Results and Future Prospects from NA62 and Other Kaon Experiments

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On behalf of the NA62 Collaboration

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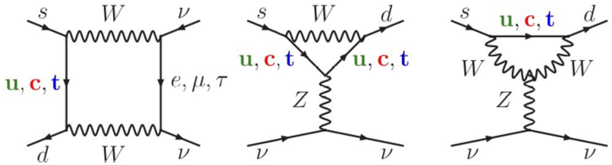
Kaon Physics at NA62

Type	Decay mode
Main goal:	$K^+ \to \pi^+ \nu \overline{\nu}$
Exotic searches: Heavy neutral lepton Dark photon A' others	 $K^+ \to l^+ N$ $K^+ \to \pi^+ \pi^0$, $\pi^0 \to A' \gamma$
Forbidden decays:	$K^+ \to \pi^- e^+ e^+$ $K^+ \to \pi^- \mu^+ \mu^+$ others
Rare decays:	$K^+ \to \pi^+ \mu^+ \mu^-$ $K^+ \to \pi^+ \gamma\gamma$ others



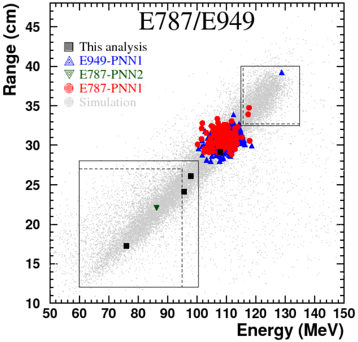
- FCNC loop process - rare meson decay naturally suppressed by the GIM mech.
- Theoreticallly very clean (no hadronic uncertainties)
- Sensitive to contributions of physics BSM
  - **MSSM** [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27], [Isidori et al. JHEP 0608 (2006) 064]
  - **Custodial Randall-Sundrum** [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
  - **Simplified Z, Z' models** [Buras, A.J., Buttazzo, D. & Knegjens, R. J. High Energ. Phys. (2015) 2015: 166]
  - **Littlest Higgs with T-parity** [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
  - **LFU violation models** [Bordone, M., Buttazzo, D., Isidori, G. et al. Eur. Phys. J. C (2017) 77: 618]

- SM prediction

  [Brod,Gorbahn,Stamou,Phys.Rev.D 83, 034030(2011)], [Buras.et.al., JHEP11(2015) 033]:
  $\mathcal{B}_{SM}(K^+ \to \pi^+ \nu\overline{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
  - Uncertainty coming mostly from CKM parameters (γ, $|V_{cb}|$)

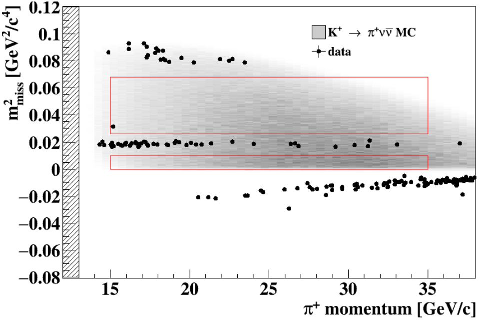
$K^+ \to \pi^+\nu\bar{\nu}$ Experimental Status

E787/E949 (BNL),
K^+ decays at rest



- [Phys.Rev.D 79, 092004(2009)]
- $\mathcal{B}_{\text{exp.}} = \left(\mathbf{1.73^{+1.15}_{-1.05}}\right) \times \mathbf{10^{-10}}$

NA62 (CERN),
K^+ decays in flight

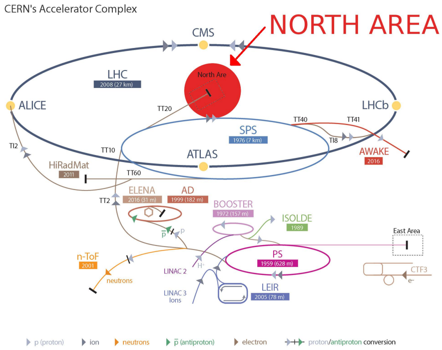


- [Phys.Lett.B 791, 156-166(2019)]
- $\mathcal{B}_{\text{exp.}} < \mathbf{14} \times \mathbf{10^{-10}}$ @ 95% CL

NA62 Experiment at CERN

MAIN GOAL: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with precision better than 10%
Requirements: $10^{13} K$ decays, Signal acceptance $\mathcal{O}(10\%)$, Bckg rejection $\mathcal{O}(10^{12})$

Other physics program: LFV/LNV searches, Exotic searches, Rare decays, π^0 decays

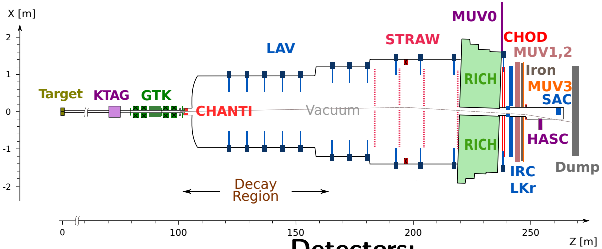


- ~200 participants, 31 institutes

NA62:

- 2014: Pilot run
- 2015: Commissioning run
- September 2016: full detector installation completed
- September-October 2016: first physics run
- **May-October 2017: second physics run**
- April-November 2018: third physics run

