UNIVERSITY OF BIRMINGHAM

RF2: weak decays of strange and light quarks

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- This talk covers the general structure of the RF2 report, and the kaon, hyperon and charged pion sections.
- CKM first-row unitarity tests and rare $\eta^{(\prime)}$ decays are covered in Emilie's talk.

Snowmass RPF Spring Meeting
Cincinnati, 16–19 May 2022

The RF2 physics case

- Flavor physics experiments probe both *very high mass scales*, and *feebly interacting hidden sectors*.
- RF2: precision measurements of kaon, hyperon, π^+ and $\eta^{(\prime)}$ decays.
  - ✓ CKM parameter measurements and unitary tests; symmetry tests; lepton flavor/number conservation tests; lepton universality tests.
  - ✓ Heavy new physics: sensitivity up to the PeV mass scale.
  - ✓ Hidden sectors: leading sensitivity below the GeV mass scale.
- Much experimental activity:
  - ✓ Ultra-rare kaon decays at NA62 and KOTO (+ future projects);
  - ✓ CPV in hyperon decays at BESIII (+ future super charm-tau factories);
  - ✓ kaon and hyperon decays at LHCb;
  - ✓ LFU and V_{ud} in pion decays at PIONEER;
  - ✓ Symmetry tests at η factories: JEF; REDTOP proposal.
- Significant advances in theory and lattice QCD: crucial for progress.

Medium-scale initiatives (many centered in Europe and Asia):
powerful physics insights, relatively short time scales,
superb training opportunities, modest investment.

White papers considered

White papers considered for the TG report:

(WP1) Rare kaon decays: theory [arXiv:2203.09524]
(WP2) Kaon decays: lattice computations [arXiv:2203.10998]
(WP3) Kaon decays: experiments [arXiv:2204.13394]
(WP4) Hidden sectors at kaon and hyperon factories [arXiv:2201.07805]
(WP5) CPV in hyperon decays at BESIII and SCTF [arXiv:2203.03035]
(WP6) Rare π^+ decays: PIONEER at PSI [arXiv:2203.05505]
(WP7) Rare $\eta^{(\prime)}$ decays: REDTOP [arXiv:2203.07651]

Further inputs for the TG report:

- ❖ The 23 LoIs, plus an update from JEF.
- ❖ CKM first row unitarity: no white papers submitted; the topic is still fully considered based on recent reviews.

TG report structure

Current report structure:

(2.1) Introduction: the physics case

(2.2) Kaon decays [theory overview, NA62, KOTO, LHCb, future projects]

(2.3) Hyperon decays [BESIII, super tau-charm factories, LHCb]

(2.4) Charged pion decays [PIONEER]

(2.5) $\eta^{(\prime)}$ decays [theory overview, JEF, REDTOP]

(2.6) CKM first row unitarity [theory + experiment overview]

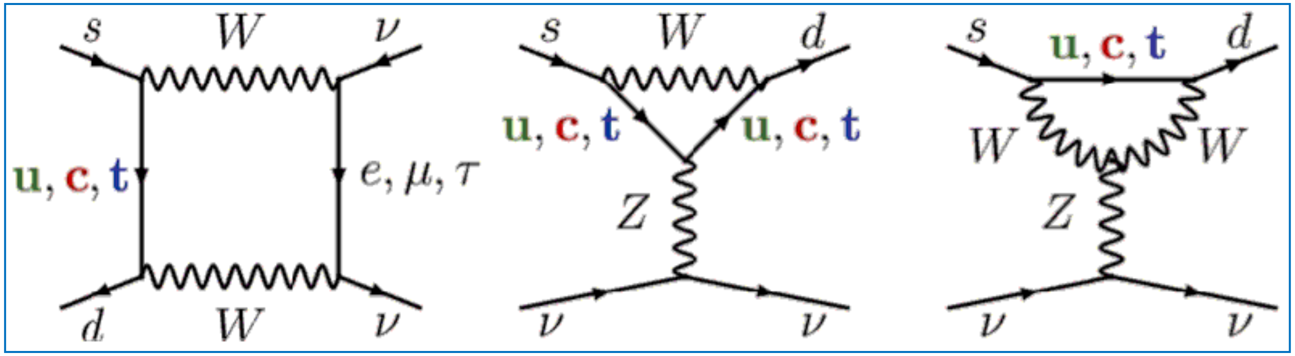
(2.7) Summary

Status of the draft:

- Sections (2.1), (2.7): drafts written.
- Sections (2.2)–(2.4): draft #1 shared with authors of (WP1)–(WP6) and the Frontier conveners on May 6th.
- Section (2.5): draft #0 shared with conveners.
- Feedback from authors of (WP1), (WP2), (WP3), (WP5), (WP6), and from the conveners, received and implemented.
- Sections (2.5), (2.6): first draft still to be finalized.
- Report draft #2 draft to be distributed to WP authors: May 20th.

K→πνν 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.

