HIKE: The High-Intensity Kaon Experiments at CERN

Proposal for Phase 1 and 2

Prof. Cristina Lazzeroni
University of Birmingham,
on behalf of HIKE

High Intensity Kaon Experiments

HIKE: 194 collaborators from 41 institutions in the Proposal of HIKE Phase 1 and 2

SPSC Open Session, 5 September 2023, CERN

Exploring flavour physics through Kaon decays

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

Sensitive to unprecedented mass scales (well beyond those reachable at LHC). [arXiv:1408.0728]

Presently, main limitation to the investigation of several modes comes from the experimental precision.

The primary goal of HIKE is to improve the accuracy.

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

$K_S \to \pi^0 l^+ l^-$

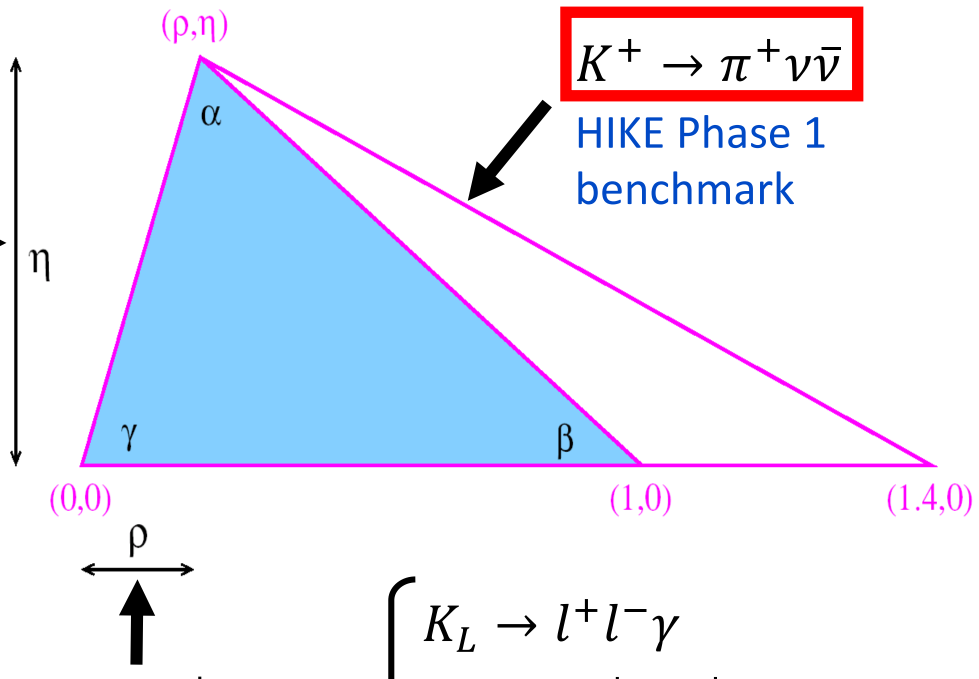
$K_L \to \pi^0 \gamma\gamma$

$K_L \to \gamma\gamma l^+ l^-$

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

HIKE Phase 2 benchmark

$K_S \to \mu^+ \mu^-$



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

$K_L \to \gamma\gamma$

$K_L \to \mu^+ \mu^-$

$K_L \to l^+ l^- \gamma$

$K_{L,S} \to l^+ l^- l^+ l^-$

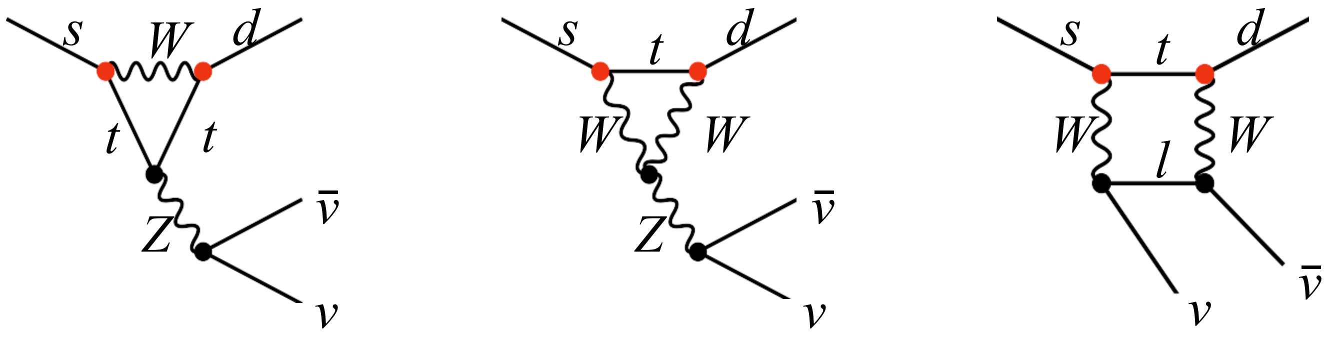
$K_{L,S} \to e^+ e^- \mu^+ \mu^-$

HIKE will address many of these channels

Only experiment worldwide that is able to do so

The HIKE broad physics programme consists of phases using shared detectors and infrastructure

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



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

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

[JHEP 1511 (2015) 033]

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

Present error budget presently dominated by CKM inputs

[JHEP 1511 (2015) 033]

[arXiv:2203.11960, arXiv:2109.11032] [arXiv:2105.02868, arXiv2203.09524]

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).

"Free" from hadronic uncertainties

Exceptional SM precision

SM predictions accuracy may improve over the next decade due to lattice QCD progress on the charm contribution [arXiv:1806.11520, arXiv:1910.10644]

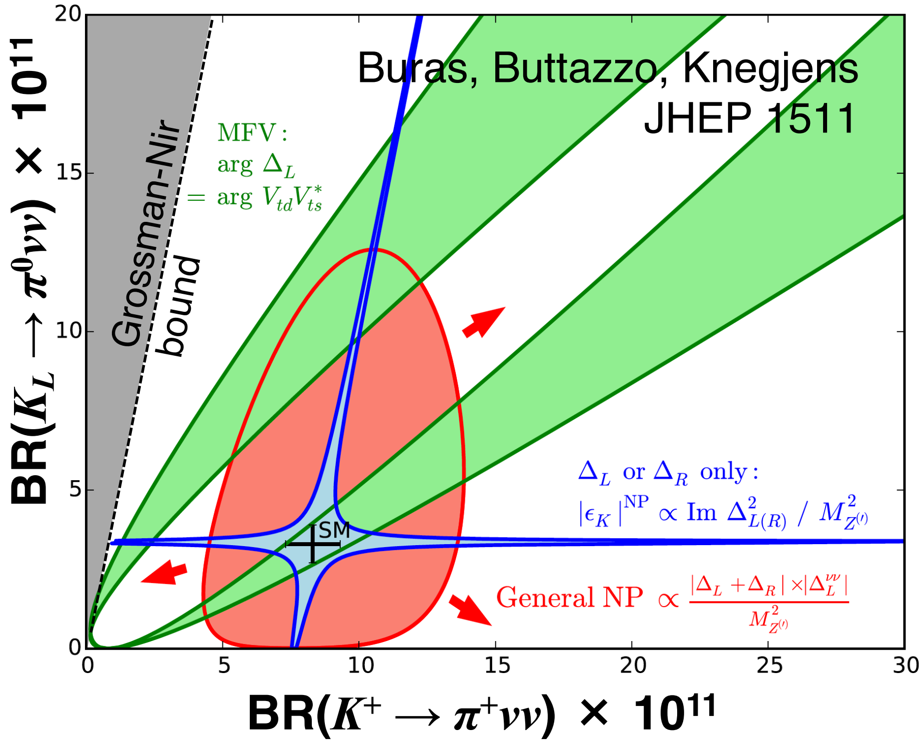
Non-parametric uncertainty:
1.5% for K_L, 3.5% for K^+

Clear opportunity in the kaon sector

NA62 will measure $K^+ \rightarrow \pi^+ \nu\nu$ to $O(15\%)$ precision with Run1&2 data

After LS3, HIKE approaches theory error and show possible evidence of deviation from SM

High sensitivity to NP (non-MFV):
significant variations wrt SM
BSM affects K^+ and K_L differently
Measurements of both discriminate NP



- 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

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]

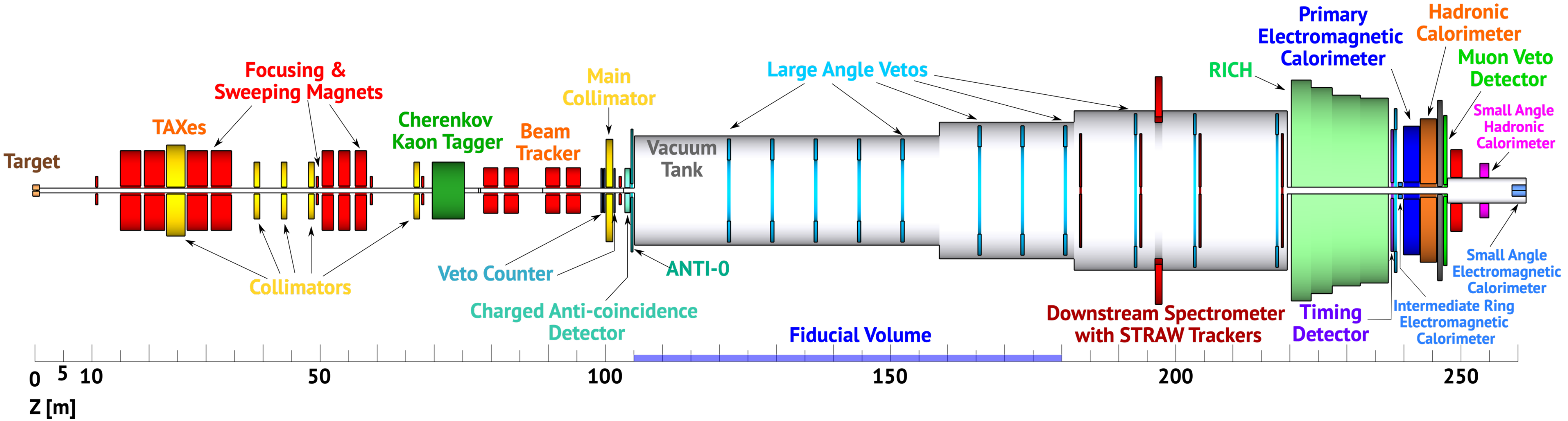
NP scenarios	Process
Z-FCNC	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
Z'	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε'/ε, ΔM_K
Simplified models	$K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
LHT	All K decays
331 models	Small effects in $K \to \pi\nu\bar{\nu}$
Vector-like quarks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

[Table from arXiv:2203.09524]

[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]

HIKE design: Phase 1

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



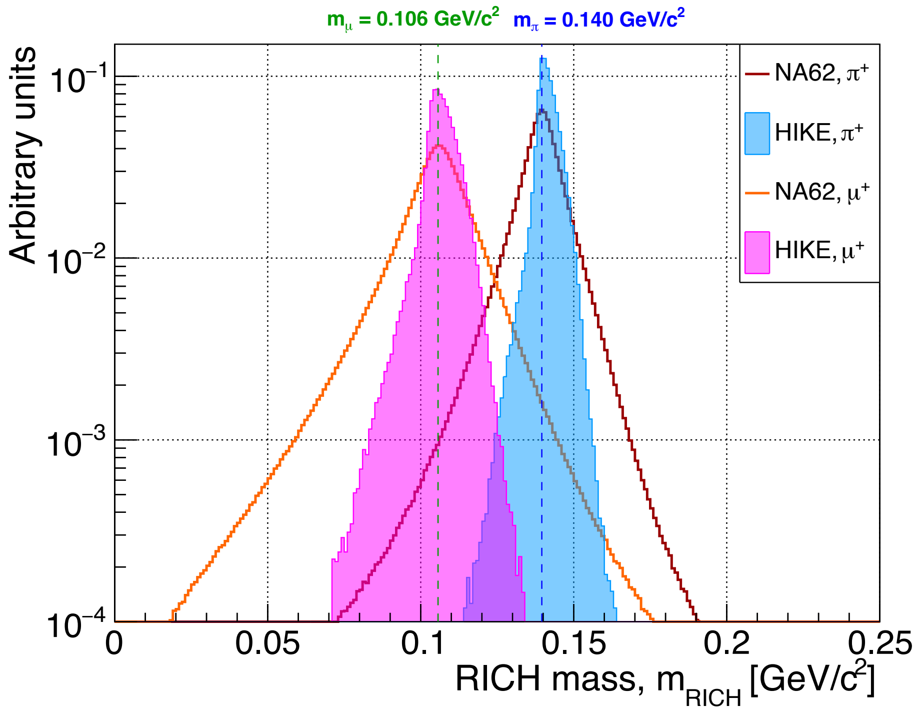
NA62-like design will work @high intensity.
Improved timing is the crucial element
to be able to increase intensity 4 x NA62.

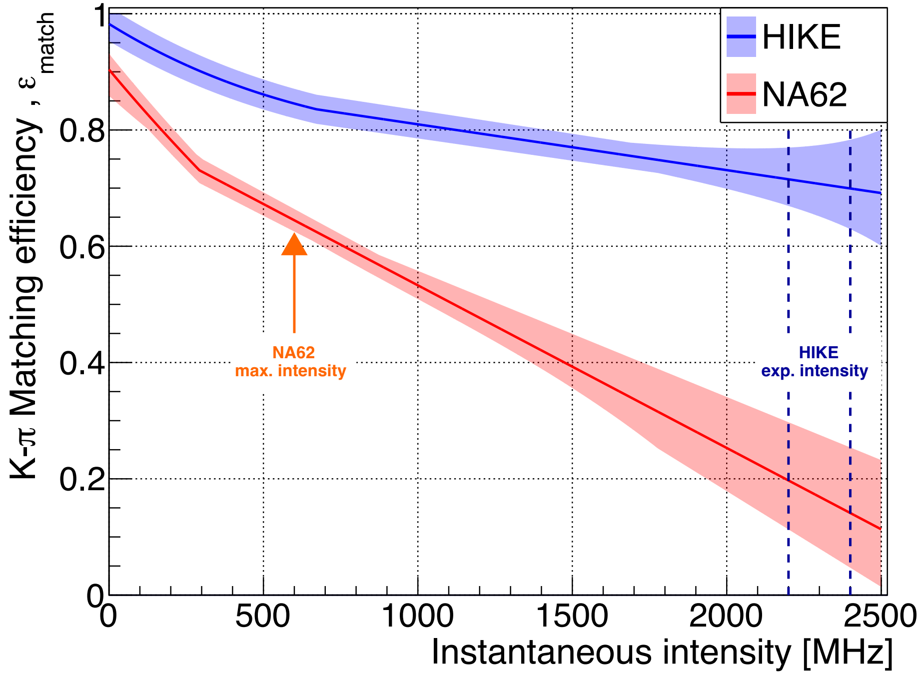
Statistical power:
2 10^{13} Kaon decays in decay volume
per year (7.2 10^{18} POT / year)

Detector keystones:
1) High-efficiency and high-precision tracking
2) High-precision time measurements
3) High-performance particle identification system
4) Comprehensive and hermetic veto systems

Technological solutions exist for all detectors

HIKE Phase 1 $K^+ \rightarrow \pi^+\nu\bar{\nu}$ Physics sensitivity: K/π ID





RICH PID for π with 15 < p < 45 GeV/c.
RICH reconstruction efficiency: photon yield and photodetector time resolution to resolve rings overlapping in space.
RICH granularity increased, x2 QE, 100ps time resolution.
Also muon plane with high granularity, x4 better timing.

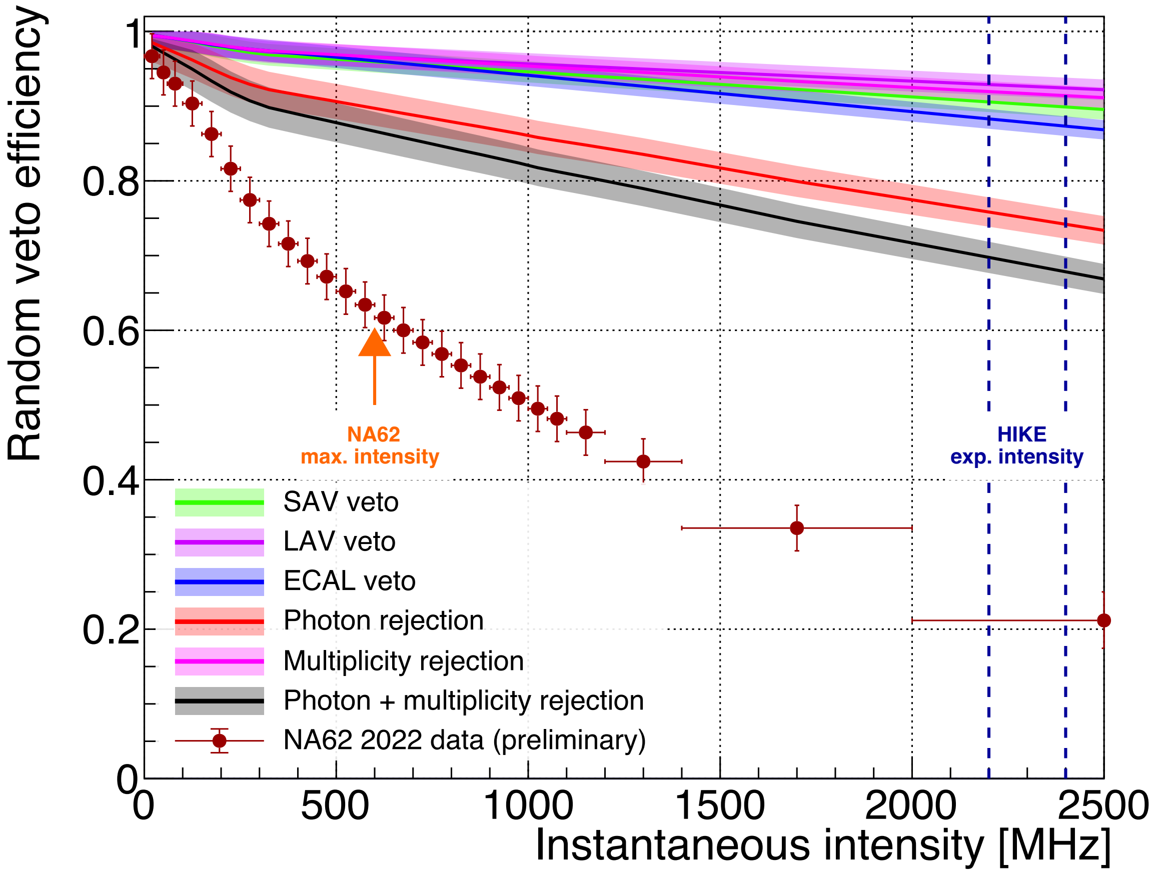
KTAG x4 better timing.
Kaon-pion matching depend on time resolution and pixel size of GTK, and resolution on slope of pion track.
x4 time resolution, x3 smaller pixel size, 40% lower material budget in STRAW.

HIKE: pion ID with at least 10% higher efficiency than NA62 when keeping same muon–pion misidentification probability.
K-pion misidentification probability ~2%, similar to NA62. Kaon–pion efficiency ×1.1 higher than NA62.

HIKE Phase 1 $K^+ \to \pi^+\nu\bar{\nu}$ Physics sensitivity : random veto

Criteria to veto photons and extra activity in-time in detectors induce intensity-dependence signal loss: "random veto" due to sharp cuts on the time of the signals recorded by the various subdetectors.

Critical performance indicator: "random veto efficiency" versus beam intensity, measured on data: $K^+ \to \mu^+ \nu$



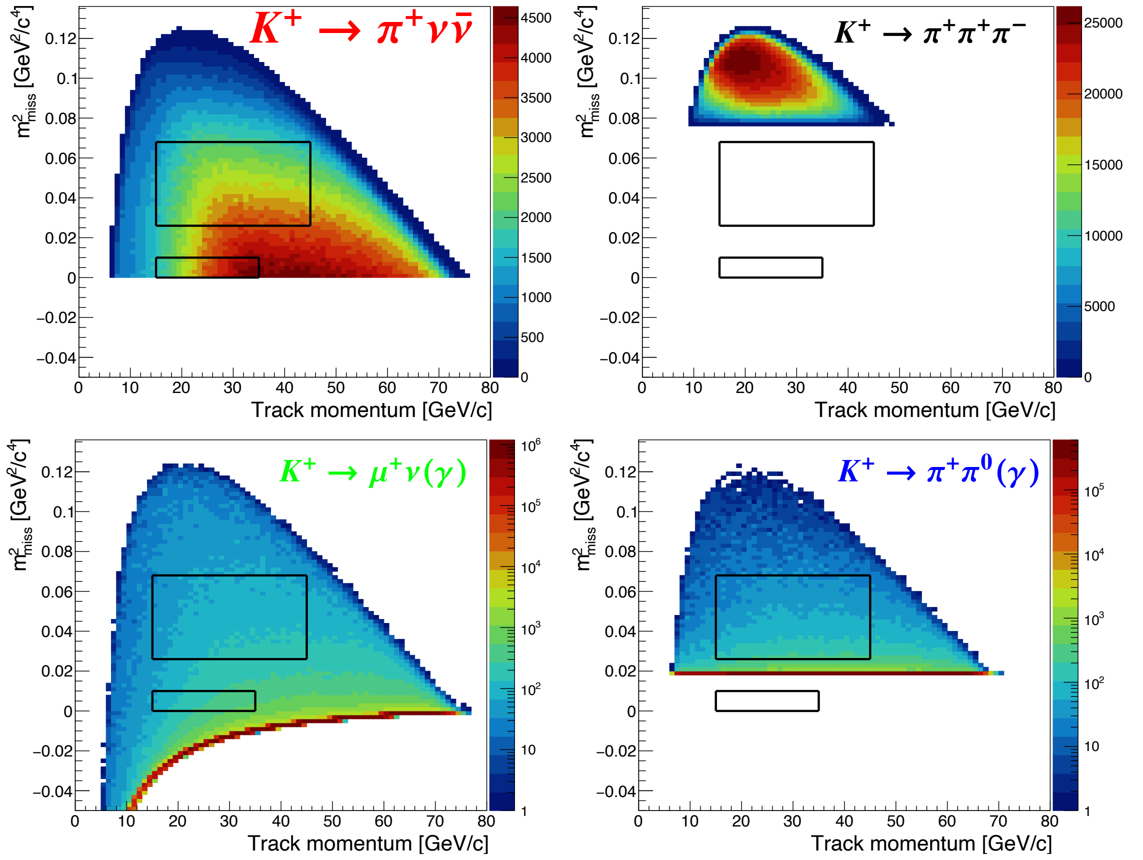
NA62: Signal selection efficiency ~65% at max beam intensity in Run2

Quasi-linear dependence on the instantaneous beam intensity.
Limiting factor is the timing precision of the detectors
(and double pulse resolution).

