Latest results from NA62 and NA48/2 experiments

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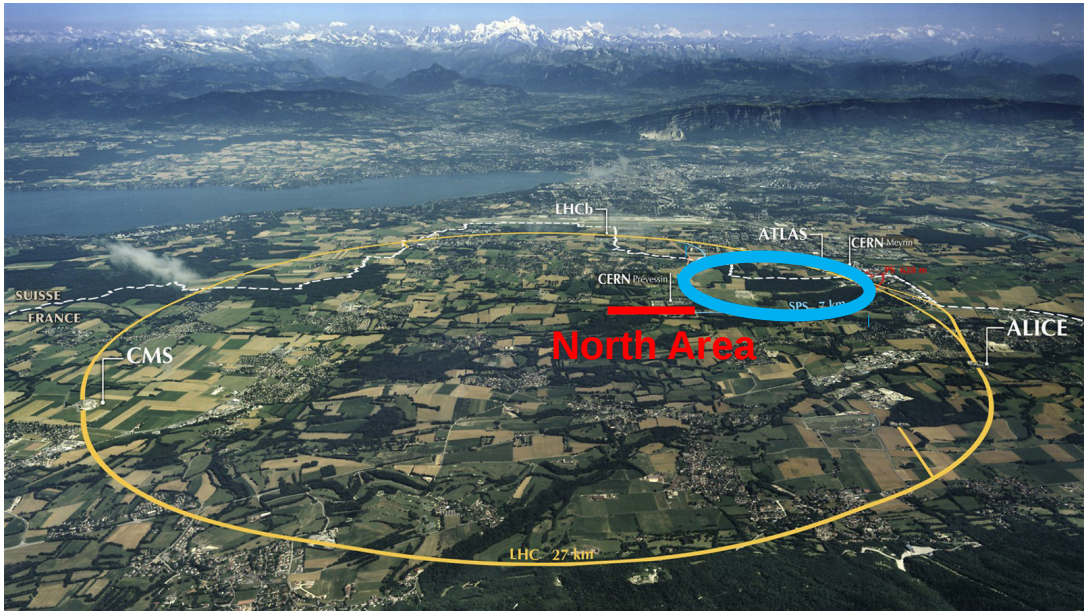
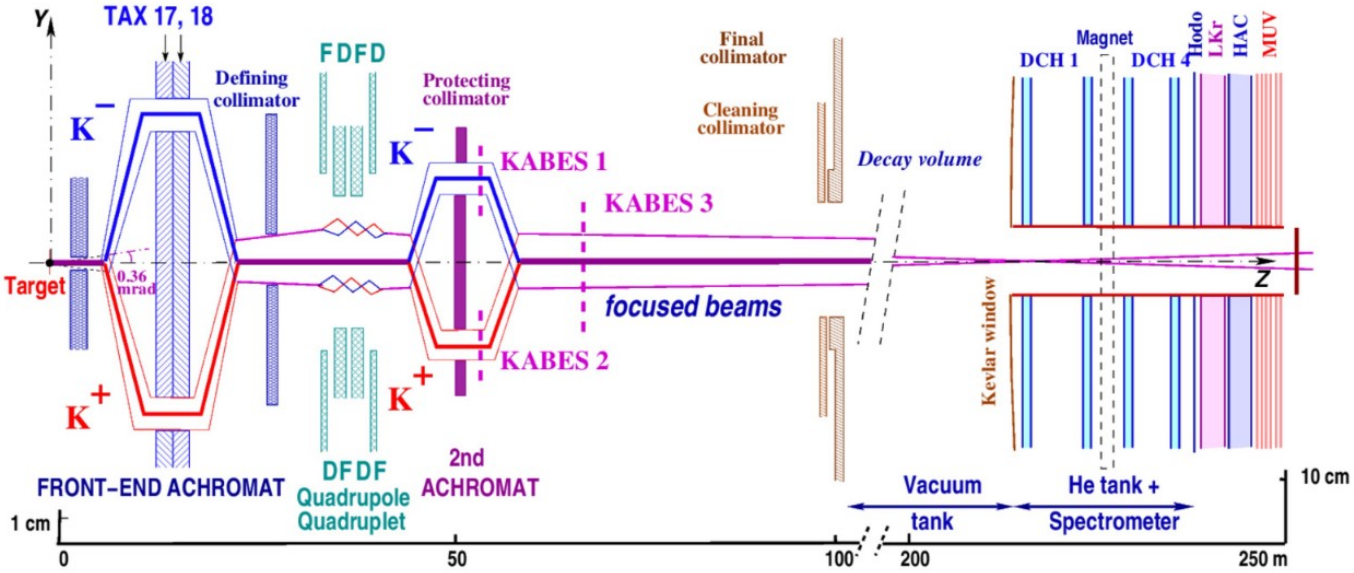
QCD@Work, Lecce (Italy), 30/06/2022

Kaon physics at CERN



Years	Experiment	Beam	Main goals
1984-1990	NA31	K_L/K_s	First evidence of direct CPV
1997-2001	NA48	K_L/K_s	Discovery of direct CPV
2002	NA48/1	K_s , hyperons	Rare Ks and hyperons decays
2003-2004	NA48/2	K^+/K^-	Direct CPV and rare K+/K- decays
2007-2008	NA62-RK	K^+/K^-	LFU test
2016-	NA62	K^+	$BR(K^+ \to \pi^+\nu\bar{\nu})$

NA48/2: beam line



6% Kaons from target

$$P_{K^\pm} \approx 60\ GeV/c$$

$$\Delta P/P = 3.8\%$$

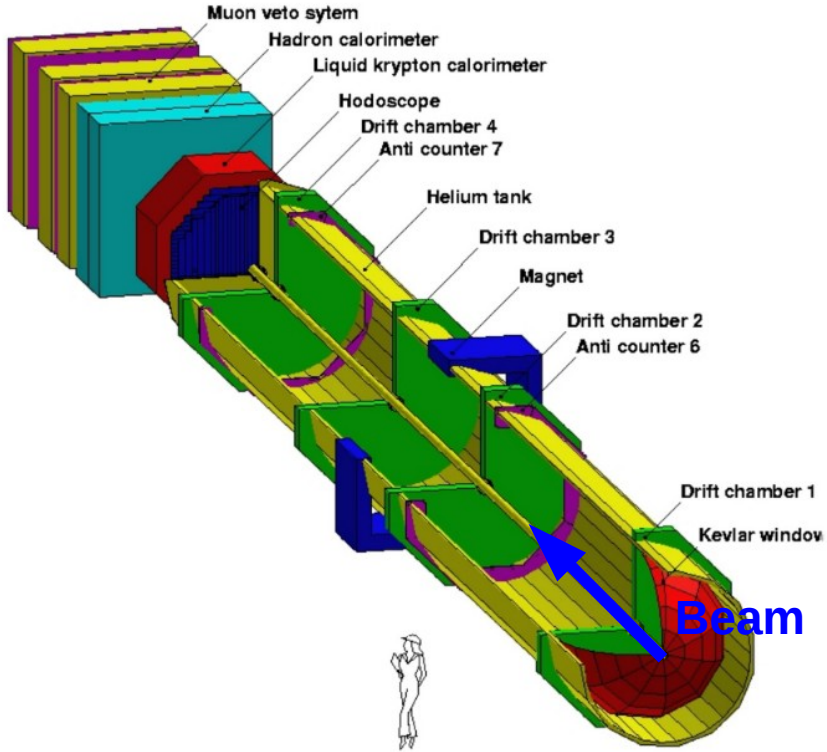
KAon BEam Spectrometer (KABES):

