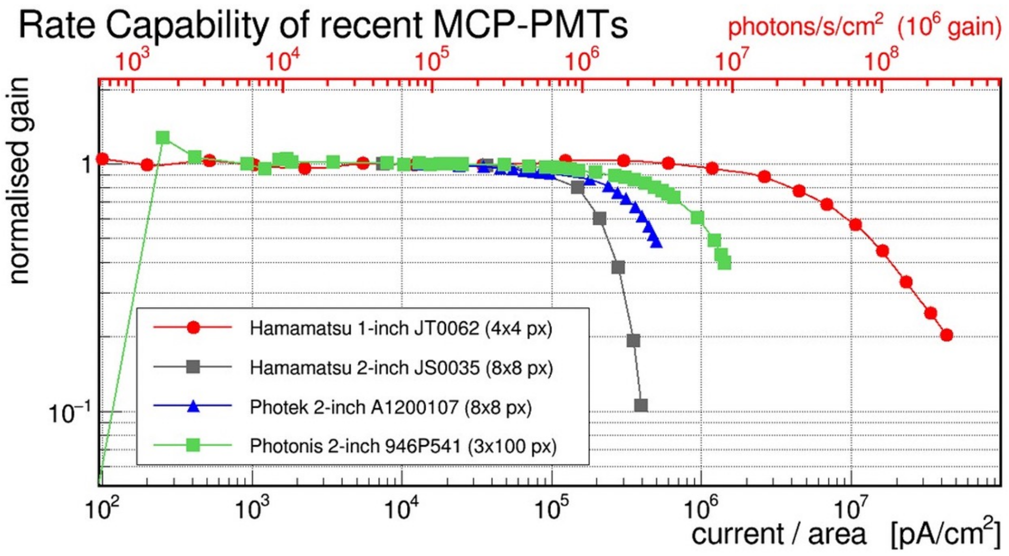
- Input rate capability ~MHz/cm²
- Low dark noise, high gain, good QE & filling factor

Limitation: PC aging due to ion feedback

- Main issue for high intensity experiments is QE degradation
- Standard MCP: poor lifetime (<200 mC/cm² IAC)
- ALD coating of MCP pores → ~100x PC lifetime increase
- **No QE degradation for Photonis MCP-PMT (R2D2) >34 C/cm²**

→ HIKE-KTAG expected IAC ~ 4-5C/cm²/year

PANDA Tests



Limitation: Gain decreases at high photon rates (τ = RC)

- 2-inch MCP-PMTs: ~1 MHz/cm² (with 10^6 gain)
- 1-inch Hamamatsu R10754 ≥10 MHz/cm²
- Rate capability depends on MCP resistance

Increasing rate capability in MCP-PMTs

- Lower MCP resistance (ranging at tens of MΩ) or capacitance
- Lower gain operation

MCP-PMT Tests in Birmingham

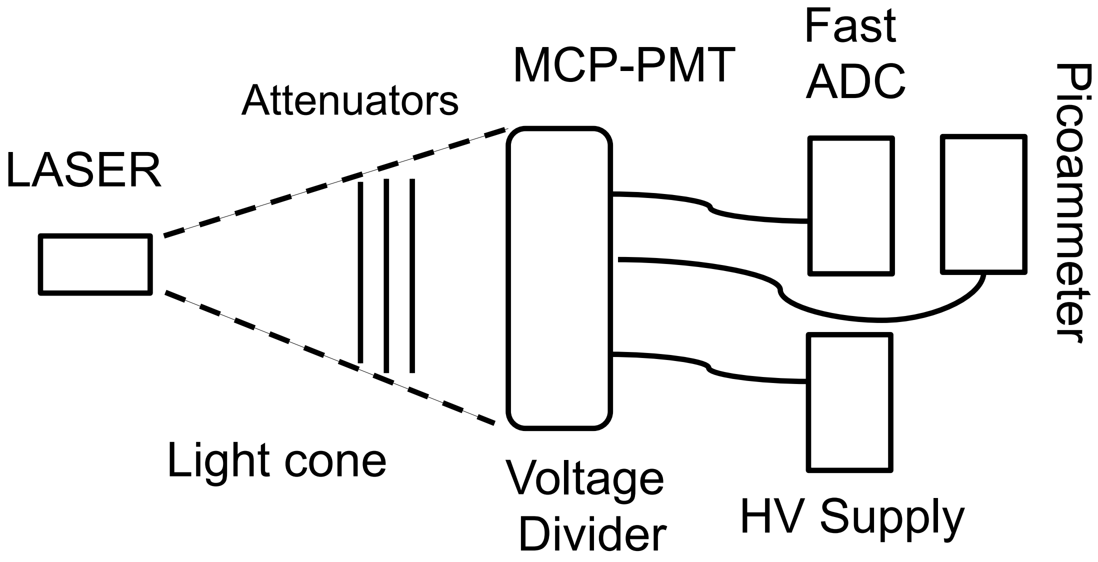
Lab equipment:
- ✓ PILAS ps pulsed diode laser (405nm, 0-40 MHz)
- ✓ Diffuser for homogenous illumination of the device area
- ✓ Attenuators to reduce intensity to single-photon level
- ✓ HV supply
- ✓ Fast sampling ADC
- ✓ Picoammeter device (to measure IAC)