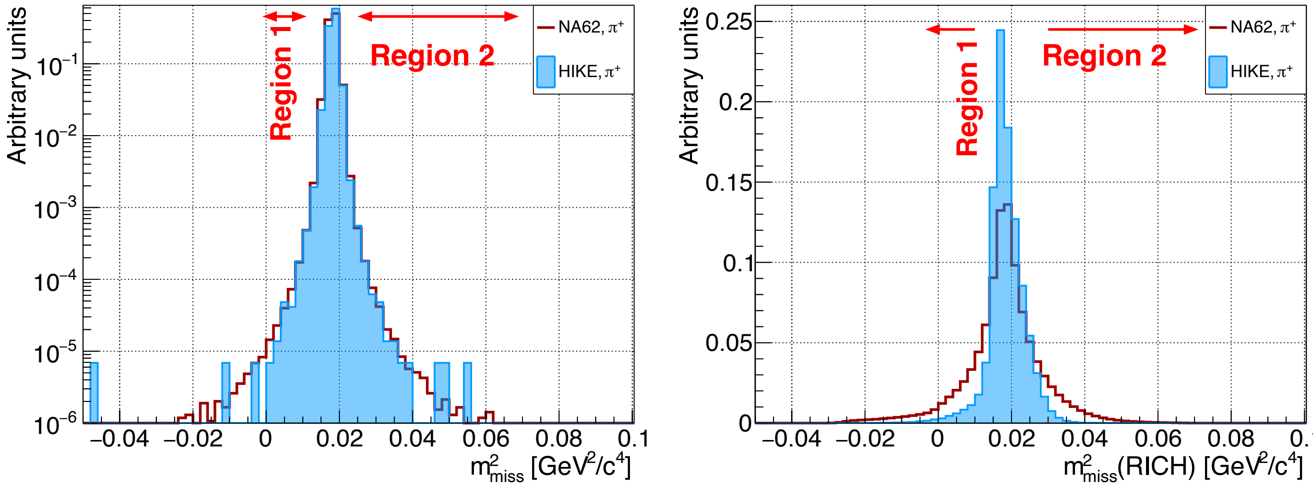
HIKE: maintain or improve the random-veto efficiency.
Requires an improvement in the time resolution for the veto systems at least by the same factor as the intensity increase.

HIKE Phase 1 $K^+ \to \pi^+\nu\bar{\nu}$ Physics sensitivity : Kinematics

Simulated kinematic distribution of missing mass



Missing mass tails for $K^+ \to \pi^+ \pi^0$



NA62 MC extensively validated with data.

The main kaon decay modes enter the signal regions via resolution tails in the reconstructed value of missing mass.

Choice of signal regions is determined by resolution.

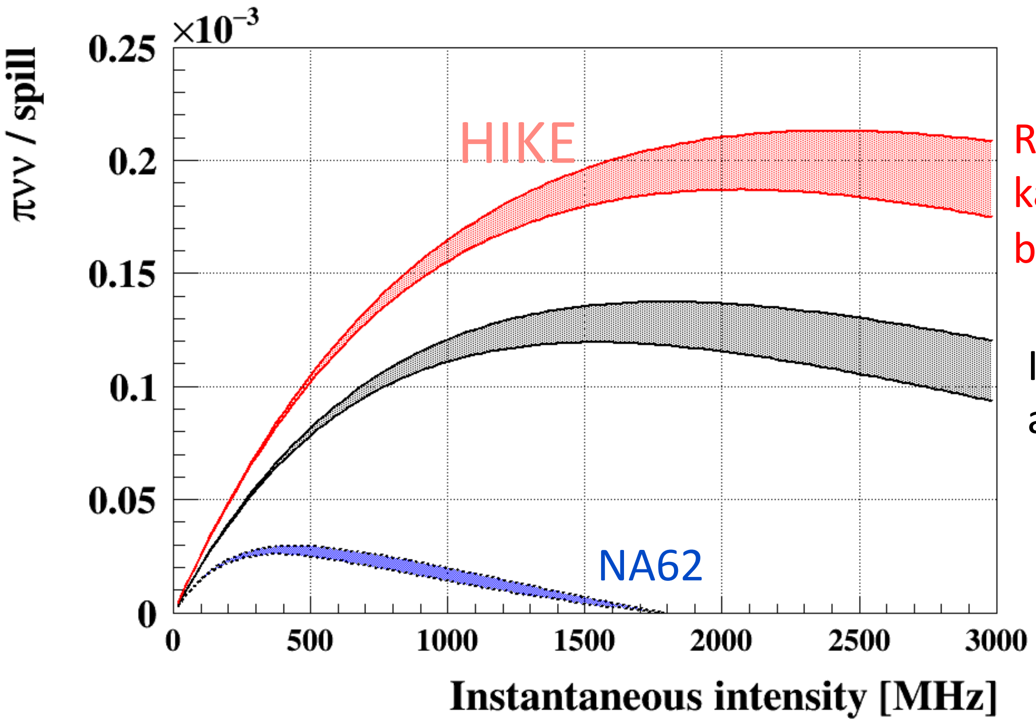
Slightly better missing mass resolution at HIKE vrt NA62 (40% less material budget in Straw).

Missing mass with RICH much improved.

HIKE can optimise the signal regions to increase the signal acceptance by 10% compared to NA62, while maintaining the resolution tails at the same level.

HIKE Phase 1: $K^+ \rightarrow \pi^+\nu\bar{\nu}$ Physics sensitivity

Components describing signal intensity dependence:
1) Dead-time-equivalent paralyzable model that accounts for intensity dependence of the trigger, DAQ, and all selection criteria (except Random Veto).
2) Polynomial description of the random veto efficiency



Recovery of LocalTriggerUnit dead-time, kaon-pion association, improved RICH, better kinematic resolution.

Improved timing, software trigger and new DAQ

Background from K decays to remain the same fraction of signal.

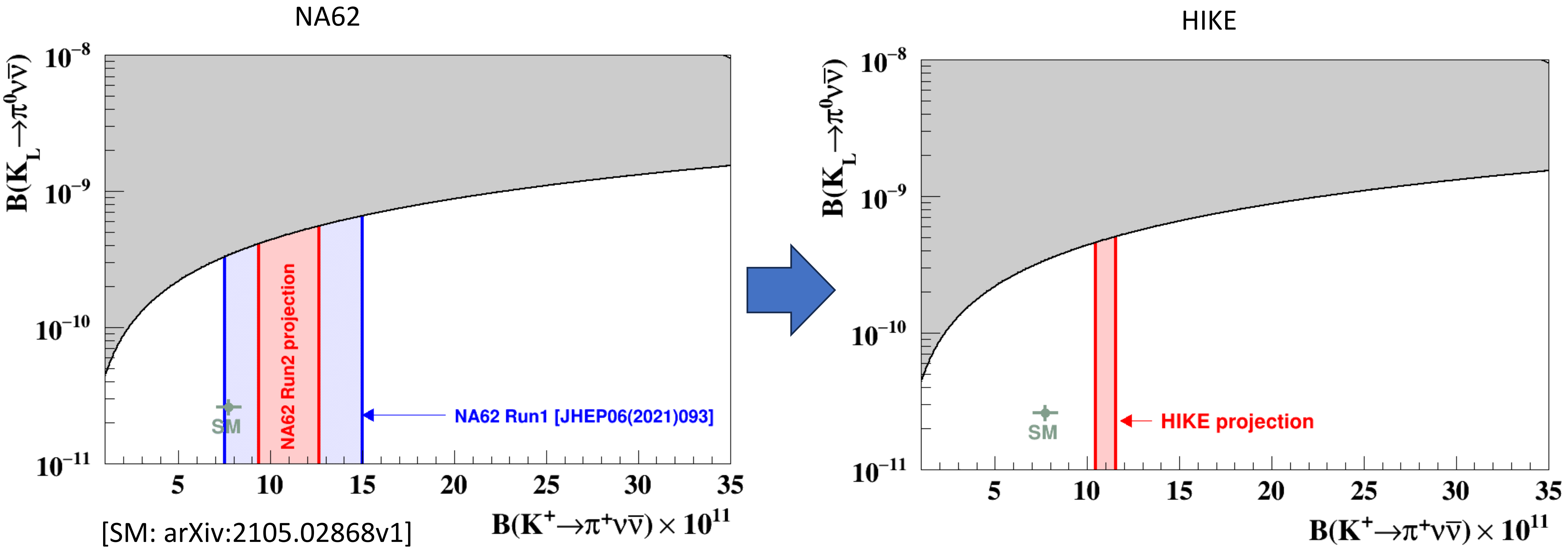
Upstream background reduced to same level as K background.
Improved coverage and design of upstream background veto.
Improved time resolution allows corresponding reduction of time windows.

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%

HIKE Phase 1: physics reach

Precision test of the Standard Model:

Measurement of branching ratio offers model-independent standard candle that can constrain any BSM scenarios, present or future

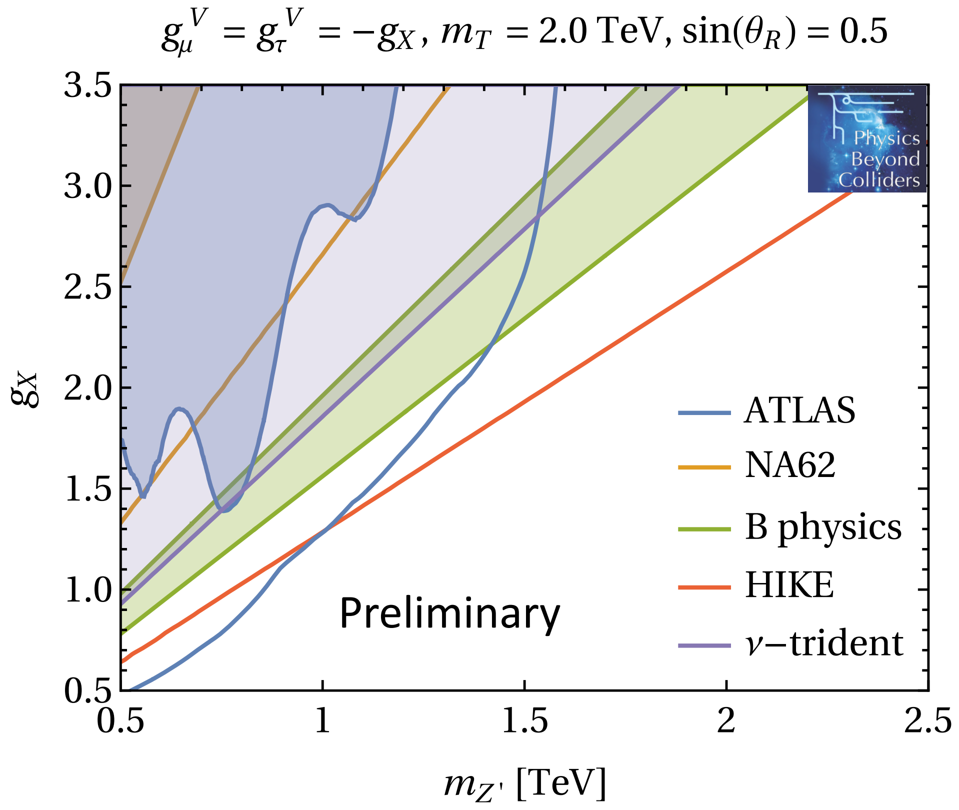


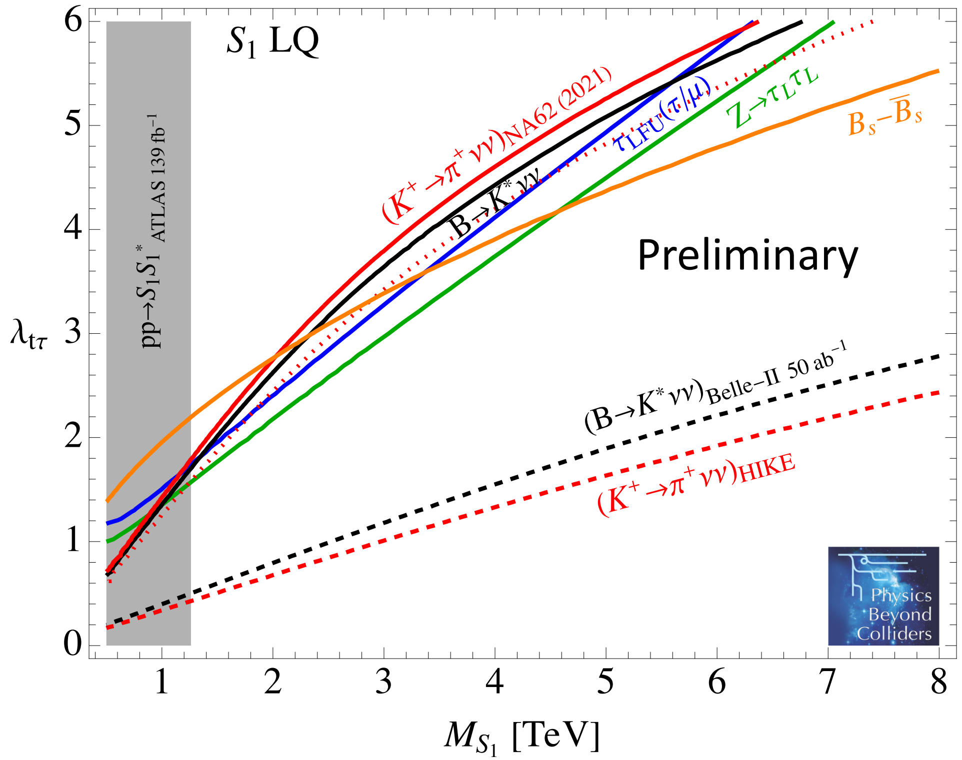
[SM: arXiv:2105.02868v1]

Blue = measurements Red = projections

HIKE Phase 1: examples of specific BSM models

[CERN Physics Beyond Colliders Document, in preparation]





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].

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

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

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

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

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

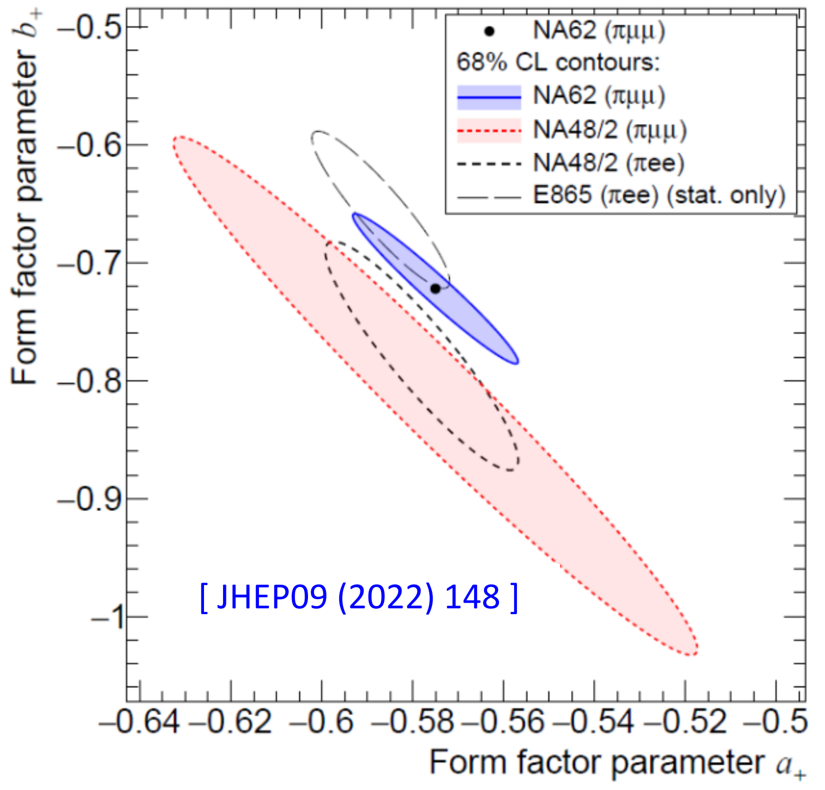
Long-distance contribution to the difference cancels out and is sensitive only to short-distance effects

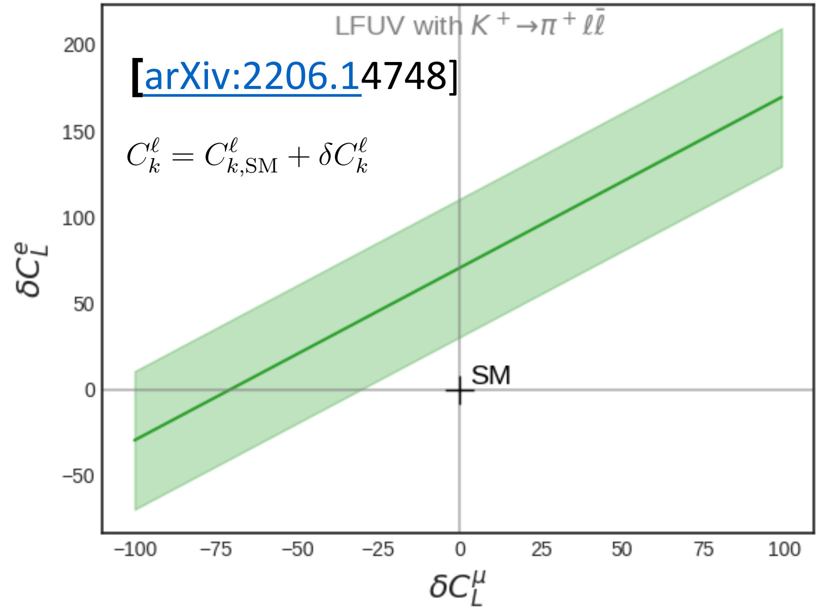
Difference correlated to possible anomalies in B physics

HIKE Phase 1: Collect > 5×10^5 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





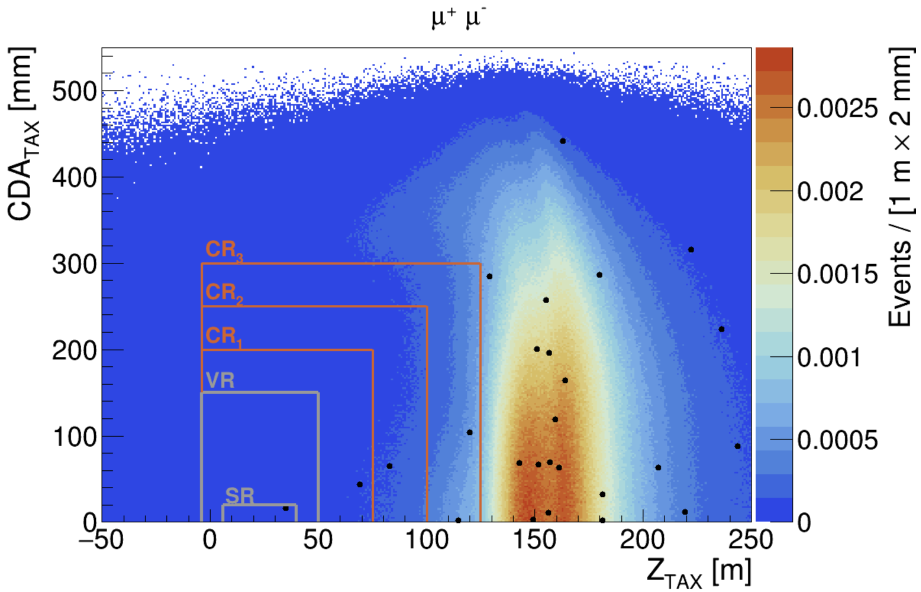
Feebly interacting particles (FIPs)

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: $K^+ \to l^+ N, K^+ \to \pi^+ X, \ldots$

Dump mode is 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.

1.4×10^{17} protons collected by NA62 in 2021 in beam-dump mode: data analysis shows that residual background is negligible, in particular when searching for two-body decays of new-physics mediators. Collected 4 10^{17} POT so far in 2021-2023.



Condition	$N_{exp} \pm \delta N_{exp}$	N_{obs}	$p(L < L_{obs})$
$e\mu$ PID	2905 ± 1455	2896	0.97
$e\mu$ PID, ANTI-0	8.6 ± 6.1	12	0.61
$e\mu$ PID, LAV	728 ± 365	645	0.94
$e\mu$ PID, LAV+ANTI-0	0	2	0.25*
$e\mu$ PID, CR	50 ± 26	49	0.98
$e\mu$ PID, SR	2.5 ± 1.8	3	0.83
$e\mu$ PID, LAV+ANTI-0, CR	0	0	–
$e\mu$ PID, LAV+ANTI-0, SR	0	0	–

[arXiv: 2303.08666]

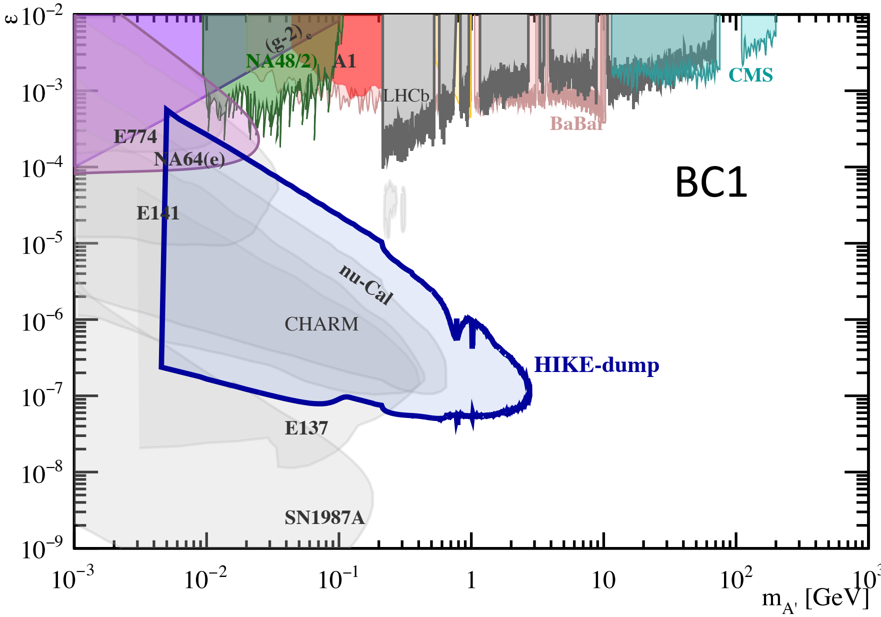
For 5 x 10^{19} POT:

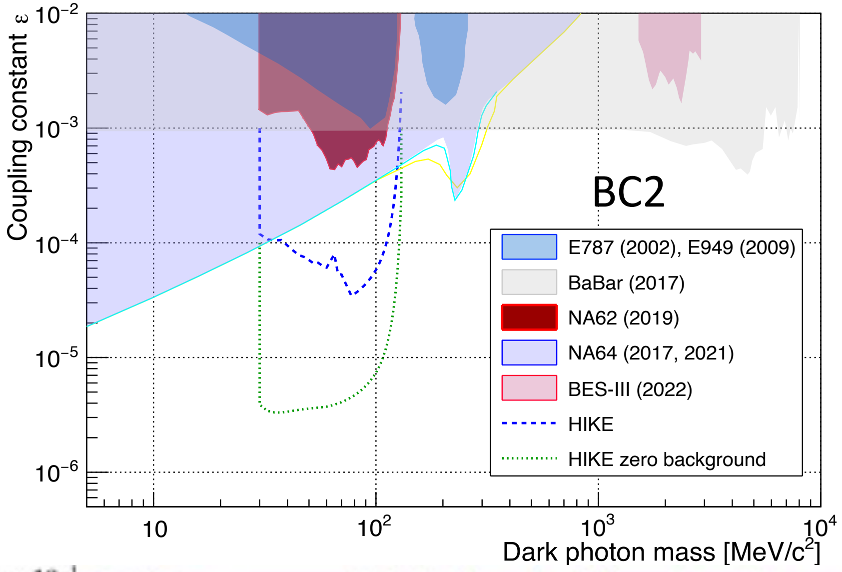
Final state	Expected background
$\mu^+\mu^-$	< 0.02
e^+e^-	< 0.9
$\pi^+\pi^-(\gamma)$	< 0.09
$\mu^\pm\pi^\mp$, $e^\pm\pi^\mp$	< 0.1
$\gamma\gamma$	work in progress

HIKE Phase 1: FIPs sensitivity

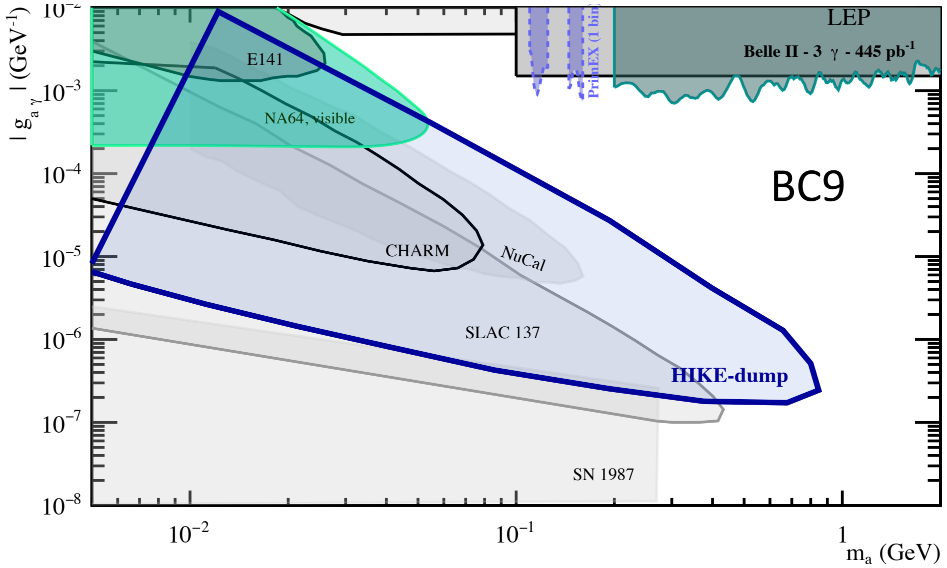
5 x 10^{19} POT in dump mode are assumed, taken in 4 years concurrently with SHADOWS operation, with 2 × 10^{13} POT over 4.8 s.

