HIKE: The High-Intensity Kaon Experiments at CERN

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on behalf of HIKE

HIKE: 175 collaborators from 37 institutions

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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

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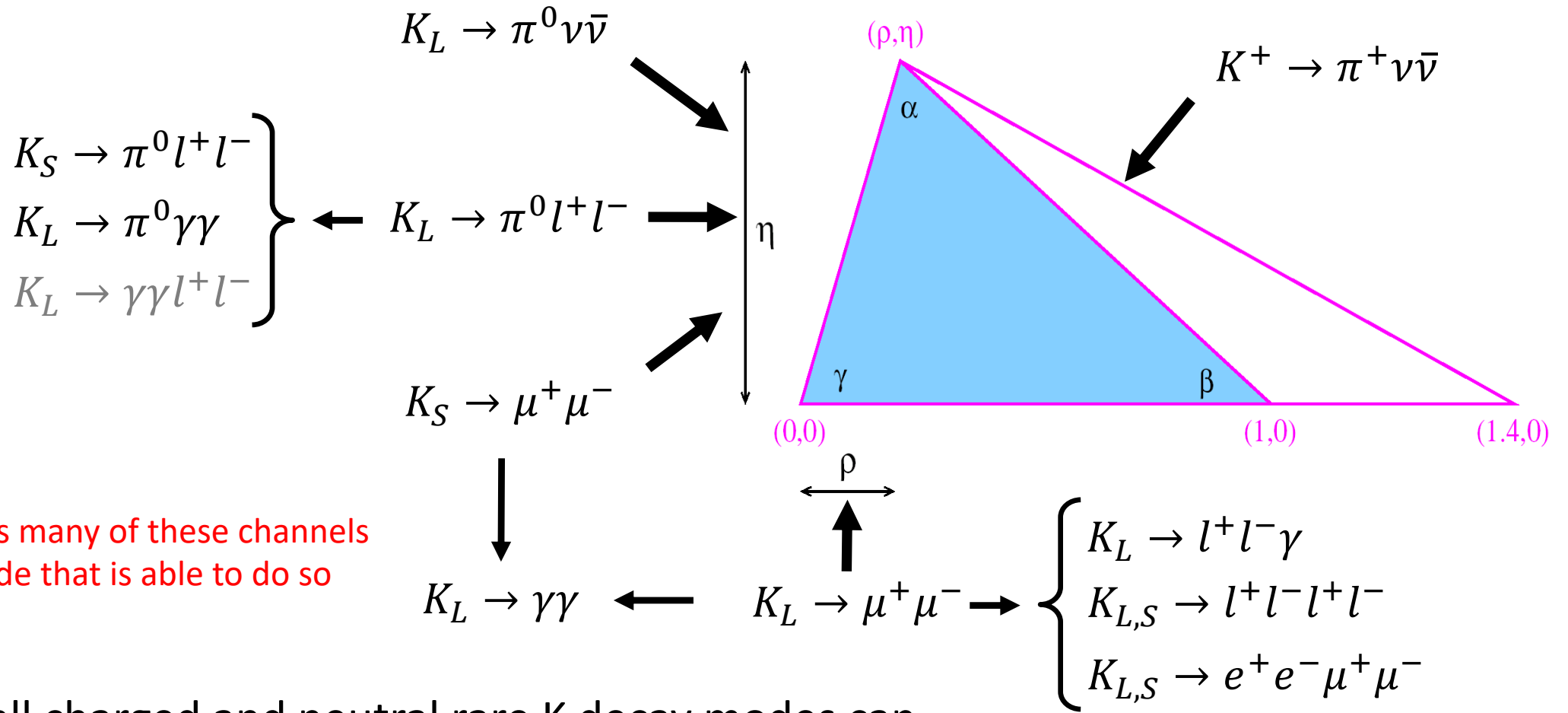
Because of the relatively small number of kaon decay modes and the relatively simple final states, combined with the relative ease of producing intense kaon beams, kaon decay experiments are in many ways the quintessential intensity-frontier experiments.

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]

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

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

$$\left.\begin{array}{l} K_S \to \pi^0 l^+ l^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to \gamma\gamma l^+ l^- \end{array}\right\} \leftarrow K_L \to \pi^0 l^+ l^- \rightarrow$$

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

(ρ,η)

α

η

γ β

$(0,0)$ $(1,0)$ $(1.4,0)$

ρ

HIKE will address many of these channels
Unique worldwide that is able to do so

$$K_L \to \gamma\gamma \leftarrow K_L \to \mu^+ \mu^- \rightarrow \left\{\begin{array}{l} K_L \to l^+ l^- \gamma \\ K_{L,S} \to l^+ l^- l^+ l^- \\ K_{L,S} \to e^+ e^- \mu^+ \mu^- \end{array}\right.$$

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

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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 $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio to a 5% relative precision, matching the SM theoretical uncertainty.
- Precision measurements of $K^+ \to \pi^+ l^+ l^-$ 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 $K_L \to \pi^0 l^+ l^-$ or establishment of stringent upper limits at $O(10^{-11})$ level
- Measurement of the $K_L \to \mu^+ \mu^-$ 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 $K_L \to \pi^0 \nu \bar{\nu}$ 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 $K \rightarrow \pi \nu \bar{\nu}$
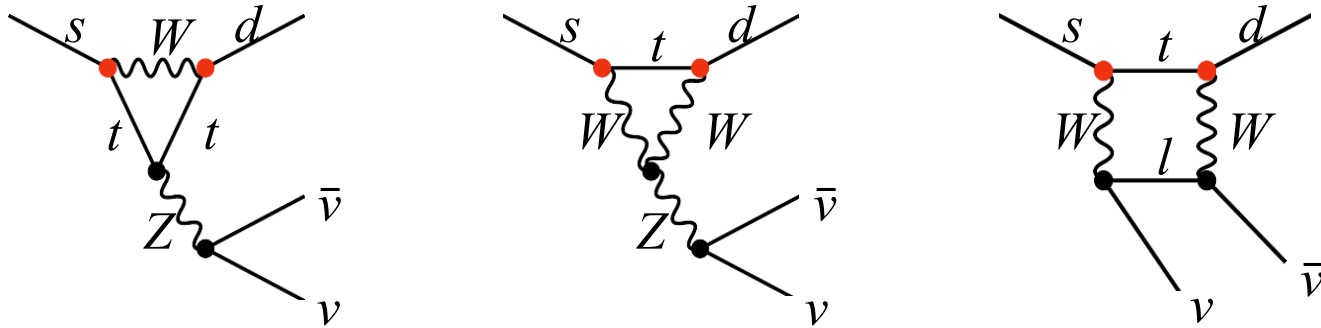
A high-order process with highest CKM suppression:

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

Extremely rare decays, rates very precisely predicted in SM

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

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

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

[arXiv:2203.11960, arXiv:2109.11032]   [arXiv:2105.02868]

"Free" from hadronic uncertainties
Exceptional SM precision

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

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

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

See recent example later in this talk

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, arXiv:2109.11032, arXiv: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, arXiv:1910.10644]

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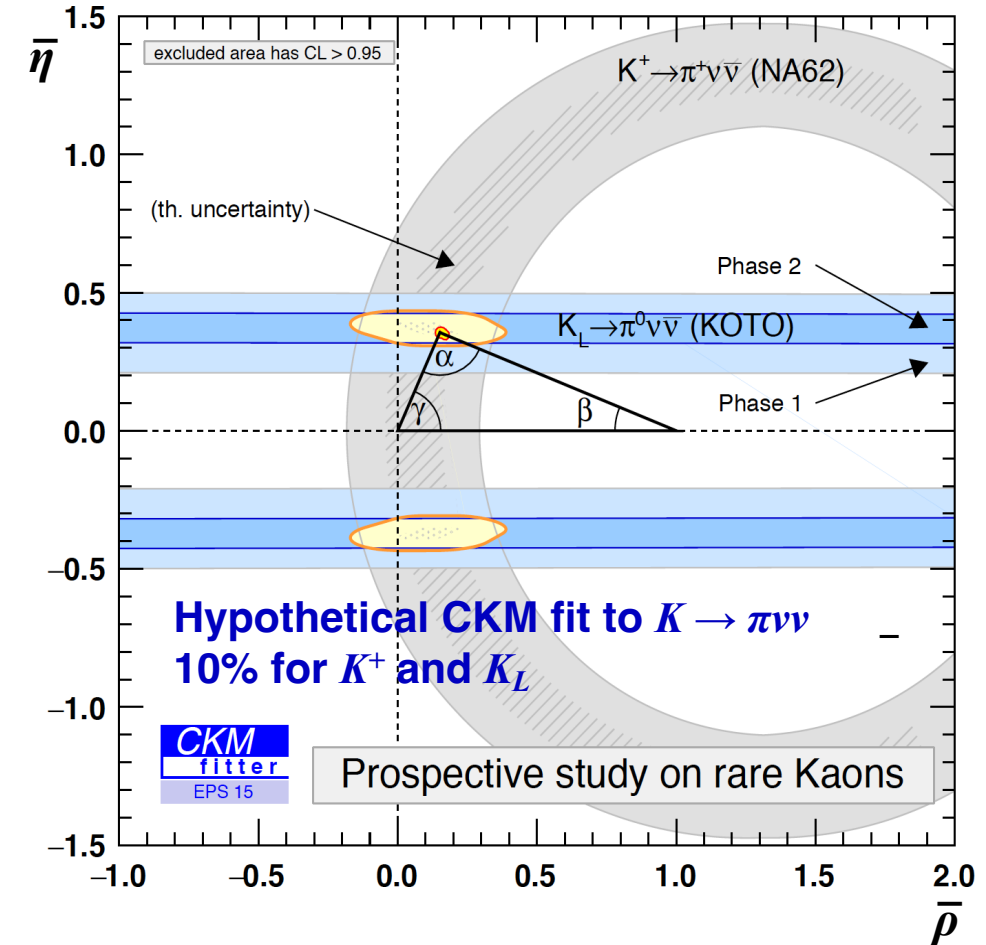
Clear opportunity in the kaon sector

NA62 will measure $K^+ \to \pi^+ \nu\nu$ 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
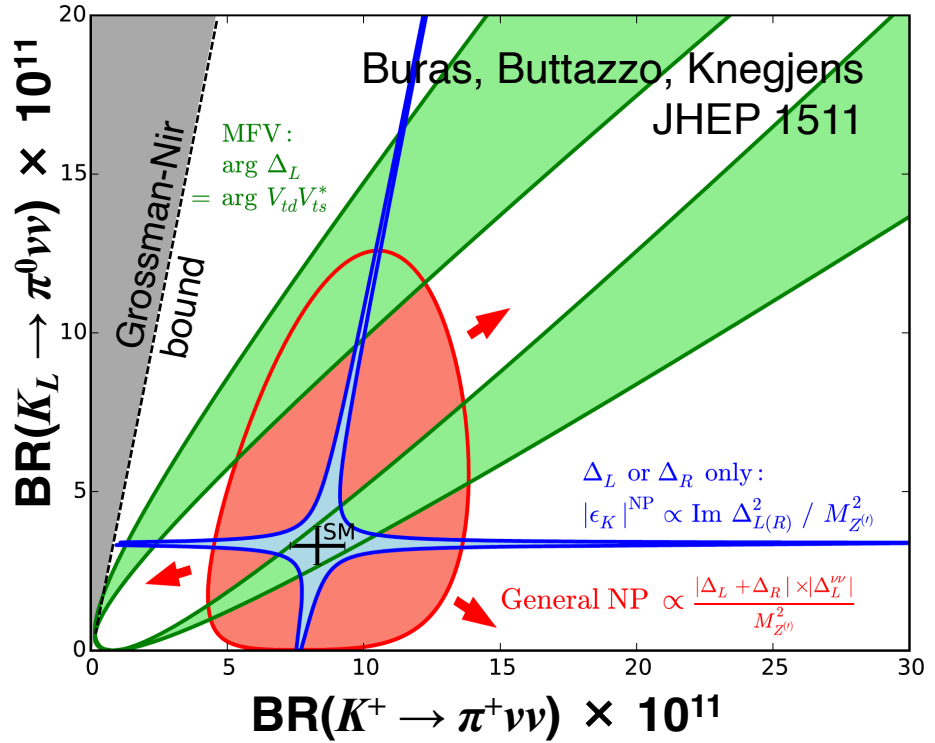
- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum

Going beyond 10% measurement on $K \to \pi + \nu\nu$
Precision measurements of $K \to \pi\nu\nu$ 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]

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

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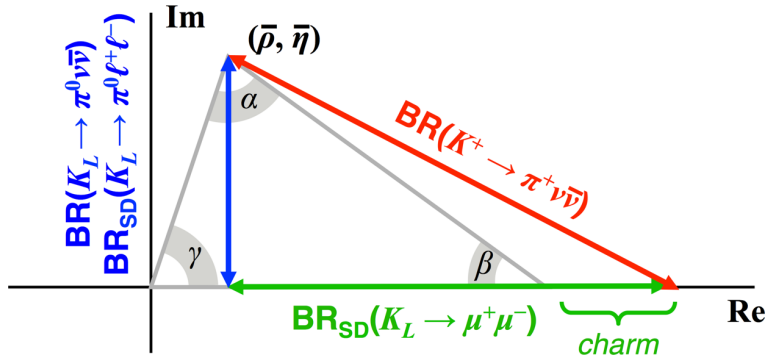
$K_L \rightarrow \pi^0 \ell^+ \ell^-$ CPV amplitude constrains UT in same way as BR($K_L \rightarrow \pi^0 \nu\nu$)

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 × 10⁻¹¹**   Phys. Rev. Lett. 93 (2004) 021805
BR($K_L \rightarrow \pi^0 \mu^+ \mu^-$) < 38 × 10⁻¹¹   Phys. Rev. Lett. 84 (2000) 5279–5282
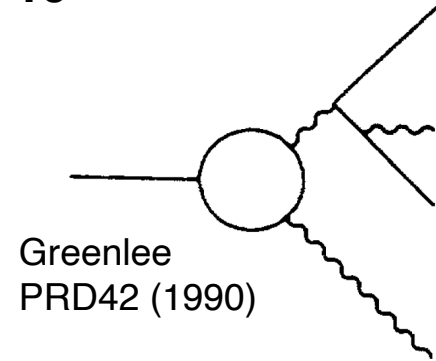
Main background: $K_L \rightarrow \ell^+ \ell^- \gamma\gamma$

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

BR($K_L \rightarrow e^+ e^- \gamma\gamma$) = (6.0 ± 0.3) × 10⁻⁷ $E_\gamma^* > 5$ MeV
BR($K_L \rightarrow \mu^+ \mu^- \gamma\gamma$) = 10$^{+8}_{-6}$ × 10⁻⁹ $m_{\gamma\gamma} > 1$ MeV

Greenlee PRD42 (1990)

Theoretical work should be updated

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$K^0 \rightarrow \mu^+ \mu^-$
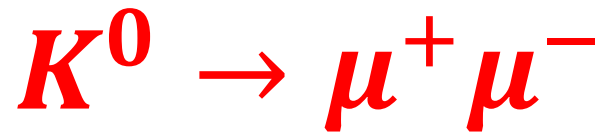
FCNC: SD + important contributions from LD

[arXiv:1707.06999, arXiv:2104.06427]