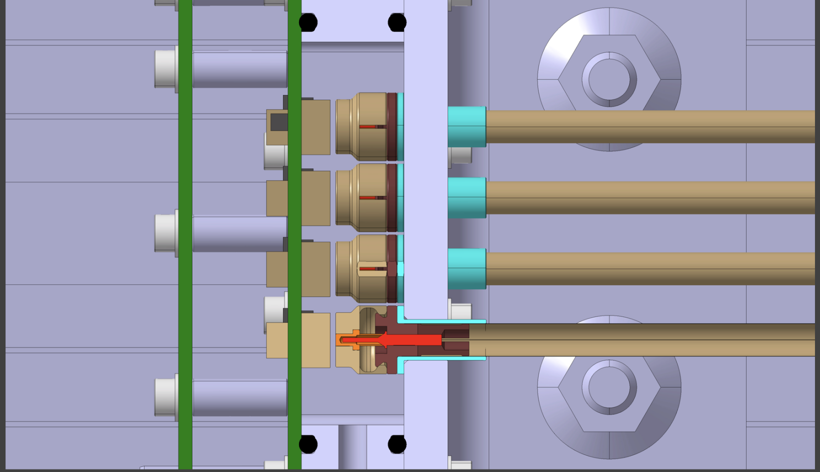
MCP-PMT Prototype + HV divider to arrive soon

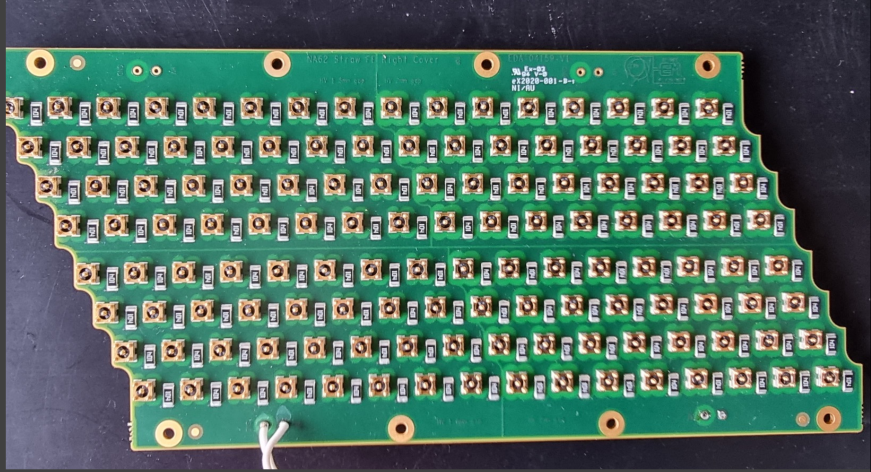
Planned test measurements:
- ➢ Lifetime: QE vs IAC
- ➢ Rate capability: Gain vs photon rate
- ➢ Time resolution: ΔT with respect to reference