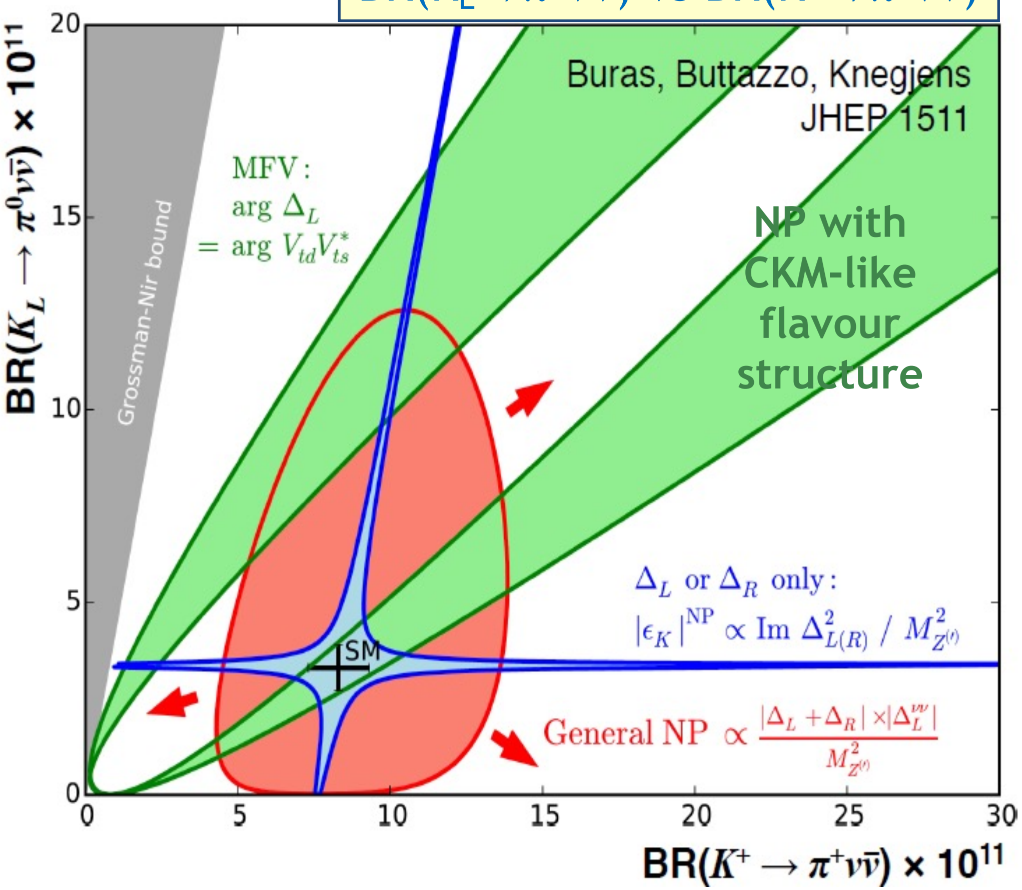
Mode	Expected BR_{SM}	Experimental status
$K^+\to\pi^+\nu\nu$	$(8.60\pm0.42)\times10^{-11}$	$(10.6\pm4.0)\times10^{-11}$ (NA62 Run 1)
$K_L\to\pi^0\nu\nu$	$(2.94\pm0.15)\times10^{-11}$	$BR<300\times10^{-11}$ at 90% CL (KOTO 2015 data)

Standard Model **BR**: a 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 (NB: within SM, this allows for a clean the 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

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

Kaons: other opportunities

- Direct and indirect CP violation in $K^0 \to \pi\pi$ decays (ε, ε'), and the $K_L - K_S$ mass difference (ΔM_K) [no experiments planned]
  - ✓ Improving capabilities of lattice QCD to provide accurate SM predictions: opportunities for discovery of new physics.
  - ✓ SM precision on ε'/ε can match that of the experiment within a decade, motivating a new measurement.

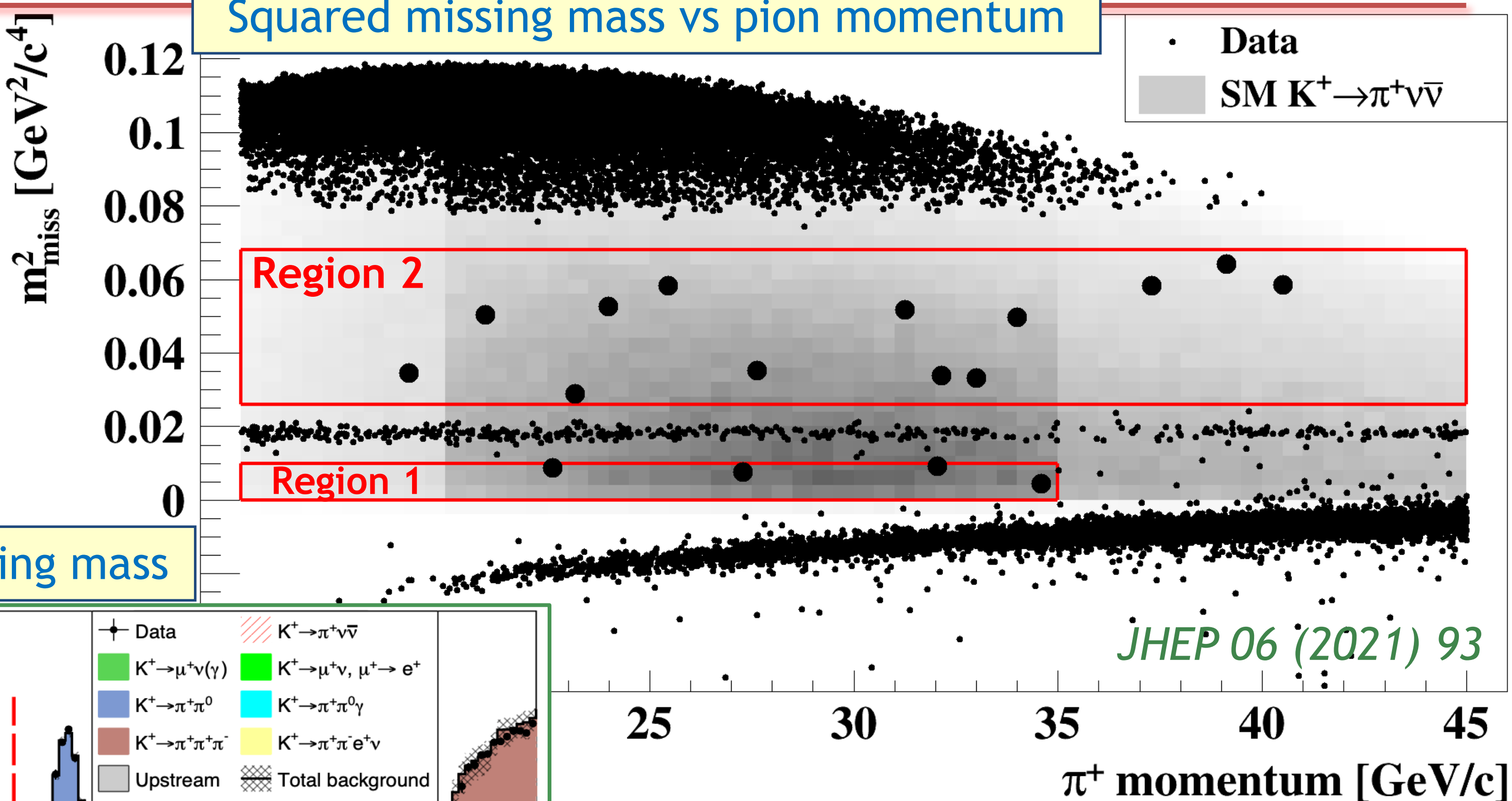
- Measurement of V_{us} with $K \to \pi \ell \nu$ decays. [no experiments planned]
  - ✓ V_{us} accounts for **50%** of the uncertainty in the first-row CKM unitarity test.
  - ✓ Uncertainty in V_{us}: equal contributions from experiment [$BR(K \to \pi \ell \nu)$] and theory [decay constants f_K/f_π, form-factor $f_+(0)$].
  - ✓ Improvements on lattice QCD expected, motivating new measurements.

