An overview of HIKE Phase 1 & 2

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High Intensity Kaon Experiments

Kaons @ CERN workshop – CERN – 12/09/2023

The golden modes

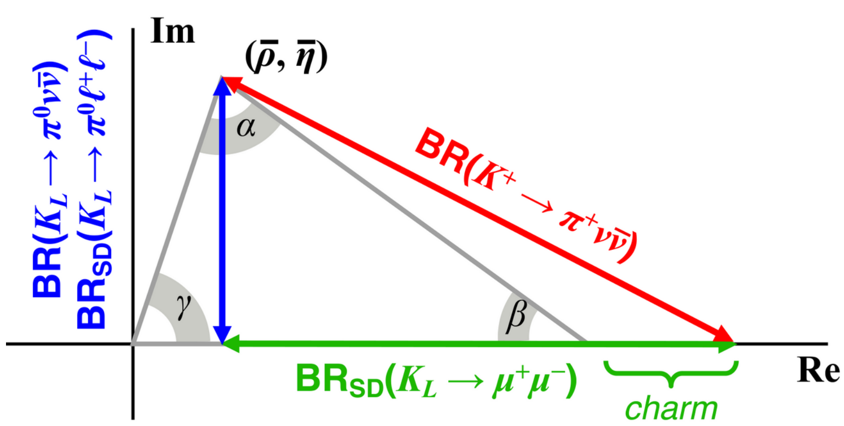
High Intensity Kaon Experiments

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

} high sensitivity to new physics

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.94 ± 0.15	< 200	KOTO	2023
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4	$10.6^{+4.0}_{-3.4} \pm 0.9$	NA62	2021
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000

* approximate error on LD-subtracted rate excluding parametric contributions



$K_L \to \pi^0 \ell^+ \ell^-$ vs $K \to \pi\nu\nu$:

- Larger theoretical uncertainties from LD physics
  - SD CPV amplitude: γ/Z exchange
  - LD indirect CPV amplitude: $K_L \to K_S$
  - LD CPC amplitude from 2γ exchange
- Explore helicity suppression in FCNC decays

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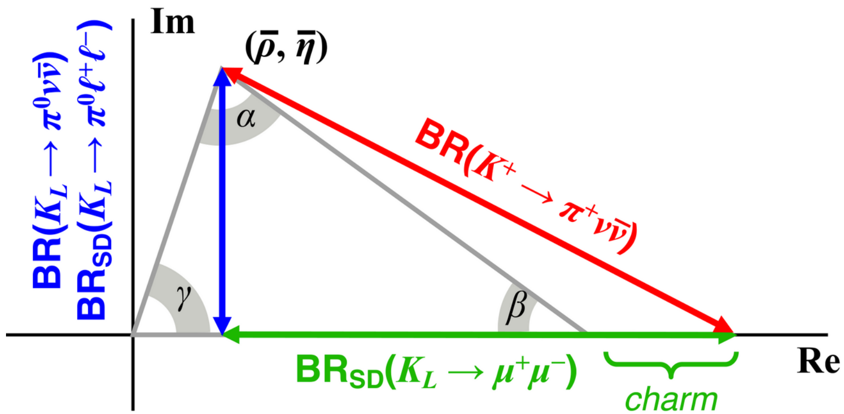


Principal HIKE physics goals:

<u>Phase1:</u>

- Measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at 5% precision
- Lepton universality in $K^+ \to \pi^+ \ell^+ \ell^-$ decays

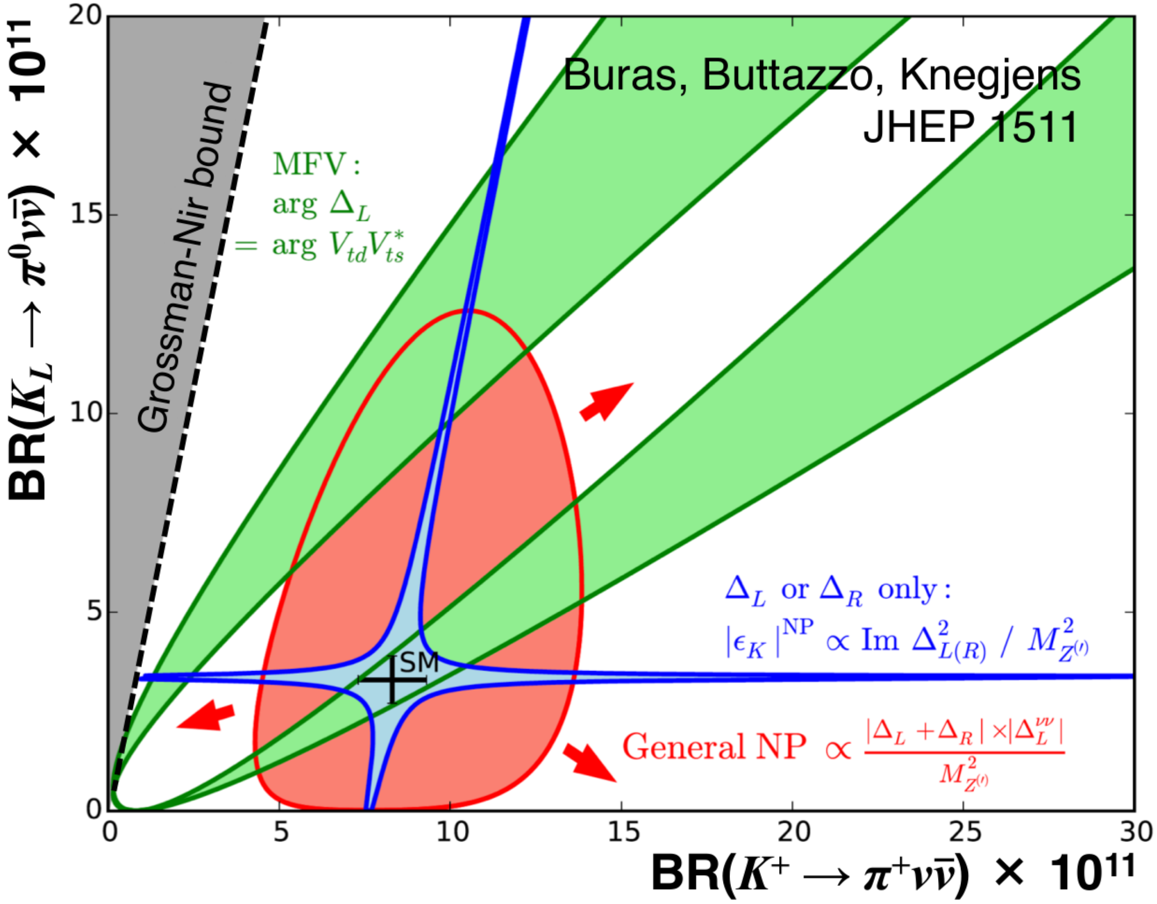
<u>Phase2:</u>

- Measurement of $BR(K_L \to \pi^0 \ell^+ \ell^-)$ at 20% precision

$K \to \pi\nu\bar{\nu}$: new physics scenarios

New physics affects K^+ and K_L BRs differently

Measurements of both can discriminate among NP scenarios



Models with:

- CKM-like flavor structure
  - MFV
- New flavor-violating interactions with dominant LH or RH couplings
  - Z/Z′ with pure LH/RH couplings
  - Littlest Higgs with T parity
- None of the above constraints
  - Randall-Sundrum

Grossman-Nir bound

Model-independent relation

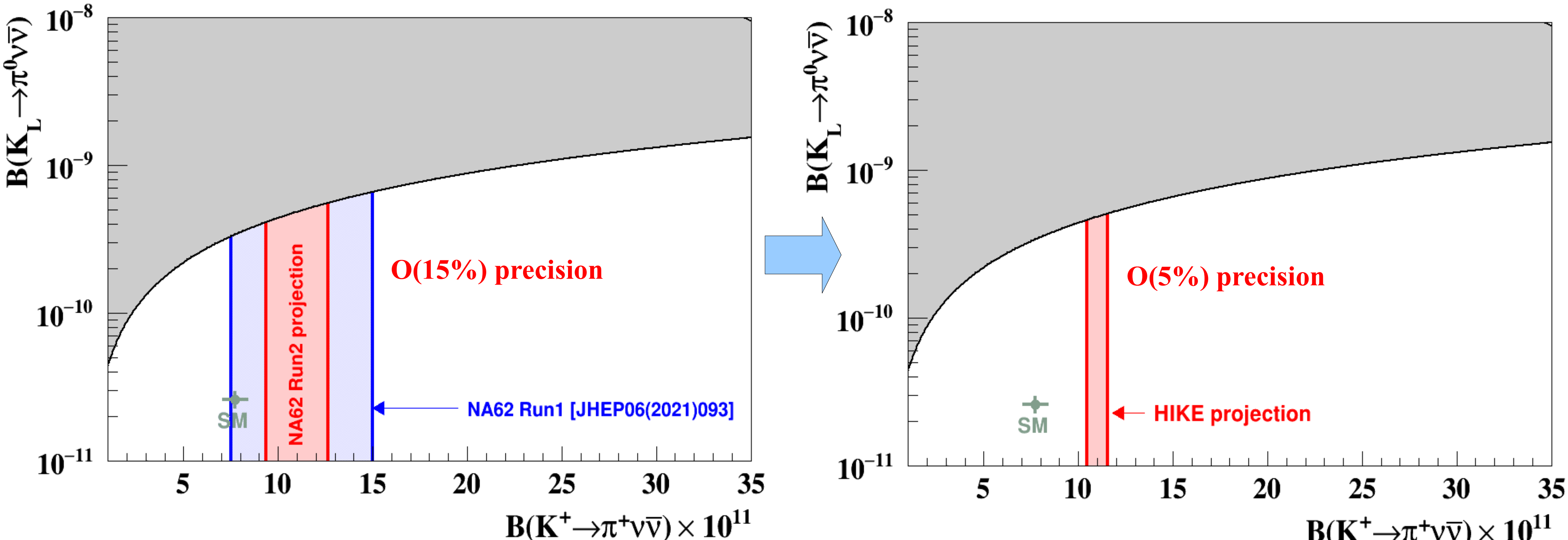
$$\frac{\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})}{\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

$K^+ \to \pi^+ \nu\bar{\nu}$ @ HIKE: physics reach

High Intensity Kaon Experiments

Measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$): precision test of the Standard Model

Model-independent standard candle constraining many BSM scenarios, present or future



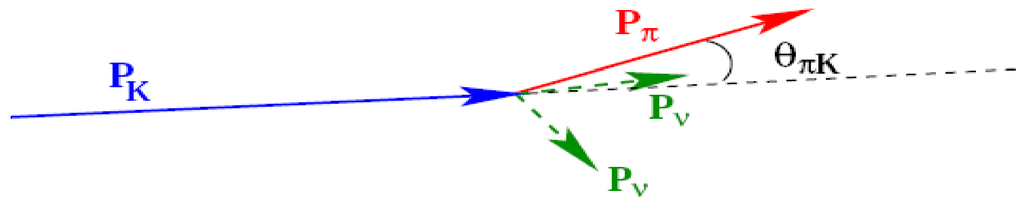
[SM: arXiv:2105.02868v1]

From NA62 to HIKE: precision on BR($K^+ \to \pi^+ \nu\bar{\nu}$) improved by 3x!

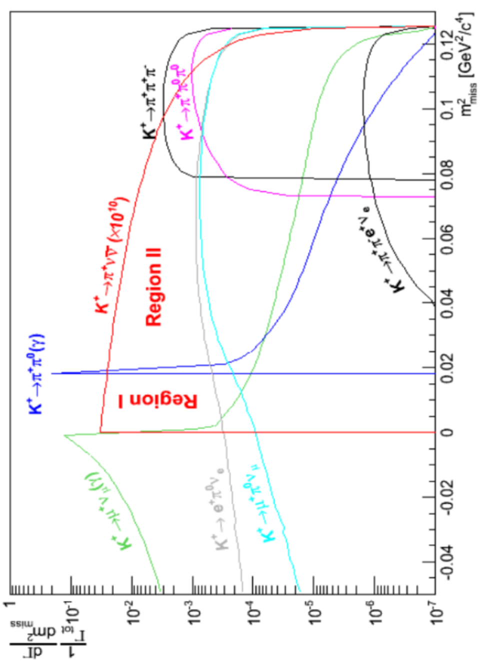
$K^+ \rightarrow \pi^+ \nu\bar{\nu}$: decay-in-flight technique

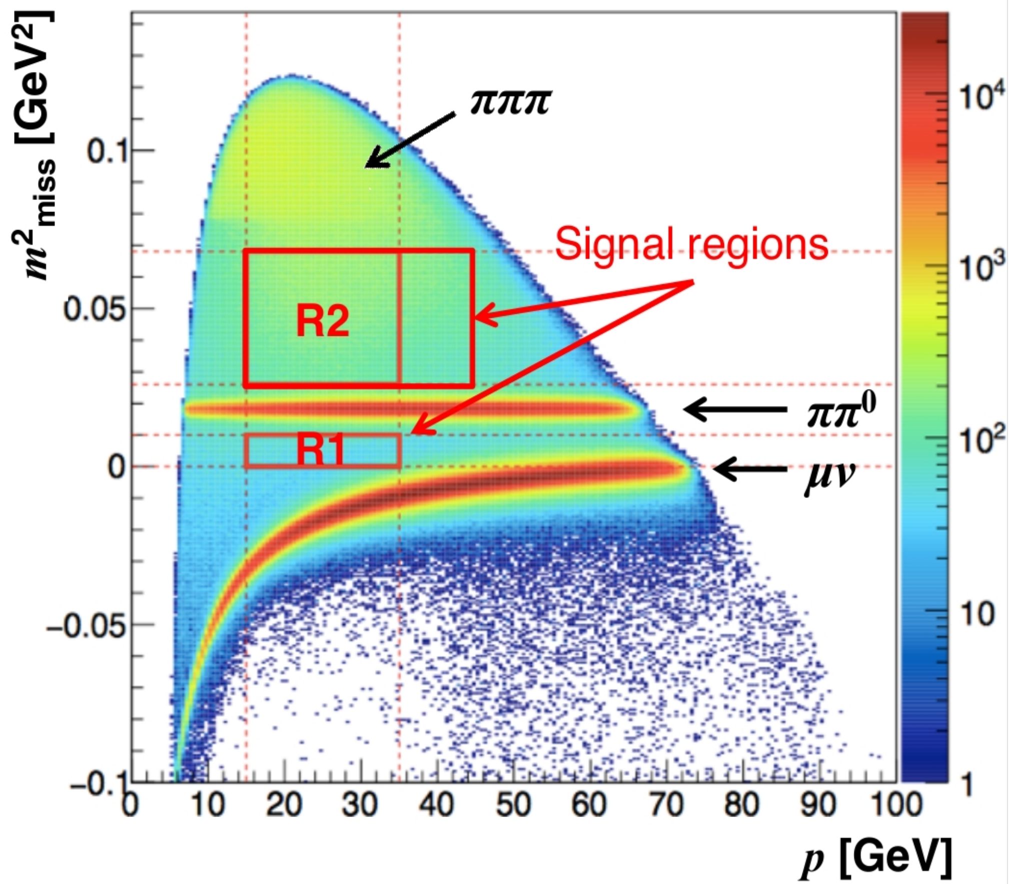
The NA62 decay-in-flight technique is now well established!

