Rare strange particle decays

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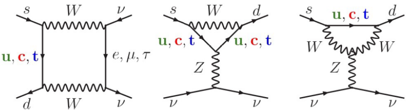
Outline

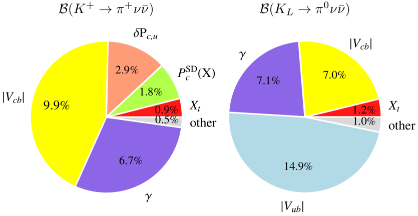
- **Theoretical motivation for $\mathrm{K} \to \pi\nu\bar{\nu}$ decays**
- $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$**: Experiment NA62 @CERN**
  - Experiment description
  - Results of 2016 data
  - Analysis of 2017 sample
  - Prospects for 2018 sample and future
- $\mathrm{K_L} \to \pi^0\nu\bar{\nu}$**: Experiment KOTO @J-PARC**
  - Experiment description
  - Results of 2013 data
  - Results of 2015 data
  - Current status and future
- **Other Kaon decays at NA62 experiment**

Theoretical motivation - Standard Model

- **FCNC loop process**
  - **s $\to$ d coupling** and highest CKM suppression (BR$\sim |V_{ts} \times V_{td}|^2$)



- **Very clean theoretically**
  - Short distance contribution and no hadronic uncertainties
  - Hadronic matrix element extracted from well-known decay $K^+ \to \pi^0 e^+ \nu$
  - Theoretical error budget dominated by CKM parameters



- **SM predictions**
  [Buras et al., JHEP 1511 (2015) 033]

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0) \cdot 10^{-11}$$

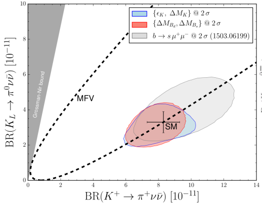
$$BR(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{0.00388}\right)^{2} \left(\frac{|V_{cb}|}{0.0407}\right)^{2} \left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6) \cdot 10^{-11}$$

Theoretical motivation - Beyond the Standard Model

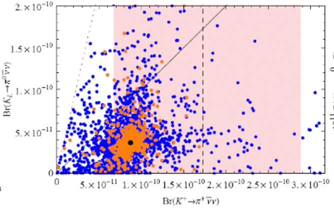
- Simplified Z, Z' models [Buras, Buttazzo,Knegjens, JHEP 1511 (2015) 166]
- Littlest Higgs with T-parity [Blanke, Buras, Recksiegel, EPJ C76 (2016) no.4 182]
- Custodial Randall-Sundrum [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- MSSM non-MFV [Blazek, Matak Int.J.Mod.Phys.A29 (2014) 1450162; Tanimoto, Yamamoto PTEP (2015) 053B07; Isidori et al. JHEP 0608 (2006) 064]
- LFU violation models [Isidori et. al., Eur. Phys. J. C (2017) 77]

- Constraints from existing measurements (correlations model dependent): Kaon mixing and CPV, CKM fit, K,B rare meson decays, NP limits from direct searches
- $\mathrm{K} \to \pi\nu\bar{\nu}$ **can discriminate among different new physics scenarios**