- Lepton universality tests, lepton flavor and number conservation tests.
  - ✓ $BR(K^+ \to (\pi^0) e^+ \nu)/BR(K^+ \to (\pi^0) \mu^+ \nu)$, $BR(K^+ \to \pi^+ e^+ e^-)/BR(K^+ \to \pi^+ \mu^+ \mu^-)$; searches for $K^+ \to \pi^+ (\pi^0) \ell \ell$, $K_L \to (\pi^0)(\pi^0) \mu e$, $K_L \to 2\mu 2e$, …

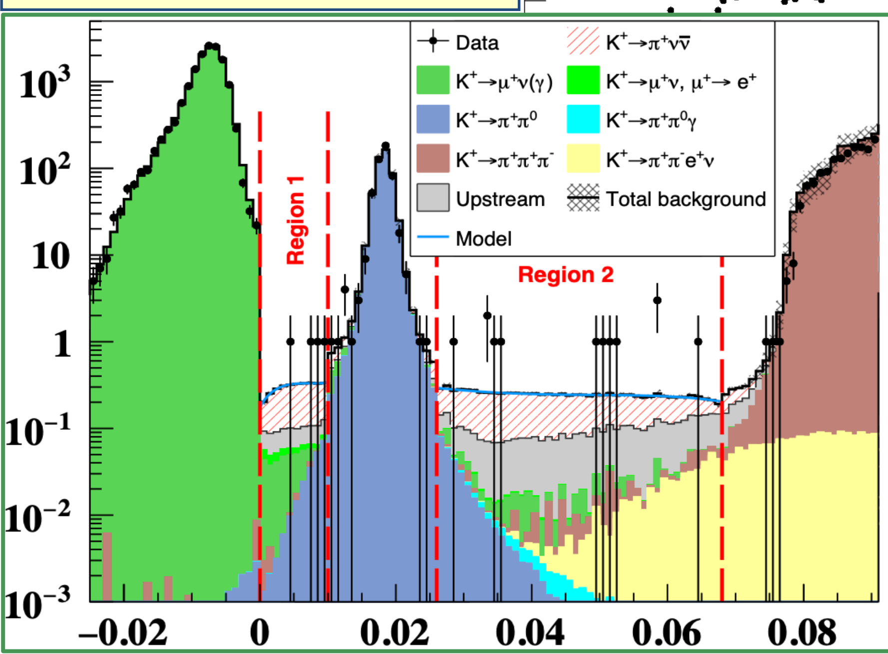
- Searches for light hidden sectors [see RF6]: unique sensitivity due to large datasets and suppression of the kaon decay width.

NA62 (Run 1): the $K^+ \to \pi^+ \nu\nu$ signal

Squared missing mass vs pion momentum



Squared missing mass



Full Run 1 (2016–18) dataset:

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

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

Expected SM events:

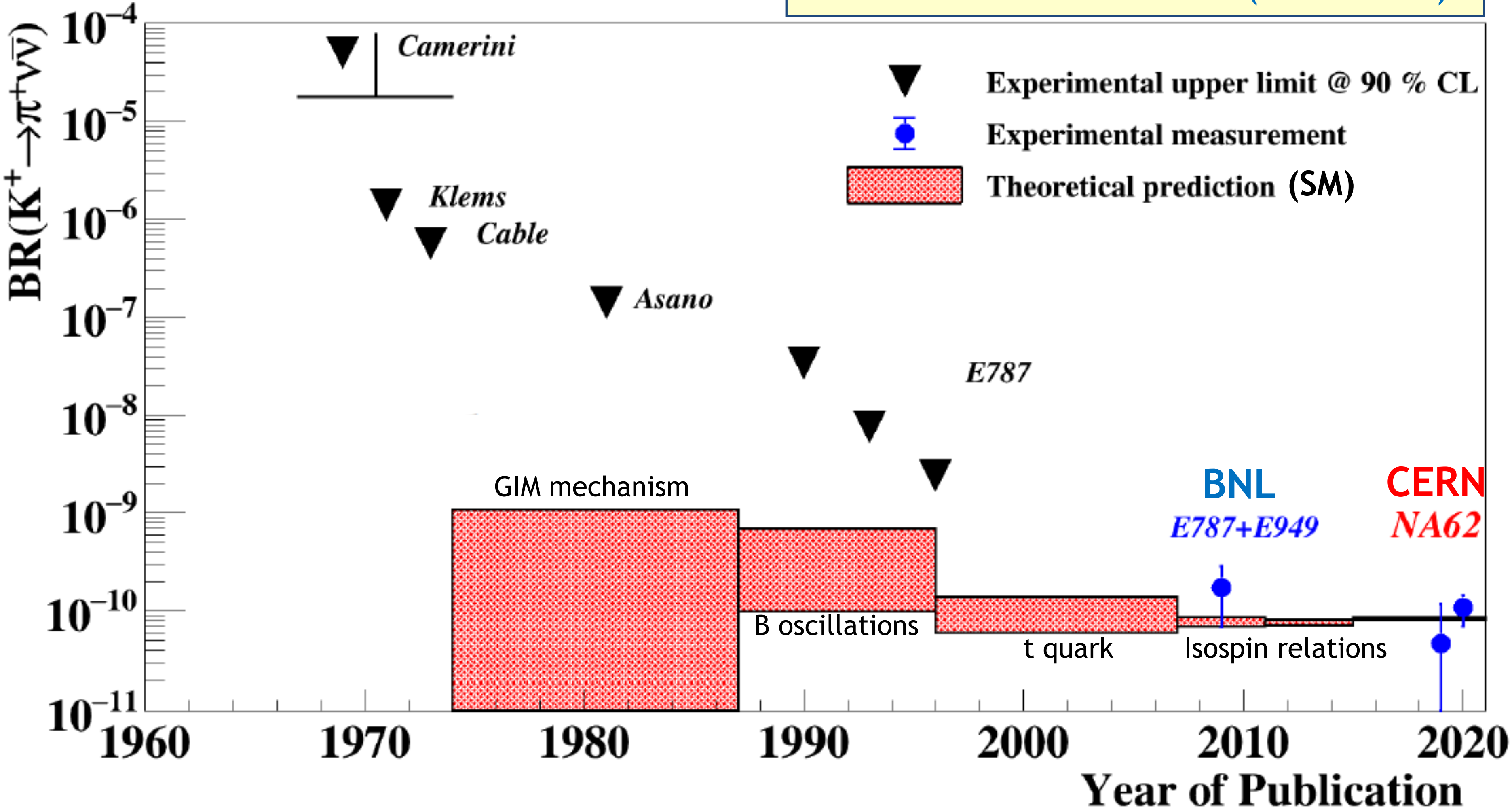
$\mathbf{10.01 \pm 0.42_{syst} \pm 1.19_{ext}}$