$$\sigma(X,Y) = 800\ \mu m$$

$$\sigma(P) = 1\%$$

$$\sigma(T) = 600\ ps$$

NA48/2: detectors



Main detectors:

- Drift chambers
  $\sigma(X,Y) = 90\ \mu m$ per chamber
- Hodoscope
  $\sigma(T) \sim 150\ ps$
- Liquid Krypton calorimeter

$$\sigma(X,Y) = (0.42/\sqrt{\frac{E}{1\ GeV}} \oplus 0.06)\ cm$$

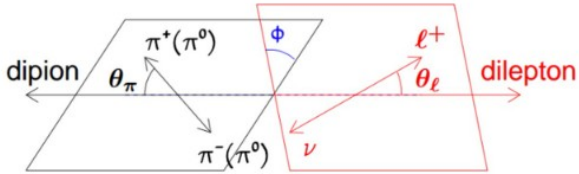
$$\sigma(E_\gamma)/E_\gamma = (3.2/\sqrt{\frac{E}{1\ GeV}} \oplus 9.0/\frac{E}{1\ GeV} \oplus 0.42)\%$$

- Hadronic calorimeter
- Muon veto

Measurement of $BR(K^{\pm} \to \pi^0\pi^0\mu^{\pm}\nu)$

K_{l4} decays are described by F,G,R,H form-factors

Mode	BR [x10^{-5}]	N$_{cand}$	Experiment
$K^{\pm}_{e4}$	4.26 ± 0.04	1108941	NA48/2
K^{00}_{e4}	2.55 ± 0.04	65210	NA48/2 (2014)
$K^{\pm}_{\mu4}$	1.4 ± 0.9	7	Bisi et al. (1967)
$K^{00}_{\mu4}$	-	0	



Cabibbo-Maksymowicz variables:

S_π (dipion mass), S_l (dilepton mass), θ_π, θ_l and Φ

for $K^{00}_{\mu4}$ s-wave for $\pi^0\pi^0$, only F and R contribute

Main background contribution for muon channels:

$K^{\pm} \to \pi\pi(\pi^{\pm} \to \mu^{\pm}\nu)$

Event selection

Normalization channel: $K^{\pm} \to \pi^{\pm}\pi^0\pi^0 \quad (K^{00}_{3\pi})$

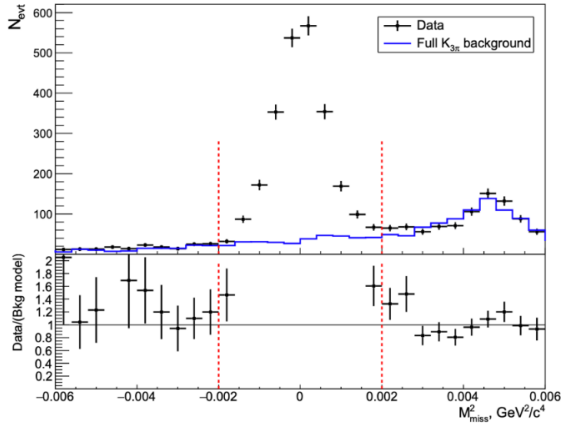
Selection:

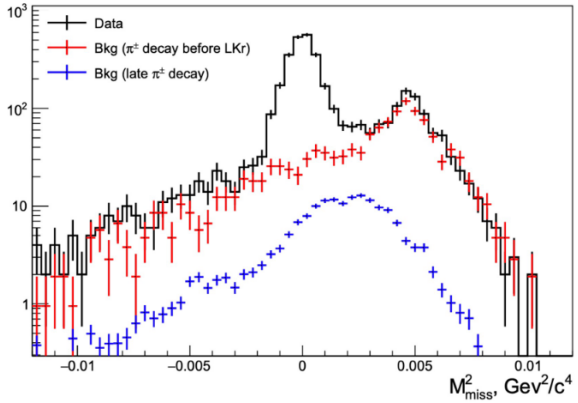
- 4 isolated photons in Lkr compatible with a pair of π^0
- Charged track associated to MUV activity
- Downstream event matched to a KABES track

Background rejection:

- Cut on 3-pion mass, p_t, missing mass, $cos(\theta_l)$

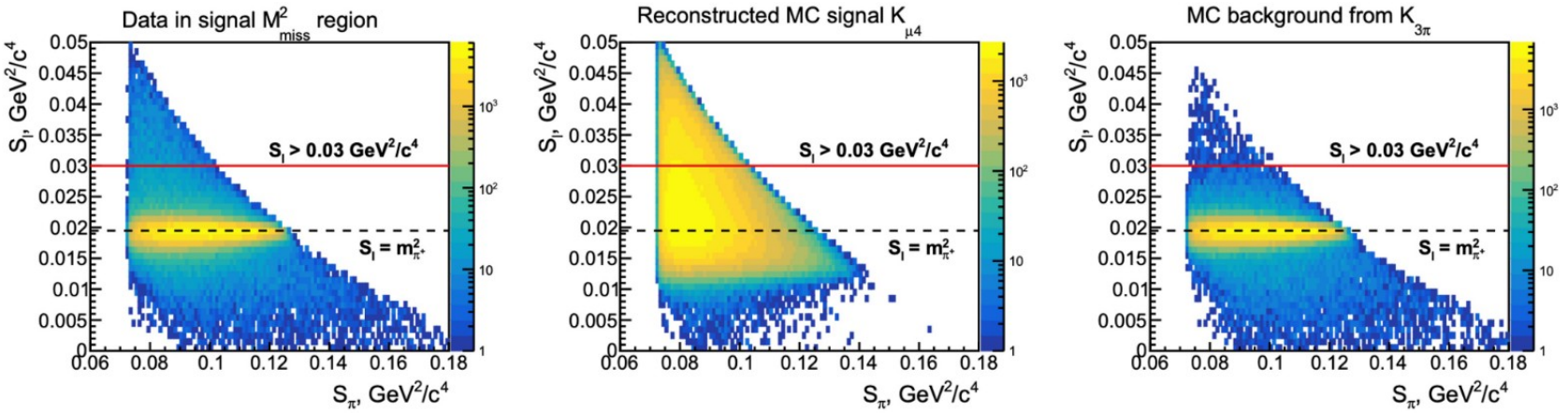
Background estimated using signal sidebands in the missing mass distribution





