Physics Beyond the Standard Model with NA62

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on behalf of the **NA62 Collaboration**

INFN Laboratori Nazionali di Frascati

New Frontiers in Lepton Flavor 15-17 May 2023

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

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

Search for lepton flavour and number violation, rare and forbidden decays:

$$K^+ \to \pi^\pm \mu^\mp e^+$$
$$K^+ \to \pi^- l^+ l^+$$
$$K^+ \to \mu^+ \nu X$$
$$(K^+ \to \pi^+ \pi^0)\, \pi^0 \to \text{invisible}$$

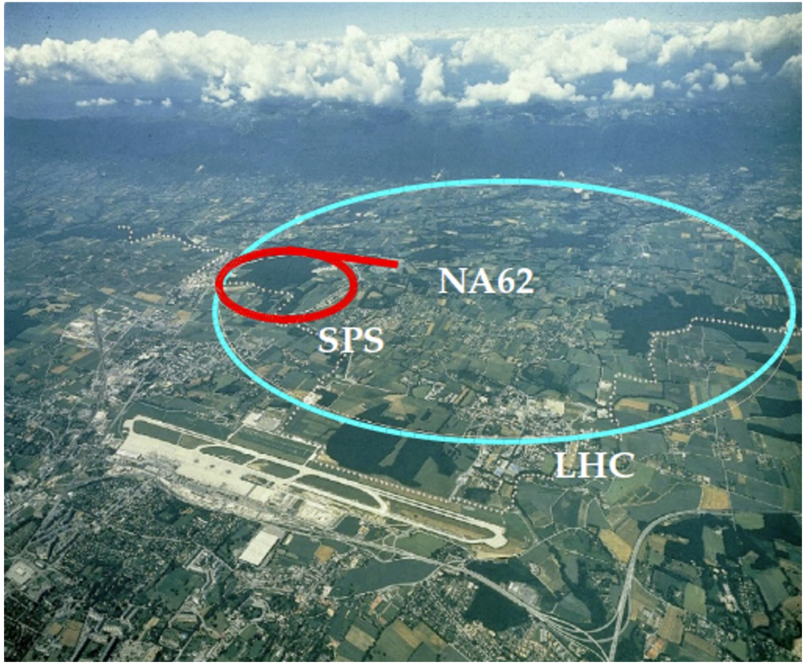
Hidden sector Physics

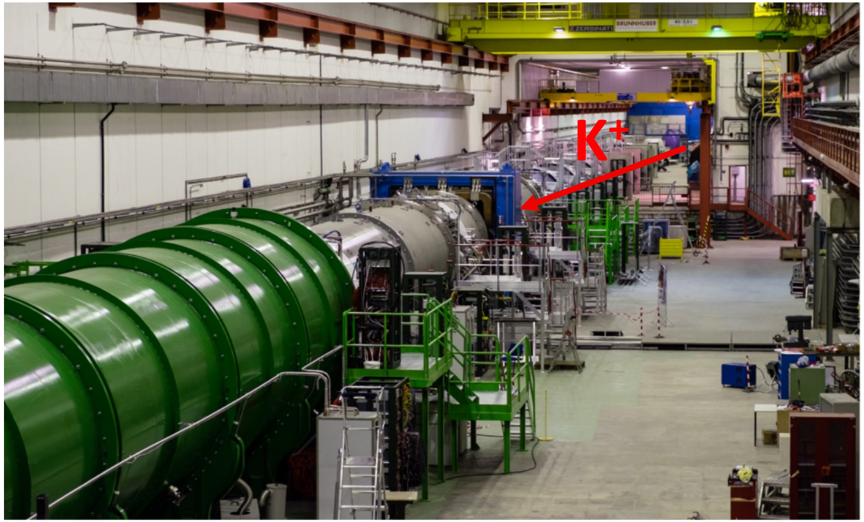
Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$$K^+ \to l^+ N$$

The NA62 experiment at the SPS





NA62 @ CERN North Area, exploits a 400 GeV/c primary proton beam from the SPS. 2×10^{12} protons/spill

p on 40 cm Be target.

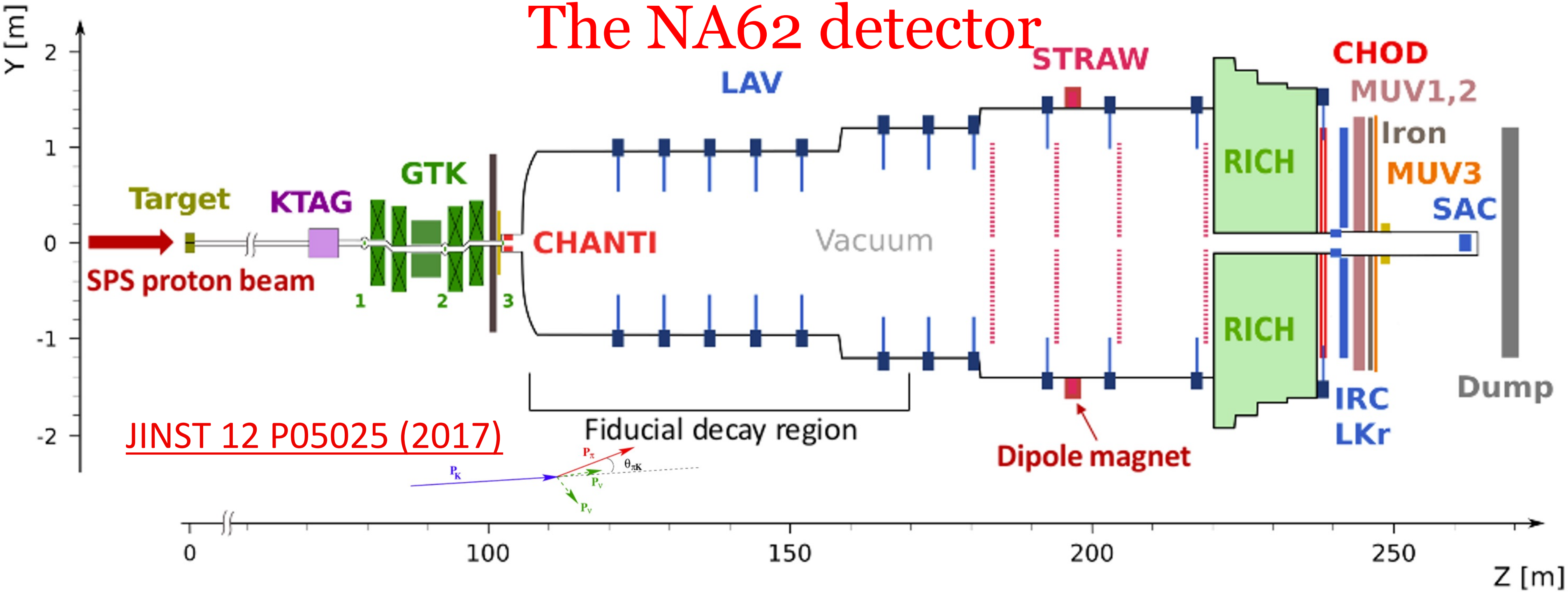
75 GeV/c unseparated hadrons beam:

π^+(70%), K^+ (6%), p(24%).

100 mrad divergence (RMS)

60x30 mm^2 transverse size.

The NA62 detector



JINST 12 P05025 (2017)

Upstream particle:

KTAG: Differential Cherenkov for K^+ ID

GTK: Si pixel tracker

CHANTI: Anti-counter for inelastic interactions

Decay region detectors (π^+):

STRAW: Track momentum spectrometer

CHOD: Scintillator hodoscope

RICH: For $\pi/\mu/e$ ID

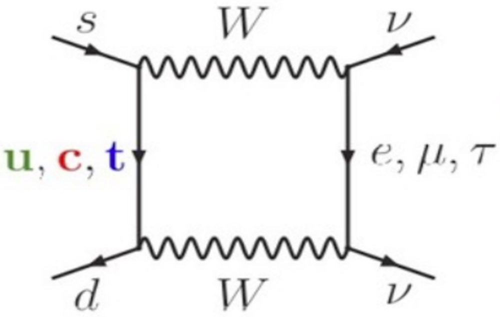
LKR/MUV1/2: Calorimetric systems

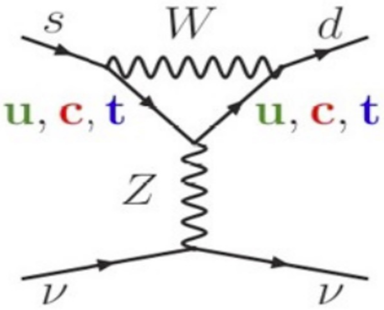
Vetos:

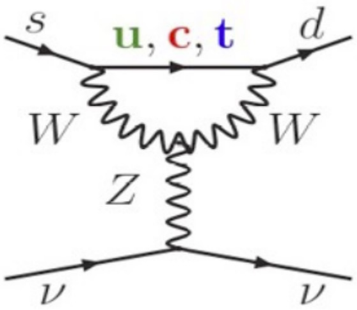
LAV/IRC/SAC: photons

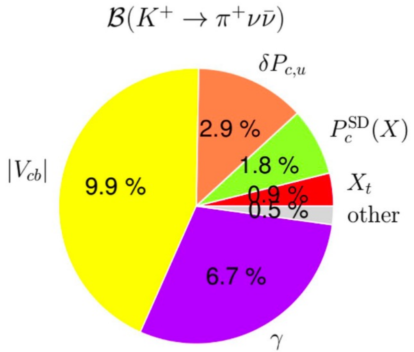
MUV3: muons

$K^+ \to \pi^+ \nu\bar{\nu}$ decay









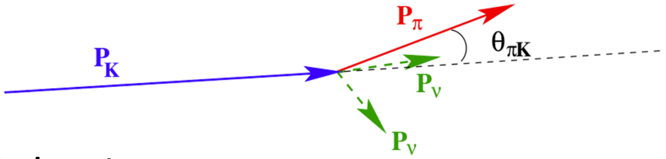
Uncertainties

[Buras et al., JHEP11(2015)033]

- FCNC loop process s →d coupling with high CKM suppression
- Clean theoretical prediction: short distance contributions
- Hadronic matrix elements: obtained from Kl3 measurements and SU(2) isospin symmetry

$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (0.84 \pm 0.03) \times 10^{-10} \left(\frac{|V_{cb}|}{0.0407}\right)^{2.8} \left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (0.84 \pm 0.10) \times 10^{-10}$$

- Channel sensitive to physics BSM



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ selection

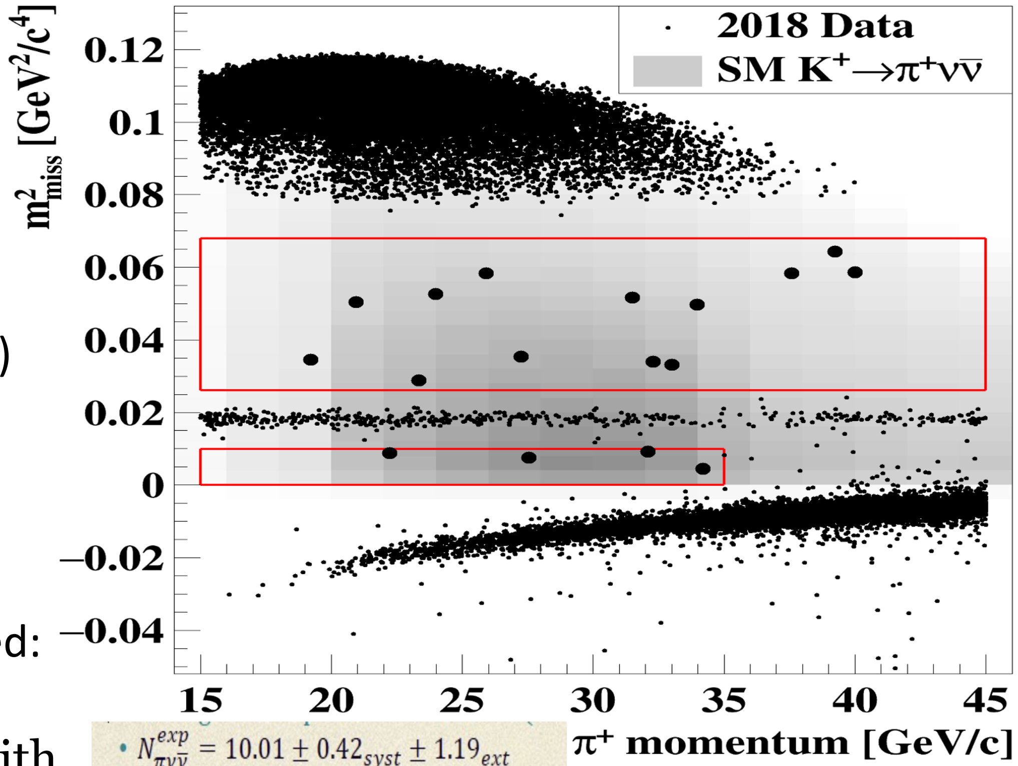
$m^2_{miss} = (P_K - P_\pi)^2$

Selection steps:

- K^+ and π^+ track reconstruction
  - L0: presence of charged particles and μ/γ veto
  - L1: K^+ ID+ photon veto
- K^+- π^+ matching
  - Excellent time resolution O(100ps)
- Decay vertex FV + other cuts
- π^+ ID (μ^+ rejection ~ 10^{-7})
- Photon rejection (~ 10^{-7})
- Kinematic cuts (m^2_{miss}, p_π):

  Signal regions + control regions defined:

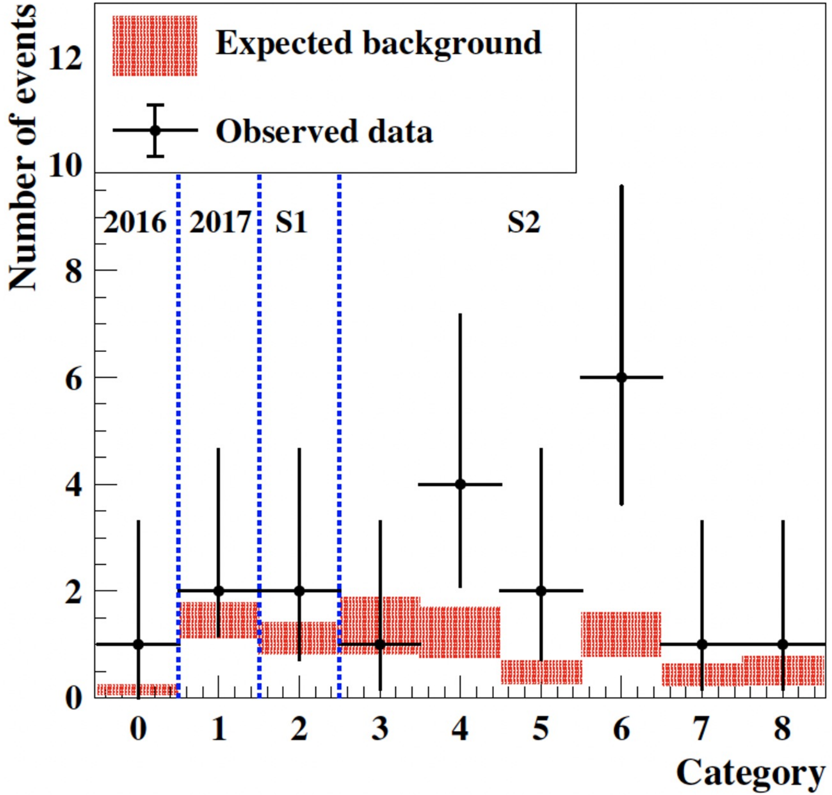
  blind analysis performed
- Normalized wrt $K^+ \rightarrow \pi^+\pi^0$ acquired with a Downscaled minimum bias trigger



- $N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$
- $N^{exp}_{bg} = 7.03^{+1.05}_{-0.82}$
- $SES = (0.839 \pm 0.053_{syst}) \times 10^{-11}$

