HIKE: High Intensity Kaon Experiments at CERN

High Intensity Kaon Experiments

Evgueni Goudzovski

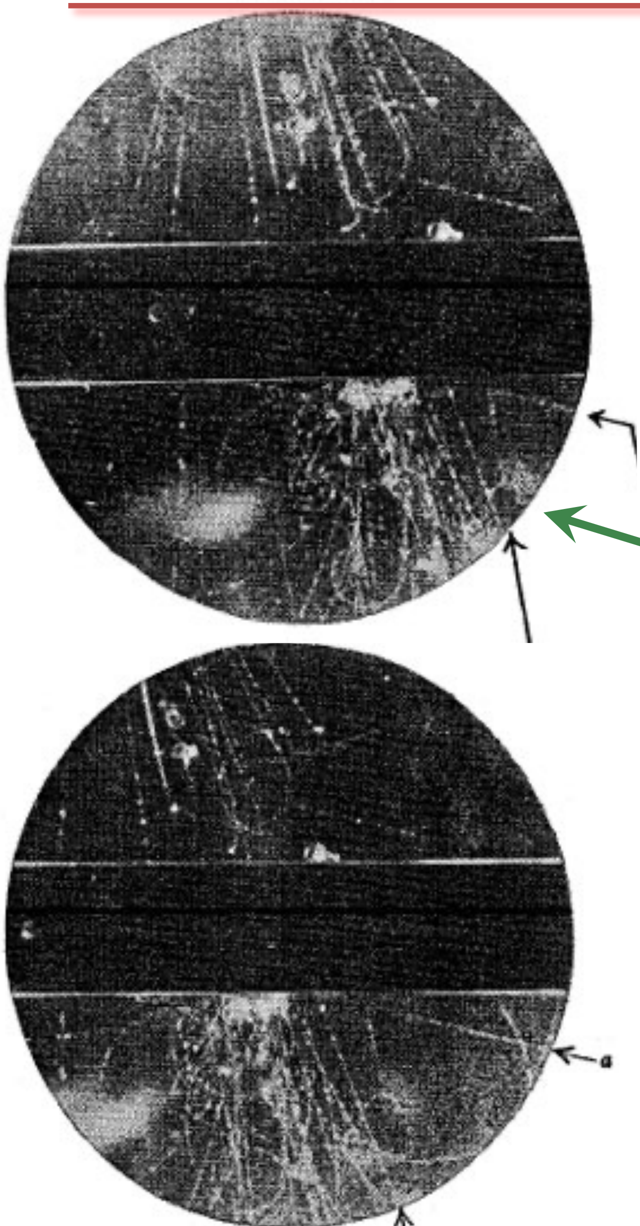
UNIVERSITY OF BIRMINGHAM

Outline:

1) Introduction: rare kaon decays
2) HIKE Phase 1: $K^+\to\pi^+\nu\nu$ and other measurements
3) HIKE Phase 2: $K_L\to\pi^0\ell^+\ell^-$ measurement
4) Summary

Windows on the Universe
Quy Nhon, Vietnam • 8 August 2023

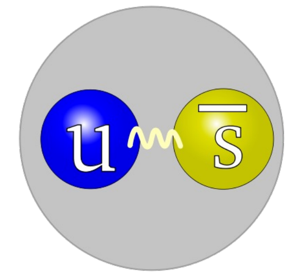
Kaon decay physics



No. 4077 December 20, 1947 NATURE

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER AND Dr. C. C. BUTLER



Stereoscopic cloud chamber kaon decay image: $K_S \to \pi^+\pi^-$

- One of the lightest unstable particles; the "minimal flavour laboratory".
- High production rates, simple final states: high sensitivity, low systematic errors.
- Essential in establishing the foundations of particle physics (quark mixing, CPV).
- Current focus: searches for new physics (TeV mass scale) with rare/forbidden decays.

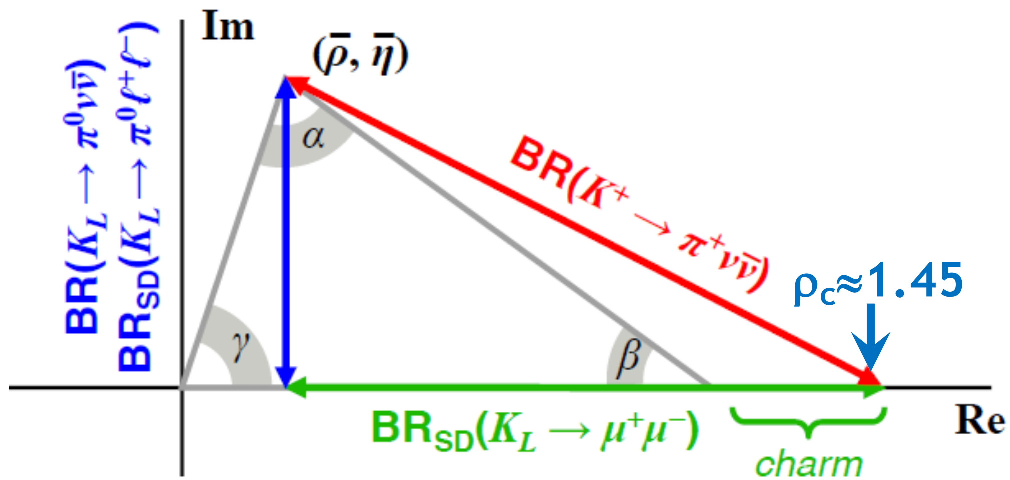
Rare kaon decays

Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11}
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28 (@ 90% CL)
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	< 38
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	**8.6±0.4**	**10.6±4.0**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	**3.0±0.2**	< 300

