Recent kaon decay results from NA62

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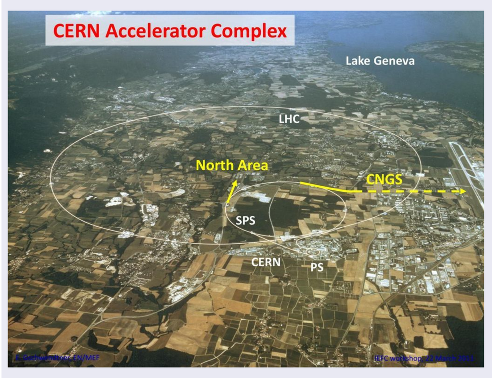
Introduction

In this poster we will describe the NA62 experiment at CERN. NA62 is an experiment dedicated to the study of rare kaon decays. Important results such as advances in measuring the Branching Ratio of $K^+ \to \pi^+\nu\bar{\nu}$, the search for heavy neutral leptons and the search for lepton number violating kaon decays will be shown.
NA62 has around 200 participants from Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Merced, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

NA62: the Experiment

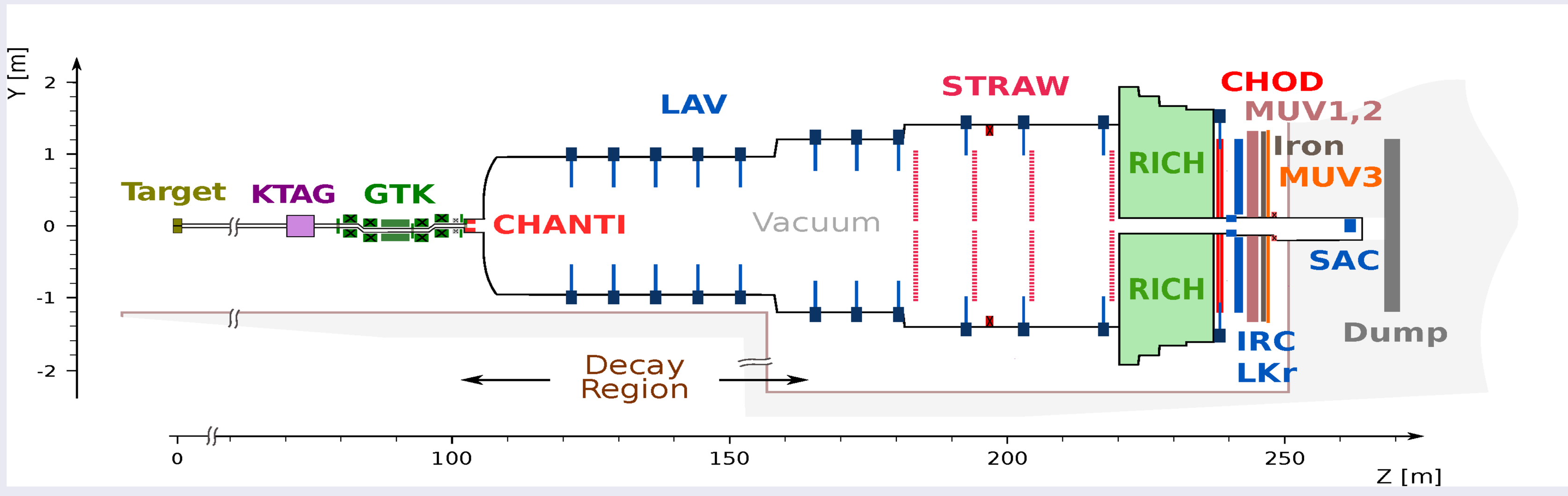


NA62 is the latest generation kaon experiment at the CERN SPS. The experiment is located in CERN in the North Area and extracts protons from the SPS accelerator at 650 GeV/c.