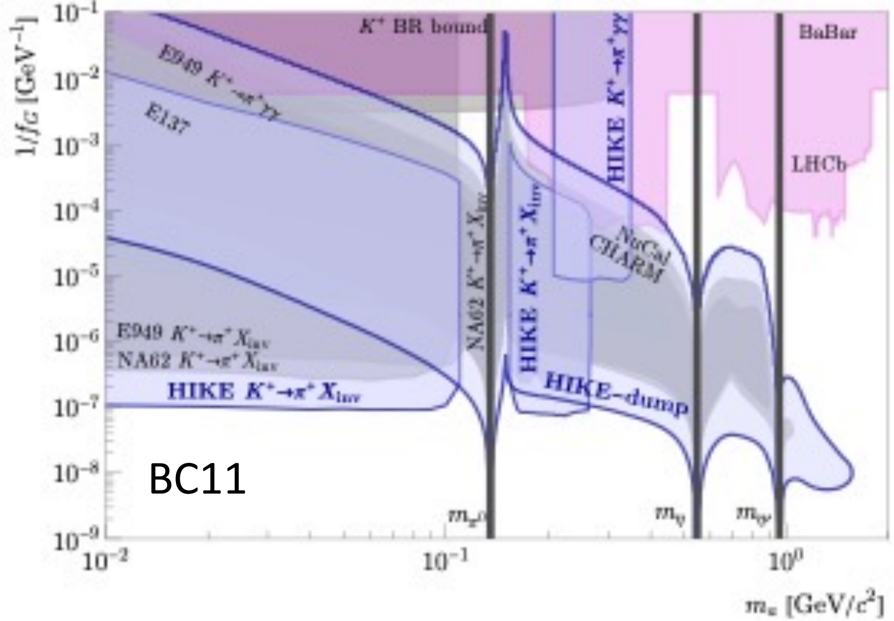
HIKE has unique complementarity between kaon and dump modes. HIKE sensitive to all BC benchmarks except BC3,BC5.





Selection of benchmarks shown here.
For the others, see HIKE Proposal.
Complementary phase space to SHADOWS.

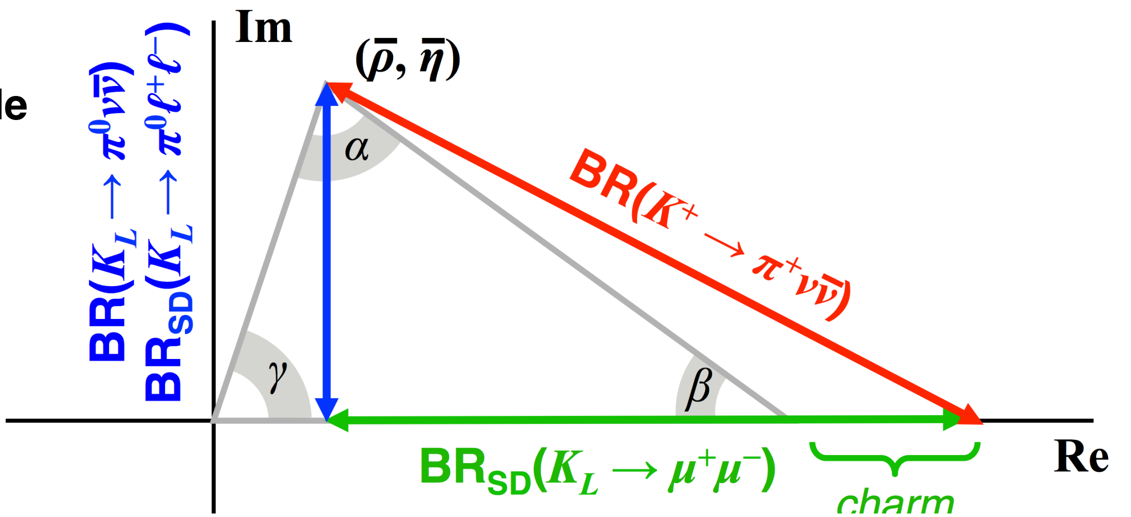




In kaon mode, sensitivity also to non minimal scenarios.

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

$K_L \to \pi^0 \ell^+ \ell^-$ **CPV amplitude constrains UT η**



Contributions from long-distance physics

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

- $K_S \to \pi^0 \ell^+ \ell^-$ will help reducing theoretical uncertainties
  - 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

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

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

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

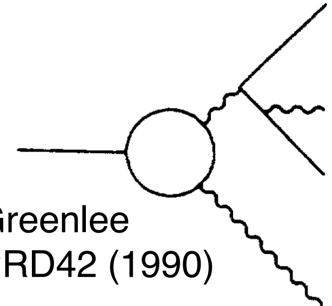
Experimental bounds from KTeV:

$BR(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$ — Phys. Rev. Lett. 93 (2004) 021805
$BR(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$ — 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

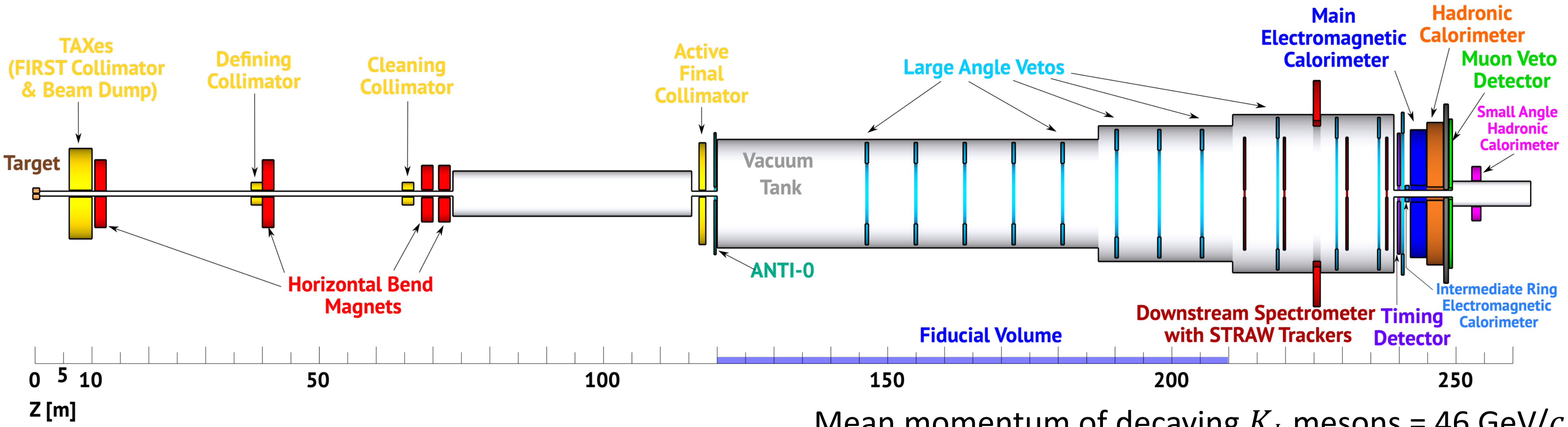
$BR(K_L \to e^+ e^- \gamma\gamma) = (6.0 \pm 0.3) \times 10^{-7}$ $\quad E_\gamma^* > 5$ MeV
$BR(K_L \to \mu^+ \mu^- \gamma\gamma) = 10^{+8}_{-6} \times 10^{-9}$ $\quad m_{\gamma\gamma} > 1$ MeV



Greenlee PRD42 (1990)

HIKE design: Phase 2

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

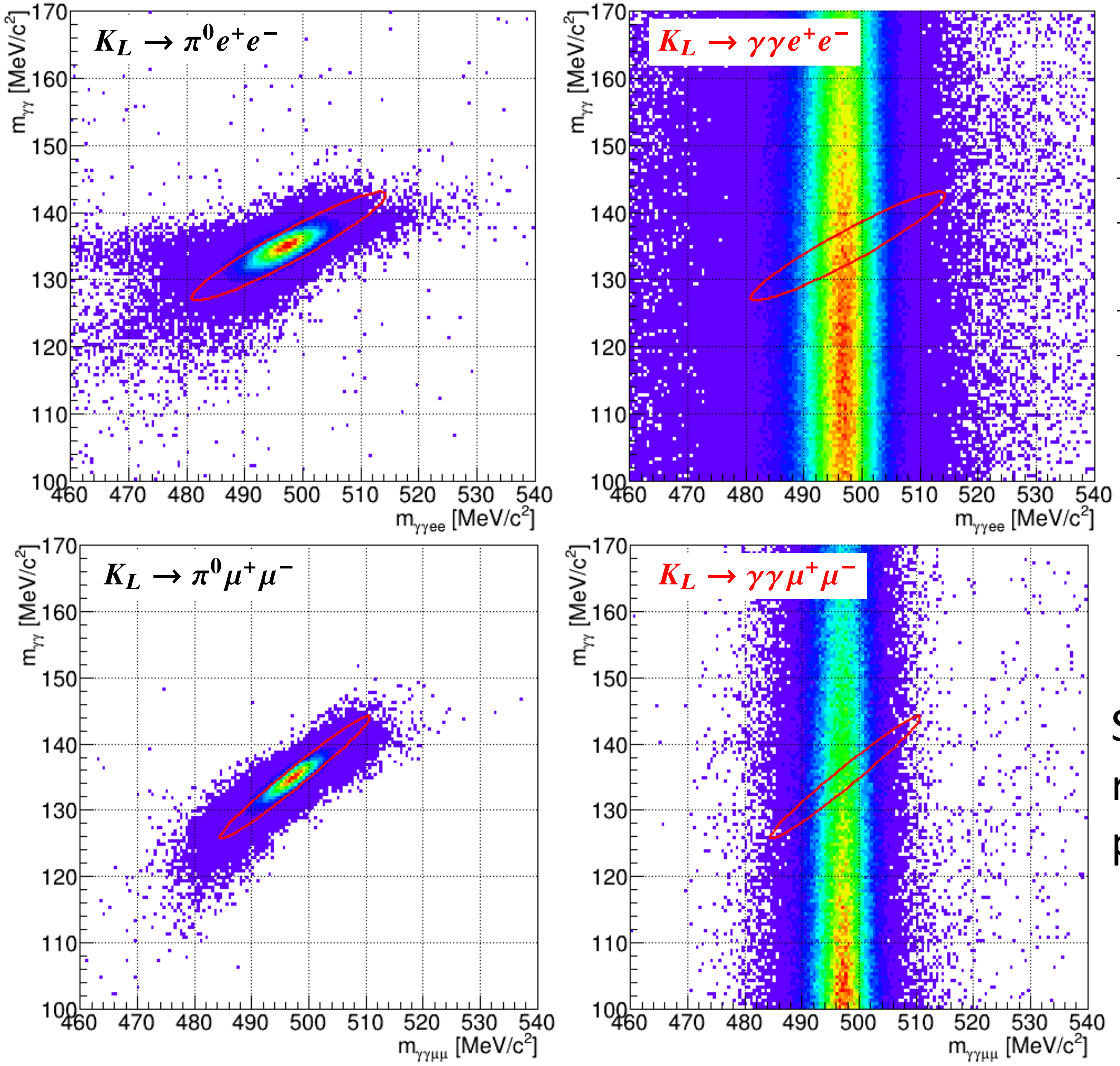


Mean momentum of decaying K_L mesons = 46 GeV/c

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

Statistical power:
3.8 10^{13} Kaon decays in decay volume per year (1.2 10^{19} POT/year)

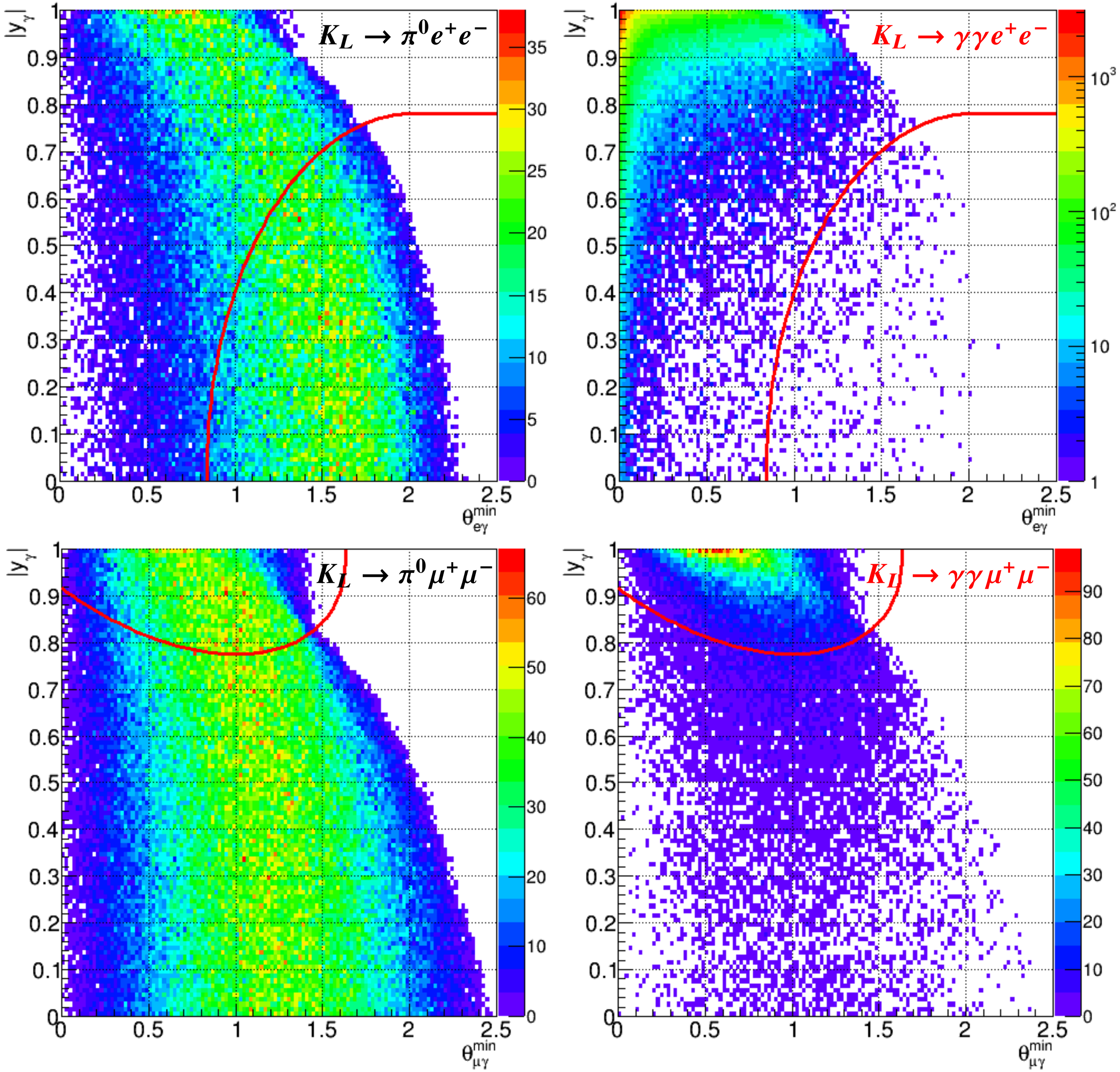
HIKE Phase 2: signal and background



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

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



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

P = kaon four-momentum
k = photon four-momenta

$$x = (m_{ee}/m_K)^2$$

$$x_\gamma = (m_{\gamma\gamma}/m_K)^2$$

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

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

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

HIKE Phase 2: Physics sensitivity

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%

First observation, with a significance above 5σ, 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: form-factor parameter a_S to 5% relative precision.

Assuming constructive interference, determine the CKM parameter λ_t :

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

➡ 20% precision on CKM parameter λ_t

Kaon Global Fit

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell \qquad O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

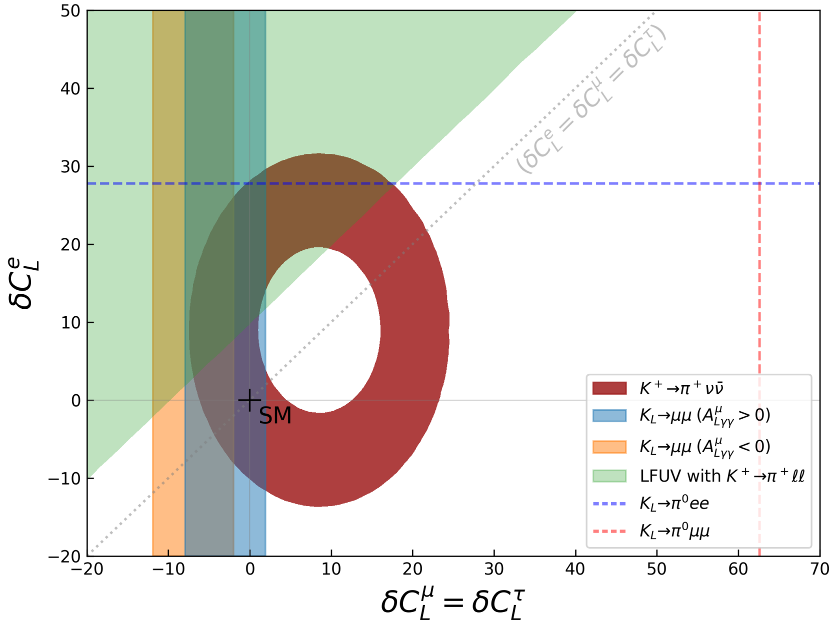
$$C_k^\ell = C_{k,\rm SM}^\ell + \delta C_k^\ell$$

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

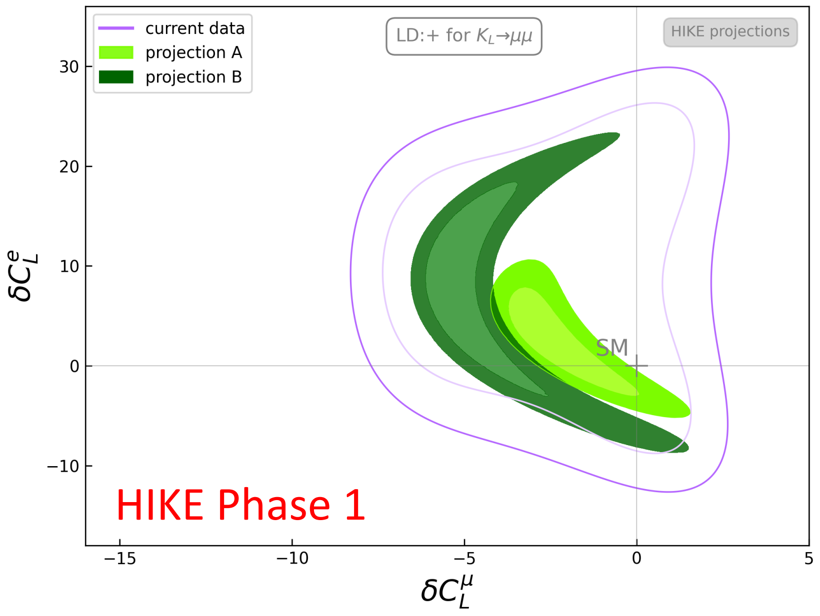
Global fits to set of kaon measurements, in the framework of lepton universality. Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

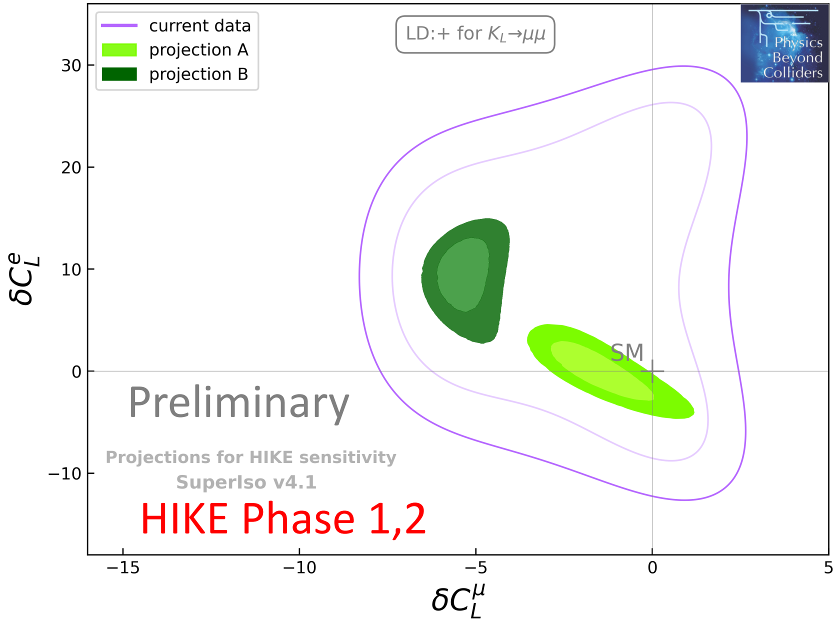
[CERN Physics Beyond Colliders Document in preparation, and paper In preparation by D'Ambrosio, Mahmoudi, Neshatpour]

