Kaons: NA62 and beyond

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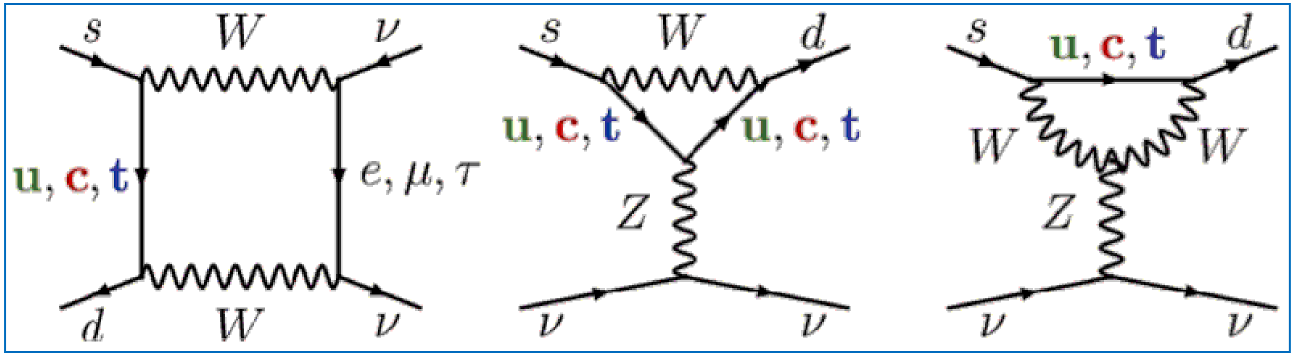
Outline:

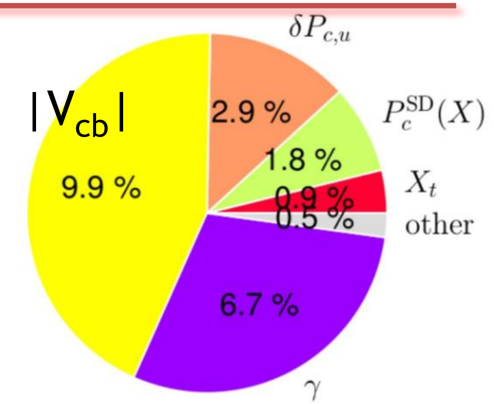
1) Introduction: rare kaon decays
2) NA62 status and UK leadership
3) The flagship $K^+ \to \pi^+ \nu\nu$ measurement
4) Short-term and long-term plans
5) Summary

PPAP community meeting
20 November 2020

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

SM: Z-penguin and box diagrams





BR($K^+\to\pi^+\nu\nu$): error budget

"Golden modes": ultra-rare decays, precise SM predictions.

- Maximum CKM suppression: $\sim(m_t/m_W)^2|V^*_{ts}V_{td}|$.
- Hadronic matrix element extracted from measured BR(K_{e3}) via isospin rotation.
- Complementarity to measurements in the B-sector.
- An **essential scientific activity** according to European strategy update 2020.

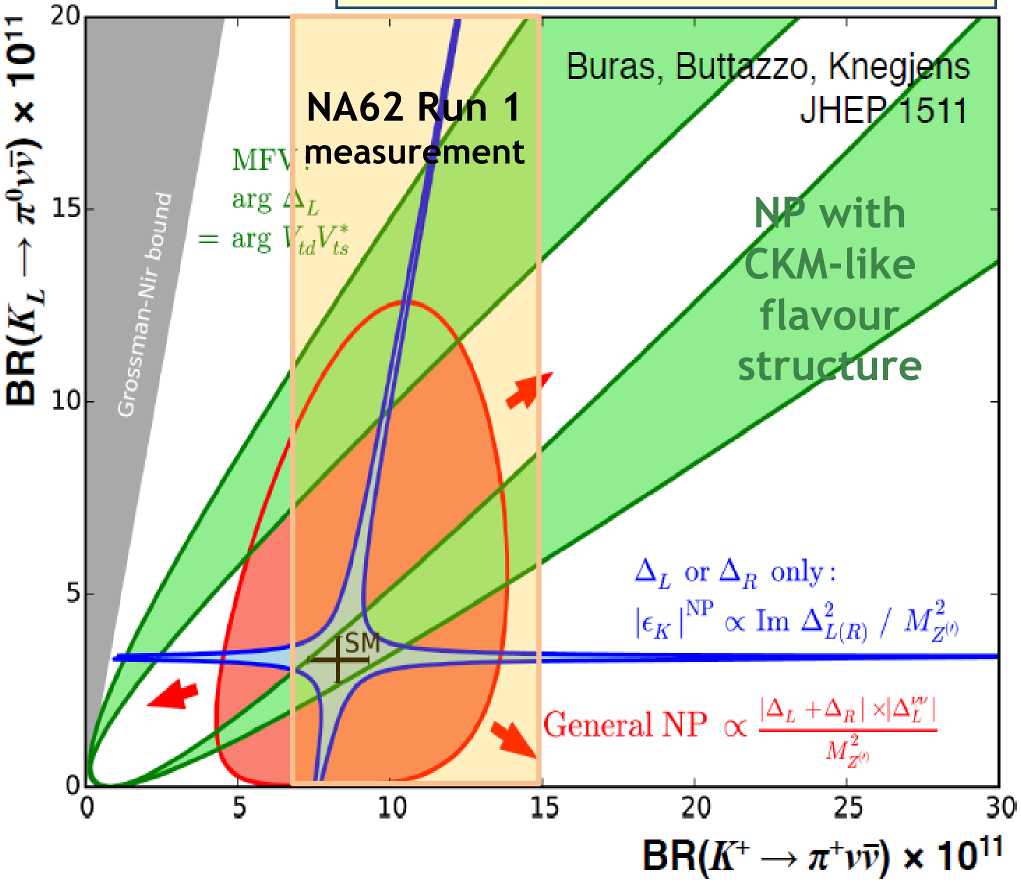
Mode	Expected BR_{SM}	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.4\pm1.0)\times10^{-11}$	BR=$(11\pm4)\times10^{-11}$ (NA62 Run 1 data: 20 candidates)
$K_L\to\pi^0\nu\nu$	$(3.4\pm0.6)\times10^{-11}$	BR$<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

