Prospects for rare kaon decays

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Outline:

1) Rare kaon decays in the Standard Model and beyond
2) Status and plans at J-PARC: $K_L \to \pi^0 \nu\nu$
3) Status and plans at CERN: $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$
4) Summary

Topical group RF2: weak decays of light & strange quarks

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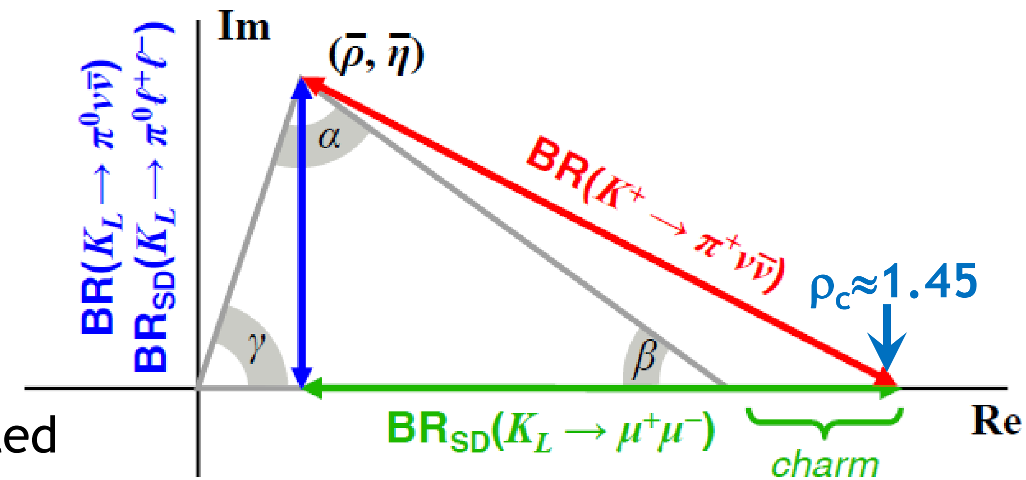
Snowmass RPF kick-off meeting, 27 July 2020

Introduction: 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%	8.4 ± 1.0	**<17.8**
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	3.4 ± 0.6	< 300

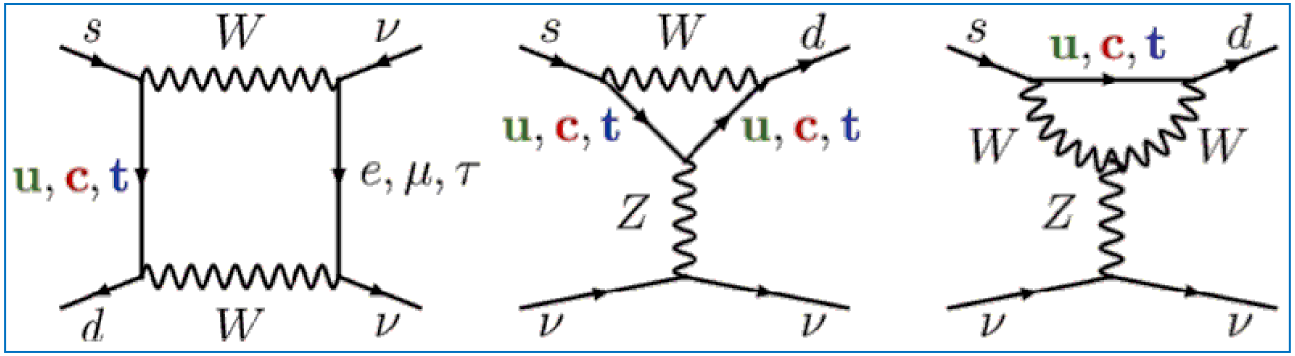
*Approx. error on LD-subtracted rate excluding parametric contributions

- FCNC processes dominated by **Z**-penguin and box diagrams.
- SM rates related to V_{CKM} with minimal non-parametric uncertainties.
- Golden modes $K\to\pi\nu\nu$: uniquely clean theoretically.
- Decays to charged leptons: affected by larger hadronic uncertainties.



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

SM: Z-penguin and box diagrams



"Golden modes": ultra-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	Expected BR_{SM}	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.4\pm1.0)\times10^{-11}$	$BR<17.8\times10^{-11}$ at 90% CL (three candidates, NA62 2016+17 data)
$K_L\to\pi^0\nu\nu$	$(3.4\pm0.6)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

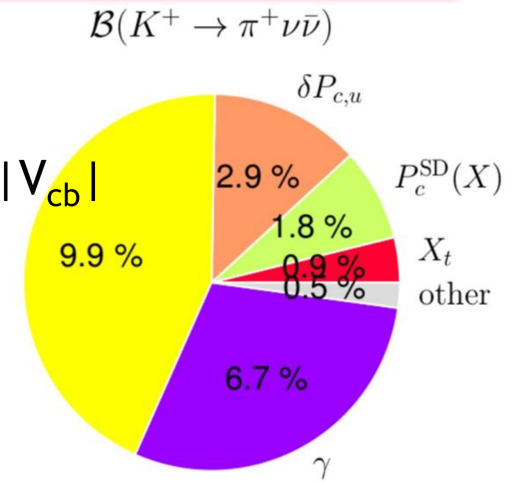
BR_{SM}: Buras et al., JHEP 1511 (2015) 33; tree-level determination of CKM elements

K→πνν and the unitarity triangle

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^{2.8} \cdot \left[\frac{\gamma}{73.2^\circ}\right]^{0.74}$$

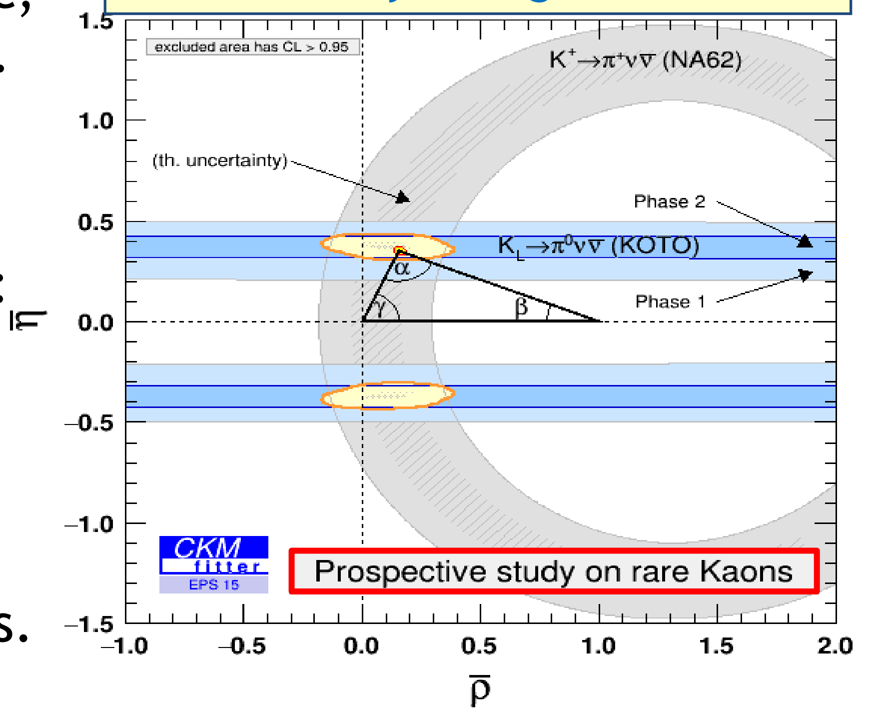
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{|V_{ub}|}{3.88 \times 10^{-3}}\right]^2 \cdot \left[\frac{|V_{cb}|}{0.0407}\right]^2 \cdot \left[\frac{\sin\gamma}{\sin 73.2^\circ}\right]^2$$