[arXiv:2206.14748]



[arXiv:2206.14748]





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

Other physics opportunities: 2 examples

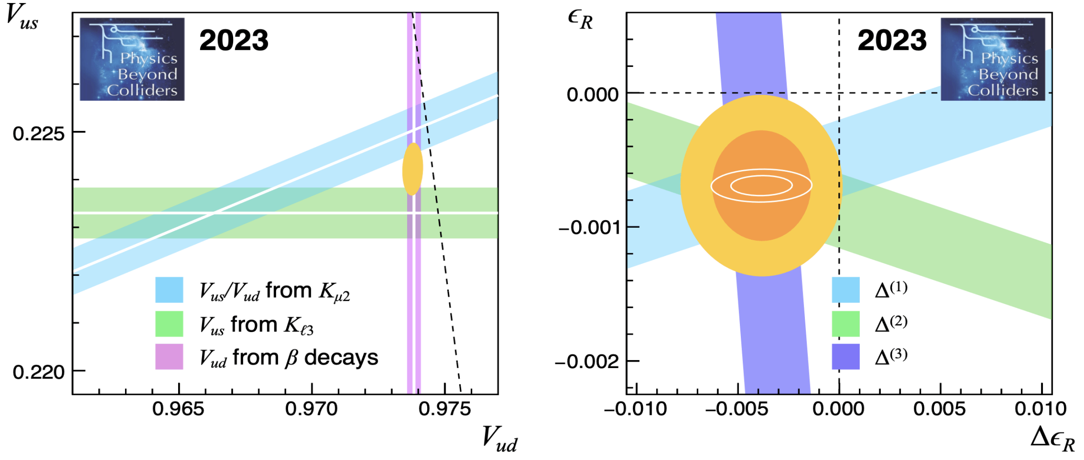
Test of Lepton Universality and Flavour/Number Violation: sensitivity O(10^{-12} - 10^{-13}) in K^+ and K_L decays

Cabibbo Angle Anomaly

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

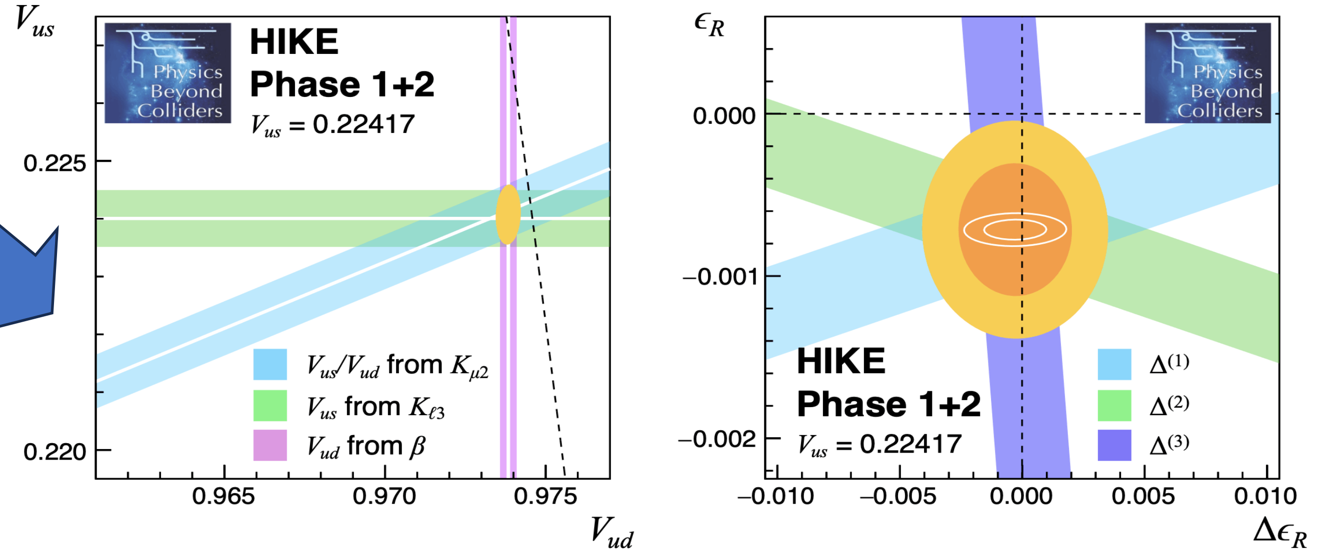
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$

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



HIKE can clarify the origin of the Cabibbo anomaly.
In scenario illustrated, **HIKE resolves tension between kμ2 and kl3 but confirms anomaly due to V_{ud}**

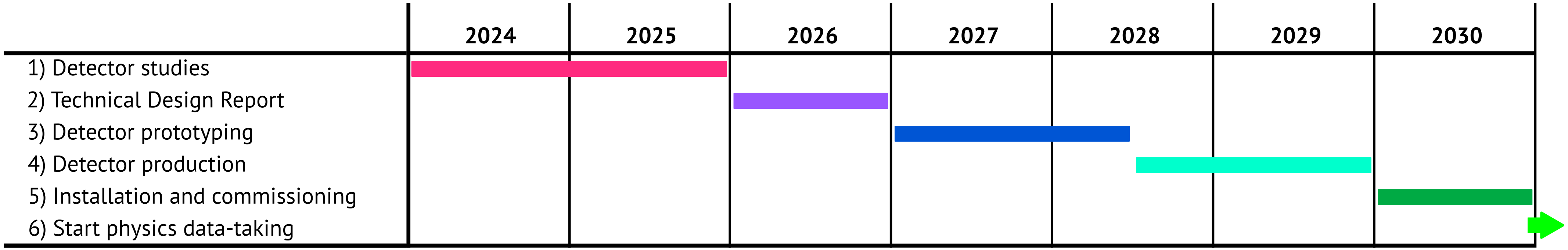
Constraints from CKM unitarity on the contributions to the leptonic and semileptonic kaon decay amplitudes from right-handed quark currents



HIKE: detector

Detector	Phase 1	Phase 2	Comment	Preliminary group interests
Cherenkov tagger	upgraded	removed	faster photo-detectors	UK
Beam tracker	replaced	removed	3D-trenched or monolithic 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

Detector estimated cost: 27.5 M CHF

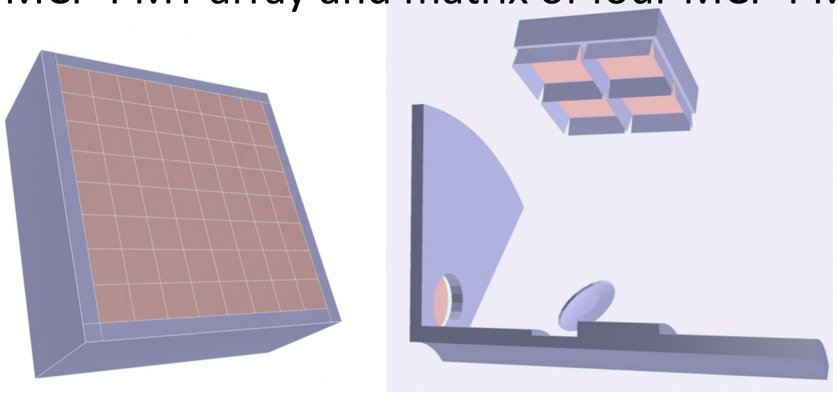


HIKE: Kaon and Pion identification

K ID for 4x intensity

- **Max detected photon rate**: >8 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

MCP-PMT array and matrix of four MCP-PMT



Differential Cherenkov detector

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

RICH detector using neon at atmospheric pressure

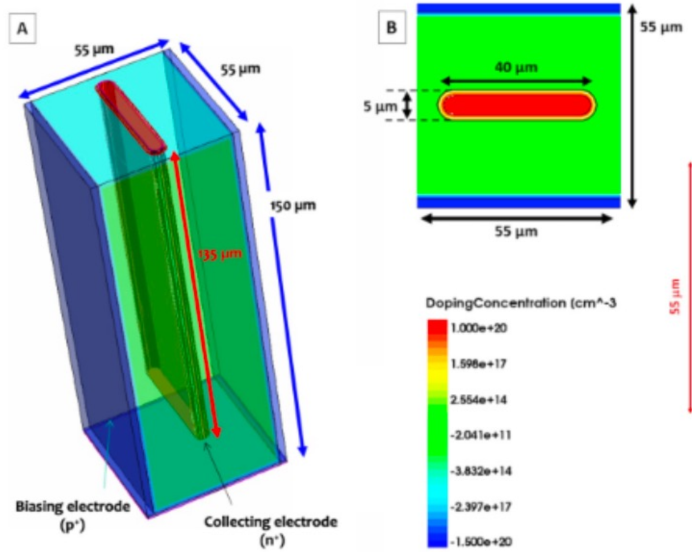
SiPM		3x3 mm^2	62K	2.3 mm	0.66 mm
		6x6 mm^2	16K	2.8 mm	0.78 mm
		9x9 mm^2	7K	3.4 mm	0.95 mm

HIKE: Tracking

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

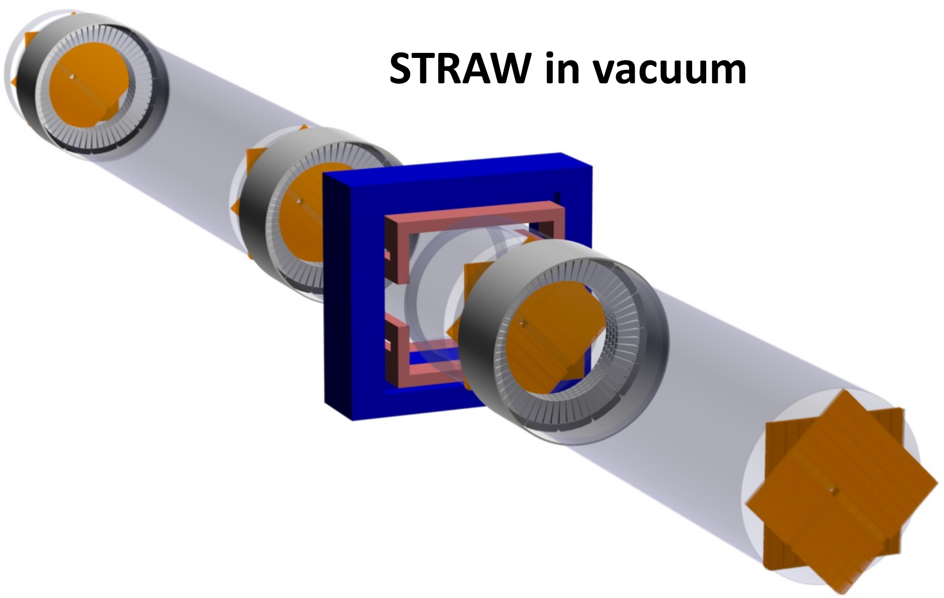
TimeSPOT



Hybrid 3D-trenched technology

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



STRAW in vacuum

Electromagnetic Calorimeter

Main electromagnetic calorimeter requirements:
excellent efficiency and time resolution (~100ps), good two-cluster separation, good energy resolution

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

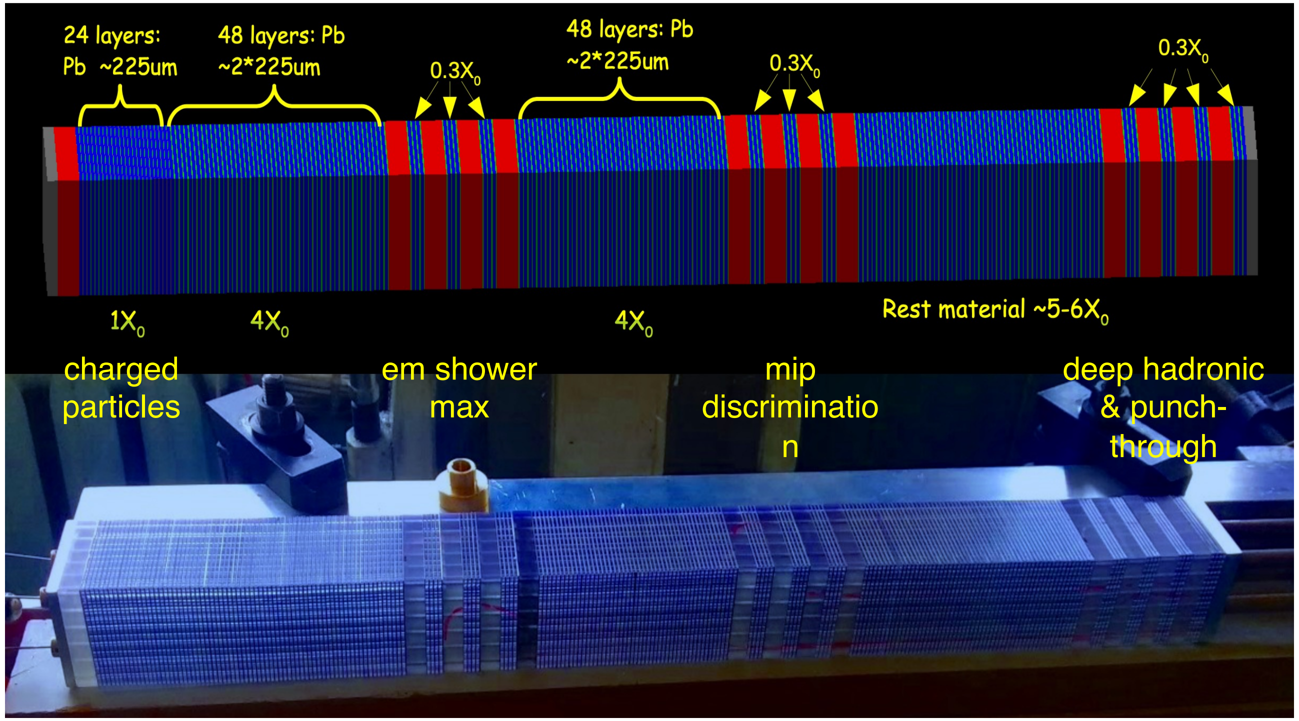
$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

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

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

Efficiency/energy resolution suitable for Phase 1
Time resolution needs 4x improvement for HIKE

Main Electromagnetic Calorimeter:



Fine-sampling shashlyk based on PANDA forward EM calorimeter

PANDA prototypes:

- $\sigma_E/\sqrt{E}$ **~ 3%** $/\sqrt{E}$ (GeV)
- σ_t **~ 72 ps** $/\sqrt{E}$ (GeV)
- σ_x **~ 13 mm** $/\sqrt{E}$ (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.
Also for LAV and SAC.

Summary

HIKE offers excellent sensitivity for new physics at higher mass scales than those accessible at colliders – in certain channels, higher than B physics.
A unique system in which BSM and flavour dynamics can be explored, complementary to B.

HIKE provides 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.

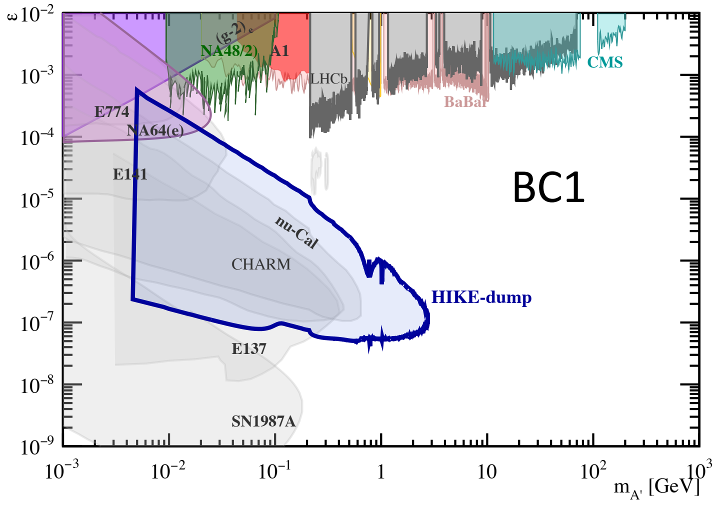
Only place worldwide where this programme is addressed experimentally.

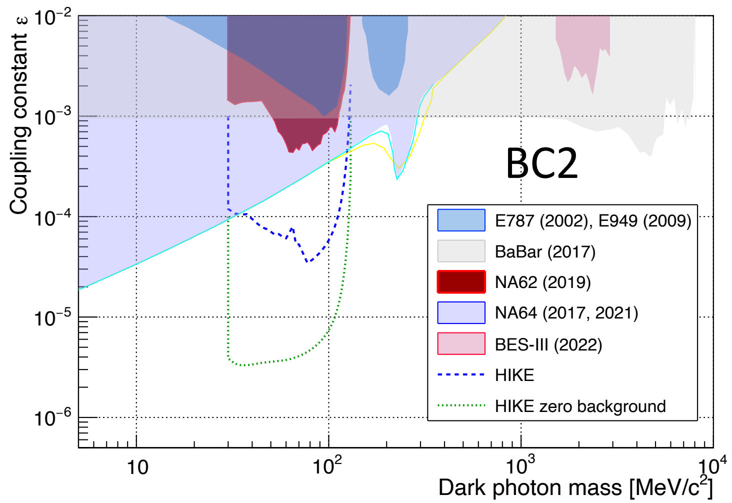
The experimental programme is based on a phase approach involving charged and neutral kaon beams, as well as operation in beam-dump mode, relying on a common infrastructure and set of detectors. Complementary to SHADOWS sensitivity in dump mode.
Synergetic detector challenges with LHC programme.

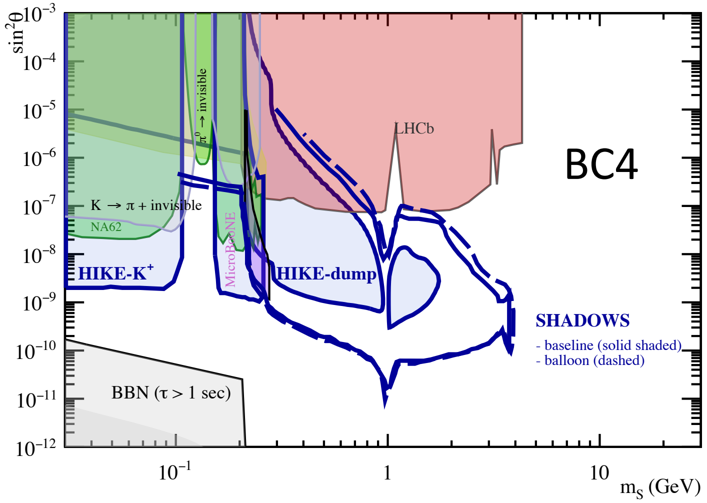
Unique and timely opportunity to address a strongly motivated physics case at CERN NA facility

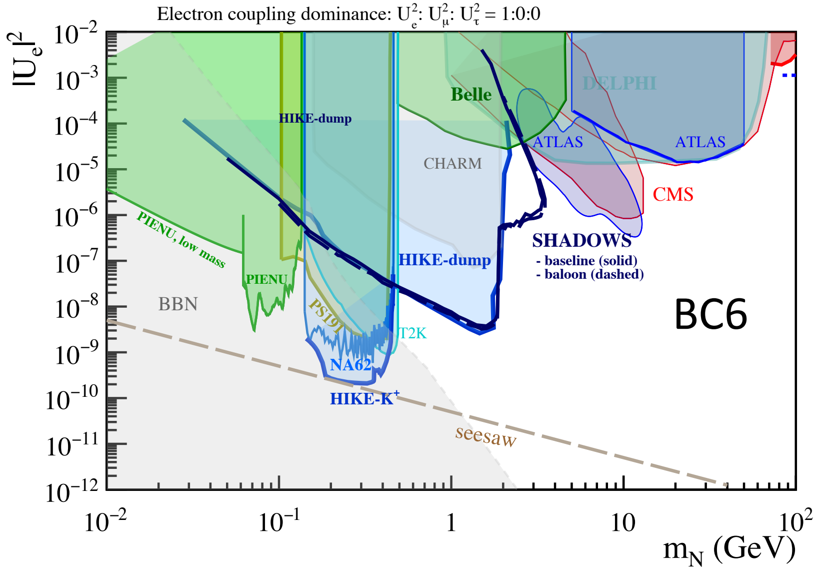
Thank you for listening !

