Kaons decay experiments: NA62, HIKE, KOTO

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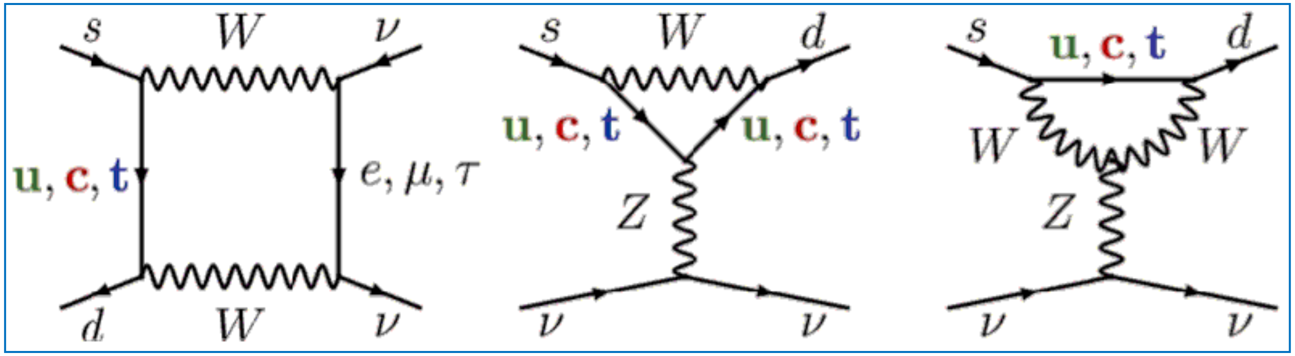
Outline:

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) KOTO at J-PARC: search for $K_L \to \pi^0 \nu\nu$
5) Summary

PPAP community meeting
Manchester, 22 September 2022

$K \to \pi\nu\nu$ 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 **essential activity**.

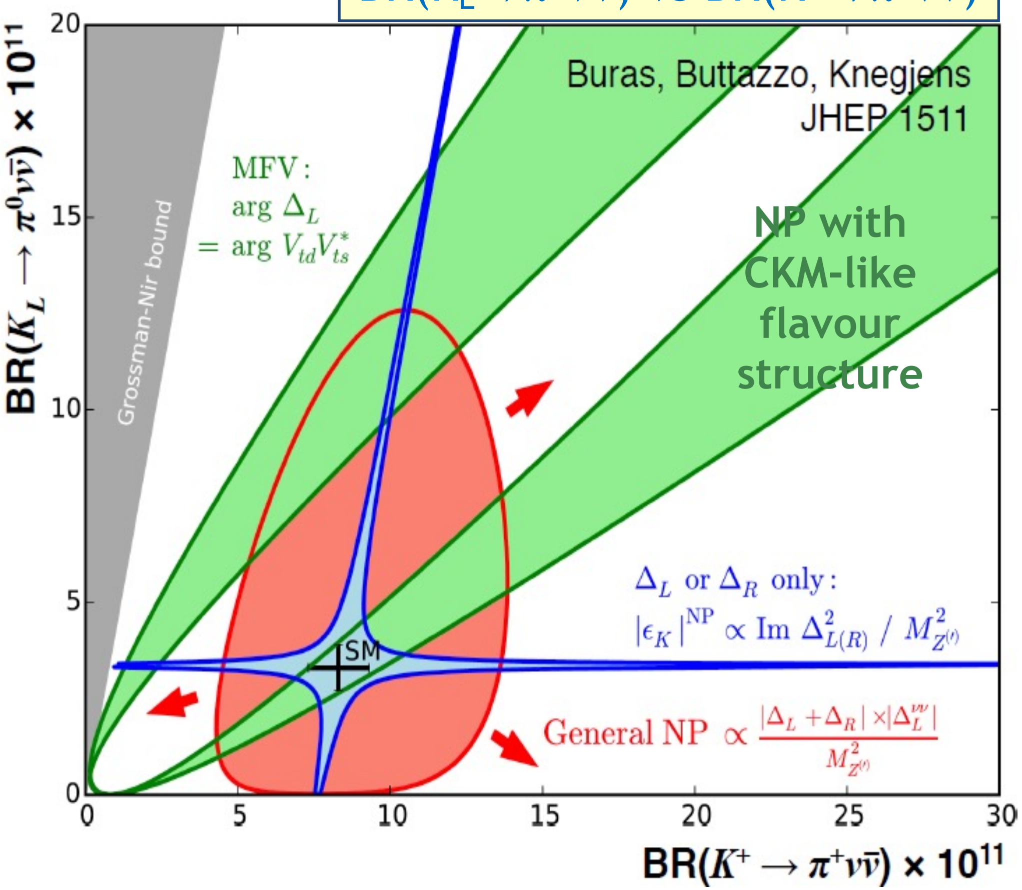
Mode	Standard Model BR	Experimental status
$K^+ \to \pi^+\nu\nu$	$(8.60 \pm 0.42) \times 10^{-11}$	$(10.6 \pm 4.0) \times 10^{-11}$ (NA62 Run 1)
$K_L \to \pi^0\nu\nu$	$(2.94 \pm 0.15) \times 10^{-11}$	$BR < 300 \times 10^{-11}$ at 90% CL (KOTO 2015 data)

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

K→πνν 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]*

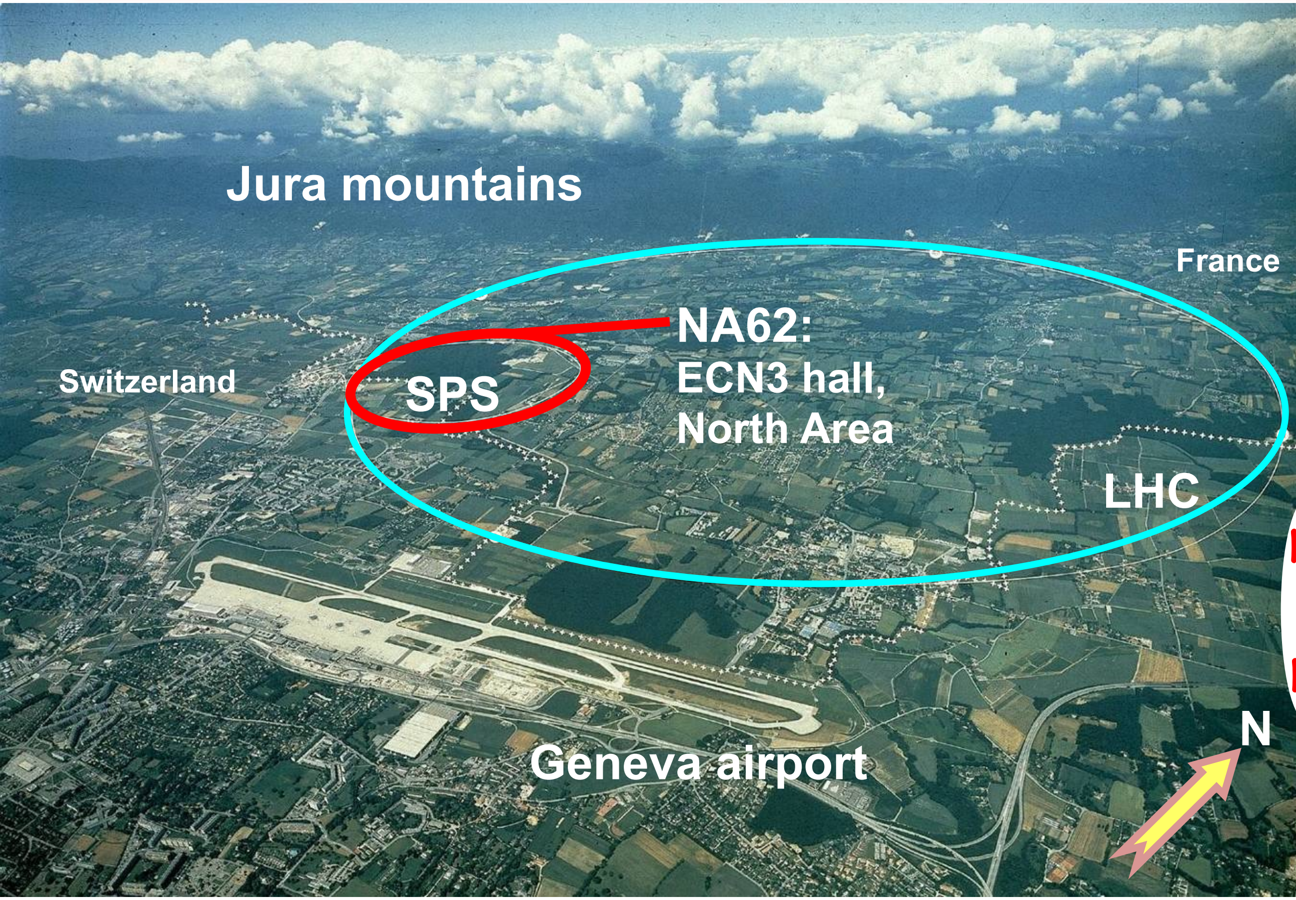
BR($K_L\to\pi^0\nu\bar{\nu}$) vs BR($K^+\to\pi^+\nu\bar{\nu}$)



