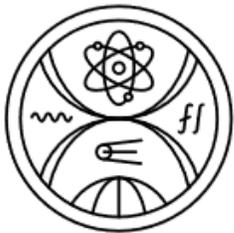
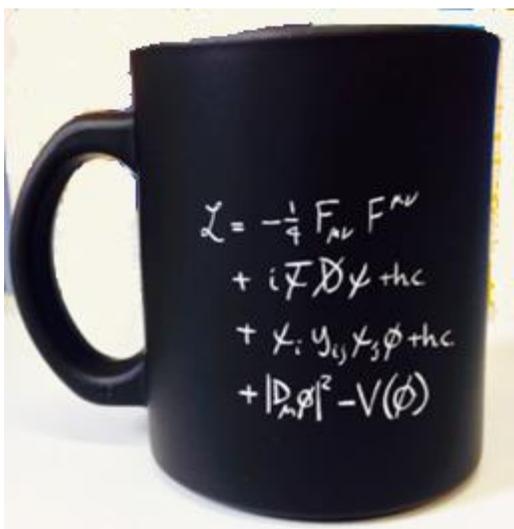


## NA62 Experiment at CERN and Physics Beyond the Standard Model

Tomáš Blažek (Comenius University Bratislava)  
*on behalf of the NA62 Collaboration*

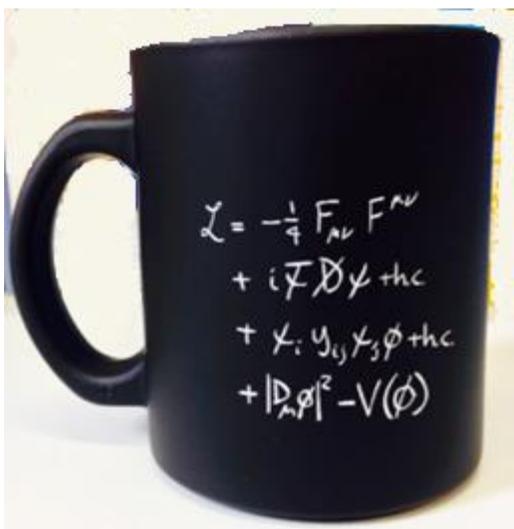


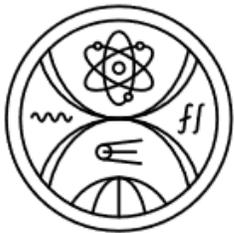
## NA62 Experiment at CERN and Physics Beyond the Standard Model



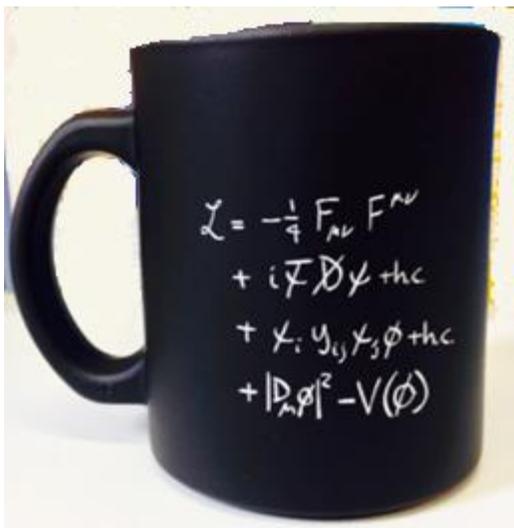


## NA62 Experiment at CERN and Physics Beyond the Standard Model





## NA62 Experiment at CERN and Physics Beyond the Standard Model



+





## Outline:

The NA62 Experiment

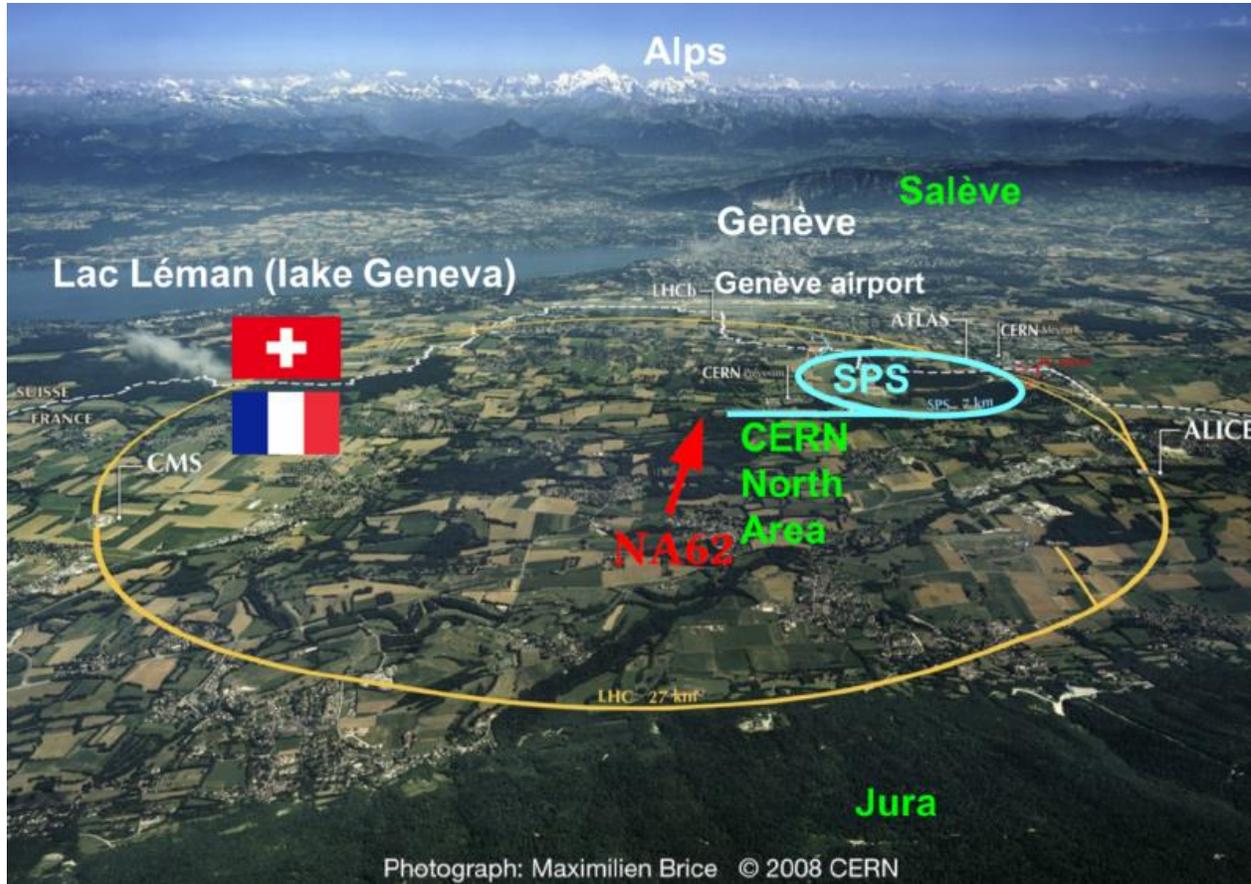
First *evidence* for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  decay

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

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

Beam Dump Mode: Searches for new feebly interacting particles

# The NA62 Experiment at CERN



~ 30 institutes, ~ 300 collaborators

K<sup>+</sup> 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*

## NA62 dataset

### Run I (this talk)

- 2016: 30 days,  $2 \times 10^{11}$  useful K decays
- 2017: 161 days,  $2 \times 10^{12}$  useful K decays
- 2018: 217 days,  $4 \times 10^{12}$  useful K decays

