Kaon physics: Recent Results, Status, and Prospects

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12th International Workshop on the CKM Unitarity Triangle, Santiago de Compostela – Spain – 18th of September 2023

Kaon physics: why?

Kaons: protagonists of many discoveries since 1947!

Kaon decay experiments: the quintessential precision frontier experiments

- few decay modes
- simple final states
- large statistics

→ Long history of successes!

- **Hot topics – experiment:**
  - Rare Kaon decays
    [especially the **"golden modes": $K\to\pi\nu\bar{\nu}$, $K_L\to\pi^0\ell^+\ell^-$, $K_{L,S}\to\mu^+\mu^-$**]
  - CKM unitarity tests
  - Low-energy QCD tests
  - BSM searches (e.g. LNV/LFV decays, on-shell BSM particles)
- **Hot topics – theory:**
  - Precise SM predictions
  - Lattice QCD

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  - Lattice QCD

Kaon physics @ CKM 2023

Rare K decays & Low-energy QCD tests

133. Rare kaon and charm decays at LHCb
Paras Naik (University of Liverp...
18/09/2023, 15:10
WG 3

137. Update and outlook of rare K decays at NA62
Michal Koval (Charles University (...
19/09/2023, 15:10
WG 3

138. Search for $K_L \to \pi^0 \nu\nu$ at KOTO
koji shiomi (High Energy Acceler..., koji shiomi (Kyoto university)
19/09/2023, 15:35
WG 3

Precise SM predictions

36. K->mumu in the continuum
Stefan Schacht (University of Manch...
18/09/2023, 14:45
WG 3

37. Perturbative aspects of rare K and B decays
Martin Gorbahn (Liverpool University)
18/09/2023, 15:35
WG 3

112. Improved radiative corrections for Kℓ3 decays and superallowed beta decays
Misha Gorshteyn
21/09/2023, 11:30
WG 1

CKM unitarity tests

108. Global fit, proposal for Kμ3/Kμ2 measurement, CKM first row unitarity
Matthew Moulson (INFN e Laboratori N...
20/09/2023, 09:00
WG 1

109. New measurement of KS → πev at KLOE-2
Antonio Passeri (Universita e INFN R...
20/09/2023, 09:30
WG 1

Lattice QCD

38. K->mumu on the lattice
En-Hung Chao (Columbia University)
18/09/2023, 16:00
WG 3

39. Rare kaons on the lattice
Ryan Hill
19/09/2023, 14:45
WG 3

Recent results

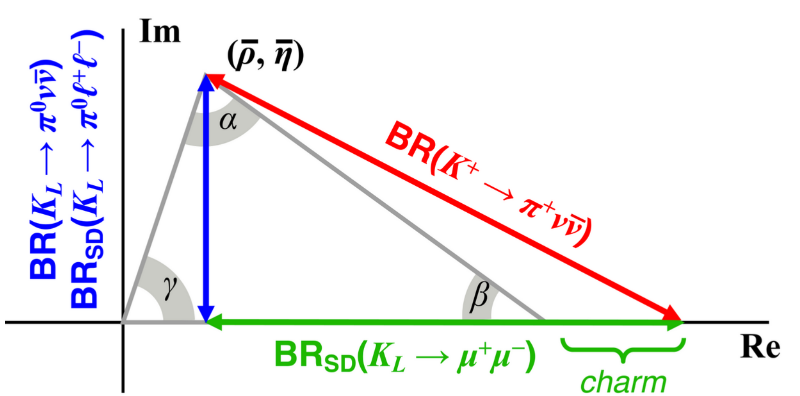
The golden modes

- FCNC forbidden at tree level: 1-loop contributions as leading order
- Highest CKM suppression: $BR \sim |V_{ts}^{*}V_{td}|^{2} \sim \lambda^{10}$

} high sensitivity to new physics

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11} (before KAON19)	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.94 ± 0.15	< 300	KOTO	2019
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4	$17.3^{+11.5}_{-10.5}$	BNL-787/949	2009
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000
$K_S \to \mu^+ \mu^-$	4%	>30%	0.52 ± 0.15	< 80	LHCb	2017

* approximate error on LD-subtracted rate excluding parametric contributions



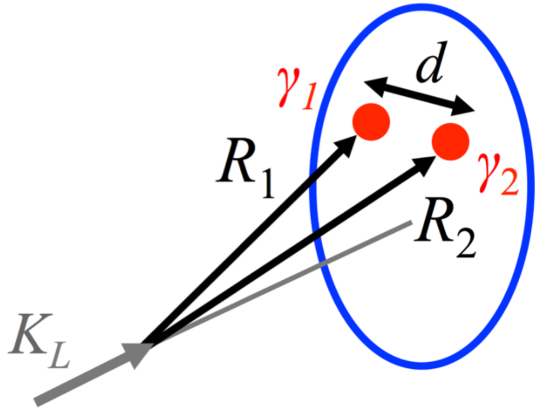
$K_L \to \pi^0 \ell^+\ell^-$ vs $K \to \pi\nu\nu$:

- Larger theoretical uncertainties from LD physics
  - SD CPV amplitude: γ/Z exchange
  - LD indirect CPV amplitude: $K_L \to K_S$
  - LD CPC amplitude from 2γ exchange
- Explore helicity suppression in FCNC decays

$K_L \to \pi^0 \nu\bar{\nu}$ at KOTO: strategy

K. Shiomi, 19th Sept, WG3

$K_L \to \pi^0 \nu\bar{\nu}$ signature: 2γs + missing p_T + nothing else!



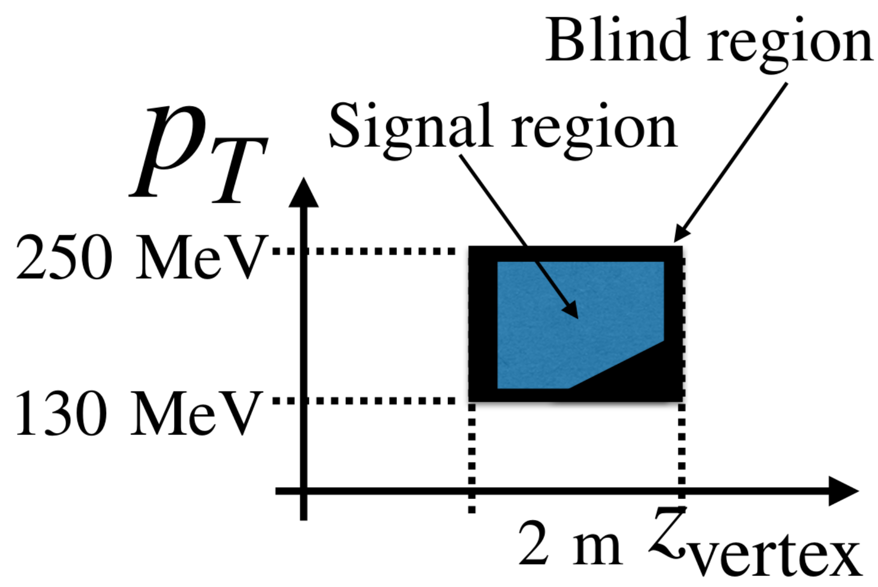
- K_L momentum not known → Kinematics with p_T
- Decay vertex reconstructed assuming M(γγ) = m(π^0)

$$m^2_{\pi^0} = 2E_1E_2\,(1 - \cos\theta)$$

$$R_1 \approx R_2 \equiv R = \frac{d\sqrt{E_1E_2}}{m_{\pi^0}}$$

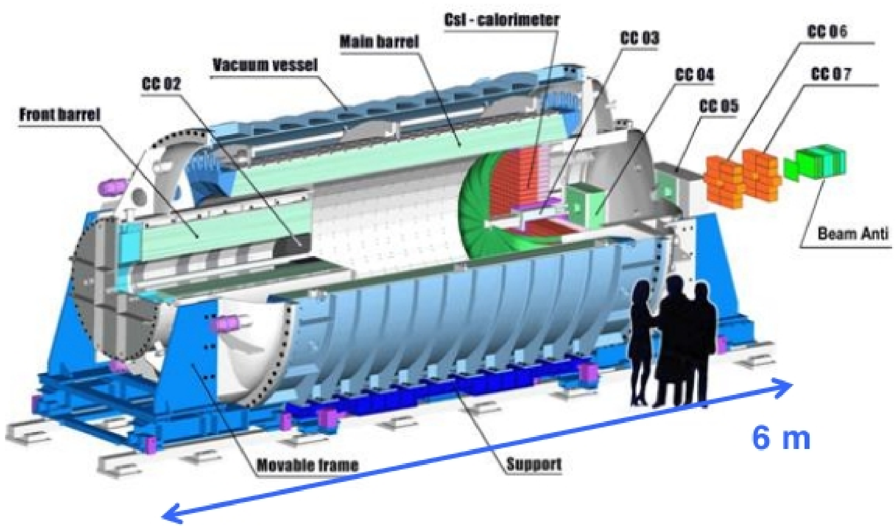
- <u>Particle veto is essential</u>:
  All other K_L decays have ≥ 2 extra γs or ≥ 2 tracks to veto,
  except $K_L \to \gamma\gamma$: 2γs + nothing else (but p_T = 0)

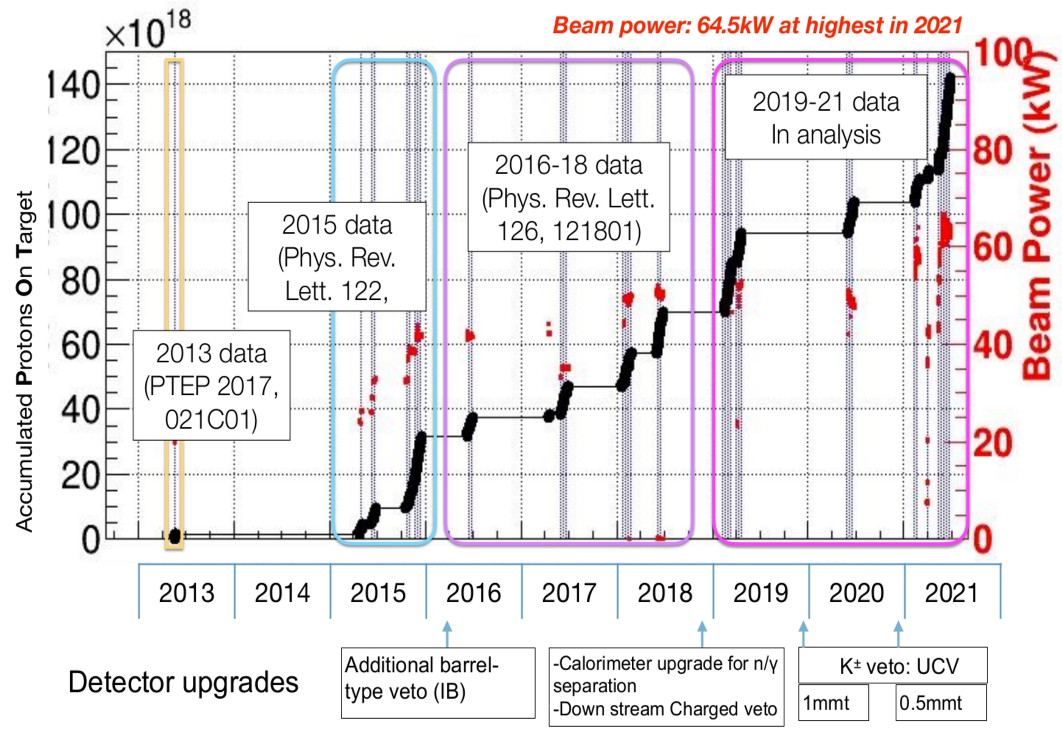
KOTO Keystones:
– Pencil neutral beam (precise p_T)
– Photon rejection
– Charged particle veto



