

HIKE: The High-Intensity Kaon Experiments at CERN

Status of the project

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University of Birmingham,
on behalf of HIKE



HIKE: 175 collaborators from 37 institutions

Kaon Experiments at CERN

A long and illustrious history !

HIKE will build on the experience of studying kaon physics at CERN over past four decades

$$\varepsilon_K, \Delta M_K$$

$$\varepsilon'/\varepsilon$$

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

$$K_L \rightarrow \pi^0 \nu \bar{\nu}$$

A.J. Buras KAON2016

$$K_L \rightarrow \mu^+ \mu^-$$

$$K_L \rightarrow \pi^0 e^+ e^-$$

$$K_L \rightarrow \pi^0 \mu^+ \mu^-$$

They all can give some information about very short distance scales but to identify new physics, correlations with $B_{s,d}$ and D observables, EDMs, Lepton physics crucial

Importance of kaon physics highlighted in the last European Strategy: findings of the last European Particle Physics Strategy Group in the deliberation document **CERN-ESU-014 “Rare kaon decays at CERN and KEK”** mentioned in Section 4 as

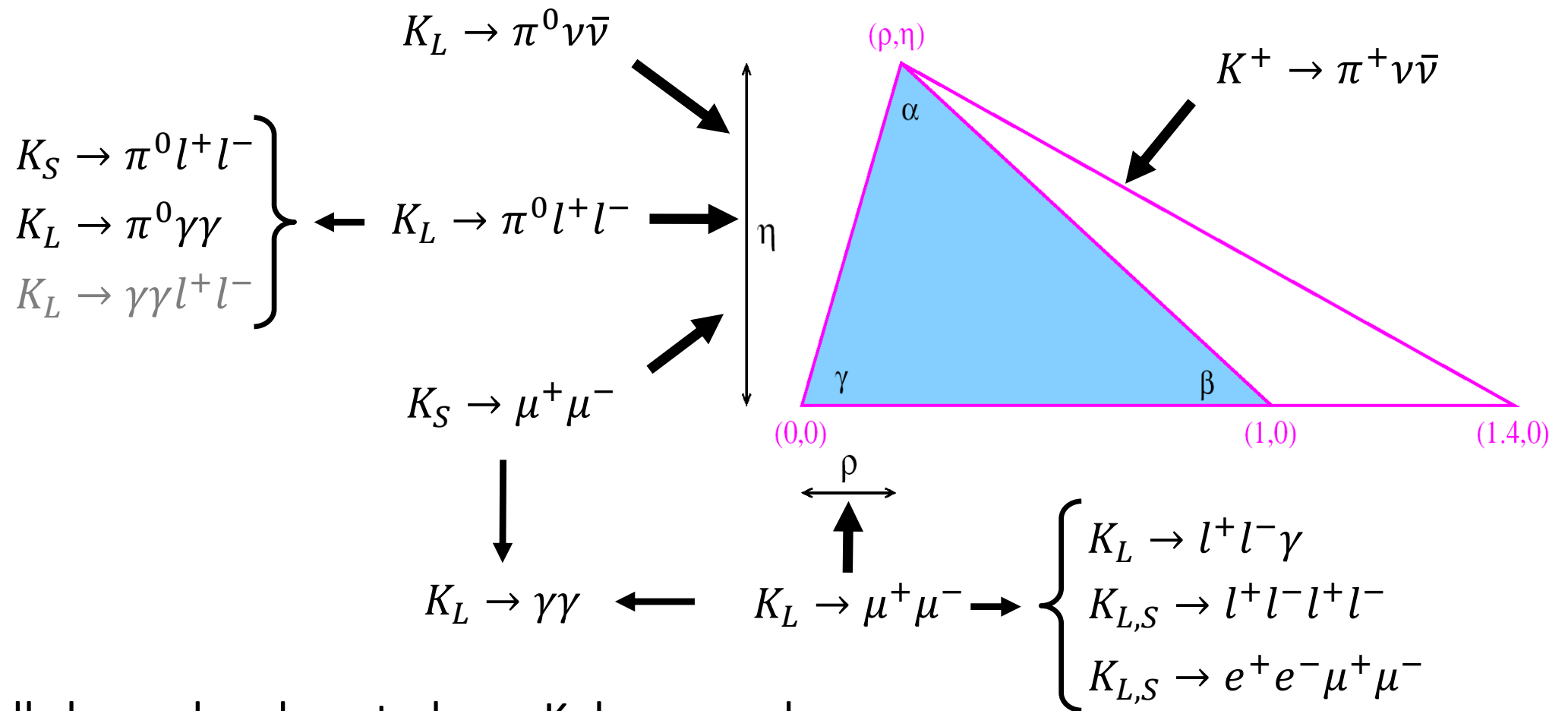
“Other essential activities for particle physics”.

Because of the relatively small number of kaon decay modes and the relatively simple final states, combined with the relative ease of producing intense kaon beams, kaon decay experiments are in many ways the quintessential intensity-frontier experiments.

Seeking new physics through Kaon decays

Over-constraining unitary triangle via kaon decays is a crucial compatibility test of the SM

Can reach unprecedented mass scales (well beyond those reachable at LHC) [arXiv:1408.0728]



Measuring all charged and neutral rare K decay modes can give clear insight about the new physics flavour structure

Scientific goals of HIKE

The HIKE comprehensive programme consists of several phases using shared detectors and infrastructure:

Phase 1: K^+

A multi-purpose K^+ experiment (after LS3)

Scrutiny the K^+ physics with the highest precision:

- Measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio to a 5% relative precision, matching the SM theoretical uncertainty.
- Precision measurements of $K^+ \rightarrow \pi^+ l^+ l^-$ decays, and a precision lepton universality test.
- Searches for lepton flavour/number violating decays and lepton universality tests
- Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision
- Improvement of other existing rare decay modes
- Searches for production of feebly-interacting particles in K^+ decays.
- Collection of a dataset in the beam-dump mode

Scientific goals of HIKE

Phase 2 and 3 : K_L (not before LS4)

Phase 2: a multi-purpose K_L experiment

Measure K_L modes of particular interest:

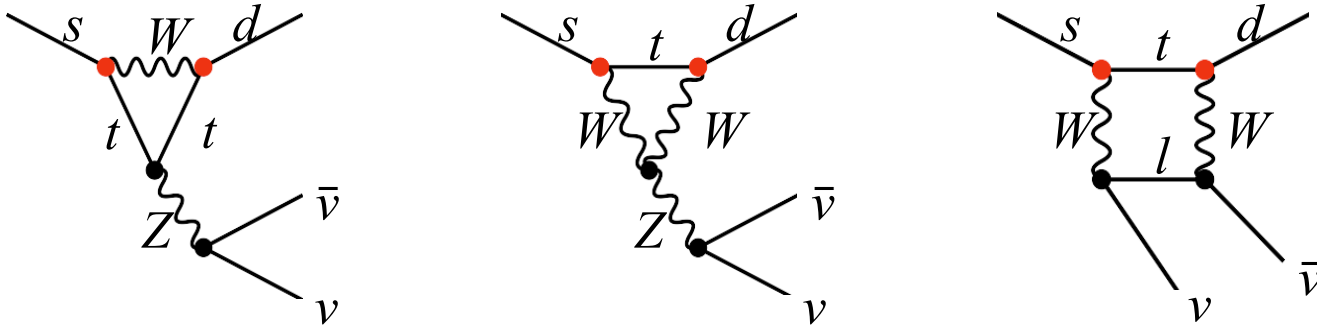
- Observation of the ultra-rare decays $K_L \rightarrow \pi^0 l^+ l^-$ or establishment of stringent upper limits at $O(10^{-11})$ level
- Measurement of the $K_L \rightarrow \mu^+ \mu^-$ decay branching ratio to a 1% relative precision
- Search for lepton flavour violating decays at the $O(10^{-12})$ sensitivity
- Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision
- Collection of a further dataset (up to 5×10^{19} POT) in the beam-dump mode (with appropriate time sharing with kaon mode)
- Characterisation of the neutral beam necessary to proceed to the third phase of HIKE.

Phase 3 (KLEVER):

Measure $K_L \rightarrow \pi^0 \nu \bar{\nu}$ to 20% relative precision

- Search for production and decay of feebly-interacting particles
- Search for additional FCNC K_L decays and forbidden K_L decays

Ultra-rare Kaon Decays $K \rightarrow \pi \nu \bar{\nu}$



A high-order process with highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

Extremely rare decays, rates very precisely predicted in SM

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407} \right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ} \right]^{0.74} \quad [\text{JHEP 1511 (2015) 033}]$$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}} \right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407} \right]^2 \cdot \left[\frac{\sin \gamma}{\sin 73.2^\circ} \right]^2$$

Error budget dominated by CKM inputs
[JHEP 1511 (2015) 033]

[[arXiv:2203.11960](https://arxiv.org/abs/2203.11960), [arXiv:2109.11032](https://arxiv.org/abs/2109.11032)] [[arXiv:2105.02868](https://arxiv.org/abs/2105.02868)]

“Free” from hadronic uncertainties
Exceptional SM precision

Non-parametric uncertainty:
1.5% for K_L , 3.5% for K^+

$K \rightarrow \pi \nu \bar{\nu}$ and flavour

Use measurements in global fit in order to factor out parametric uncertainties.

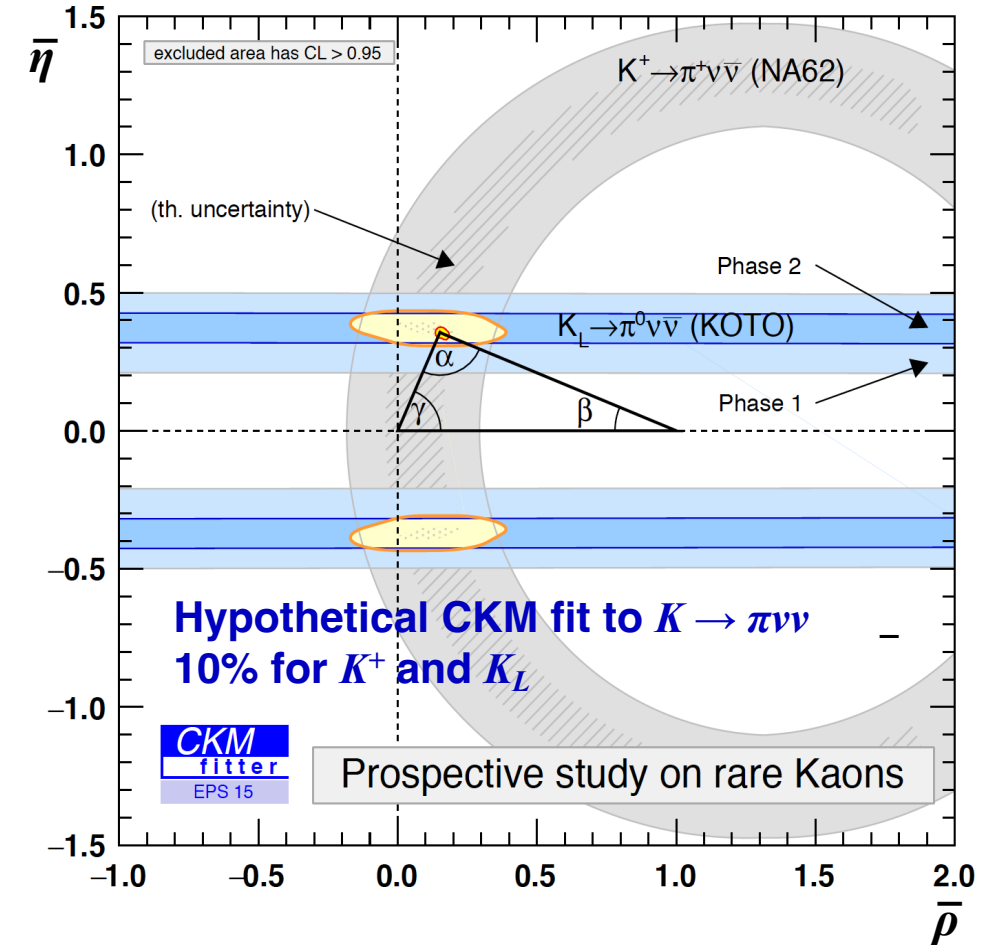
See recent example later in this talk, and in Felix's talk.