SD: CPV for KS, CPC for KL

Long distance (LD)
Short distance (SD) [example]
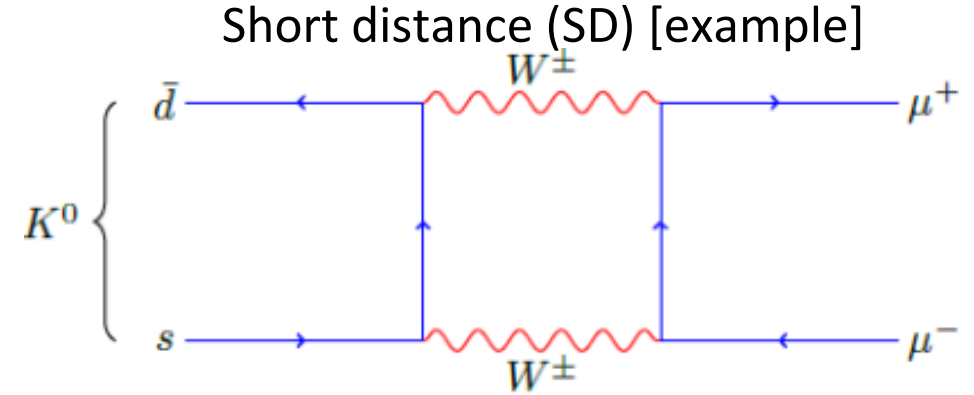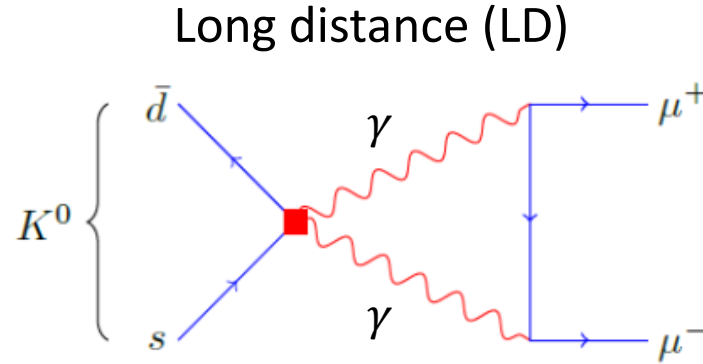
$$\mathcal{B}(K_L \rightarrow \mu^+ \mu^-)_{SM} \propto \left| A_L^{LD} + A_L^{SD} \right|^2, \left| A_L^{SD} \right|^2 \propto |1 - \bar{\rho}|^2$$

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

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

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

Theory work ongoing

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

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

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Test of Lepton Universality and Explicit SM Violation

Lepton Universality tests:

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

Search for LFV and/or LNV :

PDG 2022

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

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

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

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)
(non pert. QCD)

$K_{3\pi}$ loop term
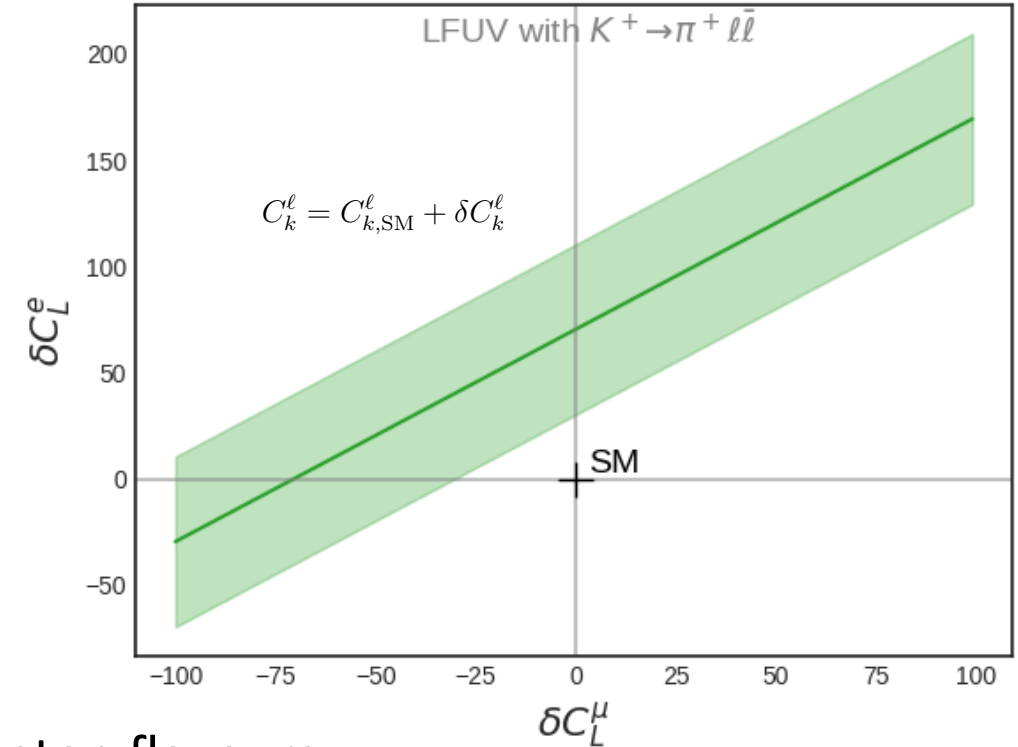
Long-distance effects are purely universal and same for all lepton flavours

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

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

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

Difference correlated to possible anomalies in B physics

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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	$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, \varepsilon'/\varepsilon$
Z'	$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, \varepsilon'/\varepsilon, \Delta M_K$
Simplified models	$K_L \to \pi^0 \nu\bar{\nu}, \varepsilon'/\varepsilon$
LHT	All K decays
331 models	Small effects in $K \to \pi\nu\bar{\nu}$
Vector-like quarks	$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, \Delta M_K$
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	$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, \varepsilon_K$
Vector-like compositeness	$K^+ \to \pi^+ \nu\bar{\nu}, K_L \to \pi^0 \nu\bar{\nu}, \varepsilon_K$

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
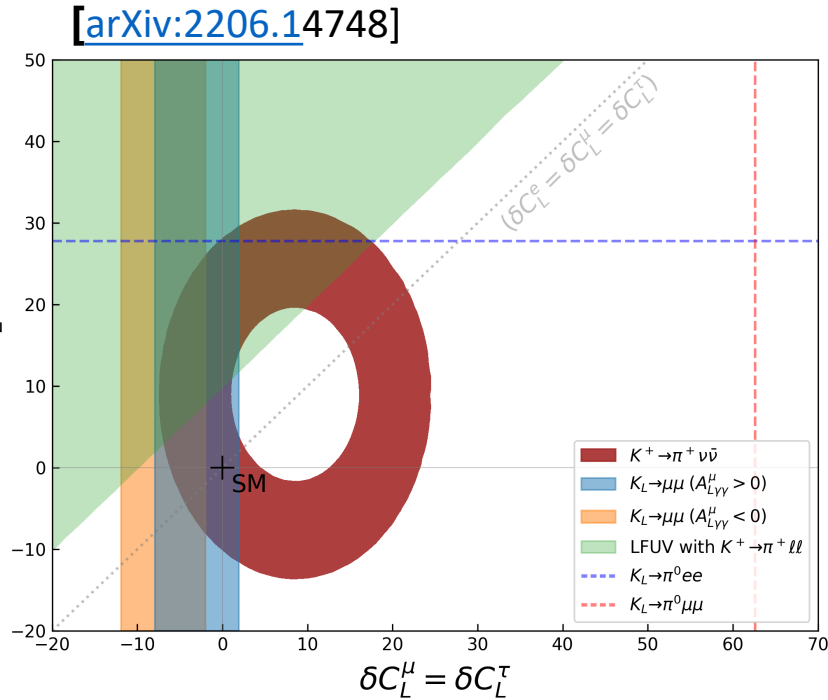
Kaon Global Fit

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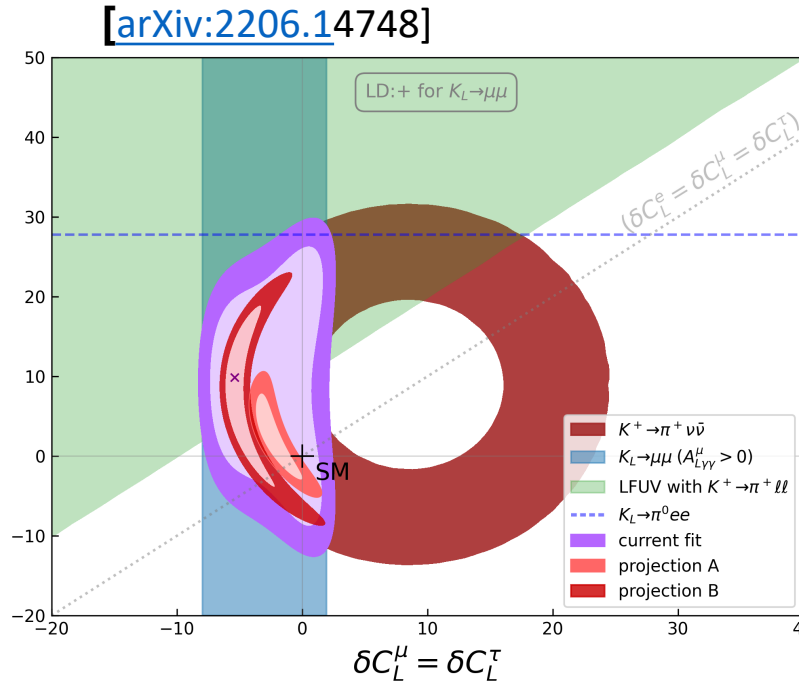
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} \lambda_t^{sd} \frac{\alpha_e}{4\pi} \sum_k C_k^\ell O_k^\ell$$

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

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

[arXiv:2206.14748]

[arXiv:2206.14748]

[https://indico.cern.ch/event/1137276/]

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

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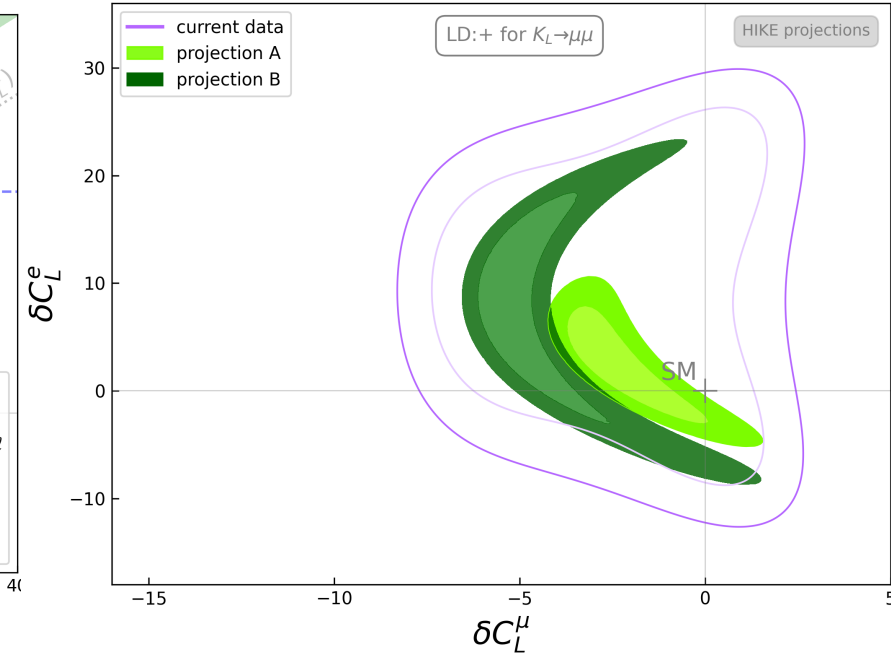
Feebly interacting particles (dump phase)

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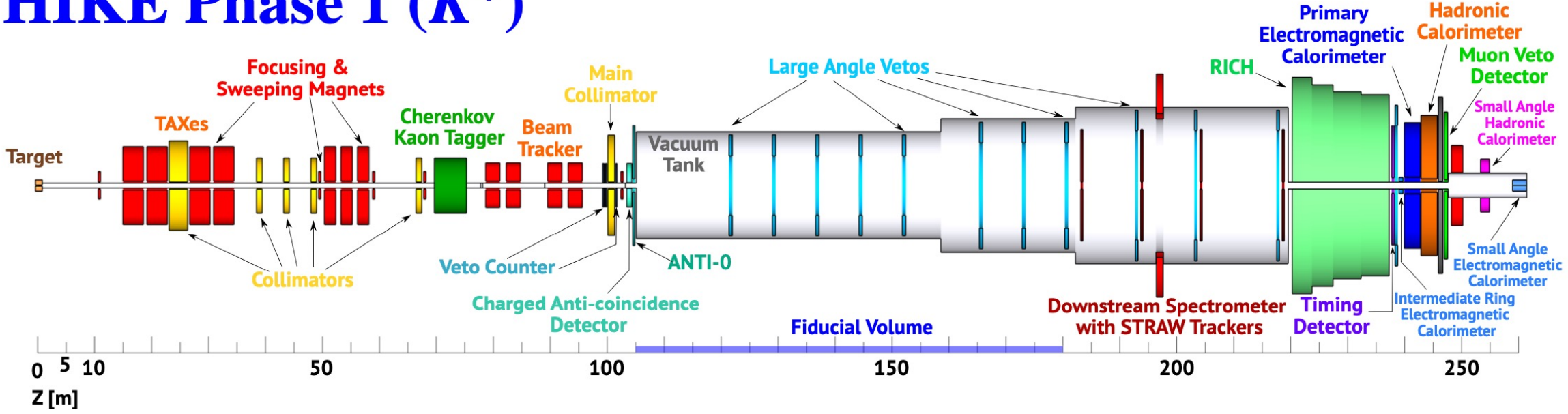
K$^+$: 1.2 10^{13} protons on T10 per spill (4.8 sec)

- 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 10^{13} Kaon decays in decay volume per year (7 10^{18} POT / 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

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
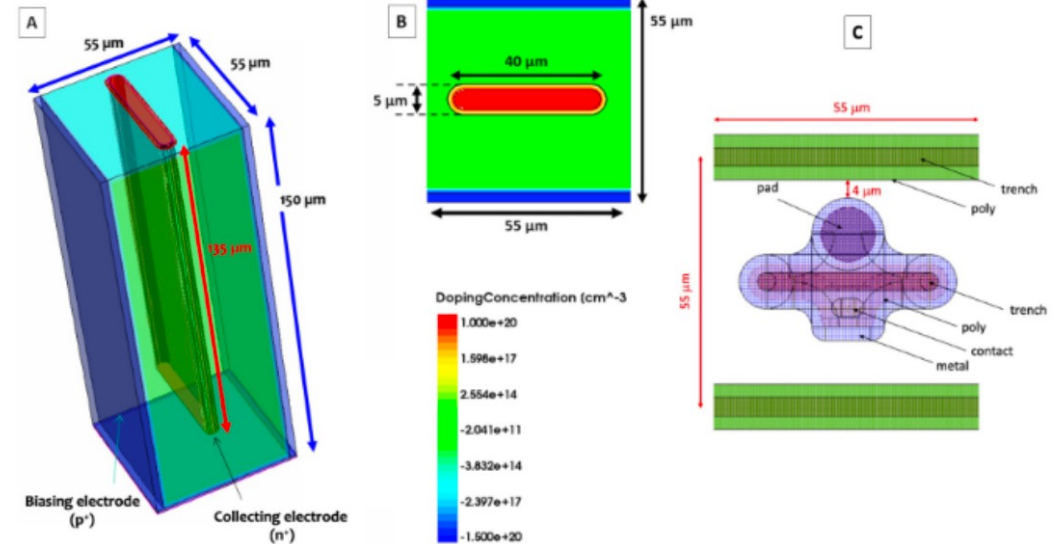
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STRAW detector