*Approx. error on LD-subtracted rate excluding parametric contributions

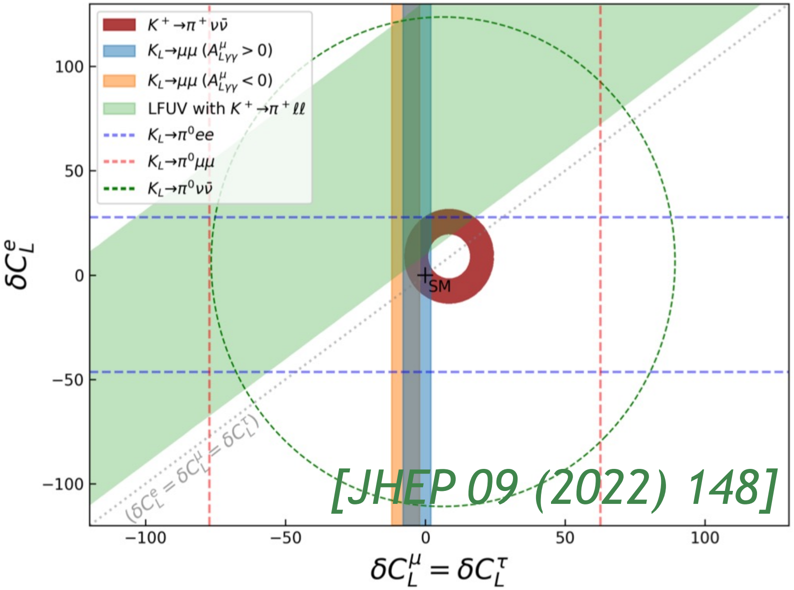
(see also arXiv:2203.09524)

- FCNC processes dominated by Z-penguin and box diagrams.
- SM rates determined by V_{CKM}, with minimal non-parametric "theory" uncertainties.
- Theory errors are being reduced *[Lattice QCD, e.g. arXiv:2203.10998]*.
- The current focus is on K→πνν: uniquely clean theoretically.



LFU test with K decays

LFU test with K decays

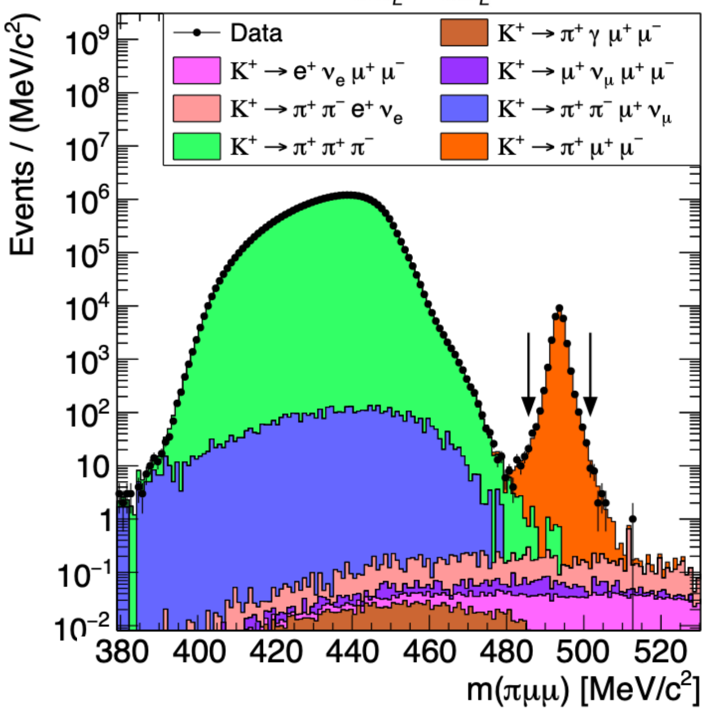


Rare kaon decays provide an LFU test.
Special role of **$K^+\to\pi^+\ell^+\ell^-$** decays (**BR~10^{-7}**):

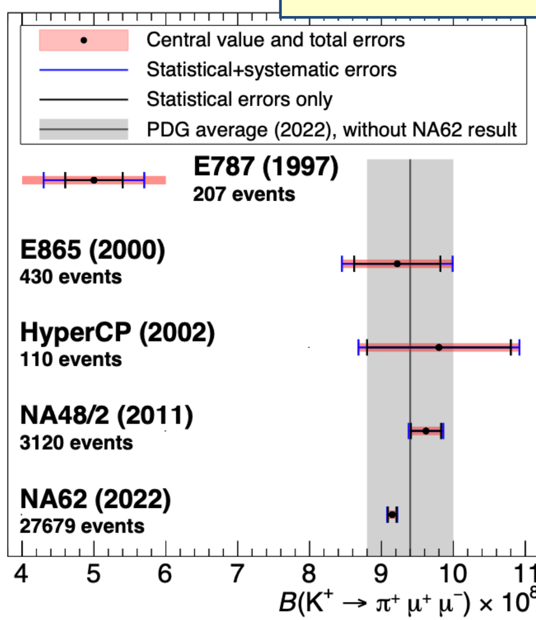
$$d\Gamma/dz \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

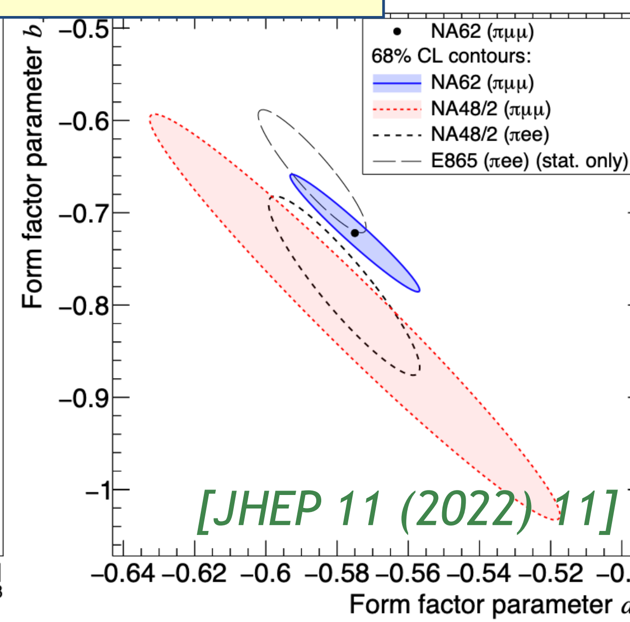
$$a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$$