NA62 Beam and Detector



Beam:

- Primary (SPS) proton beam with momentum 400 GeV/c
- 2×10^{12} protons per 3.5s spill
- Beryllium target
- Secondary positive beam with momentum $\sim$ 75 GeV/c
- Secondary beam content: K^+ (6%), π^+ (70%), p (24%)
- 2017 Intensity: 450 MHz @ GTK3
- Kaon decay rate $\sim$ 3 MHz

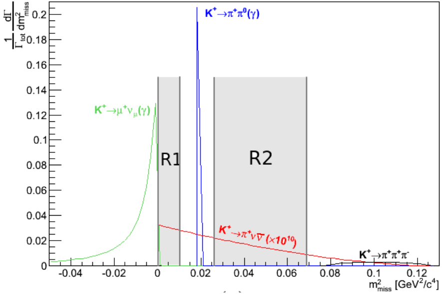
Detectors:

- KTAG - Cherenkov det. for K^+ tagging
- GTK - beam spectrometer
- Decay region - 60 m long, in vacuum
- STRAW - downstream spectrometer
- CHOD - charged particle hodoscope
- LAV, IRC, SAC - photon veto
- RICH, LKr - Cherenkov detector and calorimeter for PID
- MUV3 - muon veto

[JINST 12(2017) P05025]

Measurement strategy:

- $K^+ \to \pi^+\nu\bar{\nu}$ signature: one K^+ in the initial state, one π^+ and missing energy (neutrinos) in the final state
- Two kinematic signal regions
- Blind analysis
- Trigger streams (HW+SW): PNN and Control (minimum bias)



True m^2_{miss} computed under the hypothesis that the charged particle is π^+.

Main background processes:

Process	BR
$K^+ \to \mu^+\nu(\gamma)$	0.6356
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067
$K^+ \to \pi^+\pi^+\pi^-$	0.0558

Keystones:

- $\mathcal{O}(100$ ps) timing between subdetectors
- $\sim \mathcal{O}(10^3)$ kinematic background suppression
- PID background suppression (μ^+ and π^0) $> 10^7$

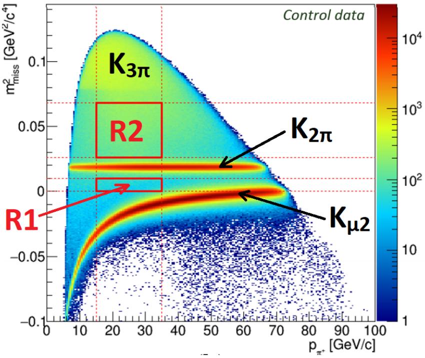
Main kinematic variable:

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$

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

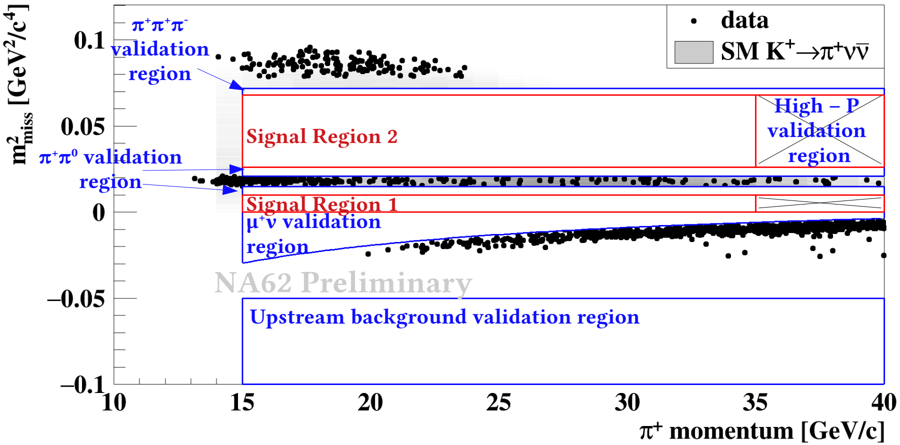
Signal selection:

- Single track topology
- K^+ and π^+ momentum reconstruction (GTK, STRAW)
- $K^+ - \pi^+$ matching
- K^+ decays in the fiducial region
- π^+ identification ($\epsilon_{\pi^+} \sim 64\%$)
- γ rejection
- Multi-track event rejection
- Upstream background suppression
- 15 GeV $< P_{\pi^+} <$ 35 GeV
- Signal regions defined by $m^2_{miss}(\pi^+)$



Reconstructed m^2_{miss} (assuming π^+ mass) as a function of the track momentum for control data before PID and γ and multi-track rejection.
[Phys.Lett.B 791, 156-166(2019)]

Data After Signal Selection (2017 Dataset)



- Validation regions dedicated to background validation
- Signal and validation regions blinded

Single Event Sensitivity (SES) (2017 Dataset)

$$N^{exp}_{\pi\nu\nu} \approx N_{\pi\pi}\epsilon_{trig}\epsilon_{RV}\frac{A_{\pi\nu\nu}}{A_{\pi\pi}}\frac{\mathcal{B}(\pi\nu\nu)}{\mathcal{B}(\pi\pi)} \quad \Rightarrow \quad SES = \frac{\mathcal{B}(\pi\nu\nu)}{N^{exp}_{\pi\nu\nu}}$$