NA62 straw chamber

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

optimised layout for new STRAW detectors
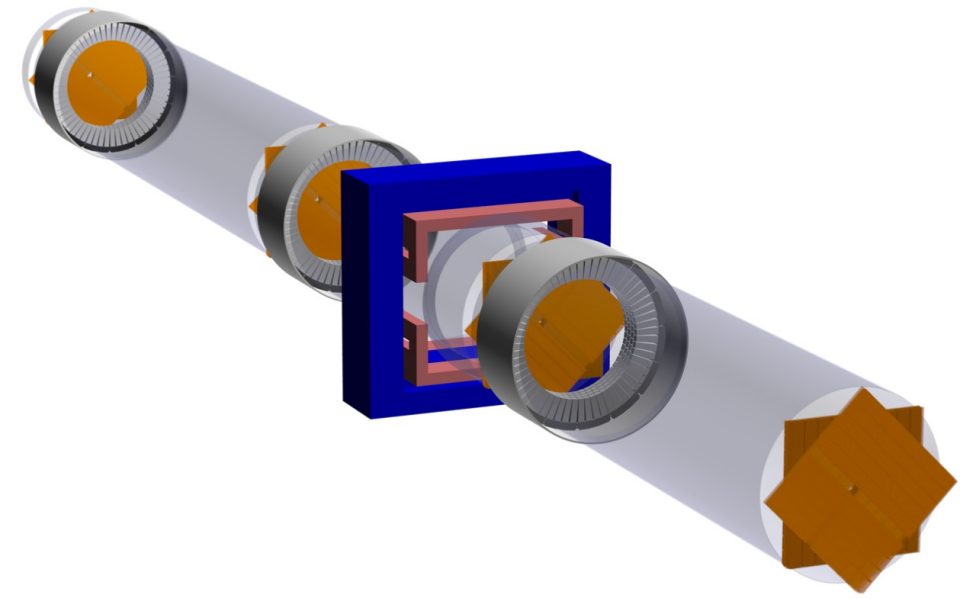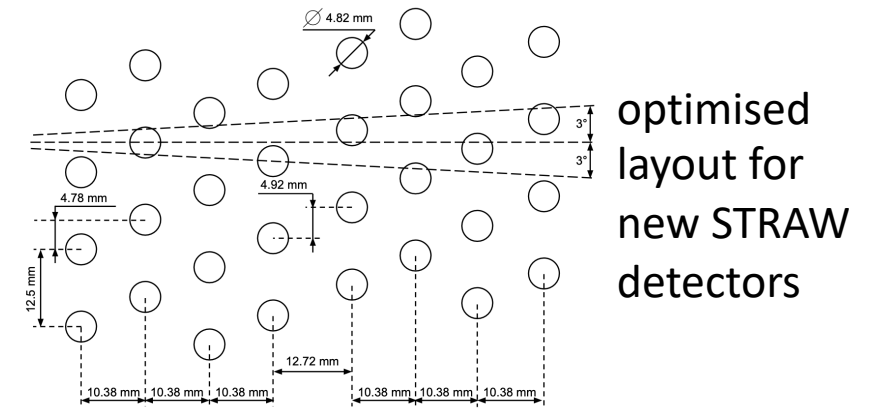
Track momentum resolution
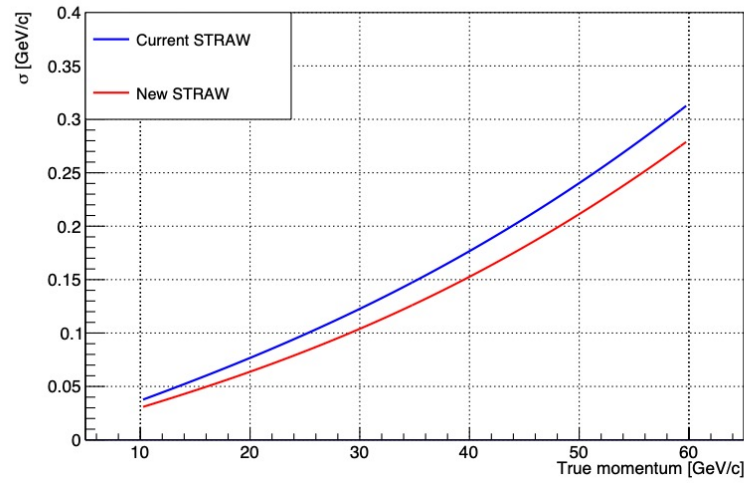
Track angular X resolution
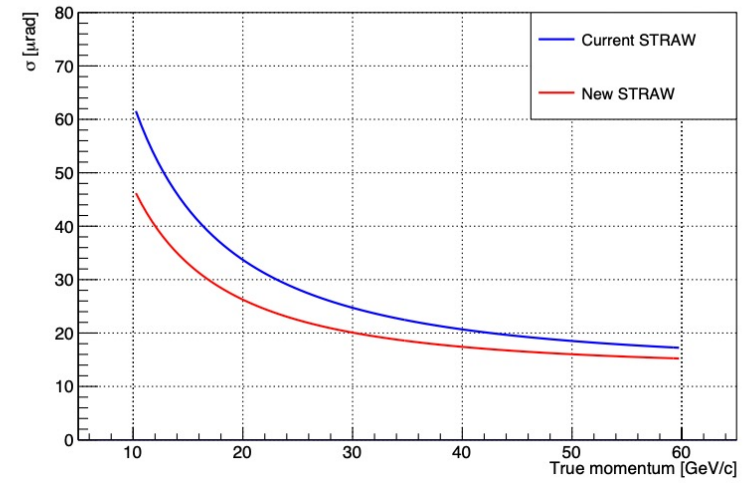
HIKE Phase 1: Physics sensitivity

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

$\varepsilon_A \simeq 0.1$

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

$N(\pi\nu\nu)$/year $\simeq 100$

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

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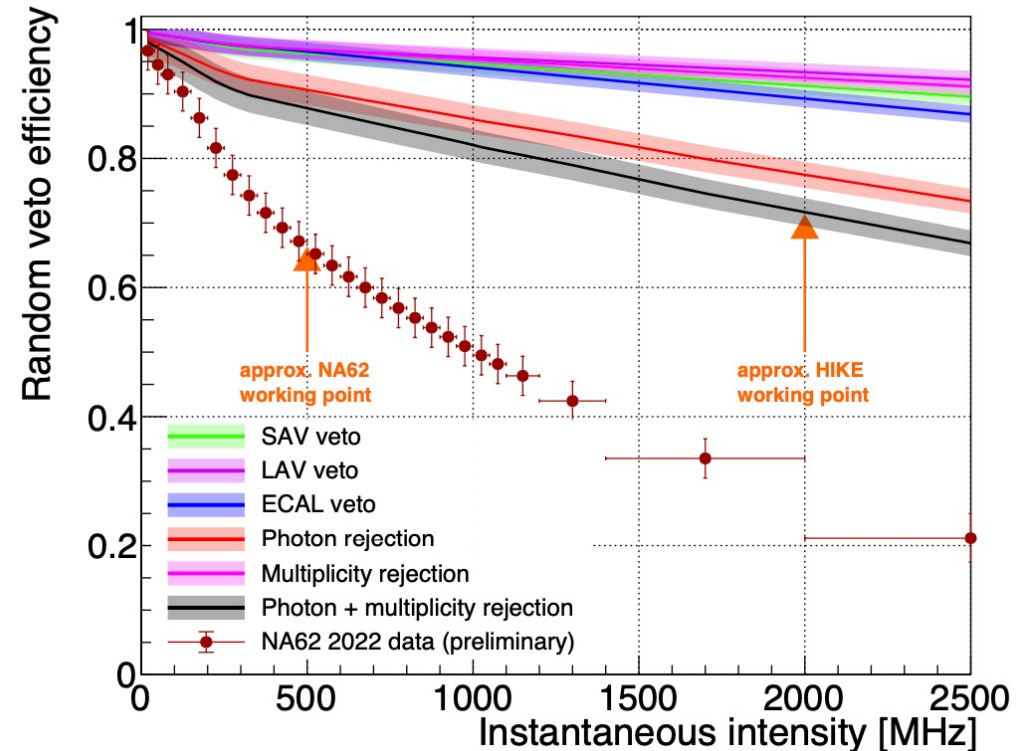
$K^+ \to \pi^+ l^+ l^-$ Precision measurement

NA62 recent result:

Model independent measurement of $BR(K^+ \to \pi^+ \mu^+ \mu^-)$

Measurement of $d\Gamma/dz$ and extraction of FF

Data RUN 1,   almost background-free selection

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

*Crivellin et al. PRD 93 074038 (2016)
D'Ambrosio et al. JHEP 02 049 (2019)

$N_{obs} = 27679$

$a_+ = -0.575 \pm 0.013$

$b_+ = -0.722 \pm 0.043$

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

[arXiv:2209.05076 acc. JHEP]

HIKE will build on the experience of NA62

HIKE: Collect background-free samples of several times 10^5 events of both $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+ \mu^+ \mu^-$

Measure difference of the form-factor parameters a+ and b+ btw two decay modes to ±0.007 and ±0.015 precision
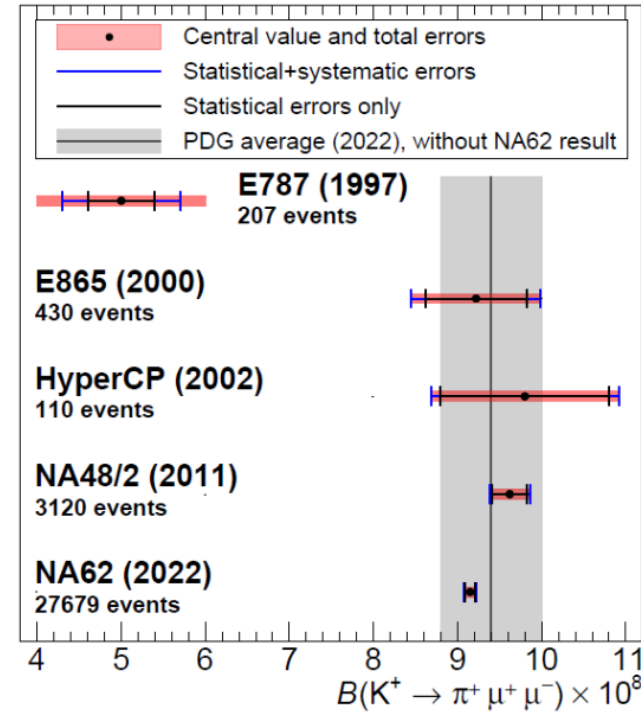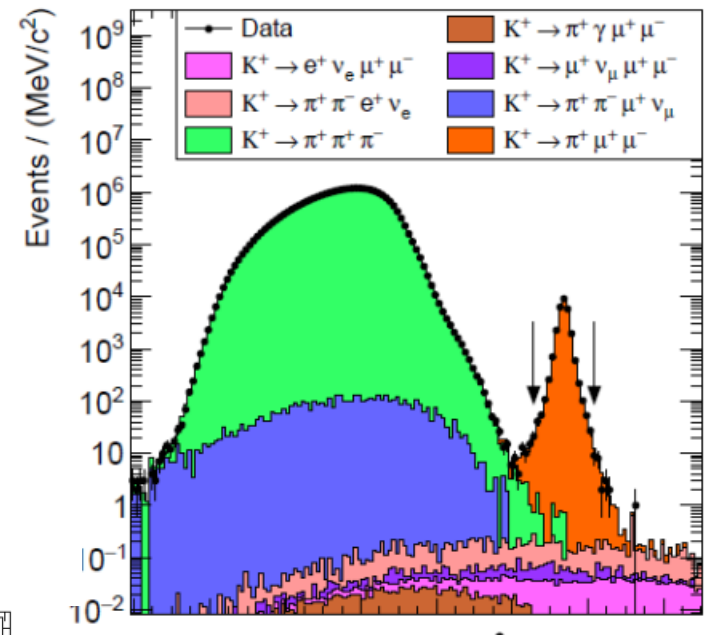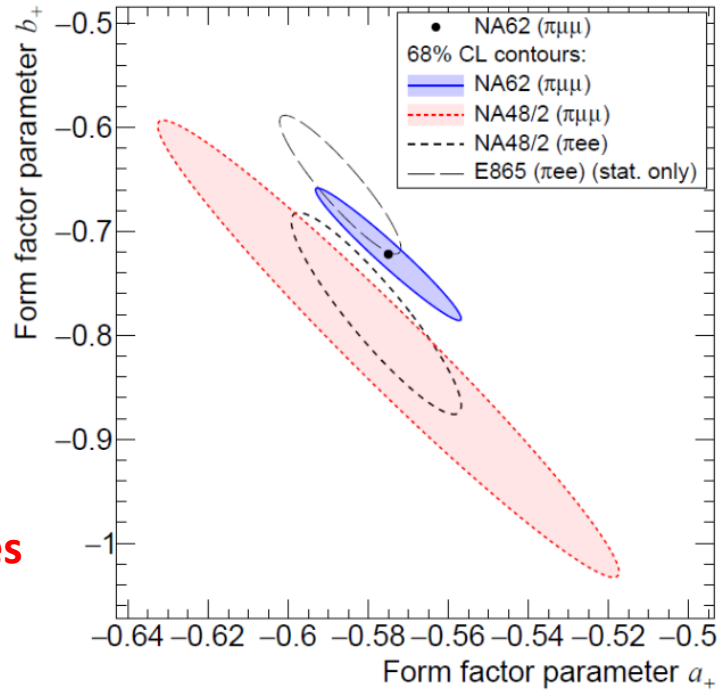
HIKE Phase 1: Physics sensitivity

Sensitivity to feebly interacting particles (decay and production)

Example:
Axion-like, BC10
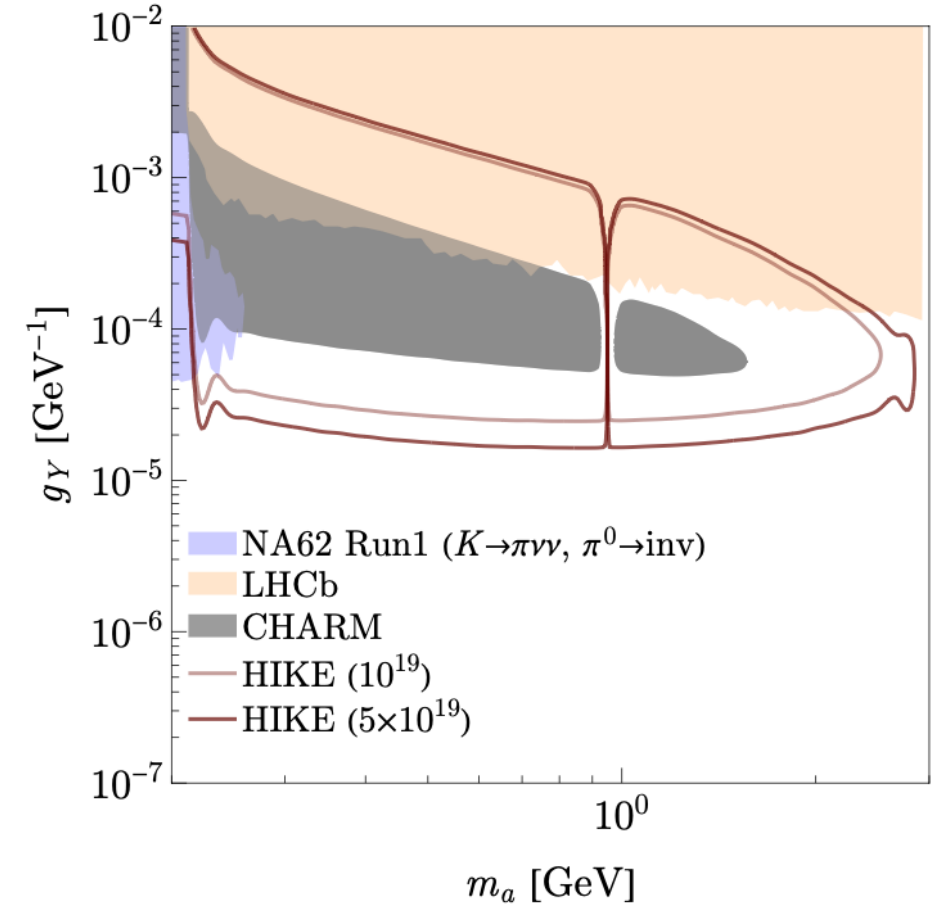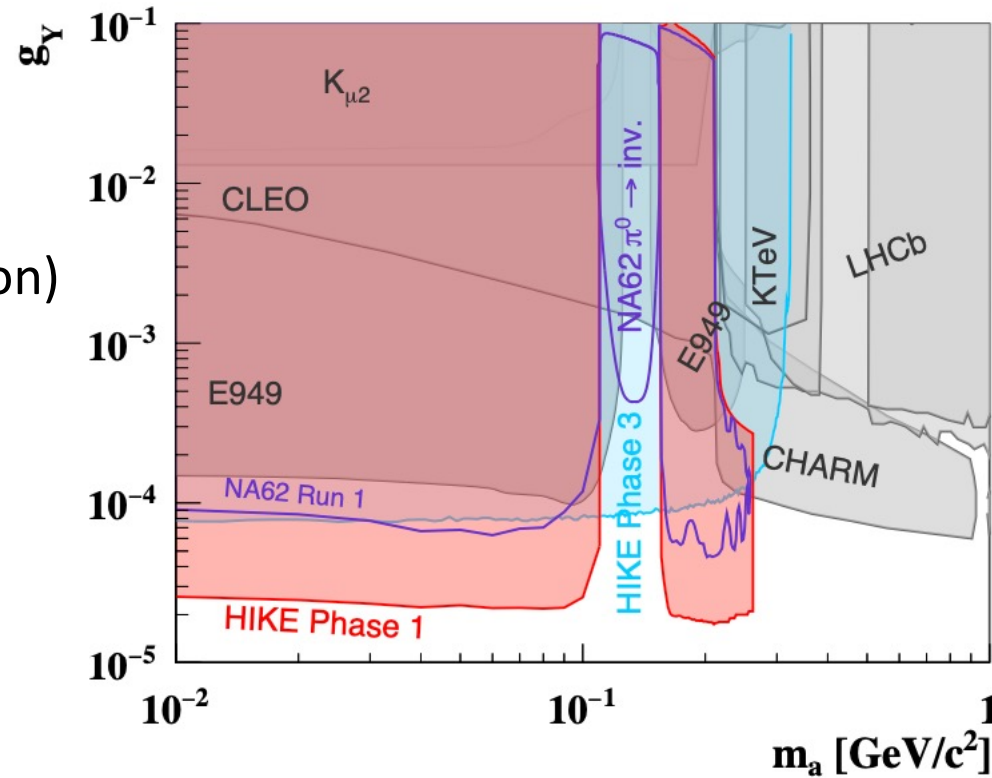
- HIKE Phase 1: **increase world samples of many rare K^+ decays by an order of magnitude**.
  Many rare decay measurements to a new level of precision.
- **Searches for K^+ and π^0 decays violating LN or LF, not limited by background**
  HIKE Phase 1 sensitivity: expected to improve almost linearly with size of the dataset, to $O(10^{-12})$