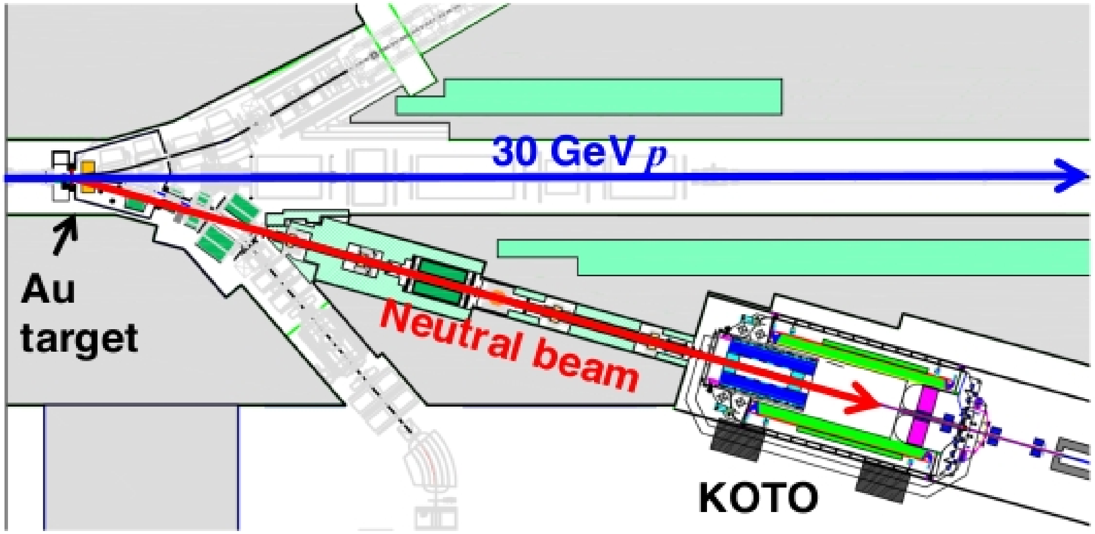
$K_L \to \pi^0 \nu\bar{\nu}$ at KOTO

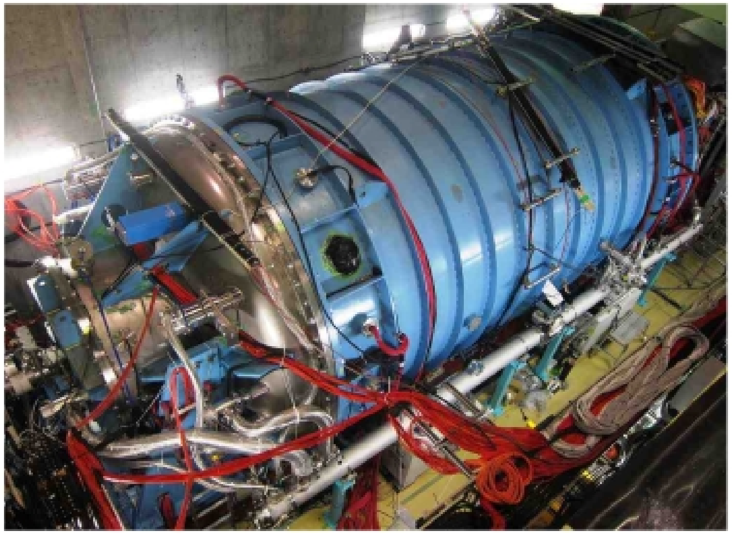
K. Shiomi, 19th Sept, WG3





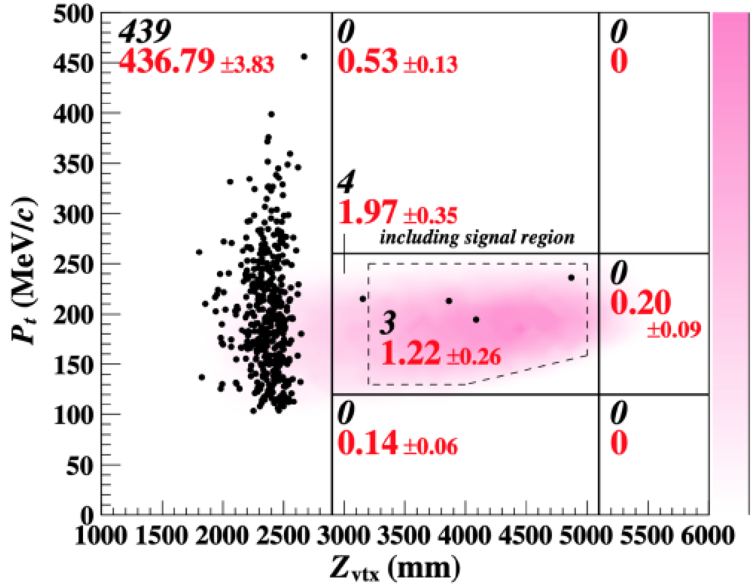
Primary beam:
30 GeV/c protons from J-PARC
Neutral beam (16°), 8 μsr "pencil" beam, $\langle p(K_L)\rangle = 2.1$ GeV





Review of KOTO 2016-2018 result

K. Shiomi, 19th Sept, WG3



PRL 126 (2021) 121801

Expected: 0.04 signal + 1.22 background events
Observed: 3 events in the signal box

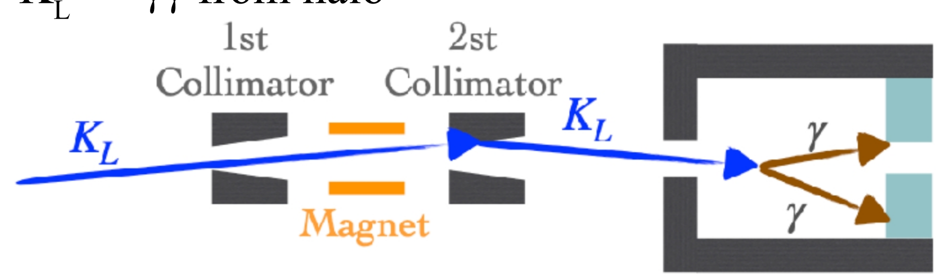
$$\mathbf{BR(K_L \to \pi^0 \nu \bar{\nu}) < 4.9 \times 10^{-9}\ (90\%\ CL)}$$

Expected backgrounds

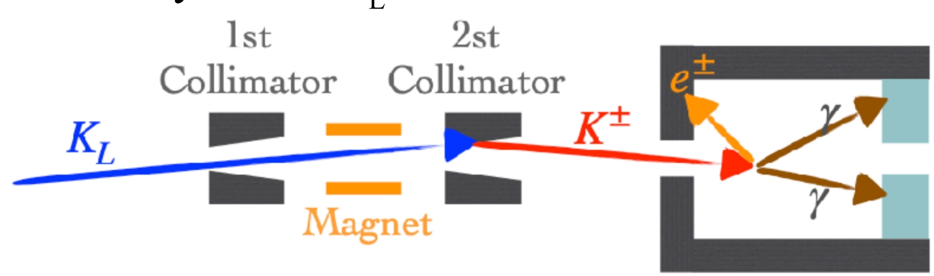
Source	Expected (68%CL)
$K_L \to \pi^0\pi^0\pi^0$	0.01 ± 0.01
$K_L \to \gamma\gamma$ halo	0.26 ± 0.07
Other K_L decays	0.005 ± 0.005
$K^\pm_{e3} + K^\pm_{\mu 3} + K^\pm_{\pi 2}$	0.87 ± 0.25
n interaction in CsI	0.017 ± 0.002
η from n in CV	0.03 ± 0.01
π^0 from upstream int.	0.03 ± 0.03
Total	**1.22 ± 0.26**

<u>Main backgrounds found:</u>

– $K_L \to \gamma\gamma$ from halo



– $K^\pm$ decays from $K_L \to K^\pm$ conversion

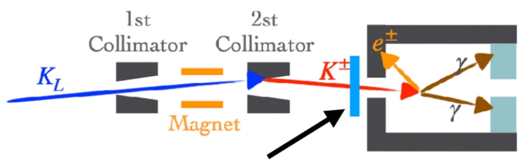


$K_L \to \pi^0 \nu\bar{\nu}$ at KOTO: 2021 result

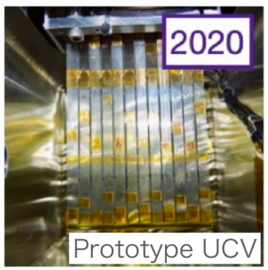
K. Shiomi,
19th Sept, WG3

Suppression of dominant backgrounds

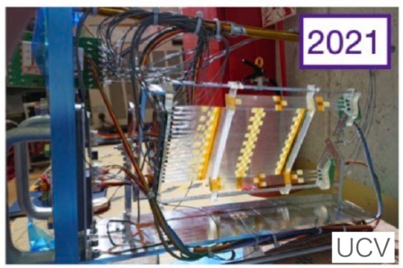
K± BG ($K^{\pm} \to \pi^0 e^{\pm} \nu$)



- Installed Upstream Charged Veto(UCV) for K± detection
- A plane of square scintillation fibers read by MPPC

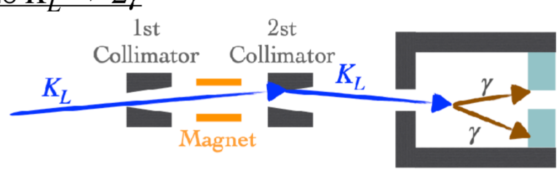


1 mm-square fibers



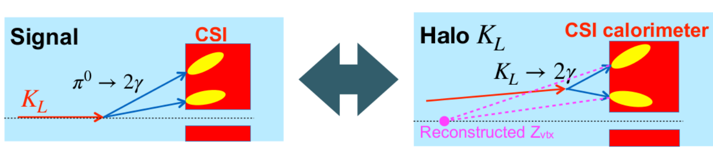
0.5 mm-square fibers
tilted 25 degree

Halo $K_L \to 2\gamma$

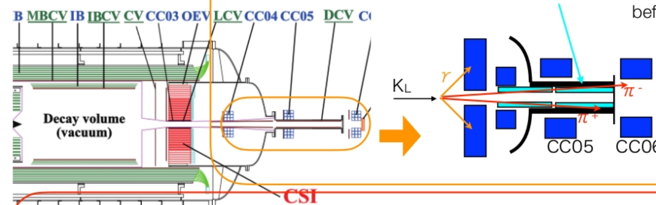


- Developed new cuts based on the difference of kinematical distributions or shower shape

Shower shape Likelihood

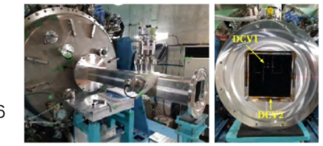


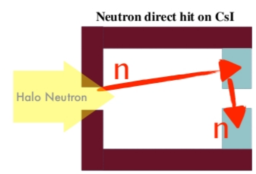
Suppression of other backgrounds



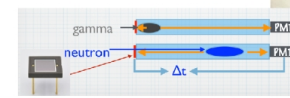
- Downstream charged veto(DCV)

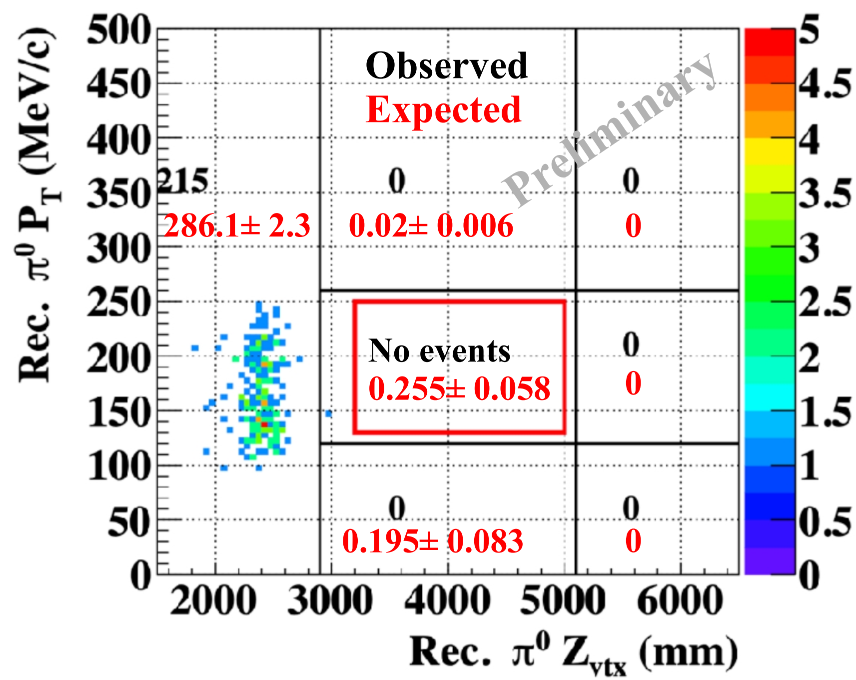
Installed in the vacuum to detect charged particles before hitting the down stream beam pipe





