Kaon physics: present and future

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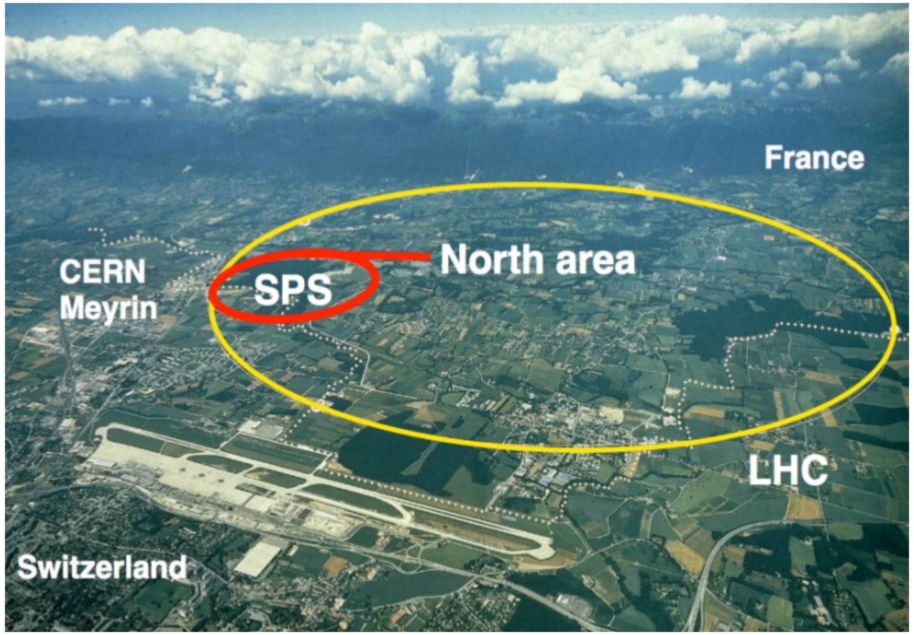
Kaon physics

Kaons: protagonists of many discoveries since 1947 !
Have been fundamental in the development of the Standard Model flavour sector.
CERN kaon experiments at the SPS have been at the forefront of kaon physics for decades:

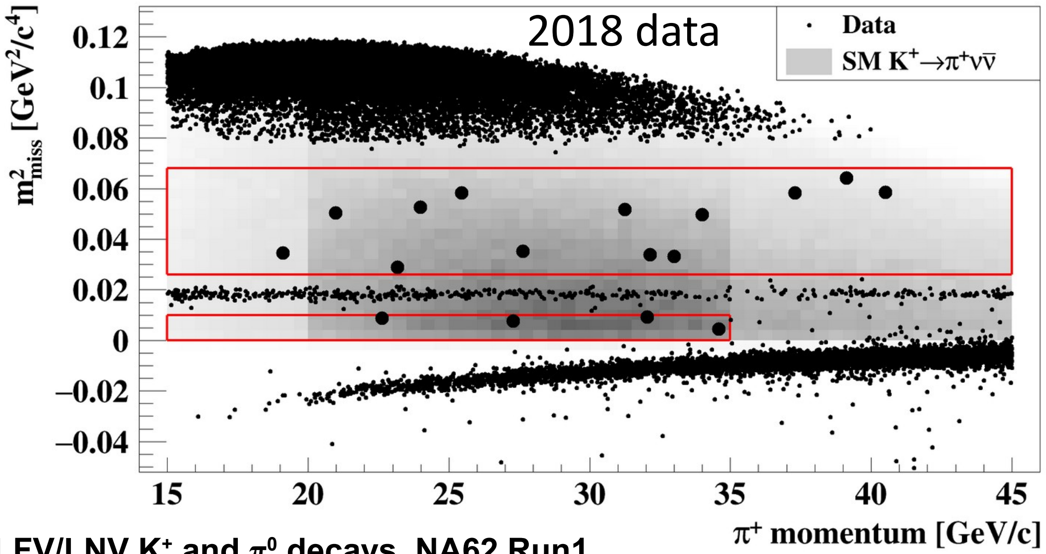


NA31	1982-1993:	1st generation experiment to measure $\mathrm{Re}\ \varepsilon'/\varepsilon$
NA48	1992-2000:	Next generation measurement of $\mathrm{Re}\ \varepsilon'/\varepsilon$
NA48/1	2000-2002:	Rare K_S decays, e.g., $K_S \to \pi^0 \ell^+ \ell^-$
NA48/2	2003-2007:	Multi-purpose rare charged K decay exp
NA62	2007-2008:	Measurement of $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ with NA48
	2007-2015:	Design, construction, installation, commissioning
NA62	Run1 (2016-2018):	$K^+ \to \pi^+ \nu\nu$, rare K^+ and π^0 decays
	Run2 (2021-LS3) :	on-going

NA62 is the last from a long tradition of fixed-target Kaon experiments in the CERN North Area
KOTO at JPARC is addressing $K^0 \to \pi^0 \nu\nu$

NA62 experiment (strong UK leadership)

$K^+ \to \pi^+ \nu\nu$ result from Run1



JHEP 06 (2021) 093

Combined NA62 2016-2018 data

SES = $(8.39 \pm 0.53_{syst}) \times 10^{-12}$

Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

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

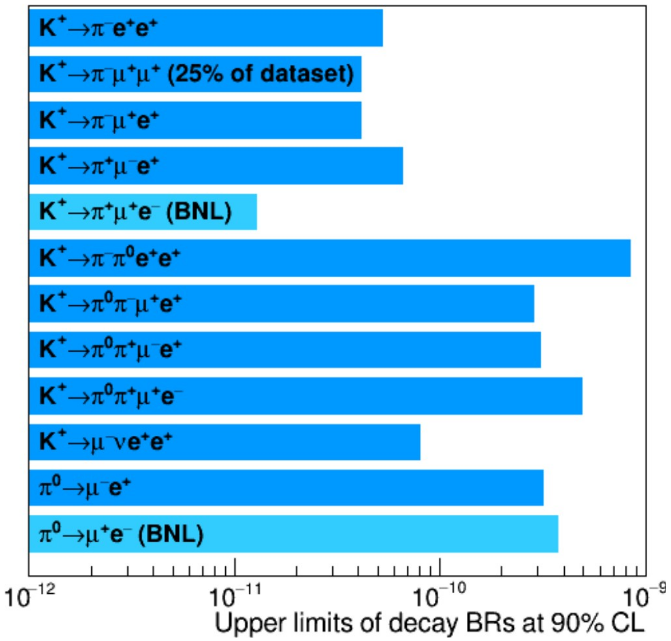
Observed: 20 (1+2+17) events

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

3.4σ significance, most precise measurement to date!

Expected NA62 final precision ~ O(15%)

