

# HIKE: The High-Intensity Kaon Experiments at CERN

## Proposal for Phase 1 and 2

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



HIKE: 195 collaborators from 41 institutions  
in the Proposal of HIKE Phase 1 and 2

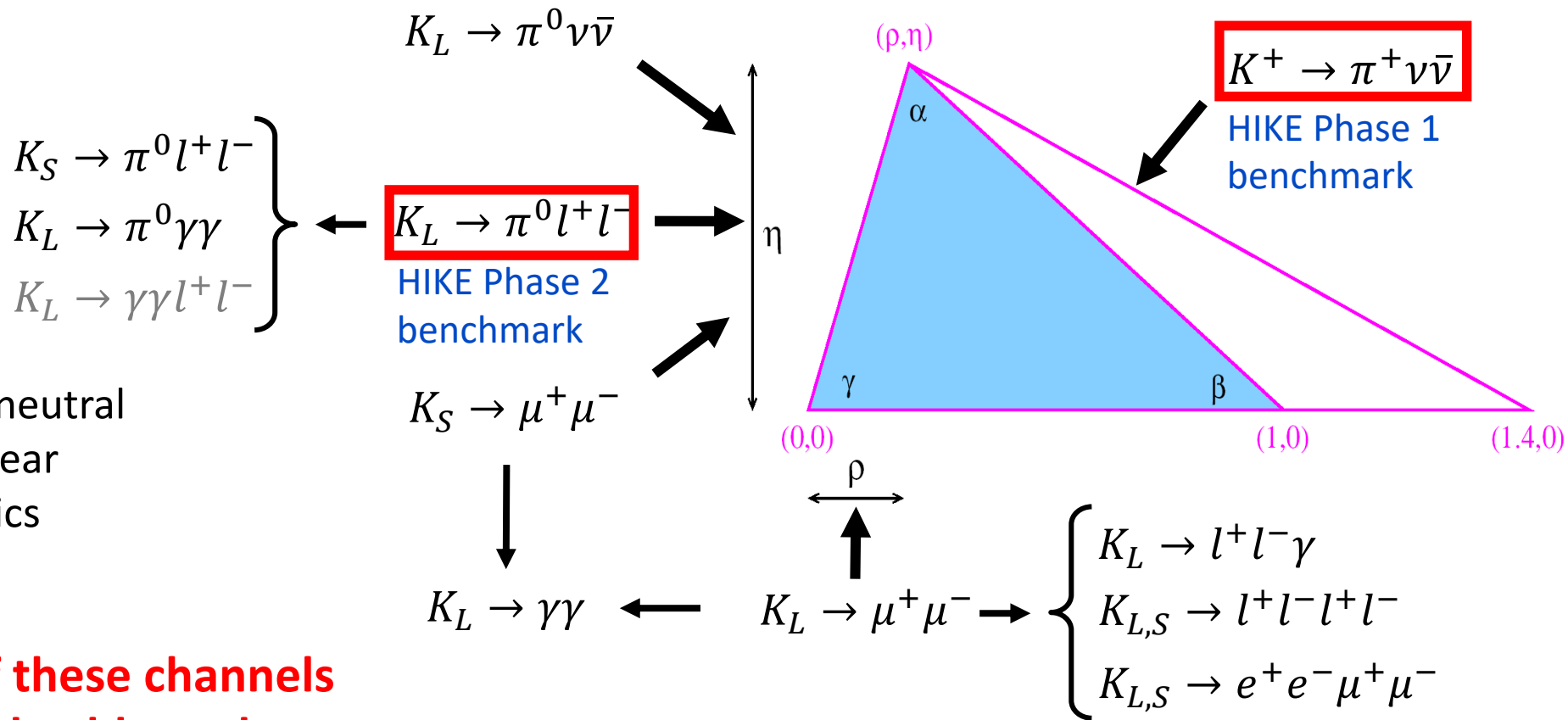
# Exploring flavour physics through Kaon decays

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.



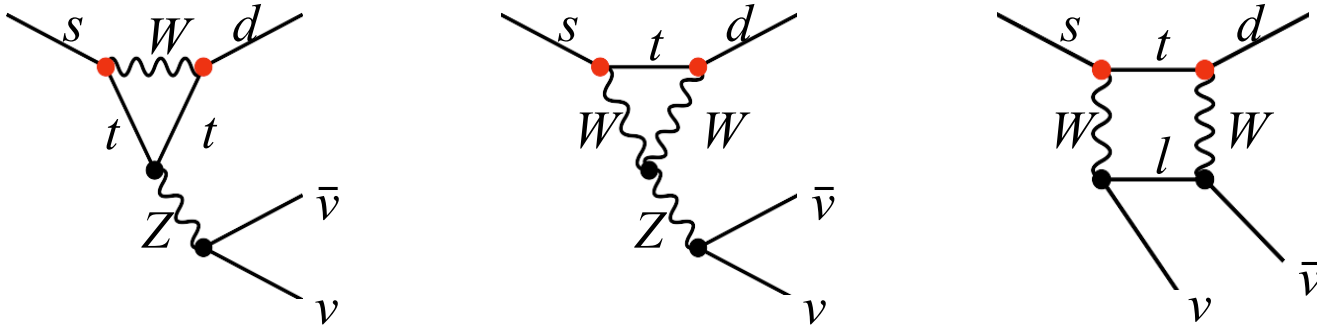
Measuring all charged and neutral rare K decay modes gives clear insight about the new physics flavour structure

HIKE will address many of these channels

Only experiment worldwide able to do so

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

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



A high-order process with highest CKM suppression:

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

**Extremely rare decays, rates very precisely predicted in SM**

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

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

Present error budget presently dominated by CKM inputs

[JHEP 1511 (2015) 033]

[[arXiv:2203.11960](https://arxiv.org/abs/2203.11960), [arXiv:2109.11032](https://arxiv.org/abs/2109.11032)] [[arXiv:2105.02868](https://arxiv.org/abs/2105.02868), [arXiv:2203.09524](https://arxiv.org/abs/2203.09524)]

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  $\epsilon_k$  depends only on  $\beta$  and are well predicted, allowing experimental tests).

**“Free” from hadronic uncertainties**  
**Exceptional SM precision**

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

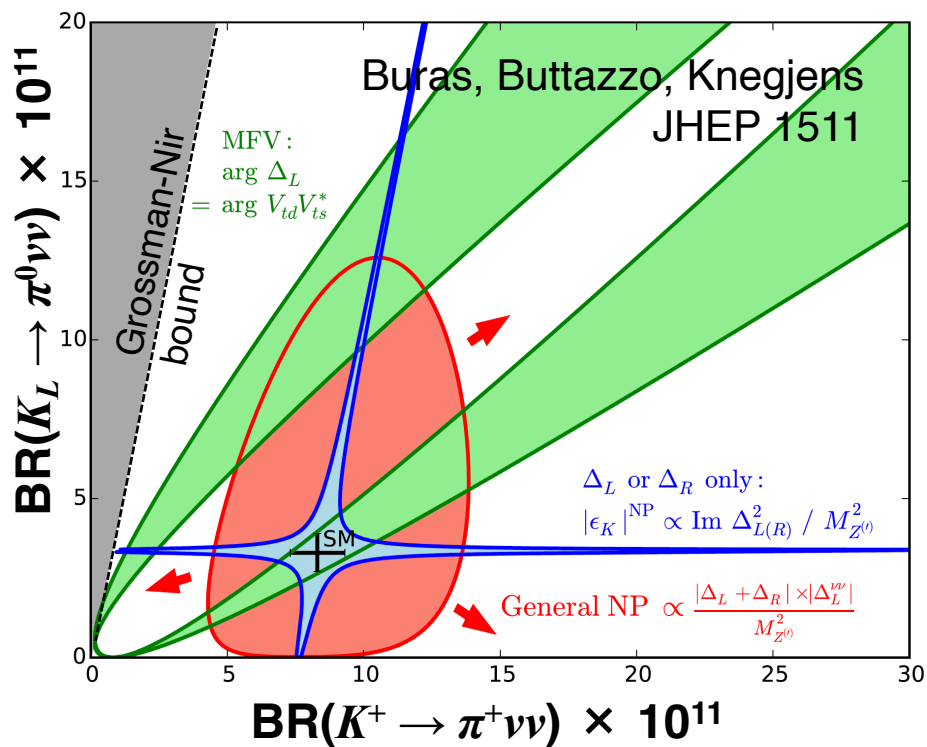
Non-parametric uncertainty:  
1.5% for  $K_L$ , 3.5% for  $K^+$

# 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



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

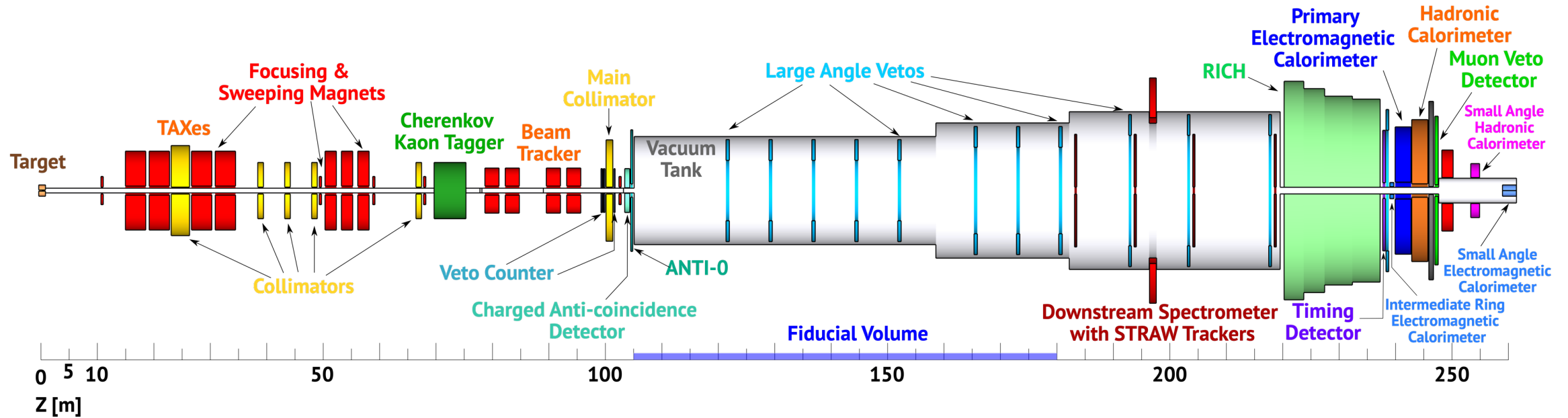
[Table from arXiv:2203.09524]

[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

$K^+$  :  $1.2 \cdot 10^{13}$  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:

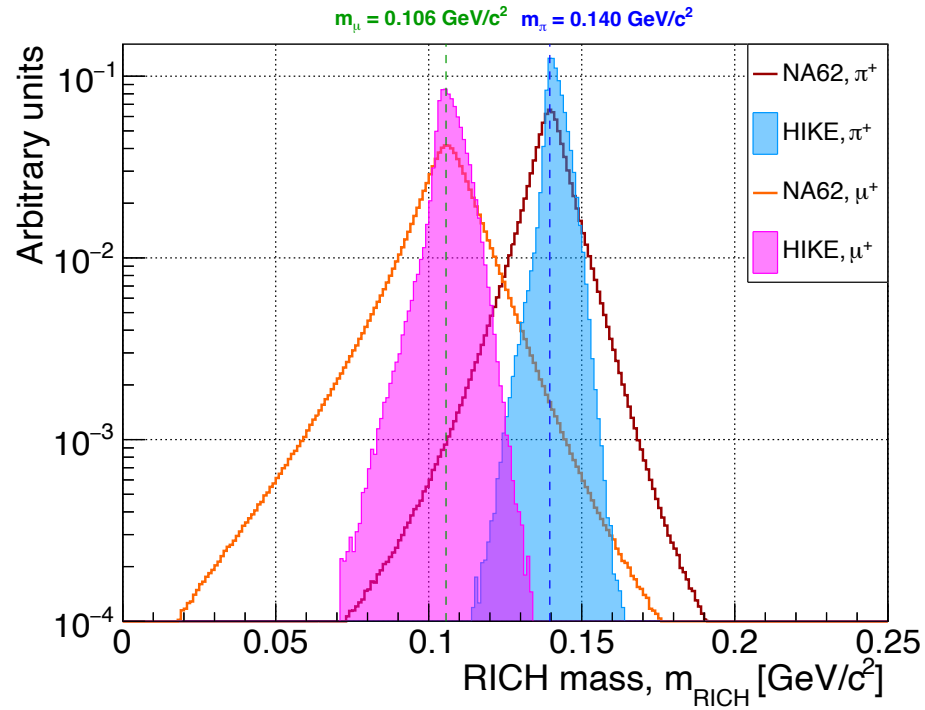
$2 \cdot 10^{13}$  Kaon decays in decay volume  
per year ( $7.2 \cdot 10^{18}$  POT / year)

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/ $\pi$ ID

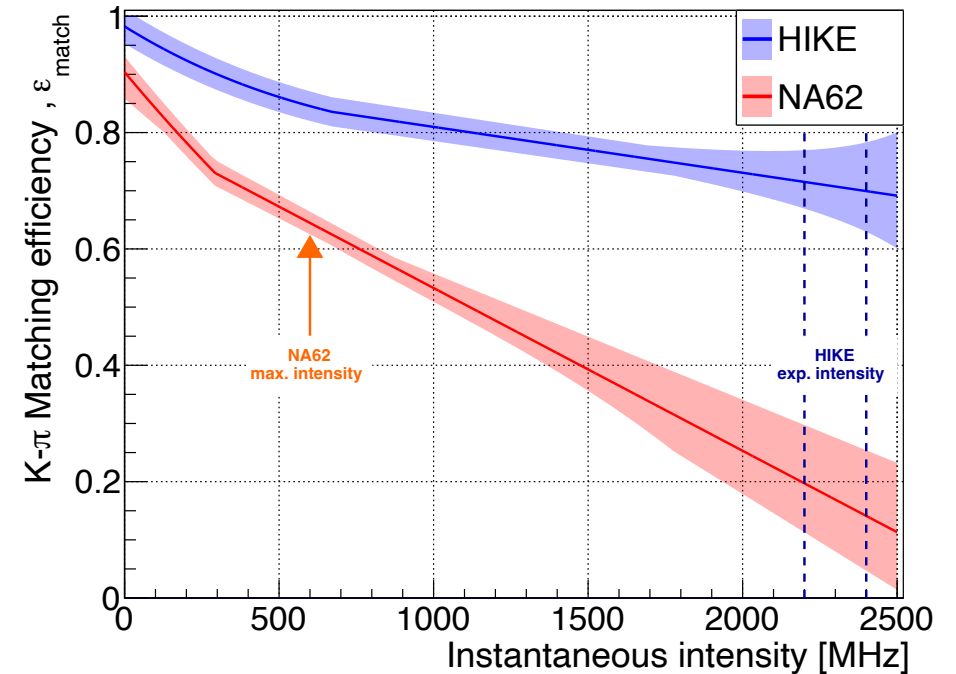


RICH PID for  $\pi$  with  $15 < p < 45 \text{ GeV}/c$ .  
RICH granularity increased, better photodetectors  
(x2 QE, 100ps time resolution).  
Improved photon yield and time resolution

## HIKE:

$\pi$  ID efficiency:  $> 10\%$  higher than NA62, keeping same  $\mu/\pi$  misID probability.

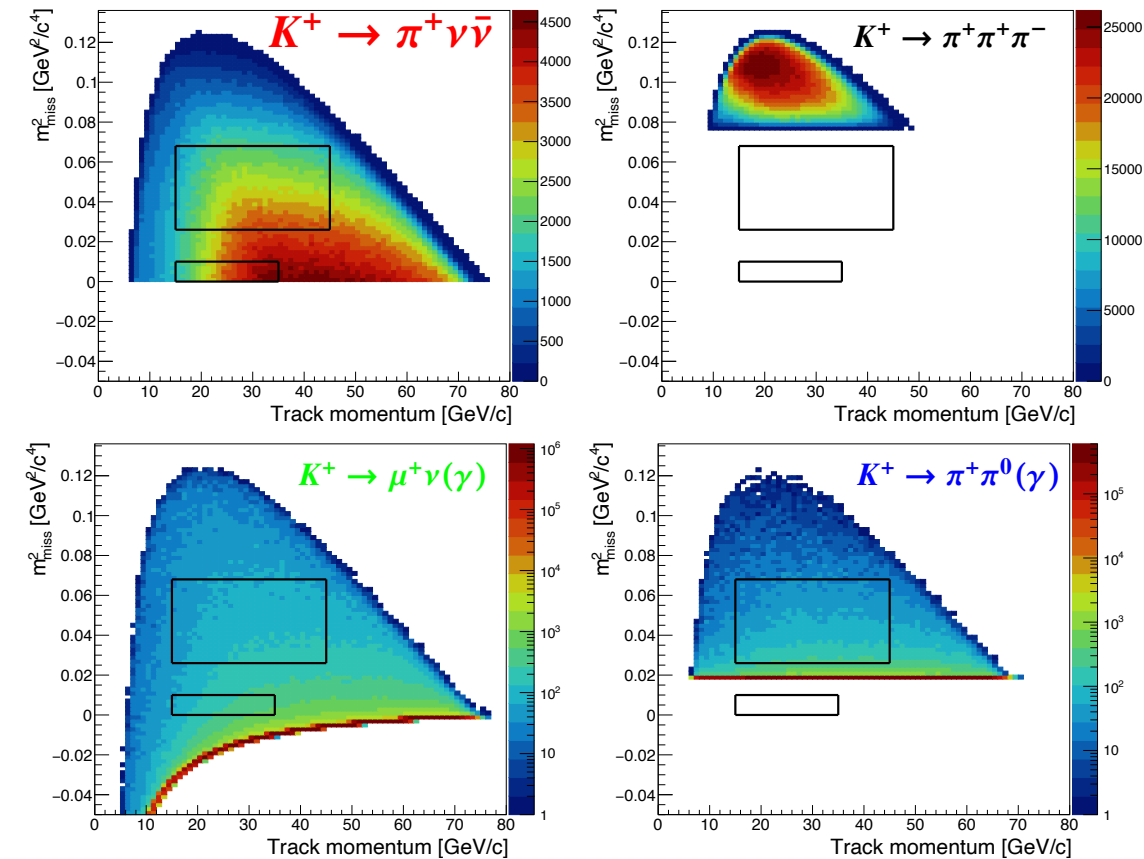
K- $\pi$  efficiency:  $\sim 10\%$  higher than NA62. K- $\pi$  misID probability  $\sim 2\%$ , similar to NA62.



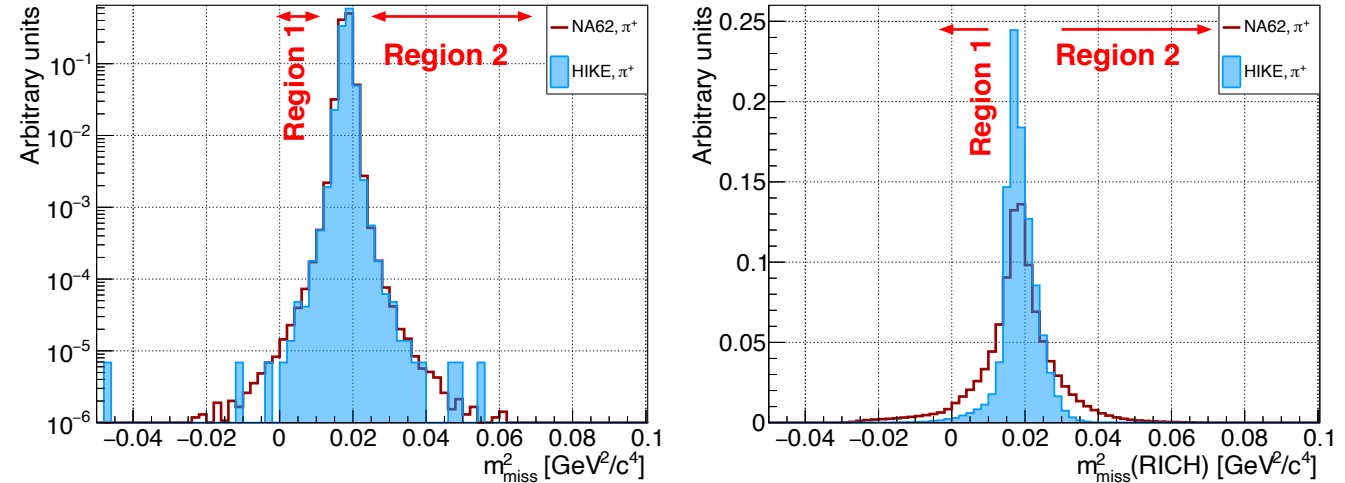
Kaon-pion matching: x4 better timing.  
x3 smaller pixel size in beam tracker.  
40% lower material budget in STRAW.

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

Simulated kinematic distribution of missing mass



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



**NA62 MC extensively validated with data.**

Main kaon decay modes enter the signal regions via resolution tails in the reconstructed value of  $m_{\text{miss}}^2$

Signal regions is determined by resolution.

Better  $m_{\text{miss}}^2$  resolution at HIKE vrt NA62 (40% less material budget in Straw).