- Calorimeter's both-end readout against Hadron cluster background

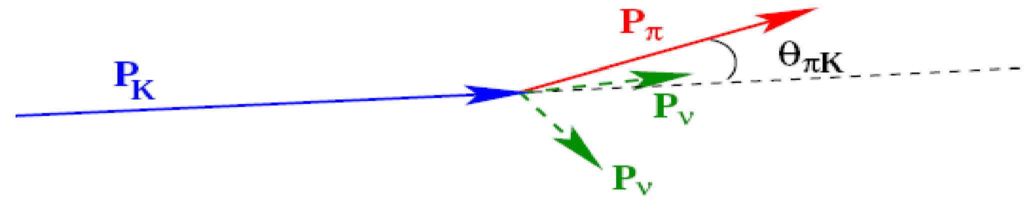




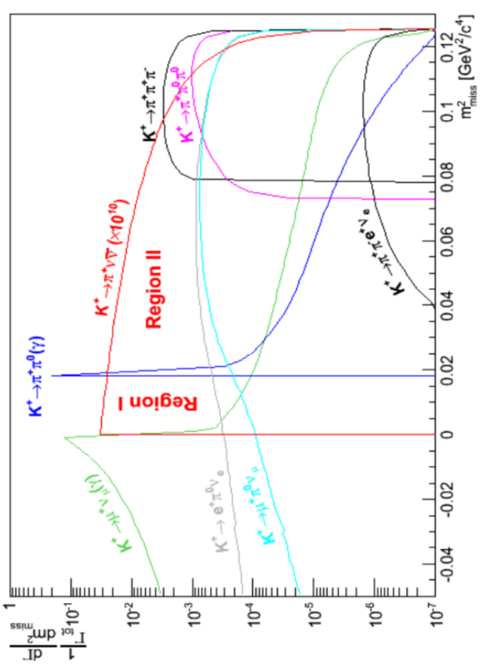
$BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.0 \times 10^{-9}$ (90% CL)

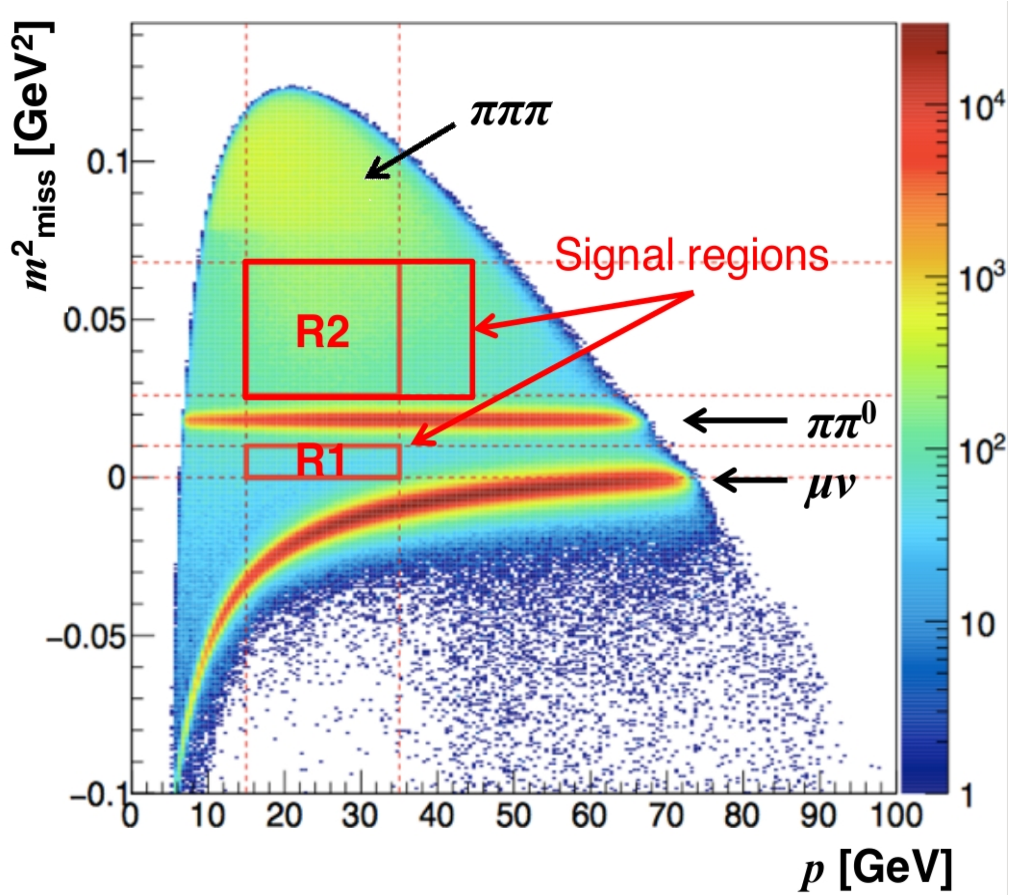
$K^+ \to \pi^+ \nu\bar{\nu}$ at NA62: strategy

$K^+ \to \pi^+ \nu\bar{\nu}$ signature:
Kaon track +
Pion track +
NOTHING ELSE



$$m^2_{miss} \approx m^2_K \left(1 - \frac{|p_\pi|}{|p_K|}\right) + m^2_\pi \left(1 - \frac{|p_K|}{|p_\pi|}\right) - |p_K||p_\pi|\theta^2_{\pi K}$$



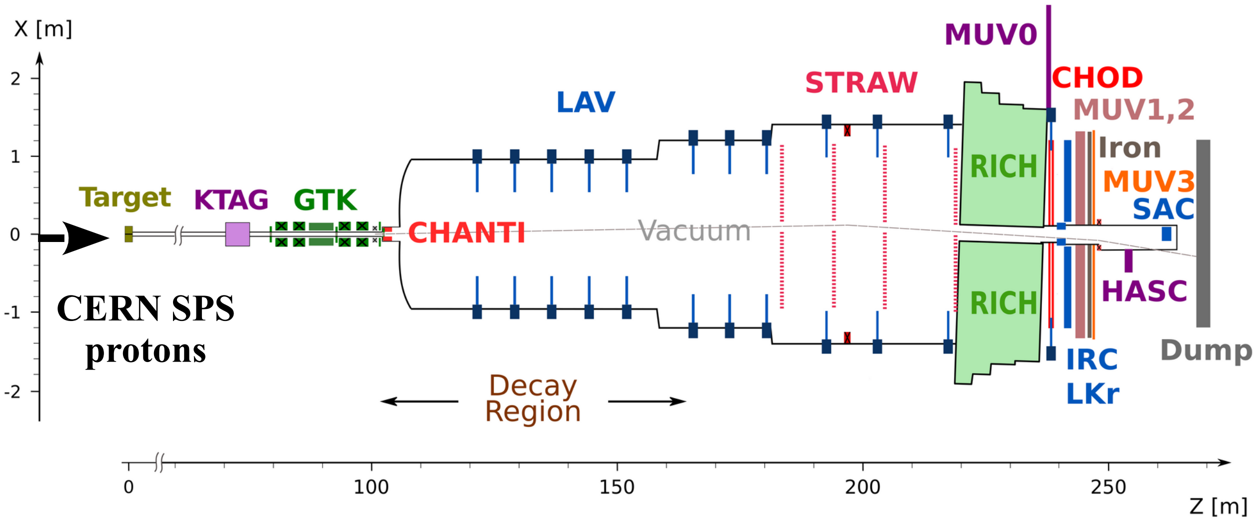


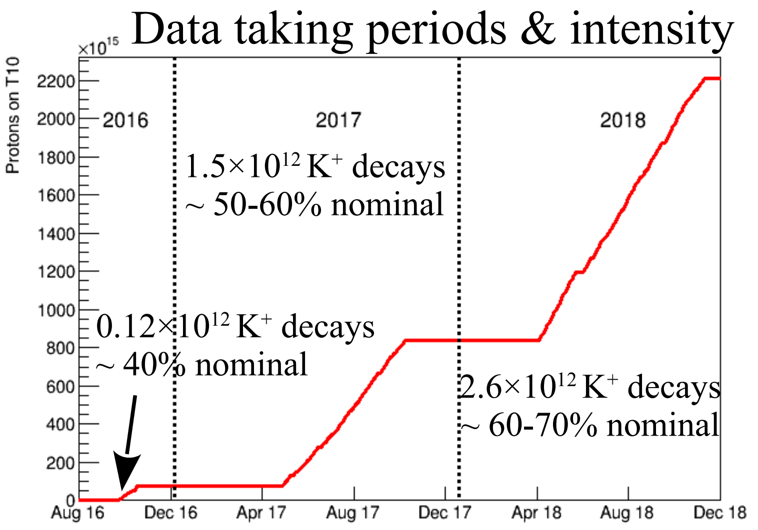
Main backgrounds:
$BR(K^+ \to \mu^+\nu) = 63.5\%$
$BR(K^+ \to \pi^+\pi^0) = 20.7\%$

NA62 keystones:
- Precise tracking
- PID (in particular π/μ)
- Photon rejection
- Precise timing

Background rejection at ~ 10^{11} level

The NA62 experiment



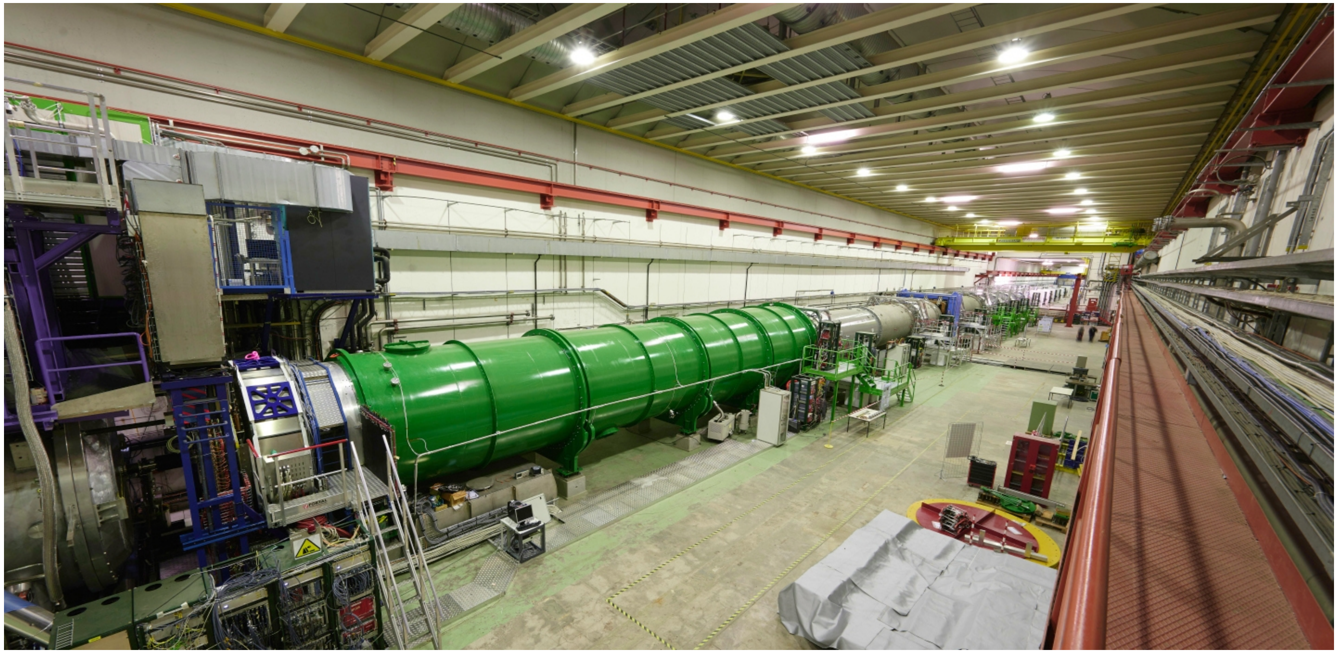


Nominal intensity: ~ 3 × 10^{12} POT/spill → 750 MHz hadron beam

Primary beam:
- 400 GeV CERN SPS protons

Secondary hadron beam:
- K^+ (6%) / π^+ (70%) / p (24%)
- p = 75 GeV, $\Delta p/p \sim 1\%$
- 60 × 30 mm^2 transverse size

Decay region:
- 60 m long fiducial volume
- Vacuum ~ O(10^{-6} mbar)
- ~ 5 MHz K^+ decay rate

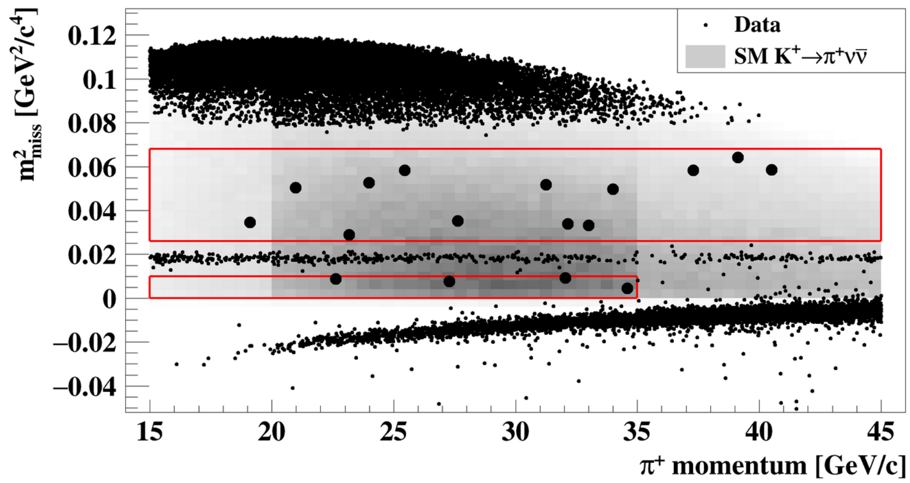


NA62 Run1 (2016-2018) result

2018 data:

JHEP 06 (2021) 093

Background	Subset S1	Subset S2
$\pi^+\pi^0$	0.23 ± 0.02	0.52 ± 0.05
$\mu^+\nu$	0.19 ± 0.06	0.45 ± 0.06
$\pi^+\pi^-e^+\nu$	0.10 ± 0.03	0.41 ± 0.10
$\pi^+\pi^+\pi^-$	0.05 ± 0.02	0.17 ± 0.08
$\pi^+\gamma\gamma$	< 0.01	< 0.01
$\pi^0 l^+\nu$	< 0.001	< 0.001
Upstream	$0.54^{+0.39}_{-0.21}$	$2.76^{+0.90}_{-0.70}$
Total	$1.11^{+0.40}_{-0.22}$	$4.31^{+0.91}_{-0.72}$



Expected: 7.6 signal + 5.4 background events

Observed: 17 $K^+ \to \pi^+\nu\nu$ candidates!