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ 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($K^+ \rightarrow \mu^+\nu$) = 63.5%
BR($K^+ \rightarrow \pi^+\pi^0$) = 20.7%

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

Background rejection at ~ 10^{11} level

See Augusto's talk from yesterday for details on NA62!

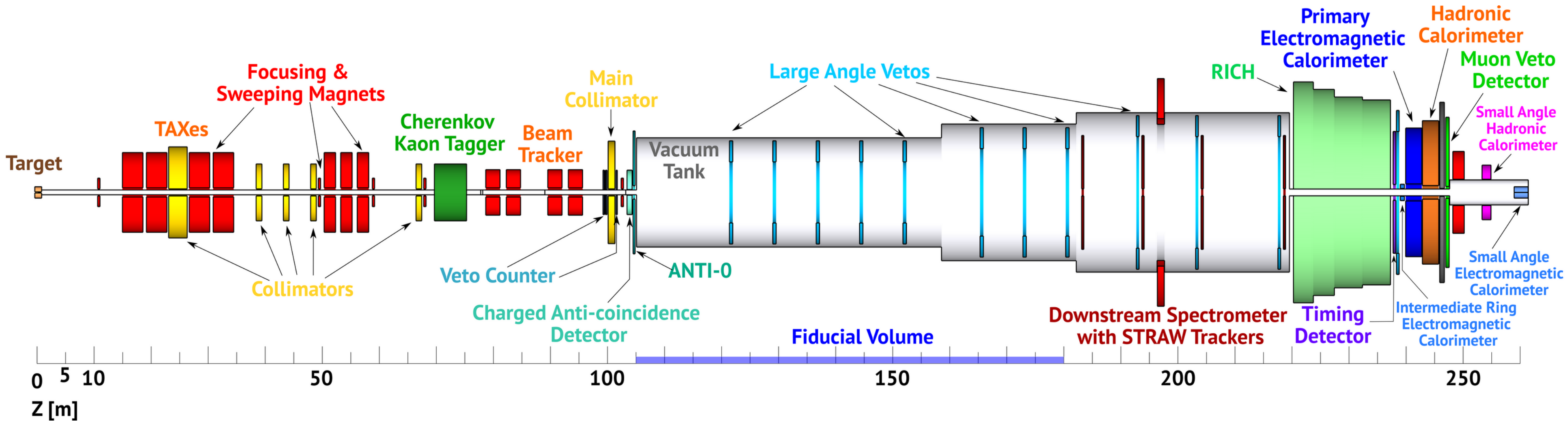
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN: HIKE-Phase1

→ Max possible intensity in HIKE-Phase1 (after major beamline upgrades):

1.2×10^{13} POT / spill = 4x NA62 max beam intensity

Statistical power: 2×10^{13} Kaon decays in decay volume per year (7×10^{18} POT / year)

NA62-like design of experiment will work at high intensity



<u>HIKE-Phase1 improvements wrt NA62:</u>

– **Improved timing is the crucial element** to be able to stand the intensity increase
– **Equal or better key performances** at high-rate to keep background under control [e.g. kinematic rejection, photon rejection, PID]
– Up to x2 **increase in signal acceptance** thanks to new, more granular/performant detectors [higher efficiency in K-π association, PID, kinematic rejection] & fully-software trigger
– Further **suppress dominant background** from upstream K^+ decays

$K^+ \to \pi^+ \nu \bar{\nu}$ at CERN: HIKE-Phase1

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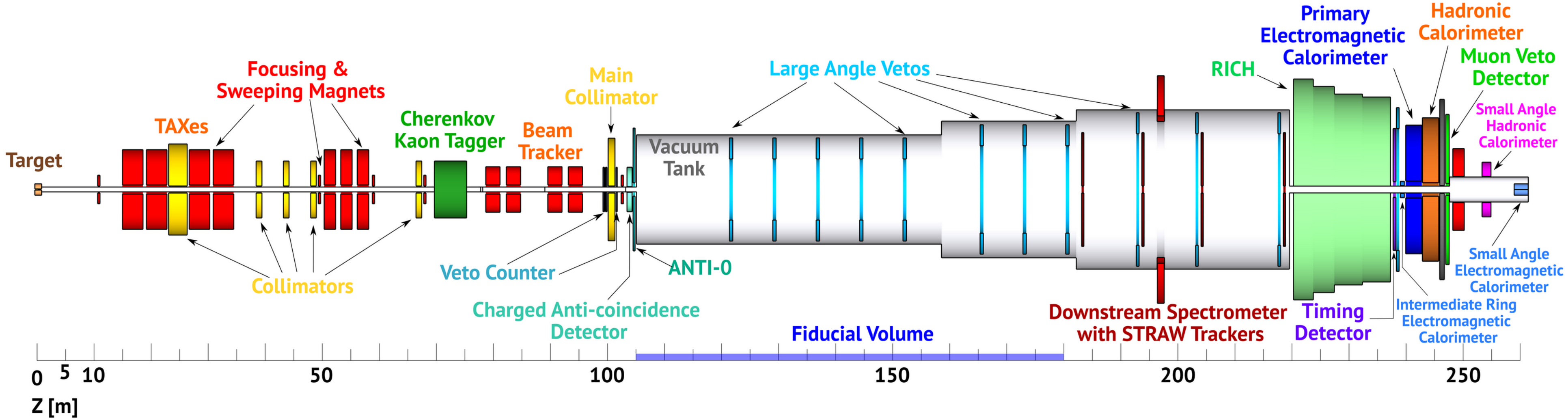
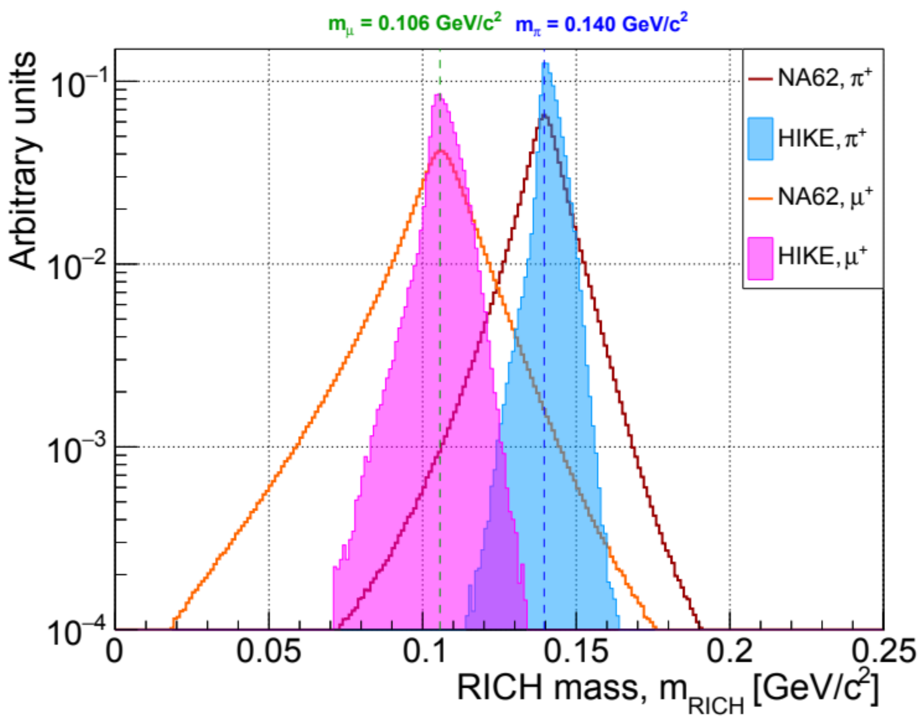


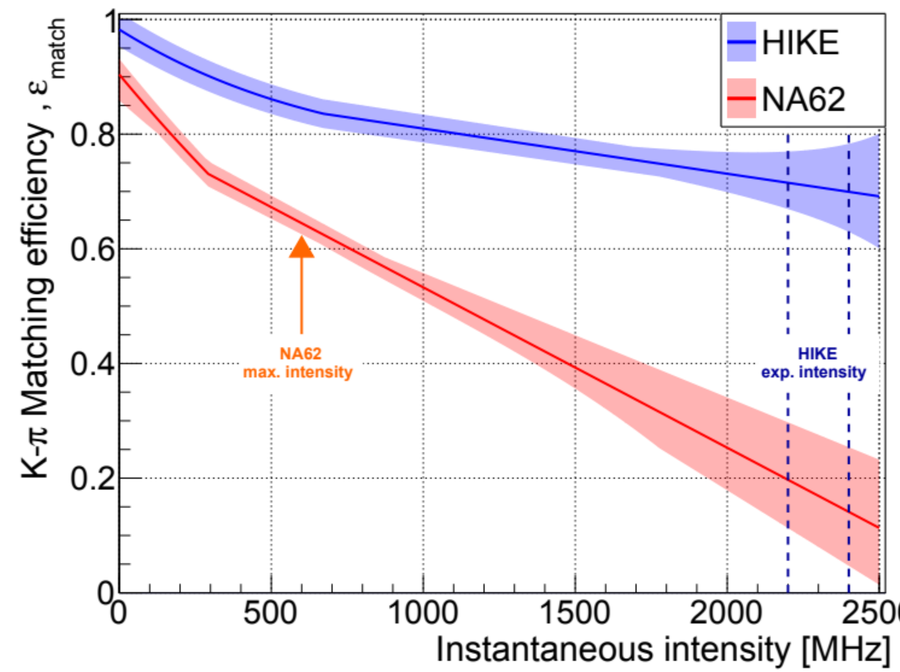
Technological solutions exists for all detectors

Synergies with Hi-Lumi LHC projects and next generation flavor/dark matter experiments

- Next-generation **silicon detectors** for beam spectrometer
- Design studies in progress for downstream spectrometer with **5-mm diameter** straws

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





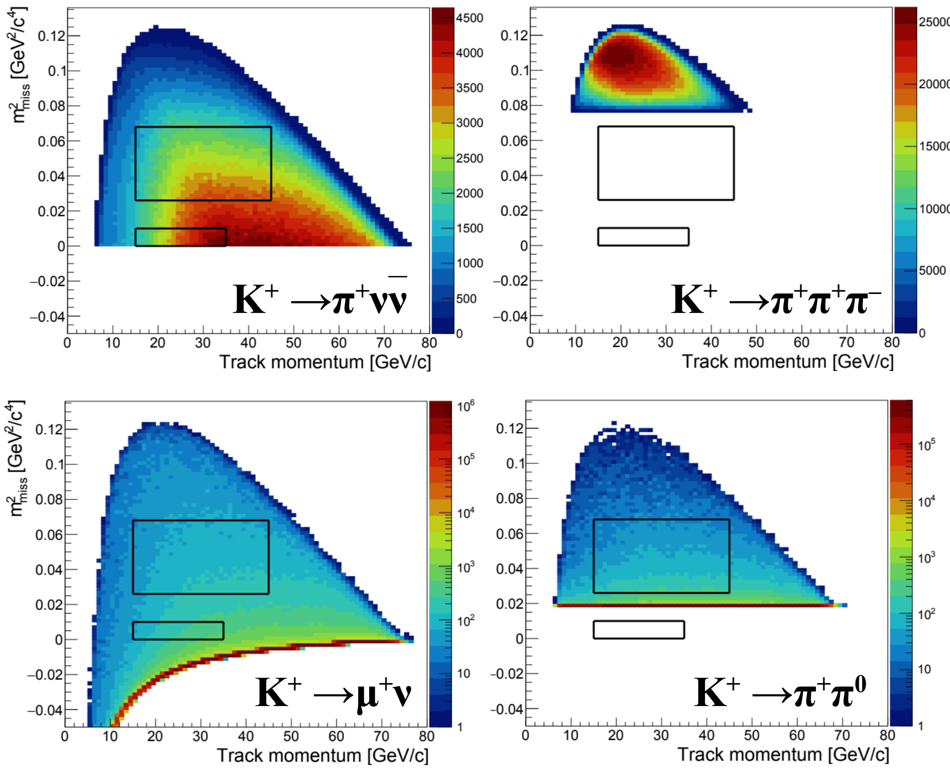
RICH PID for π with 15 < p < 45 GeV/*c*.
RICH granularity increased
+ better photodetectors (x2 Quantum Efficiency, time resolution: 300→100ps)
→ Improved photon yield and time resolution