17 events observed

Br ($K^+ \rightarrow \pi^+ \nu\bar{\nu}$) results

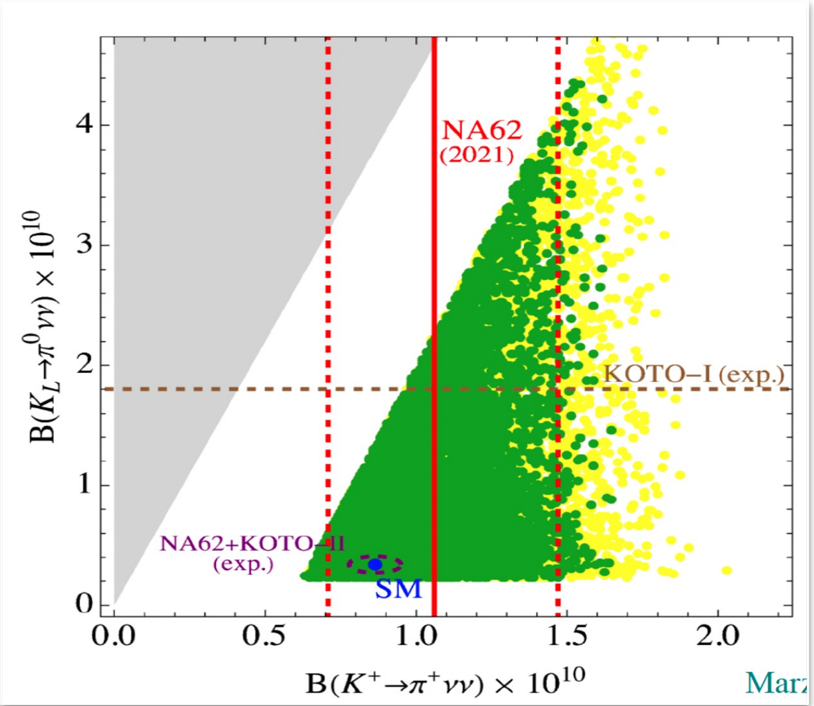


- Maximum likelihood fit using observed data and background expectations in each category
- 2016, 2017, 2018 with old collimator (S1) and 2018 with new collimator (S2)
- S2: sample split in 5 GeV/c wide bins from 15-45 GeV/c to increase sensitivity

JHEP 06 (2021) 093

$$BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

$K^+ \to \pi^+ \nu\bar{\nu}$ and New Physics



Marzocca et al., Eur. Phys. J. C (2022)

Generic scalar Leptoquark model addressing B anomalies

- Large deviation from the SM expectation seems to be excluded
- A more precise measurement is needed: Run2 (2021- LS3) with the goal of reaching $\mathcal{O}(10\%)$ uncertainty measurement

See also, for example:

Buras et al., JHEP11 (2015) 166

Isidori et al., Eur. Phys.J. C (2017) 77

Tessio B. de Melo et al., *Phys.Rev.D* 103 (2021) 11

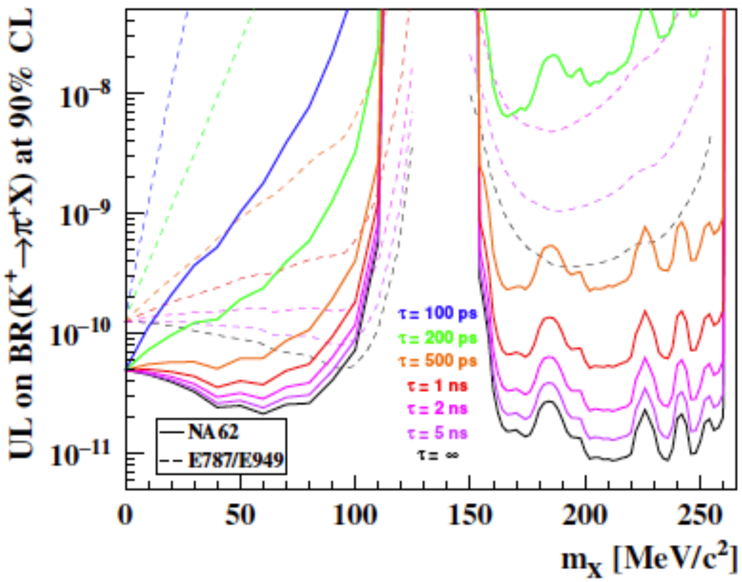
JHEP 06 (2021) 093

Feebly interacting particles $K^+ \rightarrow \pi^+ X_{inv}$

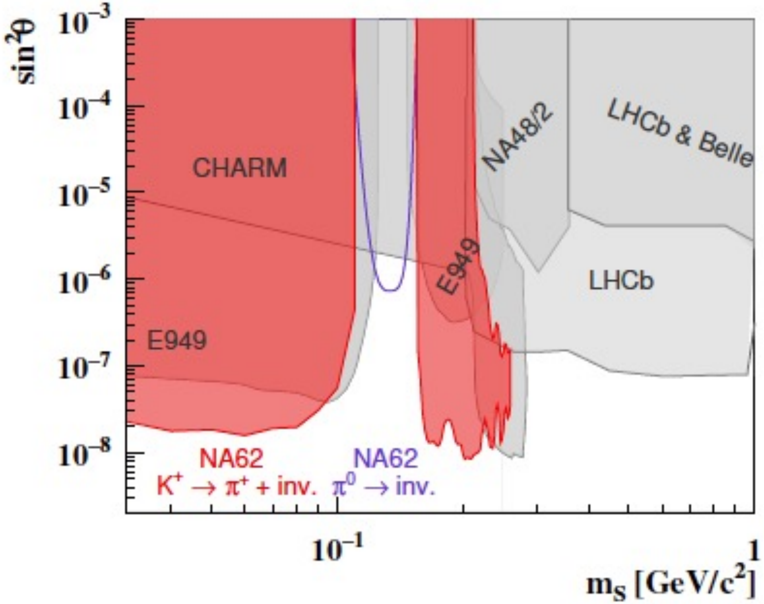
Feebly interacting scalar or pseudaoscalar X: $K^+ \rightarrow \pi^+ X_{inv}$ has same signature as $K^+ \rightarrow \pi^+ \nu\nu$

Searches performed looking for a peaking signal in the $m^2_{miss} = m^2_X$ distribution

Upper limits @90% CL for a stable or decaying X particle with lifetime τ



Dark scalar S decaying into visile SM particles and mixing with the H boson according to $\sin^2 \theta$



NA62

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Motivation for LNV and LFV searches

- Lepton Number (**L**) and Lepton Flavour (**L_e, L_μ, L_τ**) are foreseen in some BSM theories: conservation laws in SM are not imposed by any local gauge symmetry

- Observation of neutrino oscillations provided the first proof of LF non conservation, however no evidence of LNV has been observed so far

- Searches for K decays violating LV and LN conservation are powerful probes of BSM models at mass scales up to $\mathcal{O}$(100TeV)

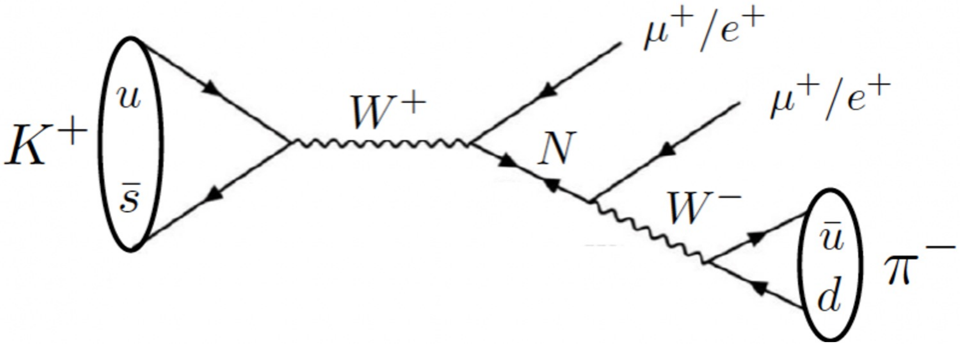
- K meson decays complement searches in B meson or lepton decays:

- Pure leptonic LFV processes: $\mu \rightarrow e\gamma$ or $\mu \rightarrow 3e$ **(MEG, MU2E, MU3E)**
- Quark-lepton LFV processes of the type **d** $\rightarrow$ **dμe** as the neutrino-less conversion $\mu + (A, Z) \rightarrow e + (A, Z)$
- Quark-lepton LFV processes of the type **s** $\rightarrow$ **dμe** as the kaon decays: $K^+ \rightarrow \pi^+\mu e$ **(NA62)**
- Lepton number violating decays as the neutrino-less 2β-decay or $K^+ \rightarrow \pi^- l^+l^+$, $B^+ \rightarrow X^- l^+l^+$, where $X = \pi, K, \rho$ **(NA62, LHCb, Belle II)**

LFV and LNV in Kaon decays

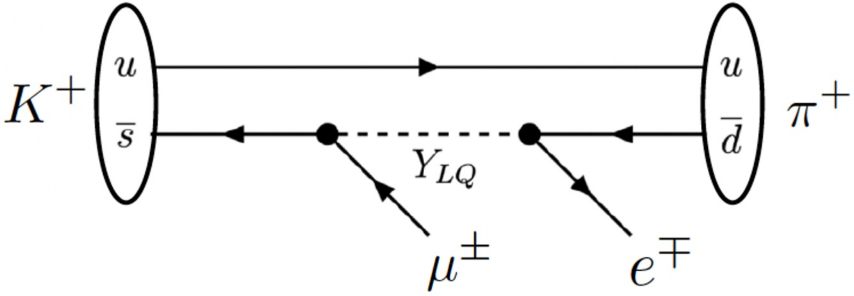
Lepton Number (**L**) and Lepton Flavour (**L_e, L_μ, L_τ**)

- **Lepton number violation:**



eg: $K^+ \rightarrow \pi^- \mu^+ e^+$
$\Delta L=2$ via Majorana neutrinos, Type I see-saw mechanism

- **Lepton flavour violation:**



eg: $K^+ \rightarrow \pi^+ \mu^- e^+$
$\Delta L_e=1$ and $\Delta L_\mu=1$
Via leptoquark (couples with fermions of more than one family) , Z' (family non universal coupling) , FV ALPs..

LNV and LFV analysis strategy

- Blinded analysis strategy: signal region kept closed until final background validation in control regions
- Track selection: momentum direction from STRAW, time from CHOD + RICH
- Reconstruct the 3 particle decay vertex within the FV
- Particle identification PID LKr, MUV3, RICH. Photon veto LAV
- The invariant mass M of the three selected tracks build under the PID hypothesis is used to distinguish between signal and background (typically σ_M~1.4 MeV)

$$M_{inv} = \sqrt{(\sum_i P_i)^2}$$

where P_i is the four momentum of the selected track

- Normalization channel chosen according to the different final states, in order to optimise the cancellation of systematic effects such as trigger efficiency or intrinsic detector inefficiencies
- Different trigger Downscaling factors are kept into account when applicable

LNV and LFV analysis strategy

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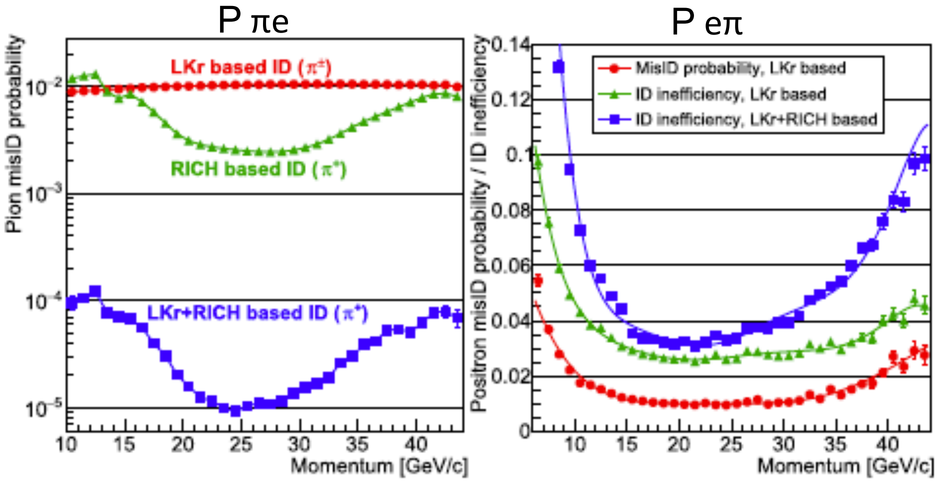
Trigger line	Downscaling	L0 triggers $[10^3]$	L1 triggers $[10^3]$
PNN	1	1540	74
Non-μ	200	30	12
MT	100	39	4
2μMT	2	150	30
eMT	8	193	22
μMT	5	99	10
DV-μ	5	140	0.3
DV-2μ	3	160	5
Neutrino	15	10	3
Control	400	94	94

- Different trigger Downscaling factors are kept into account when applicable

Background sources

1. Mis-identification (mis-ID) probabilities measured from data as not well modelled in MC:
   $P_{\pi e}$: $\pi^\pm \to e^\pm$ from sample $K^+ \to \pi^+ \pi^+ \pi^-$
   $P_{e\pi}$: $e^\pm \to \pi^\pm$ from sample $K^+ \to \pi^0 e^+ \boldsymbol{\nu}$

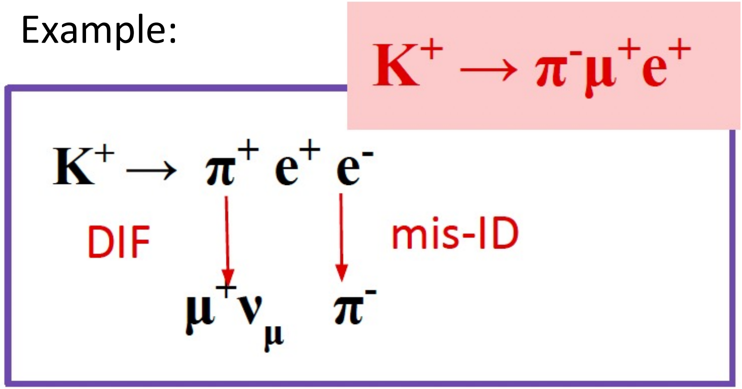
   $\pi^\pm \to \boldsymbol{\mu}^\pm$ and $\boldsymbol{\mu}^\pm \to e^\pm$ have been considered (accidentals in muon detector (MUV3)).
   $P_{\pi\boldsymbol{\mu}}$: (2-3) $\times 10^{-3}$. $P_{e\boldsymbol{\mu}}$: (10^{-8})



2. Decay in Flight (DIF)
   $\pi^\pm \to \mu^\pm \nu_\mu$
   $\mu^\pm \to e^\pm \nu_e$
   $\pi^0 \to e^+ e^- \gamma$ (Dalitz decay)

   Pion decays accurately described in the simulation → Biased MC with forced decay

Example:



3. Accidental background. Mostly due to pile-up muons coming from beam particle decay

Search for $K^+ \rightarrow \pi^- \mu^+\mu^+$

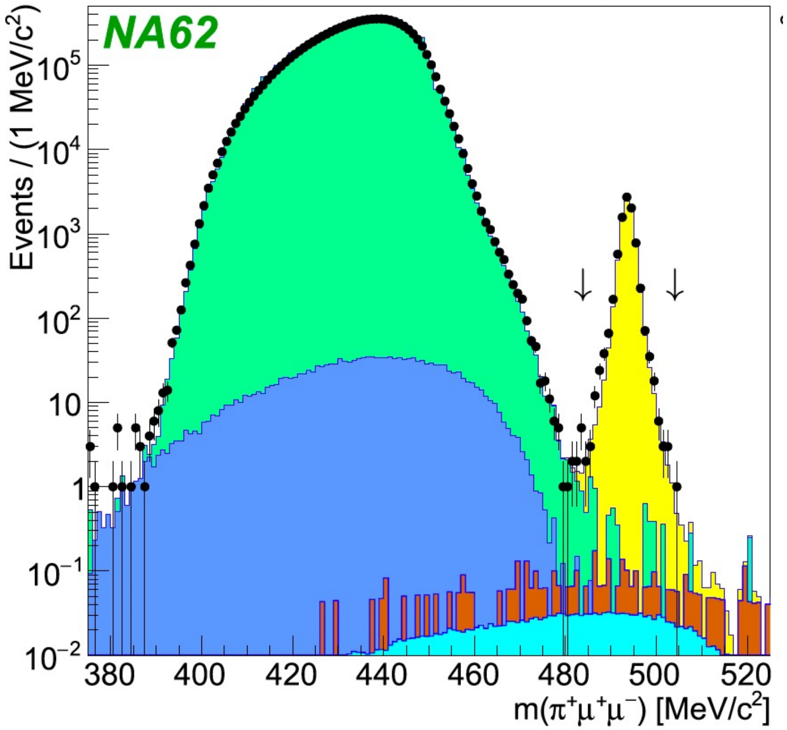
PLB 797 134794 (2019)