Phase space

BR($K^{00}_{\mu 4}$) measured in the restricted phase space, extrapolation to full phase space depends on theory



$K^{00}_{\mu 4}$ **simulation used parametrization of F from** K^{00}_{e4} **decay: [NA48/2 JHEP 08 (2014) 159]**

R obtained from ChPT theory:
[J. Bijnes, G. Colangelo, J. Gasser, Nucl. Phys. B 427 (1994) 427]

Branching Ratio

$$BR(K^{00}_{\mu 4}) = \frac{N_S}{N_N} \cdot \frac{A_N}{A_S} \cdot K_{trig} \cdot BR(K^{00}_{3\pi})$$

Signal events (after background subtraction): $2083 \pm 59_{stat}$ $S/B = 5.89 \pm 0.66_{stat}$

Normalization events: $N_N = 72.99 \times 10^6$

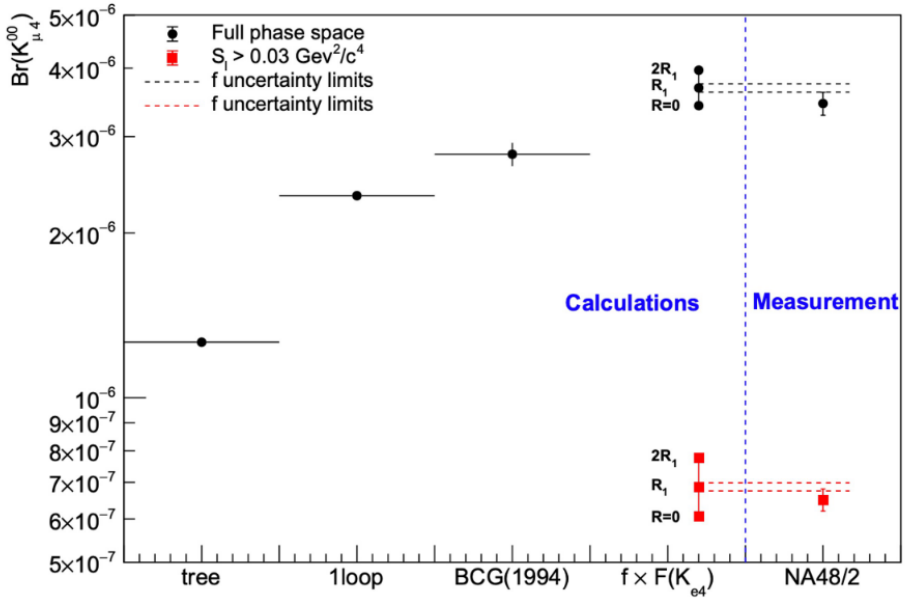
Acceptances: $A_N = (4.477 \pm 0.002)\%$ $A^r_S = (3.453 \pm 0.007)\%$ $A_S = (0.651 \pm 0.001)\%$

Trigger corrections: $K_{trig} = 0.999 \pm 0.002$

From PDG: $BR(K^{00}_{3\pi}) = (1.760 \pm 0.023)\%$

Results

Full phase-space result: $BR(K^{00}_{\mu 4}) = (3.45 \pm 0.17) \times 10^{-6}$



Consistent with the predicted value with 1-loop contribution from R, as expected from ChPT

The NA62 experiment

Fixed target, high intensity (~800 MHz) kaon beam

Main goal: measurement of $BR(K^+ \to \pi^+ \nu\bar{\nu})$ at 10% precision

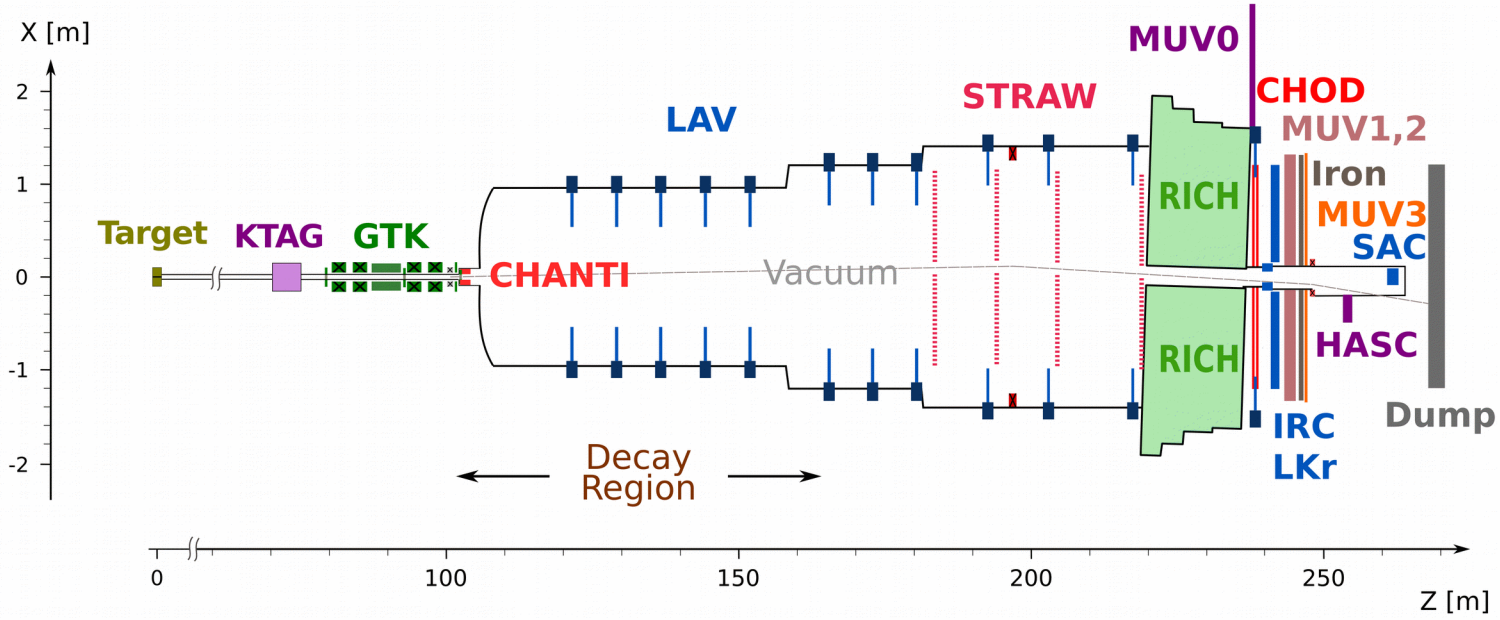
Broad physics program:

- Precision measurement of kaon decays: $BR(K^+ \to \pi^0 e^+ \nu\gamma)$, $BR(K^+ \to \pi^+ \mu^+ \mu^-)$
- Rare kaon decays: $BR(K^+ \to \mu^+ \nu\nu\nu)$, search for Heavy Neutral Leptons, search for Lepton Number and Lepton Flavour Violation

Data collected: Run1 (2016-2018), Run2 (2021-ongoing)

Topics of this talk

NA62 experimental layout



75 GeV/c , ~ 45 MHz
Kaon beam

O(70 ps) time resolutions from KTAG, GTK, RICH

Large background suppression of decays with neutral pions and muons in the final state

Motivations for $BR(K^+ \to \pi^+ \nu\bar{\nu})$

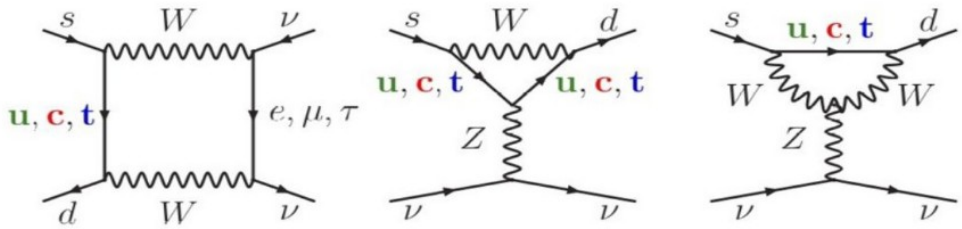
FCNC process, suppressed by CKM

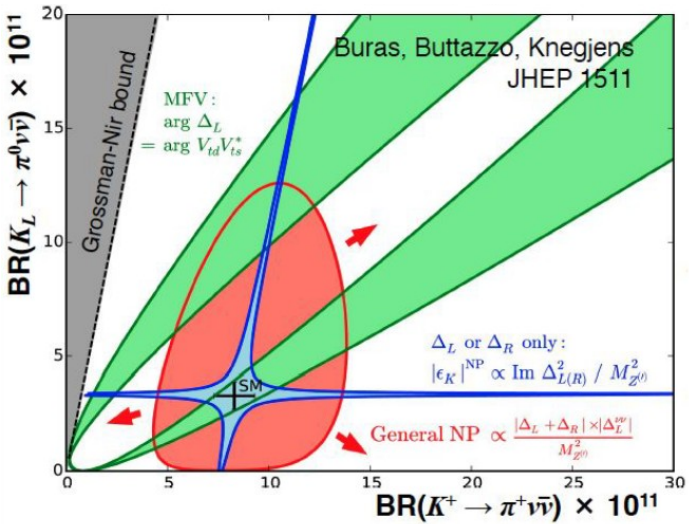
$$BR_{th}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

[Buras et al. , JHEP 1511 (2015)]

$K \to \pi\nu\bar{\nu}$ **decays are very powerful tools to discriminate among NP scenarios:**

Randall-Sundrum
Littlest Higgs with T parity
Minimal Flavour Violation





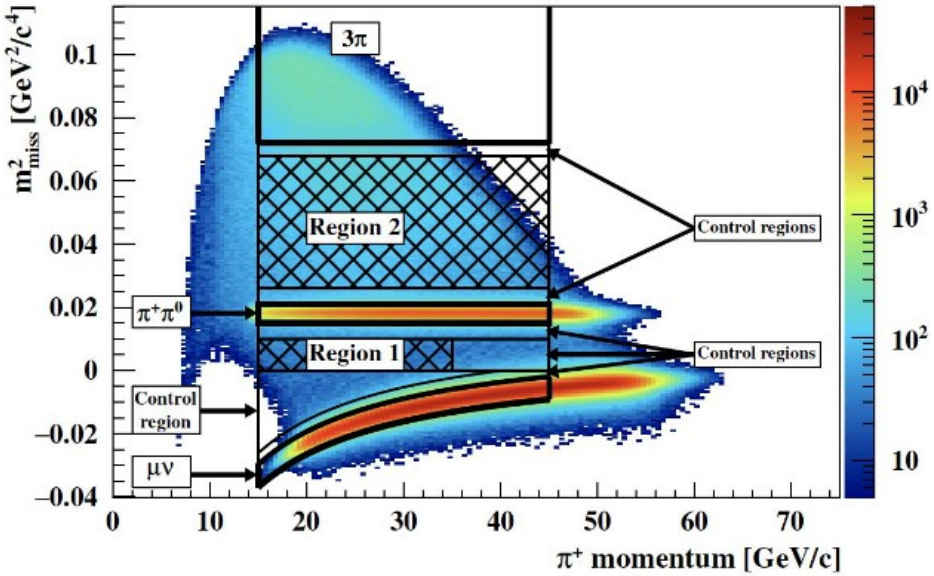
Experimental strategy

Poor experimental signature: only 1 charged track in the final state, neutrinos undetected

Event selection:

- K – π matching, O(100 ps) timing
- Cuts on decay vertex, CDA
- Pion identification
- Photon rejection
- Kinematic cuts, signal regions kept blind
- Normalization channel: $K^+ \to \pi^+\pi^0$

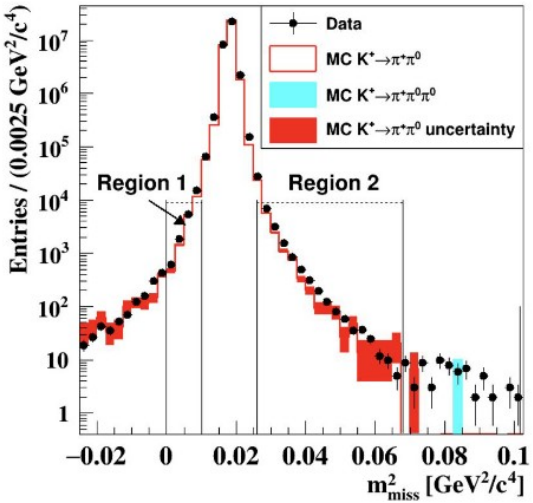
$$m^2_{miss} = (P_K - p_\pi)^\mu (P_K - p_\pi)_\mu$$