Or find combination of parameters that are less / not sensitive to New Physics: approach proposed recently to eliminate dependence on V_{cb} and gamma leads to 5% precision. Correlations with ε_k depends only on β and are well predicted, allowing experimental tests

[[arXiv:2203.11960](https://arxiv.org/abs/2203.11960), [arXiv:2109.11032](https://arxiv.org/abs/2109.11032), [arXiv:2203.09524](https://arxiv.org/abs/2203.09524)]

SM predictions accuracy expected to improve over the next decade also due to lattice QCD progress on the charm contribution

[[arXiv:1806.11520](https://arxiv.org/abs/1806.11520), [arXiv:1910.10644](https://arxiv.org/abs/1910.10644)]



Clear opportunity in the kaon sector

NA62 will measure $K^+ \rightarrow \pi^+ \nu \nu$ with O(10%) precision with Run1&2 data

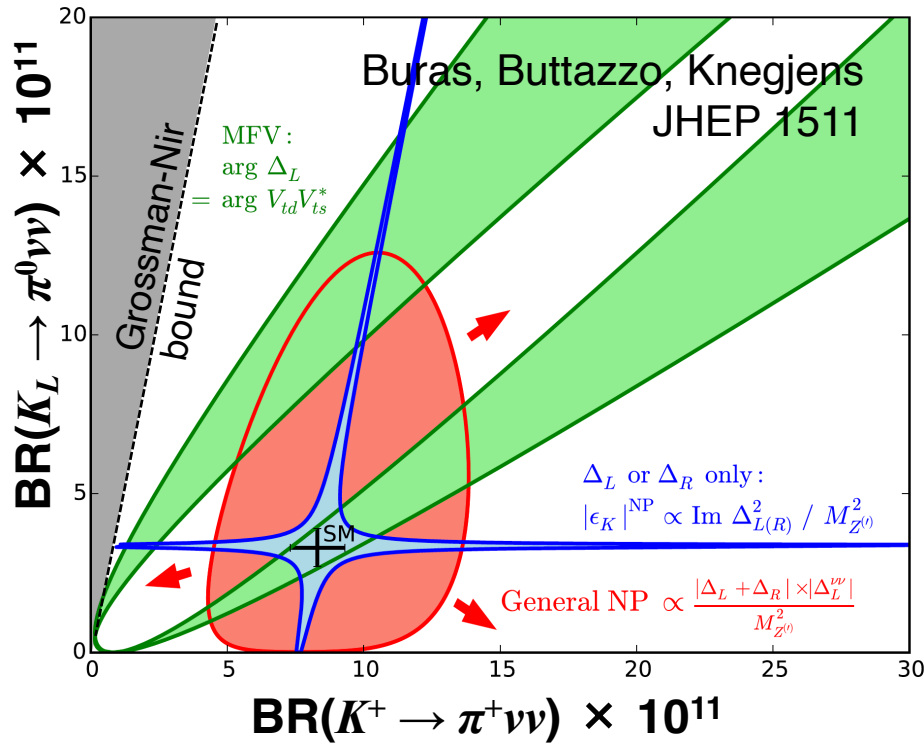
After LS3, experiments to approach theory error and show possible evidence of deviation from SM

High sensitivity to NP (non-MFV): significant variations wrt SM

New physics affects K^+ and K_L BRs differently

Measurements of both can discriminate among NP scenarios

Weak constraints from other observables



- Models with CKM-like flavor structure
 - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
 - Z/Z' models with pure LH/RH couplings
 - Littlest Higgs with T parity
- Models without above constraints
 - Randall-Sundrum

Going beyond 10% measurement on $K \rightarrow \pi + \nu \nu$
Precision measurements of $K \rightarrow \pi \nu \nu$ BRs provide model-independent tests for NP with sensitivity to O(100) TeV scale

[arXiv:1408.0728]

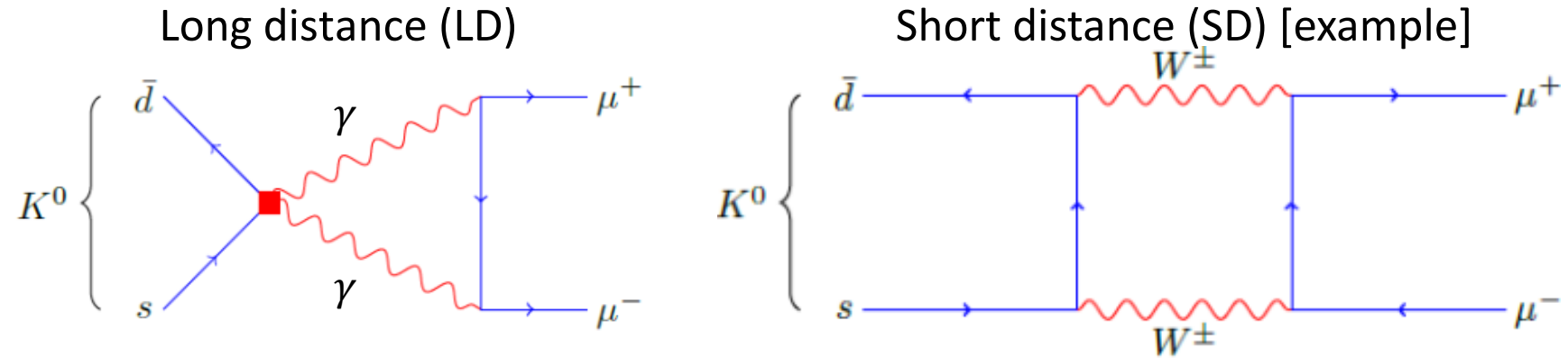
[JHEP 1511 (2015) 166, EPJ C76 (2016) 182, JHEP 0903 (2009) 108, PEPT 2016 123802, JHEP 0608 (2006) 064, EPJ C77 (2017) 618, arXiv:1705.10729, arXiv:2207.00018, arXiv:2203.09524]

$$K^0 \rightarrow \mu^+ \mu^-$$

FCNC: SD + important contributions from LD

[arXiv:1707.06999, arXiv:2104.06427]

SD: CPV for K_S , CPC for K_L



$$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{SM} \propto |A_L^{LD} + A_L^{SD}|^2, |A_L^{SD}|^2 \propto |1 - \bar{\rho}|^2$$

[Buras, and Fleisher,
Adv. Ser. Direct. High Energy Phys. 15, 65 (1998)]

$$\bullet \mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{meas} = (6.84 \pm 0.11) \times 10^{-9} \sim |A_L^{LD}|^2 \quad [\text{PRL 84, 1389 (2000) [B871]}]$$

- Prediction depends on the sign of the $K_L \rightarrow \gamma\gamma$ amplitude that determines the effect of the SD – LD interference contribution

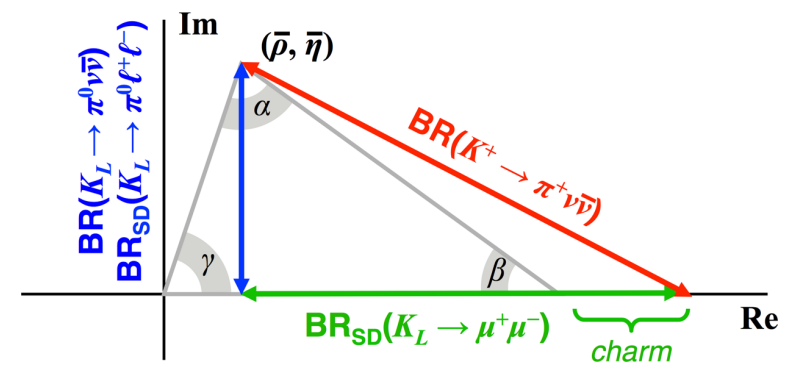
[Buras, and Fleisher,
Adv. Ser. Direct. High Energy Phys. 15, 65 (1998)]

$$[\text{LD+}]: \left(6.82_{-0.24}^{+0.77} \pm 0.04\right) \times 10^{-9}, \quad [\text{LD-}]: \left(8.04_{-0.97}^{+1.66} \pm 0.04\right) \times 10^{-9}$$

$K_L \rightarrow \pi^0 \ell^+ \ell^-$

[arXiv:hep-ph/0404127,arXiv:hpe-ph/0404136
 arXiv:hep-ph/0606081]
 [arXiv:0705.2025, arXiv:1812.00735, arXiv:1906.03046]

- Contributions from long-distance physics
 - SD CPV amplitude: γ/Z exchange
 - LD CPC amplitude from 2γ exchange
 - LD indirect CPV amplitude: $K_L \rightarrow K_S$
- $K_S \rightarrow \pi^0 \ell^+ \ell^-$ will help reducing theoretical uncertainties
 - measured NA48/1 with limited statistics
 - planned by LHCb Upgrade
- $K_L \rightarrow \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays



**$K_L \rightarrow \pi^0 \ell^+ \ell^-$ CPV amplitude
 constrains UT in same way as
 $BR(K_L \rightarrow \pi^0 \nu \nu)$**

SM:

$$\mathcal{B}(K_L \rightarrow \pi^0 e^+ e^-) = 3.54^{+0.98}_{-0.85} \left(1.56^{+0.62}_{-0.49} \right) \times 10^{-11}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \mu^+ \mu^-) = 1.41^{+0.28}_{-0.26} \left(0.95^{+0.22}_{-0.21} \right) \times 10^{-11}$$

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

**Experimental bounds
 from KTeV:**

$BR(K_L \rightarrow \pi^0 e^+ e^-) < 28 \times 10^{-11}$
 $BR(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$

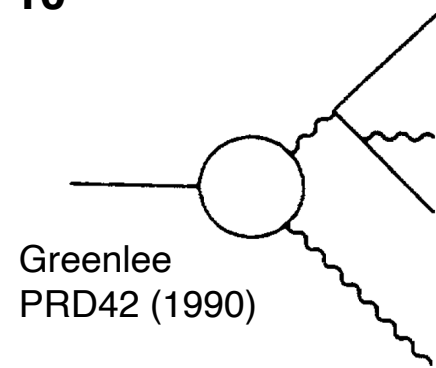
Phys. Rev. Lett. 93 (2004) 021805
 Phys. Rev. Lett. 84 (2000) 5279–5282