HIKE design

HIKE Phase 2 (K_L)
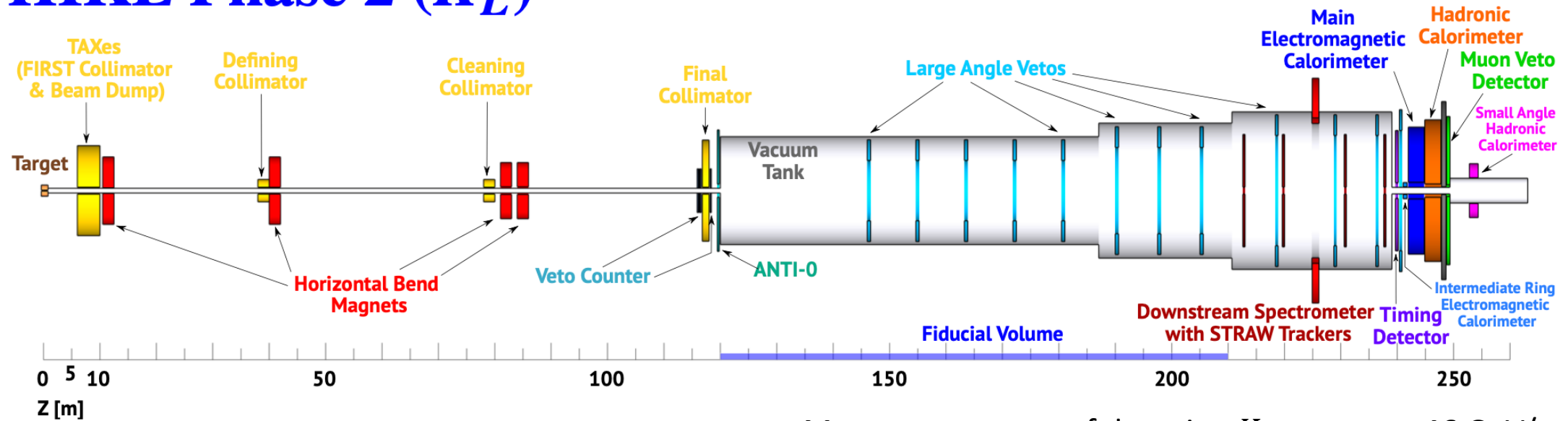
Mean momentum of decaying K_L mesons = 46 GeV/c

K_L + tracking: 2 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 10^{13} Kaon decays in decay volume per year (1.2 10^{19} POT/year)

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Electromagnetic Calorimeter

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

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

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$
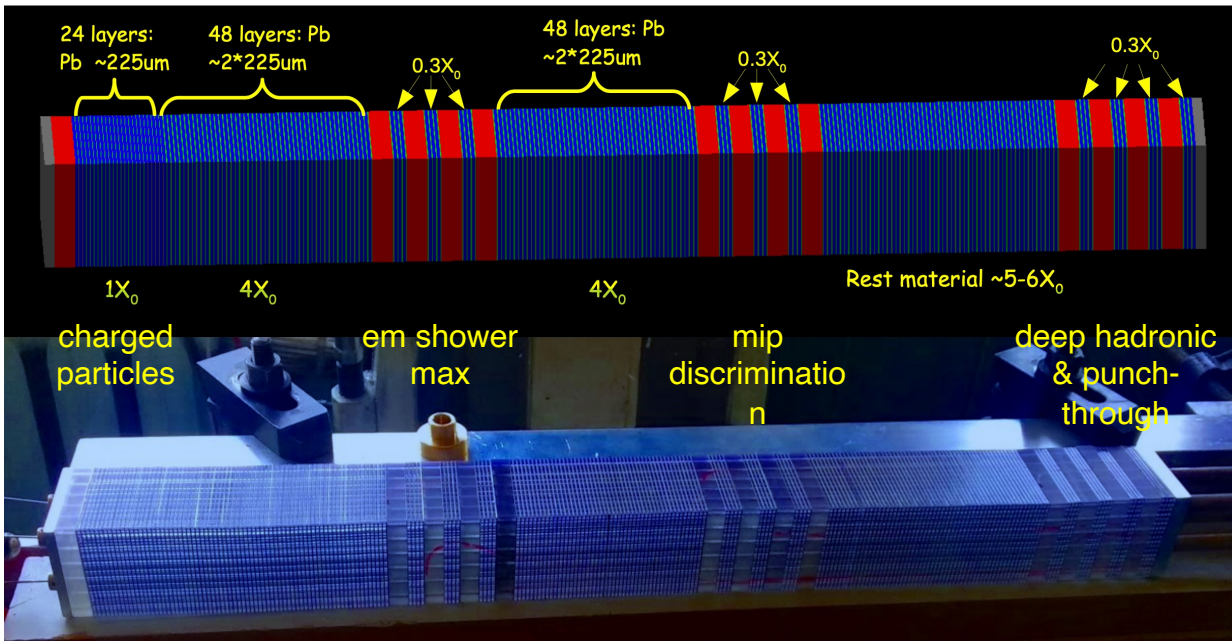
$1 - \varepsilon < 10^{-5}$ for $E_\gamma > 10$ GeV

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

**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

24 layers: Pb ~225um
48 layers: Pb ~2*225um
$0.3 X_0$
48 layers: Pb ~2*225um
$0.3 X_0$
$0.3 X_0$

$1 X_0$ $4 X_0$ $4 X_0$ Rest material ~5-6X_0

charged particles   em shower max   mip discrimination   deep hadronic & punch-through

Fine-sampling shashlyk based on PANDA forward EM calorimeter

PANDA prototypes:
- $\sigma_E / \sqrt{E} \sim$ **3%** $/\sqrt{E}$ (GeV)
- $\sigma_t \sim$ **72 ps** $/\sqrt{E}$ (GeV)
- $\sigma_x \sim$ **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

HIKE Phase 2: Physics sensitivity

Mode	Assumed branching ratio	Acceptance	Signal yield in five years
$K_L \to \pi^0 e^+ e^-$	3.5×10^{-11}	2.1%	140
$K_L \to \pi^0 \mu^+ \mu^-$	1.4×10^{-11}	6.0%	160
$K_L \to \mu^+ \mu^-$	7×10^{-9}	17%	2.3×10^5
$K_L \to \mu^\pm e^\mp$	–	16%	–
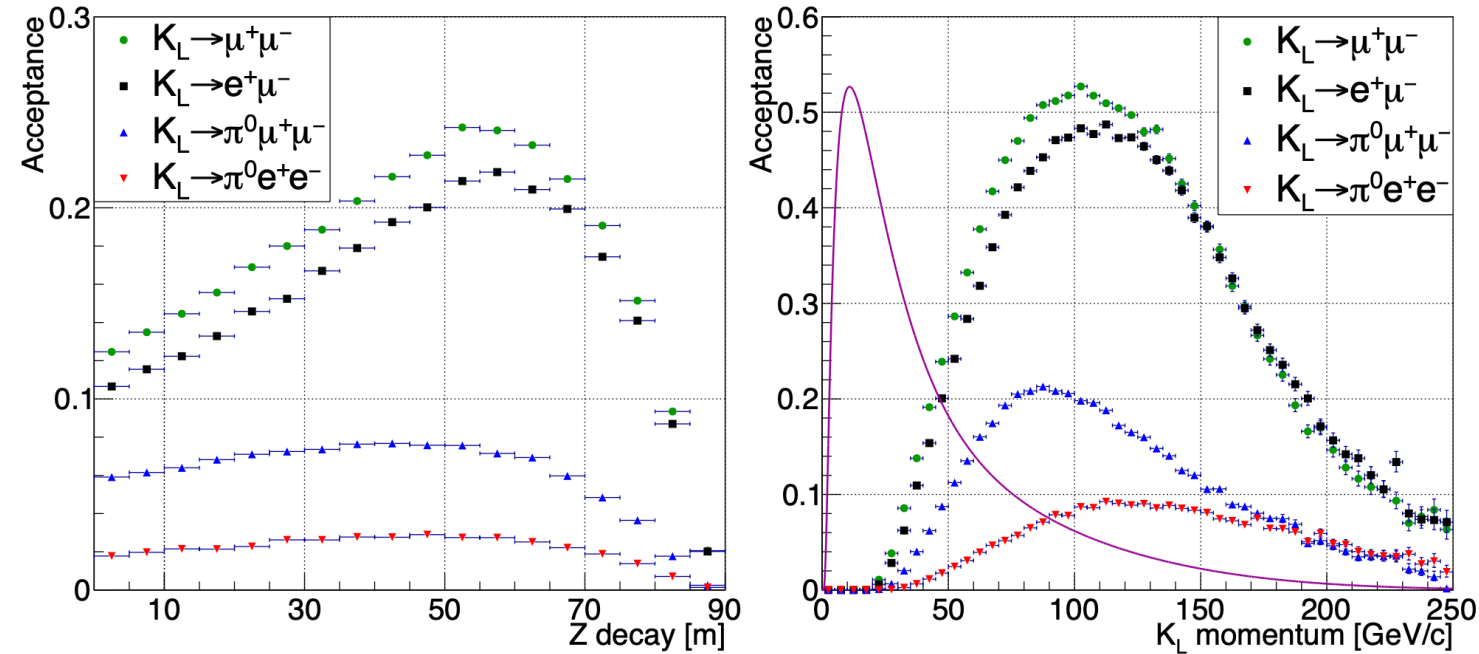
Single-event sensitivities for $K_L \to \pi^0 l^+ l^-$ **improve by more than two orders of magnitude on previous searches by kTeV experiment**

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

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

Background estimation for the $K_L \to \pi^0 l^+ l^-$ 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

$K_L \to \mu^+ \mu^-$ **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)
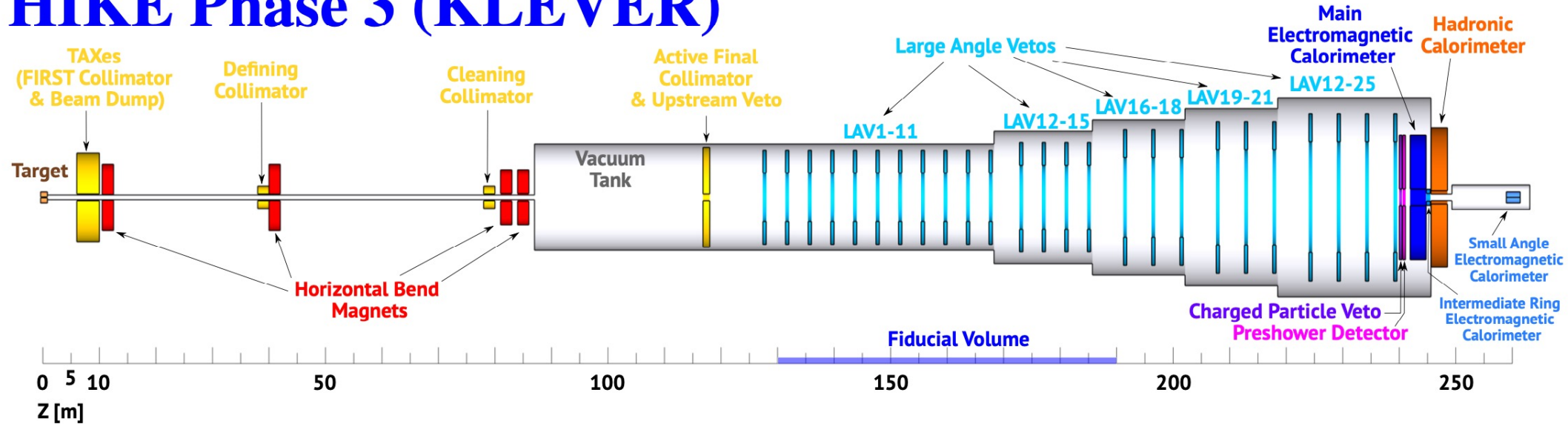
baseline configuration, without the extension of the beamline by 150 m

K_L (KLEVER): 2 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 10^{13} Kaon decays in decay
volume per year (1.2 10^{19} POT/year)

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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**

- $\sigma_t < 100$ **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 in Phase 3 (KLEVER)

Beam comp.	Rate (MHz)	Req. $1 - \varepsilon$
$\gamma, E > 5$ 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.

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

PbF$_2$ Cherenkov calorimeter

16 X$_0$ 20 cm   20 cm   2 cm   2 cm   Oriented   Not oriented

23
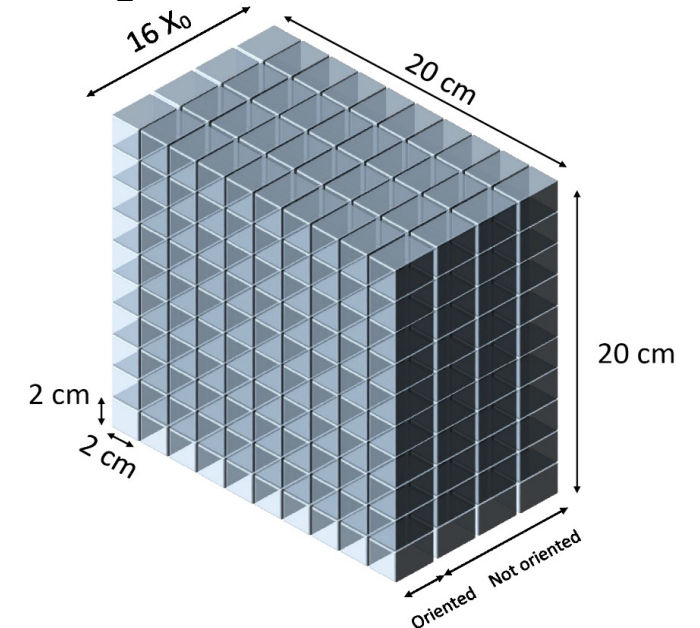
HIKE Phase 3: KLEVER Physics sensitivity

Target sensitivity of 60 SM $K_L \to \pi^0 \nu \bar{\nu}$ 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.

~50 $K_L \to \pi^0 \nu \bar{\nu}$ and ~100 $K_L \to \pi^0 \pi^0$ in 5 years
Very large background from $\boldsymbol{\Lambda \to n \pi^0}$ makes a beamline extension necessary

After beamline extension, Λ background suppressed by 4 orders of magnitudes, to ~50 events
With cut-and-count analysis: ~25 $K_L \to \pi^0 \nu \bar{\nu}$ and ~100 $K_L \to \pi^0 \pi^0$ 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 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.

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.

Only place worldwide where this programme is addressed experimentally.

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.
Synergetic detector challenges with LHC programme.

