Search for new physics in kaon decays at NA62

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Outline:

1) Introduction: rare kaon decays
2) NA62 at CERN: $K^+ \to \pi^+ \nu\nu$ and other measurements
3) HIKE at CERN: long-term plans for kaon experiments
4) Summary

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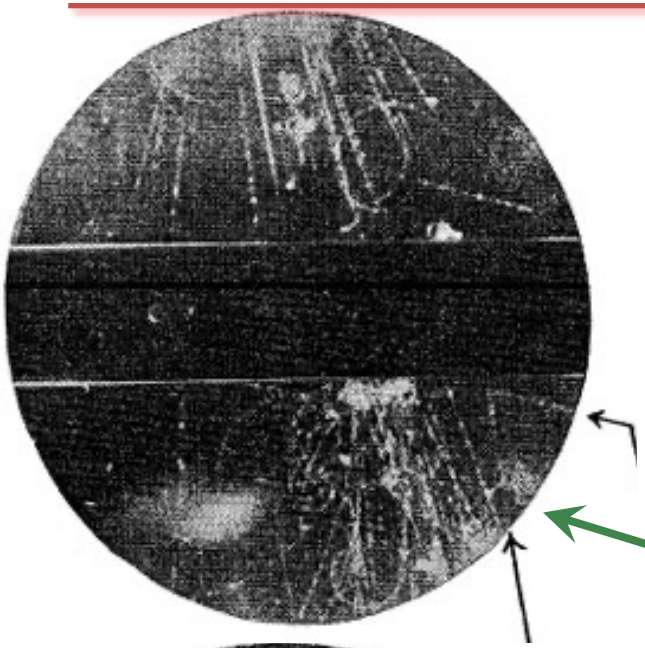
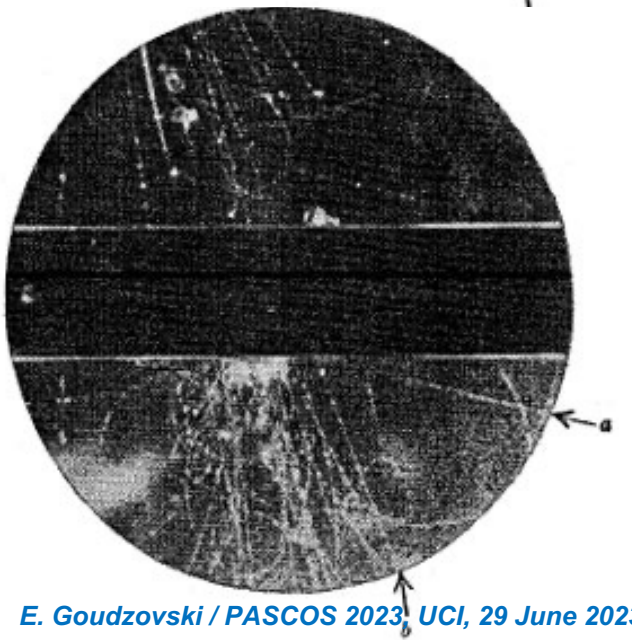
Kaon decay physics

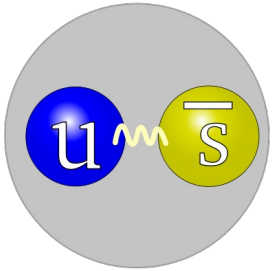




No. 4077 December 20, 1947 NATURE

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

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

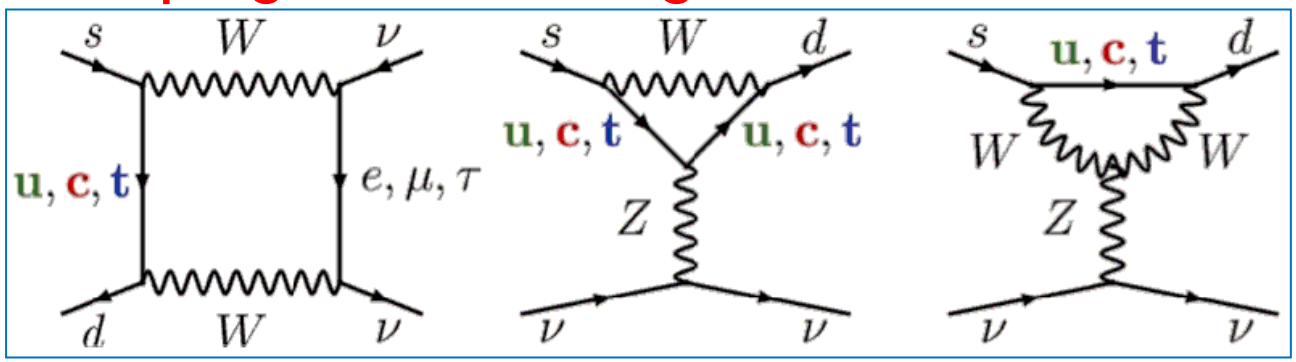


Stereoscopic cloud chamber kaon decay image: $K_S \to \pi^+\pi^-$

- 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.

$K \to \pi\nu\nu$ in the Standard Model

SM: Z-penguin and box diagrams



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

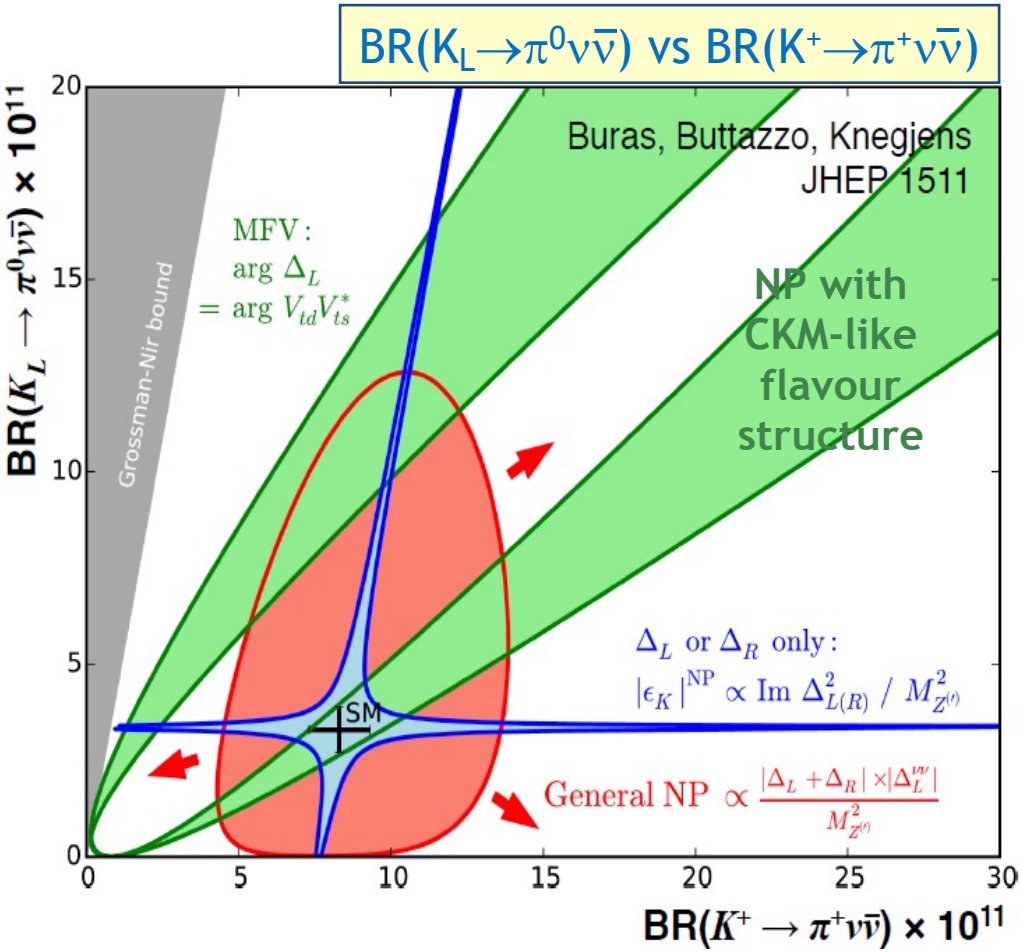
- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- No long-distance contributions from amplitudes with intermediate photons.
- Hadronic matrix element extracted from measured **BR(K_{e3})** via isospin rotation.
- European strategy update 2020: recognised as an **essential activity**.