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

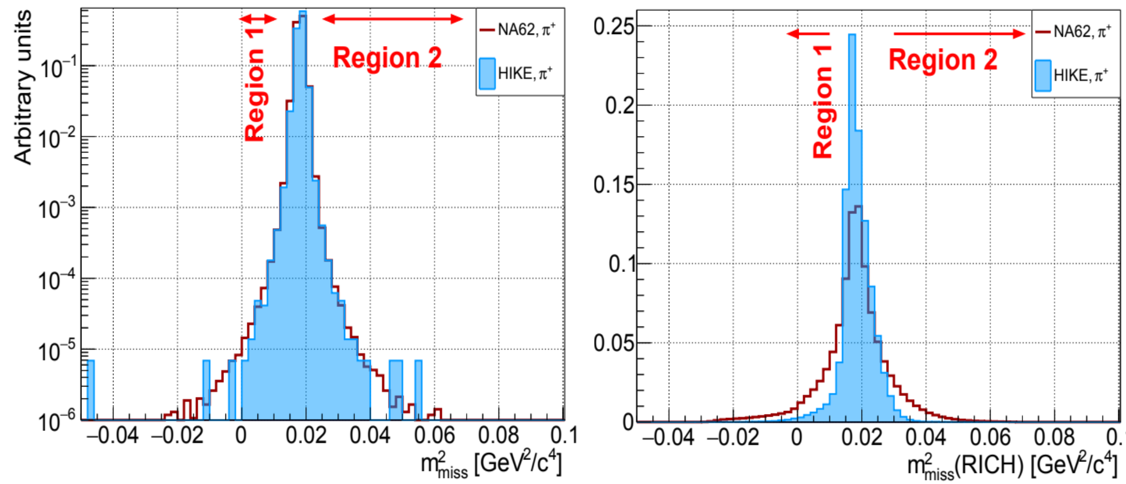
<u>HIKE:</u>
- π ID efficiency: > 10% higher than NA62, keeping same μ/π misID probability.
- K–π efficiency: ~ 10% higher than NA62. K-π misID probability ~2%, similar to NA62.

$K^+ \to \pi^+ \nu\bar{\nu}$ @ HIKE: Kinematics

Simulated m^2_{miss} distribution vs momentum



m^2_{miss} distribution for $K^+ \to \pi^+\pi^0$



NA62 MC extensively validated with data.

Main kaon decay modes enter the signal regions via resolution tails in the reconstructed value of m^2_{miss}

- Signal regions determined by resolution
- Slightly better m^2_{miss} resolution at HIKE wrt NA62 (40% less material budget in STRAW spectrometer)
- Missing mass with RICH much improved

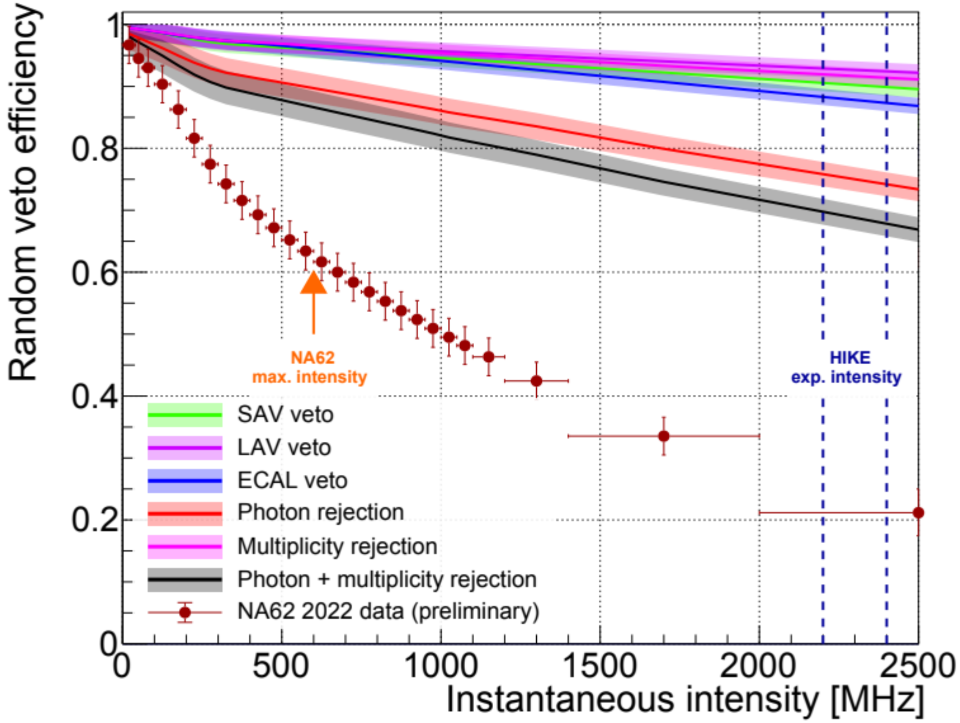
HIKE signal regions can be optimised:
signal acceptance 10% higher than NA62, keeping same level of kinematic rejection

$K^+ \to \pi^+ \nu\bar{\nu}$ @ HIKE: Random veto

Criteria to veto photons and extra activity in-time + pileup = intensity-dependent signal loss
Critical performance indicator: "random veto efficiency", measured on data (with $K^+ \to \mu^+\nu$)

<u>NA62:</u>

- Signal selection efficiency ~ 65% at max beam intensity
- Quasi-linear dependence on the instantaneous beam intensity.
- Limiting factor: timing precision of the detectors (and double pulse resolution).



<u>HIKE:</u> 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

$K^+ \to \pi^+ \nu\bar{\nu}$ @ HIKE: Physics sensitivity

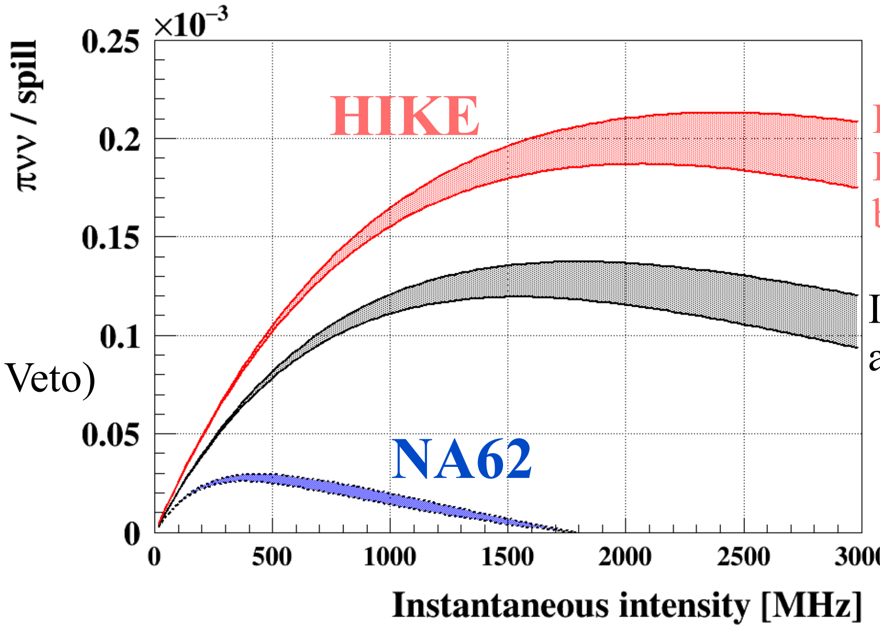
HIKE High Intensity Kaon Experiments

Signal intensity dependence:

Dead-time-equivalent paralyzable model accounting for intensity dependence of the trigger, DAQ, and all selection criteria (except Random Veto)

×

Polynomial description of the random veto efficiency



Background from K decays to remain the same fraction of signal

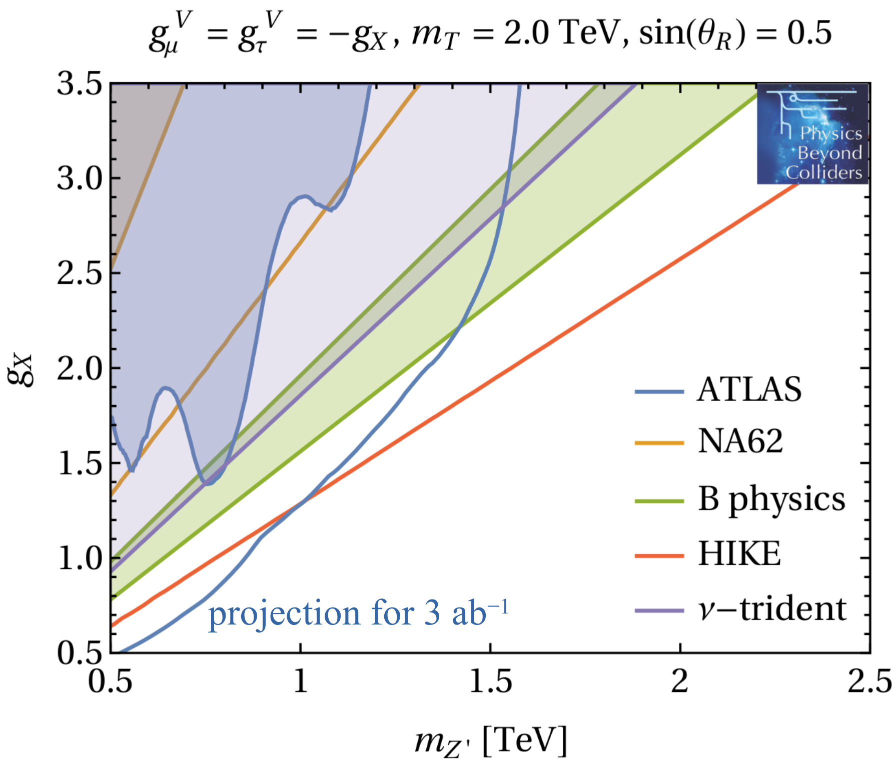
Improved coverage and design of upstream background veto
→ Upstream background reduced to same level as K background

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

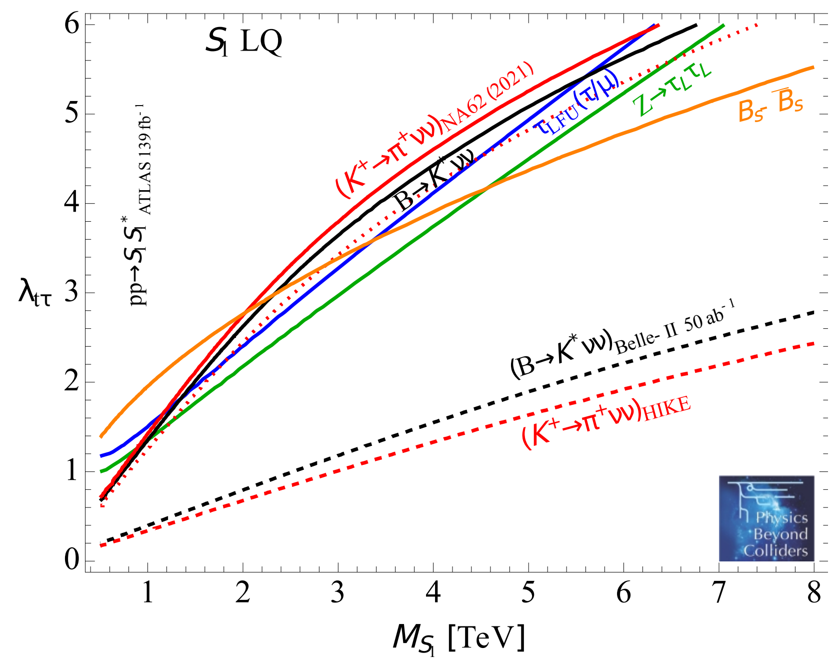
With background contamination and systematic uncertainty under control, measurement of **BR($K^+ \to \pi^+ \nu\bar{\nu}$) at O(5%) precision in 4 years** of data-taking

$K^+ \to \pi^+ \nu\bar{\nu}$ @ HIKE: specific models

[CERN Physics Beyond Colliders Document, in preparation]



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



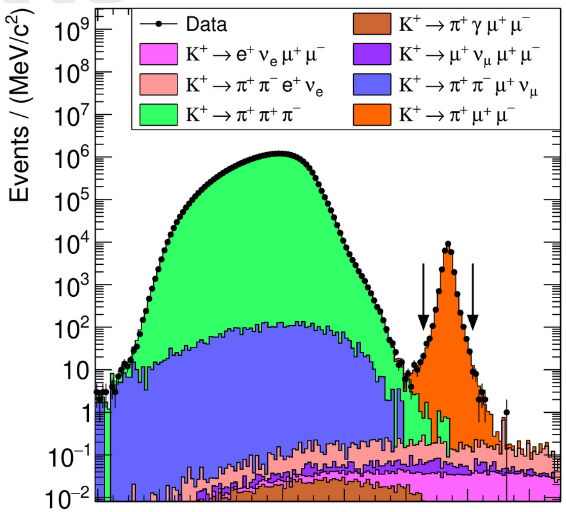
Leptoquark model: (revisited by D.Marzocca)

Constraints on a top-philic Z’, on mass vs gauge coupling [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.

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].