Buras et al., JHEP 1511 (2015) 33



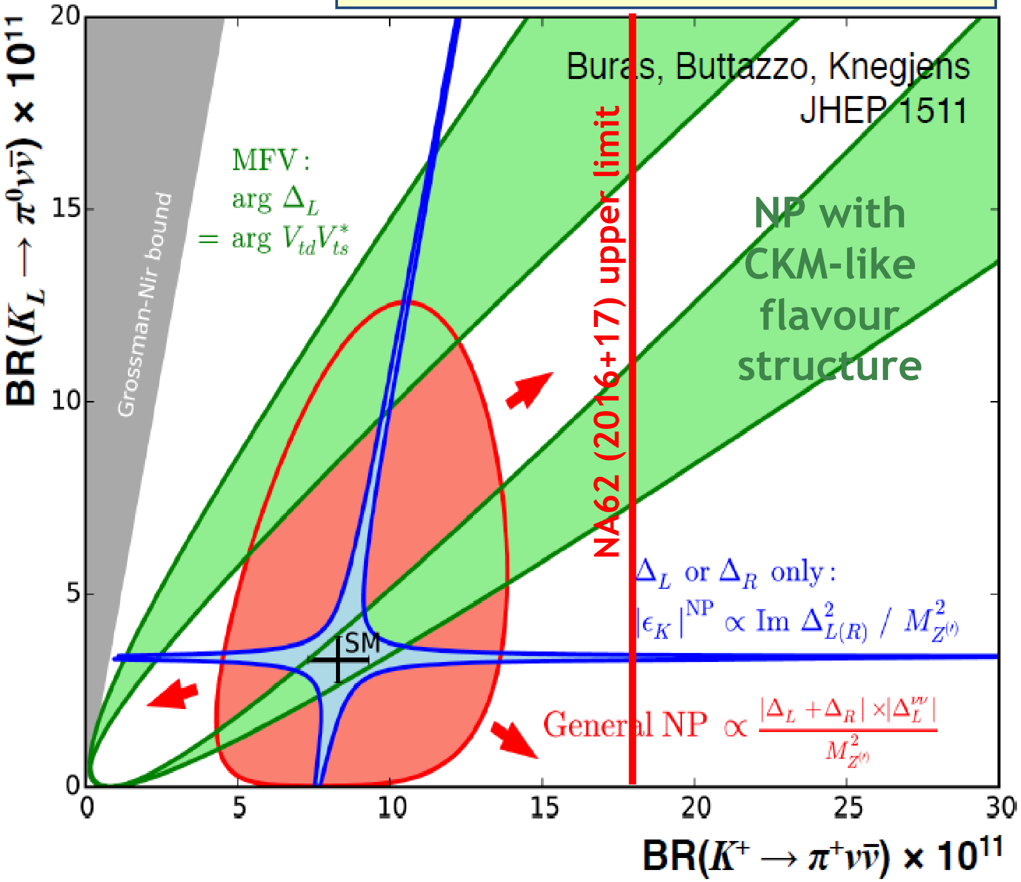
- Dominant uncertainties: CKM parametric; intrinsic theory uncertainties are **O(1%)**.
- Work to decrease theory uncertainties *[e.g. Christ et al., PRD 100 (2019) 114506]*.
- Measurements of both **K^+** and **K_L** decays: a clean **sin(2β)** measurement, an independent CKM unitarity test.
- Complementarity to measurements in the **B**-sector. Over-constraining the CKM matrix: reveal the nature of new physics.

