
BREAKING NEWS > New catalyst developed for sustainable propylene production from biomass

Physicists Just Discovered The Rarest Particle Decay Ever

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TECHNOLOGY

Kaon and pion experiments

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Outline

1) Current kaon experiments: NA62 at CERN, KOTO at J-PARC
2) Next-generation kaon experiment: KOTO-II
3) Rare pion decays: PIONEER at PSI
4) Summary

CERN

ECFA-UK meeting on European Strategy

IPPP Durham • 25 September 2024

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Kaons: European and UK strategy

European Strategy 2020

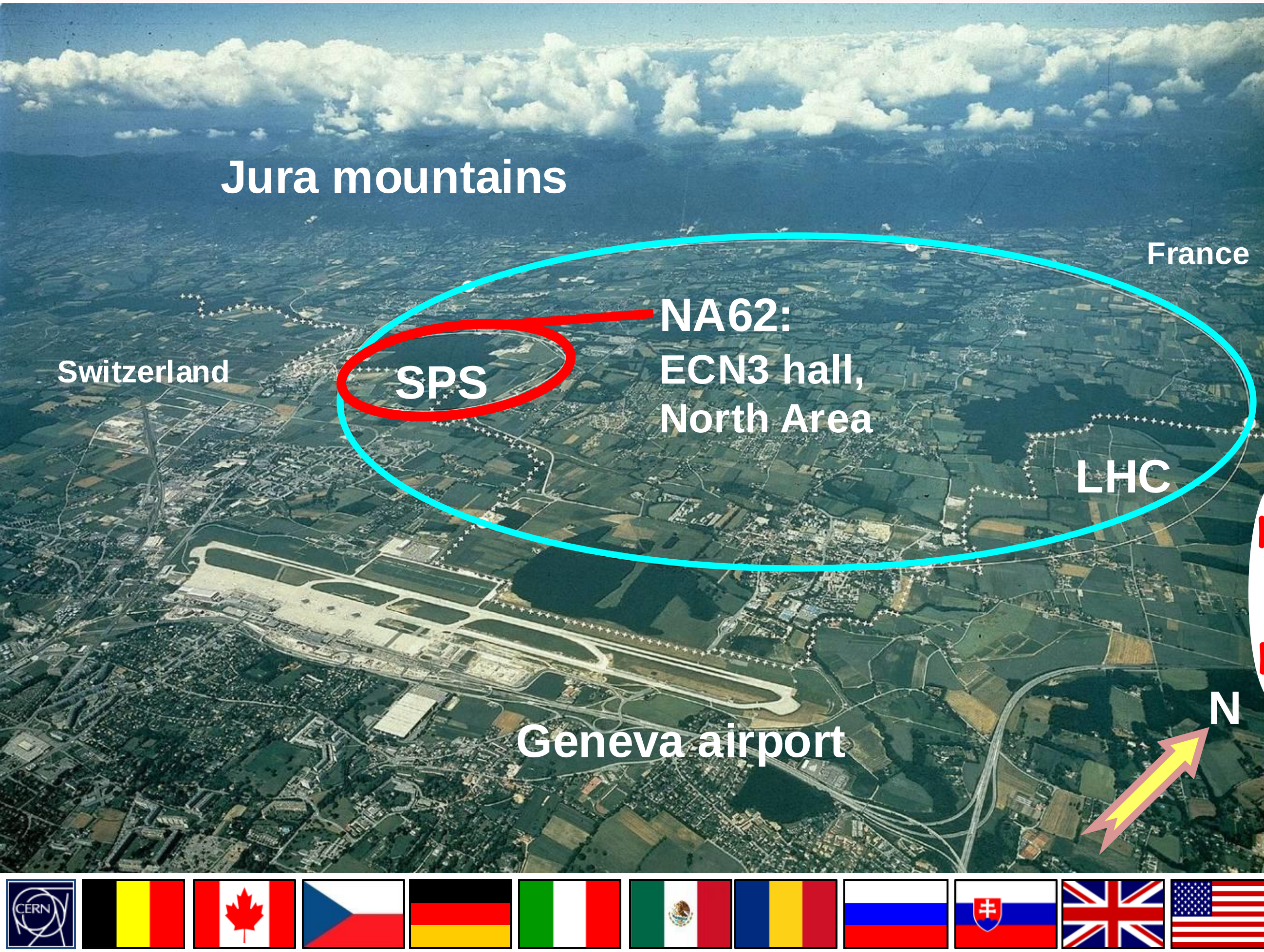
- “Other essential scientific activities for particle physics”
  - ✓ “… exploration of flavour and fundamental symmetries are crucial components of the search for new physics”
  - ✓ “These [experiments] include measurements of … *rare kaon decays at CERN and KEK*”

PPAP Roadmap 2021

- Recommendation 5.2: “The UK has a leading role in the scientific exploitation of the current generation of kaon experiments. The UK should … invest into the *future CERN kaon experiments*”

Current kaon experiments

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: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests
- 2008: $K^\pm_{e2}/K^\pm_{\mu2}$ | tests

NA62
- 2015: commissioning
- 2016–18: Run 1
- 2021–LS3: Run 2

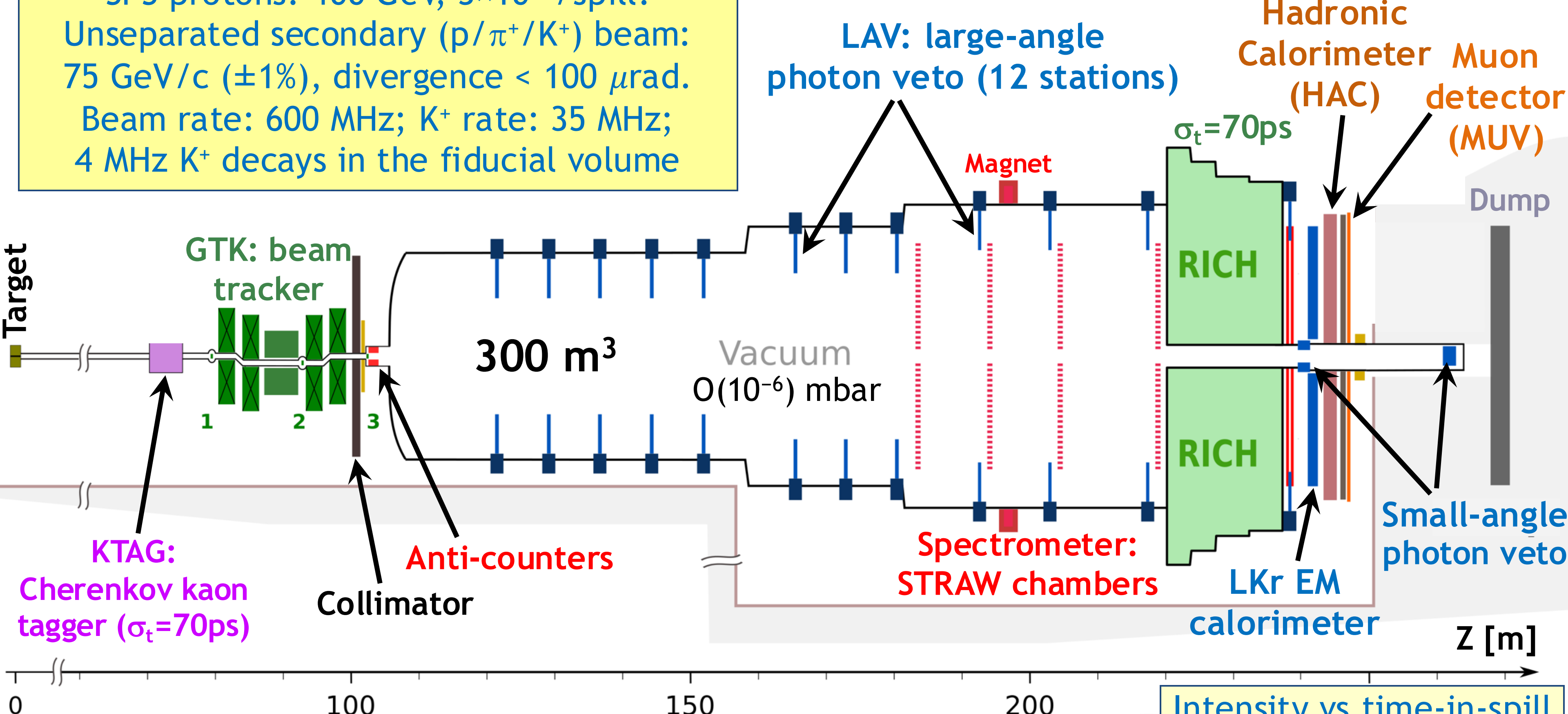
NA62: a multi-purpose K^+ (and π^0) decay experiment focused on $K^+\to\pi^+\nu\nu$ measurement to 15% precision