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

Thank you for listening !

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

arXiv:2209.05076 acc. JHEP

$N_{obs} = 27679$

$a_+ = -0.575 \pm 0.013$

$b_+ = -0.722 \pm 0.043$

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

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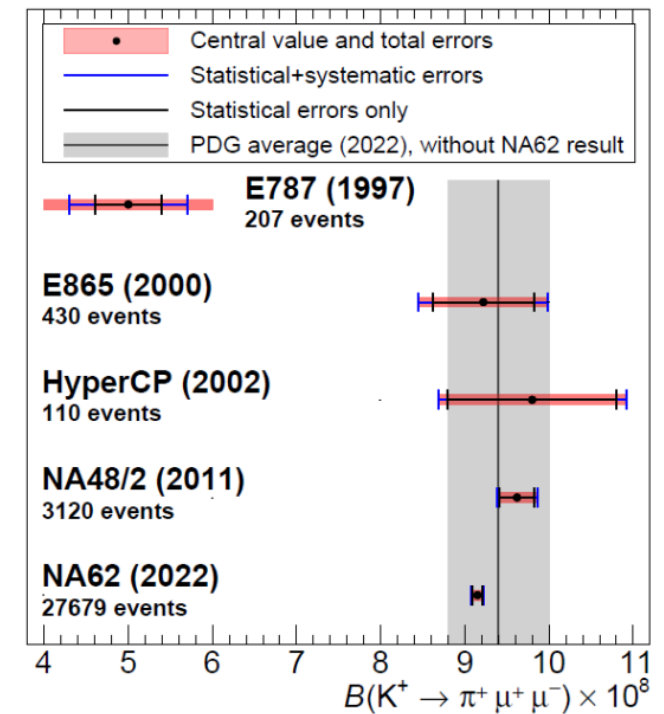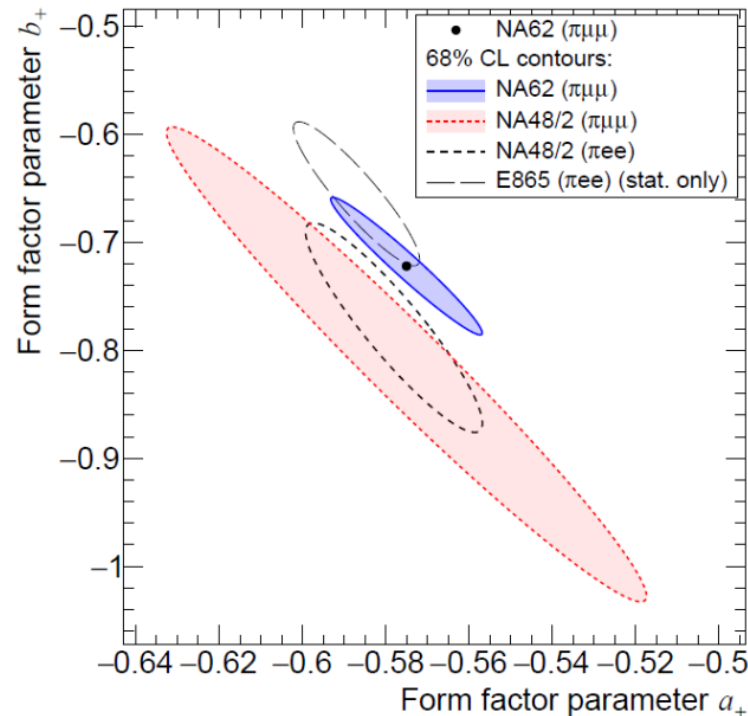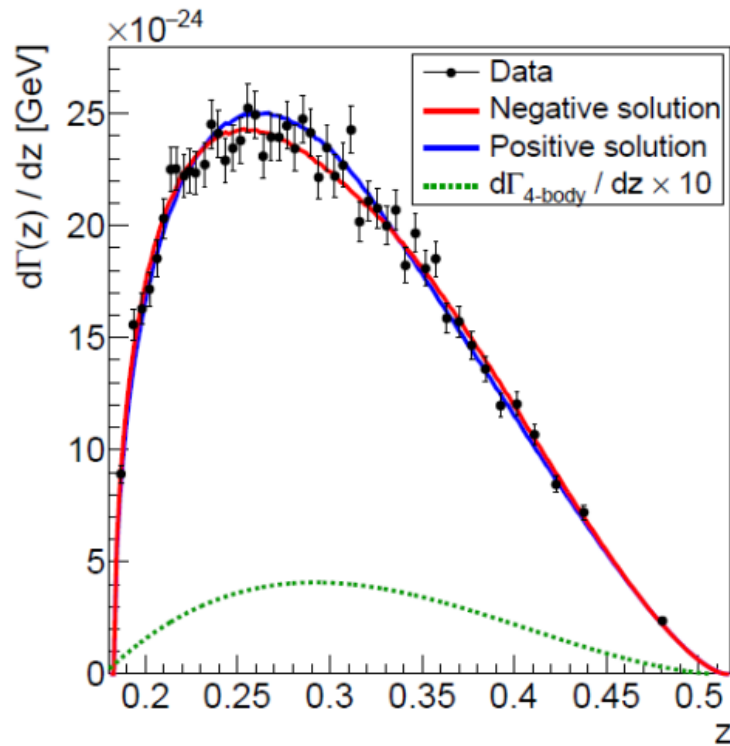
$K^+ \to \pi^+\gamma\gamma$ Precision measurement

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

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

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

D'Ambrosio, Portoles PLB 386 403 (1996)

NA62 Goal: Measurement of $BR(K^+ \to \pi^+\gamma\gamma)$ and $\hat{c}$

KAON2022

Analysis: 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

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

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

$$BR(K^+ \to \pi^+\gamma\gamma) = (9.73 \pm 0.17_{stat} \pm 0.08_{syst}) \times 10^{-7}$$
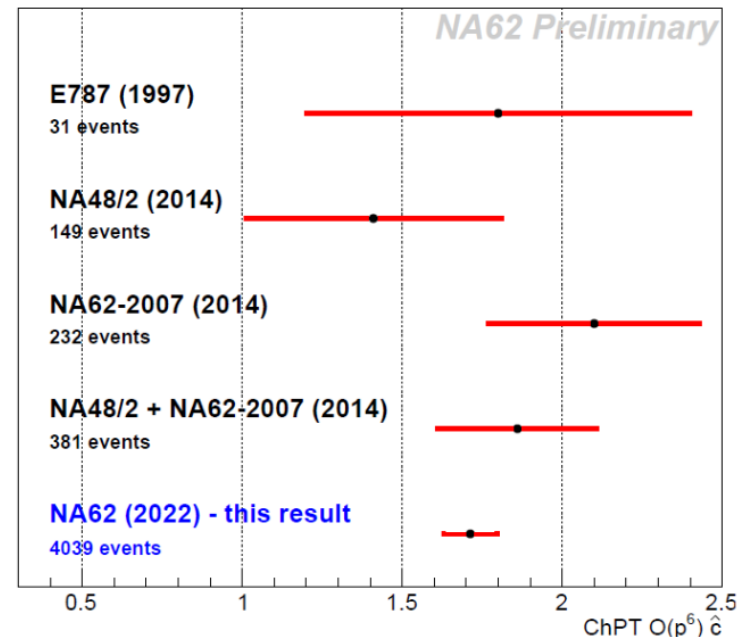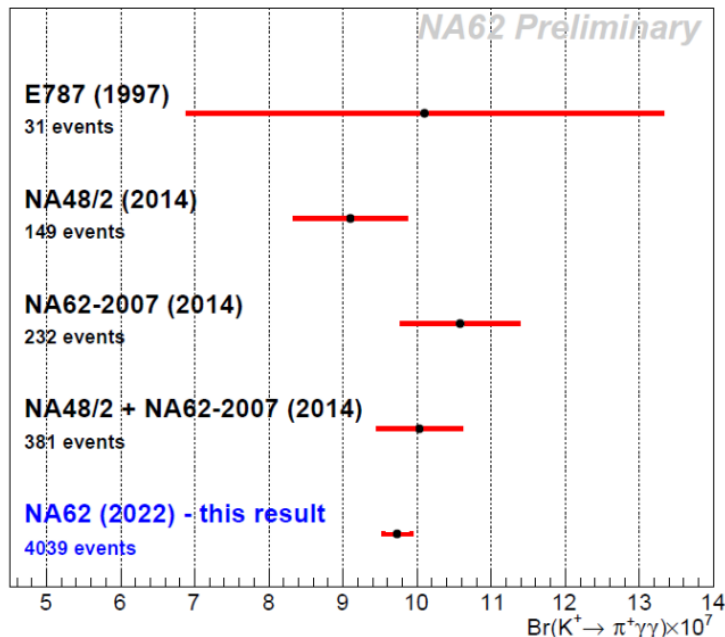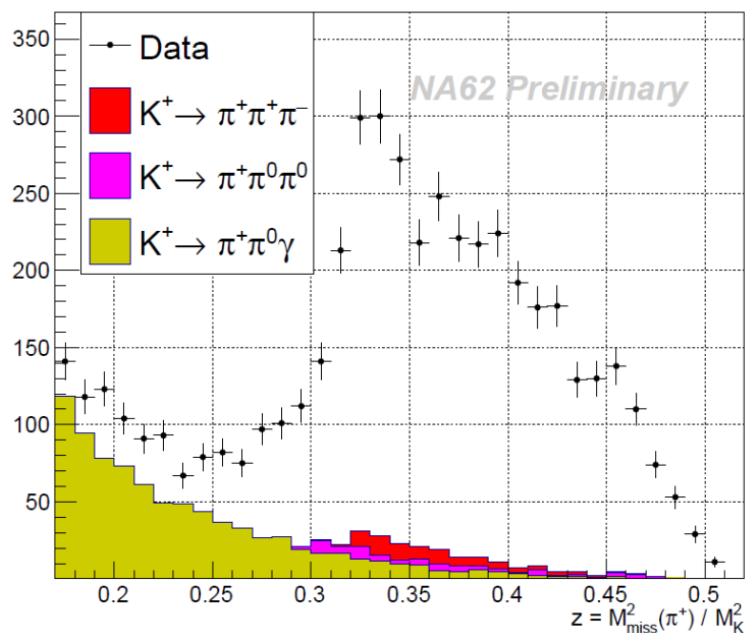
LNV and LFV decays in NA62 RUN1

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

NA62: Several channels studied with RUN1 data

Analysis: Most recent results (90% CL)

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

$$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1 \times 10^{-11} \quad (\times 4 \text{ better})$$
KAON2022

$$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11} \quad (\times 200 \text{ better})$$
PLB830(2022)137172

$$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-11} \quad (\text{first search})$$
PLB830(2022)137172

$K^+ \to \pi^+ e^+ e^-$ (SM allowed)

$K^+ \to \pi^- e^+ e^+$ (LNV)
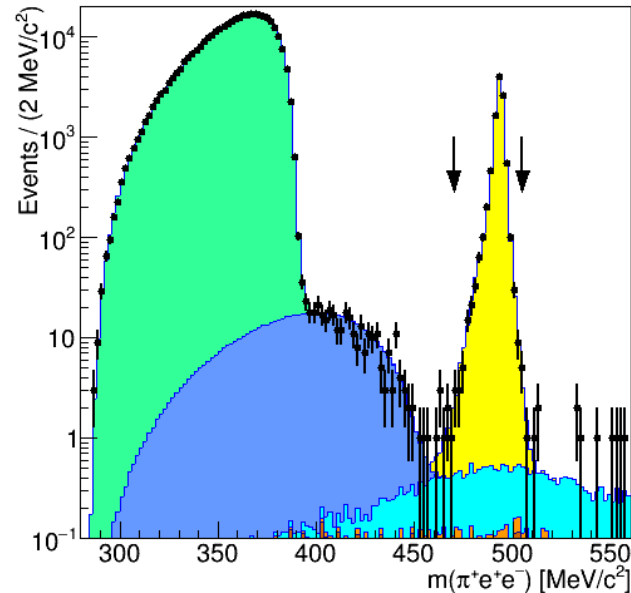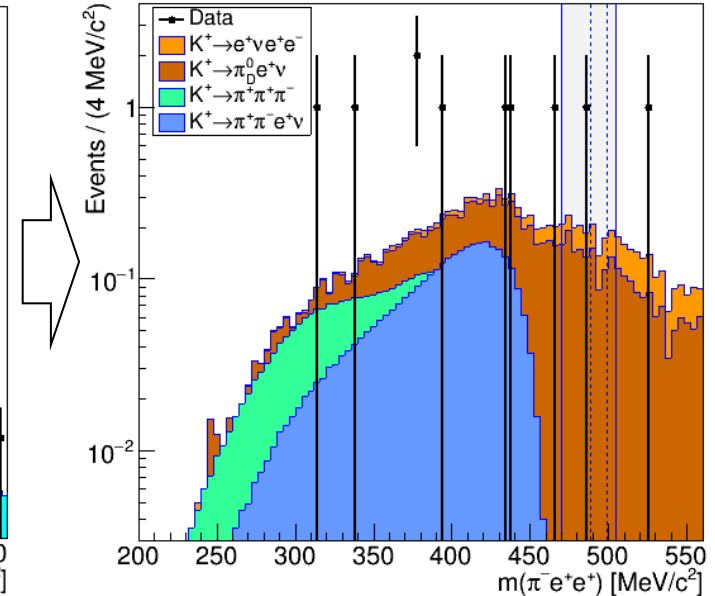
Dark Photon Search $A' \to \mu^+\mu^-$ in NA62 RUN2

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
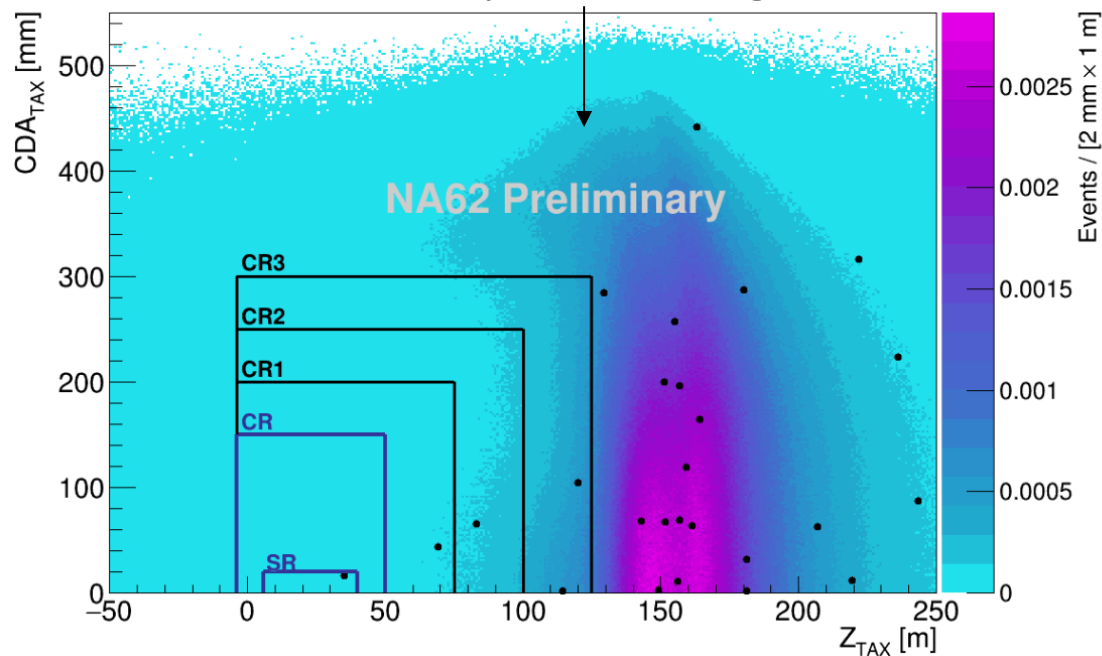
1 event observed in signal region
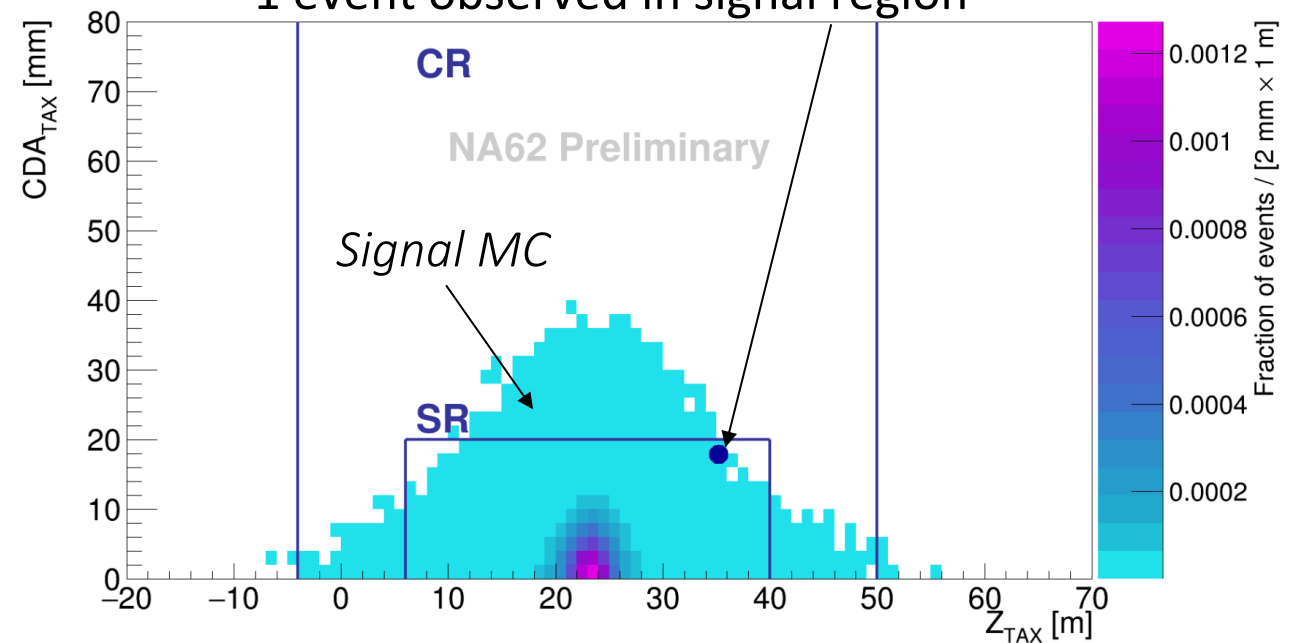
Dark Photon Search $A' \to \mu^+ \mu^-$ in NA62 RUN2