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



$K^+\to\pi^+\ell^+\ell^-$ measurements

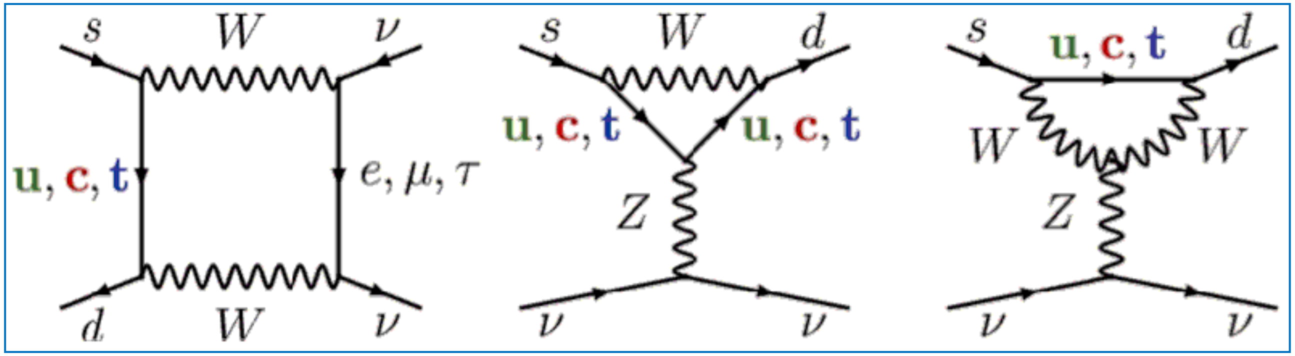




$K \to \pi\nu\nu$: theory and experiment

[More details: talk by Monica Pepe]

SM: Z-penguin and box diagrams



"Golden modes": extremely rare decays, precise SM predictions.

- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- No long-distance contributions from amplitudes with intermediate photons.
- Hadronic matrix element extracted from measured $BR(K_{e3})$ via isospin rotation.

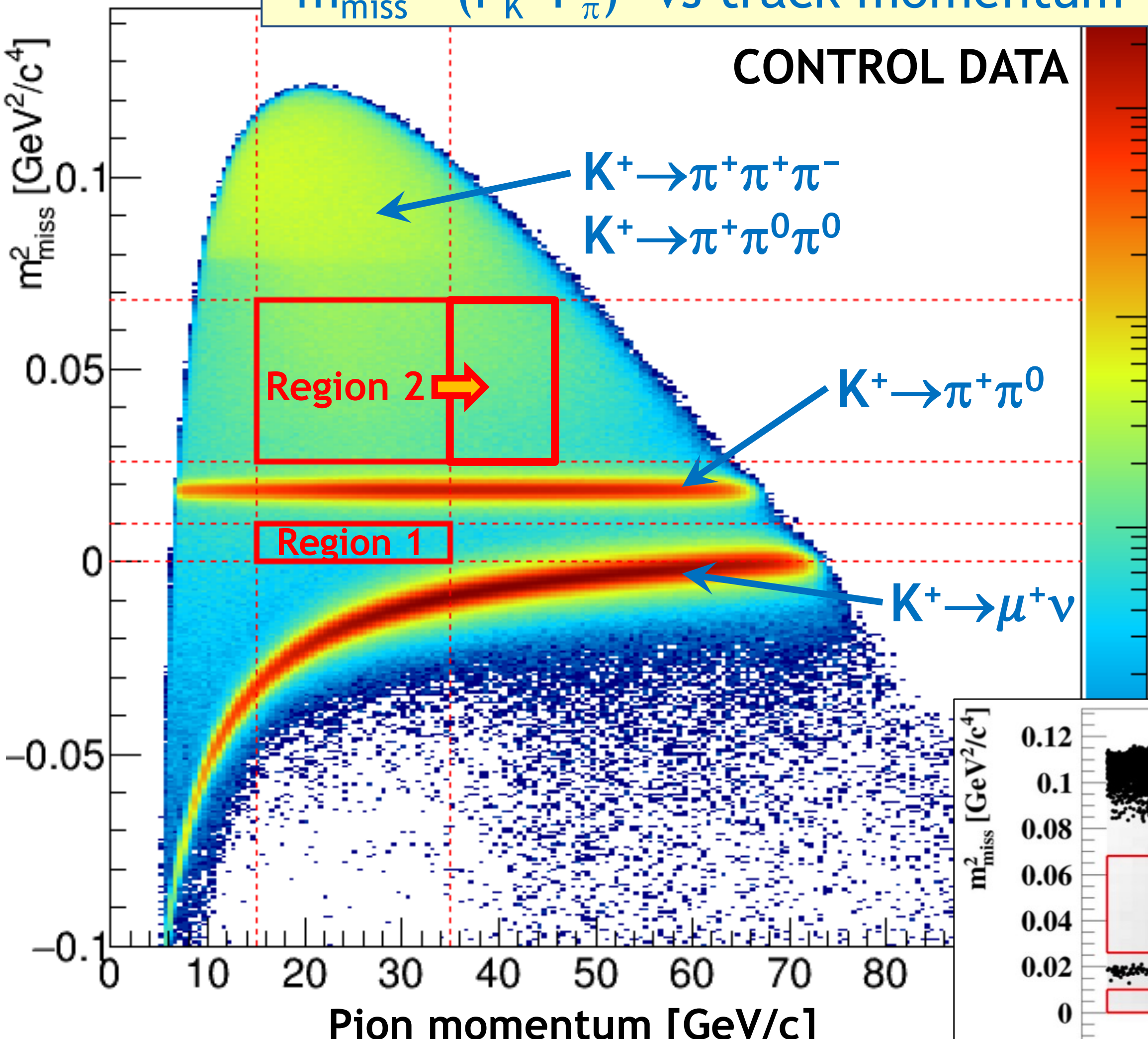
Mode	Standard Model BR	Experimental status
$K^+ \to \pi^+\nu\nu$	$(8.60\pm0.42)\times10^{-11}$	$(10.6\pm4.0)\times10^{-11}$ (NA62 Run 1)
$K_L \to \pi^0\nu\nu$	$(2.94\pm0.15)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

Standard Model BR: a recent $|V_{cb}|$ and γ-independent determination.
[Buras and Venturini, arXiv:2109.11032]

$K_{\pi\nu\nu}$ measurement at NA62

[More details: talk by Monica Pepe]

