UNIVERSITY OF BIRMINGHAM

NA62

High Intensity Kaon Experiments at CERN SPS

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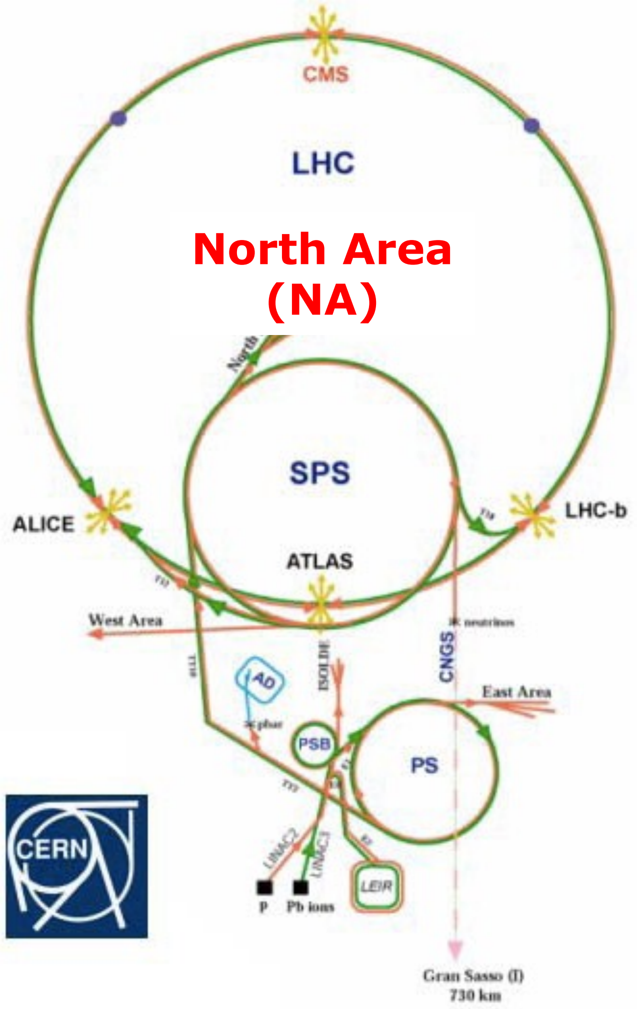
HIKE
High Intensity Kaon Experiments

HIKE Phase 1 & 2 proposal: 205 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 crucial 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., $K_S \to \pi^0 \ell^+ \ell^-$
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:	$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10^{+4.0}_{-3.4}\vert_{stat} \pm 0.9_{syst}) \times 10^{-11}$
	2021-LS3:	Aim at 15% precision on $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$

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

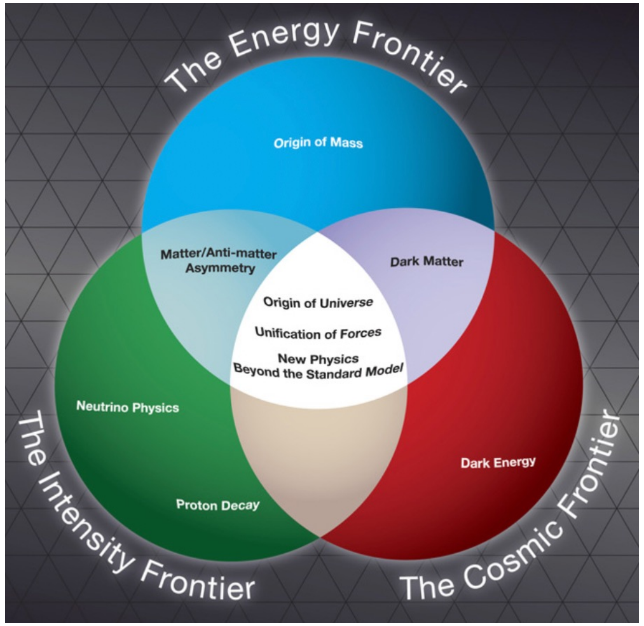
HIKE: a multi-purpose physics approach

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 4x wrt nominal intensity in NA62 (NA 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

HIKE-dump → Proton beam → Hidden Sector

Kaon beam → Hidden Sector

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

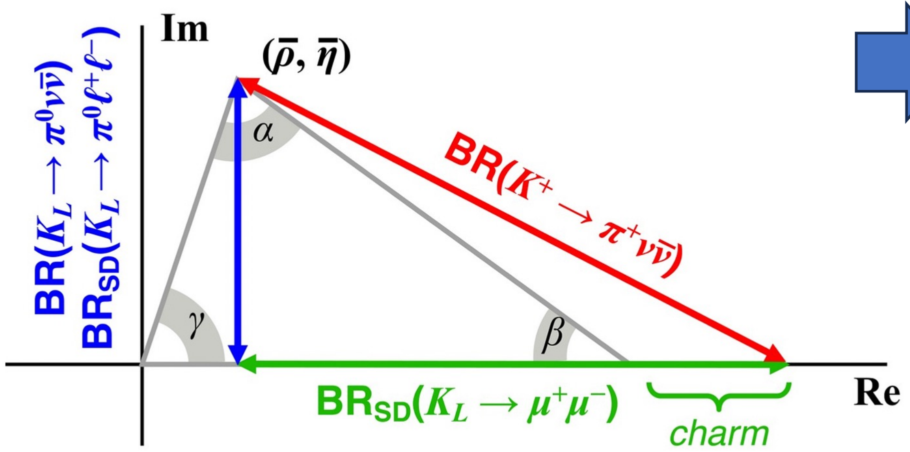
Precise tests of **Lepton Flavour Universality** and searches for **lepton flavour and number violation** → LFU, LFV/LNV

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), Axion-Like Particle (ALP)..

Rare Kaon Decays

Decay	Γ_{SD}/Γ	Theory Error*	SM BR x10^{11}	EXP BR x 10^{11}	EXPERIMENT	YEAR
$K_L \rightarrow \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 200	KOTO	2023
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$	90%	4%	8.4 ± 1.0	$10.6\,^{+4.0}_{-3.6} \pm 0.9$	NA62	2021
$K_L \rightarrow \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	<28	KTeV	2004
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	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



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

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

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%	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
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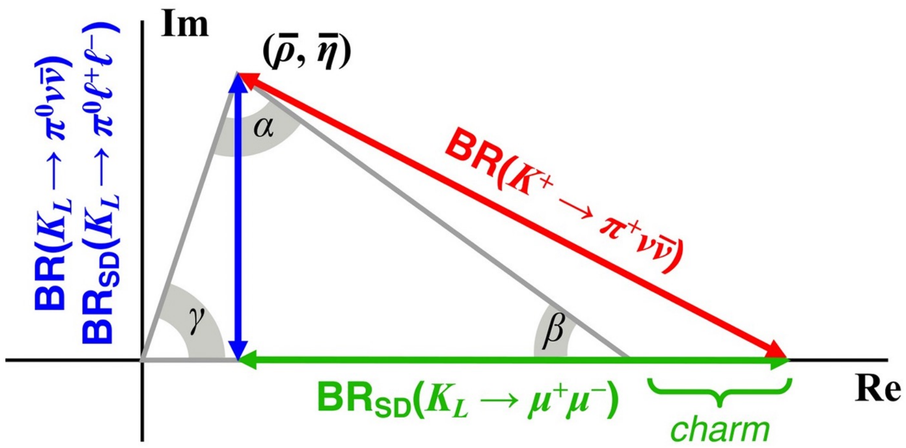


Principal HIKE Physics goals:

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

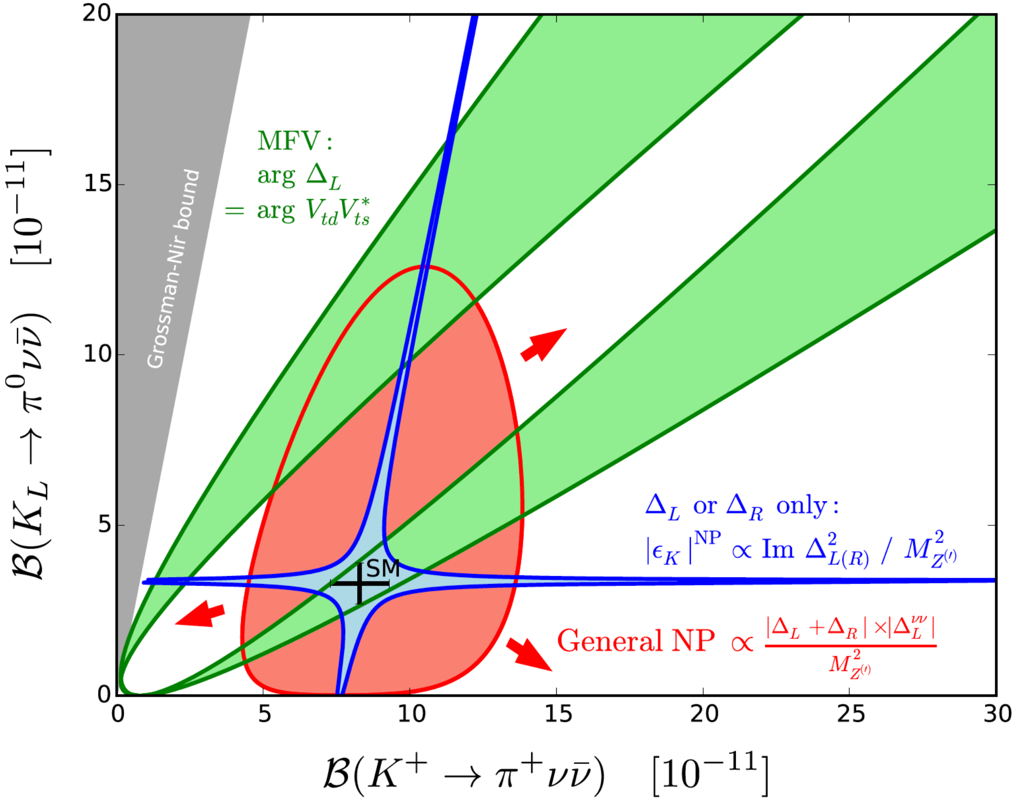
Phase 2:
- Measure $BR(K_L \to \pi^0 l^+ l^-)$ at 20% precision

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

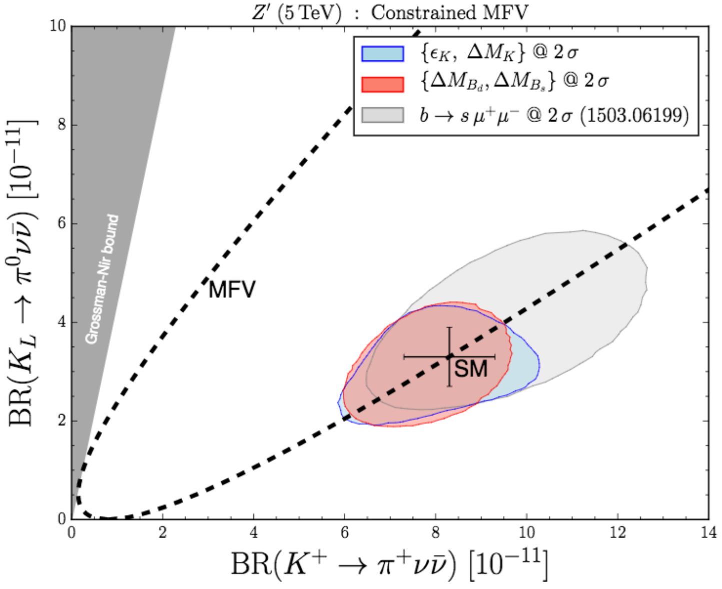
Indirect searches of New Physics with high precision studies of rare K decays

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

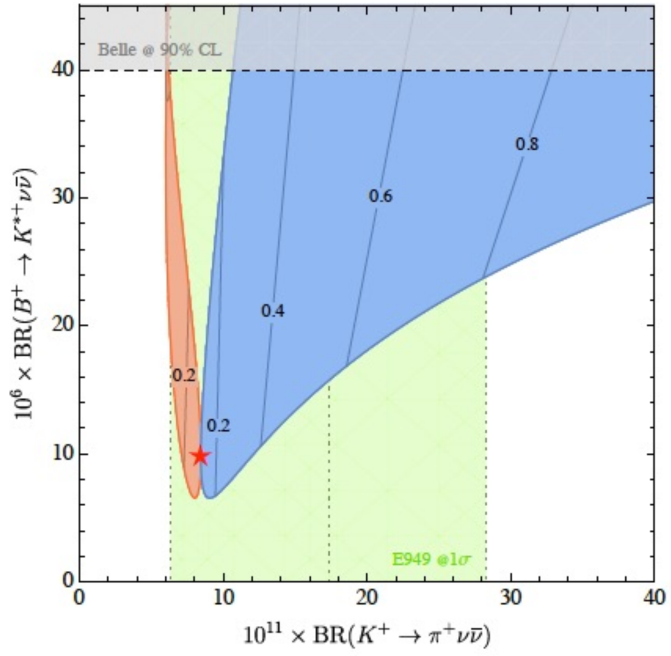
[Buras, Buttazzo, Knegjens, JHEP1511 (2015) 166]



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]

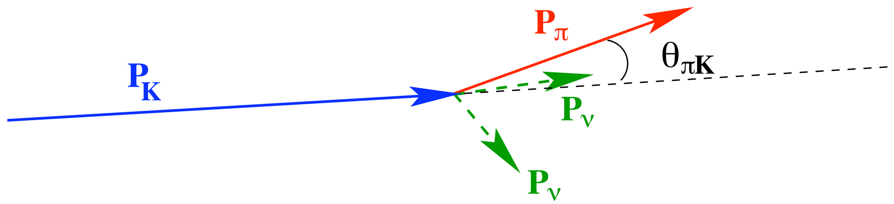
$K^+ \to \pi^+ \nu\bar{\nu}$ at HIKE: experimental strategy

