Kaon Experiments

Elizabeth Worcester, for the KOTO, LHCb, and NA62/KLEVER collaborations and the US Kaon Interest Group

Snowmass Rare and Precision Measurements Frontier Spring Meeting

May 17, 2022

Thank you to M. Moulson for the use of his slides

Please see the Snowmass whitepaper for details:
https://arxiv.org/abs/2204.13394

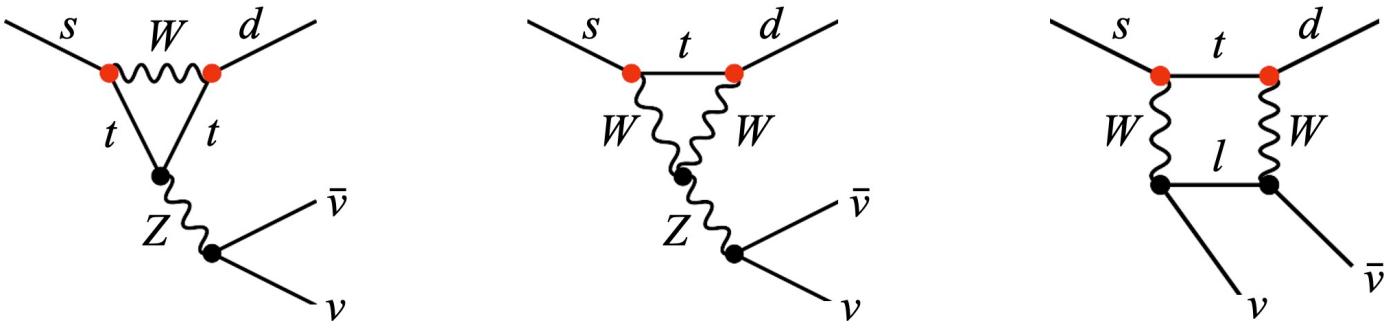
Searches for new physics with high-intensity kaon beams

Contributed paper to Snowmass 2021

The KOTO[1], LHCb[2], and NA62/KLEVER[3] Collaborations
and the US Kaon Interest Group[4]

[4]W. Altmannshofer, L. Bellantoni, E. Blucher, G.J. Bock, N.H. Christ, D. Denisov, Y. Grossman, S.H. Kettell, P. Laycock, J.D. Lewis, H. Nguyen, R. Ray, J.L. Ritchie, P. Rubin, R. Tschirhart, Y. Wah, E. Worcester, E.D. Zimmerman; Contact person: Elizabeth Worcester (etw@bnl.gov)

$K \to \pi\nu\bar{\nu}$ in the Standard Model



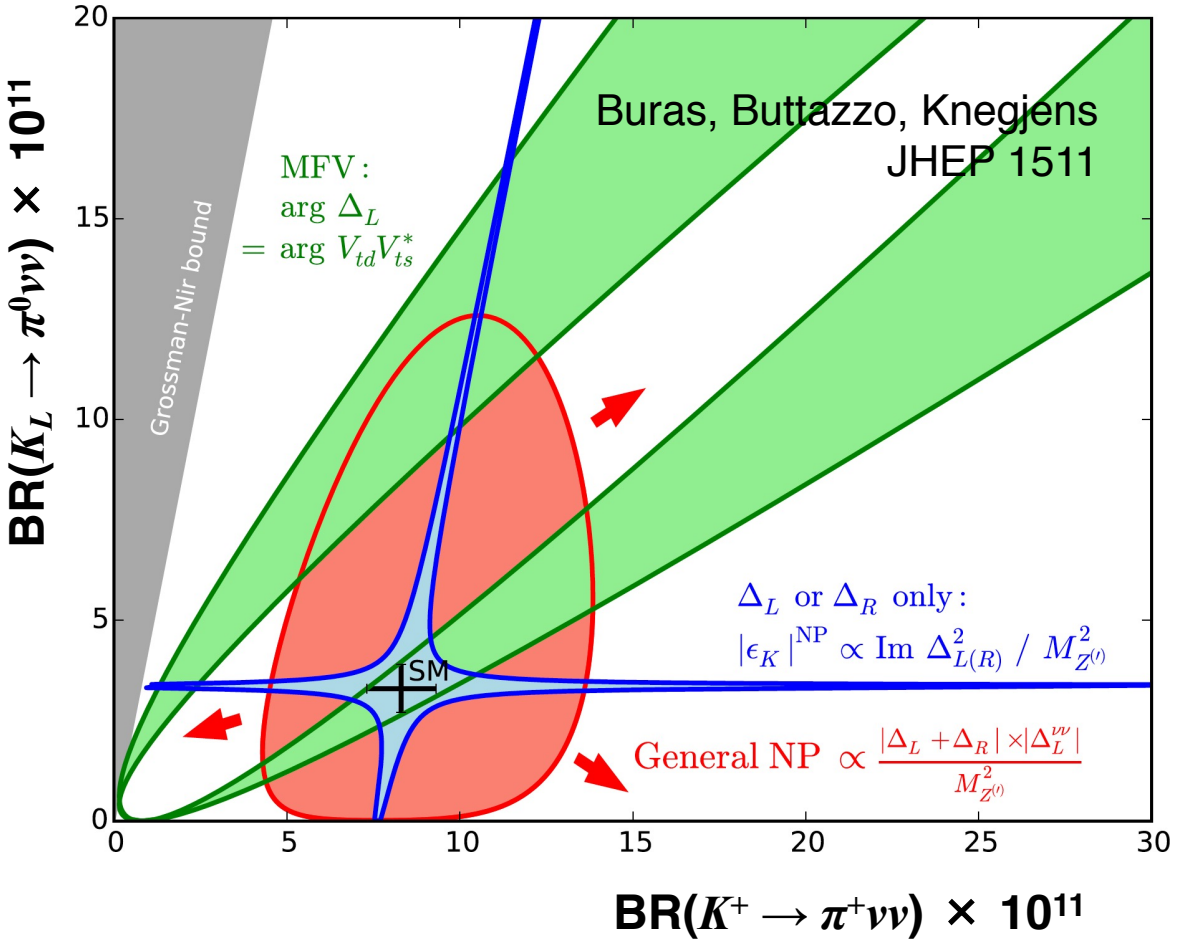
Extremely rare decays with rates very precisely predicted in SM:

- Hard GIM mechanism + pattern of CKM suppression ($V_{ts}^* V_{td}$)
- No long-distance contributions from amplitudes with intermediate photons
- Hadronic matrix element obtained from BR(K_{e3}) via isospin rotation

	SM predicted rates Buras et al, JHEP 1511* *Tree level CKM matrix elements	**Experimental status (before Sep 2019)**
$K^+ \to \pi^+\nu\nu$	**BR = (8.4 ± 1.0) × 10^{-11}**	**BR = (17.3 $^{+11.5}_{-10.5}$) × 10^{-11}** Stopped K^+, 7 events observed BNL 787/949, PRD79 (2009)
$K_L \to \pi^0\nu\nu$	**BR = (3.4 ± 0.6) × 10^{-11}**	**BR < 300 × 10^{-11} 90%CL** KOTO, PRL122 (2019)

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

- **New physics affects K^+ and K_L BRs differently**
- Measurements of both can discriminate among NP scenarios



- 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
- **Grossman-Nir bound**

  Model-independent isospin relation

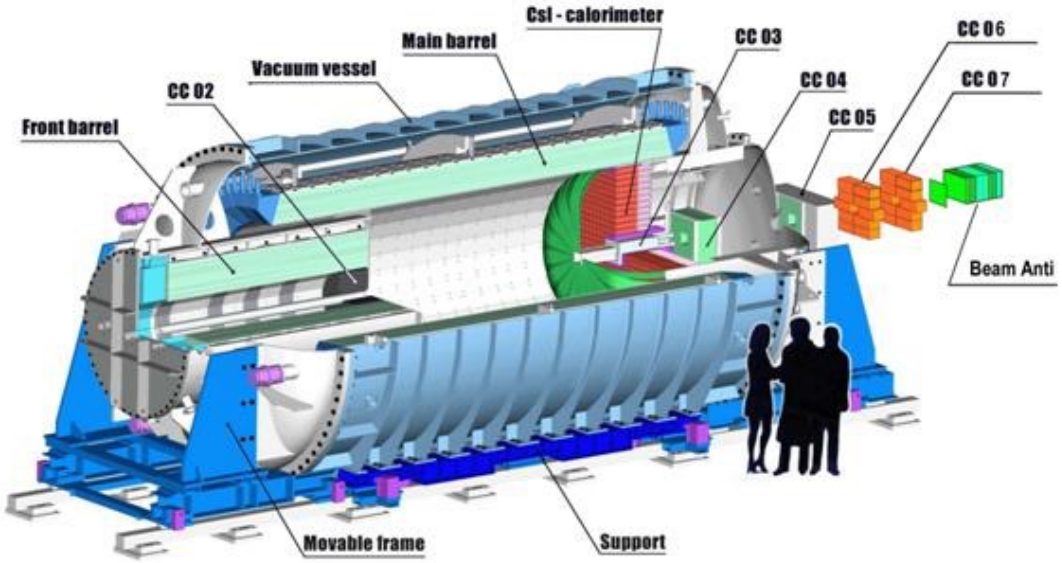
$K_L \to \pi^0 \nu\nu$ at J-PARC

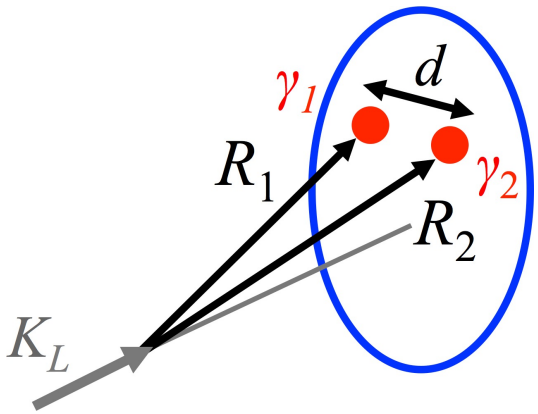
Proton beam: 30 GeV

Neutral beam:

8 μsr “pencil” beam

$\langle p(K_L) \rangle$ = 2.1 GeV





Essential signature: 2γ with unbalanced p_T + nothing else!