- NA48 (1997-2001): Beam of K_L/K_S
  - Discovery of direct CPV
- NA48/1 (2002): Beam of K_s/hyperons
- NA48/2 (2003-2004): Beam of K^+/K^-
  - $K^\pm \to \mu^\pm N, N \to \mu\pi$
- NA62-R_k (2007-2008): Beam of K^+/K^-
  - $K^+ \to \mu^+ N$
- NA62 (Since 2014): Beam of K^+
  2014: pilot run
  2015: Commissioning run
  - $K^+ \to \ell^+ N$

  2016-2018 $K^+ \to \pi^+\nu\bar{\nu}$

- 2014 Pilot run
- 2015 Commissioning run
- Full detector installation completed in september 2016
- First $\pi\nu\bar{\nu}$ data set in 2016
- Continuous data taking until the end of 2018



The aim of the experiment is to measure the BR of the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% accuracy, which requires a high kinematic rejection power, effective photon and muon rejection and excellent particle identification. We produce a secondary positive hadron beam with a central momentum of 75 GeV/c and 1% momentum spread (rms). Kaons from the secondary beam are tagged by a differential Cherenkov counter. Beam particle momenta are measured by a silicon pixel detector (GTK). A 75m long fiducial decay volume in vacuum (FV) follows the last GTK station. In the decay region, a spectrometer made of 4 chambers with straw tubes in vacuum and a dipole magnet measures track directions and momenta (STRAW). Pions and muons are separated by a ring imaging Cherenkov (RICH) detector and muon detectors (MUV1-3). A system of calorimeters (LKr, LAVs, IRC, SAC) detects photons at different acceptances. The nominal instantaneous beam particle rate is 750 MHz, mostly due to π^+ (70%), protons (23%) and K^+ (6%). About 13% of the kaons decay in the FV, leading to about 5 M Hz nominal K^+ rate in the FV. Details of the NA62 beam and detector can be found in [6]

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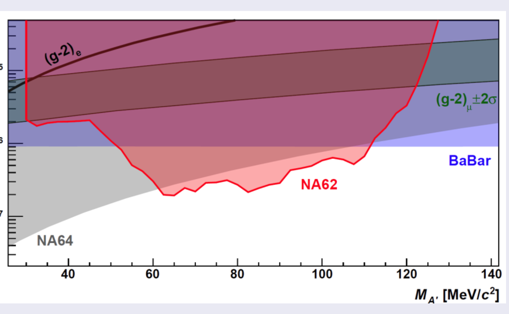
Dark Photons



arXiv:1903.0876, accepted in JHEP

One of the possible extensions of the SM aimed at explaining the abundance of dark matter in our universe predicts a new $U(1)$ gauge-symmetry sector, with a vector mediator field A' named as "dark photon". In a simple realization of such a scenario [14, 15], the $A\prime$ field would (feebly) interact with the SM photon through a "kinetic mixing" Lagrangian with a coupling parameter ϵ. In a general picture, the kinetic mixing Lagrangian might be accompanied by further interactions, both with SM matter fields and with a secluded, hidden sector of possible dark-matter candidate fields. If these are lighter than the $A\prime$, the dark photon would decay mostly "invisibly", so that a missing-energy signature might reveal its presence.
A search for an invisible dark photon $A\prime$ has been performed. The NA62 photon-veto rejection, precisely studied in the context of the analyses for $K^+ \to \pi^+\nu\bar{\nu}$ and for the search for π^0 decays to invisible final states, is paramount for the A' search.

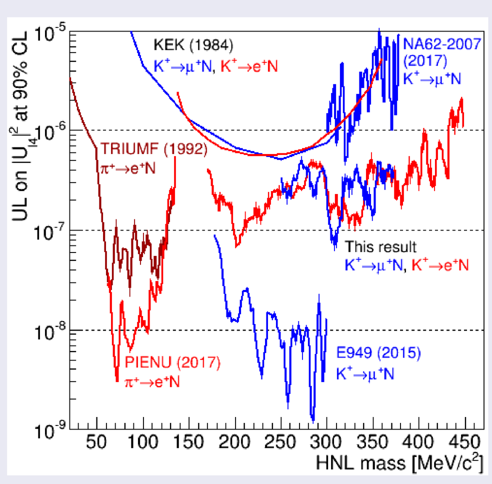
Detailed information about this analysis was given in J. Engelfried's talk in this congress.