Combined NA62 2016-2018 data

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

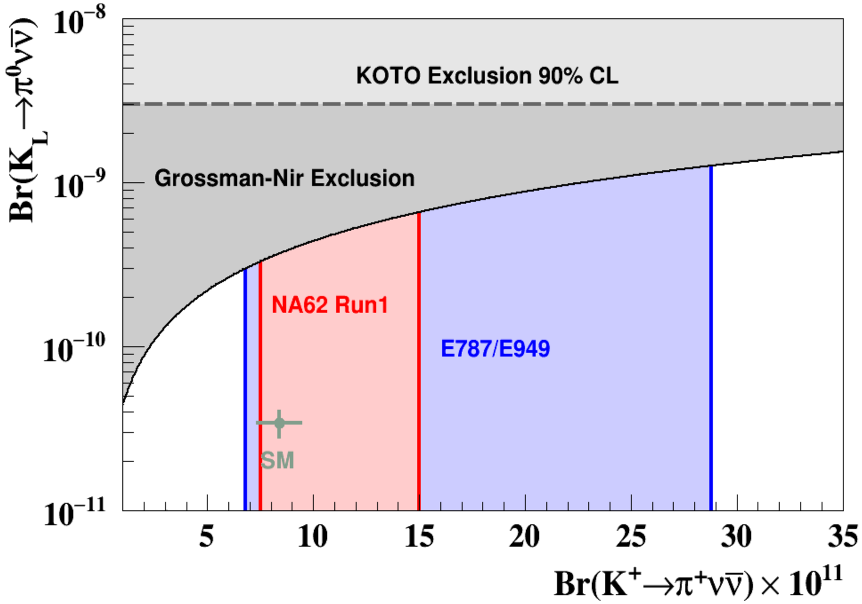
Expected signal: $10.01 \pm 0.42_{syst} \pm 1.19_{ext}$

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

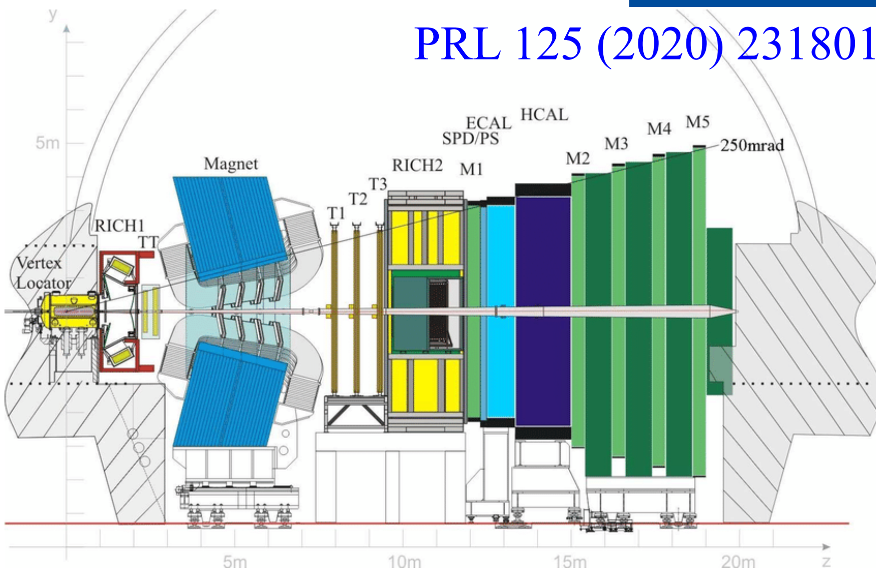
Observed: 20 (1+2+17) events

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

3.4σ significance, most precise measurement to date!



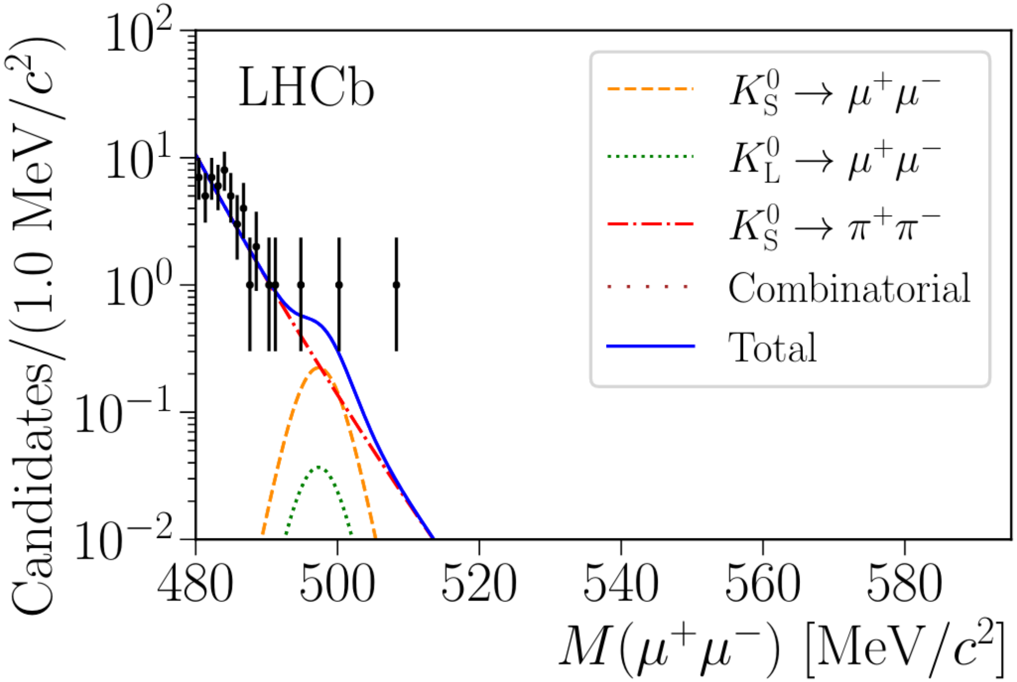
$K_s \to \mu^+\mu^-$ at LHCb

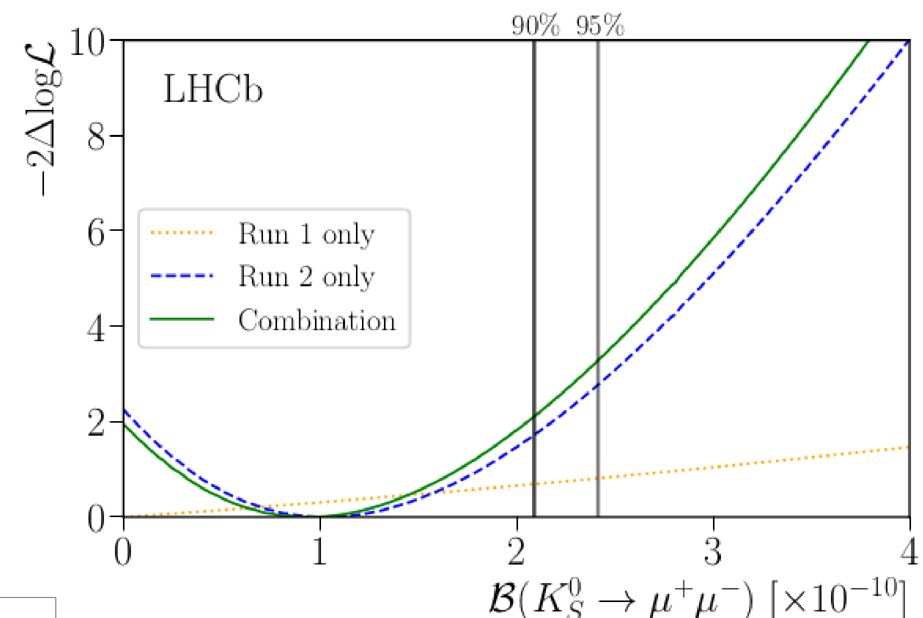


PRL 125 (2020) 231801

Data samples:

- **Run 1:** 3 fb^{-1} (2011-2012 data) at 7-8 TeV
- **Run 2:** 5.6 fb^{-1} (2016-2018 data) at 13 TeV





Run1+Run2 result:

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

The golden modes – today

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.94 ± 0.15	< 200	KOTO	2023
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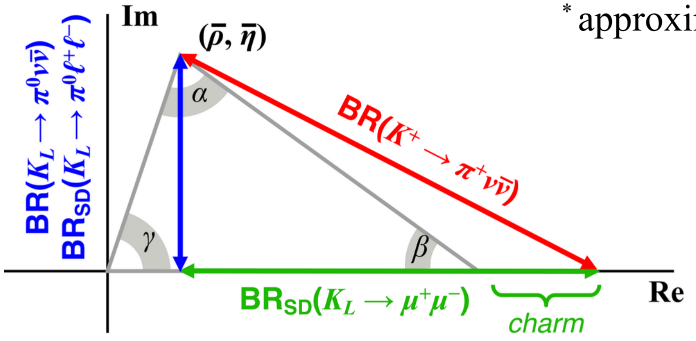
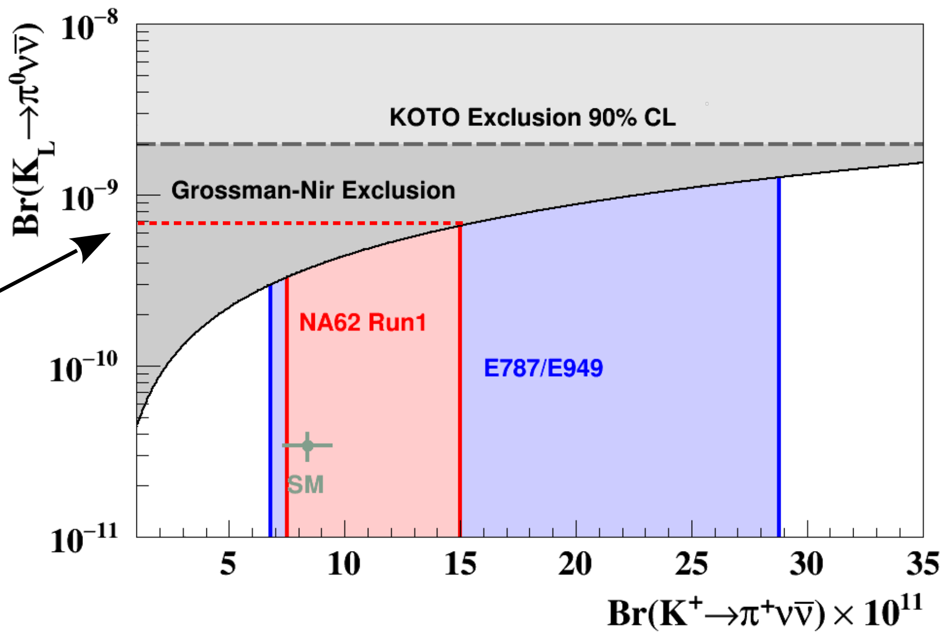
* approximate error on LD-subtracted rate excluding parametric contributions