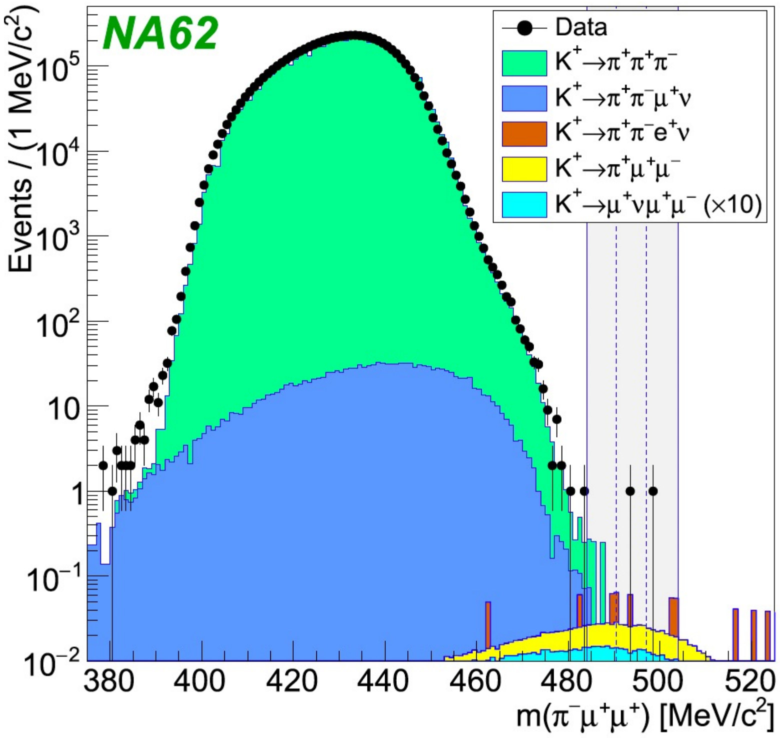
Normalization channel: $K^+ \rightarrow \pi^+ \mu^+\mu^-$

BR($K^+ \rightarrow \pi^+ \mu^+\mu^-$)= $(0.962 \pm 0.025) \times 10^{-7}$

from PRL 697,2 (2011)

Partial data sample, not full RunI





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Partial data sample, not full RunI

Error on the bkg is dominated by statistics

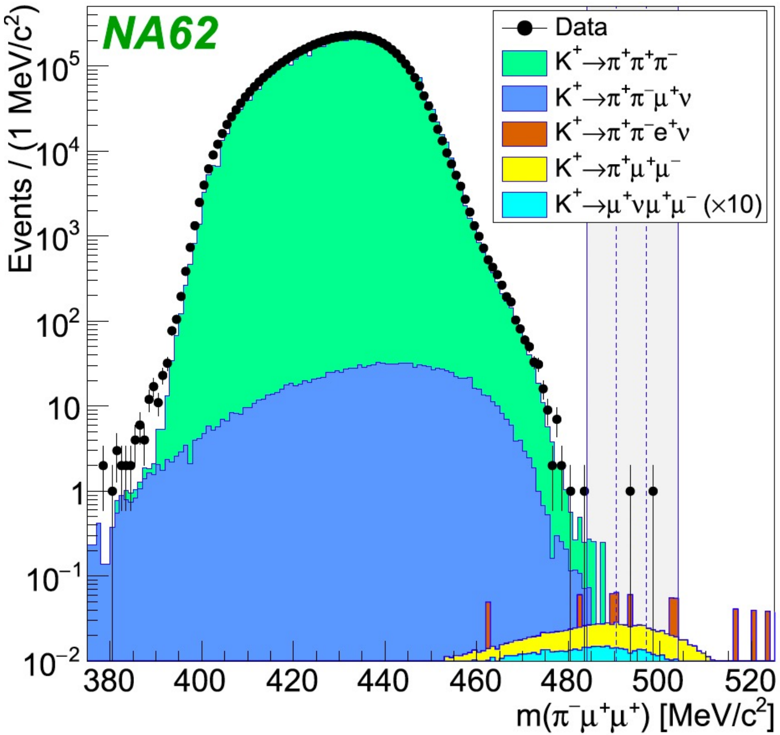
Process	Expected background
$K_{3\pi}$ (no $\pi^\pm$ decays)	0.007 ± 0.003
$K_{3\pi}$ (one $\pi^\pm$ decay)	0.25 ± 0.25
$K_{3\pi}$ downstream (at least two $\pi^\pm$ decays)	0.20 ± 0.20
$K_{3\pi}$ upstream (at least two $\pi^\pm$ decays)	0.24 ± 0.24
$K^+ \to \pi^+\mu^+\mu^-$	0.08 ± 0.02
$K^+ \to \pi^+\pi^-\mu^+\nu$	0.05 ± 0.05
$K^+ \to \pi^+\pi^-e^+\nu$	0.07 ± 0.05
$K^+ \to \mu^+\nu\mu^+\mu^-$	0.01 ± 0.01
Total	0.91 ± 0.41

LNV $A_{\pi\mu\mu}$= 9.81% assuming uniform phase space densities

SES = (1.28 ± 0.04) x 10^{-11}

N_{obs} = 1

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



Search for $K^+ \to \pi^- e^+ e^+$

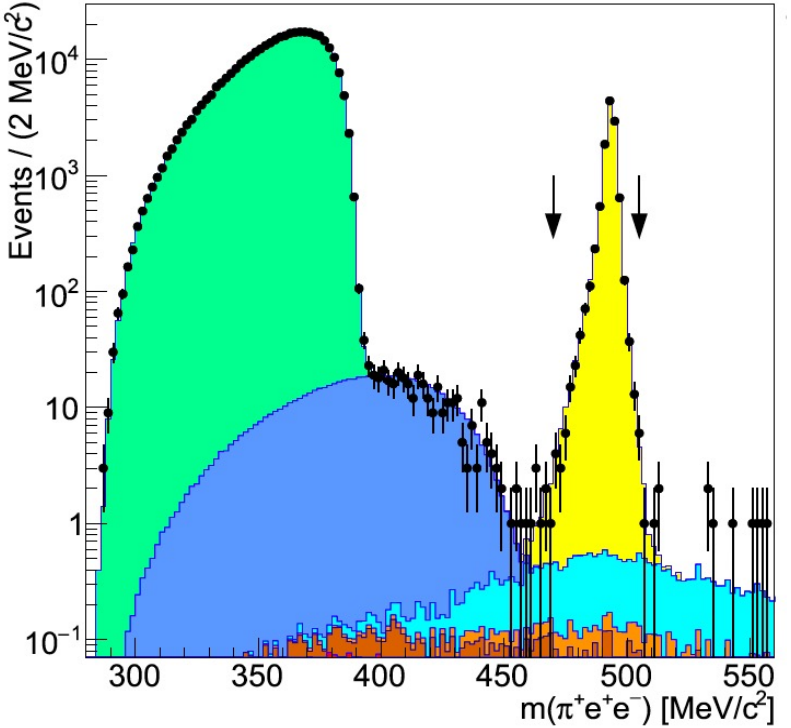
PLB 830 137172 (2022)

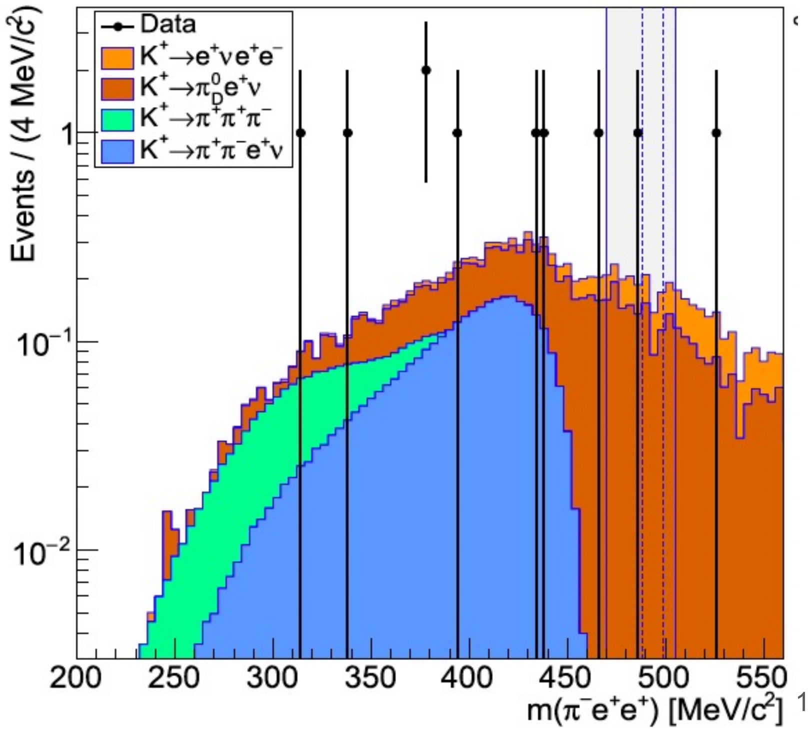
Normalization channel: $K^+ \to \pi^+ e^+ e^-$

BR($K^+ \to \pi^+ e^+ e^-$)= $(3.00 \pm 0.09) \times 10^{-7}$

from PDG, PTEP, 083C01 (2020)

Data sample: full RunI





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Data sample: full RunI

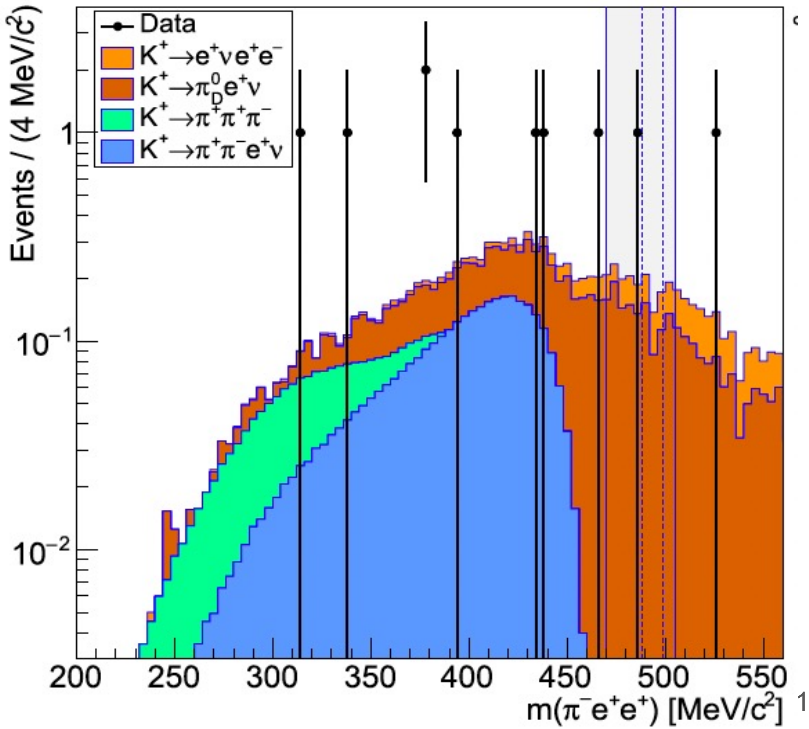
Mode	Lower region	Upper region	Masked region	Signal region
$K^+ \to \pi^+\pi^+\pi^-$	0.9	–	–	–
$K^+ \to \pi^+\pi^- e^+\nu$	3.3	–	–	–
$K^+ \to \pi^+\pi^0_D$	–	0.02	0.01	–
$K^+ \to \pi^0_D e^+\nu$	3.7 ± 0.7	1.20 ± 0.24	1.23 ± 0.25	0.29 ± 0.06
$K^+ \to e^+\nu e^+ e^-$	0.7 ± 0.1	0.76 ± 0.15	0.47 ± 0.09	0.14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

LNV $A_{\pi ee}$= (4.32) % assuming uniform phase space densities

SES = $(2.28 \pm 0.07) \times 10^{-11}$

$N_{obs} = 0$

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



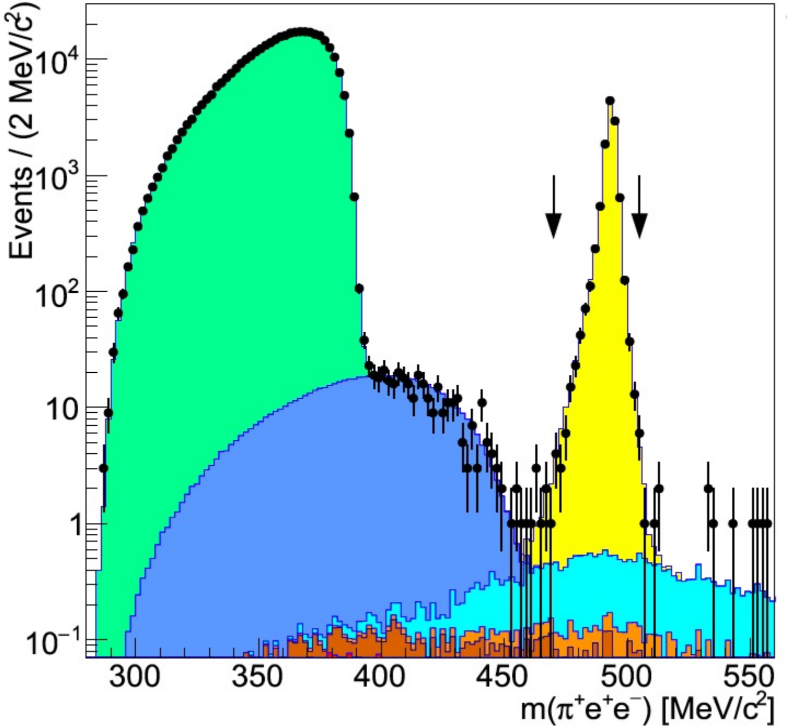
Search for $K^+ \to \pi^- \pi^0 e^+ e^+$ PLB 830 137172 (2022)

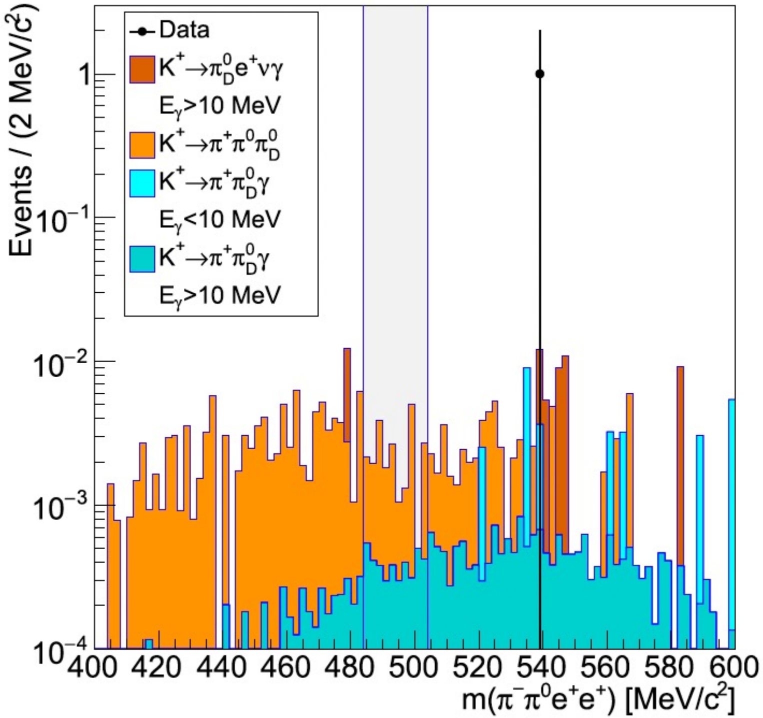
Normalization channel: $K^+ \to \pi^+ e^+ e^-$

BR($K^+ \to \pi^+ e^+ e^-$)= $(3.00 \pm 0.09) \times 10^{-7}$

from PDG, PTEP, 083C01 (2020)

Data sample: full RunI





Search for $K^+ \to \pi^-\pi^0e^+e^+$

PLB 830 137172 (2022)

Normalization channel: $K^+ \to \pi^+ e^+e^-$

BR($K^+ \to \pi^+ e^+e^-$)= $(3.00 \pm 0.09) \times 10^{-7}$

from PDG, PTEP, 083C01 (2020)