$m_{miss}^2=(P_K-P_\pi)^2$ vs track momentum



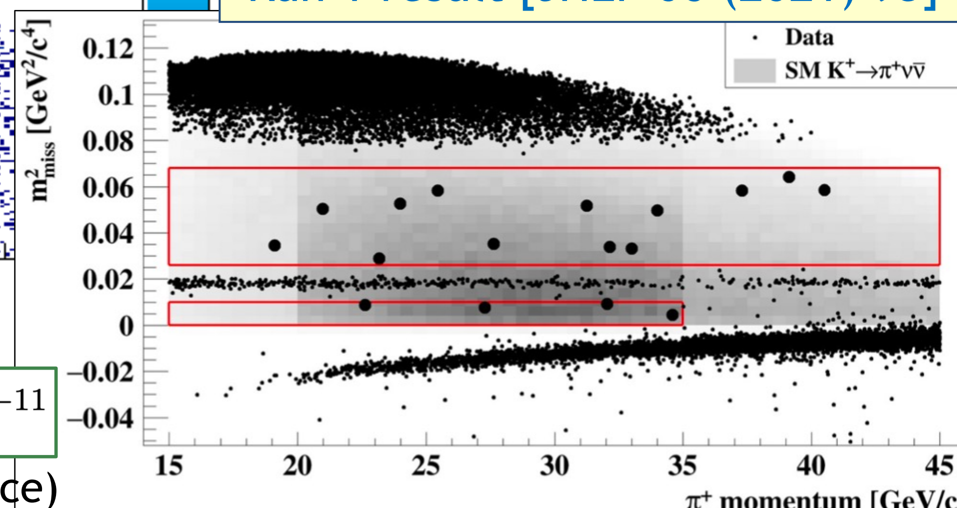
Kinematic suppression of main backgrounds:

- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

- ✓ PID (calorimeters & RICH): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection of 1.4×10^{-8}.

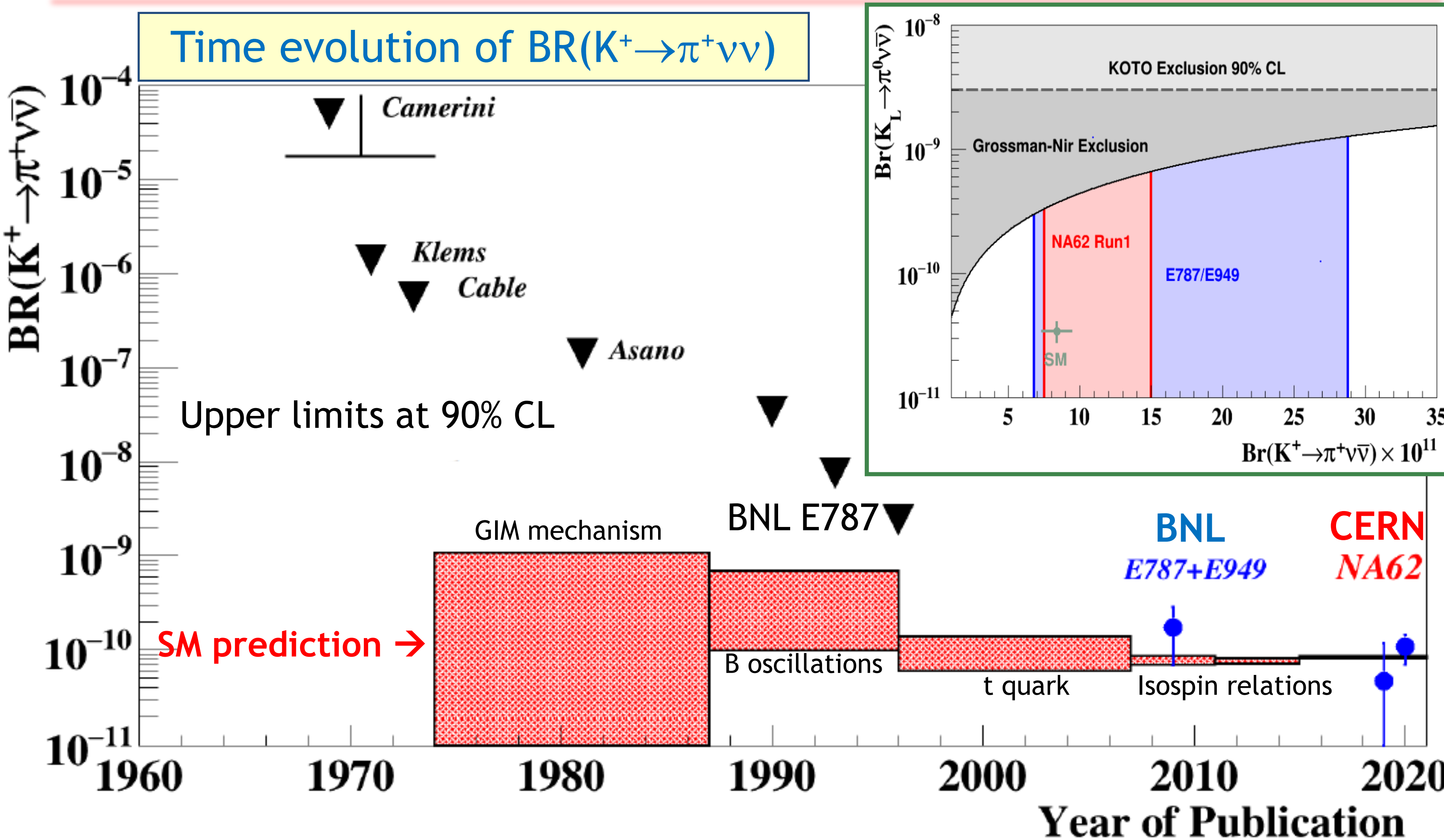
Run 1 result [JHEP 06 (2021) 93]



$$BR(K^+\to\pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst})\times10^{-11}$$

(3.4σ significance)