Indirect boundary
on $K_L \to \pi^0 \nu\bar{\nu}$ by NA62

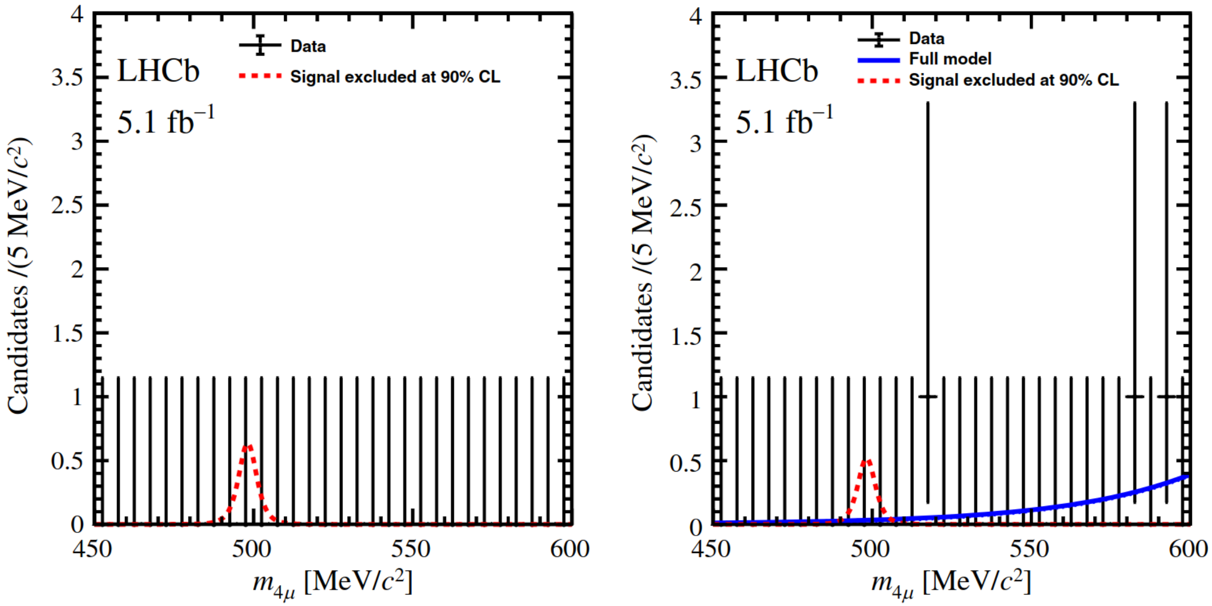


Rare Kaon decays

P. Naik, 18th Sept, WG3
M. Koval, 19th Sept, WG3

$K_{S,L} \to \mu^+\mu^-\mu^+\mu^-$

PRD 108 (2023) L031102



SM prediction [EPJ C73 (2013) 2678]**:**

$BR(K_S \to \mu^+\mu^-\mu^+\mu^-) \sim (1\text{–}4)\times10^{-14}$

$BR(K_L \to \mu^+\mu^-\mu^+\mu^-) \sim (4\text{–}9)\times10^{-13}$

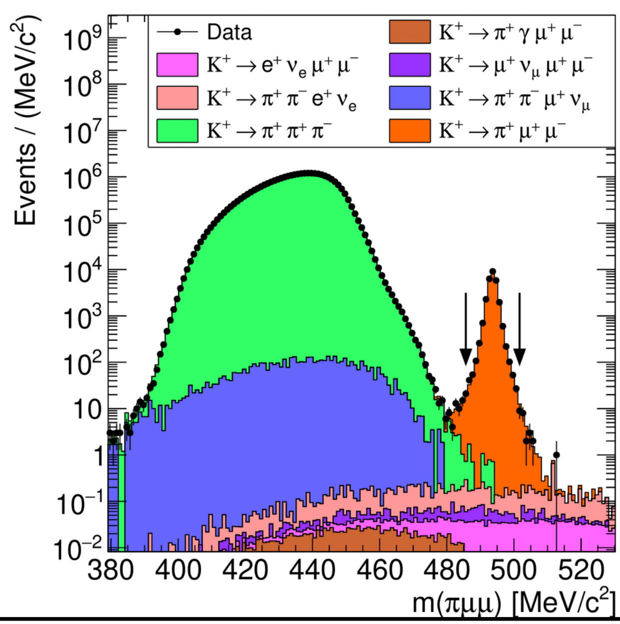
$BR(K_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1\times10^{-12}$

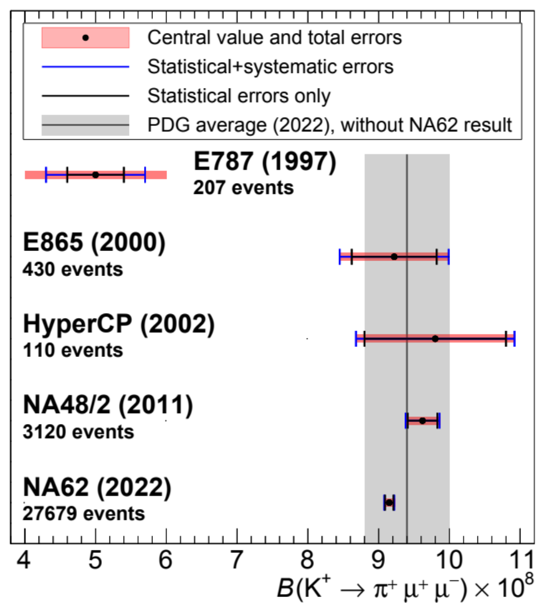
$BR(K_L \to \mu^+\mu^-\mu^+\mu^-) < 2.3\times10^{-9}$

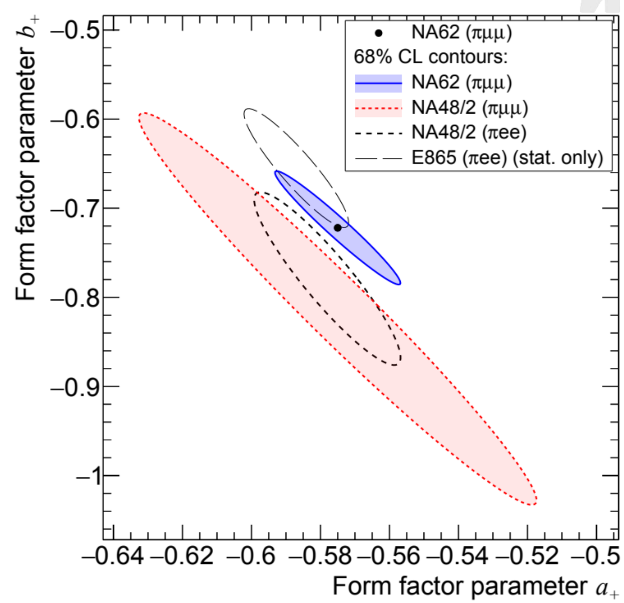
$K^+ \to \pi^+\mu^+\mu^-$

→ Test of Lepton Universality

JHEP11 (2022) 011





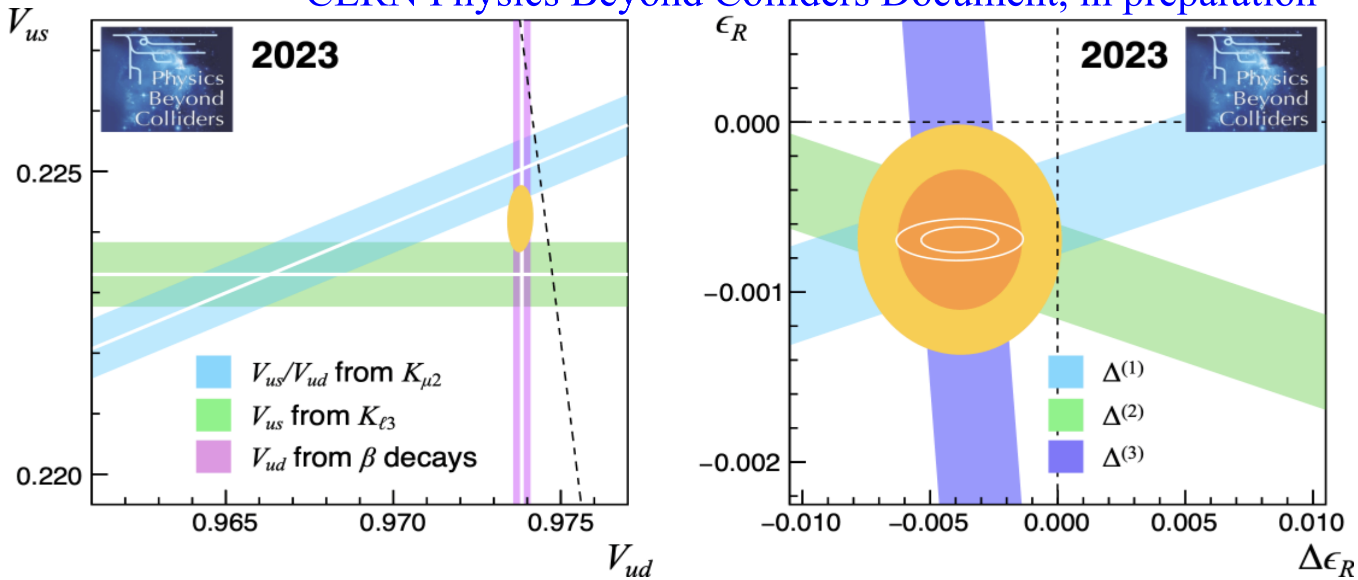


CKM unitarity tests

<u>Cabibbo Angle Anomaly</u>: Disagreement leads to (apparent?) violation of CKM unitarity

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

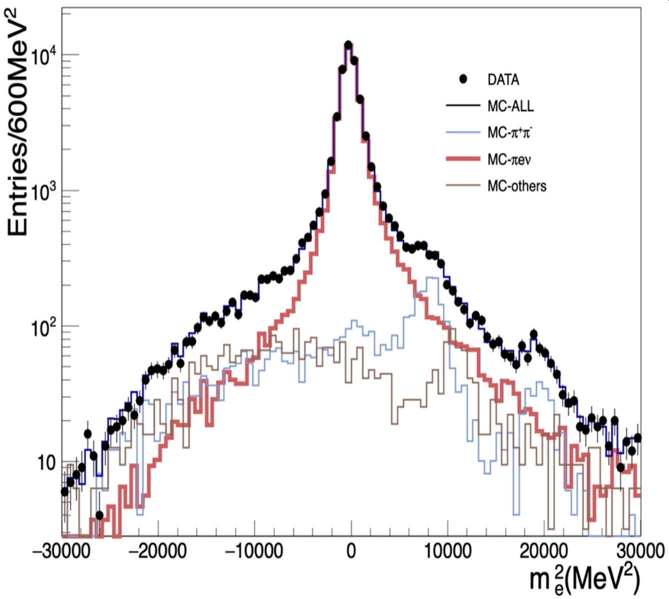
CERN Physics Beyond Colliders Document, in preparation



Motivate new measurements in the **Kaon sector**:
V_{us} from leptonic/semileptonic decays
but also of
$BR(K^+ \to \pi^0 \mu^+ \nu)/BR(K^+ \to \mu^+ \nu)$ [PLB 838 (2023) 137748]