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

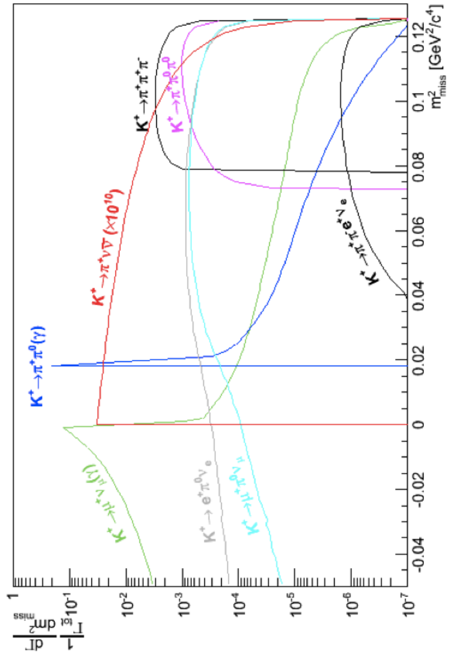


Main kaon decay backgrounds

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

NA62/HIKE-Phase1 keystones:

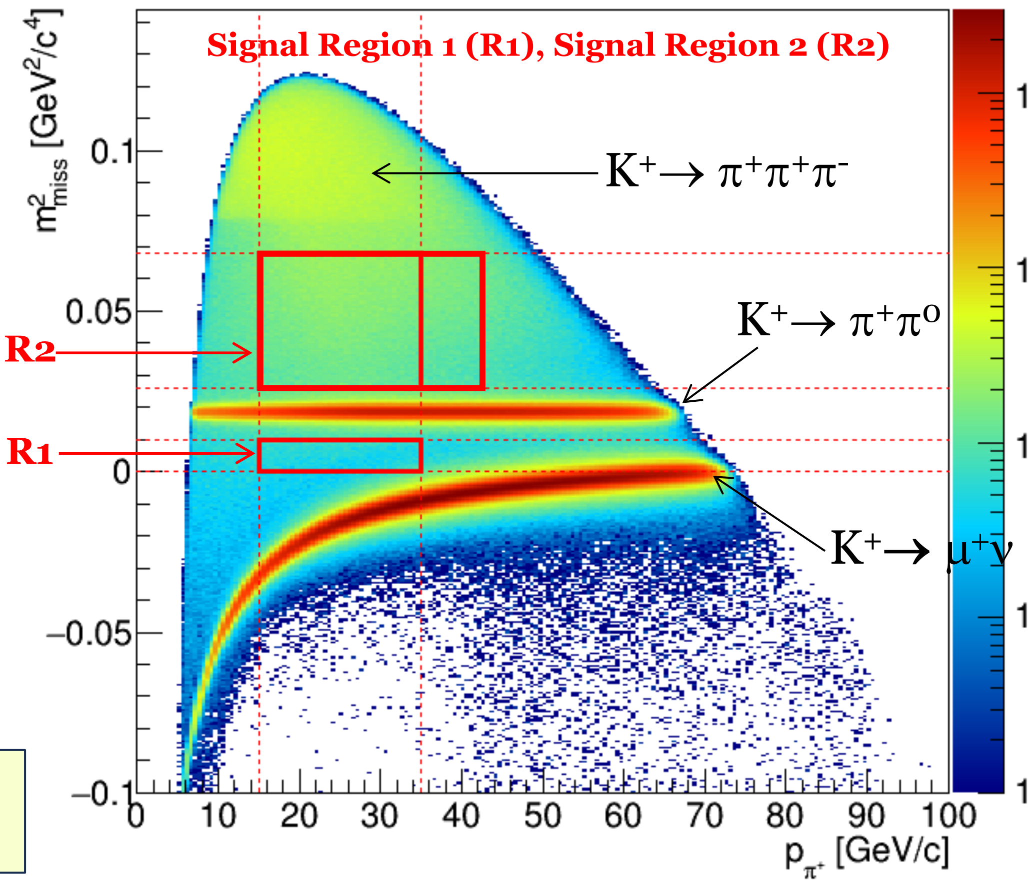
- precise tracking
- PID (in particular π/μ)
- photon veto
- precise timing



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

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

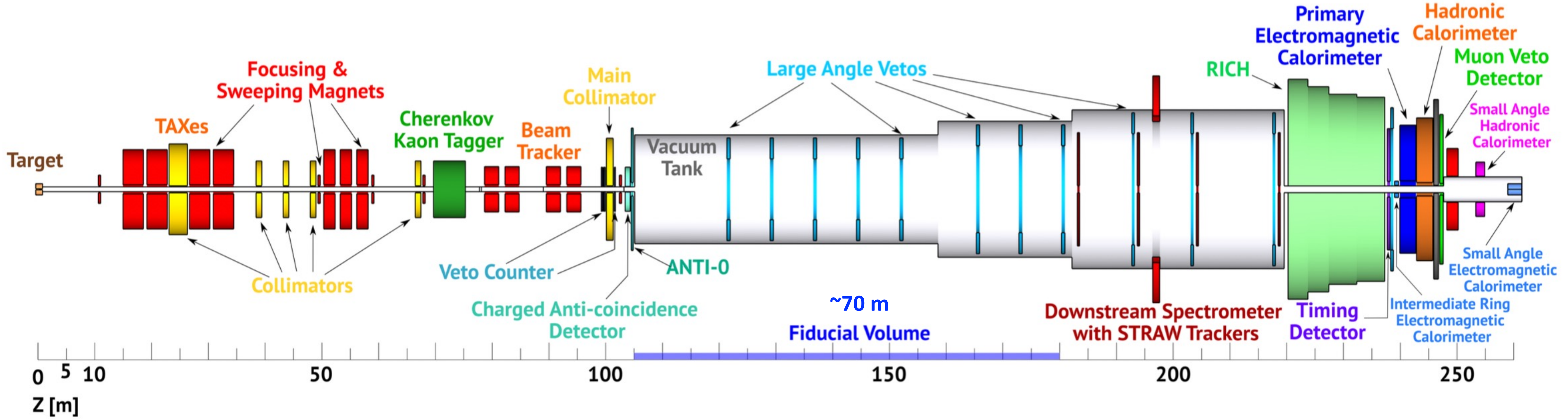
$m^2_{miss} = (P_K - P_\pi)^2$; m_π mass hypothesis



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 $\times 10^{13}$ POT / spill = 4x NA62 max beam intensity
Statistical power: 2×10^{13} Kaon decays in decay volume per year (7×10^{18} POT / year)



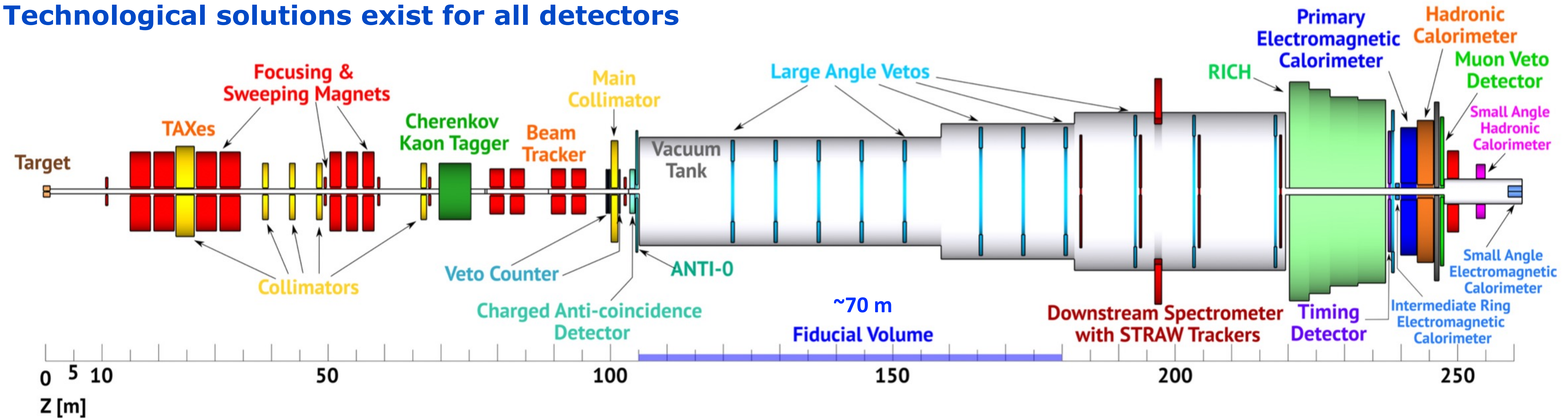
NA62-like design of experiment will work at high intensity

HIKE-Phase1 Experimental Layout

HIKE-Phase1 improvements wrt NA62:

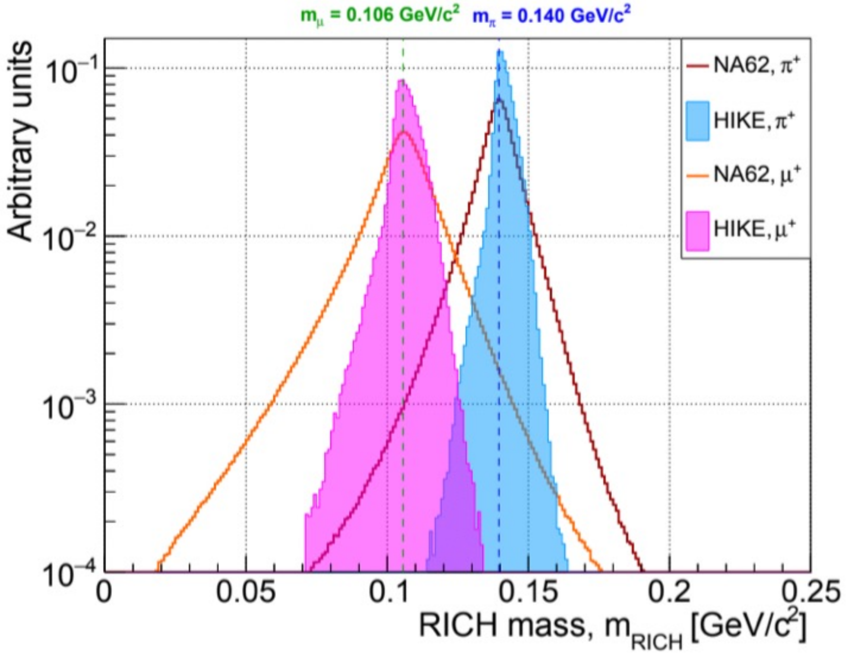
- **improved timing and double pulse resolution are crucial elements** to withstand the beam intensity increase
- **equal or better key performance** at high-rate to achieve background rejection at ~10^{11} level
- up to x2 **increase in signal acceptance** (improved detector performance, software trigger)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

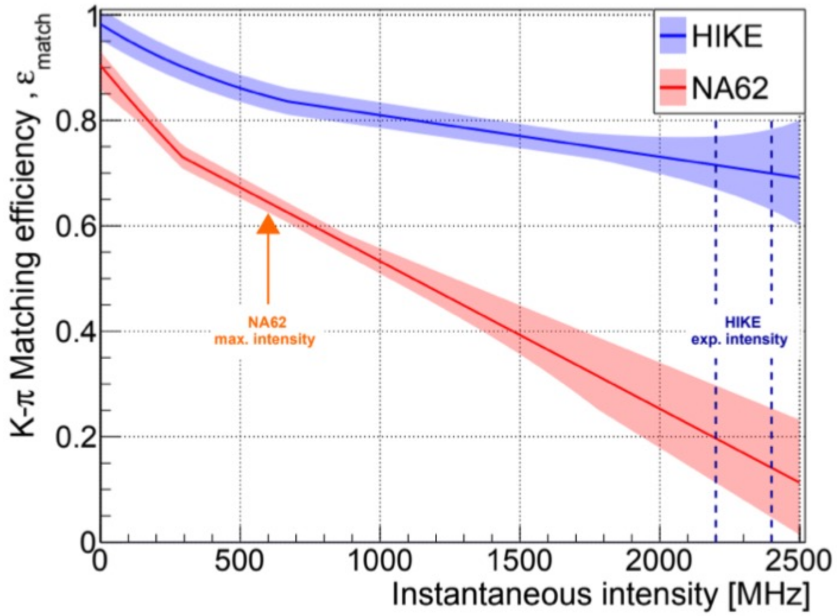
Technological solutions exist for all detectors



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





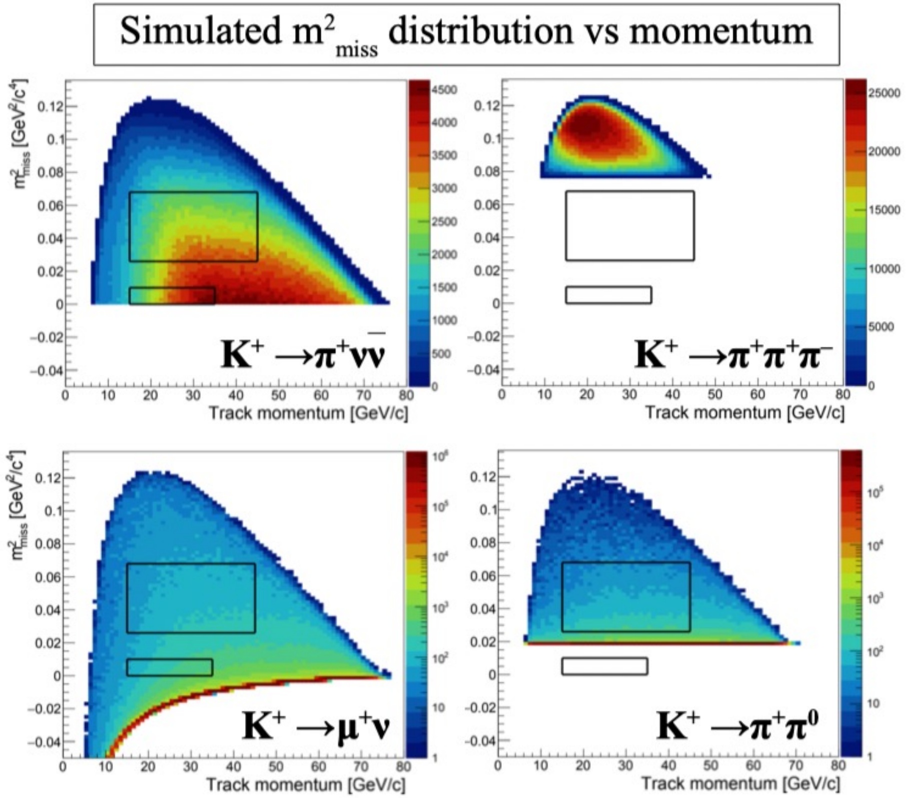
RICH PID for π with $15 < p < 45$ GeV/c.
RICH granularity increased
+ better photodetectors (x2 Quantum Efficiency,
time resolution: 300→100ps)
→ Improved photon yield and time resolution

