30th Anniversary of the Rencontres du Vietnam
Windows on the Universe: Particle Physics
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Physics beyond the Standard Model with the NA62 experiment

On behalf of the NA62 collaboration

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Outline

- NA62 experiment overview
- Searches for heavy neutral leptons (HNL), dark scalar and axion-like-particles (ALP) in the dedicated PBC benchmark models
- $K^+ \to \mu^+ \nu\nu\nu$, $K^+ \to \mu^+ \nu X$
- Lepton flavour/number violating decays
- Summary

NA62 experiment (decay-in-flight)

- Main goal is measure ultra rare kaon decay $K^+ \to \pi^+ \nu\nu$ with 10% precision

- SM prediction:

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

[Buras et al., JHEP 1511 (2015) 033]

- Experimental value

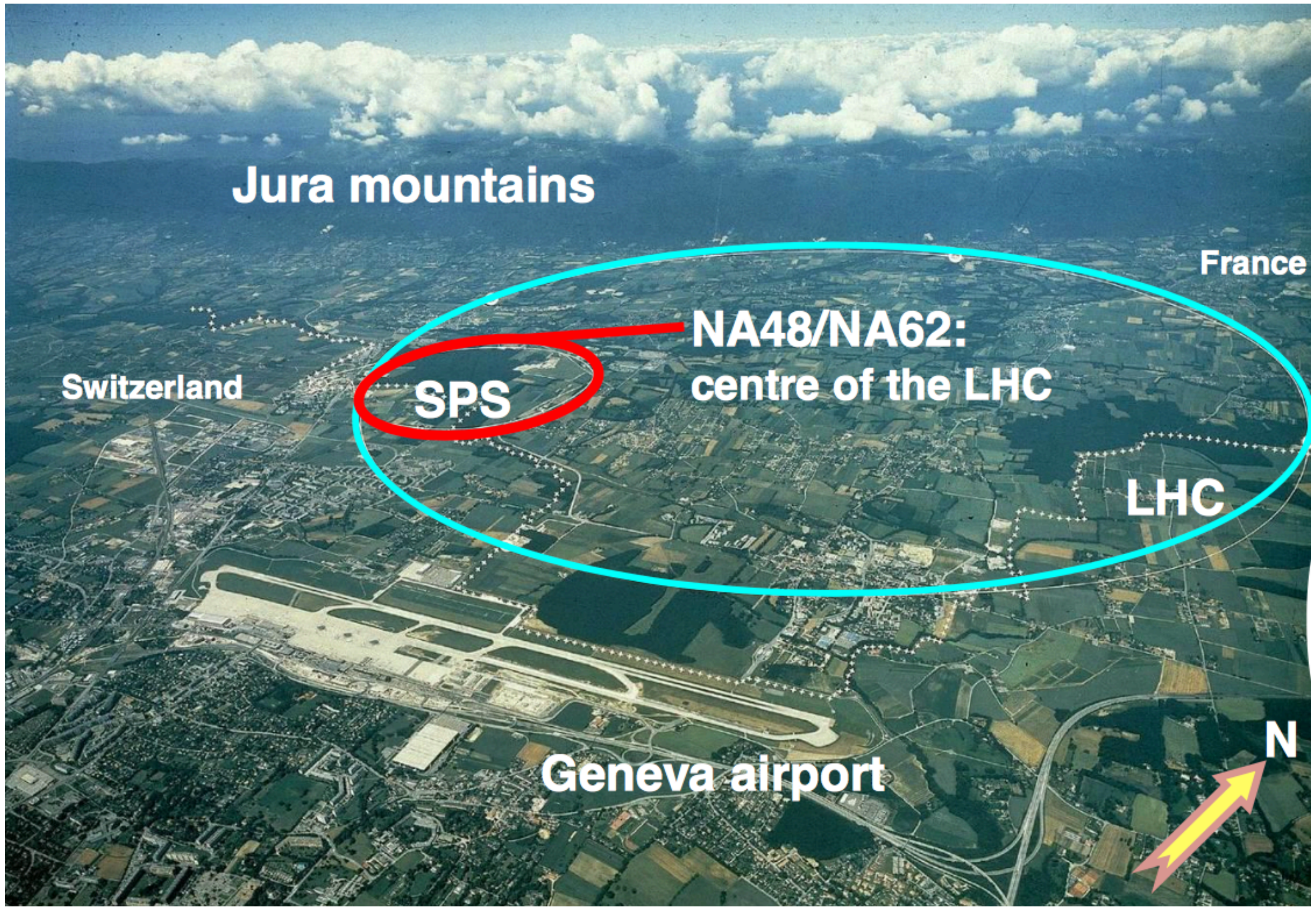
$$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$$

[E949/E787 PRL 101 (2008) 191802]

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

[NA62, JHEP06 (2021) 093]