Strong UK leadership at all levels

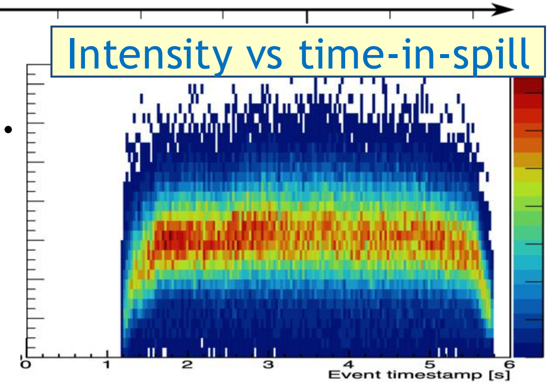
NA62 experiment at CERN

JINST 12 (2017) P05025

SPS protons: 400 GeV, 3×10^{12}/spill.
Unseparated secondary ($p/\pi^+/K^+$) beam:
75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 600 MHz; K^+ rate: 35 MHz;
4 MHz K^+ decays in the fiducial volume

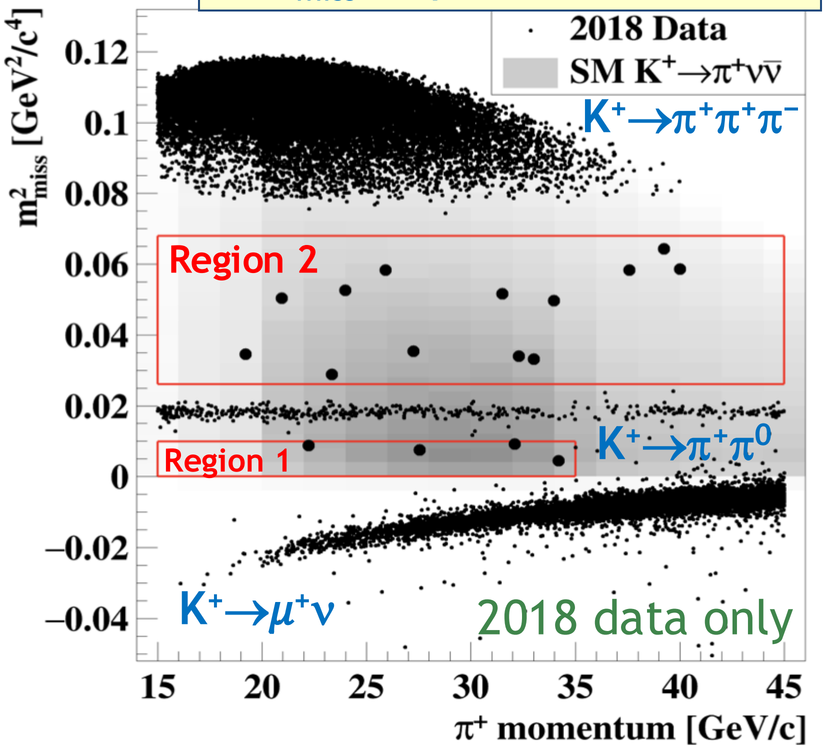


- One year ≈ 2×10^{18} protons on target ≈ 5×10^{12} K^+ decays.
- Beam structure: ideally, uniform over a 4.8 s long spill.
- In practice, significant variations of instantaneous beam intensity during the spill.