CKM unitarity triangle with kaons



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

- 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]*

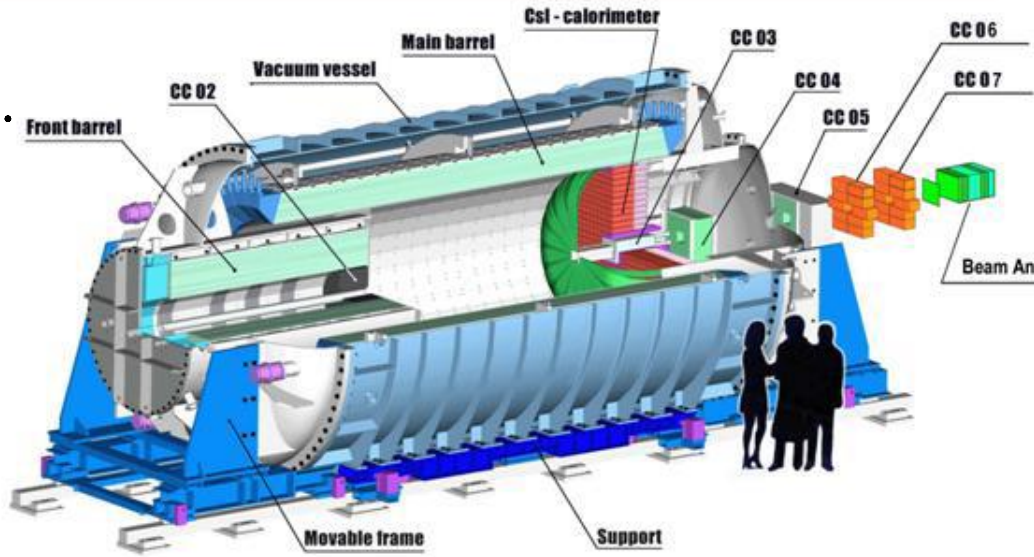


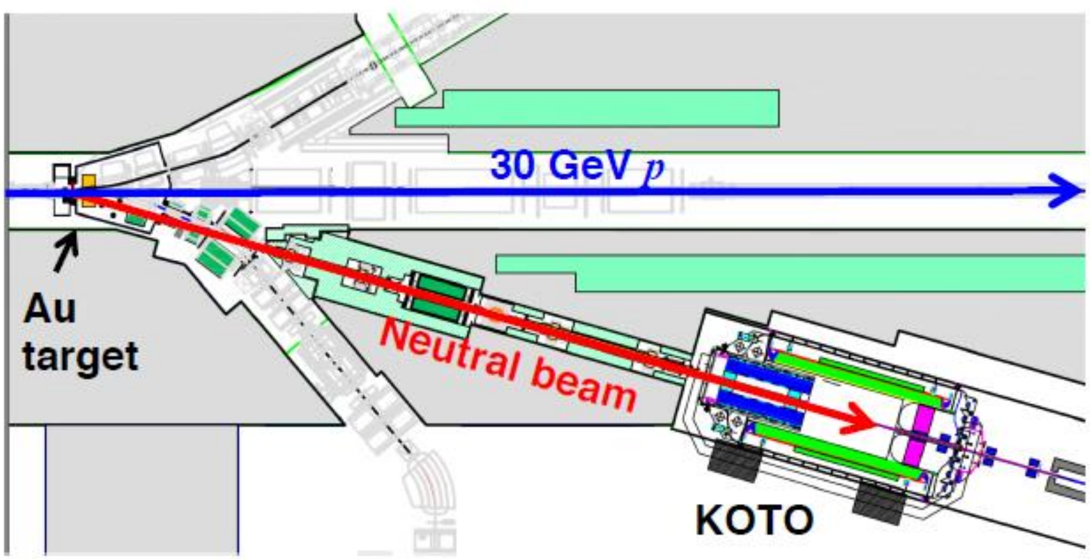
- **Green:** models with CKM-like flavour structure
  - ✓ Models with MFV
- **Blue:** models with new flavour-violating interactions in which LH or RH couplings dominate
  - ✓ Z′ models with pure LH/RH couplings
- **Red:** general NP models without the above constraints
- **The Grossman-Nir bound:**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

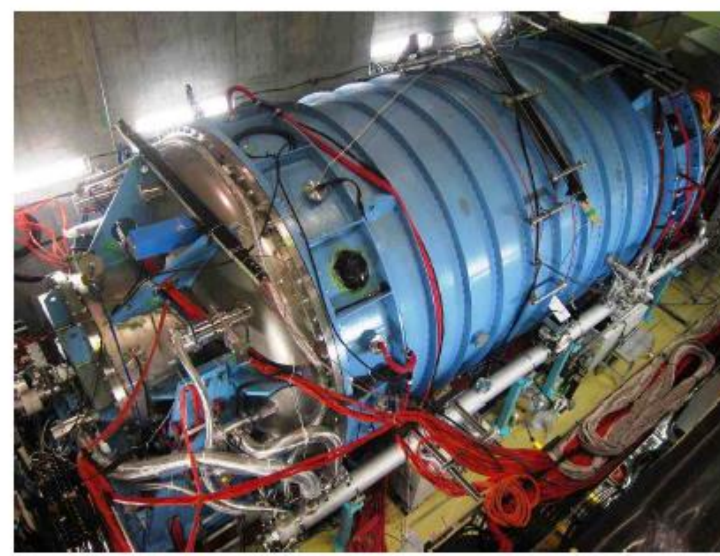
$$\frac{BR(K_L \to \pi^0 \nu\bar{\nu})}{BR(K^+ \to \pi^+ \nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \le 1$$

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

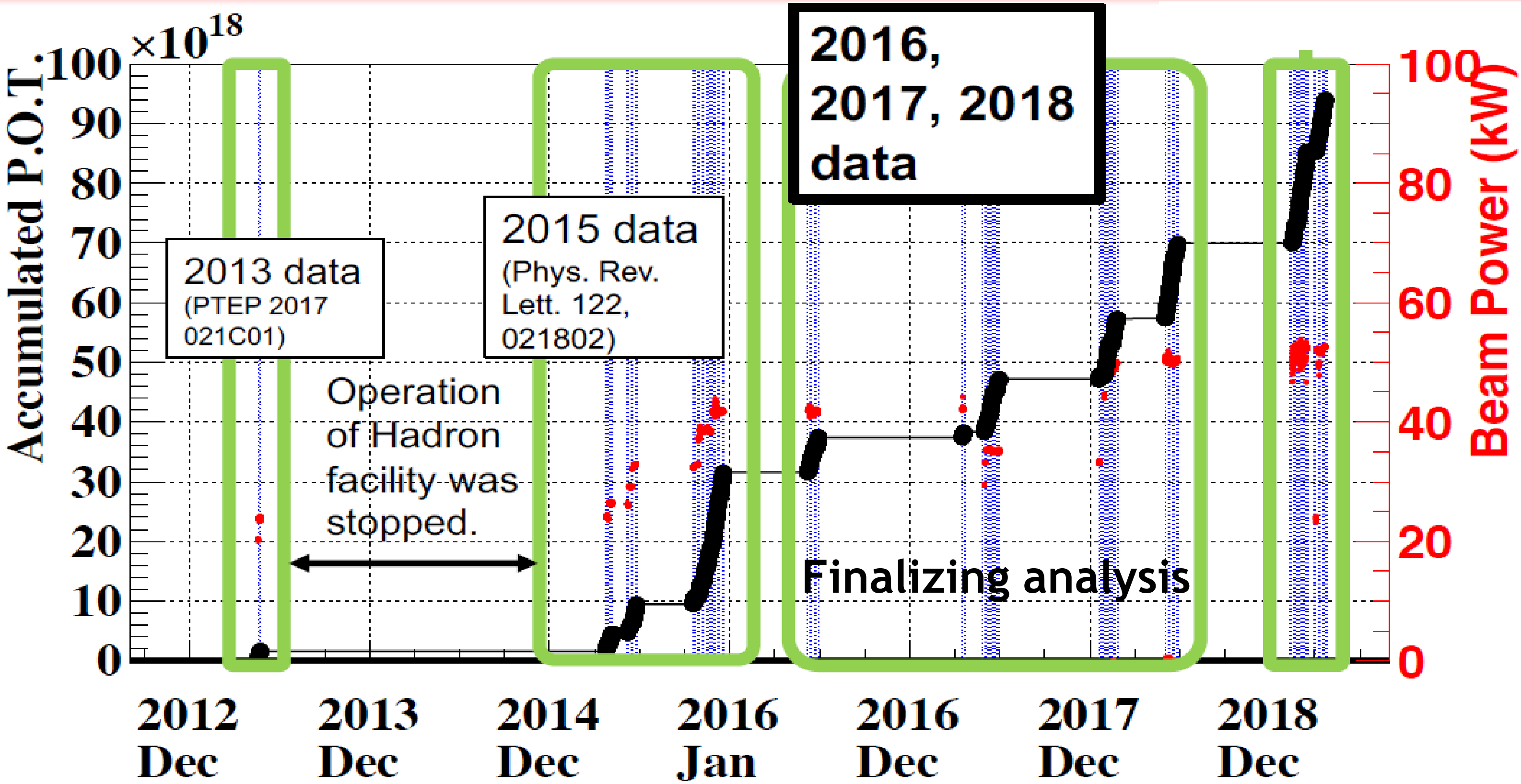
- Primary beam: **30 GeV** protons; **50 kW = 5.5×10^{13} p/5.2 s** as of 2019.
- Neutral "pencil" beam (at **16°**): **$\langle p(K_L)\rangle$ = 2.1 GeV**, with **50%** in the **(0.7–2.4) GeV** range.
- Beam composition: K_L, neutrons, photons.
- Fiducial decay region length: **3 m**.
- CsI calorimeter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







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.

2019 run

- Analysis in progress.