### Run2 (analysis in progress)

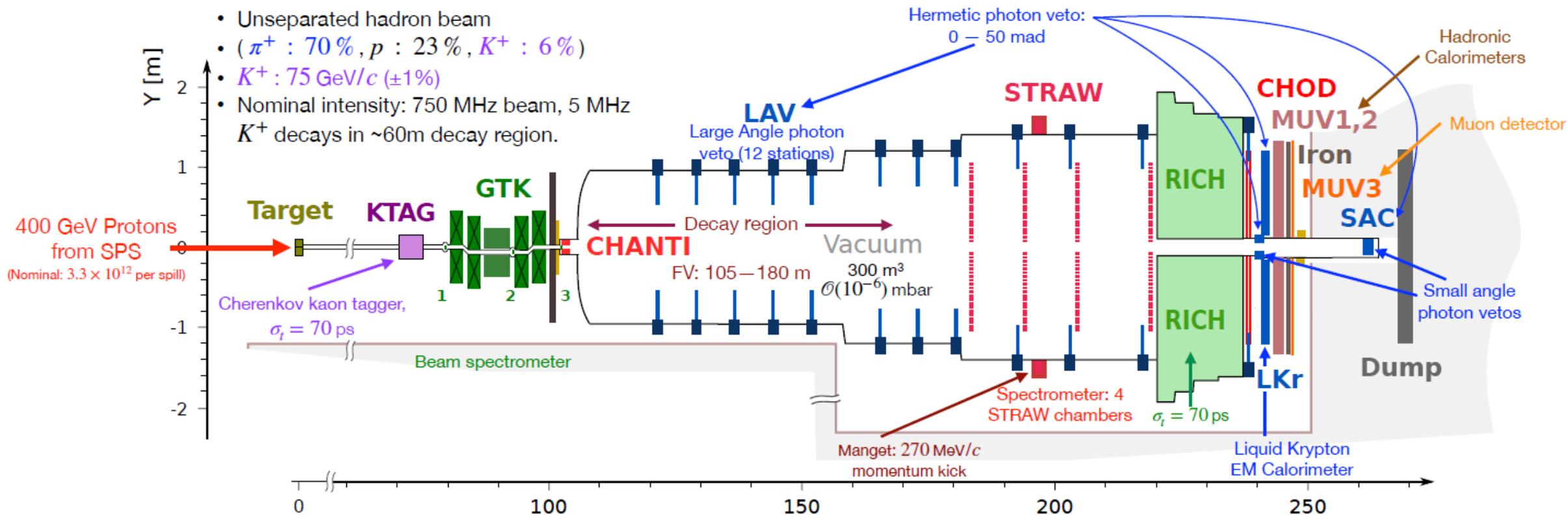
- 2021: 85 days
- 2022: 215 days
- 2023 – LS3: ongoing

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

Other rare or SM forbidden K<sup>+</sup> decays  
Beam Dump Mode - Exotics searches

# The NA62 Experiment at CERN

## NA62 Beamline & Detector



**K<sup>+</sup> 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

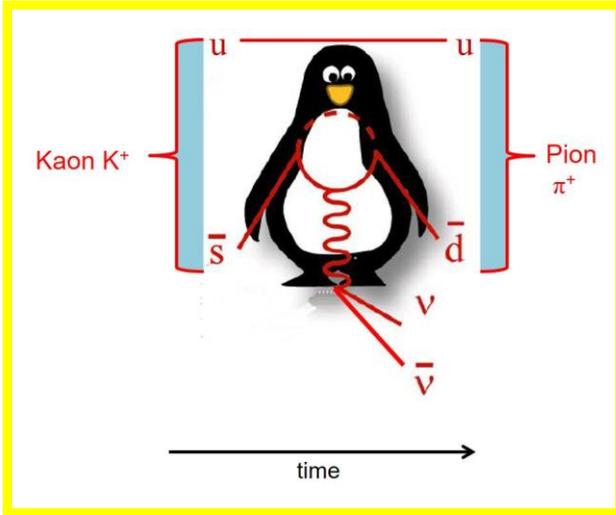
# The NA62 Experiment at CERN

## Comenius University contribution

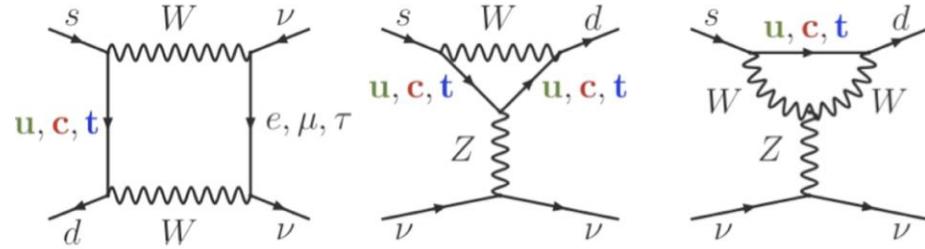
- Local Trigger Unit software (dominant contribution by *V. Černý*)
- Data Acquisition
- Straw spectrometer: experts, efficiency improved, 2025 update
- GTK experts, coordinator (*A. Kleimenova, Z. Kučerová*)
- Dalitz  $\pi^0$  decay analysis (*PhD. M. Koval'*)
- $K$  to  $\pi\mu\mu$  analysis (*PhD. L. Bičian*)
- $K^+ \pi^+$  matching and  $K^+$  to  $\pi^+ \nu\bar{\nu}$  (*Phd. Z. Kučerová*)
- $K$  to  $\pi X$  analysis (*R. Volpe*)
- Exotics searches (*A. Kleimenova*)



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



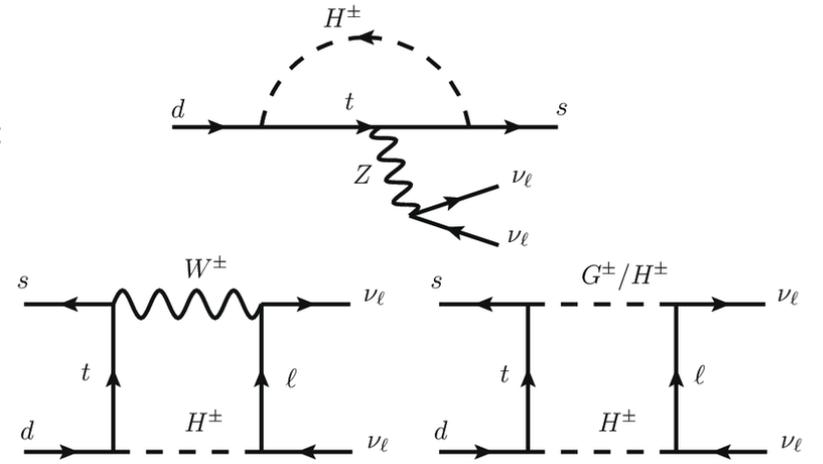
In Standard Model:



Theoretically clean,  $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.6 \pm 0.42) \times 10^{-11}$  dubbed „Golden Channel“  
 A. Buras: [arXiv:2205.01118v2](https://arxiv.org/abs/2205.01118v2), *Eur.Phys.J.C* 83 (2023) 1, 66  
 A.Buras, E.Venturini: *Acta Phys. Polon. B* 53 (9, 2021) A1

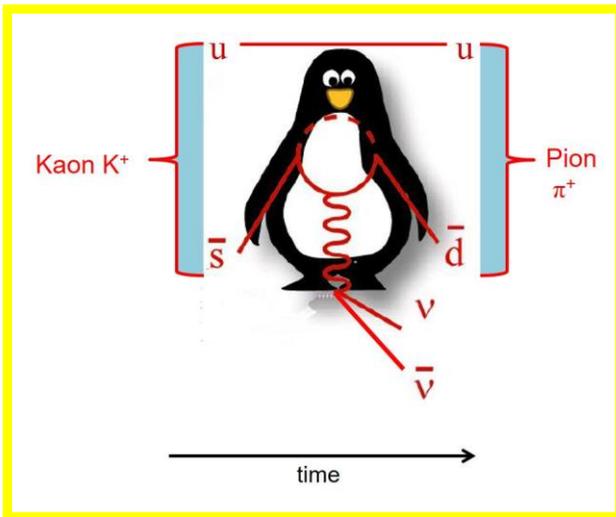
VERY RARE !!