- **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

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

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

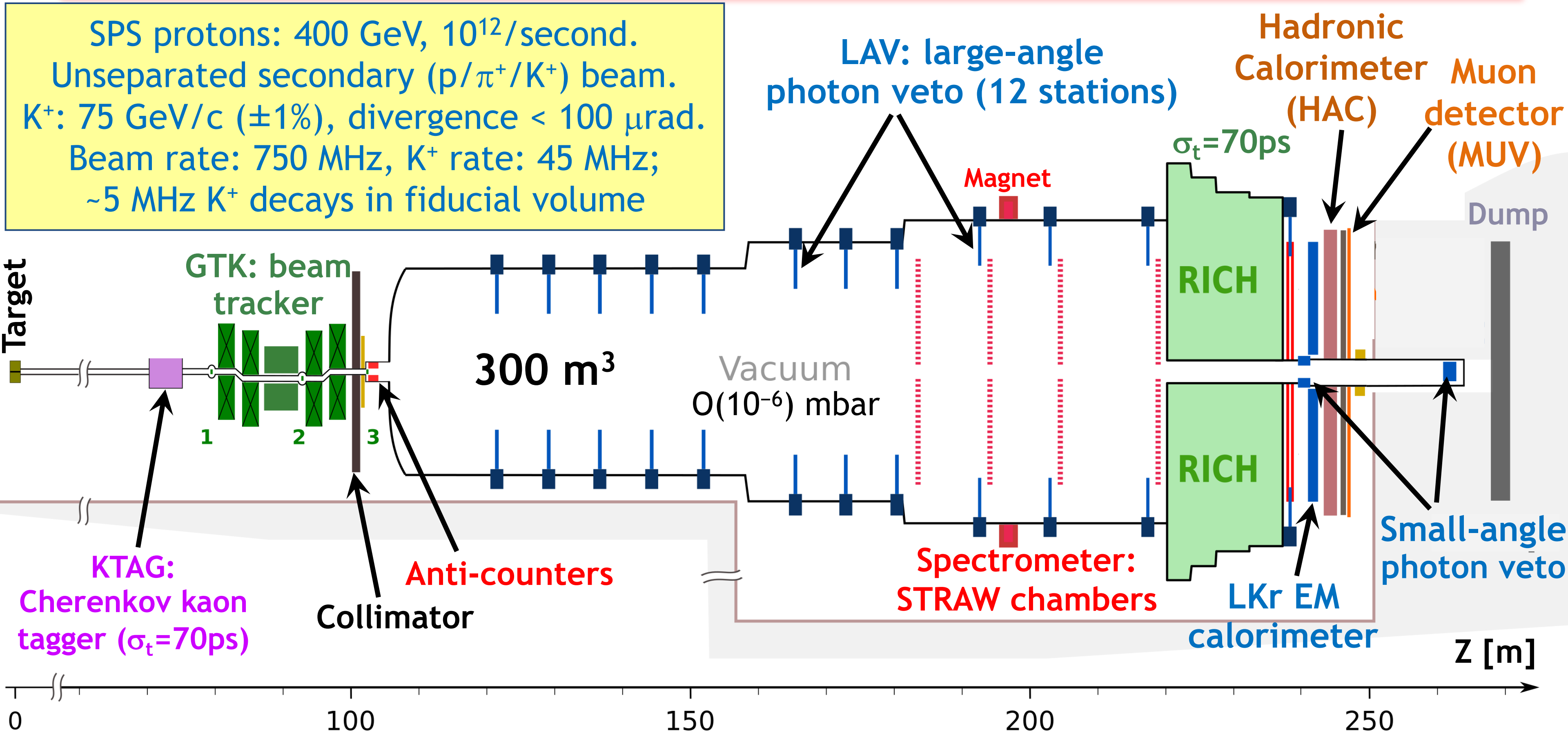
Main NA62 goal: $K^+ \to \pi^+ \nu\nu$ measurement to 10% precision with a novel decay-in-flight technique.

NA62UK: Birmingham, Bristol, Glasgow, Lancaster (10% of the collaboration).

NA62 collaboration,
JINST 12 (2017) P05025

Beamline & detector

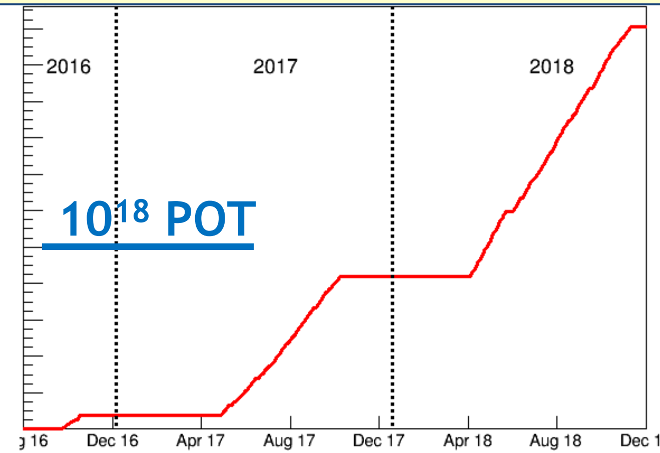
SPS protons: 400 GeV, 10^{12}/second.
Unseparated secondary ($p/\pi^+/K^+$) beam.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Beam rate: 750 MHz, K^+ rate: 45 MHz;
~5 MHz K^+ decays in fiducial volume



- ❖ 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



2.2×10^{18} POT collected
(3×10^{16} from 50h in dump mode)

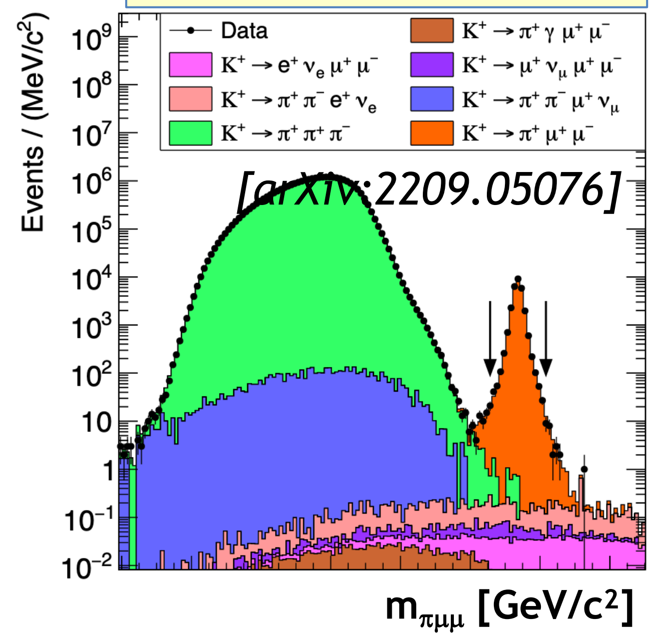
- **Run 1 (2016–18)**:
  - ✓ Sample **2016** (30 days, **~1.3×10^{12} ppp**): **2×10^{11}** useful **K^+** decays.
  - ✓ Sample **2017** (160 days, **~1.9×10^{12} ppp**): **2×10^{12}** useful **K^+** decays.
  - ✓ Sample **2018** (217 days, **~2.3×10^{12} ppp**): **4×10^{12}** useful **K^+** decays.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

UK leadership in NA62

UK roles in NA62 collaboration:

- Spokesperson (2019–22).
- Conference Committee chair (2022–25).
- Rare decay analysis convener.
- Two Editorial Board members.
- KTAG subdetector: full M&O responsibility.
- High-Level Trigger coordination.
- Software and distributed computing (in-kind support via GridPP).

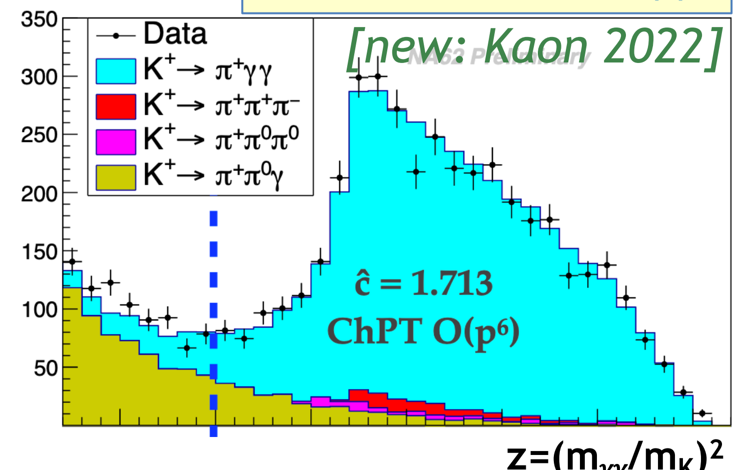
New result: $K^+ \to \pi^+\mu^+\mu^-$



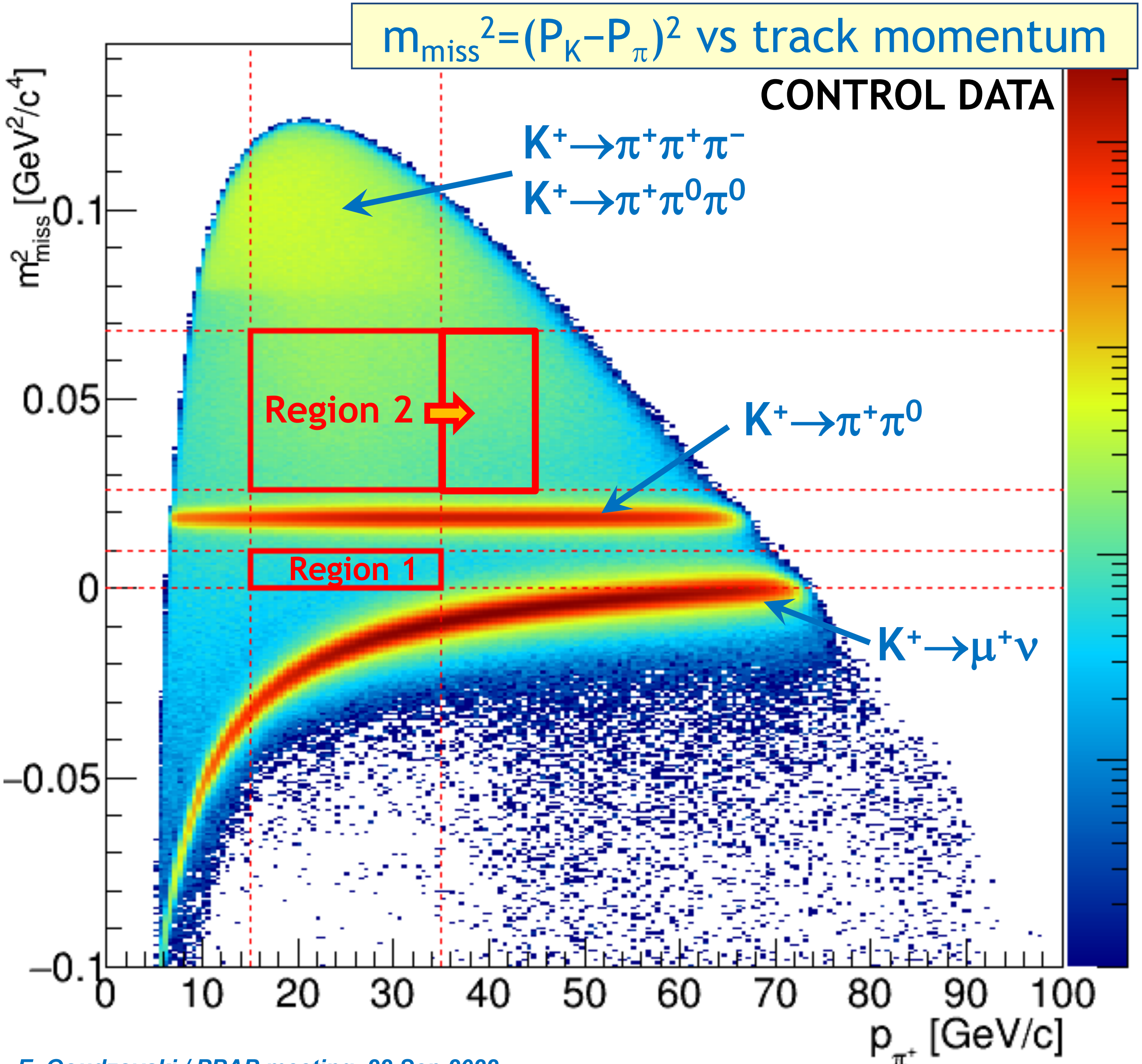
UK leadership in Run 1 physics analysis:

- The flagship $K^+ \to \pi^+\nu\nu$ measurement.
- Rare decays ($K^+ \to \pi^+\mu^+\mu^-$, $K^+ \to \pi^+\gamma\gamma$, …), world's largest samples by far.
- Searches for hidden sectors and lepton number/flavour violation in K^+ decays.