- Sensitive to New Physics



27 institutes, ~200 participants

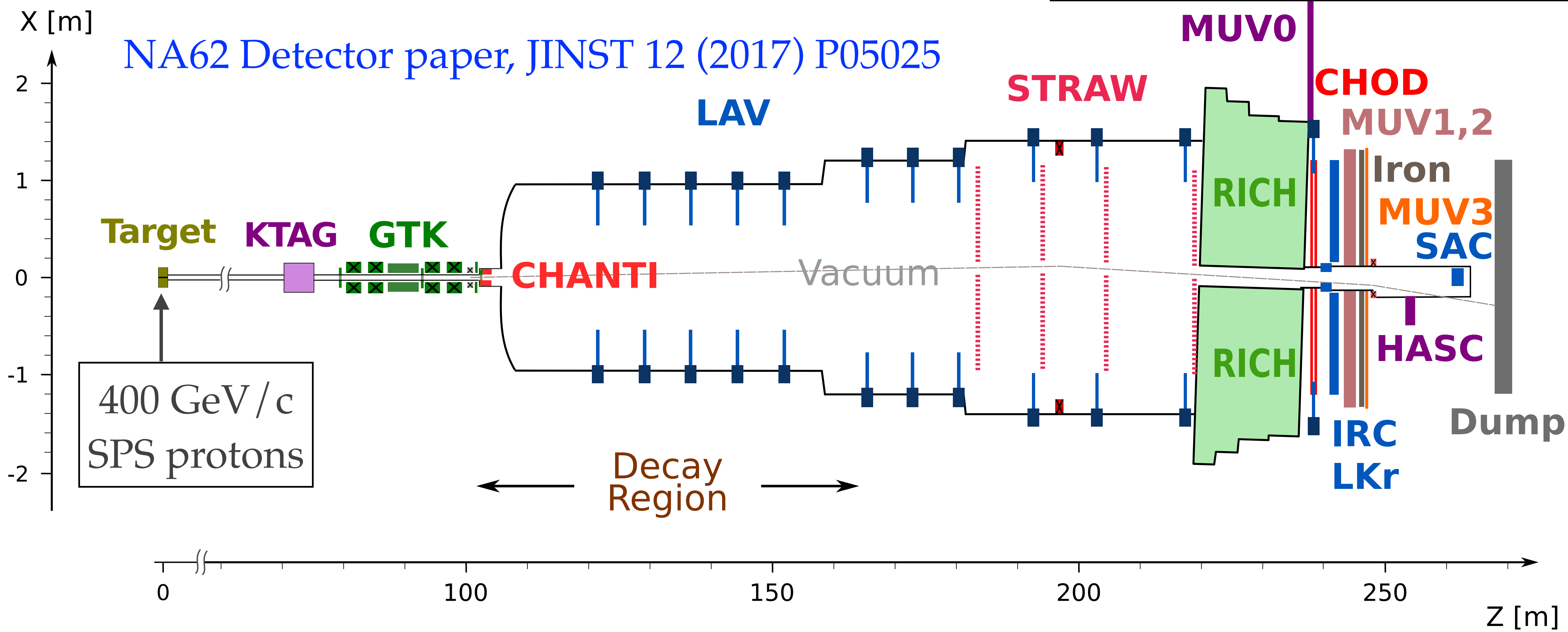
See M.Pepe's talk for more details about $K^+ \to \pi^+ \nu\nu$

The NA62 detector

Unseparated secondary beam:

- K^+(6%), π^+(70%), p(24%)
- 800 MHz rate; 45 MHz K^+ rate
- Momentum: 75 GeV/c

NA62 Detector paper, JINST 12 (2017) P05025



- Timing between sub detectors O(100 ps)
- Kaon ID and direction (KTAG, GTK)
- Particle ID and direction (STRAW, RICH, LKr, HASC, MUV): μ^+ rejection O(10^7)
- Photon veto (LAV, LKr, IRC, SAC): $\pi^0\to\gamma\gamma$ rejection O(10^7)

Data collection

2016: 30 days, 2×10^{11} useful kaon decays
2017: 161 days, 2×10^{12} useful kaon decays
2018: 217 days, 4×10^{12} useful kaon decays

Run1

2021: 85 days [10 beam dump]
2022: 215 days
2023: ongoing

Run2,
approved till LS3

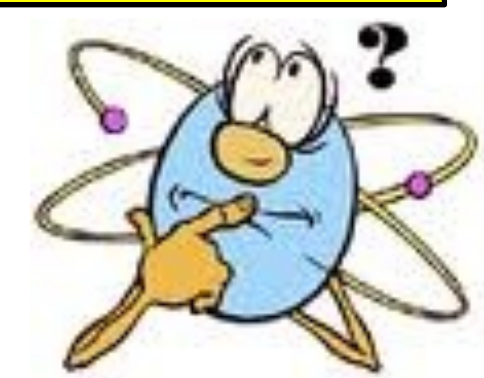
Trigger streams:

- $\pi\nu\nu$ trigger: 1 track, $\boldsymbol{\gamma}/\mu$ veto
- Minimum bias triggers: samples for normalization, background estimation
- 3-track triggers: samples for lepton flavour violation study

Beyond the Standard Model

Neutrino oscillation	Baryon asymmetry of the Universe	Dark matter and dark energy

There is New Physics beyond the Standard Model, but we don't know exactly what is it



Search for New Physics:

- Study of rare decays of the SM particles (like $K^+\to\pi^+\nu\nu$) (M.Pepe's talk)
- Search for new particles (HNL, ALP, dark photon etc.)
  - Kaon mode
  - Beam-dump mode (A.Kleimenova's talk)
- Search for forbidden (in the SM framework) processes

All methods are available at NA62

Heavy Neutral Leptons (HNL)

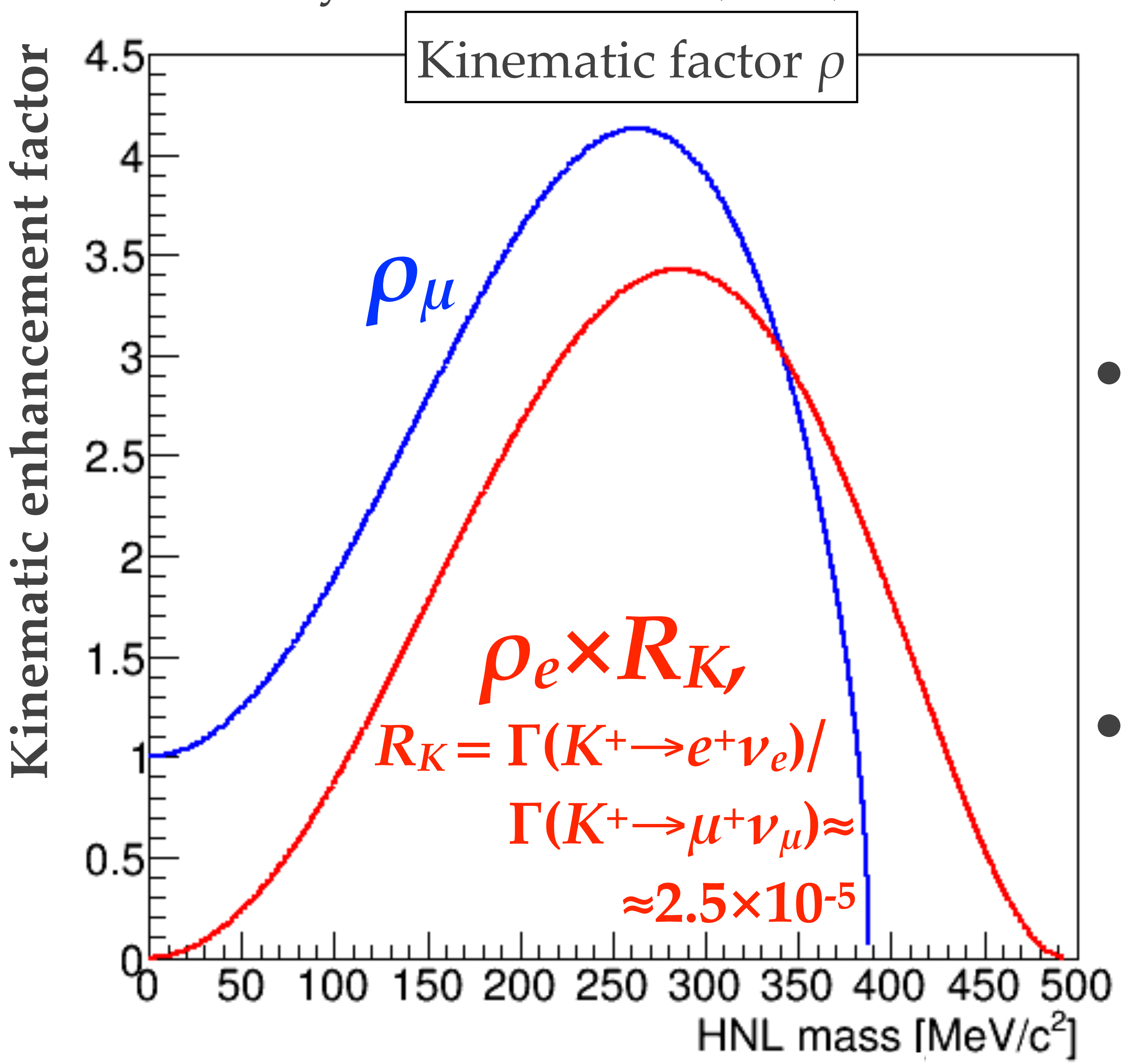
- The νMSM (Asaka et al., Phys.Lett.B 620 (2005) 17) is an extension of the SM to explain simultaneously neutrino oscillations, dark matter and baryon asymmetry of the Universe.
  - SM + 3 right-handed sterile neutrinos:
    - N_1: m_1 ~ 10 keV — dark matter candidate
    - $N_{2,3}$: $m_{2,3}$ ~ 100MeV — 100 GeV — baryon asymmetry
- GeV-scale HNLs can be observed via their production and decay (both searches are possible at NA62)

HNL production in K^+ decays

$$\Gamma(M^+ \to l^+ \nu_H) = \rho \times \Gamma(M^+ \to l^+ \nu_l) \times |U_{lH}|^2$$

O(1)

R.E.Shrock, Phys.Rev.D24 1232 (1981)