In Minimal SUSY Model:



+ sparticle diagrams

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



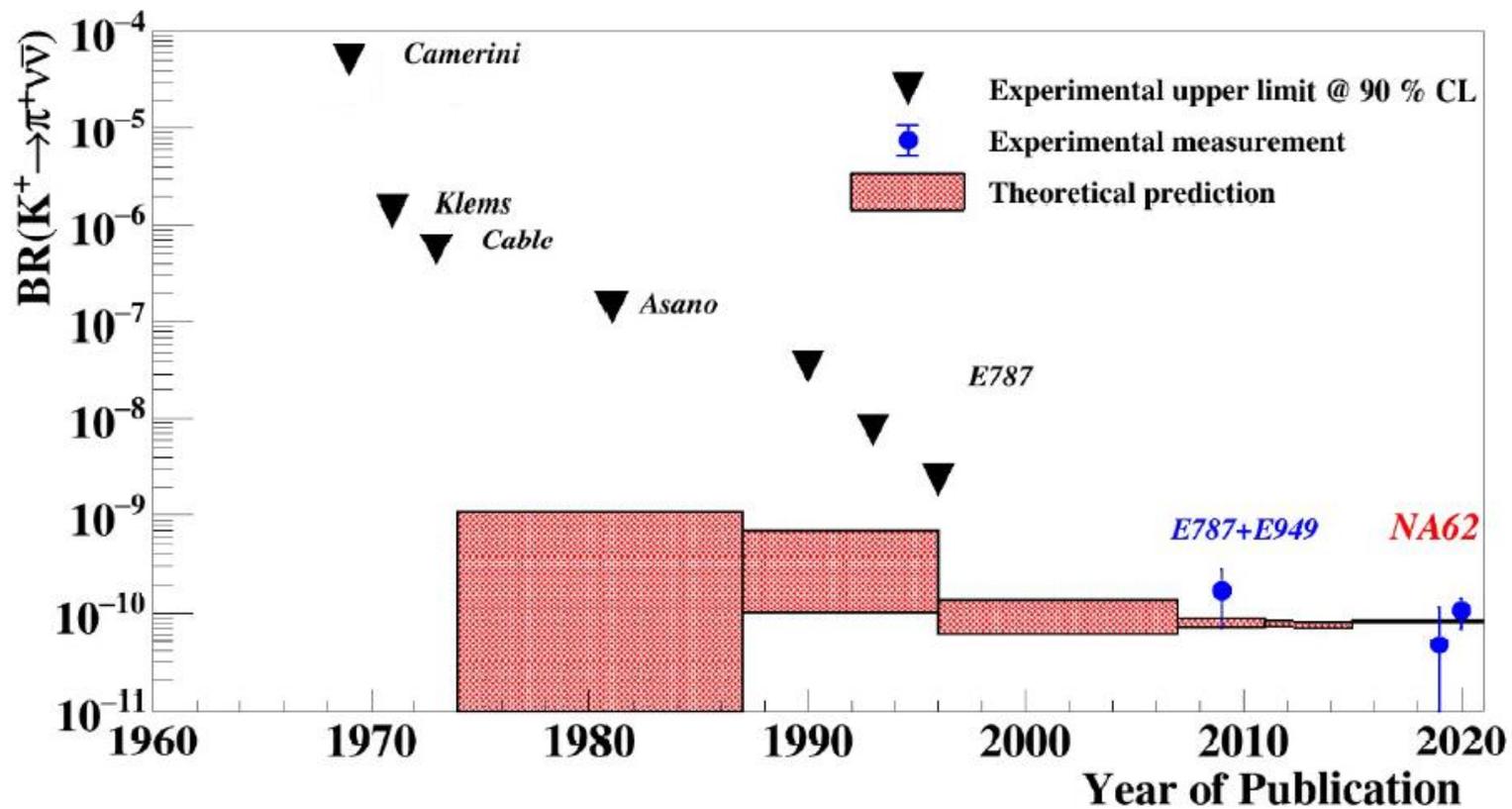
NA62 Experiment: 20 signal events from 2016 - 2018

2021 – 2025 MORE TO COME !!

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

JHEP 06 (2021) 093

SM:  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.6 \pm 0.42) \times 10^{-11}$   
 A. Buras: [arXiv:2205.01118v2](https://arxiv.org/abs/2205.01118v2)