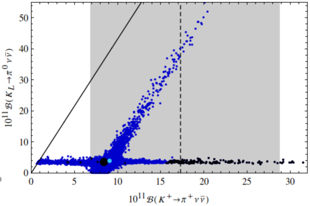
Z'(5 TeV) in ConstrainedMFV



Randall – Sundrum

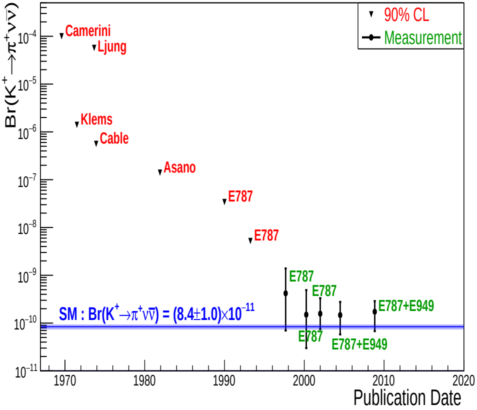


LittlestHiggs

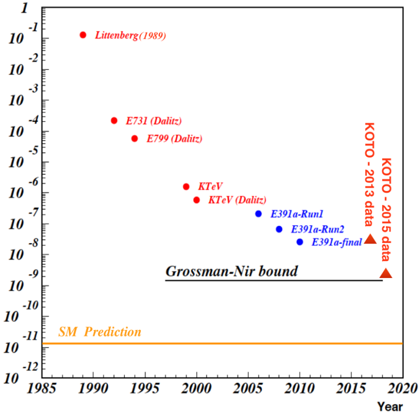


$K \to \pi\nu\bar{\nu}$: *Experimental status*

$K^+ \to \pi^+\nu\bar{\nu}$



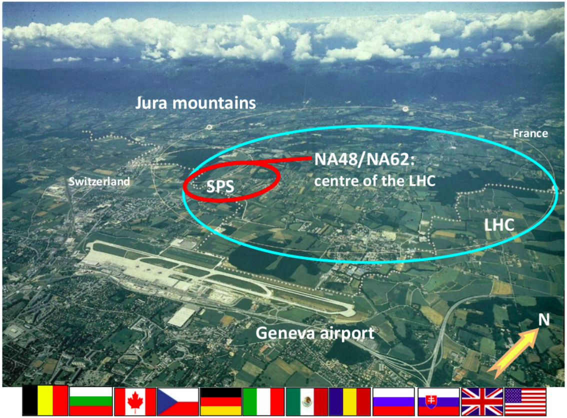
$K_L \to \pi^0\nu\bar{\nu}$



$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$ [PRD 77, 052003 (2008), PRD D 79, 092004 (2009)]

$$BR(K^0_L \to \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$$ [PRD 81, 072004 (2010)]

Kaons at CERN



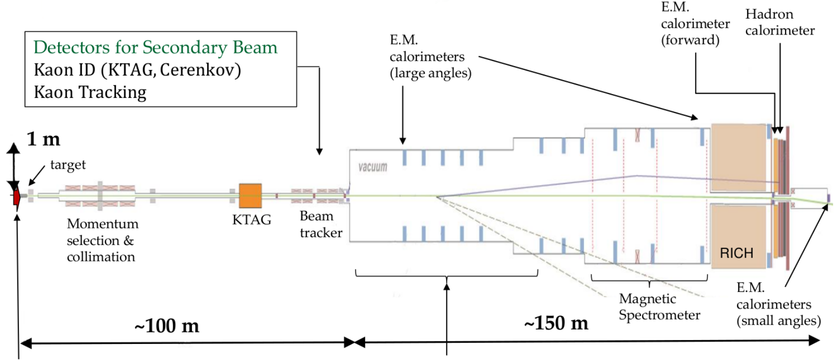
Kaon decay in flight experiments.
NA62: ~**200** participants, ~ **30** institutes

Earlier: NA31

NA48 (discovery of direct CPV)	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
	2003: K^+/K^-	
NA48/2	2004: K^+/K^-	
NA62 R_K phase	2007: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests
	2008: $K^{\pm}_{e2}/K^{\pm}_{\mu2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – : $K^+\to\pi^+\nu\nu$ run	
	2017 – : $K^+\to\pi^+\nu\nu$ run	
	2018 – : $K^+\to\pi^+\nu\nu$ run	

- **Main goal:**
  - Collect O(100) signal events $\Rightarrow 10^{13}$ Kaon decays
  - Measure BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% precision
- **Other program and future plans:**
  - Measure $|V_{td}|$ with ~10% accuracy
  - Probe several NP scenarios in $K^+ \to \pi^+ \nu\bar{\nu}$
  - Probe NP in similar processes (e.g. $K^+ \to \pi^+ X$)
- **Beyond the baseline:**
  - LFV/LNV decays with 3 tracks in the final state
    - Di-muon trigger stream: $\sim 2 \times 10^{12}$ K^+ decays; SES $\sim 10^{-11}$
    - Decays to μe and ee pairs: $\sim 5 \times 10^{11}$ K^+ decays; SES $\sim 10^{-10}$
    - Other 3-track decays: $\sim 5 \times 10^{10}$ K^+ decays; SES $\sim 10^{-9}$
  - Heavy neutrino searches
  - π^0 decays
  - Dark photon searches

- $\sim$ 5MHz of nominal K^+ decay rate



SPS proton
400 GeV
10^{12} p/s

Secondary Beam
$p = 75$ GeV/c
$\Delta p/p \sim 1\%$
X,Y Divergence < 100 μrad
$K(6\%), \pi(70\%), p(23\%)$
750 MHz
Beam size: 6.0 × 2.7 cm²

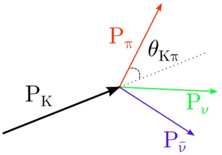
Kaon Decay
$\sim$5 MHz
$4.5 \times 10^{12}/year$
60 m length
10^{-6} mbar vacuum

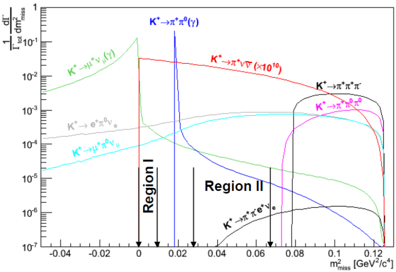
Detectors for decay products
Charged particle tracking
Charged particle Time Stamping
Photon detection
Charged particle ID
Pion and muon identification

Analysis strategy for $K^+ \to \pi^+\nu\bar{\nu}$

Kaon decays in flight

- **Signal:** Time and space $K^+ - \pi^+$ matching
- **Regions defined by:** $m^2_{miss} = (P_K - P_\pi)^2$
- The analysis is mostly cut based
- **Blind analysis:** Signal and background ctrl regions are kept blind throughout the analysis