Missing mass with RICH much improved.

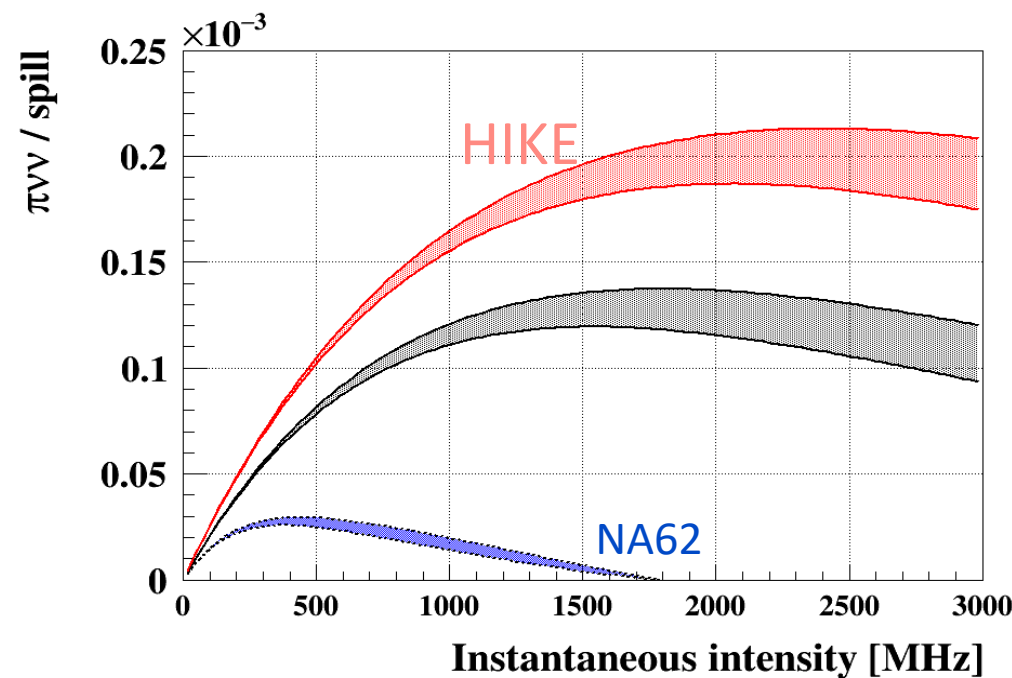
HIKE signal regions can be optimised:

signal acceptance 10% higher than NA62, maintaining same level of kinematic rejection

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

Signal intensity dependence:  
Dead-time-equivalent paralyzable model  
that accounts for intensity  
dependence of the trigger, DAQ, and all  
selection criteria (except Random Veto).

x  
Polynomial description of the random  
veto efficiency



Recovery of LTU dead-time,  
K- $\pi$  association, improved RICH,  
better kinematic resolution.

Improved timing, software trigger  
and new DAQ

Background from K decays to remain the same fraction of signal.  
Improved coverage and design of upstream background veto  
→ Upstream background reduced to same level as K background

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

Number of spills	$2.4 \times 10^6$
Protons on target	$3.2 \times 10^{19}$
$K^+$ decays in FV	$8.0 \times 10^{13}$
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: x 2 for acceptance, x 4 for beam intensity  
Measurement of  $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  at O(5%) precision in 4 years of data-taking

# HIKE Phase 1: physics reach

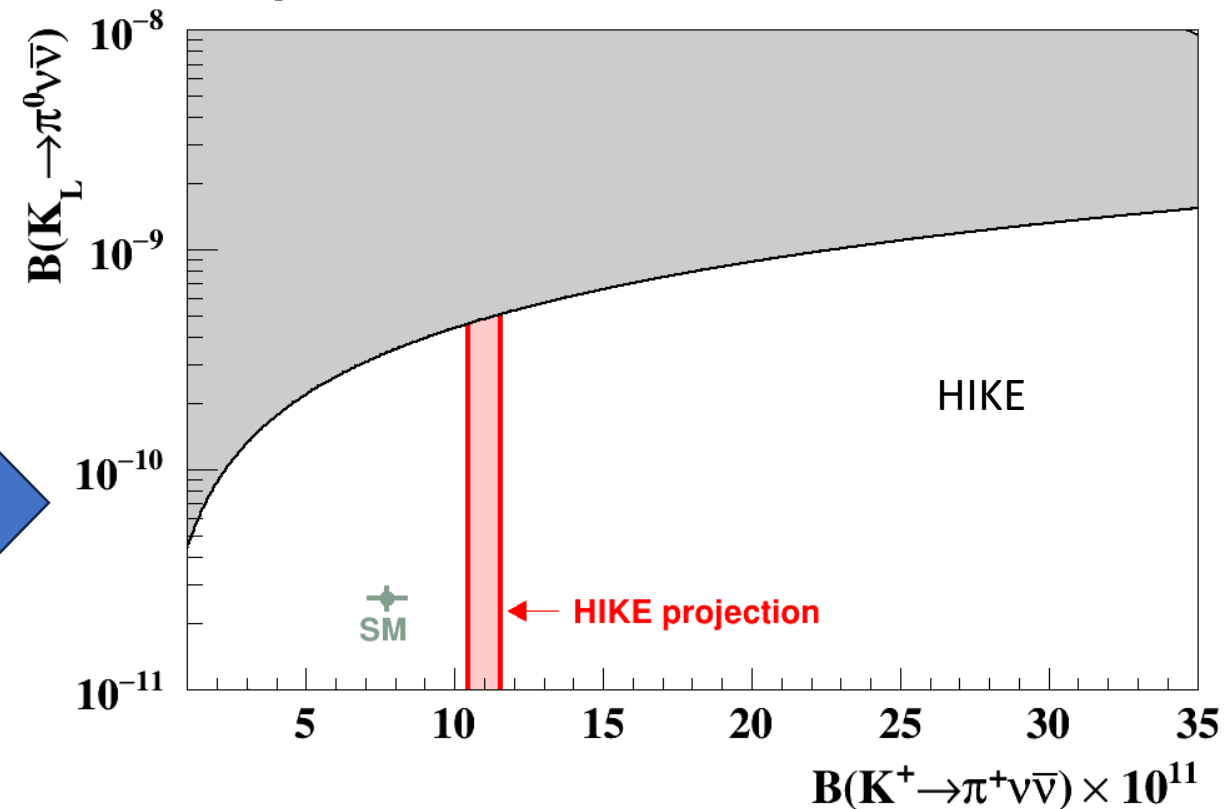
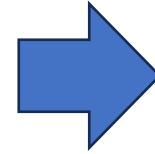
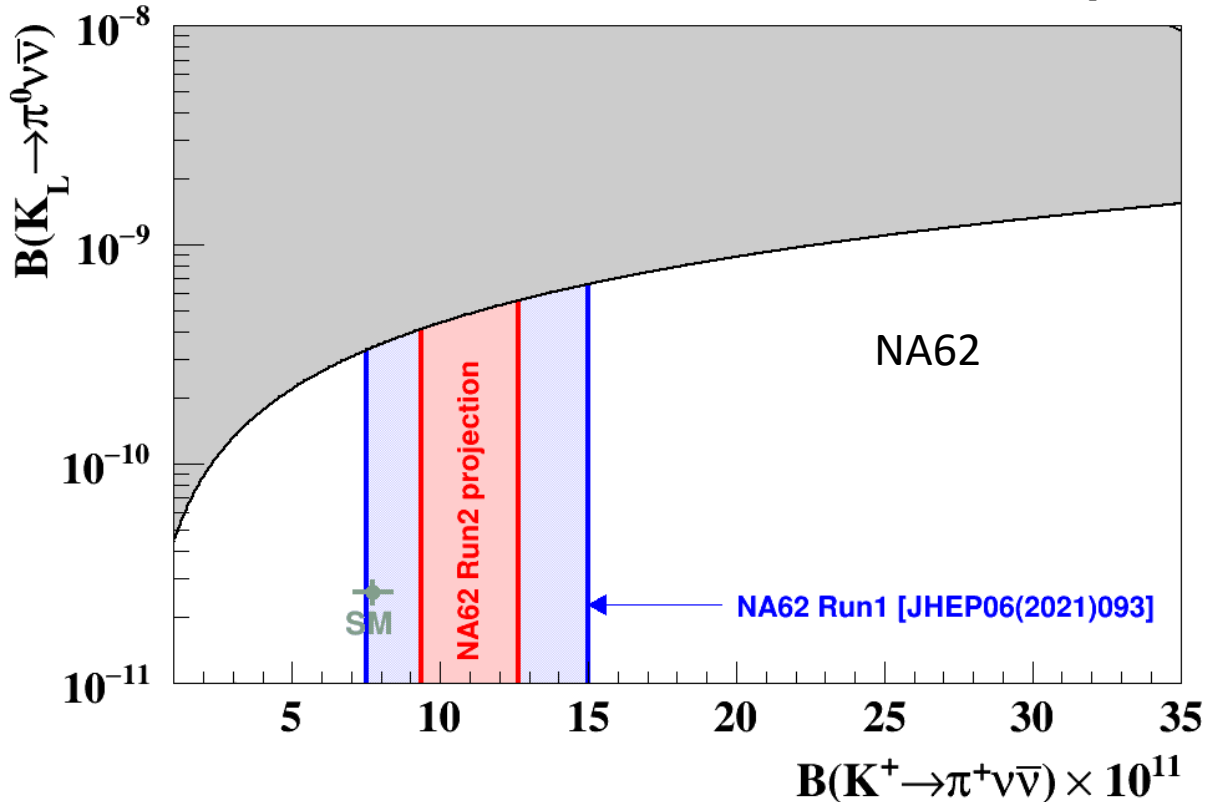
Precision test of the Standard Model:

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

Blue = measurements

[SM: arXiv:2105.02868v1]