K_L momentum generally is not known

$M(\gamma\gamma) = m(\pi^0)$ is the only sharp kinematic constraint, used for vertex reconstruction

KOTO Status and Outlook

- 2016-2018 final result: **BR($K_L \to \pi^0 \nu\nu$) < 4.9 × 10^{-9} (90%CL)**
  - ~1.2 background events expected, 3 in signal box

PRL 126 (2021) 121801

- Detector improvements for 2019-2021
  - Calorimeter dual sided readout installed for 2019 run (x50 reduction in neutron bg)
  - Upstream charged particle veto installed for 2021 (x20 reduction in K^+ background)
- Data set from 2019-2021(comparable statistics to 2016-2018) analysis in progress
- Need 20x more statistics to reach SM SES
  - Beam power will double after 2022
  - Expect to reach SM SES by mid 2020s

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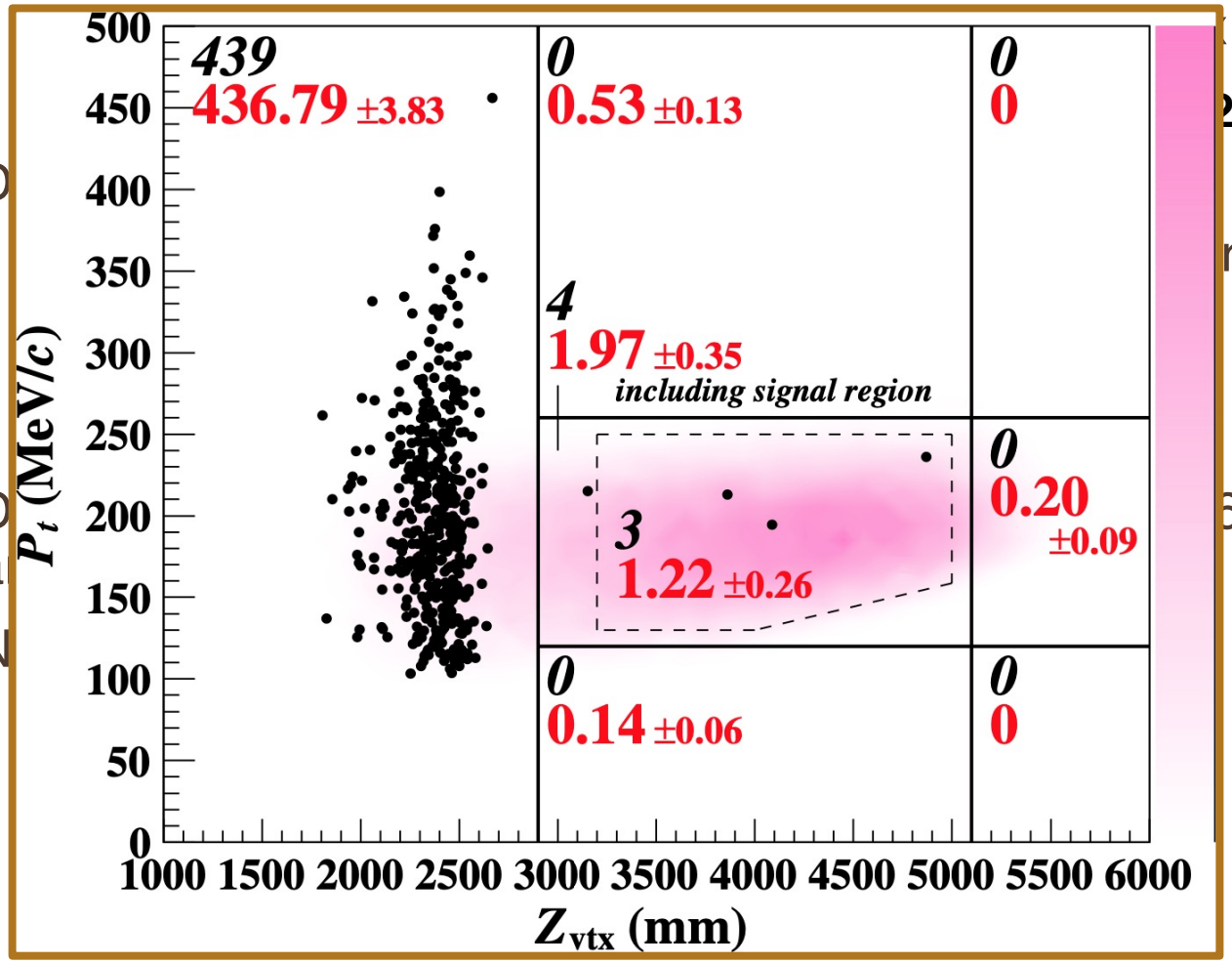