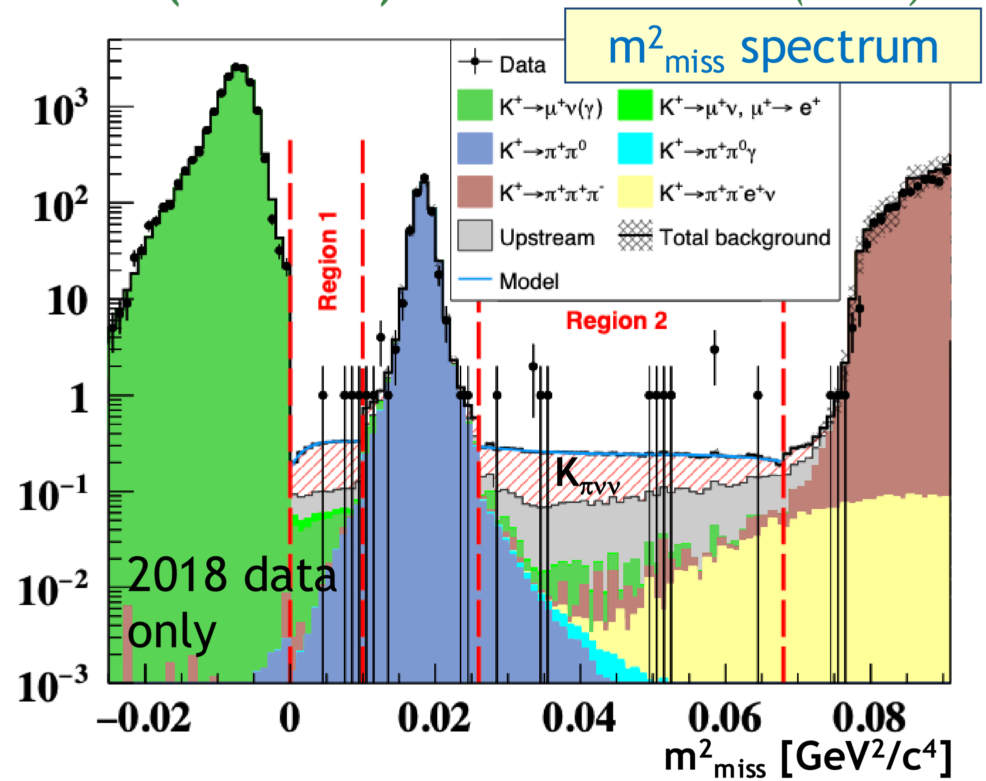


$K_{\pi\nu\nu}$@NA62: 3.4σ evidence

m^2_{miss} vs pion momentum



Run 1 (2016–18) dataset: *JHEP 06 (2021) 93*

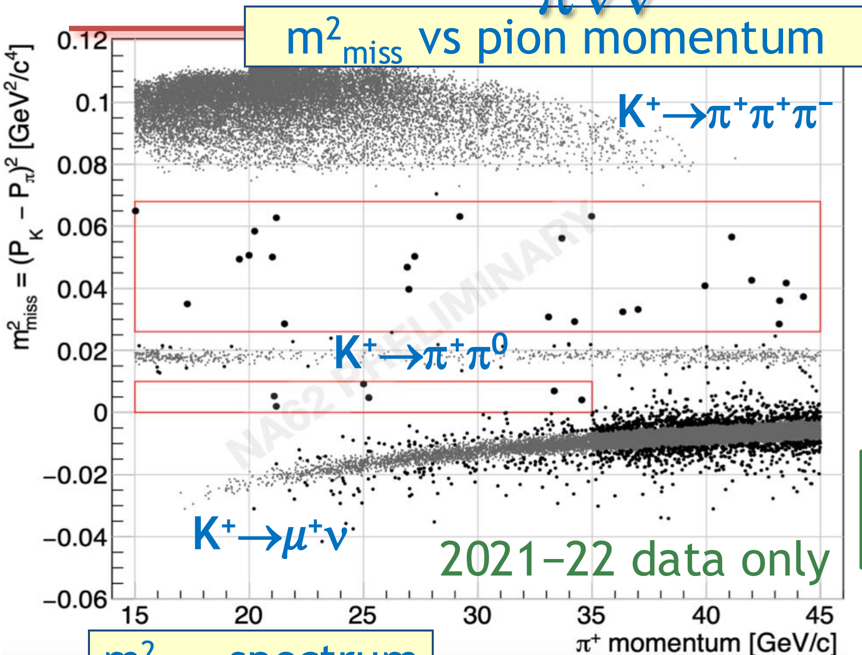


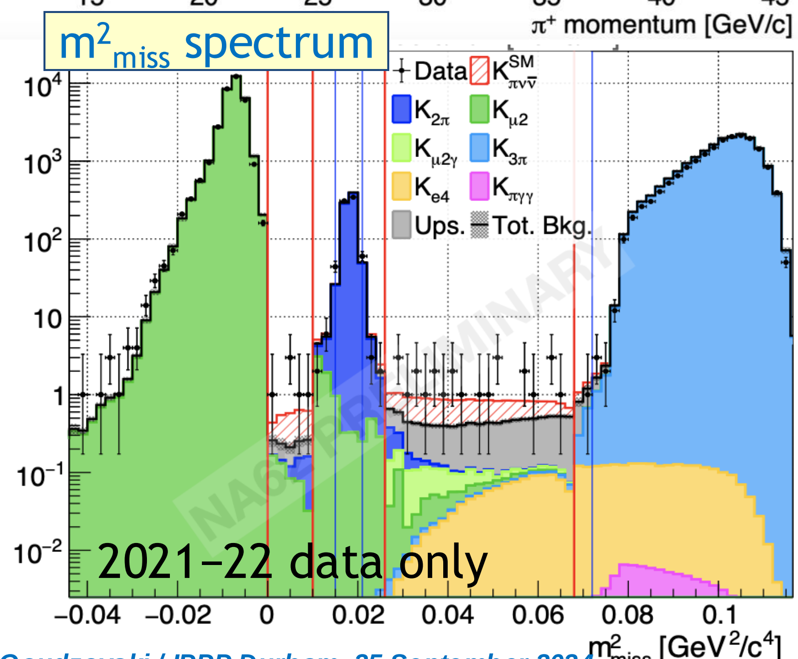
Run 1 dataset: **20** candidates observed; expected background: $7.03^{+1.05}_{-0.82}$

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

- NA62 Run 2 started in **2021**: upgraded setup, **~30%** higher beam intensity.
- Signal yield per SPS spill improved by **50%** wrt Run 1.
- Full NA62 dataset (by **LS3**) projected to be about **×5** the Run 1 dataset.

$K_{\pi\nu\nu}$@NA62: 5σ observation



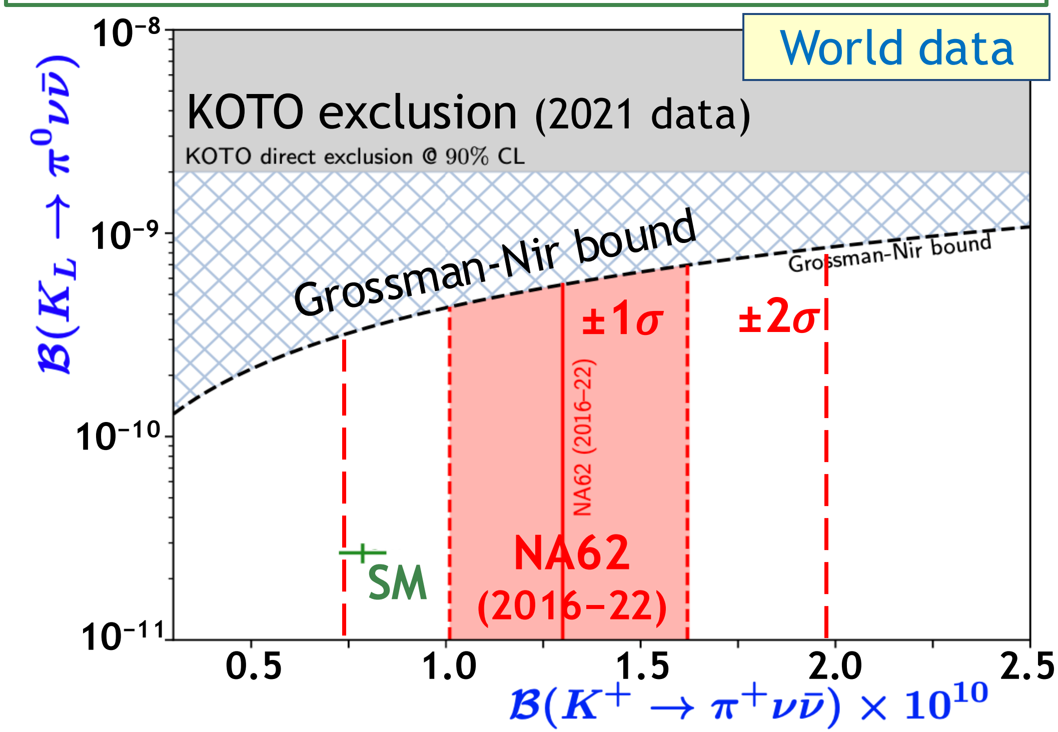


New: *CERN EP seminar, 24 Sep 2024*

The **2021–22** dataset has been analysed.
In the full **2016–22** dataset,
candidates observed: **51**;
expected background: $18.1^{+2.3}_{-1.6}$

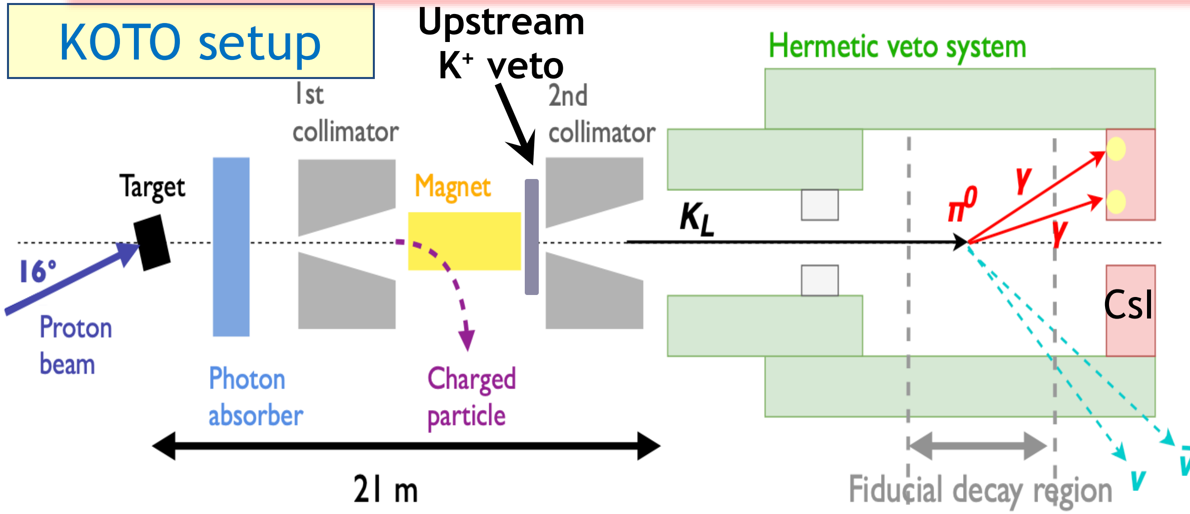
Combined 2016–22 result (**5σ observation**):