HIKE-Phase1: $K^+ \to \pi^+ \ell^+ \ell^-$ decays

NA62 JHEP11 (2022) 011



Long-distance (LD) dominated, mediated by $K^+ \to \pi^+ \gamma^*$

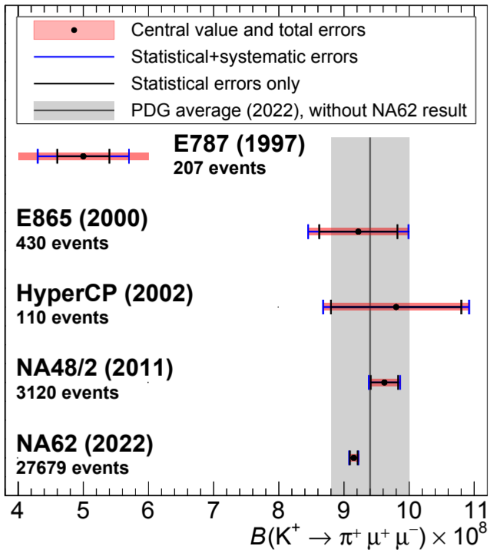
$$d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

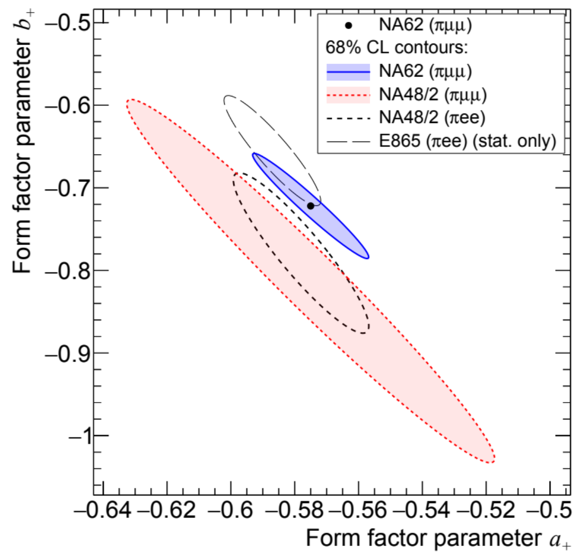
$z = m(l^+l^-)^2/M_K^2$ — Form factors (FF) (non pert. QCD) — $K_{3\pi}$ loop term

LD effects are purely lepton universal (same **a** & **b** for ℓ = e, μ).

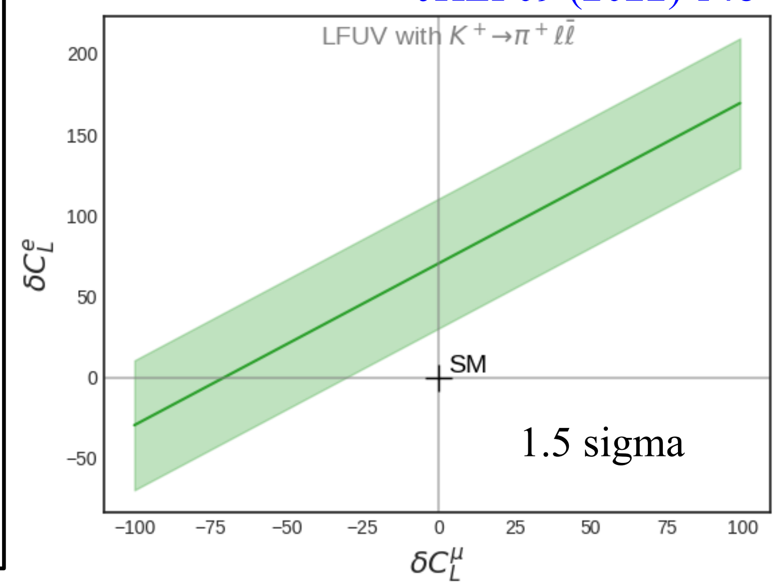
$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$$ PRD93 (2016) 074038

$\mathbf{a_+^{\mu\mu} - a_+^{ee}}$ is sensitive to LFUV in short-distance contributions





JHEP09 (2022) 148



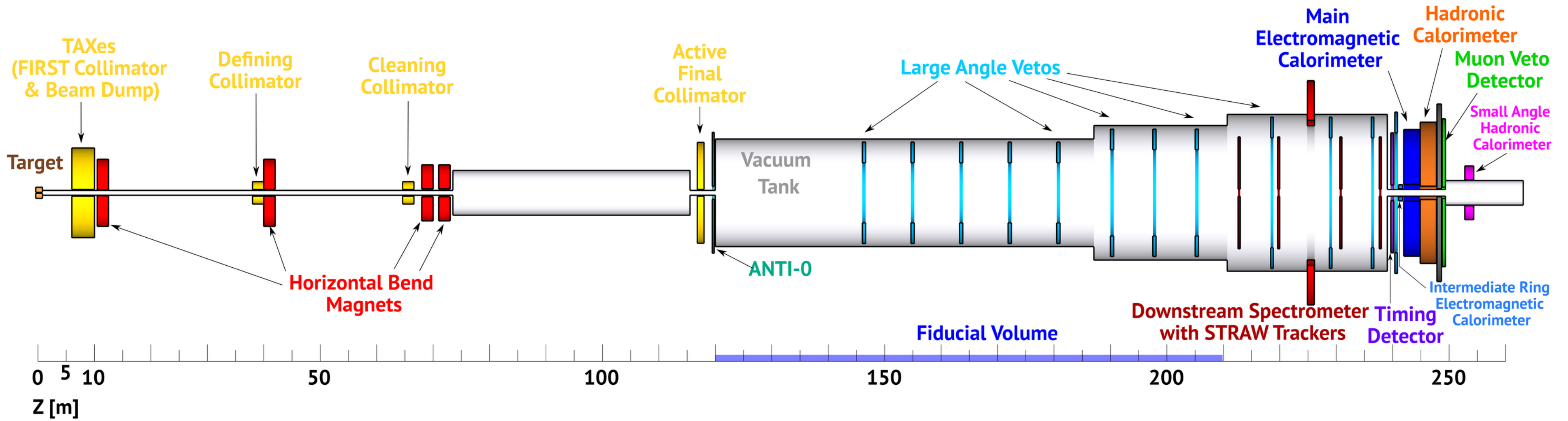
HIKE-Phase1: >2x increased precision on $a_+^{\mu\mu} - a_+^{ee}$ measurement

$K_L \rightarrow \pi^0 \ell^+ \ell^-$ at CERN: HIKE-Phase2

A multi-purpose K_L decay experiment focussed on $K_L \rightarrow \pi^0 \ell^+ \ell^-$ decays

→ Max possible intensity in HIKE-Phase2: **2 ×10^{13} POT / spill**

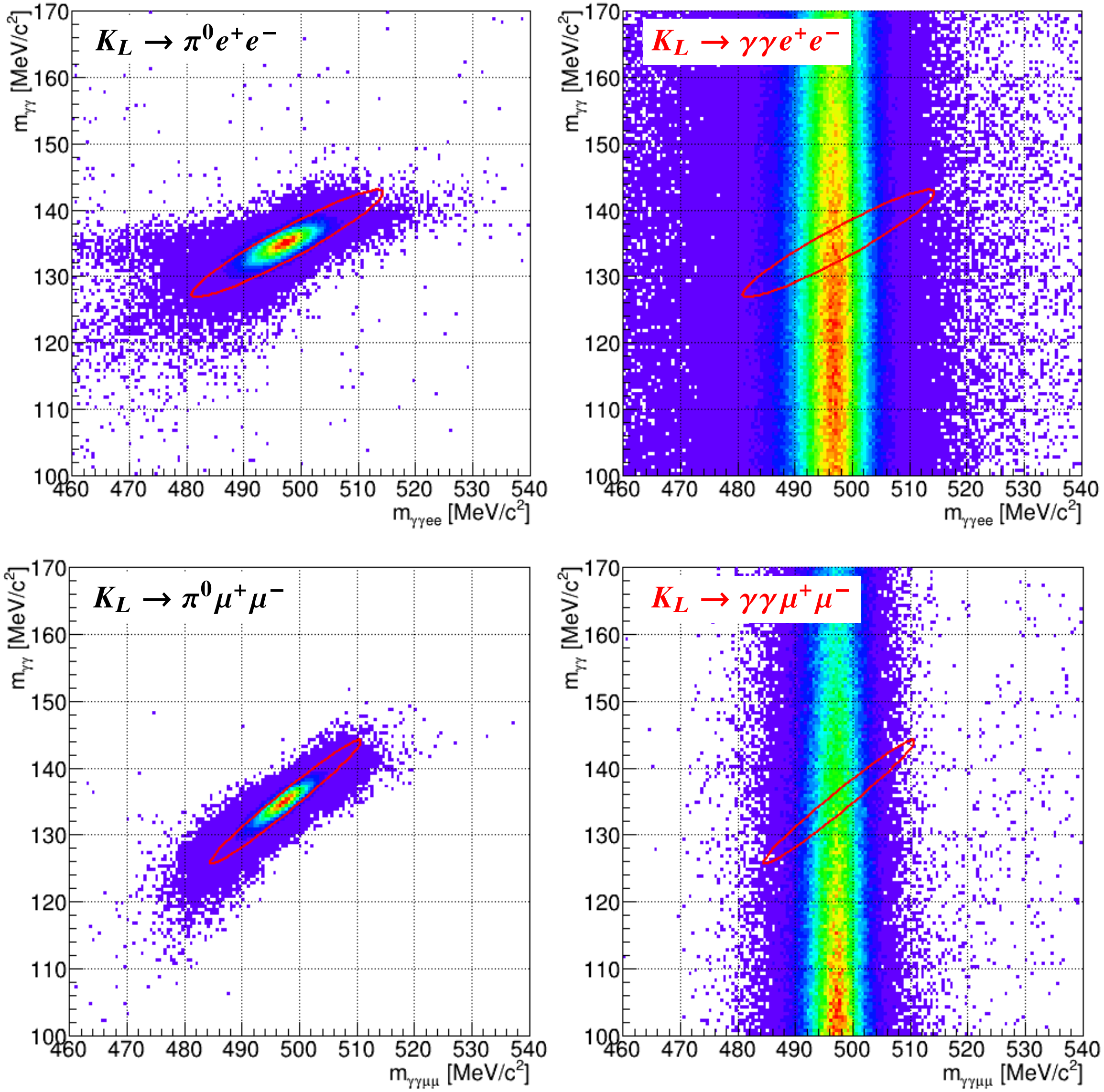
Statistical power: 3.8×10^{13} Kaon decays in decay volume per year (1.2×10^{19} POT / year)



- 120 m long neutral beamline:
  - Secondary beam opening angle = 0.4 mrad; 2.4 mrad production angle
  - Mean momentum of decaying K_L mesons = 46 GeV/c
- Reconfigured HIKE-Phase1 detector:
  - Kaon tagger, beam spectrometer, RICH, small-angle calorimeter removed
  - STRAW spectrometer shortened, chambers realigned

HIKE-Phase2: signal & background

Main background: $K_L \rightarrow \gamma\gamma\ell^+\ell^-$ [Greenlee, PRD42 (1990)]

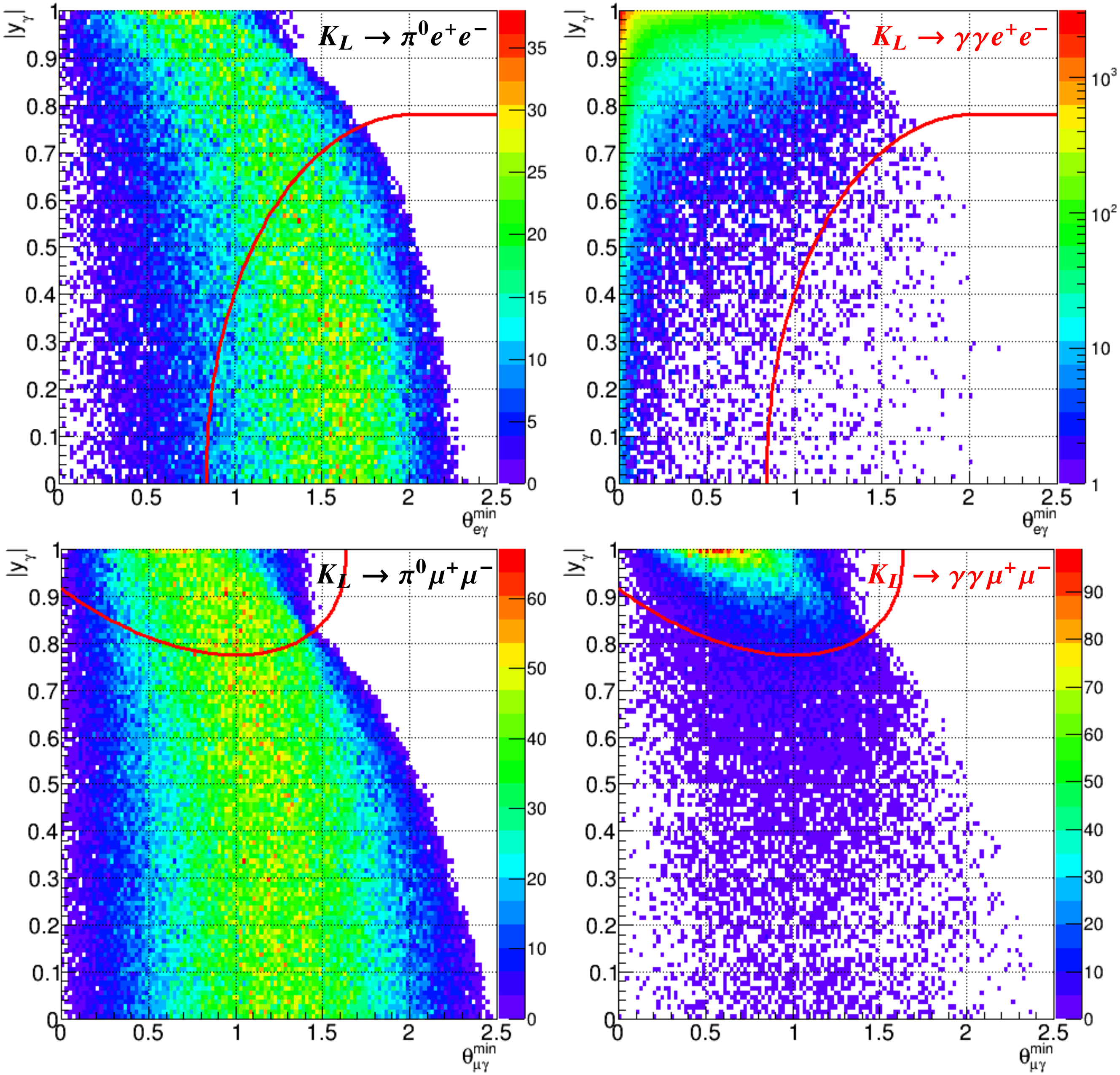


Mode	Phase space region	Branching ratio
$K_L \rightarrow \gamma\gamma e^+ e^-$	$x = (m_{ee}/m_K)^2 > 0.05$, $x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.55 \pm 0.05) \times 10^{-7}$
$K_L \rightarrow \gamma\gamma \mu^+ \mu^-$	$x_\gamma = (m_{\gamma\gamma}/m_K)^2 > 0.01$	$(1.49 \pm 0.28) \times 10^{-9}$