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

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

$BR(K_L \rightarrow e^+ e^- \gamma \gamma) = (6.0 \pm 0.3) \times 10^{-7}$
 $BR(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = 10^{+8}_{-6} \times 10^{-9}$

$E_\gamma^* > 5 \text{ MeV}$
 $m_{\gamma\gamma} > 1 \text{ MeV}$



**Theoretical work
 should be updated**

Test of Lepton Universality and Explicit SM Violation

Lepton Universality tests:

$$K^+ \rightarrow \pi^+ \mu^+ \mu^- \text{ vs } K^+ \rightarrow \pi^+ e^+ e^-, \quad R_K \equiv \Gamma(K^+ \rightarrow e^+ \nu) / \Gamma(K^+ \rightarrow \mu^+ \nu)$$

Search for LFV and/or LNV :

PDG 2022				
LFV mode	90% CL upper limit	Experiment	Yr./Ref.	Type
$K^+ \rightarrow \pi^+ e^- \mu^+$	1.3×10^{-11}	BNL-865	2005/ [16]	LFV
$K^+ \rightarrow \pi^+ e^+ \mu^-$	6.6×10^{-11}	NA62	2021/ [17]	LFV
$K_L \rightarrow \mu e$	4.7×10^{-12}	BNL-871	1998/ [18]	LFV
$K_L \rightarrow \pi^0 e \mu$	7.6×10^{-11}	KTeV	2008/ [19]	LFV
$K_L \rightarrow \pi^0 \pi^0 e \mu$	1.7×10^{-10}	KTeV	2008/ [19]	LFV
$K^+ \rightarrow \pi^- e^+ e^+$	5.3×10^{-11}	NA62	2022/ [20]	LNV
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	8.5×10^{-10}	NA62	2022/ [20]	LNV
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	4.2×10^{-11}	NA62	2019/ [21]	LNV
$K_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp$	4.12×10^{-11}	KTeV	2003/ [22]	LNV
$K^+ \rightarrow \pi^- \mu^+ e^+$	4.2×10^{-11}	NA62	2021/ [17]	LNFV

Search for feably interacting particle production: $K^+ \rightarrow l^+ N, K^+ \rightarrow \pi^+ X, \dots$

$$K^+ \rightarrow \pi^+ l^+ l^-$$

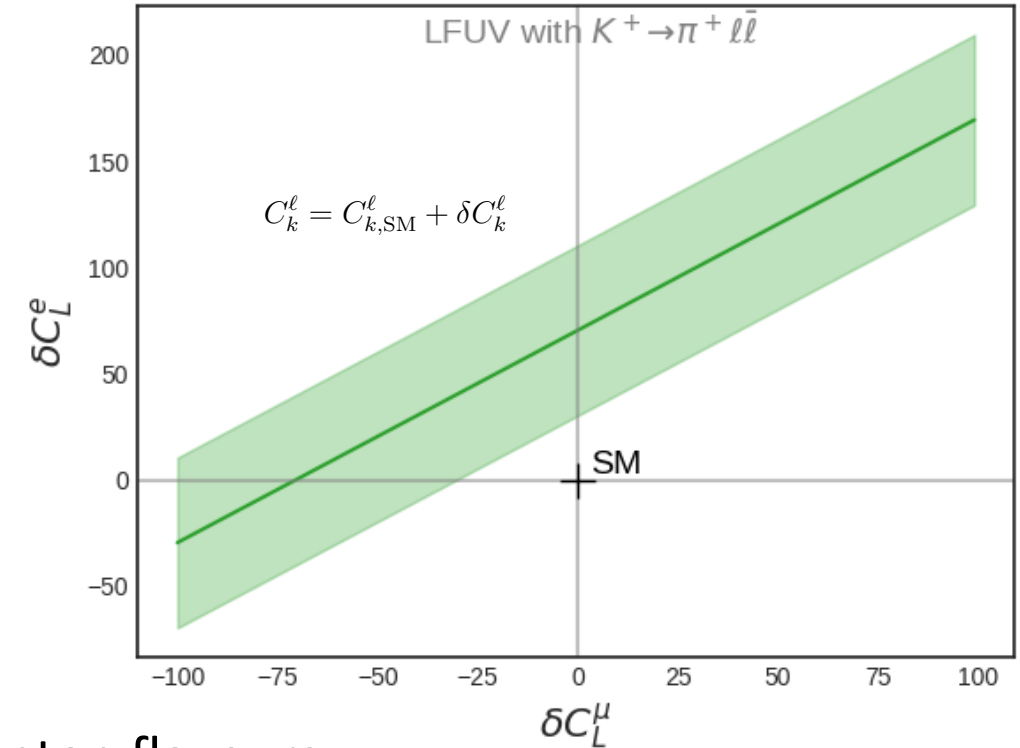
[arXiv:2206.14748]

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

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

$$z = m(l^+ l^-)^2 / M_K^2$$

Form factors (FF) $K_{3\pi}$ loop term
(non pert. QCD)



Long-distance effects are purely universal and same for all lepton flavours

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

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

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

Difference correlated to possible anomalies in B physics

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

The role of HIKE

The study of kaon sector makes HIKE complementary to LHCb and Belle II, whose physics goals focus on the B and D mesons.

Kaons provide different, and in some cases higher, sensitivity to NP than B and D mesons.

[arXiv:1408.0728]

NP scenarios	Process
Z-FCNC	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \varepsilon'/\varepsilon$
Z'	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \varepsilon'/\varepsilon, \Delta M_K$
Simplified models	$K_L \rightarrow \pi^0 \nu \bar{\nu}, \varepsilon'/\varepsilon$
LHT	All K decays
331 models	Small effects in $K \rightarrow \pi \nu \bar{\nu}$
Vector-like quarks	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \Delta M_K$
Supersymmetry	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$
2HDM	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$
Universal extra dimensions	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$
Randall-Sundrum models	All rare K decays
Leptoquarks	All rare K decays
SMEFT	Several processes in K system
SU(8)	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}$
Diquarks	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \varepsilon_K$
Vector-like compositeness	$K^+ \rightarrow \pi^+ \nu \bar{\nu}, K_L \rightarrow \pi^0 \nu \bar{\nu}, \varepsilon_K$

Presently, the main limitation to the investigation of these models comes from the experimental precision of the measurements of the kaon observables.

The primary goal of HIKE is to improve the accuracy of the measurements, in order to match and possibly challenge the theory precision, to study and measure for the first time channels not yet observed, and to search with unprecedented sensitivity for kaon decays forbidden by the SM.

[Table from arXiv:2203.09524]

The comparison between the flavour picture emerging from kaons with that from B mesons is a powerful tool to investigate indirect effects of NP

Kaon Global Fit

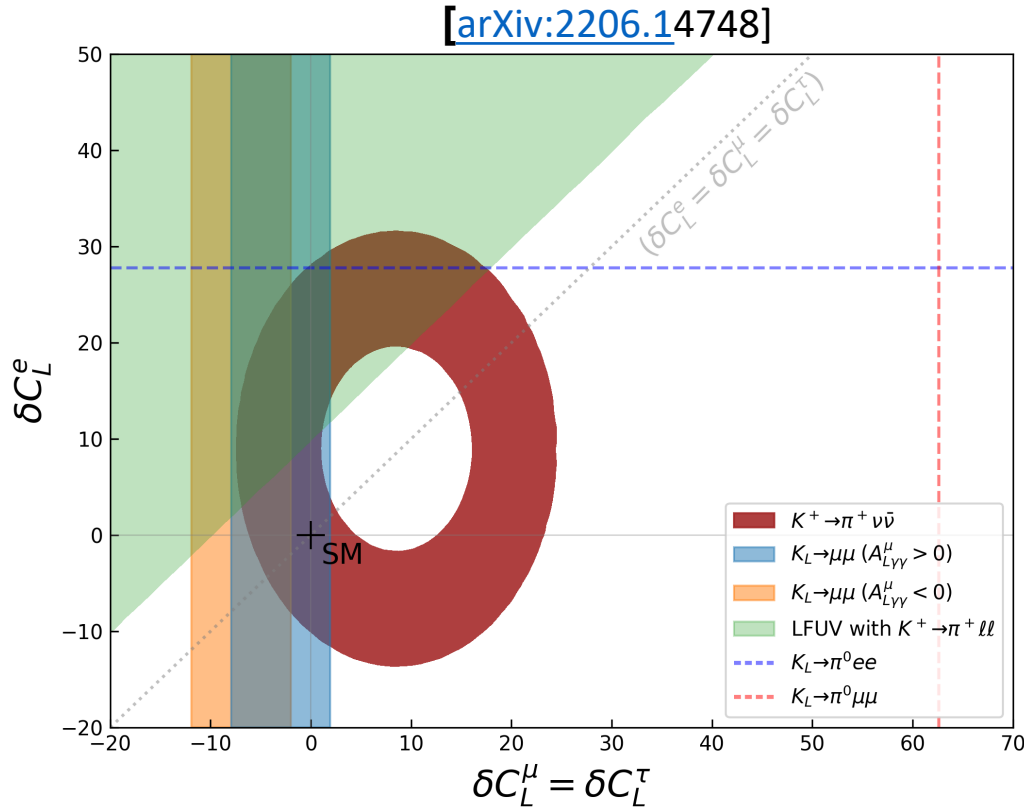
See also Felix Kahlhoefer's talk

For example, recent paper with global fits to set of kaon measurements
Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

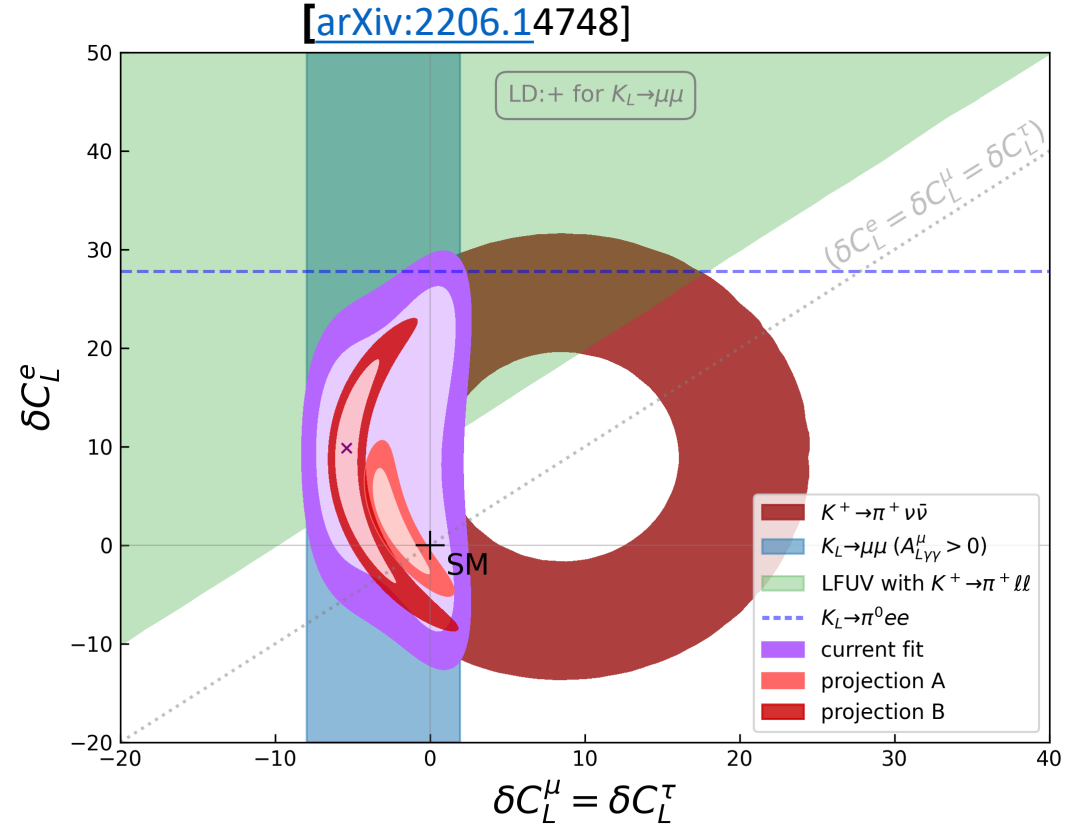
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \lambda_t^{sd} \frac{\alpha_e}{4\pi} \sum_k C_k^\ell O_k^\ell$$