JHEP 06 (2021) 93

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

JHEP 06 (2021) 93

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

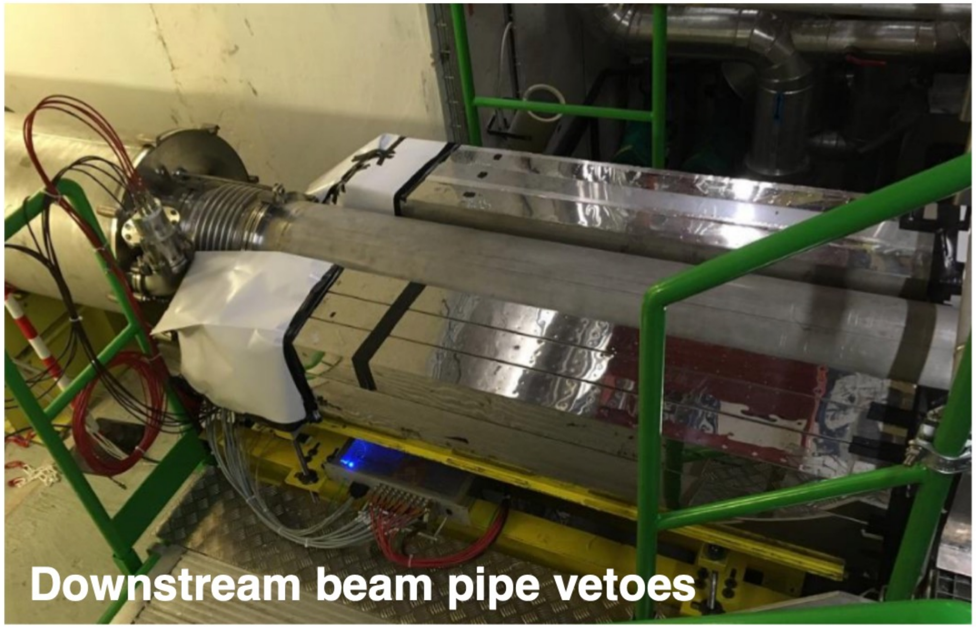


NA62 Run 1: $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$

(**3.4σ** significance)

NA62 Run 2: 2021–2025

- **The technique is firmly established**. Run 2: $K^+ \to \pi^+ \nu\nu$ measurement in a low-background, high-acceptance regime, at **O(10%)** precision.
- 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 trigger: beam intensity increased by ~30% wrt Run 1.
- Collection of 10^{18} pot in up to 90 days in beam dump mode is foreseen.



Long-term plans at CERN

- SPS fixed target runs planned to accompany LHC running **up to 2038**.
- An opportunity for an *integrated kaon programme* at the SPS to pin down new physics in kaon decays.
- Measurements of both K^+ and K_L rare decays: a clear insight into the flavour structure of new physics.
- Beam intensity up to **×6** wrt NA62 (to 1.3×10^{19} pot/year).

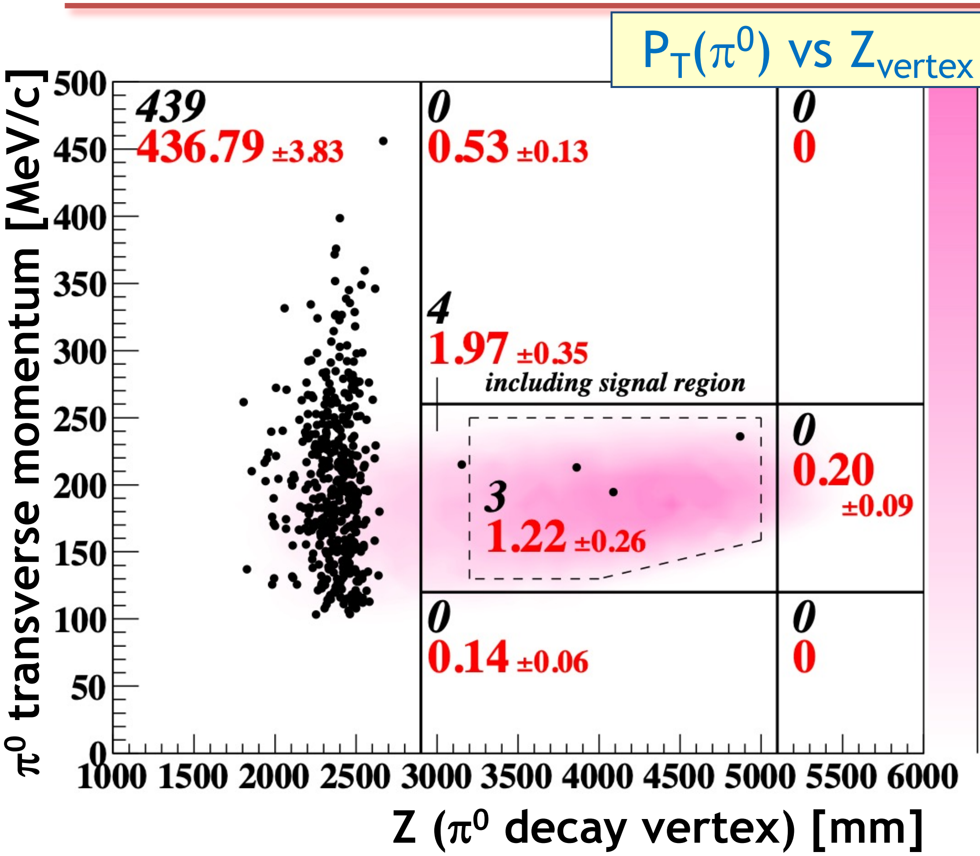
(1) An in-flight $K^+\to\pi^+\nu\nu$ experiment.
  - ✓ Goal: **400 SM** events with $S/B\gg1$, ~5% precision.
  - ✓ Challenge: **20 ps** time resolution for key detectors (aligned with HL-LHC and future flavor/dark matter experiments).