$(1.4 \pm 0.3) \times 10^{17}$ PoT

$N_{obs} = 1$

$N_{exp} = 0.016 \pm 0.002$

Signal significance $2.4\,\sigma$ (only counting)

90% CL exclusion
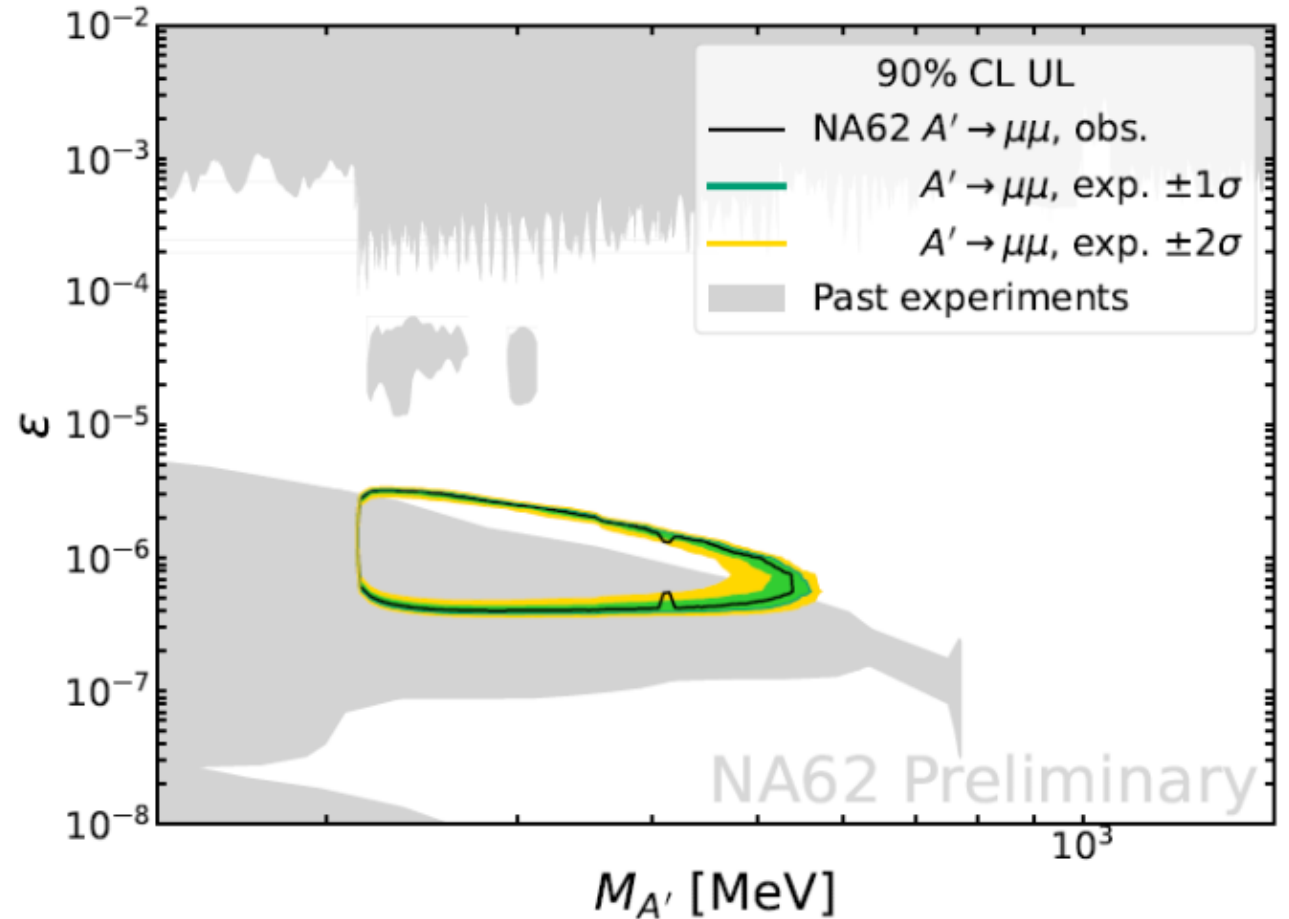
Estimated cost for detectors

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

Intensity requirements

Table 21: Summary of intensity requirements for the HIKE Phases. The number of kaon decays refers to those inside a fiducial decay volume (see Sections about physics sensitivity). For the K^+ phase, the maximum required intensity is specified; possibilities of reducing the intensity and increasing the momentum bite will be studied for the full proposal. An intensity higher than 2×10^{13} can be used by HIKE when operating in dump mode.

Phase	Protons on target/spill	K decays/year	Protons on TAX
Phase 1 (K^+)	1.2×10^{13}	2×10^{13}	-
Phase 2 (K_L+tracking)	2×10^{13}	3.8×10^{13}	-
Dump Mode	-	-	$(2\text{–}4)\times 10^{13}$
Phase 3 (K_L, KLEVER)	2×10^{13}	1.3×10^{13}	-

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
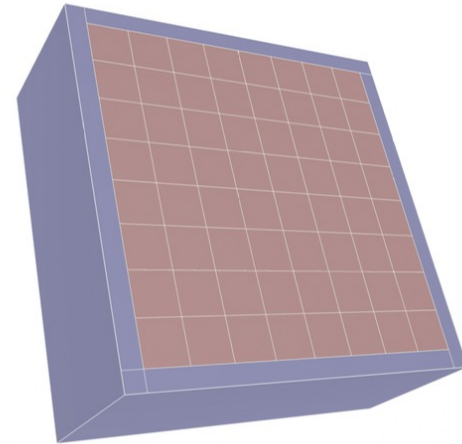
Susceptible to aging (QE drops)
Atomic layer deposition (ALD) coating increases the lifetime dramatically
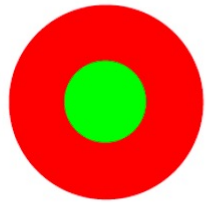
Simulation results obtained with geometrical filling factor of 75% and collection efficiency of 60% show that 15–20 ps kaon time resolution is achievable

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
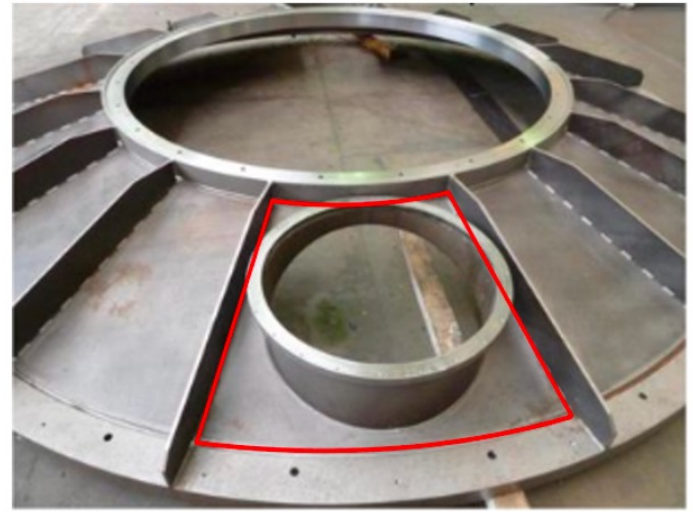
Opportunity to increase RICH acceptance for negatively-charged particles

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** ($1 - \varepsilon <$ 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
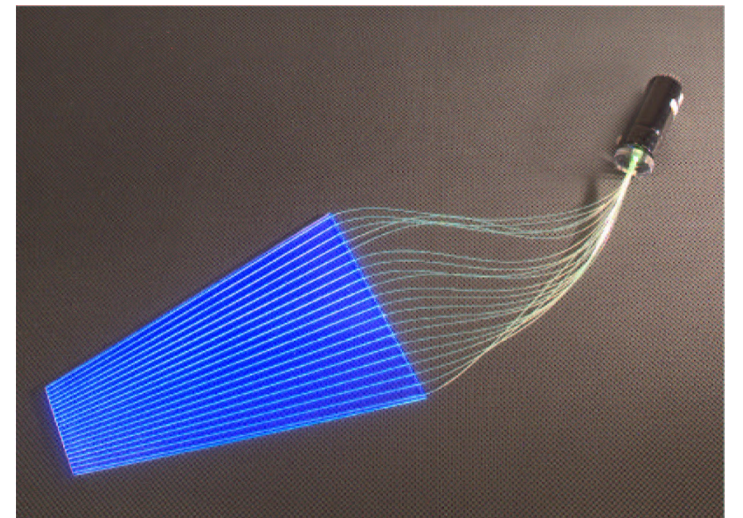
Hadron Calorimeter

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.
Two options considered for an iron-scintillator based calorimeter:

Transverse HCAL layout, 1440 cells
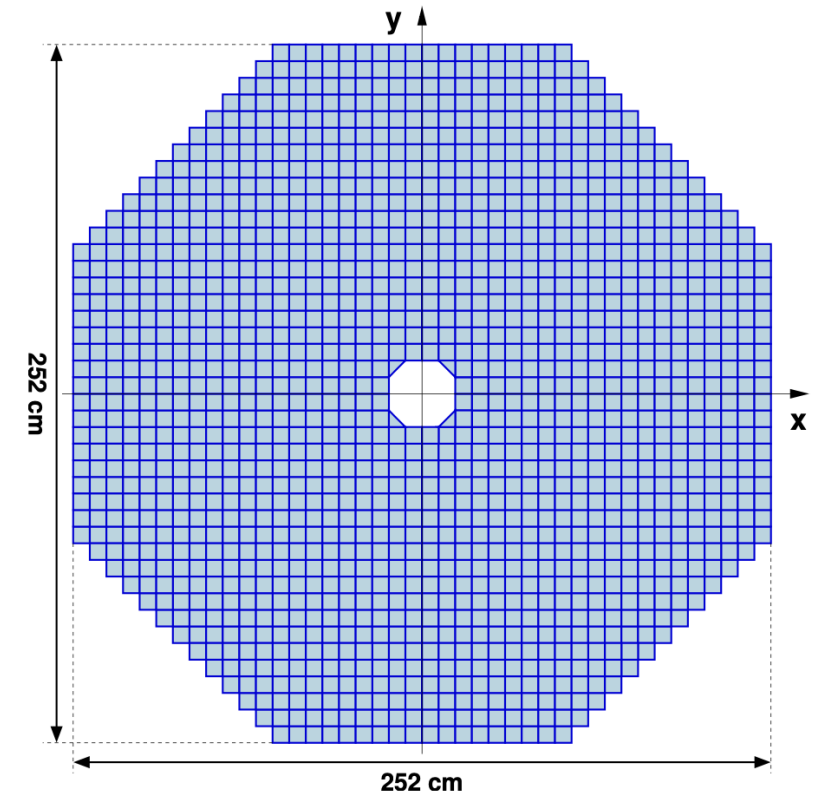
High-Granularity Analogue Calo
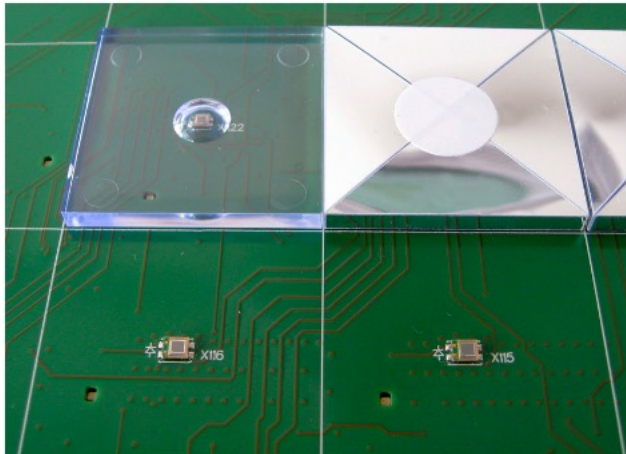