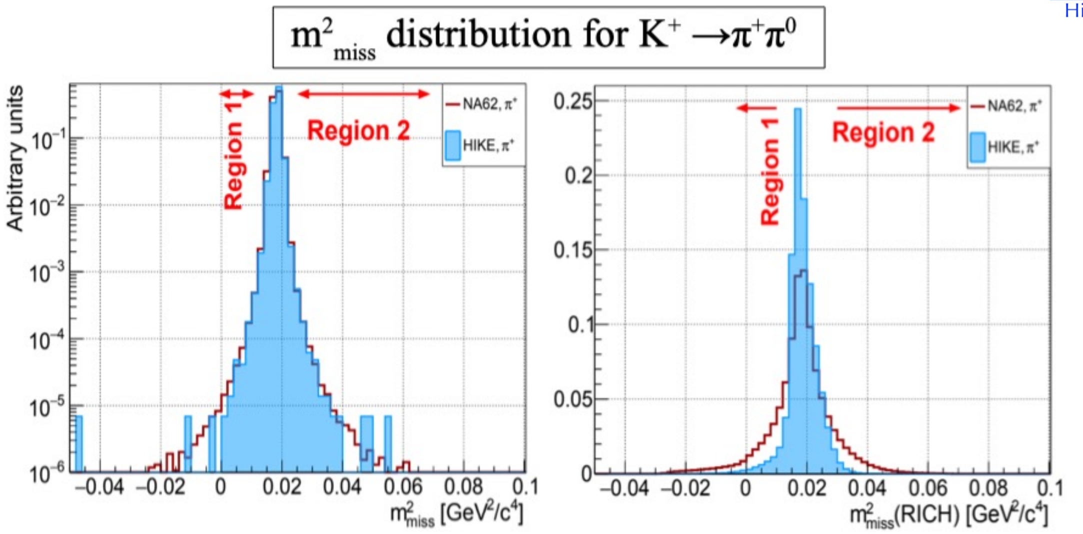
K-π matching: x4 better timing,
x3 smaller pixel size in beam tracker,
40% lower material budget in STRAW

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

High Intensity Kaon Experiments





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

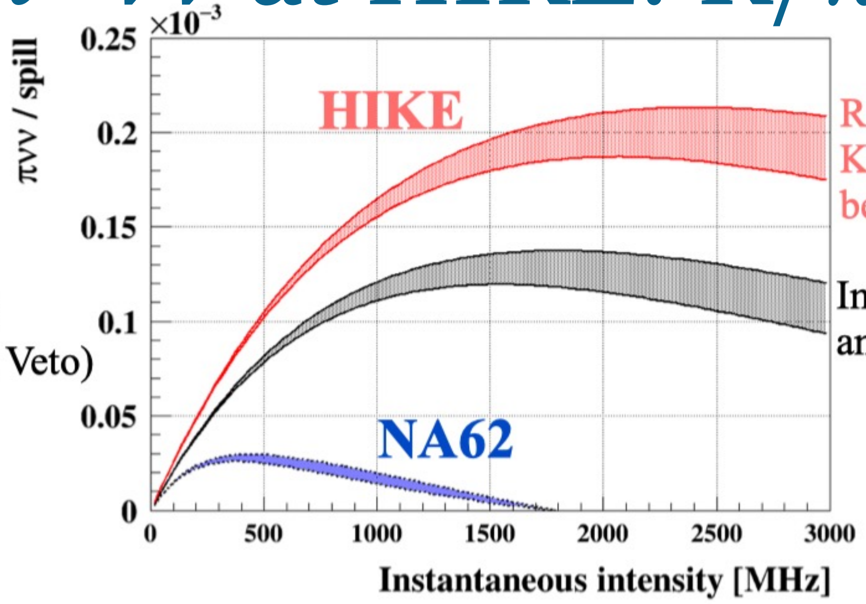
$K^+ \to \pi^+\nu\bar{\nu}$ at HIKE: K/π ID

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



Recovery of LTU dead-time, K-π association, improved RICH, better kinematic resolution

Improved timing, software trigger and new DAQ

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

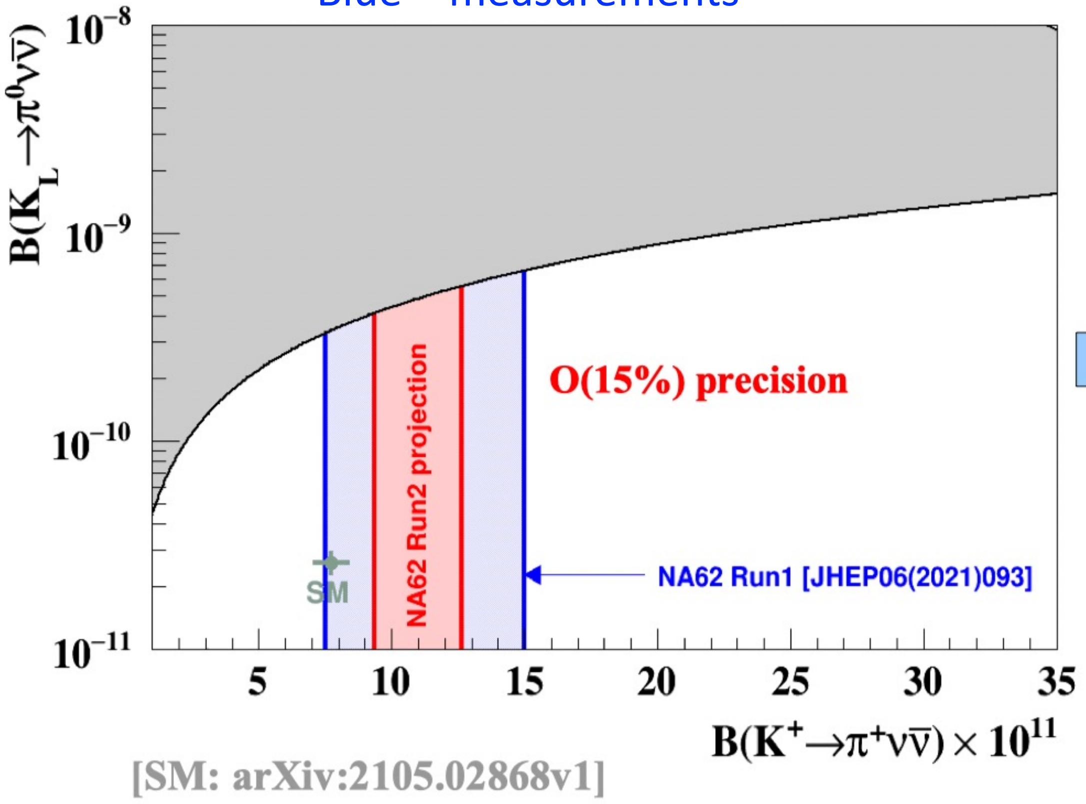
Number of spills	2.4×10^6
Protons on target	3.2×10^{19}
K^+ decays in FV	8.0×10^{13}
Expected SM $K^+ \to \pi^+\nu\bar{\nu}$	480
Background from K^+ decays	115
Upstream/accidental background	85–240
Expected statistical precision $\sigma(\mathcal{B})/\mathcal{B}$	5.4%–6.1%

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

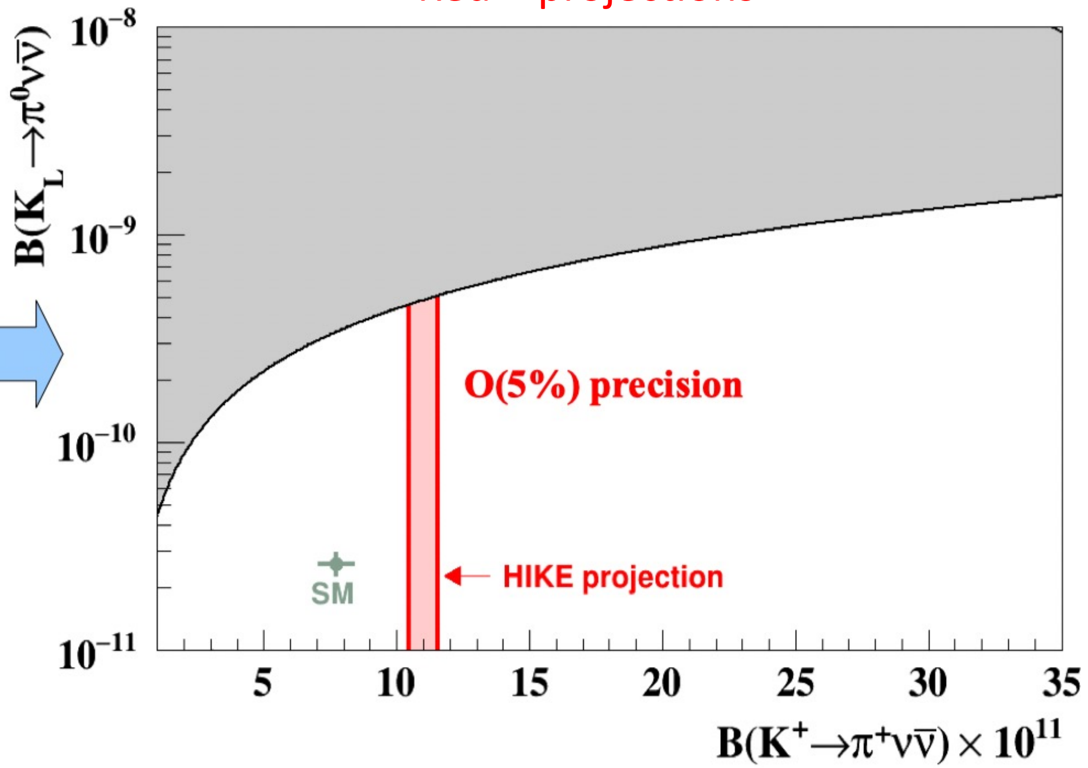
$K^+ \rightarrow \pi^+\nu\bar{\nu}$ at HIKE: physics reach