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



## General remarks

Heavy neutral lepton may be a right-handed neutrino

Observable due to mixing btw heavy neutral leptons and active neutrinos

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

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

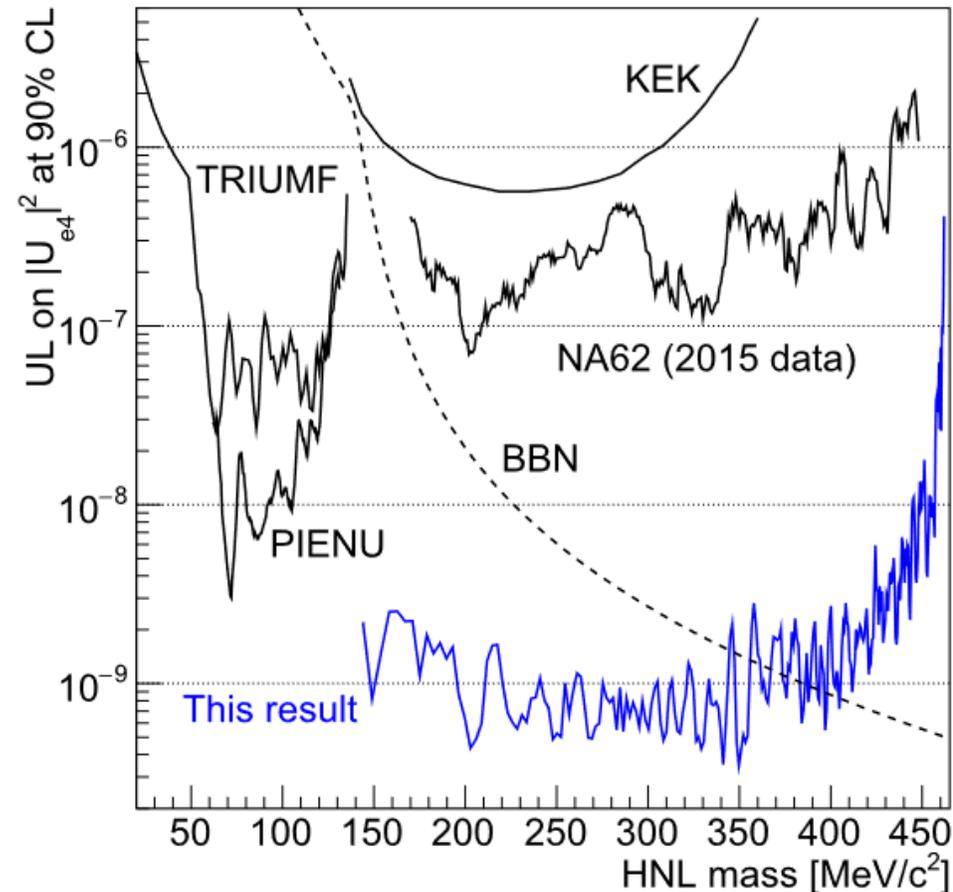
2017-2018 data were used

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



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

## Results



PLB 807 (2020) 135599

Upper Limits on mixing

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



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

PLB 816 (2021) 136259

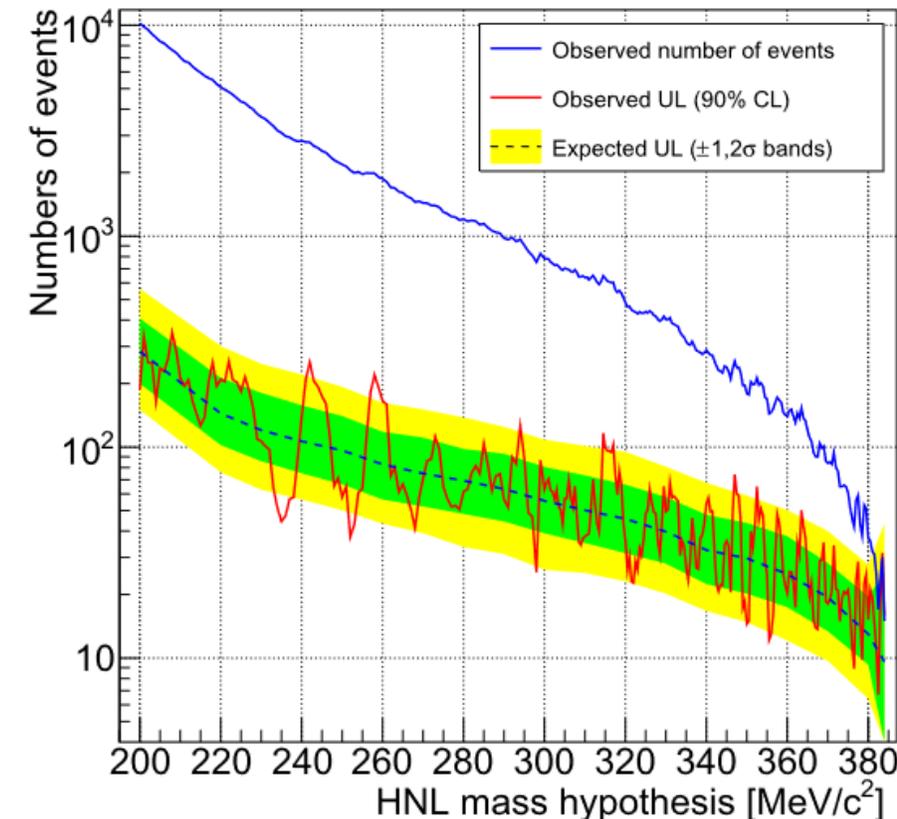
The effective number of  $K^+$  decays in the data sample  $\sim 1.14 \times 10^{10}$ ,  
from the reconstructed  $K^+ \rightarrow \mu^+ \nu$  ( $2.19 \times 10^9$  events in the sample)

Background source	Estimated background			
$K^+ \rightarrow \mu^+ \nu \gamma$	6224	$\pm$	105 <sub>stat</sub>	$\pm$ 333 <sub>PV</sub> $\pm$ 780 <sub>tail</sub>
$K^+ \rightarrow \pi^0 \mu^+ \nu$	1016	$\pm$	47 <sub>stat</sub>	$\pm$ 178 <sub>PV</sub>
$K^+ \rightarrow \pi^+ \pi^+ \pi^-$	309	$\pm$	32 <sub>stat</sub>	
<b>Total background</b>	<b>7549</b>	$\pm$	<b>119<sub>stat</sub></b>	$\pm$ 920 <sub>syst</sub>

PV = Photon Veto systematics

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

Results:



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



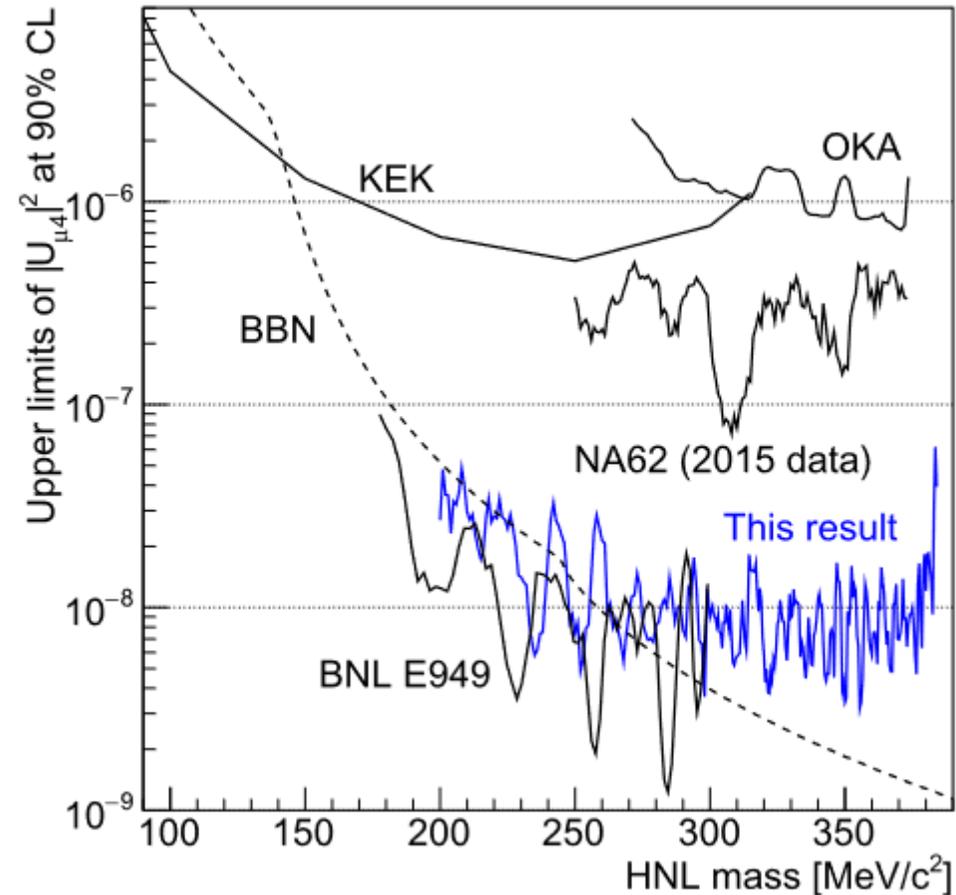
Search for heavy neutral lepton in muon mode  $K^+ \rightarrow \mu^+ N$