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

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

HIKE-Phase2: 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

HIKE-Phase2: 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 @ > 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

HIKE: many flavour observables

HIKE: rare K^+ and K_L decay programme to an unprecedented level of precision

$K^+ \to \pi^+ \nu\bar{\nu}$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 5\%$	BSM physics, LFUV
$K^+ \to \pi^+ \ell^+ \ell^-$	Sub-% precision on form-factors	LFUV
$K^+ \to \pi^- \ell^+ \ell^+$, $K^+ \to \pi\mu e$	Sensitivity $\mathcal{O}(10^{-13})$	LFV / LNV
Semileptonic K^+ decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
$R_K = \mathcal{B}(K^+ \to e^+\nu)/\mathcal{B}(K^+ \to \mu^+\nu)$	$\sigma(R_K)/R_K \sim \mathcal{O}(0.1\%)$	LFUV
Ancillary K^+ decays (e.g. $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$)	% – ‰	Chiral parameters (LECs)
$K_L \to \pi^0 \ell^+ \ell^-$	$\sigma_{\mathcal{B}}/\mathcal{B} < 20\%$	Imλ_t to 20% precision, BSM physics, LFUV
$K_L \to \mu^+\mu^-$	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 1\%$	Ancillary for $K \to \mu\mu$ physics
$K_L \to \pi^0(\pi^0)\mu^\pm e^\mp$	Sensitivity $\mathcal{O}(10^{-12})$	LFV
Semileptonic K_L decays	$\sigma_{\mathcal{B}}/\mathcal{B} \sim 0.1\%$	V_{us}, CKM unitarity
Ancillary K_L decays (e.g. $K_L \to \gamma\gamma$, $K_L \to \pi^0\gamma\gamma$)	% – ‰	Chiral parameters (LECs), SM $K_L \to \mu\mu$, $K_L \to \pi^0\ell^+\ell^-$ rates

HIKE: Kaon Global fit

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

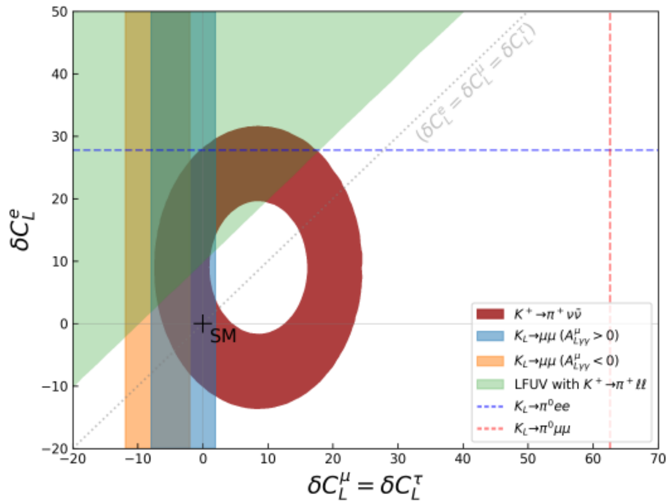
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\lambda_t^{sd}\frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell$$

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

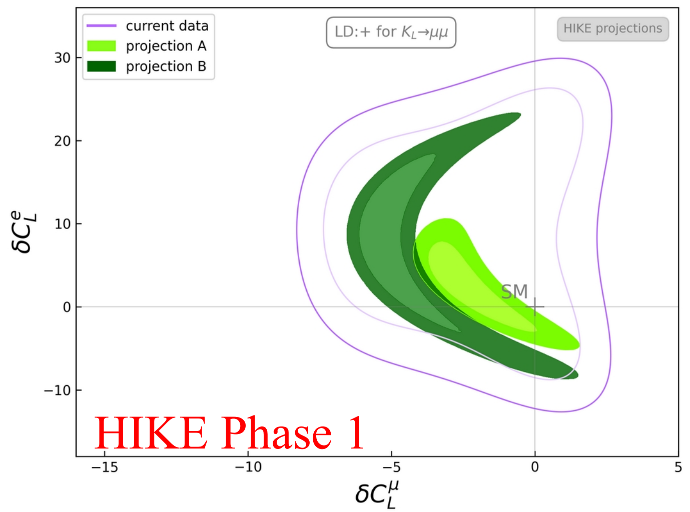
$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu(1-\gamma_5)\,\nu_\ell)$$

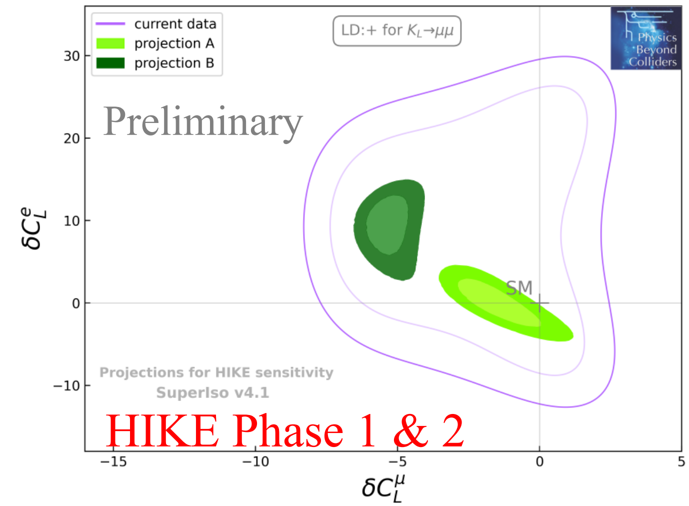
[CERN Physics Beyond Colliders Document in preparation, and paper in preparation by D'Ambrosio, Mahmoudi, Neshatpour]

[arXiv:2206.14748]



[arXiv:2206.14748]





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

Projections assumptions:
A: central value for existing measurements kept the same + SM expectation used for measurement with upper bounds
B: central value of all observables is projected to the best-fit points obtained from fits to existing data

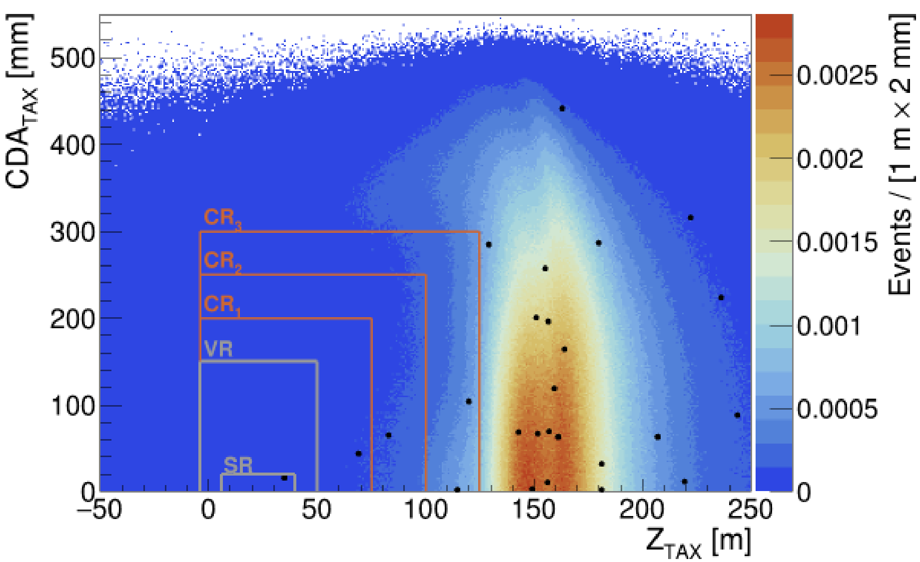
Feebly-interacting particles @ HIKE

HIKE: Fixed-target configuration, long decay volume
→ suitable to **search for FIPs, in kaon and beam-dump**

Search for FIP production in **kaon mode**: $K^+ \to \ell^+ N$, $K^+ \to \pi^+ X$, …
(for details, see Evgueni's talk from yesterday)

Dump mode: most sensitive to forward processes, complementary to off-axis experiment SHADOWS.
An ad-hoc setting of the dipoles allows a substantial reduction of the rate of muons emitted by pion decays in the proton-induced hadronic showers in the TAX.

$\mu^+ \mu^-$ [arXiv: 2303.08666]

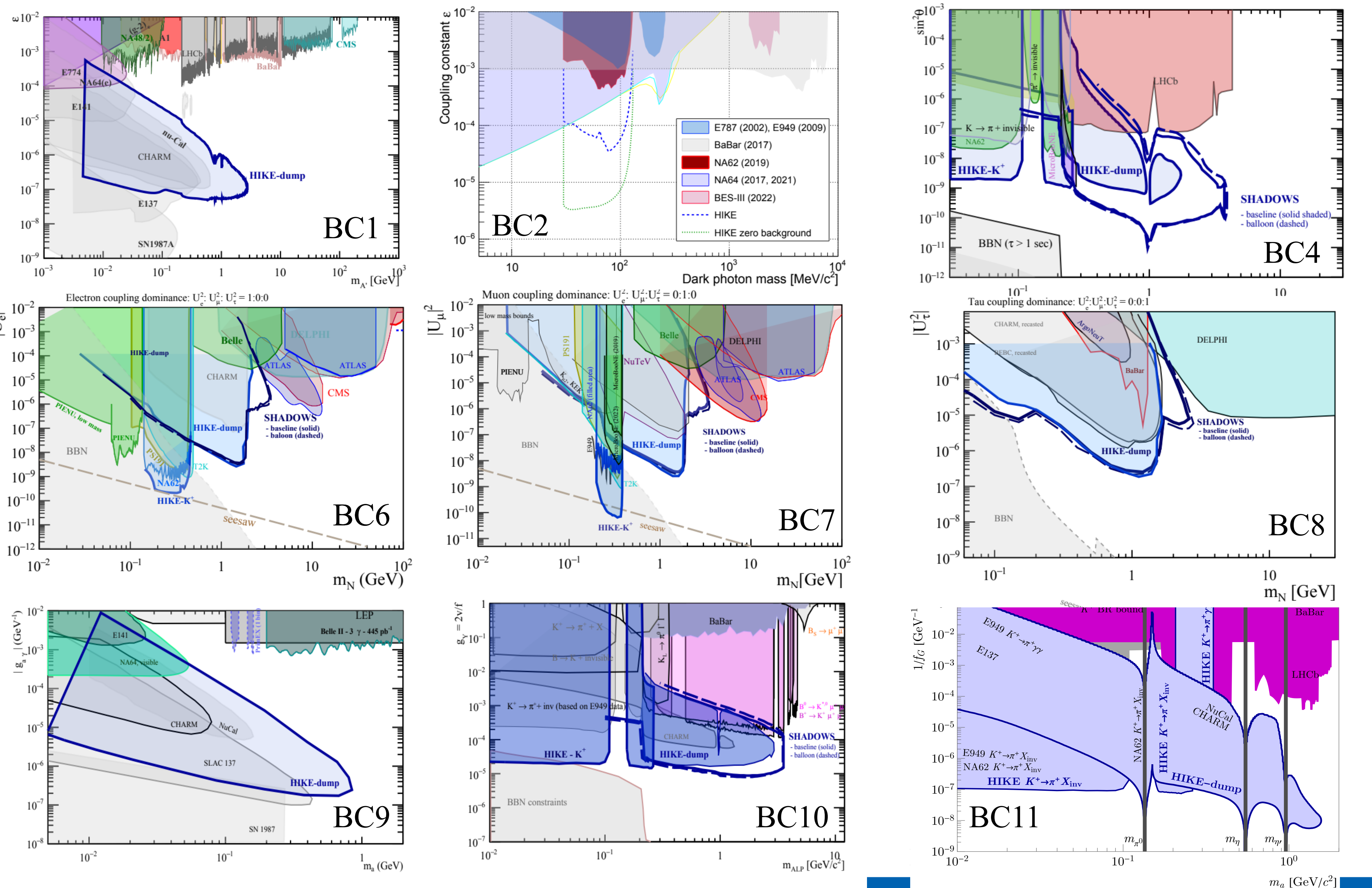


Expected background in HIKE-dump (5×10^{19} POT) based on extrapolation from 1.4×10^{17} POT collected by NA62 in 2021 in beam-dump mode