$K_S \to \pi e \nu$

JHEP 02 (2023) 098



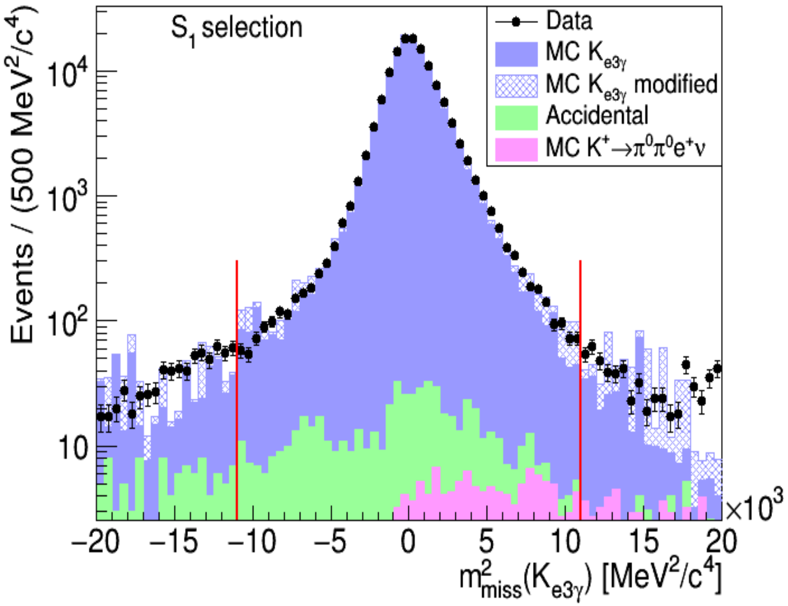
$f_+(0)|V_{us}| = 0.2170 \pm 0.009$

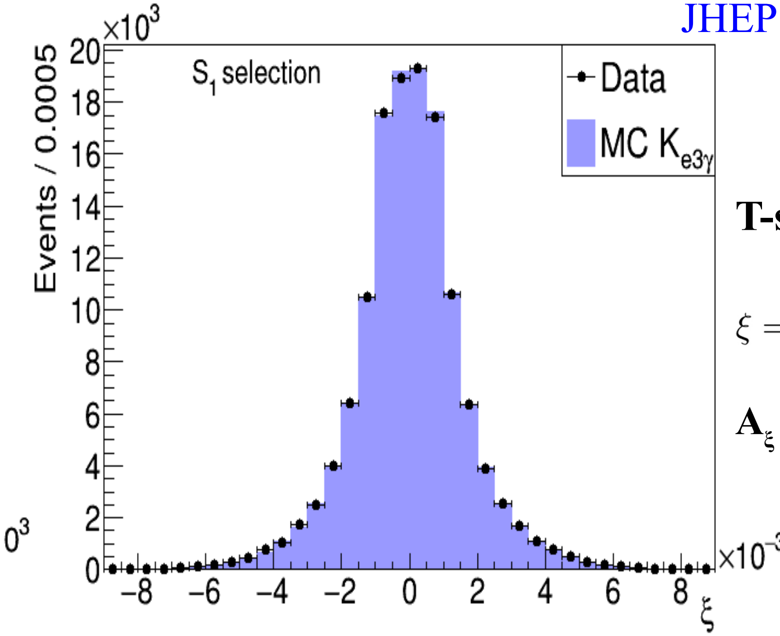
Low-energy QCD tests

M. Koval,
19th Sept, WG3

$K^+ \to \pi^0 e^+ \nu \gamma$

JHEP 09 (2023) 040





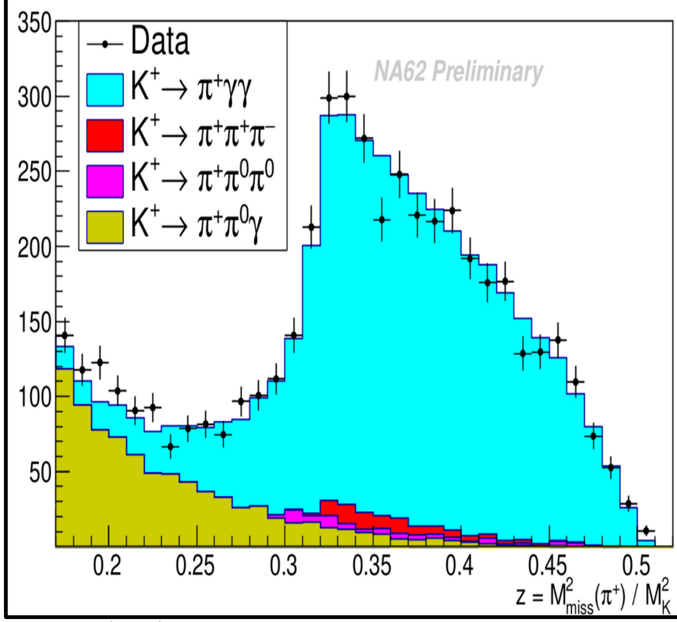
T-symmetry violation test:

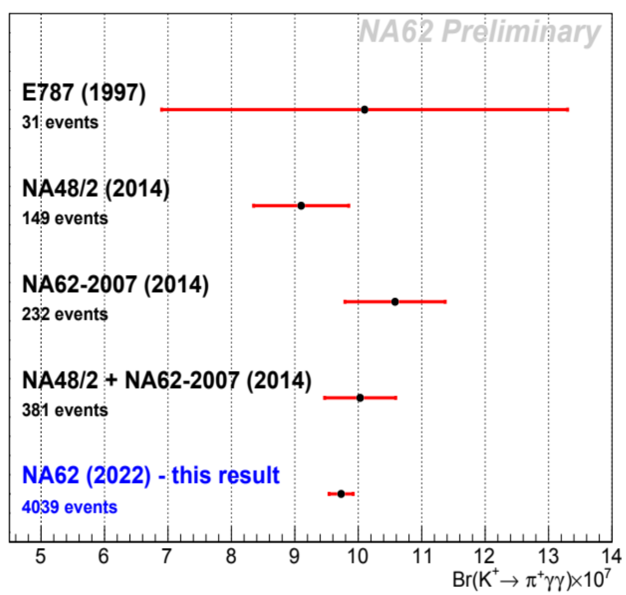
$$\xi = \frac{\vec{p_\gamma} \cdot (\vec{p_e} \times \vec{p_\pi})}{(M_K \cdot c)^3}, \quad A_\xi = \frac{N_+ - N_-}{N_+ + N_-},$$

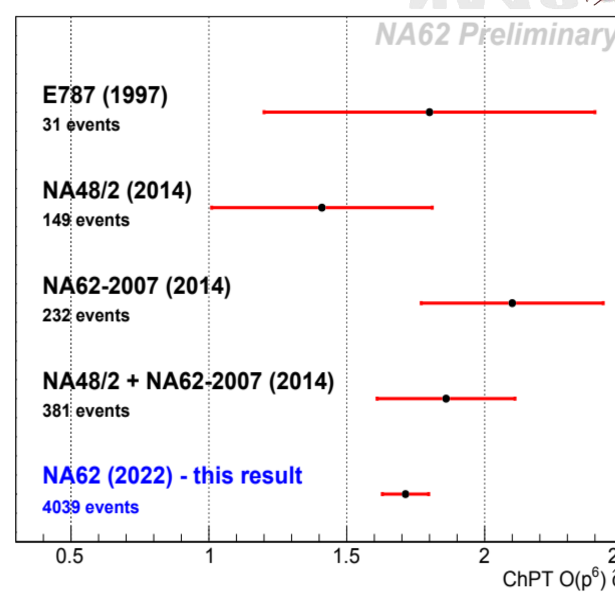
$$A_\xi = (-1.2 \pm 2.8_{stat} \pm 1.9_{syst}) \times 10^{-3}$$

$K^+ \to \pi^+ \gamma\gamma$

Paper in preparation

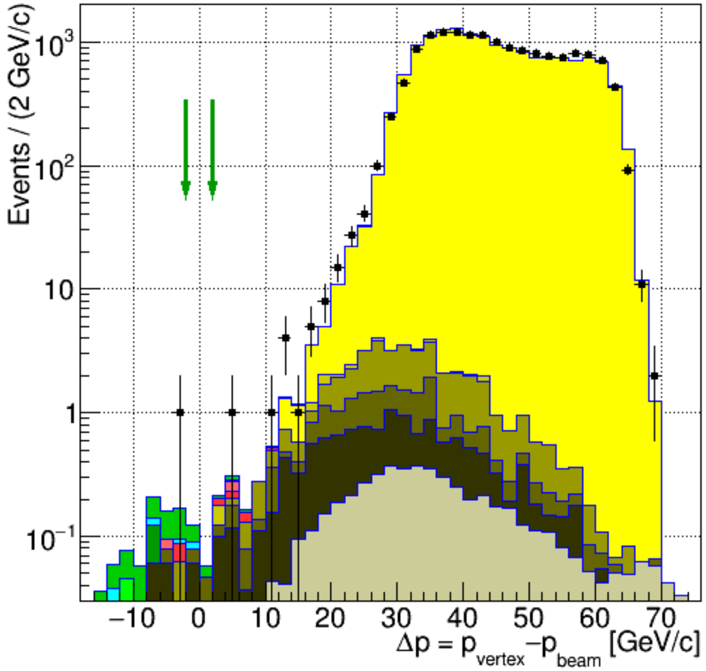


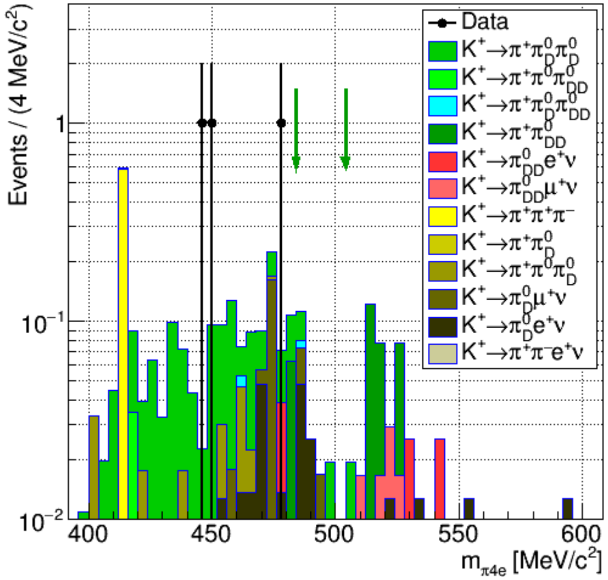




BSM searches in Kaon decays

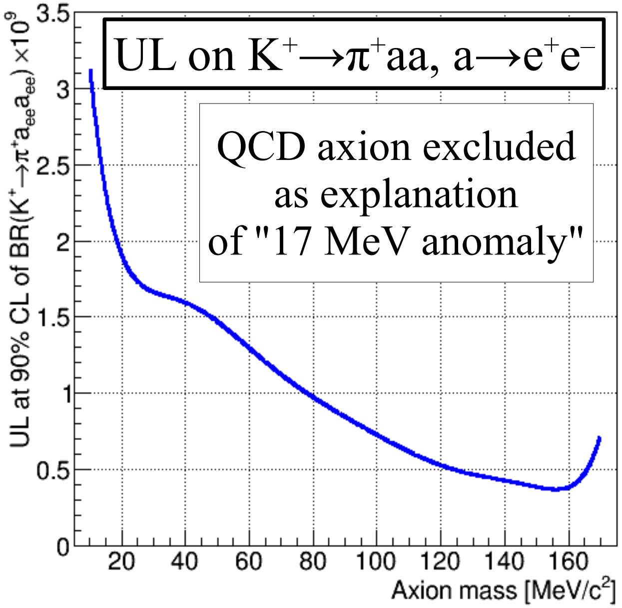
$K^+ \to \pi^+ e^+ e^- e^+ e^-$





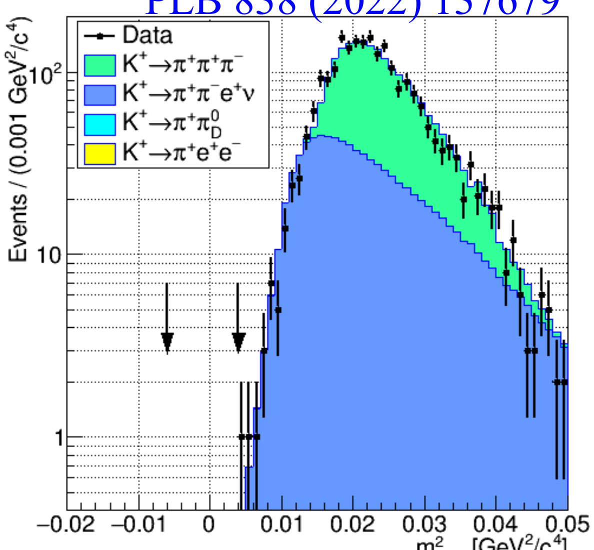
$BR(K^+ \to \pi^+ e^+ e^- e^+ e^-) < 1.4\times10^{-8}$

arXiv:2307.04579

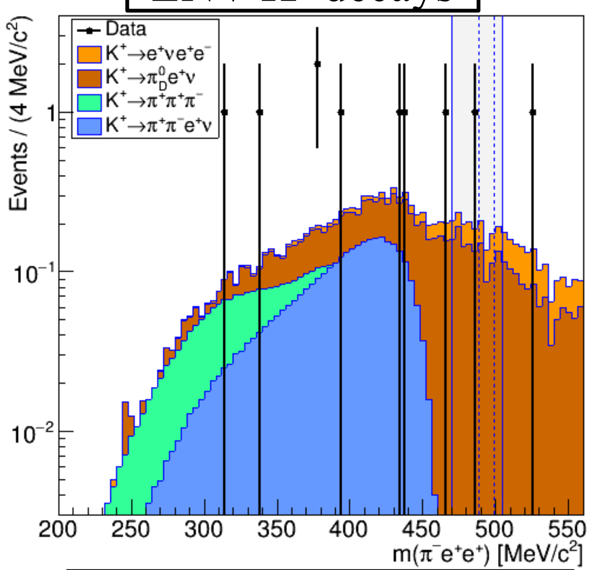


LNV K^+ decays

PLB 838 (2022) 137679

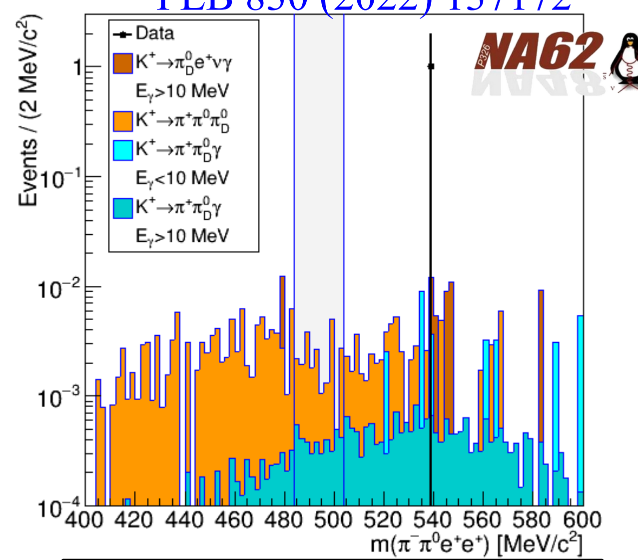


$BR(K^+ \to \mu^- \nu e^+ e^+) < 8.1\times10^{-11}$



$BR(K^+ \to \pi^- e^+ e^+) < 5.3\times10^{-11}$

PLB 830 (2022) 137172



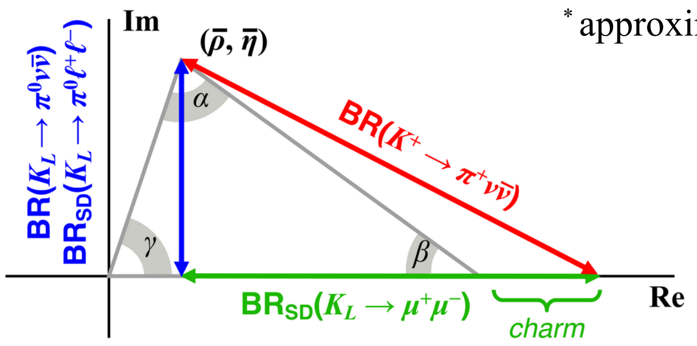
$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5\times10^{-10}$