Data sample: full RunI

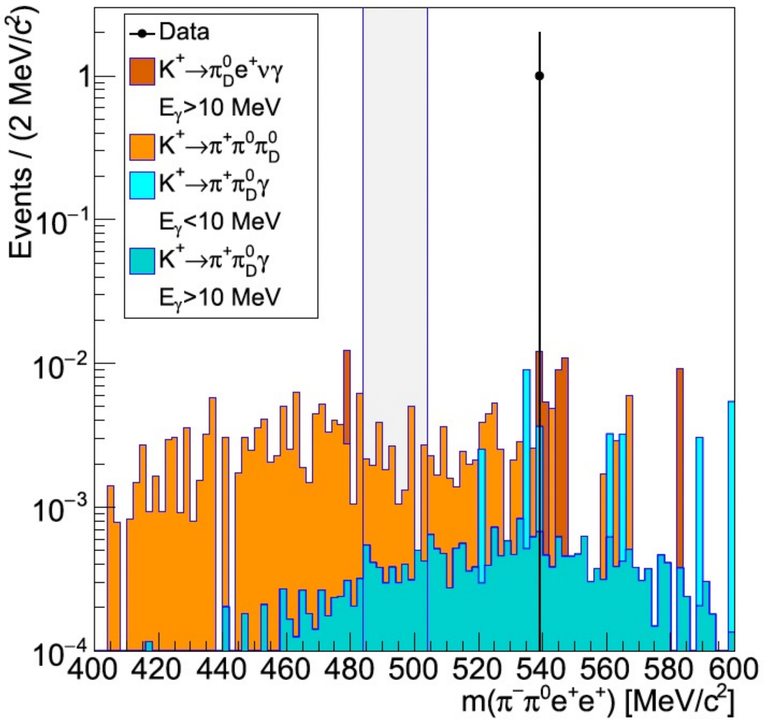
Mode	Control region	Signal region
$K^+ \to \pi^+\pi^0\pi^0_D$	0.16 ± 0.01	0.019
$K^+ \to \pi^+\pi^0_D\gamma$	0.06 ± 0.01	0.004
$K^+ \to \pi^0_D e^+\nu\gamma$	0.05 ± 0.02	–
$K^+ \to \pi^+\pi^0 e^+e^-$	0.01	0.001
Pileup	0.20 ± 0.20	0.020 ± 0.020
Total	0.48 ± 0.20	0.044 ± 0.020
Data	1	0

LNV $A_{\pi\pi ee}$= (0.271±0.003 sys) % assuming uniform phase space densities

SES = $(3.69 \pm 0.12) \times 10^{-10}$

$N_{obs} = 0$

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



Search for $K^+ \to \pi^\pm \mu^\mp e^+$ ($\pi^0 \to \mu^- e^+$)

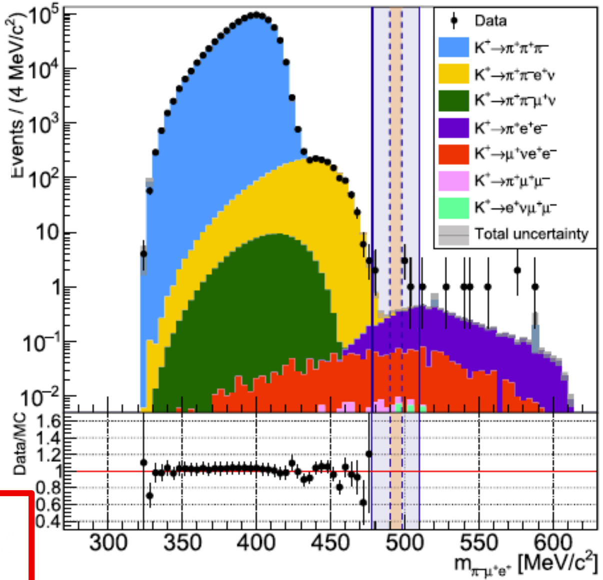
PRL 127 131802 (2021)

Normalization channel: $K^+ \to \pi^+ \pi^+ \pi^-$

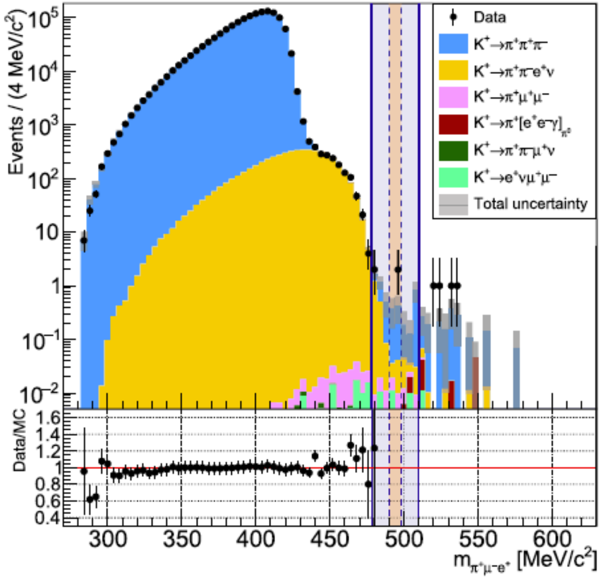
$BR(K^+ \to 3\pi) = (5.583 \pm 0.024)\, 10^{-2}$ from PDG, PTEP, 083C01 (2020)

Source	$K^+ \to \pi^- \mu^+ e^+$	$K^+ \to \pi^+ \mu^- e^+$	$\pi^0 \to \mu^- e^+$
$K^+ \to \pi^+ \pi^+ \pi^-$	0.22 ± 0.15	0.84 ± 0.34	0.22 ± 0.15
$K^+ \to \pi^+ e^+ e^-$	0.63 ± 0.13	negligible	negligible
$K^+ \to \mu^+ \nu_\mu e^+ e^-$	0.13 ± 0.02	negligible	negligible
$K^+ \to \pi^+ \pi^- e^+ \nu_e$	0.07 ± 0.02	0.05 ± 0.03	0.01 ± 0.01
$K^+ \to \pi^+ \mu^+ \mu^-$	0.01 ± 0.01	0.02 ± 0.01	negligible
$K^+ \to e^+ \nu_e \mu^+ \mu^-$	0.01 ± 0.01	0.01 ± 0.01	negligible
Total	1.07 ± 0.20	0.92 ± 0.34	0.23 ± 0.15

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



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



$$\mathcal{B}(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11};$$
$$\mathcal{B}(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11};$$
$$\mathcal{B}(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}.$$

$$K^+ \to \pi^- \mu^+ e^+:\ n_{bg} = 1.07 \pm 0.20, \quad n_{obs} = 0;$$
$$K^+ \to \pi^+ \mu^- e^+:\ n_{bg} = 0.92 \pm 0.34, \quad n_{obs} = 2;$$
$$\pi^0 \to \mu^- e^+:\ n_{bg} = 0.23 \pm 0.15, \quad n_{obs} = 0.$$

Search for $K^+ \rightarrow \mu^- \nu e^+ e^+$

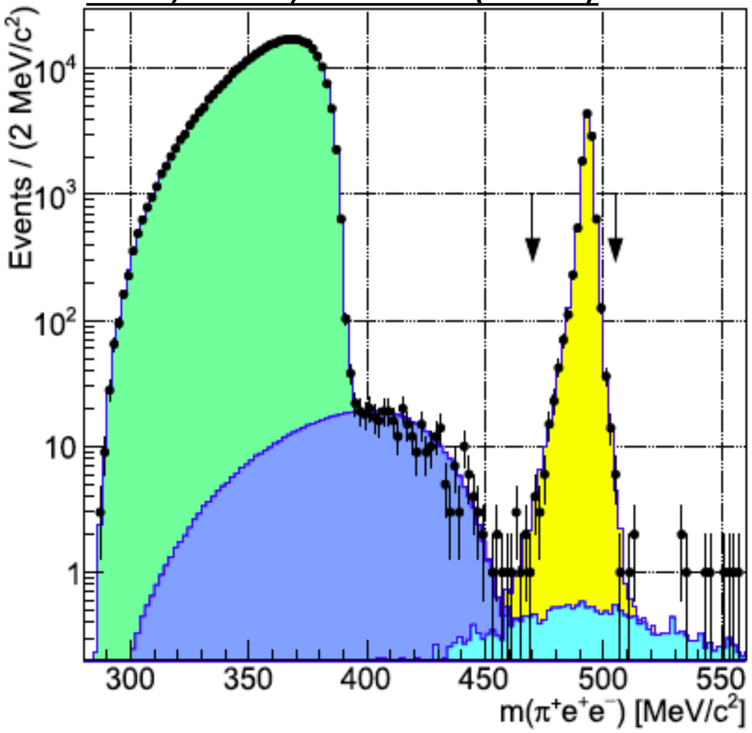
PLB 838 137679 (2023)

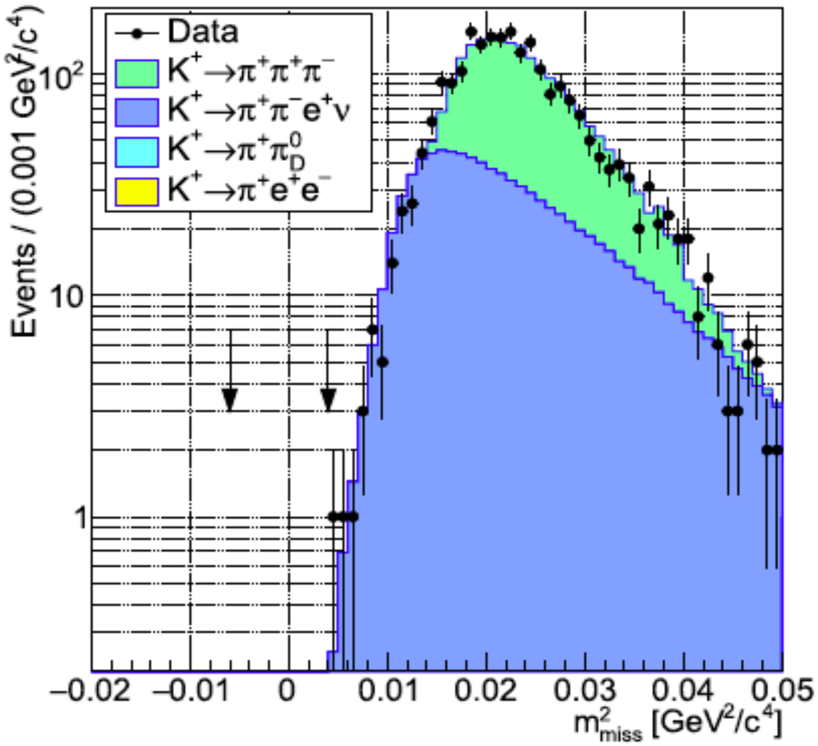
Normalization channel: $K^+ \rightarrow \pi^+ e^+ e^-$

BR($K^+ \rightarrow \pi^+ e^+ e^-$)= $(3.00 \pm 0.09) \times 10^{-7}$

from PDG, PTEP, 083C01 (2020)

Data sample: full RunI





Search for $K^+ \rightarrow \mu^- \nu e^+ e^+$

PLB 838 137679 (2023)

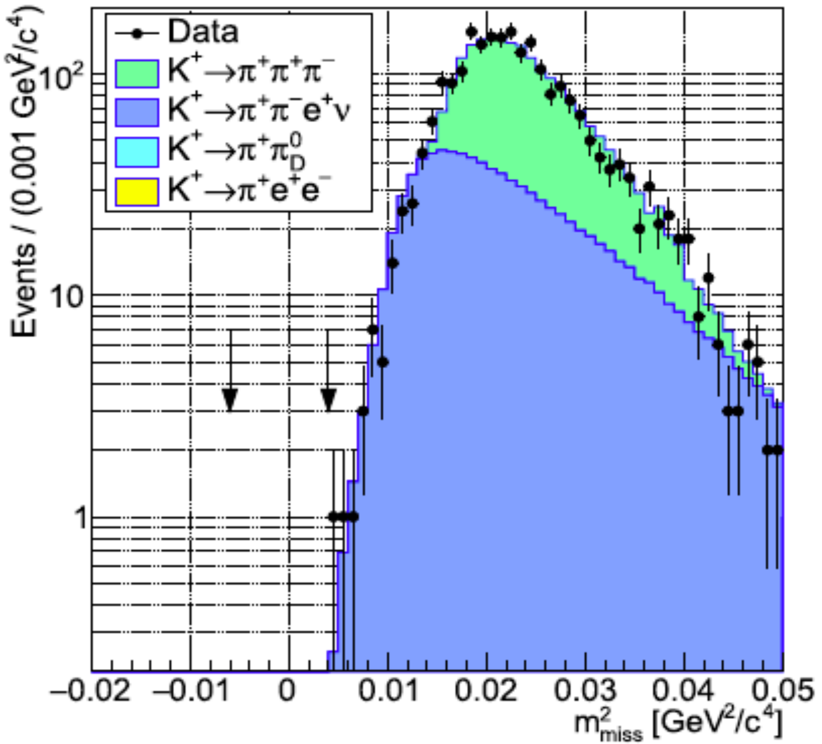
Normalization channel: $K^+ \rightarrow \pi^+ e^+ e^-$

BR($K^+ \rightarrow \pi^+ e^+ e^-$)= $(3.00 \pm 0.09) \times 10^{-7}$

from PDG, PTEP, 083C01 (2020)

Data sample: full RunI

Mode / Region	Lower	Signal	Upper
$K^+ \to \pi^+\pi^+\pi^-$	< 0.07	< 0.07	1412 ± 11
$K^+ \to \pi^+\pi^-e^+\nu$	0.01 ± 0.01	0.16 ± 0.02	867 ± 1
$K^+ \to \pi^+\pi^+\pi^-$ (upstream)	< 0.03	0.06 ± 0.03	1.5 ± 0.3
$K^+ \to \pi^+\pi^-e^+\nu$ (upstream)	0.01 ± 0.01	0.01 ± 0.01	0.14 ± 0.03
$K^+ \to \pi^0_D e^+\nu$	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
$K^+ \to e^+\nu\mu^+\mu^-$	< 0.01	< 0.01	0.05 ± 0.02
Total expected	0.04 ± 0.02	0.26 ± 0.04	2281 ± 11
Data	0	0	2271



LNV $A_{\mu\nu ee}$= (± sys) % assuming uniform phase space densities

SES = $(3.53 \pm 0.12) \times 10^{-11}$

$N_{obs} = 0$

BR($K^+ \rightarrow \mu^- \nu\, e^+ e^+$) < $8.1\ 10^{-11}$ @ 90% CL

NA62 LNV and LFV searches recap

Decay channel	Previous $\mathcal{B}$ UL (PDG)	NA62 $\mathcal{B}$ UL	statistics	improvement
$K^+ \to \pi^-\mu^+\mu^+$	8.6×10^{-11}	4.2×10^{-11}, ref [6]	25% of Run 1	$\sim$ factor 2
$K^+ \to \pi^-e^+e^+$	6.4×10^{-10}	5.3×10^{-11}, ref [7]	full Run 1	$\sim$ factor 12
$K^+ \to \pi^-\pi^0e^+e^+$	–	8.5×10^{-11}, ref [7]	full Run 1	–
$K^+ \to \pi^-\mu^+e^+$	5.0×10^{-10}	4.2×10^{-11}, ref [8]	2017-18	$\sim$ factor 12
$K^+ \to \pi^+\mu^-e^+$	5.2×10^{-10}	6.6×10^{-11}, ref [8]	2017-18	$\sim$ factor 8
$\pi^0 \to \mu^-e^+$	3.4×10^{-9}	3.2×10^{-10}, ref [8]	2017-18	$\sim$ factor 10
$K^+ \to \mu^-\nu e^+e^+$	2.1×10^{-8}	8.1×10^{-11}, ref [9]	full Run 1	$\sim$ factor 250

NA62 is significantly contributing to these searches

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Experiment main goal:

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

Search for lepton flavour and number violation, rare and forbidden decays:

$K^+ \to \pi^\pm \mu^\mp e^+$

$K^+ \to \pi^- l^+ l^+$

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

$(K^+ \to \pi^+ \pi^0)\, \pi^0 \to \text{invisible}$

Hidden sector Physics

Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**), Heavy neutral Lepton(**N**)

$K^+ \to l^+ N$

Heavy neutral lepton searches

- Right handed neutrinos or Heavy Neutral Leptons (HNL) are included in several extension of the Standard Model
- Search for HNL produced in K decays: $K^+ \rightarrow \mu^+ N$, $K^+ \rightarrow e^+ N$ due to mixing with standard model neutrinos

Production: $K^+ \longrightarrow l^+ N$

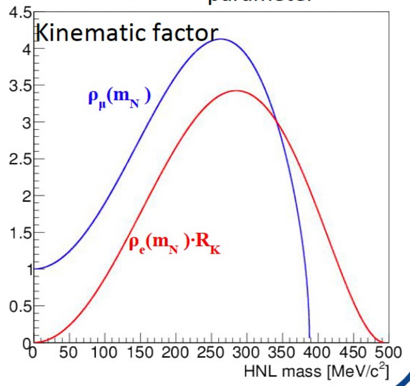
Search for a peak in $m_N^2 = m_{miss}^2 = (P_K - P_l)^2$

$$\Gamma(K^+ \longrightarrow l^+ \nu_h) = \Gamma(K^+ \longrightarrow l^+ \nu) \cdot \rho_l(m_N) \cdot |U_{l4}|^2$$

Width of the K + leptonic decay involving SM neutrino

squared neutrino mixing parameter

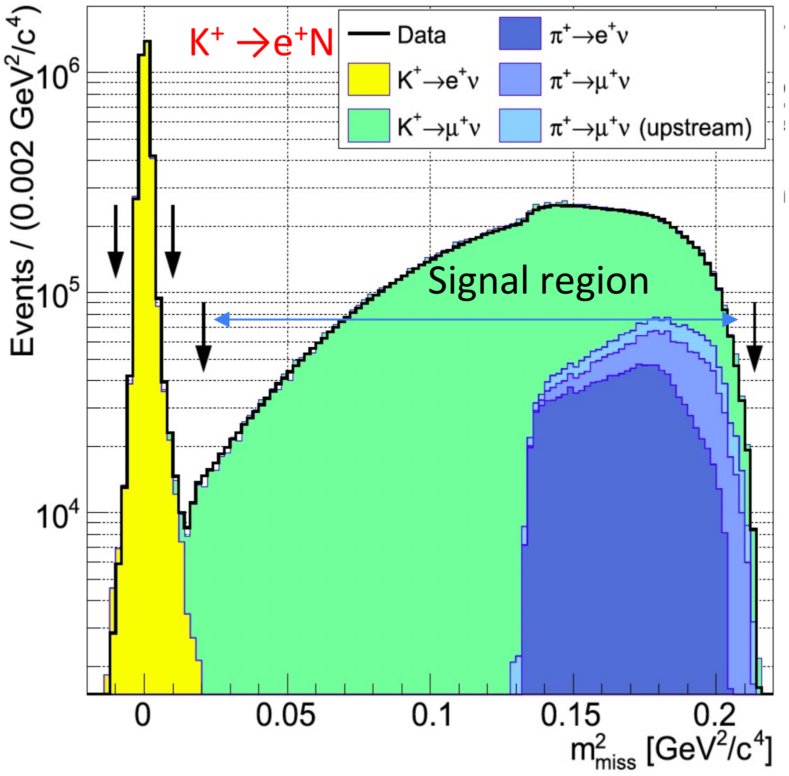
HNL production is enhanced kinematically wrt SM decays (except near kinematic endpoints). Factor ~10^5 enhancement in the $K^+ \rightarrow e^+ N$ case: helicity suppression is relaxed.