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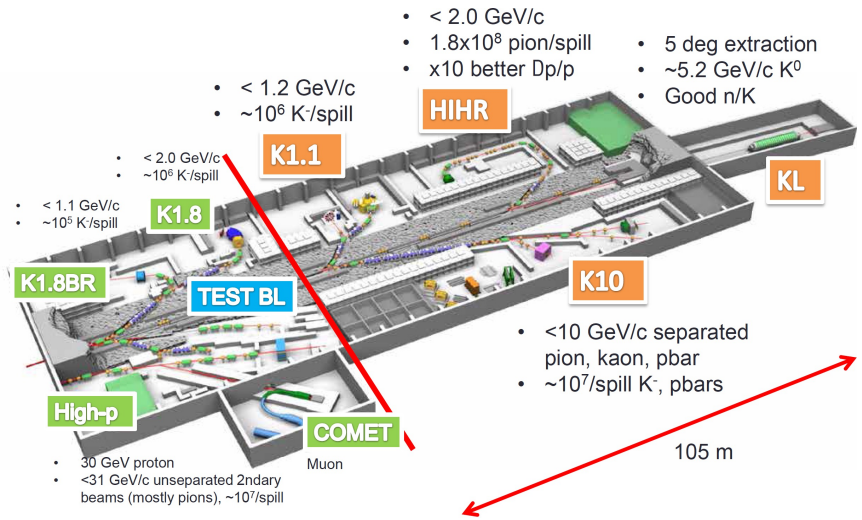
KOTO Step-2

- **Plan outlined in 2006 proposal to upgrade to O(100) SM event sensitivity**
- **Now beginning design work for a new experiment to achieve this sensitivity**

  - Increase beam power to > 100 kW
  - New neutral beamline at 5°
    $\langle p(K_L) \rangle$ = 5.2 GeV
  - Increase FV from 2 m to 12 m
    Complete rebuild of detector
  - **Requires hadron-hall extension**



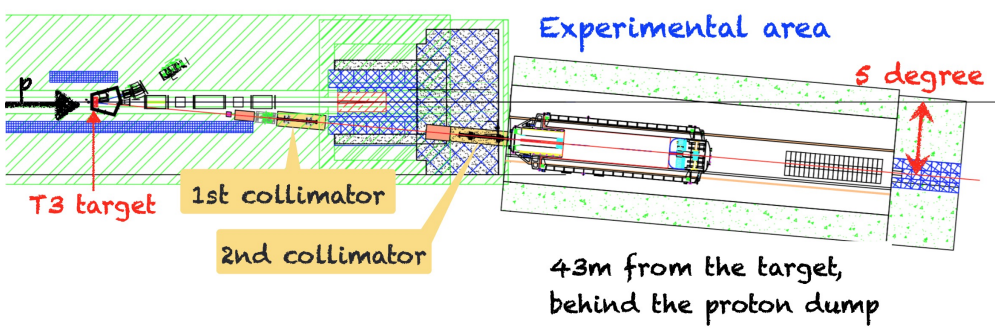
- Hadron-hall extension is a joint project with nuclear physics community -- KOTO Step-2 is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027
- Focused review conducted in Aug 2021, with KOTO providing Step-2 input

KOTO Step-2

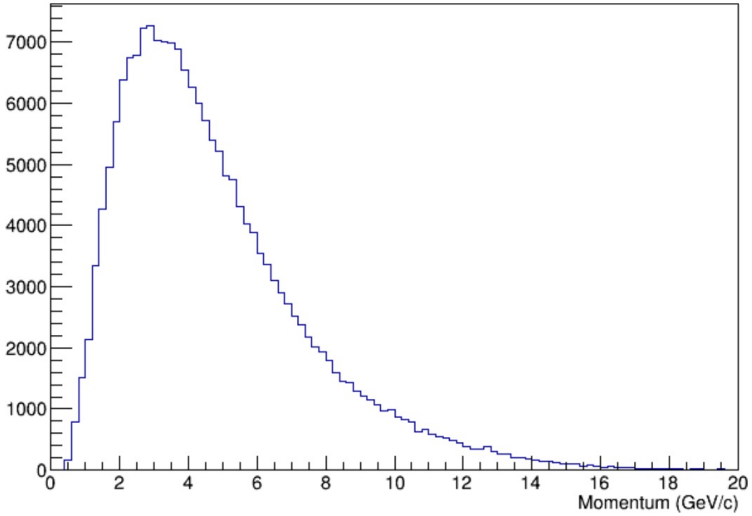
~ 60 SM evts with S/B ~ 1 at 100 kW beam power (3×10^7 s)