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

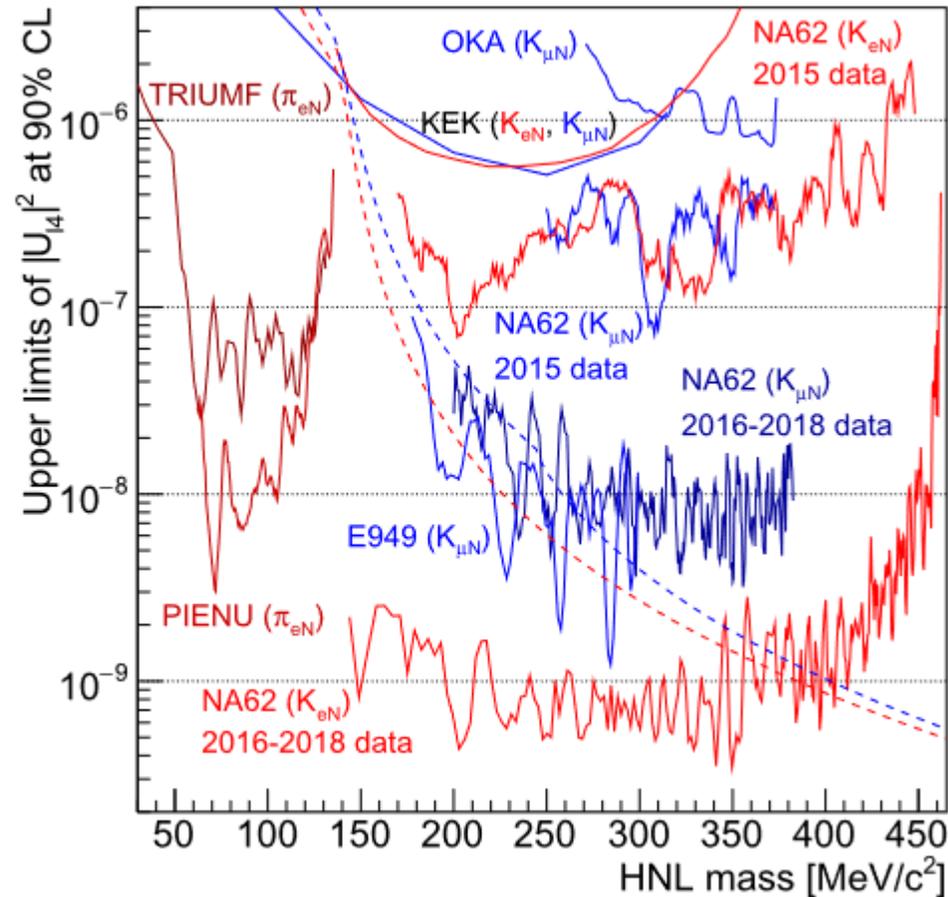


# Searches for $K^+ \rightarrow e^+ N$ , $K^+ \rightarrow \mu^+ N$ , $K^+ \rightarrow \mu^+ \nu X$ decays



Combined Results compared

PLB 816 (2021) 136259



Upper Limits on mixing with  $\nu_\mu$

Upper Limits on mixing with  $\nu_e$

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

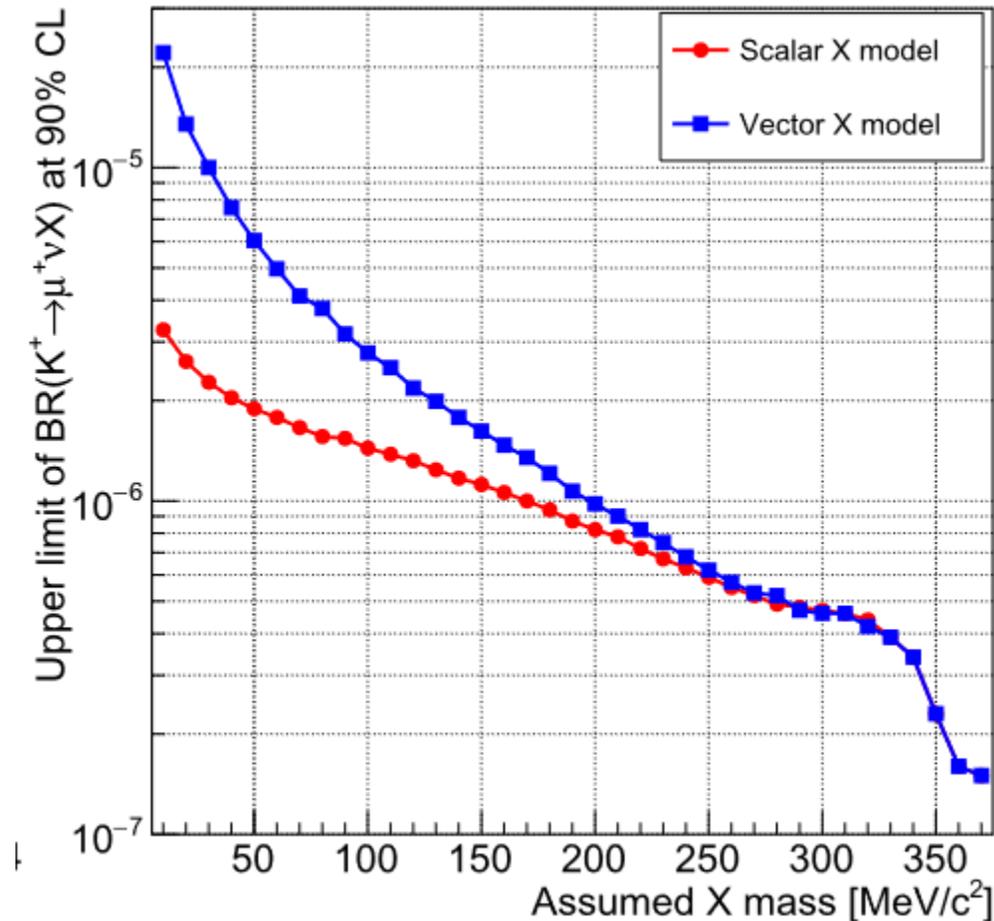


Search for heavy scalar or vector mediator  $X$ :  $K^+ \rightarrow \mu^+ \nu X$

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  $m_{\text{miss}}$  than in the vector mode

Note:  
Update on  $K^+ \rightarrow \pi^+ X$  decays  
can be found in:  
2023 Rep. Prog. Phys. 86 016201  
arXiv: 2201.07805

# Searches for $K^+ \rightarrow \mu^+ \nu \nu \nu$ decays



PLB 816 (2021) 136259

$N_{\text{obs}} = 6894$  events are observed in the signal region  $m_{\text{miss}}^2 > 0.1 \text{ GeV}^2/c^4$ , with an expected background of  $N_{\text{exp}} = 7549 \pm 928$  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  $N_S = N_K \cdot \mathcal{B}(K^+ \rightarrow \mu^+ \nu \nu \bar{\nu}) \cdot A_{\mu\nu\nu}$ , where a reduced signal acceptance  $A_{\mu\nu\nu} = 0.103$  and the sample from the search for heavy neutral lepton in muon mode  $K^+ \rightarrow \mu^+ N$  is used.

Result:

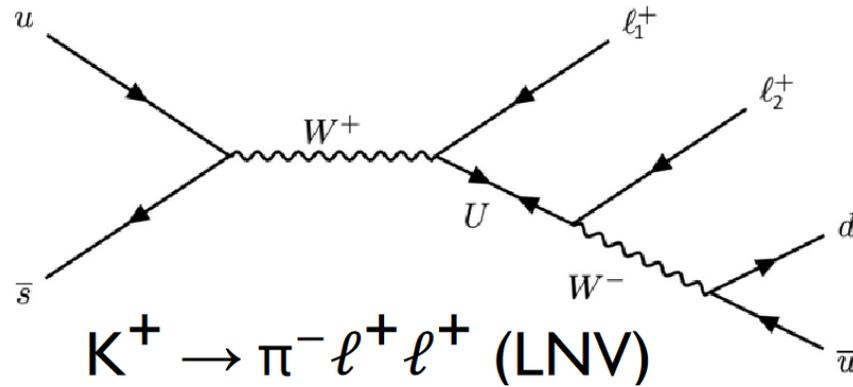
$$\mathcal{B}(K^+ \rightarrow \mu^+ \nu \nu \bar{\nu}) < 1.0 \times 10^{-6} \quad \text{at 90\% CL.}$$

# Searches for Lepton Flavor/Number Violation in $K^+$ decays

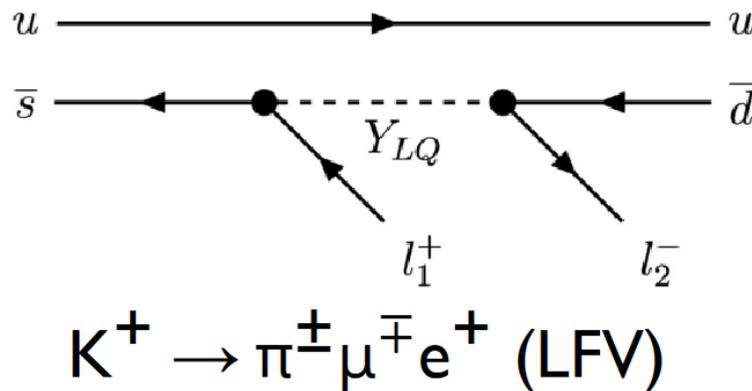
LF / LN are global symmetries in SM with  $m_\nu=0$ . LFV observed in  $\nu$  oscillations.