(2) An in-flight $K_L\to\pi^0\nu\nu$ experiment (KLEVER).
  - ✓ Goal: **60 SM** events with $S/B\sim1$, ~20% precision.

(3) An intermediate experiment: rare K_L decays with charged particle detection: $K_L\to\pi^0\ell^+\ell^-$ as the main goal; K_L beam characterization.

KOTO: the 2016–18 result

[PRL 126 (2021) 121801]



Single-event sensitivity:
$BR_{SES}=(7.2\pm0.7)\times10^{-10}$ ($=25\times BR_{SM}$)

Main backgrounds:

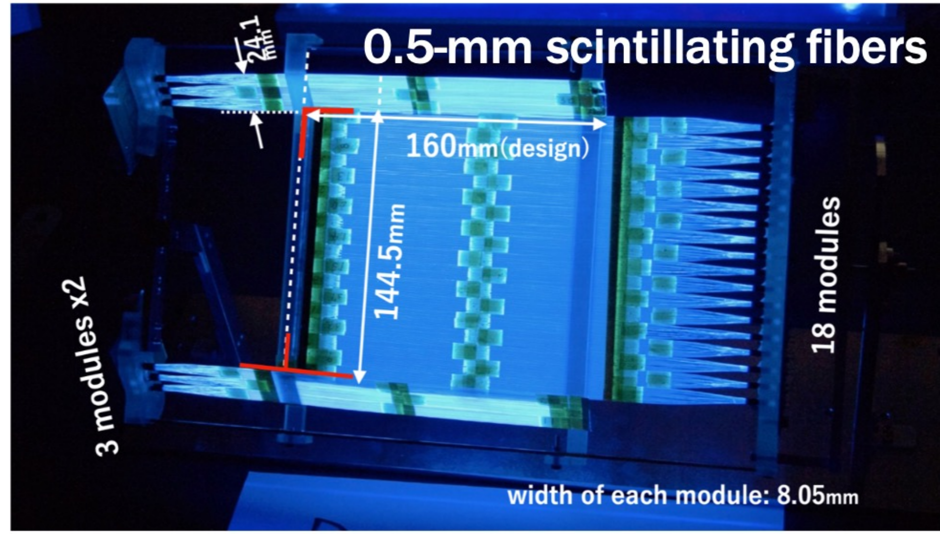
source		Number of events
K_L	$K_L \to 3\pi^0$	0.01 ± 0.01
	$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07 [a]
	Other K_L decays	0.005 ± 0.005
$K^\pm$		0.87 ± 0.25 [a]
Neutron	Hadron cluster	0.017 ± 0.002
	CV η	0.03 ± 0.01
	Upstream π^0	0.03 ± 0.03
total		1.22 ± 0.26

- Number of K_L decays (from $K_L \to 2\pi^0$): $N_K = 6.8\times10^{12}$.
- 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** observed in the signal region.
- The strongest limit is still from the 2015 data: $BR(K_L\to\pi^0\nu\nu)<3.0\times10^{-9}$.

[PRL 122 (2019) 021802]

KOTO up to 2025

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.

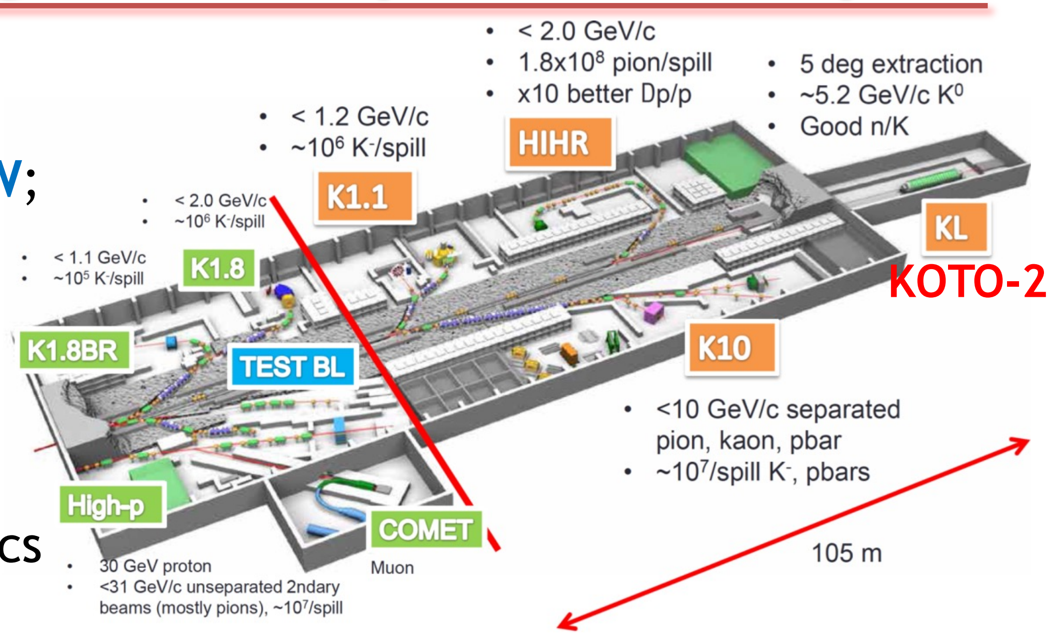
The 2019–21 dataset is twice as large as the 2016–18 dataset, analysis is in progress.

- KOTO is restarting in the fall of 2022.
- Beam power to be gradually increased (60→100 kW).
- Expect to reach the SM single-event sensitivity $O(10^{-11})$ by 2025, operating in a low-background regime.