$K^+ \to l^+ \nu_H$,
$l = e, \mu$

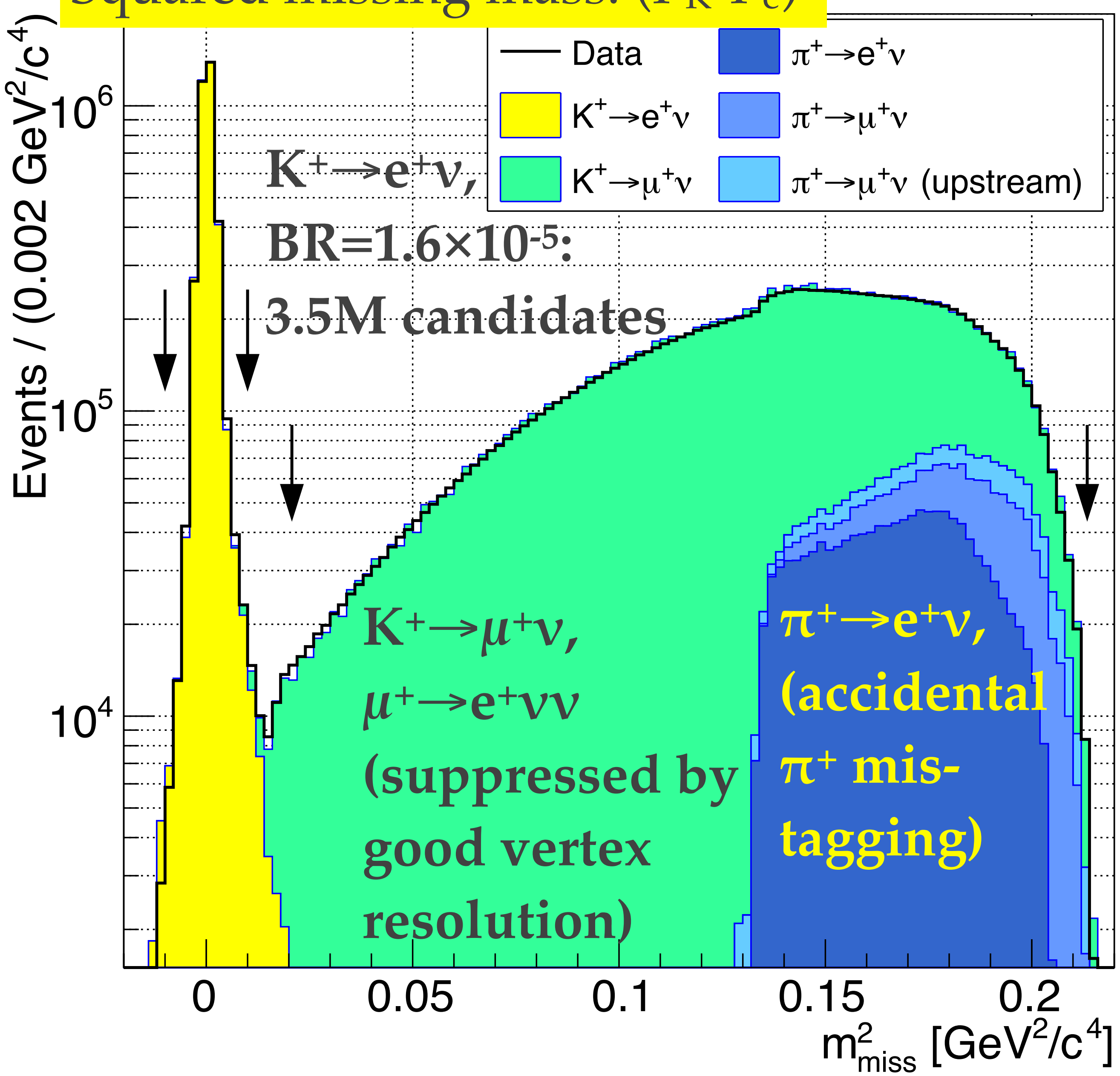
- HNL production is enhanced kinematically with respect to SM decays, except near kinematic endpoints
- Enhancement ~10^5 in the $K^+ \to e^+ \nu_H$ case as the helicity suppression is relaxed

$$\rho = \frac{[x + y - (x-y)^2]\sqrt{1 + x^2 + y^2 - 2(x + y + xy)}}{x(1-x)^2}, \quad x = m_l^2/m_M^2 \ , \ y = m_{\nu_H}^2/m_M^2$$