New result: $K^+ \to \pi^+\gamma\gamma$



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:

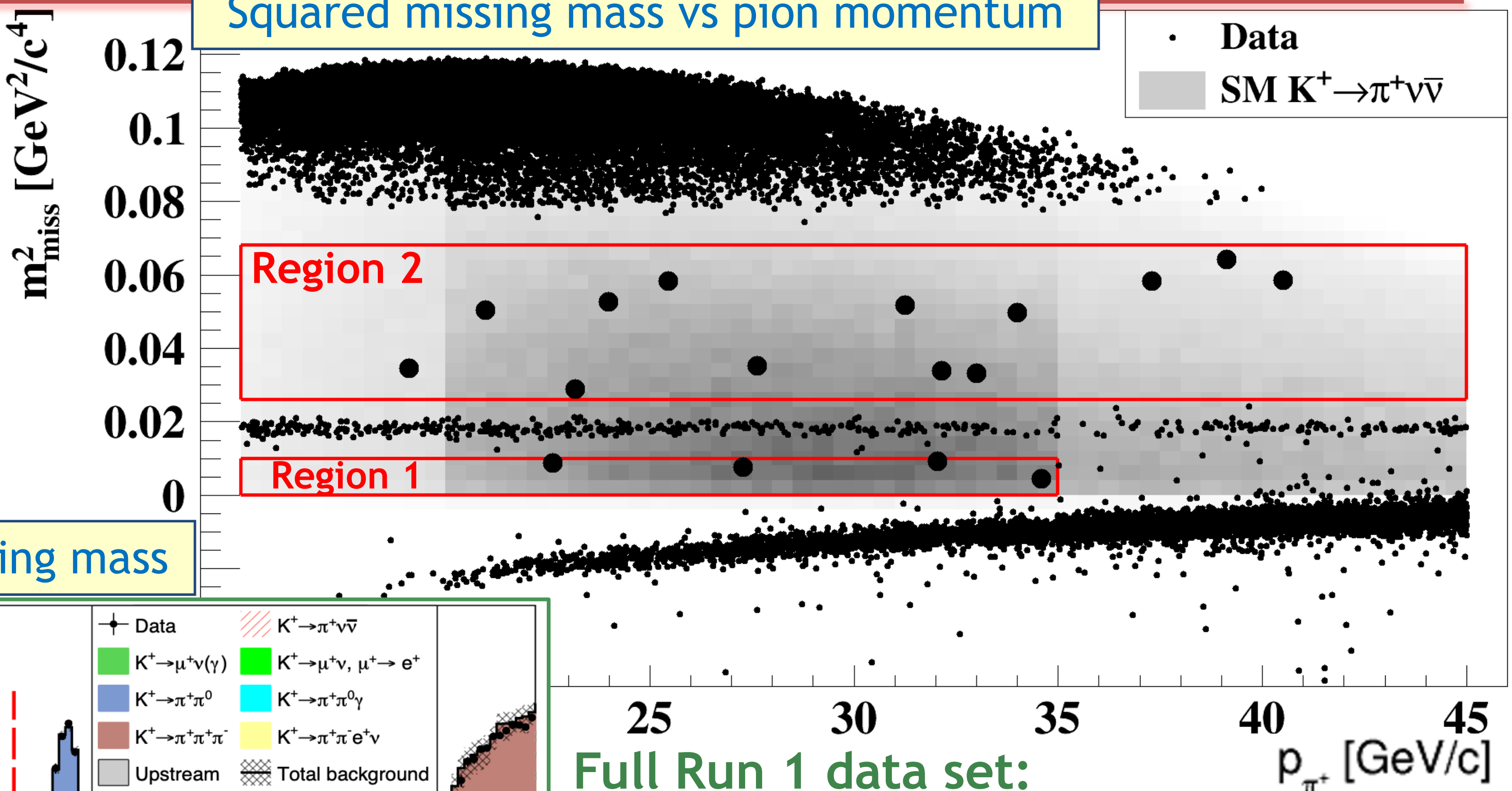
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

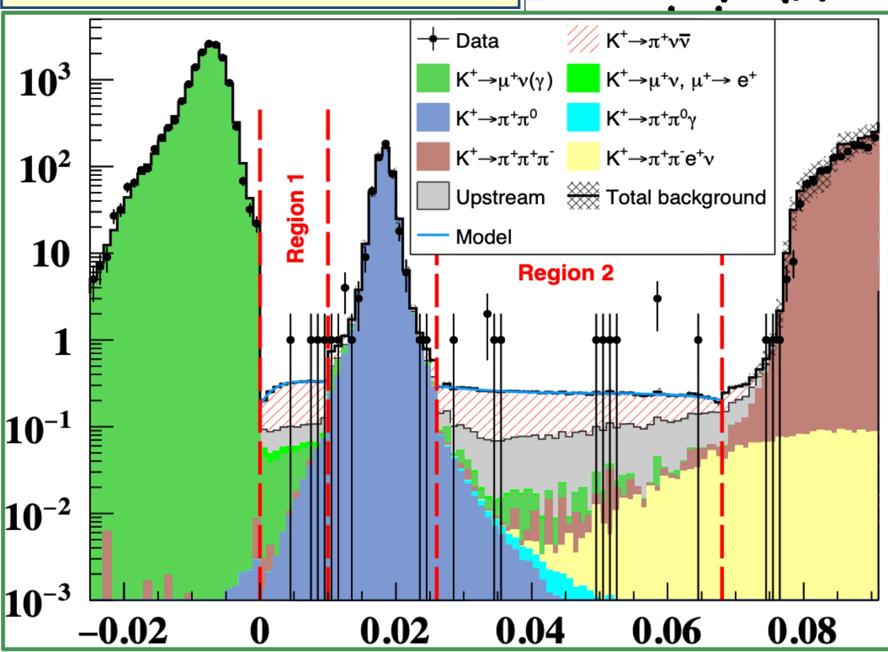
- ✓ PID (calorimeters & RICH): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

Opening the box (2018 data)

Squared missing mass vs pion momentum



Squared missing mass



Full Run 1 data set:

Candidates observed: 20

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

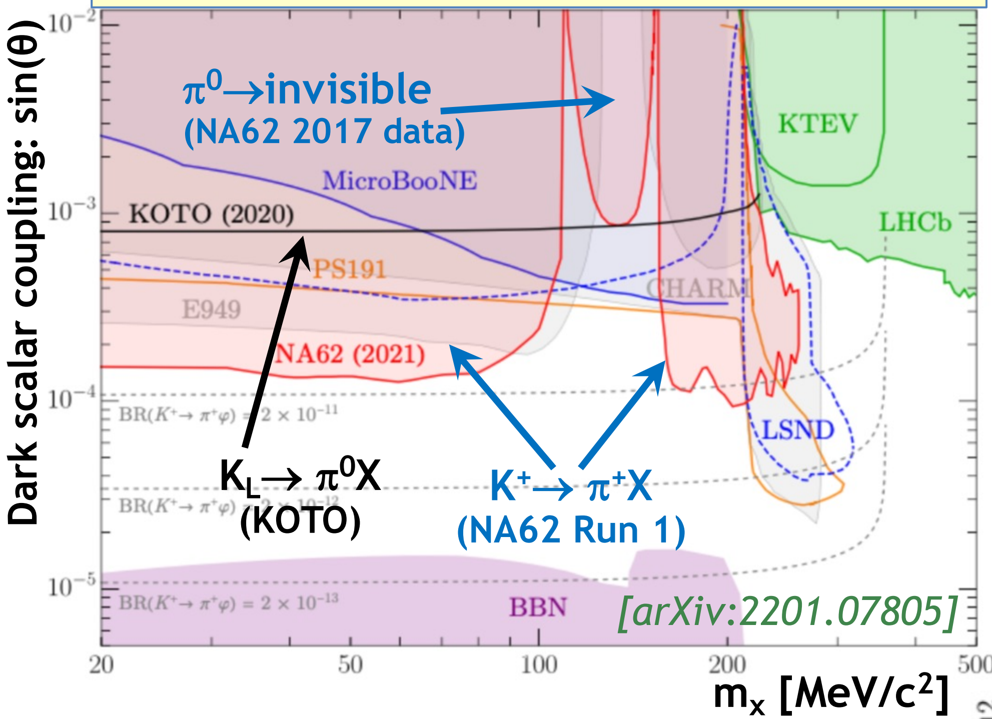
mainly "upstream"

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

[JHEP 06 (2021) 93] (3.4σ significance)