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$



KOTO experiment at J-PARC

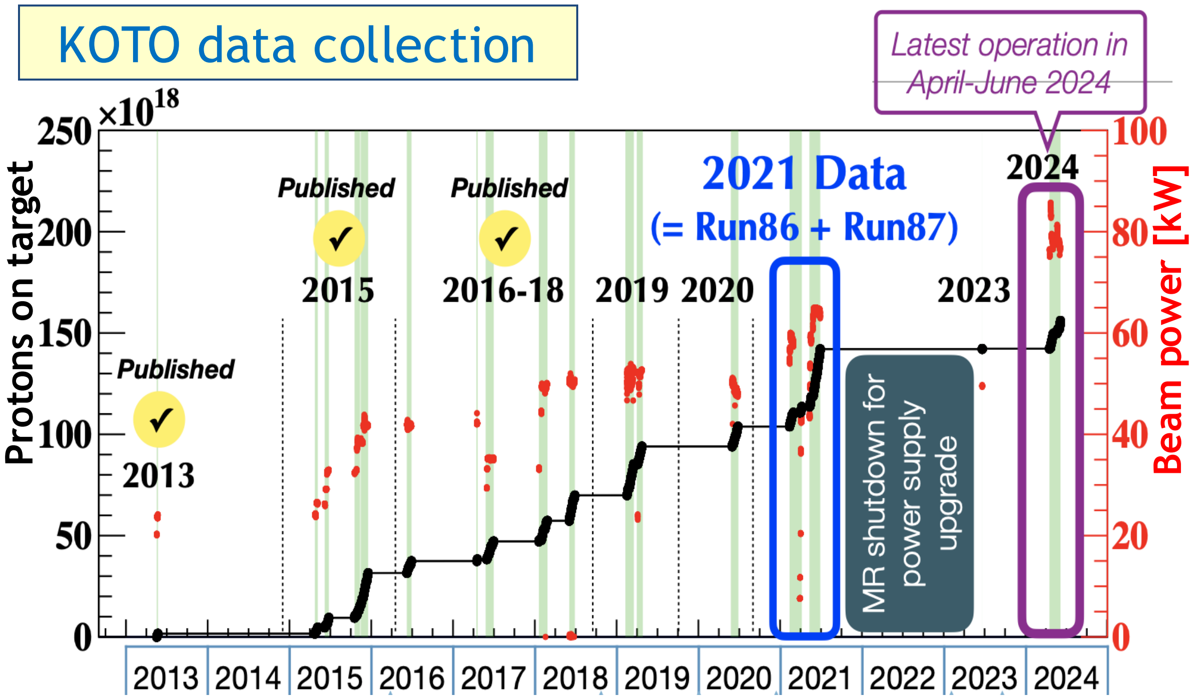
KOTO setup



Primary KOTO goal: search for $K_L \to \pi^0 \nu\nu$, single-event sensitivity $<10^{-10}$

- Primary proton beam: **30 GeV**; **60 kW = 6.6×10^{13}/5.2 s**.
- Secondary K_L beam: peak momentum **1.4 GeV/c**.
- Beam composition: K_L, neutrons, photons.
- Decay region length: **~2 m**.
- Hermetic photon detector, including CsI calorimeter.
- Progressive improvements to the setup; upstream K^+ veto installed in **2020**.

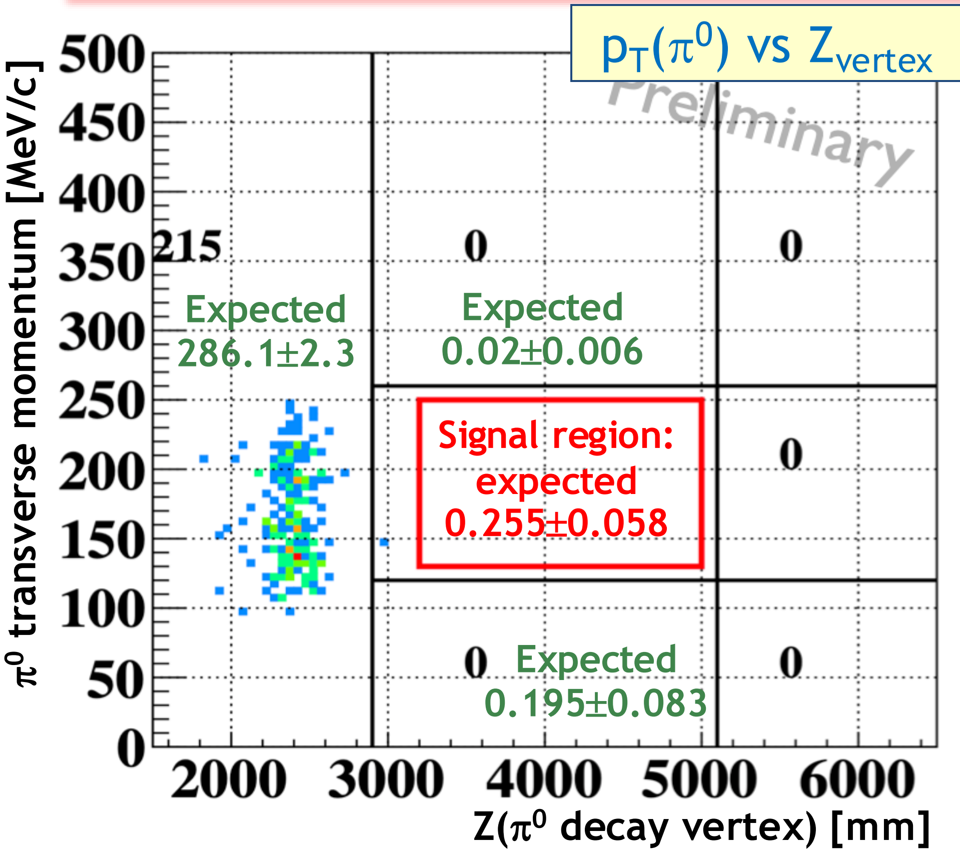
KOTO data collection



PTEP 2017 (2017) 021C01
PRL 122 (2019) 021802
PRL 126 (2021) 121801

KOTO: $K_L \to \pi^0 \nu\nu$ (2021 dataset)

[Preliminary; EPJ C84 (2024) 377]



- Number of K_L decays: $N_K=6.8\times10^{12}$.
- Single-event sensitivity: $BR_{SES}=8.7\times10^{-10}$ ($30\times BR_{SM}$).
- Background: 0.255±0.058 events (upstream π^0, $K_L\to2\pi^0$, $K^+\to\pi^0 e^+\nu$, scattered $K_L\to2\gamma$, hadron clusters).
- No candidates observed in the data.
- Preliminary result: $BR(K_L\to\pi^0\nu\nu)<2.0\times10^{-9}$ at 90% CL.

KOTO plans:

- Accumulate ×10 the 2021 dataset by 2027 (beam power up to 100 kW).
- Reduce B/S by a factor of 2 (improved beam; hardware upgrades).
- Reach a single-event sensitivity of $(5-8)\times10^{-11}$.
- Reach the Grossman-Nir bound, $BR(K_L) < 4.3\times BR(K^+)$.

Next-generation kaon experiment: KOTO-II

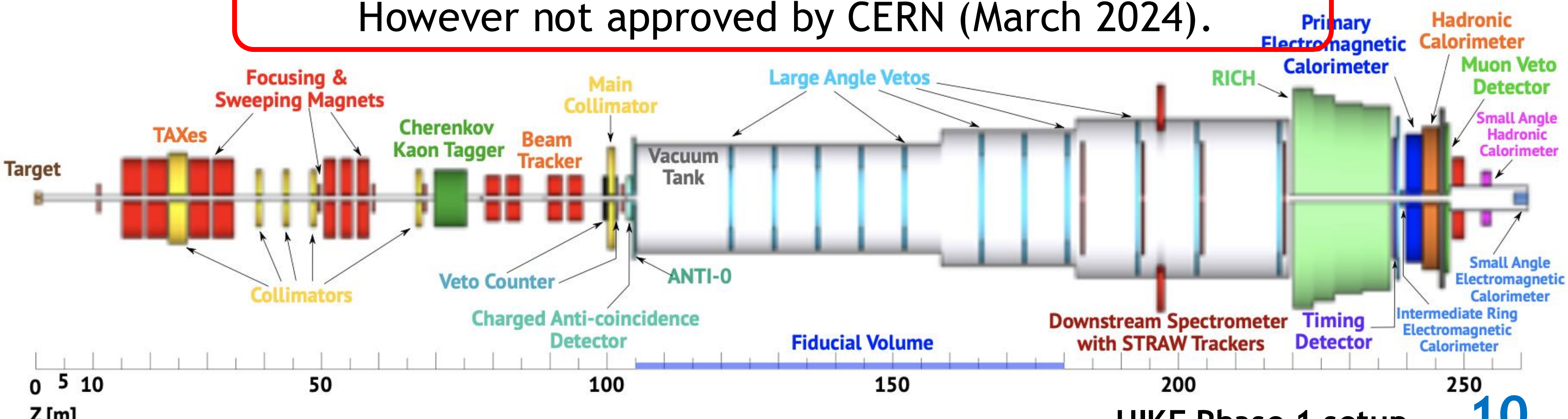
HIKE proposal at CERN

CERN-SPSC-2023-031, arXiv:2311.08231

Proposal for a staged high-intensity (**5×NA62**) kaon programme at the CERN SPS, with a strong UK leadership.