Shashlik calorimeter
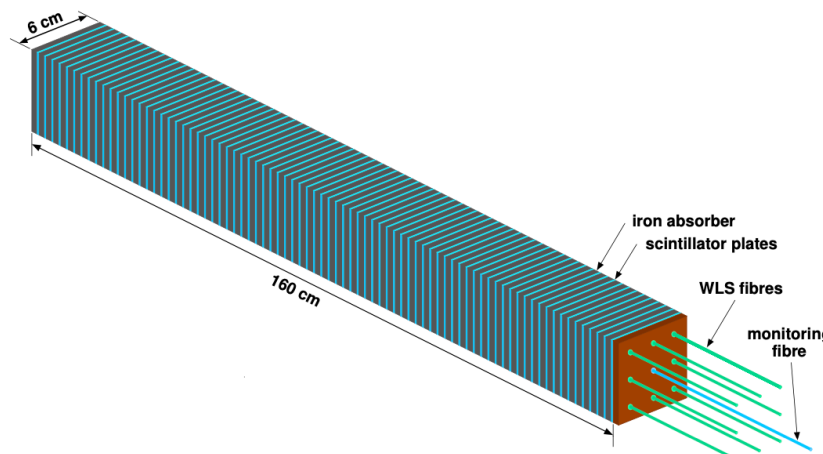
HIKE Phase 1: Physics sensitivity
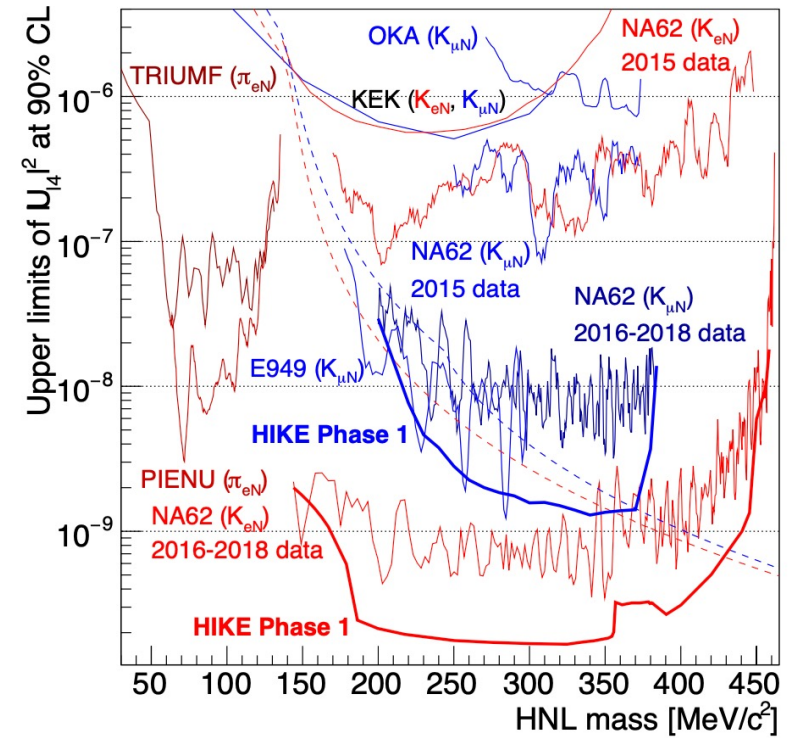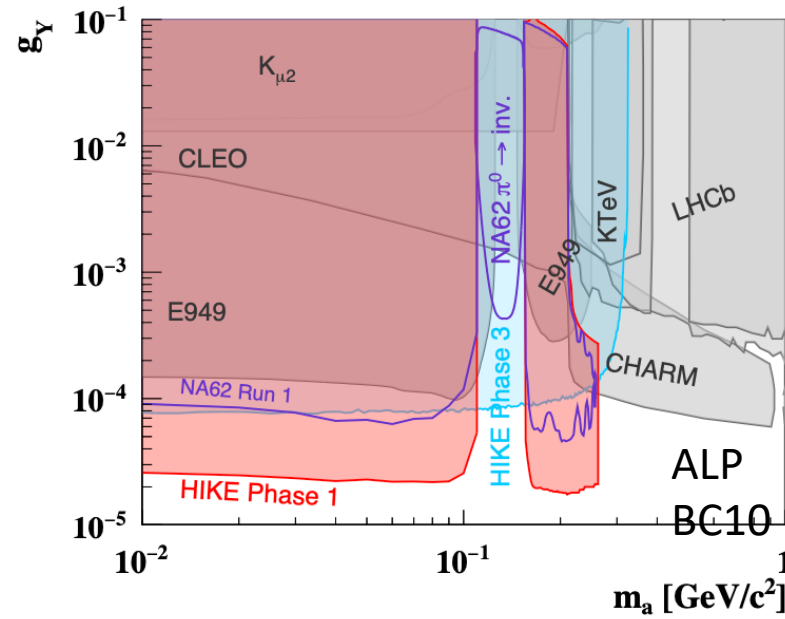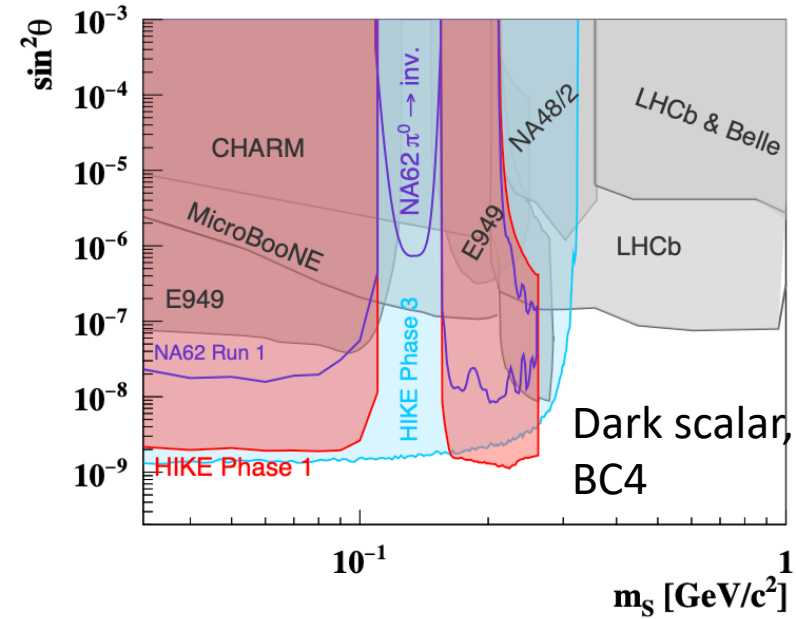
HIKE Phase 1: increase world samples of many rare K^+ decays by an order of magnitude.
Many rare decay measurements to a new level of precision.

Collect background-free samples of several times 10^5 events of both $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+ \mu^+ \mu^-$
Measure difference of the form-factor parameter 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 $O(10^{-12})$
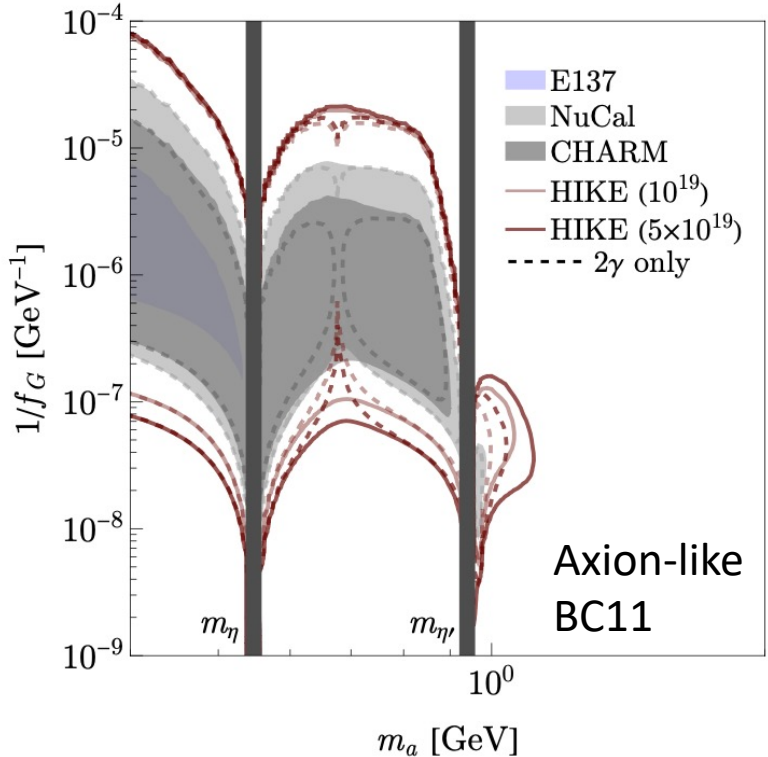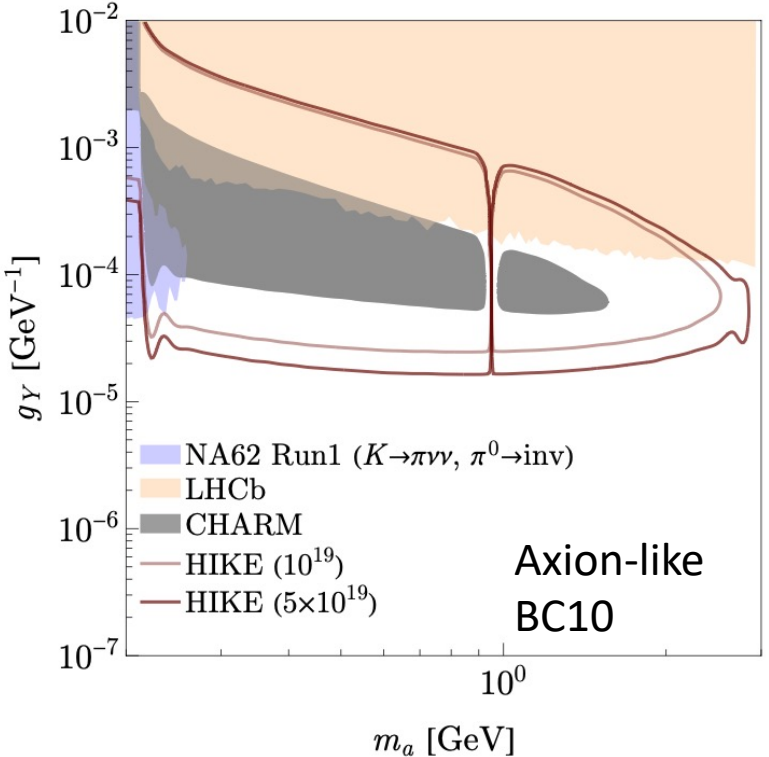
Beam dump mode

$A' \to l^+l^-$
BC1
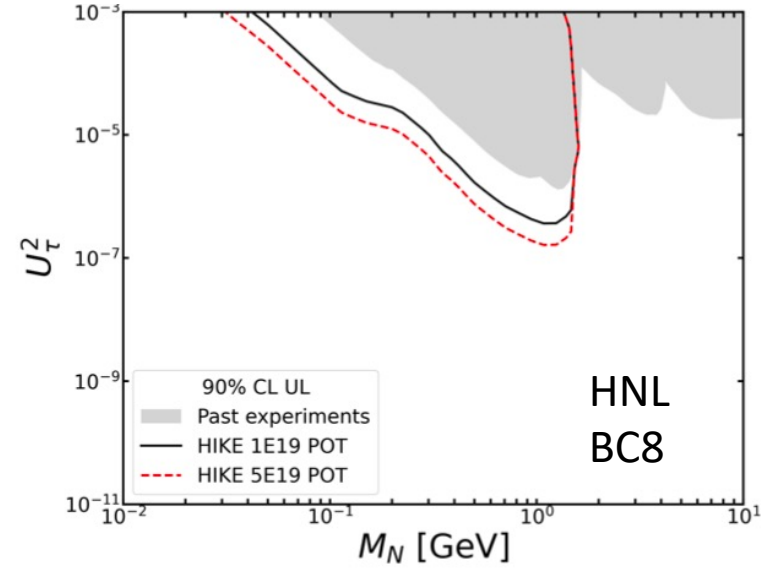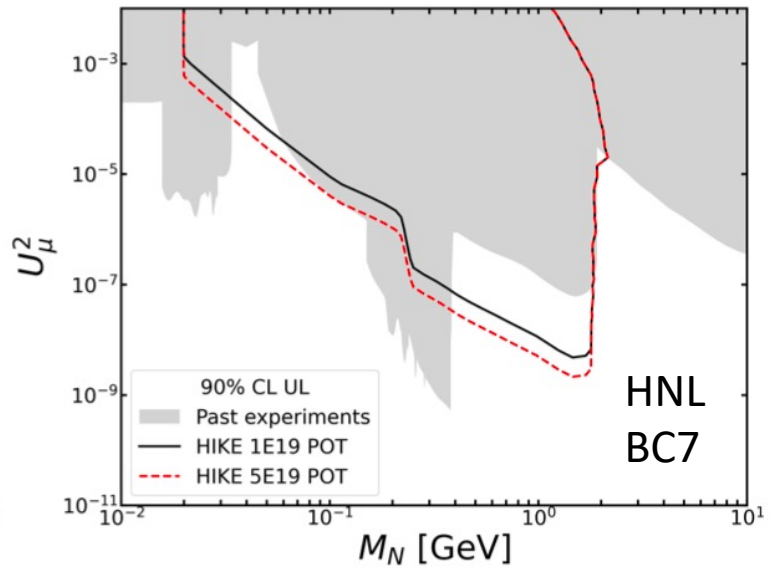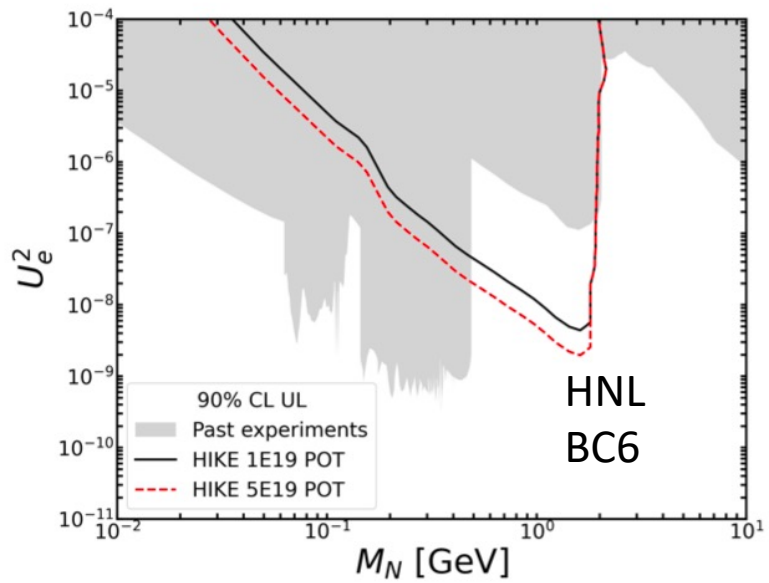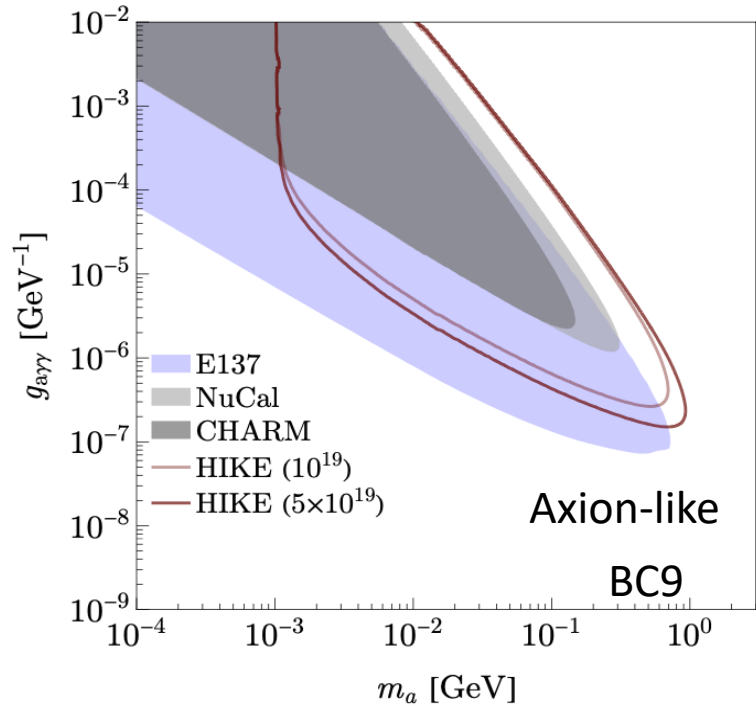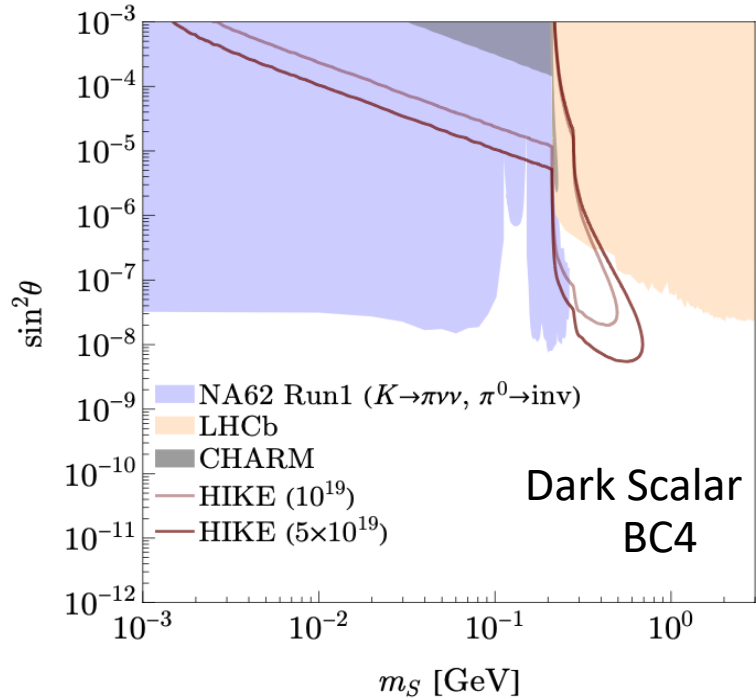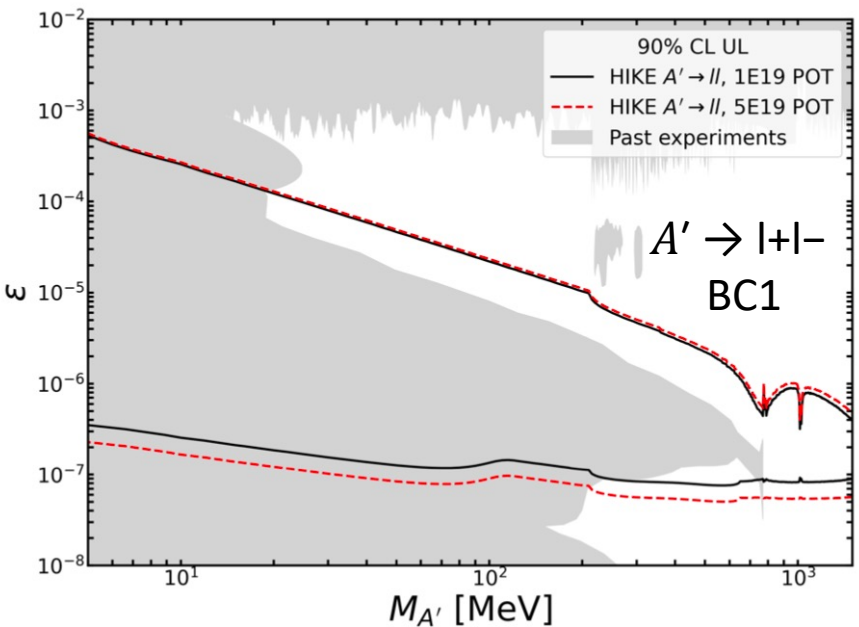
Dark Scalar
BC4