- $N^{exp}_{\pi\nu\nu}$ = expected number of $K^+ \to \pi^+\nu\overline{\nu}$ events
- $N_{\pi\pi}$ = Number of $\pi^+\pi^0$ events from Control sample with $\pi\nu\nu$-like selection without γ/multiplicity rejection
- ϵ_{trig} = efficiency of PNN trigger
- ϵ_{RV} = $K^+ \to \pi^+\nu\overline{\nu}$ loss due to γ/multi-track rejection bc of random activity
- $A_{\pi\nu\nu,\pi\pi}$ = MC acceptances for $K^+ \to \pi^+\nu\overline{\nu}$ ($\sim$3%) and $K^+ \to \pi^+\pi^0$ ($\sim$8.5%)
- $\mathcal{B}(\pi\pi)$ = PDG branching ratio for $K^+ \to \pi^+\pi^0$
- $\mathcal{B}(\pi\nu\nu)$ = SM branching ratio for $K^+ \to \pi^+\nu\overline{\nu}$

- Ratio of acceptances allows for cancellation of systematic effects
- Computation in bins of π^+ momentum and instantaneous beam intensity

Measured single event sensitivity:

$$\mathbf{SES} = (\mathbf{3.89} \pm \mathbf{0.21}) \times \mathbf{10}^{-11} \qquad \text{(Preliminary)}$$

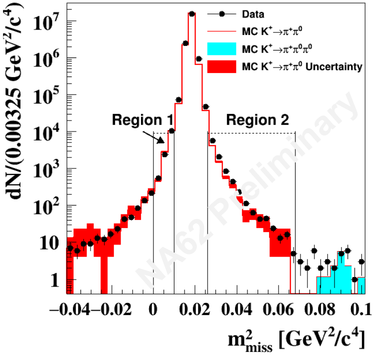
Expected number of $K^+ \to \pi^+\nu\overline{\nu}$ events in both signal regions combined:

$$\mathbf{N^{exp}_{\pi\nu\nu}} = \mathbf{2.16} \pm \mathbf{0.12} \pm \mathbf{0.26_{ext}} \qquad \text{(Preliminary)}$$

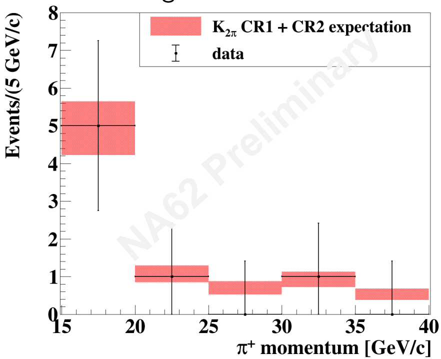
External error coming from $\mathcal{B}(\pi\nu\nu)$.

$K^+ \to \pi^+\pi^0$ Background

$K^+ \to \pi^+\pi^0$ Control data used to study tails of m^2_{miss} distribution



Expected and observed $K^+ \to \pi^+\pi^0$ bckg in validation regions after PNN selection



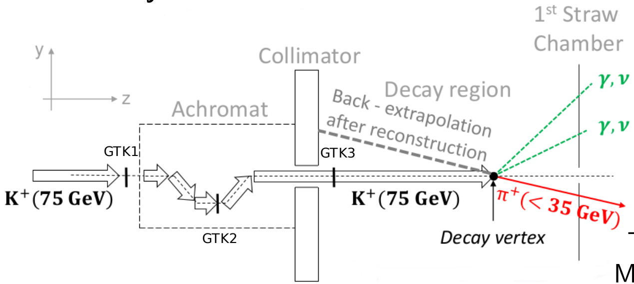
$$N^{exp}_{\pi\pi}(\text{region}) = N(\pi^+\pi^0) \cdot f^{kin}(\text{region})$$

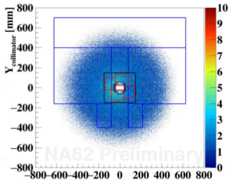
- $N^{exp}_{\pi\pi}$(region) = Expected $K^+ \to \pi^+\pi^0$ events in signal region after PNN selection
- $N(\pi^+\pi^0)$ = Data in $\pi^+\pi^0$ peak after PNN selection
- f^{kin}(region) = Fraction of $K^+ \to \pi^+\pi^0$ in signal region measured on Control data

By-product: $\mathcal{B}(\pi^0 \to \text{invisible}) < 4.4 \times 10^{-9}$ 90% CL

Upstream Background

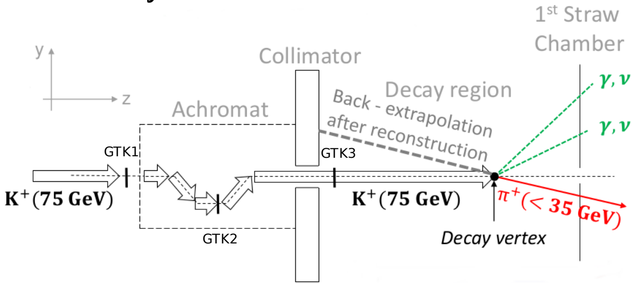
Normal decay of K^+:

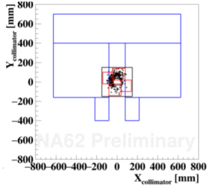




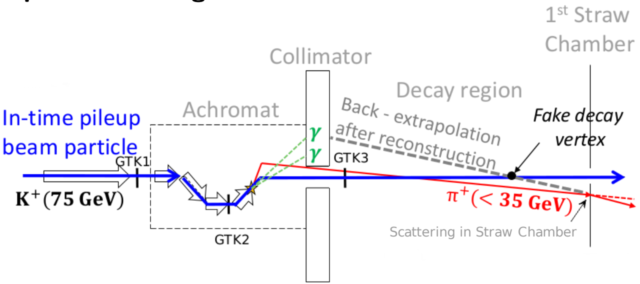
Track from $K^+ \to \pi^+ \nu \overline{\nu}$ MC projected at collimator

Normal decay of K^+:





Upstream Background:



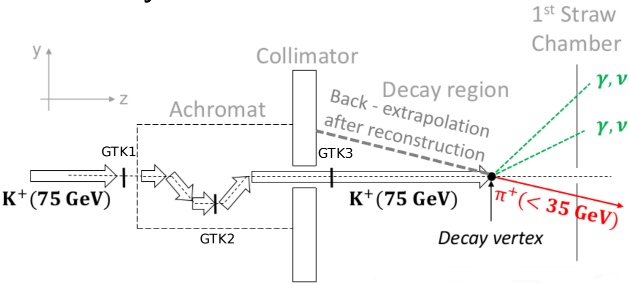
Upstream bckg:

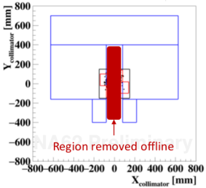
- K^+ decays/interacts in the achromat
- Secondary π^+ downstream
- Beam elements block additional particles
- π^+ scattering in Straw Chamber 1
- Pileup beam particle tagged as K^+

Sketches from G. Ruggiero

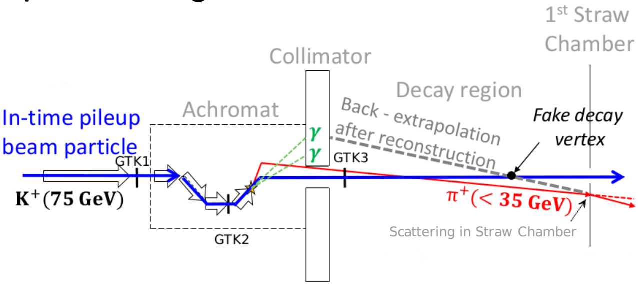
Upstream Background

Normal decay of K^+:





Upstream Background:



Upstream bckg:

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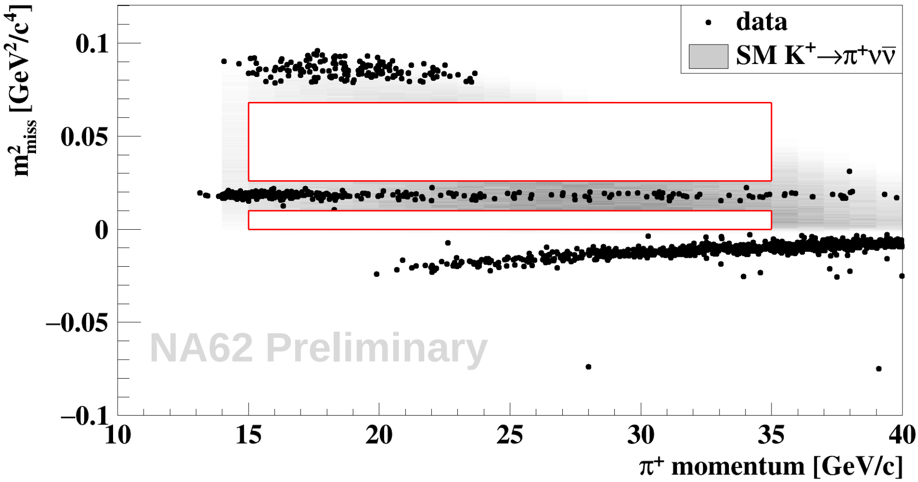
Sketches from G. Ruggiero

Background Summary (2017 Dataset)

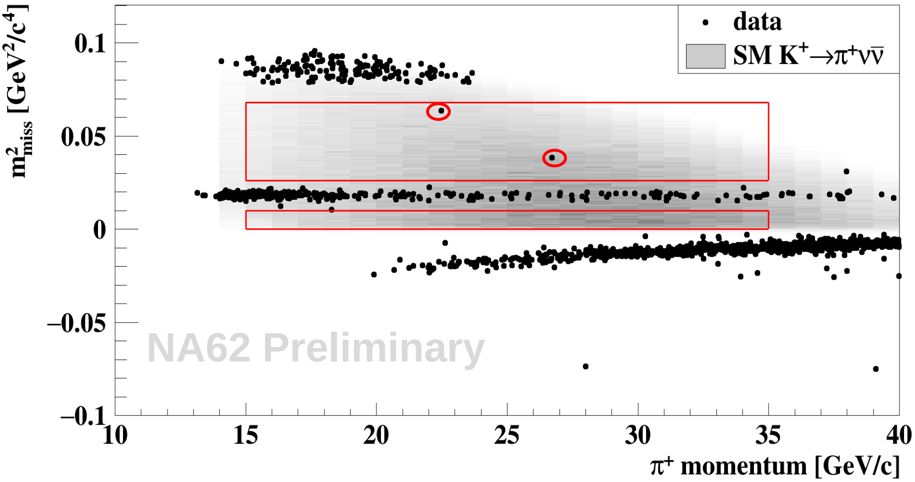
Expected number of events in both signal regions combined (Preliminary):