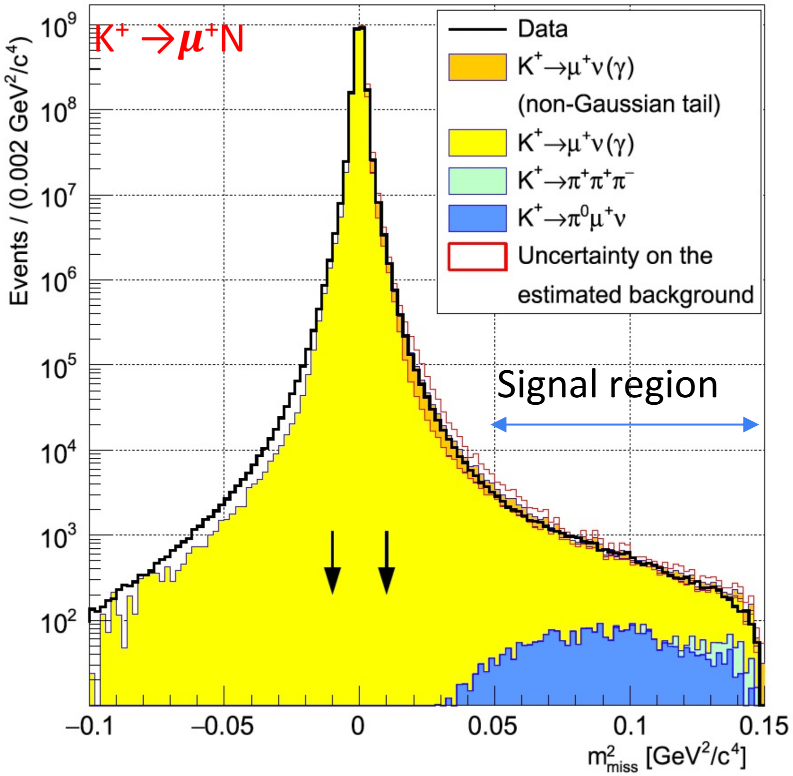


HNL N can be considered stable in production experiments

Search for HNL production in K^+ decays to leptons

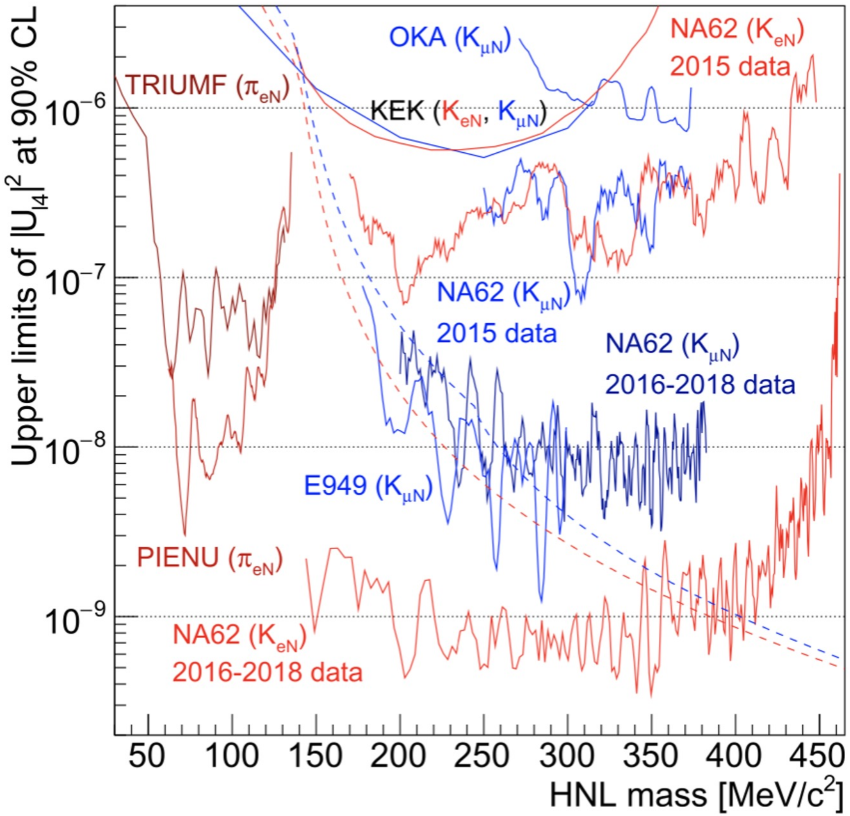
- Precise tracking and PID to reconstruct e^+/ μ^+: matching the two tracks together
- Veto every other in time activity $\mathcal{O}$(100ps)
- $K^+ \to l^+N$ decay should appear as a positive sharp bump in m^2_{miss} at the side of the $K^+ \to l^+\nu$ peak





Search for HNL in Run I

Right handed neutrinos or Heavy Neutral Leptons (HNL) are included in several extension of the Standard Model



- **$\mathcal{O}(10^{-9})$ limits on $|Ue4|^2$**
- Big Bang nucleosynthesis (BBN) allowed range (dashed lines) improved up to 340 MeV/c^2

- **$\mathcal{O}(10^{-8})$ limits on $|U\mu4|^2$** over the HNL mass range of 200–384 MeV/c^2
- Results consistent with E949 experiment and UL extends at higher masses

- More than 2(1) order of magnitude improvement for e^+(μ^+) Run I results compared to 2015 results

PLB 807 (2020) 135599 PLB 816 (2021) 136259

LETTER of INTENT CERN-SPSC-2022-031

Phase I Proposal:

HIKE
High Intensity Kaon Experiments

Flavour Physics

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$K^+ \to l^+ N$

Phase II and Phase III proposal: multiporpose K_L experiment and $K_L \to \pi^0 \nu \nu$

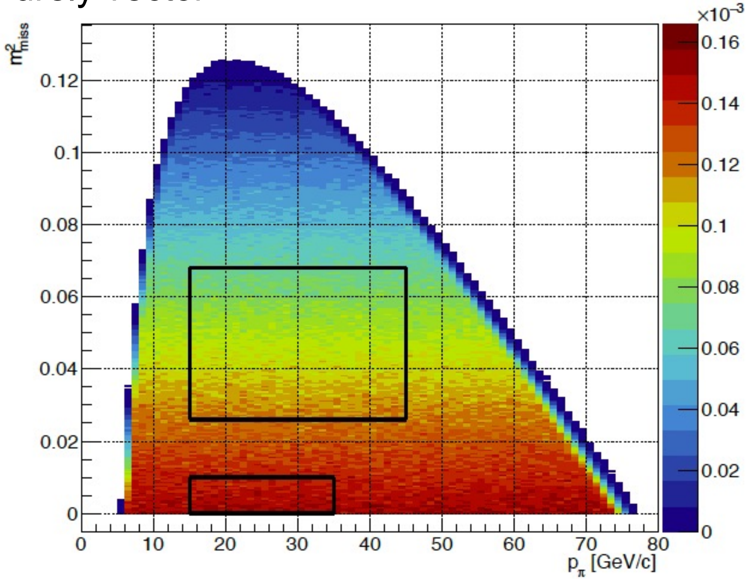
$K^+ \to \pi^+\nu\nu$ BSM in HIKE

- Goal of the experiment is to have a statistics after acceptance, eff : $N\pi\nu\nu$/year ~ 100
- In the SM, $K^+ \to \pi^+\nu\nu$ has only vector nature
- In BSM theories, LNV/LFV contribution can arise

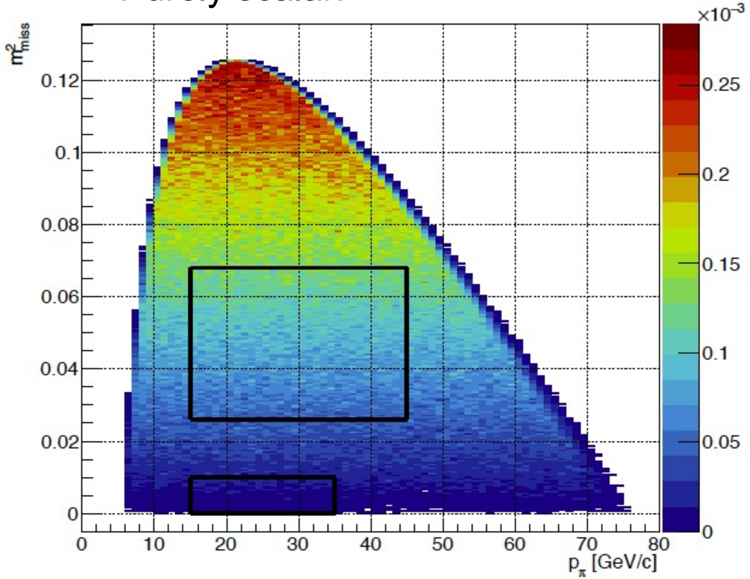
Deppisch et al, JHEP 186 (2020)

$$\mathcal{B}(K^+ \to \pi^+ \nu \overset{\leftrightarrow}{\nu}) = \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})_{\rm SM} + \sum_{i \le j}^{3} \mathcal{B}(K^+ \to \pi^+ \nu_i \nu_j)_{\rm LNV}.$$

From simulation:
Purely vector



Purely scalar:

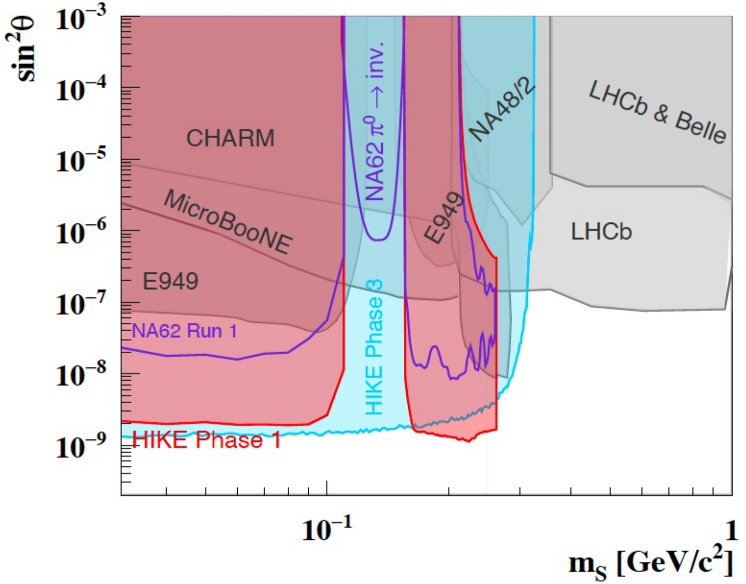


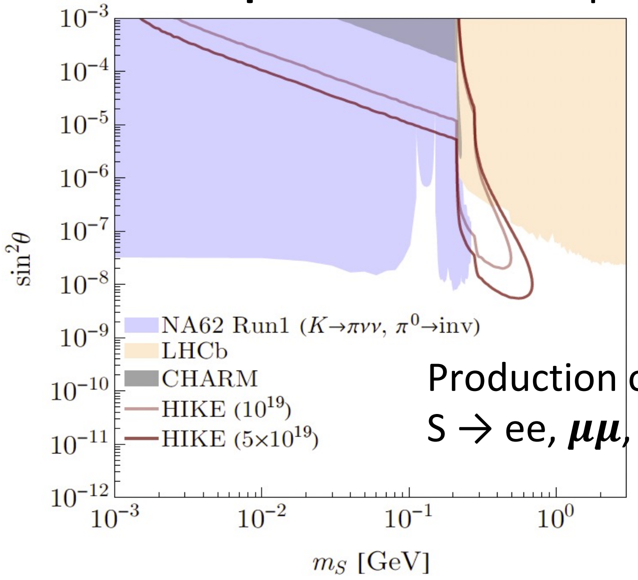
Feebly interacting particles $K^+ \rightarrow \pi^+ X_{inv}$ in HIKE

Feebly interacting scalar or pseudaoscalar X: $K^+ \rightarrow \pi^+ X_{inv}$ has same signature as $K^+ \rightarrow \pi^+ \nu\nu$

Searches performed looking for a peaking signal in the $m^2_{miss} = m^2_X$ distribution

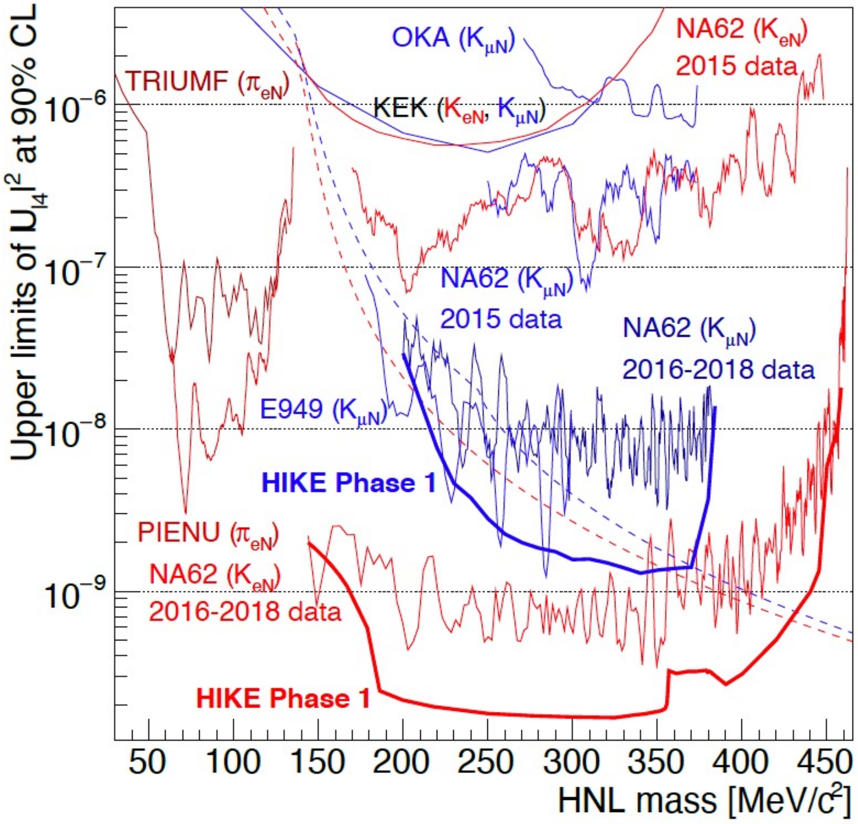
- X_{inv} : either dark scalar mixing with the Higgs Boson
- Projection of the sensitivity for the search for HIKE phase I assuming x40 statistics wrt NA62 runI (Kaon mode, left)
- The same measurement is accessible in **HIKE beam-dump mode** with complementary sensitivity (right)