BR_{SM}: Buras et al., JHEP 1511 (2015) 33; tree-level determination of CKM elements

K→πνν beyond the SM

- Correlations between BSM contributions K^+ and K_L BRs. *[JHEP 1511 (2015) 166]*
- Need to measure both K^+ and K_L to discriminate among BSM scenarios.
- Correlations with other observables (ε'/ε, ΔM_K, B decays). *[arXiv:2006.01138]*

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

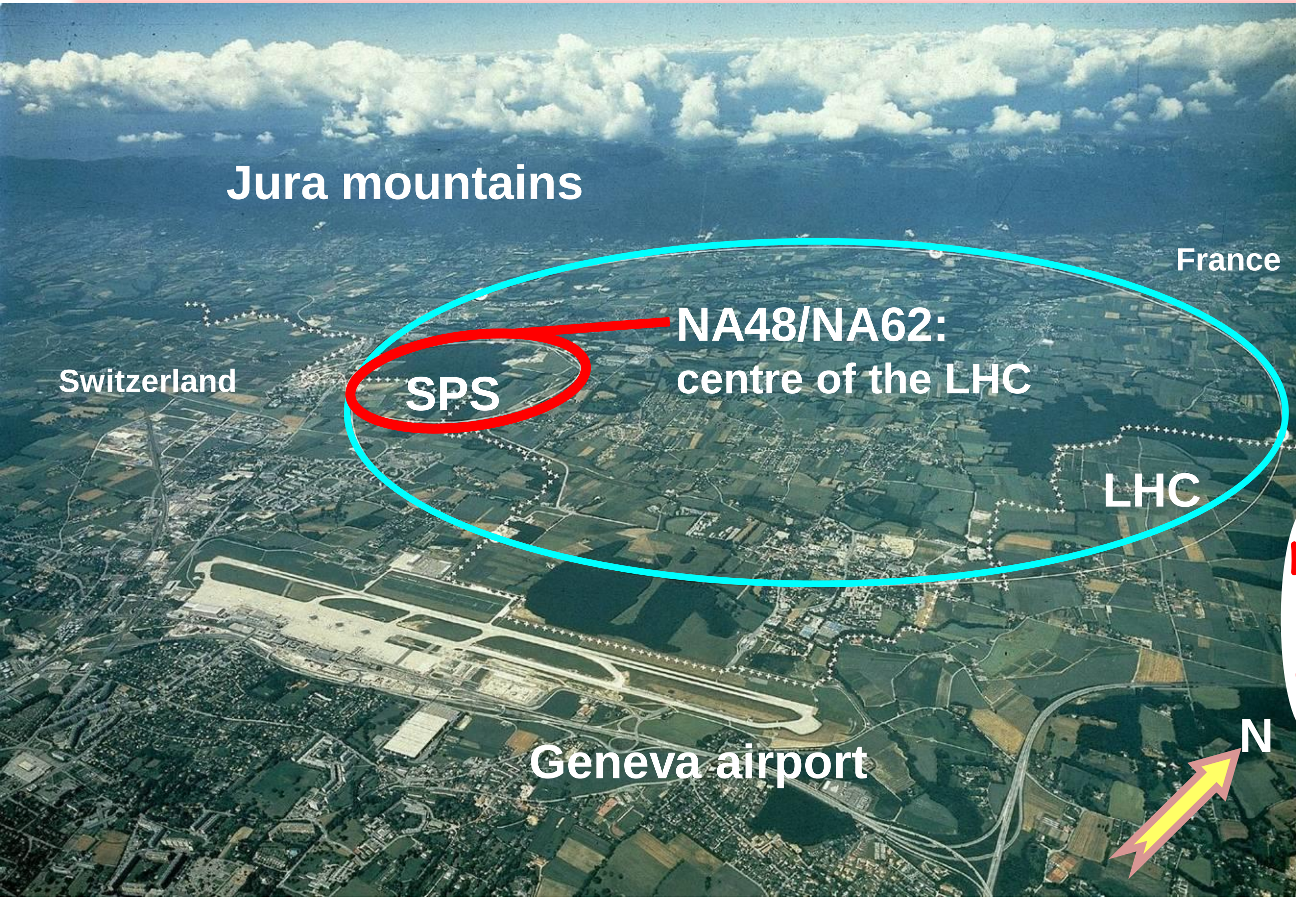


- **Green:** models with CKM-like flavour structure
  - ✓ Models with MFV
- **Blue:** models with new flavour-violating interactions in which LH or RH couplings dominate
  - ✓ Z′ models with pure LH/RH couplings
- **Red:** general NP models without the above constraints
- **The Grossman-Nir bound:**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

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

NA62 status and UK leadership

NA62 experiment 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

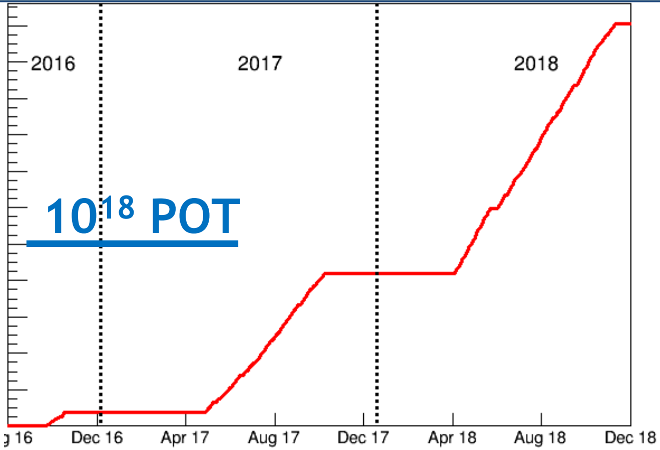
NA62
- 2015: commissioning
- 2016-18: physics run 1
- 2021-: physics run 2

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

NA62UK: Birmingham, Bristol, Glasgow, Lancaster (9% of the collaboration).