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

Blue = measurements



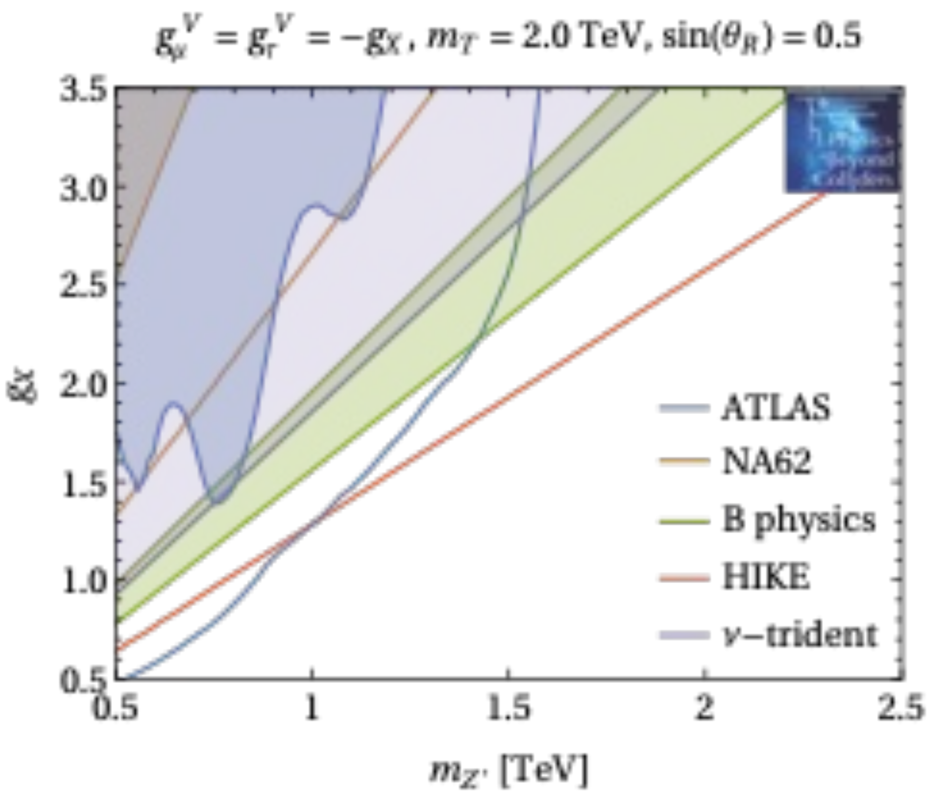
Red = projections

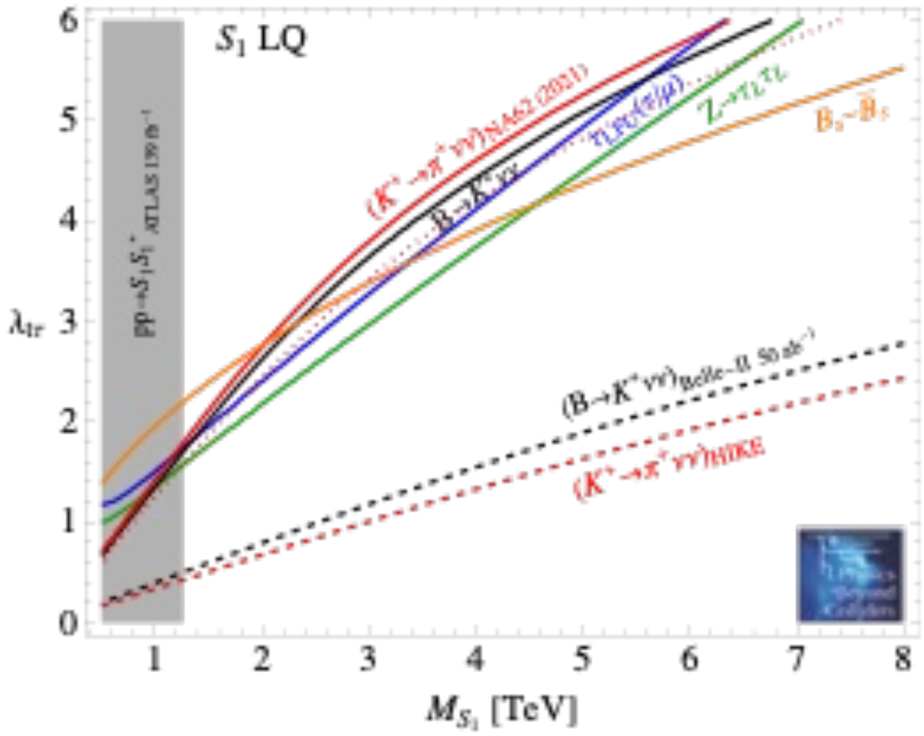


From NA62 to HIKE (Phase 1): Precision on BR($K^+ \rightarrow \pi^+\nu\bar{\nu}$) improved by a factor of 3

HIKE Phase1: specific BMS models

arXiv:2310.17726





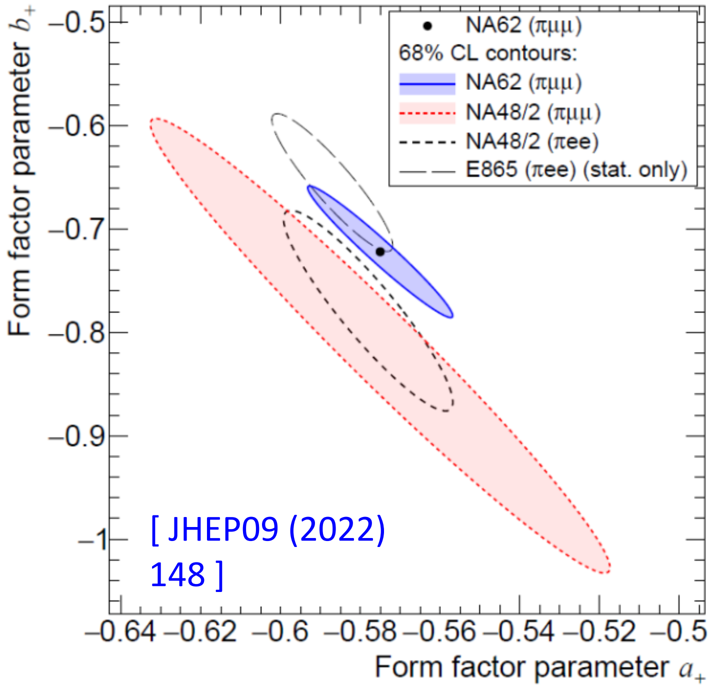
Top-philic Z': (revisited by F. Kahlhoefer)

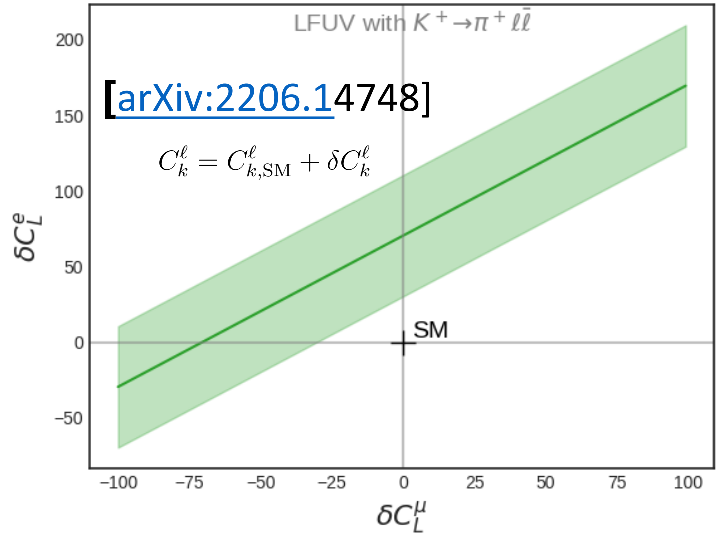
Constraints on a top-philic Z', on mass vs gauge coupling, see Refs. [JHEP 03 (2018) 074, Phys. Rev. D 97 (2018) 035002]. Assumed vector couplings to muons and tau leptons, and couplings to top quarks induced via mixing with a vector-like quark with mass 2 TeV and mixing angle 0.5. Lepton couplings are 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





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

$z = m(l^+l^-)^2/M_K^2$ — 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 $l = e, \mu$

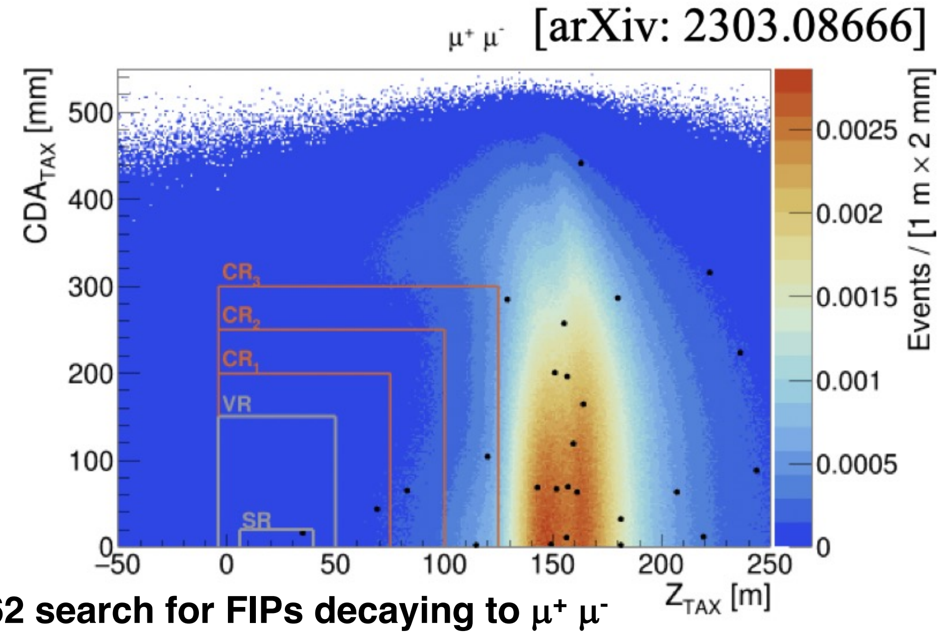
HIKE Phase 1: Collect > $5\text{x}10^5$ background-free $K^+ \to \pi^+l^+l^-$
Measure Δa and Δb to ±0.007 and ±0.015 precision

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.



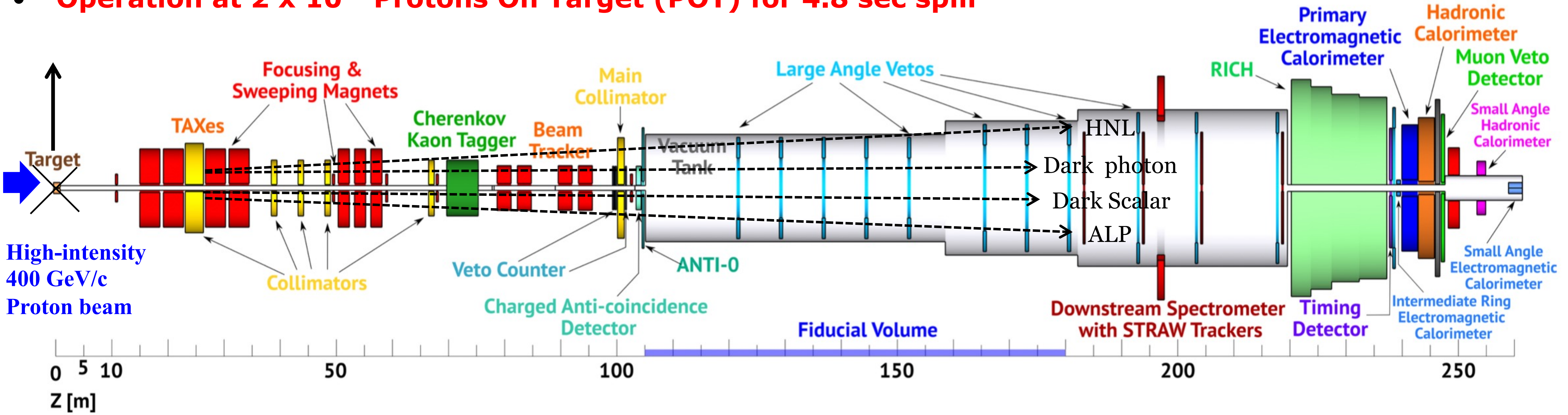
NA62 search for FIPs decaying to $\mu^+ \mu^-$

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

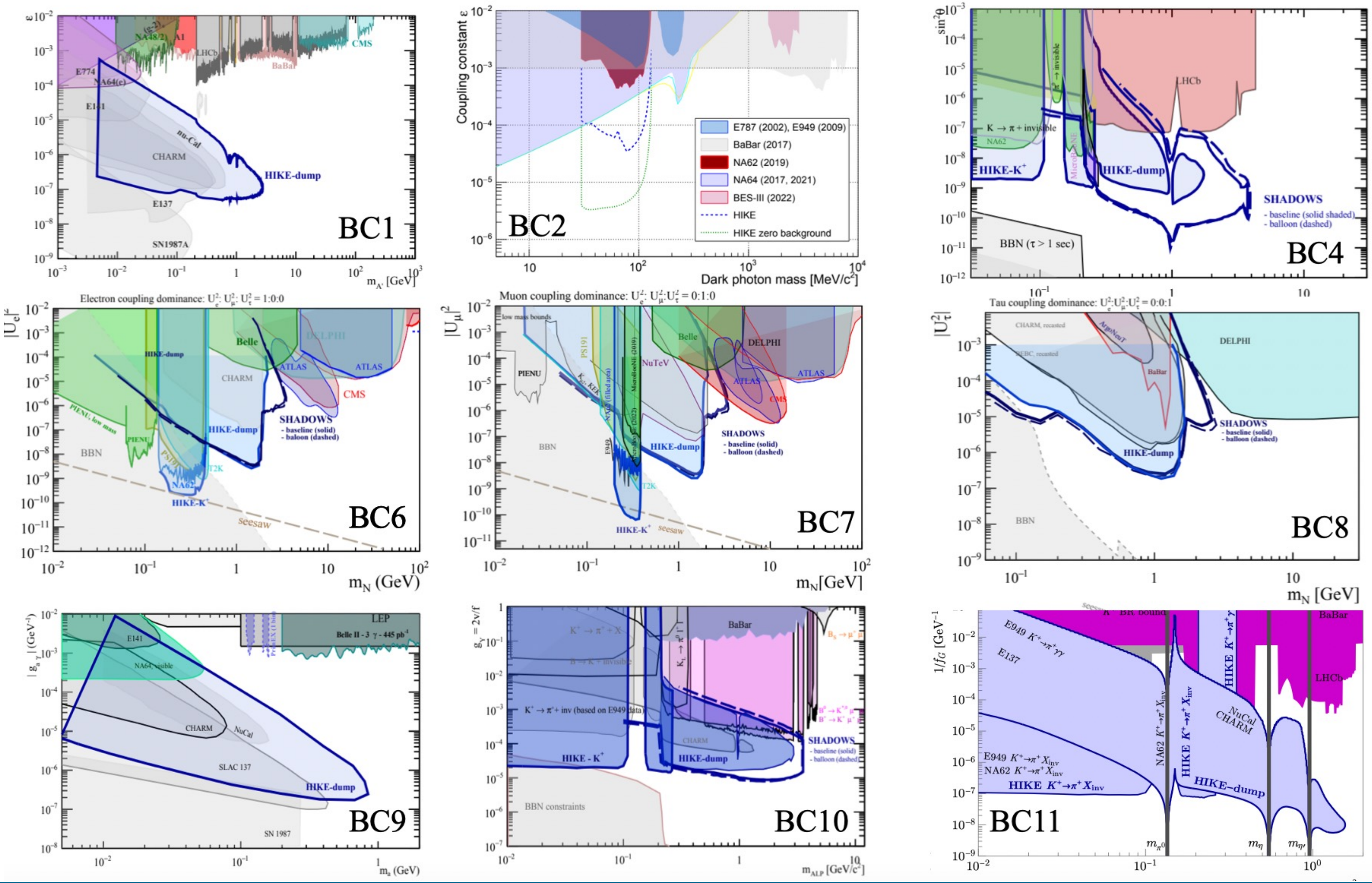
HIKE-Dump Experimental Layout

- 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 Target (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)