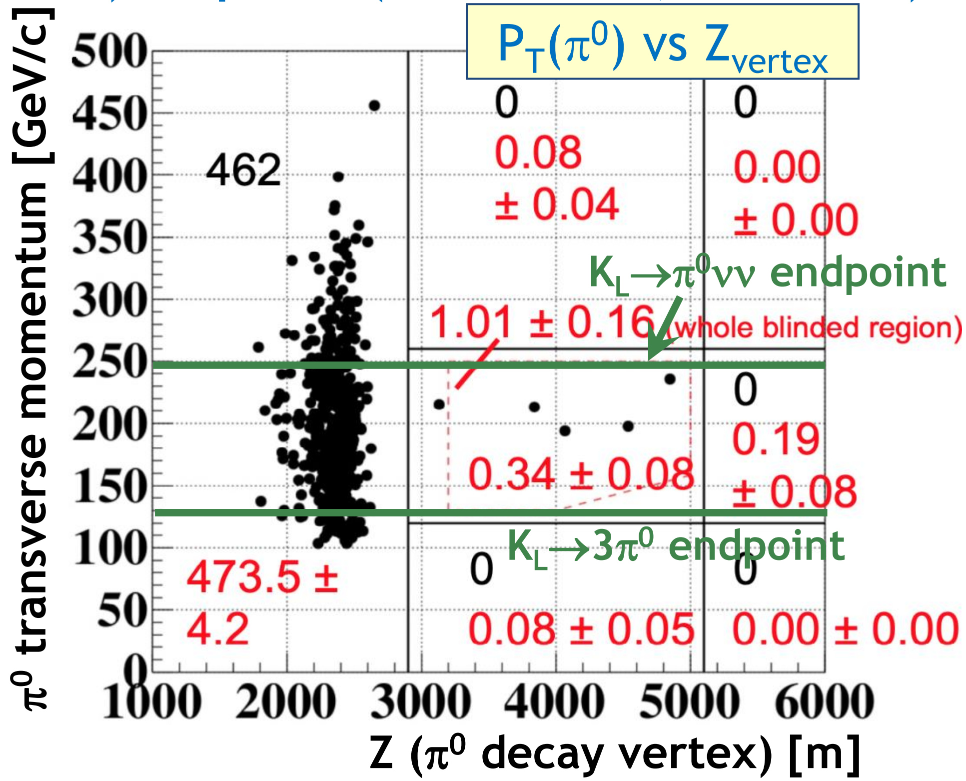
KOTO: 2016–18 data analysis

Preliminary result (Kaon2019, Sep 2019) + update (J-PARC PAC, Jan 2020)

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

Major backgrounds:

Source	Expected (68%CL)
$K_L \to \pi^0\pi^0$	<0.05
$K_L \to \pi e \nu$ overlap pulse	<0.05
$K_L \to ee\gamma$	<0.05
$K_L \to \gamma\gamma$ core	<0.06
$K_L \to \gamma\gamma$ halo	<0.10
$K^+ \to \pi^0 e^+ \nu$ charge-exch	0.29 ± 0.08
π^0 from n in CV	<0.05
Total	**0.34 ± 0.08**



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

- One event demonstrated to be background (timing in a veto counter).
- Analysis in progress, the background estimate is being revised.
- No $BR(K_L\to\pi^0\nu\nu)$ result reported yet.
- Excess of events above the Grossman-Nir bound: interpretations include hidden-sector physics ($K_L\to\pi^0X$). *[e.g. PRL124 (2020) 071801,191801]*

Short-term plans: KOTO step-1

Signal: need 20 times more (flux × acceptance) to reach SM sensitivity.

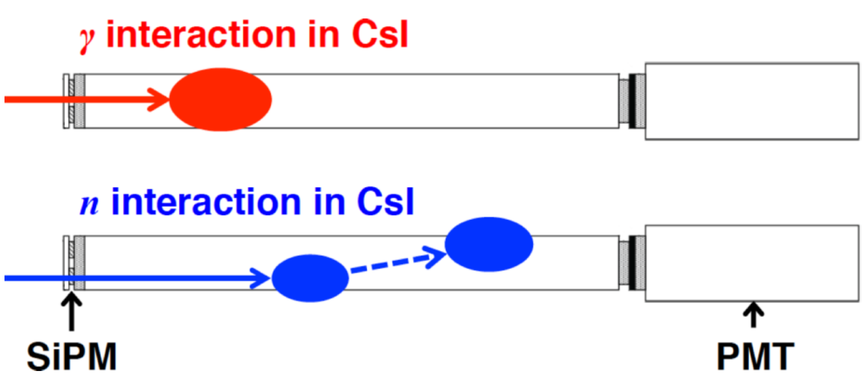
- ✓ Increase the beam power (50→100 kW) gradually by 2024.
- ✓ 8–16 months of additional running planned in 2020–2024.

Background: need ~10 times improvement in background rejection to obtain S/B ≈ 1, assuming SM signal rate.

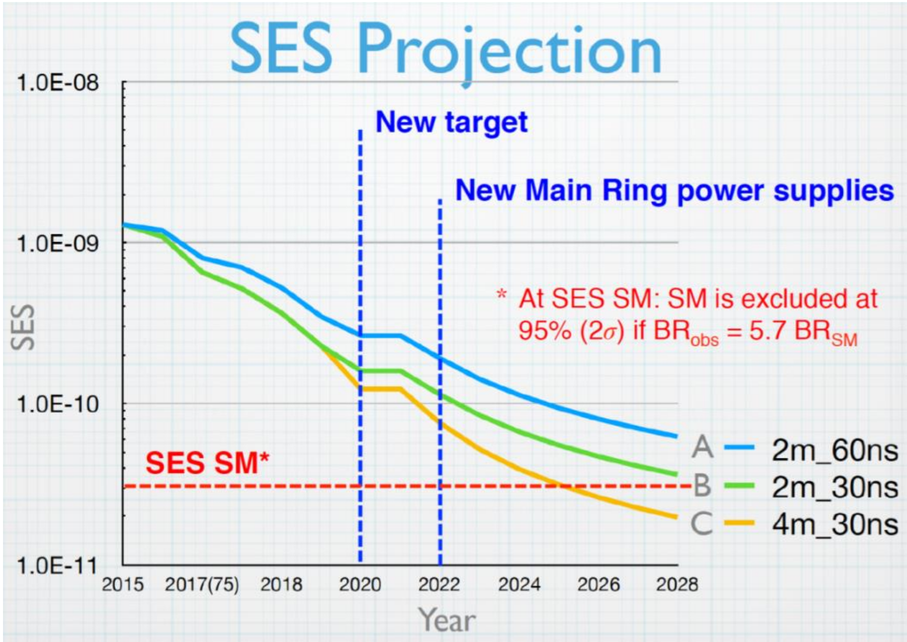
- ✓ Continuing programme of incremental detector upgrades.