Production of $B \rightarrow K^{(*)}S$, $S \rightarrow ee$, $\mu\mu$, $\pi\pi$, KK decays

Heavy neutral leptons in HIKE



- Upper limits at 90% CL of the HNL mixing parameters for NA62 and sesitivity for HIKE PhaseI
- Highly downscaled software trigger is coservatively assumed
- One order of magnitude improvement foreseen if a triggerless data taking is implemented

Conclusions

The NA62 experiment is contributing to Flavor physics and complements BSM searches

- Evidence of the $K^+ \to \pi^+\nu\nu$ decay has been measured in Run I with ~40% uncertainty on the BR. A $\mathcal{O}(10\%)$ uncertainty measurements is expected at the end of Run II
- Large improvements on most LN and LF violating K^+ and π^0 decays ULs: upper limits down to 10^{-11}
- A search for HNL production in K^+ decays to leptons has been performed, imposing upper limits on the $|U_{4l}|^2$ down to 10^{-9} covering a large mass range

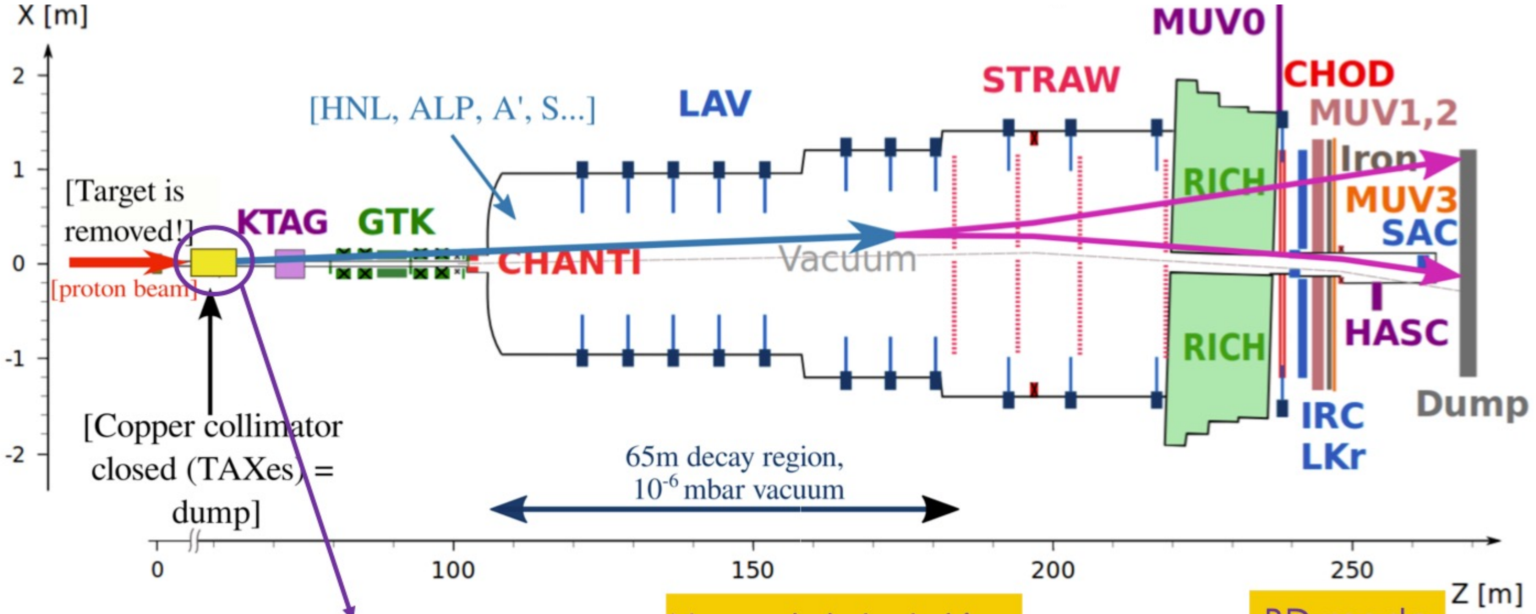
- A new experiment, HIKE, is at proposal state with exciting prospects:
  - BSM physics can be discriminated with a $K^+ \to \pi^+\nu\nu$ measurement more precise than 10%
  - LN and LF violating decays are limited by statistics: expect improvements with Run2 and HIKE (one order of magnitude in the SES)

Spare slides

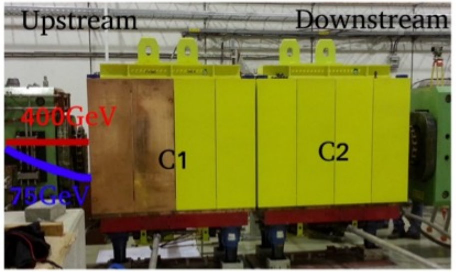
Aebischer et al, arXiv: 2203.09524 [hep-ph]

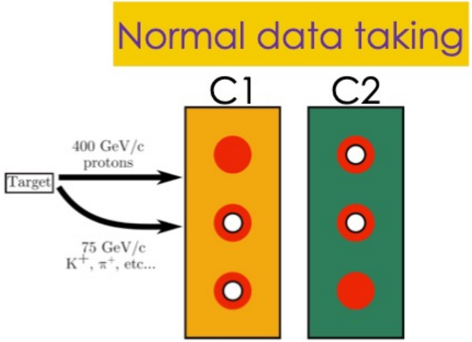
NP Scenario	References	Decays
Z-FCNC	[100, 101, 107, 108, 113]	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
Z'	[56, 100, 101, 105, 106],	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, ΔM_K, ε'/ε
Simplified Models	[76]	$K_L \to \pi^0\nu\bar{\nu}$, ε'/ε
LHT	[114–116]	All K decays
331 Models	[105]	Small effects in $K \to \pi\nu\bar{\nu}$
Vector-Like Quarks	[58]	$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$ and ΔM_K
Supersymmetry	[117–120], [121–125]	$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$
2HDM	[126, 127]	$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$
Universal Extra Dimensions	[128, 129]	$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$
Randall-Sundrum models	[81, 130–133]	All rare K decays
Leptoquarks	[86, 109, 110]	all rare K decays
SMEFT	[101, 134]	several processes in K and B system
SU(8)	[135]	$b \to s\ell^+\ell^-$, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
Diquarks	[136, 137]	ε_K, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$
Vectorlike compositeness	[138]	$R(K^{(*)})$, $R(D^{(*)})$, ε_K, $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$

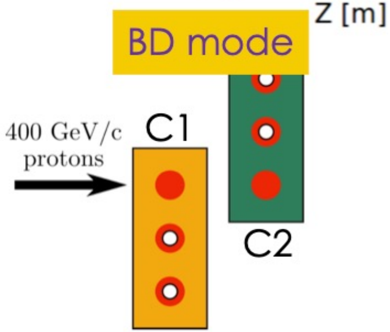
NA62 in beam dump mode



Data taken in dump mode in **2021**

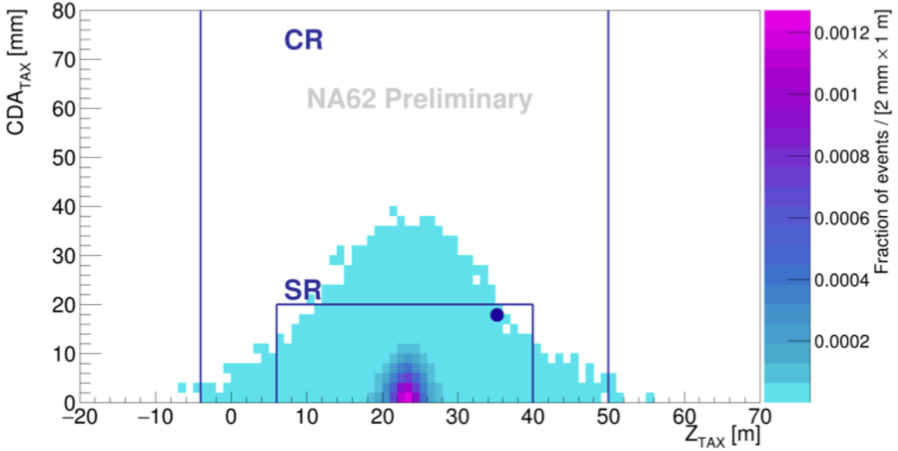






Search for A' → $\mu^+\mu^-$

Expected signal:

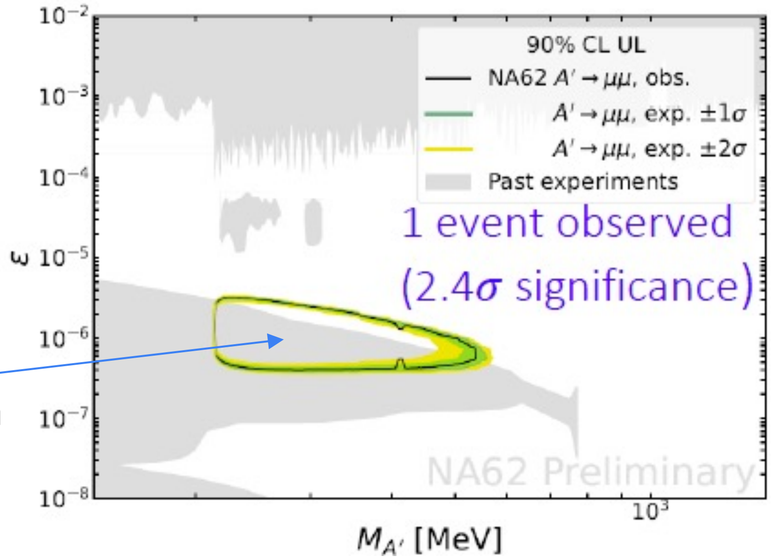


CDA_{TAX} closest distance of approach between the beam direction at the TAX entrance

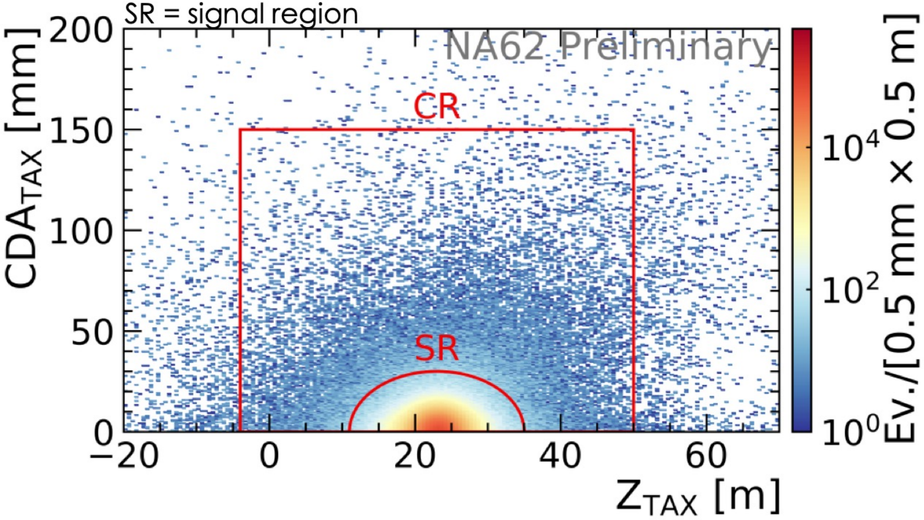
Z_{TAX} – longitudinal position

Background mainly from random time superposition of two uncorrelated muons: 0.016 ± 0.002

arXiv2303.08666 (2023), submitted to JHEP

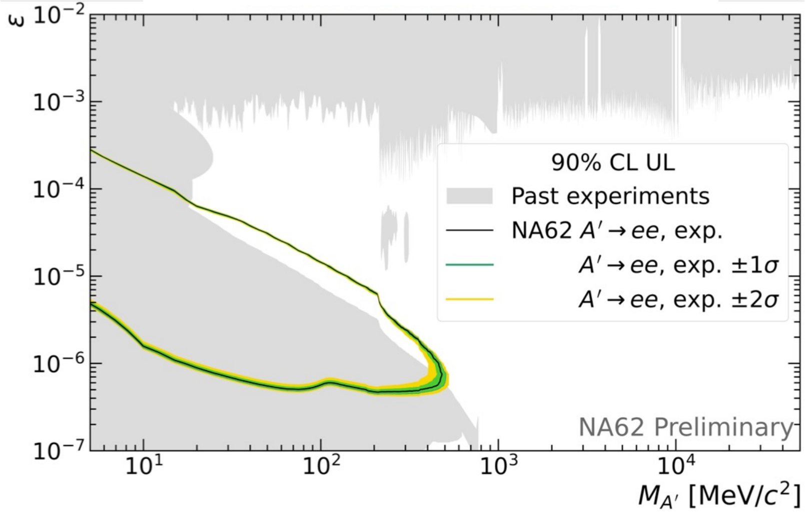


Search for A’ → e^+e^-



Background mainly secondaries of particle’s interactions with traversed material (“prompt”):

$$0.0094^{+0.049}_{-0.009} \text{ @ } 90\% \text{ CL}$$



No data event has been observed in the Signal Region

NA62 LNV and LFV searches recap

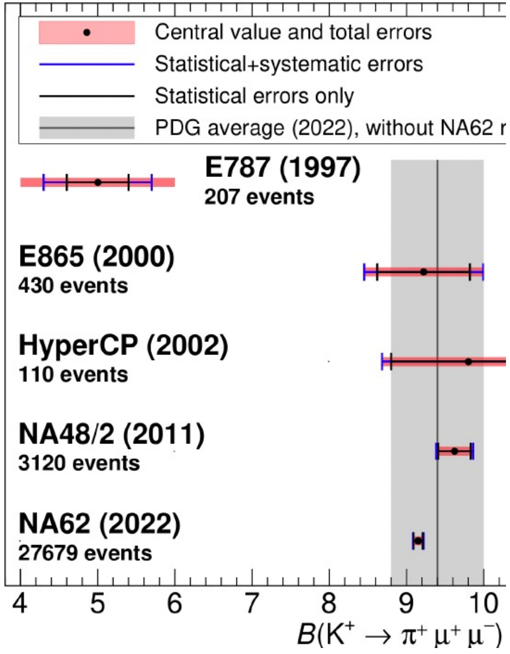
	Previous UL @ 90% C.L	NA62 UL @ 90% C.L	
$K^+ \to \pi^- \mu^+ \mu^+$	8.6×10^{-11}	4.2×10^{-11}	2017 data → improved by factor 2
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	5.3×10^{-11}	2017+2018 data → improved by factor 12
$K^+ \to \pi^- \pi^0 e^+ e^+$	no limit	8.5×10^{-10}	2017+2018 data → first limit
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	4.2×10^{-11}	2017+2018 data → improved by factor 12
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	6.6×10^{-11}	2017+2018 data → improved by factor 8
$\pi^0 \to \mu^- e^+$	3.4×10^{-9}	3.2×10^{-10}	2017+2018 data → improved by factor 13
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	-	sensitivity similar to the previous search
$\pi^0 \to \mu^+ e^-$	3.8×10^{-10}	-	sensitivity similar to the previous search
$K^+ \to \mu^- \nu e^+ e^+$	2.1×10^{-8}	8.1×10^{-11}	2017+2018 data → improved by more than 2 order of magnitude
$K^+ \to e^- \nu \mu^+ \mu^+$	no limit	-	Ongoing analysis: 2017+2018 data *S.E.S* ~ 10^{-11}

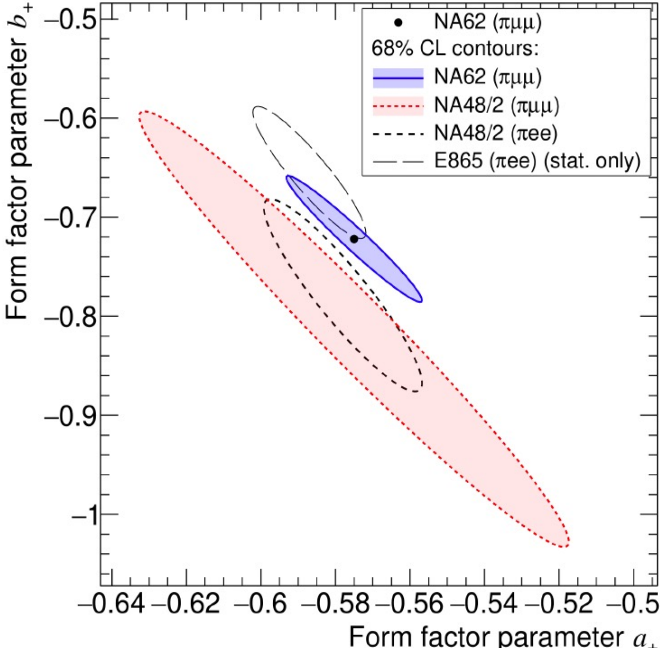
$K^+ \rightarrow \pi^+ \mu^+ \mu^-$ results