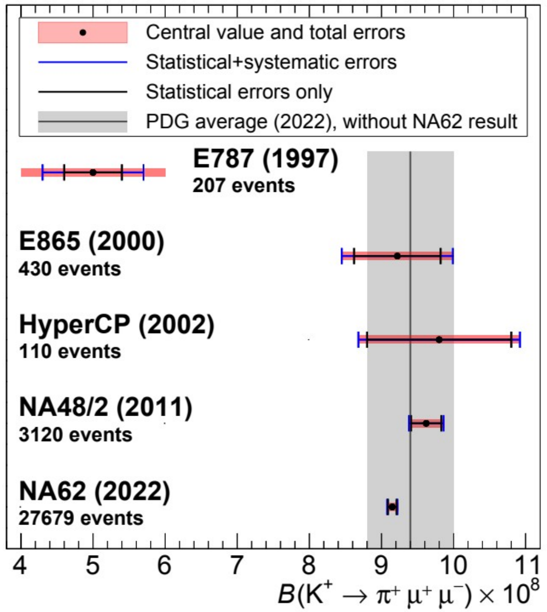
LFV/LNV K^+ and π^0 decays, NA62 Run1

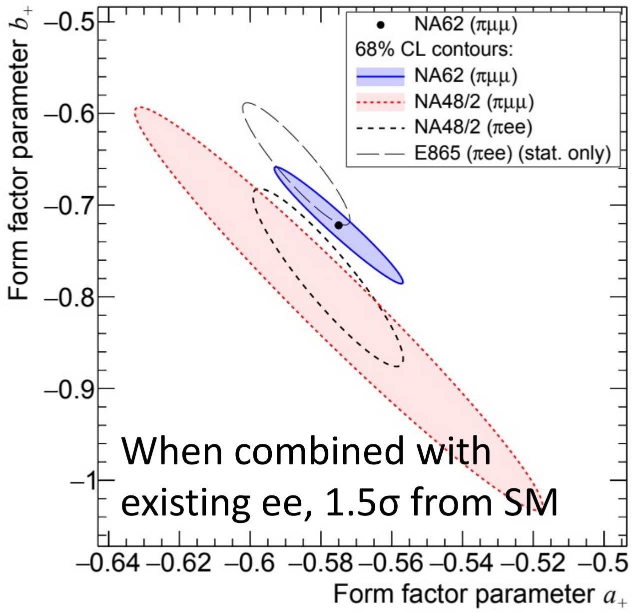


Expect to reach O(10^{-12}) sensitivity on LFV/LNV tests

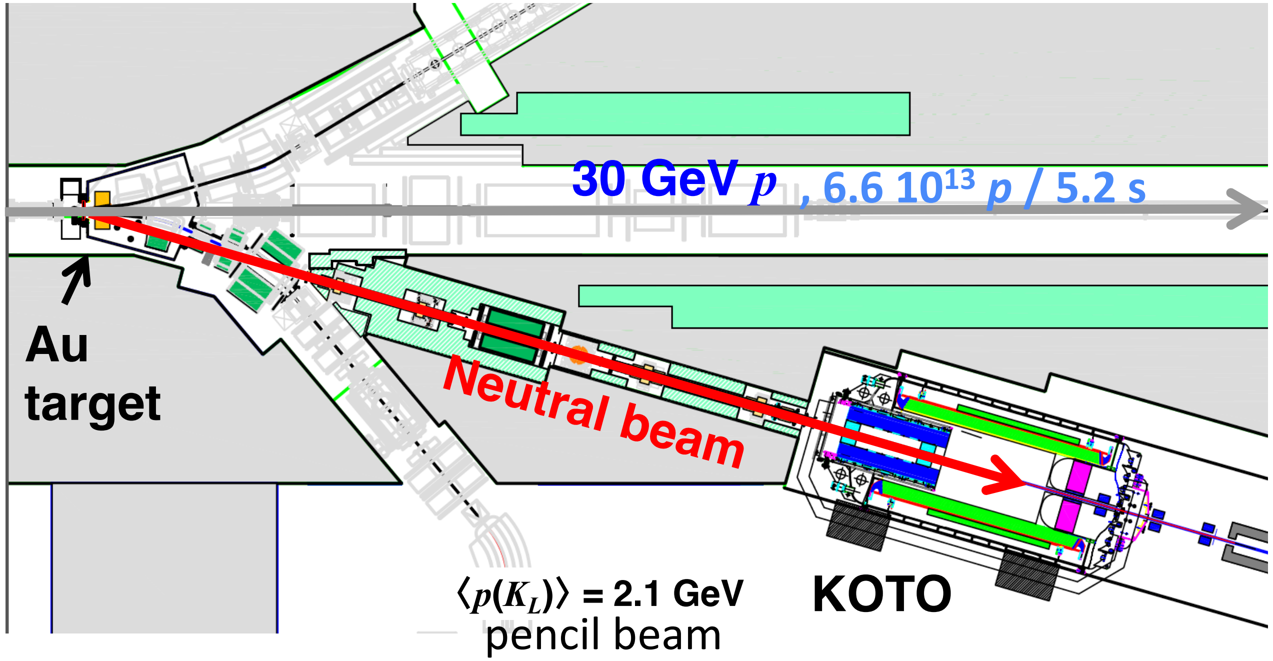
And O(‰) sensitivity on LFUV tests

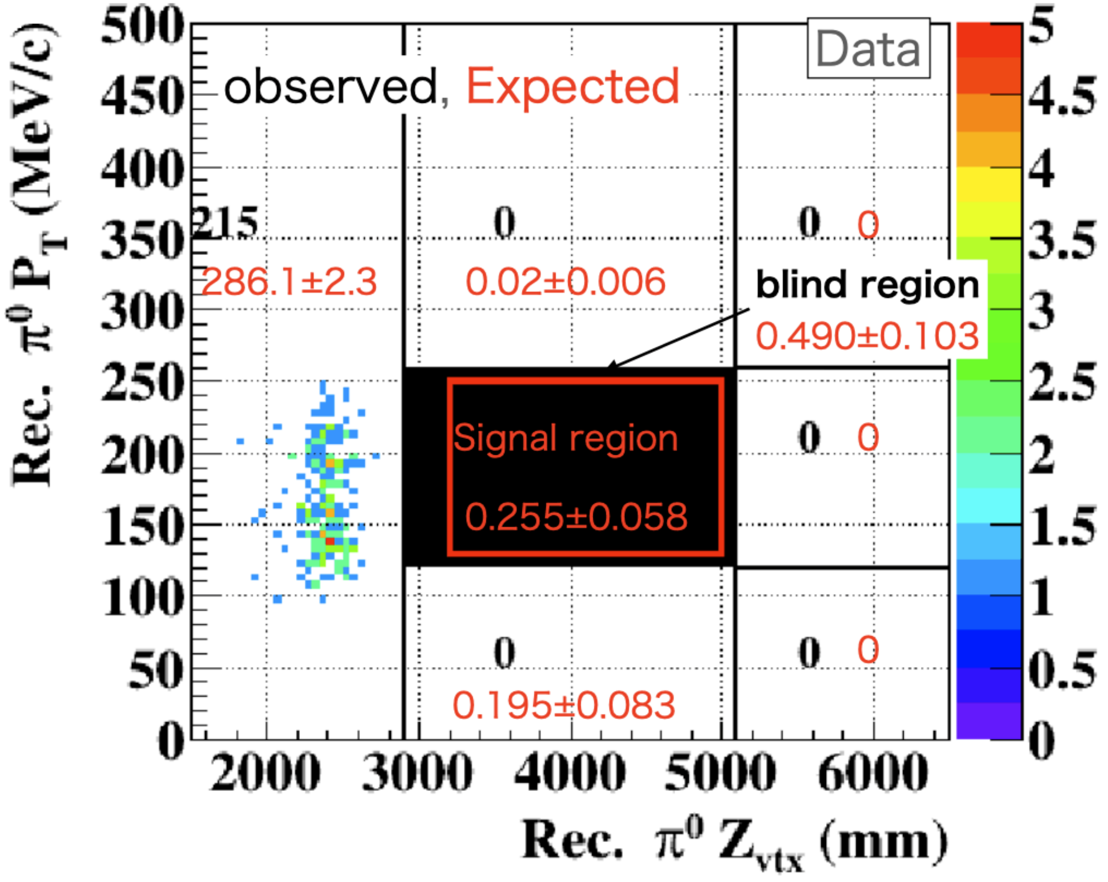
Lepton Universality test





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





KOTO 2023 preliminary:

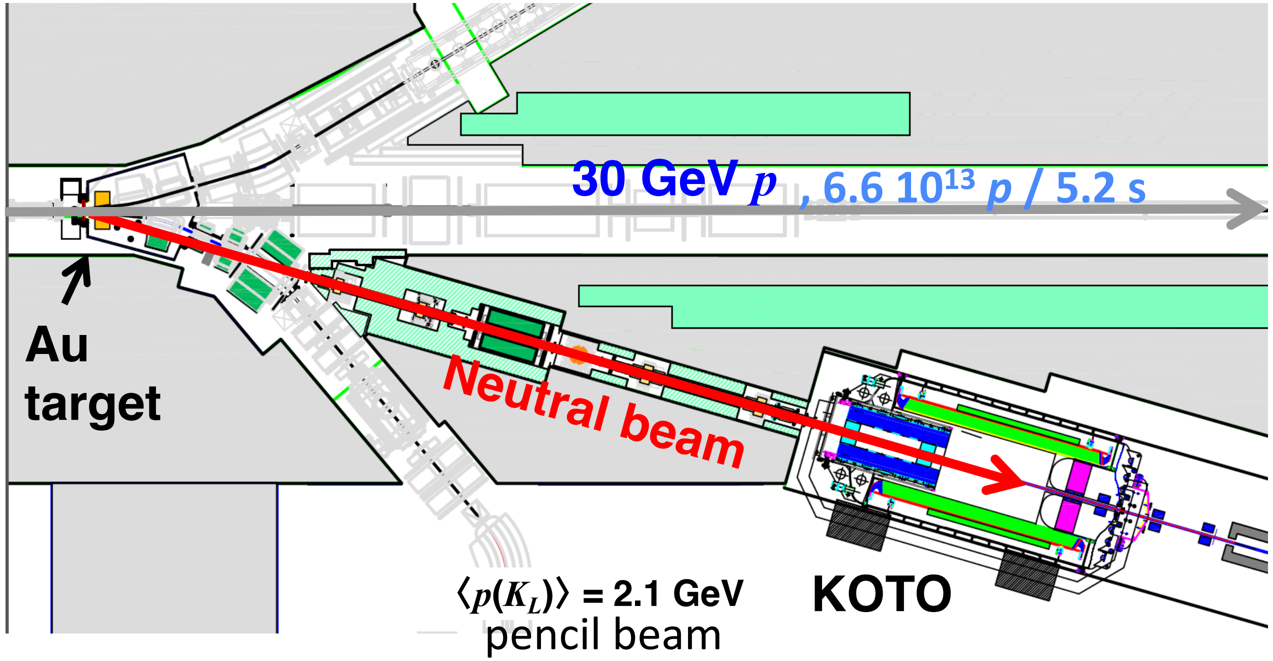
0.034 signal + 0.255 background events expected