Process	Expected events
$K^+ \to \pi^+ \nu \bar{\nu}$ (SM)	$2.16 \pm 0.12_{stat} \pm 0.26_{ext}$
$K^+ \to \pi^+ \pi^0 (\gamma)$ IB	$0.29 \pm 0.03_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu_\mu (\gamma)$ IB	$0.11 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+ \nu_\mu (\mu^+ \to e^+ \text{decay})$	$0.04 \pm 0.02_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	$0.12 \pm 0.05_{stat} \pm 0.03_{syst}$
$K^+ \to \pi^+ \pi^- \pi^+$	$0.02 \pm 0.02_{syst}$
$K^+ \to \pi^+ \gamma \gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+ \pi^0 \nu_l$	negligible
Upstream background	$0.9 \pm 0.2_{stat} \pm 0.2_{syst}$
Total background	$1.5 \pm 0.2_{stat} \pm 0.2_{syst}$

$K^+ \to \pi^+ \pi^0 (\gamma)$, $K^+ \to \mu^+ \nu (\gamma)$, $\mathrm{K}^+ \to \pi^+ \pi^- \pi^+$ and upstream backgrounds estimated from Control data and validated using the validation regions.
Other backgrounds estimated from the MC simulations validated on data.


data
SM K⁺→π⁺νν̄
NA62 Preliminary
0.1
0.05
0
−0.05
−0.1
10
15
20
25
30
35
40
π⁺ momentum [GeV/c]
m²miss [GeV²/c⁴]

Opening the Boxes (2017 Dataset)

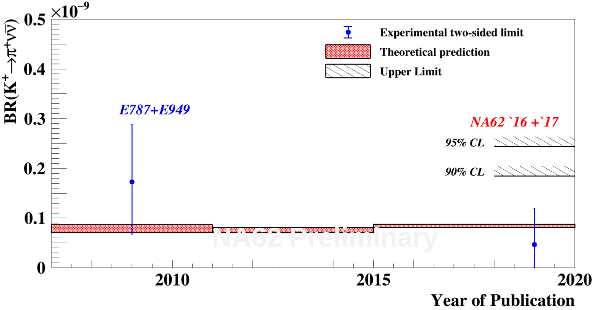


Single event sensitivity	$(0.346 \pm 0.017) \times 10^{-10}$
Expected number of background events	1.65 ± 0.31
Observed number of events	**3**

Observed upper limits:

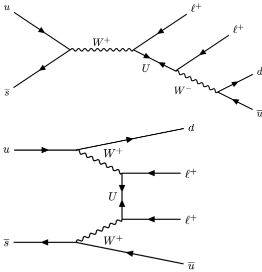
- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) < 1.85 \times 10^{-10}$ @ 90% CL (Preliminary)
- $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) < 2.44 \times 10^{-10}$ @ 95% CL (Preliminary)

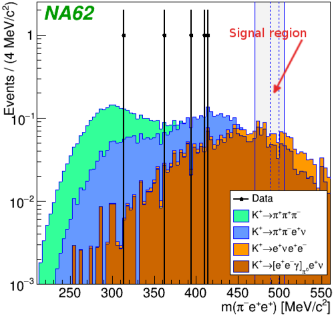
Grossman-Nir limit: $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu}) < 8.14 \times 10^{-10}$ @ 90% CL (Preliminary)

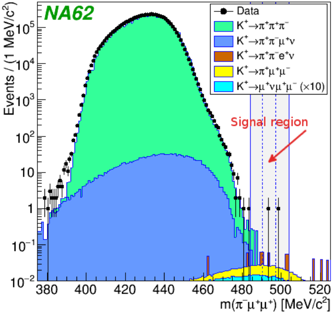


Forbidden Decays (LNV) at NA62

- Study of $K^+ \to \pi^- \mu^+ \mu^+$ and $K^+ \to \pi^- e^+ e^+$ ($\Delta L_l = 2$)
- Processes in BSM with massive Majorana neutrinos U
  [JHEP 0905 (2009) 030], [Phys. Lett. B491(2000) 285]
- Signal selection using $|M(\pi^- l^+ l^+) - M(K^+)|$ and PID
- 2017 results [Phys. Lett. B797 (2019) 134794]
  $\longrightarrow$ **improvement by factor 2-3 wrt previous result:**
  - $\mathcal{B}(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ @ 90% CL
  - $\mathcal{B}(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ @ 90% CL
- Full data-sample (2016-2018): $3\times$ more statistics



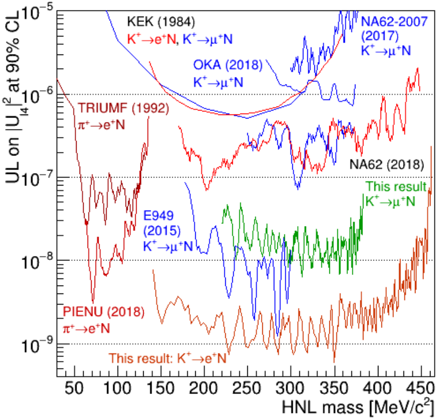




Hidden Sector Searches: Heavy Neutral Leptons (HNL)