Main background sources

Decay mode	BR	Main rejection tools
$K^+ \to \mu^+\nu(\gamma)$	63%	μ–ID + kinematics
$K^+ \to \pi^+\pi^0(\gamma)$	21%	γ-veto + kinematics
$K^+ \to \pi^+\pi^+\pi^-$	6%	multi + kinematics
$K^+ \to \pi^+\pi^0\pi^0$	2%	γ-veto + kinematics
$K^+ \to \pi^0 e^+\nu_e$	5%	e–ID + γ-veto
$K^+ \to \pi^0\mu^+\nu_\mu$	3%	μ–ID + γ-veto

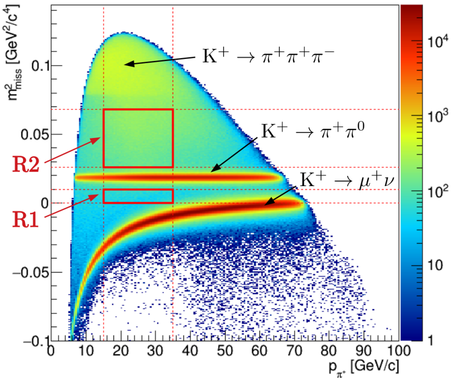
Requirements

- $\mathcal{O}$(100ps) timing between sub-detectors
- $\mathcal{O}(10^4)$ background suppression with kinematics
- $\mathcal{O}(10^7)$ μ-suppression ($K^+ \to \mu^+\nu$)
- $\mathcal{O}(10^7)$ γ-suppression ($K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$)

Event selection

Signal regions

- Three different ways to calculate m_{miss} to avoid mis-reconstruction:
  - $m^2_{miss} = (STRAW,\ GTK)$
  - $m^2_{miss} = (RICH,\ GTK)$
  - $m^2_{miss} = (STRAW,\ Beam)$

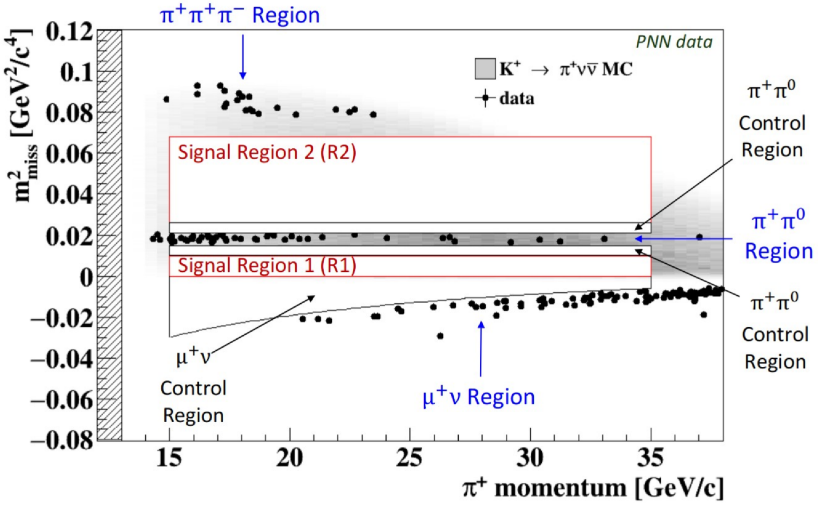


Selection

- Single track in final state topology
- π^+ identification
- Photon rejection
- Multi-track rejection
- $105 < Z_{vertex} < 165$ m
- $15 < P_{\pi^+} < 35$ GeV$/c$ (best μ/π discrimination in RICH & to leave at least 40 GeV of E_{miss})

Performance

- $\varepsilon(\mu) = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
- $\varepsilon(\pi^0) = 1 \cdot 10^{-8}$
- $\sigma(m_{miss}) = 1 \cdot 10^{-3}$ GeV$^2/c^4$
- $\sigma(t) \sim \mathcal{O}(100)$ ps



π+π+π− Region
PNN data
K+ → π+νν̄ MC
data
π+π0 Control Region
Signal Region 2 (R2)
π+π0 Region
Signal Region 1 (R1)
π+π0 Control Region
μ+ν Control Region
μ+ν Region
m2miss [GeV2/c4]
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
15
20
25
30
35
π+ momentum [GeV/c]