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

Feebly-interacting particles @ HIKE

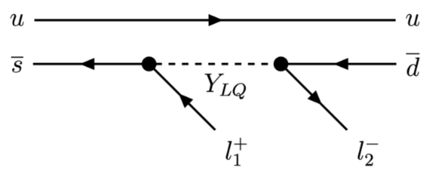
HIKE sensitive to all BC benchmarks except BC3 & BC5



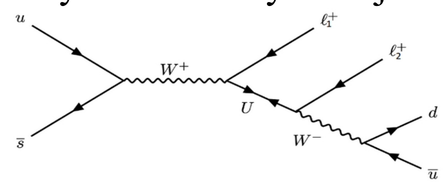
HIKE: LNV/LFV decays

Lepton Number/Flavor Violation: many decay modes, forbidden in SM

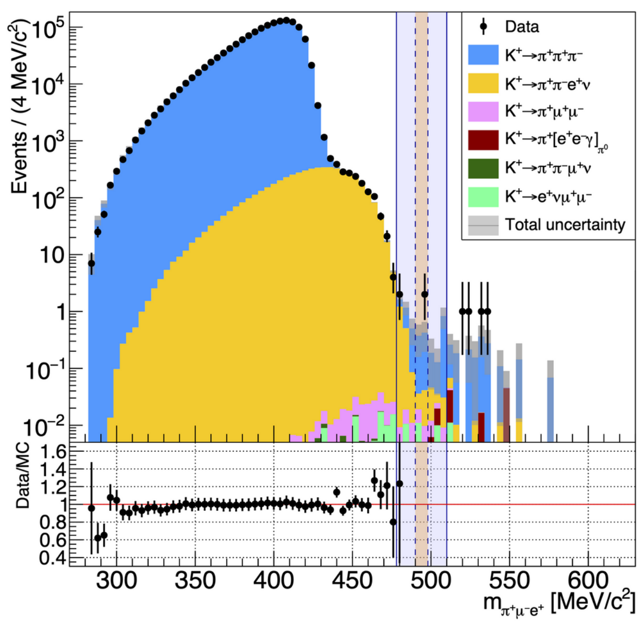
LFV possibly mediated by leptoquark:



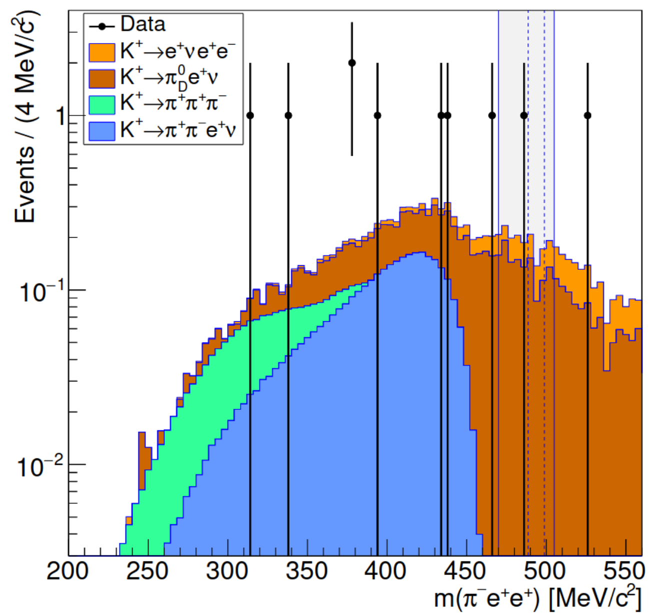
LNV possibly mediated by a Majorana neutrino:



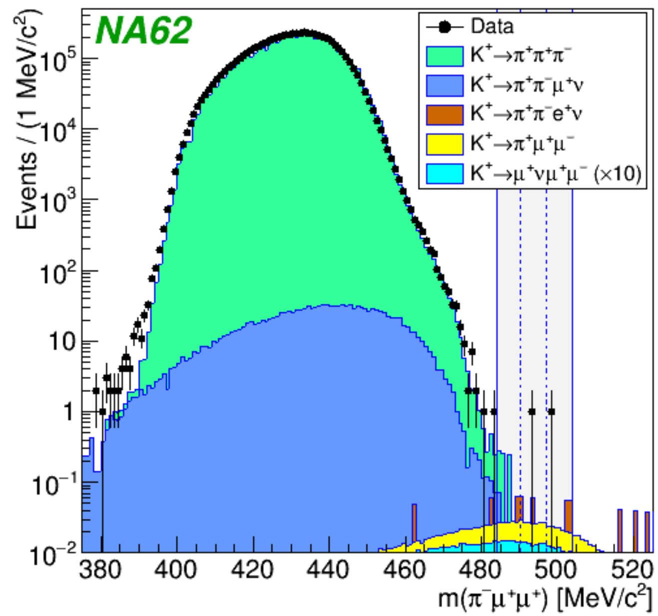
$K^+ \to \pi\mu e$ [PRL127(2021)131802]



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



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



NA62: $O(10^{-11})$ limits on BR of LNV/LFV K^+ decays

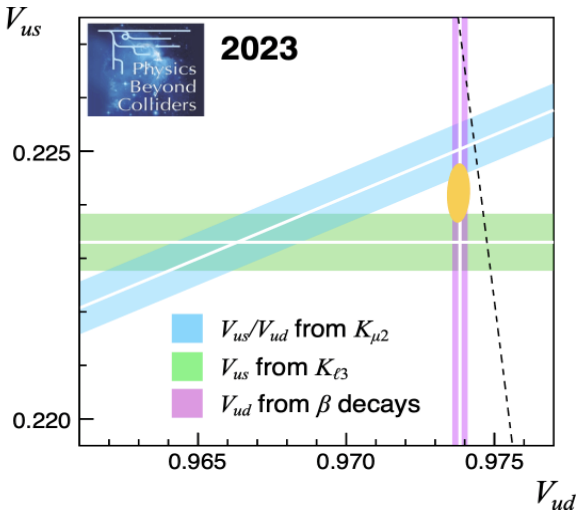
[$K^+ \to \pi^-(\pi^0)\ell_1^+\ell_2^+$, $K^+ \to \pi\mu e$, $K^+ \to \pi^-(\pi^0)\ell_1^-\nu\ell_2^+\ell_2^+$, $\pi^0 \to \mu e$, …]

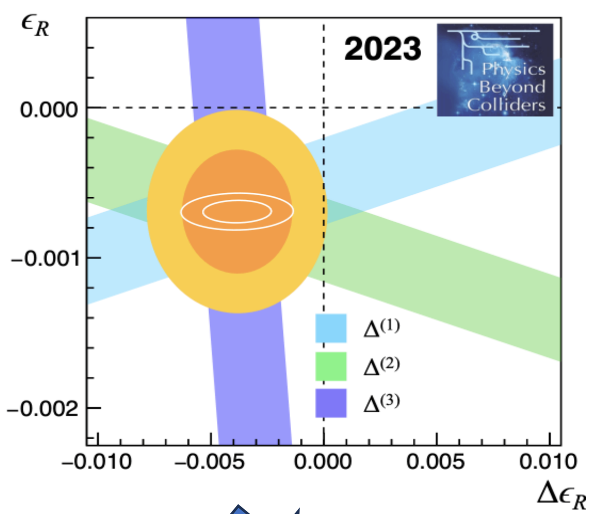
HIKE: $O(10^{-12}$-$10^{-13})$ sensitivity on BR of LNV/LFV K^+ and K_L decays

HIKE: Cabibbo angle anomaly

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

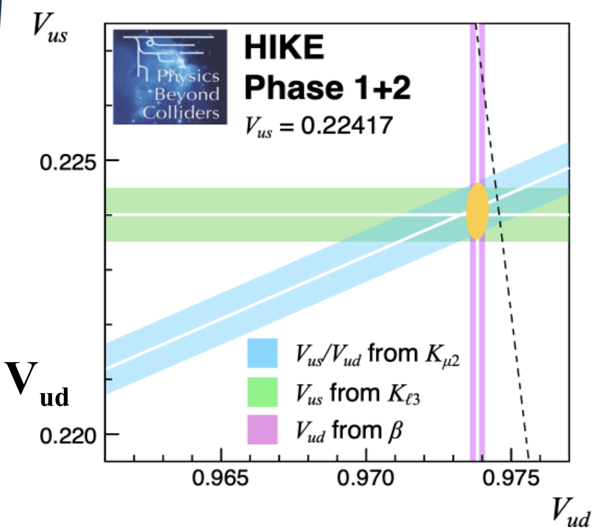
$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$

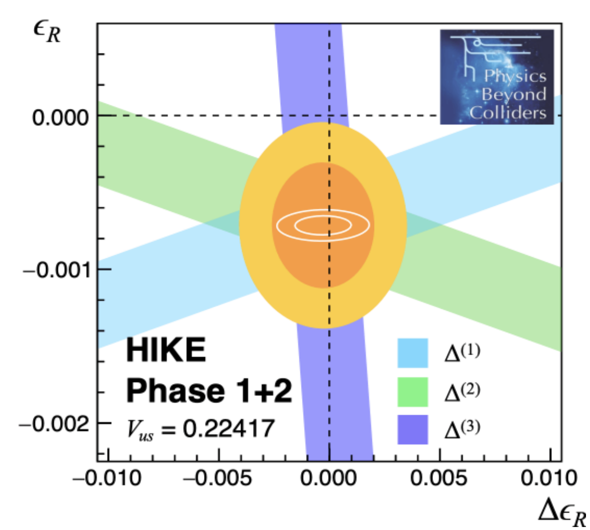




V_{us} from kaon and tau decays,
V_{ud} from super-allowed beta decays

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



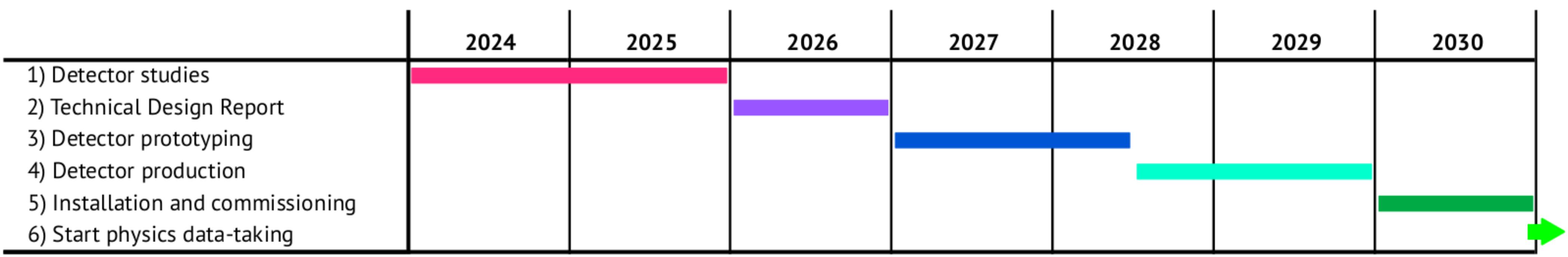


<u>HIKE can clarify the origin of the Cabibbo angle anomaly</u>

In the scenario illustrated,
HIKE resolves tension between $K_{\mu2}$ and K_{l3} but confirms anomaly due to V_{ud}

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



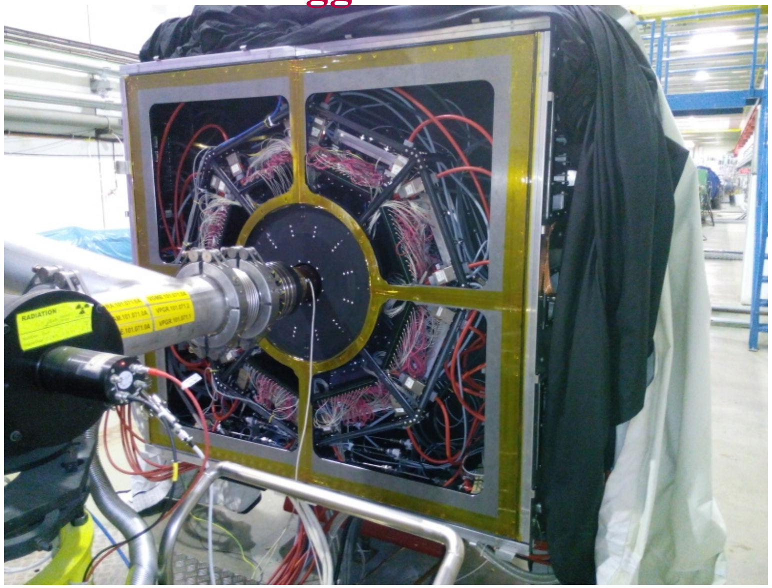
Kaon ID

Differential Cherenkov detector, refurbished readout

K ID for 4x intensity

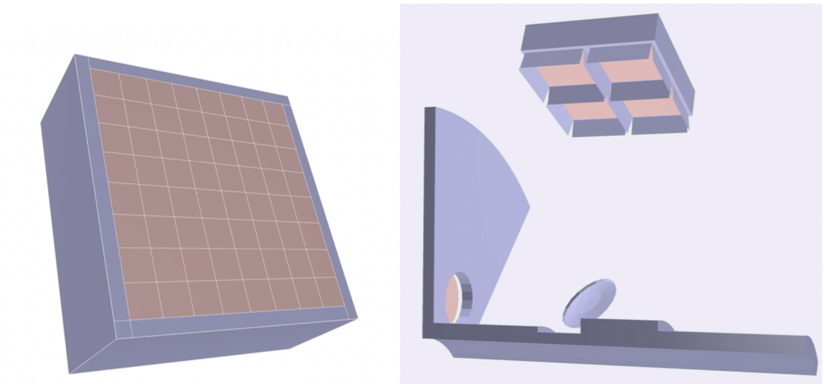
- **Max detected photon rate**: >8 MHz/cm^2
- High granularity
- **Single-photon capability with σ_t (Kaon) = 15-20 ps**
- K^+ tagging efficiency with 4 sectors: > 95%
- Good radiation resistance