NA62 status: Run 1 completed

Run 1 integrated luminosity



2.2×10^{18} POT collected

- Commissioning run 2015: minimum bias data ($\sim3\times10^{10}$ protons/pulse).
- Physics run 2016 (30 days, $\sim1.3\times10^{12}$ ppp): 2×10^{11} useful K^+ decays.
- Physics run 2017 (160 days, $\sim1.9\times10^{12}$ ppp): 2×10^{12} useful K^+ decays.
- Physics run 2018 (217 days, $\sim2.3\times10^{12}$ ppp): 4×10^{12} useful K^+ decays.
- Run 2 to start after the LS2 in 2021 ($\sim3\times10^{12}$ ppp).

UK leadership in NA62

Key UK roles in the Collaboration:

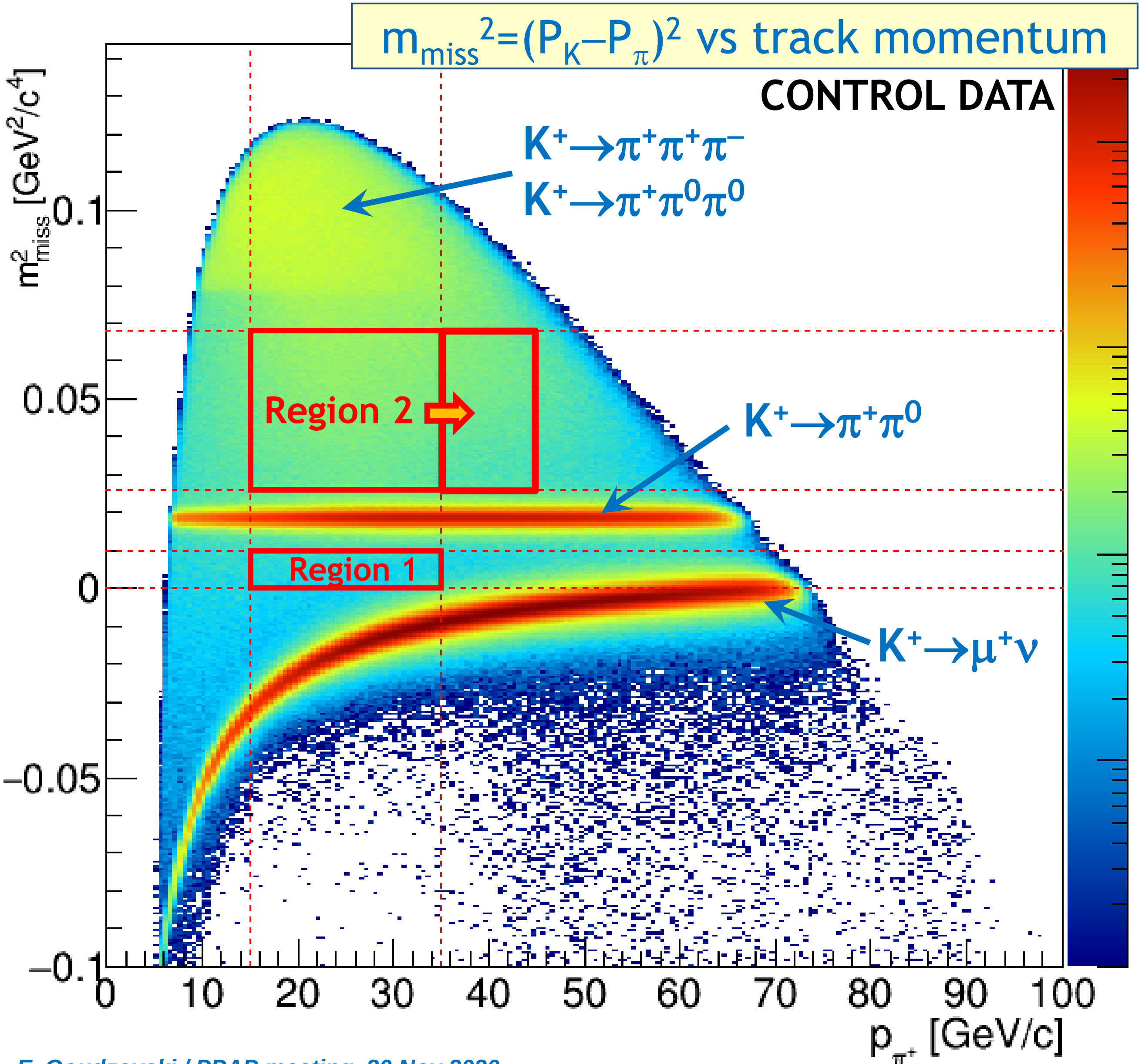
- The **spokesperson** and a **deputy spokesperson**.
- Two (out of four) **physics analysis conveners**.
- Three (out of 12) **Editorial Board members**.
- Full responsibility for the **KTAG subdetector**.
- Coordination of the **High Level Trigger**.
- Leadership in **distributed computing** (in-kind support via GridPP), central MC productions, and key parts of offline software.

Firm UK leadership in NA62 Run 1 physics analysis:

- **75%** of the NA62 physics papers published **2018–20** have UK corresponding authors, including
  - ✓ $K^+ \to \pi^+ \nu\nu$ measurement and search for $K^+ \to \pi^+ S$;
  - ✓ searches for lepton number violating K^+ decays;
  - ✓ searches for heavy neutral lepton production in K^+ decays.