Example:

Dual side readout for CsI calorimeter modules installed at end of 2018 run



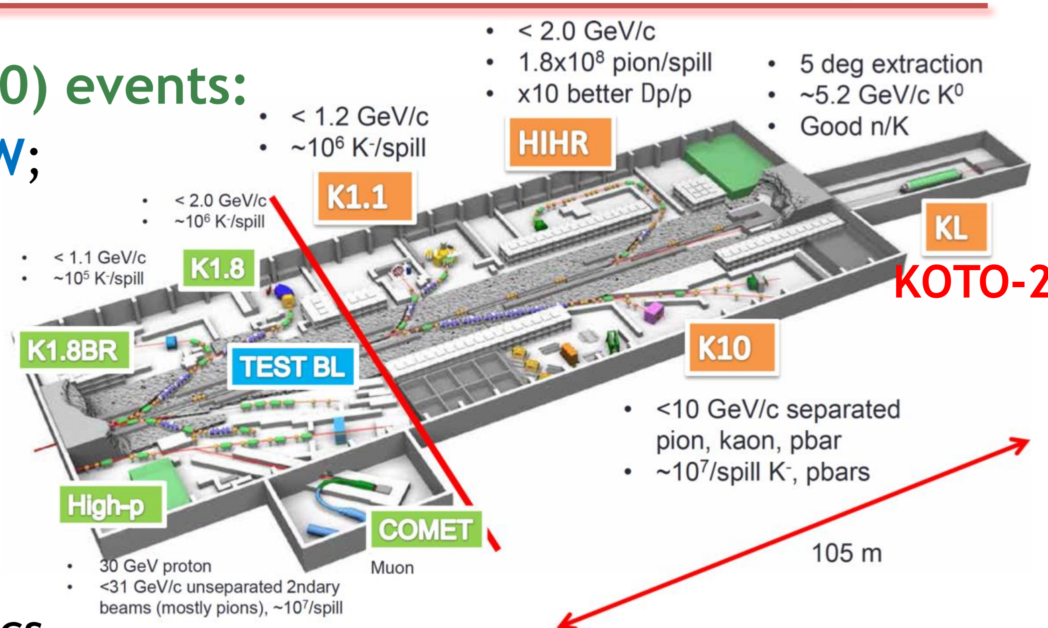
Resolve γ/n interaction depth by reading light from front CsI face with a SiPM



Long-term plans: KOTO step-2

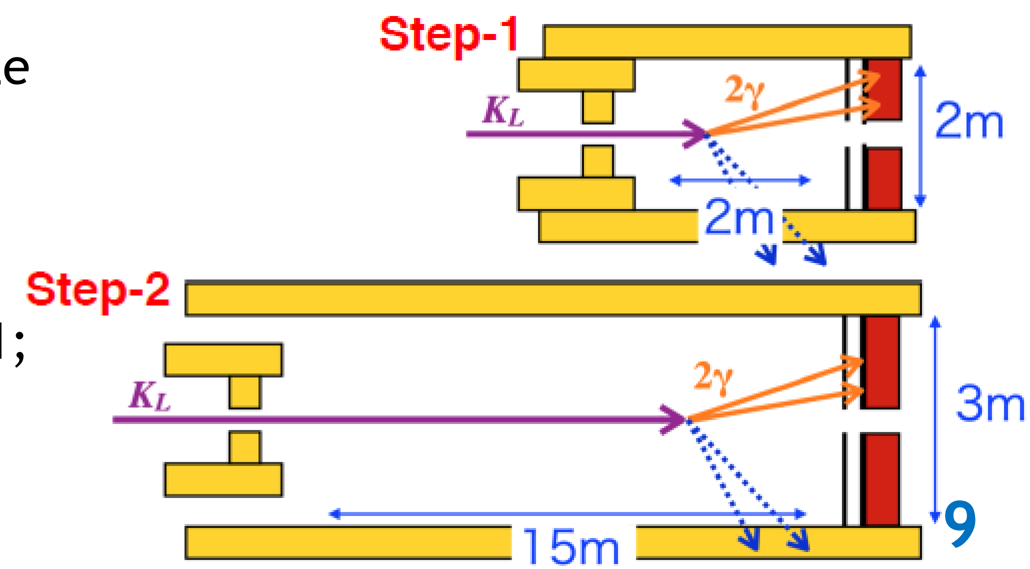
To reach the original goal of O(100) events:

- 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:

- a joint project with nuclear physics community;
- on the list of KEK future large-scale projects, with medium priority.



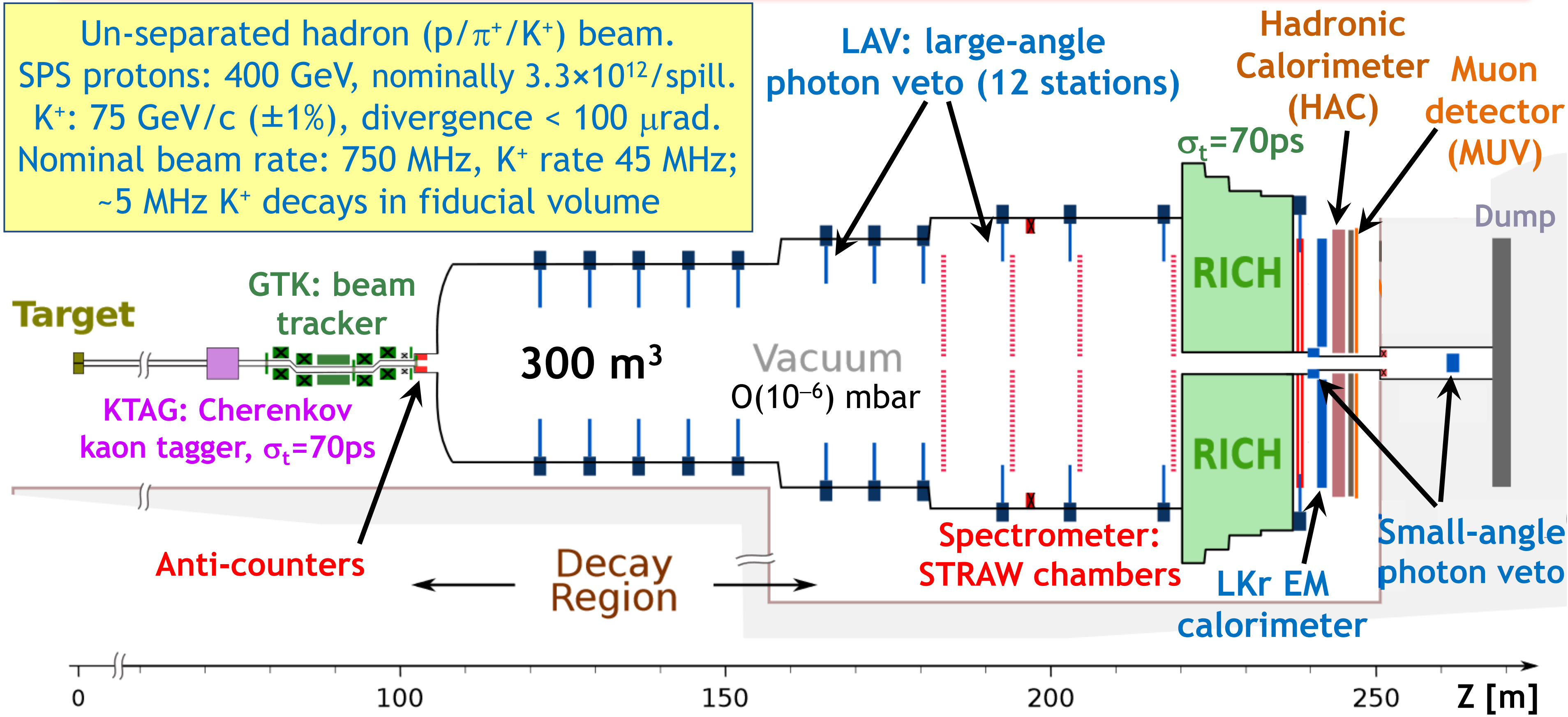
Expected sensitivity:

- signal acceptance: **5×** KOTO step-1;
- 60 SM events with **S/B~1** at **100 kW** beam power (**3×10^7 s**).