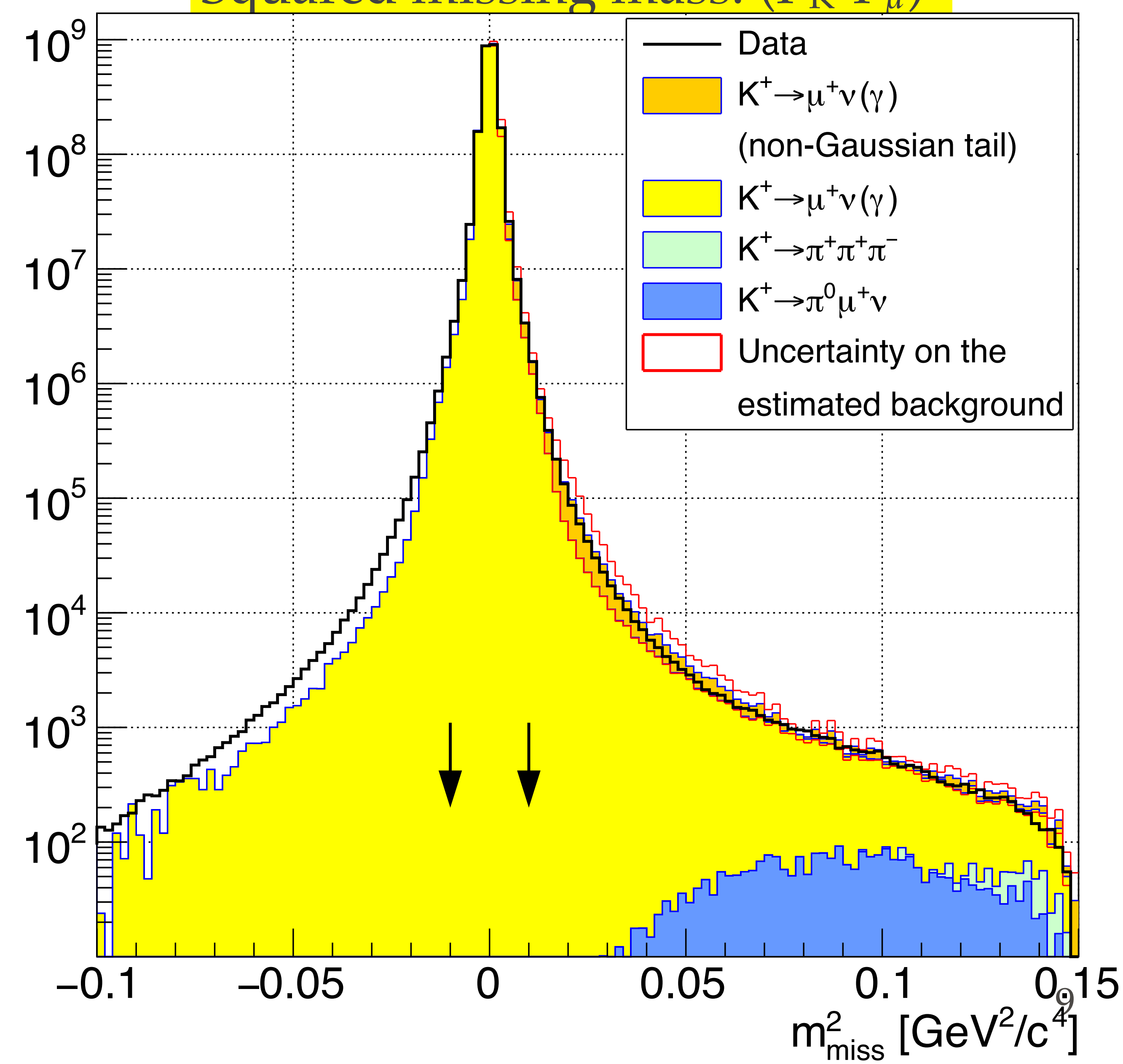
Heavy Neutral Leptons (HNL)

- Triggers: the main $K_{\pi\nu\nu}$ for $K^+ \to e^+\nu_H$, Control / 400 for $K^+ \to \mu^+\nu_H$
- Number of kaon decays in the fiducial volume:
  $(3.52 \pm 0.02) \times 10^{12}$ for $K^+ \to e^+\nu_H$, $(1.14 \pm 0.02) \times 10^{10}$ for $K^+ \to \mu^+\nu_H$
- Peak search in the missing mass distribution $(P_K - P_l)^2$, P_K is kaon four-momentum, P_l is lepton four-momentum, use GTK and STRAW