$K^+ \to \pi^+ \nu\nu$ measurement

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 kinematical background suppression:

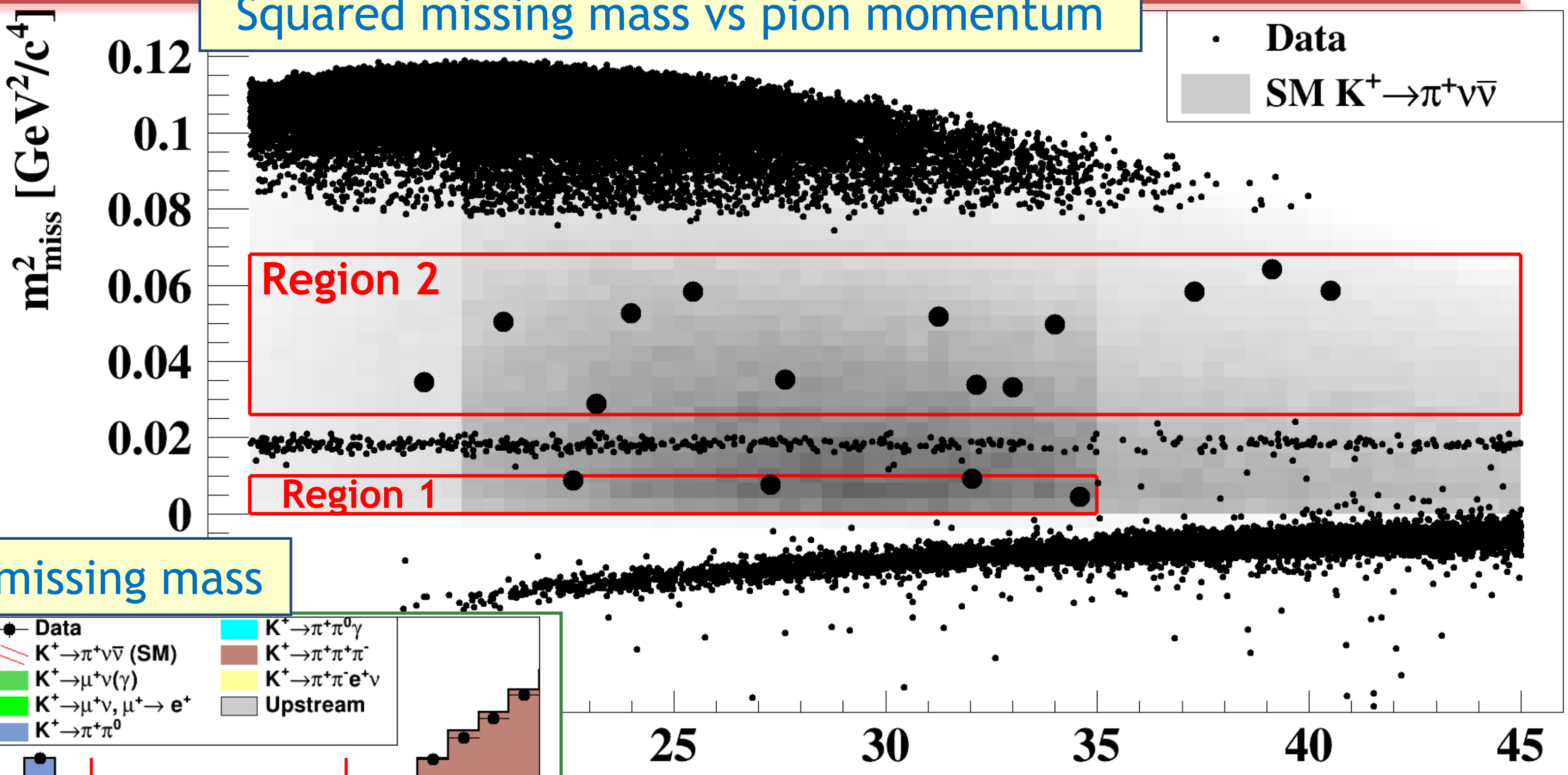
- ✓ $K^+\to\pi^+\pi^0$: 1×10^{-3};
- ✓ $K^+\to\mu^+\nu$: 3×10^{-4}.

Further background suppression:

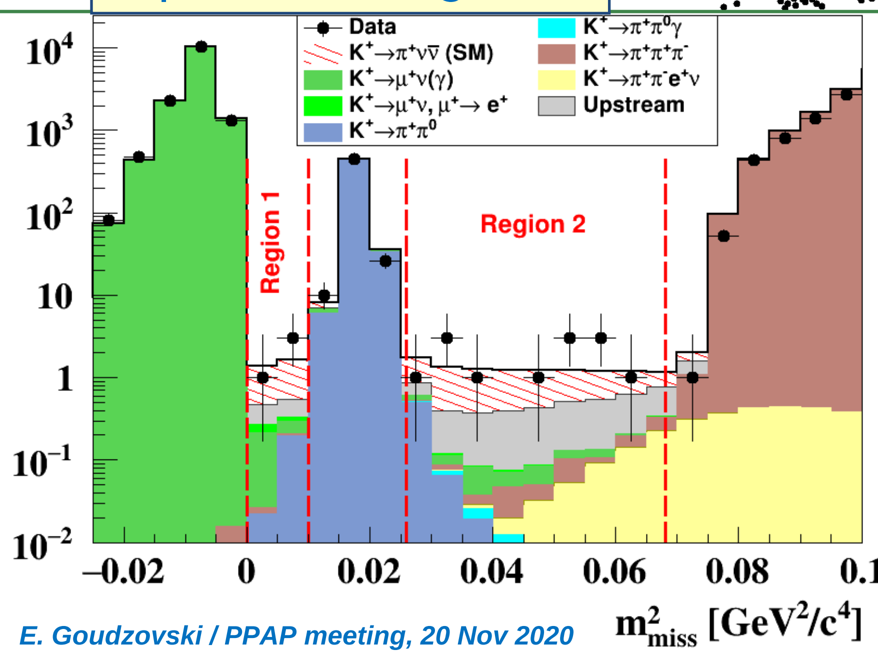
- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

$K^+ \to \pi^+ \nu \nu$: opening the box (2018)