Single event sensitivity - 2016 Data

SES ingredients

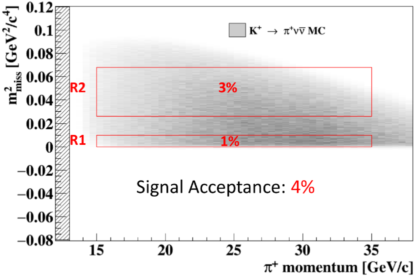
- N_K from $K^+ \to \pi^+\pi^0$ control trigger: $(1.21 \pm 0.02) \times 10^{11}$
- $K^+ \to \pi^+\nu\bar{\nu}$ acceptance: $(4.0 \pm 0.1) \times 10^{-2}$
- Random Veto Efficiency: 0.76 ± 0.04
- Trigger Efficiency: 0.87 ± 0.2

$$SES = \frac{1}{N_K \sum_j (A^j_{\pi\nu\nu} \cdot \epsilon^j_{RV} \cdot \epsilon^j_{trig})}$$

j = π⁺ momentum bin

N_K: number of K⁺ decays; $A^j_{\pi\nu\nu}$: signal acceptance; ϵ^j_{RV}: random veto efficiency; ϵ^j_{trig}: trigger efficiency

SES: $3.15 \pm 0.01_{stat} \pm 0.24_{syst} \times 10^{-10}$

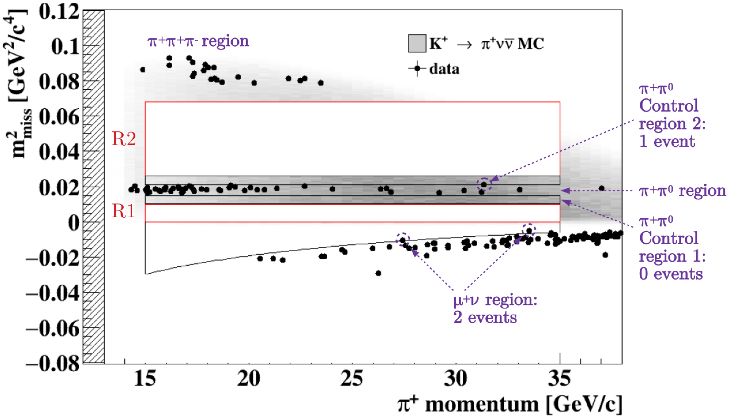


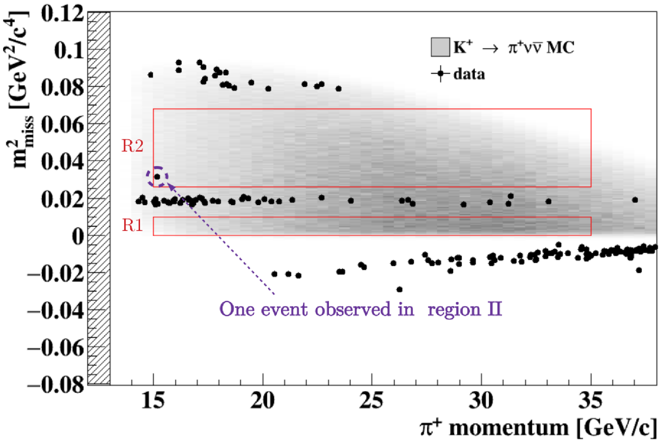
Process	Expected events in R1+R2
$K^+ \to \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.018^{+0.024}_{-0.017}\|_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream background	$0.050^{+0.090}_{-0.030}\|_{stat}$

Source	δ SES (10^{-10})
Random veto	± 0.17
Definition of $\pi^+\pi^0$ region	± 0.10
Simulation of π^+ interactions	± 0.09
N_K	± 0.05
Trigger efficiency	± 0.04
Extra activity	± 0.02
GTK pileup simulation	± 0.02
Momentum spectrum	± 0.01
Total	± 0.24

Expected background in control regions

	$\pi^+\pi^0$		$\mu^+\nu$
CR1	$0.52 \pm 0.08_{stat} \pm 0.03_{syst}$	CR	$1.02 \pm 0.16_{stat}$
CR2	$0.94 \pm 0.14_{stat} \pm 0.05_{syst}$		



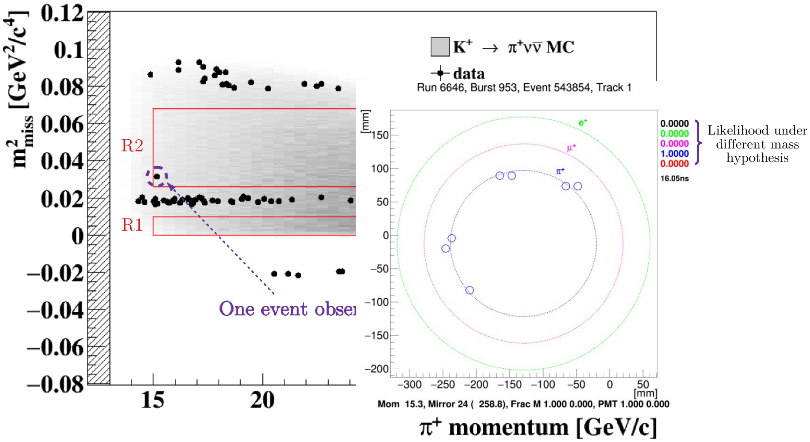


The results are compatible with the SM

$$BR(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10} \text{ @ } 90\% \ CL$$

$$BR(\mathrm{K}^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10} \text{ @ } 95\% \ CL$$