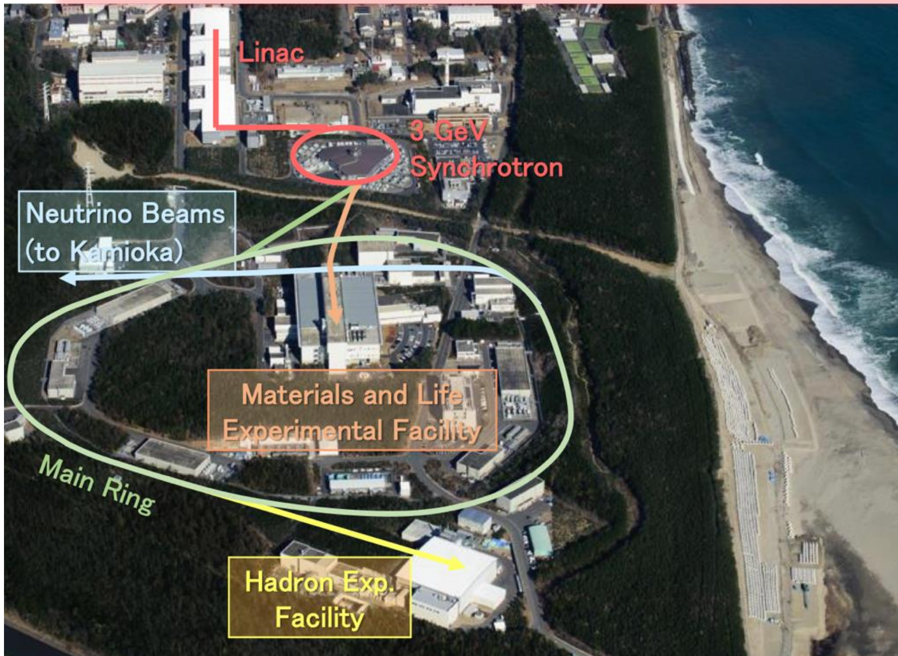
- Phase 1: a multi-purpose K^+ experiment; $BR(K^+ \to \pi^+ \nu\nu)$ to **5%** precision.
  - ✓ Four years of data collection with K^+ beam.
  - ✓ Four years in beam-dump mode, along with SHADOWS exp (5×10^{19} pot).
- Phase 2: a multi-purpose K_L experiment; $BR(K_L \to \pi^0 \ell^+ \ell^-)$ to **15%** precision.
  - ✓ Five years of data collection with K_L beam.
- Phase 3: a dedicated $K_L \to \pi^0 \nu\nu$ experiment.

CERN research board conclusion: excellent physics case.
However not approved by CERN (March 2024).