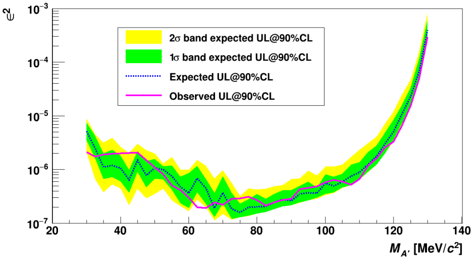
- Study of $K^+ \to l^+ N$ ($l = e, \mu$) – production search
- νMSM – mixing of three massive sterile neutrinos (HNL) with the three ordinary active neutrinos – fermion portal to a hidden sector
- Kinematic variable: squared missing mass $m^2_{miss} = (P_K - P_l)^2$
- Signal: a spike above continuous missing mass spectrum
- Mass scan in the range of 141–462 (220–383) MeV/c^2 in the e^+ (μ^+) case

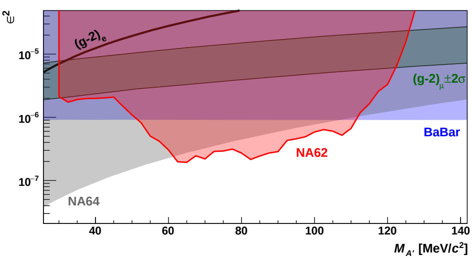
- Last published results: 2015 dataset [Phys. Lett. B778 (2018)]
- Preliminary 2016+2017 results $\longrightarrow$ **new upper limit on mixing parameter $|U_{l4}|^2$** [Goudzovski, KAON 2019]
- Improvement by less than a factor of 2 with full dataset (2016-2018)
- Intention to collect data in beam-dump mode in 2021-2023 for HNL decay (and other) searches



Hidden Sector Searches: Dark Photon A'

- Search for dark photon using $K^+ \to \pi^+\pi^0$, $\pi^0 \to A'\gamma$, decay chain with A' decaying to invisibles – vector portal to a hidden sector
- SM extension – new vector field A' mixing with the SM γ
- Signal signature: π^0 decay, one γ and missing energy, no additional activity
- Kinematic variable: squared missing mass $\mathrm{m}^2_{\mathrm{miss}} = (\mathrm{P}_K - \mathrm{P}_{\pi^+} - \mathrm{P}_\gamma)^2$
- Signal: a spike above continuous missing mass spectrum
- Mass scan in range 30–130 MeV/c^2 of $\mathrm{M}_{A'}$
- 2016 results $\longrightarrow$ no statistically significant excess identified $\longrightarrow$ **new upper limit on ϵ^2 coupling of A' to γ** [JHEP 05 (2019) 182]
- Expected $\sim$100$\times$ more statistics from full 2016–2018 dataset





Prospects for NA62

All physics analyses ongoing (2017 and/or 2018 datasets):

- 2018 $K^+ \to \pi^+ \nu\overline{\nu}$ dataset
  - Analysis ongoing
  - $2\times$ more data than in 2017
  - Optimization studies to increase signal efficiency
  - New collimator installed – increased signal acceptance

NA62 After 2021 (LHC Run 3):

- Plans to modify the beamline setup in order to strongly suppress upstream background
- Add 4^{th} GTK station to reduce K^+–π^+ mistagging probability
- Plans for new vetoes in the beamline to detect extra particles
- Plans for data-taking:
  - $K^+ \to \pi^+ \nu\overline{\nu}$ at nominal beam intensity
  - Rare decays + Exotics
  - NA62++:
    - Beam dump experiment (closed TAX) with 10^{18} POT
    - Decays of exotic particles
    - New ANTI0 detector under construction to veto muons produced in the TAX
    - Studies to increase proton beam intensity by 20-50% above nominal

Kaon Facility (2026 Onwards)

NA62 has initiated feasibility study for running at considerably higher intensity...

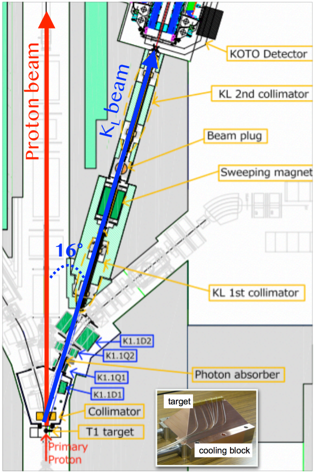
- Physics goals:
  - NA62×4 – improve precision on $K^+ \to \pi^+ \nu \overline{\nu}$
  - KLEVER – measure $\mathcal{B}(K_L \to \pi^0 \nu \overline{\nu})$, complementary to NA62 and KOTO
- 4× higher intensity in K^+ mode, 6× higher intensity in K_L mode
  - Challenging for tracking and beam detectors (K^+ mode)
  - Challenging for calorimetry and photon detection (K_L mode)
- Large commonality in terms of upgrades required (hardware, readout)