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

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



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



With projections: central value for existing measurements kept the same, A upper bounds extrapolated to central value consistent with SM, B central value of all observables is projected to the best-fit points obtained from fits to existing data

Feebly interacting particles (dump phase)

Physics goals for operation in dump mode:

Search for visible decays feebly-interacting new-physics particles

Fixed-target configuration and the high beam intensity requirement make HIKE suitable to search for decays of FIPs, exploring regions mainly below the D mass, but with unprecedented sensitivity

Advantages of Kaon experiments:

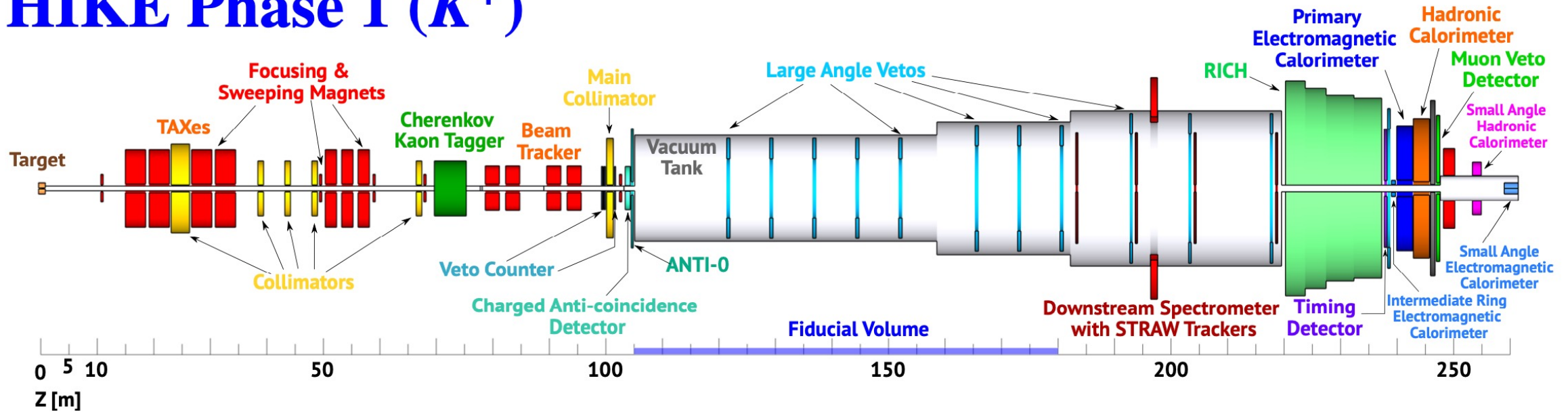
- Long decay volume and detector characteristics/performances suitable to search for feebly-interacting long-lived particles
- Extend Dark Particle mass range $> M(K)$ (D , B associated production)
- Low rate in detector allows for potentially very high beam intensity

Dump mode is most sensitive to forward processes, complimentary to off-axis experiments

In 2021, 1.4×10^{17} protons were collected in 10 days of NA62 data taking in beam-dump mode: data analysis shows that residual background is negligible, in particular when searching for two-body decays of new-physics mediators.

HIKE design

HIKE Phase 1 (K^+)



K^+ : $1.2 \cdot 10^{13}$ protons on T10 per spill (4.8 sec)

- Decay in flight technique, experience from NA62 and similar layout
- Essential K^+ ID, momentum, space and time
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

Improved timing is the crucial element to be able to increase intensity 4 x NA62

Statistical power:
 $2 \cdot 10^{13}$ Kaon decays in decay volume
per year

Technological solutions exists for all detectors

Beam Tracker

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

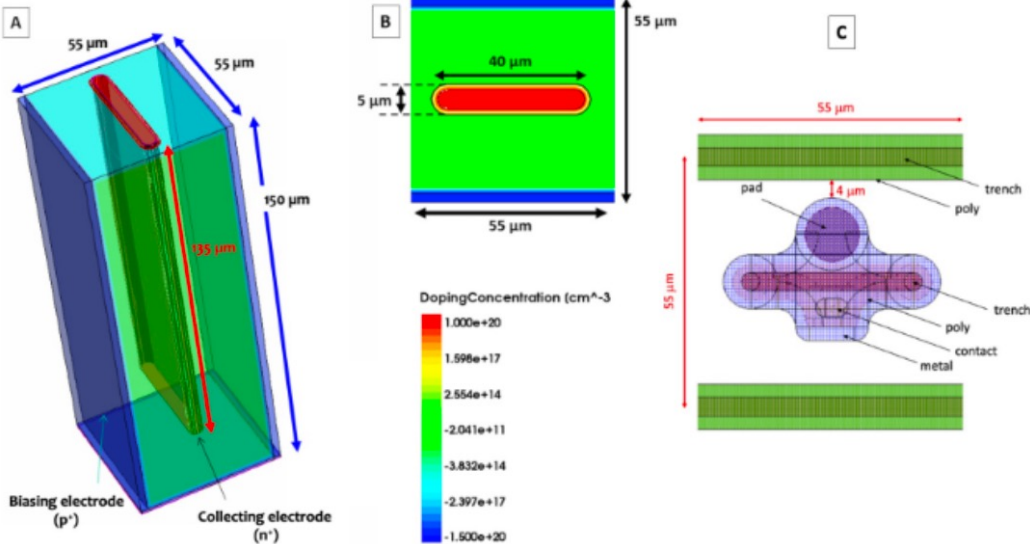
Interest for silicon detectors with fast timing information capable to operate in a high- radiation environment is shared among different experiments, including the LHC experiments for the high luminosity phase of the collider.

Hybrid 3D-trenched technology can satisfy all requirements.

Pixel electrode geometry optimised for timing performance. Able to withstand very large irradiation. Excellent detection efficiencies by operating the sensor inclined by angle 20° wrt beam incidence

Associated 28nm ASIC: first prototype TIMESPOST1

TimeSPOT

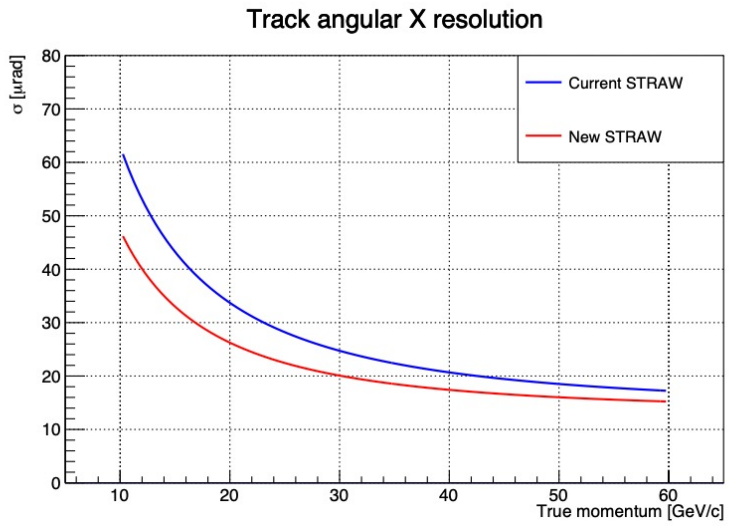
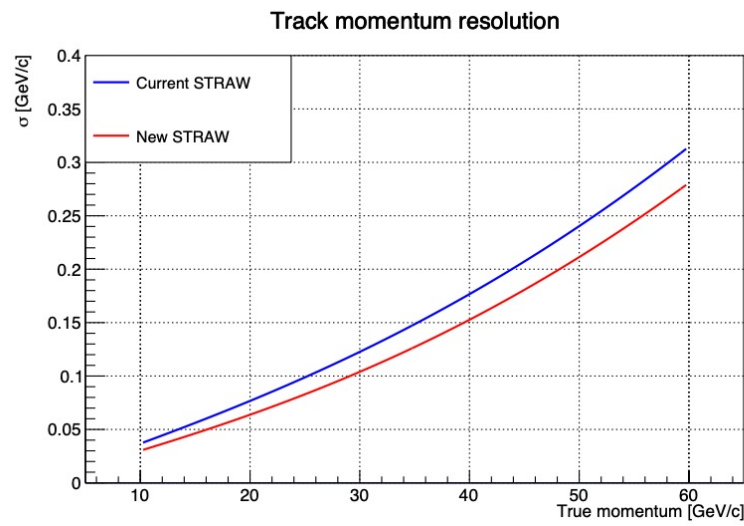
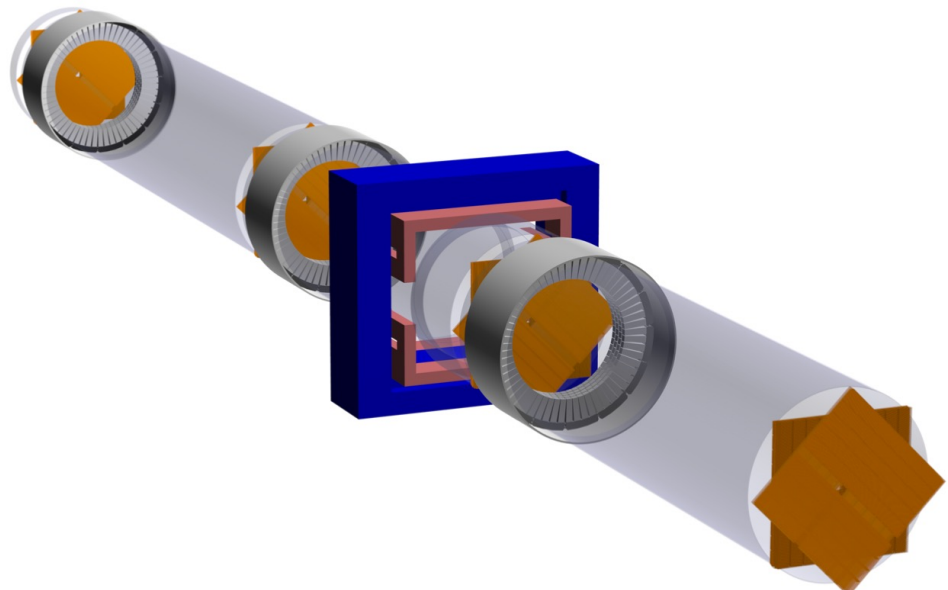
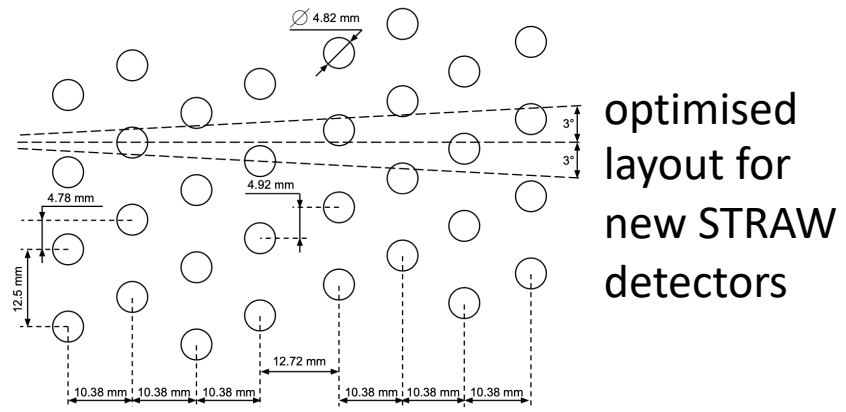
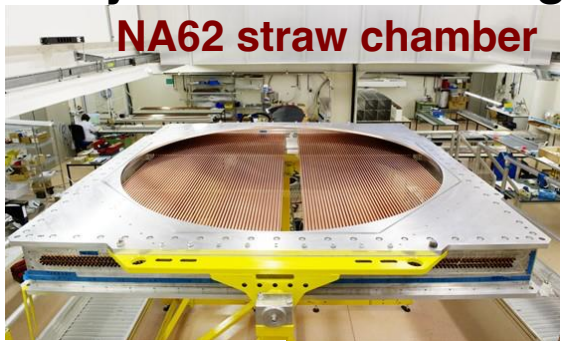