Squared missing mass vs pion momentum



Squared missing mass



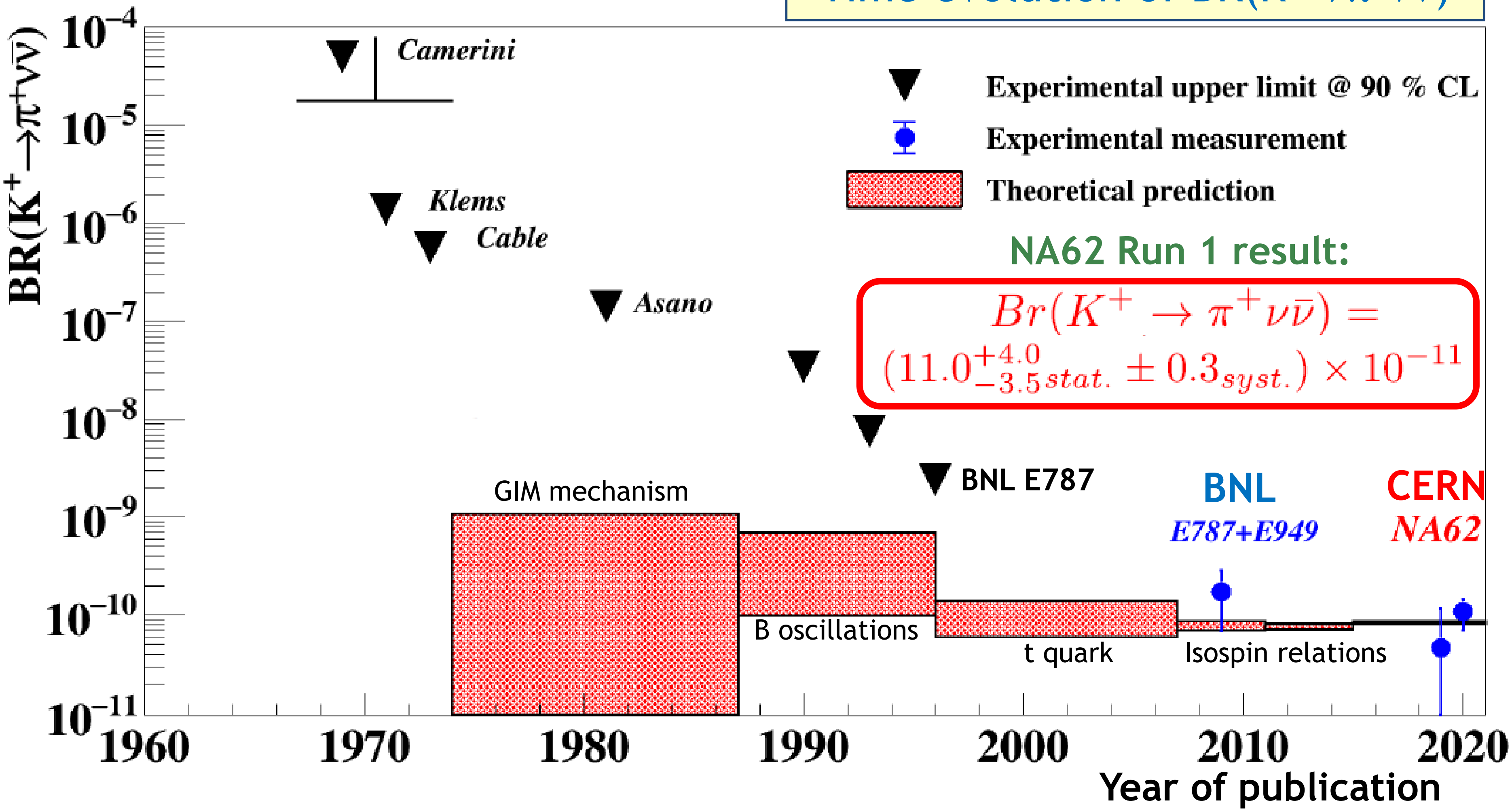
The 2018 data set:

Candidates observed: **17**
Expected background: **5.3±1.0**
Expected SM events: **7.6**

With the full **Run 1** data, first observation of $K^+ \to \pi^+ \nu \nu$ decay (3.5σ). One of the rarest decays to be observed.