Red = projections

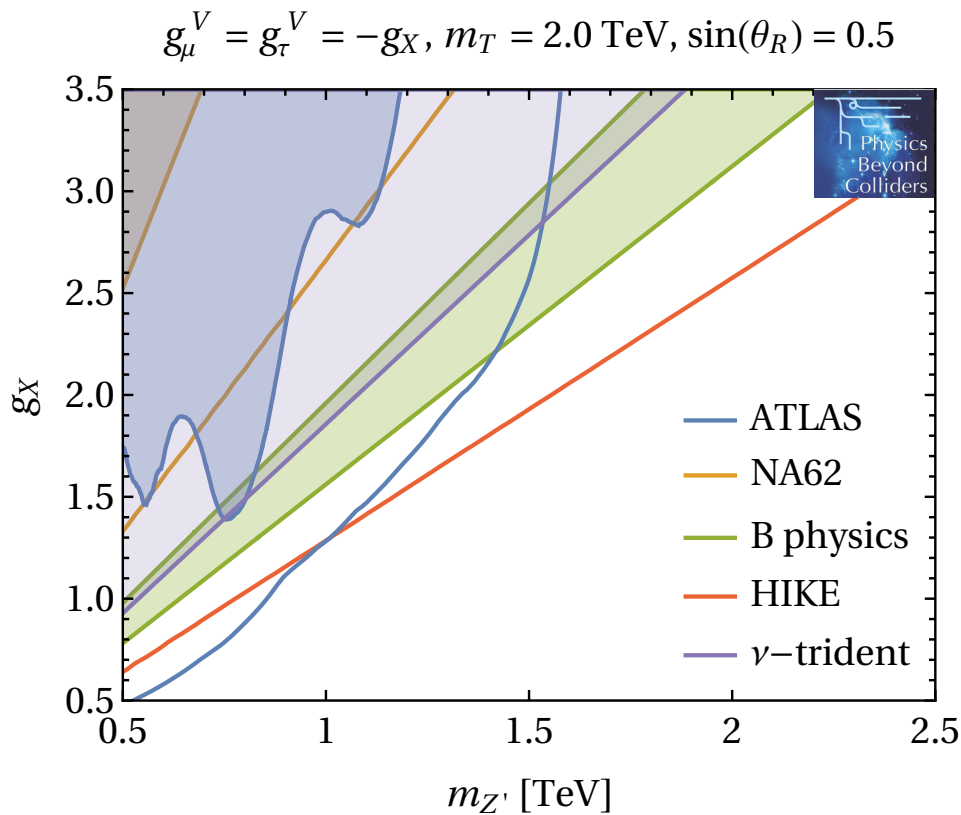


From NA62 to HIKE: precision improved by factor x 3

The first comprehensive analysis of the  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay spectrum will probe its nature

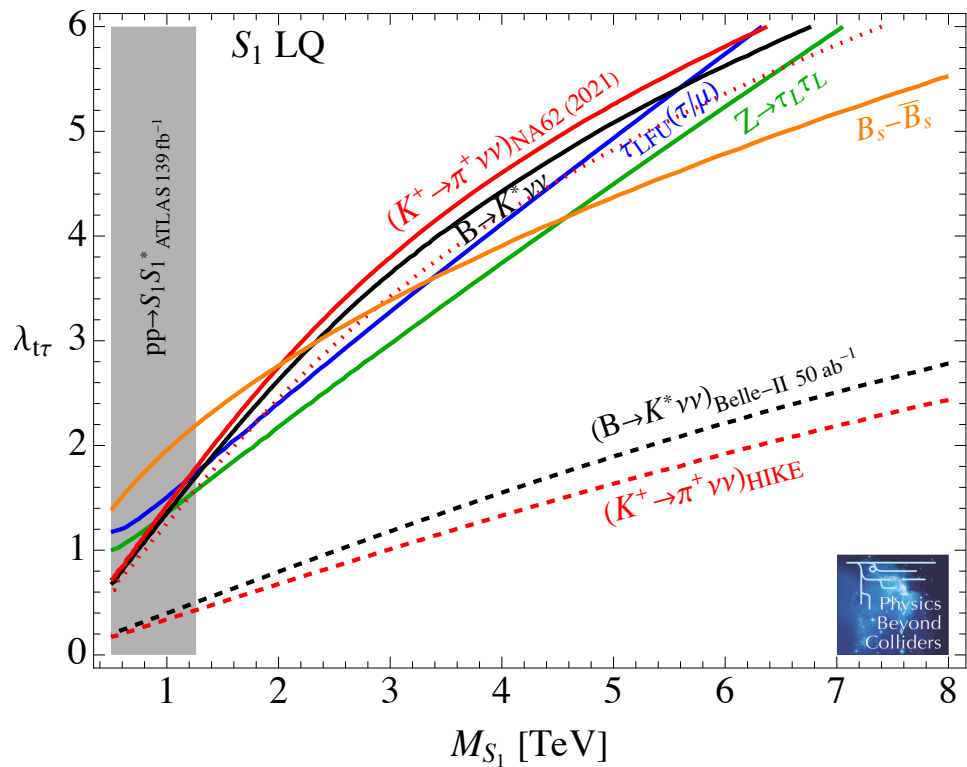
# HIKE Phase 1: examples of specific BSM models

[CERN Physics Beyond Colliders Document, [arXiv:2310.17726](https://arxiv.org/abs/2310.17726)]



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

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



Leptoquark model:  
(revisited by  
D.Marzocca)

Constraints on coupling of  **$S_1$  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].

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

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

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

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

Long-distance effects are purely universal

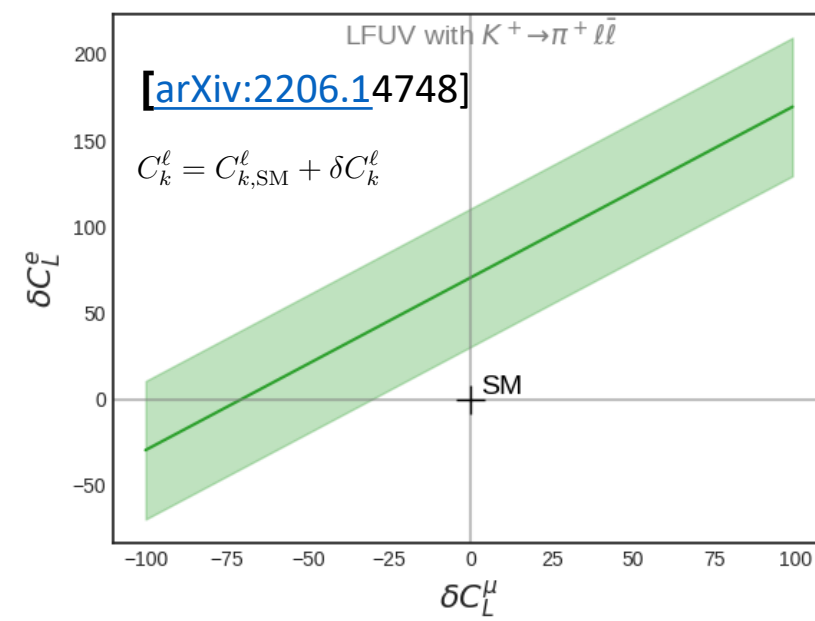
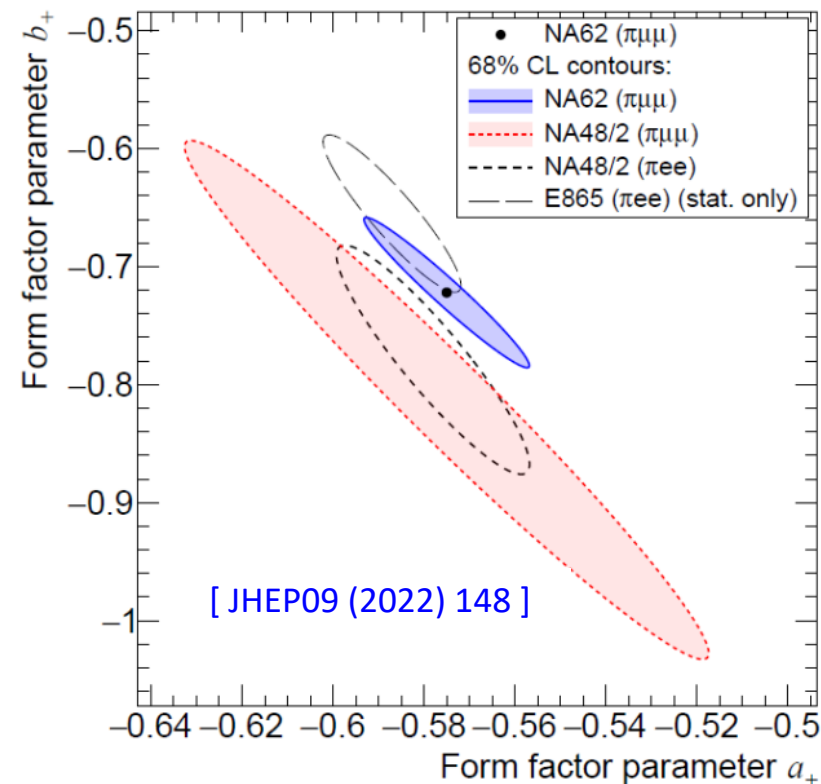
$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2} \operatorname{Re} [V_{td} V_{ts}^* (C_9^\mu - C_9^e)] \quad [\text{JHEP 02 049 (2019), PRD 93 074038 (2016)}]$$

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

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

**HIKE Phase 1: Collect  $> 5 \times 10^5$  background-free  $K^+ \rightarrow \pi^+ l^+ l^-$**   
**Measure  $\Delta a$  and  $\Delta b$  to  $\pm 0.007$  and  $\pm 0.015$  precision**

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





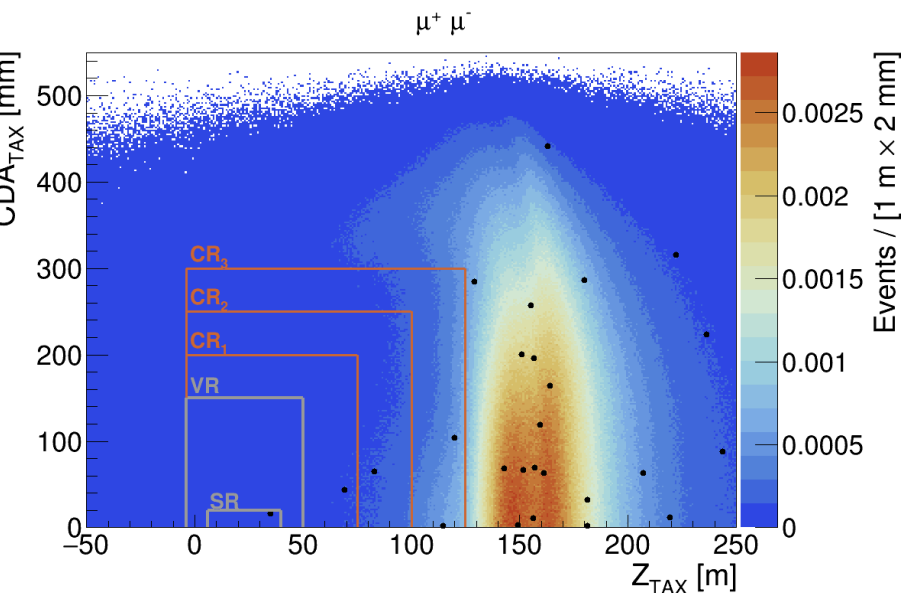
# Feebly interacting particles (FIPs)

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:  $K^+ \rightarrow l^+ N, K^+ \rightarrow \pi^+ X, \dots$

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.