[Phys. Lett. B 791 (2019) 156-166]



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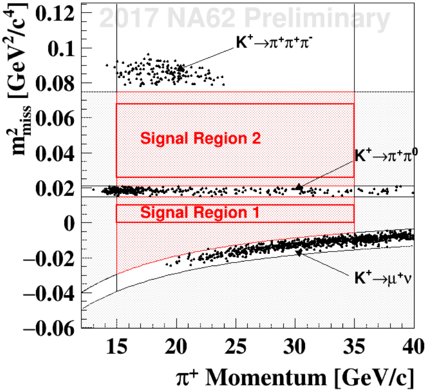
[Phys. Lett. B 791 (2019) 156-166]

Selection and SES

- 2016-like selection
- Comparable to 2016 analysis performance
  - Better treatment of pileup in IRC and SAC
  - 40% lower π^0 rejection inefficiency compared to 2016
  - Slightly improved usage of RICH variables

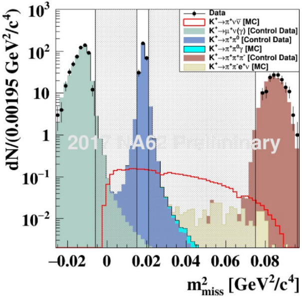


PRELIMINARY

N_K	$(13 \pm 1) \times 10^{11}$
SES	$(0.34 \pm 0.04) \times 10^{-10}$
Expected SM $K^+ \to \pi^+\nu\bar{\nu}$	2.5 ± 0.4

Background summary

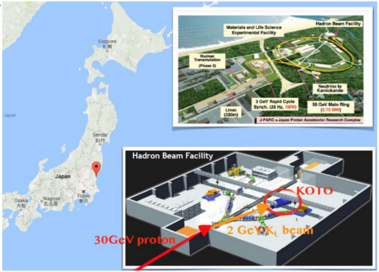
- 2017 data allows detailed comparison between data and background models
  - Shape differs between signal regions, and changes with pion momentum
- Good agreement between modeled m_{miss} and data confirms validity of estimated background from kaon decays



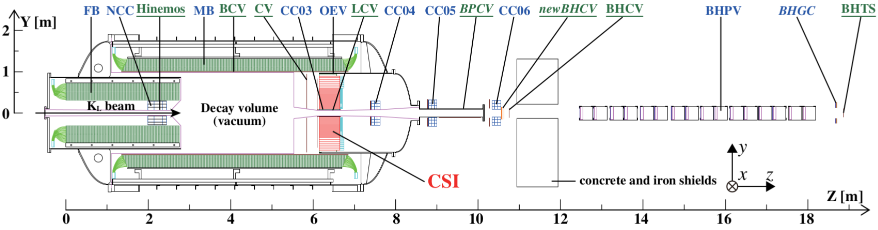
Process	Expected events in signal regions
$K^+ \to \pi^+\nu\bar{\nu}$	2.5 ± 0.4 (Preliminary)
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.015 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to \ell^+\pi^0\nu_\ell$	$0.012 \pm 0.012_{syst}$
Upstream background	Analysis on-going

Study of $K_L \to \pi^0 \nu \bar{\nu}$ **@JPARC** 30GeV Main Ring
Goal is to search for New Physics at *BR* $\sim 10^{-11}$

- Primary 30 GeV/c protons on gold target
- Secondary neutral beam (K_L, neutrons, photons)
- P = 1.4 GeV/c peak
- Transverse size: 80 × 80 mm^2
- Fiducial decay region ∼ 2 m



Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga & Yamagata

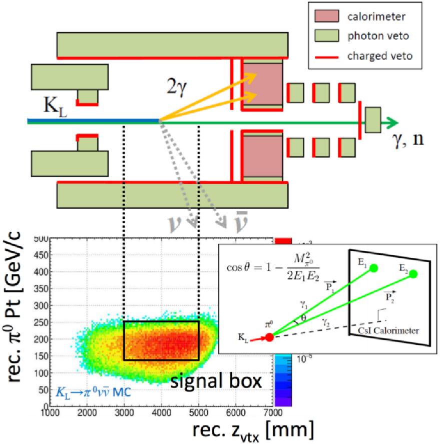


$K_L \to \pi^0 \nu \bar{\nu}$

- 2γ with high P_T = signal

Hermetic Detector

- no signal in veto detectors



Main background sources

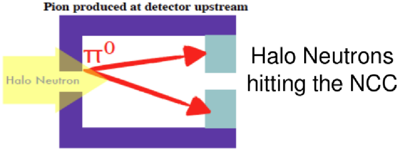
Decay mode	BR [%]	Rejection tools
$K_L \to \pi^{\pm} e^{\mp} \nu$	40.6	charged, non-EM
$K_L \to \pi^{\pm} \mu^{\mp} \nu$	27.0	charged, non-EM
$K_L \to \pi^{+} \pi^{-} \pi^{0}$	12.5	charged, low π^0 P_T
$K_L \to \pi^{0} \pi^{0} \pi^{0}$	19.5	extra γ
$K_L \to \gamma\gamma$	$5.5 \cdot 10^{-4}$	low P_T, symmetry
$K_L \to \pi^{+} \pi^{-}$	$2.0 \cdot 10^{-3}$	charged, non-EM
$K_L \to \pi^{0} \pi^{0}$	$8.6 \cdot 10^{-4}$	extra γ