NA62 kaon tagger



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



MCP-PMT array and matrix of four MCP-PMT

QE Susceptible to aging: 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

	NA62 GigaTracker	New beam tracker
Single hit time resolution	< 200 ps	< 50 ps
Track time resolution	< 100 ps	< 25 ps
Peak hit rate	2 MHz/mm^2	8 MHz/mm^2
Pixel efficiency	> 99 %	> 99 %
Peak fluence / 1 year [10^{14} 1 MeV n_{eq}/cm^2]	4	16

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

TimeSPOT

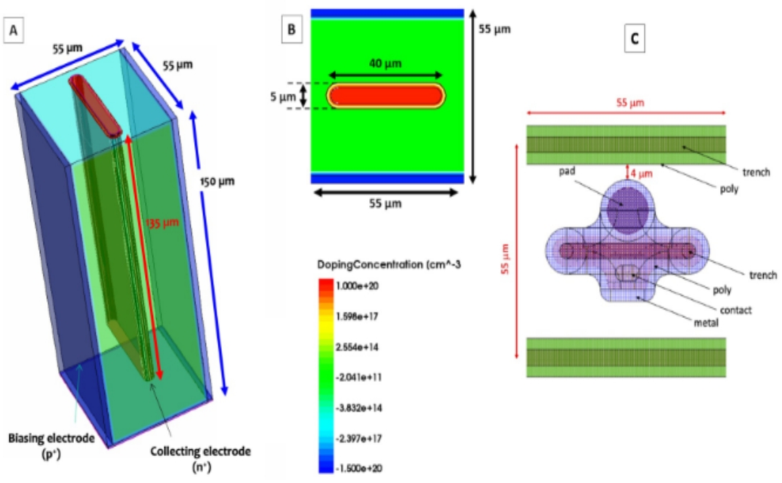
Hybrid 3D-trenched technology can satisfy all requirements.

Pixel electrode geometry optimised for timing performa

Able to withstand very large irradiation.

Excellent detection efficiencies by operating the sensor inclined by angle 20◦ wrt beam incidence

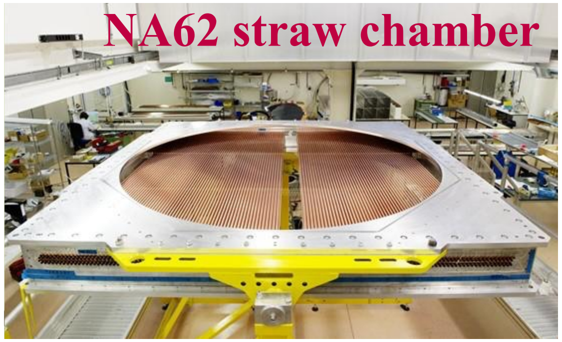
Associated 28nm ASIC: first prototype

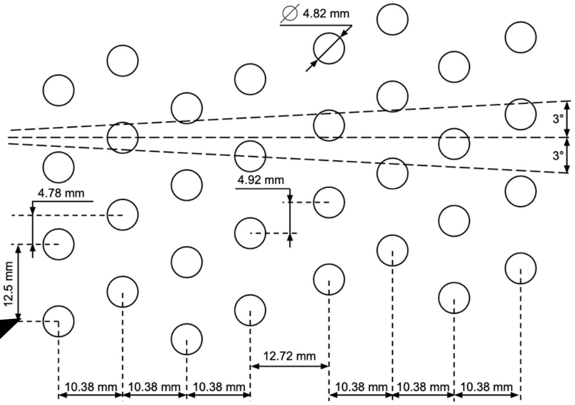


STRAW detector

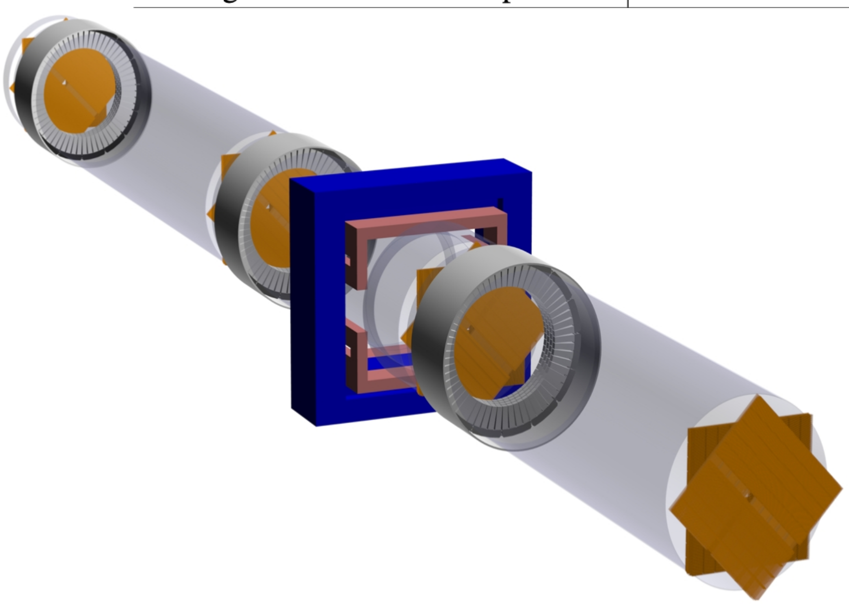
NA62 has developed techniques for making
state-of-the-art straws by ultrasonic welding

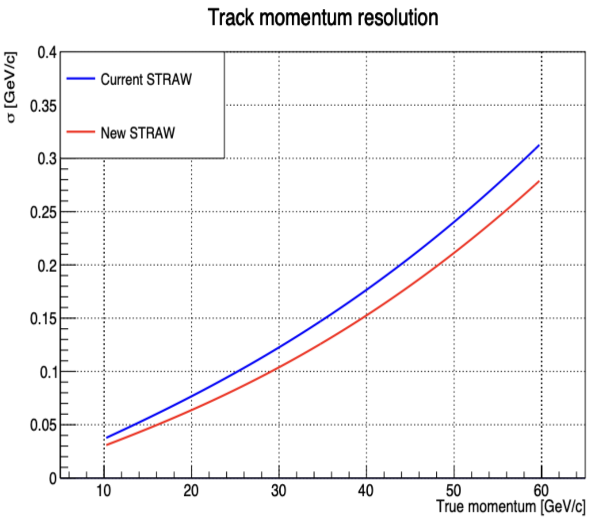
	Current NA62 spectrometer	New straw spectrometer
Straw diameter	9.82 mm	4.82 mm
Straw length	2100 mm	2100 mm
Planes per view	4	8
Straws per plane	112	~160
Straws per chamber	1792	~5200
Mylar thickness	36 μm	(12 or 19) μm
Anode wire diameter	30 μm	(20 or 30) μm
Total material budget	1.7% X_0	(1.0 – 1.5)%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

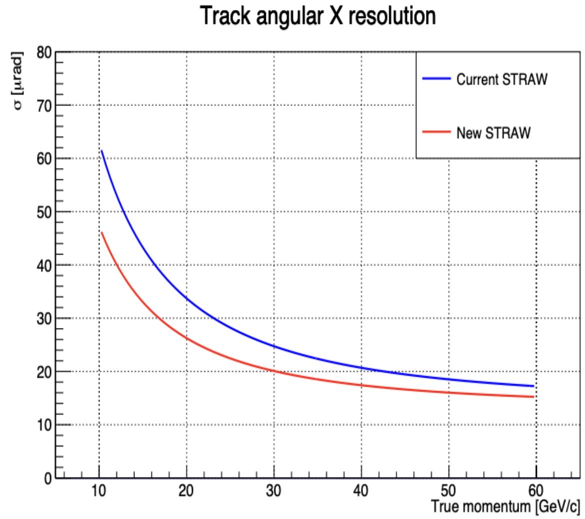




Optimised layout for new STRAW detectors







Pion ID: RICH

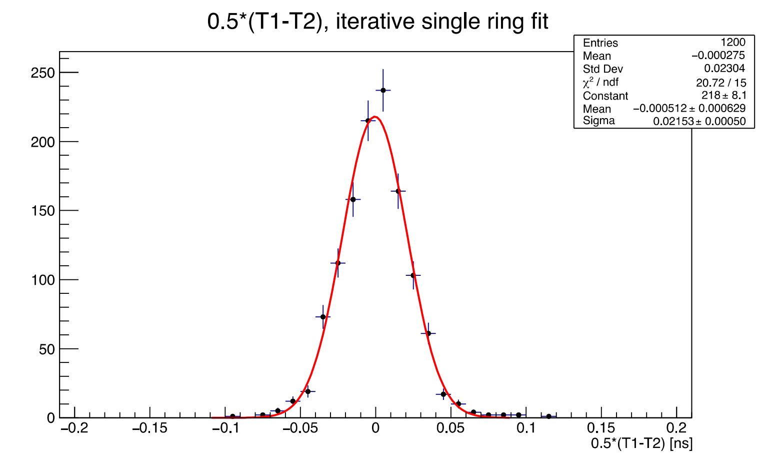
	NA62 RICH	HIKE RICH
Sensor type	PMT	SiPM
Sensor time resolution	240 ps	100 ps
Sensor quantum efficiency	20%	40%
Number of hit for π^+ at 15 GeV/c	7	14
Number of hit for π^+ at 45 GeV/c	12	24
Time resolution for π^+ at 15 GeV/c	90 ps	27 ps
Time resolution for π^+ at 45 GeV/c	70 ps	20 ps

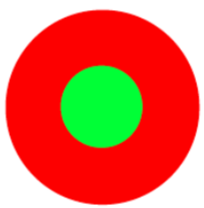
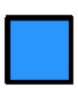
NA62 RICH detector

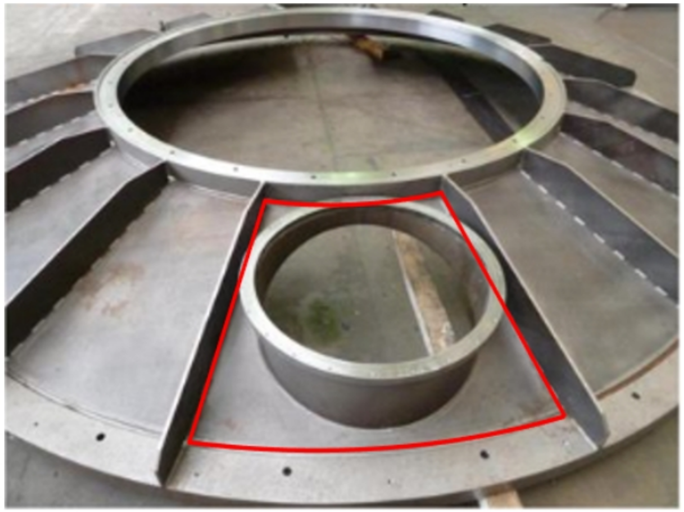
Radiator: neon at atmospheric pressure

Major changes: 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



Main Electromagnetic calorimeter

Fine-sampling shashlyk based on PANDA forward EM calorimeter

Main electromagnetic calorimeter requirements:

excellent efficiency and time resolution (~100ps), good two-cluster separation, good energy resolution

PANDA prototypes:

- $\sigma_E/\sqrt{E}$ ~ **3%** $/\sqrt{E}$ (GeV)
- σ_t ~ **72 ps** $/\sqrt{E}$ (GeV)
- σ_x ~ **13 mm** $/\sqrt{E}$ (GeV)

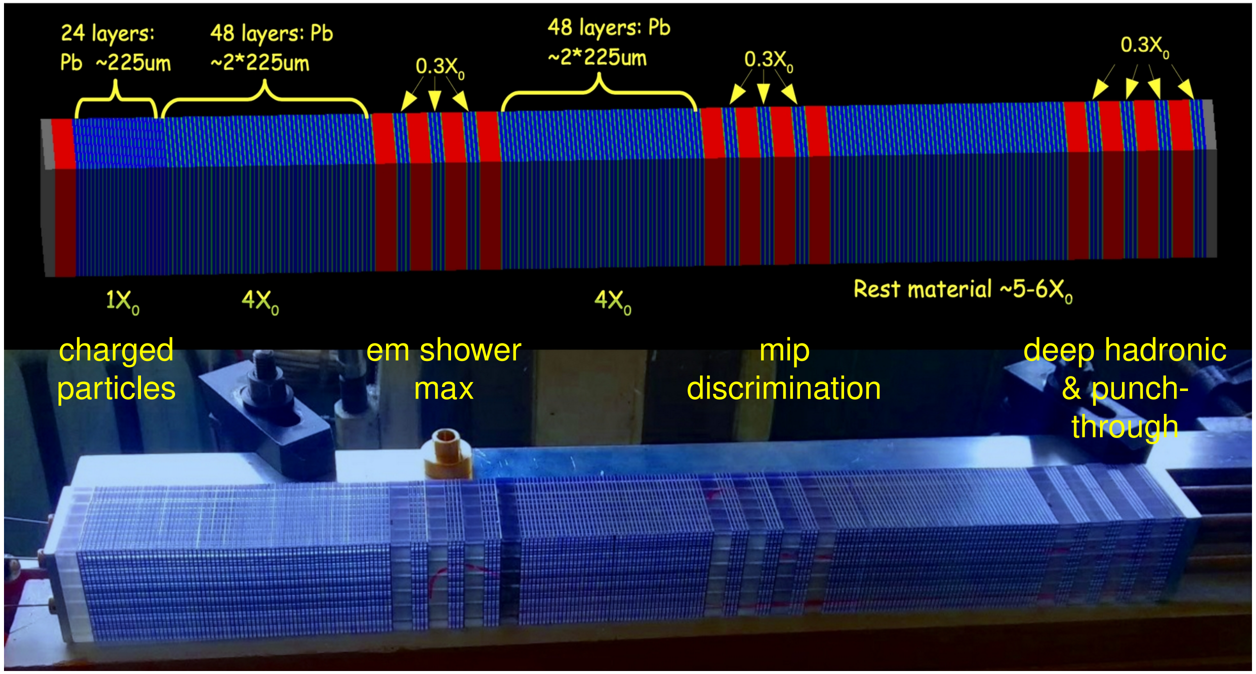
Quasi-homogeneous ionization calorimeter, $27X_0$ of LKr @ NA62