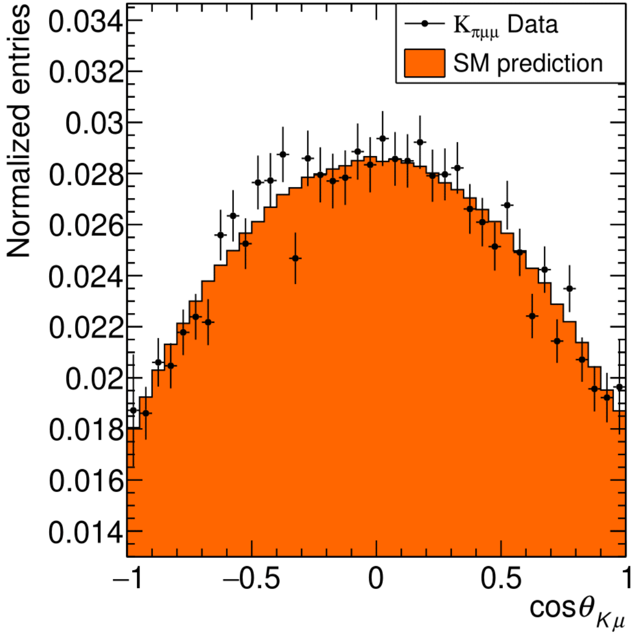
JHEP11(2022)011

- Model indipendent measurement of the $B\pi\mu\mu$ branching fraction
- Determine the form-factor parameters a_+ b_+
- Forward-backward asymmetry

$a_+ = -0.575 \pm 0.013$
$b_+ = -0.722 \pm 0.043$
$BR(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$







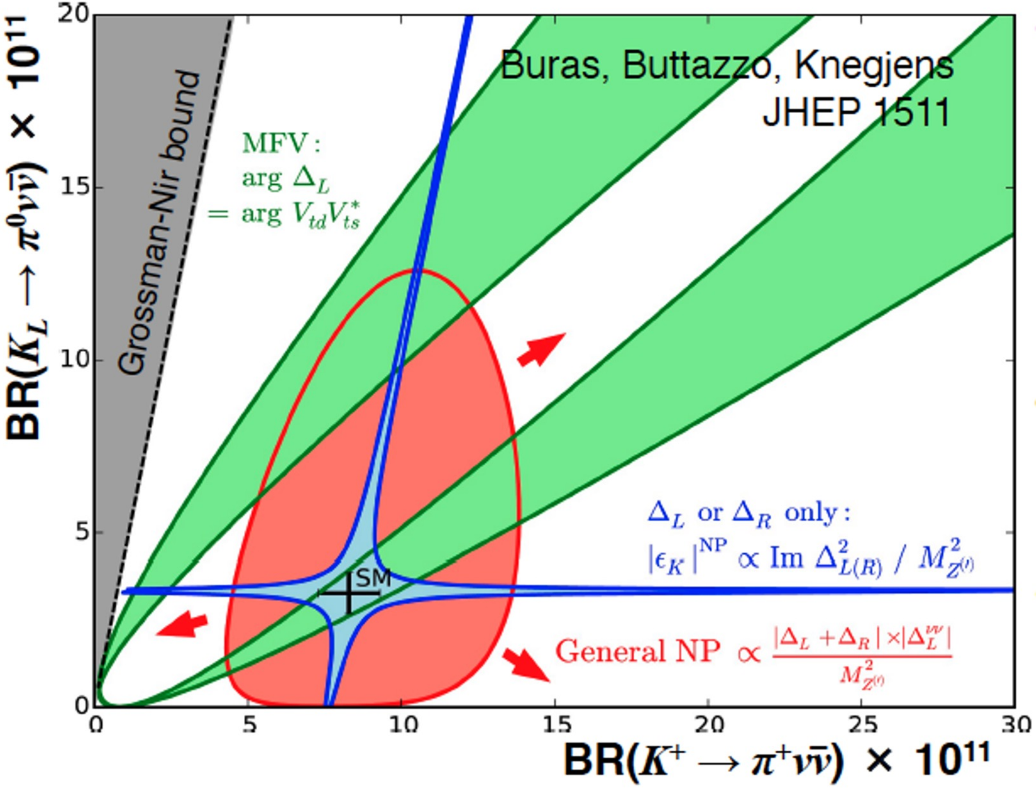
Form factors (FF)

$$d\Gamma/dz \propto G_F M_K^2(a + bz) + W^{\pi\pi}(z) \quad [z = m(l^+l^-)^2/M_K^2]$$

Lepton universitality: same a, b for $l = e, \mu$

$K^+ \to \pi^+\nu\bar{\nu}$ New Physics

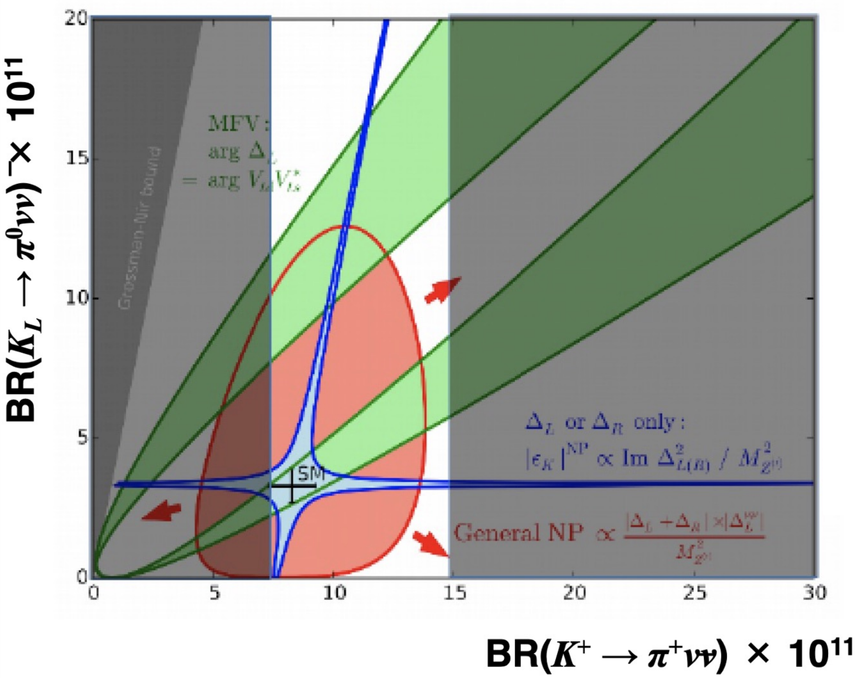
NP affects K^+ and K_L BRs differently: measure of both can discriminate among new physics scenarios



- Models with CKM-like flavor structure:
  - Minimal Flavor Violating models
- Models with new flavor-violating interactions in which either LH or RH couplings dominate:
  - Z/Z' models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models with general LH and RH NP couplings
- Grossman-Nir bound:
  - Model independent relation

$$\frac{\text{BR}(K_L \to \pi^0\nu\bar{\nu})}{\text{BR}(K^+ \to \pi^+\nu\bar{\nu})} \times \frac{\tau_+}{\tau_L} \leq 1$$

$K^+ \to \pi^+\nu\nu$ and New Physics

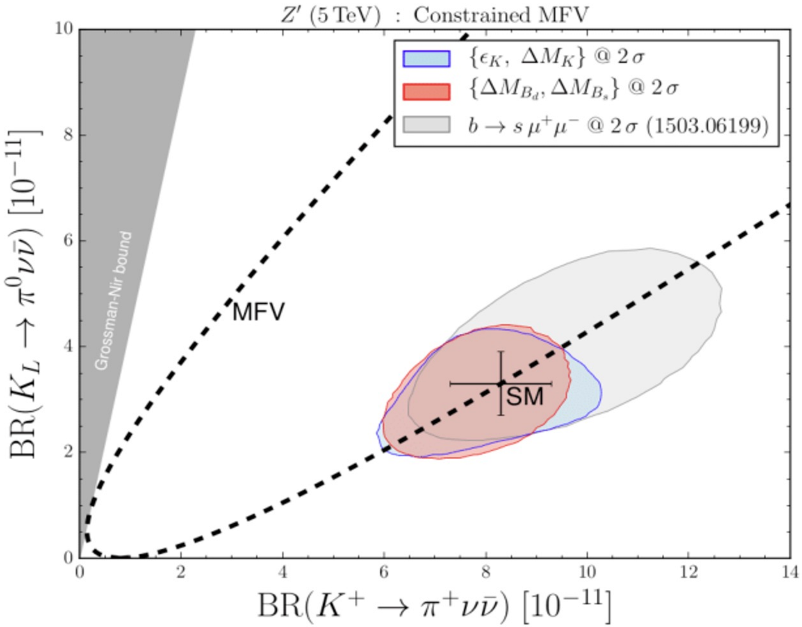


- Large deviation from the SM expectation seems to be excluded
- A more precise measurement is needed: Run2 (2021- LS3) with the goal of reaching $\mathcal{O}(10\%)$ uncertainty measurement

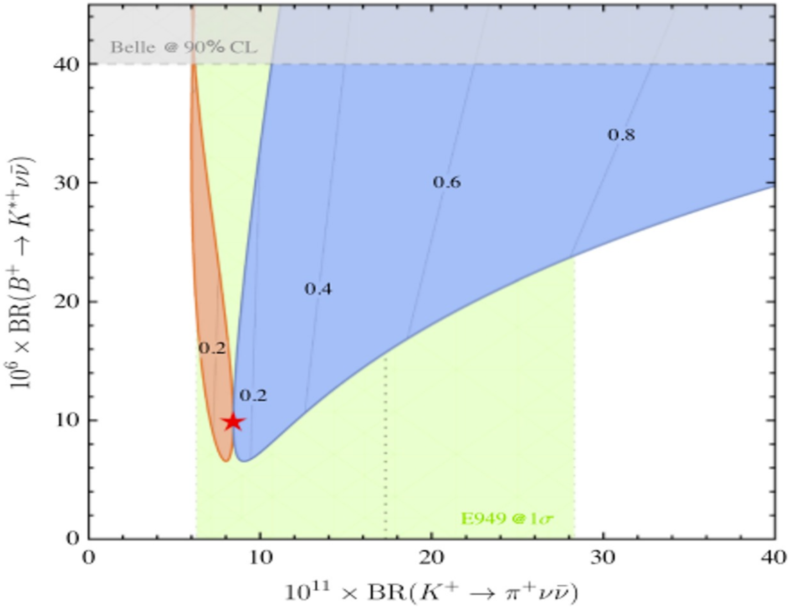
$$BR(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}{}_{stat.} \pm 0.9_{syst.}) \times 10^{-11} (3.4\sigma \text{ significance})$$

$K^+ \to \pi^+\nu\nu$ beyond the Standard Model

Buras et al.,JHEP11 (2015) 166



Isidori et al., Eur. Phys.J. C (2017) 77



New Physics: BR sensitive to the highest mass scale

New Physics Models: MFV; Simplified Z, Z'; LFU violation;MSSM; Leptoquarks..

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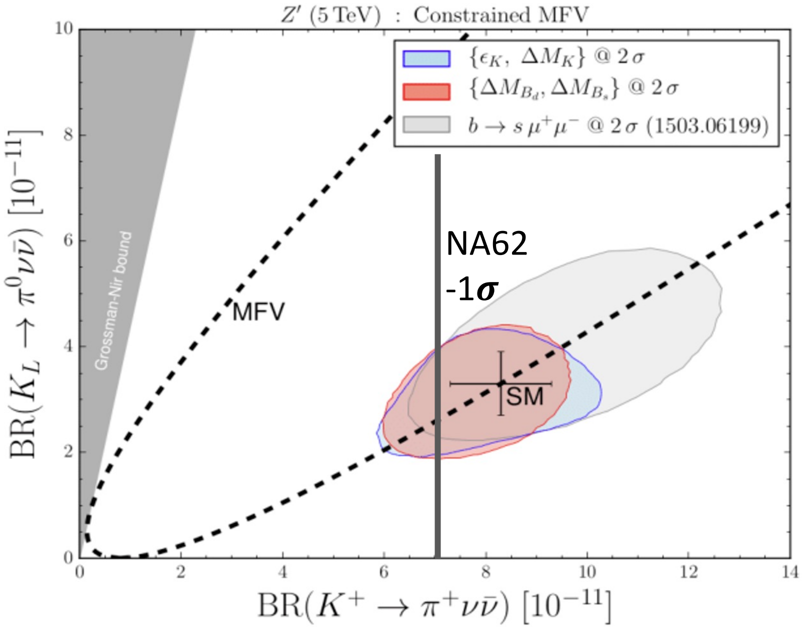
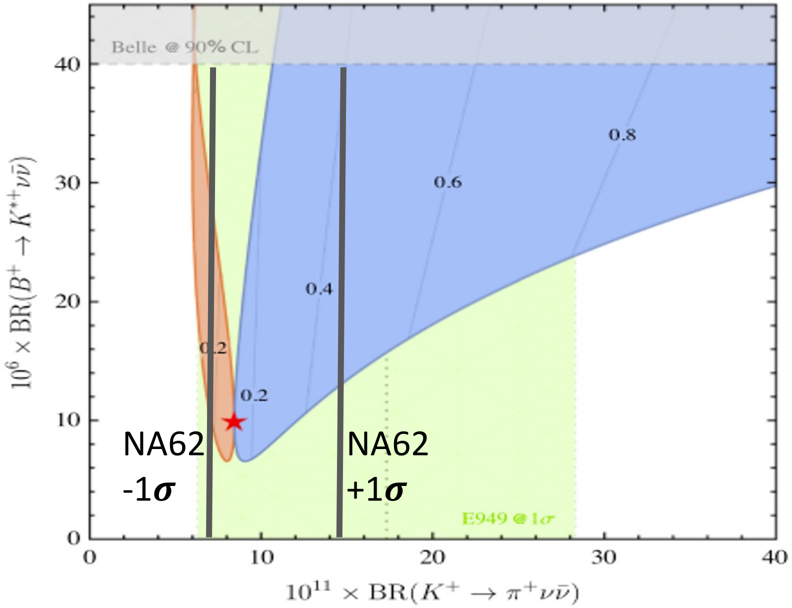
Buras et al.,JHEP11 (2015) 166



Isidori et al., Eur. Phys.J. C (2017) 77



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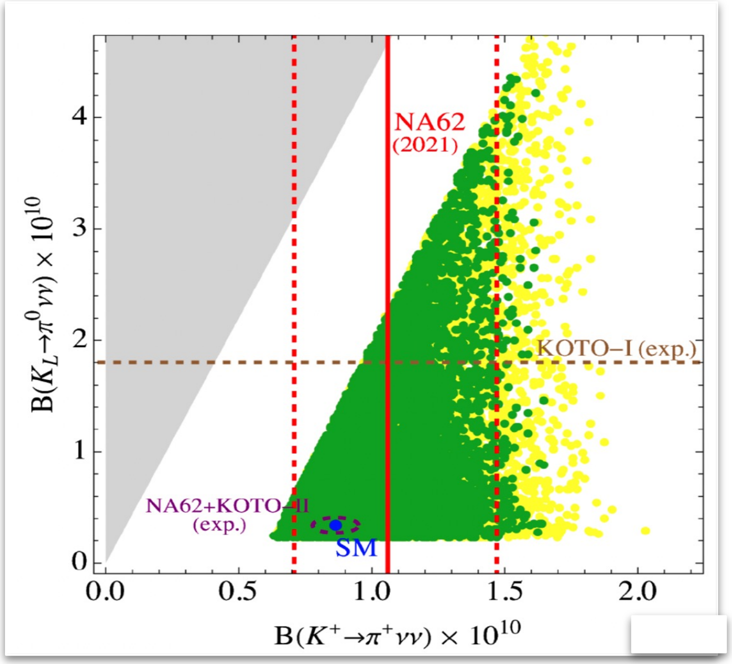
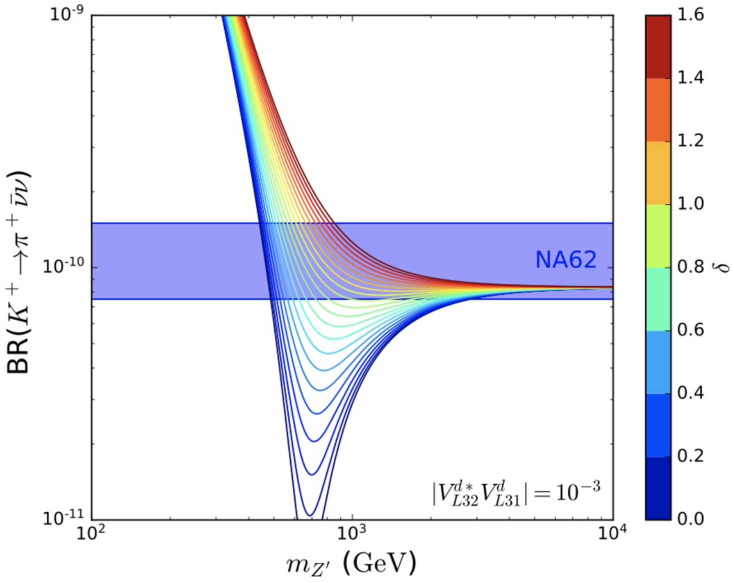
$K^+ \rightarrow \pi^+\nu\nu$ and New Physics