$K_L \to \pi^0 l^+ l^-$ at HIKE

Contributions from long-distance physics

- SD CPV amplitude: γ/Z exchange
- LD CPC amplitude from 2γ exchange
- LD indirect CPV amplitude: $K_L \to K_S$

- $K_S \to \pi^0 \ell^+ \ell^-$ help reducing theoretical uncertainties, measured $|a_S|$
  - measured NA48/1 with limited statistics
  - planned by LHCb Upgrade
- $K_L \to \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays, give unique access to SD BSM effects in the photon coupling via the tau loop

$$\mathcal{B}(K_L \to \pi^0 e^+ e^-) = 3.54^{+0.98}_{-0.85} \left(1.56^{+0.62}_{-0.49}\right) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-) = 1.41^{+0.28}_{-0.26} \left(0.95^{+0.22}_{-0.21}\right) \times 10^{-11}$$

(2 sets of values corresponding to constructive (destructive) interference btw direct and indirect CP-violating contributions)

Experimental bounds from KTeV:

BR($K_L \to \pi^0 e^+ e^-$) < 28 × 10^{-11} Phys. Rev. Lett. 93 (2004) 021805

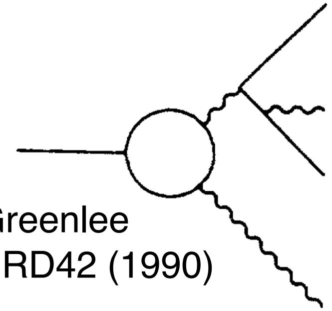
BR($K_L \to \pi^0 \mu^+ \mu^-$) < 38 × 10^{-11} Phys. Rev. Lett. 84 (2000) 5279–5282

Main background: $K_L \to \ell^+ \ell^- \gamma\gamma$

- Like $K_L \to \ell^+ \ell^- \gamma$ with hard bremsstrahlung

BR($K_L \to e^+ e^- \gamma\gamma$) = (6.0 ± 0.3) × 10^{-7} $E_\gamma^* > 5$ MeV

BR($K_L \to \mu^+ \mu^- \gamma\gamma$) = 10^{+8}_{-6} × 10^{-9} $m_{\gamma\gamma} > 1$ MeV

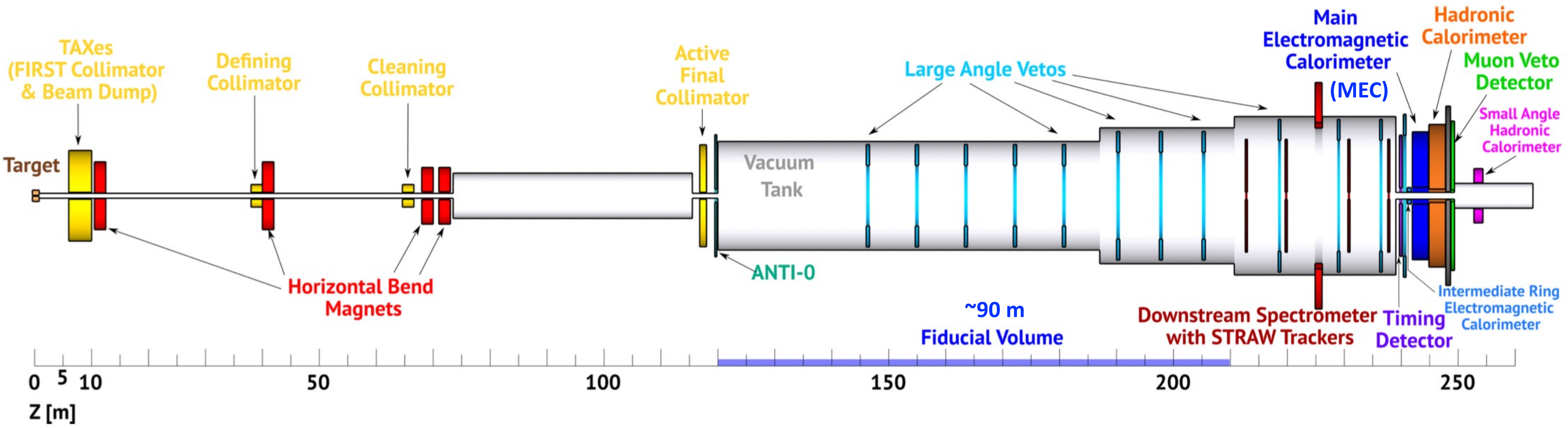


Greenlee PRD42 (1990)

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

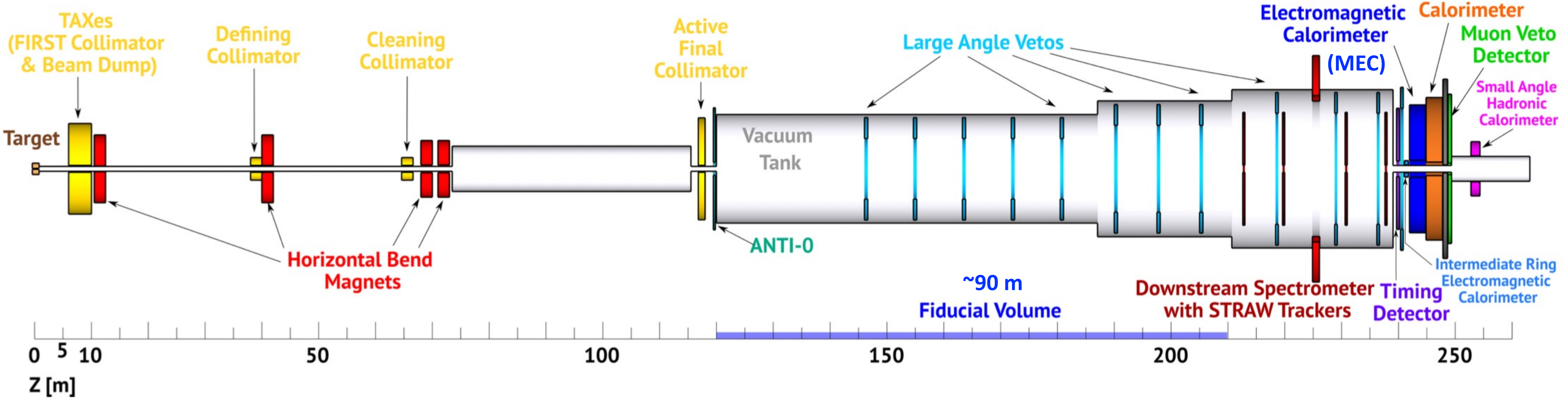
HIKE High Intensity Kaon Experiments

A 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

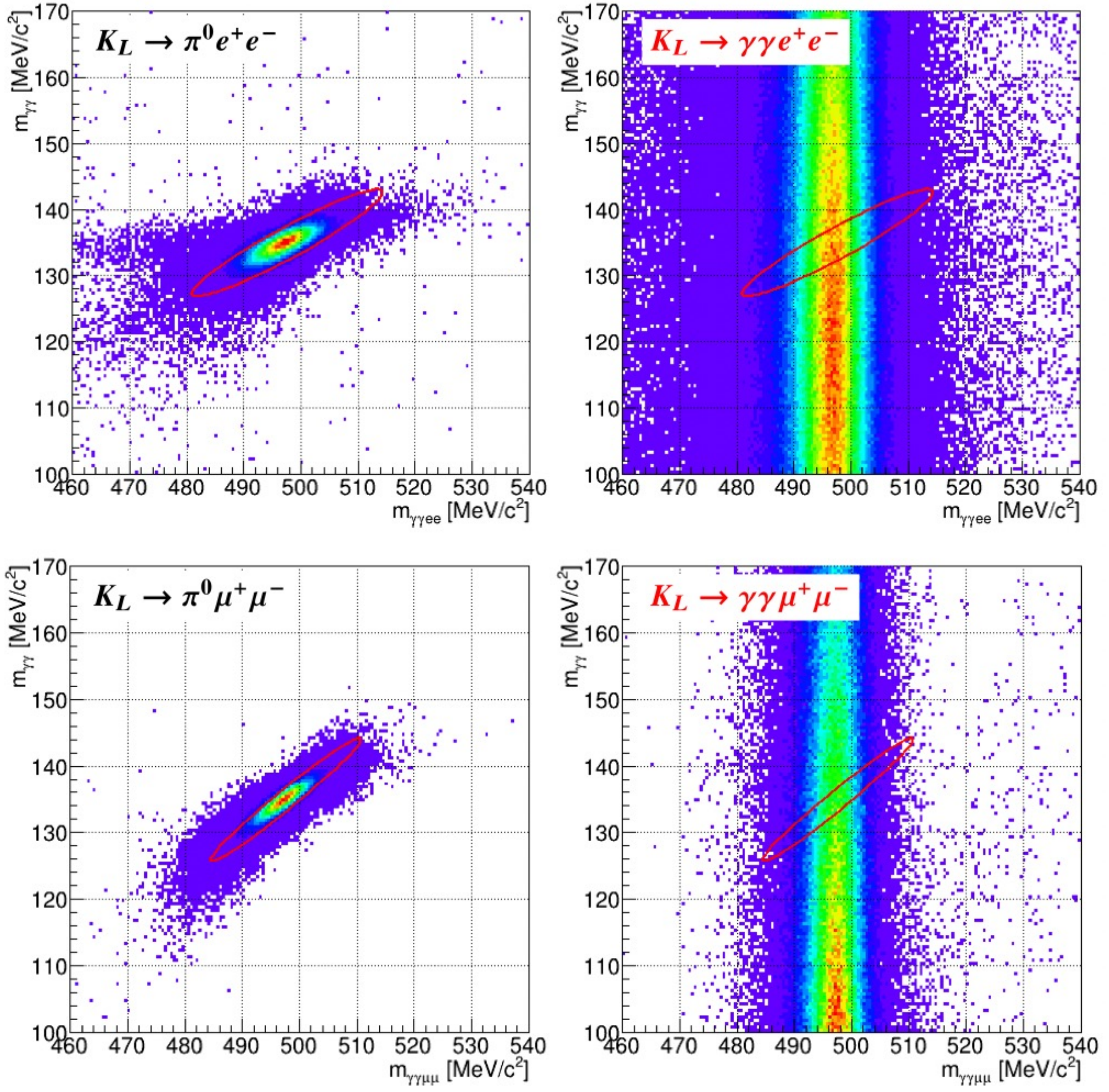
Reconfigured HIKE-Phase1 detector:

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



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)]

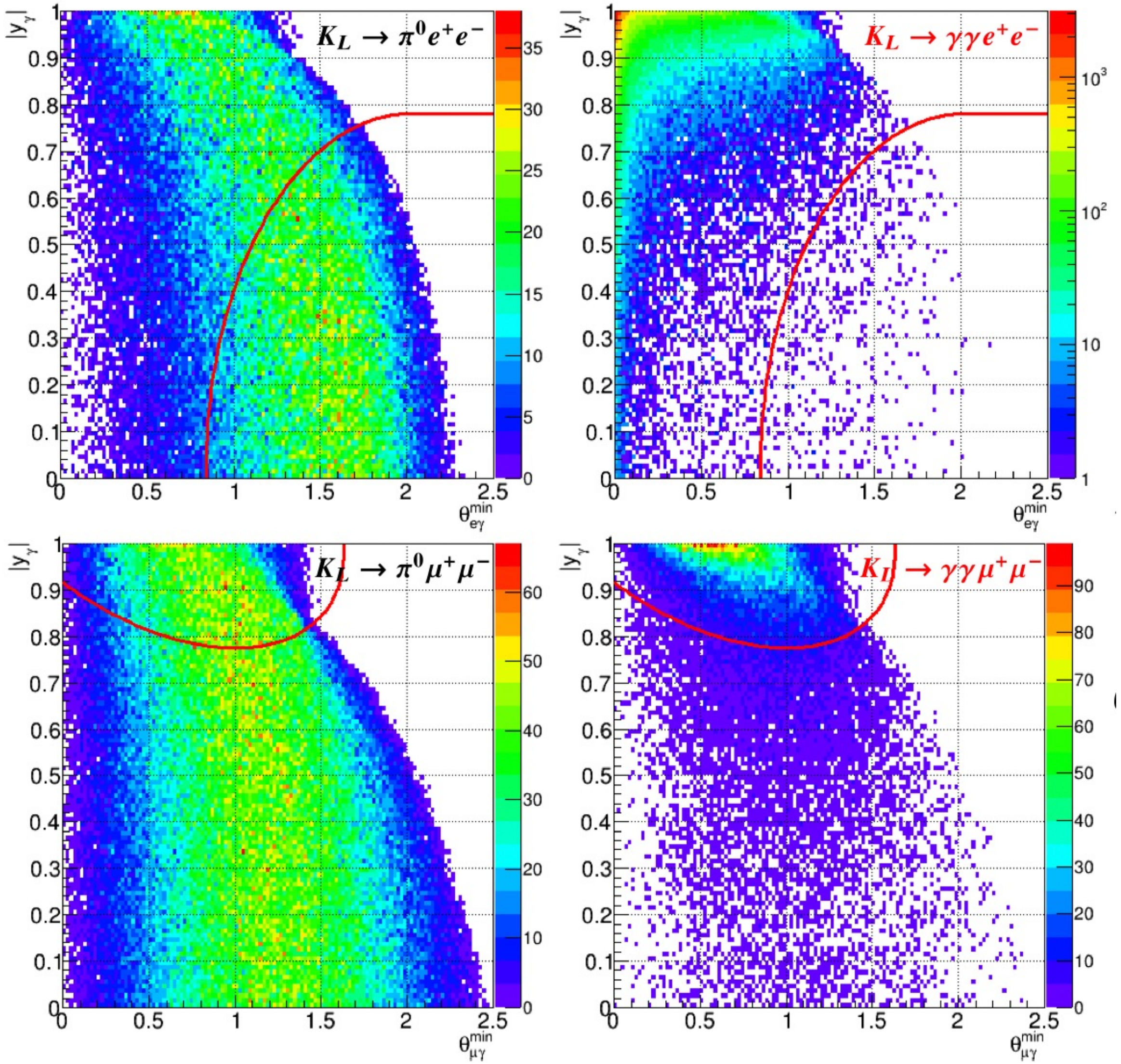
Mode	Phase space region	Branching ratio
$K_L \to \gamma\gamma e^+e^-$	$x = (m_{ee}/m_K)^2 > 0.05$, $x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.55 \pm 0.05) \times 10^{-7}$
$K_L \to \gamma\gamma\mu^+\mu^-$	$x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.49 \pm 0.28) \times 10^{-9}$

$K_L \to \pi^+\pi^-\pi^0$ 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

High Intensity Kaon Experiments



The kinematic selection is based on two reconstructed variables:

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

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

HIKE
High Intensity Kaon Experiments

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

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

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

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 $\lambda_t = V_{ts}^* V_{td}$:

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

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.