Axion-like

BC9

HNL
BC6

HNL
BC7

HNL
BC8

Beam dump mode

BC10 assumes HIKE sensitivity to ALP production from B meson decays and to the ALP decays $a \to ee$ and $a \to \mu\mu$

BC11 assumes HIKE sensitivity to $a \to \gamma\gamma$ decays (dashed contour) and also to the hadronic decays $a \to \pi{+}\pi{-}\gamma$, 3π, $2\pi\eta$, etc. (full contour)

Kaon Global Fit

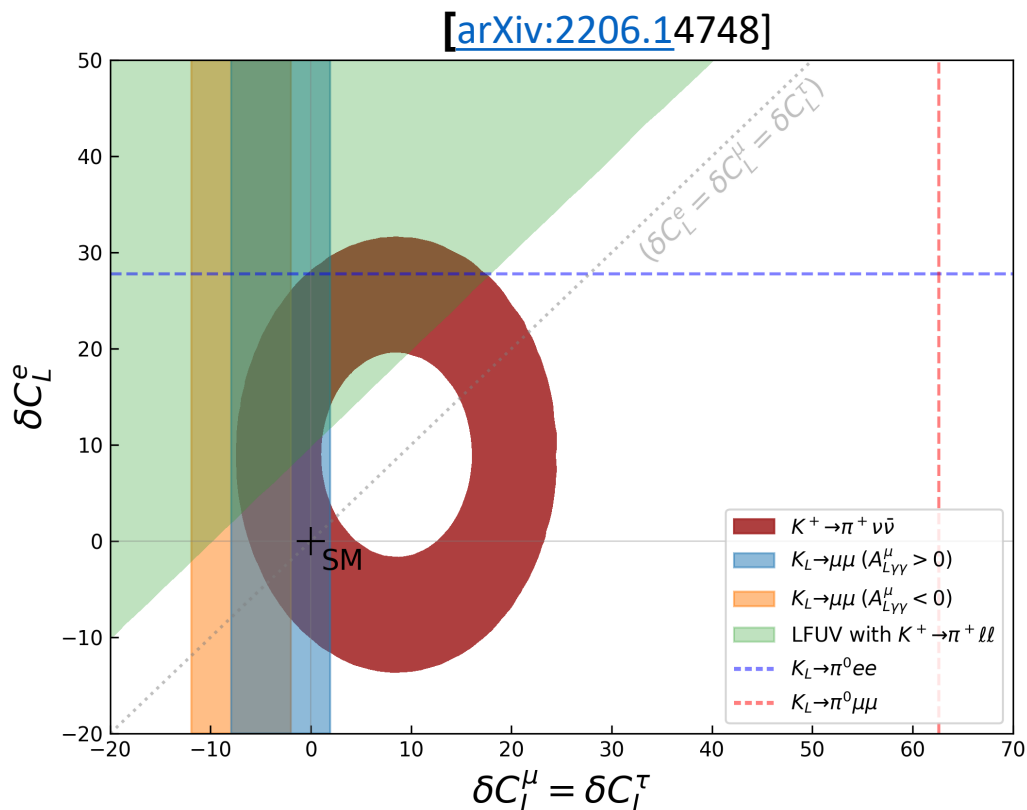$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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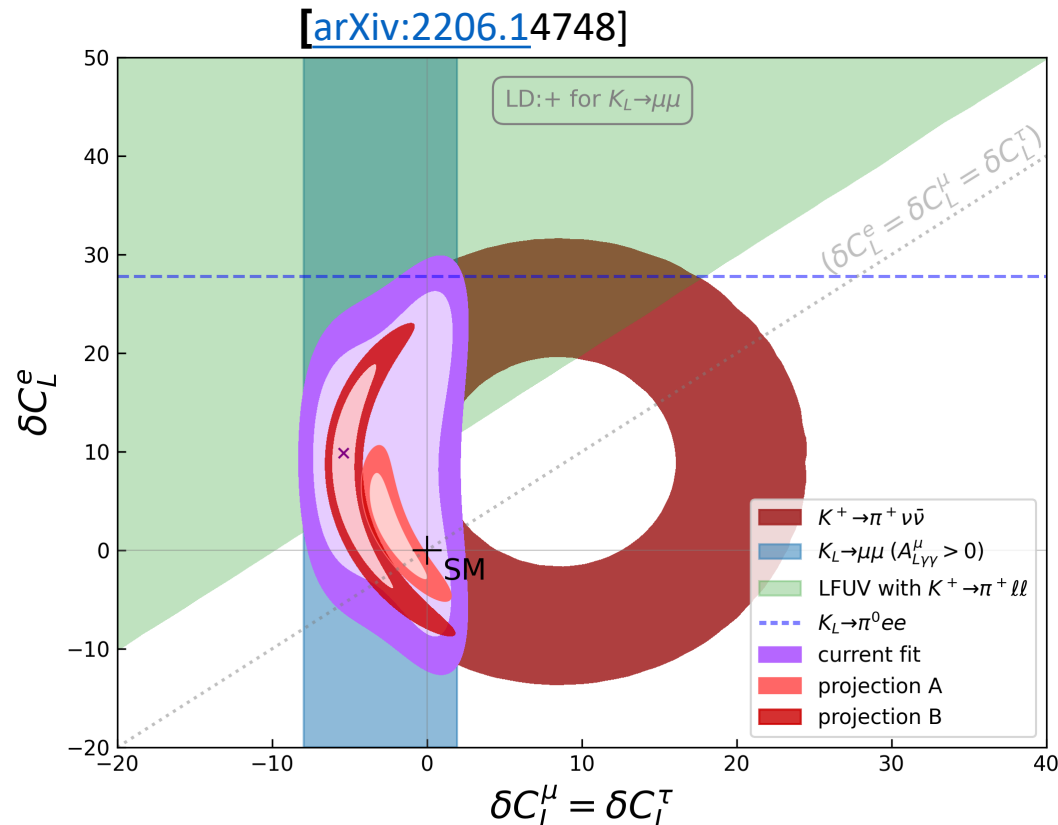
$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

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

[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

Observable	SM prediction	Exp results	Exp	Experimental Error Projections
$\mathrm{BR}(K^+ \to \pi^+ \nu\nu)$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	**NA62**	5% (**HIKE-Phase1**)
$\mathrm{BR}(K^0_L \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL	KOTO	20% (**HIKE-Phase3**)
$\mathrm{LFUV}(a^{\mu\mu}_+ - a^{ee}_+)$	0	-0.031 ± 0.017	NA48/2, **NA62**	± 0.005 for each mode (**HIKE-Phase1**)
$\mathrm{BR}(K_L \to \mu\mu)\ (+)$	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$			
$\mathrm{BR}(K_L \to \mu\mu)\ (-)$	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	BNL-871	experimental uncertainty 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	KTeV	
$\mathrm{BR}(K_L \to \pi^0 ee)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	KTeV	observation (**HIKE-Phase2**) (assume 100% error)
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			
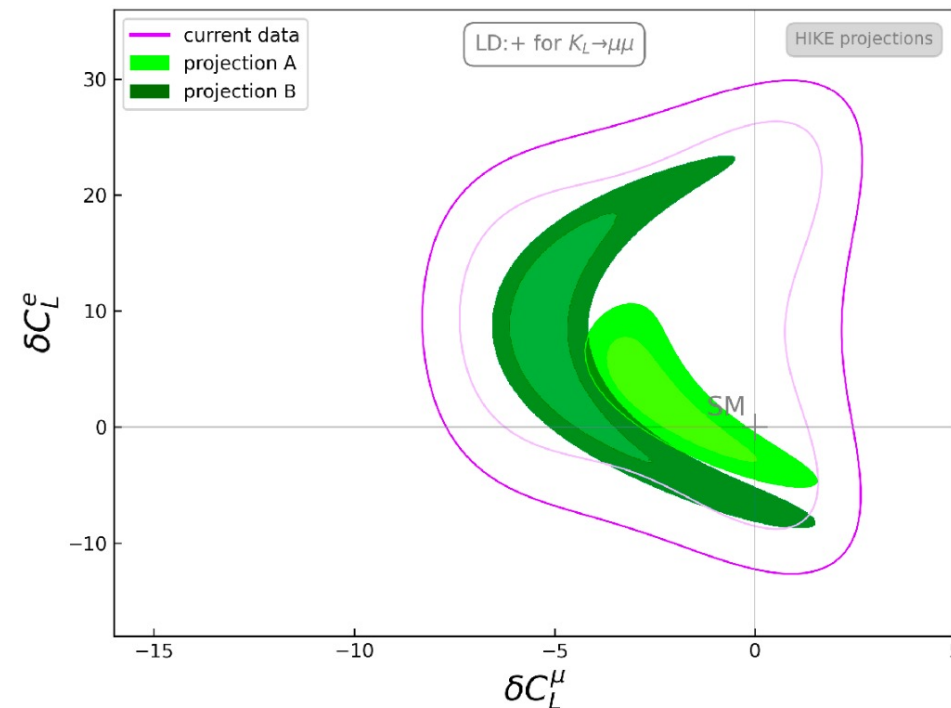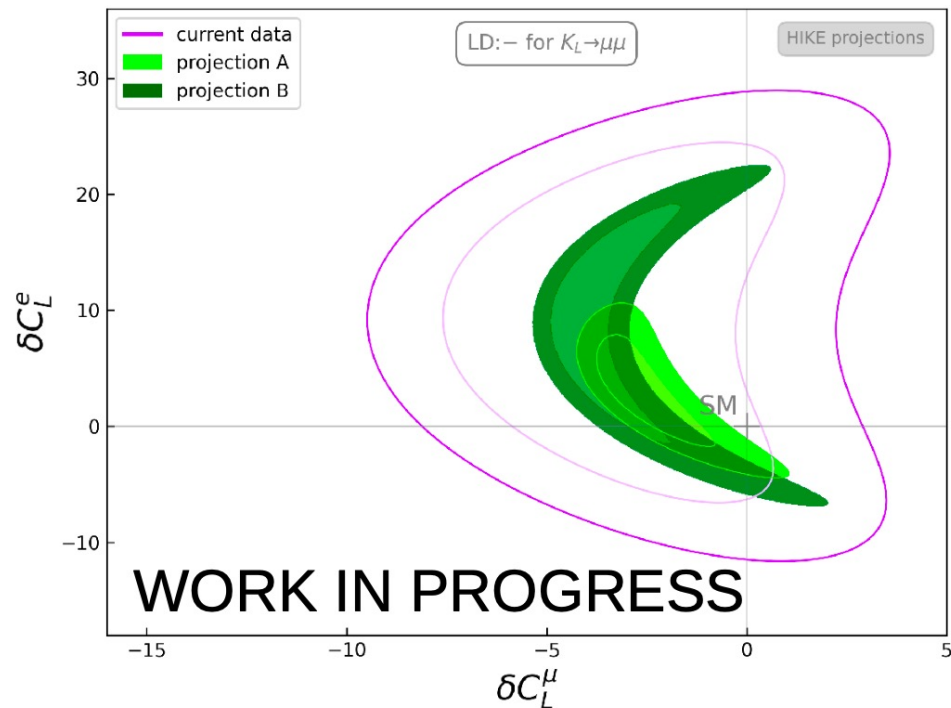
Cabibbo Angle Anomaly

- V_{ud} from super-allowed beta decays

- V_{us} from Kaon and tau decays

- Disagreement leads to a (apparent) violation of CKM unitarity

legend:
— τ decays
— $K \to \pi \ell \nu$
— $K \to \mu\nu/\pi \to \mu\nu$
— $0^+ - 0^+$
SM fit 68% CL

SGPR

CMS

V_{us}
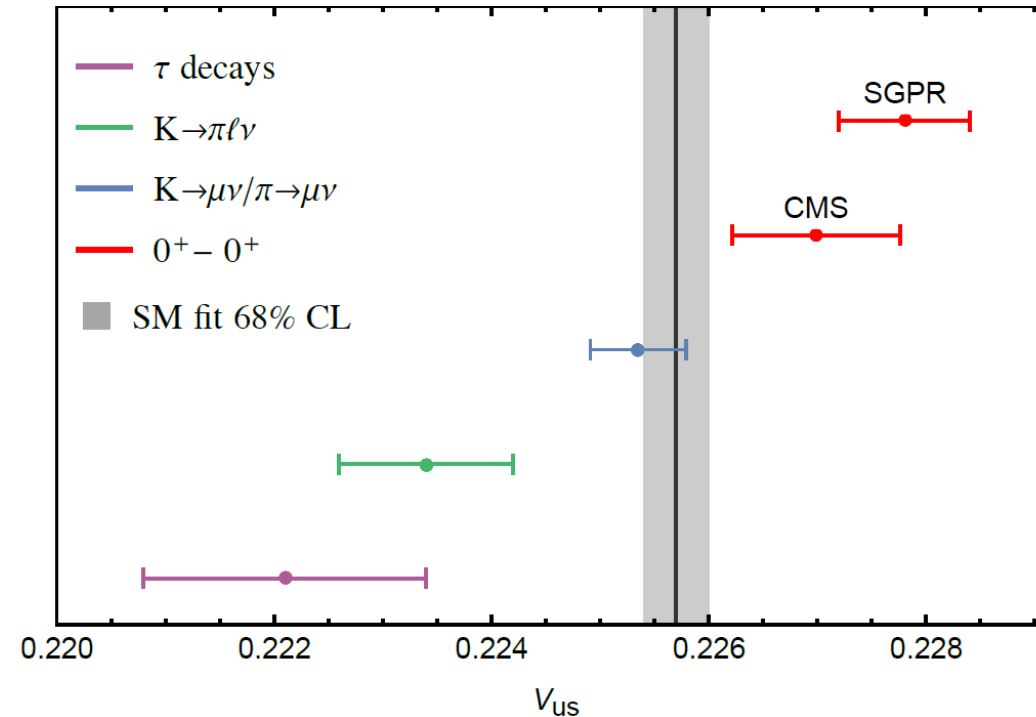
CMS, SGPR: radiative corrections

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

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

$$\text{BR}(K^+ \to \pi^+ \nu\nu) = (11.0\ ^{+4.0}_{-3.5\ \text{stat}} \pm 0.3_{\text{syst}}) \times 10^{-11}$$ [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% → 100%), control random veto

Measure BR($K^+ \to \pi^+ \nu\nu$) to O(10%) by LS3