Searches for hidden sectors

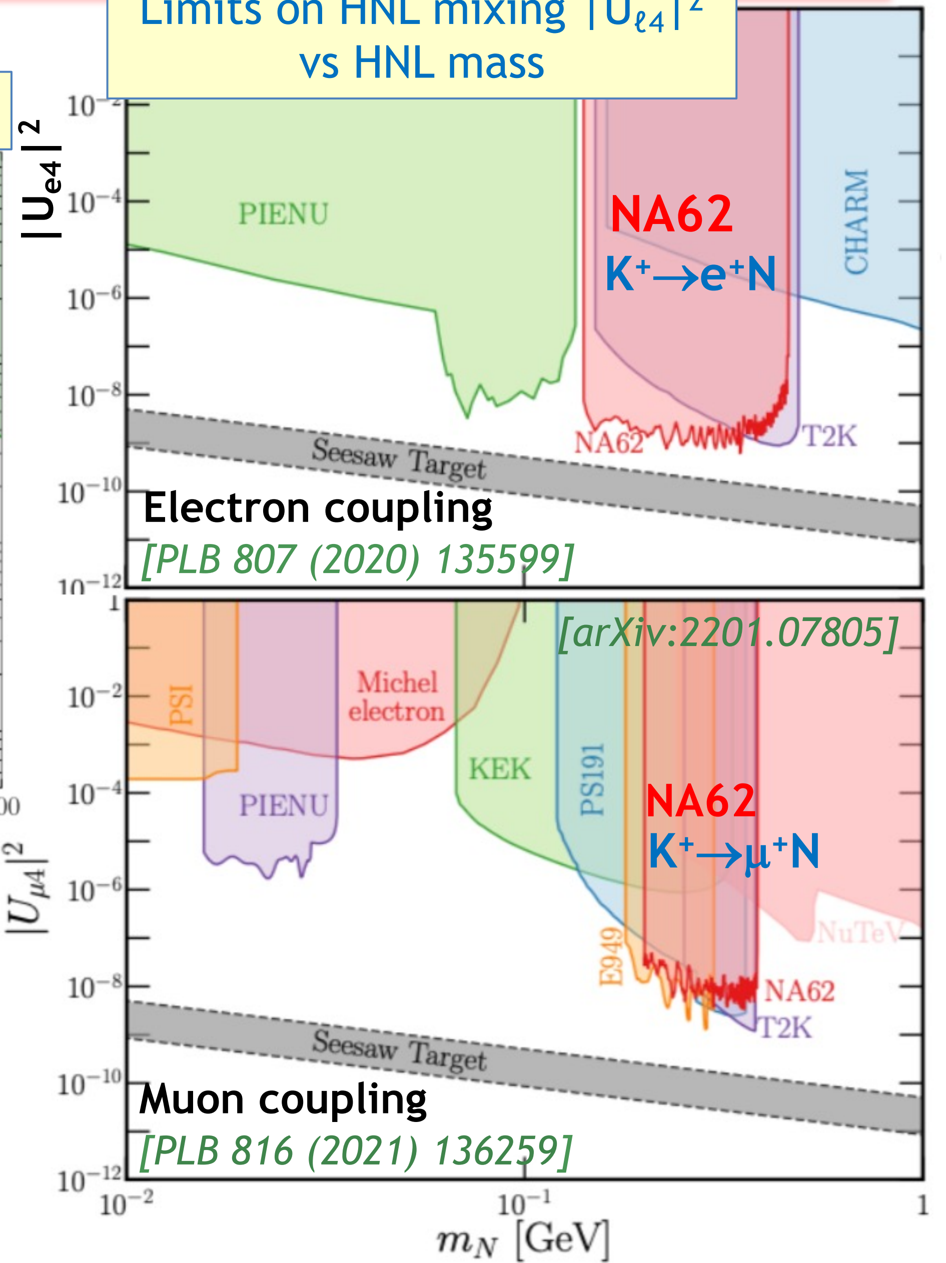
Dark scalar searches below the K mass



NA62 limits on dark-scalar production, directly from the $K^+ \to \pi^+ \nu\nu$ analysis

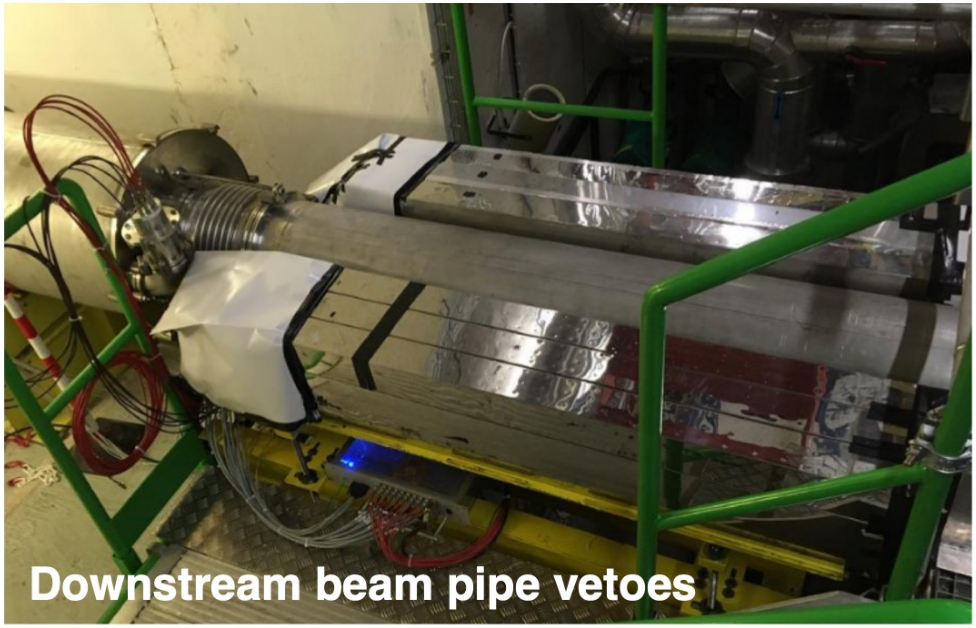
[JHEP 02 (2021) 201, JHEP 06 (2021) 93]

Limits on HNL mixing $|U_{\ell 4}|^2$ vs HNL mass



NA62 Run 2: 2021–LS3

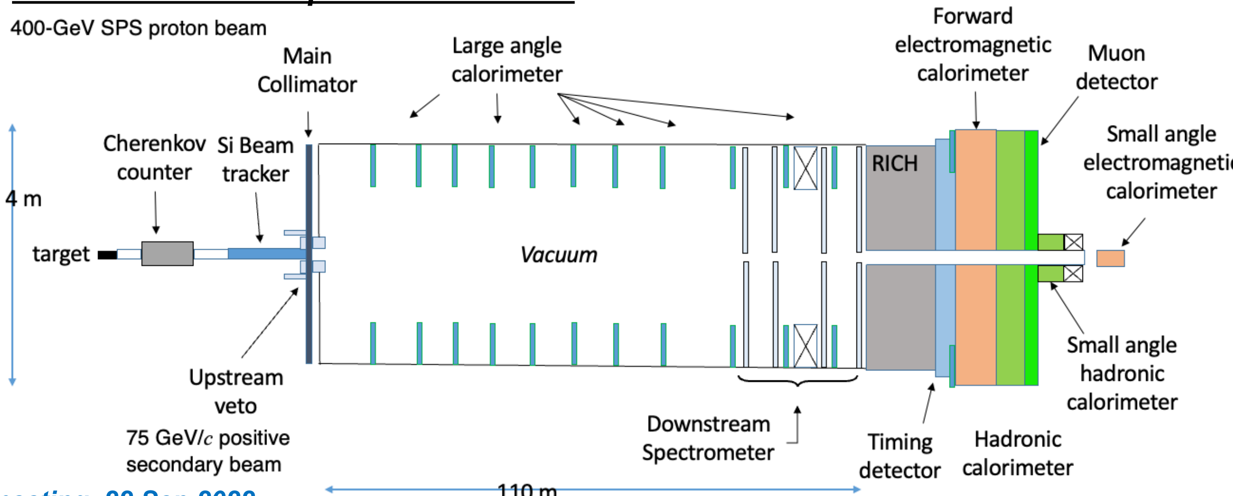
- Run 2: $K^+ \to \pi^+ \nu\nu$ measurement at O(10%) precision in a low-background, high-acceptance regime, with an established technique.
- Modifications of the setup for **background reduction**:
  - ✓ fourth kaon beam tracker (GTK) station;
  - ✓ rearrangement of beamline elements around the GTK achromat;
  - ✓ new veto hodoscopes upstream of the decay volume;
  - ✓ an additional veto counter around downstream beam pipe.
- Improved TDAQ: beam intensity increased by ~30% wrt Run 1.
- Collection of 10^{18} pot in up to 90 days in beam dump mode is foreseen.



Fixed target runs at CERN SPS

- 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.
- A series of K^+ and K_L decay experiments, located in the NA62 hall.
- 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 contributed paper: *arXiv:2204.13394*.
- LoI to be submitted to the SPSC in **Nov 2022**.

HIKE-K^+ conceptual sketch



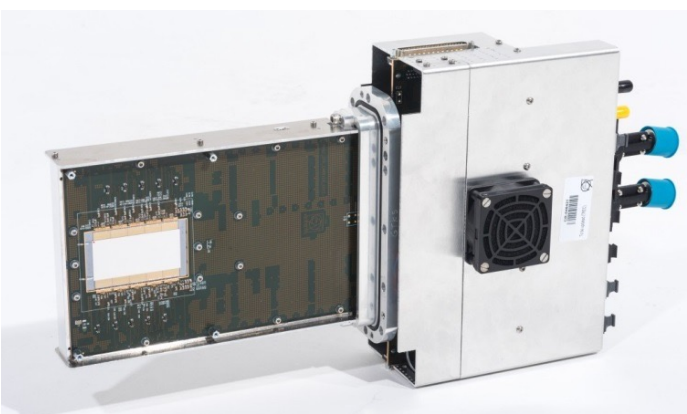
HIKE step 1: $K^+\to\pi^+\nu\nu$

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):

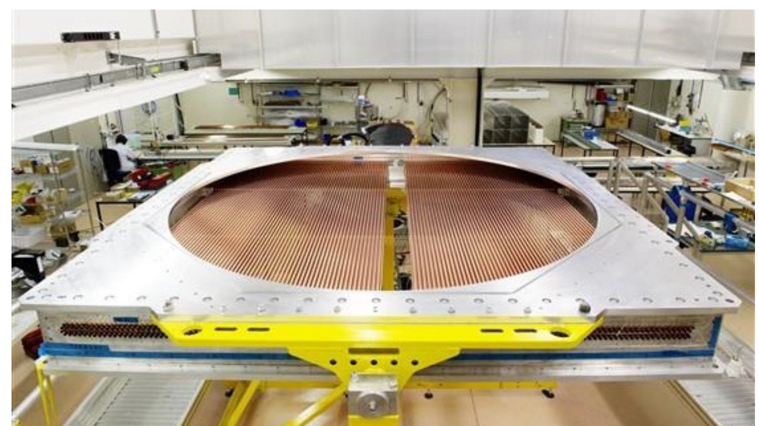
time resolution: <50 ps per plane;
pixel size: <300×300 μm²;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: >3 GHz on 30×60 mm²;
peak intensity: >8.0 MHz/mm².



A current NA62 GTK station

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.