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]

$K \to \pi\nu\nu$ and new physics

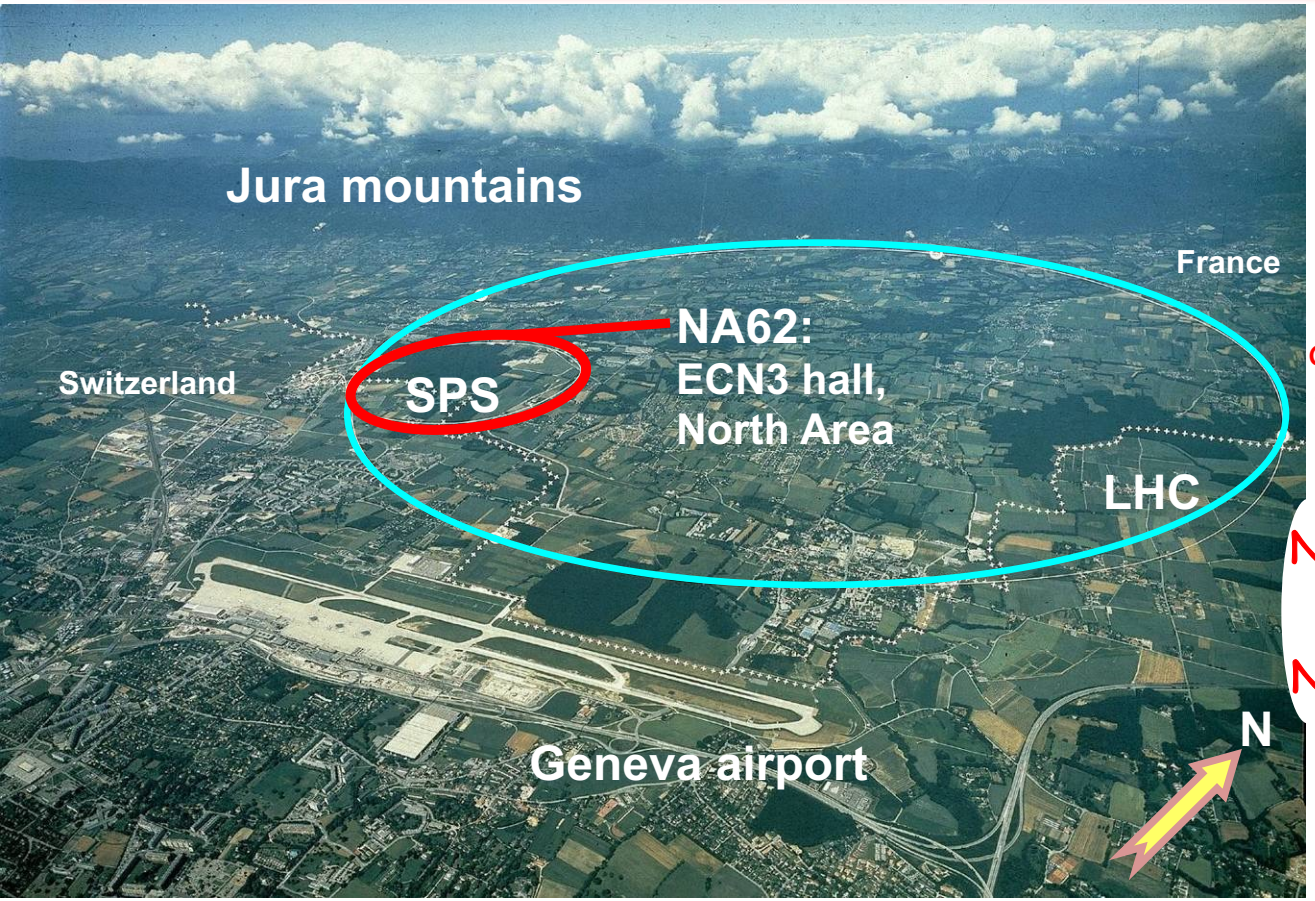
- Correlations between BSM contributions to K^+ and K_L BRs. *[JHEP 11 (2015) 166]*
- Need to measure both K^+ and K_L to discriminate among BSM scenarios (within SM, this allows for a clean β angle measurement).
- Correlations with other observables (ε'/ε, ΔM_K, B decays). *[JHEP 12 (2020) 97]*



- **Green:** CKM-like flavour structure
  - ✓ Models with MFV
- **Blue:** new flavour-violating interactions in which LH or RH couplings dominate
  - ✓ Z′ models with pure LH/RH couplings
- **Red:** general NP models without the above constraints
- **The Grossman-Nir bound:** a model-independent relation

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

Kaon experiments at CERN



Earlier: NA31

NA48 discovery of direct CPV
- 1997: ε'/ε: K_L+K_S
- 1998: K_L+K_S
- 1999: K_L+K_S | K_S HI
- 2000: K_L only | K_S HI
- 2001: K_L+K_S | K_S HI

NA48/1
- 2002: K_S/hyperons

NA48/2
- 2003: K^+/K^-
- 2004: K^+/K^-

NA62 R_K run
- 2007: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests
- 2008: $K^{\pm}_{e2}/K^{\pm}_{\mu 2}$ | tests

NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

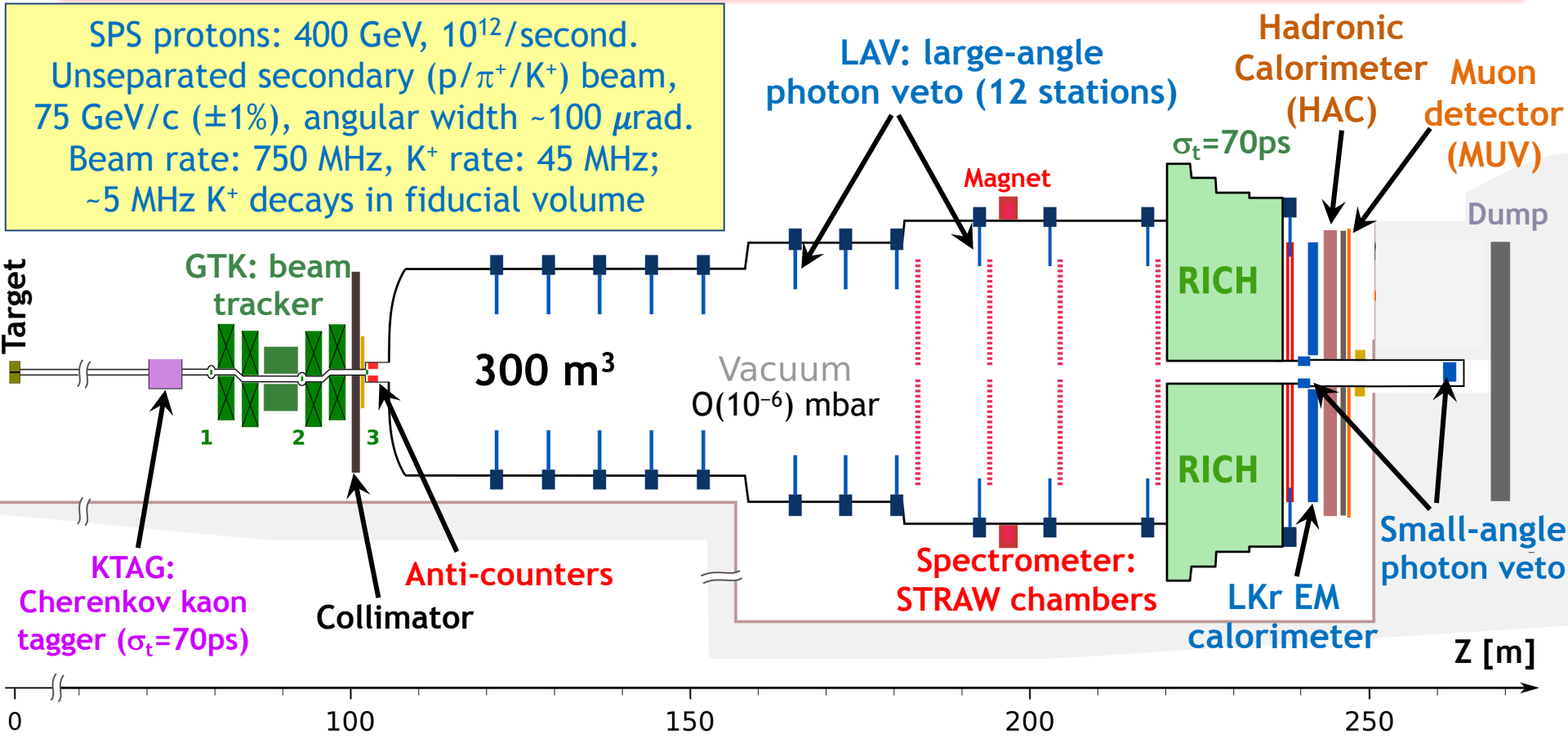
Main NA62 goal: $K^+ \to \pi^+ \nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

Currently ~300 participants from ~30 institutions.

NA62 collaboration, JINST 12 (2017) P05025

The NA62 experiment

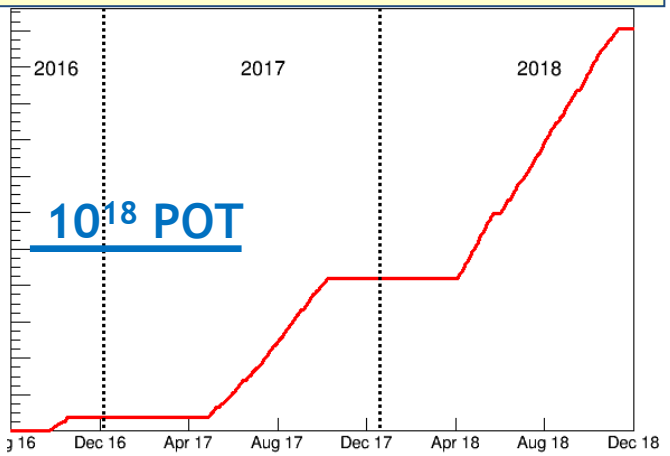
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam,
75 GeV/c (±1%), angular width ~100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- In 2018, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- Single event sensitivities for K^+ decays: approaching BR~10^{-12}.
- Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi0}$>40 GeV) ~10^{-8}.
- Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