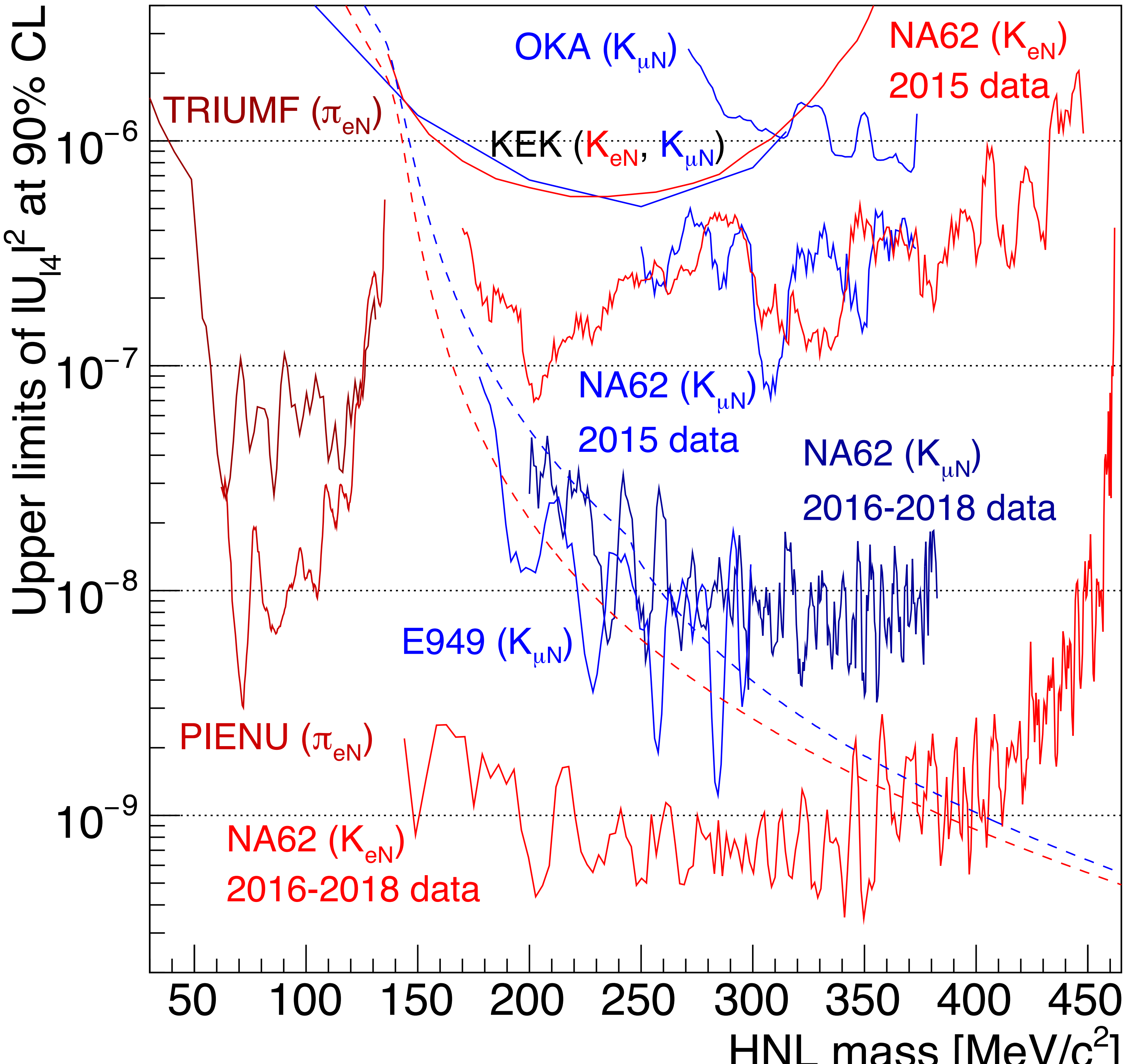
Squared missing mass: $(P_K - P_e)^2$



Squared missing mass: $(P_K - P_\mu)^2$



HNL Results



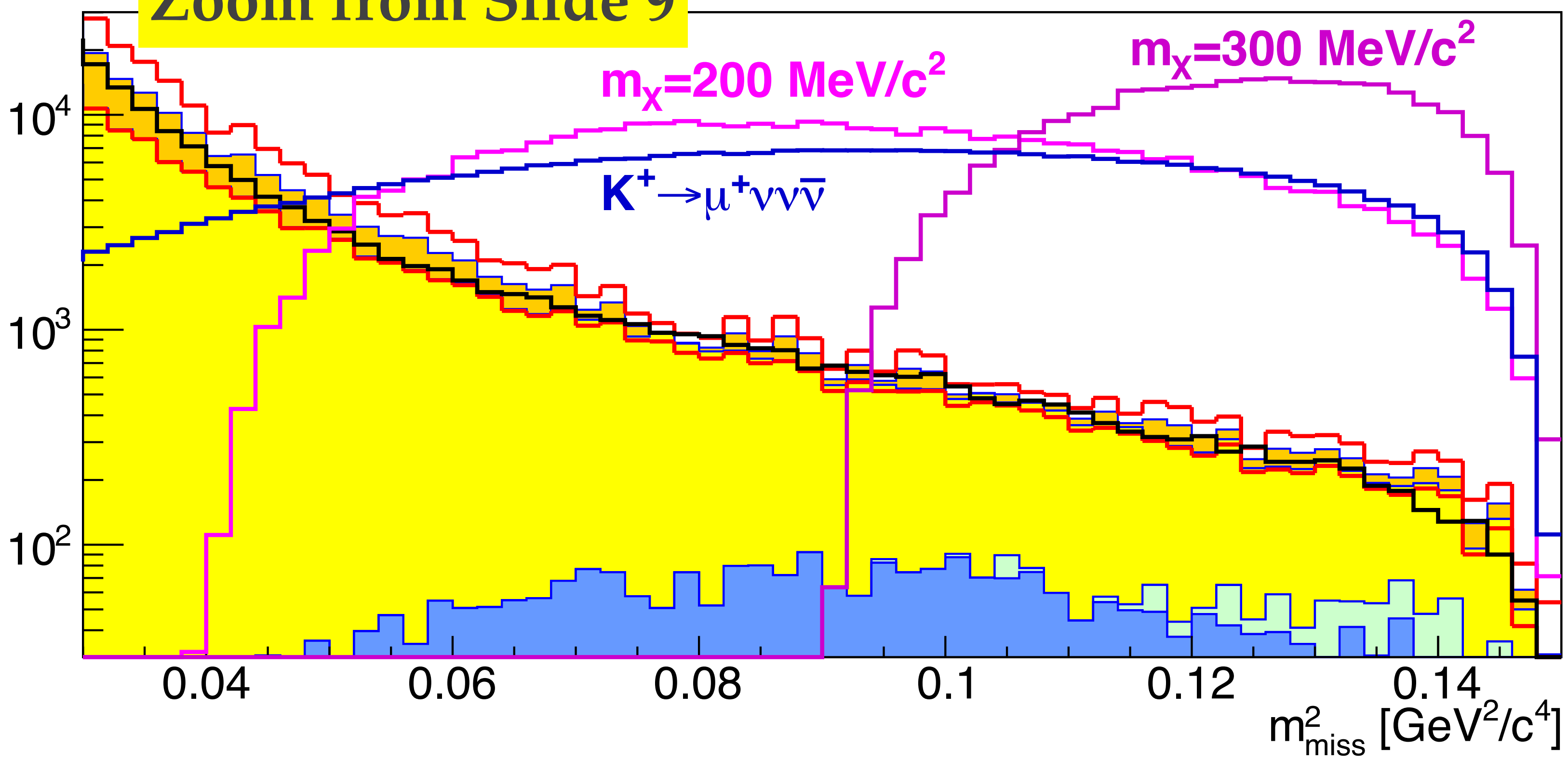
- No signal observed
- Full 2016-18 (RunI) data set is analyzed
- Close related study: $K^+ \to l^+ \nu\nu\nu$ and $K^+ \to l^+ \nu X$, X is invisible: predict background from MC simulation