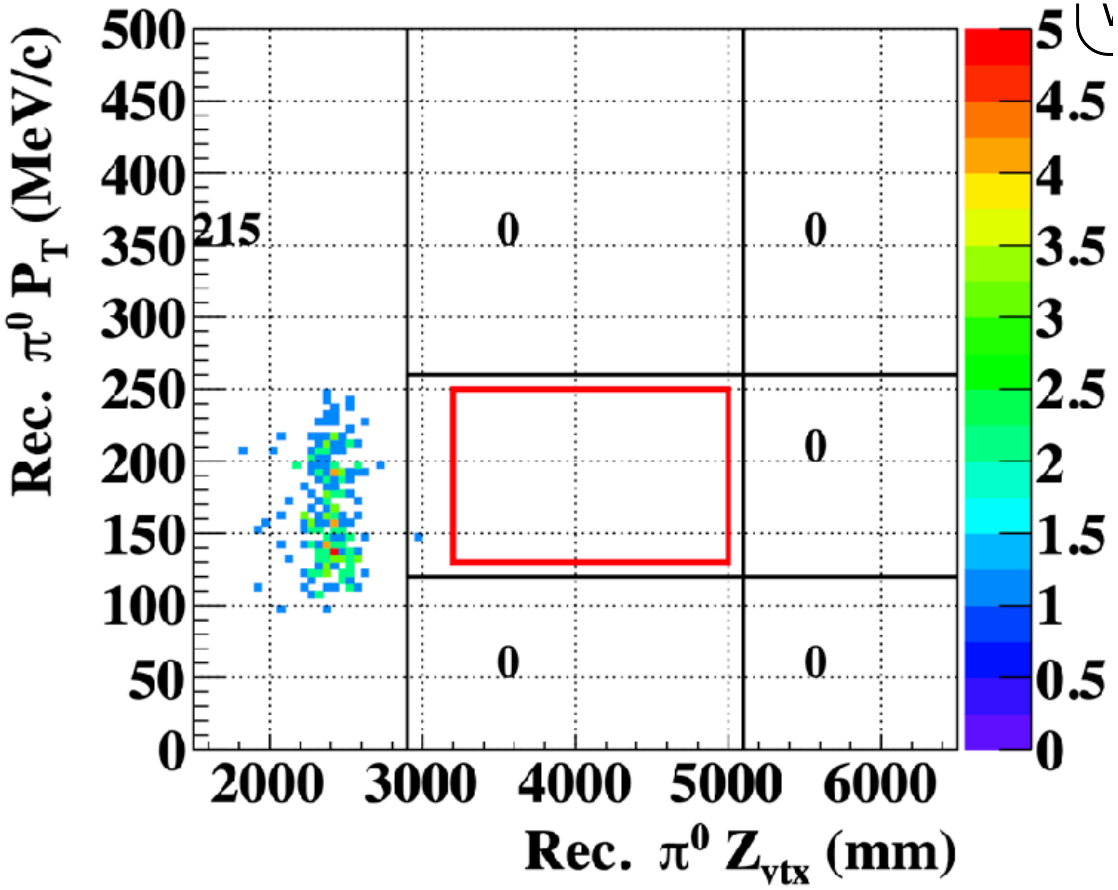
No events in signal box

BR($K_L \to \pi^0 \nu\nu$) < 2.0×10^{-9} (90%CL)

Expect to reach SES < 10^{-10} by end of KOTO running in 2027

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





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The end of dedicated kaon-physics experiments at CERN

Original plan: HIKE, a multi-phase general-purpose kaon experiment to succeed NA62 after LS3 with a new high-intensity beam and extend its physics program into the HL-LHC era and beyond.
$K^+ \to \pi^+ \nu\nu$ to 5%, $K_L \to \pi^0\, l^+ l^-$ to 12-18% , LFV/LNV & other rare decays.

SPSC: "High-intensity ECN3 offers opportunities for high-impact physics programmes complementary to energy-frontier colliders and in line with the recommendations of the latest update of the European Strategy for Particle Physics."
CERN Research Board: " The SPSC has reviewed two options for the initial exploitation of the ECN3 upgrade: a Beam Dump Facility with the SHiP experiment; or the HIKE and SHADOWS experiments that could share the experimental area. (……)
After a year of intense review, both options are found to have a strong physics case and to be technically feasible.
Part of the physics community has been consulted and is split in its preference between the two options, both of which are considered to be **excellent**. This is also the conclusion of the SPSC.
The decision cannot therefore be taken purely on physics grounds. Instead, more strategic aspects will need to be considered."

Decision of CERN Directorate at Research Board (Mar 2024): SHiP experiment approved in ECN3 after LS3.
HIKE physics case judged excellent, but decision made on "strategic" grounds.
HIKE-UK: 10 institutes, 21 "senior" physicists.

NA62 will conclude with LS3. Full exploitation of NA62 data.
The UK kaon community is evaluating facilities where parts of HIKE programme can be done.
In short term, take advantage of existing facilities (KOTO-2 for rare K decays, PIONEER for LFU).
Possibility to investigate new facilities in a longer term.

Kaon physics: why ?

Energy scale

- Heavy New physics
- Standard Model
- Light (Dark) New physics

Flavour physics
Virtual NP contributions
in SM-suppressed processes

$K\to\pi\nu\bar{\nu}$, $K\to\pi\ell^+\ell^-$
$K^+\to e^+\nu/K^+\to\mu^+\nu$
LFV/LNV K decays
($K\to\pi\mu e$, $K^+\to\pi^-\ell^+\ell^+$)

Dark sector
Direct search for light NP
produced in meson decays

$K^+\to\pi^+X$ ($X\to$invisible,
$X\to\ell^+\ell^-$, $X\to\gamma\gamma$)
$K^+\to\ell^+N$,
$K\to\pi aa$ ($a\to e^+e^-$)

Kaon decay experiments: the quintessential precision frontier experiments

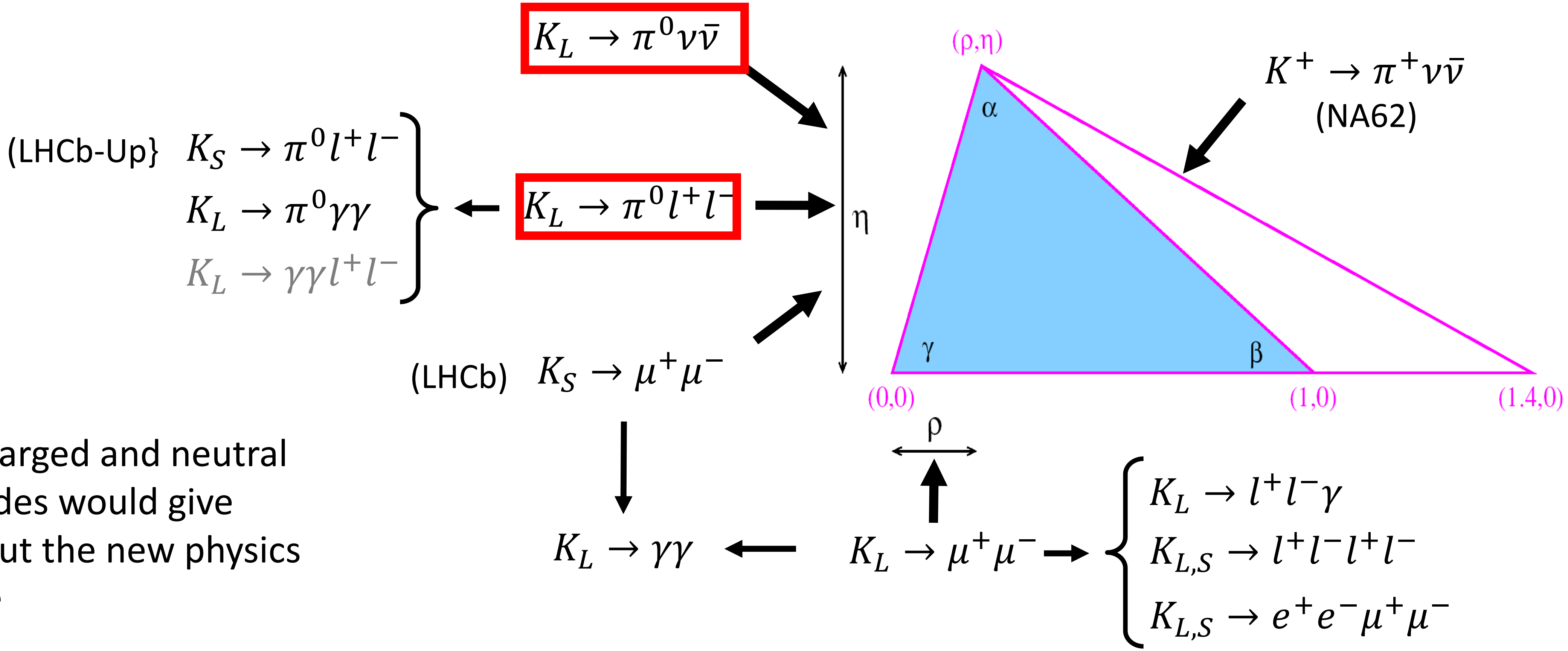
- few decay modes
- simple final states
- large statistics

Exploring flavour physics through Kaon decays

Over-constraining unitary triangle via kaon decays is a crucial test of the SM.

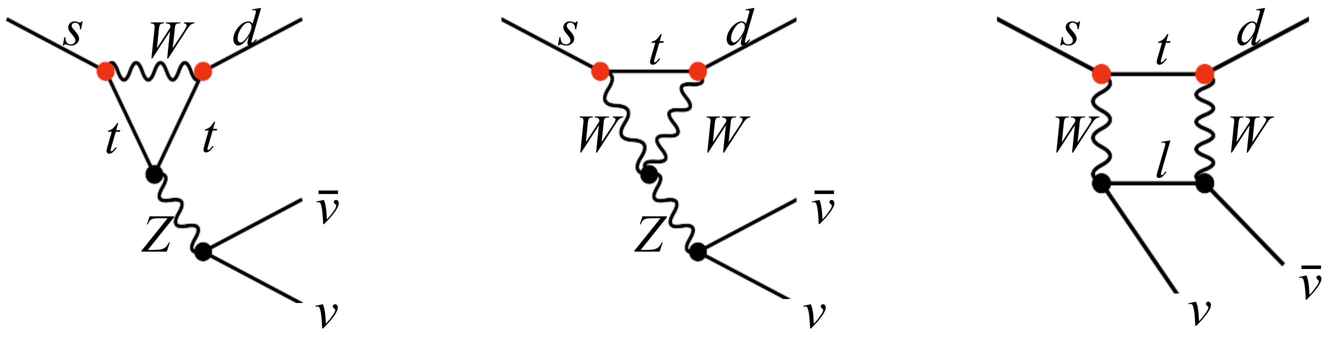
Sensitive to **unprecedented mass scales (well beyond those reachable at LHC)**. [arXiv:1408.0728]

Main limitation to the investigation of several modes comes from the experimental precision.