$K^+ \to \pi^+ \nu\nu$: historical perspective

Time evolution of $BR(K^+ \to \pi^+ \nu\nu)$



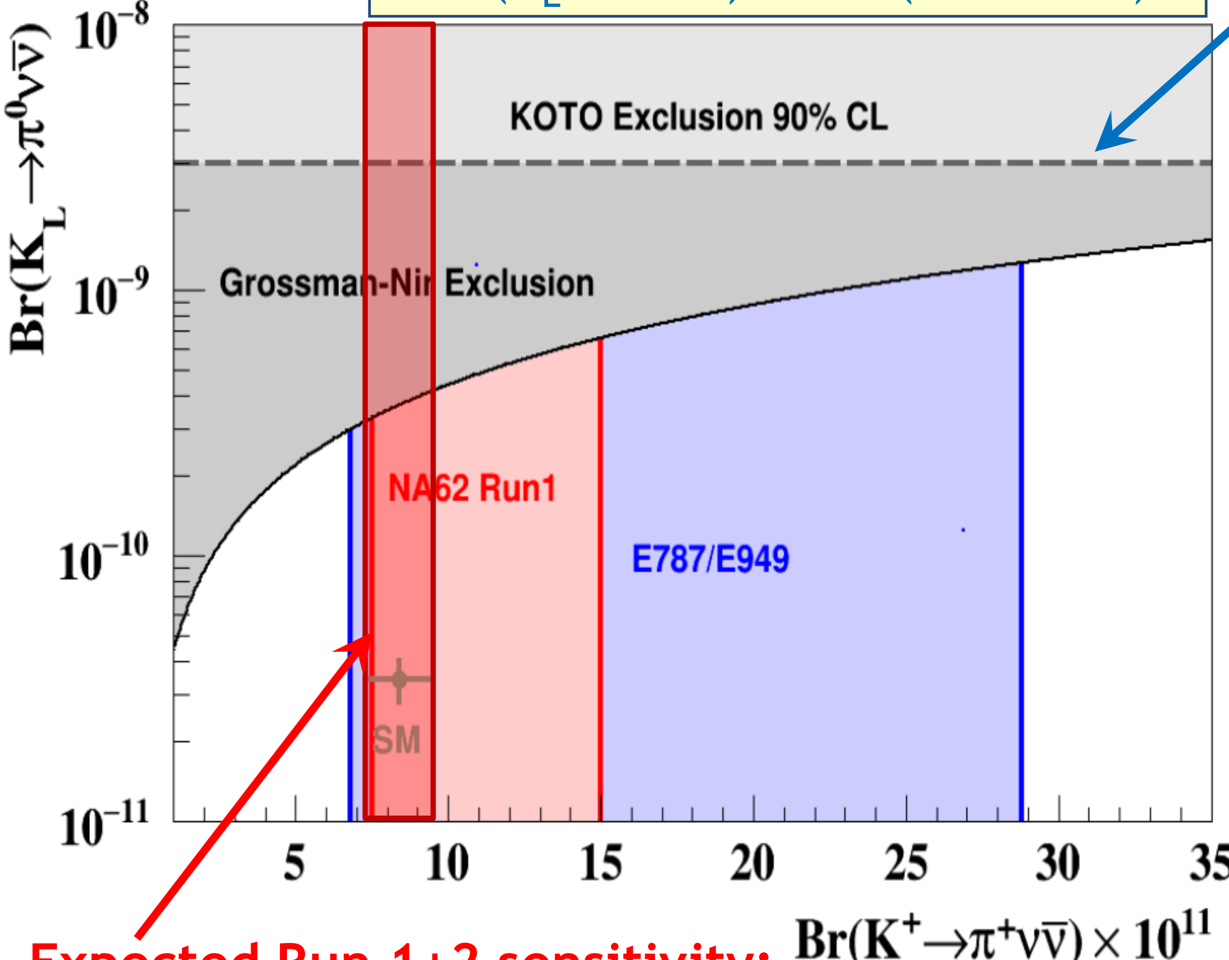
NA62 Run 1 result:

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (11.0^{+4.0}_{-3.5\,stat.} \pm 0.3_{syst.}) \times 10^{-11}$$

The NA62 decay-in-flight technique is firmly established

Short-term plans: NA62 Run 2

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



KOTO result with 2015 data:
BR($K_L \to \pi^0 \nu\nu$) < 3.0×10^{-9}
PRL 122 (2019) 021802

Expected Run 1+2 sensitivity: δBR/BR ≈ 10%

NA62 Run 2 (2021–24):

- Improved trigger: higher beam intensity.
- Optimized beamline, new veto detectors: reduced upstream background, higher acceptance.
- Fourth kaon beam tracker station.
- Aim to reach **O(10%)** precision on $K^+ \to \pi^+ \nu\nu$.

Long-term plans

A possible next step after LS3 (~2028): an in-flight $K^+ \to \pi^+ \nu\nu$ experiment with ×4 beam intensity, aiming at ~5% precision.

- ✓ Challenge: 20–40 ps time resolution for key detectors to keep random veto under control, while maintaining other performances.

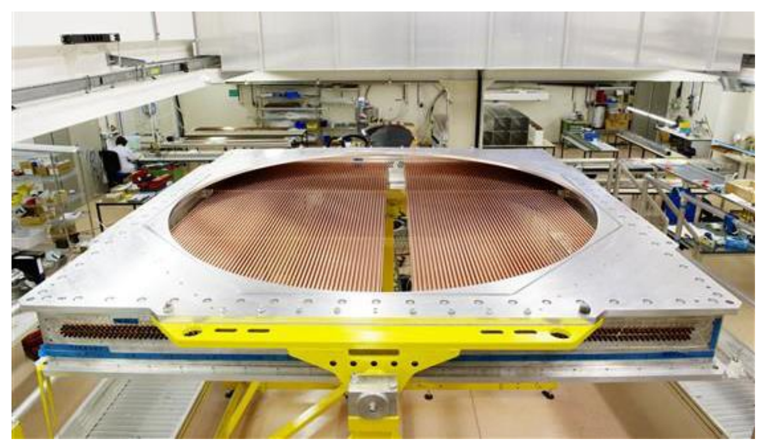
New pixel beam tracker (GTK):

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.

A current NA62 GTK station

New STRAW spectrometer:

operation in vacuum;
straw length/diameter: 2.2 m/5 mm;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
material budget: 1.5%X_0.