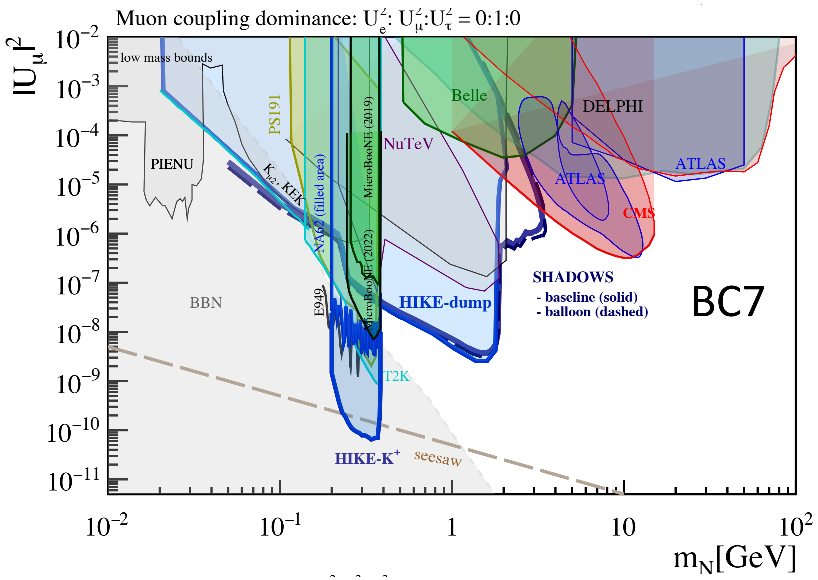
HIKE Phase 1: FIPs sensitivity

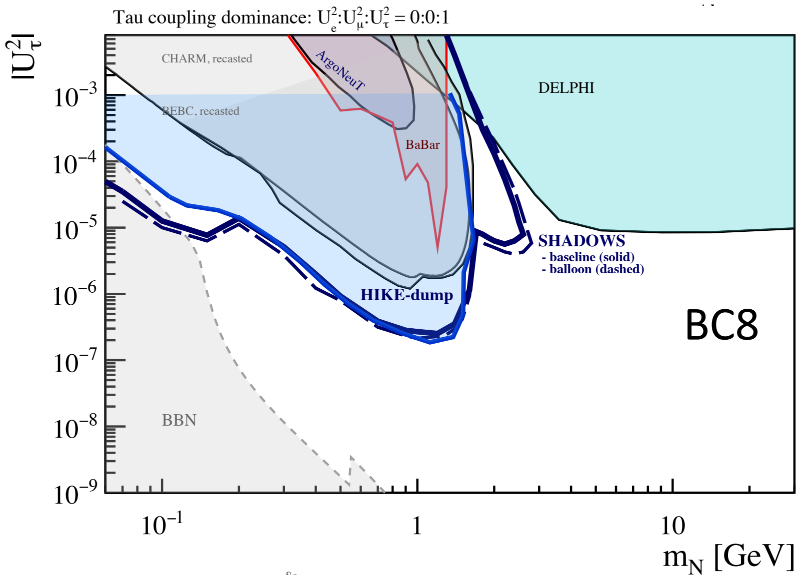




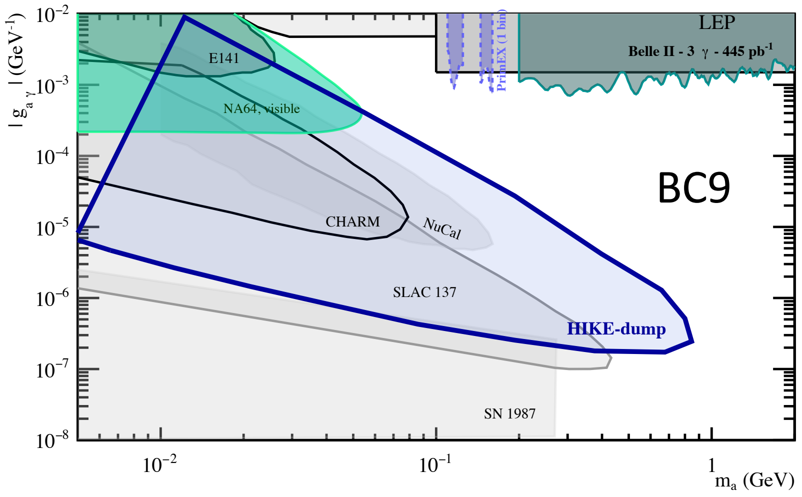


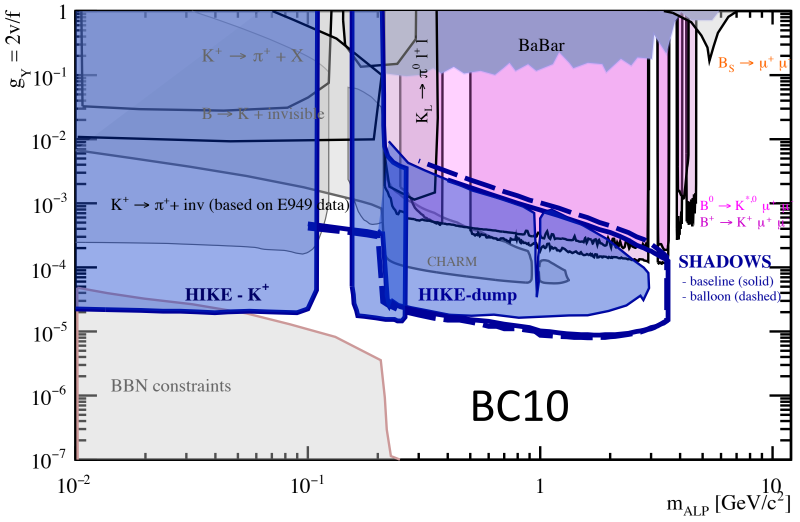


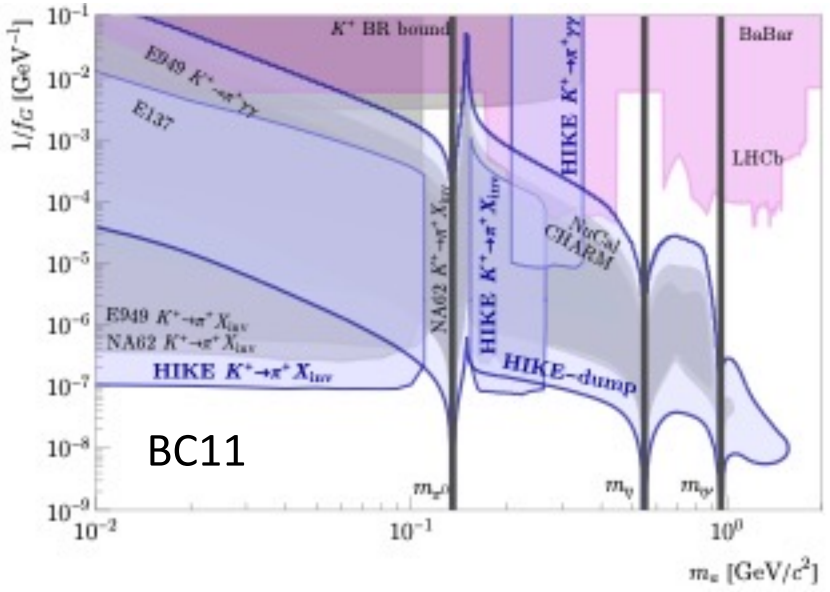




HIKE Phase 1: FIPs sensitivity

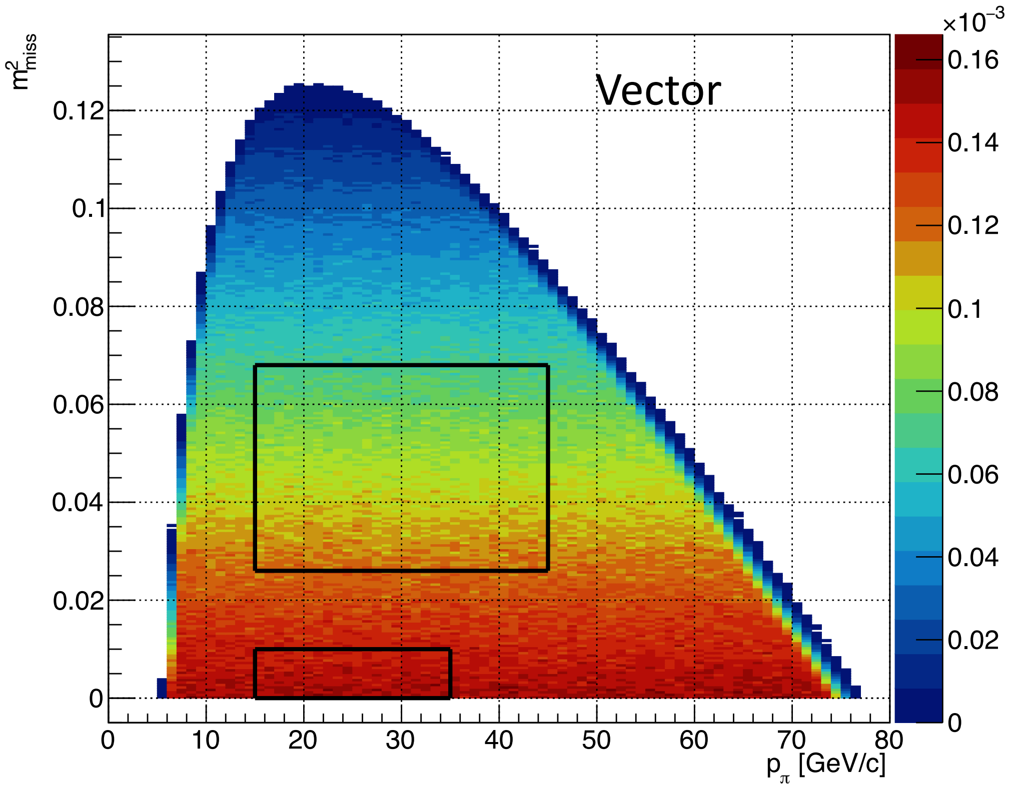


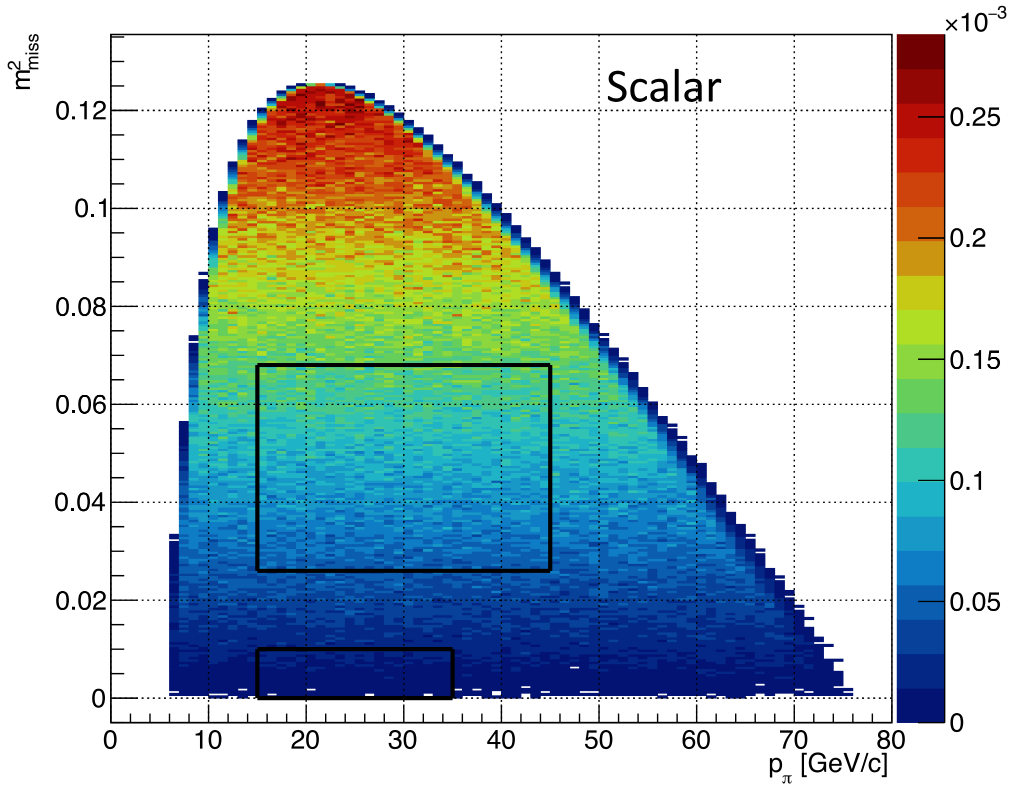




HIKE Phase 1: Beyond the branching ratio

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \mathcal{B}_{\rm SM}(K^+ \to \pi^+ \nu\bar{\nu}) + \sum_{i \le j}^{3} \mathcal{B}_{\rm LNV}(K^+ \to \pi^+ \nu_i \nu_j) = \mathcal{B}_{\rm V}^{\rm SM} + \mathcal{B}_{\rm S}^{\rm LNV}$$





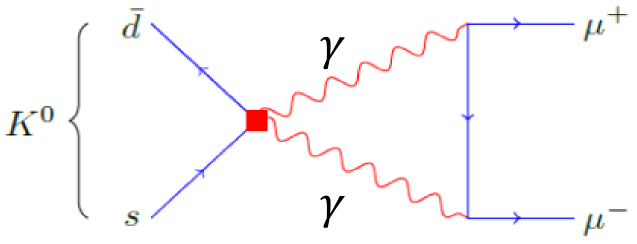
Scalar component fraction at the level of 10^{-11} is observable at HIKE

Shape analysis in progress

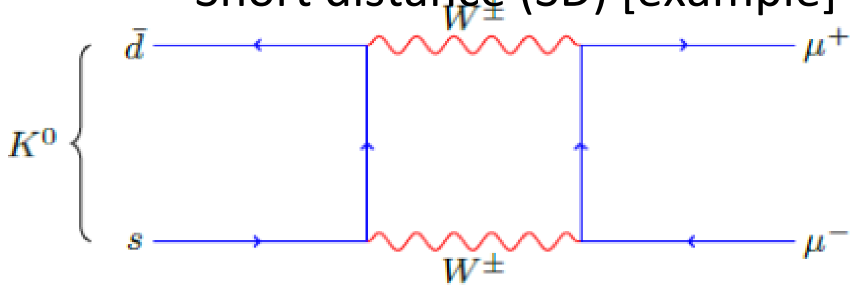
$K^0 \to \mu^+\mu^-$

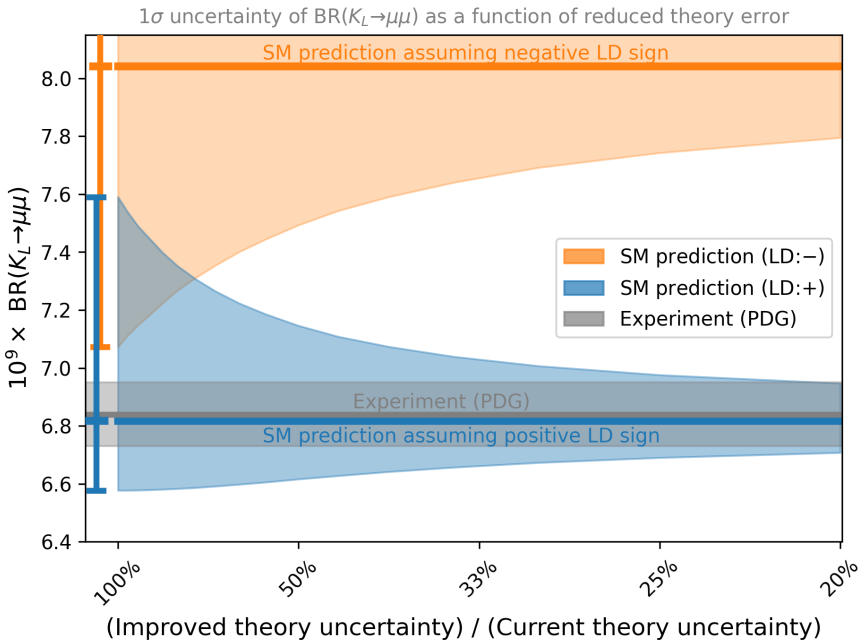
FCNC: SD + important contributions from LD.   SD: CPV for KS, CPC for KL   [arXiv:1707.06999, arXiv:2104.06427]

Long distance (LD)



Short distance (SD) [example]





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

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

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

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

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

Theory work ongoing

HIKE Phase 2: sensitivity to $K_L \to \mu^+\mu^-$ to 1% (stat+syst)

Sensitivities of O(10^{-12}) for branching ratios of a broad range of rare and forbidden K_L decay modes

Scenarios

At HIKE, kaon physics is the highest priority while the sensitivity to FIPs is an extension to the flavour programme that adds value and scheduling flexibility.
The sharing between kaon and beam-dump modes is a matter of scientific scheduling, that by 2031 will take into account the physics priorities at that time and the results from current experiments.
The possibility of switching rapidly between kaon and beam-dump modes adds flexibility to the programme and opportunities for optimisation and best exploitation of the available beam time, also when fitting into the overall SPS schedule.

Scenario	Fraction of time in kaon mode over HIKE lifetime	Integrated POT in dump mode	Years to Phase 1 goals	Years to Phase 1+2 goals
A (for comparison)	100%	–	5	11
B	92%	10^{19}	6	12
C	50% in first 8 years, 100% afterwards	5×10^{19}	9	15

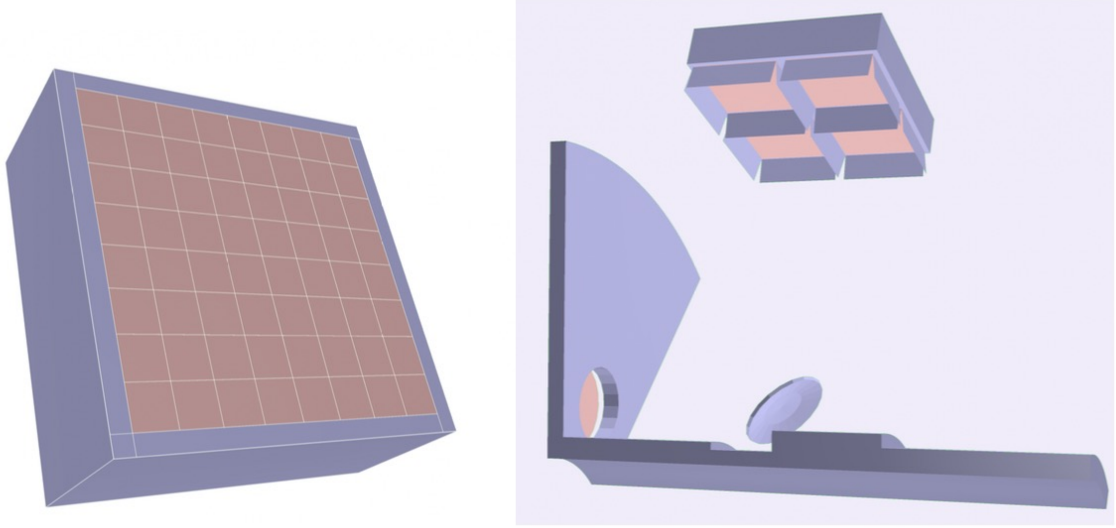
Kaon ID with Cherenkov

Differential Cherenkov detector, refurbished readout

K ID for 4x intensity

- **Max detected photon rate**: >8 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

MCP-PMT array and matrix of four MCP-PMT



Microchannel plate (MCP) PMTs

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

Susceptible to aging (QE drops)

Atomic layer deposition (ALD) coating increases the lifetime dramatically

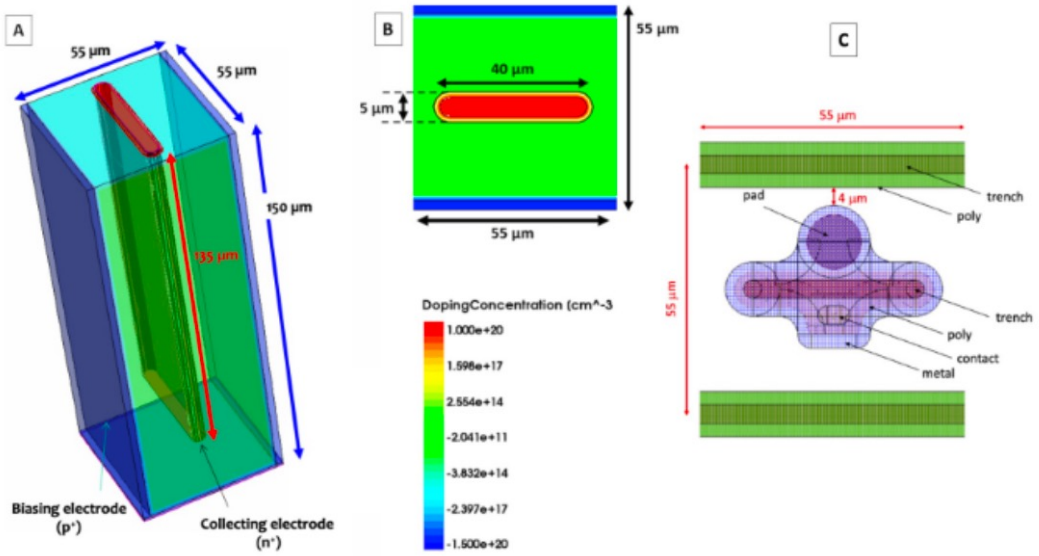
Simulation results obtained with geometrical filling factor of 75% and collection efficiency of 60% show that 15–20 ps kaon time resolution is achievable

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

TimeSPOT



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

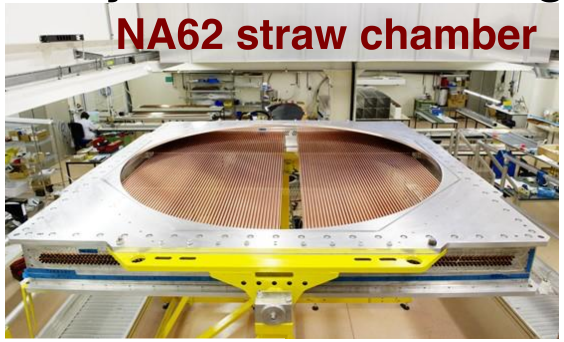
Associated 28nm ASIC: first prototype

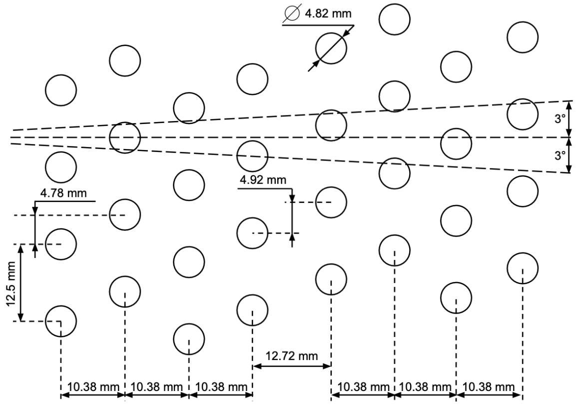
STRAW detector

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

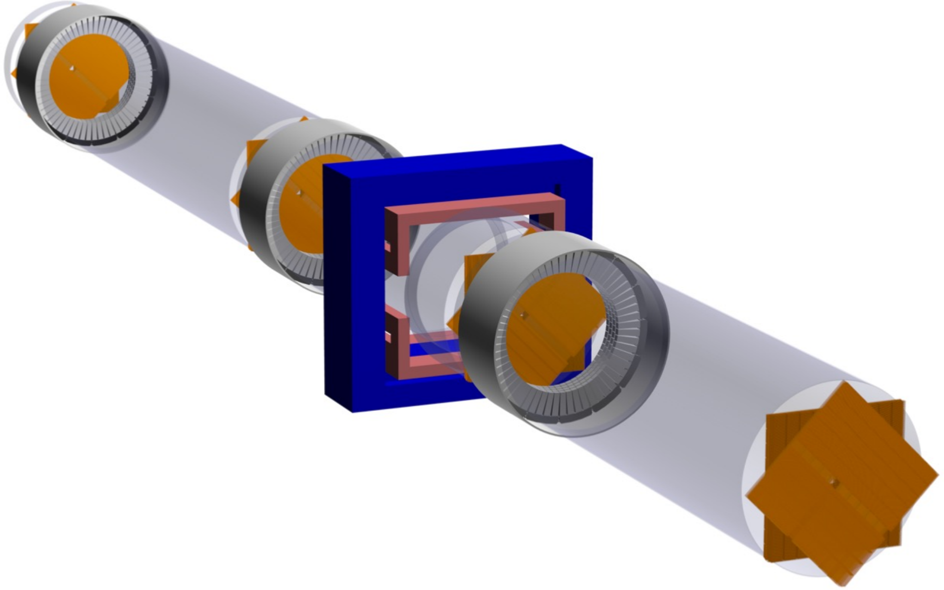
for 4x intensity

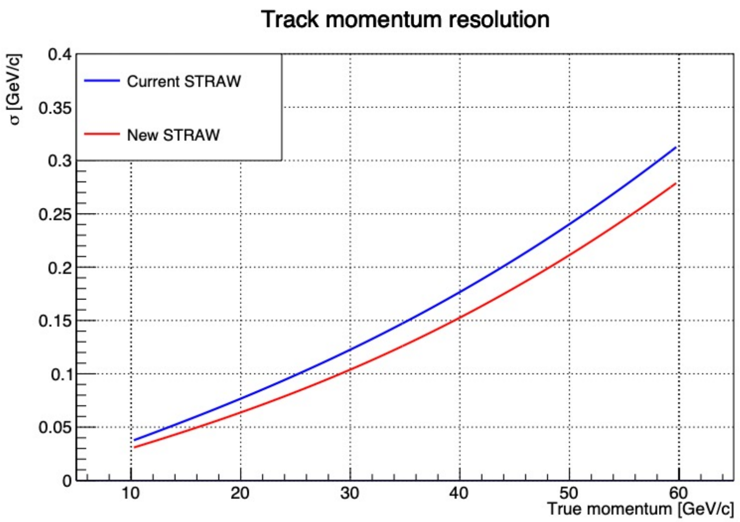
	Current NA62 spectrometer	New straw spectrometer
Straw diameter	9.82 mm	4.82 mm
Straw length	2100 mm	2100 mm
Planes per view	4	8
Straws per plane	112	~160
Straws per chamber	1792	~5200
Mylar thickness	36 µm	(12 or 19) µm
Anode wire diameter	30 µm	(20 or 30) µm
Total material budget	1.7% X_0	(1.0 – 1.5)% 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