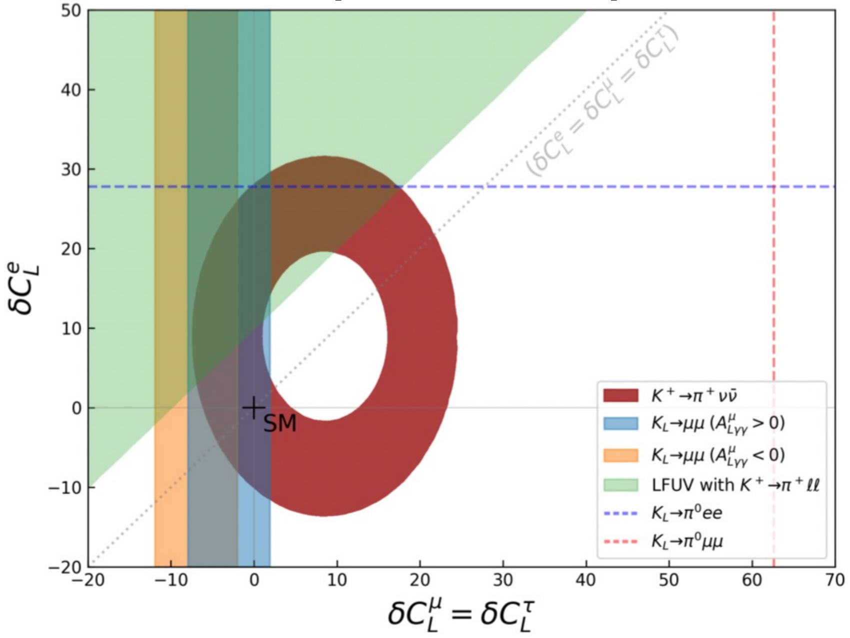
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

$$C_k^\ell = C_{k,\rm SM}^\ell + \delta C_k^\ell$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

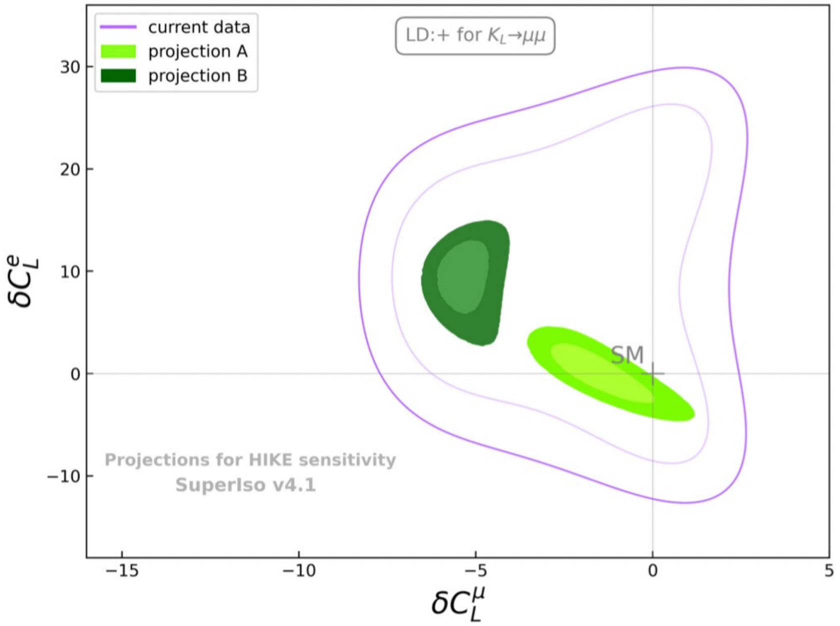
$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

[arXiv:2206.14748]

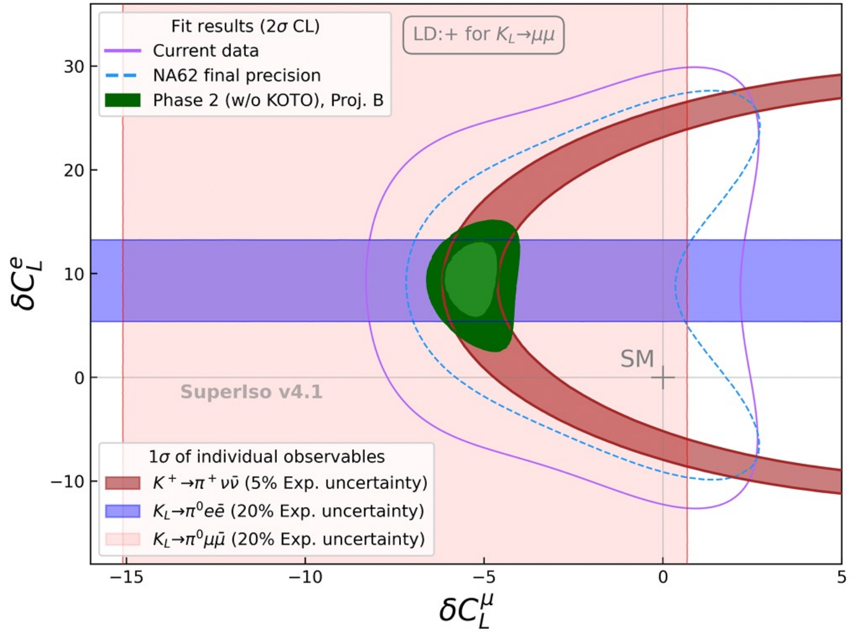


Bounds from individual observables.
Colored regions are 68% CL measurements
Dashed lines are 90% CL upper limits

[arXiv:2207.04956]



[arXiv:2311.04878]



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

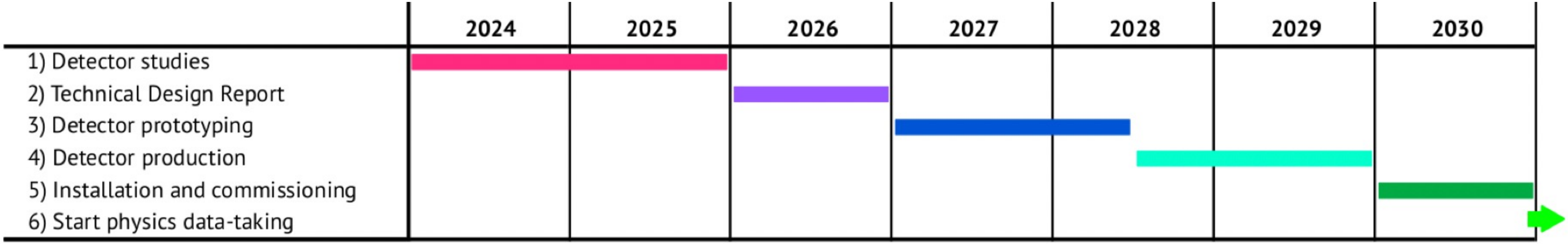
HIKE Kaon Physics Programme

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
Cherenkov K^+ tagger	upgraded	removed	faster photo-detectors
Beam tracker	replaced	removed	3D-trenchec silicon sensor
Upstream veto detectors	replaced	kept	SciFi
Large-angle vetos	replaced	kept	lead/scintillator tiles
Downstream spectrometer	replaced	kept	STRAW (ultra-thin straws)
Pion identification (RICH)	upgraded	removed	faster photo-detectors
Main EM calorimeter	replaced	kept	fine-sampling shashlyk
Timing detector	upgraded	kept	higher granularity
Hadronic calorimeter	replaced	kept	high-granularity sampling
Muon detector	upgraded	kept	higher granularity
Small-angle calorimeters	replaced	kept	oriented high-Z crystals
HASC	upgraded	kept	larger coverage



New Beam Tracker for HIKE

NA62 GigaTracker design:

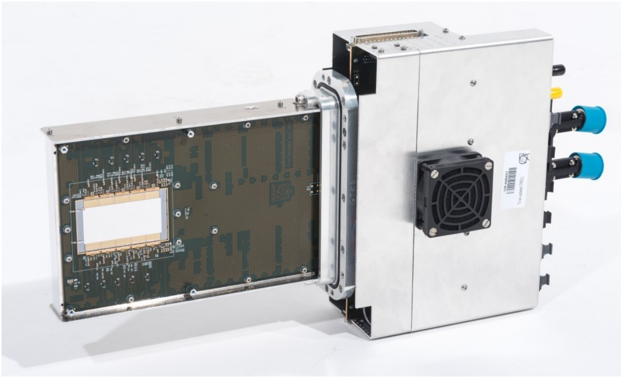
- Material budget: 0.5% X_0 per layer
- Use minimum number of planes, time mmts to constrain event reconstruction
- 200 µm planar silicon sensors
- TDCPix readout chips
- Cooled with silicon microchannel plates

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)

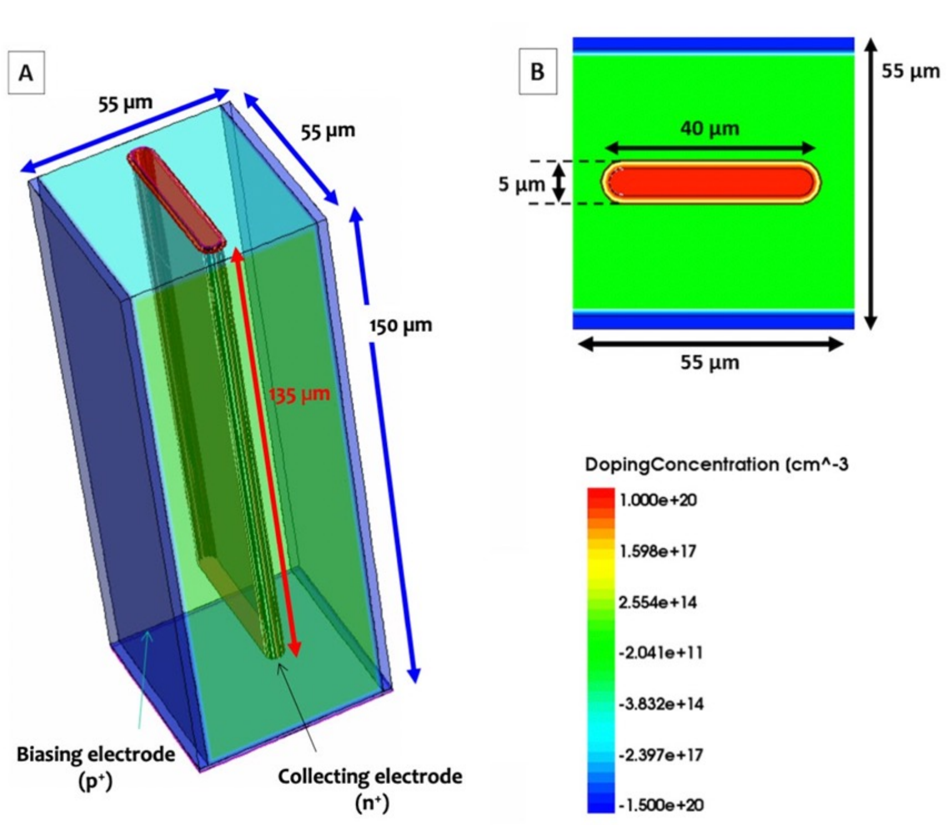
- $\sigma_s \approx 10$ µm (→ pixel pitch ≈ 40-60 µm)
- $\sigma_t \leq 50$ ps on full chain ($\sigma_t = \sigma_{sensor} \oplus \sigma_{FE} \oplus \sigma_{TDC}$)
- Radiation hardness to $\Phi = 10^{16} \div 10^{17}$ 1 MeV n_{eq}/cm^2
- Detection efficiency >99% per layer
- Material budget < 1÷0.5% X_0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

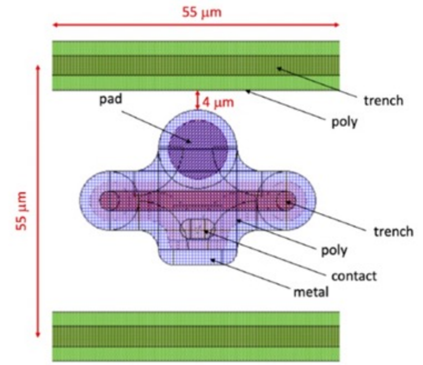
Silicon detectors with fast timing information capable to operate in a high-radiation environment → shared interest with HL-LHC experiments