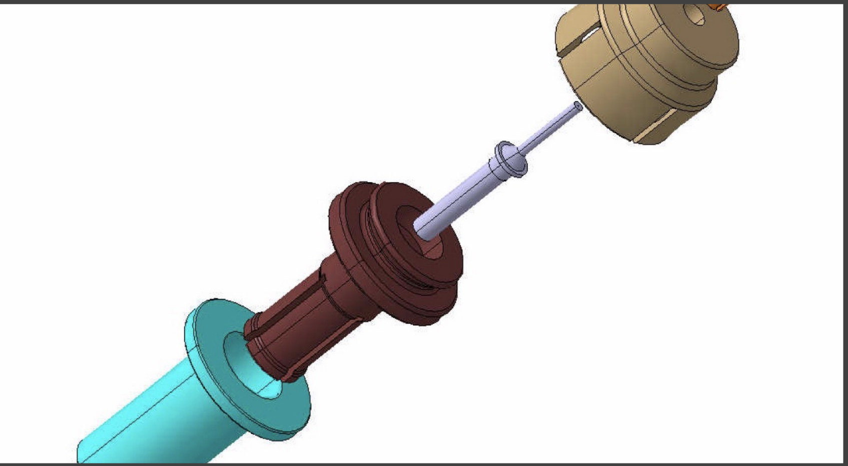
Goals:
- ❖ reach level of expected IAC in HIKE (~25C/cm^2 per 5 years)
- ❖ Test rate capability and find working point (gain)

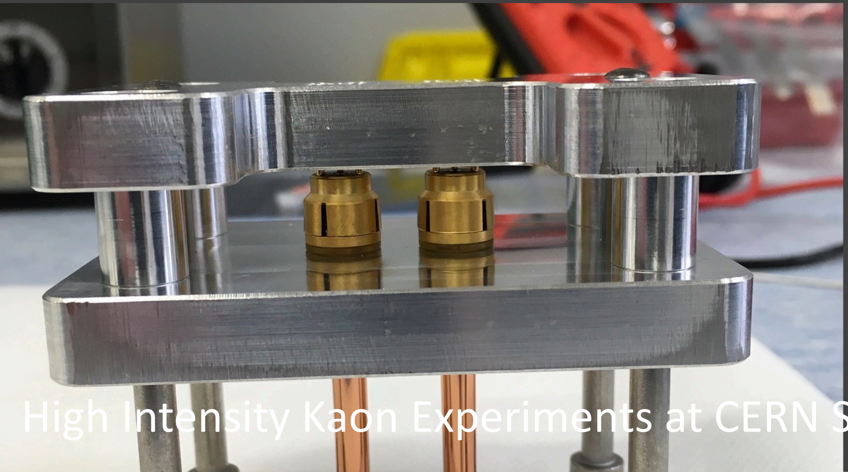
Lab test setup in Birmingham











Design of short (0.5m) STRAW prototype is complete

Prototype assembly and validation of connectivity, assembly procedures and tooling are on-going

Start design of a full-length (2.1m straw) prototype with 19 μm wall thickness by the end of 2023

The Main Electromagnetic Calorimeter (MEC)

Baseline option: Fine-sampling shashlyk based on PANDA forward EM calorimeter

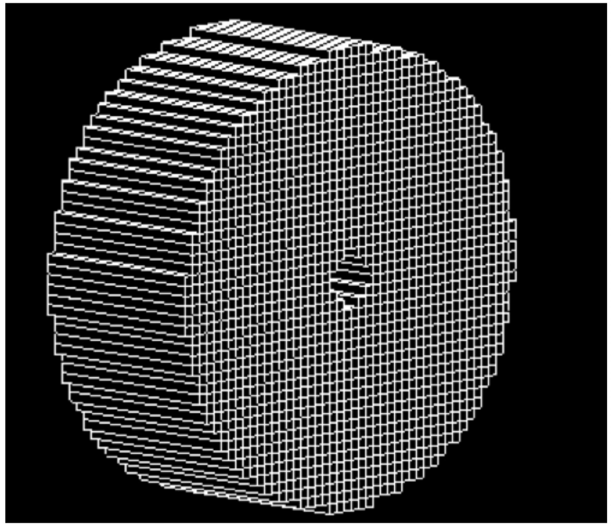
Sampling: 0.275 mm Pb + 1.5 mm scintillator. Transverse module size: 55 x 55 mm^2

Composition: Moliere radius ~59mm, X_0 ~3.80 cm, sampling fraction ~39%

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)