Background contributions

- **Kaon decays in FV**
  - $K^+ \to \pi^+\pi^0$, $K^+ \to \mu^+\nu$, $K^+ \to \pi^+\pi^+\pi^-$ from their background regions

$$N^{exp}_{decay} = N_{bkgd} \cdot f_{kin}$$

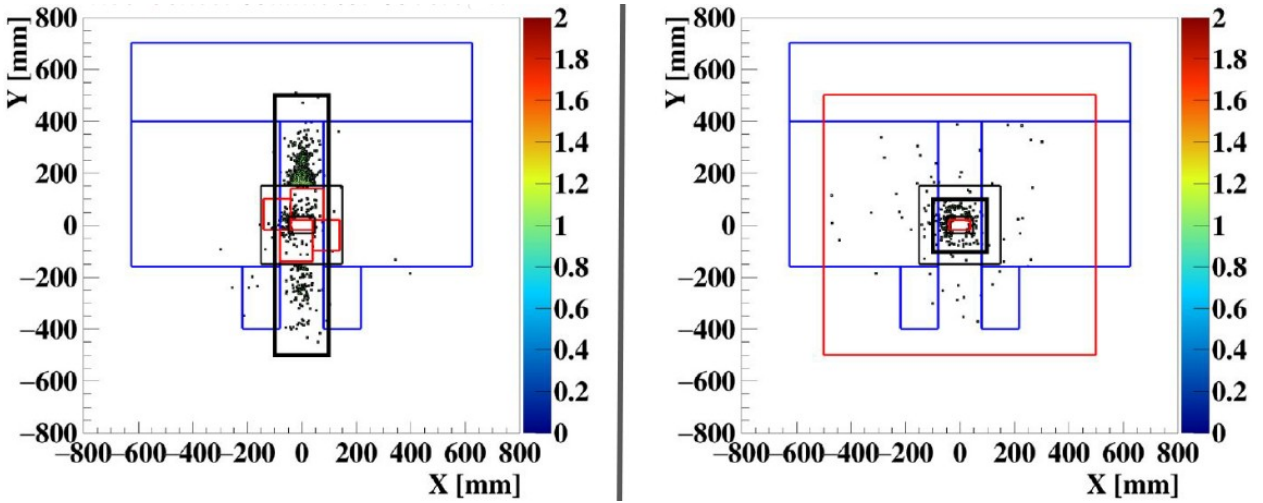


  - Background from other kaon decays estimated with MC simulations

Background contributions

- **Upstream background**
  - Pion from K decays before GTK last station, matched to a pileup kaon
  - Pion from beam interaction with the beamline material

S1 sample,
Old collimator



S2 sample,
New collimator

Single Event Sensitivity

SES is defined as:

$$SES = \frac{\mathrm{BR}(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig}}^{\mathrm{PNN}}}$$

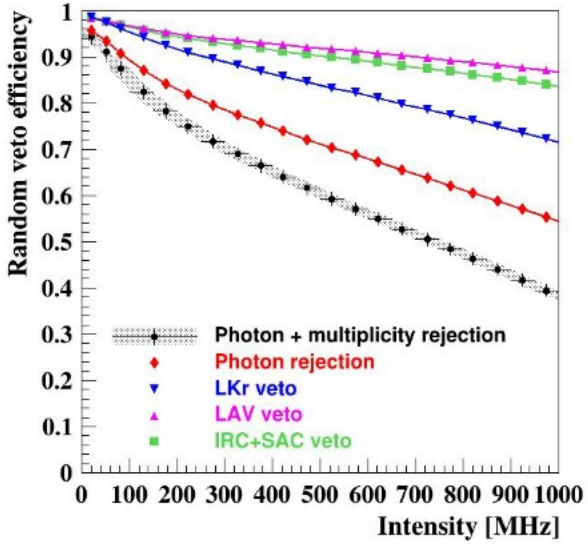
Single Event Sensitivity

SES is defined as:

$$SES = \frac{\mathrm{BR}(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig}}^{\mathrm{PNN}}}$$

Downscale factor between signal and normalization trigger streams

Random veto



Single Event Sensitivity

SES is defined as:

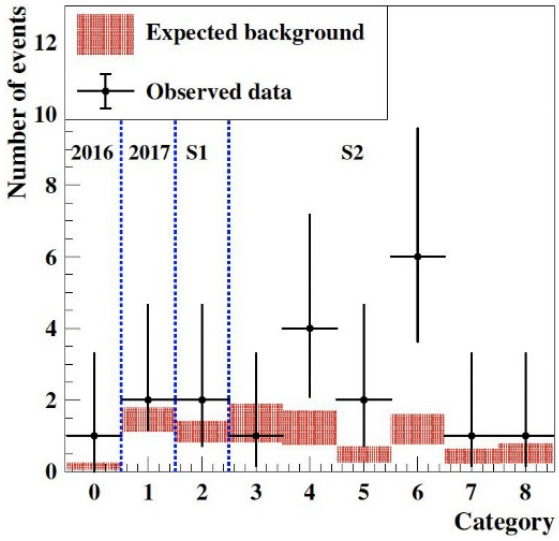
$$SES = \frac{\mathrm{BR}(K^+ \to \pi^+\pi^0) \cdot A_{\pi\pi}}{D \cdot N_{\pi\pi} \cdot A_{\pi\nu\bar{\nu}} \cdot \epsilon_{\mathrm{RV}} \cdot \epsilon_{\mathrm{trig}}^{\mathrm{PNN}}}$$

	S1 subsample	S2 subsample
$N_{\pi\pi}[\times 10^7]$	3.14	11.6
$A_{\pi\pi}[\times 10^{-2}]$	7.62 ± 0.77	11.77 ± 1.18
$A_{\pi\nu\bar{\nu}}[\times 10^{-2}]$	3.95 ± 0.40	7.62 ± 0.77
ϵ_{trig}^{PNN}	0.89 ± 0.05	7.62 ± 0.77
ϵ_{RV}	0.66 ± 0.01	7.62 ± 0.77
$SES[\times 10^{-10}]$	0.54 ± 0.04	7.62 ± 0.77
$N_{\pi\nu\bar{\nu}}^{exp}$	1.56 ± 0.77 ± 0.19	6.02 ± 0.39 ± 0.72