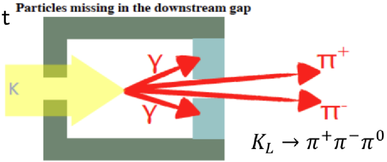
2013 Data sample

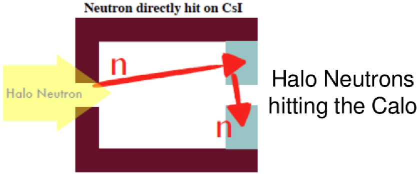
- $N(K_L) \sim 2.4 \times 10^{11}(SES 1.3 \times 10^{-8})$
- Upper limit on $\mathrm{BR}(\mathrm{K_L} \to \pi^0 \nu \bar{\nu})$
$< 5.1 \times 10^{-8}$ @90% CL *[PTEP 2017, 021C01]*

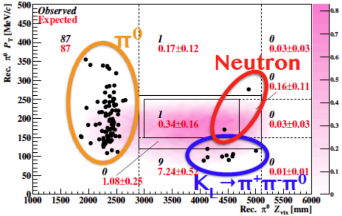
Improvements

- Thinner vacuum window: 125→12 μm
- Beam Profile Monitor for better beam alignment
- Beam Pipe Charged Veto added
- 1/10 reduction of $\mathrm{K_L} \to \pi^+\pi^-\pi^0$ background
- Special run with Al target to collect neutron enriched events
- Better photon-neutron ID in CsI







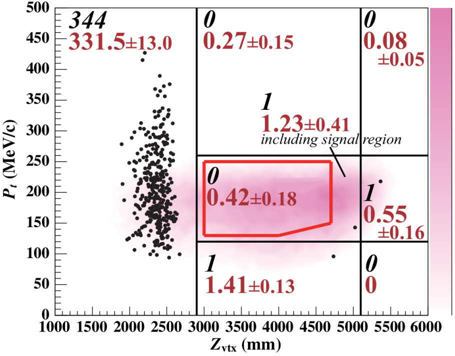


2015 Data sample

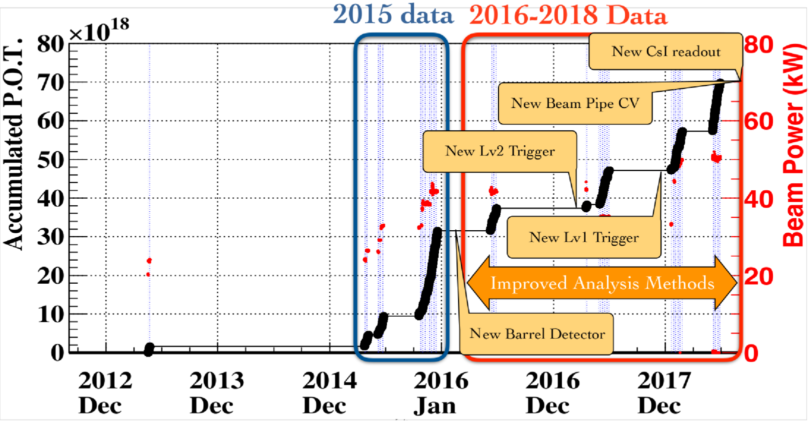
- Based on 40% data collected before major upgrades
- SES $= 1.3 \times 10^{-9}$
- $\mathrm{BR}(\mathrm{K_L} \to \pi^0 \nu \bar{\nu}) < 3.0 \times 10^{-9}$ [PRL.122.021802]

Backgrounds

source	N_{events}
$\mathrm{K_L}$ decay	
$\mathrm{K_L} \to \pi^+\pi^-\pi^0$	0.05 ± 0.02
$\mathrm{K_L} \to \pi^0\pi^0$	0.02 ± 0.02
other $\mathrm{K_L}$ decays	0.03 ± 0.01
neutron induced	
hadron cluster	0.24 ± 0.17
upstream-π^0	0.04 ± 0.03
CV-η	0.04 ± 0.02
total	0.42 ± 0.18