$1.4 \times 10^{17}$  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  $4 \times 10^{17}$  POT so far in 2021-2023.



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

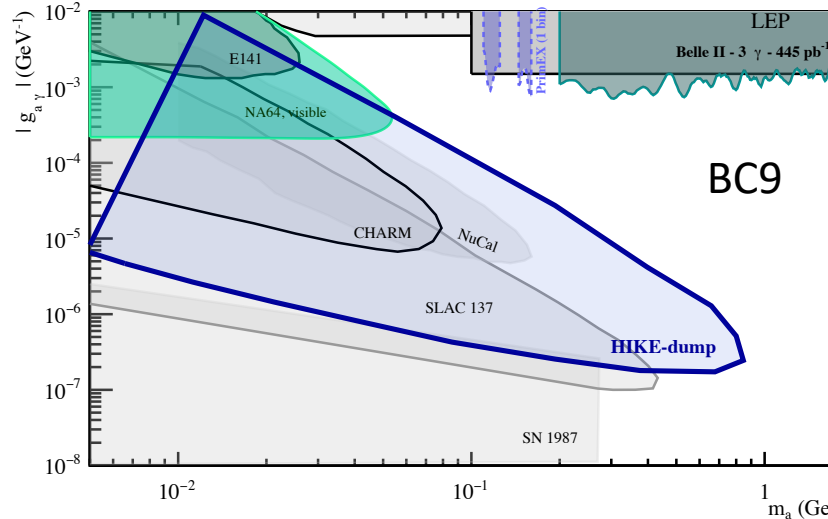
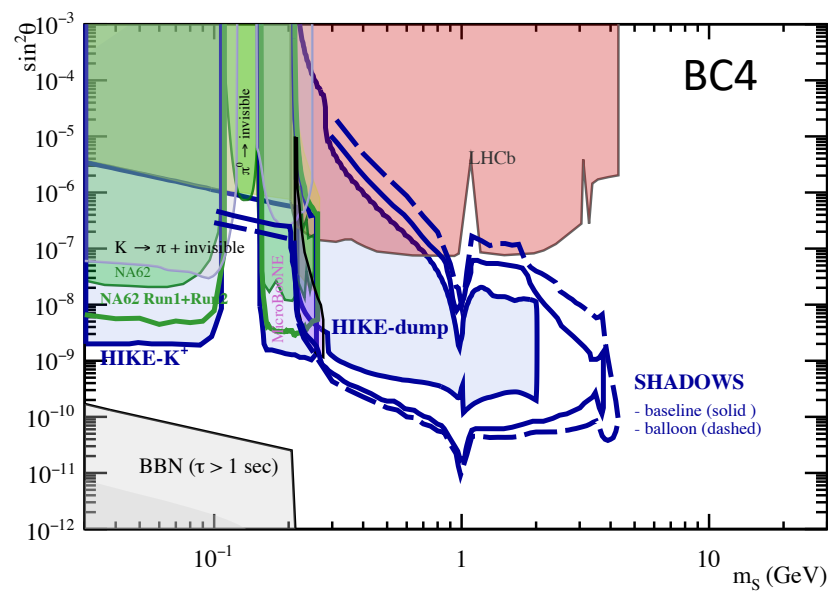
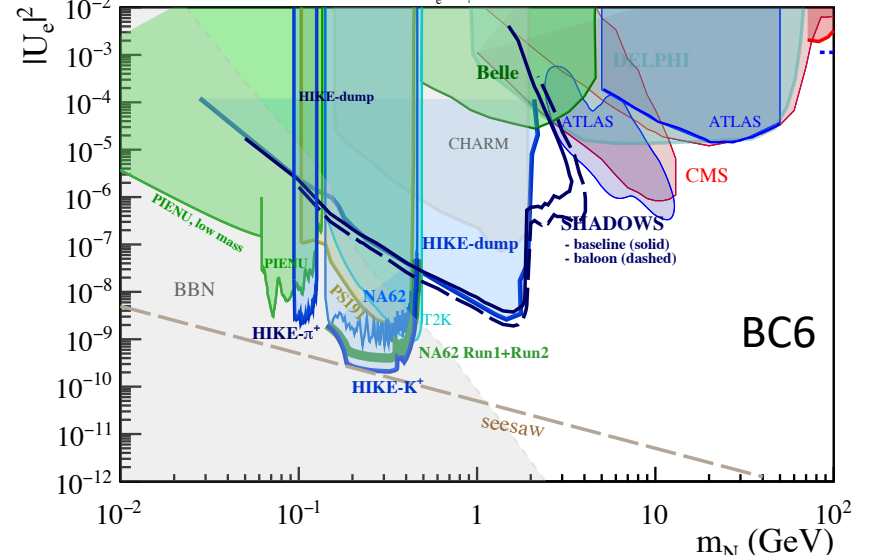
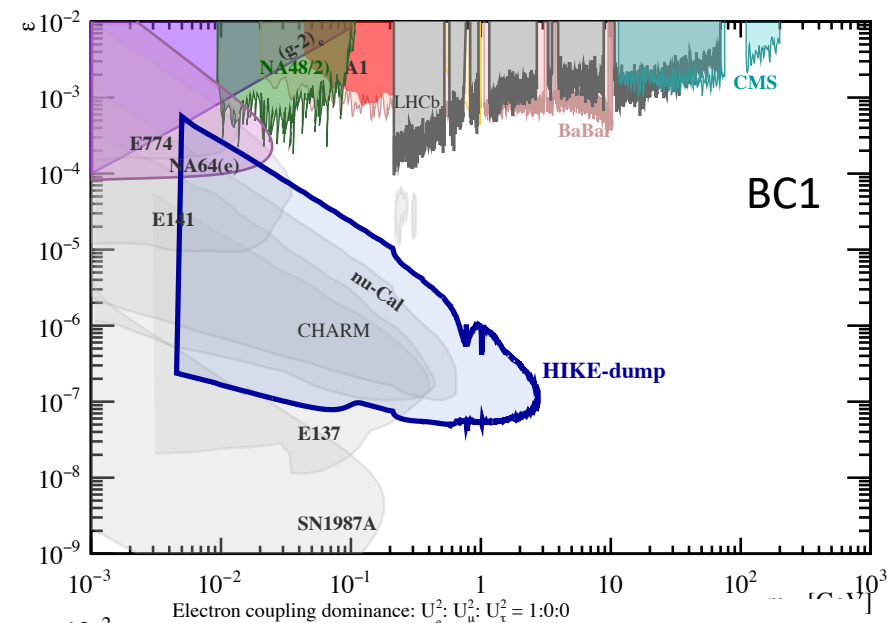
[doi: [10.1007/JHEP09\(2023\)035](https://doi.org/10.1007/JHEP09(2023)035)]

For $5 \times 10^{19}$ 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

$5 \times 10^{19}$  POT in dump mode are assumed, taken in 4 years concurrently with SHADOWS operation, with  $2 \times 10^{13}$  POT over 4.8 s. HIKE has unique complementarity between kaon and dump modes. HIKE sensitive to all BC benchmarks except BC3.



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

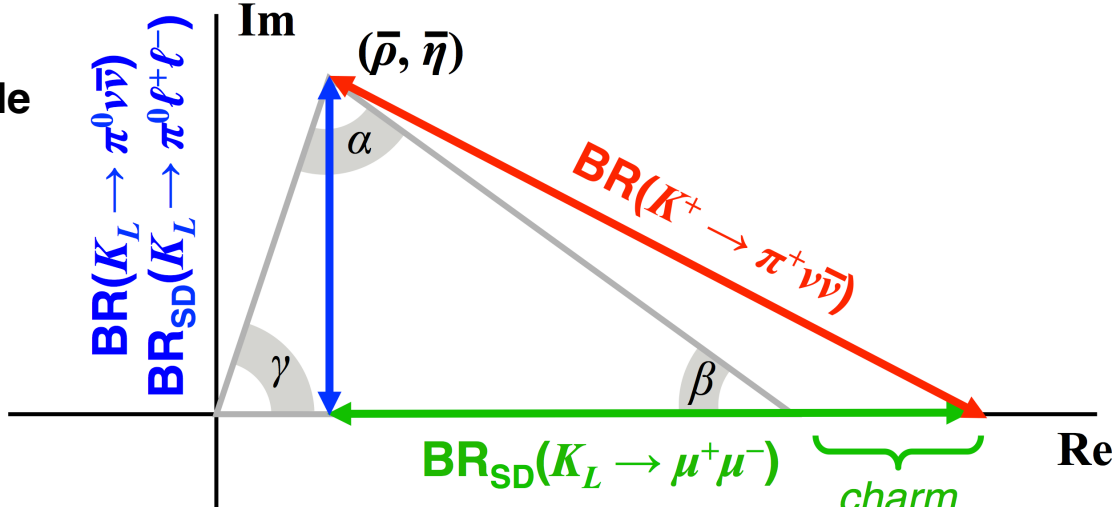
In kaon mode, sensitivity also to non minimal scenarios.

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

Contributions from long-distance physics

- SD CPV amplitude:  $\gamma/Z$  exchange
- LD CPC amplitude from  $2\gamma$  exchange
- LD indirect CPV amplitude:  $K_L \rightarrow K_S$
- $K_S \rightarrow \pi^0 \ell^+ \ell^-$  will help reducing theoretical uncertainties, measure  $\text{Im } a_S$ 
  - 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, give unique access to SD BSM effects in the photon coupling via the tau loop

$K_L \rightarrow \pi^0 \ell^+ \ell^-$  CPV amplitude  
constrains UT  $\eta$



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

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

[arXiv:hep-ph/0404127, arXiv:hpe-ph/0404136, arXiv:hep-ph/0606081]  
[arXiv:0705.2025, arXiv:1812.00735, arXiv:1906.03046, <https://indico.cern.ch/event/1196830/>]

**Experimental bounds  
from KTeV:**

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

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

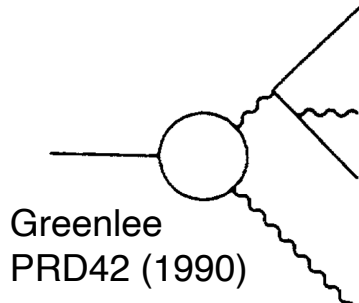
**Main background:**  $K_L \rightarrow \ell^+ \ell^- \gamma \gamma$

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

$\text{BR}(K_L \rightarrow e^+ e^- \gamma \gamma) = (6.0 \pm 0.3) \times 10^{-7}$