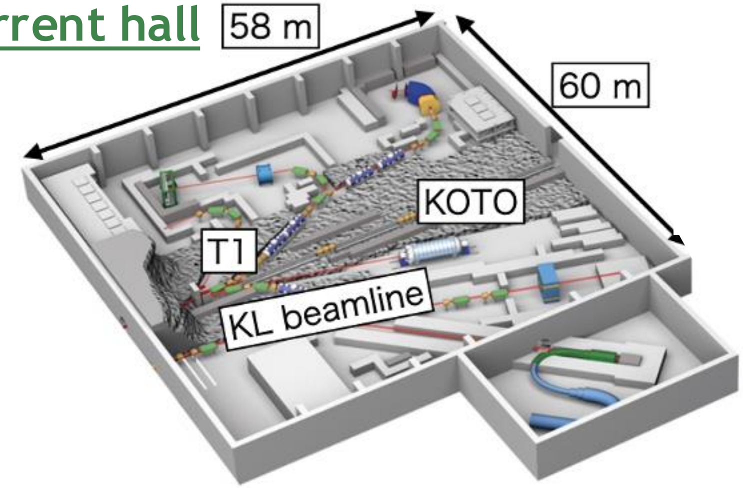


HIKE Phase 1 setup

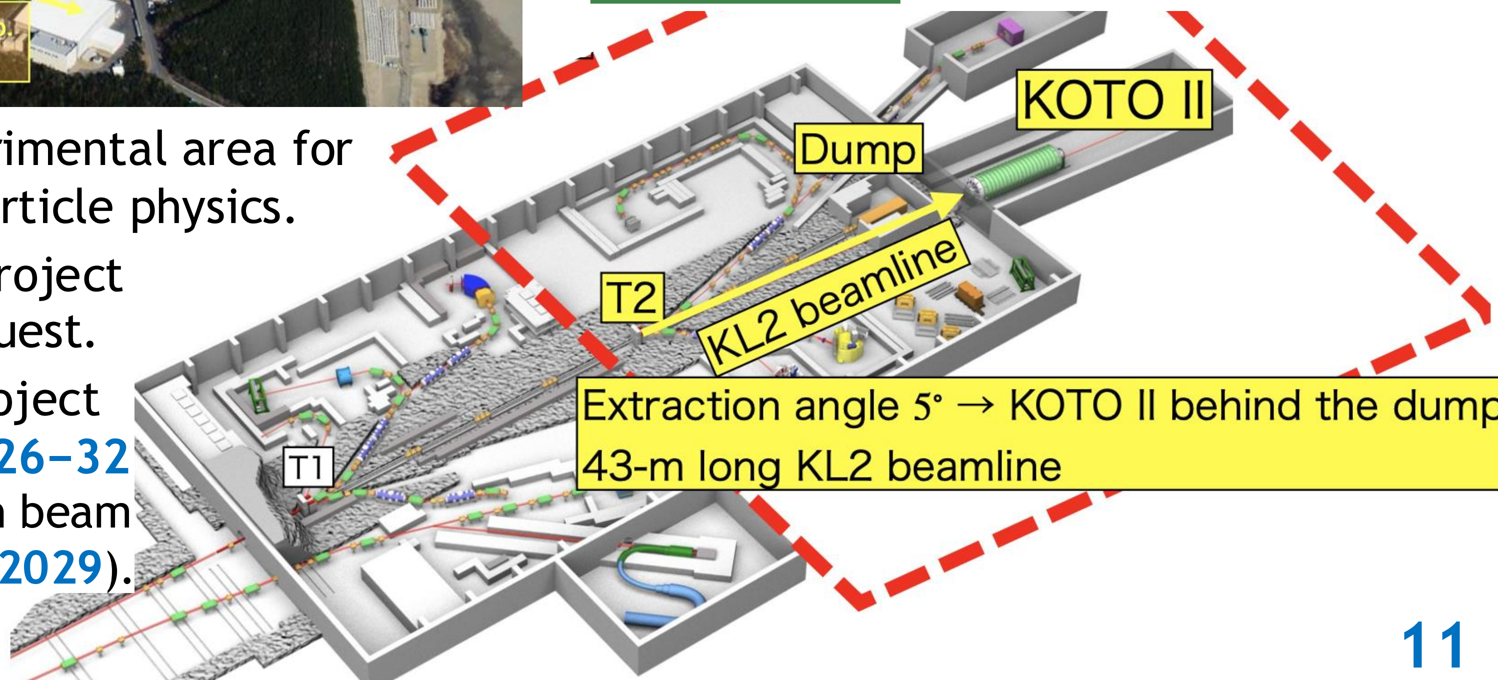
J-PARC Hadron Hall extension



Current hall



Extended hall

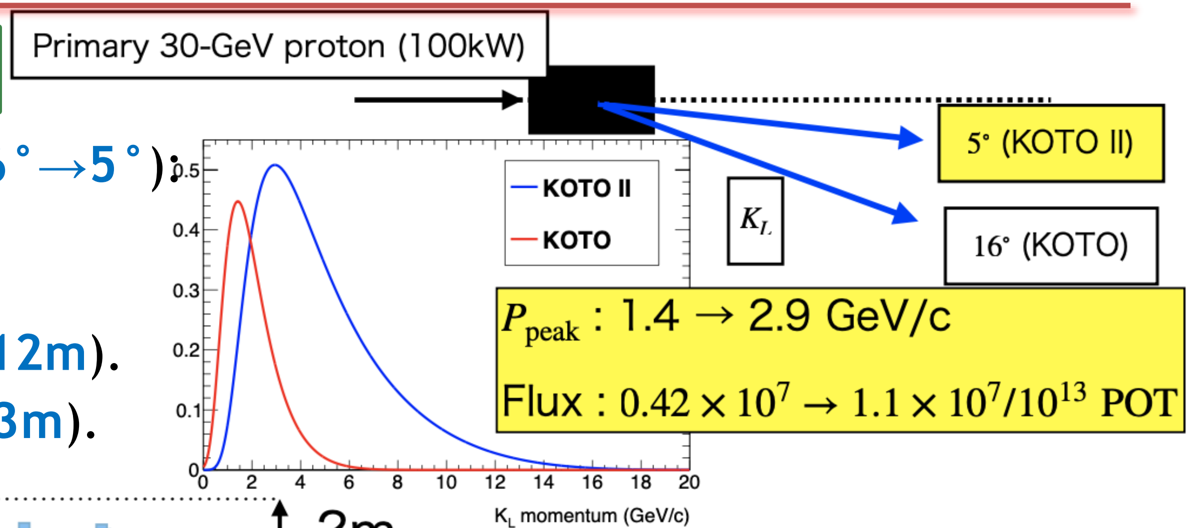


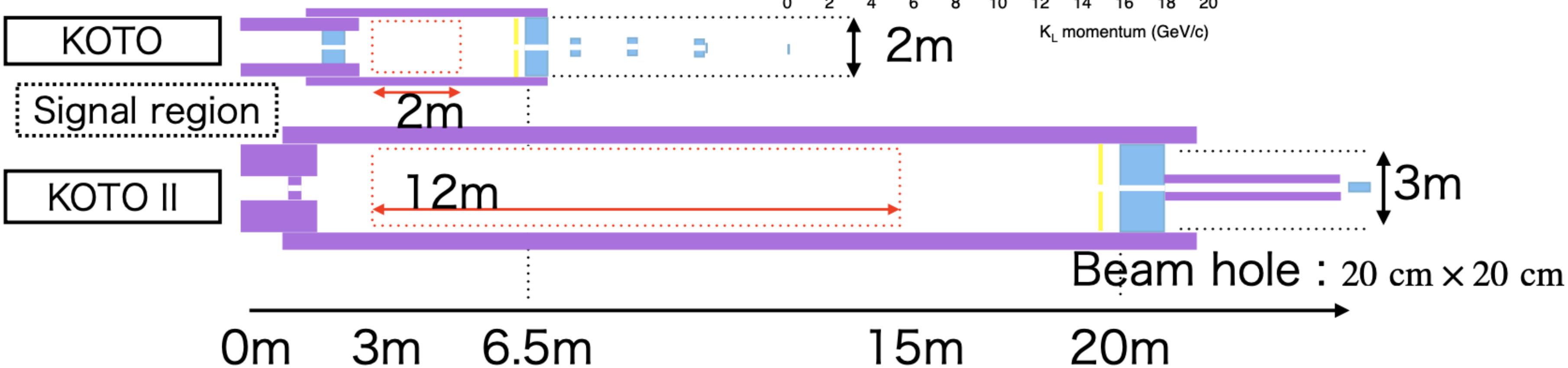
- ❖ Doubling experimental area for nuclear and particle physics.
- ❖ First-priority project for budget request.
- ❖ Anticipated project time scale: **2026–32** (in parallel with beam operation until **2029**).
- ❖ Cost ≈ **$100M**.

KOTO-II proposal at J-PARC

Goal: $K_L \to \pi^0 \nu\nu$ observation

- Smaller production angle (16°→5°); higher K_L flux (×2.6); harder K_L spectrum.
- Longer decay volume (2m→12m).
- Larger calorimeter (D=2m→3m).