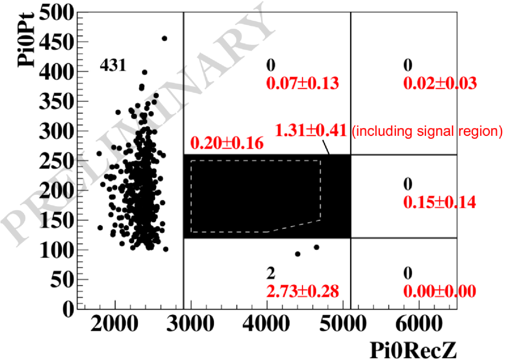


KOTO Time line



Analysis Status: 2016-2018 Data sample

- SES $= 8.2 \times 10^{-10}$ (without new veto window)
- Background under control
- Results coming soon in summer 2019



	# of BG inside signal region
$K_L \to 2\pi^0$	0.09±0.09
$K_L \to \pi^+\pi^-\pi^0$	0.02±0.02
Hadron cluster	0.07±0.13
CV-pi0	< 0.19
CV-eta	0.02±0.01
Total	**0.20±0.16**

Future Run toward SES(10^{-11}) with 100kW Beam Power

NP searches in kaon decays @NA62

- Search for Majorana neutrinos in LNV $K^+ \to \pi^- \ell^+ \ell^+$ decays

  [Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]]

  - DM + Baryon Asymmetry + low mass of SM ν
    can be explained by adding three sterile Majorana neutrinos to the SM
  - Current limits *[[PLB 769 (2017) 67-76] for $\mu\mu$ set by NA48/2]*

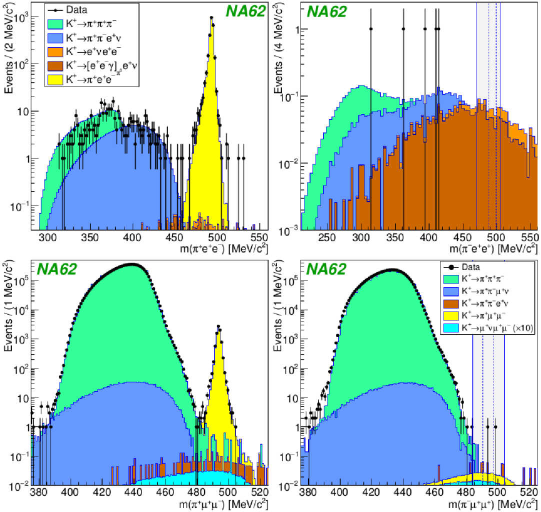
$$\mathrm{BR}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} \quad @\ 90\%\ \mathrm{CL}$$
$$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$$

- Search for resonances (N, X, etc.) in the opposite-sign leptons sample

  [Shaposhnikov-Tkachev model [PLB 639 (2006) 414]]

  - νMSM + real scalar field (inflaton X) with scale invariant couplings
  - Explains universe homogeneity and isotropy on large scales/structures on smaller scales
  - Current limits in opposite sign muons:
    - HN peak search in $K^+ \to \mu^+(\pi^+\mu^-)$
    - Inflatons peak search in $K^+ \to \pi^+(\mu^-\mu^+)$

    Limits set at $\sim 10^{-9}$ (90% CL) by NA48/2
  - Searches in $K^+ \to \pi^+ X$, $X^+ \to e^+ e^-$



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

- Bkg. Prediction: $N_{SR}^{tot} = 0.16 \pm 0.03$
- Observed: $n_{SR} = 0$
- $N_K = (2.14 \pm 0.07) \times 10^{11}$
- $SES = (0.87 \pm 0.03) \times 10^{-10}$

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

- Bkg. Prediction: $N_{SR}^{tot} = 0.91 \pm 0.41$
- Observed: $n_{SR} = 1$
- $N_K = (7.94 \pm 0.23) \times 10^{11}$
- $SES = (1.28 \pm 0.03) \times 10^{-11}$

Decay	BR UL @90% CL	PDG UL @90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11}

NP searches in kaon decays @NA62

- Search for HNL in $K^+ \to l^+ N$ with undecayed N
  - $K^+ \to l^+ N$ events would appear as peaks in the $K^+ \to l^+ \nu$ m^2_{miss}
  - Searches are model independent

- Searches for LNV/LFV decays $K^+ \to \pi \mu e$, including $\pi^0 \to \mu e$

$$\mathrm{BR}(\pi^- \mu^+ e^+) < 5.0 \times 10^{-10}$$
$$\mathrm{BR}(\pi^+ \mu^- e^+) < 5.2 \times 10^{-10}$$
$$\mathrm{BR}(\pi^+ \mu^+ e^-) < 1.3 \times 10^{-11}$$

Limits set by BNL E865, E777

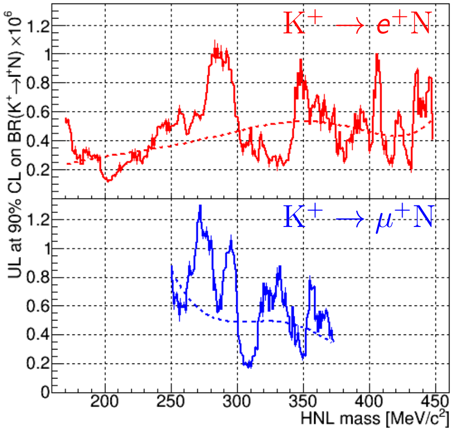
$$\mathrm{BR}(\pi^0 \to \mu^\pm e^\mp) < 3.6 \times 10^{-10}, \ \mathrm{kTeV} \ @ \ \mathrm{FNAL}$$