STRAW detector

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

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



HIKE Phase 1: Physics sensitivity

Keystones to achieve a branching ratio measurement with O(5%) precision:

- 1) **High efficiency and high-precision tracking** of both K^+ upstream and π^+ downstream, giving O(10^3) kinematic suppression of background
- 2) **High precision time measurements**, allowing time-matching between upstream and downstream detectors with O(20 ps) precision. From simulation: effect of higher intensity is totally compensated in matching between upstream and downstream tracks, without losing signal efficiency or increasing of background
- 3) **High-performance particle identification system**, suppressing background with muons by factor O(10^7)
- 4) **Comprehensive and hermetic veto systems**

Critical performance indicator: “random veto efficiency”

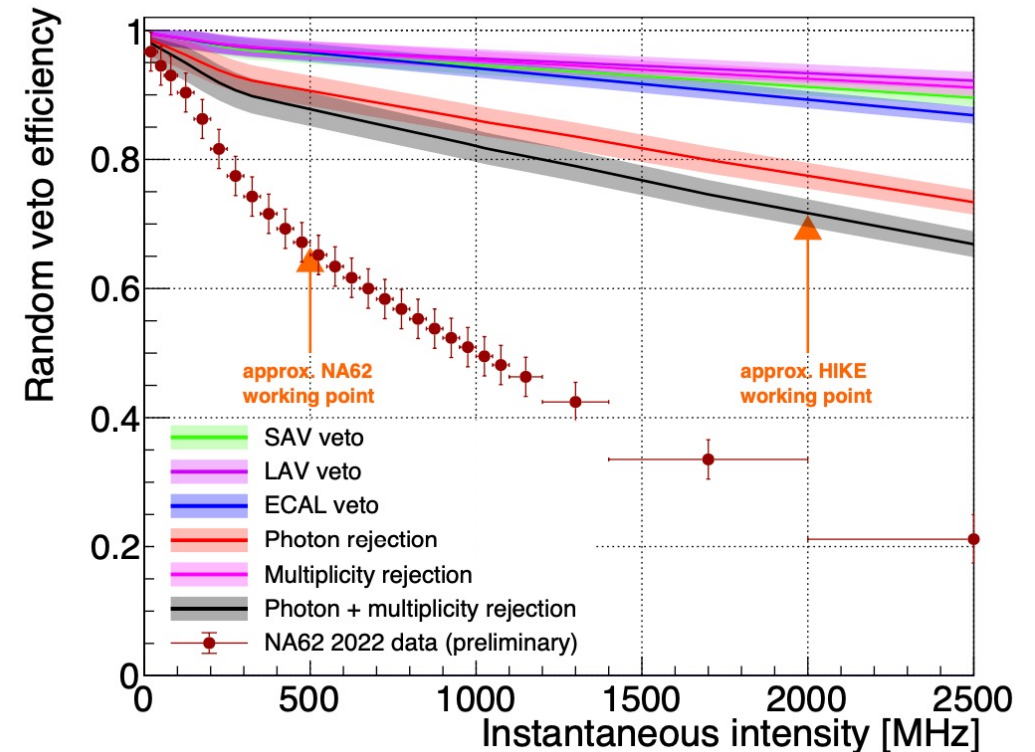
$$N_K/\text{year} \simeq 2 \times 10^{13}$$

$$\varepsilon_A \simeq 0.1$$

$$\varepsilon_{RV} \simeq 0.7, \varepsilon_{\text{trig}} \simeq 0.9$$

$$N(\pi\nu\nu)/\text{year} \simeq 100$$

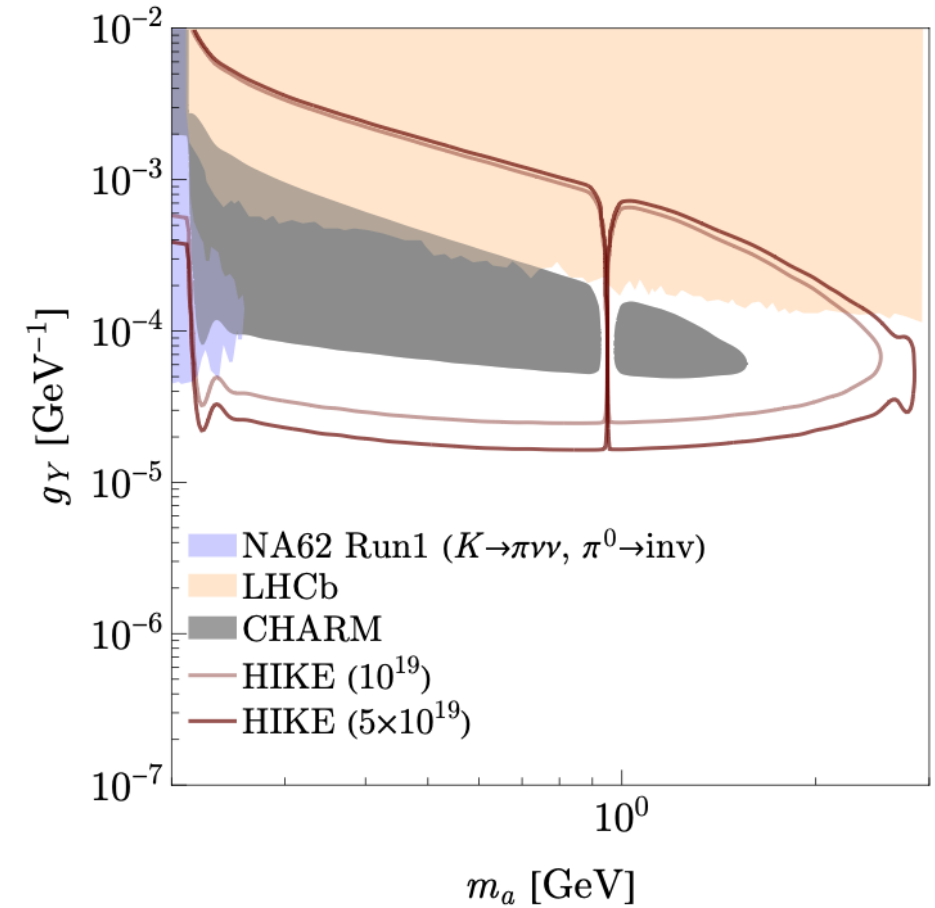
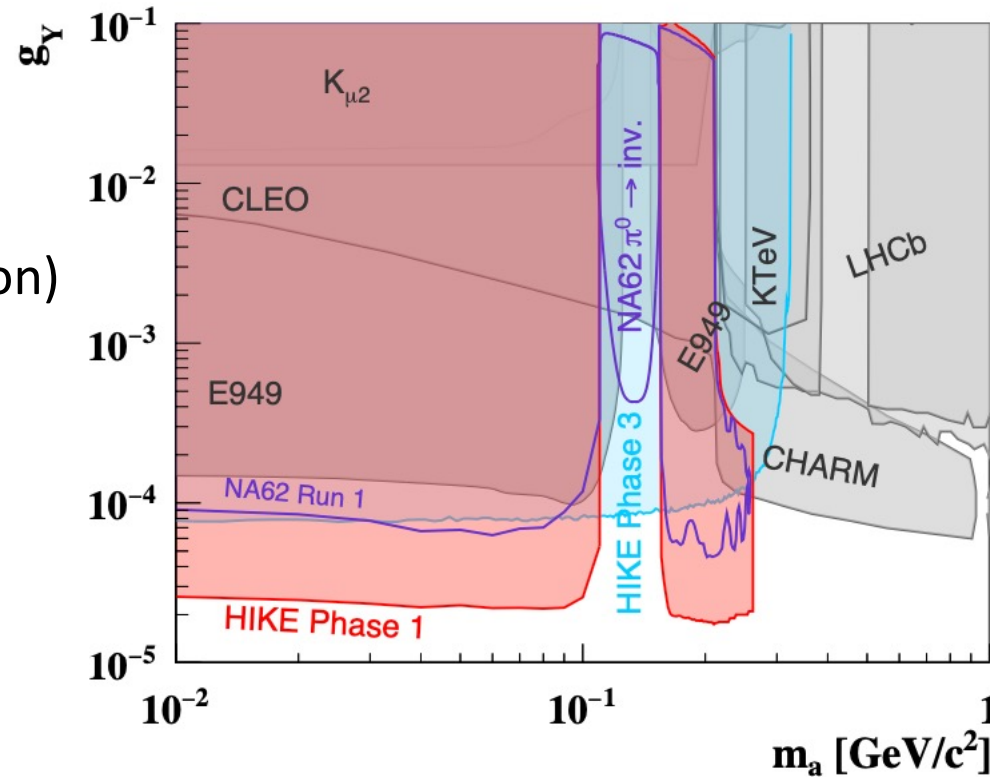
With O(10%) relative background contamination and systematic uncertainty under control, measurement of $B(K^+ \rightarrow \pi^+\nu\bar{\nu})$ to O(5%) precision done by HIKE in 4 years of data-taking



HIKE Phase 1: Physics sensitivity

Sensitivity to feebly interacting particles (decay and production)