NA62 datasets

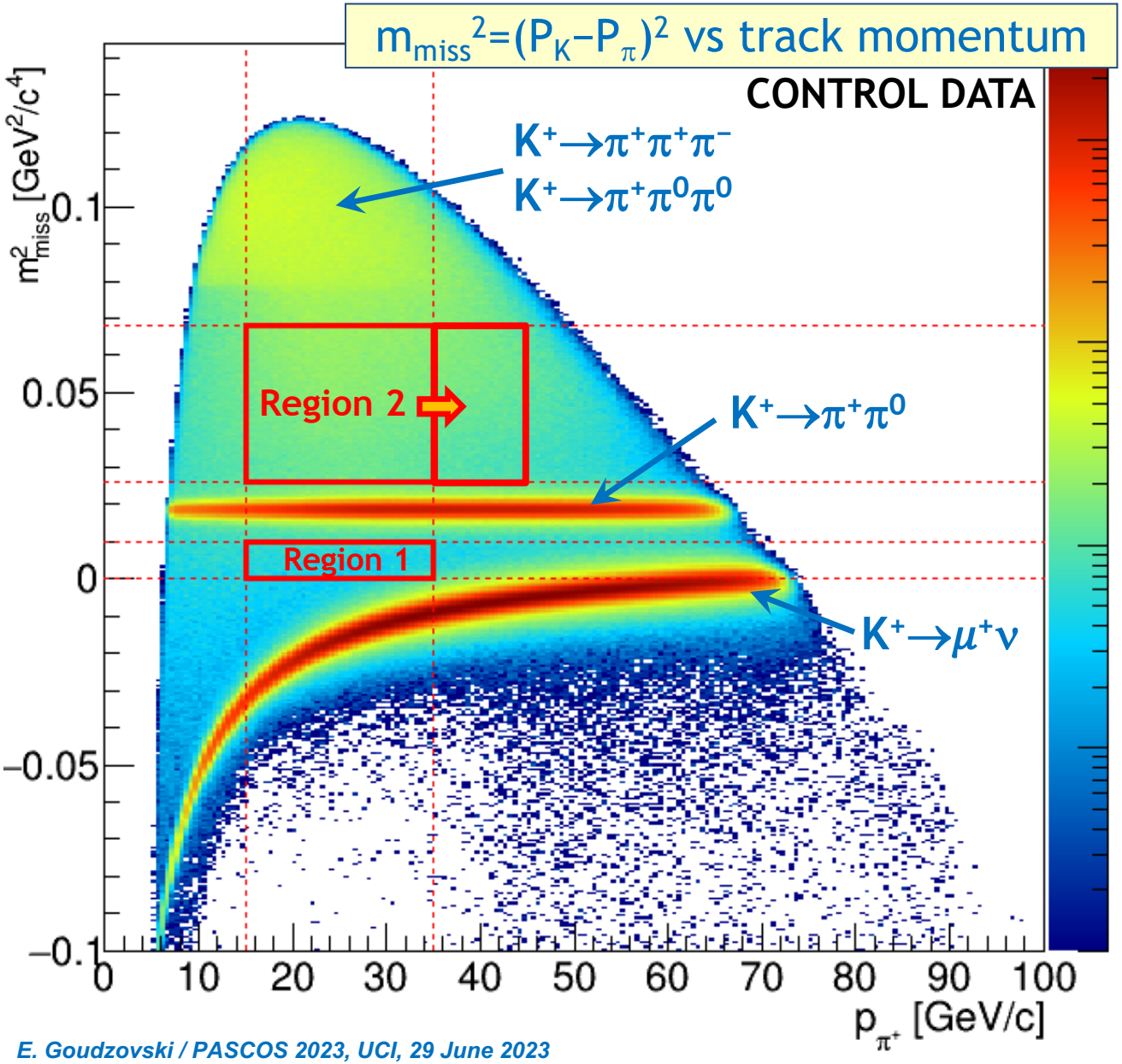
Run 1 integrated luminosity



Run 1: 2.2×10^{18} POT collected
(also 1.4×10^{17} POT in beam-dump mode in 2021)

- **Run 1 (2016–18)**:
  - ✓ Sample **2016** (30 days, **~1.3×10^{12} ppp**): **2×10^{11}** useful **K^+** decays.
  - ✓ Sample **2017** (160 days, **~1.9×10^{12} ppp**): **2×10^{12}** useful **K^+** decays.
  - ✓ Sample **2018** (217 days, **~2.3×10^{12} ppp**): **4×10^{12}** useful **K^+** decays.
- **Run 2 (2021–)**: on track (**~3×10^{12} ppp**), approved till **LS3**.

NA62: $K_{\pi\nu\nu}$ signal regions



Main K^+ decay modes (>90% of BR) rejected kinematically.

Resolution on m^2_{miss}: $\sigma=1.0\times10^{-3}$ GeV^4/c^2.

Measured kinematic background suppression:

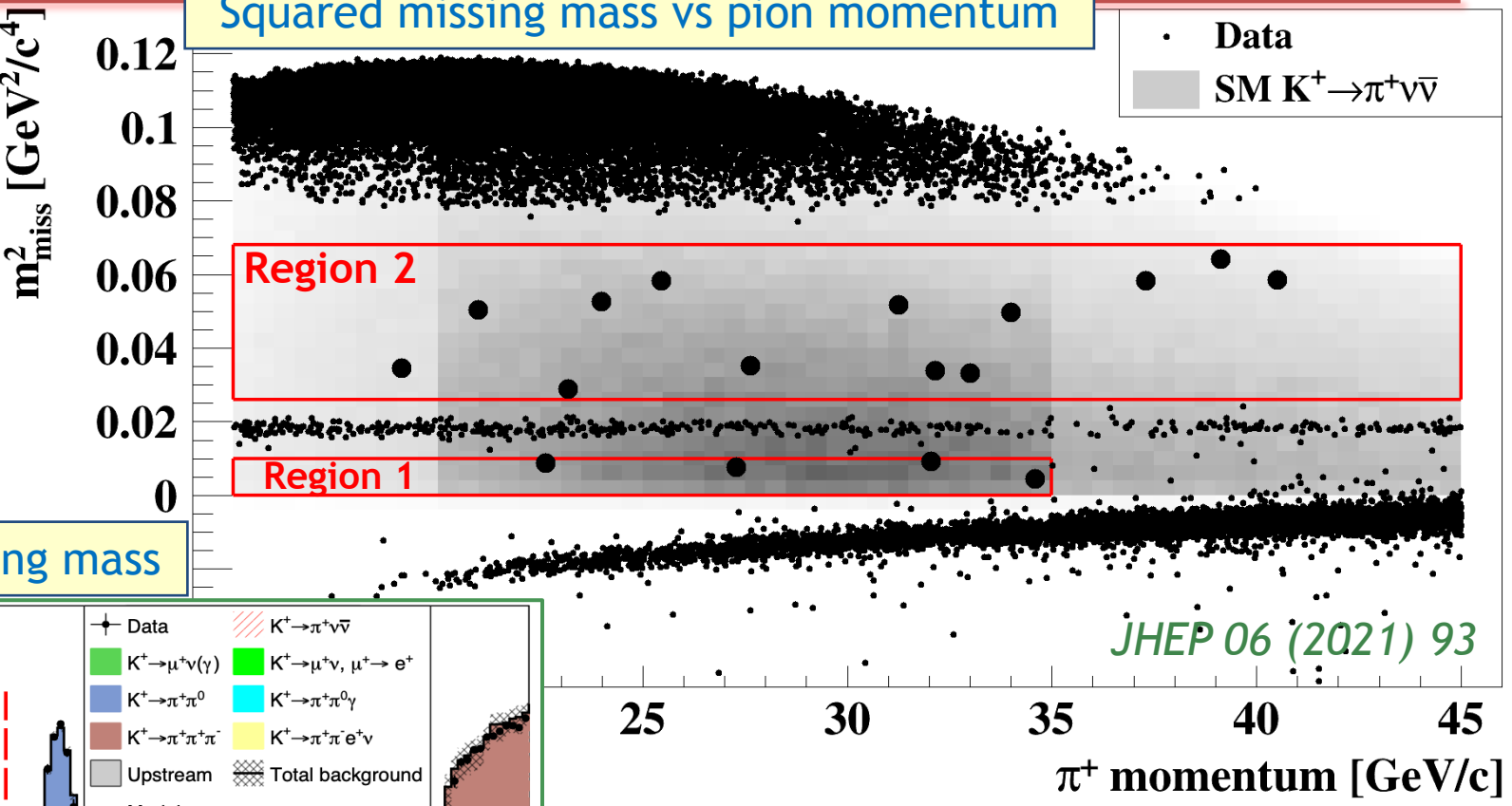
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

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

Opening the box (2018 data)

Squared missing mass vs pion momentum



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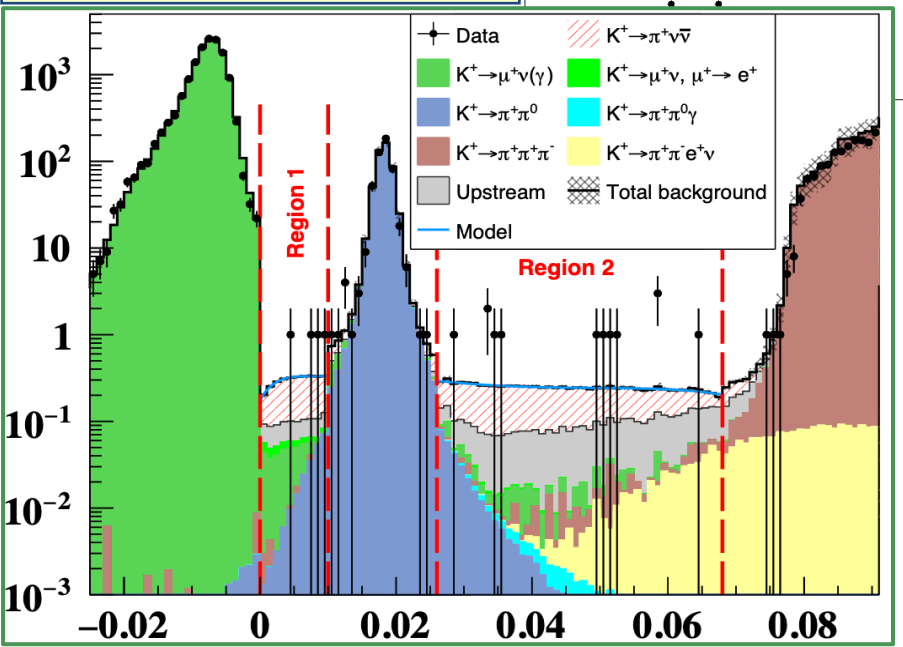
Squared missing mass