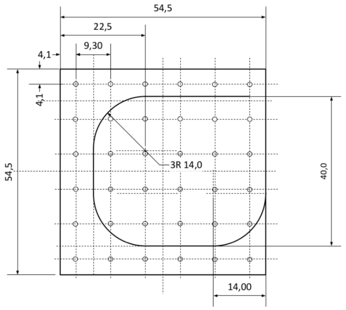
HIKE MEC Geant4 Simulation

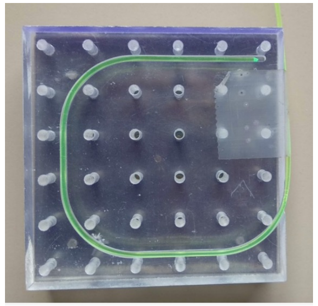


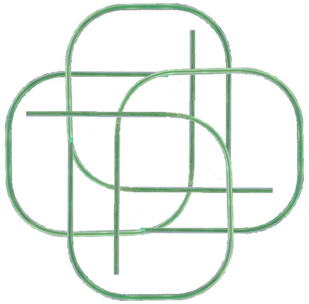
New for Phase2: Longitudinal shower information from spy tiles

- PID information: identification of μ, π, n interactions
- Shower depth information: improved time resolution for EM showers
- Spy tiles optically isolated from shashlyk stack and read out by dedicated WLS fibers (romashka design = chamomile)

1st prototype assembled in Protvino and tested at OKA in April 2018

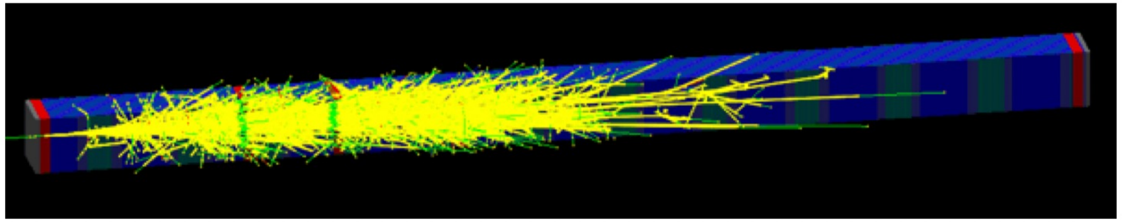




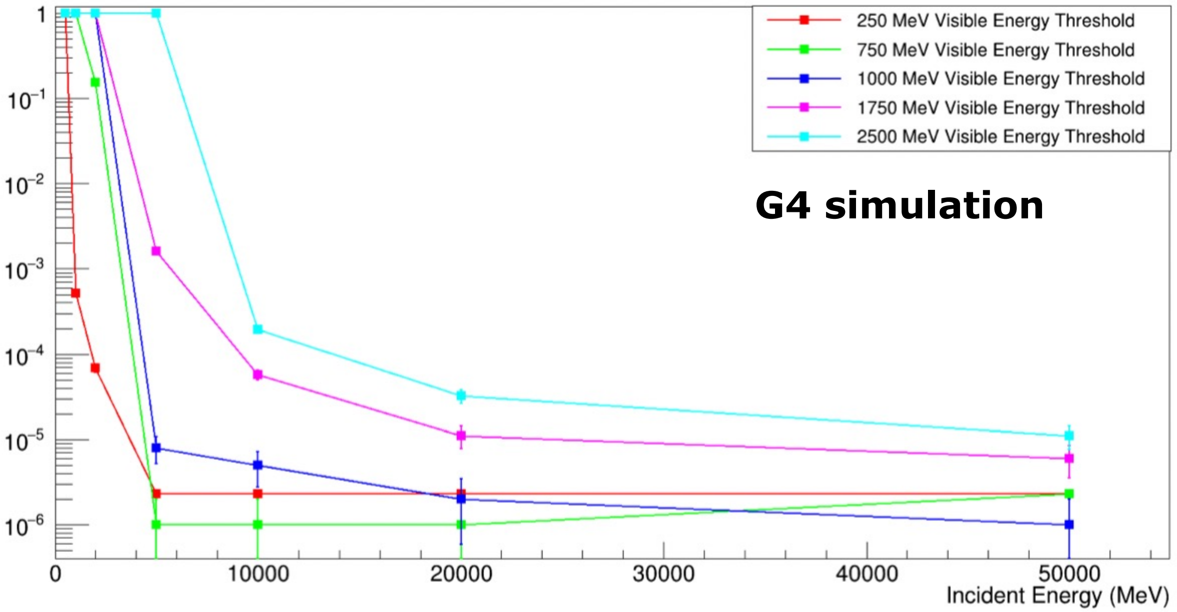


MEC simulation and test beams

G4 simulation of 5 GeV photon shower in MEC module



Detection efficiency vs incident particle energy



Fine-sampling shashlyk design satisfies HIKE efficiency requirements

Test Beam at DESY (in collaboration with LHCb) with 14 X_0 shashlyk prototype:

- ➢ Significant leakage (transverse + longitudinal) affecting small prototype
- ➢ Energy fractions in spy layers qualitatively reproduced
- ➢ Time resolution ~170 ps at E_e = 5 GeV
- ➢ Time resolution for spy layers significantly worse (400-600 ps) → acceptable since event time determined by main shashlyk signal

Design and construct a full-depth prototype (25 X_0) of baseline solution with conventional scintillator and uniform shashlyk stack for test beam in 2024

Shashlyk Test Beam at DESY

Module tested and compared to standard shashlyk

LHCb beam test at DESY T24 November 2019

e^+ **beam, 5 kHz**
E = **1-6 GeV** (steps of 0.2 GeV)

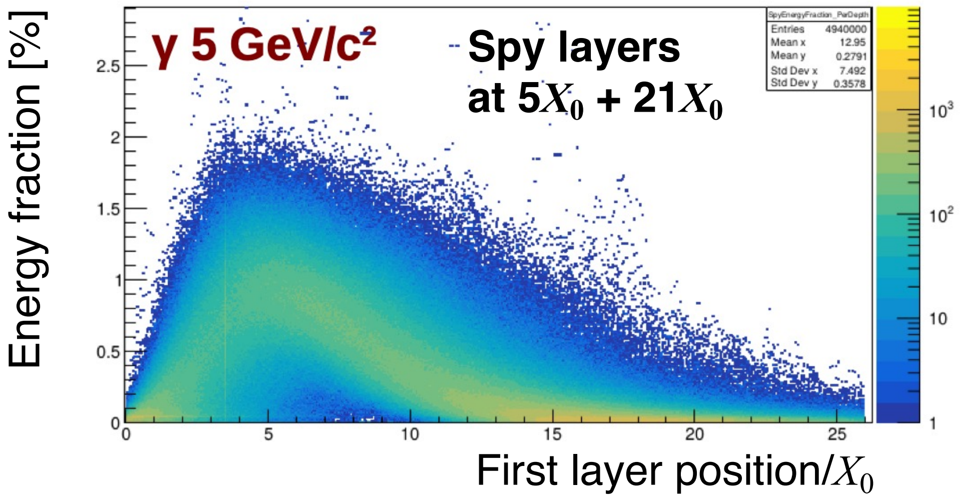
Silicon tracker/MWPC beam telescope

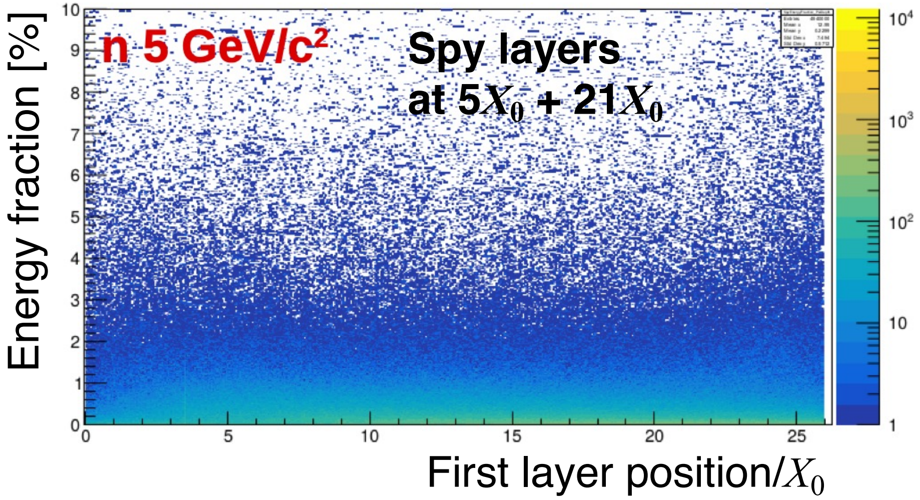
Beam tagging with $\sigma_t < 20$ ps

Observations:

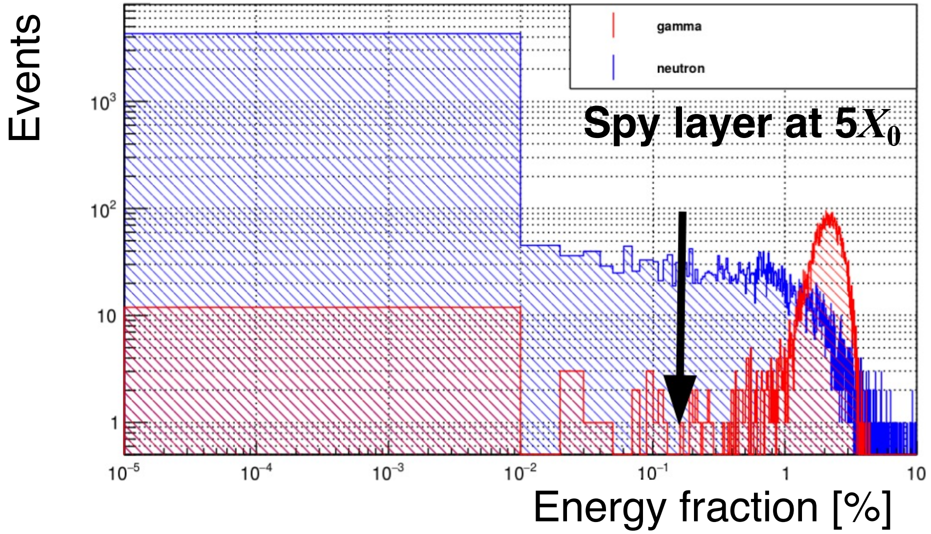
- **Significant leakage (transverse + horizontal) affecting small prototype**
  - **More testing with larger assembly of modules needed for validation**
- Energy fractions in spy layers qualitatively reproduced
- Time resolution ~170 ps at E_e = 5 GeV
  - Includes ~150 ps constant term attributed to leakage
  - Statistical term ~140 ps similar to standard shashlyk
- Time resolution for spy layers significantly worse (400-600 ps)
  - May be acceptable since event time determined by main shashlyk signal

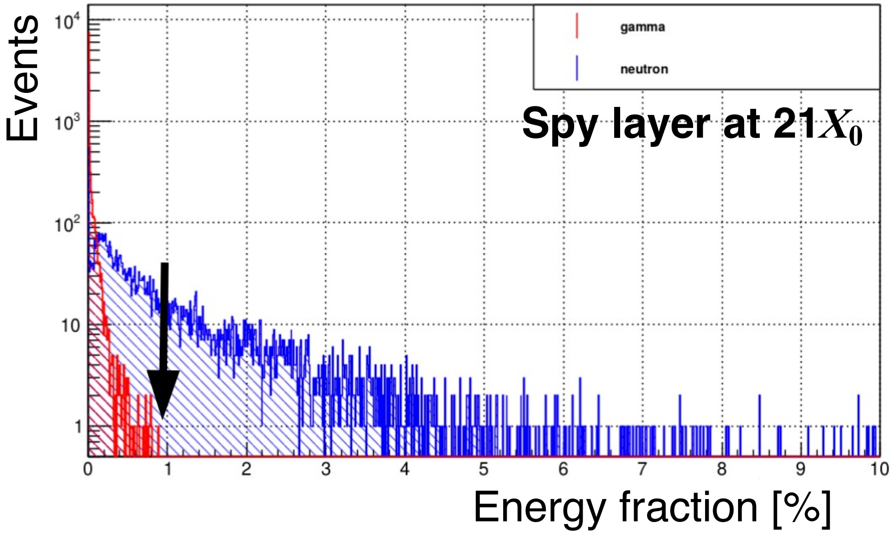
MEC: Simulation of γ/n separation





Energy fraction in spy group = energy deposited in spy tiles/ deposited in shashlyk