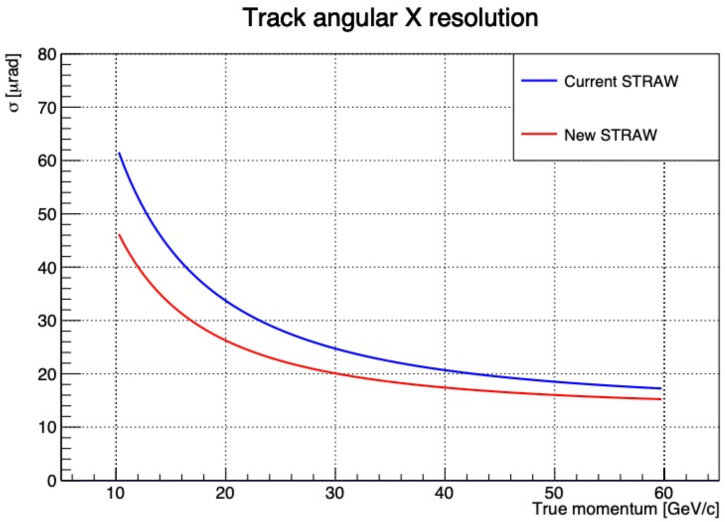




optimised layout for new STRAW detectors



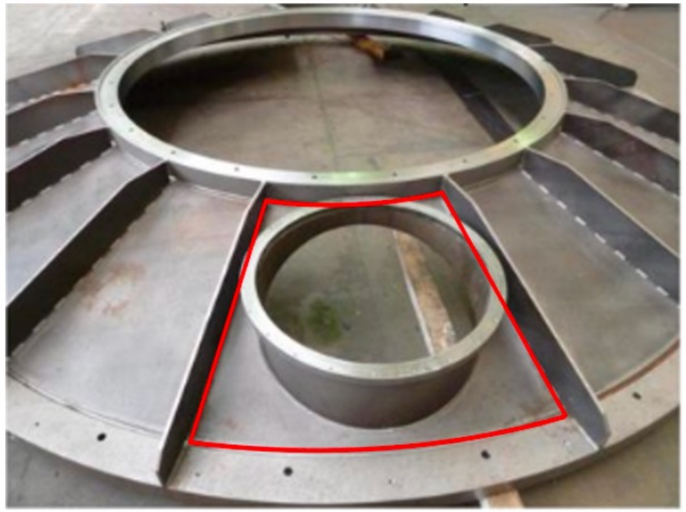




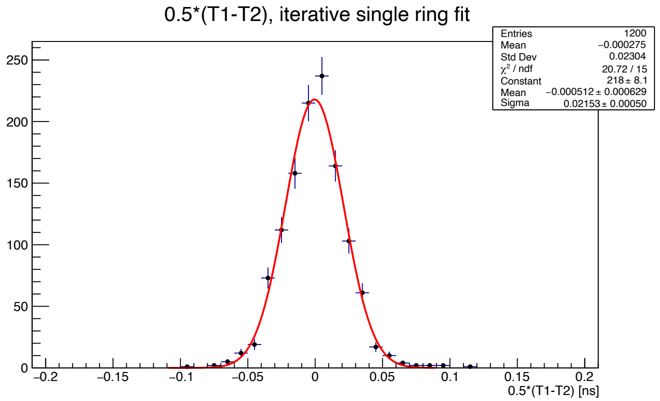
Pion ID with Cherenkov: RICH detector

	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

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. Opportunity to increase acceptance.



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



Large-angle photon vetoes

Time resolution for current NA62 LAVs ~ 1 ns

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

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**

($1 - \varepsilon <$ few 10^{-4} at at least 100 MeV)

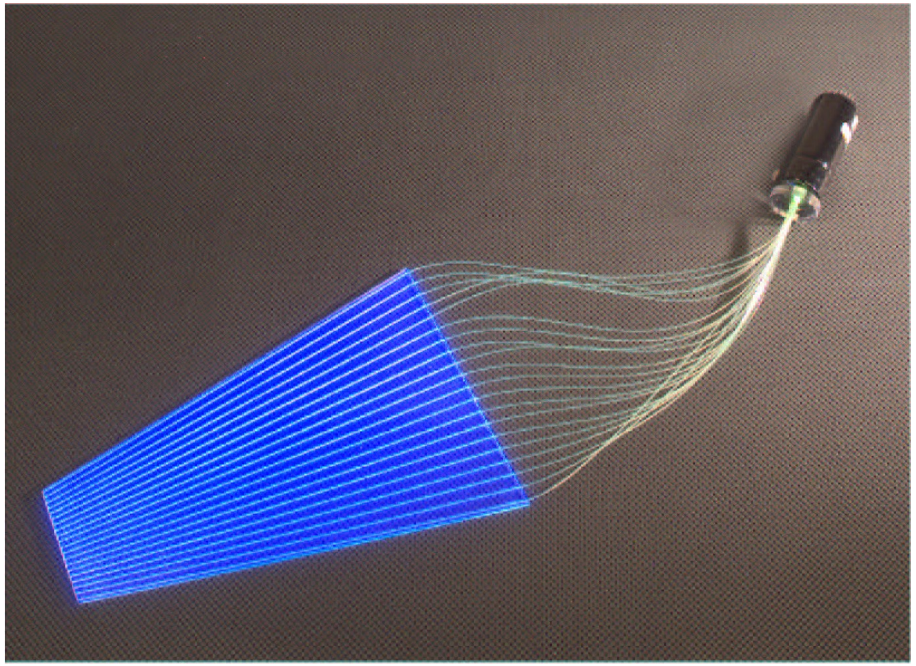
- **Full digitization, segmentation in depth**

Baseline technology:

Lead/scintillator tile with WLS readout

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

Light read out with SiPM arrays



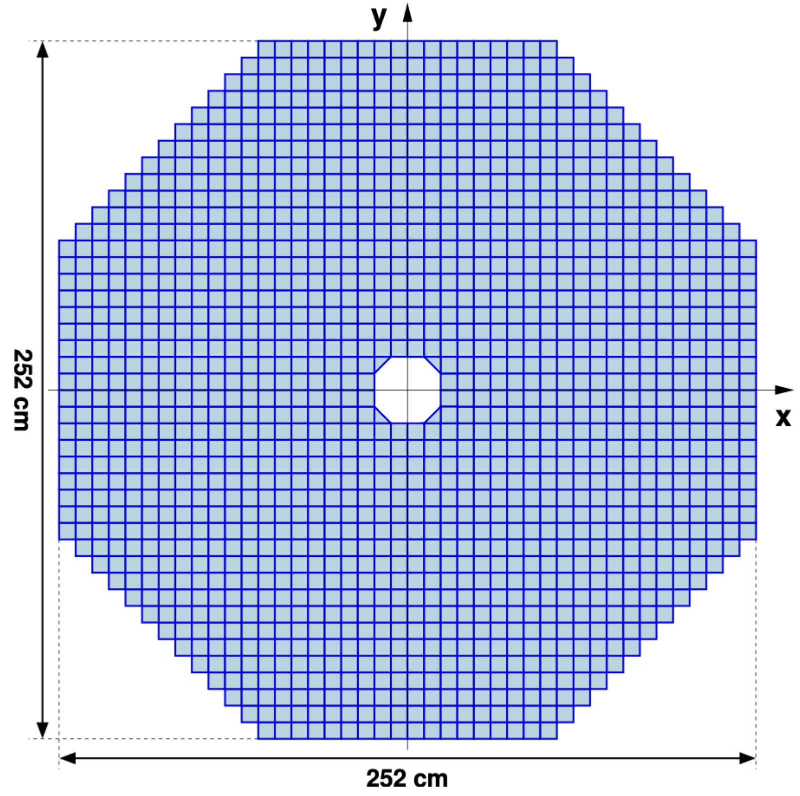
Hadron Calorimeter

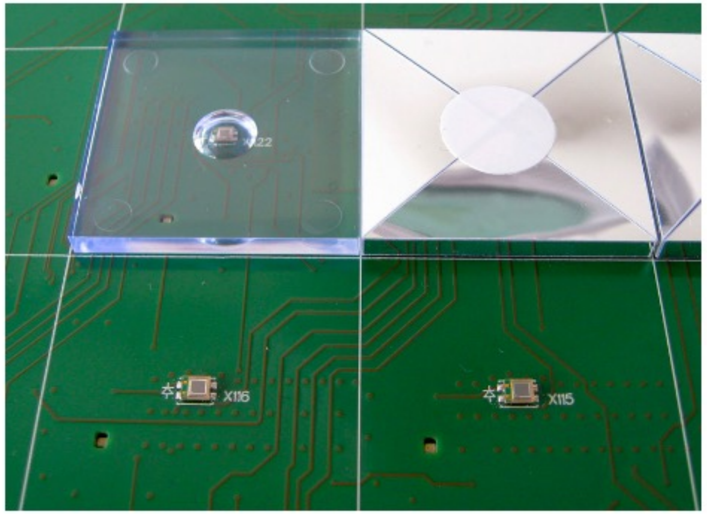
HCAL) is the main detector for π/μ identification and separation (including catastrophically interacting muons, which deposit all or large fraction of their energy in the calorimeter)

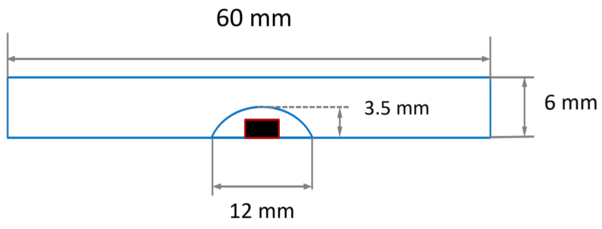
Average muon misidentification probability of $O(10^{-6})$ over momentum range 10 - 50 GeV is necessary

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

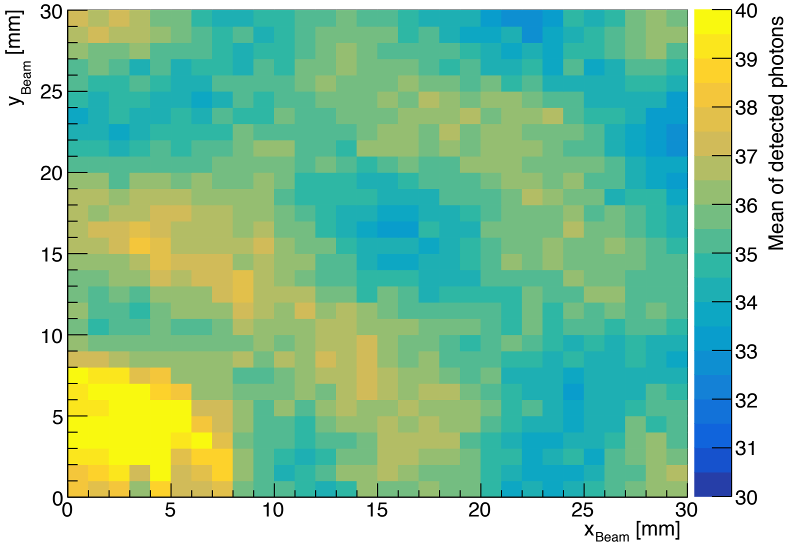
Transverse HCAL layout, 1440 cells







High-Granularity Analogue Calo



Small-angle photon veto

- Rejects high-energy γs 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**
- **σ_t < 100 ps**
- **2 pulse separation at ~ 1 ns**
- **Radiation-hardness:** 10^{14} n/cm^2 and 10^5-10^6 Gy
- **Longitudinal and transverse segmentation** for PID

SAC necessary from Phase 1 but the most stringent requirements for the SAC are for K_L beam

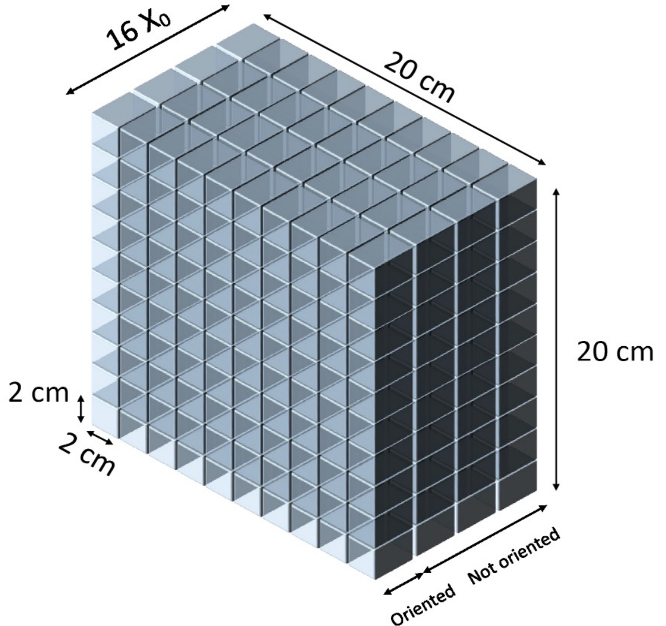
Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

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.

Possible solution:

Compact Cherenkov calorimeter with oriented high-Z crystals

PbF_2 Cherenkov calorimeter



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

$K^+ \to \pi^+ l^+ l^-$ Precision measurement

[JHEP09 (2022) 148]

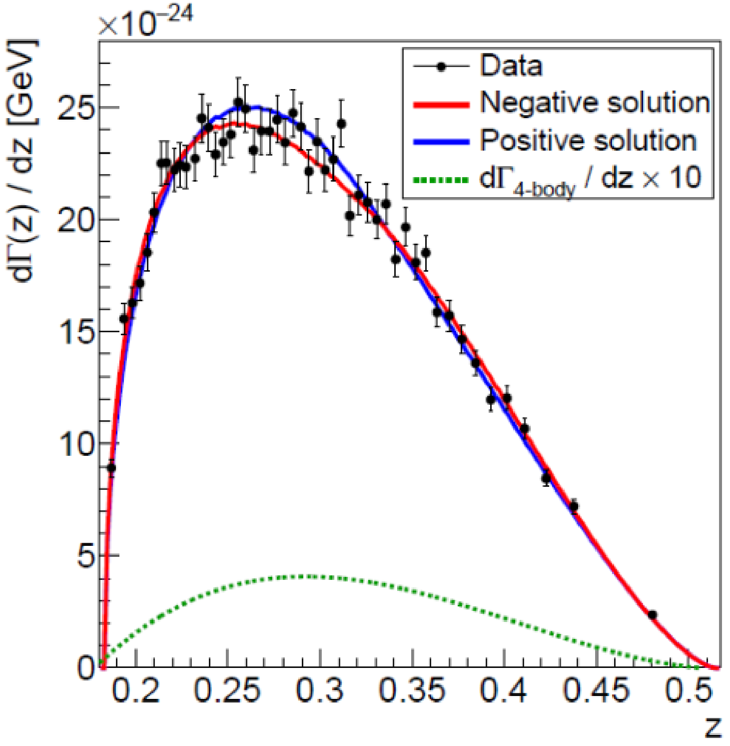
$N_{obs} = 27679$

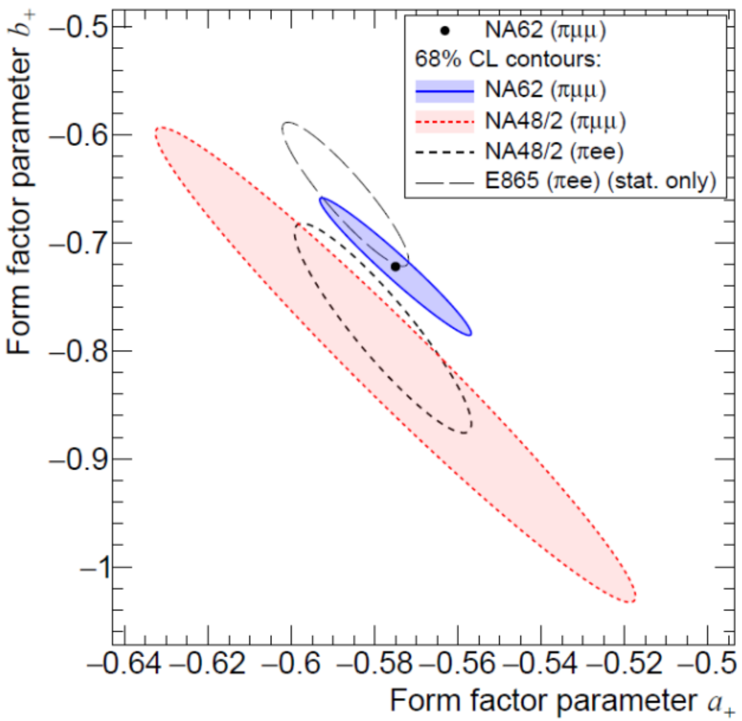
$a_+ = -0.575 \pm 0.013$

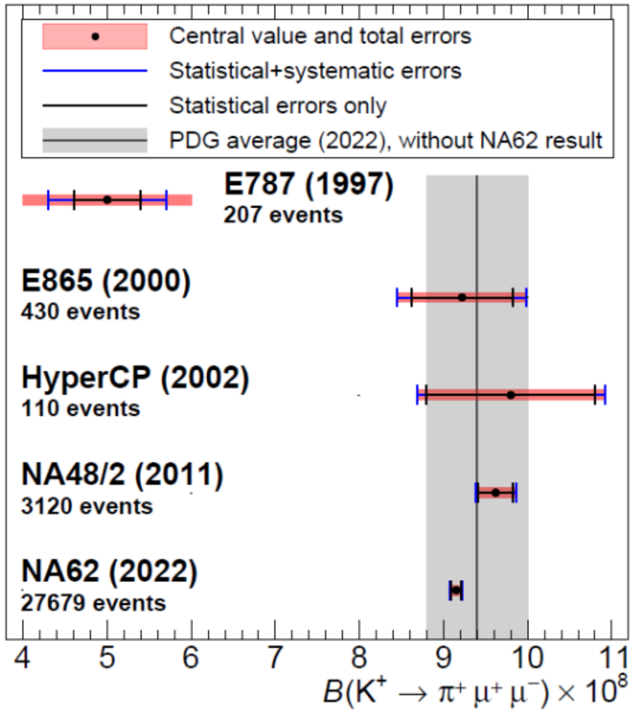
$b_+ = -0.722 \pm 0.043$

$BR(K^+ \to \pi^+ \mu^+ \mu^-) = (9.15 \pm 0.08) \times 10^{-8}$

	δa_+	δb_+	$\delta \mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical uncertainty	0.012	0.040	0.06
Trigger efficiency	0.002	0.008	0.02
Reconstruction and particle identification	0.002	0.007	0.02
Size of the simulated $K_{\pi\mu\mu}$ sample	0.002	0.007	0.01
Beam and accidental activity simulation	0.001	0.002	0.01
Background	0.001	0.001	—
Total systematic uncertainty	0.003	0.013	0.03
$K_{3\pi}$ branching fraction	0.001	0.003	0.04
$K_{\pi\mu\mu}$ radiative corrections	0.003	0.009	0.01
Parameters α_+ and β_+	0.001	0.006	—
Total external uncertainty	0.003	0.011	0.04







$K^+ \to \pi^+\gamma\gamma$ Precision measurement

LD dominated, test of Chiral Perturbation Theory, kin. variables

$$z = \left(\frac{m_{\gamma\gamma}}{m_K}\right)^2 \quad y = \frac{P_K(Q_{\gamma_1} - Q_{\gamma_2})}{m_K^2}$$

D'Ambrosio, Portoles PLB 386 403 (1996)

$d\Gamma/(dydz)$ depends on the chiral parameter $\hat{c}$ + external parameters

Measurement of $BR(K^+ \to \pi^+\gamma\gamma)$ and $\hat{c}$

NA62 recent: Data RUN 1, ~10% background

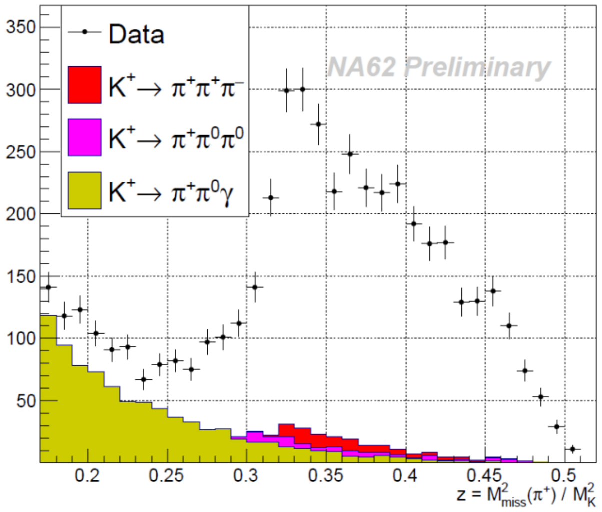
norm $K^+ \to \pi^+\pi^0$, $\hat{c}$ from $d\Gamma/(dydz)$

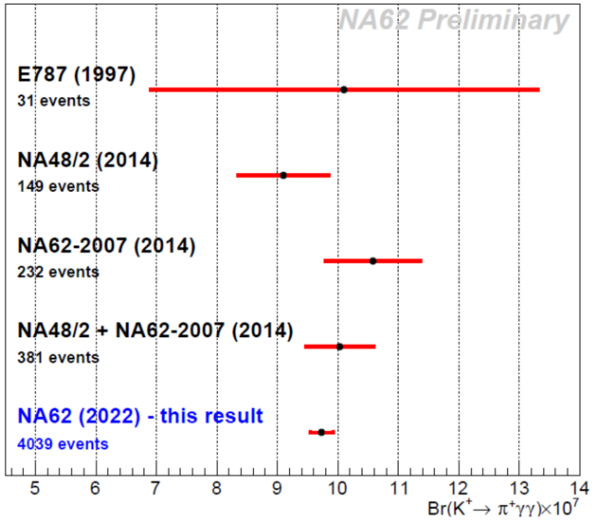
external parameters from $K \to 3\pi$ fit

