Physics Beyond the Standard Model with NA62

Tomáš Blažek (Comenius University Bratislava)

Tomas.Blazek@fmph.uniba.sk

30 years of Slovak Republic at CERN

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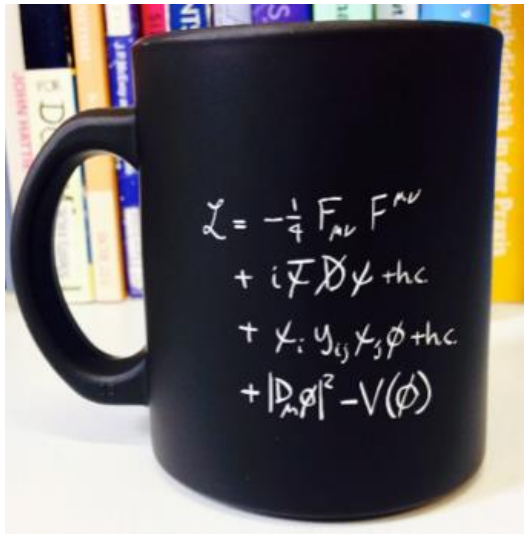

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NA62

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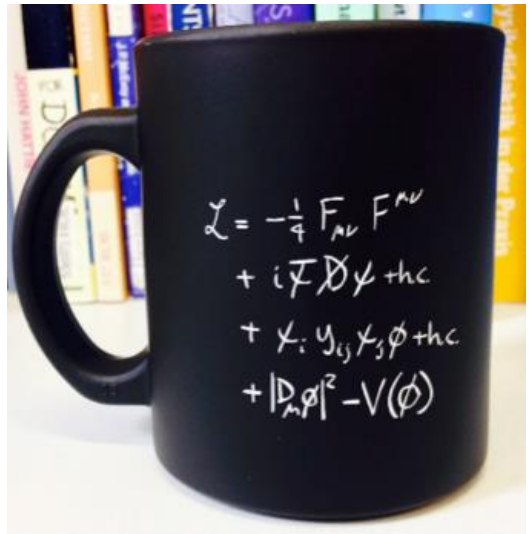

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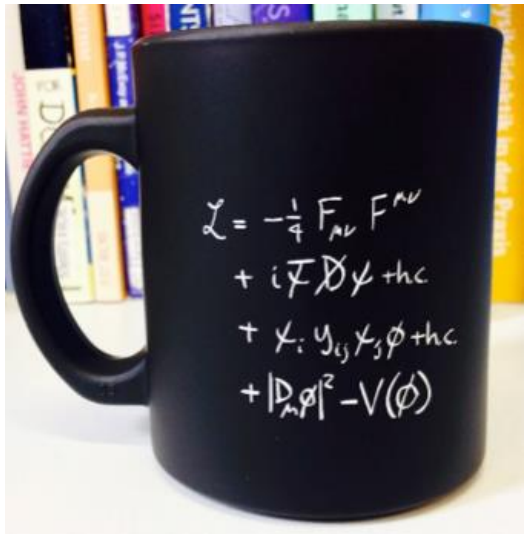

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NA62 Collaboration Week Bratislava 2022

NA62 Collaboration Week Bratislava 2022

Contents:

The NA62 Experiment

First *evidence* for $K^+ \to \pi^+ \nu\,\bar{\nu}$ decay

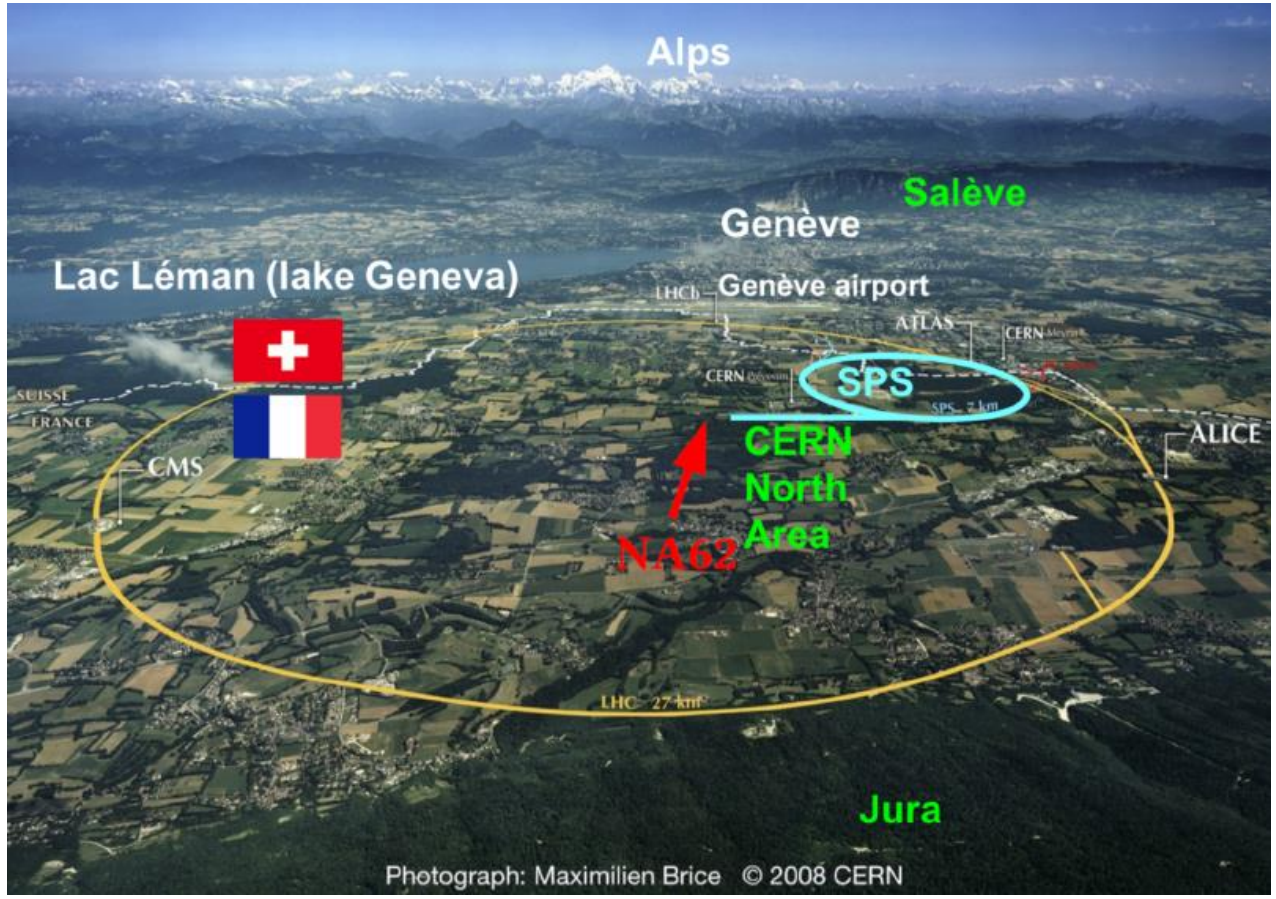
Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Searches for Lepton Flavor/Number violation in K^+ decays

Beam Dump Mode: Searches for new feebly interacting particles

More on NA62 results on 28/6 by Zdenko Híveš

The NA62 Experiment at CERN



~ 30 institutes, ~ 300 collaborators

K^+ decays in flight

Data taking

- 2016 Commissioning + Physics run (45 days).
- 2017 Physics run (160 days).
- 2018 Physics run (217 days).
- 2021 Physics run (85 days [10 beam dump]).
- 2022 Physics run (215 days).
- 2023 Physics run ongoing…