Prospects

The golden modes – short-term

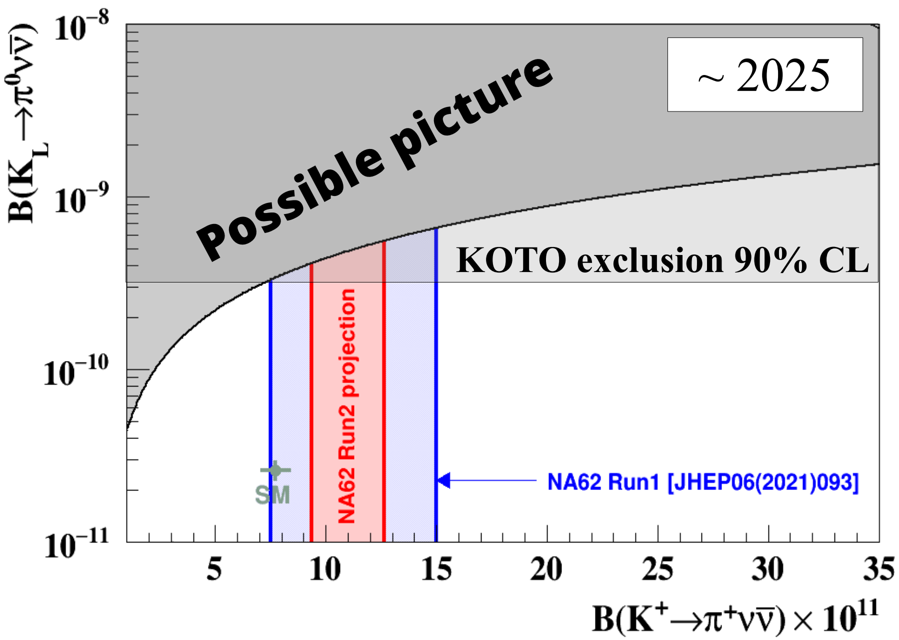
Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.94 ± 0.15	< 30	KOTO	~ 2025
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4	~ 15% precision	NA62	~ 2025
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	< 28	KTeV	2004
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	< 38	KTeV	2000
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11	BNL-871	2000
$K_S \to \mu^+ \mu^-$	4%	>30%	0.52 ± 0.15	< 21	LHCb	2020

* approximate error on LD-subtracted rate excluding parametric contributions



KOTO: Further improvements in $K^{\pm}$ background suppression in 2023
Expect SES ~ 10^{-10} in a few years

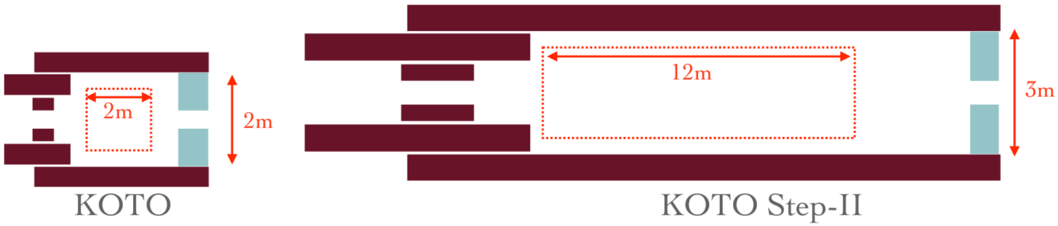
NA62: Run2 (2021-2025) data taking with improved upstream background suppression
Expect BR precision ~ 15% by 2025



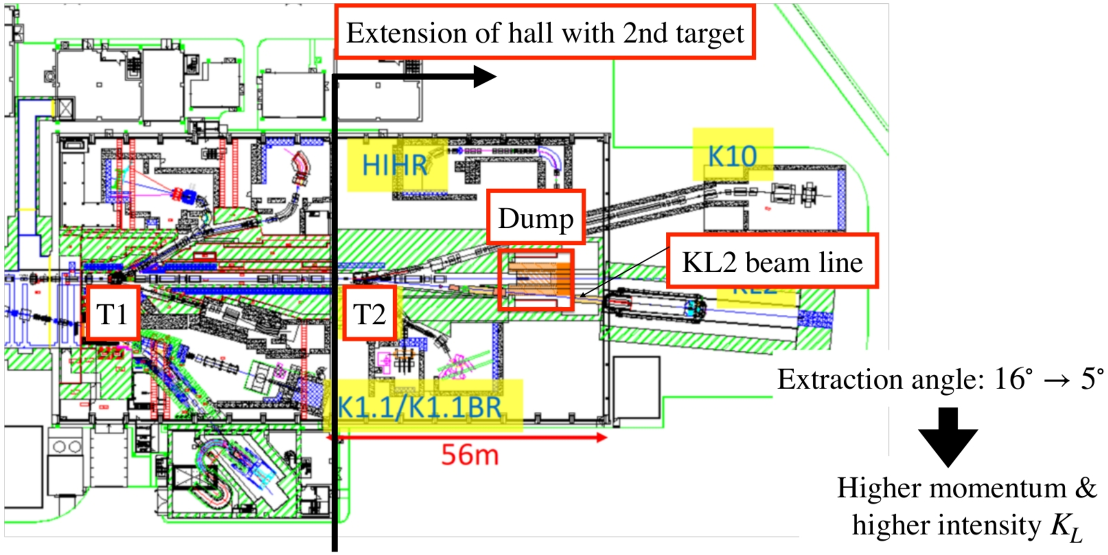
$K_L \to \pi^0 \nu\bar{\nu}$ at JPARC: KOTO-II

- Long-term plan (from 2006) to upgrade to reach O(100) SM event sensitivity
- Now beginning design work for a new KOTO-II experiment

- Increase FV from 2 m to 12 m
  → Complete rebuild of detector



- Increase beam power to > 100 kW
- New neutral beamline at 5° → Larger K_L yield



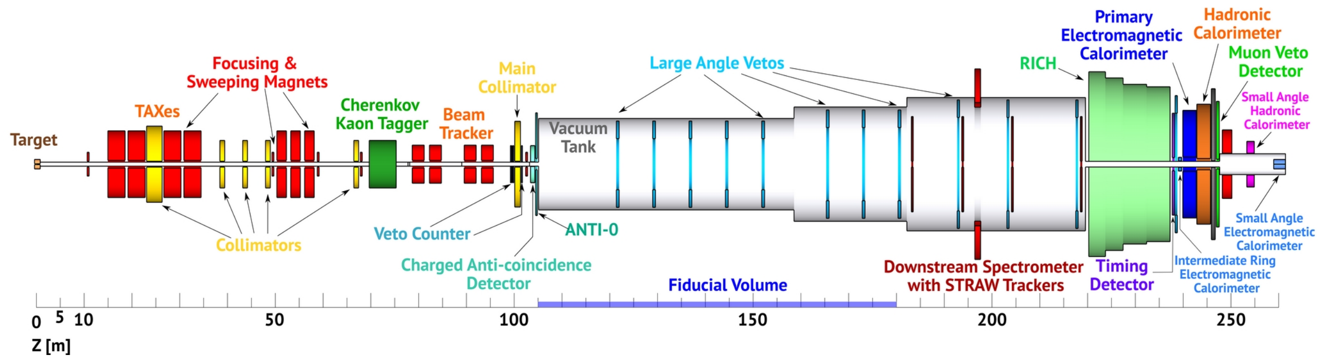
Requires hadron-hall extension
- Joint project with nuclear physics community
- KOTO-II is a flagship project
- Described in KEK Road Map 2021 for research strategy 2022-2027

Hall extension works ~ 6 years

Sensitivity studies for smaller beam angle & larger detector:
~ 35 SM events with S/B ~ 1 at 100 kW beam power (3×10^7 s)

$K^+ \to \pi^+ \nu\bar{\nu}$ at CERN: HIKE-Phase1

NA62-like design of experiment will work at high intensity



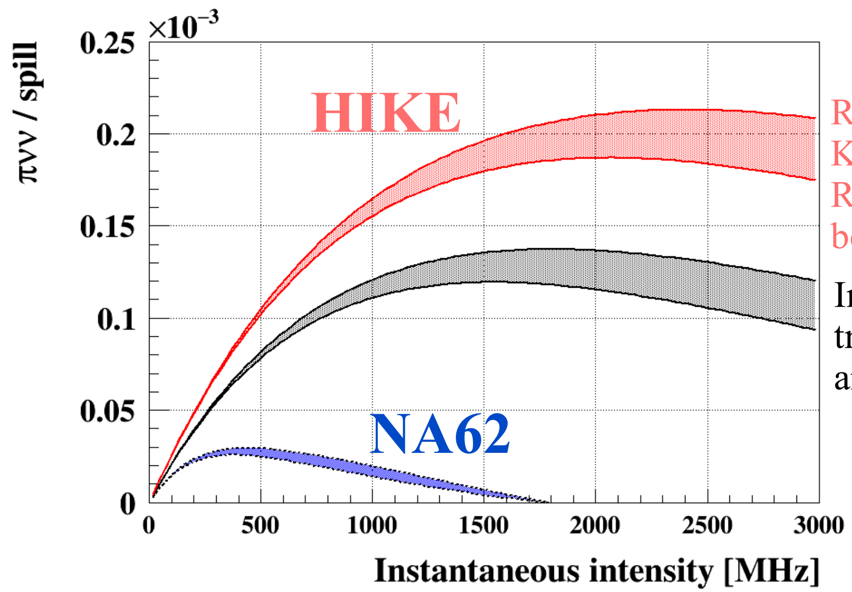
HIKE-Phase1 improvements wrt NA62:

– **Improved timing** to be able to stand the intensity increase (x4)

– **Equal or better key performances** at high-rate to keep background under control [e.g. kinematic rejection, photon rejection, PID]

– Up to x2 **increase in signal acceptance** thanks to new, more granular/performant detectors [higher efficiency in K-π association, PID, kinematic rejection] & fully-software trigger

– Further **suppress dominant background** from upstream K^+ decays



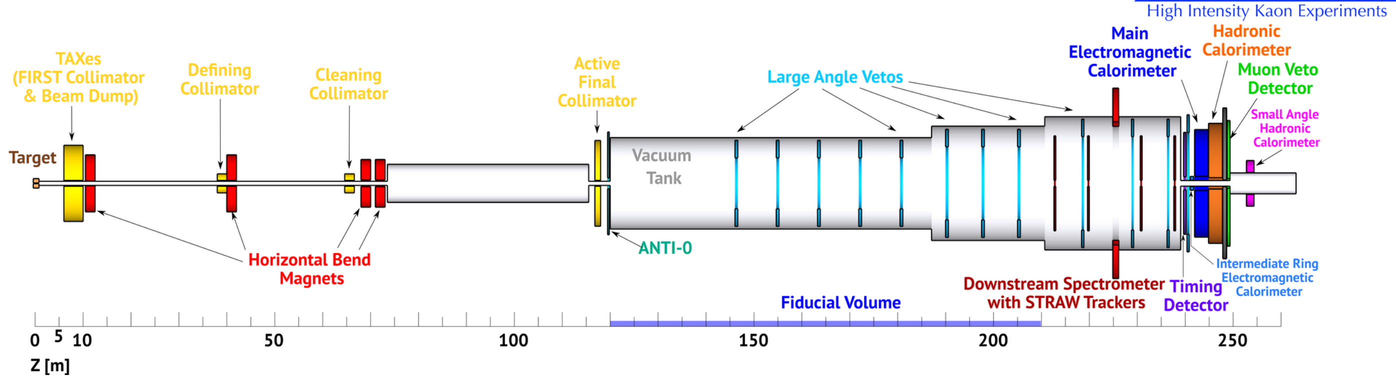
Recovery of LTU dead-time, K-π association, improved RICH, better kinematic resolution