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

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



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



# Searches for Lepton Flavor/Number Violation in K<sup>+</sup> decays

NA62 Searches in 2016-2018 data:

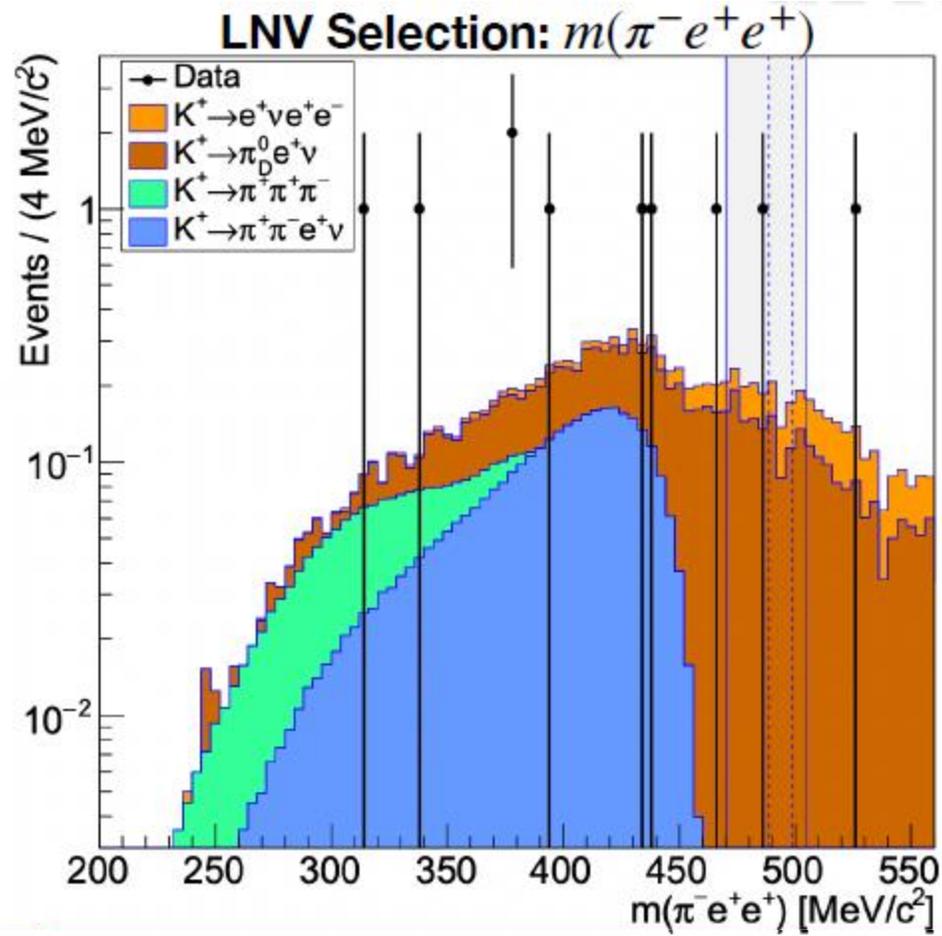
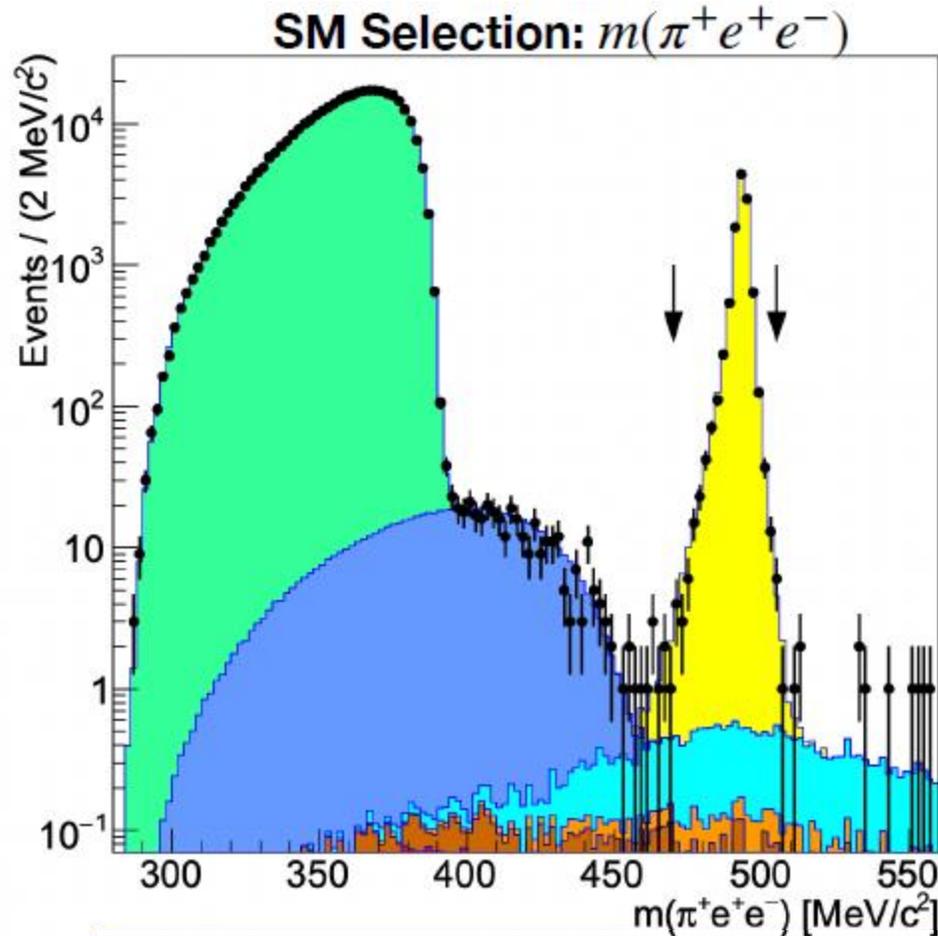
$K^+ \rightarrow \mu^- \nu e^+ e^+$	$BF < 8.1 \times 10^{-11}$	PLB 838 (2023) 137679
$K^+ \rightarrow \pi^- e^+ e^+$	$BF < 5.3 \times 10^{-11}$	PLB 830 (2022) 137172
$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$	$BF < 8.5 \times 10^{-10}$	
$K^+ \rightarrow \pi^- \mu^+ \mu^+$	$BF < 4.2 \times 10^{-11}$	PLB 797(2019)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

All Limits are at 90% C.L.