Full Run 1 data set:

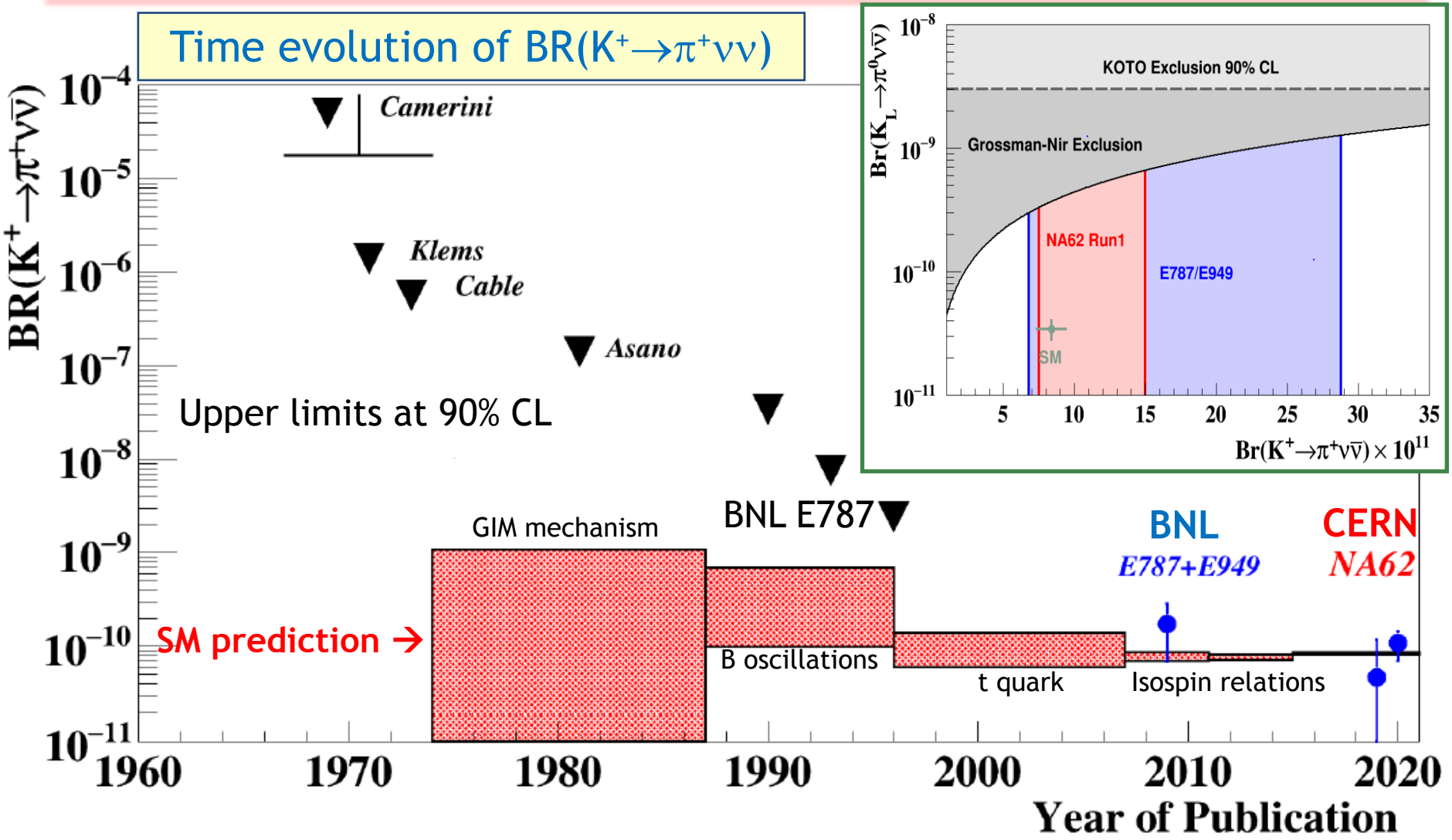
Candidates observed: **20** (**17** in 2018 data)

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

Expected SM events:

$10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

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

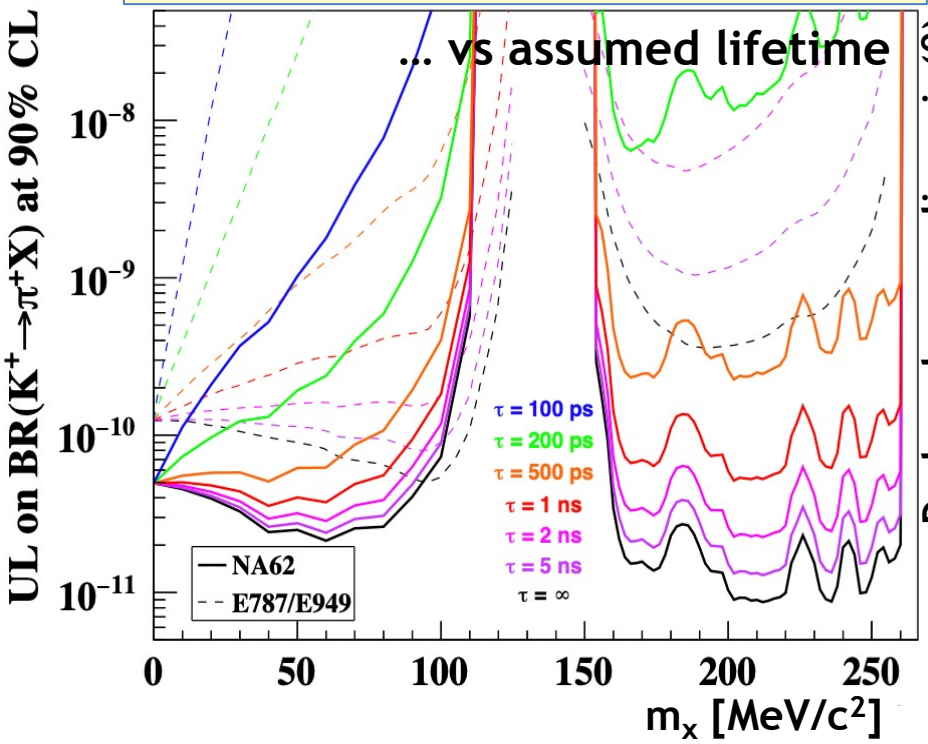


NA62 Run 1: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

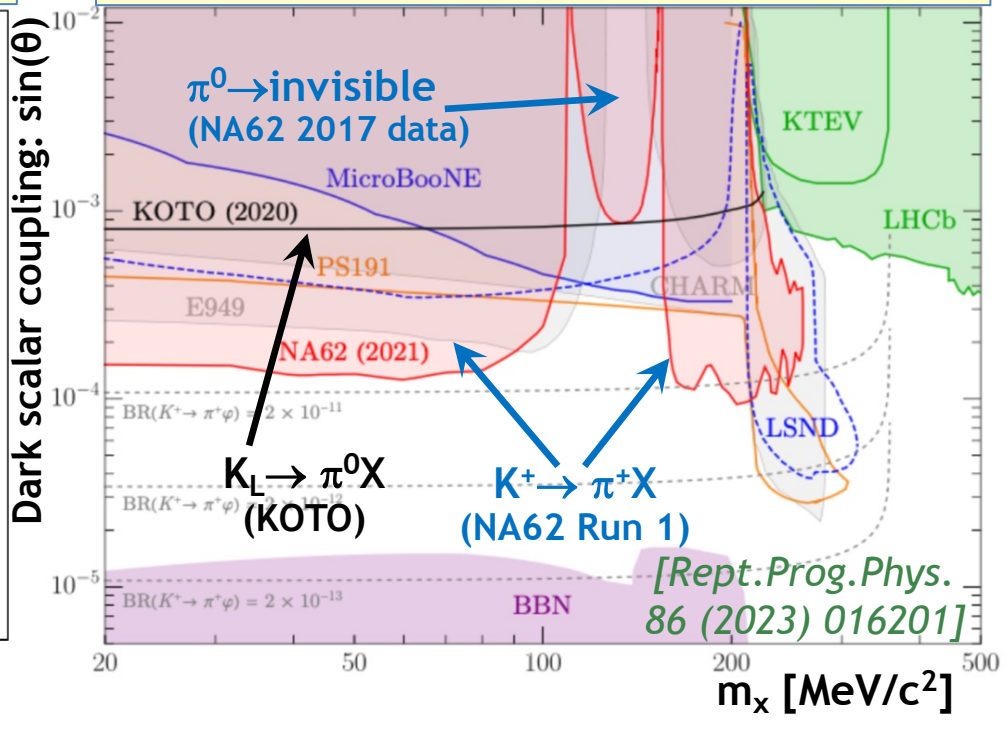
(3.4σ significance)

Search for $K^+ \to \pi^+ X$ (Run 1)

UL at 90% CL of BR($K^+ \to \pi^+ X$) vs m_X



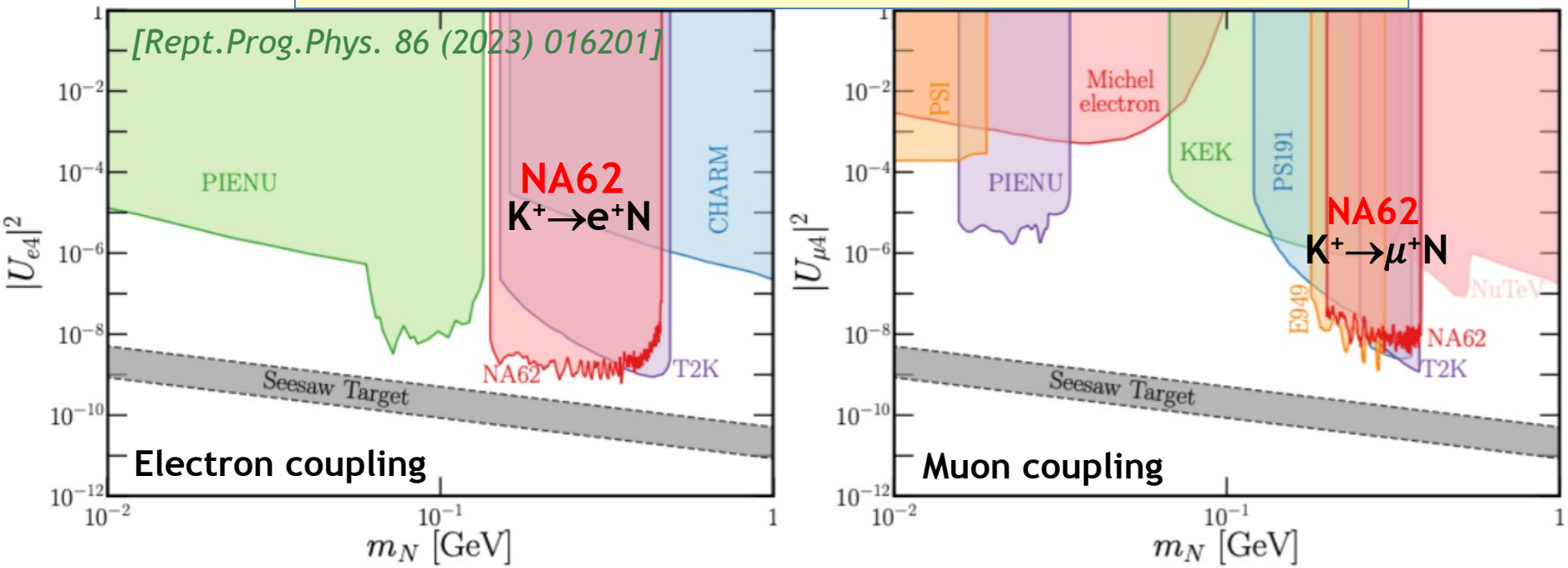
Dark scalar searches below the K mass



- Mass resolution improves with m_X and is $\delta m_x \sim 40$ MeV/c^2 at $m_X=0$.
- Upper limits of BR($K^+ \to \pi^+ X$) established depending on X mass and lifetime.
- Improvement on BNL-E949 *[PRD79 (2009) 092004]* over most of m_x range.
- Interpreted within the dark scalar and ALP (fermionic coupling) models
  [EPJ C81 (2021) 1015; Rept.Prog.Phys. 86 (2023) 016201]
- Note the **KOTO** result based on 2016–18 data. *[PRL125 (2021) 021801]*

Search for HNL production

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches



- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+N$ at BNL-E949.
- In both cases, complementary to HNL *decay* searches at T2K.
- Future kaon and pion experiments will approach the seesaw bound.

- An upper limit at 90% CL: $BR(K^+ \to \mu^+\nu\nu\nu) < 1.0 \times 10^{-6}$, and similar limits on $BR(K^+ \to \mu^+\nu X)$, with X=invisible.