Measuring all charged and neutral rare K decay modes would give clear insight about the new physics flavour structure

Ultra-rare Kaon Decays $K \longrightarrow \pi\nu\bar{\nu}$



A high-order process with highest CKM suppression:

$A \sim (m_t/m_W)^2 |V^*_{ts} V_{td}| \sim \lambda^5$

Extremely rare decays, rates very precisely predicted in SM

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

[JHEP 1511 (2015) 033]

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

Present error budget presently dominated by CKM inputs

[JHEP 1511 (2015) 033]

[arXiv:2203.11960, arXiv:2109.11032] [arXiv:2105.02868, arXiv2203.09524]

Combination of parameters that are less / not sensitive to New Physics: approach proposed recently to eliminate dependence on V_{cb} and gamma leads to 5% precision. (Correlations with ε_k depends only on β and are well predicted, allowing experimental tests).

[arXiv:1806.11520, arXiv:1910.10644]

“Free” from hadronic uncertainties

Exceptional SM precision

Non-parametric uncertainty:

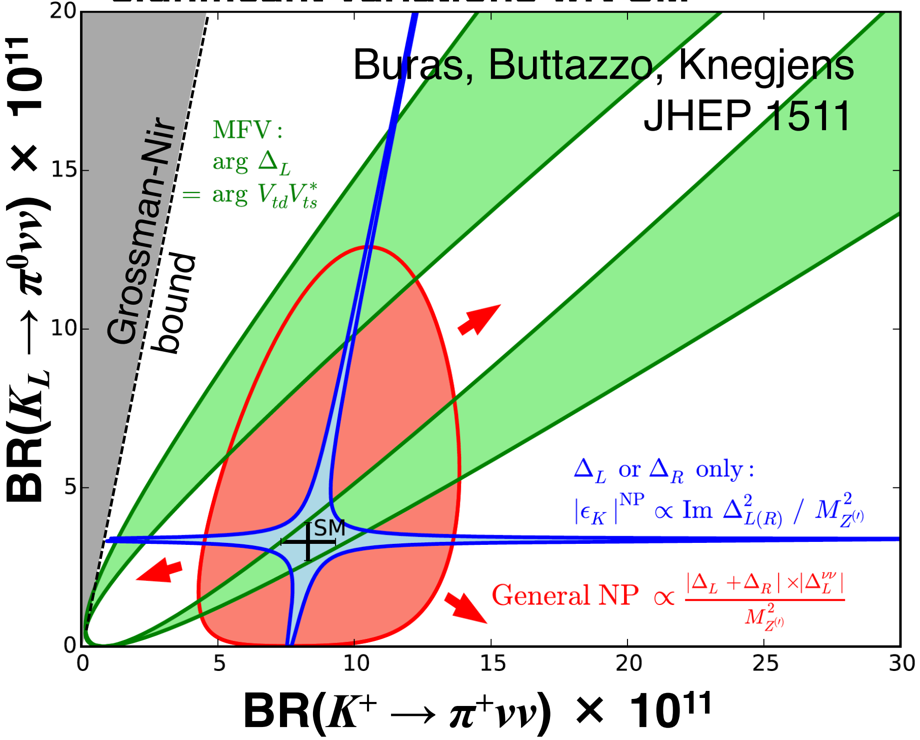
1.5% for K_L, 3.5% for K^+

BSM in the kaon sector

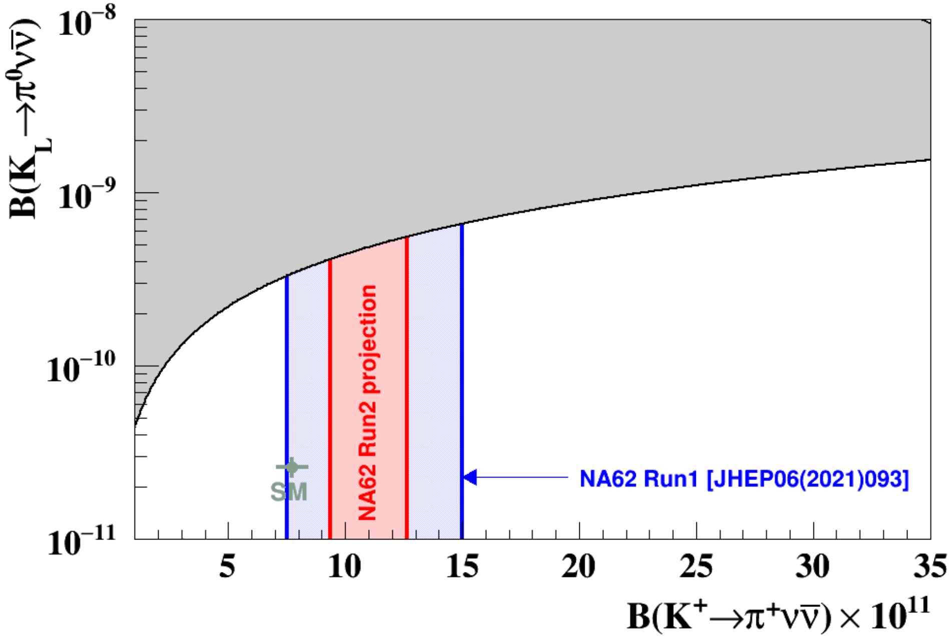
NA62 will measure $K^+ \to \pi^+ \nu\nu$ to $O(15\%)$ precision with Run1&2 data

Precision measurements of $K \to \pi\nu\nu$ BRs provide model-independent tests for NP with sensitivity to O(100) TeV scale [arXiv:1408.0728]

High sensitivity to NP (non-MFV): significant variations wrt SM



- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
  - Randall-Sundrum



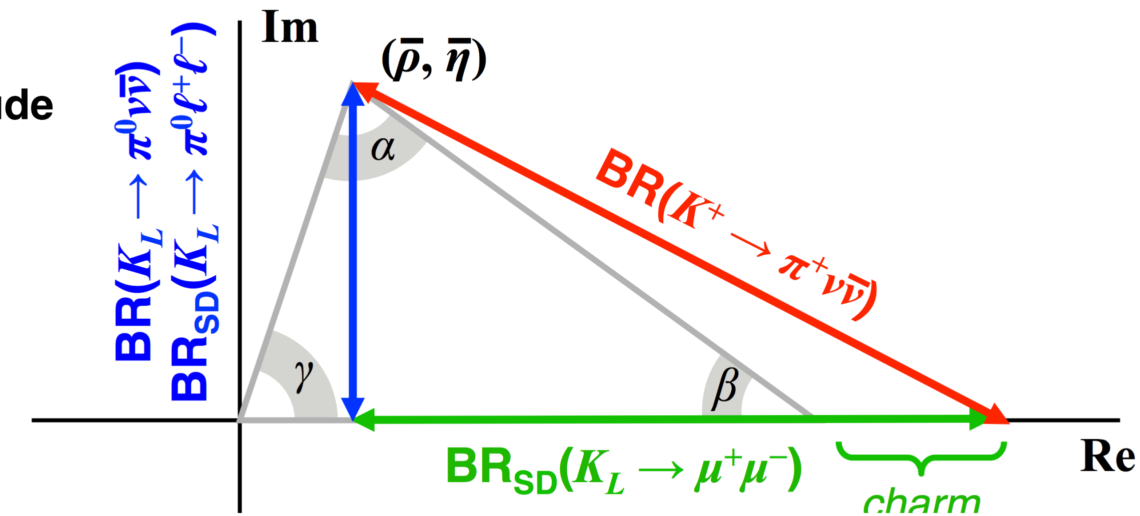
NP scenarios	Process
Z-FCNC	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
Z'	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε'/ε, ΔM_K
Simplified models	$K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
LHT	All K decays
331 models	Small effects in $K \to \pi\nu\bar{\nu}$
Vector-like quarks	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ΔM_K
Supersymmetry	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
2HDM	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
Universal extra dimensions	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
Randall-Sundrum models	All rare K decays
Leptoquarks	All rare K decays
SMEFT	Several processes in K system
SU(8)	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
Diquarks	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε_K
Vector-like compositeness	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε_K

[Table from arXiv:2203.09524]

[JHEP 1511 (2015) 166, EPJ C76 (2016) 182, JHEP 0903 (2009) 108, PEPT 2016 123802, JHEP 0608 (2006) 064, EPJ C77 (2017) 618, arXiv:1705.10729, arXiv:2207.00018, arXiv:2203.09524]

$K_L \to \pi^0 \ell^+ \ell^-$

$K_L \to \pi^0 \ell^+ \ell^-$ **CPV amplitude constrains UT η**



Contributions from long-distance physics

- SD CPV amplitude: γ/Z exchange
- LD CPC amplitude from 2γ exchange
- LD indirect CPV amplitude: $K_L \to K_S$

- $K_S \to \pi^0 \ell^+ \ell^-$ will help reducing theoretical uncertainties, measure $|a_S|$
  - measured NA48/1 with limited statistics
  - planned by LHCb Upgrade
- $K_L \to \pi^0 \ell^+ \ell^-$ can be used to explore helicity suppression in FCNC decays, give unique access to SD BSM effects in the photon coupling via the tau loop

$$\mathcal{B}(K_L \to \pi^0 e^+ e^-) = 3.54^{+0.98}_{-0.85} \left(1.56^{+0.62}_{-0.49}\right) \times 10^{-11}$$
$$\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-) = 1.41^{+0.28}_{-0.26} \left(0.95^{+0.22}_{-0.21}\right) \times 10^{-11}$$

(2 sets of values corresponding to constructive (destructive) interference btw direct and indirect CP-violating contributions)

[arXiv:hep-ph/0404127,arXiv:hpe-ph/0404136, arXiv:hep-ph/0606081]
[arXiv:0705.2025, arXiv:1812.00735, arXiv:1906.03046, https://indico.cern.ch/event/1196830/]

Experimental bounds from KTeV:

$BR(K_L \to \pi^0 e^+ e^-) < 28 \times 10^{-11}$
$BR(K_L \to \pi^0 \mu^+ \mu^-) < 38 \times 10^{-11}$