Improved timing, software trigger and new DAQ

Overall, HIKE-Phase1 statistics ~ 8x wrt NA62
→ **O(5%) precision expected**

$K_L \to \pi^0 \ell^+ \ell^-$ at CERN: HIKE-Phase2

Minimal changes to Phase1 setup would allow a beautiful K_L programme at CERN



A multi-purpose K_L decay experiment focussed on $K_L \to \pi^0 \ell^+ \ell^-$ decays

- 120 m long neutral beamline:
  - Secondary beam opening angle = 0.4 mrad; 2.4 mrad production angle
  - Mean momentum of decaying K_L mesons = 46 GeV/c
- Reconfigured HIKE-Phase1 detector:
  - Kaon tagger, beam spectrometer, RICH, small-angle calorimeter removed
  - STRAW spectrometer shortened, chambers realigned

Number of spills	3×10^6			
Protons on target	6×10^{19}			
K_L decays in FV	1.9×10^{14}			
Mode	N_S	N_B	$N_S/\sqrt{N_S + N_B}$	$\delta\mathcal{B}/\mathcal{B}$
$K_L \to \pi^0 e^+ e^-$	70	83	5.7	18%
$K_L \to \pi^0 \mu^+ \mu^-$	100	53	8.1	12%

First observation @ > 5σ and measurement of both ultra-rare decay modes

$K_s \to \mu^+\mu^-$ at LHCb: prospects

LHCb Upgrade II TDR

7.6.1 Rare kaon decays

In the SM, the $K^0_S \to \mu^+\mu^-$ decay is long-distance dominated, with subdominant short-distance contributions. However, the long-distance contribution is still very small in absolute terms, and the decay rate is very suppressed. For example, the SM prediction [384–386] $\mathcal{B}(K^0_S \to \mu^+\mu^-)_{\rm SM} = (5.18 \pm 1.50_{\rm LD} \pm 0.02_{\rm SD}) \times 10^{-12}$ can be compared with the current experimental upper limit [387] $\mathcal{B}(K^0_S \to \mu^+\mu^-)_{\rm Exp} < 8 \times 10^{-10}$ at 90% CL. Therefore, even small BSM contributions and BSM–SM interferences can compete with the SM rate. This has been proven to be the case in leptoquark models [388, 389] as well as supersymmetric models [390]. In the latter, $\mathcal{B}(K^0_S \to \mu^+\mu^-)$ can have values anywhere in the range $[0.78 - 35] \times 10^{-12}$ (see Fig. 7.9, left) or even saturate the current experimental bound in certain narrow regions of the parameter space [390]. The *CP* asymmetry of the $K^0 \to \mu^+\mu^-$ decay is also sensitive to BSM contributions and experimentally accessible by means of a tagged analysis.

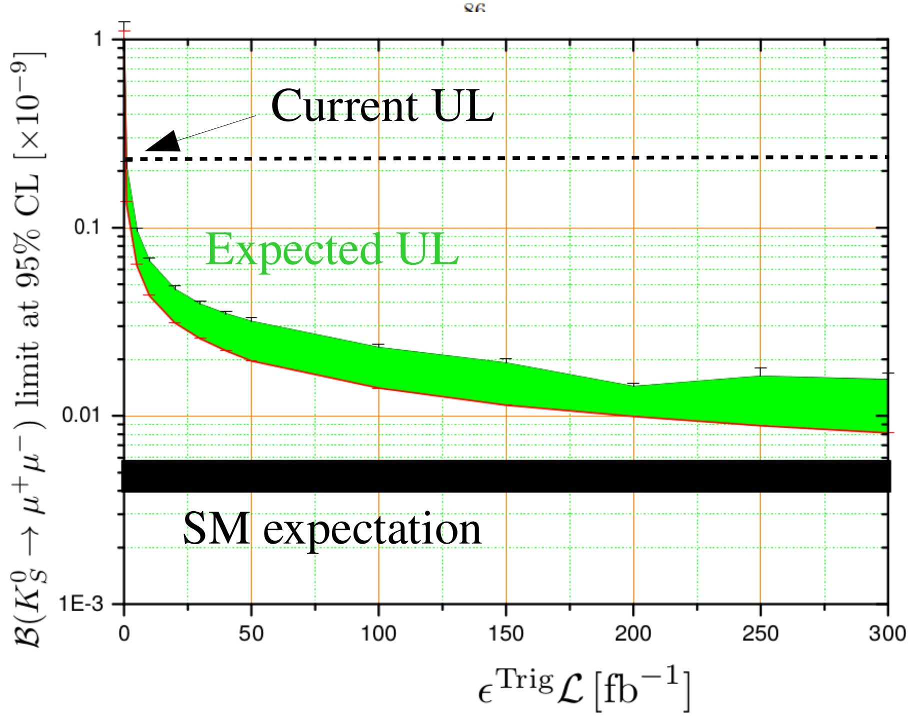
The LHCb prospects for the search for $K^0_S \to \mu^+\mu^-$ decays are excellent. With 2011 data the experiment overtook the previous world best upper limit by a factor of thirty [391], and has recently gained another order of magnitude [387]. The right hand side of Fig. 7.9 shows the expected upper limit for $\mathcal{B}(K^0_S \to \mu^+\mu^-)$ as a function of the integrated luminosity multiplied by the trigger efficiency. It can be seen that if the trigger efficiency is high, as expected from a full software trigger, LHCb can explore branching fractions down to near the SM prediction.

Currently, the only existing measurement of $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ comes from the NA48 experiment [392]

$$\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}.$$

In the Upgrade II LHCb can achieve a statistical precision of 0.11×10^{-9} with 300 fb^{-1} of integrated luminosity, assuming a trigger efficiency of 100% [393]. Assuming a trigger efficiency of 50% LHCb will still be able to significantly improve on the NA48 measurement. Apart from the branching fraction, the differential decay rate in the dimuon mass contains interesting information about the form factor parameters a_S and b_S [394]. The LHCb Upgrade II can reach a 10% statistical precision on the form factor term $|a_S|$ with free b_S [395].

Other kaon decays that can be studied at LHCb include $K^+ \to \pi\mu\mu$ (both with opposite-sign and same-sign muon pairs), $K^0_S \to 4\mu$, or decays involving electrons in order to test Lepton Universality [395]. The LHCb acceptance is such that it favours the sensitivity to K^0_S modes over K^0_L modes by about a factor 1000 due to the longer K^0_L lifetime.[3]



10^{13} K_s/fb^{-1} produced in LHCb acceptance
→ **~1 strange hadron/event!**

Vast K program for Run 3

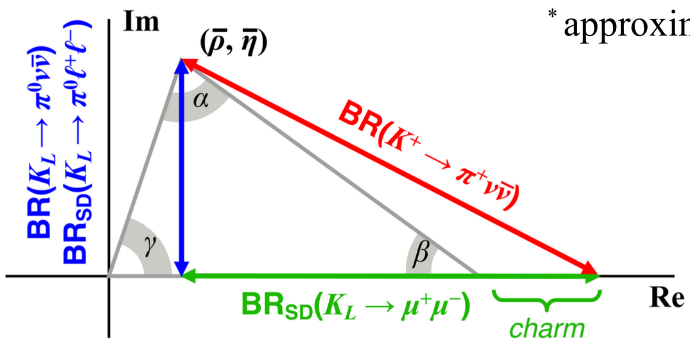
Expected improvements on:

- $K_S \to \mu^+\mu^-$
- $K_S \to \pi^0\mu^+\mu^-$
- $K_S \to \mu^+\mu^-\mu^+\mu^-$
- …

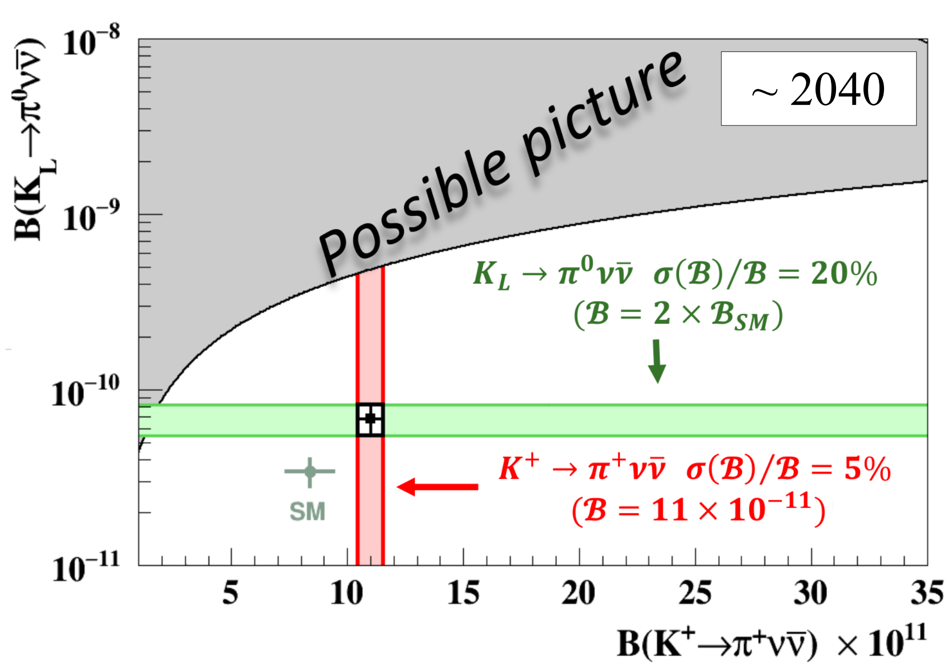
The golden modes – long-term

Decay	Γ_{SD}/Γ	Theory error*	SM BR × 10^{11}	Experimental BR × 10^{11}	Experiment	Year
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.94 ± 0.15	20% precision	KOTO-II	~ 2040
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4	5% precision	HIKE - phase1	~ 2035
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	20% precision	HIKE - phase2	~ 2040
$K_L \to \pi^0 \mu^+ \mu^-$	30%	15%	1.5 ± 0.3	20% precision	HIKE - phase2	~ 2040
$K_L \to \mu^+ \mu^-$	10%	30%	79 ± 12 (SD)	1% precision	HIKE - phase2	~ 2040
$K_S \to \mu^+ \mu^-$	4%	>30%	0.52 ± 0.15	SM sensitivity	LHCb	~ 2040

* approximate error on LD-subtracted rate excluding parametric contributions



Ambitious programme
at J-PARC & at CERN



Conclusions

Rich physics programme with Kaons

→ Recent results:

- Rare Kaon decays:
  - Golden modes: $K_L \to \pi^0 \nu\bar{\nu}$ (KOTO), $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62) and $K_s \to \mu^+\mu^-$ (LHCb)
  - $K^+ \to \pi^+\mu^+\mu^-$ (NA62) and $K_{L,s} \to \mu^+\mu^-\mu^+\mu^-$ (LHCb)
- CKM unitarity tests:
  - Cabibbo angle anomaly: motivate new measurements of V_{us} with kaons
  - New measurement of V_{us} from $K_S \to \pi e \nu$ (KLOE)
- Low-energy QCD:
  - $K^+ \to \pi^0 e^+ \nu\gamma$ (NA62), $K^+ \to \pi^+\gamma\gamma$ (NA62)
- BSM searches:
  - $K^+ \to \pi^+ e^+ e^- e^+ e^-$ analysis & $K^+ \to \pi^+ aa$ ($a \to e^+e^-$) interpretation (NA62)
  - Many LFV/LNV modes (NA62)

Prospects:

[Short-term] **Clear strategy defined for experimentally improving on golden modes:**

- Reduce current main sources of background
- Run at higher beam intensity

[Long-term] **Next-generation of Kaon experiments currently being designed**

- J-PARC: Plans for KOTO-II to measure BR($K_L \to \pi^0 \nu\bar{\nu}$) at 20% precision
- CERN: Proposal for HIKE to measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) at 5% precision and to measure BR($K_L \to \pi^0 \ell^+ \ell^-$) at 20% precision

→ Bright future for experimental kaon physics!