Marzocca et al., Eur. Phys. J. C (2022)

Generic scalar Leptoquark model addressing B anomalies

Tessio B. de Melo et al., *Phys.Rev.D* 103 (2021) 11

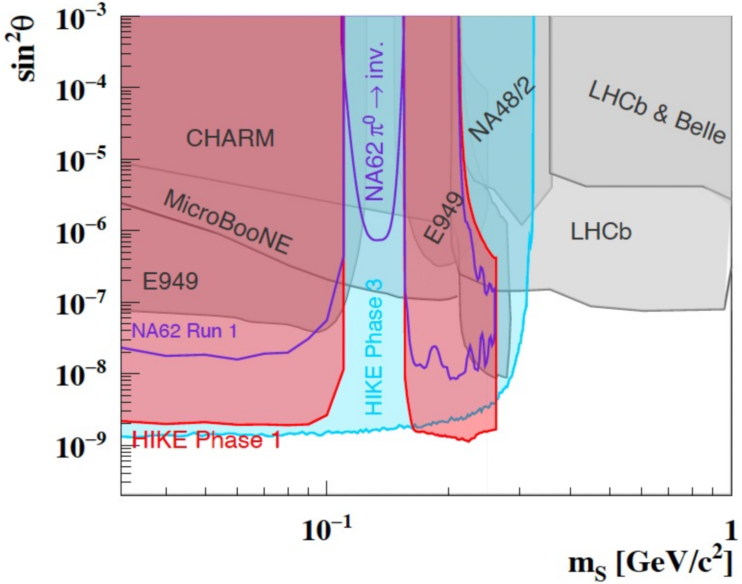
Z' mediated interactions, setting lower limits on the Z' mass mZ'~5TeV at $\boldsymbol{\delta}$=0

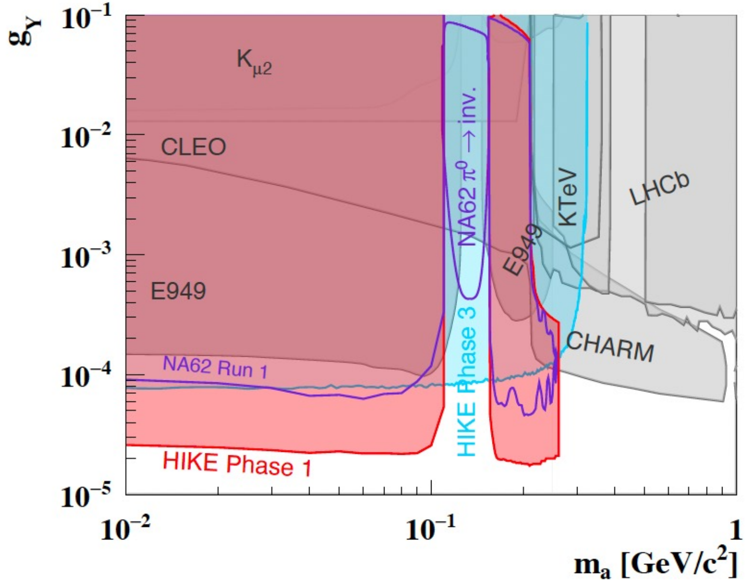
Feebly interacting particles $K^+ \to \to \pi^+ X_{inv}$ in HIKE

Feebly interacting scalar or pseudaoscalar X: $K^+ \to \pi^+ X_{inv}$ has same signature as $K^+ \to \pi^+ \nu\nu$

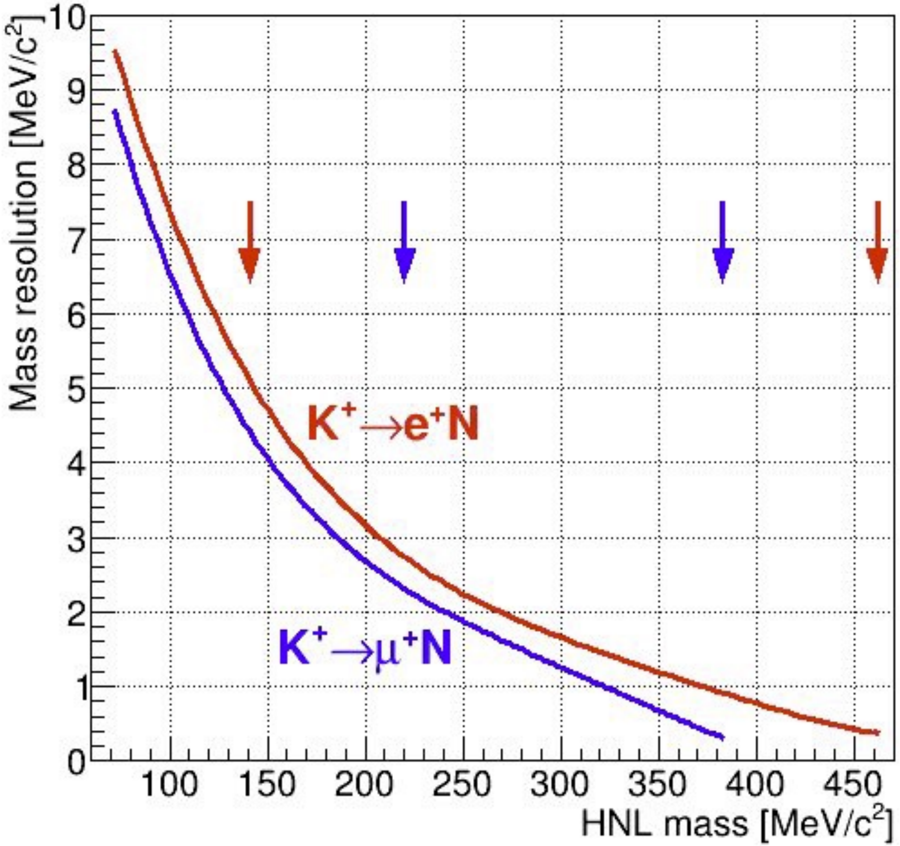
Searches performed looking for a peaking signal in the $m^2_{miss} = m^2_X$ distribution

- Projection of the sensitivity for the search for HIKE phase I assuming x40 statistics wrt NA62 runI
- X_{inv} : either dark scalar mixing with the Higgs Boson (left) or an ALP with fermionic coupling





HNL mass resolution



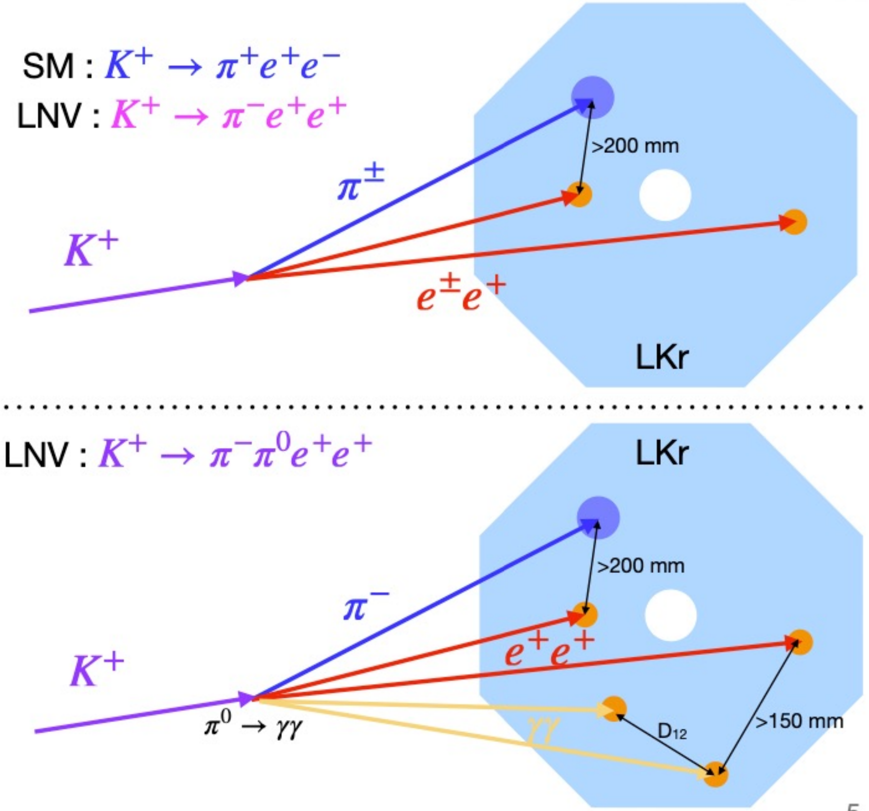
- Selection for each HNL mass hypothesis (m_N) requires

  $|m_{miss} - m_N| < 1.5\boldsymbol{\sigma}_m$

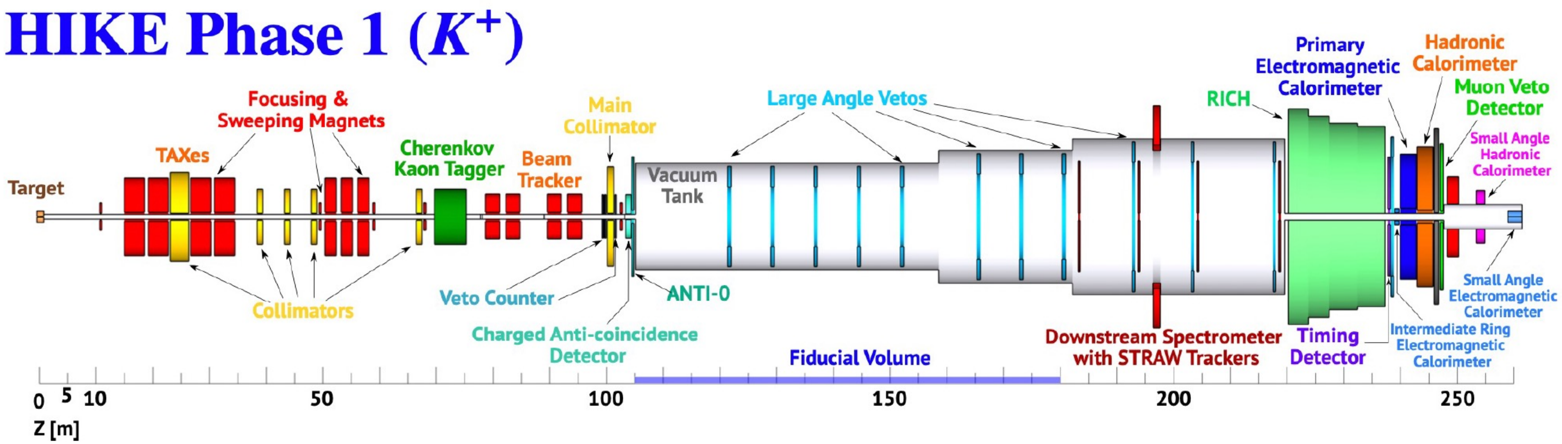
Selection Sketch

- Select 3-track events forming a Q=+1 vertex in the FV.
- Each track has momentum of 6—44 GeV/c with >200mm separation at LKr.
- $|p_{\pi ee(\pi\pi ee)} - p_{beam}| < 2(3)$ GeV/c, $p_T < 30\, MeV/c$.
- LAV photon veto
- For $K^+ \to \pi^-\pi^0 e^+ e^+$ search reconstruct $\pi^0 \to \gamma\gamma$ decay from 2 isolated LKr clusters (neutral & charged vertices must be consistent).

$$z_{\rm N} = z_{\rm LKr} - D_{12}\sqrt{E_1 E_2}/m_{\pi 0}$$



HIKE design



K^+ : 1.2 10^{13} protons on T10 per spill (4.8 sec)

- Decay in flight technique, experience from NA62 and similar layout
- Essential K^+ ID, momentum, space and time
- High-rate, precision tracking of pion
- Minimize material
- Highly efficient PID for photons, pions, electrons and muon vetoes
- Highly efficient and hermetic photon vetoes
- High-performance EM calorimeter (energy resolution, time, granularity)

Improved timing is the crucial element to be able to increase intensity 4 x NA62

Statistical power:
2 10^{13} Kaon decays in decay volume per year

Technological solutions exists for all detectors

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Test of Lepton Universality and Explicit SM Violation

Lepton Universality tests:

$K^+ \to \pi^+\mu^+\mu^-$ vs $K^+ \to \pi^+e^+e^-$, $R_K \equiv \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$

Search for LFV and/or LNV :

PDG 2022

LFV mode	90% CL upper limit	Experiment	Yr./Ref.	Type
$K^+ \to \pi^+e^-\mu^+$	1.3×10^{-11}	BNL-865	2005/ [16]	LFV
$K^+ \to \pi^+e^+\mu^-$	6.6×10^{-11}	NA62	2021/ [17]	LFV
$K_L \to \mu e$	4.7×10^{-12}	BNL-871	1998/ [18]	LFV
$K_L \to \pi^0 e\mu$	7.6×10^{-11}	KTeV	2008/ [19]	LFV
$K_L \to \pi^0\pi^0 e\mu$	1.7×10^{-10}	KTeV	2008/ [19]	LFV
$K^+ \to \pi^-e^+e^+$	5.3×10^{-11}	NA62	2022/ [20]	LNV
$K^+ \to \pi^-\pi^0e^+e^+$	8.5×10^{-10}	NA62	2022/ [20]	LNV
$K^+ \to \pi^-\mu^+\mu^+$	4.2×10^{-11}	NA62	2019/ [21]	LNV
$K_L \to e^\pm e^\pm\mu^\mp\mu^\mp$	4.12×10^{-11}	KTeV	2003/ [22]	LNV
$K^+ \to \pi^-\mu^+e^+$	4.2×10^{-11}	NA62	2021/ [17]	LNFV

Search for feably interacting particle production: $K^+ \to l^+N$, $K^+ \to \pi^+X$, ...

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Scientific goals of HIKE

The HIKE comprehensive programme consists of several phases using shared detectors and infrastructure:

Phase 1: K^+

A multi-purpose K^+ experiment (after LS3)

Scrutiny the K^+ physics with the highest precision:

•Measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio to a 5% relative precision, matching the SM theoretical uncertainty.

•Precision measurements of $K^+ \to \pi^+ l^+ l^-$ decays, and a precision lepton universality test.

•Searches for lepton flavour/number violating decays and lepton universality tests

•Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision

•Improvement of other existing rare decay modes

•Searches for production of feebly-interacting particles in K^+ decays.

•Collection of a dataset in the beam-dump mode

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Scientific goals of HIKE

Phase 2 and 3 : K_L (not before LS4)

Phase 2: a multi-purpose K_L experiment

Measure K_L modes of particular interest:

•Observation of the ultra-rare decays $K_L \to \pi^0 l^+ l^-$ or establishment of stringent upper limits at $O(10^{-11})$ level
•Measurement of the $K_L \to \mu^+\mu^-$ decay branching ratio to a 1% relative precision
•Search for lepton flavour violating decays at the $O(10^{-12})$ sensitivity
•Measurement of the ratios of the branching ratios of the main decay modes to permille relative precision
•Collection of a further dataset (up to 5×10^{19} POT) in the beam-dump mode (with appropriate time sharing with kaon mode)
•Characterisation of the neutral beam necessary to proceed to the third phase of HIKE.

Phase 3 (KLEVER):

Measure $K_L \to \pi^0 \nu\bar{\nu}$ to 20% relative precision
•Search for production and decay of feebly-interacting particles
•Search for additional FCNC K_L decays and forbidden K_L decays

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