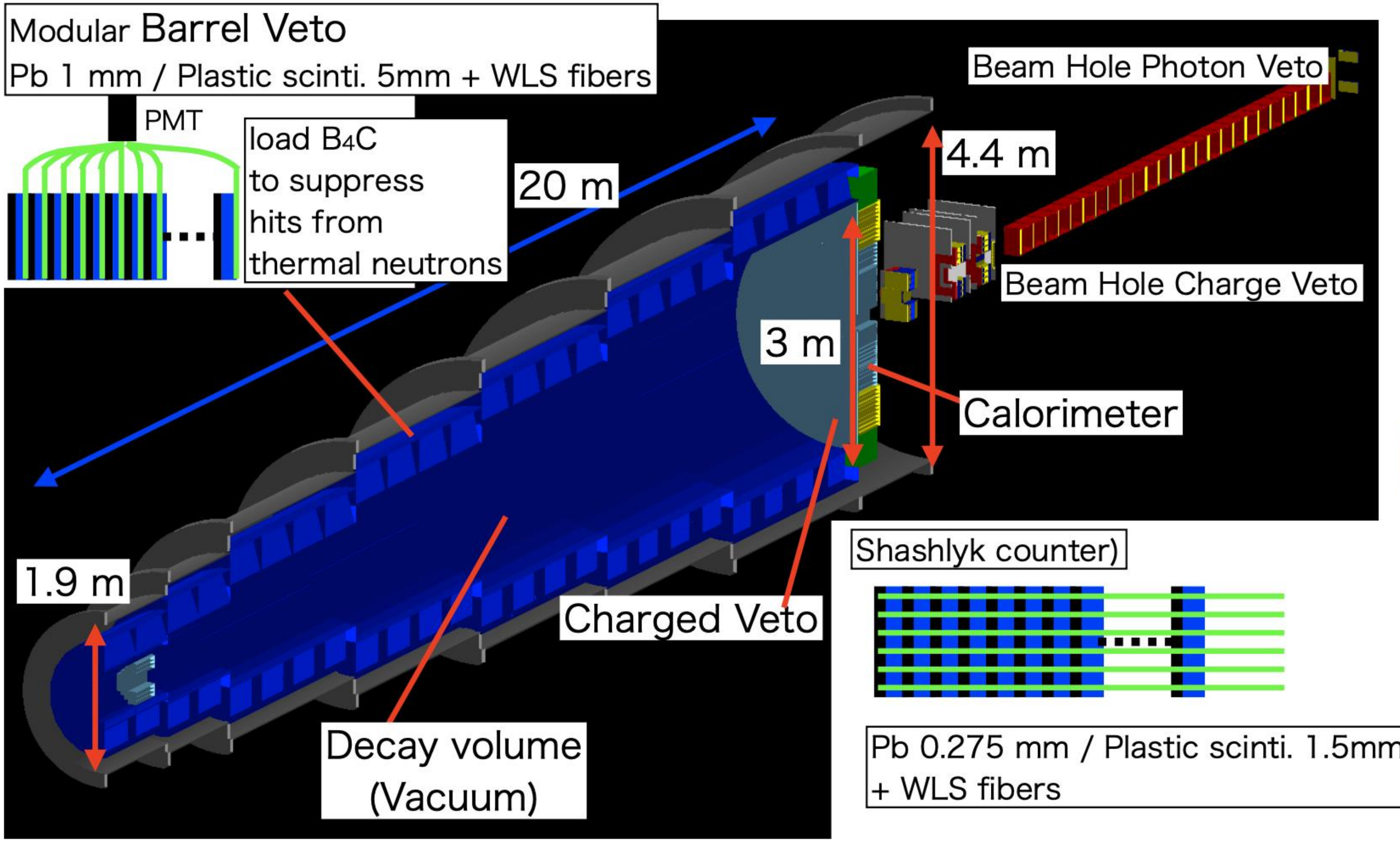


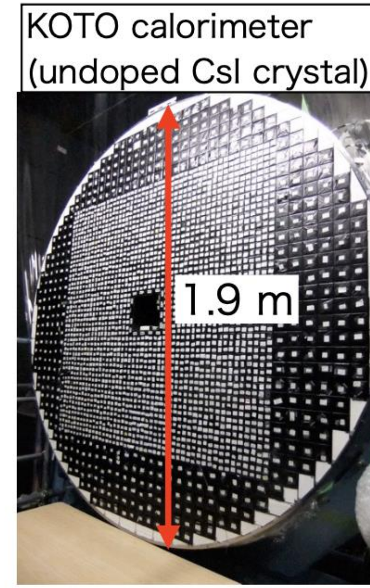


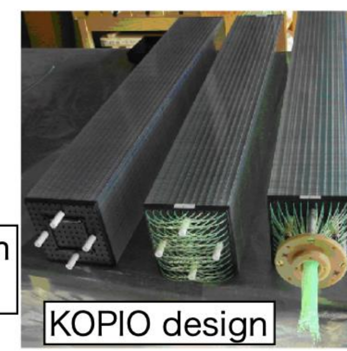
- Four years of operation starting in 2034: 35 signal + 40 background events.
- Observation of the SM $K_L \to \pi^0 \nu\nu$ decay (>5σ); ΔBR/BR=25%.
- UK leads the expansion of the physics programme to measure $K_L \to \pi^0 \ell^+ \ell^-$.
- Letter of Intent to be submitted to J-PARC in December 2024.

KOTO-II detector concept

Detector concept is based on the KOTO setup:







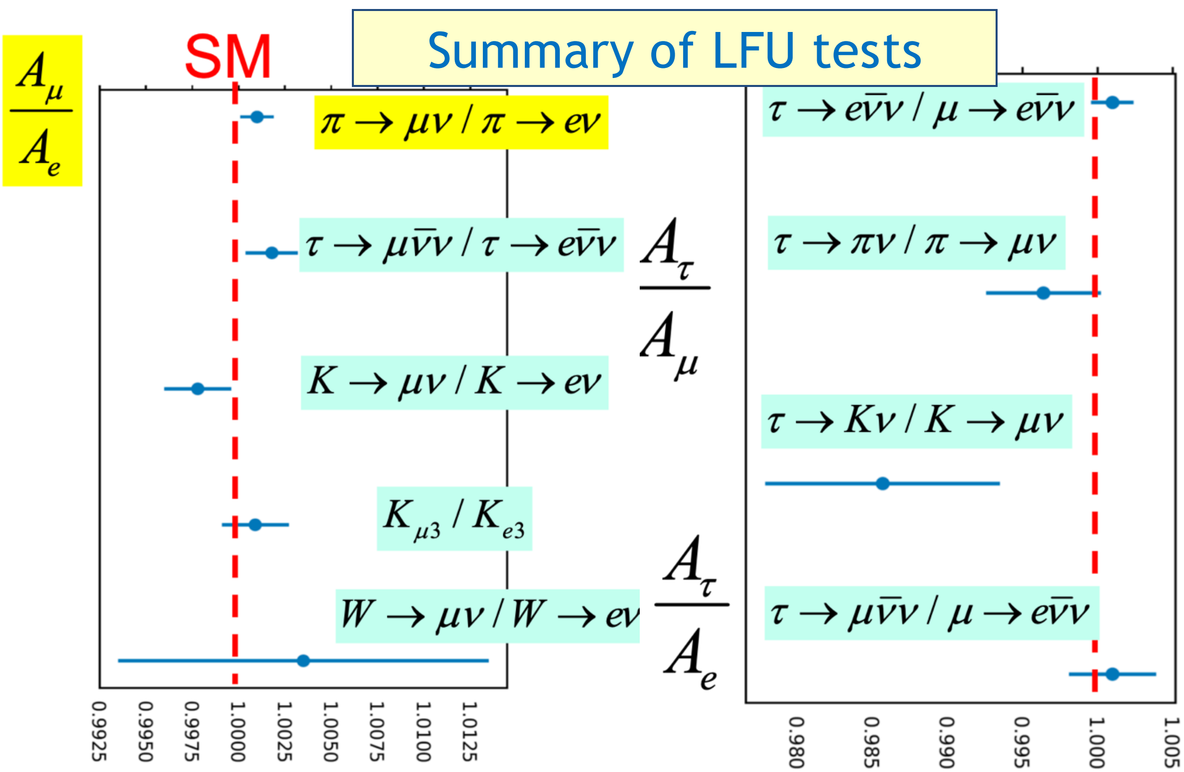
- ❖ Several UK groups are interested in joining KOTO-II.
- ❖ UK can take a **major role**: tracker for $K_L \to \pi^0 \ell^+ \ell^-$ measurement, Beam Hole Charge Veto, DAQ, trigger, simulations, physics analysis.

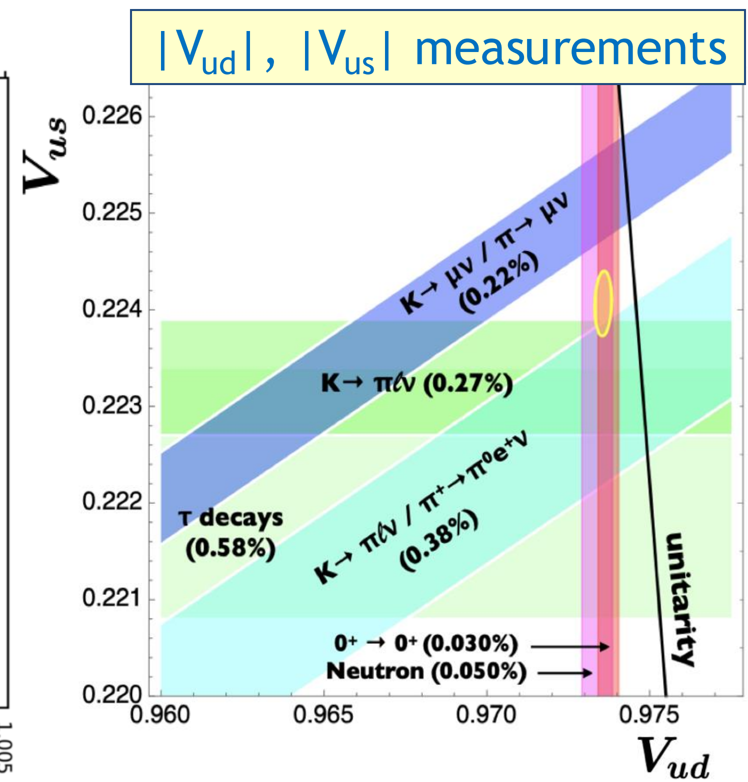
Next-generation pion experiment: PIONEER

PIONEER at PSI: motivation

arXiv:2203.01981

- Lepton flavour universality is tested at **O(10^{-3})** level.
- CKM first-row unitarity deficit: $|V_{ud}|^2 + |V_{us}|^2 - 1 = (-19.5 \pm 5.3) \times 10^{-4}$
  [Bryman, Cirigliano, Crivellin, Inguglia, Ann.Rev.Nucl.Part.Sci. 72 (2022) 69; arXiv:2111.05338]
- PIONEER at PSI: a next-generation π^+ decay experiment based on the experience of PIENU@TRIUMF and PEN@PSI.
- Phase I: **BR($\pi^+ \to e^+\nu$)/BR($\pi^+ \to \mu^+\nu$)~10^{-4}** to a **10^{-4}** relative precision (**3** years).
- Phases II and III: **BR($\pi^+ \to \pi^0 e^+\nu$)~10^{-8}** to **0.04%**; **$|V_{ud}|$** to **0.02%** (**4+4** years).