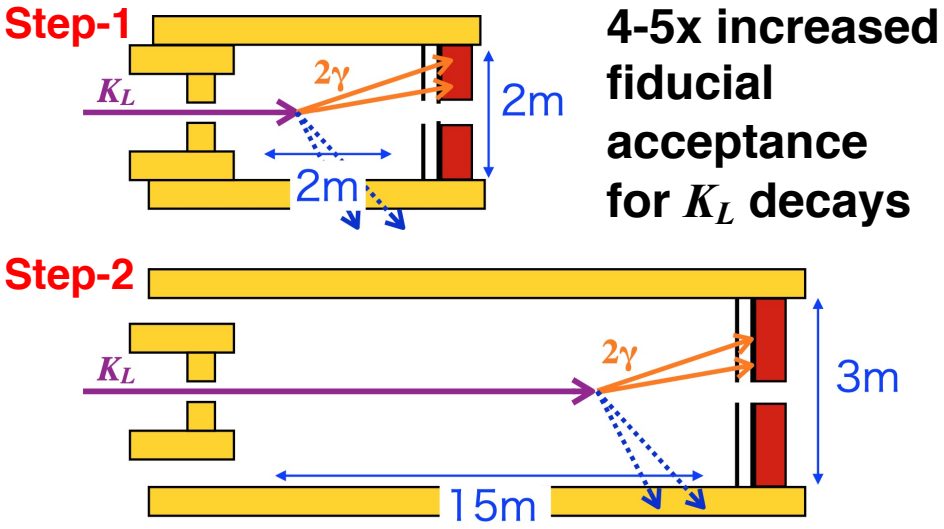
Step-2 beamline setup in hadron-hall extension

- Smaller angle (16˚ → 5 ˚)
- Longer beamline (20 → 43 m)
- 2 collimators



K_L spectrum at beam exit

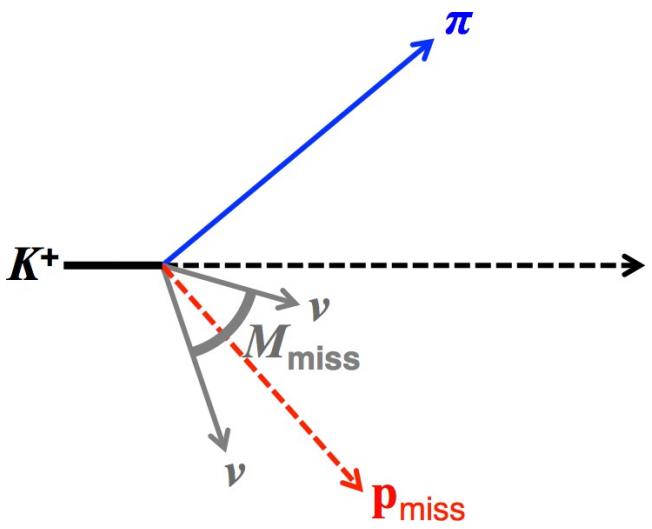


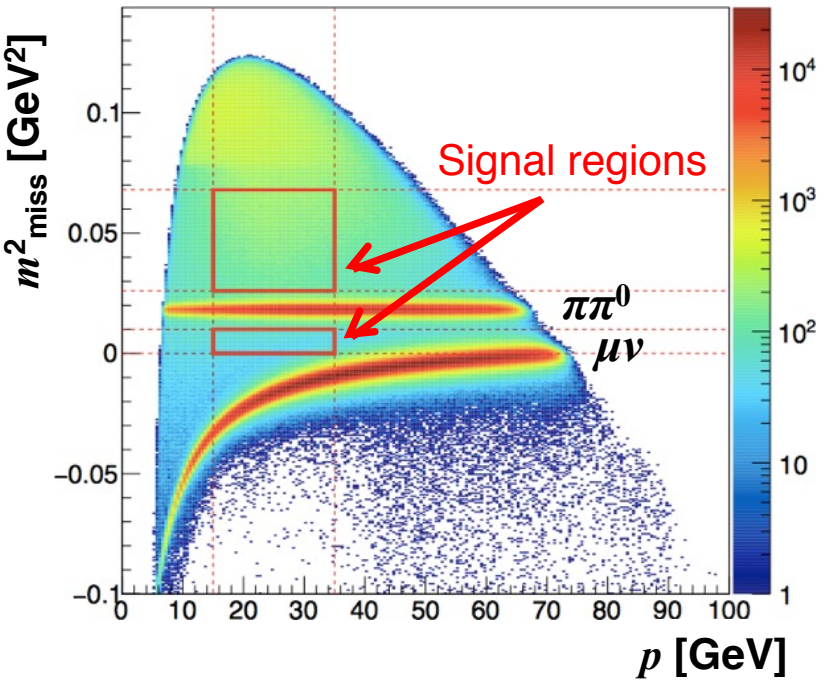


4-5x increased fiducial acceptance for K_L decays

$K^+ \to \pi^+ \nu\nu$ with the NA62 Experiment

Decay in Flight Experiment





Main backgrounds:

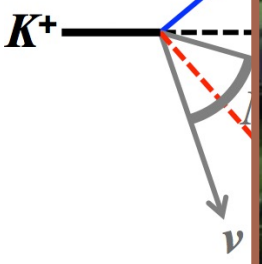
$K^+ \to \mu^+ \nu(\gamma)$	BR = 63.5%
$K^+ \to \pi^+ \pi^0(\gamma)$	BR = 20.7%