Continues long history of Kaon Physics at CERN

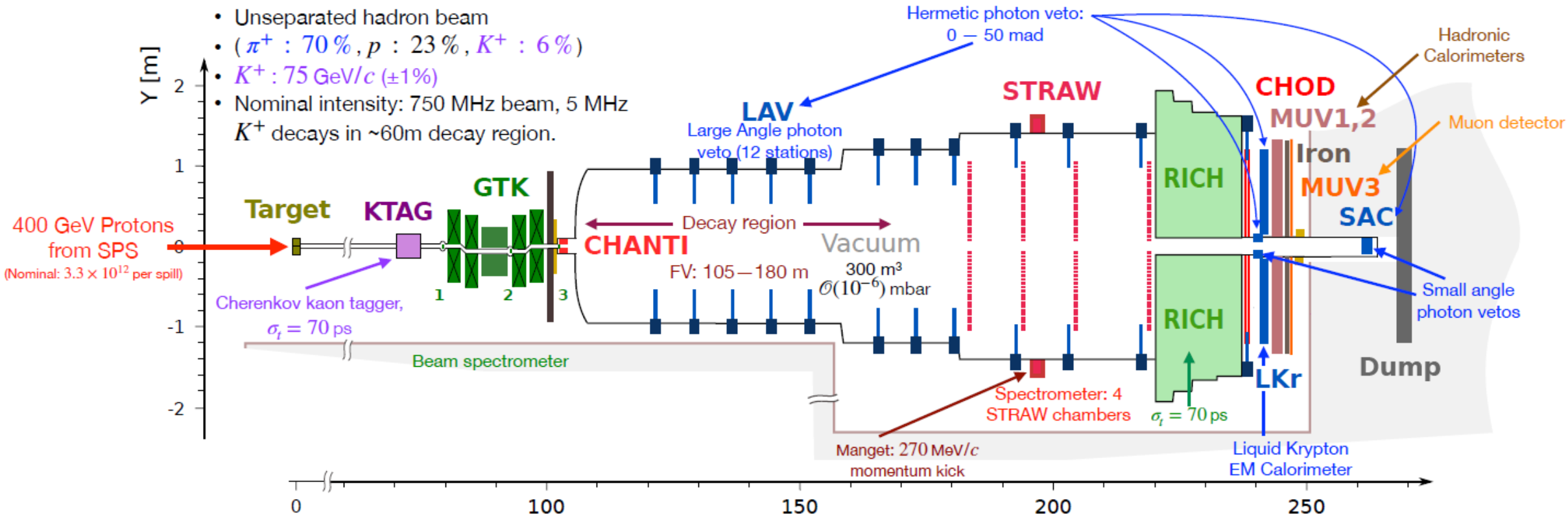
Primary goal: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

Other rare or SM forbidden K+ decays

Beam Dump Mode - Exotics searches

The NA62 Experiment at CERN

NA62 Beamline & Detector



K+ decays inside the detector

JINST 12 (2017) P05025

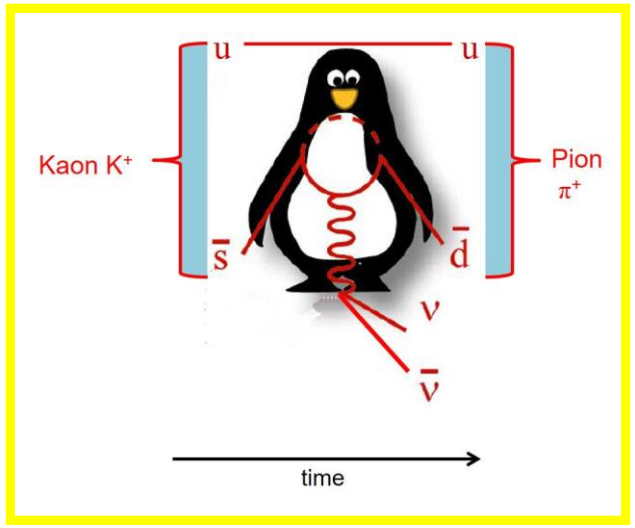
Particle Tracking: upstream GTK, decay region STRAW
P. Identification : upstream KTAG, downstream RICH, LKr, MUVs
Veto: CHANTI, LAV, IRC, SAC

The NA62 Experiment at CERN

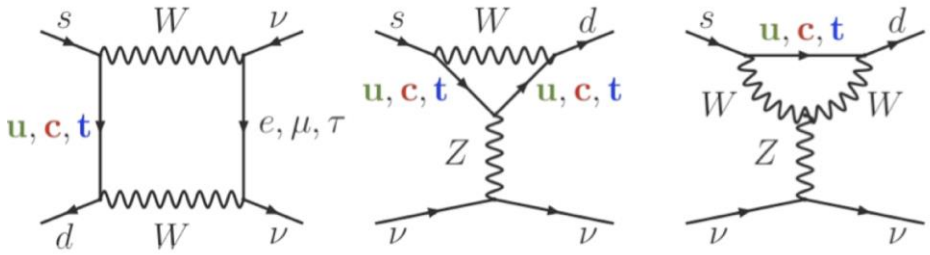
Comenius University contribution

- Local Trigger Unit software (dominant contribution by *V. Černý*)
- Data Acquisition
- Straw spectrometer: experts, efficiency improved, 2025 update
- GTK experts, coordinator (*A. Kleimenova, Z. Kučerová*)
- Dalitz π0 decay analysis (*PhD. M. Koval'*)
- K to πμμ analysis (*PhD. L. Bičian*)
- K+ π+ matching and K+ to π+ νν-bar (*Phd. Z. Kučerová*)
- K to πX analysis (*R. Volpe*)
- Exotics searches (*A. Kleimenova*)

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



In **Standard Model**:

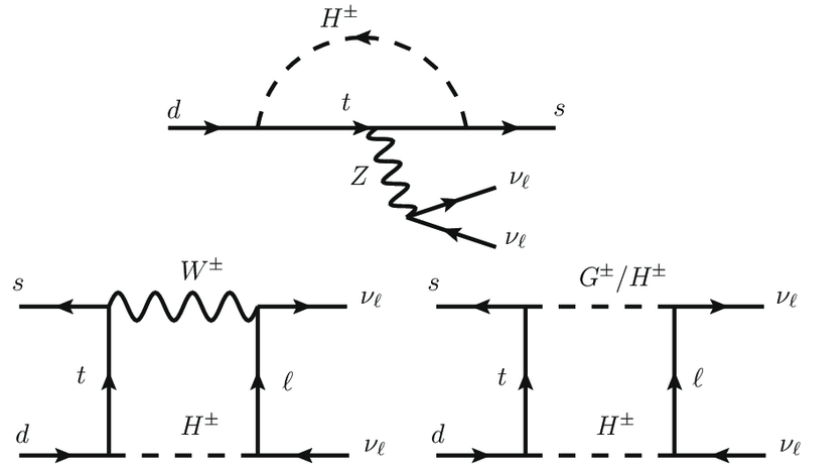


Theoretically clean, BR($K^+ \to \pi^+ \nu$ ν-bar) = (8.6 ± 0.42) x 10^{-11} dubbed „Golden Channel“

A. Buras: arXiv:2205.01118v2

VERY RARE !!

In **Minimal SUSY Model**:

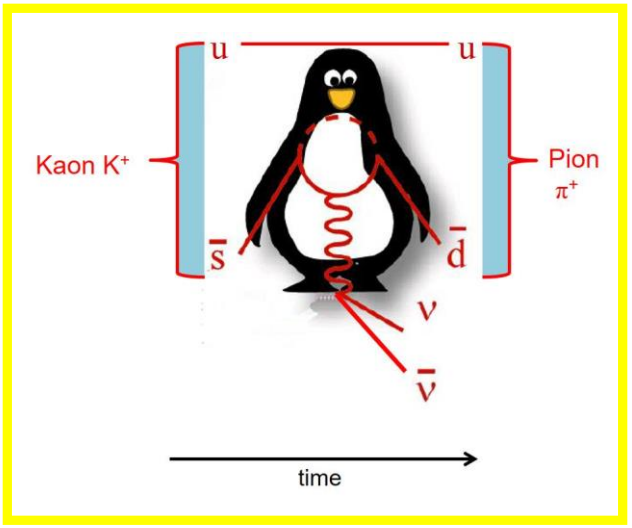


\+ sparticle diagrams

T.Blažek, P.Maták: *Int.J.Mod.Phys. A29 (2014)* 1450162

Also papers by other authors

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



NA62 Experiment: 20 signal events from 2016 - 2018

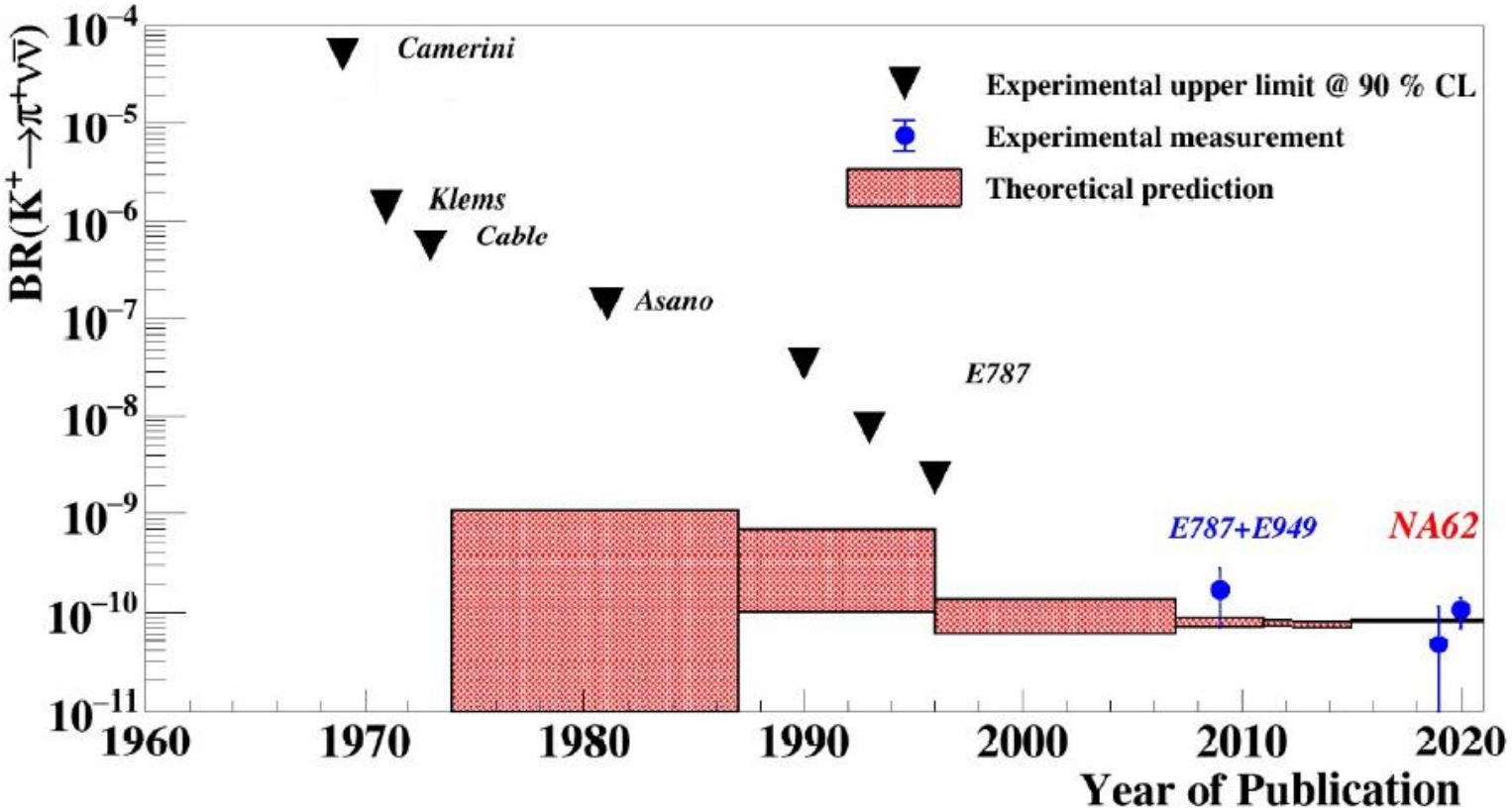
2021 – 2025 MORE TO COME !!

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

JHEP 06 (2021) 093

SM: BR($K^+ \to \pi^+ \nu$ ν-bar) = (8.6 ± 0.42) x 10^{-11}

A. Buras: arXiv:2205.01118v2



Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

General remarks

Heavy neutral lepton may be a right-handed neutrino

Observable due to mixing btw heavy neutral leptons and active neutrinos

$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

PLB 96 (1980) 159
PRD 24 (1981) 1232

$$\rho_\ell(m_N) = \frac{(x+y) - (x-y)^2}{x(1-x)^2} \cdot \lambda^{1/2}(1, x, y)$$

... a kinematic factor
with $x = (m_\ell / m_K)^2$, $y = (m_N / m_K)^2$ and
$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ac)$

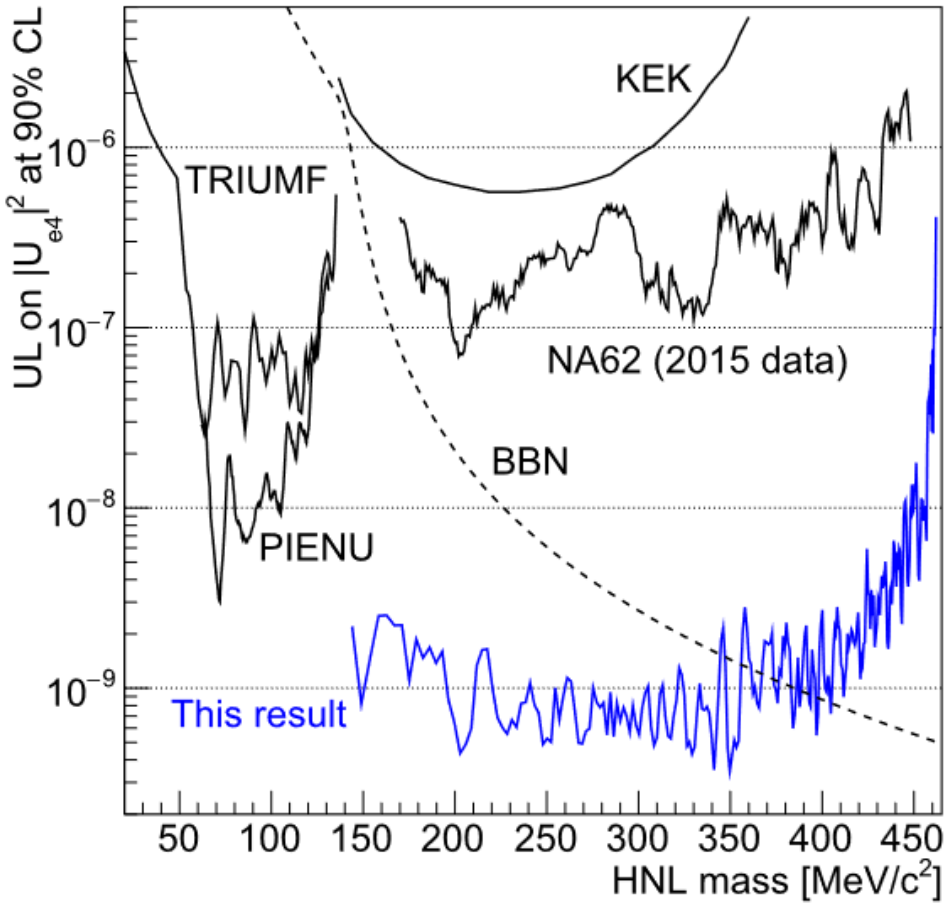
For $|U_{\ell 4}|^2 < 10^{-4}$ the heavy neutral lepton can be treated as stable, since it interacts too weakly with SM particles

2017-2018 data were used

Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Search for heavy neutral lepton in positron mode $K^+ \to e^+ N$

Results



PLB 807 (2020) 135599

Upper Limits on mixing

Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Search for heavy neutral lepton in muon mode $K^+ \to \mu^+ N$