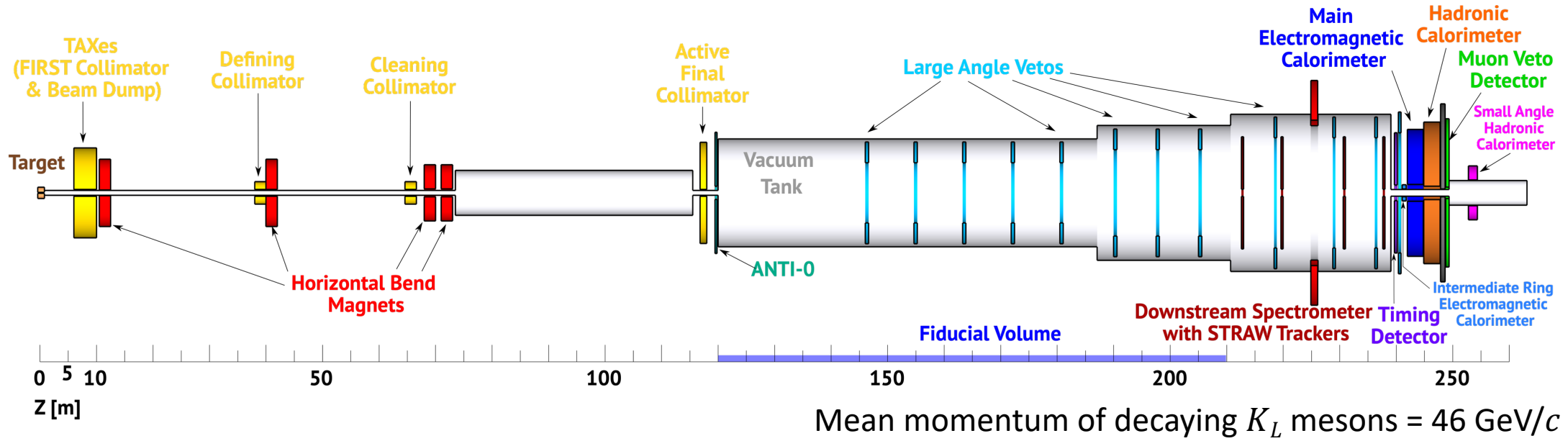
$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma \gamma) = 10^{+8.6}_{-6} \times 10^{-9}$

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



# HIKE design: Phase 2

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

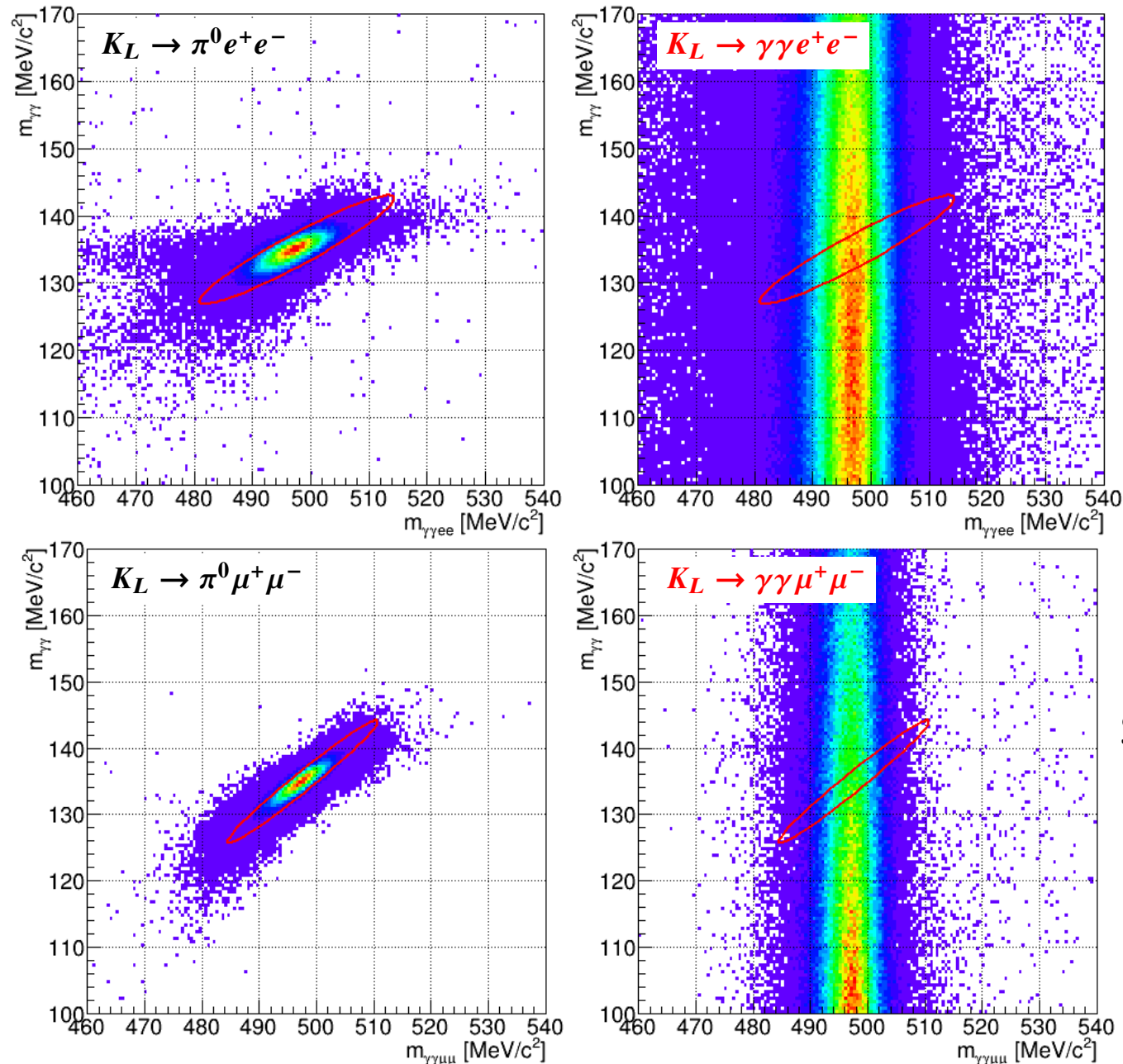


- 120 m long neutral beamline, secondary beam opening angle = 0.4 mrad
- 2.4 mrad production angle
- using detectors of previous phase, with some modifications
- minor modifications to make left/right symmetric and optimize geometrical acceptance. Reduction of dipole-magnet field by about 20%.

Statistical power:

$3.8 \cdot 10^{13}$  Kaon decays in decay volume per year ( $1.2 \cdot 10^{19}$  POT/year)

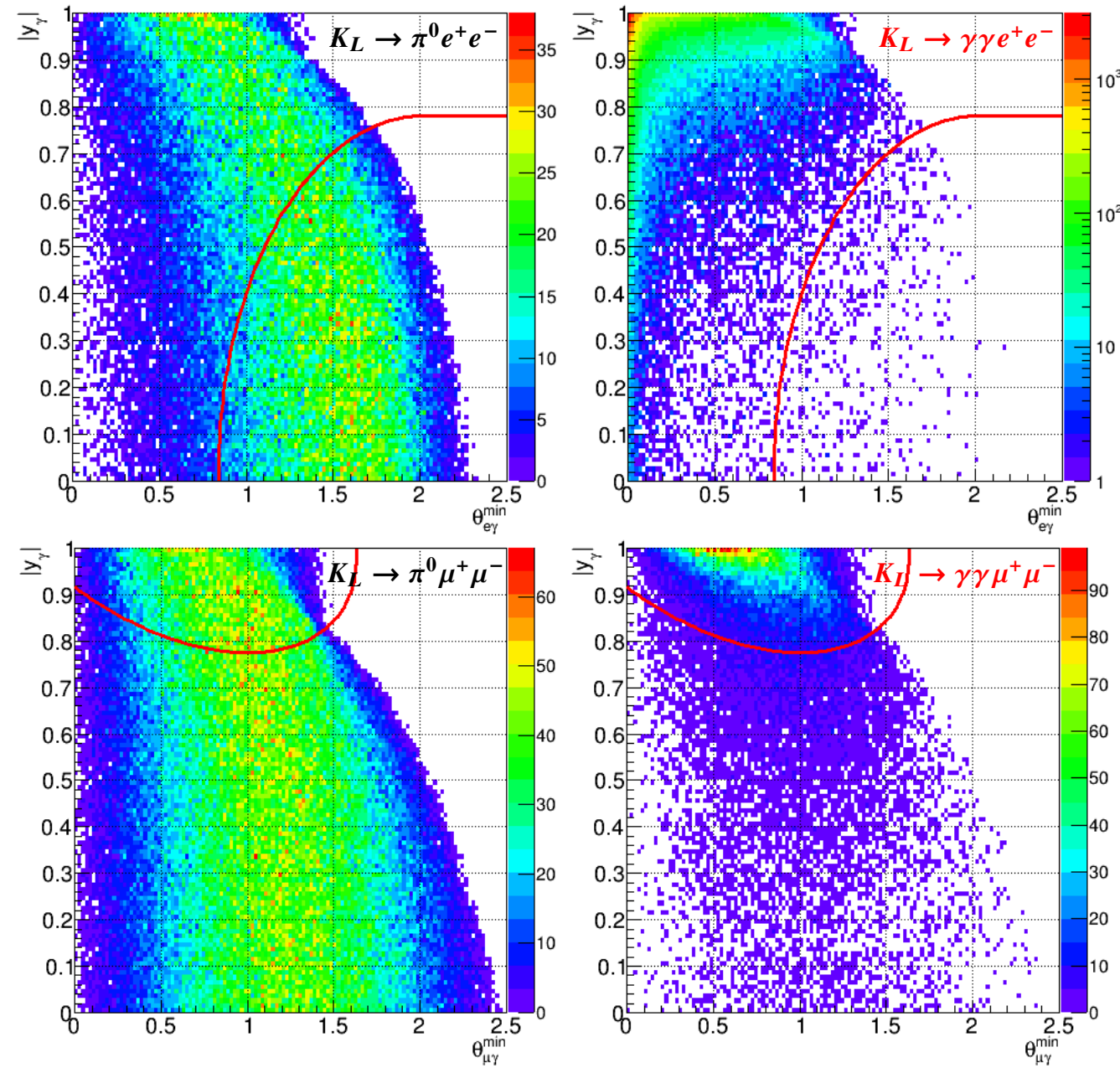
# HIKE Phase 2: signal and background



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

Suppression of the  $K_L \rightarrow \gamma\gamma l^+ l^-$  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

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

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

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

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

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

# HIKE Phase 2: Physics sensitivity

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

First observation, with a significance above  $5\sigma$ , and measurement of both ultra-rare decay modes

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


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

LHCb Phase-I upgrade: form-factor parameter  $a_S$  to 5% relative precision.