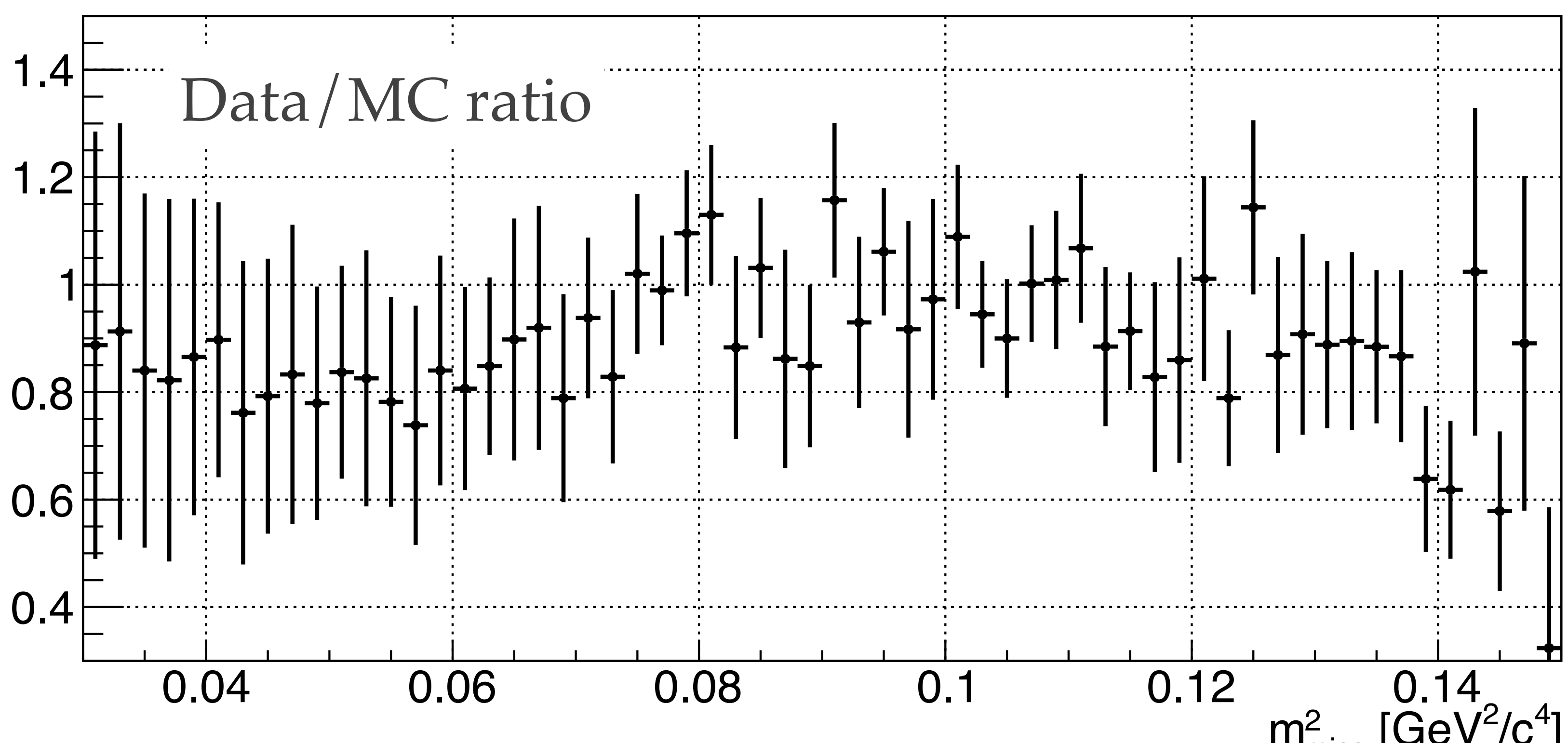
PLB807 (2020) 135599
PLB816 (2021) 136259