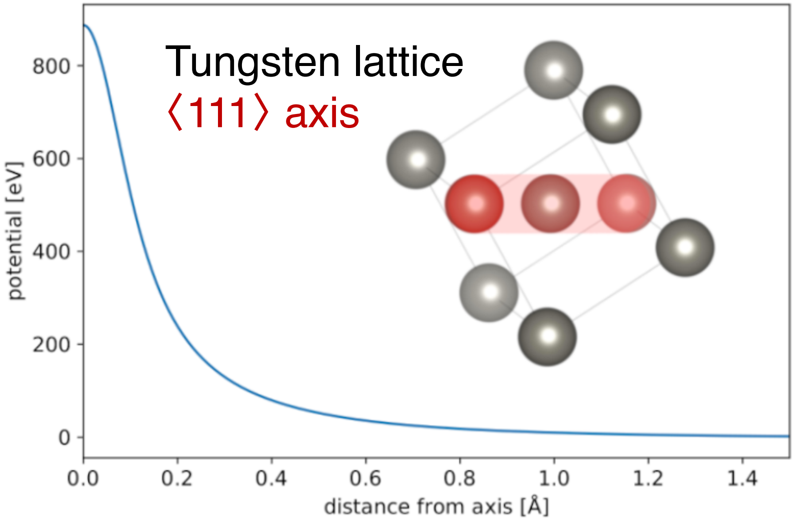
Info from spy tiles provides:

- 5-10x improvement in neutron rejection
- **Overall neutron rejection at level of 10^3**

Coherent effects in crystals

Coherent effects increase cross-section for electromagnetic shower processes (bremsstrahlung, pair production)

- **Decrease effective value of X_0**
- **Exploit coherent effects for calorimetry?**



Coherent superposition of Coulomb fields

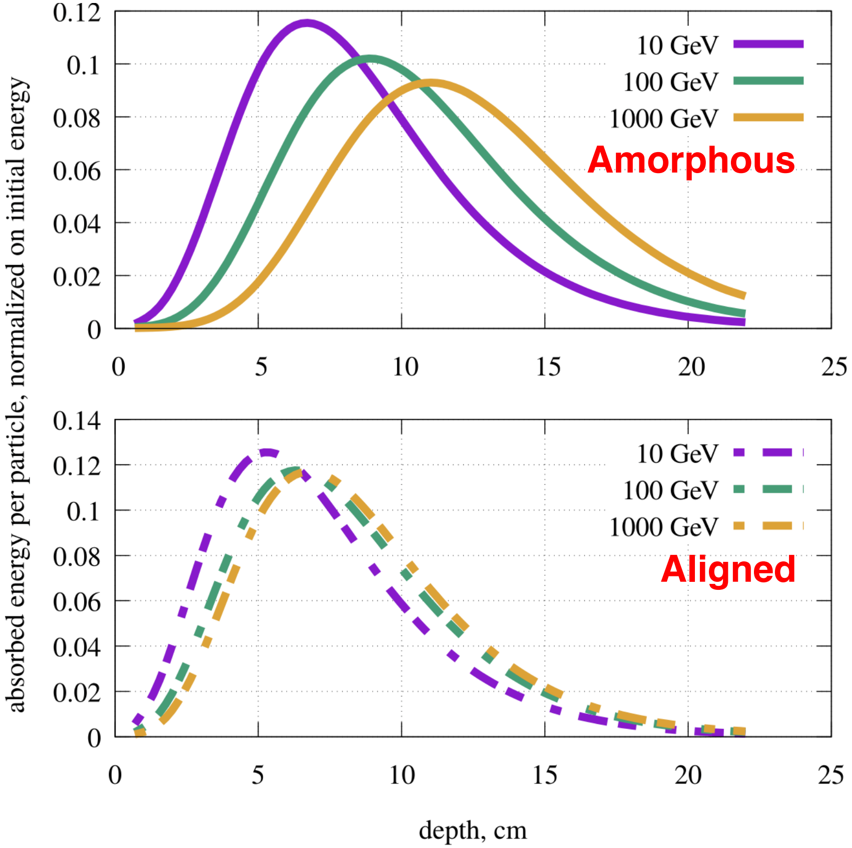
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

Effective field $\varepsilon' = \gamma_{\text{eff}}$ ($\gamma_{\text{eff}} = E/m_e c$)

For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate

Geant4 simulation

Bandiera et al., NIMA 936 (2019)



- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

Pair production enhanced by coherent effects at small θ_γ and high E_γ