KOTO long-term plan: step-2

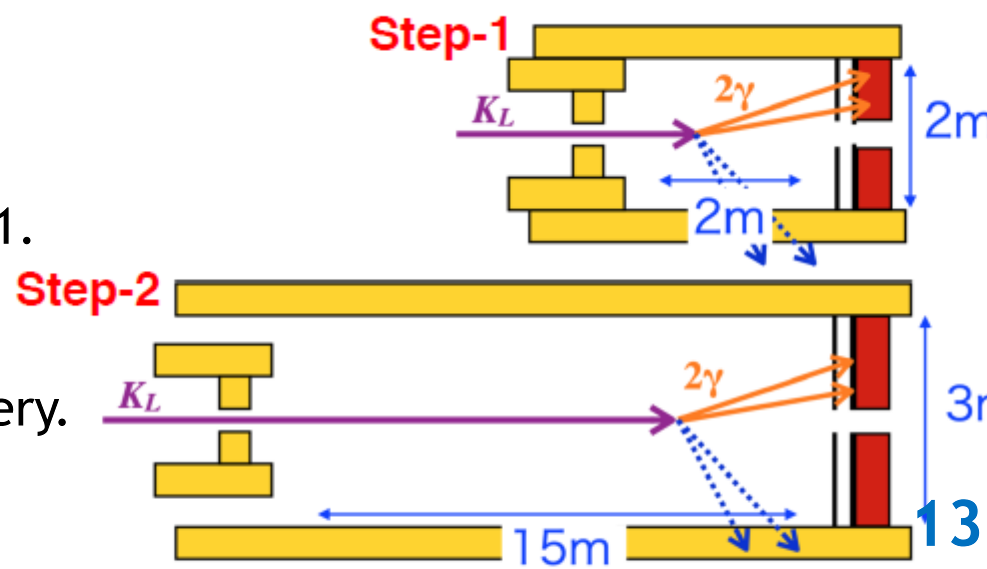
To reach O(100) signal events:

- 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: a joint project with nuclear physics community;
- *design work is in progress*.

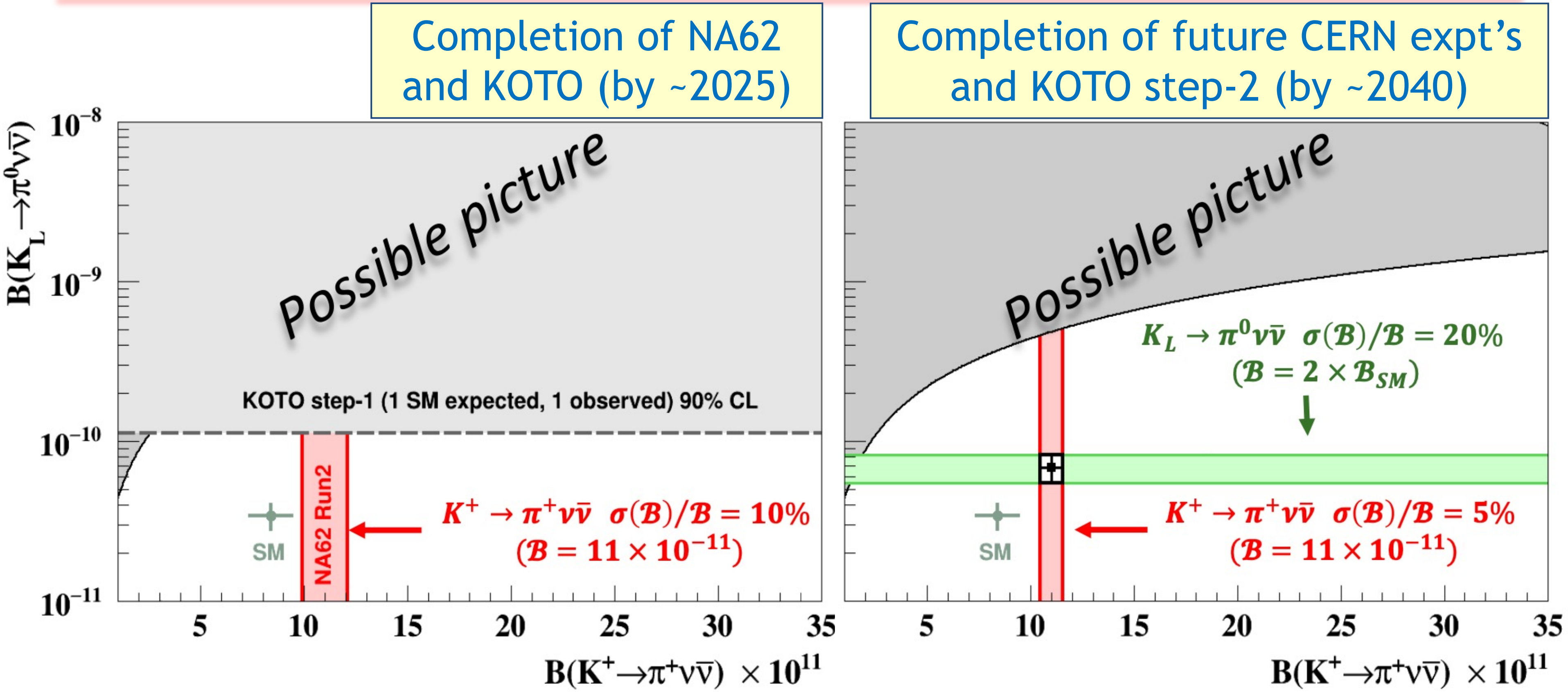


Expected step-2 sensitivity:

- 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 $K_L \rightarrow \pi^0 \nu\nu$ discovery.



$K^+ \to \pi^+ \nu\nu$: experimental projections



- 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.