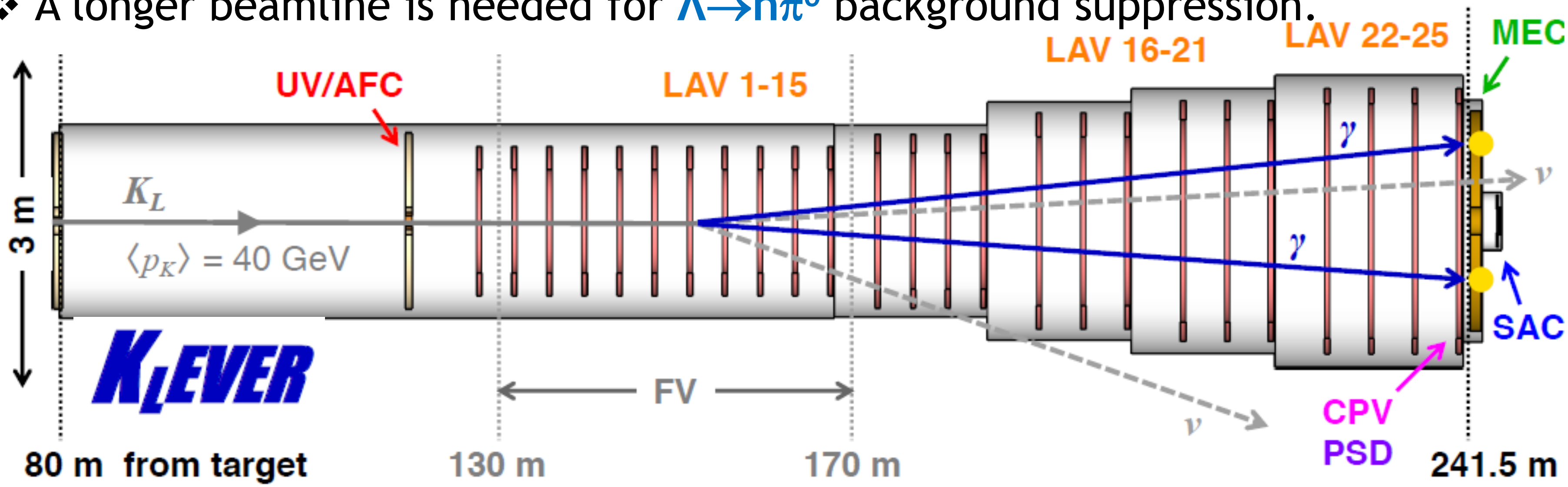
A current NA62 STRAW chamber

HIKE step 2: neutral (K_L) beam

- A K_L rare-decay experiment with charged-particle detection and PID:
  - ✓ a high-energy K_L beam (up to **80 GeV/c** mean momentum);
  - ✓ minor layout modifications wrt step 1; some detectors removed.
- Physics objectives:
  - ✓ $K_L \to \pi^0 \ell^+ \ell^-$: excellent $\pi^0 \to \gamma\gamma$ mass resolution is essential to reduce the Greenlee background ($K_L \to \gamma\gamma\ell^+\ell^-$);
  - ✓ lepton flavour violation at 10^{-12} level: $K_L \to (\pi^0)(\pi^0)\mu e$, $K_L \to 2\mu 2e$;
  - ✓ precision measurements of rare K_L decays;
  - ✓ searches for hidden sector mediators in K_L decays.
- Characterisation of the neutral beam for a future $K_L \to \pi^0 \nu\nu$ experiment:
  - ✓ measurements of K_L, **n**, Λ and beam halo fluxes;
  - ✓ KOTO experience suggests this to be critical.

HIKE step 3: $K_L \to \pi^0 \nu\nu$

- **KLEVER**: a dedicated $K_L \to \pi^0 \nu\nu$ experiment, $\langle p(K_L) \rangle$ = 40 GeV/c.
- Photons from K_L decays boosted forward: veto coverage only up to 100 mrad.
- Vacuum tank layout and fiducial volume similar to NA62.
- A longer beamline is needed for $\Lambda \to n\pi^0$ background suppression.



Main detector/veto systems:

UV/AFC	Upstream veto/Active final collimator
LAV1-25	Large-angle vetoes (25 stations)
MEC	Main electromagnetic calorimeter
SAC	Small-angle vetoes
CPV	Charged particle veto
PSD	Pre-shower detector

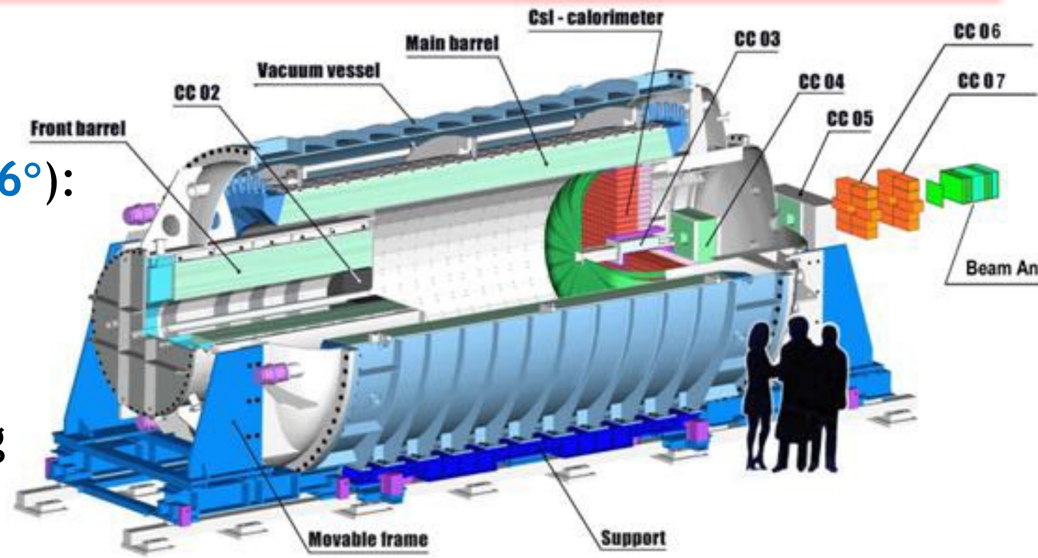
Target sensitivity:

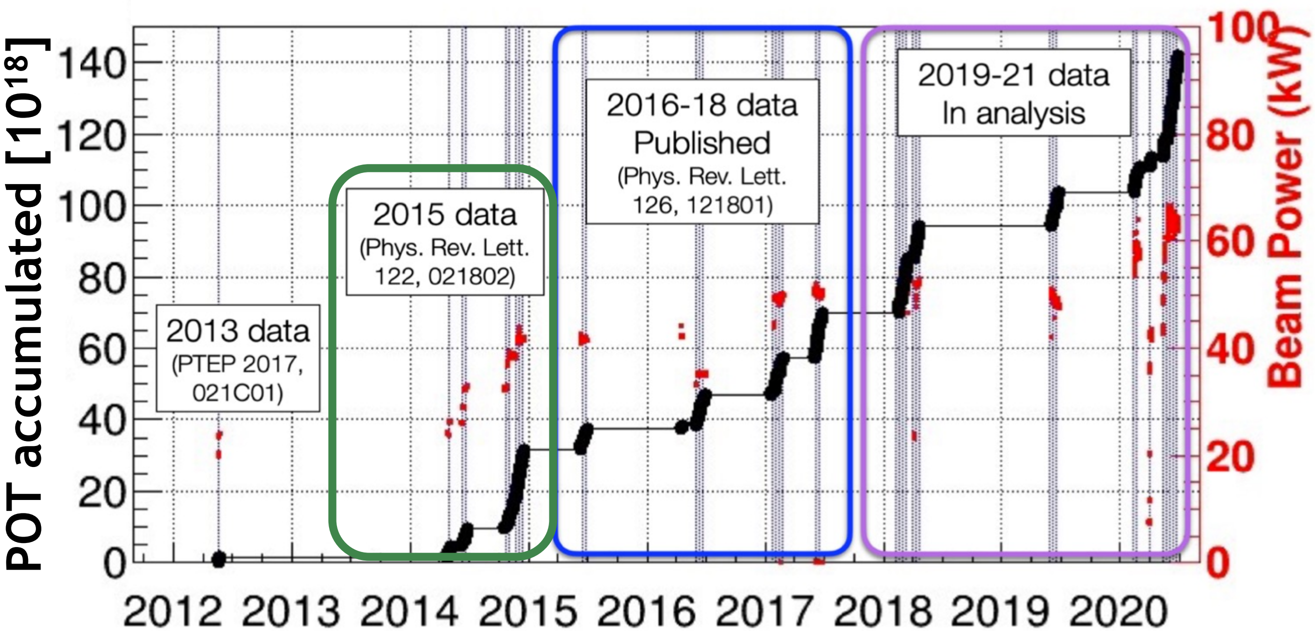
60 SM $K_L \to \pi^0 \nu\nu$ events with S/B~1 in 5 years of operation;

$\delta BR(K_L \to \pi^0 \nu\nu)/BR(K_L \to \pi^0 \nu\nu) \sim 20\%$.

KOTO at J-PARC: $K_L \to \pi^0 \nu\nu$

- Primary beam: 30 GeV protons;
  60 kW = 6.6×10^{13}/5.2 s (in 2021).
- Neutral pencil beam (produced at 16°):
  $\langle p(K_L) \rangle$ = 2.1 GeV/c.
- Composition: K_L, neutrons, photons.
- Decay region length: ~2 m.
- Hermetic photon detector, including a CsI calorimeter.