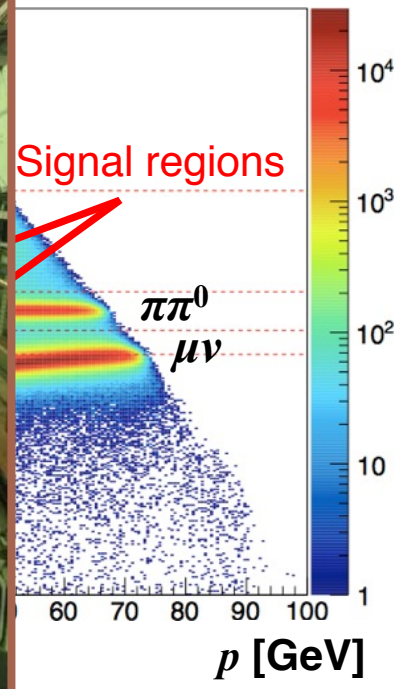
Selection criteria:

- K^+ beam identification
- Single track in final state
- π^+ identification ($\varepsilon_\mu \sim 1 \times 10^{-8}$)
- γ rejection ($\varepsilon_{\pi 0} \sim 3 \times 10^{-8}$)

$K^+ \to \pi^+ \nu\nu$ with the NA62 Experiment

Decay in Fl





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NA62 Status and Outlook

- 2016-2018 final result: $\mathrm{BR}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(10.6^{+4.0}_{-3.4}\,|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}\right) \times 10^{-11}$
  - 20 events observed
  - Expected signal ~10 events
  - Expected background ~7 events

JHEP 06 (2021) 093

- NA62 outlook from LS2-LS3
  - Resumed data taking in July 2021
  - Key modifications to reduce background from upstream decays and interactions:
    - Rearrangement of beamline elements around GTK achromat
    - 4th station added to GTK beam tracker
    - New veto hodoscope upstream of decay volume and additional veto counters around downstream beam pipe
  - Running at higher beam intensity (70% → 100%)
  - Expect order 10% measurement of BR($K^+ \to \pi^+ \nu\nu$) by LS3

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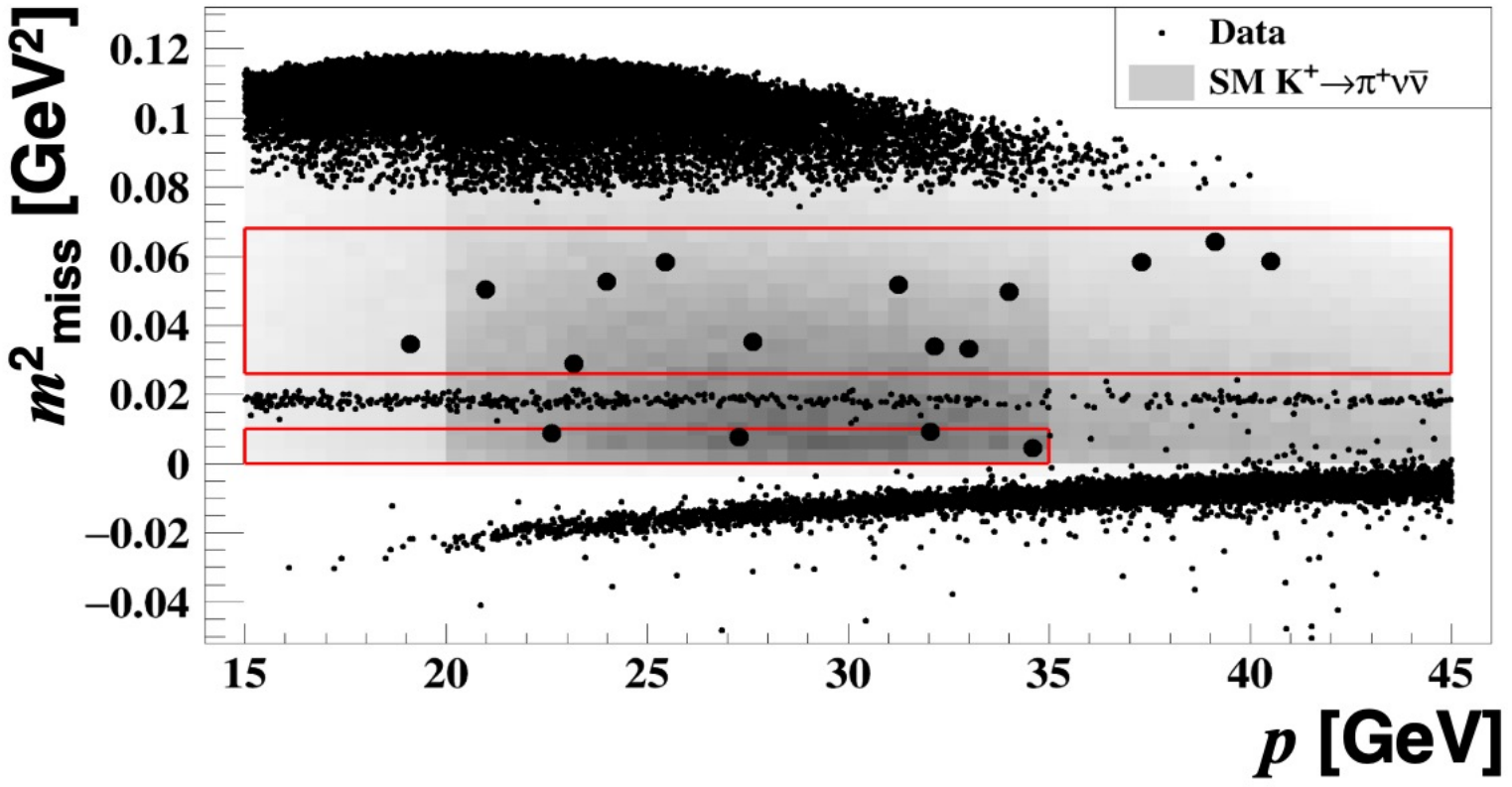
17 signal candidates in 2018 data