History of $K^+ \to \pi^+ \nu\nu$ searches

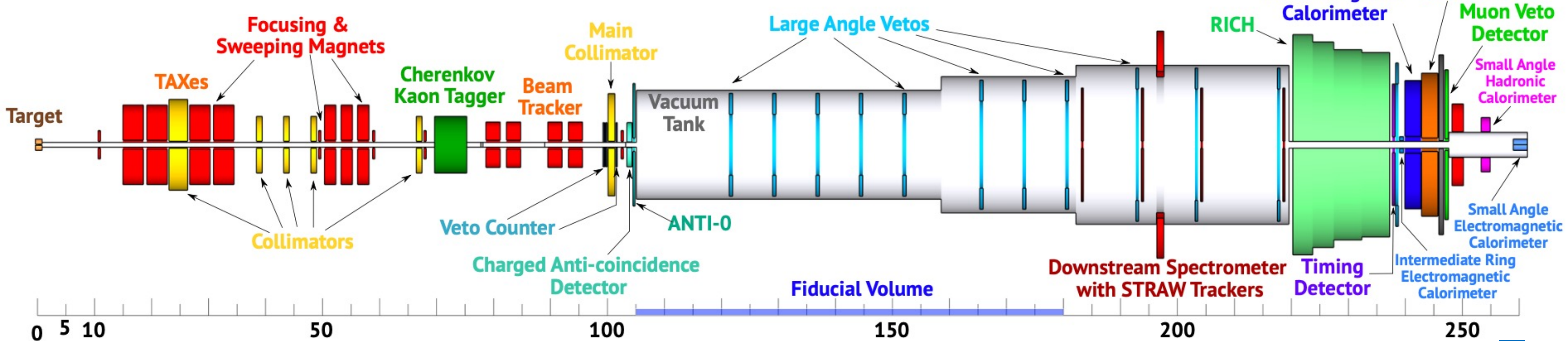


NA62 Run 2 goal: **BR($K^+ \to \pi^+ \nu\nu$)** measurement to **10–15%** precision.

The HIKE proposal

- SPS fixed target operation foreseen **until at least 2038**.
- **HIKE** (*"High-Intensity Kaon experiments"*): a long-term programme rare kaon decay programme at the SPS.
- Multiple phases: K^+ and K_L decay experiments.
- Beam intensity: **up to ×6** wrt NA62 ($\sim 1.5\times10^{19}$ pot/year).
- A clear insight into the flavour structure of new physics.
- A few times 10^{19} pot to be collected in beam dump mode.
- Snowmass paper: *arXiv:2204.13394*; LoI: *arXiv:2211.16586*.
- Proposal for Phases 1 and 2: to be submitted in **August 2023**.

HIKE Phase 1 detector



HIKE Phase 1: $K^+ \to \pi^+ \nu\nu$

A multi-purpose K^+ experiment; $K^+ \to \pi^+ \nu\nu$ at 5% precision in 4 years.

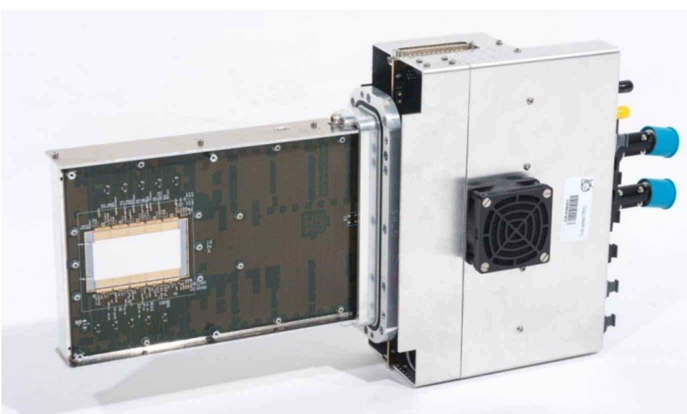
- ✓ Challenge: 20 ps time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.
- ✓ Improved signal acceptance (higher detector granularity, fully software trigger).
- ✓ Challenges aligned with HL-LHC projects and future flavour/dark matter exp.

New pixel beam tracker (GTK):

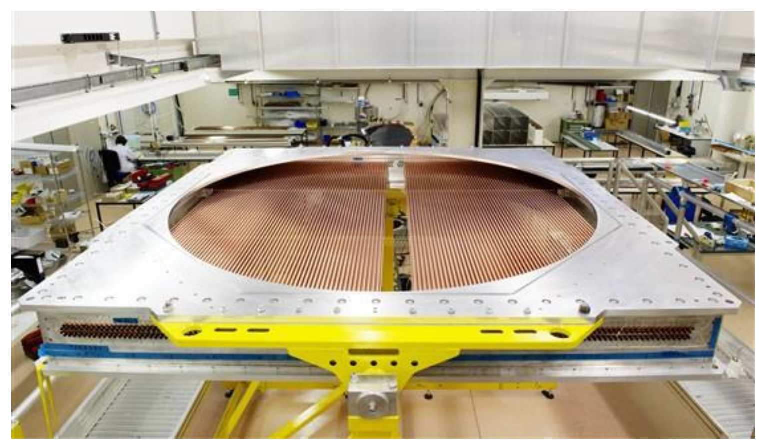
time resolution: <50 ps per plane;
pixel size: $<300\times300\ \mu m^2$;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: >3 GHz on $30\times60\ mm^2$;
peak intensity: $>8.0\ MHz/mm^2$.

New STRAW spectrometer:

operation in vacuum;
straw diameter/length: 5 mm/2.2 m;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
total material budget: 1.4% X_0.



A current NA62 GTK station



A current NA62 STRAW chamber

HIKE Phase 1: broader programme

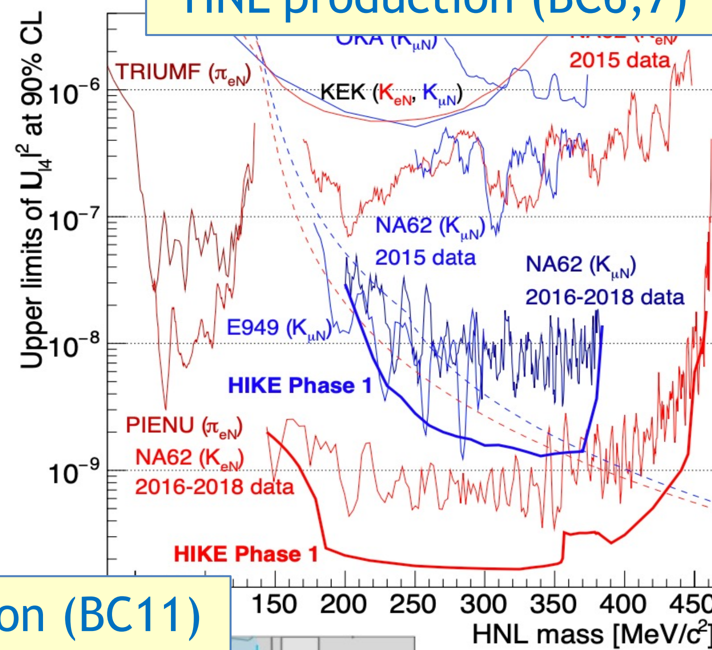
Precision studies of K⁺ decays:

- LF universality, LF/LN conservation, first-row CKM unitarity and low-energy QCD tests.