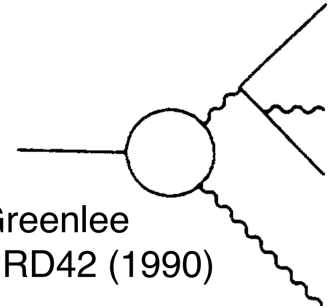
Phys. Rev. Lett. 93 (2004) 021805
Phys. Rev. Lett. 84 (2000) 5279–5282

Main background: $K_L \to \ell^+ \ell^- \gamma\gamma$

- Like $K_L \to \ell^+ \ell^- \gamma$ with hard bremsstrahlung

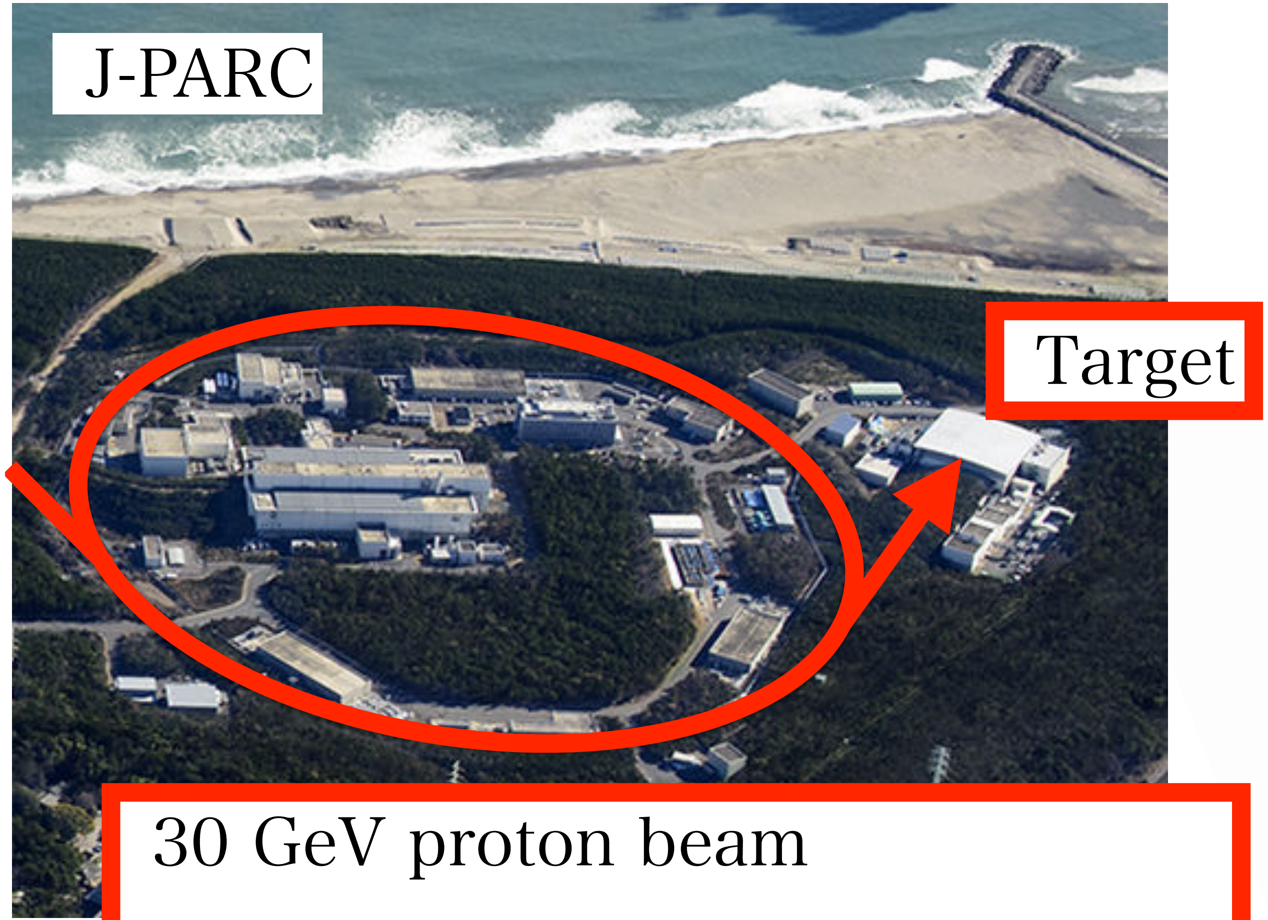
$BR(K_L \to e^+ e^- \gamma\gamma) = (6.0 \pm 0.3) \times 10^{-7}$ $\quad E_\gamma^* > 5$ MeV

$BR(K_L \to \mu^+ \mu^- \gamma\gamma) = 10^{+8}_{-6} \times 10^{-9}$ $\quad m_{\gamma\gamma} > 1$ MeV



Greenlee PRD42 (1990)