$$N_{\pi\nu\bar{\nu}}^{exp} = N_K \times SES$$

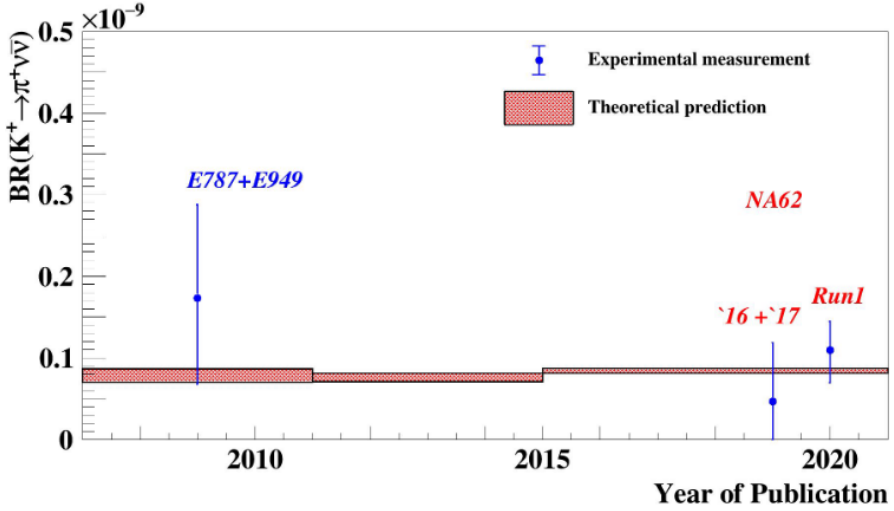
Result

20 events oberved: 1 (2016) + 2 (2017) + 17 (2018)



$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$$

3.4σ significance



Precision measurements: $BR(K^+ \to \pi^0 e^+ \nu\gamma)$

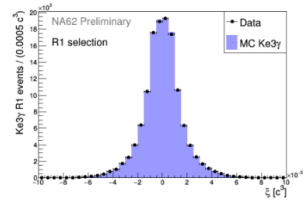
Process described by DE+IB+INT

BR predicted and measured in 3 regions of the phase space

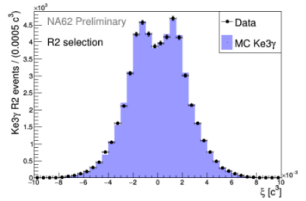
T-odd observable $\xi = \dfrac{\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\pi)}{M_K^3}$ **, test for T violation**

Experimental strategy: normalization to $K^+ \to \pi^0 e^+ \nu$ **decay, main background due to accidental activity in the LKr estimated using signal sidebands**

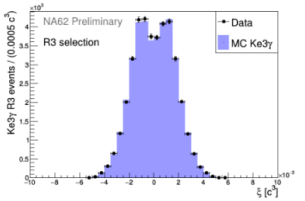
	ChPT	ISTRA+	OKA	NA62 preliminary
$R_1(\times 10^2)$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.684 \pm 0.05 \pm 0.010$
$R_2(\times 10^2)$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.599 \pm 0.003 \pm 0.005$
$R_3(\times 10^2)$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.523 \pm 0.003 \pm 0.003$



$A_\xi^{R_1} = (-0.1 \pm 0.3_{stat} \pm 0.2_{MC}) \times 10^2$



$A_\xi^{R_2} = (-0.3 \pm 0.4_{stat} \pm 0.3_{MC}) \times 10^2$



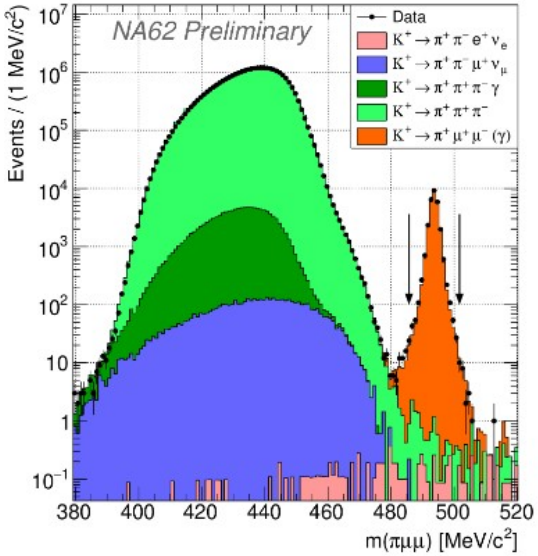
$A_\xi^{R_3} = (-0.9 \pm 0.5_{stat} \pm 0.4_{MC}) \times 10^2$

Precision measurements: $BR(K^+ \to \pi^+\mu^+\mu^-)$

FCNC process, allows to test Lepton Flavour Universality

Form factor parametrized by a and b coefficients

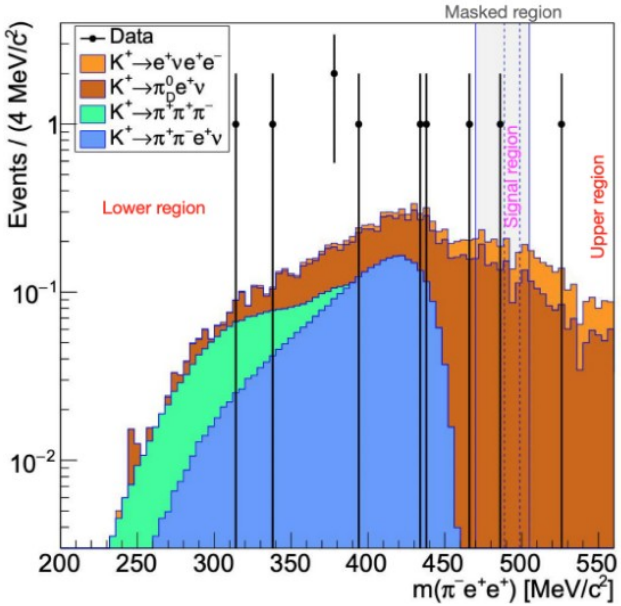
9x larger sample collected with respect to the previous measurement



	a	b	$\mathcal{B}_{\pi\mu\mu} \times 10^8$
Best fit	-0.592	-0.699	9.27
Errors	δa	δb	$\delta\mathcal{B}_{\pi\mu\mu} \times 10^8$
Statistical	0.013	0.046	0.07
Systematic			
Reconstruction efficiency	0.005	0.026	0.06
Beam & pileup simulation	0.005	0.024	0.05
Trigger efficiency	0.001	0.005	0.04
Background	0.000	0.001	0.01
Total systematic	0.007	0.035	0.08
External			
PDG error on $\mathcal{B}(K_{3\pi})$	0.001	0.003	0.04
Total	0.015	0.058	0.11

Rare decays: searches for LNV

Search for $K^+ \to \pi^- e^+ e^+$: blind analysis, normalization to SM decay $K^+ \to \pi^+ e^+ e^-$