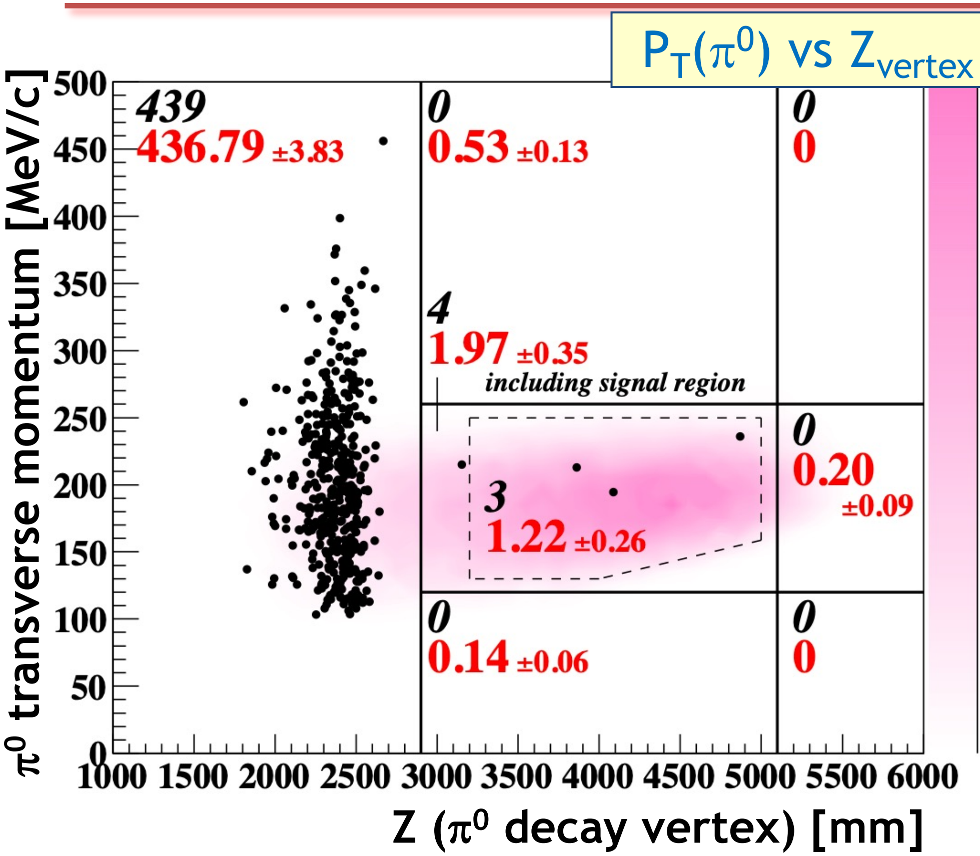
2015 run

With 2.2×10^{19} pot,
$BR(K_L\to\pi^0\nu\nu)<3.0\times10^{-9}$
[PRL 122 (2019) 021802]

2016–18 runs

With 3.05×10^{19} pot,
$BR(K_L\to\pi^0\nu\nu)<4.9\times10^{-9}$
[PRL 126 (2021) 121801]

KOTO: the 2016–18 result



[PRL 126 (2021) 121801]

Single-event sensitivity:
$BR_{SES}=(7.2\pm0.7)\times10^{-10}$ ($=20\times BR_{SM}$)

Main backgrounds:

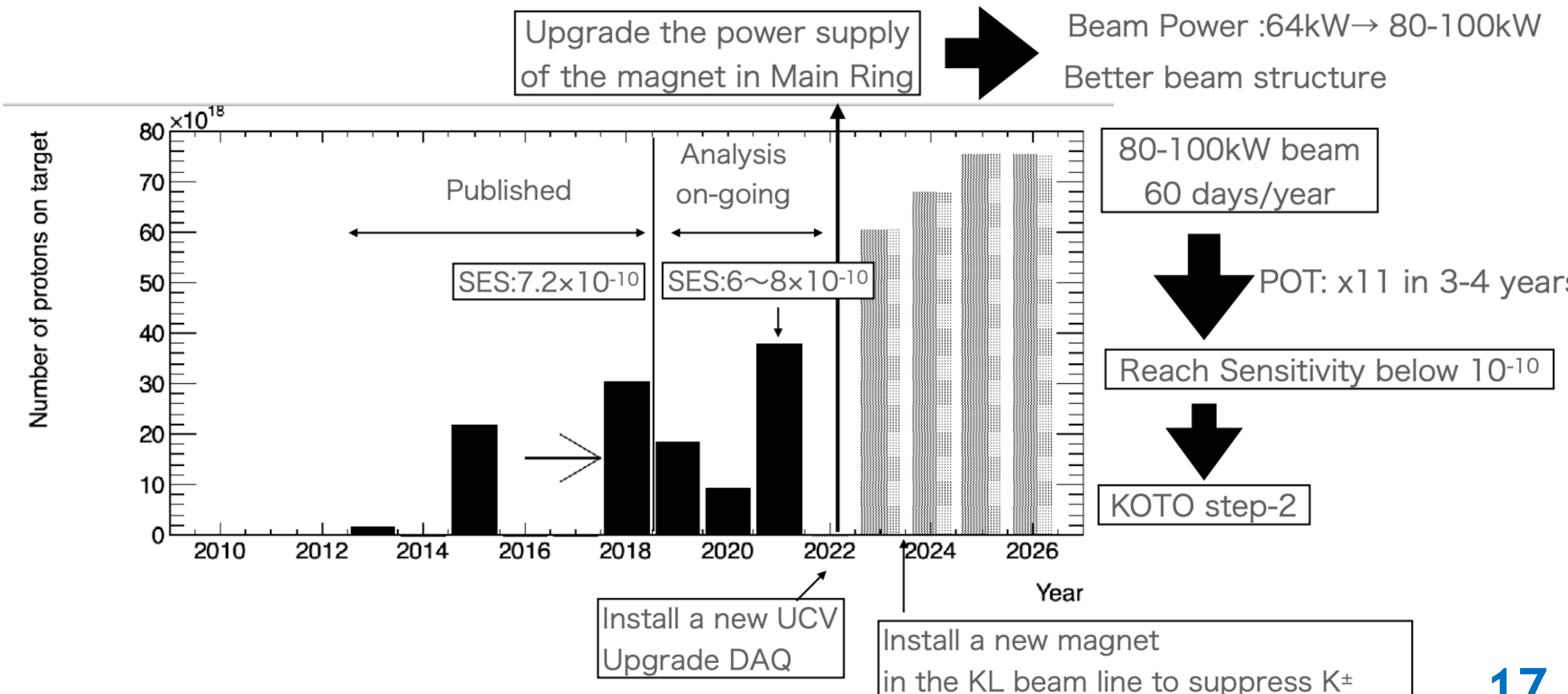
source		Number of events
K_L	$K_L\to3\pi^0$	0.01 ± 0.01
	$K_L\to2\gamma$ (beam halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25 [a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

- Number of K_L decays (from $K_L\to2\pi^0$): $N_K=6.8\times10^{12}$.
- Expected SM signal: 0.04 events, a factor 1.8 larger than for 2015 data.
- Estimated background: 1.22±0.26 events (mainly from $K^\pm$ decays).
- **Three candidate events** in the signal region [compatible with background].

KOTO short-term plans

[Koji Shiomi @ Kaon 2022]

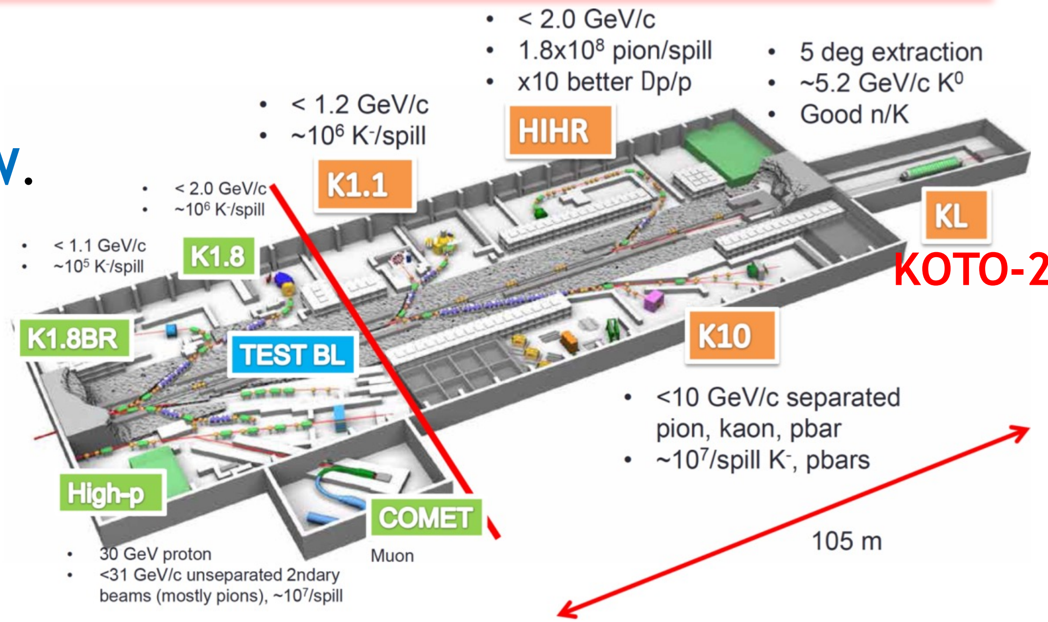
- Analysis of the **2021** dataset is being finalised.
- Beam power to be increased (**60→100 kW**).
- Further improvements to the detector.
- Single-event sensitivity below **10^{-10}** is expected by **2026**.



KOTO long-term plan: step-2

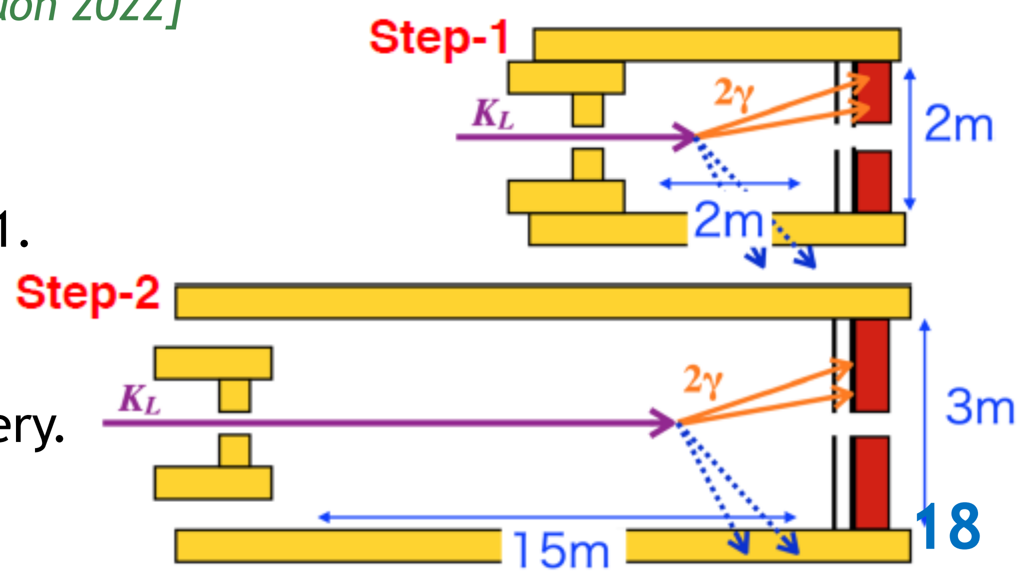
To reach O(100) signal events:

- Proton beam power above **100 kW**.
- New neutral beamline at **5°** with **$\langle p(K_L)\rangle$ = 5.2 GeV/c**.
- Larger fiducial decay volume.
- Complete rebuild of the detector.
- Hadron hall extension required, **approved by J-PARC**.
- Design work is in progress. *[arXiv:2204.13394, Hajime Nanjo @ Kaon 2022]*