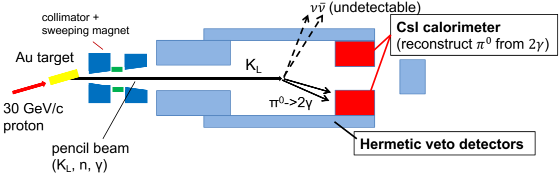
- **Search for new physics with CP-violating (and highly suppressed FCNC) process $K_L \to \pi^0 \nu \overline{\nu}$**
- SM prediction for branching ratio is $\mathcal{B}_{\mathrm{SM}} = (3.0 \pm 0.3) \times 10^{-11}$
  [Buras.et.al., JHEP11(2015) 033]

- $\sim$50 people from 16 institutes
- First physics run in 2013
- **2015 dataset:**
  - Results published in Physical Review Letters [PRL.122.021802 (2019)]
  - Measured SES: $(1.30 \pm 0.01_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}}) \times 10^{-9}$
  - Expected number of background events in the signal region: 0.42 ± 0.18
  - **No signal candidate events were observed**
  - **New upper limit for $\mathcal{B}(K_L \to \pi^0 \nu \overline{\nu}) < 3.0 \times 10^{-9}$ at 90% C.L.**
    $\longrightarrow$ **10x improvement wrt prev. limit from KEK E391a** [Phys.Rev.D 81, 072004, 2010]
- Current status of 2016-2018 data analysis presented at KAON 2019
- Future – major upgrades planned for KOTO Step-2 [Nomura, KAON 2019]

$K_L \to \pi^0 \nu \bar{\nu}$ at KOTO, J-PARC Center, Japan

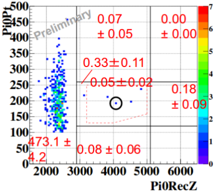
- 30 GeV/c proton beam hitting a gold target
- Secondary neutral beam (neutrons, photons, K_L) produced at an angle and transported to the decay region via neutral beamline
- Peak K_L momentum 1.4 GeV/c
- Calorimeter and hermetic veto counters for neutral and charged particles around decay region in vacuum
- **Signature: two photons + missing energy**
- Main sources of background: charged ($K_L \to \pi^\pm e^\pm \nu$, $K_L \to \pi^\pm \mu^\pm \nu$, $K_L \to \pi^+\pi^-\pi^0$, $K_L \to \pi^+\pi^-$), neutral ($K_L \to \pi^0\pi^0\pi^0$, $K_L \to \gamma\gamma$, $K_L \to \pi^0\pi^0$)





2016–2018 dataset:

- $1.4\times$ more statistics
- New veto counters
- **Current status presented at KAON 2019** $\longrightarrow$ [Shinohara, KAON 2019]:
  - Measured SES $= 6.9 \times 10^{-10}$
  - Expected number of background events in the signal region: 0.05 ± 0.02
  - **4 events found in signal region**



expectation

BG estimation related overlapped pulse

Preliminary

	#BG
KL3pi0 (overlapped pulse)	<0.04
Ke3 (overlapped pulse)	<0.09

⇒ Underestimated the BG from overlapped pulse?

- Checking the properties of the other candidates
- Did we miss other background sources?
  - planning to reevaluate other BG sources

Stay tuned...

More results from Kaon experiments coming soon...

For more Kaon related searches see presentations at KAON 2019 [KAON 2019, Perugia]

Backup

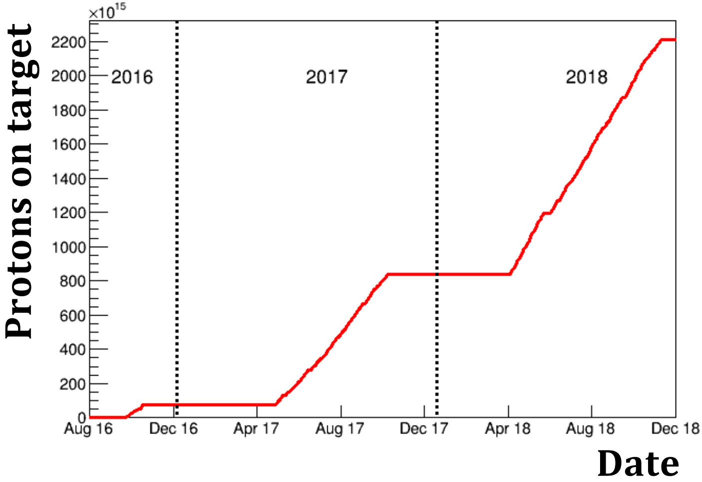
- Intensity:
  - 2016: 40% of nominal
  - 2017: 55% of nominal
  - 2018: 65% of nominal

- Kaon decays:
  - 2017: 2×10^{12} K^+ decays
  - 2016+2017+2018: 6×10^{12} K^+ decays

- 2017 signal acceptance: 1.34% (including random veto, trigger and total detector efficiency)

- Rolke-Lopez 68% confidence interval: $\mathcal{B}(K^+ \to \pi^+ \nu\overline{\nu}) = (0.47 \pm^{+0.72}_{-0.47}) \times 10^{-10}$ (for comparison with BNL)