NA62 collaboration, JINST 12 (2017) P05025

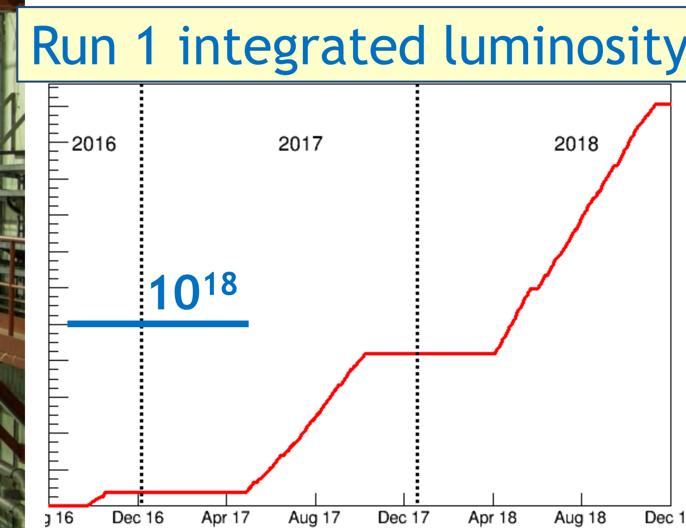
NA62 at CERN: $K^+ \to \pi^+ \nu\nu$

Un-separated hadron ($p/\pi^+/K^+$) beam.
SPS protons: 400 GeV, nominally 3.3×10^{12}/spill.
K^+: 75 GeV/c (±1%), divergence < 100 μrad.
Nominal beam rate: 750 MHz, K^+ rate 45 MHz;
~5 MHz K^+ decays in fiducial volume



- ❖ As of 2018, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- ❖ 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 $E_{\pi 0}$>40 GeV) = 1.4×10^{-8}.
- ❖ Particle ID (RICH+LKr+HAC+MUV): ~10^{-8} muon suppression.

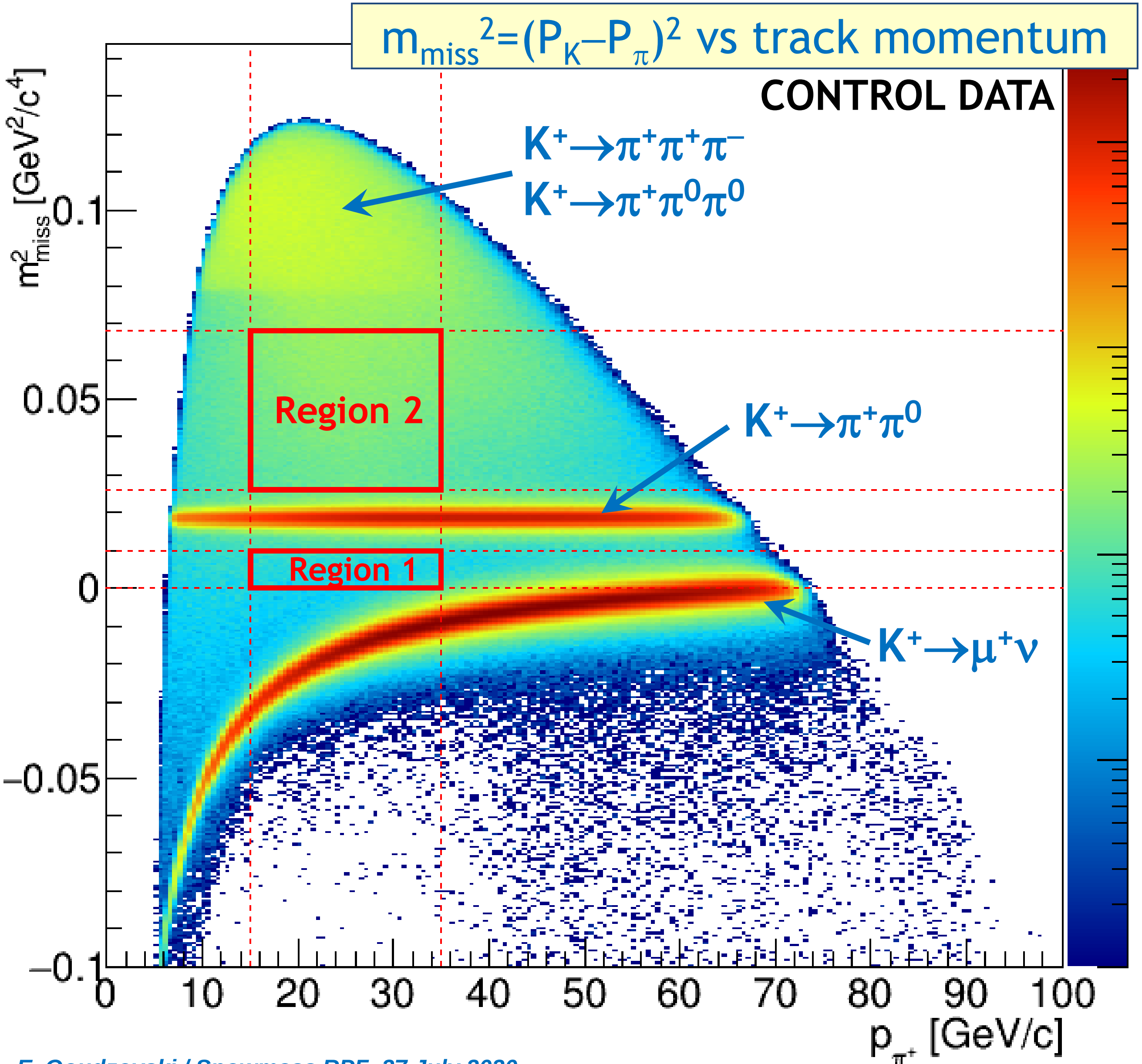
NA62 status: Run 1 completed



2.2×10^{18} POT collected

- Commissioning run **2015**: minimum bias data (**$\sim3\times10^{10}$** protons/pulse).
- Physics run **2016** (45 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** start after the Long Shutdown 2 in **2021** (**$\sim3\times10^{12}$ ppp**).