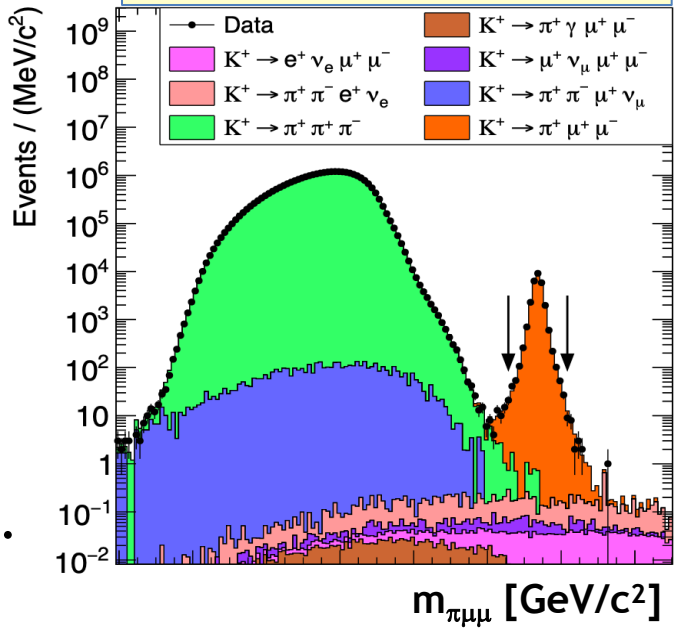
[PLB 807 (2020) 135599; PLB 816 (2021) 136259]

Other NA62 results

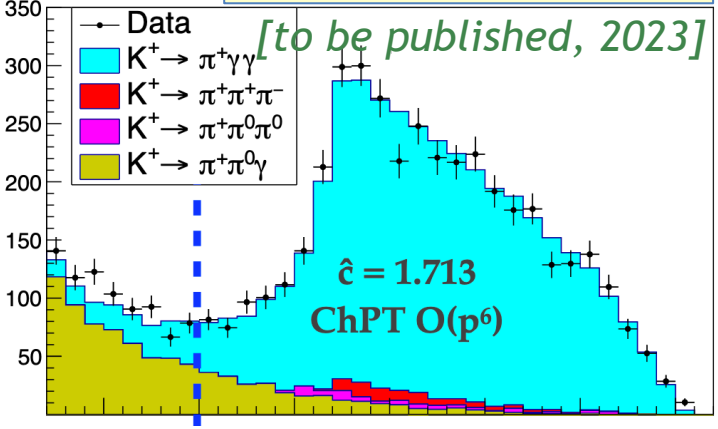
Broader NA62 physics programme:

- Precision measurements of rare K^+ decays with the world's largest samples:
  $K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^0 e^+ \nu\gamma$, $K^+ \to \pi^+\gamma\gamma$.
  [JHEP 11 (2022) 11, arXiv:2304.12271]
- Searches for LFV/LNV in K^+ decays at the $O(10^{-11})$ sensitivity:
  $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^- \pi^0 e^+ e^+$, $K^+ \to \pi^- \mu^+ \mu^+$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^+ \mu^- e^+$, $\pi^0 \to \mu^- e^+$, $K^+ \to \mu^- \nu e^+ e^+$.
  [PLB 797 (2019) 134794, PRL 127 (2021) 131802, PLB 830 (2022) 137172, PLB 838 (2023) 137679]
- Searches for hidden-sector mediator production in K^+ decays.
  [JHEP 05 (2019) 182, PLB 807 (2020) 135599, PLB 816 (2021) 136259, JHEP 02 (2021) 201, JHEP 03 (2021) 058]
- A dedicated beam-dump programme. First result: $A' \to \mu^+\mu^-$ *[arXiv:2303.08666]*

$K^+ \to \pi^+\mu^+\mu^-$ measurement

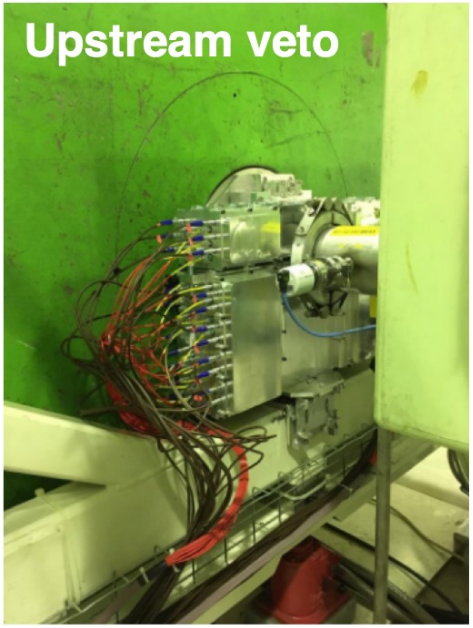


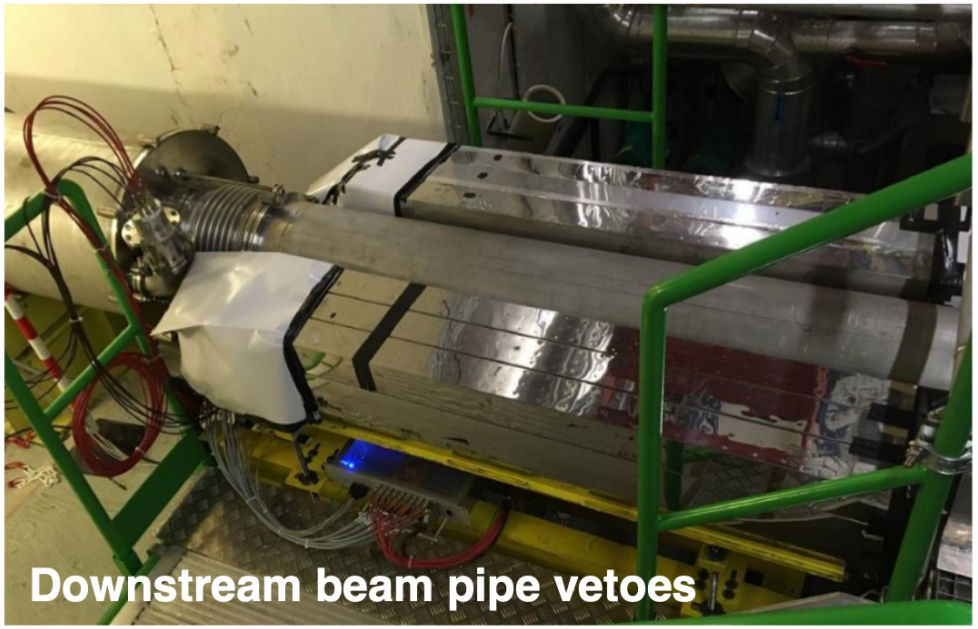
Preliminary: $K^+ \to \pi^+\gamma\gamma$ *[to be published, 2023]*



NA62 Run 2: 2021–LS3

- Run 2: $K^+ \to \pi^+ \nu\nu$ measurement at ~10% precision in a low-background, high-acceptance regime, with an established technique.
- Modifications of the setup for background reduction:
  - ✓ fourth kaon beam tracker (GTK) station;
  - ✓ rearrangement of beamline elements around the GTK achromat;
  - ✓ new veto counters upstream and downstream of the decay volume;
  - ✓ new kaon tagger with hydrogen radiator (CEDAR-H, since 2023).
- Improved TDAQ: beam intensity increased by ~30% wrt Run 1.