Heavy Neutral Leptons (HNL)

The Standard Model (SM) of particle physics requires an extension to explain, among other things, neutral lepton masses, which are very well established due to the observation of neutrino oscillations. One of this SM extensions, the Neutrino Minimal Standard Model (νMSM), propose three massive, right-handed "sterile" neutrinos, also called heavy neutral leptons (HNL), which mix with the ordinary light "active" neutrinos, explaining also dark matter and baryon asymmetry in the universe (BAU) [yumi]. The lightest HNL, with mass of $\mathcal{O}$(10 keV/c^2), is a dark matter candidate. The other two HNL have masses of $\mathcal{O}$(1 GeV/c^2), produce the SM neutrino masses through the see-saw mechanisms and introduce extra CP violating phases to account for BAU.
NA62 perform a search for $K^+ \to \ell^+ N$ decays in the HNL mass range 170-448 MeV/c^2 using a data sample collected with a minimum bias trigger at 1% of the nominal beam intensity, during the first physics data-taking in 2015. The obtained upper limits on $|U_{\ell 4}|^2$ complement, and improve on those obtained in earlier HNL production searches [1, 2, 3, 4, 5].

Upper limits have been established at the level between 10^6 and 10^7 on the HNL mixing parameters $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ in the ranges $170-448 MeV/c^2$ and $250-373 MeV/c^2$, respectively. This improves on the previous limits from HNL production searches over the whole mass range considered for $|U_{e4}|^2$, and above $m_N = 300 MeV/c^2$ for $|U_{\mu 4}|^2$.

See J. Engelfried talk in this congress.



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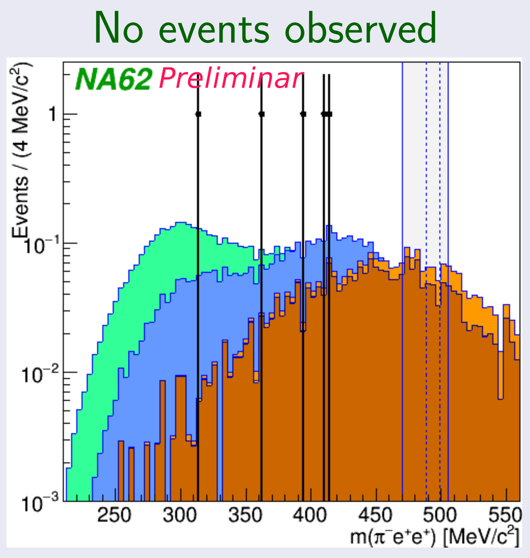
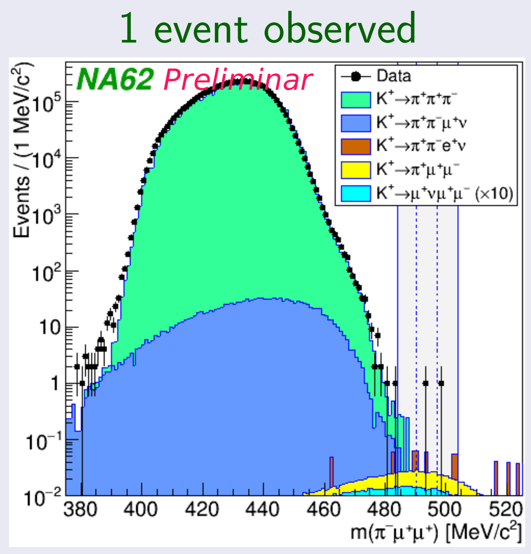
Searches For Lepton Number Violating K^+ Decays (LFV)

A class of processes which may be mediated by a massive Majorana neutrino are the neutrinoless double beta decays of the charged kaon $K^+ \to \pi^- l^+ l^+$ (where $l = e,\ \mu$) violating the lepton number by two units [7, 8]. The current upper limits at 90% CL on the branching fractions of these decays are 6.4×10^{-10} obtained by BNL E865 experiment [9], and 8.6×10^{-11} obtained by CERN NA48/2 experiment [10], respectively.
NA62 perform a search for these processes using a part of the K^+ decay in flight data sample collected in 2016-18, corresponding to about 30% of the total statistics accumulated.