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

$1 - \varepsilon < 10^{-5}$ 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



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

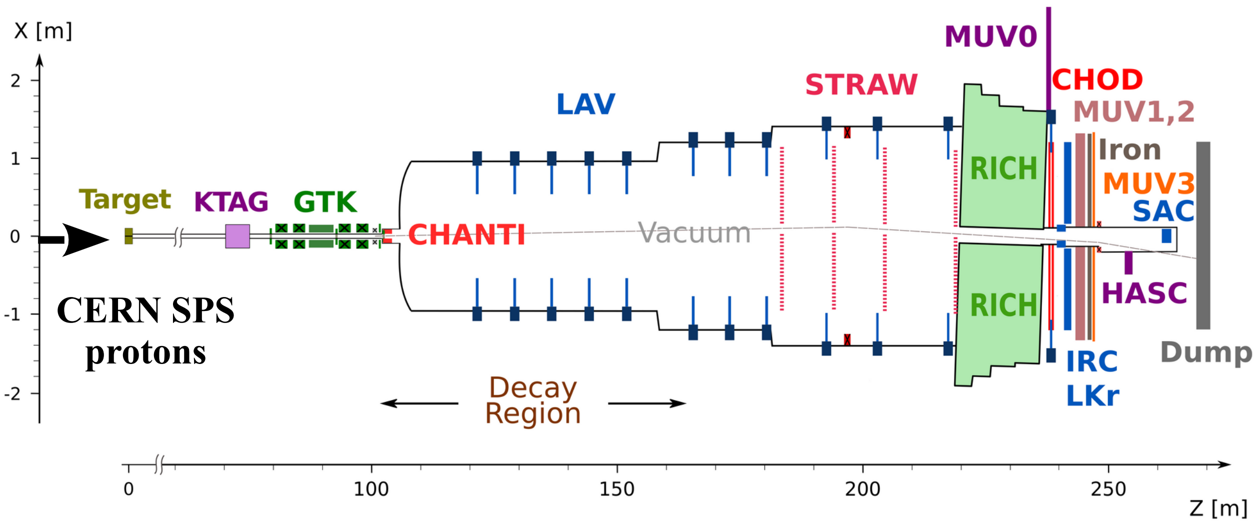
- **HIKE-Phase1:**
  - **Main physics goals:**
    - Measurement of BR($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) at 5% precision
    - Lepton universality in $K^+ \rightarrow \pi^+ \ell^+ \ell^-$ decays (x2 better precision)
  - **Build on NA62 experience:**
    - NA62-like detector + major upgrades
    - Keep same (or better) performances at 4x intensity
    - x2 signal acceptance increase from improved detector (e.g. granularity)
    - Further suppression of dominant background from upstream kaon decays

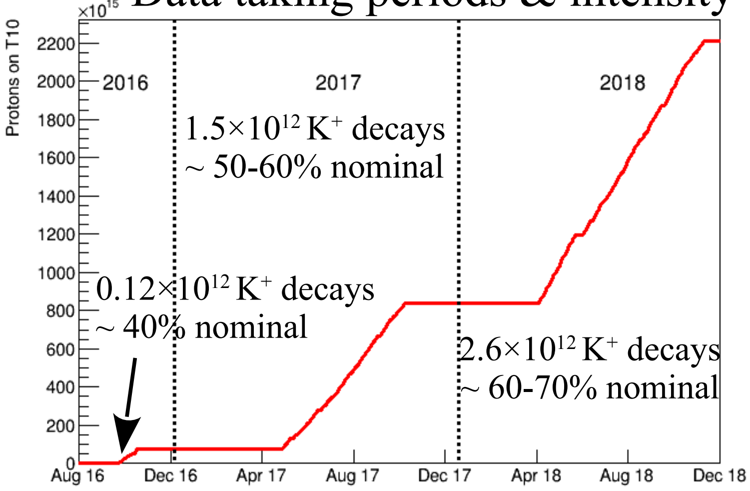
- **HIKE-Phase2:**
  - **Main physics goals:**
    - Measurement of BR($K_L \rightarrow \pi^0 \ell^+ \ell^-$) at 20% precision
  - **Expected physics sensitivity:**
    - First observation @ > 5σ and measurement of both ultra-rare decay modes
    - 20% precision on CKM parameter λ_t

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

Spares

The NA62 experiment



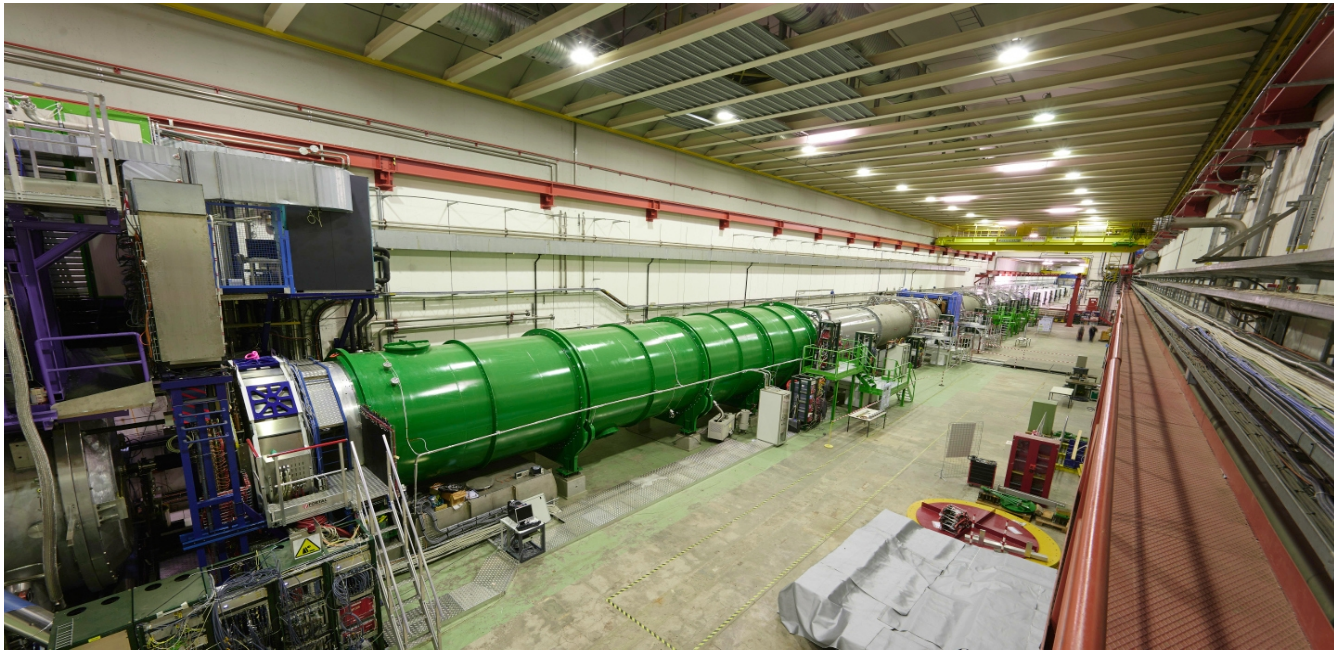


Nominal intensity: ~ 3×10^{12} POT/spill → 750 MHz hadron beam

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



NA62 Run1 (2016-2018) result

2018 data:

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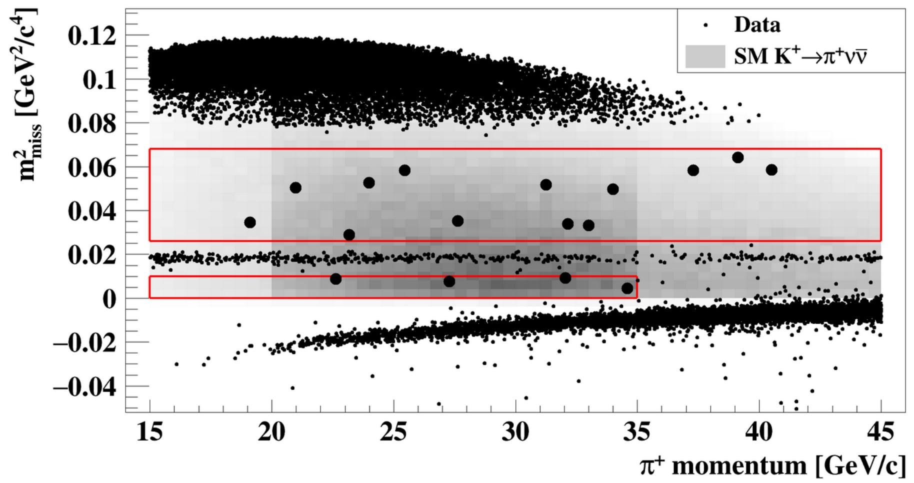
Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
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 = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

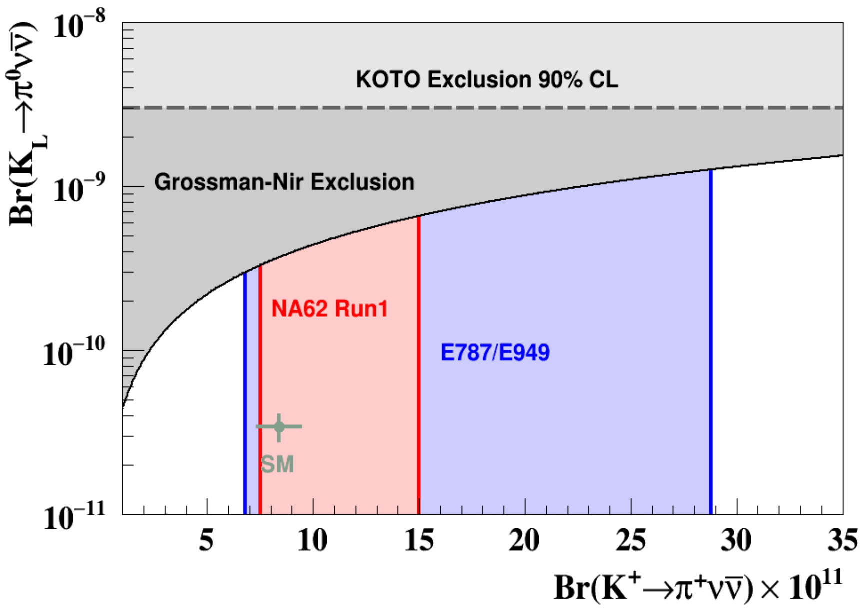
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

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 Run2 (2021-2025)

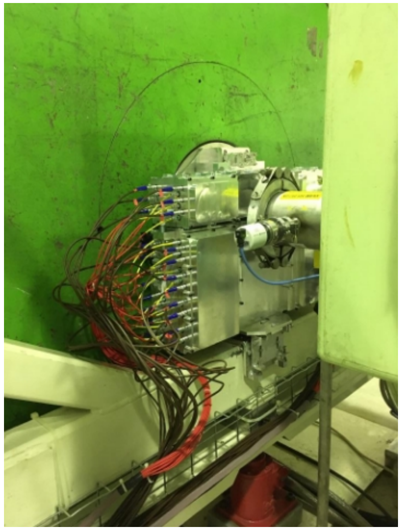
NA62 recommended by SPSC and approved by Research Board until LS3

Improvements in NA62 Run2:

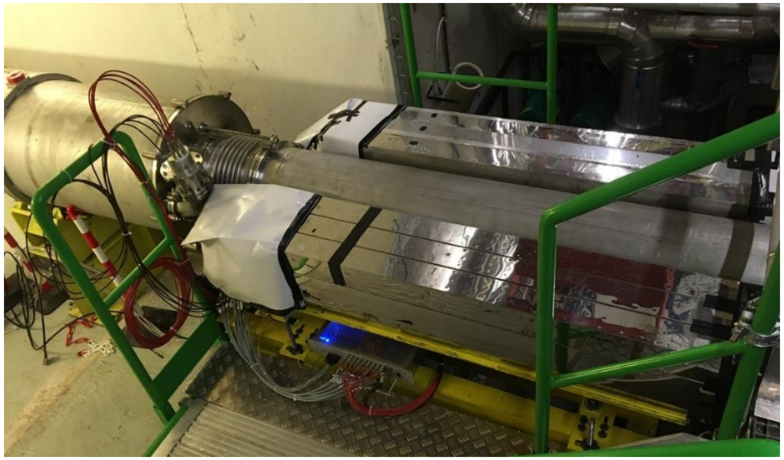
- DAQ stability improved: run at higher beam intensity (70% → 100%)
- Rearrangement of beamline elements around GTK achromat
- Added 4^{th} station to GTK beam tracker
- Additional veto counters around beam pipe (both upstream/downstream the FV)
- New veto hodoscope upstream of decay volume (ANTI0)
-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