PLB 816 (2021) 136259

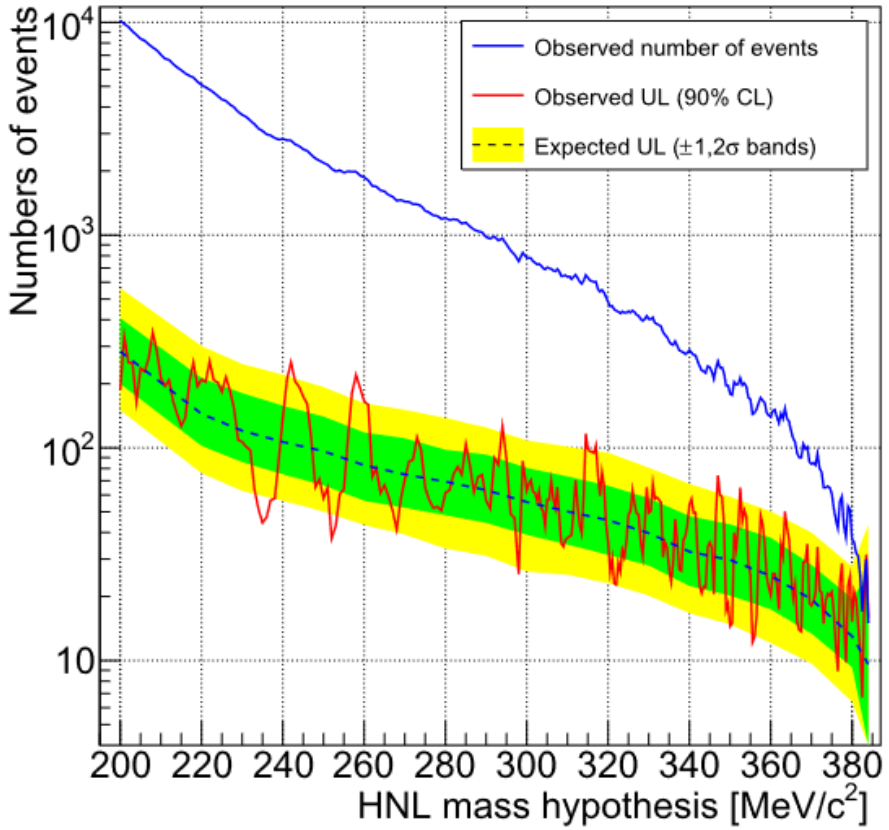
The effective number of K^+ decays in the data sample ~ 1.14 x 10^{10} ,
from the reconstructed $K^+ \to \mu^+ \nu$ (2.19 x 10^9 events in the sample)

Background source	Estimated background						
$K^+ \to \mu^+ \nu\gamma$	6224	±	105_{stat}	±	333_{PV}	±	780_{tail}
$K^+ \to \pi^0 \mu^+ \nu$	1016	±	47_{stat}	±	178_{PV}		
$K^+ \to \pi^+ \pi^+ \pi^-$	309	±	32_{stat}				
Total background	7549	±	119_{stat}	±		920_{syst}	

PV = Photon Veto systematics

$$\mathcal{B}(K^+ \to \mu^+ \nu) = 0.6356 \pm 0.0011$$

Results:



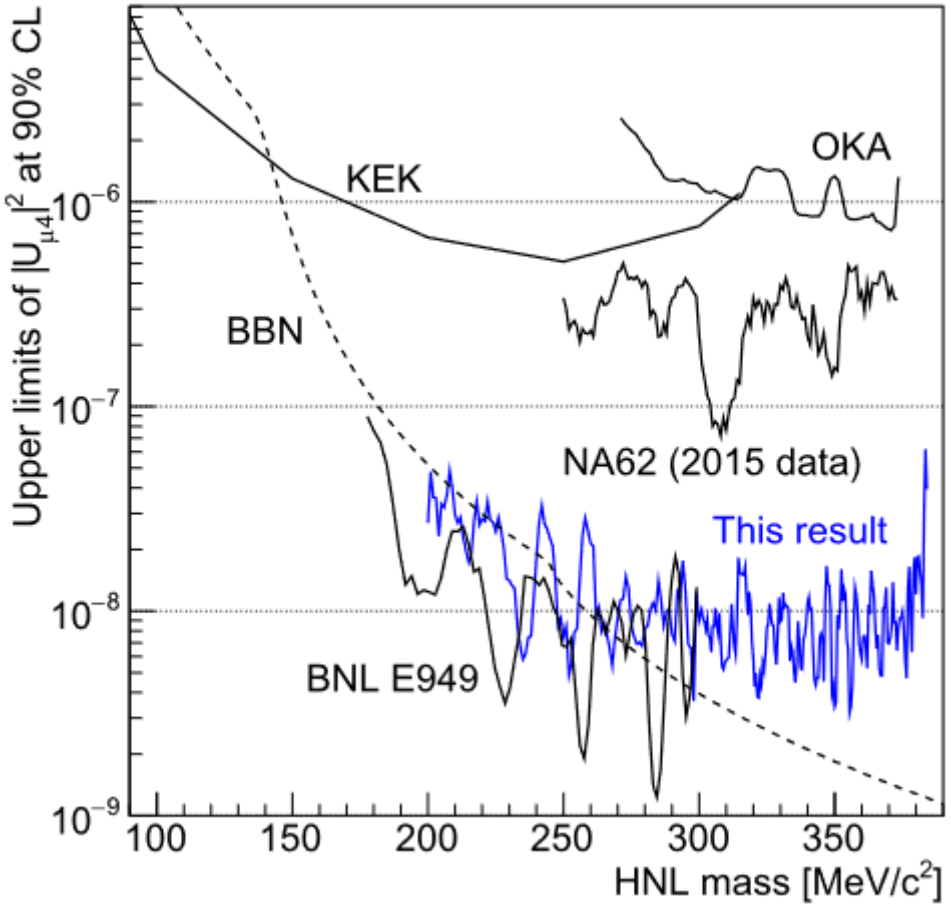
Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Search for heavy neutral lepton in muon mode $K^+ \to \mu^+ N$ PLB 816 (2021) 136259

Results compared:

Upper Limits on mixing

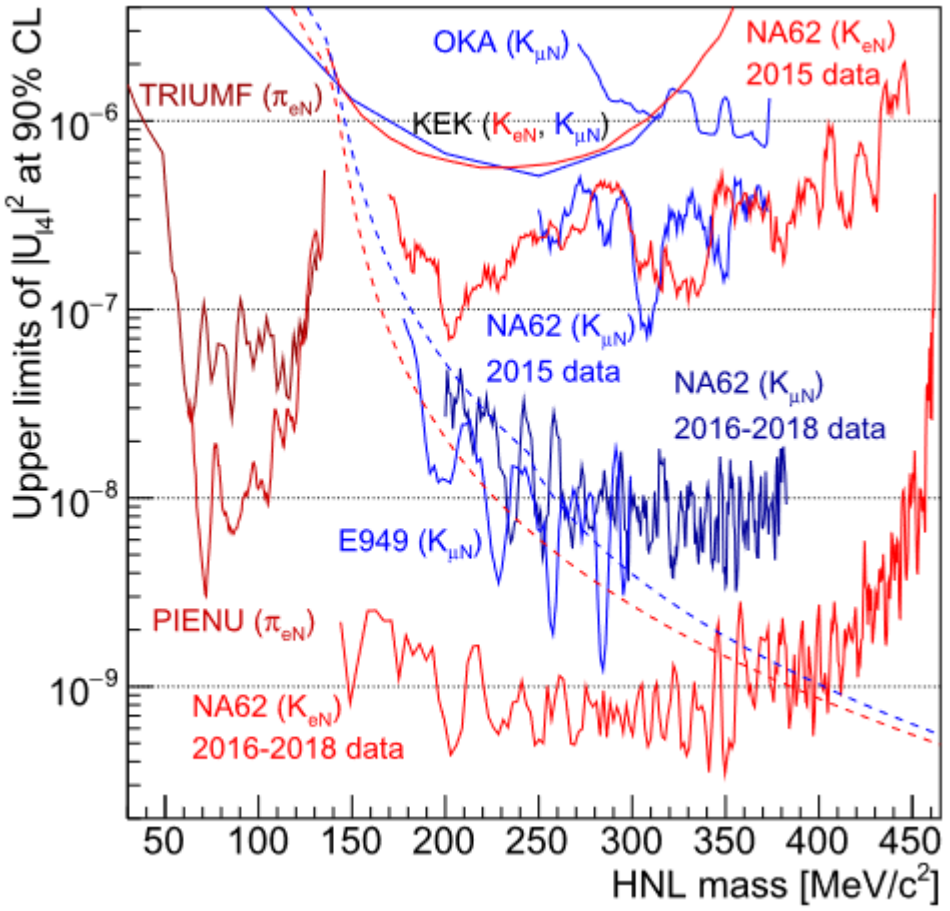
Dashed line: Lower Limits on mixing from Big Bang Nucleosynthesis (BBN) Nucl.Phys.B590 (2000) 562



Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Combined Results compared

PLB 816 (2021) 136259



Upper Limits on mixing with ν_μ

Upper Limits on mixing with ν_e

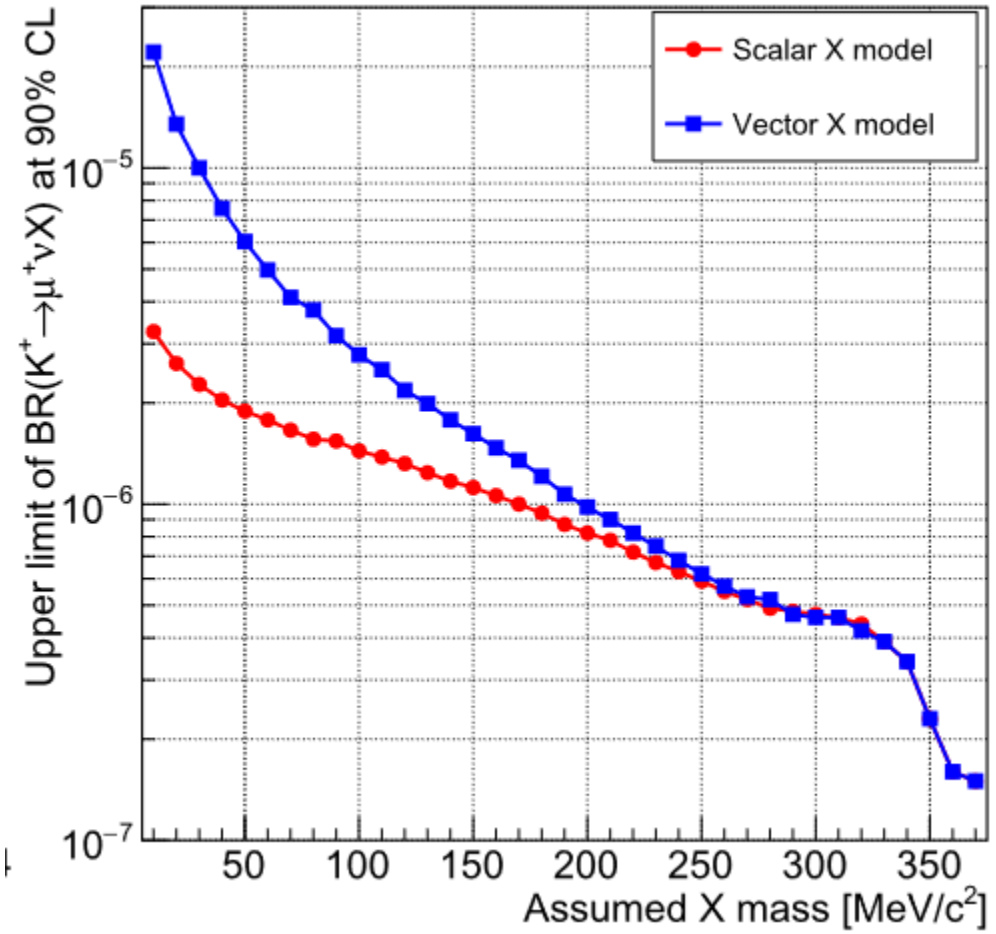
Searches for $K^+ \to e^+ N$, $K^+ \to \mu^+ N$, $K^+ \to \mu^+ \nu X$ decays

Search for heavy scalar or vector mediator X: $K^+ \to \mu^+ \nu X$

PLB 816 (2021) 136259

Assume: X is from hidden sector, it decays to invisible final states

Results



Upper Limits on the scalar mode are stronger due to larger mean m_{miss} than in the vector mode

Note:
Update on $K^+ \to \pi^+ X$ decays can be found in:

2023 Rep. Prog. Phys. 86 016201
arXiv: 2201.07805

Searches for $K^+ \to \mu^+ \nu\,\nu\,\nu$ decays

PLB 816 (2021) 136259

N_{obs} = 6894 events are observed in the signal region $m^2_{miss} > 0.1\ GeV^2/c^4$,
with an expected background of $N_{exp} = 7549 \pm 928$ events.

This leads to an observed (expected) upper limit at 90% CL of 1184 (1526) events for the number of signal events N_S.

An upper limit is established on the decay rate using the relation $N_S = N_K \cdot \mathcal{B}(K^+ \to \mu^+ \nu\nu\bar{\nu}) \cdot A_{\mu\nu\nu\nu}$, where a reduced signal acceptance $A_{\mu\nu\nu\nu} = 0.103$ and the sample from the search for heavy neutral lepton in muon mode $K^+ \to \mu^+ N$ is used.

Result:

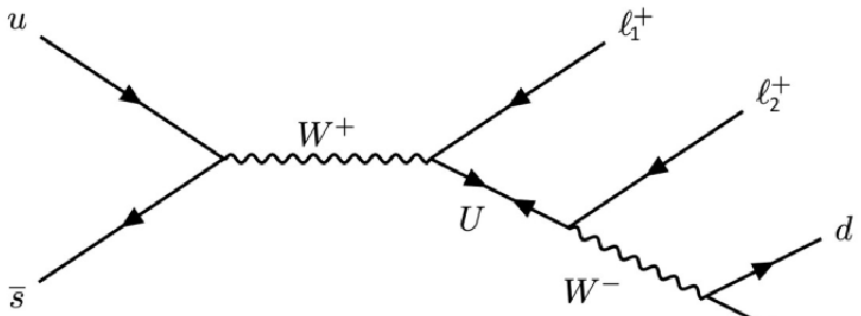
$$\mathcal{B}(K^+ \to \mu^+ \nu\nu\bar{\nu}) < 1.0 \times 10^{-6} \quad \text{at 90\% CL}$$

Searches for Lepton Flavor/Number Violation in K+ decays

LF / LN are global symmetries in SM with m_ν=0. LFV observed in ν oscillations.

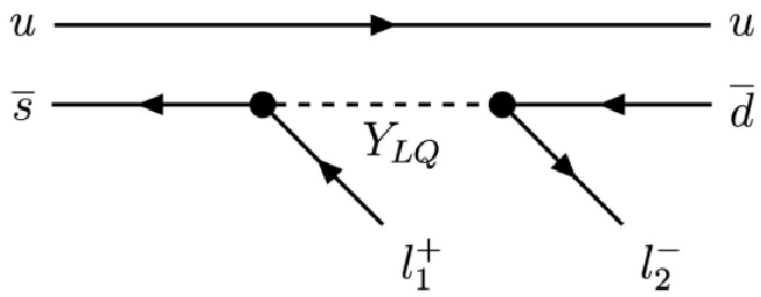
If observed in K+ decays, LFV/LNV would be clear sign of Beyond SM Physics

Example: $K^+ \to \pi^- \ell^+ \ell^+$ (LNV) Here, heavy Majorana neutrino might act similarly to the 0νββ decay



$K^+ \to \pi^- \ell^+ \ell^+$ (LNV)

Example: $K^+ \to \pi^\pm \mu^\mp e^+$ (LFV) Here, a heavy LeptoQuark might act to mediate such a decay



$K^+ \to \pi^\pm \mu^\mp e^+$ (LFV)