Assuming constructive interference, determine the CKM parameter  $\lambda_t$  :

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

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


20% precision on CKM parameter  $\lambda_t$   
Also constrain SD BSM effects in  $\gamma$  coupling



# Kaon Global Fit

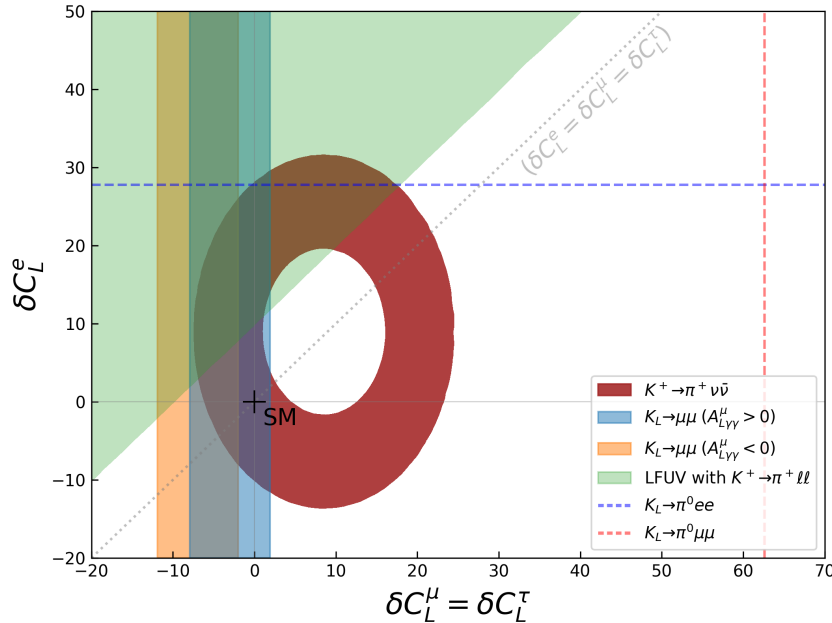
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell \quad O_L^\ell = (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell)$$

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.

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

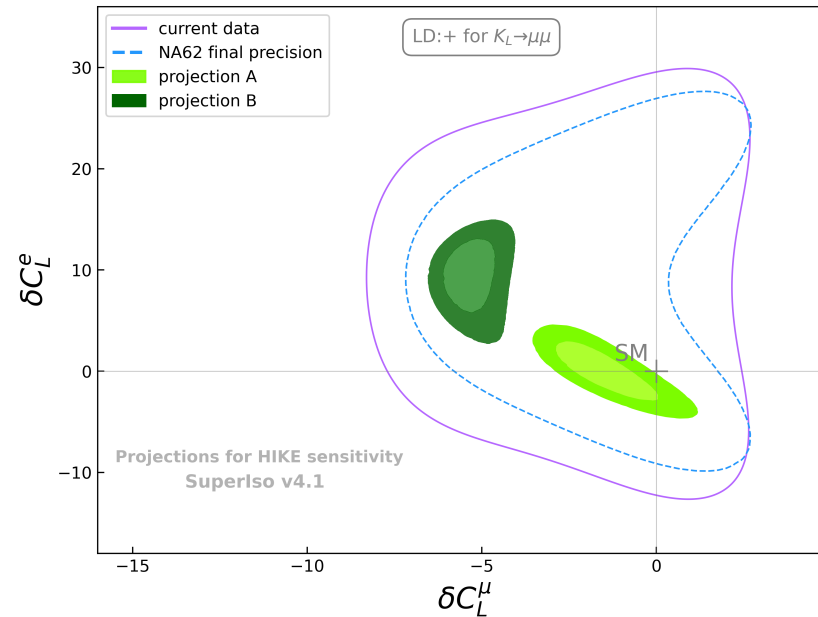
$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

[arXiv:2206.14748]



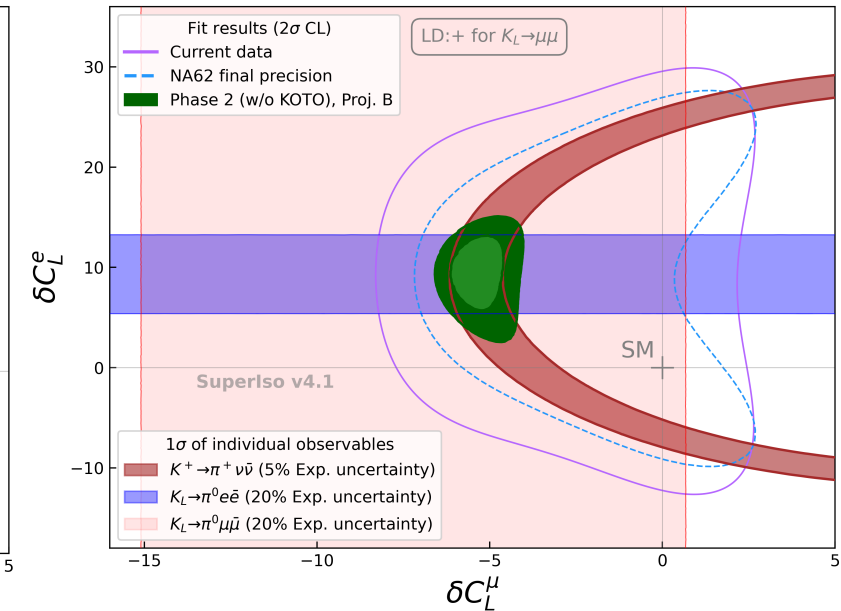
Bounds from individual observables.  
Coloured regions are 68%CL measurements  
Dashed lines are 90%CL upper limits

[arXiv:2207.04956]



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

[arXiv:2311.04878]



# Other physics opportunities: 2 examples

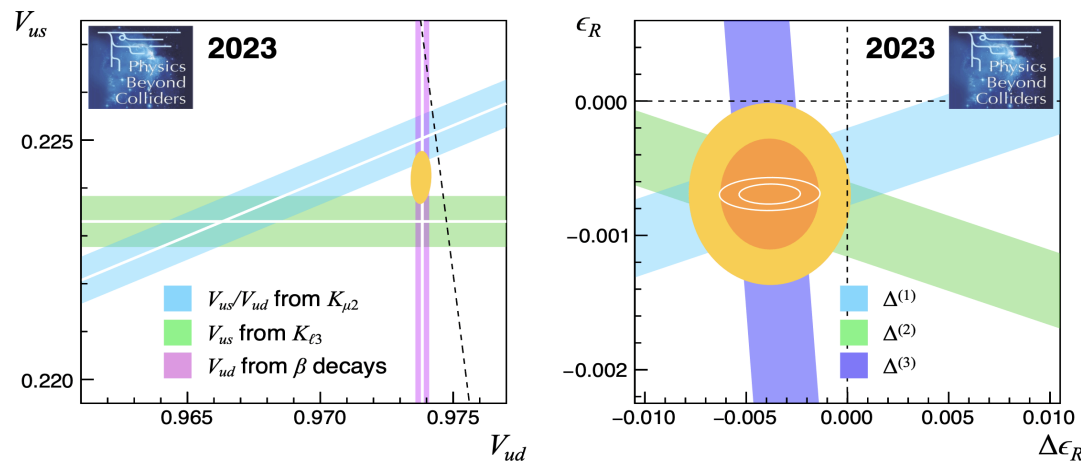
Test of Lepton Universality and Flavour/Number Violation: **sensitivity  $O(10^{-12} - 10^{-13})$**   
in  $K^+$  and  $K_L$  decays

## Cabibbo Angle Anomaly

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

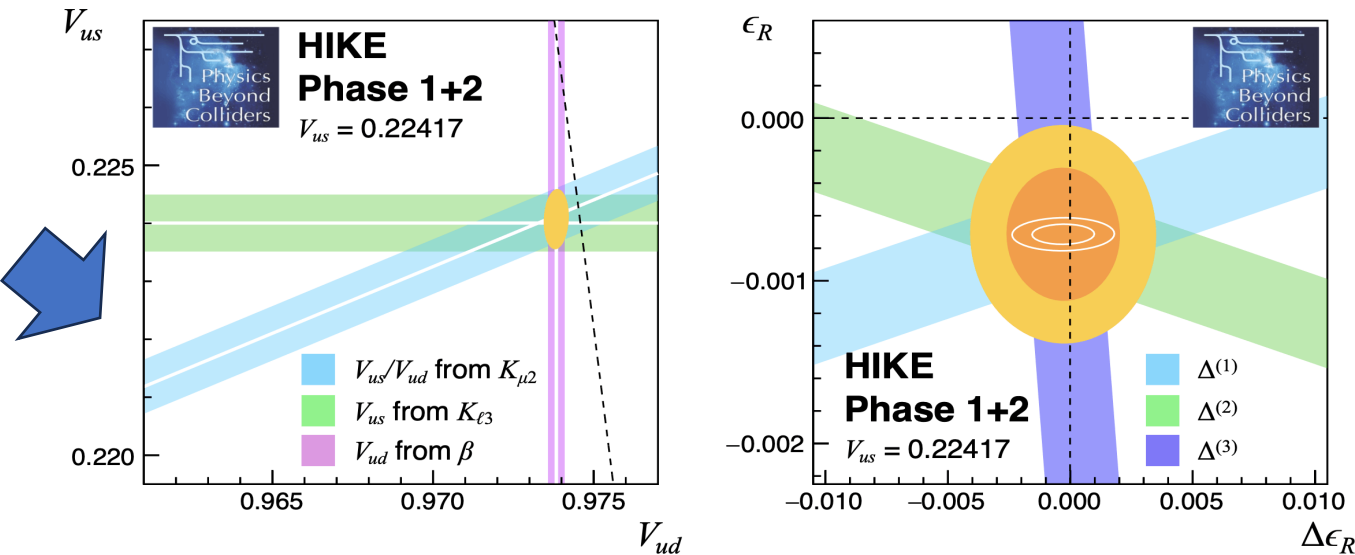
$$|V_{ud}^2| + |V_{us}^2| + |V_{ub}^2| = 0.9985 \pm 0.0005$$

$V_{us}$  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  $k_{\mu 2}$  and  $k_{l 3}$  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