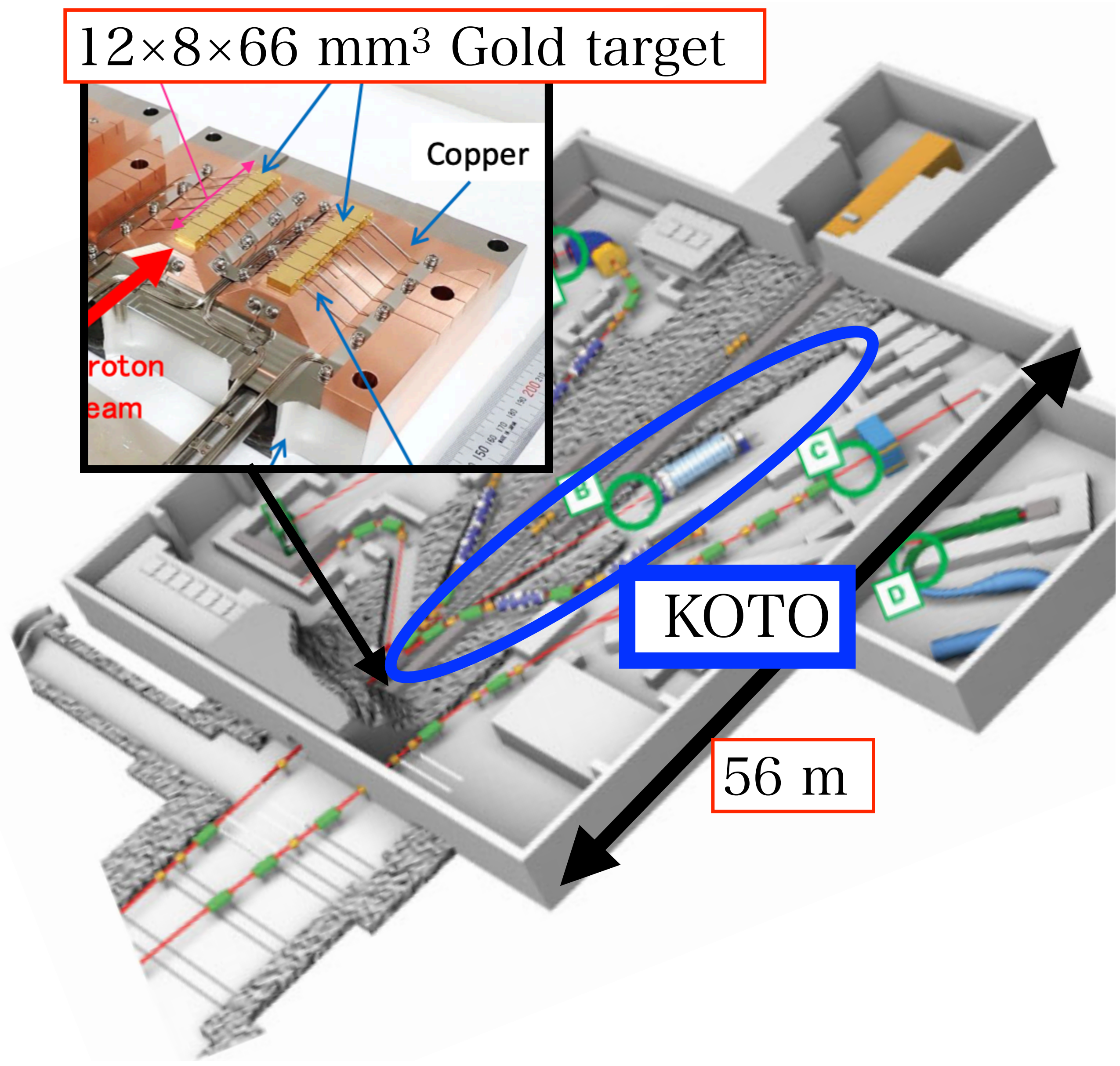
Kaons at JPARC



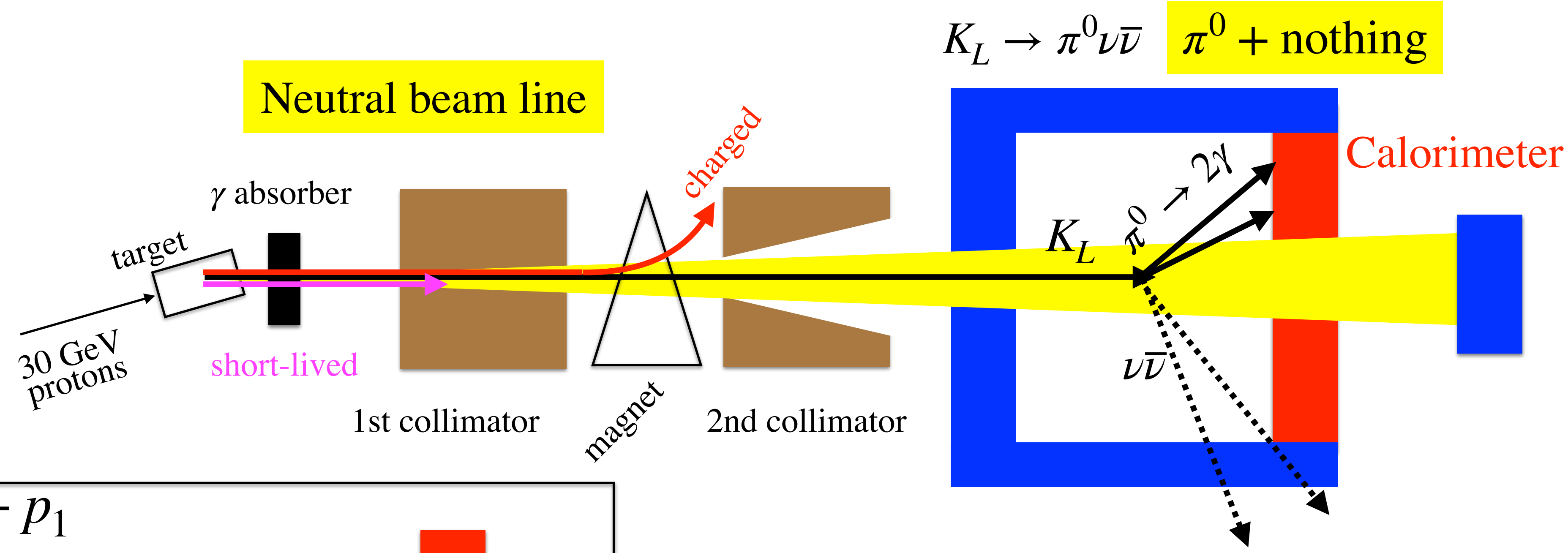
30 GeV proton beam

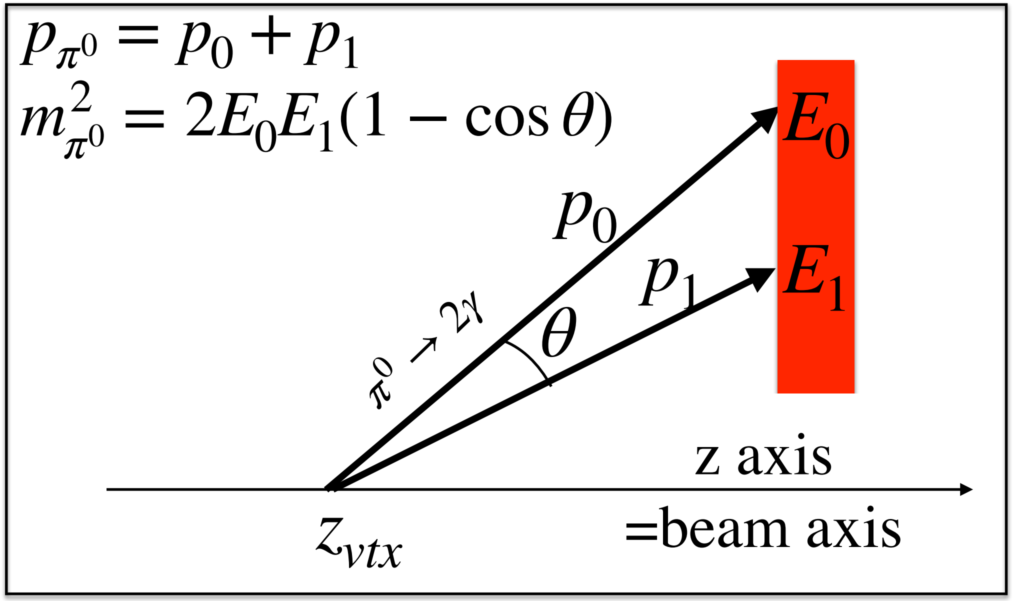
Slow extraction

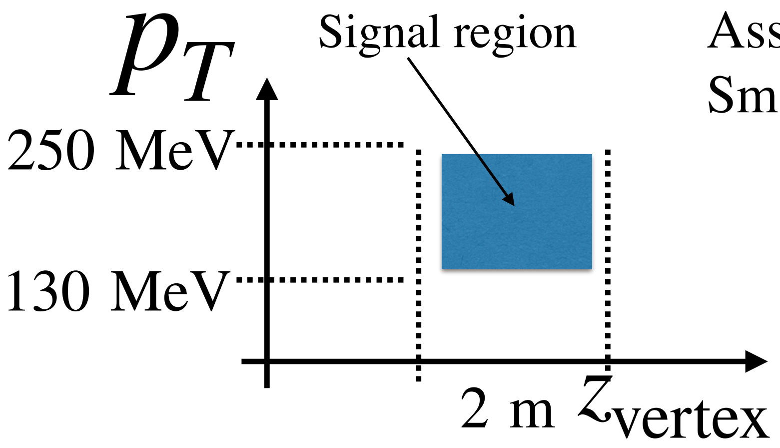
65 kW, 2-s spill / 5.2-s spill (2021)



KOTO concept





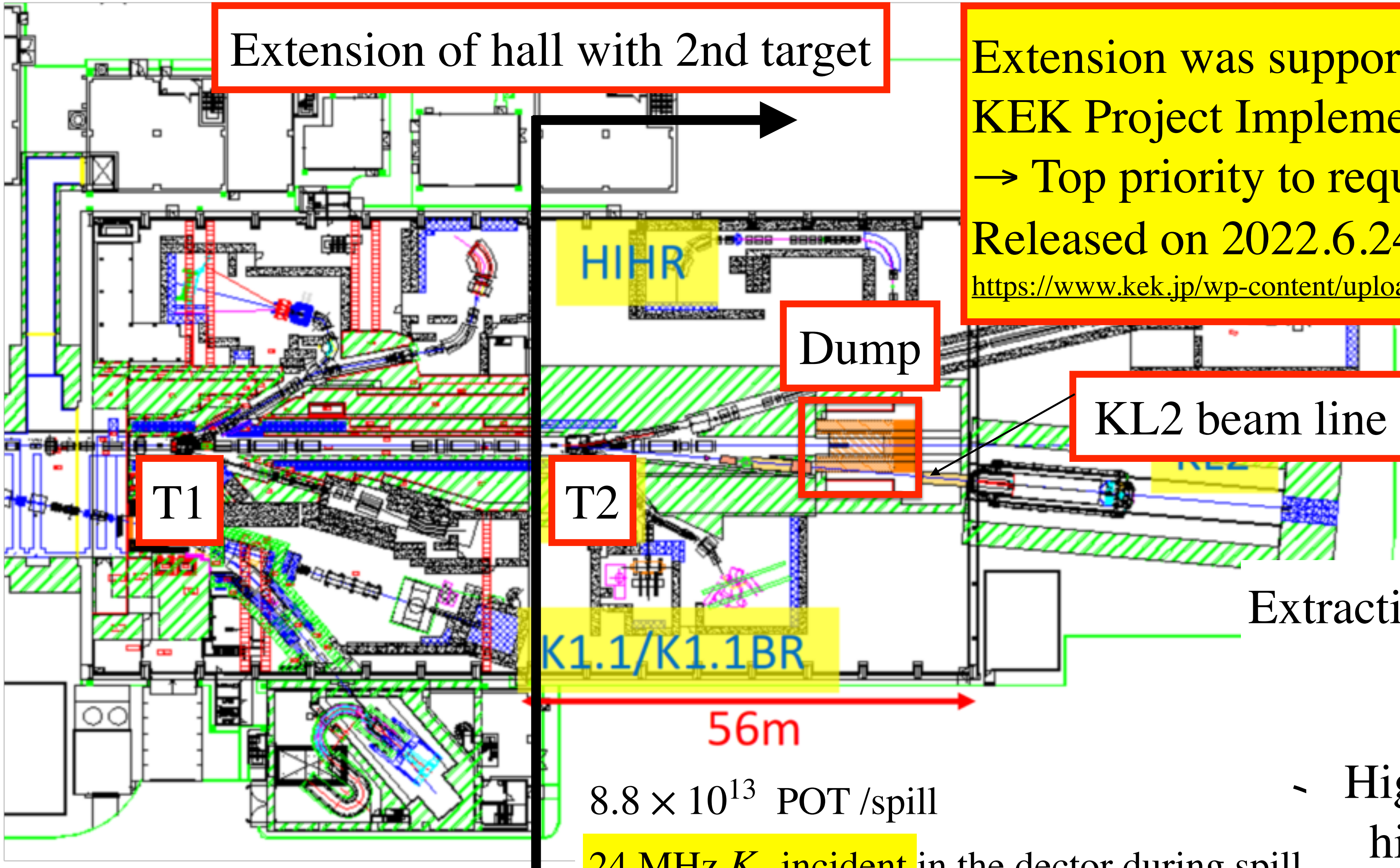


Assume the vertex on beam axis
Small beam hole for veto

⇕

Narrow beam

KOTO-2: extension of experimental hadron facility



Extension was supported by
KEK Project Implementation Plan 2022
→ Top priority to request new budget
Released on 2022.6.24
https://www.kek.jp/wp-content/uploads/2022/07/KEK-PIP2022.pdf