PLB 491 (2000) 285,
JHEP 05 (2009) 030

Searches for Lepton Flavor/Number Violation in K+ decays

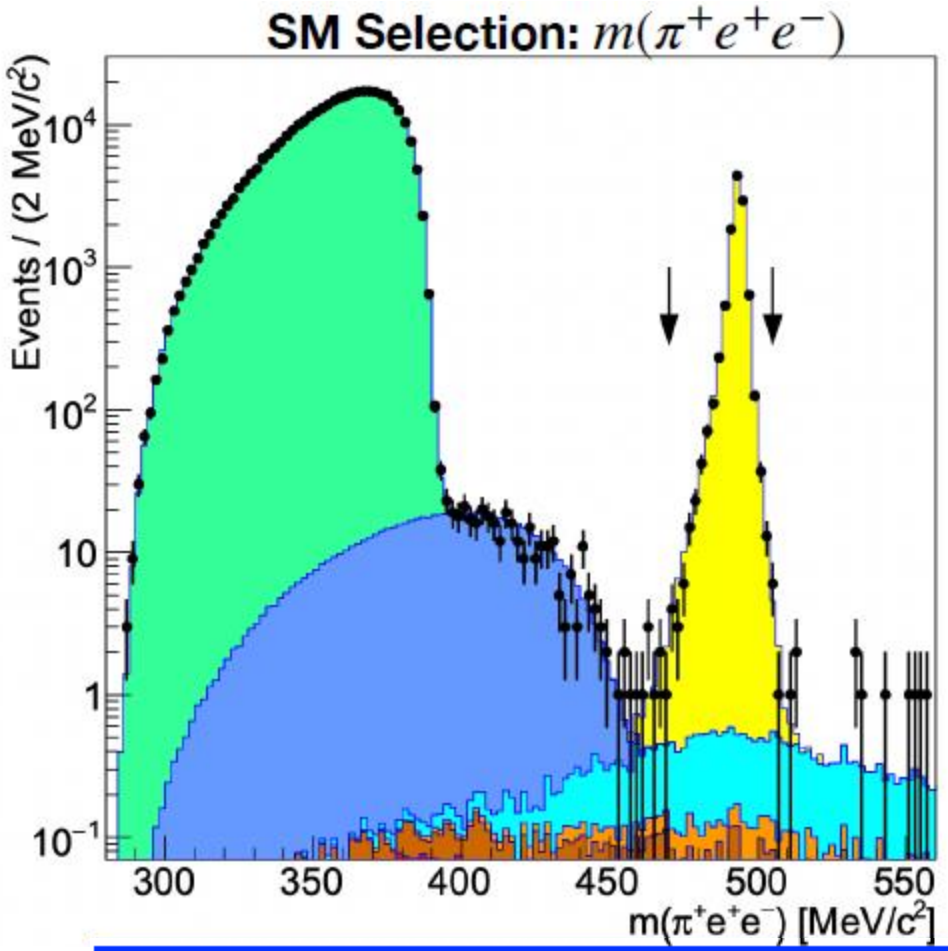
NA62 Searches in 2016-2018 data:

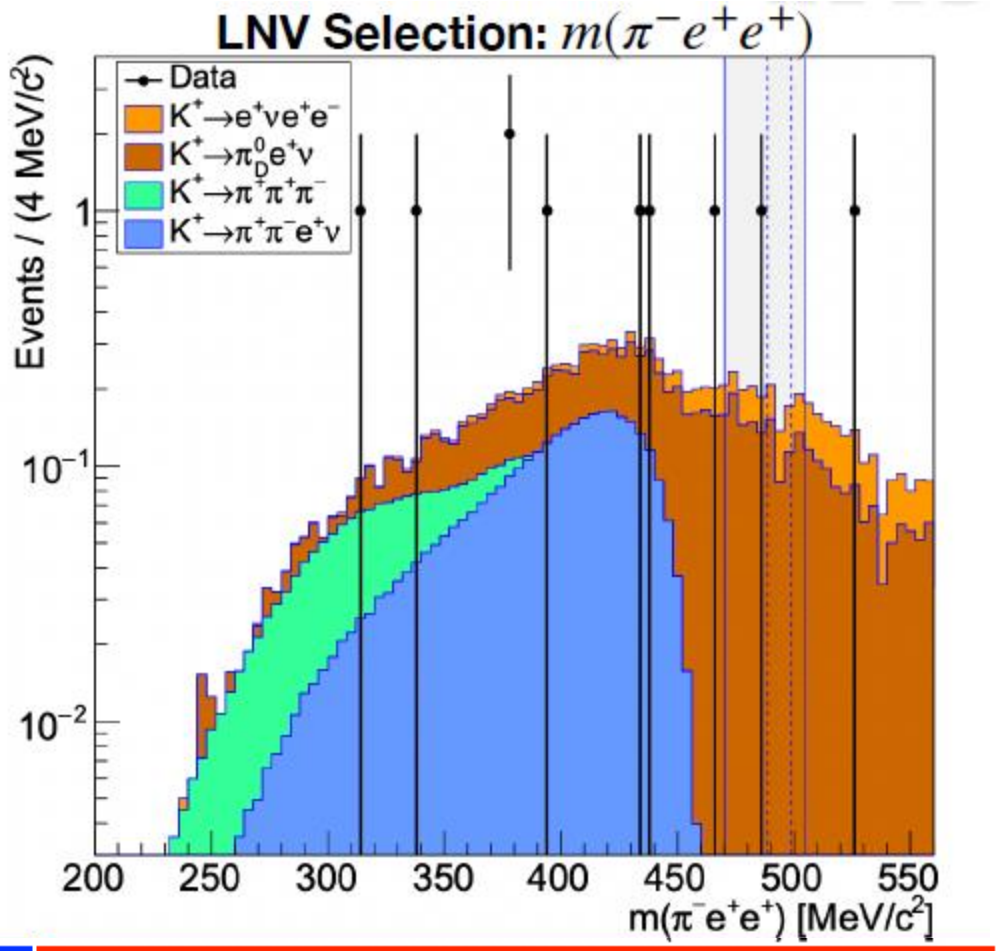
$K^+ \to \mu^- \nu e^+ e^+$	BF < 8.1×10^{-11}	PLB 838 (2023) 137679
$K^+ \to \pi^- e^+ e^+$	BF < 5.3×10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	BF < 8.5×10^{-10}	
$K^+ \to \pi^- \mu^+ \mu^+$	BF < 4.2×10^{-11}	PLB 797(2019) 134794
$K^+ \to \pi^- \mu^+ e^+$	BF < 4.2×10^{-11}	
$K^+ \to \pi^+ \mu^- e^+$	BF < 6.6×10^{-11}	PRL 127(2021) 13, 131802
$\pi^0 \to \mu^- e^+$	BF < 3.2×10^{-10}	

All Limits are at 90% C.L.