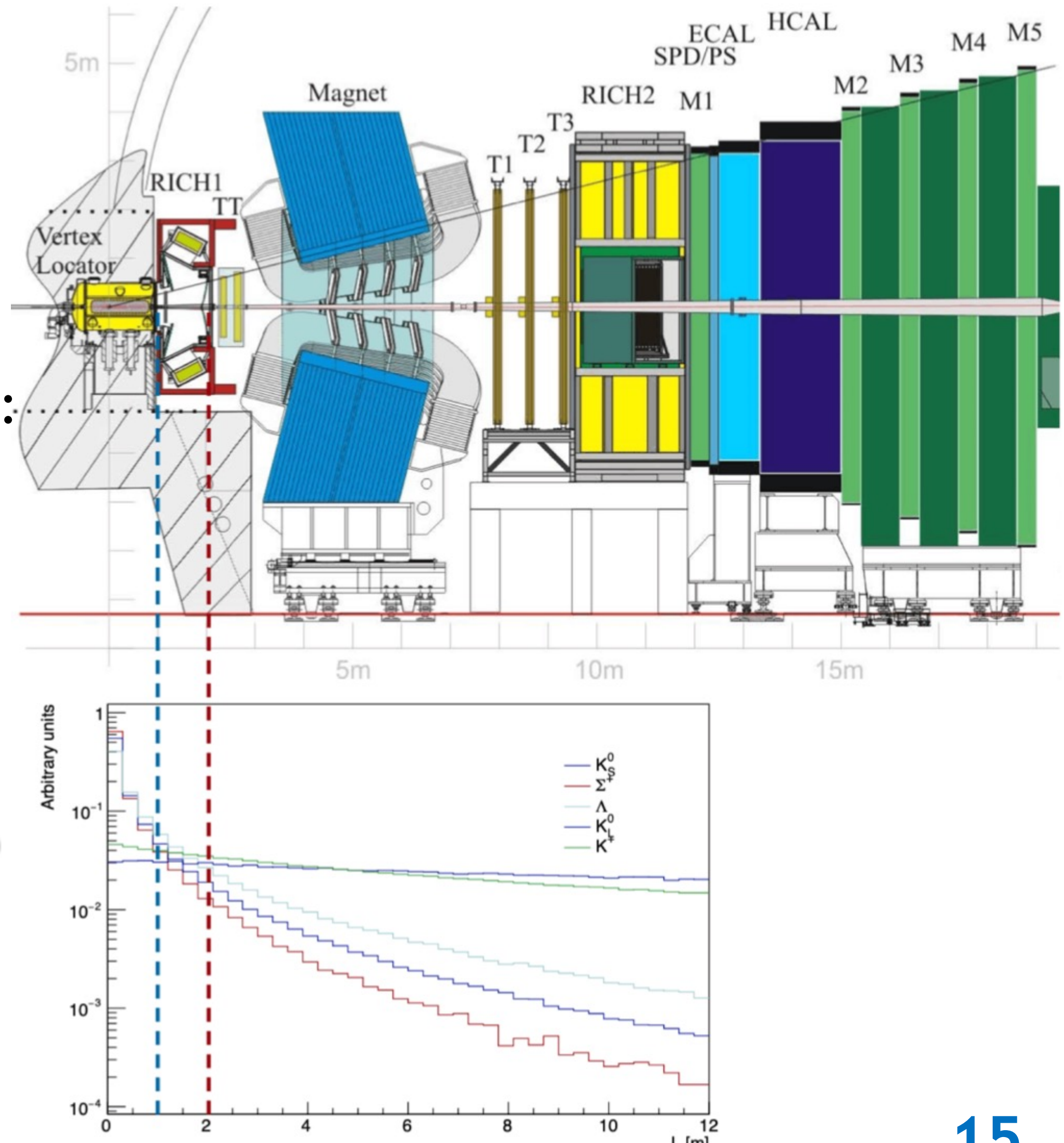
K_S decays at LHCb

- Short fiducial volume: programme mostly focused on K_S and hyperon decays.
- Kaon production at LHCb: 10^{13} K_S/fb^{-1} in acceptance.
- A broad rare decay programme:
  - $K_S \to \mu^+\mu^-$
  - $K_S \to \pi^0\mu^+\mu^-$
  - $K_S \to \pi^+\pi^-e^+e^-$
  - $K_S \to \pi^+\pi^-\mu^+\mu^-$ (?)
  - $K_S \to \ell^+\ell^-\ell^+\ell^-$
- A recent Run1+2 result:

$$\mathcal{B}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

[PRL 125 (2020) 231801]

LHCb aims to reach ultimately the SM BR of $(5.2 \pm 1.5) \times 10^{-12}$.



CPV in hyperon decays

- Hyperon decays: complementary to kaon physics, different sensitivity to BSM interactions.
- CP violation in hyperon decays is yet to be established.
- BESIII: CPV asymmetry measurements with spin-entangled hyperon-antihyperon pairs (**Λ**, **Σ**, **Ξ**) produced at the **J/ψ** resonance.
- BESIII: most precise measurement to date of direct CPV asymmetry of **Λ/anti-Λ** decay parameters from **10^{10} J/ψ** events (dataset **2017–19**), **0.5%** accuracy *[arXiv:2204.11058]*
- Next-generation **J/ψ** factories: improved statistical precision using longitudinally-polarized electron beams.
  CPV asymmetry predicted by the SM (**$\sim 10^{-5}$**) is within reach!

- Rare/forbidden hyperon decay program at BESIII and LHCb.
  An example *[LHCb, PRL 120 (2018) 221803]*:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+1.8}_{-1.3}\right) \times 10^{-8}$$

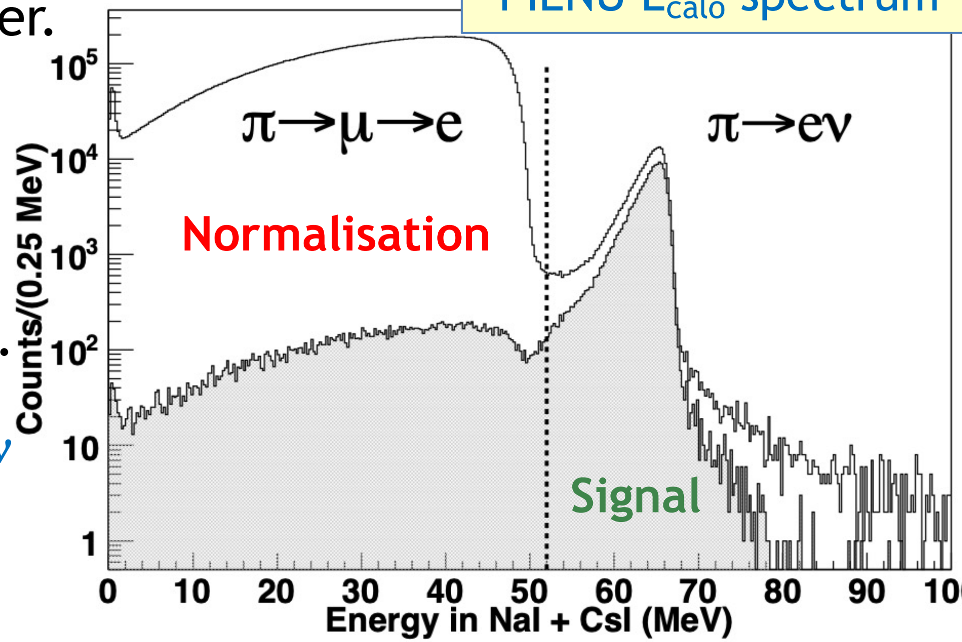
Charged pion decays

- Lepton universality test: $R_{\mu e}=BR(\pi^+\to e^+\nu)/BR(\pi^+\to\mu^+\nu)$:
  - ✓ Early insight into the **V−A** structure of weak interactions.
  - ✓ Exceptional precision of the SM prediction: $R_{\mu e}=1.2352(1)\times10^{-4}$.
  - ✓ World average (mainly PIENU at TRIUMF): $R_{\mu e}= 1.2327(23)\times10^{-4}$.