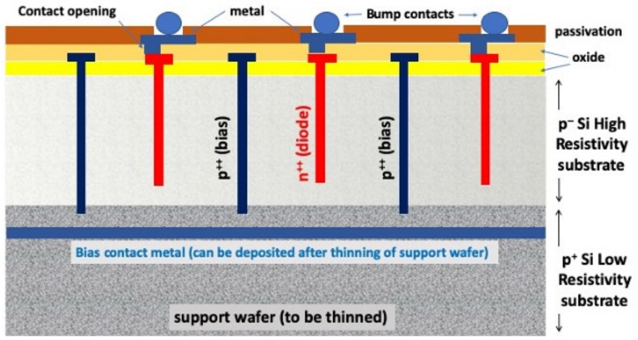
The trench-type TimeSPOT 3D pixels

High Intensity Kaon Experiments

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







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

Trench geometry improves charge collection time uniformity

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

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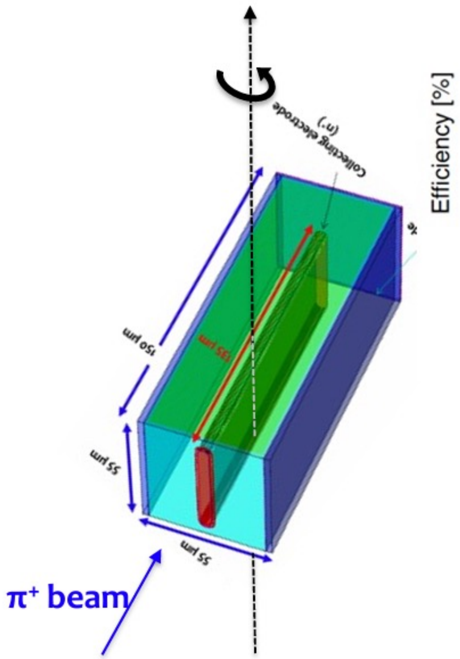
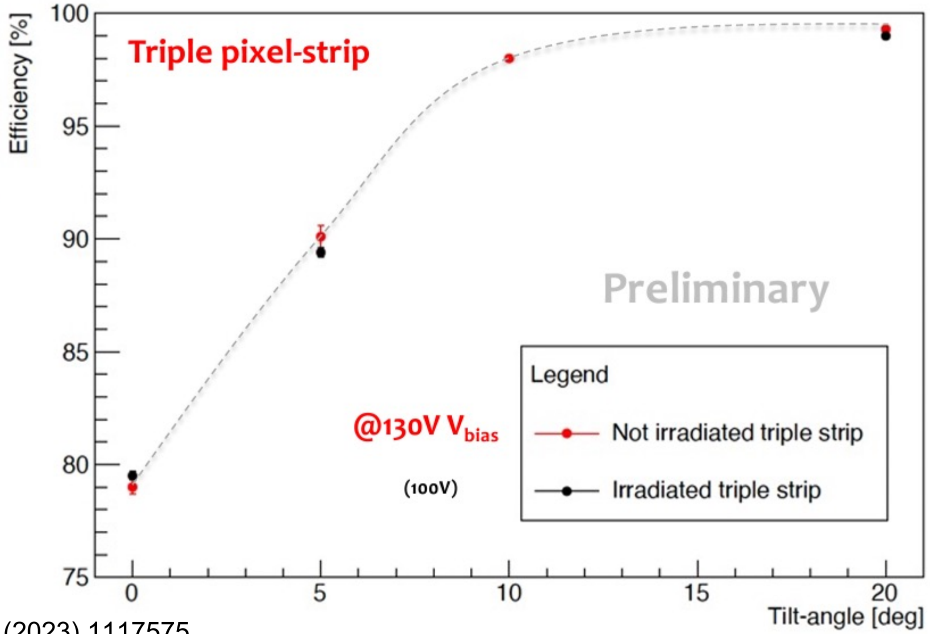
The trench-type TimeSPOT 3D pixels

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





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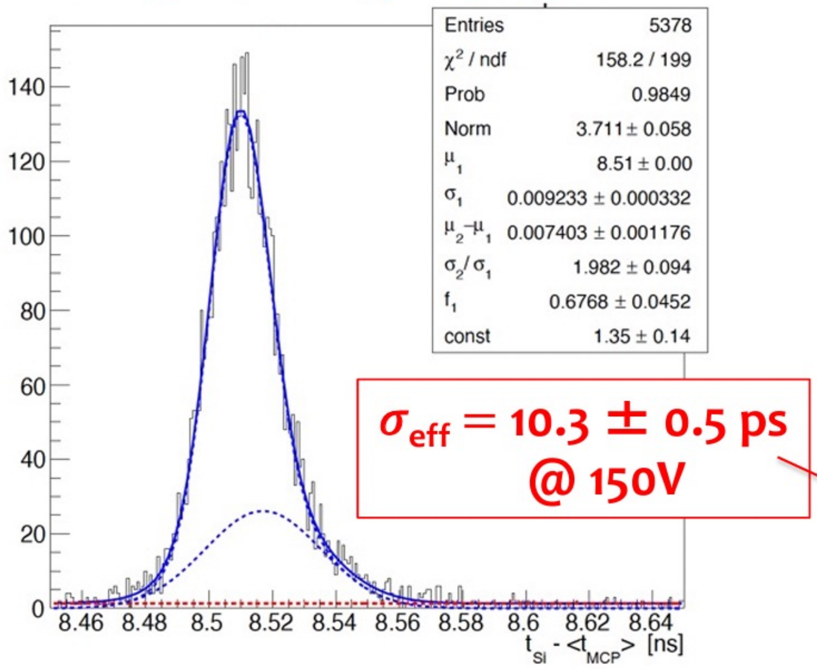
Irradiated @ 2.5 10^{16} n_{eq}/cm^2, $\alpha_{tilt} = 0°$



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/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

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

KTAG Photon Detector Design for HIKE

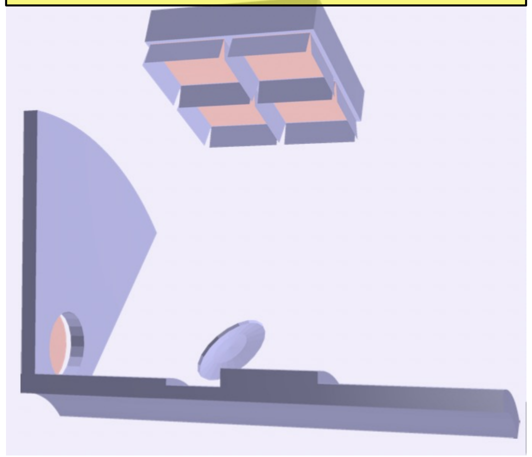
High Intensity Kaon Experiments

Replacement of existing PMTs and light guides

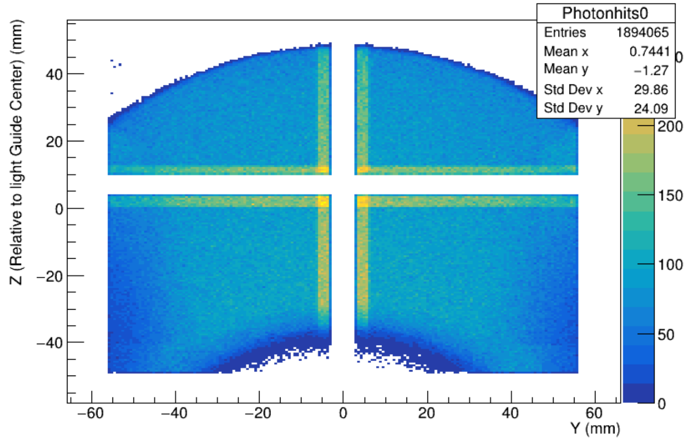
- Instrumented KTAG area/octant ~ 10cm*15cm
- Use a matrix of 4 MCP-PMTs/octant
- Expected MCP-PMT pixel/anode rate ~2-3MHz
- Total number of channels: 2048

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

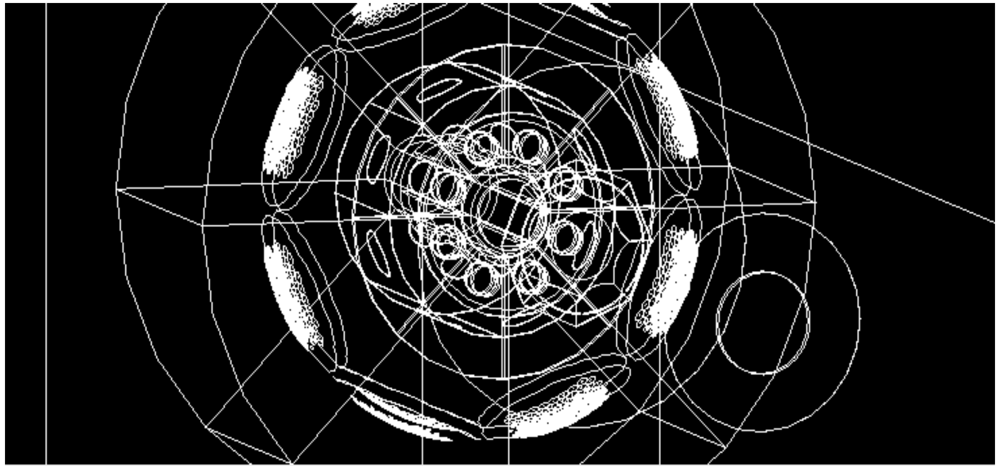


Photon distribution at MCP-PMT plane

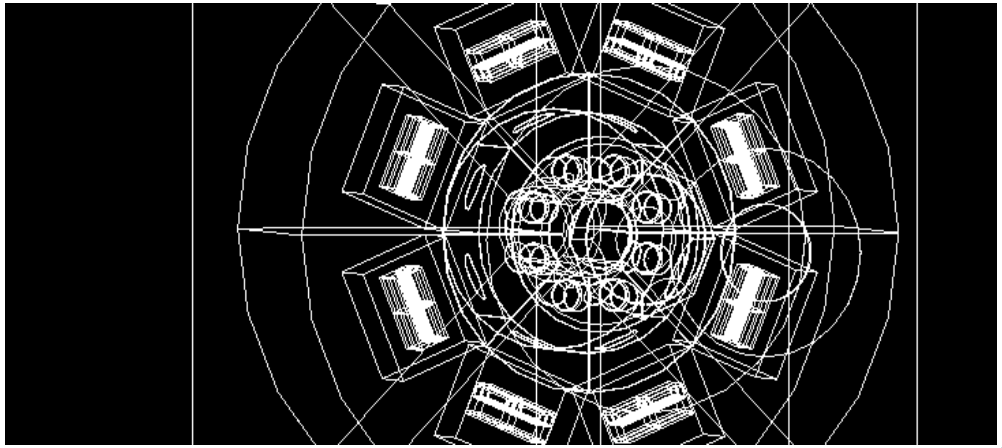


Simulations developed in Birmingham:

KTAG with PMTs for NA62



KTAG with MCP-PMTs for HIKE



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

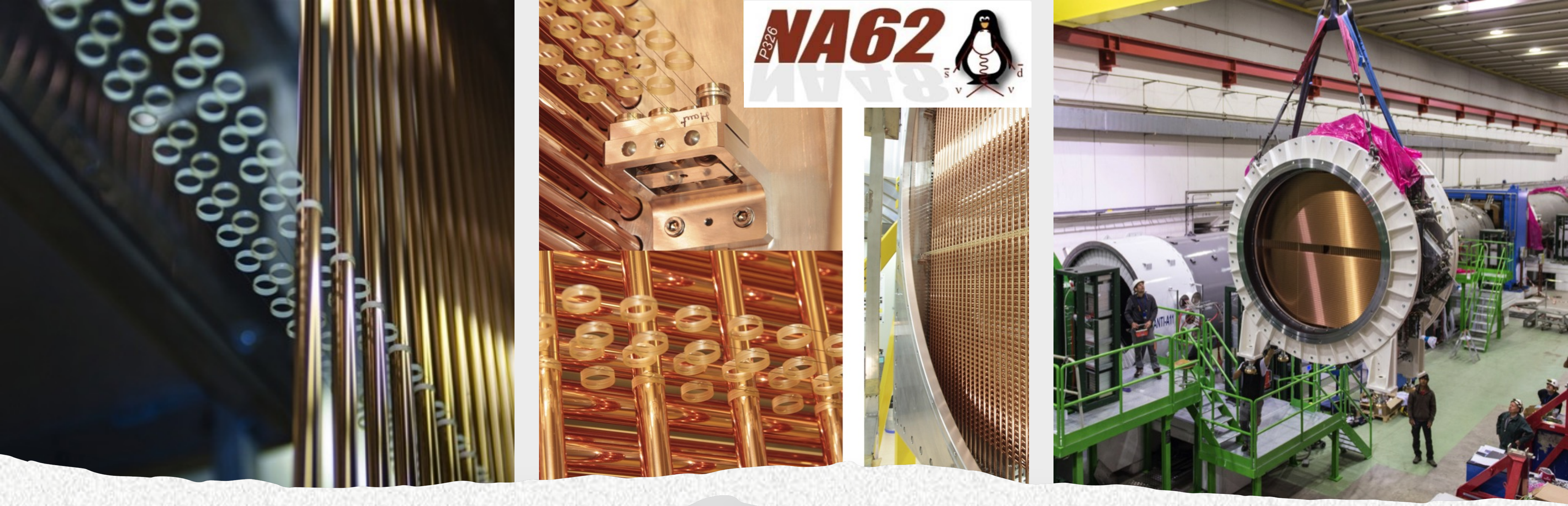
Region to be instrumented with new photo-sensors

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 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:

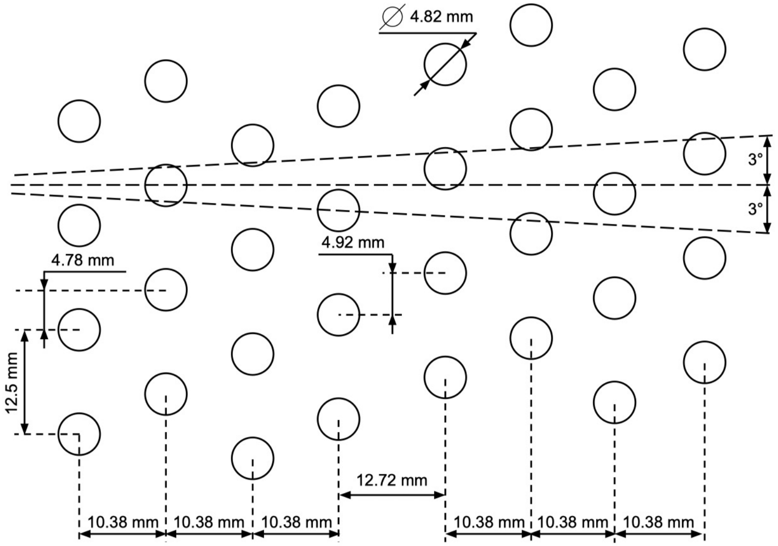
- ❖ **Increased rate capability** (reduced straw diameter, use fast shaping)
- ❖ Improved momentum resolution (reduced material budget, improve position resolution)

- ✓ **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

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

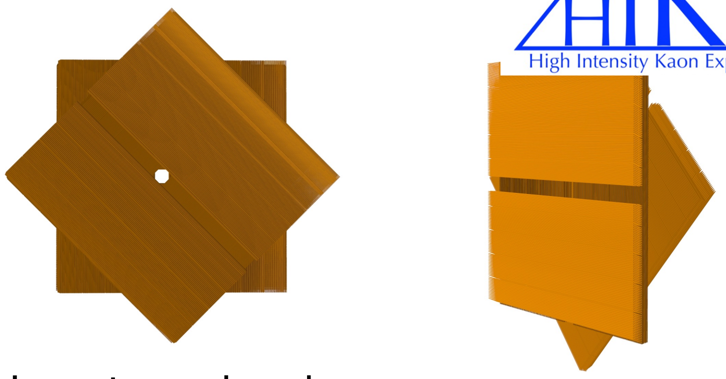
Optimised layout of straw tubes with 4.82 mm diameter in a single view



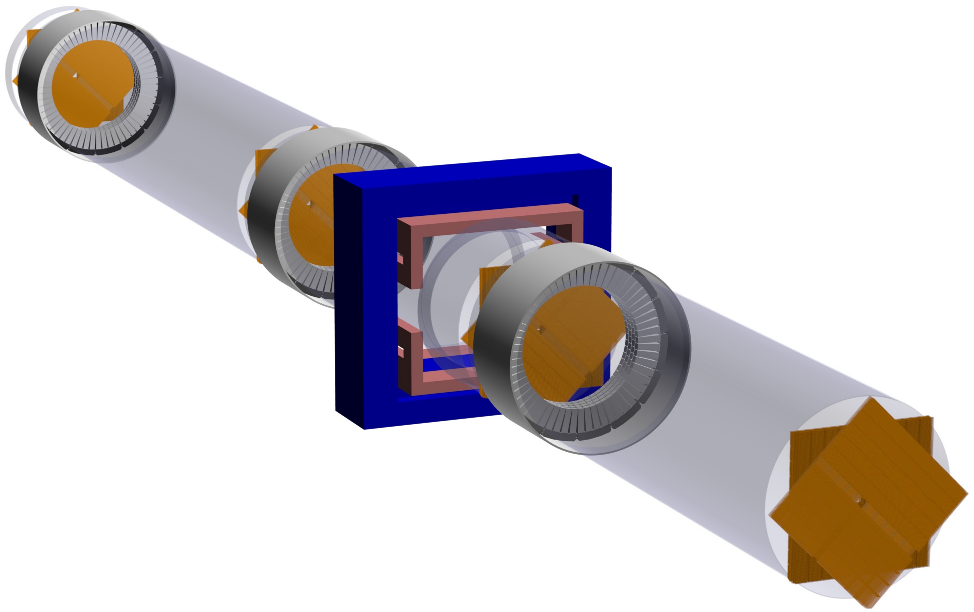
The HIKE STRAW Spectrometer

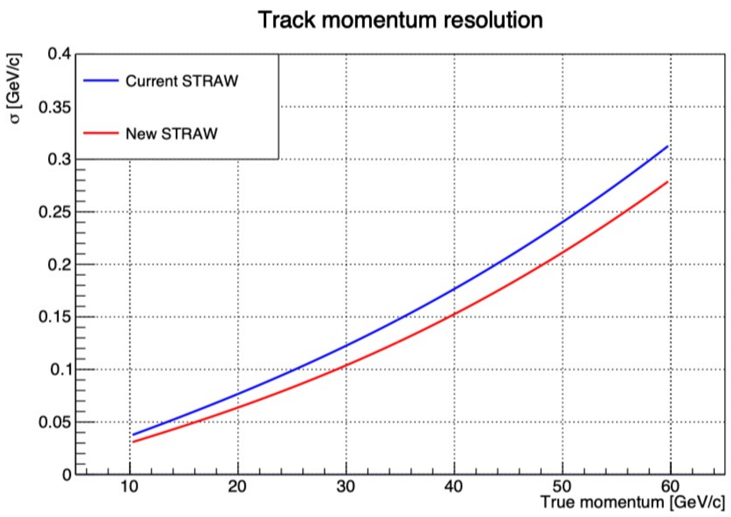
Geant4 visualization of the new STRAW spectrometer

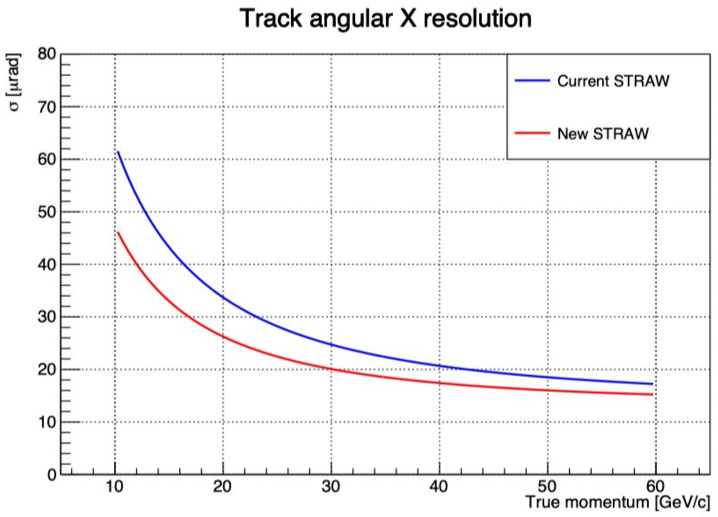
Same assumptions as in current NA62 layout:
- ✓ dimensions and positions of STRAW chambers
- ✓ number and orientation of views per chamber
- ✓ gas composition (Ar + CO_2 with 70:30 ratio)
- ✓ properties of dipole magnets



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

The HIKE Electromagnetic Calorimeter

Principal photon veto for $K^+ \to \pi^+ \nu\bar{\nu}$ (Phase1); π^0 reconstruction, PID, extra photon veto for $K_L \to \pi^0 l^+ l^-$ (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: $1-\varepsilon < 10^{-5}$ 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

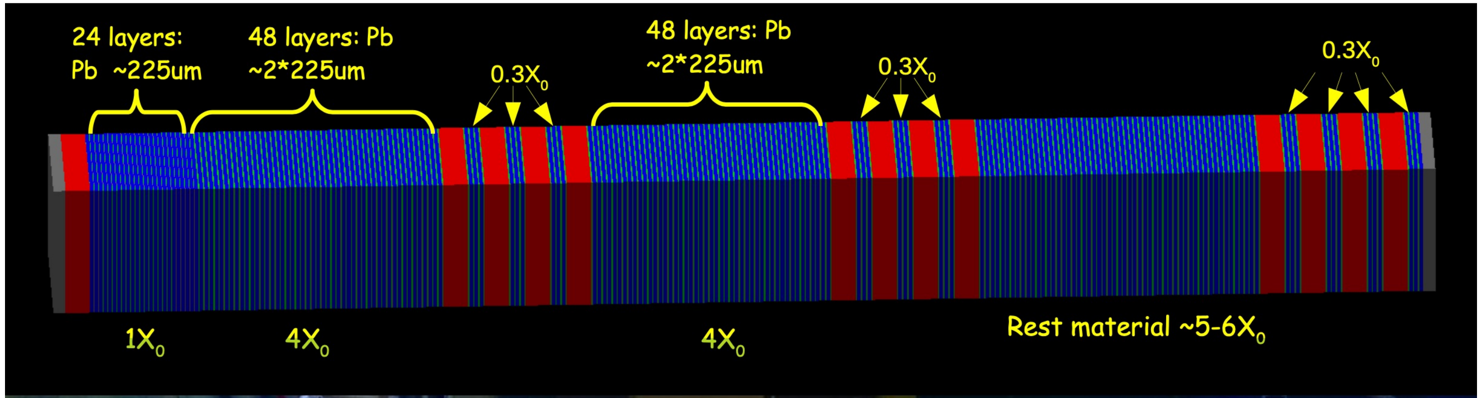
The Main Electromagnetic Calorimeter (MEC)

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)

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



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

New for Phase2: Longitudinal shower information from spy tiles

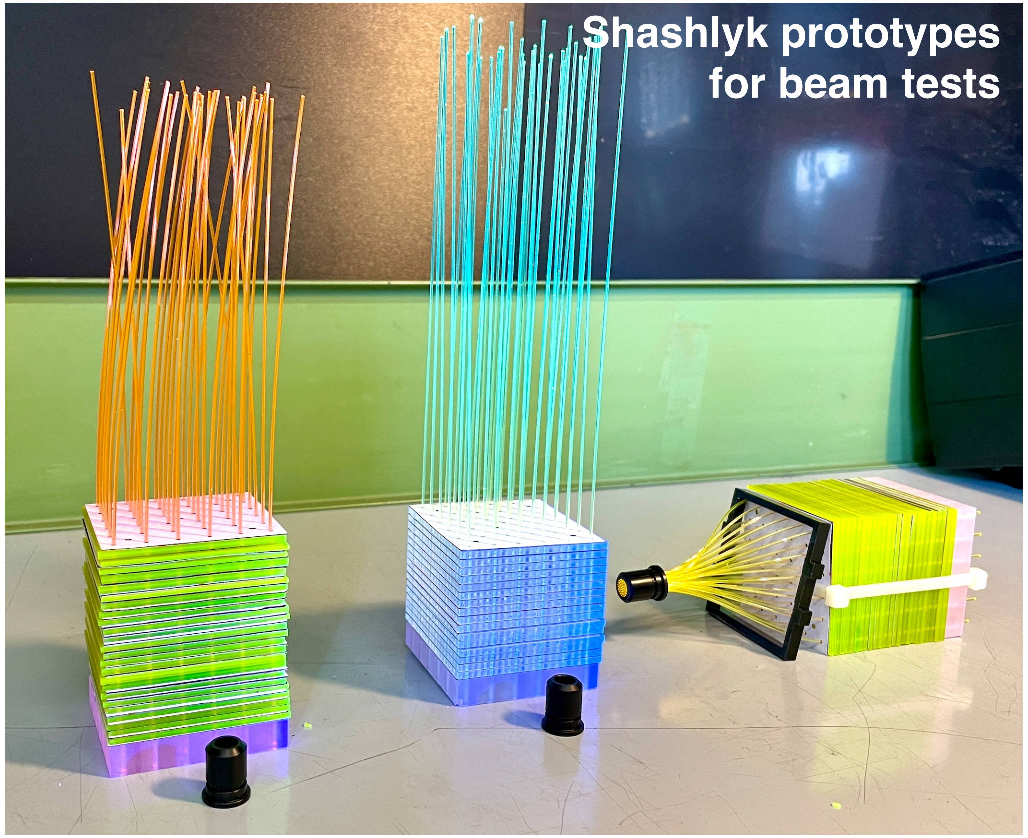
- PID additional info for γ/n separation
- 5-10x improvement in neutron rejection
- Overall neutron rejection at level of 10^3

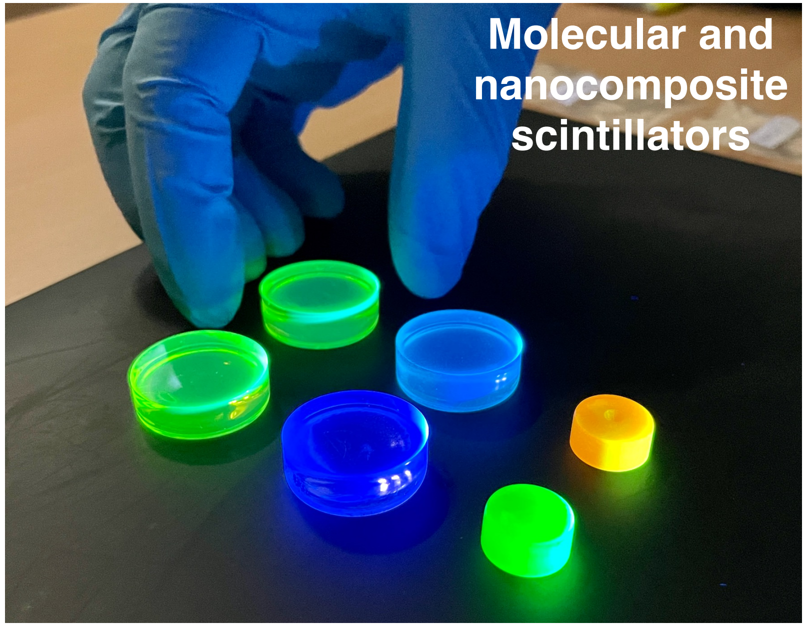
HIKE R&D on innovative scintillators

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

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($K^+ \to \pi^+ \nu\bar{\nu}$) at 5% precision
    - Measure BR($K_L \to \pi^0 l^+ l^-$) 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, oriented crystals. Ultra-fast photo-detectors

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