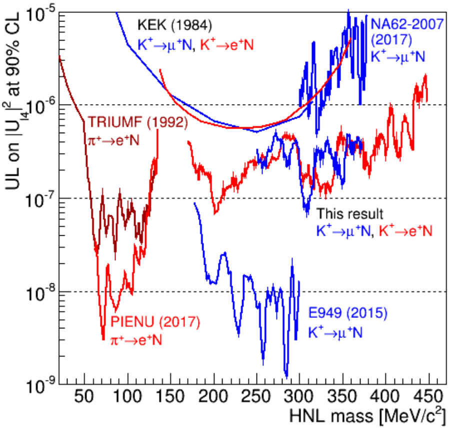
- Searches for $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to e^- \nu \mu^+ \mu^+$ decays

$$\mathrm{BR}(\mu^- \nu e^+ e^+) < 1.9 \times 10^{-8} \ @ \ \mathrm{Geneva-Saclay}, \ 1976$$

NA62 is competitive for most of these decay modes

- Local signal significance never exceeds 3σ: **no HNL signal is observed**
- Reached $10^{-6} - 10^{-7}$ limits for $|U_{e4}|^2$ in the 170-448 MeV$/c^2$ mass range
- Improved limits for $|U_{\mu4}|^2$ for $300 \leq m_N \leq 373$ MeV$/c^2$
- **Major improvement foreseen** with high intensity NA62 data





[Phys. Lett. B 778 (2018) 137-145]

HNLs: prospects with full data set

- Data sample 2016-18 in comparison to data sample 2015:
  - Beam tracker (GTK) in operation:
    - a factor ~ 2 improved HNL mass resolution σ_m
    - lower background and broader mass range accessible
    - a factor ~ 3 lower background in the $K^+ \to e^+ N$ mode ($K^+ \to \mu^+\nu,\ \mu^+ \to e^+\nu\nu$: muon decays in flight rejected geometrically)
    - lower background from upstream decays in the $K^+ \to \mu^+ N$ mode
  - Much larger data sets:
    - $K^+ \to e^+ N$ mode: the main $K^+ \to \pi^+\nu\nu$ trigger is used with reduced signal acceptance - max calorimetric energy = 30 GeV: expect $O(10^6)$ $K^+ \to e^+\nu$ events, a factor ~ 1000 improvement
    - $K^+ \to \mu^+ N$ mode: down scaled control trigger (D=400): expect $O(10^9)$ $K^+ \to \mu^+\nu$ events, a factor ~ 100 improvement
  - Expected sensitivities to $|U_{\ell 4}|^2$ with 2016-18 data:
    - better than 10^{-8} for both $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

Large data sets already collected; analysis is in progress

Conclusions for $\mathrm{K} \to \pi\nu\bar{\nu}$ *decays*

- **NA62 BR($\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$) measurement:**
  - Decay in flight technique works!
  - 1 event observed in 2016 data
  - BR($\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$) $< 14 \times 10^{-10}$ @95% CL
    [Phys. Lett. B 791 (2019) 156-166]
  - Analysis of 2017 data is ongoing - Results expected in 2019
  - Precise evaluation of the total statistics collected in 2018 is under study
  - BR measurement expected in the next few years
- **KOTO BR($\mathrm{K_l} \to \pi^0\nu\bar{\nu}$) measurement:**
  - UL on BR($\mathrm{K_L} \to \pi^0\nu\bar{\nu}$) $= 3.0 \cdot 10^{-9}$ @90% CL based on 2015 Data sample
  - 2016-2018 Data Analysis with better Detector, DAQ & Analysis Methods ongoing
  - New results expected in Summer 2019
  - Future Run toward SES(10^{-11}) with 100kW Beam Power.

Conclusions for other NA62 decays

- **Searches for LFV/LNV in 3-track decays:**
  - 3 months of 2017 data of 2 LNV/LFV decays improving over PDG limits
  - $\mathrm{BR}(\mathrm{K}^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ @90% CL
  - $\mathrm{BR}(\mathrm{K}^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ @90% CL
  - $\sim$ 3 times more data still to analyze
- **HNL result from the 2015 run:**
  - Search for HNL production in $\mathrm{K}^+ \to \ell^+ N$ decays with minimum bias data:
    $10^{-6} - 10^{-7}$ limits on $|U_{e4}|^2$ in mass range 170-448 MeV/c^2
    Improved limits for $|U_{\mu4}|^2$ for $300 \leq m_N \leq 373$ MeV/c^2
    [Phys. Lett. B 778 (2018) 137-145]
  - Major improvement in HNLs foreseen with new data.