A current NA62 STRAW chamber

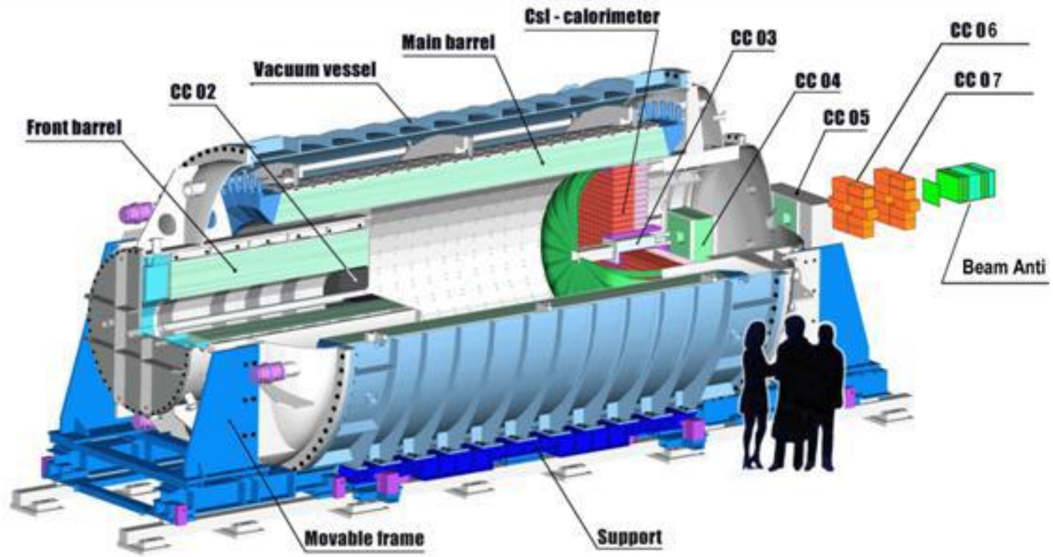
Summary

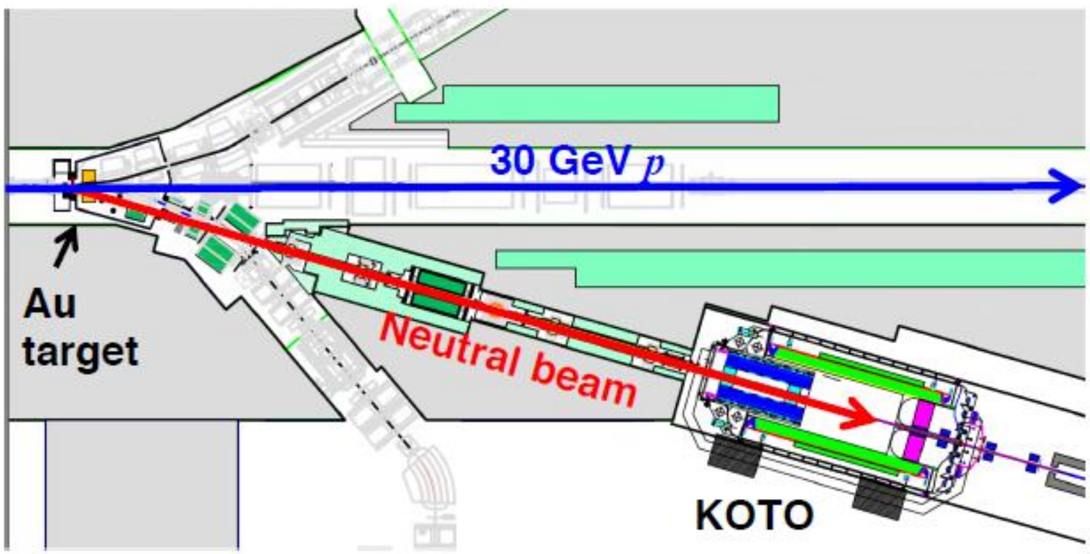
- **UK participation in NA62 since 2011:**
  - ✓ Funding during the construction phase: ERC Advanced Grant & Starting Grant, Royal Society Fellowships.
  - ✓ Exploitation phase funded by the STFC Consolidated Grant.
  - ✓ Consolidation of leadership via two STFC Rutherford fellowships.
  - ✓ Strong UK leadership: **excellent value for STFC investment**.
- **Analysis of Run 1 (2016–18) data:**
  - ✓ UK-led first observation of the $K^+\to\pi^+\nu\nu$ decay: $BR(K^+\to\pi^+\nu\nu) = (11\pm4)\times10^{-11}$, based on **20** candidates.
  - ✓ A broad UK-led rare decay and hidden-sector programme.
- **Next steps:**
  - ✓ **Run 2 (2021–24)** approved by CERN management and SPSC: upgraded detector, trigger and analysis to reach **O(10%)** precision on $BR(K^+\to\pi^+\nu\nu)$ by **2025**.
  - ✓ A high-intensity (**NA62x4**) K^+ experiment is foreseen after LS3; NA62-UK are considering a future SoI.

Backup

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

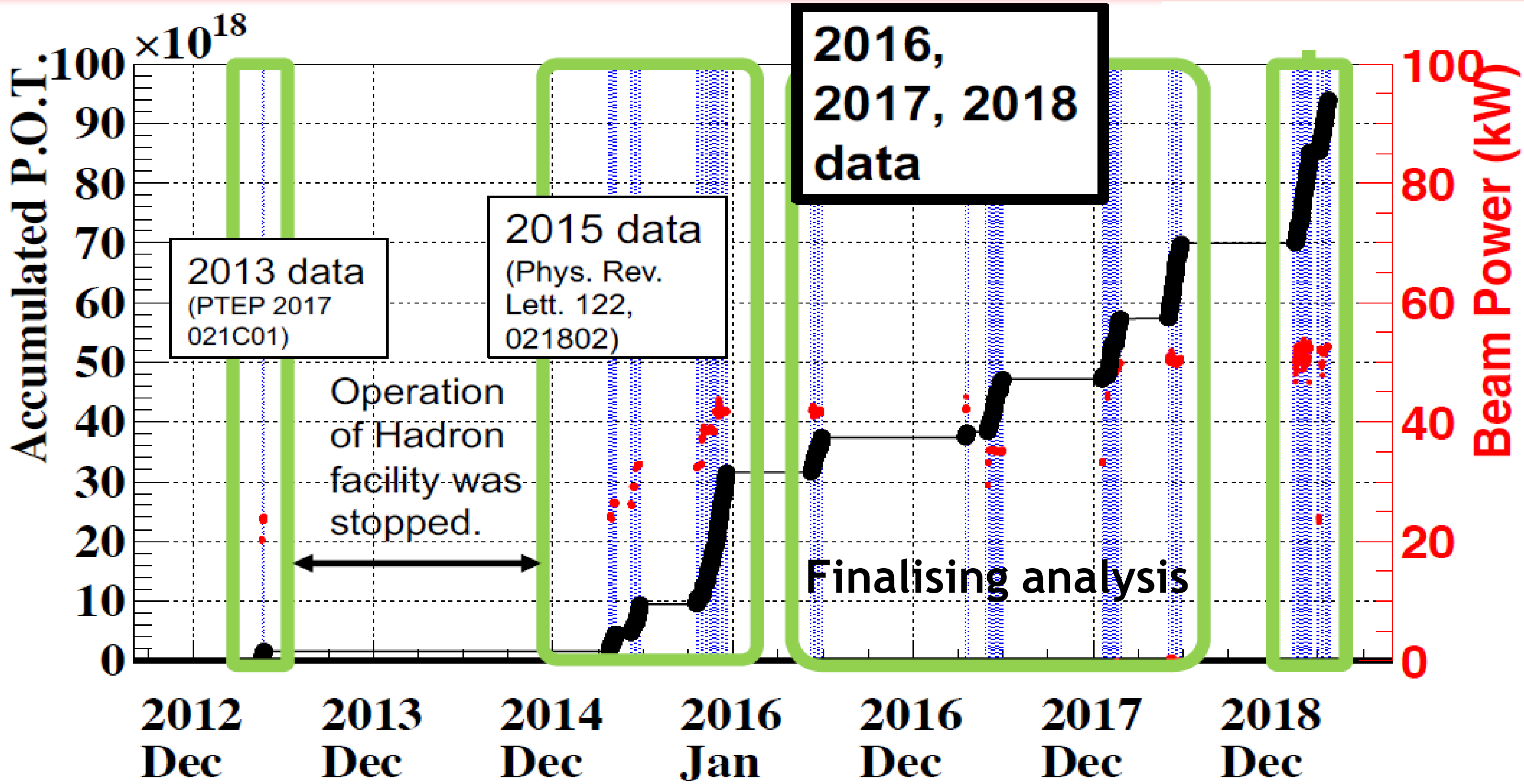
- Primary beam: **30 GeV** protons; **50 kW = 5.5×10^13 p/5.2 s** (in 2019).
- Neutral "pencil" beam (at **16°**): **$\langle p(K_L)\rangle$ = 2.1 GeV**, with **50%** in the **(0.7–2.4) GeV** range.
- Beam composition: **K_L**, neutrons, photons.
- Fiducial decay region length: **3 m**.
- CsI calorimeter + hermetic photon veto.