Hidden-sector searches in kaon decays

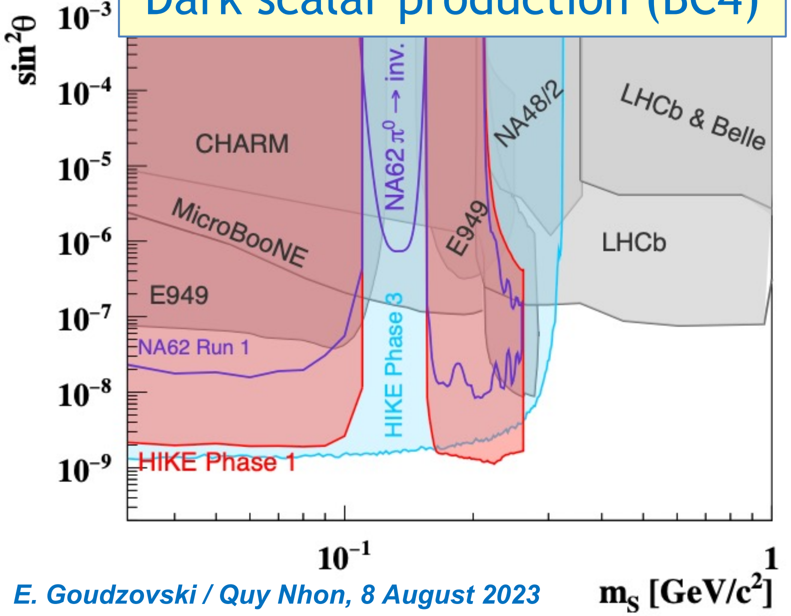
- Heavy neutral lepton (HNL) production: **$K^+ \to e^+ N$**, **$K^+ \to \mu^+ N$**, **$\pi^+ \to e^+ N$**.
- Dark scalar, ALP production: mainly analysis of the **$K^+ \to \pi^+ \nu\nu$** spectrum.

HNL production (BC6,7)

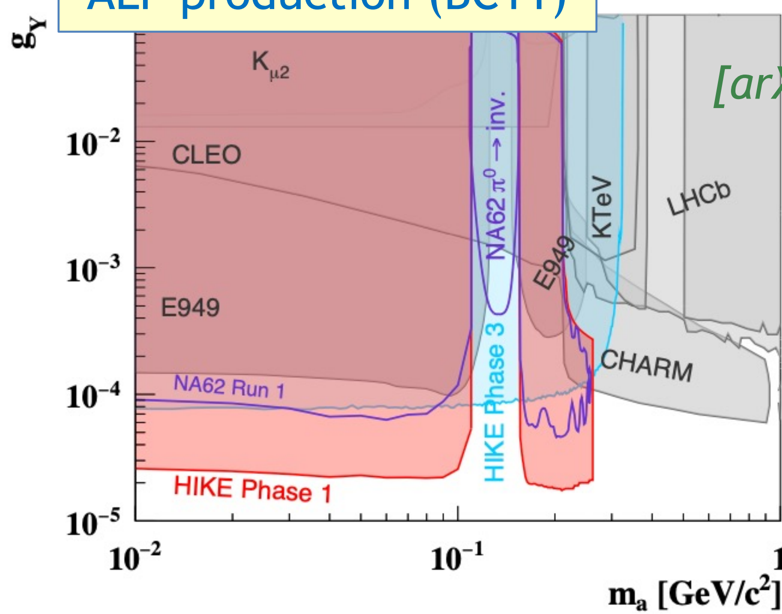


[arXiv:2211.16586]

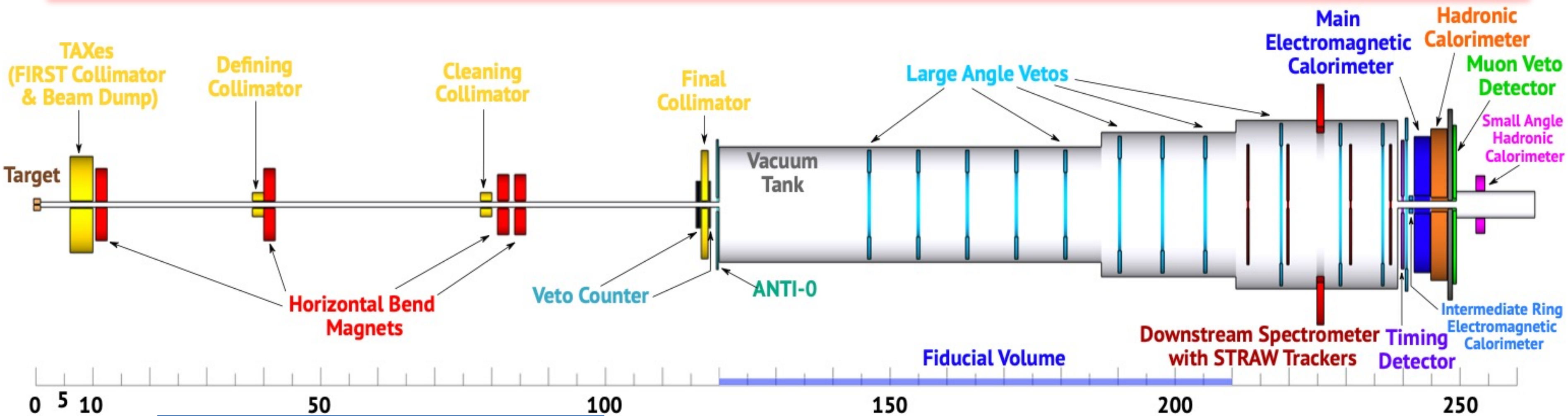
Dark scalar production (BC4)