Searches for Lepton Flavor/Number Violation in K+ decays

Search for $K^+ \to \pi^- e^+ e^+$ as an example PLB 830 (2022) 137172

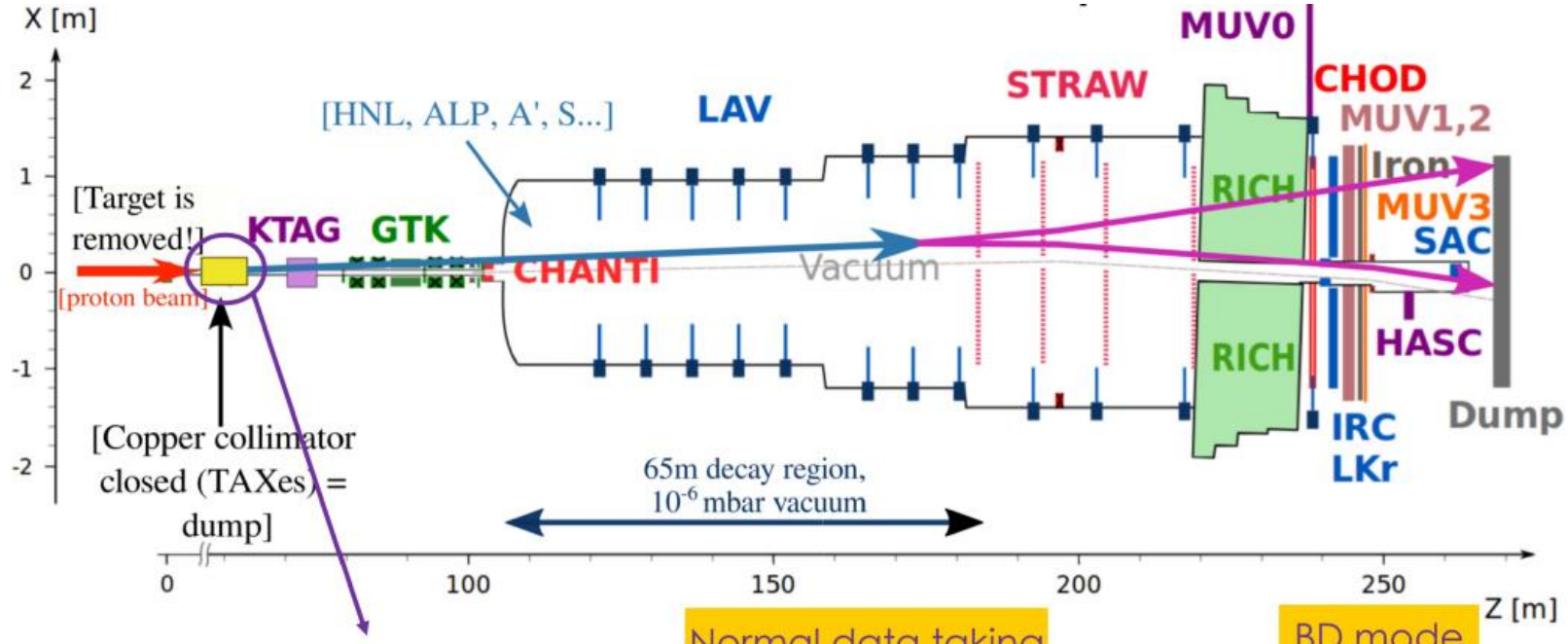


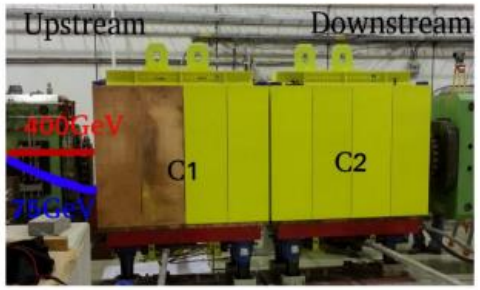


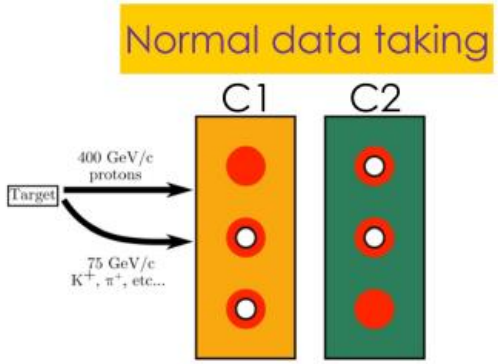
- 11041 candidates
- $\mathcal{B}(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$
- Effective # of K^+ decays in FV = $(1.015 \pm 0.031) \times 10^{12}$

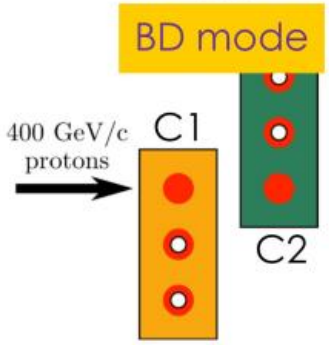
- Expected background = 0.43 ± 0.09
- Candidates observed: 0
- $\mathcal{B}(K^+ \to \pi^-e^+e^+) < 5.3 \times 10^{-11}$ at 90 % CL

NA62 Searches in Beam Dump Mode









NA62 Searches in Beam Dump Mode

Searches for Dark Photon A'_μ (gauge invariant field strength tensor $F'_{\mu\nu}$) ,

Kinetic mixing with the SM field $B_{\mu\nu}$: $\mathcal{L} \supset -\varepsilon \frac{1}{2cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$

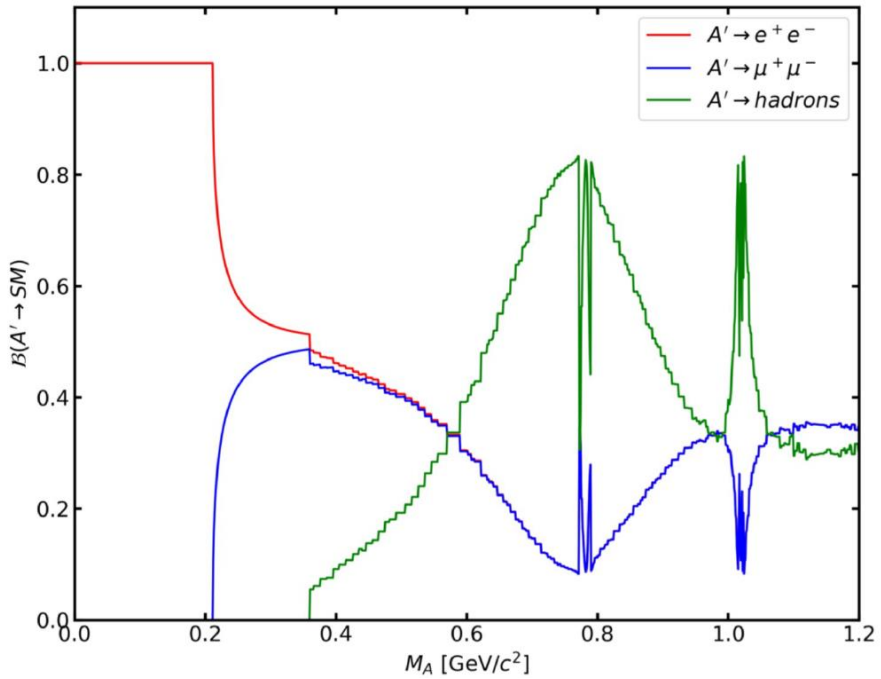
Free parameters: Mass of Dark Photon and coupling

Production: Dark Photon from p N → X A'
(bremsstrahlung)

OR

from meson decay p N → X M,
M → A' γ (π^0), where M= π^0, ω, ρ, etc.

Deacy: for DP mass < 700 MeV the decay is dominated by lepton-antilepton final states



NA62 Searches in Beam Dump Mode

Searches for Dark Photon A'_{μ}

<u>NA62 sensitivity</u> to Dark Photon:
in 2021, NA62 collected 1.4 x 10^{17} POT in 10 days

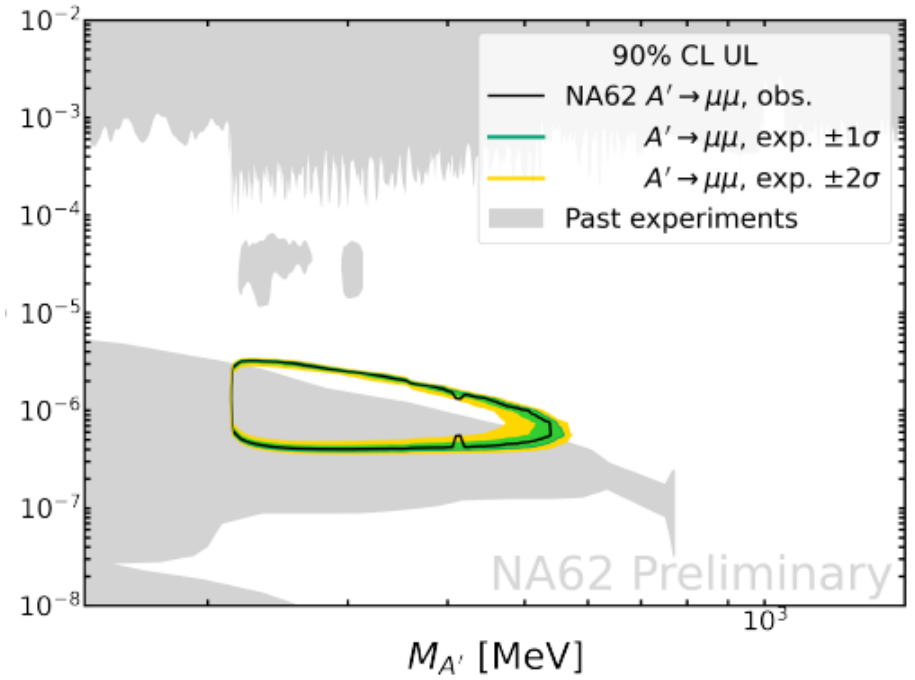
The plots show observed exclusion contours with 1σ and 2σ expected bands for the $\mu^+ \mu^-$ and $e^+ e^-$ search at NA62 in Beam Dump Mode.