Expected step-2 sensitivity:

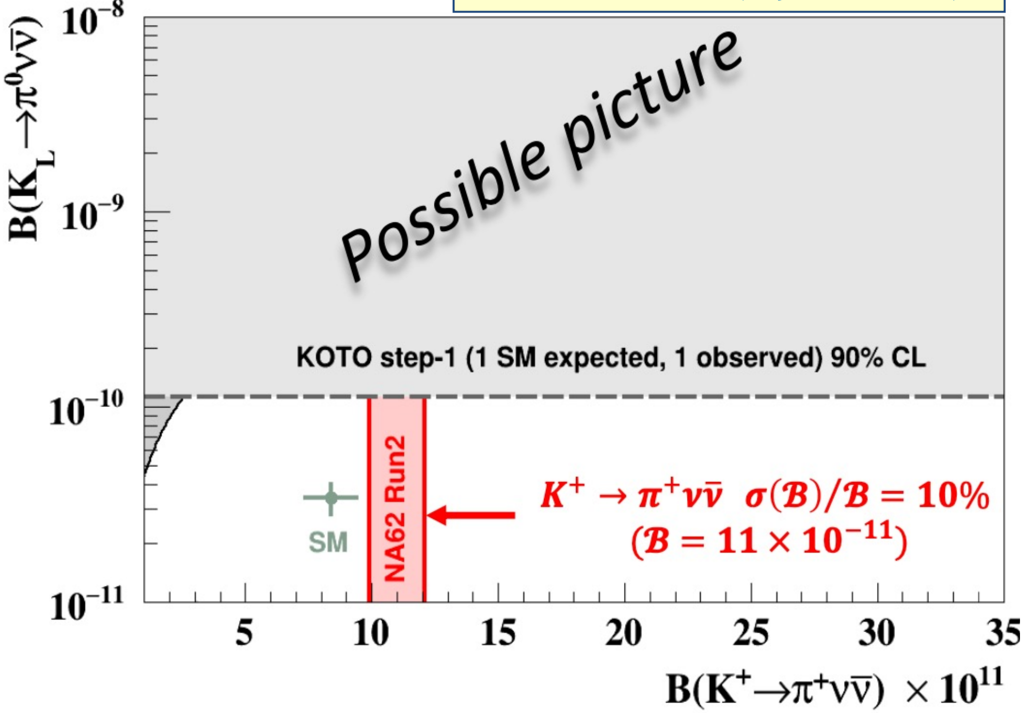
- Signal acceptance: **5×** KOTO step-1.
- 60 SM events with **S/B~1** at **100 kW** beam power (**3×10^7 s**).
- Aiming at **~5σ** SM **$K_L\to\pi^0\nu\nu$** discovery.



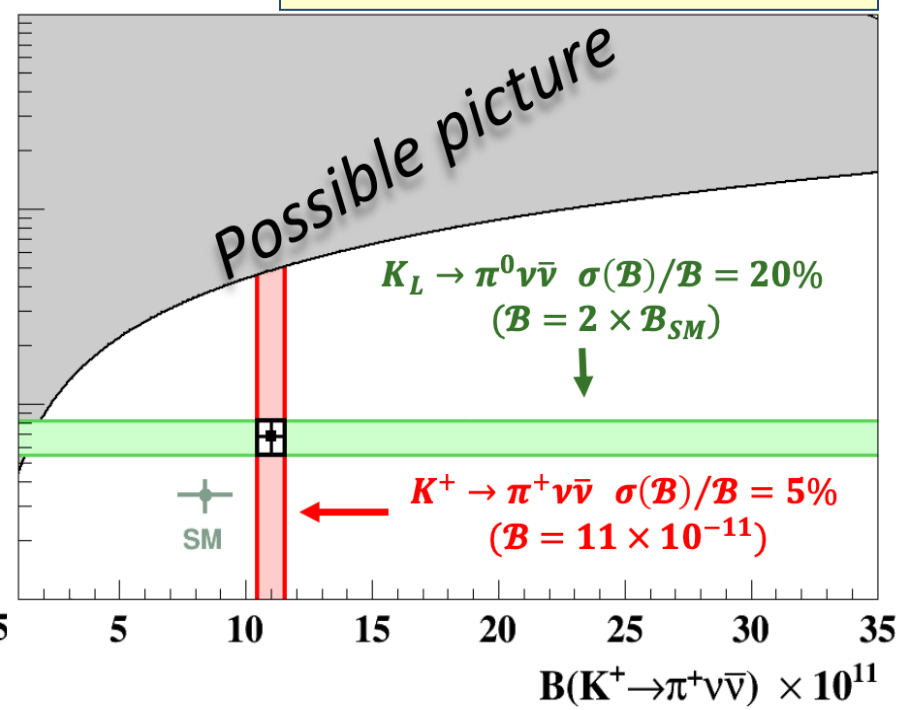
Opportunity in the kaon sector

- Measurements of $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ rates to ~10% precision: model-independent tests for new physics at the O(100 TeV) scale.
- A possibility to find a clear evidence for deviation from the SM.
- Correlations with other observables will play a crucial role.

Completion of NA62 and KOTO (by ~2025)



Completion of HIKE and KOTO step-2 (by ~2040)



Summary

❖ **UK participation in NA62 since 2011:**

- ✓ Funding during the construction phase:
  ERC Advanced & Starting Grants, two Royal Society Fellowships.
- ✓ Exploitation funded by the STFC Consolidated Grant.
- ✓ STFC Rutherford fellowships; GridPP support; EU Marie-Curie grants.
- ✓ Strong UK leadership: **excellent value for STFC investment**.

❖ **Analysis of Run 1 (2016−18) data:**

- ✓ First measurement of the $K^+ \to \pi^+ \nu\nu$ decay, led by UK:
  $BR(K^+ \to \pi^+ \nu\nu) = (10.6 \pm 4.0) \times 10^{-11}$, based on **20** candidates.
- ✓ Multiple UK-led publications on rare/forbidden decays.
  [PLB 807 (2020) 135599, PRL 127 (2021) 131802, JHEP 03 (2021) 058, PLB 816 (2021) 136259, PLB830 (2022) 137172]

❖ **Next steps:**

- ✓ **NA62 Run 2** approved until **LS3**: $K^+ \to \pi^+ \nu\nu$ measurement at **10%**.
- ✓ **HIKE:** high-intensity kaon decay programme at the SPS,
  synergistic with LHC in terms of physics and technology challenges.
  LoI to be submitted to the SPSC in **Nov 2022**.

Spares

Expected backgrounds (2018 data)

Background	Subset S1 (old collimator)	Subset S2 (new collimator)
$\pi^+\pi^0$	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	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$
$BR_{SES} \times 10^{10}$	**0.54±0.04**	**0.14±0.01**
$N^{exp}_{\pi\nu\bar{\nu}}$	**1.56±0.21**	**6.02±0.82**

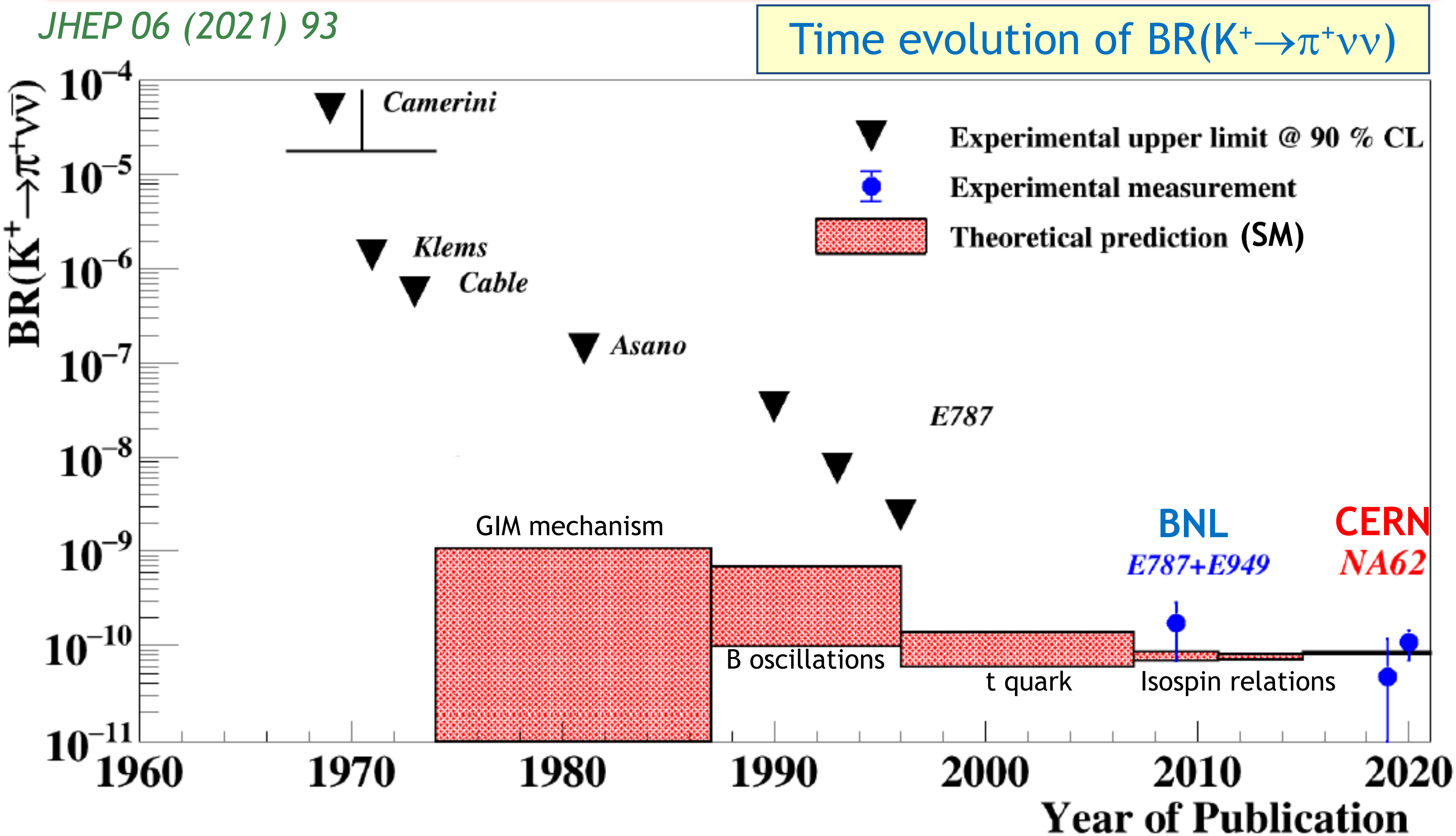
Data-driven background estimates

Dominant background: a data-driven estimate

- Most background is not due to K^+ decays in the vacuum tank.
- Improved the beamline layout and new upstream veto detectors bring the Run 2 measurement into a low-background regime.