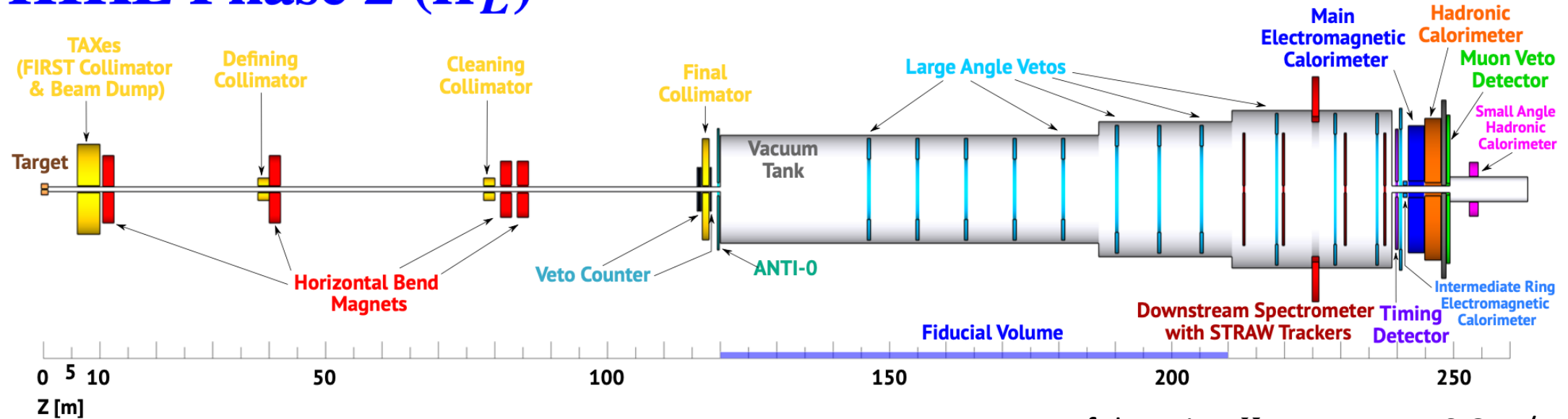
Example:
Axion-like, BC10



- HIKE Phase 1: **increase world samples of many rare K^+ decays by an order of magnitude.**
Many rare decay measurements to a new level of precision.
- **Collect background-free samples of several times 10^5 events of both $K^+ \rightarrow \pi^+ e^+ e^-$ and $K^+ \rightarrow \pi^+ \mu^+ \mu^-$**
Measure difference of the form-factor parameters a_+ and b_+ btw two decay modes to ± 0.007 and ± 0.015 precision
- **Searches for K^+ and π^0 decays violating LN or LF, not limited by background**
HIKE Phase 1 sensitivity: expected to improve almost linearly with size of the dataset, to $O(10^{-12})$

HIKE design

HIKE Phase 2 (K_L)



Mean momentum of decaying K_L mesons = 46 GeV/c

K_L + tracking: $2 \cdot 10^{13}$ protons on T10 per spill (4.8 sec)


- 120 m long neutral beamline, secondary beam opening angle = 0.4 mrad
- using detectors of previous phase, with some detectors removed, except for main calorimeter
- minor modifications to make left/right symmetric and optimize geometrical acceptance. Reduction of dipole-magnet field by about 20%.

Statistical power:
 $3.8 \cdot 10^{13}$ Kaon decays in decay volume per year

Electromagnetic Calorimeter

Main electromagnetic calorimeter requirements:

excellent efficiency and time resolution ($\sim 100\text{ps}$), good two-cluster separation, good energy resolution

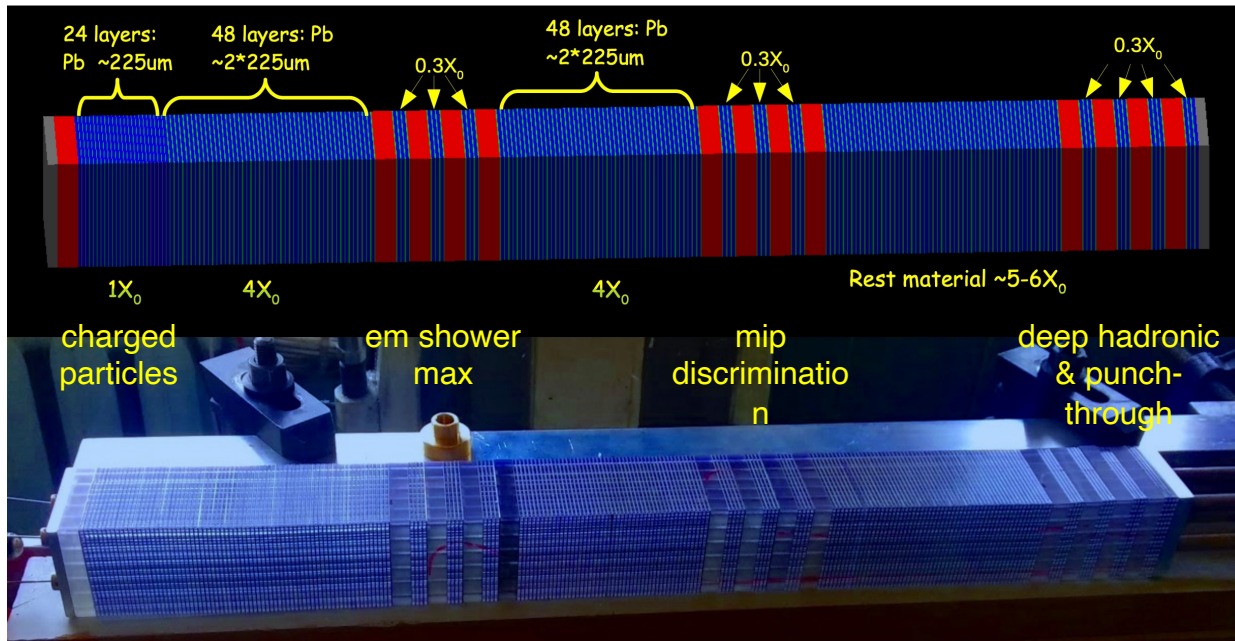
Quasi-homogeneous ionization calorimeter, $27X_0$ of LKr @ **NA62** 

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$
$$1 - \varepsilon < 10^{-5} \text{ for } E_\gamma > 10 \text{ GeV}$$
$$\sigma_t \sim 500 \text{ ps for } \pi^0 \text{ with } E_{\gamma\gamma} > 20 \text{ GeV}$$

All performances are suitable for Phase 1 but time performance

To be improved with major readout upgrade

Or alternative calorimeter, that anyway is needed for K_L



Fine-sampling shashlyk based on PANDA forward EM calorimeter

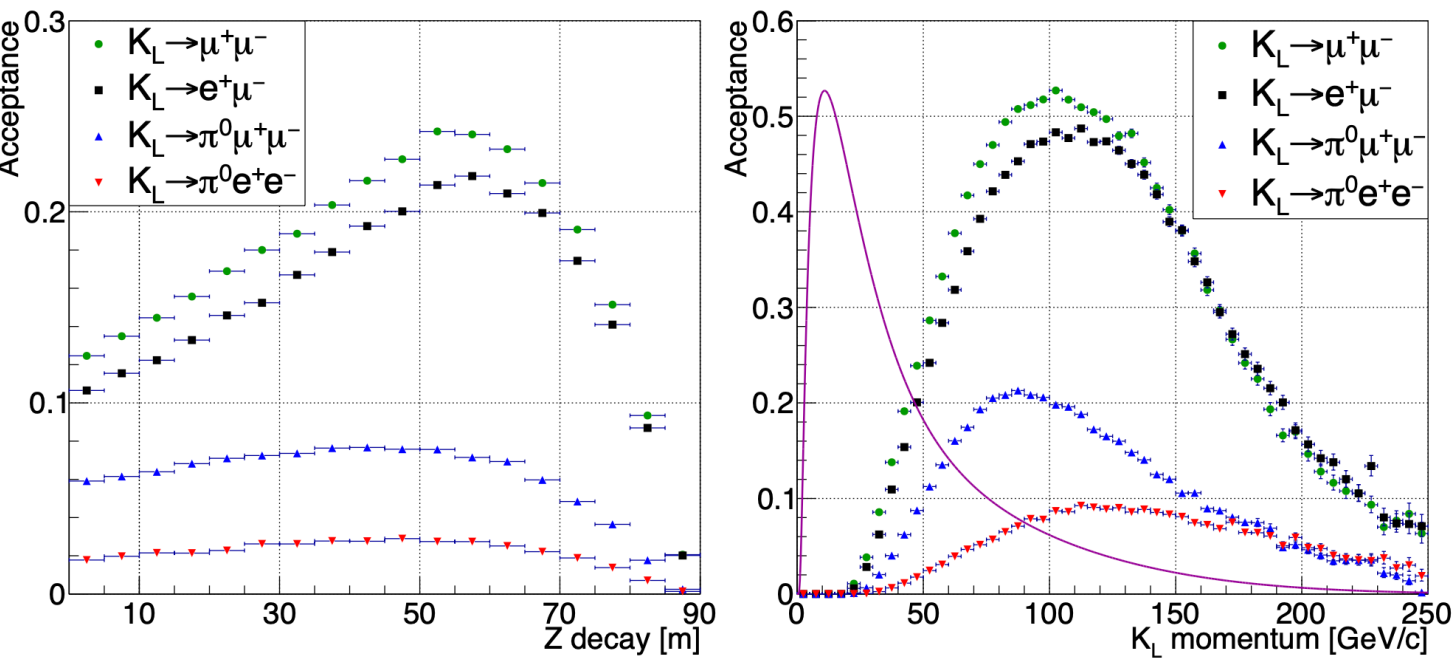
PANDA prototypes:

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

Information from spy tiles provides 5-10x improvement in neutron rejection
Overall neutron rejection at level of 10^3

In synergy with AIDAinnova, exploring the potential use of nanocomposite scintillators for faster time response and increased radiation robustness

HIKE Phase 2: Physics sensitivity



Single-event sensitivities for $K_L \rightarrow \pi^0 l^+ l^-$ improve by more than two orders of magnitude on previous searches by kTeV experiment

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

Mode	Assumed branching ratio	Acceptance	Signal yield in five years
$K_L \rightarrow \pi^0 e^+ e^-$	3.5×10^{-11}	2.1%	140
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	1.4×10^{-11}	6.0%	160
$K_L \rightarrow \mu^+ \mu^-$	7×10^{-9}	17%	2.3×10^5
$K_L \rightarrow \mu^\pm e^\mp$	—	16%	—