E. Goudzovski / PPAP meeting, 20 Nov 2020

KOTO status



2015 run

- Reached **40 kW** beam power, 3×10^{19} POT collected.
- Final 2015 result: $BR(K_L\to\pi^0\nu\nu)<3.0\times10^{-9}$ at **90%** CL.
  PRL 122 (2019) 021802

2016–2018 runs

- Reached **50 kW** beam power, 4×10^{19} POT collected.
- Preliminary results reported in 2019/20.

2019 run

- Analysis in progress.

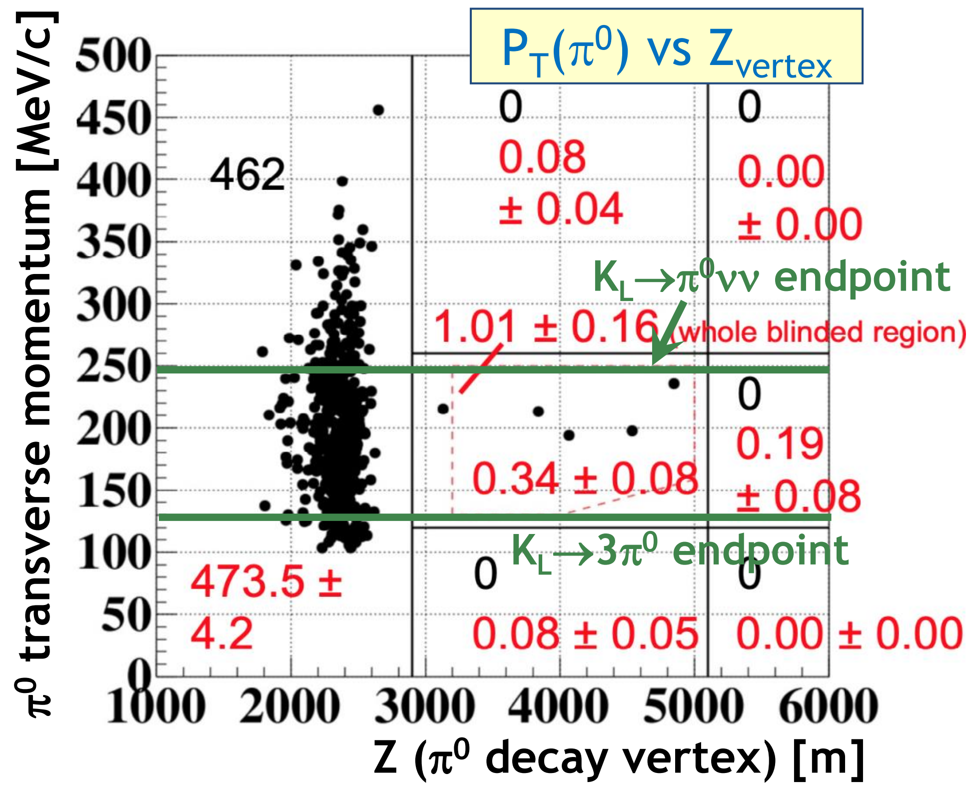
KOTO: 2016–18 data

Preliminary results (N.Shimizu at ICHEP 2020)

Single-event sensitivity:
$BR_{SES}=71\times10^{-11}$ ($=20\times BR_{SM}$)

Main backgrounds:

source		#BG (90% C.L.)	#BG (68% C.L.)
K+/-	$K^{\pm}\to\pi^0\pi^{\pm}$	0.09±0.09	0.09±0.09
	$K^{\pm}\to\pi^0 e^{\pm}\nu$	0.90±0.27	0.90±0.27
	$K^{\pm}\to\pi^0\mu^{\pm}\nu$	<0.21	<0.12
Neutron	Upstream π^0	0.001±0.001	0.001±0.001
	Hadron cluster	0.02 ±0.00	0.02 ±0.00
	CV-pi0	<0.10	<0.05
	CV-eta	0.03±0.01	0.03±0.01
Total	central value	1.05±0.28	1.05±0.28



After a blind analysis, **four candidate events** in the signal region.

- One event demonstrated to be background (timing in a veto counter).
- Background estimate (revised): **1.05±0.28** events, mainly from $K^{\pm}$ decays.
- The result on $BR(K_L\to\pi^0\nu\nu)$ is to be reported soon.