3



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High-intensity kaon beams at the SPS

There is an opportunity at the SPS for an **integrated program** to measure all rare kaon decay modes—**charged and neutral**

Experiments to measure $K \to \pi\nu\nu$ BRs at the SPS would require increases wrt present primary intensity:

- $K^+ \to \pi^+\nu\nu$
  6×10¹⁸ pot/year
  4x increase
- $K_L \to \pi^0\nu\nu$
  1×10¹⁹ pot/year
  6x increase

A kaon experiment at 6x present intensity is compatible with a diverse North Area program

Extend NA62 decay-in-flight technique to reduce BR uncertainty to 5%

- Improved timing resolution
- Maintain other performance parameters at high rate
- Synergy with high luminosity LHC?

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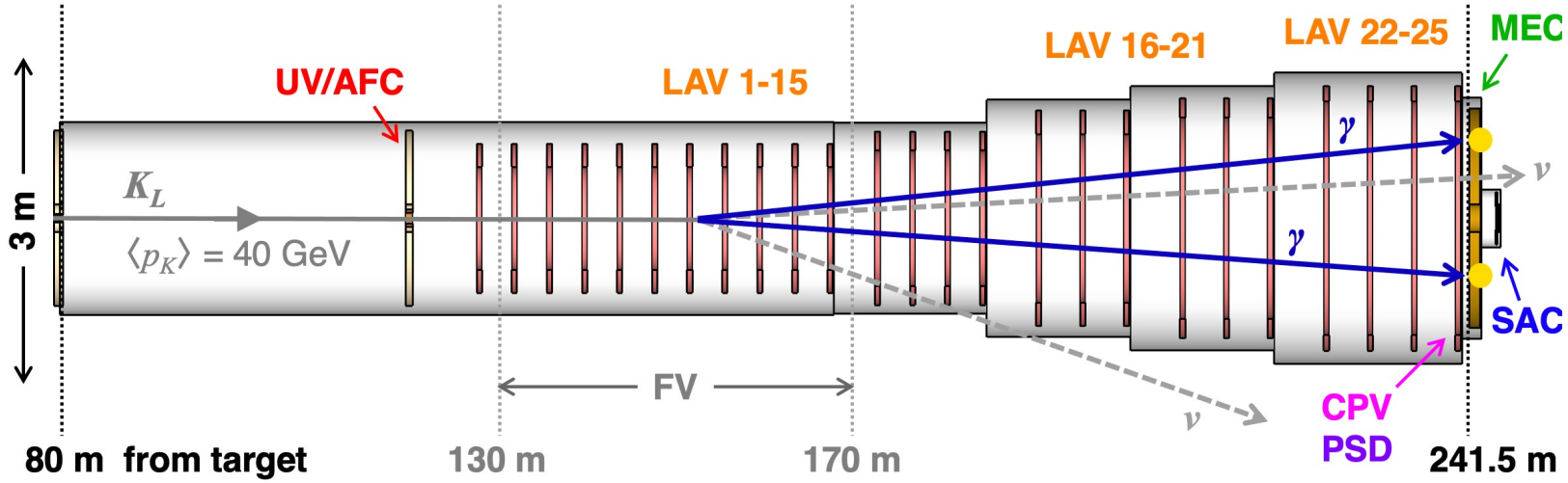
KLEVER

High-energy experiment (complementary to KOTO):

- Roughly same vacuum tank layout and fiducial volume as NA62
- 5 years starting in Run 4
- 60 SM events with S/B~1
- 20% BR measurement

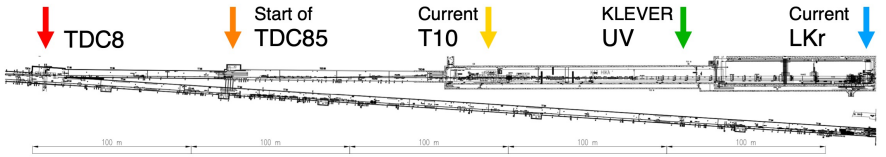
A $K_L \to \pi^0 \nu\nu$ experiment at the SPS