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

JHEP 06 (2021) 93

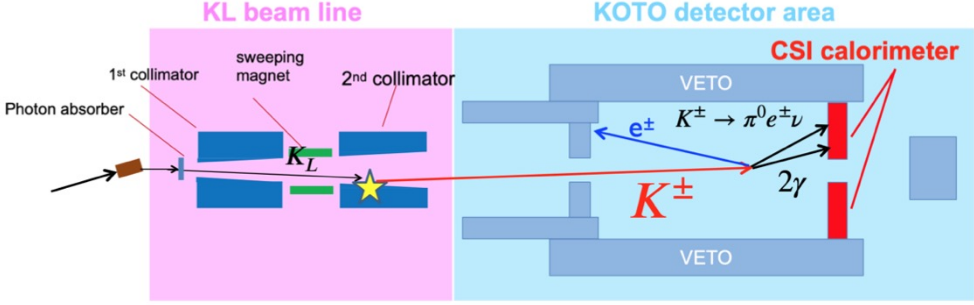


NA62 Run 1: $\boxed{\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}}$

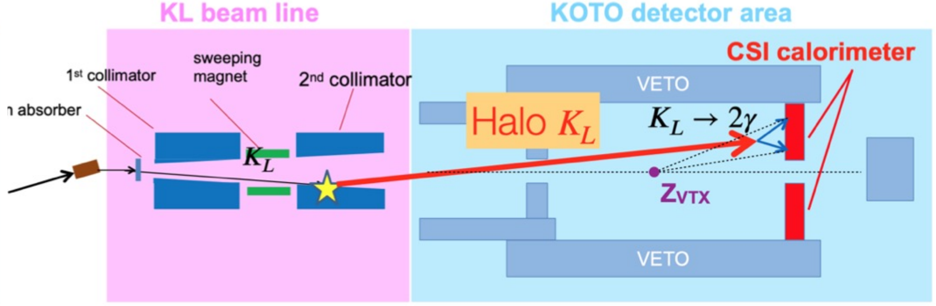
(**3.4σ** significance)

KOTO: backgrounds (2016–18)

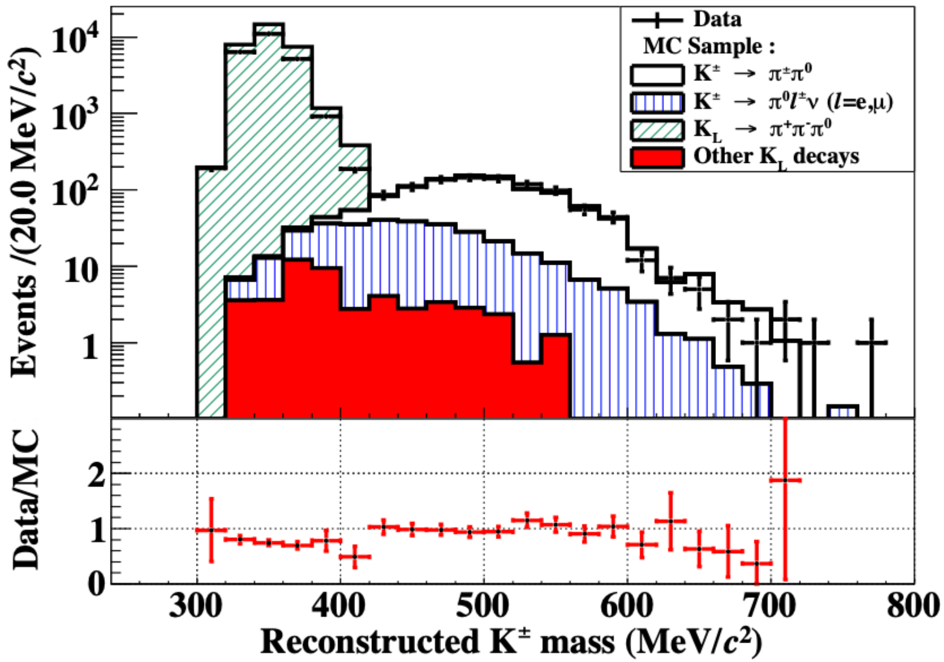
$K^{\pm}$ decays (charge exchange):



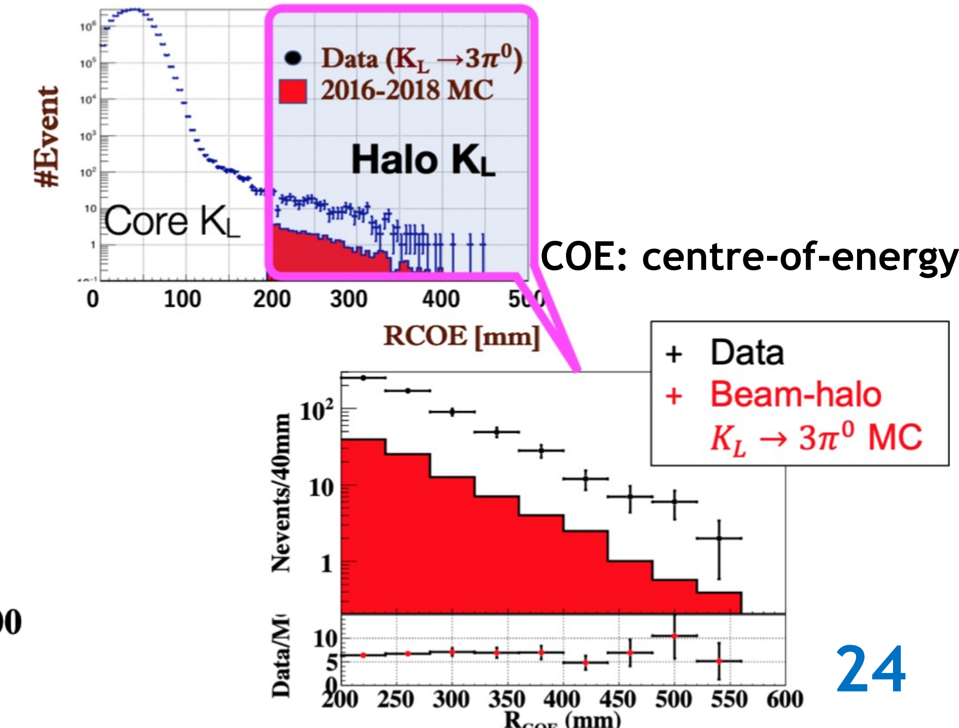
$K_L \to \gamma\gamma$ decays (scattered kaons):



- A dedicated dataset collected in **2020**: $K^{\pm}$ flux measured using $K^{\pm} \to \pi^{\pm}\pi^0$ decays.

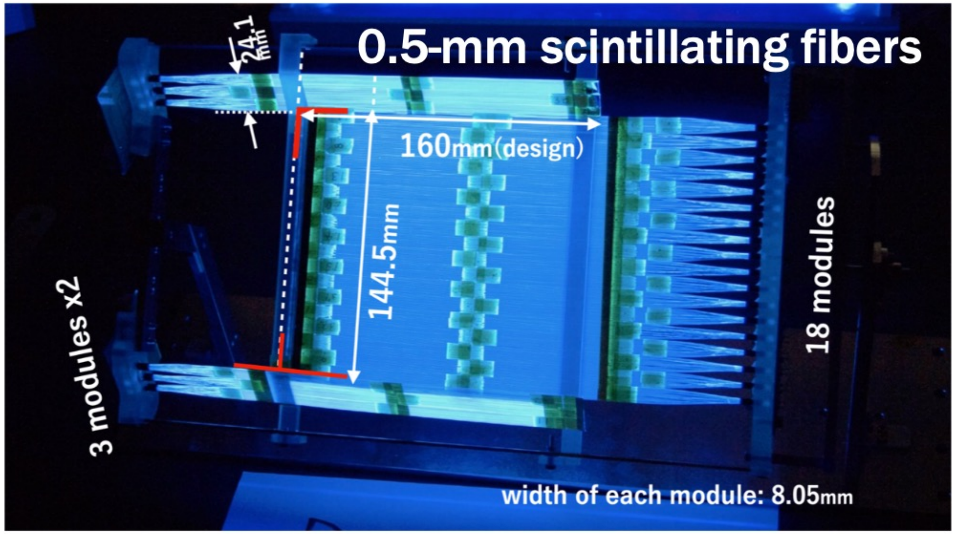


- Calibration of K_L halo in simulation using reconstructed $K_L \to 3\pi^0$ events.



KOTO: improvements in 2019–21

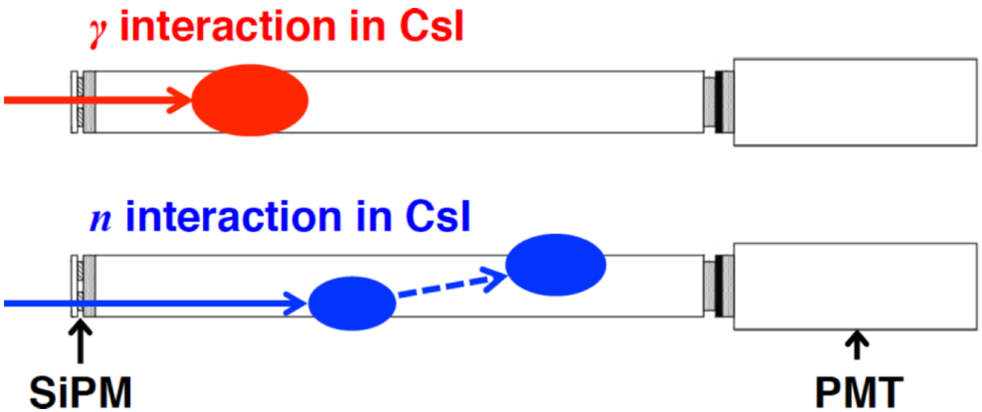
Need ~20 times improvement in background rejection to obtain S/B ≈ 1, assuming SM signal rate.



Upstream charged-particle veto: prototype installed for 2020 run, final version available in 2021.

Reduction of $K^{\pm}$ background: f~20.

Dual-side CsI calorimeter readout: installed for the 2019 run; γ/n interaction depth resolved by reading light from front CsI face with SiPMs.



Reduction of neutron bkg: f~50.

The 2019–21 dataset is the largest collected so far, analysis is in progress.