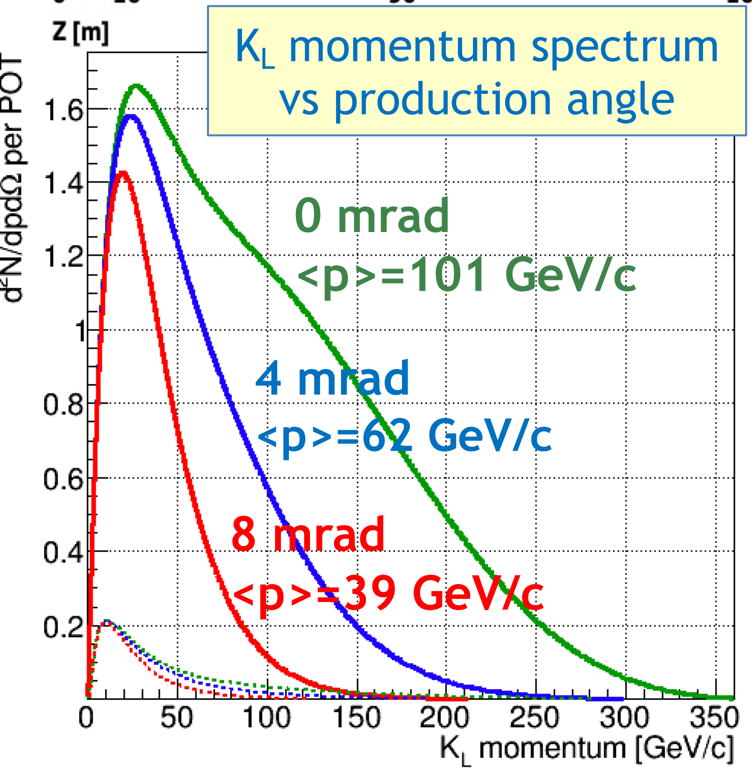


ALP production (BC11)



HIKE Phase 2: $K_L \to \pi^0 \ell^+ \ell^-$

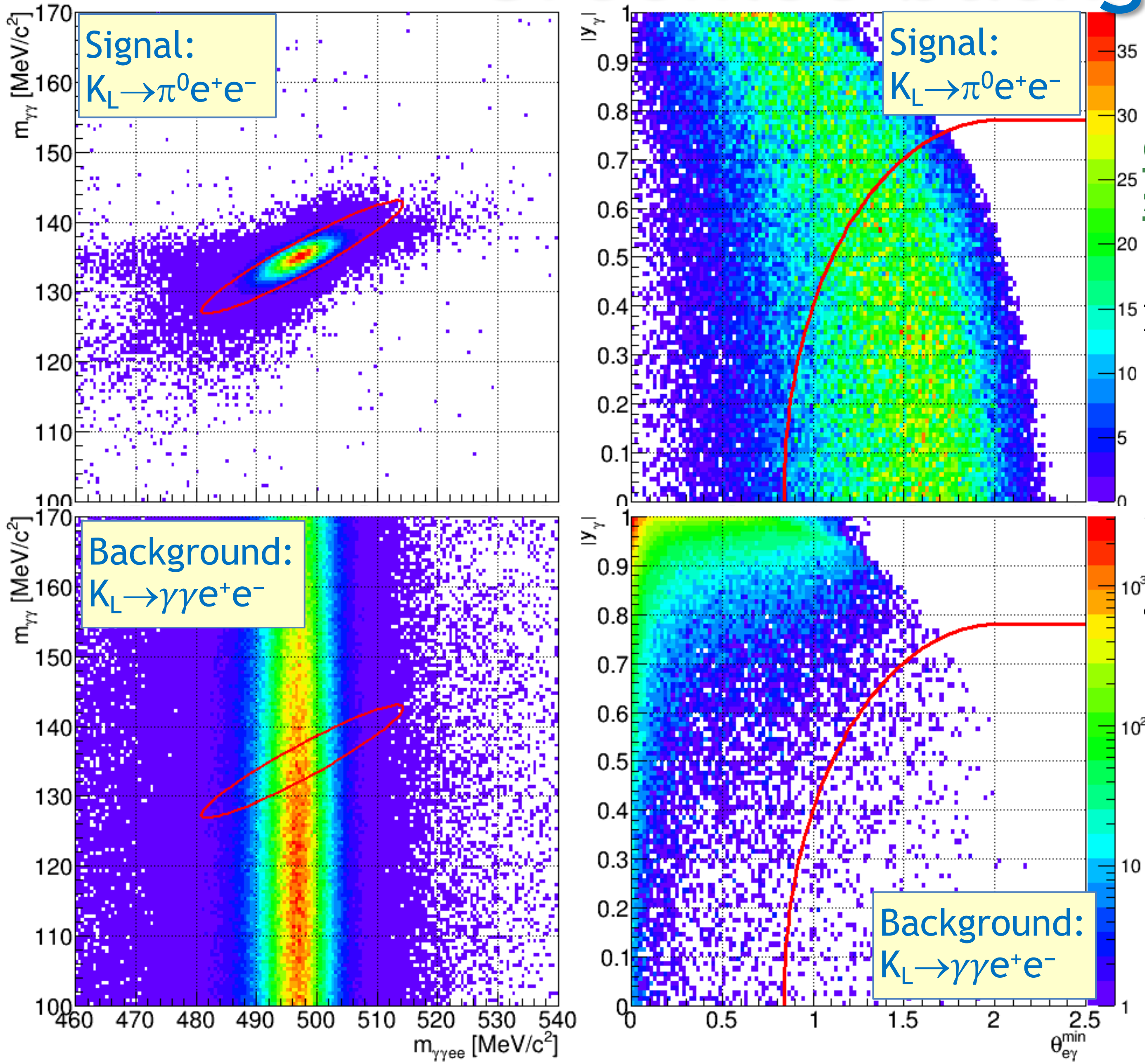




A multi-purpose K_L decay experiment focused on $K_L \to \pi^0 \ell^+ \ell^-$ decays.

- High-energy neutral kaon beam produced by **400 GeV/c** protons.
- **600k** SPS spills/year, **2×10^{13}** pot/spill.
- Production angle: **2.4 mrad**; beam opening angle: **0.4 mrad**.
- Reconfigured Phase 1 detector: kaon tagger, beam spectrometer, RICH and small-angle calorimeter removed; STRAW spectrometer realigned.