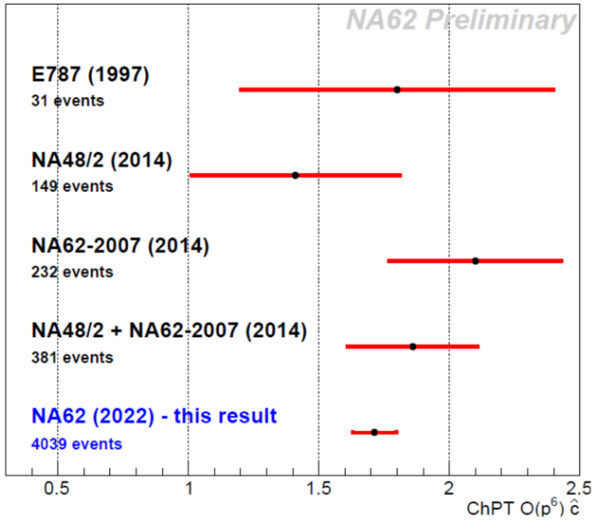
$N_{obs} = 4039 \qquad N_{bkg} = 393 \pm 20$

$\hat{c} = 1.713 \pm 0.075_{stat} \pm 0.037_{syst}$

$BR(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$







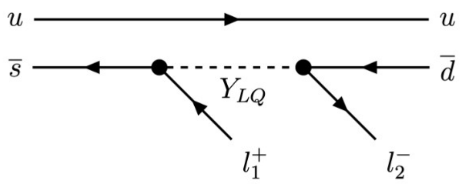
HIKE Phase 1: sensitivity to many radiative decays of interest

$K^+ \to \pi^+\gamma\gamma$ precision of few per mille

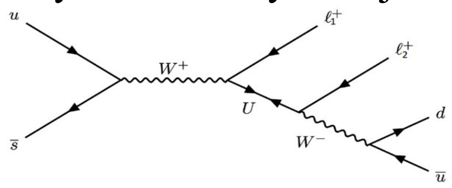
LNV and LFV tests

Direct search of NP: Majorana neutrino (LNV), Leptonquark (LFV)

LFV possibly mediated by leptoquark:



LNV possibly mediated by a Majorana neutrino:

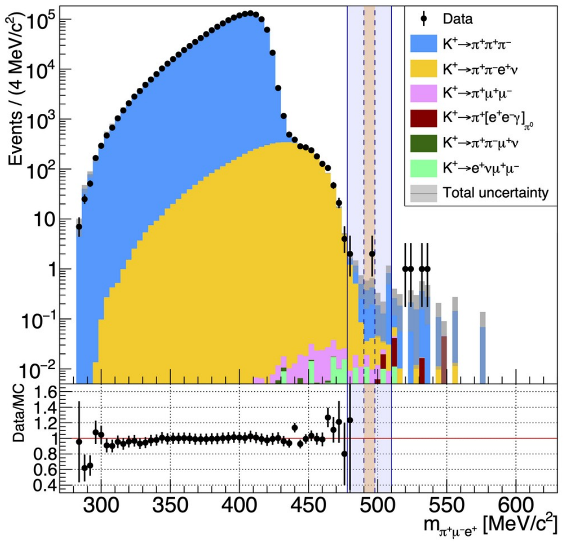


Many channels:

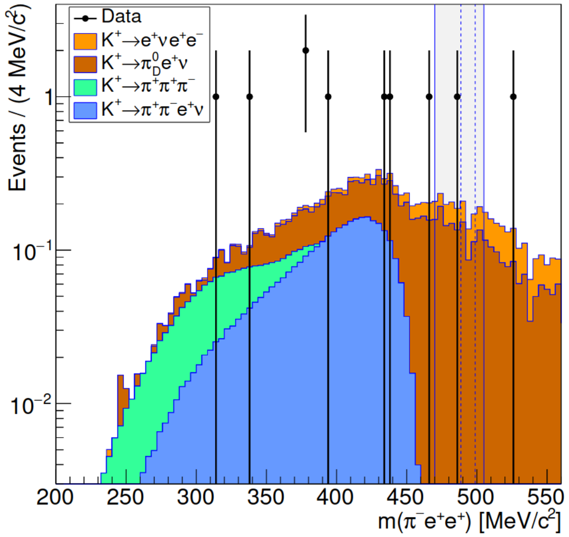
- $K^+ \to \pi^- \mu^+ \mu^+$
- $K^+ \to \mu^- \nu e^+ e^+$
- $K^+ \to \pi^- e^+ e^+$
- $K^+ \to \pi^- \pi^0 e^+ e^+$
- $K^+ \to \pi^\mp \mu^\pm e^+$
- $\pi^0 \to \mu^- e^+$

NA62 recent: Several channels studied with RUN1 data

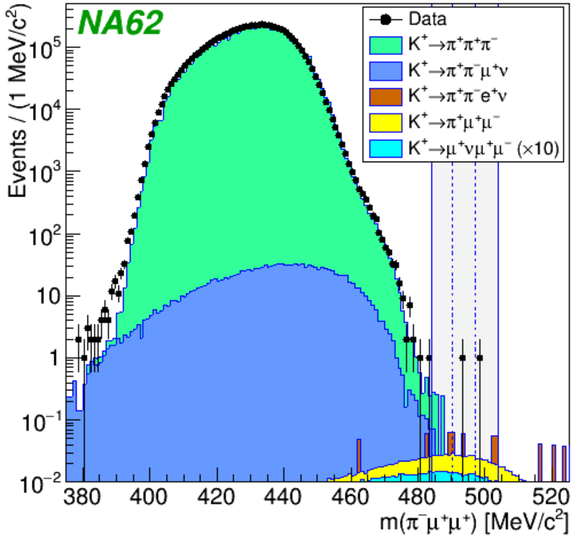
$K^+ \to \pi\mu e$ [PRL127(2021)131802]



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



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



NA62: $O(10^{-11})$ on Br of LNV and LFV K^+ decays

HIKE Phase 1: sensitivity $O(10^{-12})$ or below to LNV and LFV K^+ decays

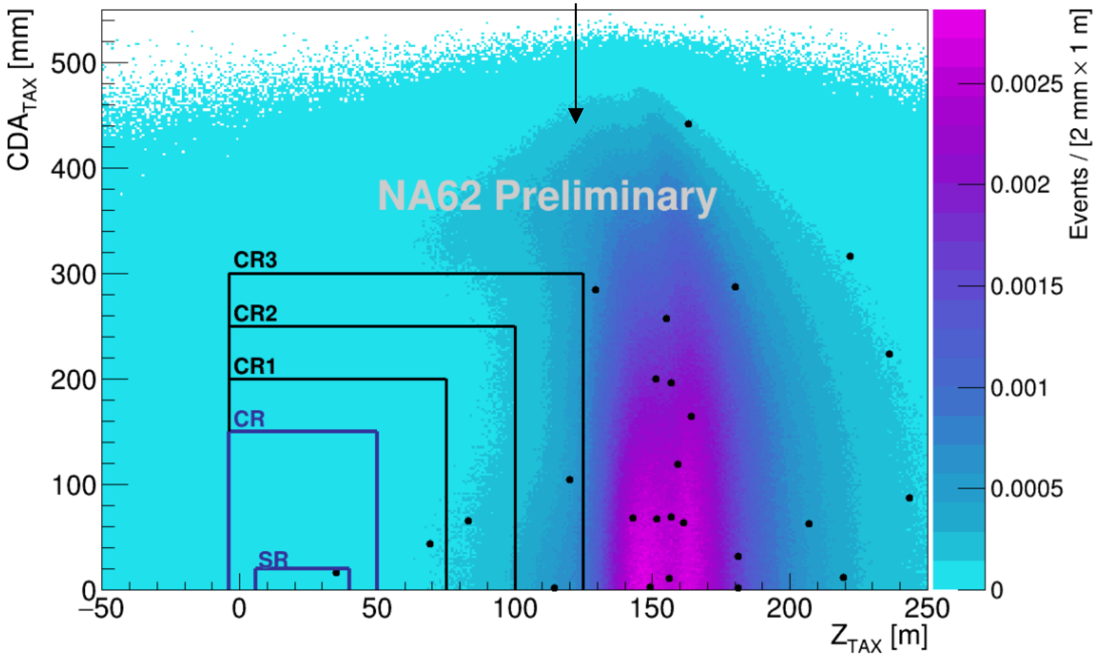
Dark Photon Search $A' \rightarrow \mu^+\mu^-$ in NA62 RUN2

Theory: SM extension in the framework of feebly interacting particle models (FIPs)
Parameters: mass $M_{A'}$, coupling to SM fields ε, If $M_{A'} < 0.7$ GeV decay to l^+l^- dominate

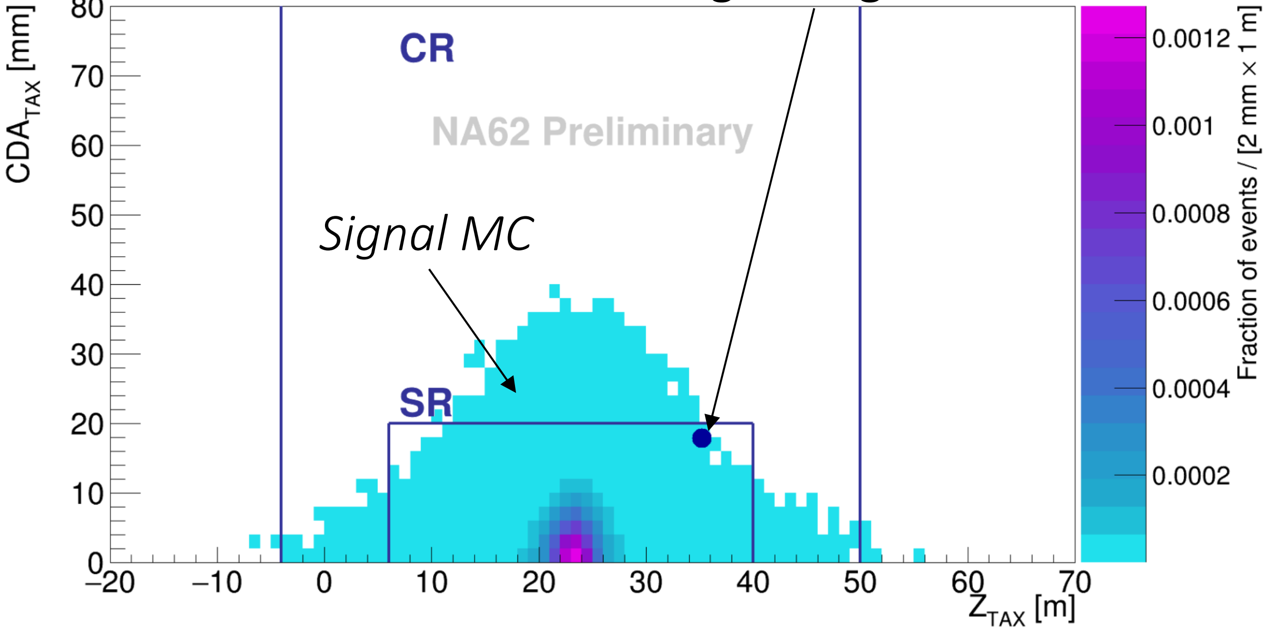
NA62: Data taken in dump mode in **2021 (RUN2),** exploitation of beam optimization and ANTI0

Analysis: blind analysis, reconstructed A' compatible with production in dump
Background from random time superposition of two uncorrelated muons (data-driven estimation)

Data-driven expected background



1 event observed in signal region



Kaon Experiments at CERN

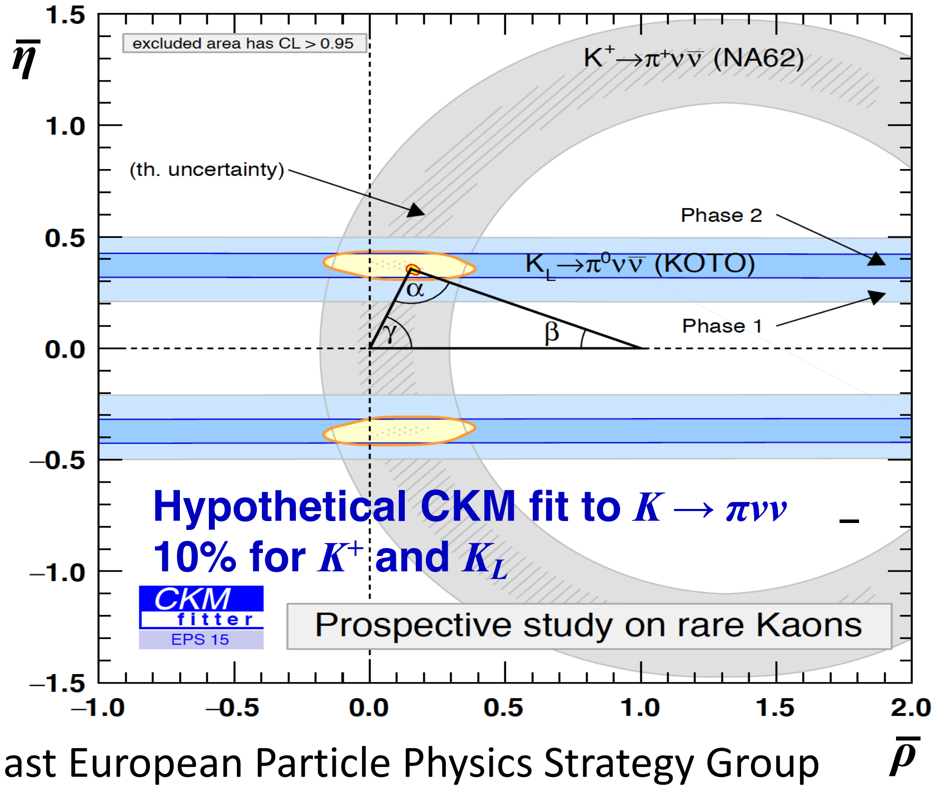
HIKE will build on the experience of studying kaon physics at CERN over past four decades

A.J. Buras KAON2016

$\varepsilon_K, \Delta M_K$ | ε'/ε | $K^+ \to \pi^+ \nu\bar{\nu}$ | $K_L \to \pi^0 \nu\bar{\nu}$

$K_L \to \mu^+\mu^-$ | $K_L \to \pi^0 e^+ e^-$ | $K_L \to \pi^0 \mu^+\mu^-$

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.

Kaon Global Fit

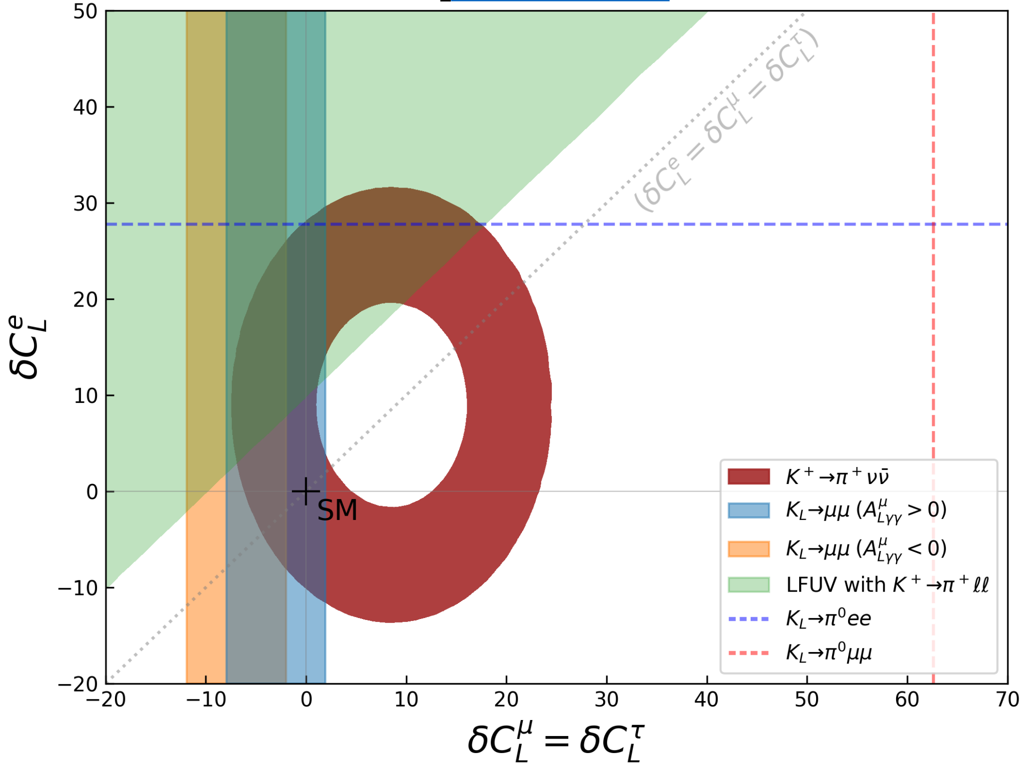
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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

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

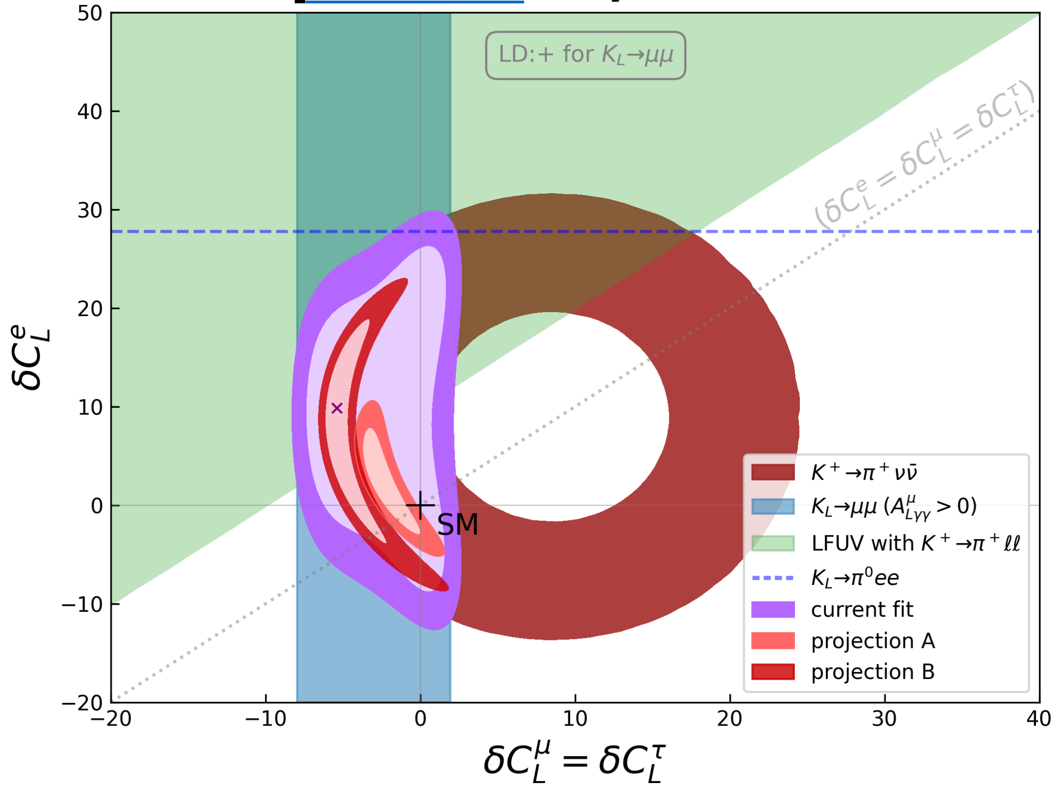
For example, recent paper with global fits to set of kaon measurements
Deviation of Wilson coefficients from SM, for NP scenarios with only left-handed quark currents.

[arXiv:2206.14748]



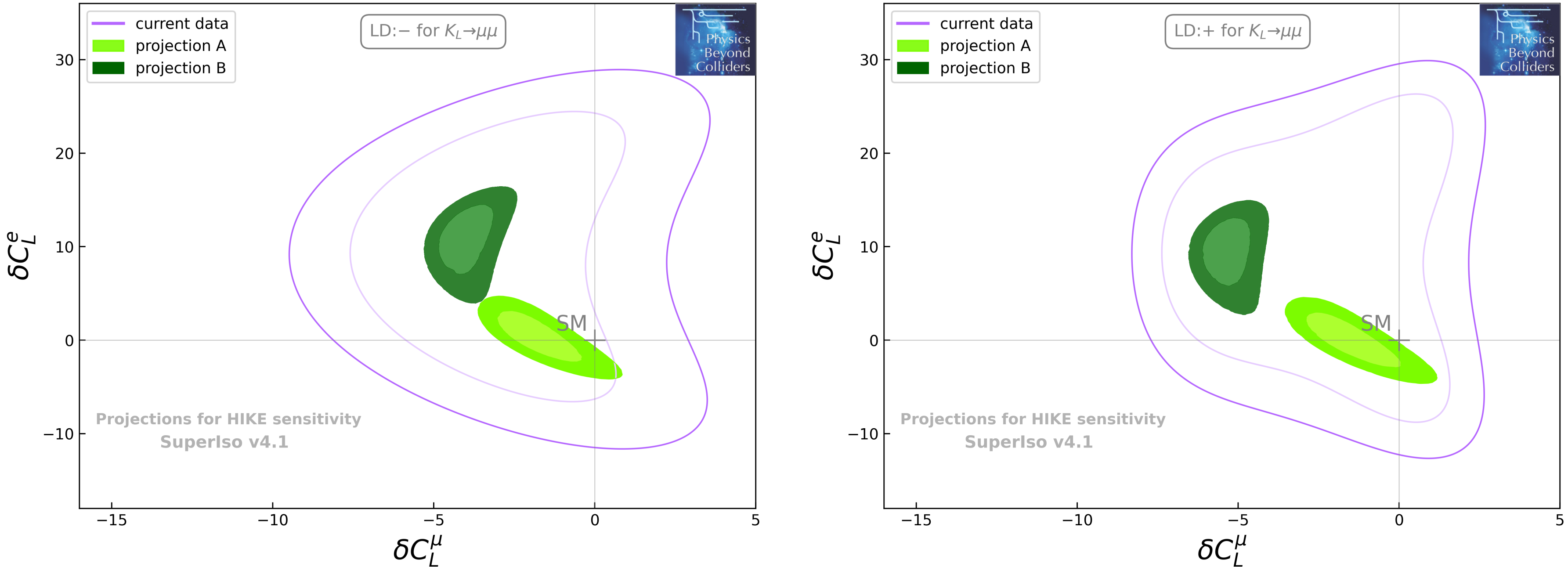
Bounds from individual observables.
Coloured regions are 68%CL measurements
Dashed lines are 90%CL upper limits

[arXiv:2206.14748]