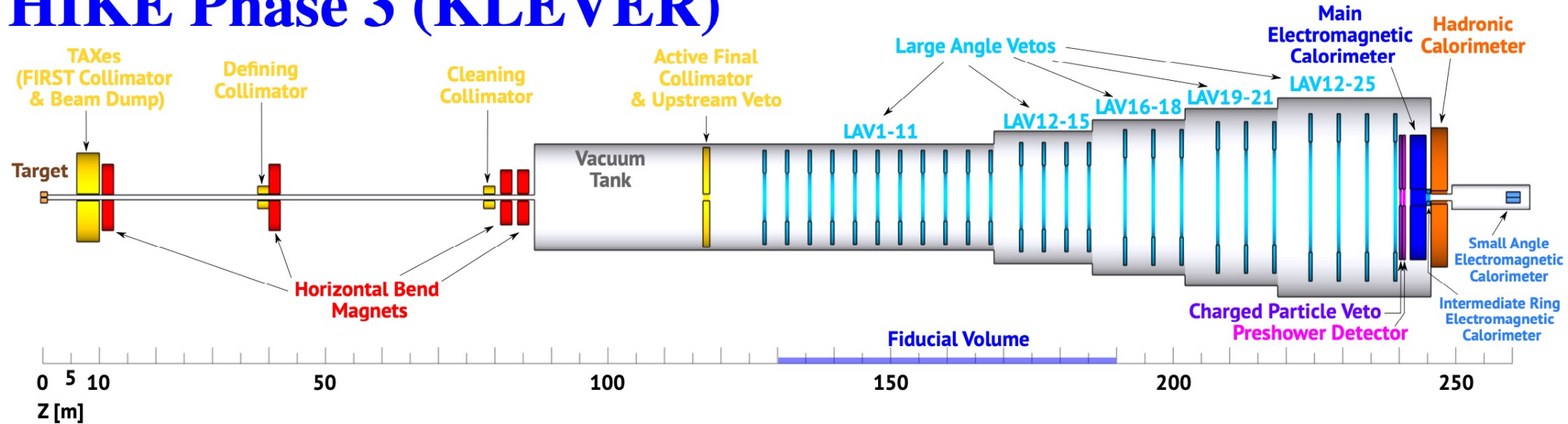
Likely first observation of the $K_L \rightarrow \pi^0 l^+ l^-$
(or surely sensitivity at the SM Br level of $O(10^{-11})$)

Background estimation for the $K_L \rightarrow \pi^0 l^+ l^-$ decays in progress, however extensive experience of NA62 lepton flavour/number violation programme in terms of background reduction suggests background suppression to $O(10^{-11})$ for rare and forbidden decays

$K_L \rightarrow \mu^+\mu^-$ signal yield: **0.2% statistical precision on decay branching ratio**
Sensitivities of $O(10^{-12})$ for branching ratios of a broad range of rare and forbidden K_L decay modes (ex. 60 times than BNL-E871)

HIKE design

HIKE Phase 3 (KLEVER)



baseline configuration, without the extension of the beamline by 150 m

K_L (KLEVER): $2 \cdot 10^{13}$ protons on T10 per spill (4.8 sec)

- neutral secondary beam for KLEVER is derived at an angle of 8 mrad
- 2γ with unbalanced p_T + nothing else
- K_L momentum generally not known
- Background rejection from Λ and neutrons, and K decays
- Background rejection mainly by vetoes
- Time-resolved particle flow
- Neutron rejection

Statistical power:
 $1.3 \cdot 10^{13}$ Kaon decays in decay
volume per year

Small-angle photon veto

- Rejects high-energy γ s from $K_L \rightarrow \pi^0 \pi^0$ escaping through beam hole
- Must be insensitive as possible to extremely high rate 430 MHz of beam neutrons in K_L mode**
- $\sigma_t < 100$ ps
- 2 pulse separation at ~ 1 ns**
- Radiation-hardness:** 10^{14} n/cm² and 10^5 - 10^6 Gy
- Longitudinal and transverse segmentation** for PID

Possible solution:

Compact Cherenkov calorimeter with oriented high-Z crystals

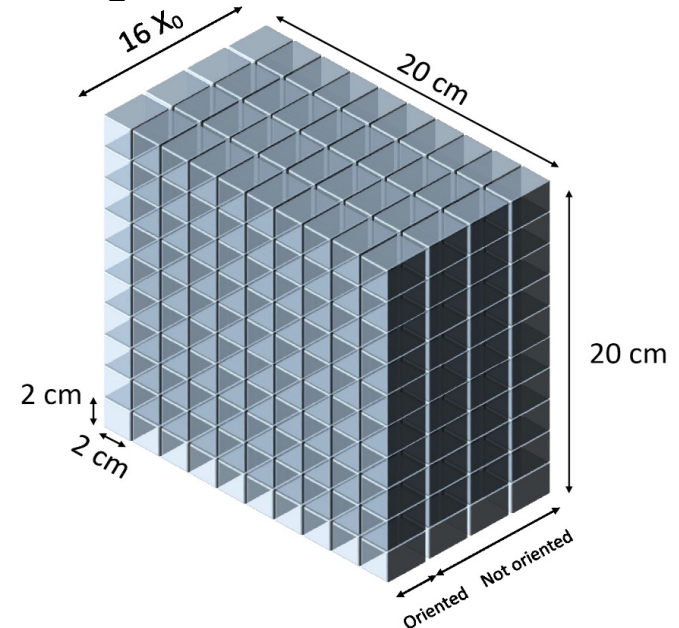
- Optimize choice of photodetectors
 - Excellent time resolution
 - Radiation hardness
- Study response to neutral hadrons
- Possibilities for γ/n discrimination

SAC necessary from Phase 1 but the most stringent requirements for the SAC are in Phase 3 (KLEVER)

Beam comp.	Rate (MHz)	Req. $1 - \epsilon$
$\gamma, E > 5$ GeV	50	10^{-2}
$\gamma, E > 30$ GeV	2.5	10^{-4}
n	430	—

For HIKE Phase 1, the requirements are slightly less stringent, remnants of the charged beam can be magnetically swept out of acceptance. Still expect rates of up to 10 MHz or more.

PbF₂ Cherenkov calorimeter



HIKE Phase 3: KLEVER Physics sensitivity

Target sensitivity of 60 SM $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events with S/B =1

At the SM BR, this would correspond to a relative uncertainty of about 20%.

For a production angle of 8 mrad, the neutral beam has a mean K momentum of 40 GeV:
5% of K_L decay inside an FV extending from 130 m to 190 m downstream of the target.
Basic selection criteria: exactly 2 isolated photons, with geometrical, Z and p_T cuts.

$\sim 50 K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $\sim 100 K_L \rightarrow \pi^0 \pi^0$ in 5 years

Very large background from $\Lambda \rightarrow n \pi^0$ makes a beamline extension necessary

After beamline extension, Λ background suppressed by 4 orders of magnitudes, to ~ 50 events

With cut-and-count analysis: $\sim 25 K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $\sim 100 K_L \rightarrow \pi^0 \pi^0$ in 5 years

Optimization still in progress

eliminate remaining Λ using hadronic calo at small angle

recover signal by extending FV in downstream direction

make better use of the pre-shower signal and improve photon veto system, especially in downstream region

use of multi-variate analysis techniques

Summary

HIKE offers excellent sensitivity for new physics at high mass scales

Unique and timely opportunity to address a strong motivated physics case at CERN NA facility

High-intensity frontier is synergetic with main LHC programme (physics and detector challenges)

Next generation high-intensity kaon experiments HIKE provide a powerful tool to perform comprehensive measurements at an unprecedented level of precision, and to search for physics beyond the Standard Model in flavour physics and beyond.

The experimental programme is based on a staged approach involving charged and neutral kaon beams, as well as operation in beam-dump mode.

The various phases will rely on a common infrastructure and set of detectors.

For more details, see the [HIKE Letter of Intent](#) submitted today to SPSC

Thank you for listening !

Estimated cost for detectors

Detector	Cost (MCHF)	Comments
Kaon ID (KTAG)	0.5	Using MCP-PMTs
Beam Tracker	2.5	Development, and production of 4 planes
Charged particle veto (CHANTI)	0.4	6 stations, with SiPMs
VetoCounter (VC)	0.2	3 stations (SciFi technology)
Anti0	0.1	1 plane, same technology as TimingPlanes
Large Angle Vetos (LAV)	8	12 modules (Phase 1)
STRAW	3.5	4 Straw chambers and associated readout
LKr upgrade OR MEC	2.5 OR 5	Readout upgrade OR new MEC
Small Angle Calorimeter (SAC)	2	High-Z crystals
Pion ID (RICH)	0.8	Using SiPMs
Timing Detector	0.2	2 planes, scint. tiles and SiPMs
Hadronic Calorimeter + Muon plane	1.5	Shashlyk technology and SiPMs
HASC	0.1	Using SiPMs
MEC (if not already in Phase 1)	5	Shashlyk technology and SiPMs (Phase 2)
Large Angle Vetoes (LAV)	9	Additional 13 modules (Phase 3)

Phase 1: K^+ 22.3 OR 24.8 MCHF
 Phase 2: K_L + tracks (5 MCHF if MEC not done before)
 Phase 3: KLEVER 9 MCHF

Kaon ID with Cherenkov

Differential Cherenkov detector, refurbished readout

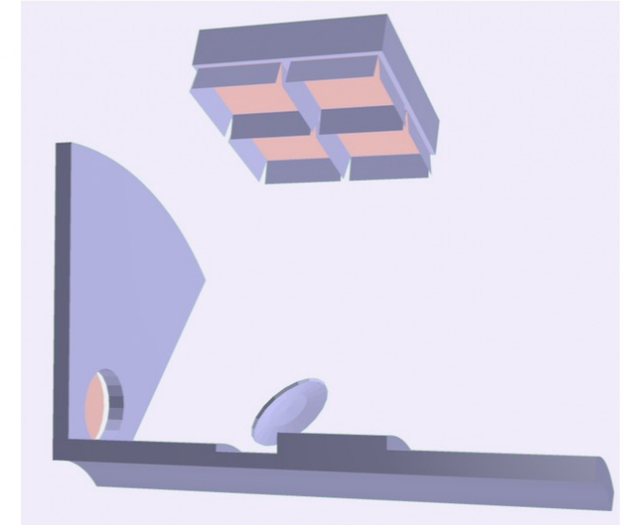
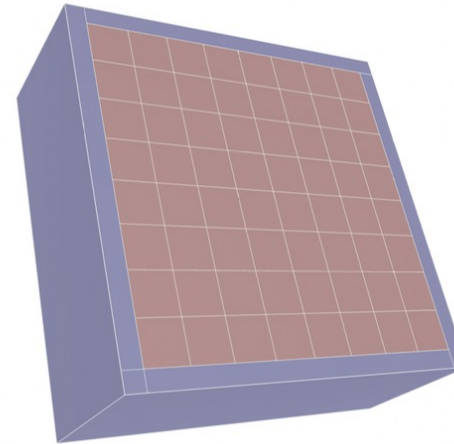
K ID for 4x intensity

- **Max detected photon rate:** $>8 \text{ MHz/cm}^2$
- High granularity
- **Single-photon capability with σ_t (Kaon) = 15-20 ps**
- K^+ tagging efficiency with 4 sectors: $> 95\%$
- Good radiation resistance

Microchannel plate (MCP) PMTs

- Excellent time resolution ($\sim 20 \text{ ps}$)
- Low dark noise, Single-photon sensitivity
- High gain, good QE
- Good filling factor
- Input rate capability $\sim \text{MHz/cm}^2$

MCP-PMT array and matrix of four MCP-PMT



Susceptible to aging (QE drops)

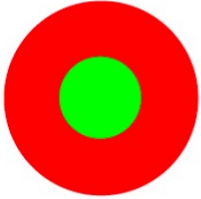



Atomic layer deposition (ALD) coating increases the lifetime dramatically

Simulation results obtained with geometrical filling factor of 75% and collection efficiency of 60% show that 15–20 ps kaon time resolution is achievable

Pion ID with Cherenkov: RICH detector

	NA62 RICH	Future 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

NA62 RICH detector, using neon at atmospheric pressure as the radiator, is well suited for HIKE
Major changes only concern the Cherenkov light sensors and flanges hosting them.