Greenlee background (1)



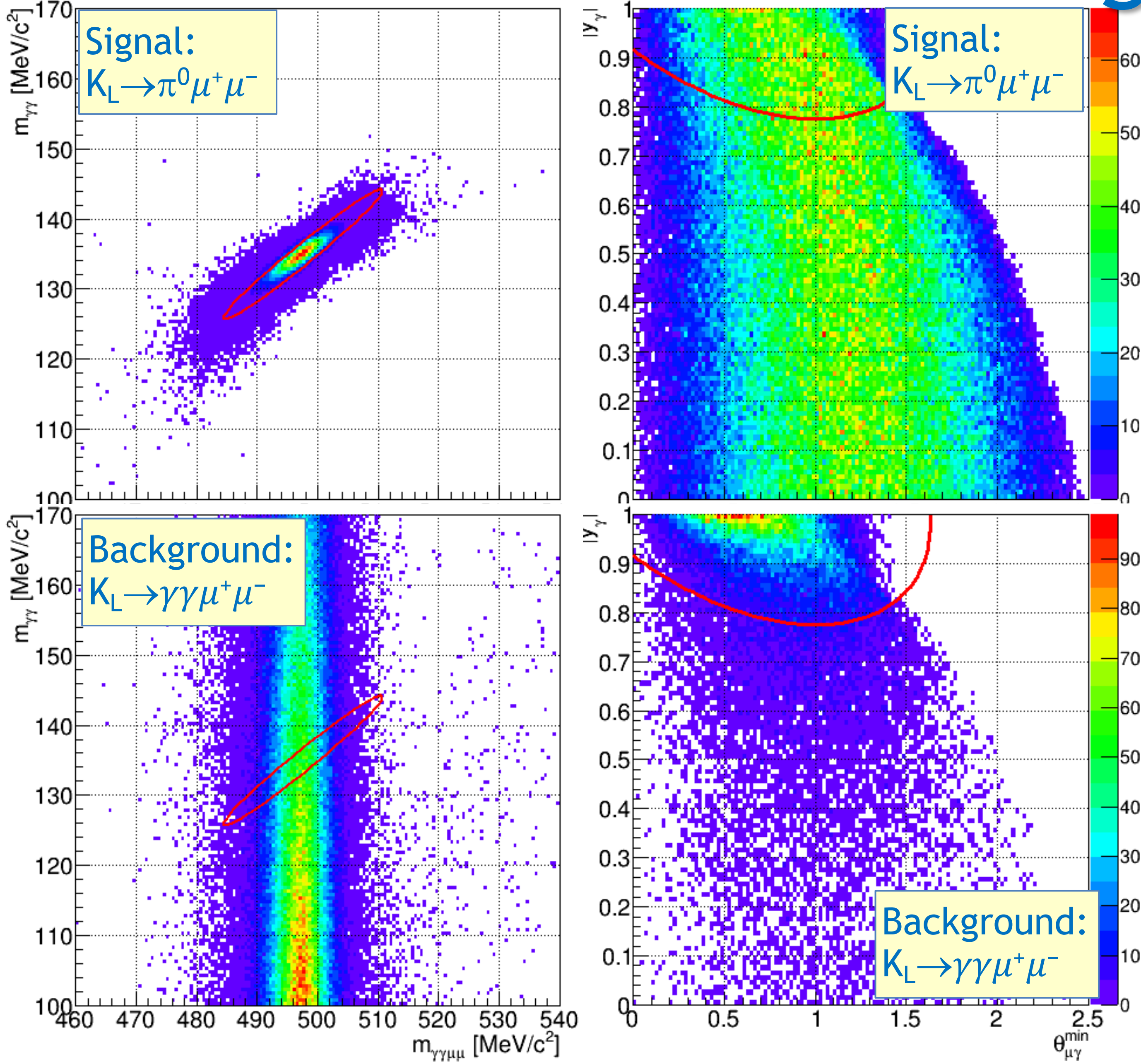
Greenlee background suppression via:

1) di-photon mass ($m_{\gamma\gamma}$);
2) photon asymmetry

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

3) minimal angle between any γ and any $\ell^\pm$ in the K_L frame.

Greenlee background (2)



Greenlee background suppression via:

1) di-photon mass ($m_{\gamma\gamma}$);
2) photon asymmetry

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

3) minimal angle between any γ and any $\ell^\pm$ in the K_L frame.

HIKE Phase 2: sensitivity

- Decay BRs in the Standard Model (assuming constructive interference):

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 e^+ e^-) = \left(15.7|a_S|^2 \pm 6.2|a_S|\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right) + 2.4\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right)^2\right) \times 10^{-12} = 3.54^{+0.98}_{-0.85} \times 10^{-11},$$

$$\mathcal{B}_{\rm SM}(K_L \to \pi^0 \mu^+ \mu^-) = \left(3.7|a_S|^2 \pm 1.6|a_S|\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right) + 1.0\left(\frac{{\rm Im}\lambda_t}{10^{-4}}\right)^2 + 5.2\right) \times 10^{-12} = 1.41^{+0.28}_{-0.26} \times 10^{-11}$$

$$\lambda_t = V_{ts}^* V_{td}$$

[Isidori, Smith, Unterdorfer, EPJ C36 (2004) 57]
[Mescia, Smith, Trine, JHEP 08 (2006) 88]

- SM signal yields and backgrounds in **5** years of operation:

Mode	N_S	N_B	$N_S/\sqrt{N_S+N_B}$
$K_L \to \pi^0 e^+ e^-$	70	83	5.7
$K_L \to \pi^0 \mu^+ \mu^-$	100	53	8.1

- Sensitivity to the CKM parameters
(assuming an improved $|a_S|$ measurement with $K_S \to \pi^0 \ell^+ \ell^-$ at LHCb):

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

Summary

- Precision measurements of both K^+ and K^0 decays:
  an essential part of the worldwide flavour physics programme.
- **HIKE at CERN:** a proposal for next-generation rare K^+ and K_L decay experiments with high-intensity beams ($\sim 1.5\times10^{19}$ pot/year).
- **HIKE Phase 1:** a multi-purpose K^+ decay experiment.
  - ✓ Building on the NA62 experience.
  - ✓ Same or better performance at **x4** beam intensity.
  - ✓ Main goal: $BR(K^+\to\pi^+\nu\nu)$ measurement at **5%** precision.
  - ✓ Other goals: LFU test in $K^+\to\pi^+\ell^+\ell^-$ decays; LF/LN conservation, first-row CKM unitarity, low-energy QCD tests; hidden sectors.
- **HIKE Phase 2:** a multi-purpose K_L decay experiment.
  - ✓ Phase 1 detectors and a new neutral beamline.
  - ✓ Main goal: first observation & measurement of $K_L\to\pi^0\ell^+\ell^-$ decays.
- Beam-dump physics with $\sim 10^{19}$ pot is part of the HIKE programme.

More details: the upcoming proposal