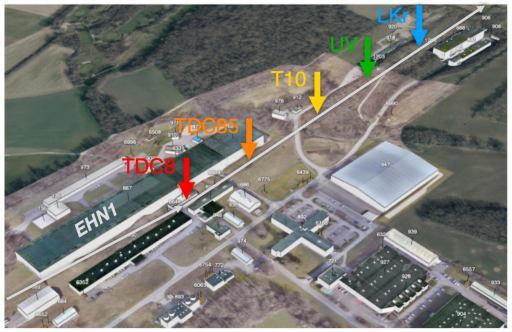


Requires a longer beamline to suppress $\Lambda \to n\pi^0$ background

Maintain θ = 8 mrad and increase length of beamline

E.g.: Move T10 from TCC8 to start of TDC85 (120 m → 270 m from T10 to UV)





- Maintain K_L momentum
  Fewer design changes for KLEVER
- Preserve K_L flux per solid angle
  Still lose 2x in K_L flux due to tighter beam collimation
- Infrastructure work needed
- RP issues for area downstream of TDC85 to be investigated
- **Alternatively, ECN3 extension would solve problem**

K_S decays at LHCb

10^{13} K_S/fb^{-1} produced in LHCb acceptance

About 1 strange hadron per event!

Production rate compensates for low trigger efficiency and long lifetime

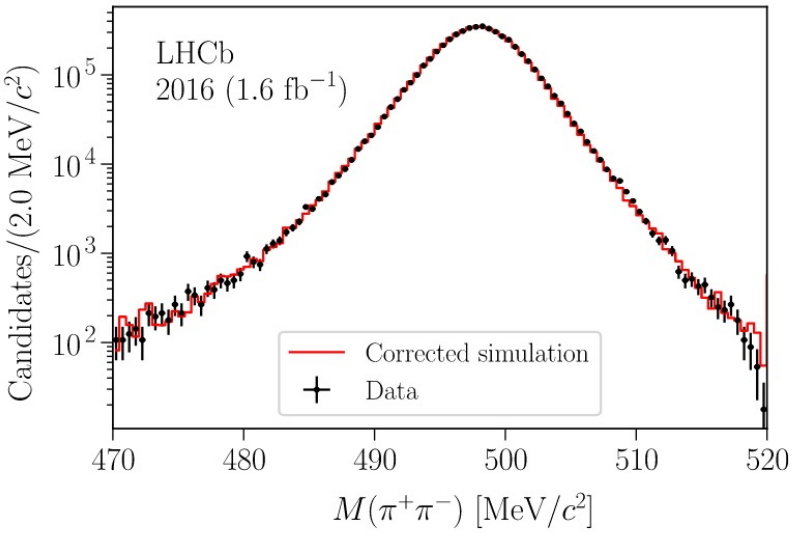
Vast K program for Run 3:

- $K_{S,L} \to \mu^+\mu^-$
- $K_S \to \pi^0\mu^+\mu^-$
- $K_S \to \pi^+\pi^- e^+e^-$
- $K_S \to \ell^+\ell^-\ell^+\ell^-$
- $K^+ \to \pi^+\ell^+\ell^-$
- + others

For example:

BR($K_S \to \mu^+\mu^-$) < 2.1 × 10^{-10} (90%CL)

PRL125 (2020) 231801



Invariant mass distribution for normalization mode

Opportunities for US Collaborators & Snowmass Message

- There are already a number of US collaborators in the current suite of experiments, making significant contributions
- All of the proposed upgrades and future experiments represent significant increase in scope relative to existing experiments – need commensurate increase in effort – many opportunities to get involved!
- Participation in kaon experiments at JPARC and/or CERN is currently the **only opportunity** for US physicists to contribute to this vital area of research [...] the US HEP community is exploring possible expansions to our physics program that could be achieved with future upgrades to the Fermilab proton accelerator complex, envisioned to take place in the 2030s. This could include additional (next-next generation) experiments exploring the physics accessible with high-intensity kaon beams. **The best way for the US HEP community to be well-positioned to take advantage of this opportunity would be to explore this physics and develop expertise in modern kaon experiments by participating in the international programs described in [the whitepaper].**

Summary

- $K \rightarrow \pi\nu\nu$ branching ratio measurements have significant potential to discover new physics & discriminate among NP scenarios
- KOTO expects to reach SM SES for $K_L \rightarrow \pi^0 \nu\nu$ by mid 2020s
- KOTO Step-2: goal of ~60 SM events with S/B~1
- NA62 expects to make a 10% measurement of BR($K^+ \rightarrow \pi^+\nu\nu$) by LS3
- Opportunity to continue study of rare kaon decays (charged and neutral) at SPS
  - 5% measurement of BR($K^+ \rightarrow \pi^+ \nu\nu$)
  - 20% measurement of BR($K_L \rightarrow \pi^0 \nu\nu$)
- Large program of K_S branching ratio measurements at LHCb run3
- Opportunity for Snowmass/P5 to have a positive impact on this exciting program by expressing support for expanded US participation