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:

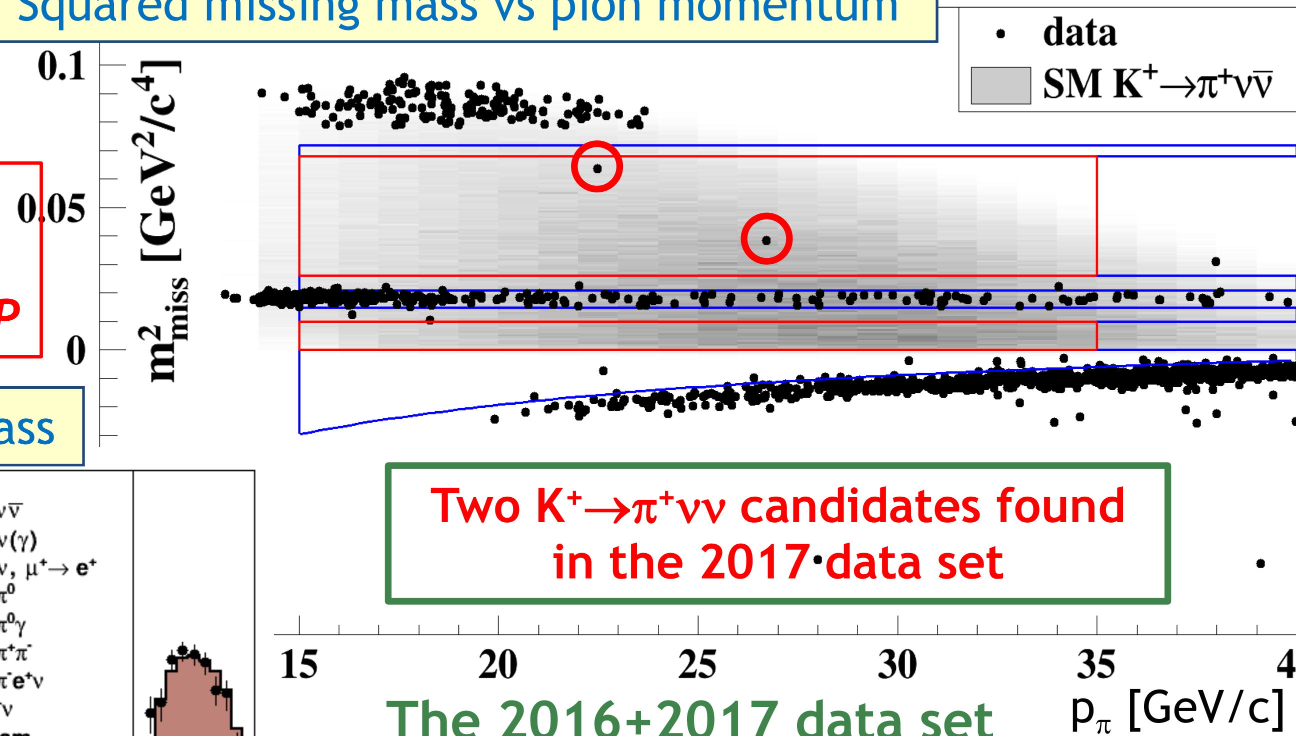
- ✓ PID (calorimeters & Cherenkov detectors): μ suppression 10^{-8}, π efficiency = 64%.
- ✓ Hermetic photon veto: $\pi^0\to\gamma\gamma$ rejection factor = 1.4×10^{-8}.

$K^+ \to \pi^+ \nu\nu$: NA62 2016+17 data

arXiv:2007.08218
submitted to JHEP

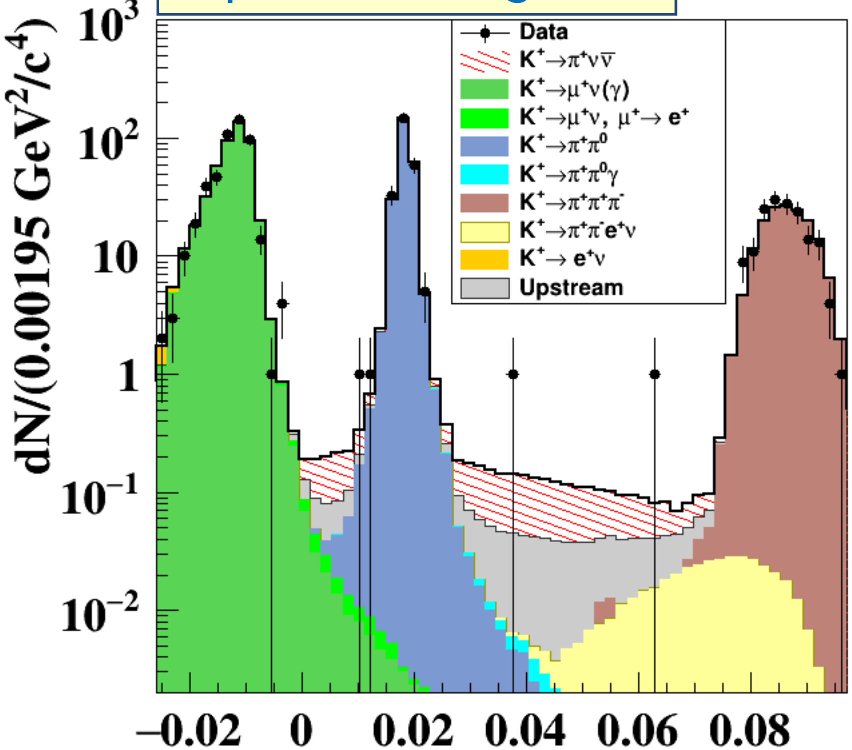
Result with the full Run 1 data set: to be presented at ICHEP

Squared missing mass vs pion momentum



Two $K^+ \to \pi^+ \nu\nu$ candidates found in the 2017 data set

Squared missing mass



The 2016+2017 data set

Candidates observed: 3

Expected background: 1.6 ± 0.3

Expected SM events: 2.4

One-sided limit at 90% CL:

$BR(K^+ \to \pi^+ \nu\nu) < 1.78 \times 10^{-10}$

One-sigma confidence interval:

$BR(K^+ \to \pi^+ \nu\nu) = (0.48\,^{+0.72}_{-0.48}) \times 10^{-10}$

Short-term plans: NA62 Run 2

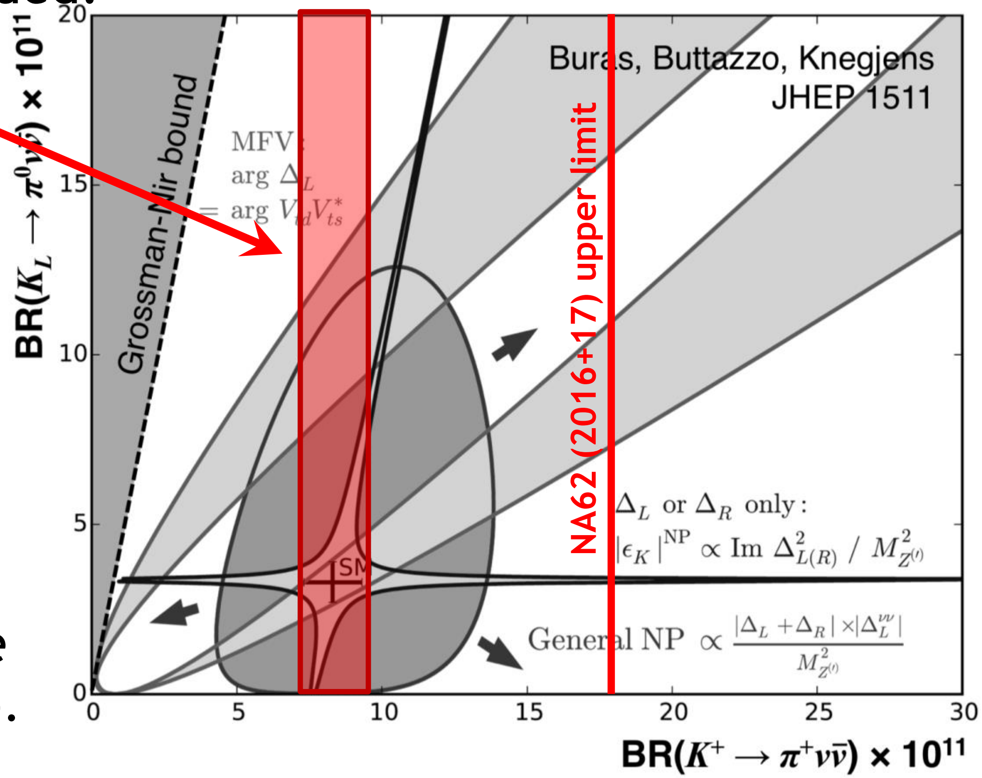
Full NA62 Run 1 (2016–18) data set:

- expected sensitivity: $BR_{SES}=O(10^{-11})$, i.e. O(10) signal events;
- the result to be presented at ICHEP 2020.

NA62 Run 2 (2021–24): higher intensity, better background suppression.

- Optimized beamline + new veto detectors to reduce the dominant “upstream background”;
- 4th kaon beam tracker station added.

Expected Run 1+2 sensitivity: δBR/BR=O(10%)



Broader NA62 programme:
(new results at ICHEP 2020)

- Rare decays: $K^+\to\pi^+\mu^+\mu^-$, $K^+\to\pi^+\gamma\gamma$, $K^+\to\pi\pi\mu^+\nu$, $\pi^0\to e^+e^-$, ...
- LFV/LNV: $K^+\to\pi^-\ell^+\ell^+$, $K^+\to\pi\mu e$, ...
- Hidden sector particle searches in in K^+ decays & in beam dump mode (e.g. $K^+\to\pi^+\nu\nu$ interpreted as $K^+\to\pi^+X$).

Long-term plans: $K^+ \to \pi^+ \nu\nu$ at CERN

- The $K^+ \to \pi^+ \nu\nu$ decay in-flight technique is firmly established, and is expected to reach an O(10%) measurement by 2024.
- A possible next step after LS3 (in ~2027): an in-flight $K^+ \to \pi^+ \nu\nu$ experiment with ×4 beam intensity (present SPS limit), aiming at ~5% precision.
  - ✓ Challenge: O(10ps) 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 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

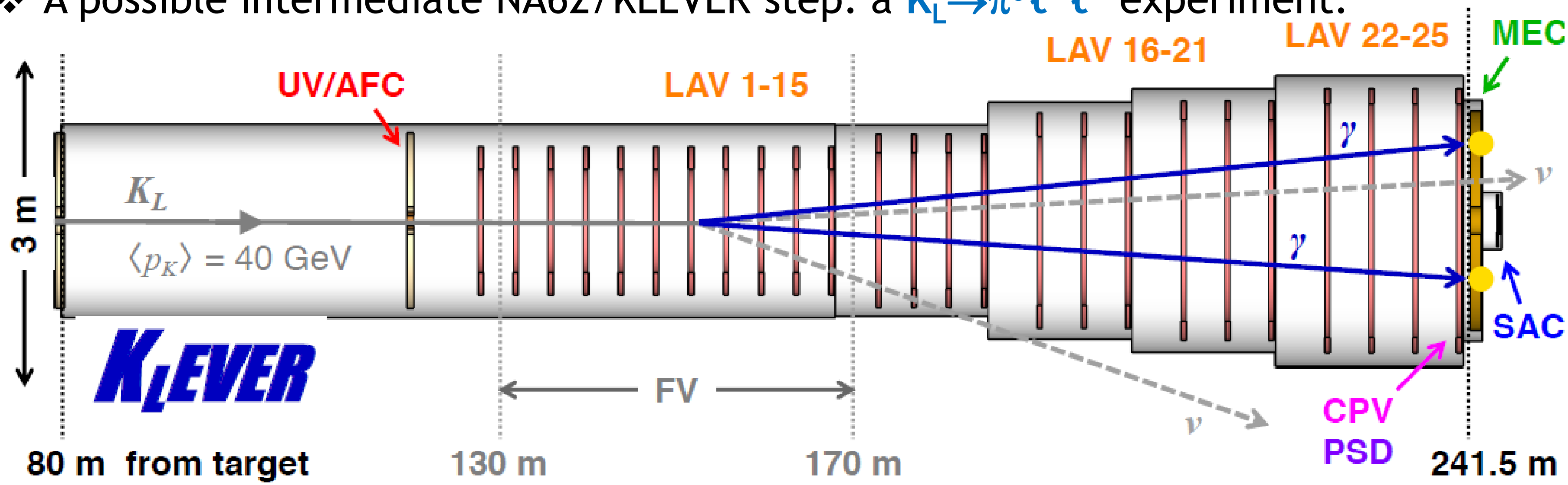
New STRAW spectrometer:

operation in vacuum;
straw 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

Long-term plans: $K_L \to \pi^0 \nu\nu$ at CERN

- A high-energy experiment (10^{19} pot/year) complementary to KOTO.
- Photons from K_L decays boosted forward: veto coverage only up to **100 mrad**.
- Roughly the same vacuum tank layout and fiducial volume as NA62.
- A possible intermediate NA62/KLEVER step: a $K_L \to \pi^0 \ell^+ \ell^-$ experiment.



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 running;

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

Summary

- Measurements of rare kaon decays: uniquely-sensitive indirect probes for new physics up to the **O(100 TeV)** mass scale.

- Current experiments are focused on the "golden" $K\to\pi\nu\nu$ modes.
  - ✓ NA62 to reach **O(10%)** precision on $BR(K^+\to\pi^+\nu\nu)$ by 2024 with an established decay in flight technique;
  - ✓ KOTO is making significant progress in background reduction, aiming to reach SM sensitivity to $BR(K_L\to\pi^0\nu\nu)$ by 2024;
  - ✓ LHCb (not covered here): rare K_S, hyperon and η decays.

- Next generation kaon beams are a powerful tool to break the SM.
  - ✓ KOTO step-2 at J-PARC: plans to measure $BR(K_L\to\pi^0\nu\nu)$;
  - ✓ CERN: **O(5%)** precision on $BR(K^+\to\pi^+\nu\nu)$ followed by a K_L experiment;
  - ✓ challenges in detector technologies; synergies with future collider and flavour experiments.

- **Other RF2 topics (covered in Emilie's talk): rare η and η' decays; hyperon decays; first-row CKM unitarity tests, LU tests.**
- **Overlaps with other topics: RF1 (weak c and b decays), RF6 (dark sector).**
- **Looking forward to the LoIs (submission by 31st August).**