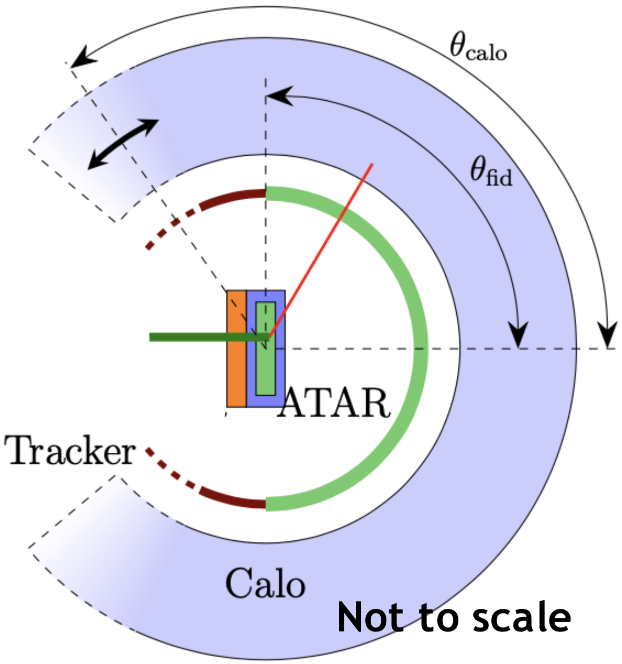


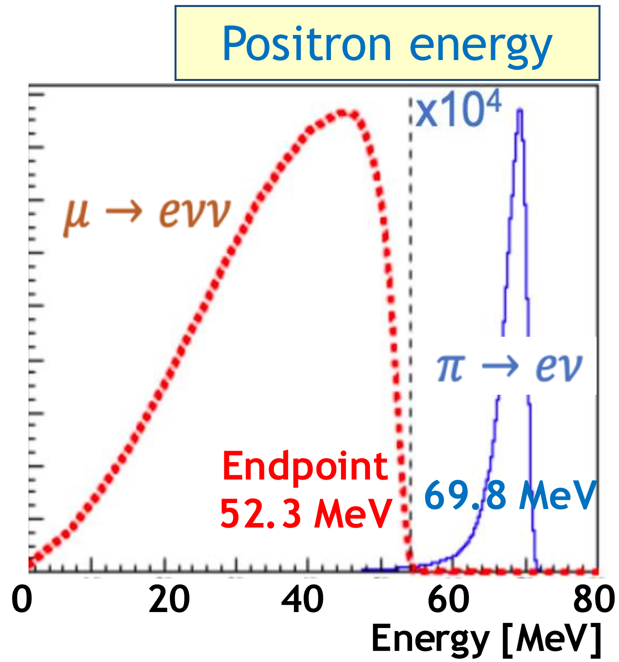
PIONEER: detector and method

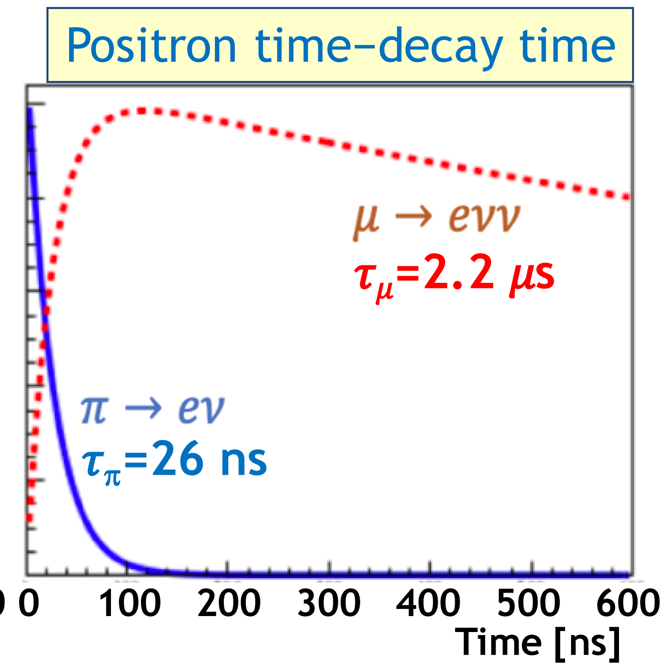
Detector design:

Approved by PSI, aiming to start data-taking in 2030

- Low-energy π^+ beam (**65 MeV/c**) stopped in an active target (ATAR), an LGAD silicon-strip detector; pion stopping rate = **300 kHz**.
- LXe/LYSO calorimeter (**R_{out}~80cm**; **$25X_0$**): **e^+** energy tail **<0.5%** below **52 MeV**.
- Spherical tracker (design to be determined).



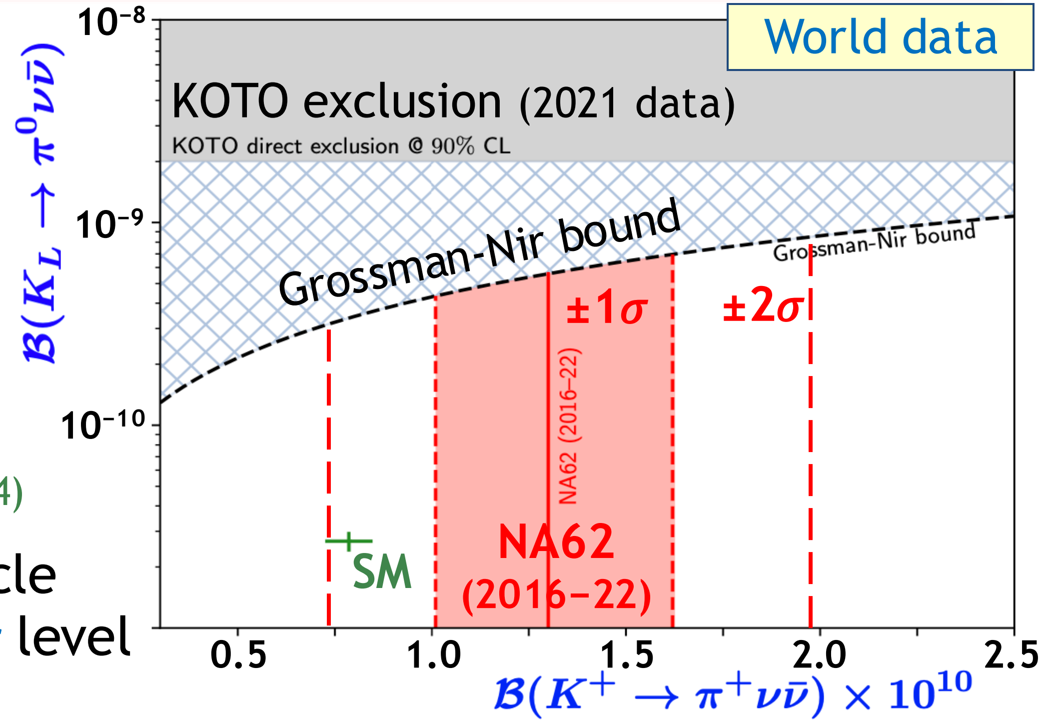




- UK (Glasgow) has been involved in PIENU at TRIUMF.
- Several UK groups are interested in contributing to software, simulations and MC productions (and eventually to physics).

Summary

- Kaon decay experiments are collecting data and advancing on rare decay measurements.
  - ✓ KOTO: improved $K_L \to \pi^0 \nu\nu$ upper limit (September 2023)
  - ✓ NA62: $K^+ \to \pi^+ \nu\nu$ observation at the 5σ level (September 2024)
  - ✓ $K^+ \to \pi^+ \nu\nu$ is the rarest particle decay established at the 5σ level



- UK groups are interested in joining next-generation experiments.
  - ✓ KOTO-II at J-PARC: $K_L \to \pi^0 \nu\nu$ observation at 5σ; rare K_L decays
  - ✓ PIONEER at PSI: $BR(\pi_{e\nu})/BR(\pi_{\mu\nu})$ to 10^{-4} precision in Phase I

Kaon and pion decay experiments should be acknowledged as **essential scientific activities** in the upcoming European Strategy and PPRP Roadmap updates