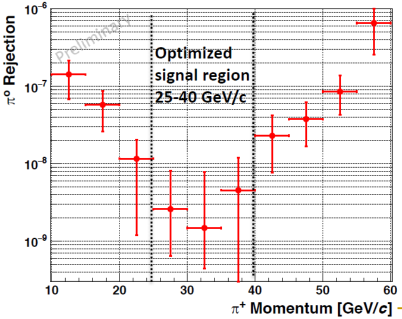
Backup


×10^15
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2016
2017
2018
Protons on target
Aug 16
Dec 16
Apr 17
Aug 17
Dec 17
Apr 18
Aug 18
Dec 18
Date

π^0 rejection and search for $\pi^0 \rightarrow$ invisible

A-priori evaluation of π^0 rejection in $K^+ \rightarrow \pi^+\pi^0$ $(0.015 < m^2_{miss} < 0.021\ \mathrm{GeV}^2/c^4)$

- Same selection, and trigger stream as $K^+ \rightarrow \pi^+\nu\bar{\nu}$, about $1/3$ of the data used for $\pi\nu\nu$
- Single-γ detection efficiency from data minimum-bias $K^+ \rightarrow \pi^+\pi^0$ (Tag & Probe)
- π^0 rejection evaluated from convolution with MC $K^+ \rightarrow \pi^+\pi^0(\gamma)$
- Validation: side-bands with expected rejection $\mathcal{O}(10^{-7})$ where $\pi^0 \rightarrow$ invisible excluded [E949, PRD72 (2005)]
- π^0 rejection expected: $(2.8^{+5.0}_{-2.1}) \times 10^{-9}$ (π^+ momentum 25-40 GeV/c)

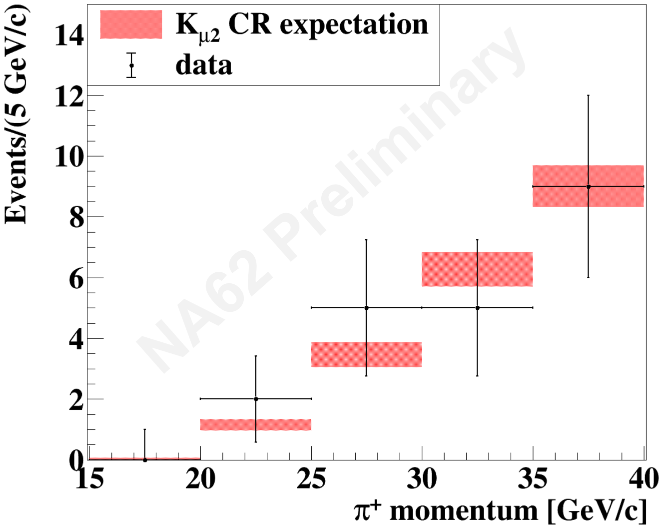


Result

- BR($\pi^0 \rightarrow$ invisible) normalized to $\pi^0 \rightarrow \gamma\gamma$
- Background expected: 10^{+22}_{-8} ($K^+ \rightarrow \pi^+\pi^0$)
- Events observed: 12

BR($\pi^0 \rightarrow$ invisible) $< 4.4 \times 10^{-9}$ @ 90% CL

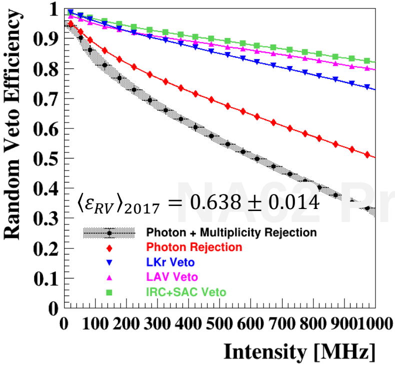
UL 60 times stronger than past measurement



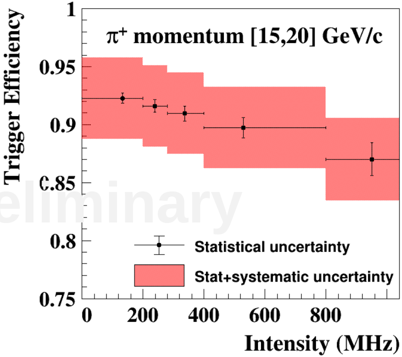
$K_{\mu 2}$ CR expectation
data
NA62 Preliminary
Events/(5 GeV/c)
0
2
4
6
8
10
12
14
15
20
25
30
35
40
π^+ momentum [GeV/c]

$\pi\nu\nu$ Single Event Sensitivity

ε_{RV} measured on $K^+ \rightarrow \mu^+\nu$ data



$\varepsilon_{trigger}$ measured on data



- Intensity measured event-by-event using Gigatracker time sidebands

$\pi\nu\nu$ S.E.S: Results

- Integrated over beam intensity and π^+ momentum

$S.E.S. = (0.389 \pm 0.021) \times 10^{-10}$

$N_{\pi\nu\nu}^{exp} = 2.16 \pm 0.12 \pm 0.26_{ext}$

- Error budget (S.E.S.)

Source	Uncertainty $\times 10^{-10}$
L0 trigger	± 0.015
Acceptance	± 0.012
Random veto	± 0.008
L1 trigger	± 0.003
Normalization background	negligible

- External error on $N_{\pi\nu\nu}^{exp}$ from $Br(\pi\nu\nu) = (0.84 \pm 0.10) \times 10^{-10}$