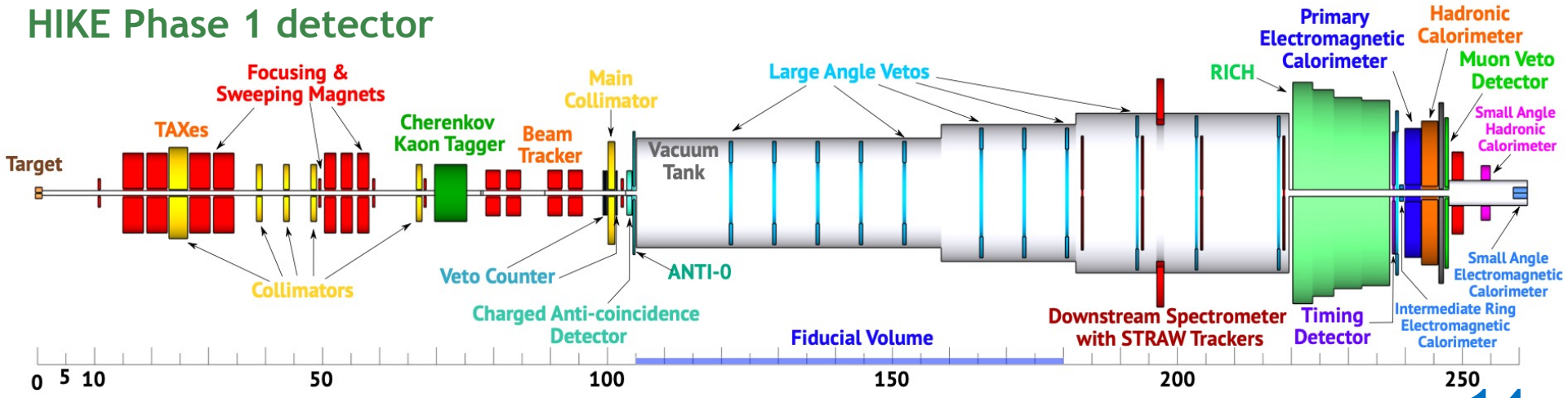




The HIKE proposal

- 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: **with up to ×6** the NA62 (**~1.5×10^{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 **2023**.

HIKE Phase 1 detector



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

A multi-purpose K^+ experiment focused on $K^+ \to \pi^+ \nu\nu$ at ~5% precision.

- ✓ Challenge: 20 ps time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.
- ✓ Challenges aligned with HL-LHC projects and future flavour/dark matter exp.

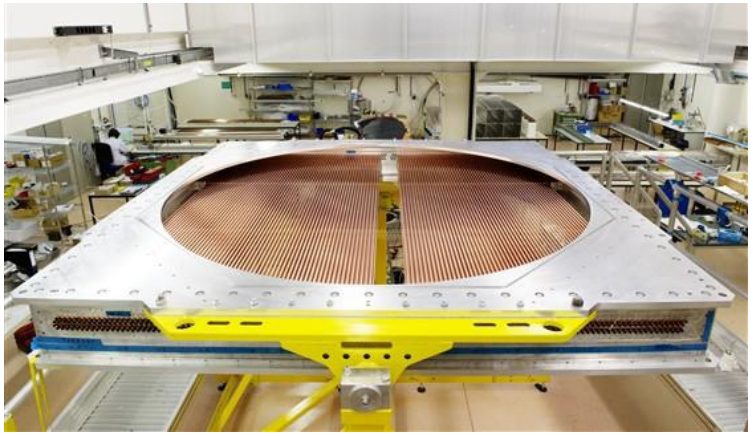
New pixel beam tracker (GTK):

time resolution: <50 ps per plane;
pixel size: <300×300 μm^2;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: >3 GHz on 30×60 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

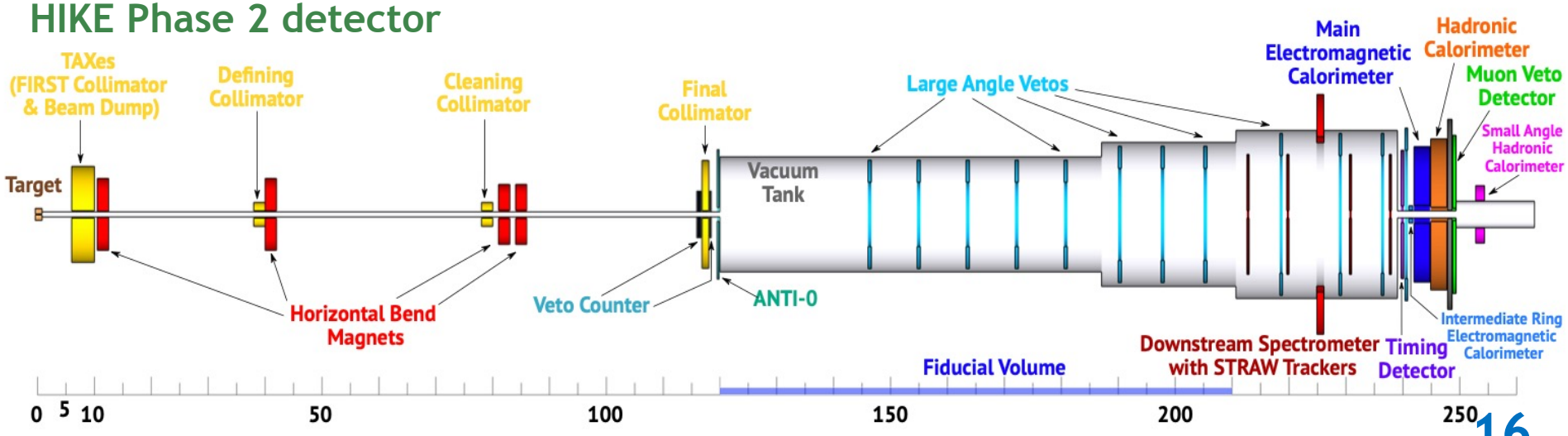


A current NA62 STRAW chamber

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

- A multi-purpose K_L experiment focused on $K_L \to \pi^0 \ell^+ \ell^-$ at ~20% precision.
  - ✓ high-energy K_L beam (80 GeV/c mean momentum);
  - ✓ reconfigured Phase 1 detector; several subdetectors removed.
- Physics objectives:
  - ✓ **BR($K_L \to \pi^0 \ell^+ \ell^-$)**: measurements to a 20% accuracy.
    Challenge: reduction of the Greenlee background ($K_L \to \gamma\gamma \ell^+ \ell^-$).
  - ✓ Search for LFV decays at 10^{-12} level: $K_L \to (\pi^0)(\pi^0)\mu e$, $K_L \to 2\mu 2e$.
  - ✓ Rare K_L decays: low-energy QCD tests; $|V_{us}|$ measurements.
  - ✓ Searches for hidden-sector mediator production in K_L decays.

HIKE Phase 2 detector



Summary

- Rare kaon decays ($K \to \pi\nu\nu$, …): unique probes for heavy new physics at the **O(100 TeV)** mass scale, and for light hidden sectors.
- NA62 Run 1 result:

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

- NA62 Run 2: aiming at **O(10%)** precision on **BR($K^+ \to \pi^+\nu\nu$)** by **2025**.
- Other NA62 Run 1 results: all aspects of **K^+** decay physics.
- Precision measurements of both **K^+** and **K^0** decays are essential.
- HIKE at CERN: a proposal for next-generation rare **K^+** and **K_L** decay experiments with high-intensity beams.