The plots assume the lepton decay mode, NA62 geometrical acceptance and zero events observed.
Mass $M_{A'}$ and coupling ε are free parameters.

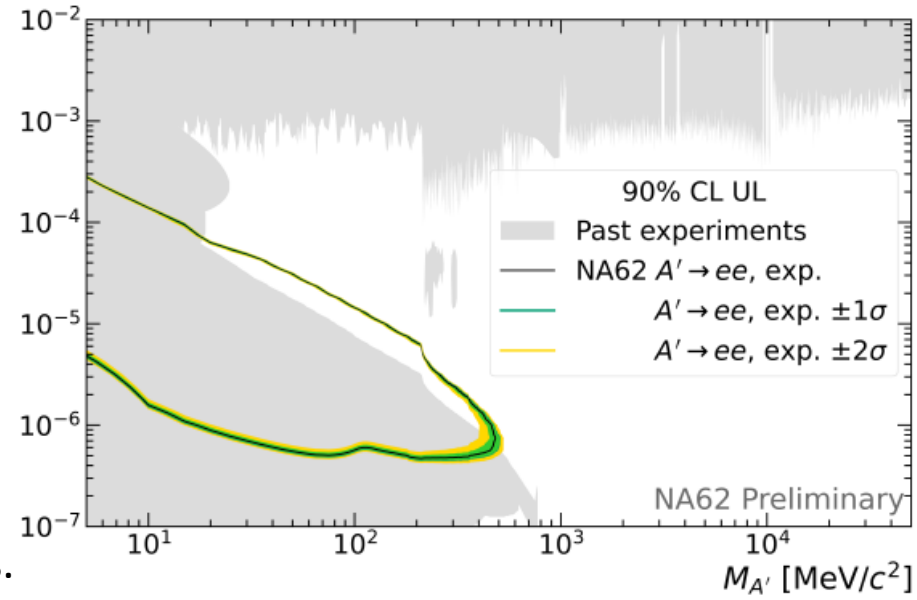
Shaded regions are excluded by other experiments.

This is the first search for production and decay of dark photons at NA62 in the beam dump mode. No evidence of a dark photon was found. Part of the exclusion regions go beyond previous experiments. Can be re-interpreted as emission of axionlike particles.

ε (epsilon)



ε (epsilon)



$A' \to \mu^+\mu^-$

- Dark Photon model – SM extension
- New vector field $F'_{\mu\nu}$ feebly interacting with SM fields
- Free parameters: mass $M_{A'}$, coupling ϵ
- $M_{A'} < 700$ MeV/c^2 $\to$ decay width dominated by l^+l^- final states

Beam-dump mode

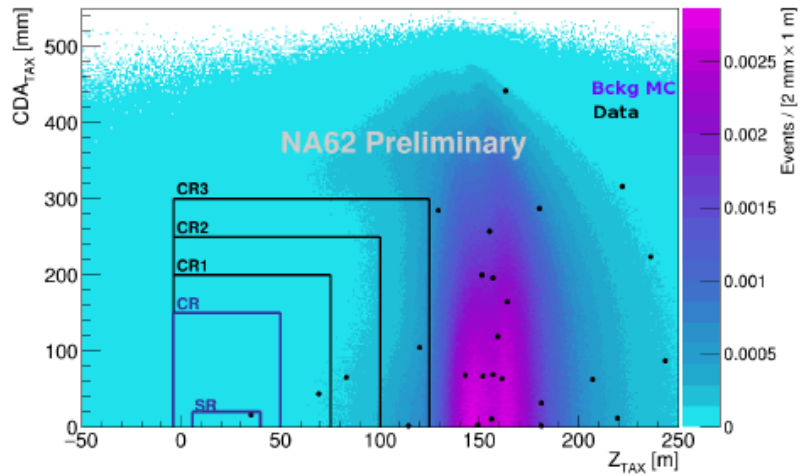
- Target removed
- 3.2 m Cu-Fe collimators put in the beam path
- 1.5 $\times$ nominal beam intensity
- $(1.40 \pm 0.28) \times 10^{17}$ POT collected in $\sim$ 10 days

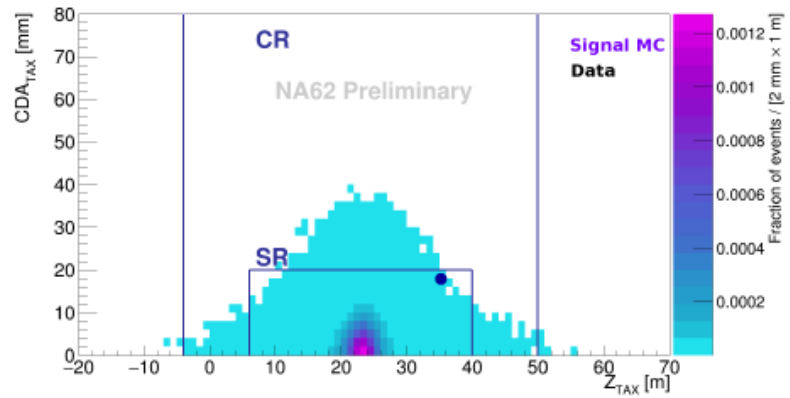
Signal selection:

- Primary vertex close to p^+ beam impact point
- l^+l^- vertex within NA62 fiducial volume
- μ identification
- Reject background from μ interactions with detector material

[contribution, KAON2022]

- Dominant background from random superposition of two uncorrelated μ
- Signal and control regions masked during analysis
- Beam optimization in 2021 $\Rightarrow$ background reduced 200$\times$ wrt 2018 despite higher intensity





Conclusions

Presented NA62 results on the Golden Channel BR($K^+ \longrightarrow \pi^+ \nu\,\nu$-bar)
and on processes only allowed in Beyond Standard Model Physics

NA62 Physics Run I (2017 - 2018)

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6\ ^{+4.0}_{-3.8}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

- Presented NEW upper limits on Heavy Neutral Lepton mixing with active neutrinos.
  on branching fractions $K^+ \to \mu^+ \nu X$ and $\mathcal{B}(K^+ \to \mu^+ \nu\nu\bar{\nu})$

- Presented NEW upper limits on LFV/LFN kaon decays
  - $K^+ \to \mu^- \nu\, e^+ e^+$ BF < 8.1×10^{-11}
  - $K^+ \to \pi^- e^+ e^+$ BF < 5.3×10^{-11}
  - $K^+ \to \pi^- \pi^0 e^+ e^+$ BF < 8.5×10^{-10}
  - $K^+ \to \pi^- \mu^+ \mu^+$ BF < 4.2×10^{-11}
  - $K^+ \to \pi^- \mu^+ e^+$ BF < 4.2×10^{-11}
  - $K^+ \to \pi^+ \mu^- e^+$ BF < 6.6×10^{-11}
  - $\pi^0 \to \mu^- e^+$ BF < 3.2×10^{-10}

NA62 Physics Run II (2021)

- Dark Photon $A'_\mu \to \mu^+ \mu^-$ and $A'_\mu \to e^+ e^-$ exclusion contours presented for the NA62 operating in Beam Dump Mode

NA62 Physics Run II ongoing … please stay tuned