Extraction angle: 16° → 5°

Higher momentum & higher intensity K_L

8.8×10^{13} POT /spill

24 MHz K_L incident in the dector during spill

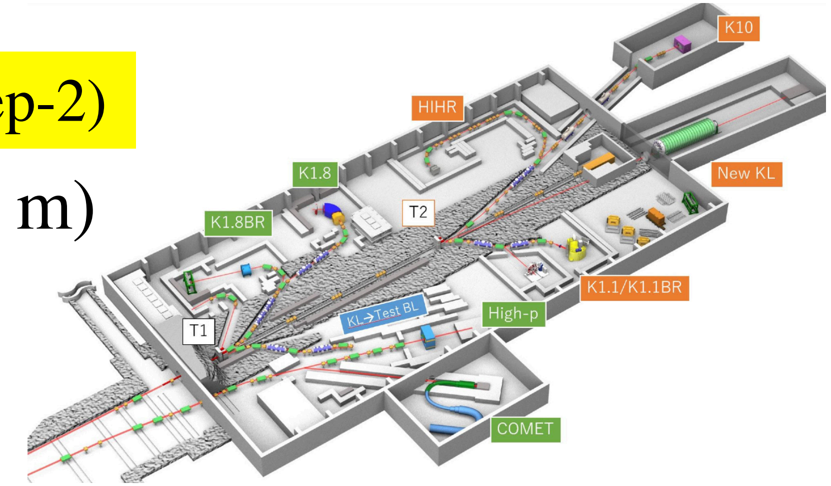
Starting beam survey in 2031, then operation

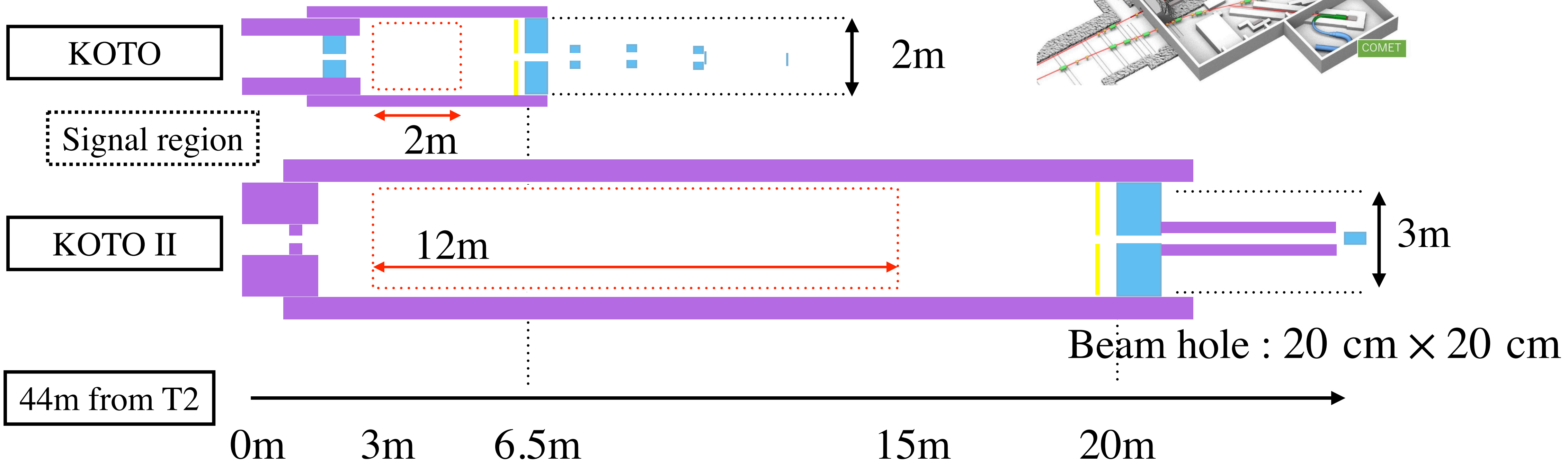
KOTO-2 detector and sensitivity

Peak K_L momentum : 1.4 GeV/c (step-1) $\rightarrow$ 3 GeV/c (step-2)

Possible to use longer decay volume (2 m $\rightarrow$ 12 m)

Larger diameter calorimeter (2 m $\rightarrow$ 3 m)





35 SM signal / 33 background events

$\Delta\mathscr{B}/\mathscr{B} = 23\,\% \rightarrow \Delta\eta/\eta = 12\,\%$

Discussions on-going over the Summer to expand K_L programme and include tracking, enabling $K_L \rightarrow \pi^0\ell^+\ell^-$

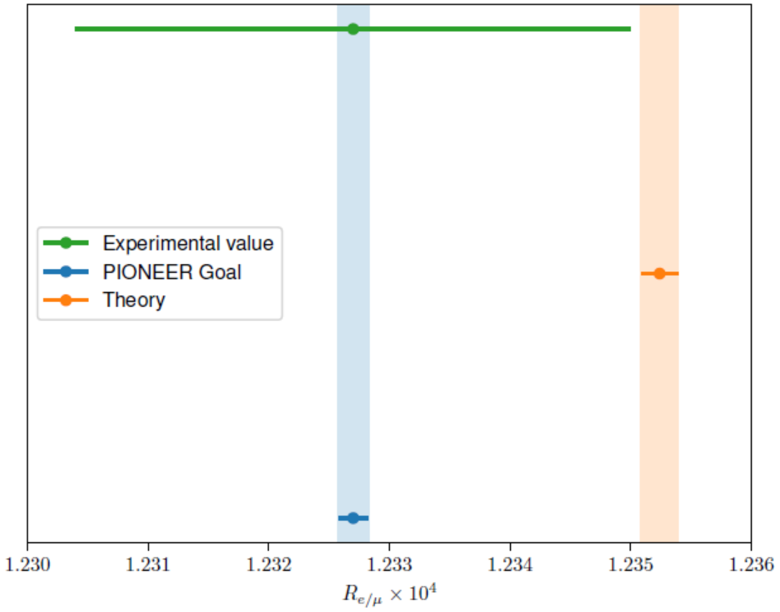
UK can be a major player (tracking, DAQ/Trigger, photo-detectors, simulation). Synergies with DRD programme

PIONEER: physics motivations

(Phase 1: LFU, Phase 2: CKM)

Test of Lepton Flavour Universality at 10^{-4} with pion decays

$$R_{e/\mu} = \frac{\Gamma[\pi^+ \to e^+\nu_e(\gamma)]}{\Gamma[\pi^+ \to \mu^+\nu_\mu(\gamma)]}$$



SM prediction, precision of 1.2 10^{-4} !

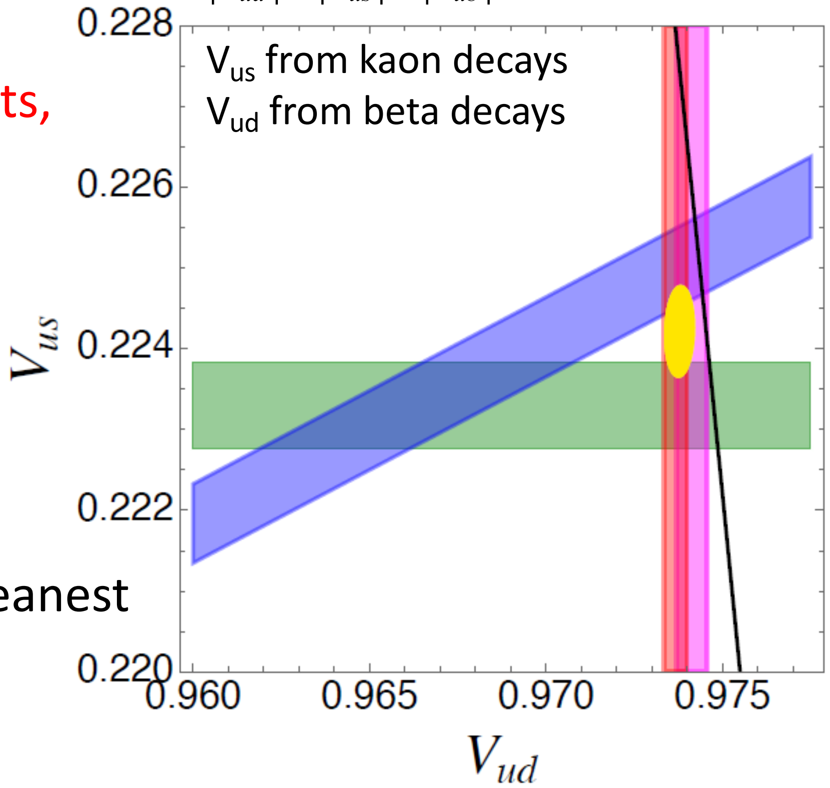
$$R^{SM}_{e/\mu} = 1.23524(15) \times 10^{-4}$$ [Cirigliano, Rosell 2007]

Current experimental value:

$$R^{exp}_{e/\mu} = 1.2327(23) \times 10^{-4}$$ [PIENU 2015]

Sensitive prove of (pseudo-)scalar currents, tests scales up to several 1000 TeV

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$



Constraints on modified W couplings

$$\mathcal{L} = -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu\left(\delta_{ij} + \varepsilon_{ij}\right)$$

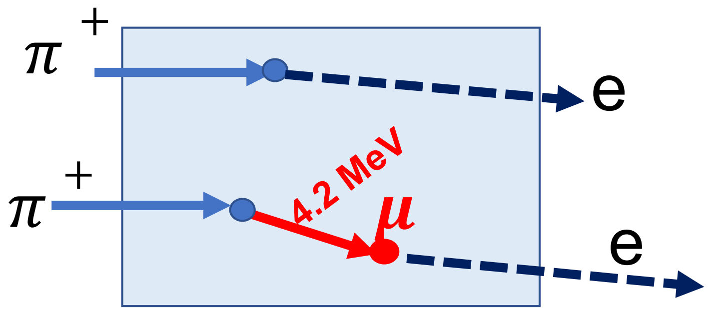
$$\frac{R^{SM}_{e/\mu}}{R^{exp}_{e/\mu}} = 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee} = 1.0010(9)$$

Possible connection with flavour hints of LFUV

Relates to CKM Unitarity: pion beta-decay $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ theoretically cleanest