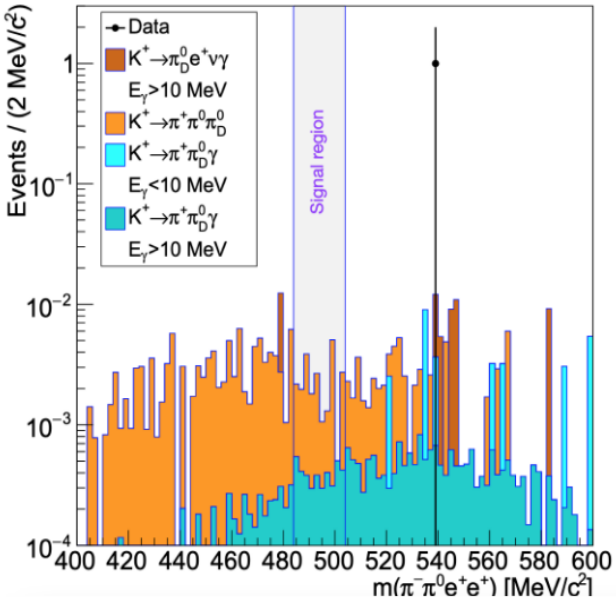
Mode	Lower region	Upper region	Masked region	Signal region
$K^+ \to \pi^+\pi^+\pi^-$	0.9	–	–	–
$K^+ \to \pi^+\pi^-e^+\nu$	3.3	–	–	–
$K^+ \to \pi^+\pi^0_D$	–	0.02	0.01	–
$K^+ \to \pi^0_D e^+\nu$	3.7 ± 0.7	1.20 ± 0.24	1.23 ± 0.25	0.29 ± 0.06
$K^+ \to e^+\nu e^+e^-$	0.7 ± 0.1	0.76 ± 0.15	0.47 ± 0.09	0.14 ± 0.03
Total	8.6 ± 0.9	1.98 ± 0.39	1.71 ± 0.34	0.43 ± 0.09
Data	8	1	1	0

$$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$$ 90% CL

[PLB830 (2022)137172]

Rare decays: searches for LNV

Search for $K^+ \to \pi^-\pi^0 e^+ e^+$: blind analysis, normalization to SM decay $K^+ \to \pi^+ e^+ e^-$



Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+ e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

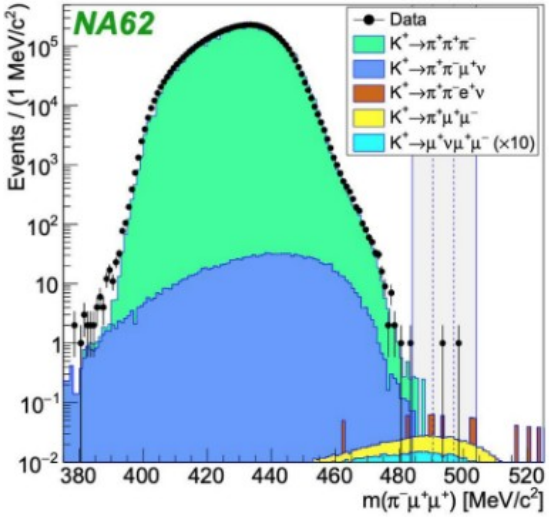
$BR(K^+ \to \pi^-\pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ 90% CL

First search for this LNV decay

[PLB830 (2022)137172]

Other LNV searches

LNV : $K^+ \to \pi^-\mu^+\mu^+$



2017 data : $N_K = (7.94 \pm 0.23) \times 10^{11}$ (di-muon trigger)

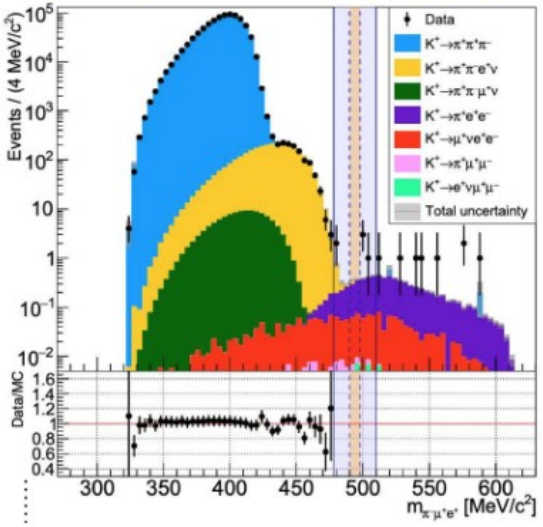
Expected background: 0.91 ± 0.41 Candidates observed: 1

$\mathcal{B}(K^+ \to \pi^-\mu^+\mu^+) < 4.2 \times 10^{-11}$ @ 90 % CL

[PLB 797 (2019) 134794]

Factor 2 improvement on NA48/2 limit [PLB 769 (2017) 67]

LNV/LFV : $K^+ \to \pi^-\mu^+e^+$



2017+18 data : $N_K = (1.33 \pm 0.02) \times 10^{12}$ (combine 3 triggers)

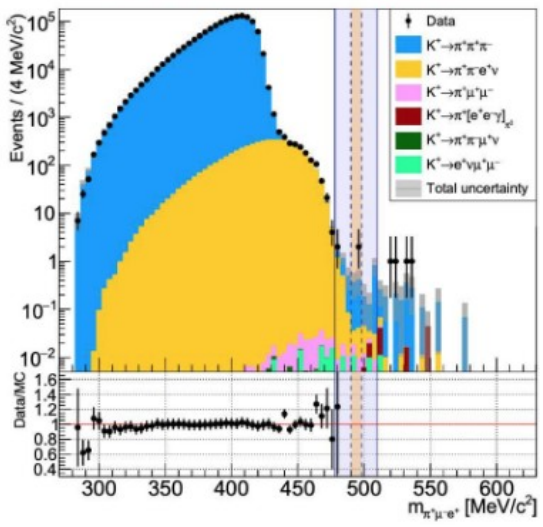
Expected background: 1.07 ± 0.20

Candidates observed: 0

$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 4.2 \times 10^{-11}$ @ 90 % CL

[PRL 127 (2021) 131802]

LFV : $K^+ \to \pi^+\mu^-e^+$



Expected background: 0.92 ± 0.34

Candidates observed: 2

$\mathcal{B}(K^+ \to \pi^-\mu^+e^+) < 6.6 \times 10^{-11}$ @ 90 % CL

From $K^+ \to \pi^+\pi^0$, $\pi^0 \to \mu^-e^+$ search:

$\mathcal{B}(\pi^0 \to \mu^-e^+) < 3.2 \times 10^{-10}$ @ 90 % CL

Improve by approximately 1 order of magnitude on previous BNL E865 results [PRL 85 (2000) 2877].