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 mm ²	62K	2.3 mm	0.66 mm
		6x6 mm ²	16K	2.8 mm	0.78 mm
		9x9 mm ²	7K	3.4 mm	0.95 mm



Opportunity to increase RICH acceptance for negatively-charged particles

Large-angle photon vetoes

Time resolution for current NA62 LAVs ~ 1 ns

- Cerenkov light is directional
- Complicated paths to PMT with multiple reflections

12 for Phase 1-2 (25 for Phase 3) new large-angle photon veto stations (LAV) – veto on a very large area

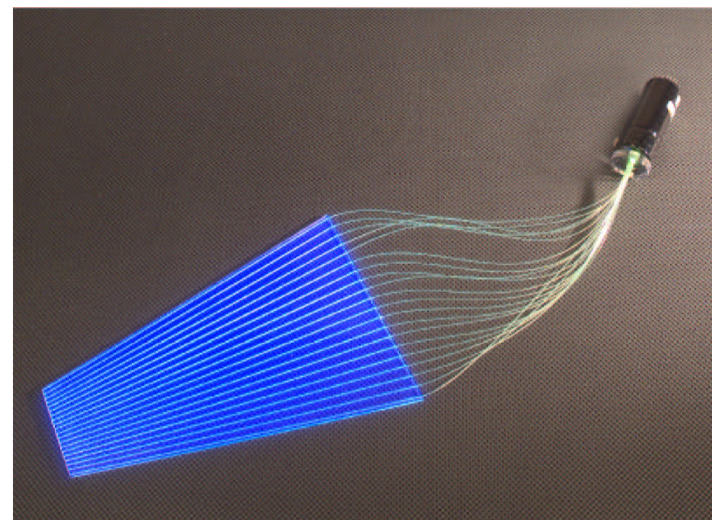
- 5 sizes, sensitive radius 0.85 to 1.5 m, at intervals of 4 to 5 m
- **Time resolution < 250 ps**
- **Hermetic coverage out to 100 mrad**
- **Need good detection efficiency at low energy** ($1 - \varepsilon < \text{few } 10^{-4}$ at at least 100 MeV)
- **Full digitization, segmentation in depth**

Baseline technology:

Lead/scintillator tile with WLS readout

- Pb/scintillating tile
- 1 mm Pb + 5 mm scint
 $f_{\text{em}} \sim 36\%$
- WLS fiber readout

Light read out with SiPM arrays



Hadron Calorimeter

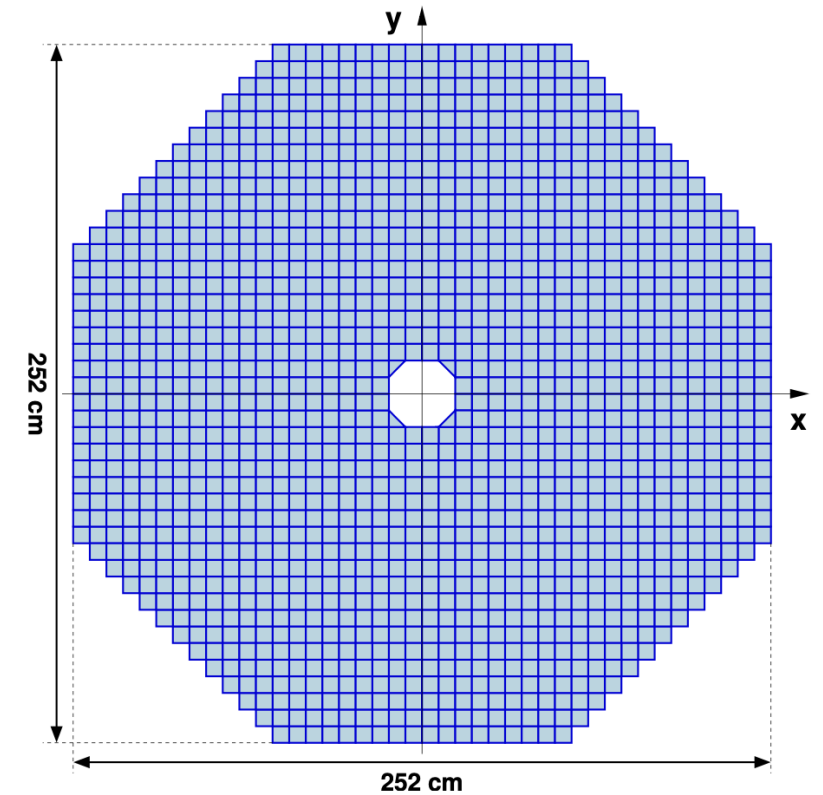
HCAL) is the main detector for π/μ identification and separation (including catastrophically interacting muons, which deposit all or large fraction of their energy in the calorimeter)

Average muon misidentification probability of $O(10^{-6})$ over momentum range 10 - 50 GeV is necessary

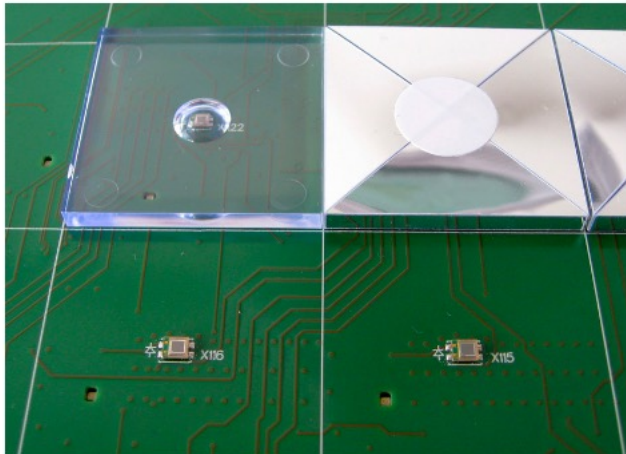
At 4 – 6 x NA62 intensity, sub-nanosecond time resolution required to avoid dead-time from random veto. Cellular layout to reduce rate on each channel and time resolution.

Two options considered for an iron-scintillator based calorimeter:

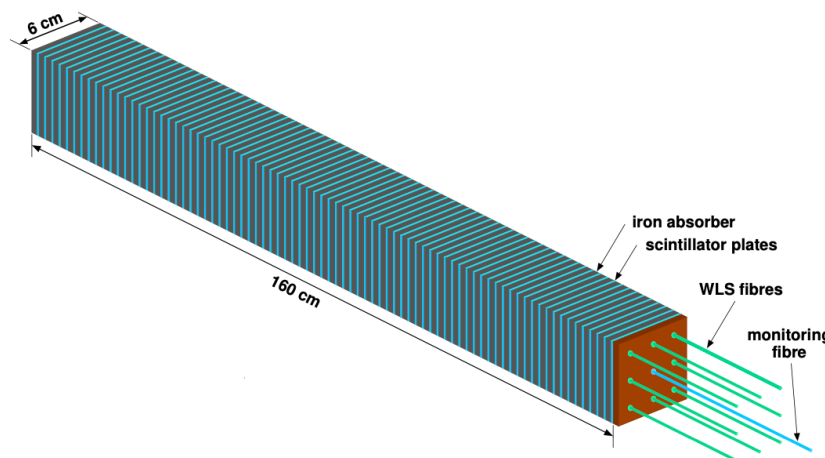
Transverse HCAL layout, 1440 cells



High-Granularity Analogue Calo

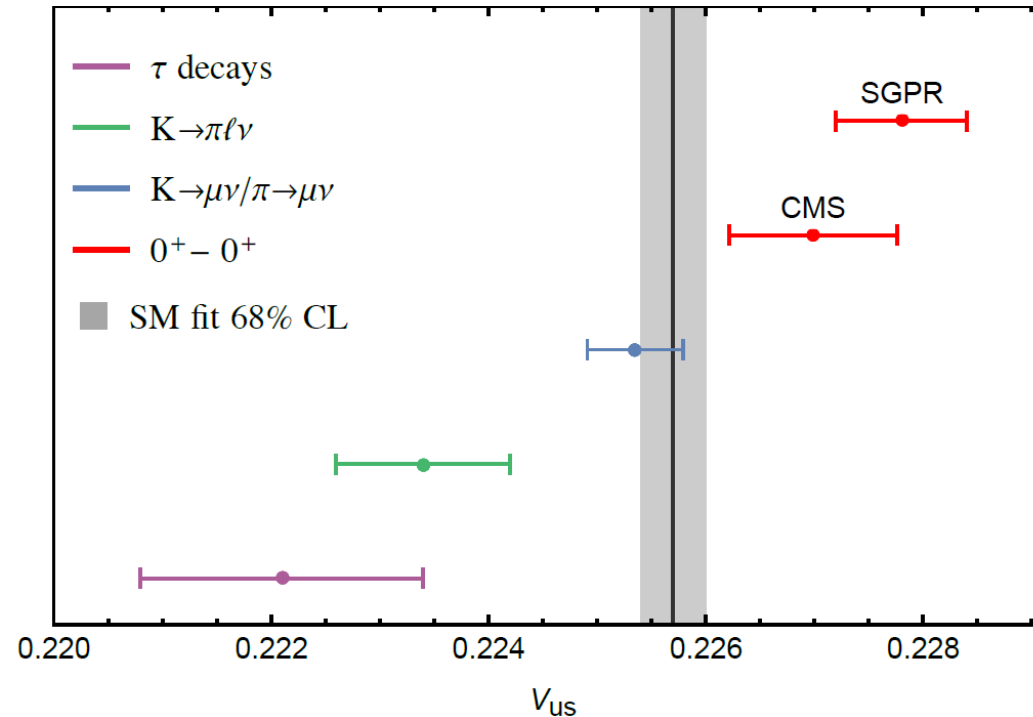


Shashlik calorimeter



Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays
- V_{us} from Kaon and tau decays
- Disagreement leads to a (apparent) violation of CKM unitarity



CMS, SGPR:
radiative corrections

$$|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 0.9985 \pm 0.0005, \quad |V_{ud}^2| + |V_{cd}^2| + |V_{td}^2| = 0.9970 \pm 0.0018$$

Deficits in 1th row and column CKM unitarity

NA62 through LS3

Summary of NA62 Run 1 (2016-2018):

- Expected signal (SM): 10 events
- Expected background: 7 events
- Total observed: 20 events
 - 3.5σ signal significance
 - Most precise measurement to date

$$\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (11.0^{+4.0}_{-3.5 \text{ stat}} \pm 0.3_{\text{syst}}) \times 10^{-11} \quad [\text{JHEP 06 (2021) 093}]$$

NA62 Run 2 (from 2021 to LS3):

Key modifications to reduce background:

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

Higher beam intensity (70% \rightarrow 100%), control random veto

Measure $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ to O(10%) by LS3