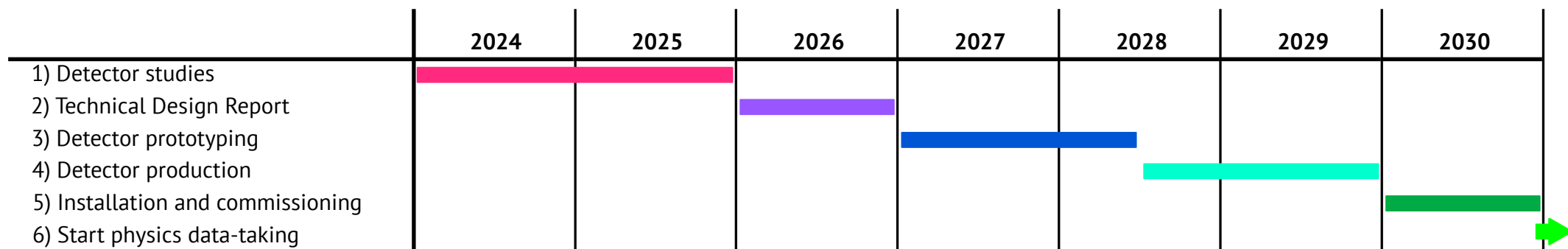
# HIKE Physics Program

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \rightarrow \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \rightarrow \pi^- \ell^+ \ell^+, K^+ \rightarrow \pi \mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic $K^+$ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	$V_{us}$ , CKM unitarity
$R_K = \mathcal{B}(K^+ \rightarrow e^+ \nu)/\mathcal{B}(K^+ \rightarrow \mu^+ \nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary $K^+$ decays (e.g. $K^+ \rightarrow \pi^+ \gamma \gamma, K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$ )	% – % <sub>00</sub>	Chiral parameters (LECs)
$K_L \rightarrow \pi^0 \ell^+ \ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Im $\lambda_t$ to 20% precision, BSM physics, LFUV
$K_L \rightarrow \mu^+ \mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \rightarrow \mu\mu$ physics
$K_L \rightarrow \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic $K_L$ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	$V_{us}$ , CKM unitarity
Ancillary $K_L$ decays (e.g. $K_L \rightarrow \gamma\gamma, K_L \rightarrow \pi^0 \gamma\gamma$ )	% – % <sub>00</sub>	Chiral parameters (LECs), SM $K_L \rightarrow \mu\mu, K_L \rightarrow \pi^0 \ell^+ \ell^-$ rates
Search for FIPs in kaon and dump mode	Sensitivity $\mathcal{O}(10^{-5})$ - $\mathcal{O}(10^{-10})$	BC1,2,4,5,6,7,8,9,10,11

# 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



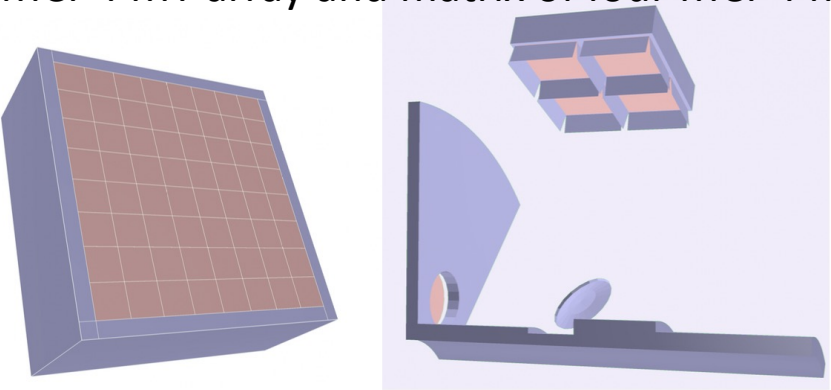
# HIKE: Kaon and Pion identification

(DRD4: photodetectors)

K ID for 4x intensity

- **Max detected photon rate:** >8 MHz/cm<sup>2</sup>
- High granularity
- **Single-photon capability with  $\sigma_t$  (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 $\pi^+$ at 15 GeV/c	7	14
Number of hit for $\pi^+$ at 45 GeV/c	12	24
Time resolution for $\pi^+$ at 15 GeV/c	90 ps	27 ps
Time resolution for $\pi^+$ at 45 GeV/c	70 ps	20 ps

RICH detector using neon at atmospheric pressure

SiPM ➔		3x3 mm <sup>2</sup>	62K	2.3 mm	0.66 mm
		6x6 mm <sup>2</sup>	16K	2.8 mm	0.78 mm
		9x9 mm <sup>2</sup>	7K	3.4 mm	0.95 mm

# HIKE: Tracking

(DRD3: solid state detectors)

	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 <sup>2</sup>	8 MHz/mm <sup>2</sup>
Pixel efficiency	> 99 %	> 99 %
Peak fluence / 1 year [10 <sup>14</sup> 1 MeV n <sub>eq</sub> /cm <sup>2</sup> ]	4	16

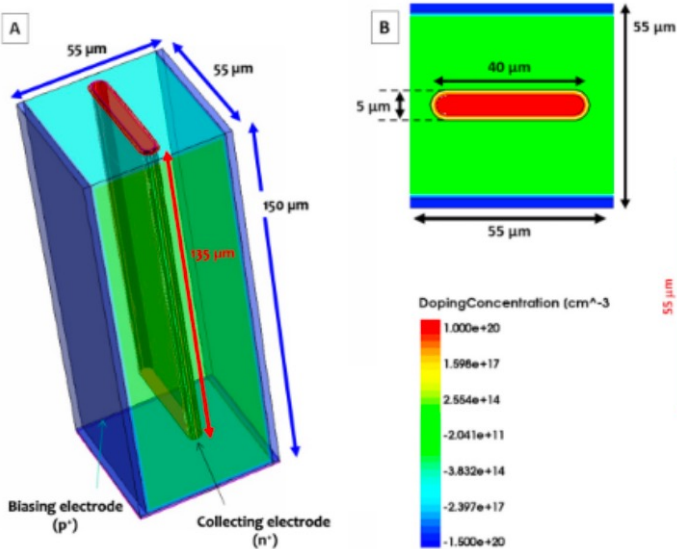
(DRD1: gaseous detectors)

	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 <sub>0</sub>	(1.0 – 1.5)% X <sub>0</sub>
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

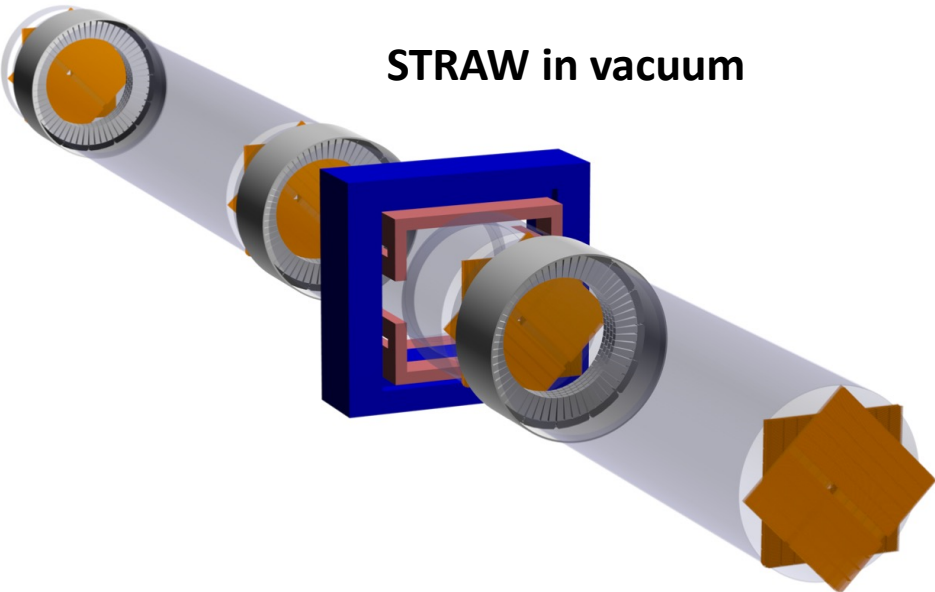
for 4x intensitv

for 4x intensity

TimeSPOT



Hybrid 3D-trenched technology




# Electromagnetic Calorimeter

(DRD6: calorimetry,  
DRD7: electronics)

Main electromagnetic calorimeter requirements:

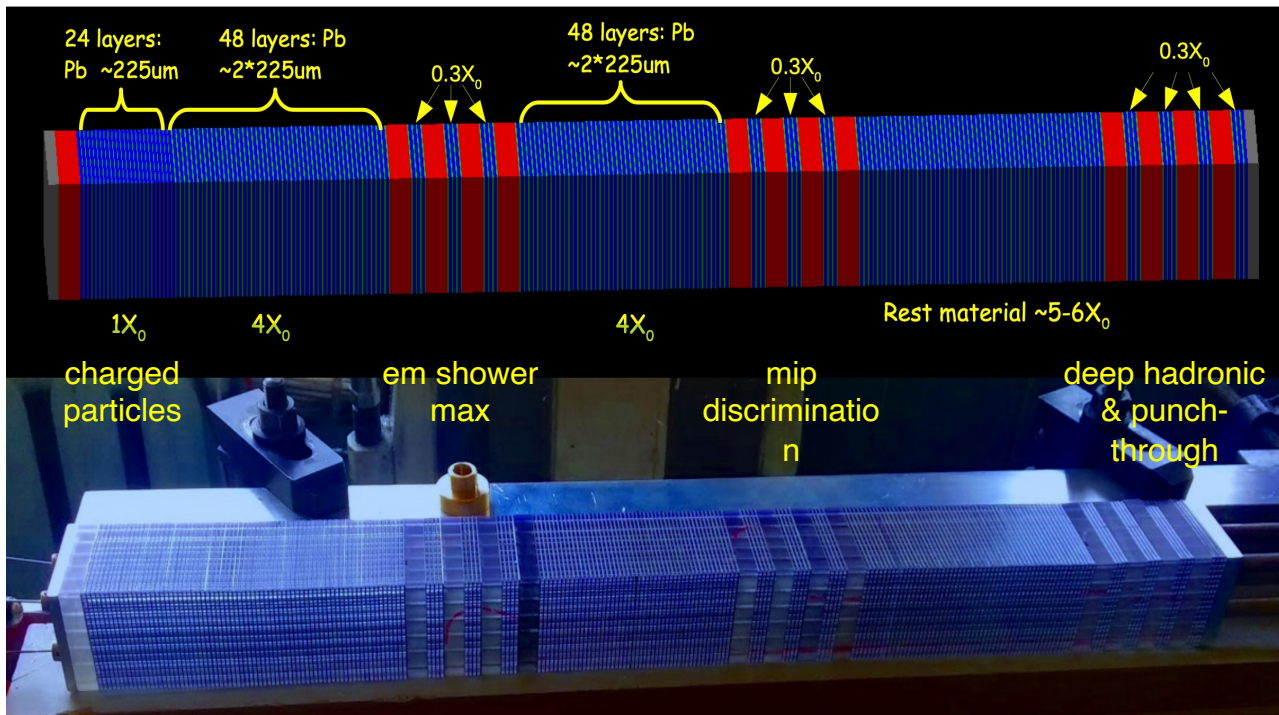
excellent efficiency and time resolution ( $\sim 100\text{ps}$ ), good two-cluster separation, good energy resolution

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

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

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:

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

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

**Thank you for listening !**