LNV channel $K^+ \to \pi^- e^+ e^+$
No events observed



LNV channel $K^+ \to \pi^- \mu^+ \mu^+$
1 event observed



Search details

- Blind analysis procedure
- Normalization from equivalent SM channels
- Main source of background from π^+ mis-identification and π^+ decays in flight
- Signal acceptance: 4.98% (e),9.81% (μ)
- $N_K = 2.14 \pm 0.07 \times 10^{11}$ (e), $N_K = 7.94 \pm 0.23 \times 10^{11}$ (μ)
- $SES = 0.94 \pm 0.03 \times 10^{-10}$ (e), $SES = 1.23 \pm 0.03 \times 10^{-11}$ (μ)

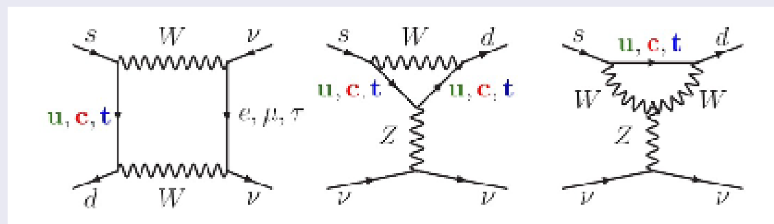
Results

- Improved world limit for $K^+ \to \pi^- e^+ e^+$ and $K^+ \to \pi^- \mu^+ \mu^+$ decays in subset of 2017 data
- Very low background (< 1) searches in both cases
- $B(K^+ \to \pi^- e^+ e^+) < 2.2 \times 10^{-10}$ (previously 6.4×10^{10} E865)
- $B(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ (previously 8.6×10^{-11} NA48/2)

Kaon Rare Decay $K^+ \to \pi^+\nu\bar{\nu}$

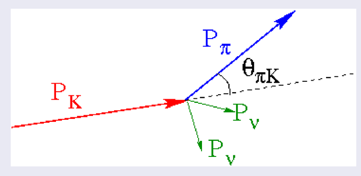
The FCNC Process $K^+ \to \pi^+\nu\bar{\nu}$

- FCNC loop processes: s $\to$ d coupling and highest CKM suppression
- Theoretically clean: Short distance contribution
- Hadronic matrix element measured with K_{l3} decays
- SM predictions: [11, 12] $BR(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30) \times 10^{-11} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2\circ}\right)^{0.74} = (8.4 \pm 1.0) \times 10^{-11}$
- Experimental result: [13] $BR(K^+ \to \pi^+\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$



Analysis Strategy

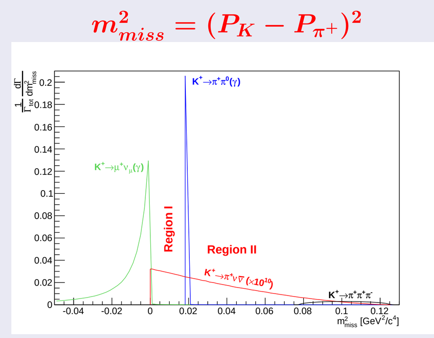
NEW Decay in flight technique



Keystones of the analysis:

- Timing between sub-detectors $\sim O(100$ ps)
- Kinematic suppression $\sim O(10^4)$
- Muon suppression $> 10^7$
- π^0 suppression (from $K^+ \to \pi^+\pi^0$)$> 10^7$

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



Signal and background control regions are kept blind throughout the analysis
$15 < P_{\pi^+} < 35 GeV/c$
Particle ID(Cherenkov detectors)
Particle ID(Calorimeters)
Photon veto

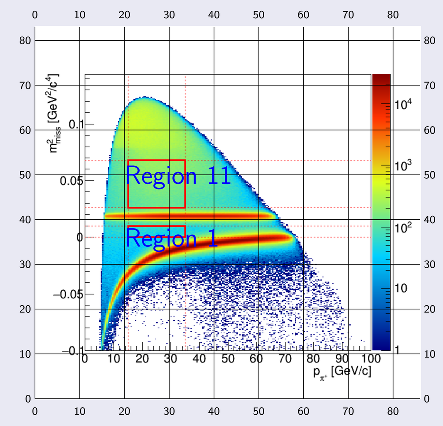
Signal Selection

Selection criteria

- Single track decay topology
- π^+ identification
- Photon rejection
- Multi-track rejection

Three ways to compute the m^2_{miss}

- $m^2_{miss}(STRAW,\ GTK)$
- $m^2_{miss}(RICH,\ GTK)$
- $m^2_{miss}(STRAW,\ Beam)$



π^+ momentum vs m^2_{miss} for single track events taken with control trigger

Single Event Sensitivity (SES)

The single event sensitivity is defined as $SES = 1/(N_k \cdot \sigma_{\pi\nu\bar{\nu}})$, where N_K is the number of K^+ decays and $\sigma_{\pi\nu\bar{\nu}}$ is the signal efficiency for the $\pi\nu\bar{\nu}$ selection.
The measurement of N_K employs a sample of $K^+ \to \pi^+\pi^0$ decays selected on control data using criteria similar to $\pi\nu\bar{\nu}$, except photon and multiplicity rejection and kinematical cuts.