- PIONEER (Phase-I) approved at PSI, physics starting in **~2029**.
  - ✓ Goal: *matching the SM precision* on $R_{\mu e}$; **1 PeV** scale new physics.
  - ✓ Stopped π^+ at high rate (**300 kHz**), focus on reduction of systematics.
  - ✓ Detectors: highly-segmented LGAD active target, positron tracker, LXe calorimeter.
  - ✓ Collection of 2×10^8 $\pi^+\to e^+\nu$ events in three years.
  - ✓ Key point: control of the $\pi^+\to e^+\nu$ signal tail in the calorimeter to a 10^{-4} precision.

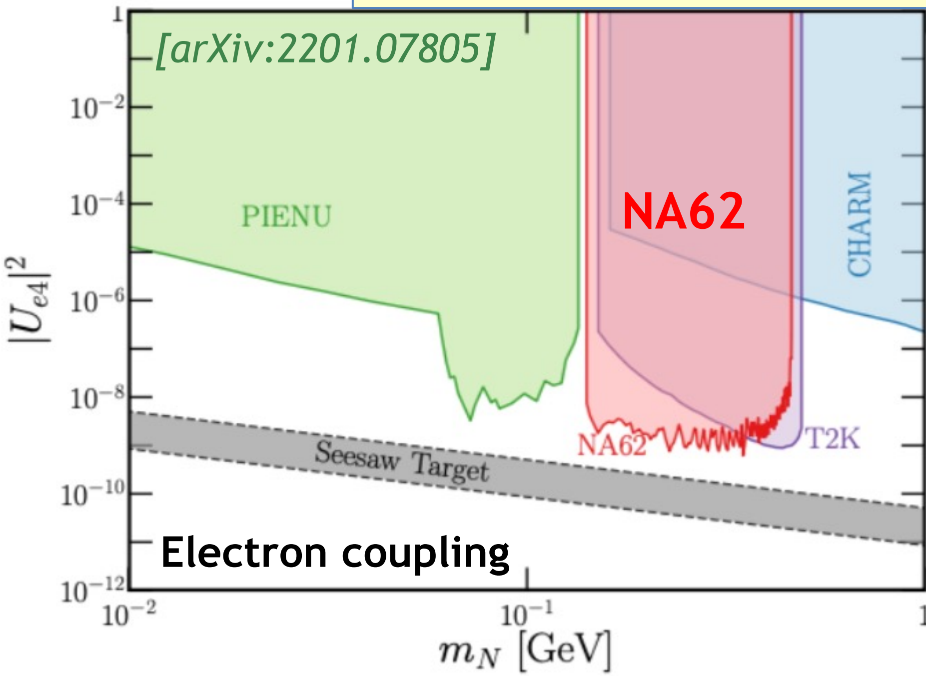
- PIONEER Phase II,III: V_{ud} from $\pi^+\to\pi^0e^+\nu$ decays to a **0.02%** level.

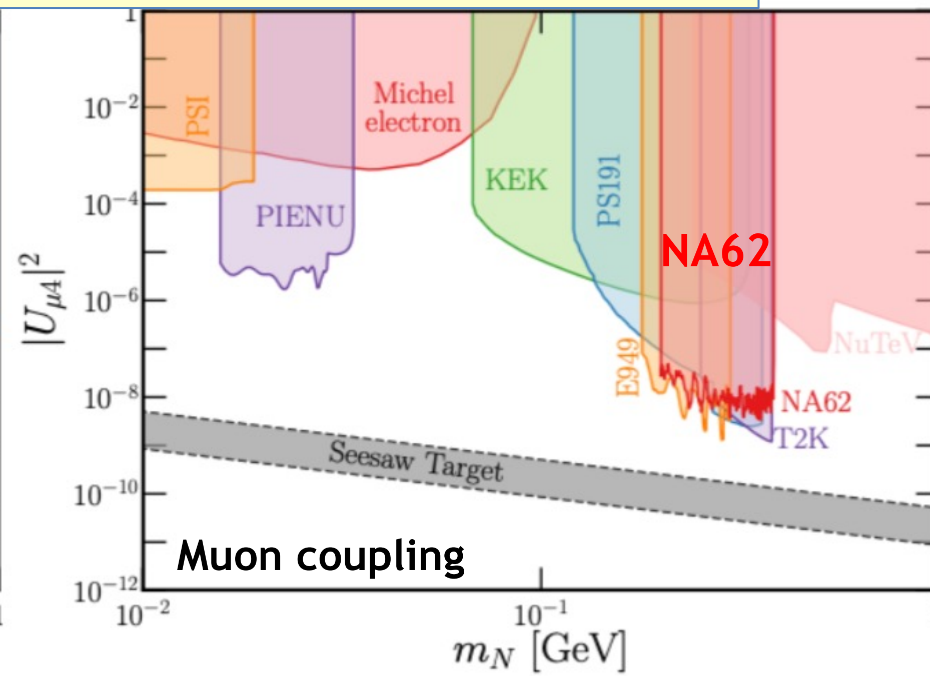
PIENU E_{calo} spectrum



A hidden-sector example: HNL

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





- Strongest $|U_{e4}|^2$ limits below **400 MeV**: **$K^+, \pi^+ \to e^+ N$** from NA62 & PIENU.
- Also important limits on $|U_{\mu 4}|^2$ from E949, NA62 and PIENU.
- NA62/E949 limits are complementary to HNL *decay* searches at T2K.
- Next-generation **K^+** and **π^+** experiments (NA62++, PIONEER) to improve by up to factor **10**, reaching the seesaw bound.

- A related NA62 result: **$BR(K^+ \to \mu^+ \nu\nu\nu) < 1.0 \times 10^{-6}$** at **90%** CL, and similar limits on **$BR(K^+ \to \mu^+ \nu X)$**, with **X=invisible**. *[PLB 816 (2021) 136259]*

Summary

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Medium-scale initiatives (many centered in Europe and Asia): powerful physics insights, relatively short time scales, superb training opportunities, modest investment.