Generally, dominant uncertainties from hadronic and nuclear corrections

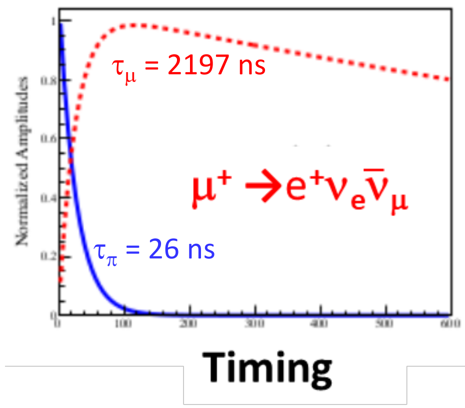
PIONEER: methodology

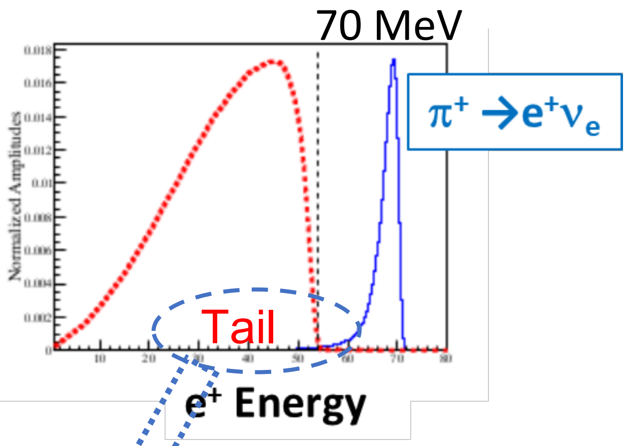


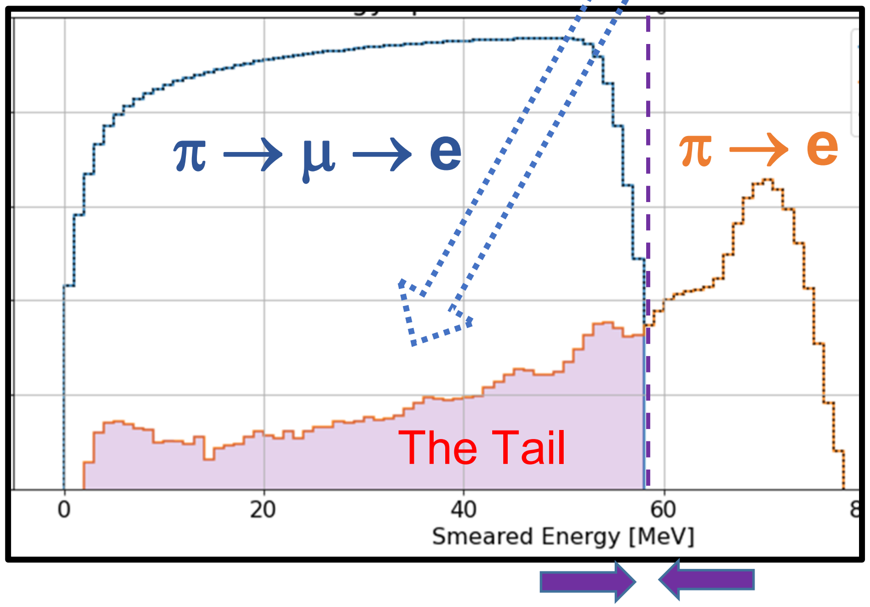
Overall uncertainty goal:

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \pm 0.01\%$$

$$\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}$$



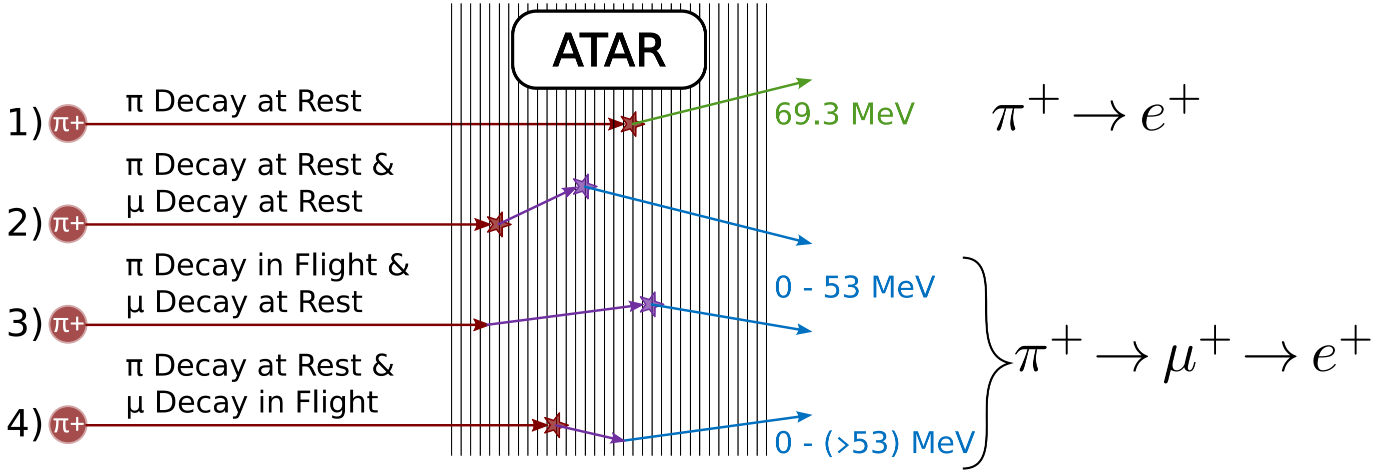




The Ratio must be independent of where we place this division

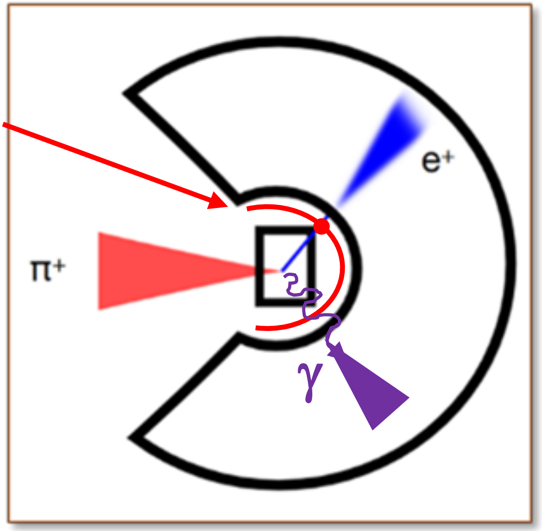
Challenges:

- Measure the fraction of $\pi \rightarrow$ e events below the Michel spectrum: "The Tail"
- Handle higher rates needed for statistical precision
- Verify Simulations with measurements

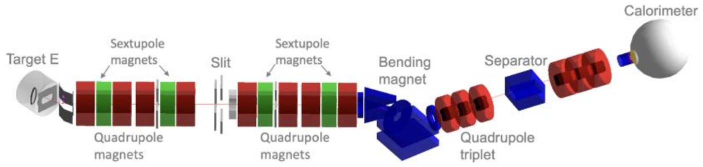


PIONEER @ PSI

Making use of world's brightest stopped pion beam

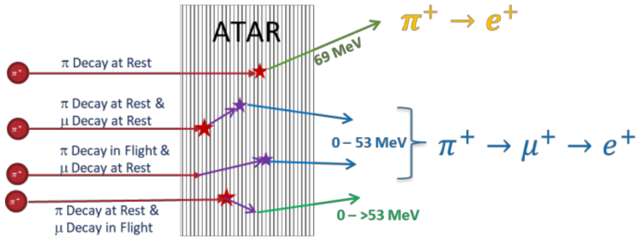


- Low-energy πE5 Pion Beam
  - PSI fully supports expt.; users to optimize tune



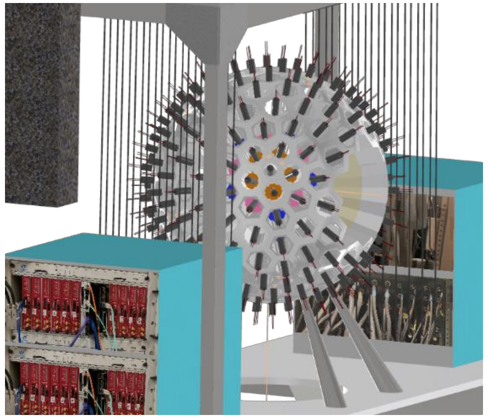
- ATAR: Active Stopping Target
  - LGAD 5D Tracking (low-gain avalanche diode)
  - 5000 channels in 20x20x6 mm^3

300k π/s stopped in ATAR



- LXe or LYXO Calorimeter
  - High Res; Fast, Uniform, Dense
  - Tail fraction below 1%

  [~80 cm outer radius]



Aim at data taking starting in 2030.

- State-of-the-art additional instrumentation
  - μRWell Tracker; fast triggering; high speed digitization and DAQ

Discussions on-going over the Summer about possible UK contribution
UK can be a major player (tracking, DAQ/Trigger, photo-detectors, software and simulation)
Synergies with DRD programme

Summary

Rare kaon decay measurements are listed as a high-priority activity both in the EU strategy and the UK PPAP roadmap.
HIKE was not approved on “strategic” grounds, its physics case judged excellent.
Sizeable HIKE-UK Kaon community.

The continuation, outside CERN, of light-quark flavour experiments with rare decays and precision measurements to challenge the SM and give breadth to the programme is important and should be highlighted in the PPAN Roadmap.

This community is now evaluating opportunities, where parts of the original programme can be done. Longer-term: find facility to address kaon programme more widely.

Initially looking at taking advantage of existing facilities at JPARC and PSI.
Discussions on-going with KOTO-2 and PIONEER – then intend to submit SoI.
UK can be a major player (tracking, DAQ/Trigger, software and simulation).
Synergies with UK-DRD programme will be explored.