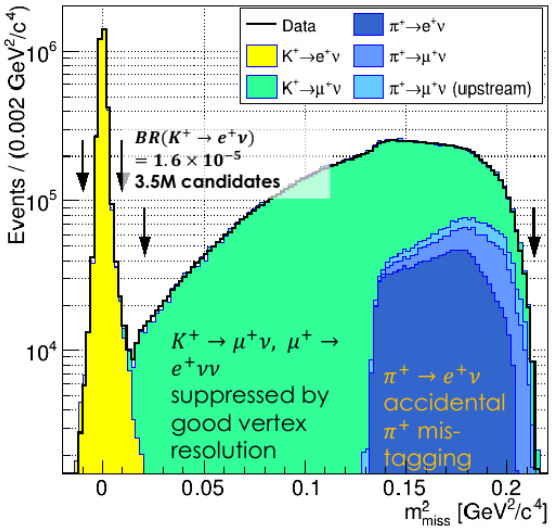
LNV/LFV summary

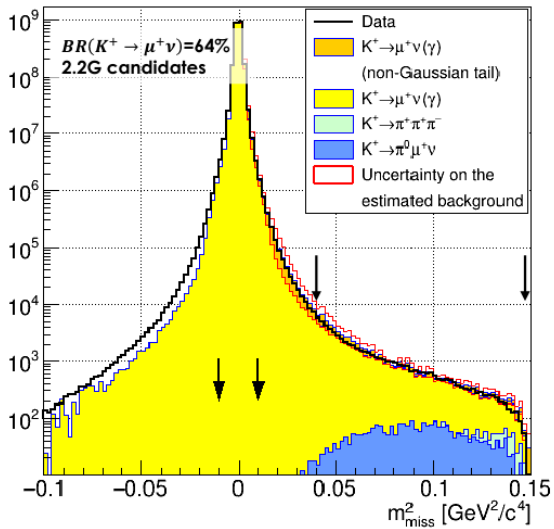
	Previous UL @90% CL	NA62 UL @90% CL			
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data	PLB 797 (2019) 134794	Factor 2 improvement
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	Run1 data	PLB 830 (2022) 137172	Factor 12 improvement
$K^+ \to \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	Run1 data	PLB 830 (2022) 137172	
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	Factor 12 improvement
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data	PRL 127 (2021) 131802	Factor 8 improvement
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data	PRL 127 (2021) 131802	Factor 13 improvement

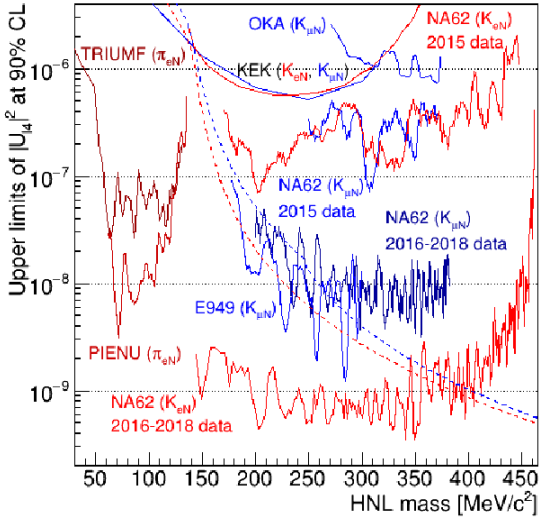
Search for Heavy Neutral Leptons (HNL)

Search for HNL production in $K^+ \to l^+ N$

Peak search performed in the squared missing mass distribution

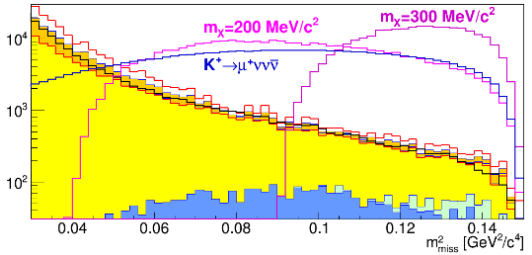


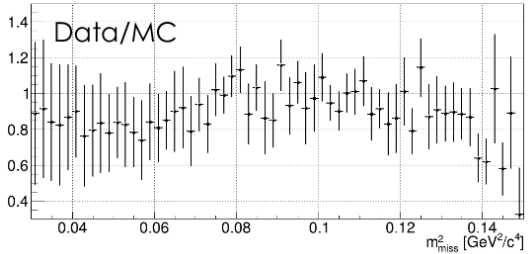




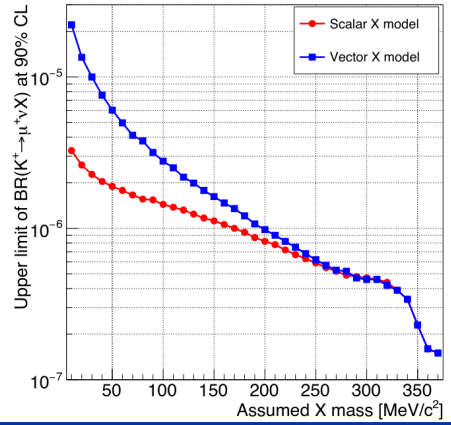
$K^+ \to \mu^+\nu\nu\nu$ and $K^+ \to \mu^+\nu X$

- $K^+ \to \mu^+\nu\nu\nu$
  - Very rare decay in the SM $BR = 1.6 \times 10^{-16}$
  - Current limit: $BR < 2.4 \times 10^{-6}$ by E949(2016)
  - Search region: $m^2_{miss} > 0.1\ GeV^2/c^4$
  - NA62 result: $BR < 1.0 \times 10^{-6}$ @ 90% CL





- $K^+ \to \mu^+\nu X$
  - X scalar or vector
  - Mass range: 10 – 370 MeV/c²
  - Compared observed and expected events for each mass hypothesis to extract limit



Conclusions

NA48/2: first measurement of BR($K^{00}_{\mu 4}$), result compatible with 1-loop calculation of R form factor from ChPT

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11}$ **most precise measurement**

Precision measurement:

Improved precision on $BR(K^+ \to \pi^0 e^+ \nu\gamma)$ and $BR(K^+ \to \pi^+ \mu^+ \mu^-)$

Rare decays:

improved limits LNV/LFV searches

improved limits in HNL searches, $K^+ \to \mu^+ \nu\nu\nu$ and $K^+ \to \mu^+ \nu X$

NA62 data taking restarted in 2021, more results to come