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

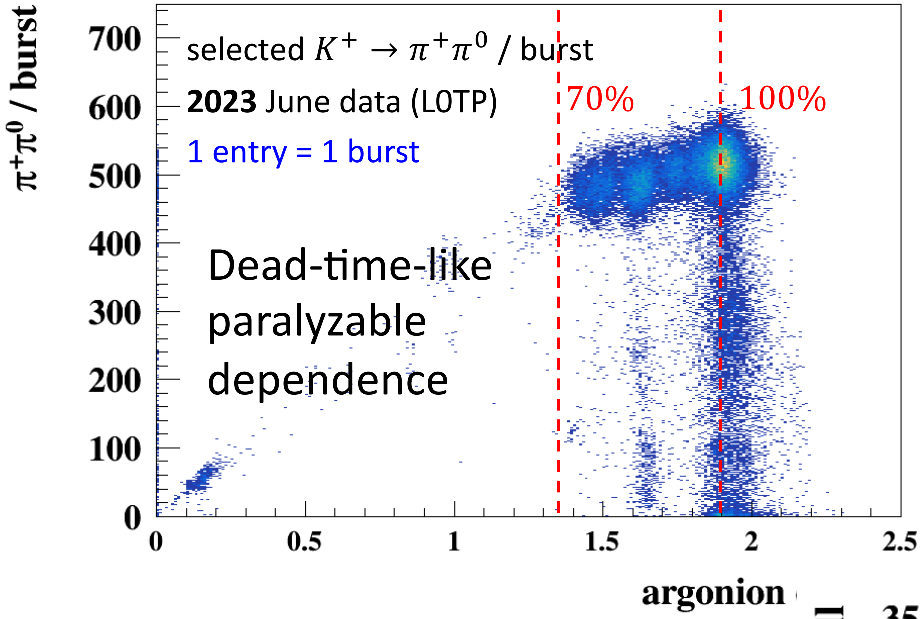
Observable	SM prediction	Experimental results	Ref.	HIKE projections
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[144]	5% (Phase 1)
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.031 ± 0.017	[207, 208]	± 0.007 (Phase 1)
$\mathrm{BR}(K_L \to \mu\mu)\ (+)$	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[209]	1% (Phase 2)
$\mathrm{BR}(K_L \to \mu\mu)\ (-)$	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$			
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	[210]	Upper bound kept to current value
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[211]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[212]	20% (Phase 2)
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

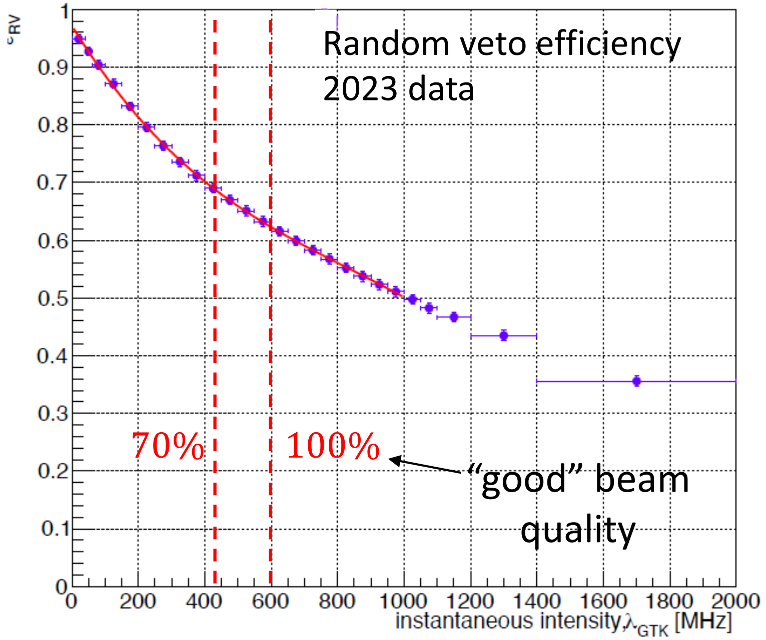


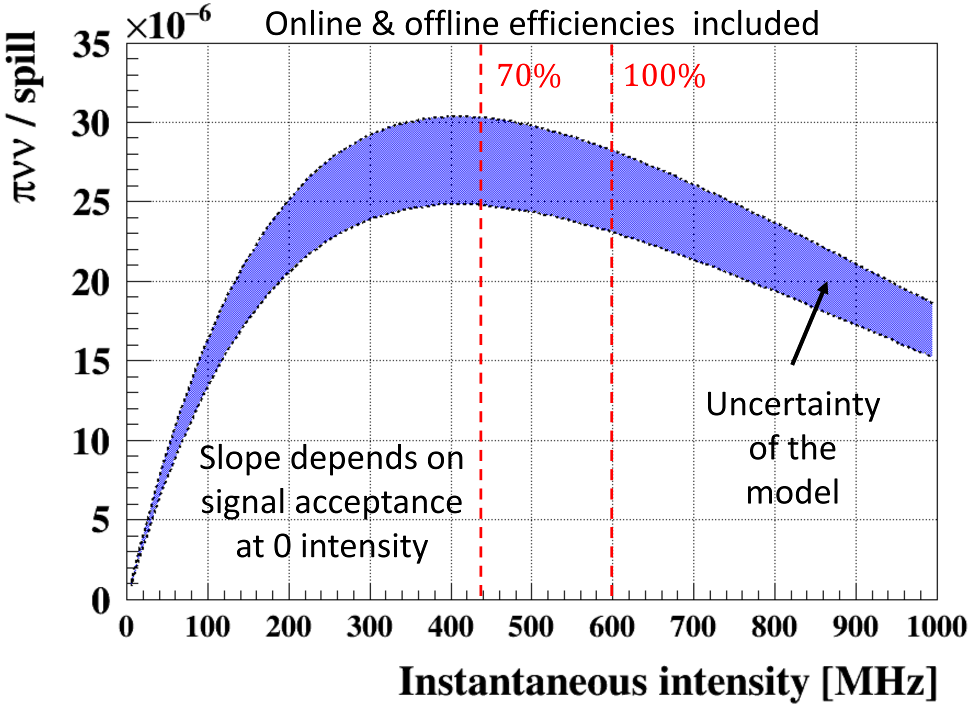
Estimated cost for detectors

Detector	Group	Cost (MCHF)
Kaon ID (KTAG)	UK	0.5
Beam tracker	Italy, CERN, UK, Belgium, Canada, France	3
Charged particle veto (CHANTI)	Switzerland	0.4
Veto counter (VC)	Switzerland	0.3
ANTI-0	Germany	0.4
Large Angle Vetos (LAV)	UK	8
STRAW	CERN, Kazakhstan, Slovakia, Czech Republic	3.5
Main calorimeter	Italy	5
Small Angle Calorimeter (SAC)	Italy	2
Pion ID (RICH)	Italy, Mexico	0.8
Timing detector	Belgium	0.4
HCAL	Germany	1.5
Muon plane	Germany	0.2
HASC	Romania	0.2
DAQ, computing	CERN, Italy, Spain, Mexico, US	1.3
Total		27.5

NA62: Limitations

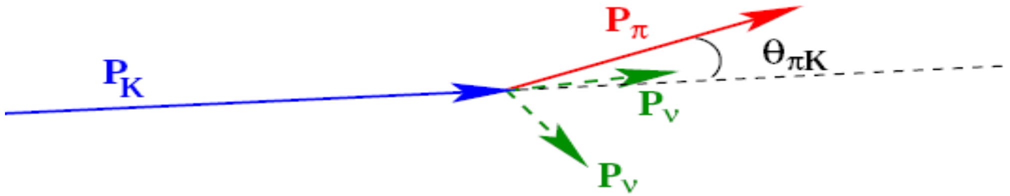




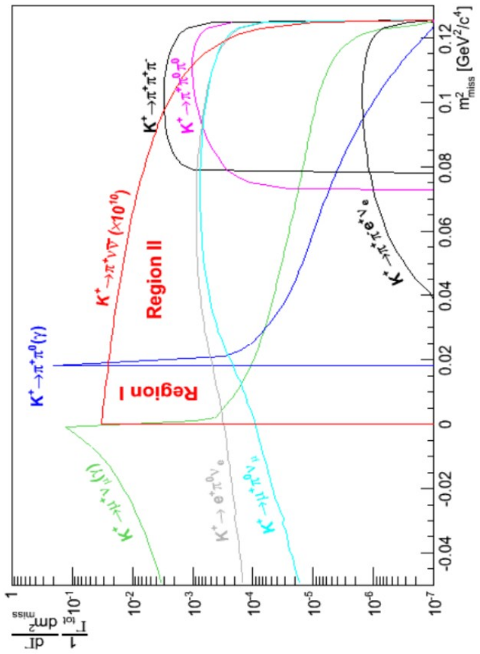


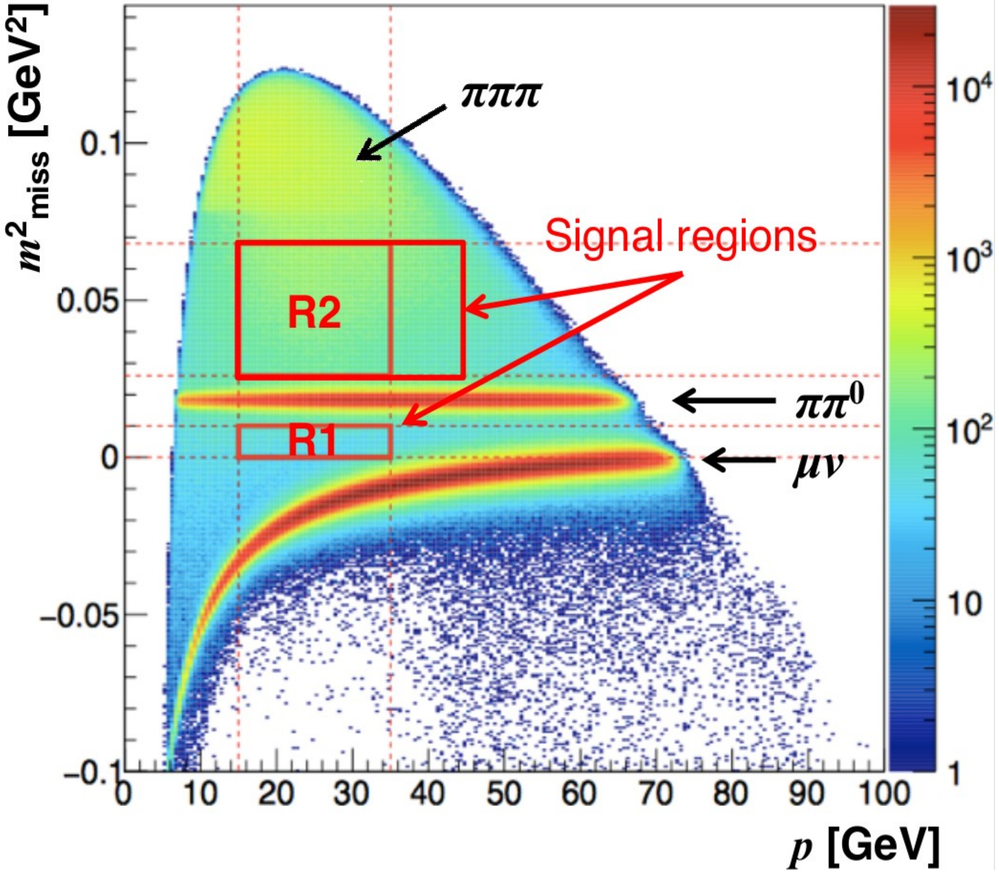
The NA62 decay-in-flight technique is now well established!

$K^+ \to \pi^+ \nu \bar{\nu}$ signature:
Kaon track +
Pion track +
NOTHING ELSE



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

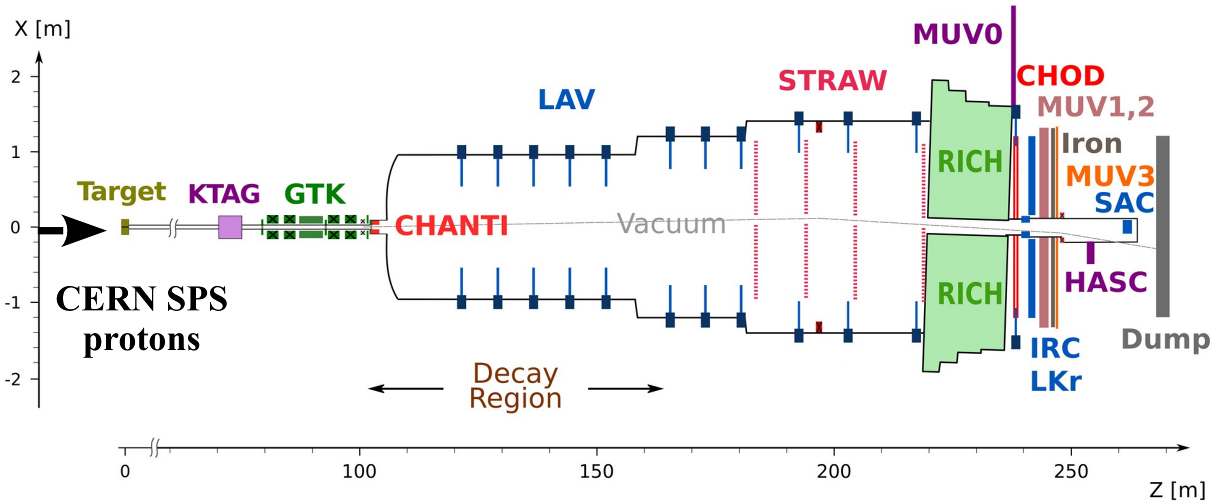


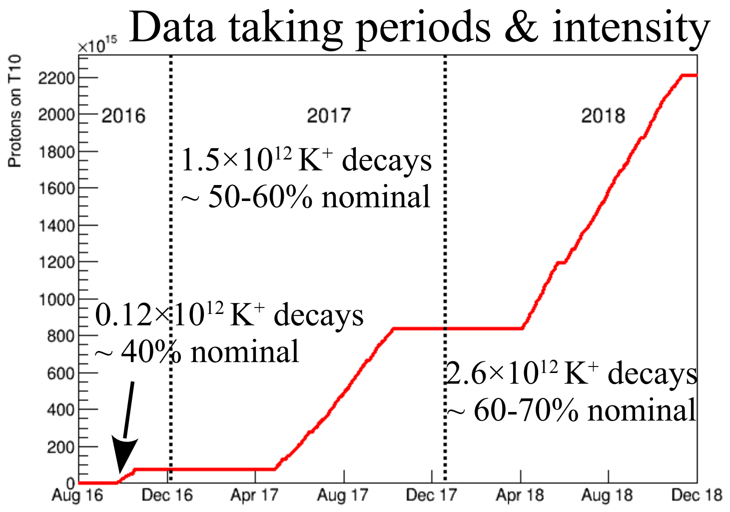


Main backgrounds:
$BR(K^+ \to \mu^+ \nu) = 63.5\%$
$BR(K^+ \to \pi^+ \pi^0) = 20.7\%$

NA62/HIKE-Phase1 keystones:
– Precise tracking
– PID (in particular π/μ)
– Photon rejection
– Precise timing

Background rejection at ~ 10^{11} level





Nominal intensity: ~ 3×10^{12} POT/spill → 750 MHz hadron beam

Primary beam:

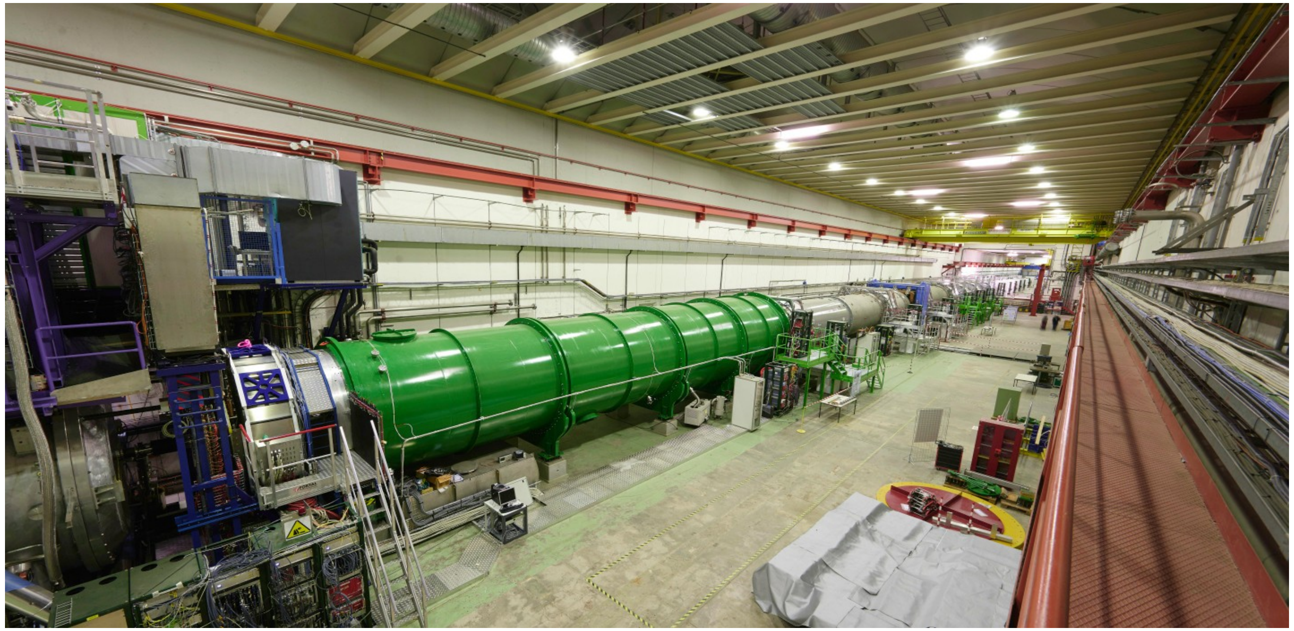
- 400 GeV CERN SPS protons

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:

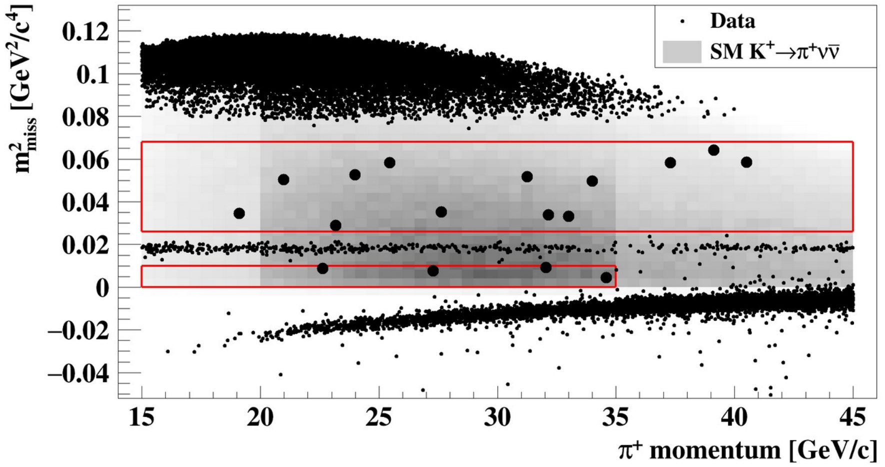
- 60 m long fiducial volume
- Vacuum ~ O(10^{-6} mbar)
- ~ 5 MHz K^+ decay rate



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 = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

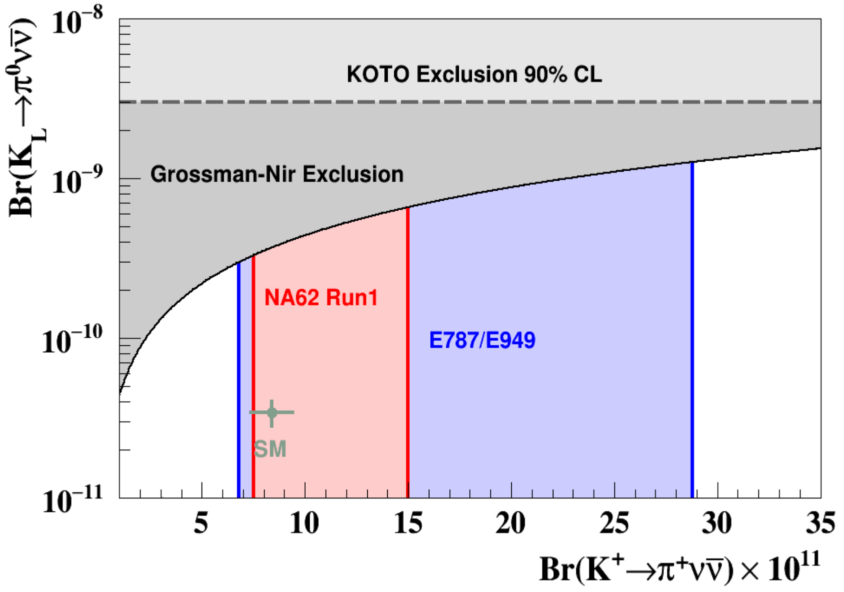
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

Expected bkg: $7.03^{+1.05}_{-0.82}$

Observed: 20 (1+2+17) events

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

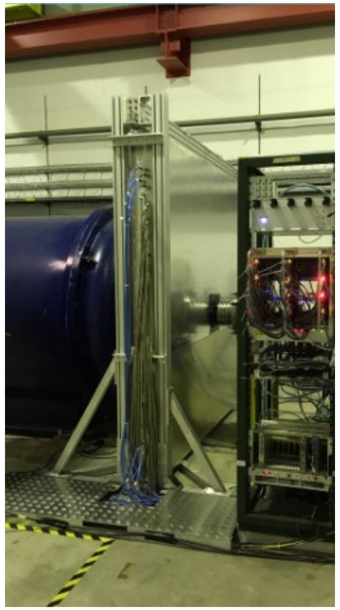
3.4σ significance, most precise measurement to date!



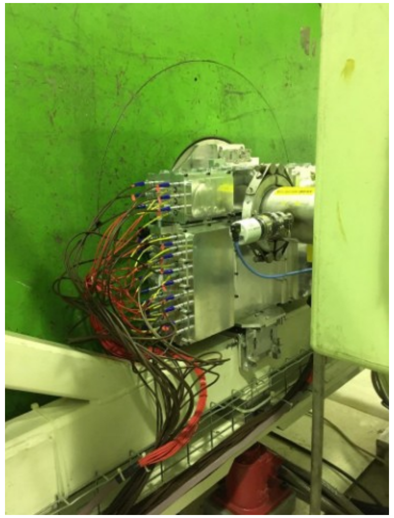
NA62 recommended by SPSC and approved by Research Board until LS3

Improvements in NA62 Run2:

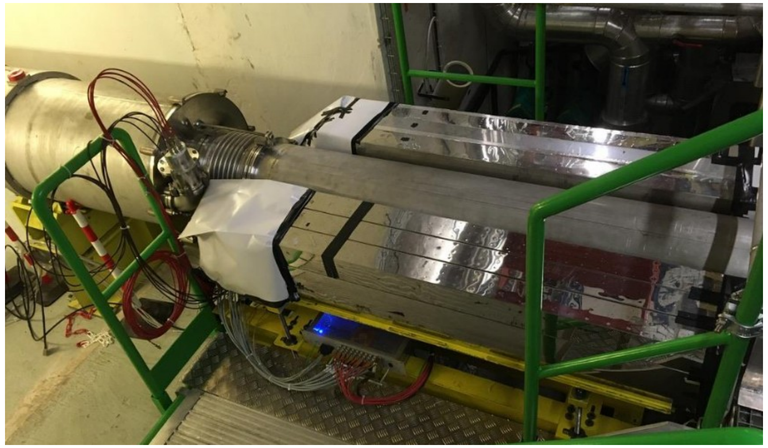
- DAQ stability improved: run at higher beam intensity (70% → 100%)
- Rearrangement of beamline elements around GTK achromat
- Added 4th station to GTK beam tracker
- Additional veto counters around beam pipe (both upstream/downstream the FV)
- New veto hodoscope upstream of decay volume (ANTI0)
- New 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