- Signal acceptance:4%
- Normalization acceptance:10%
- Number of kaon decays in the fiducial volume: $N_K = 1.21(2) \times 10^{11}$

$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

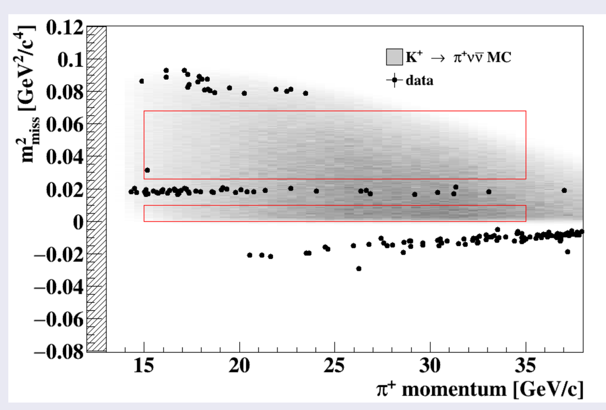
Source of inefficiency	$\delta SES(10^{-10})$
Random veto	0.09
N_K	0.05
Trigger efficiency	0.04
Definition of $\pi^+\pi^0$ region	0.10
Momentum spectrum	0.01
Simulation of π^+ interactions	0.03
Extra activity	0.02
GTK pileup simulation	0.02
Total	0.24

Background Studies

The $K^+ \to \pi^+\pi^0(\gamma)$, $K^+ \to \pi^+\pi^+\pi^0$ and $K^+ \to \pi^+\pi^- e^+\nu$ processes are the major sources of background from K^+ decays.
Sharp kinematic thresholds limit the m^2_{miss} spectrum of $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^+\pi^0$, hence only m^2_{miss} misreconstructions can cause these decays to enter the signal regions.

Process	Expected events in signal region
$K^+ \to \pi^+\pi^0(\gamma)$	$0.35 \pm 0.02_{stat} \pm 0.03_{syst}$
$K^+ \to \mu^+\nu(\gamma)$	$0.16 \pm 0.01_{stat} \pm 0.05_{syst}$
$K^+ \to \pi^+\pi^- e^+\nu$	$0.22 \pm 0.08_{stat}$
$K^+ \to \pi^+\pi^+\pi^0$	$0.15 \pm 0.008_{stat} \pm 0.015_{syst}$
$K^+ \to \pi^+\gamma\gamma$	$0.005 \pm 0.005_{syst}$
$K^+ \to l^+\pi^0\nu_l$	$0.012 \pm 0.012_{syst}$

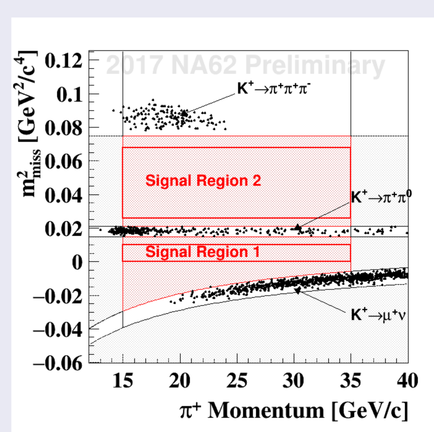
Results 2016 Data



On March 2017 we declared the analysis finished and opened the blinded box:
One event was observed in region 2. This result is compatible with the Standard Model
$BR\ K^+ \to \pi^+\nu\bar{\nu} < 14 \times 10^{-10}$ at 95% CL
The decay on flight method works!
Phys. Lett. B 791 (2019) 156-166

Preliminary Results 2017 Data

The analysis with 2017 data is ongoing, the areas are covered and will be unblinded soon. Is largely similar to 2016 analysis but is expected a factor 10 of improvement from statistics. Signal-over-background do not degrade with intensity.



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