# Searches for Lepton Flavor/Number Violation in $K^+$ decays

Search for  $K^+ \rightarrow \pi^- e^+ e^+$  as an example

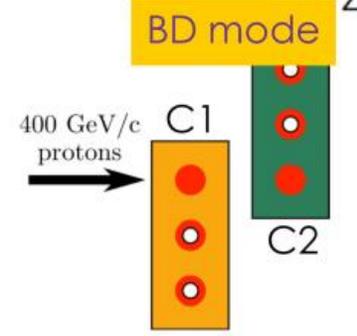
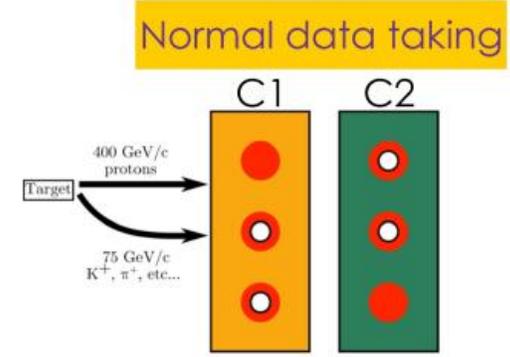
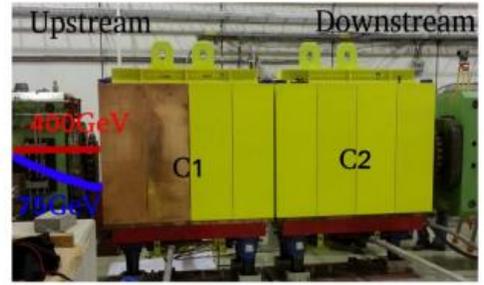
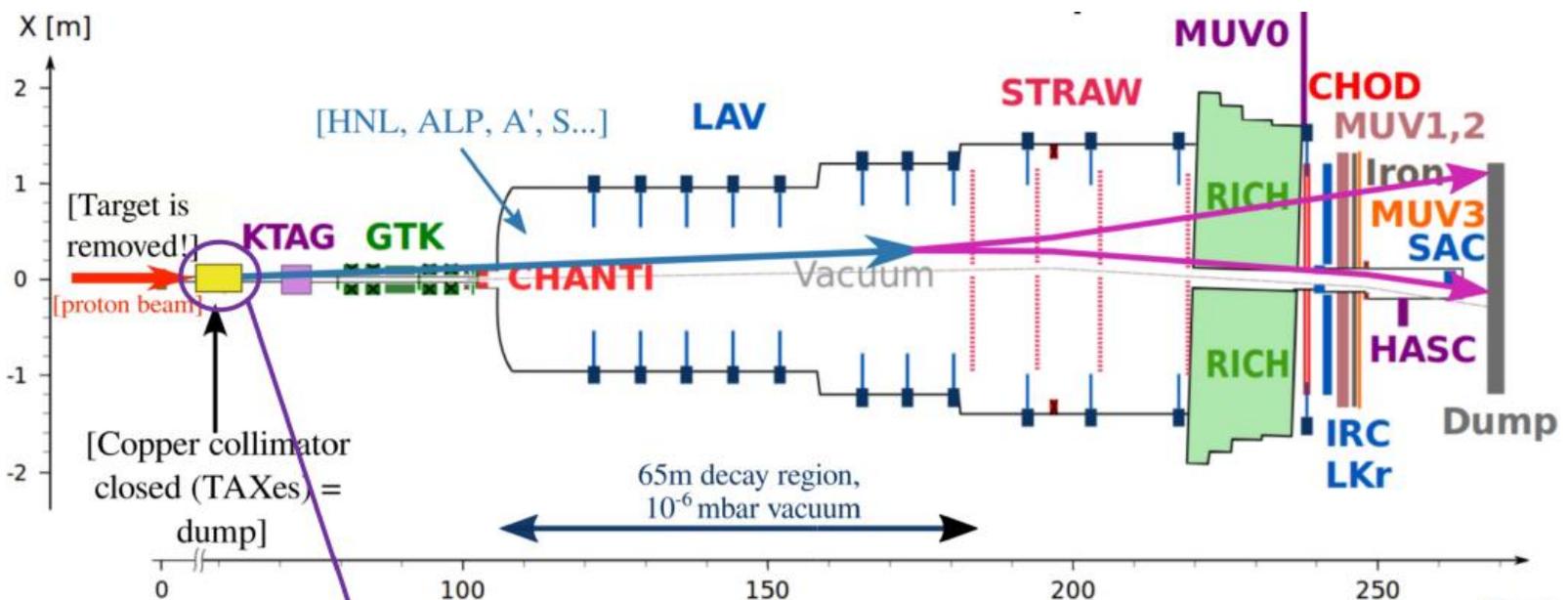
PLB 830 (2022) 137172



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

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

# NA62 Searches in Beam Dump Mode



# NA62 Searches in Beam Dump Mode

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

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

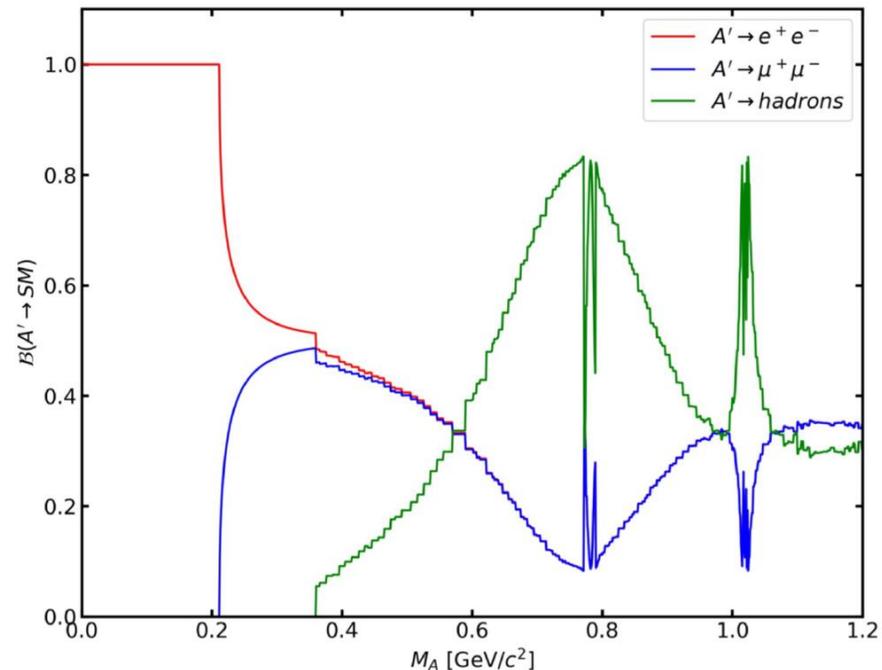
Free parameters: Mass of Dark Photon and coupling

Production: Dark Photon from  $p N \rightarrow X A'$   
(bremsstrahlung)

OR

from meson decay  $p N \rightarrow X M$ ,  
 $M \rightarrow A' \gamma$  ( $\pi^0$ ), where  $M = \pi^0, \omega, \rho$ , etc.

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



# NA62 Searches in Beam Dump Mode



Searches for Dark Photon  $A'_\mu$

NA62 sensitivity to Dark Photon:

in 2021, NA62 collected  $1.4 \times 10^{17}$  POT in 10 days

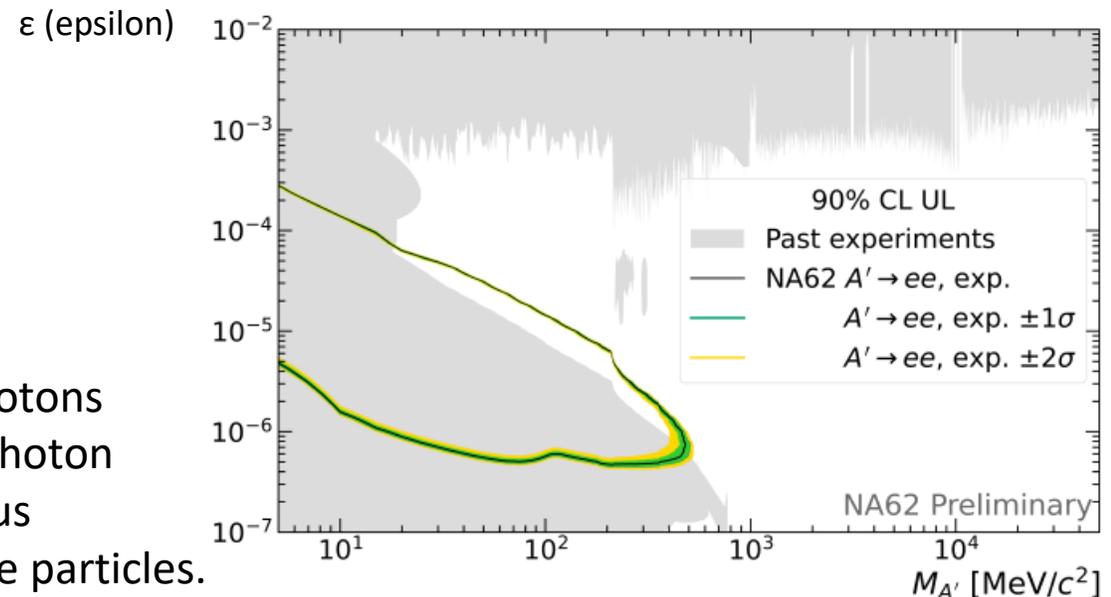
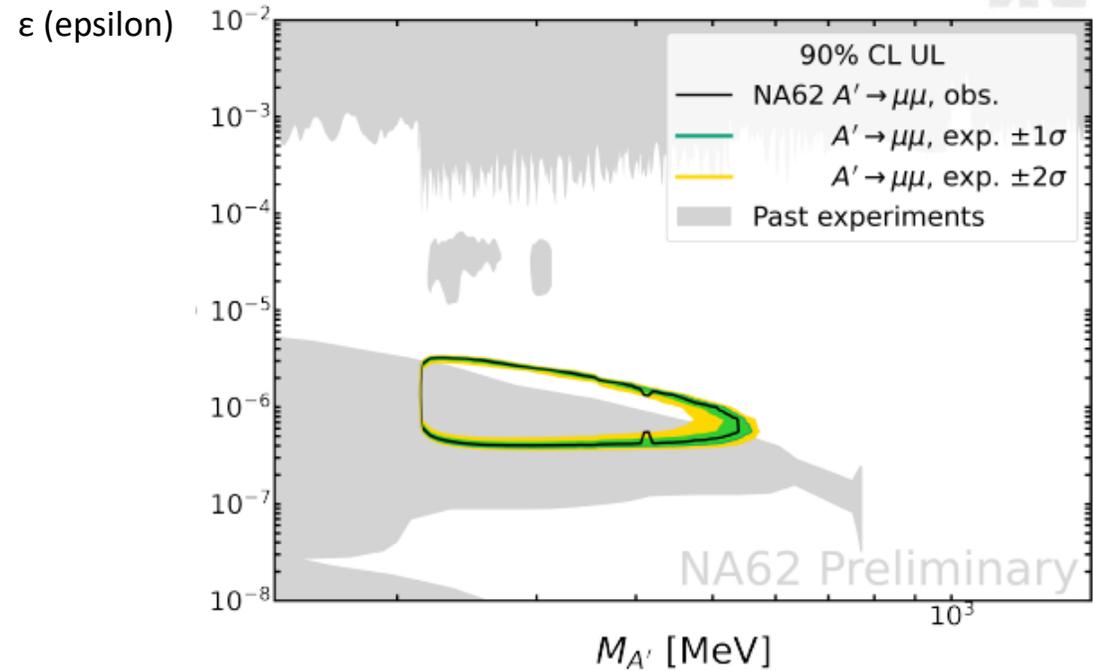
The plots show observed exclusion contours with  $1\sigma$  and  $2\sigma$  expected bands for the  $\mu^+ \mu^-$  and  $e^+ e^-$  search at NA62 in Beam Dump Mode.

The plots assume the lepton decay mode, NA62 geometrical acceptance and zero events observed.

Mass  $M_{A'}$  and coupling  $\epsilon$  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.



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

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

### Beam-dump mode

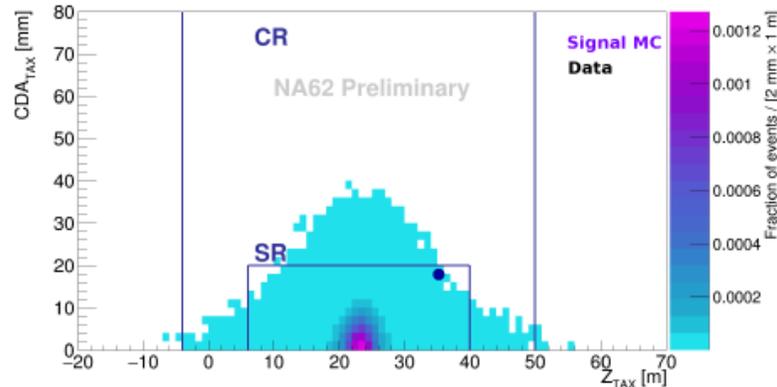
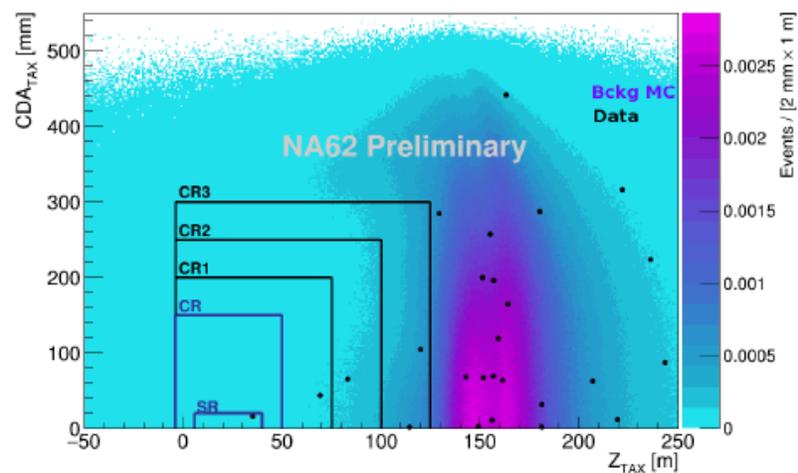
- Target removed
- 3.2 m Cu-Fe collimators put in the beam path
- $1.5 \times$  nominal beam intensity
- $(1.40 \pm 0.28) \times 10^{17}$  POT collected in  $\sim 10$  days

### Signal selection:

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

[contribution, KAON2022]

- Dominant background from random superposition of two uncorrelated  $\mu$
- 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  $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  and on processes only allowed in Beyond Standard Model Physics

## NA62 Physics Run I (2017 - 2018)

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

- Presented NEW upper limits on Heavy Neutral Lepton mixing with active neutrinos.  
on branching fractions  $K^+ \rightarrow \mu^+ \nu X$  and  $B(K^+ \rightarrow \mu^+ \nu \nu \bar{\nu})$
- Presented NEW upper limits on LFV/LFN kaon decays
  - $K^+ \rightarrow \mu^- \nu e^+ e^+$        $BF < 8.1 \times 10^{-11}$
  - $K^+ \rightarrow \pi^- e^+ e^+$        $BF < 5.3 \times 10^{-11}$
  - $K^+ \rightarrow \pi^- \pi^0 e^+ e^+$        $BF < 8.5 \times 10^{-10}$
  - $K^+ \rightarrow \pi^- \mu^+ \mu^+$        $BF < 4.2 \times 10^{-11}$
  - $K^+ \rightarrow \pi^- \mu^+ e^+$        $BF < 4.2 \times 10^{-11}$
  - $K^+ \rightarrow \pi^+ \mu^- e^+$        $BF < 6.6 \times 10^{-11}$
  - $\pi^0 \rightarrow \mu^- e^+$        $BF < 3.2 \times 10^{-10}$

## NA62 Physics Run II (2021)

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

NA62 Physics Run II ongoing ... please stay tuned, the search for BSM Physics signals is on