Benchmark models
BC6 ($|U_{e4}|^2$)
BC7 ($|U_{\mu4}|^2$)

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

Zoom from Slide 9





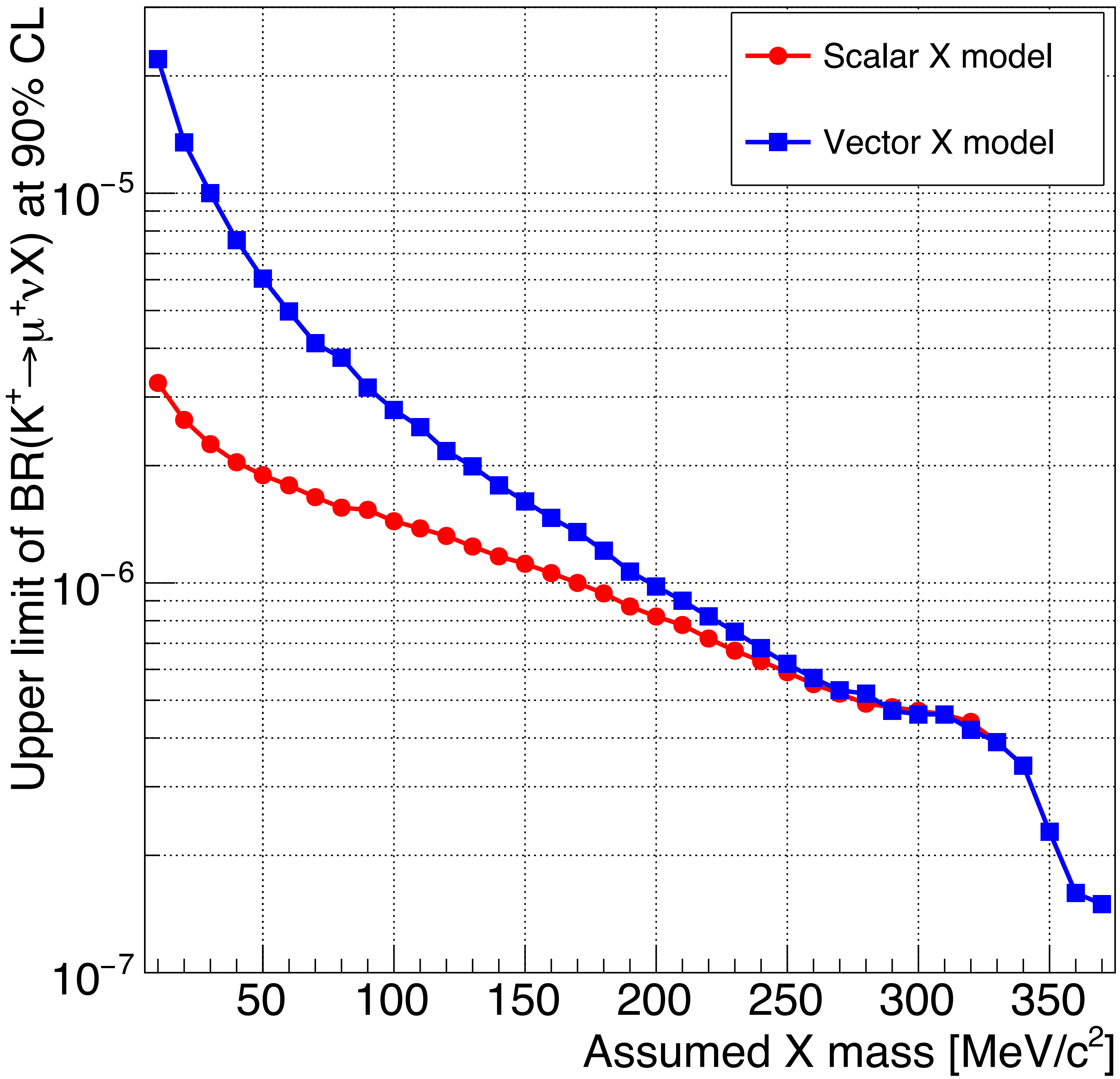
<u>$K^+ \to \mu^+ \nu\nu\nu$</u>

- Very rare in the Standard Model, BR: 1.6×10^{-16} [JHEP1610 (2016) 039]
- The current limit: $< 2.4 \times 10^{-6}$ [E949, PRD94 (2016) 032012]
- Search region $m^2_{miss} > 0.1$ GeV^2/c^4 (optimized to extract strongest limit):
  - Observed events: 6894
  - Expected from MC: 7549±928
  - Set upper limit: 1.0×10^{-6} at 90%CL in the SM framework

<u>$K^+ \to \mu^+ \nu X$, X is scalar or vector</u>

- [PRL124 (2020) 041802]
- Mass range 10—370 MeV / c^2
- Compare expected and observed number of event for each mass hypothesis and extract limit.

$K^+ \rightarrow \mu^+ \nu X$ results



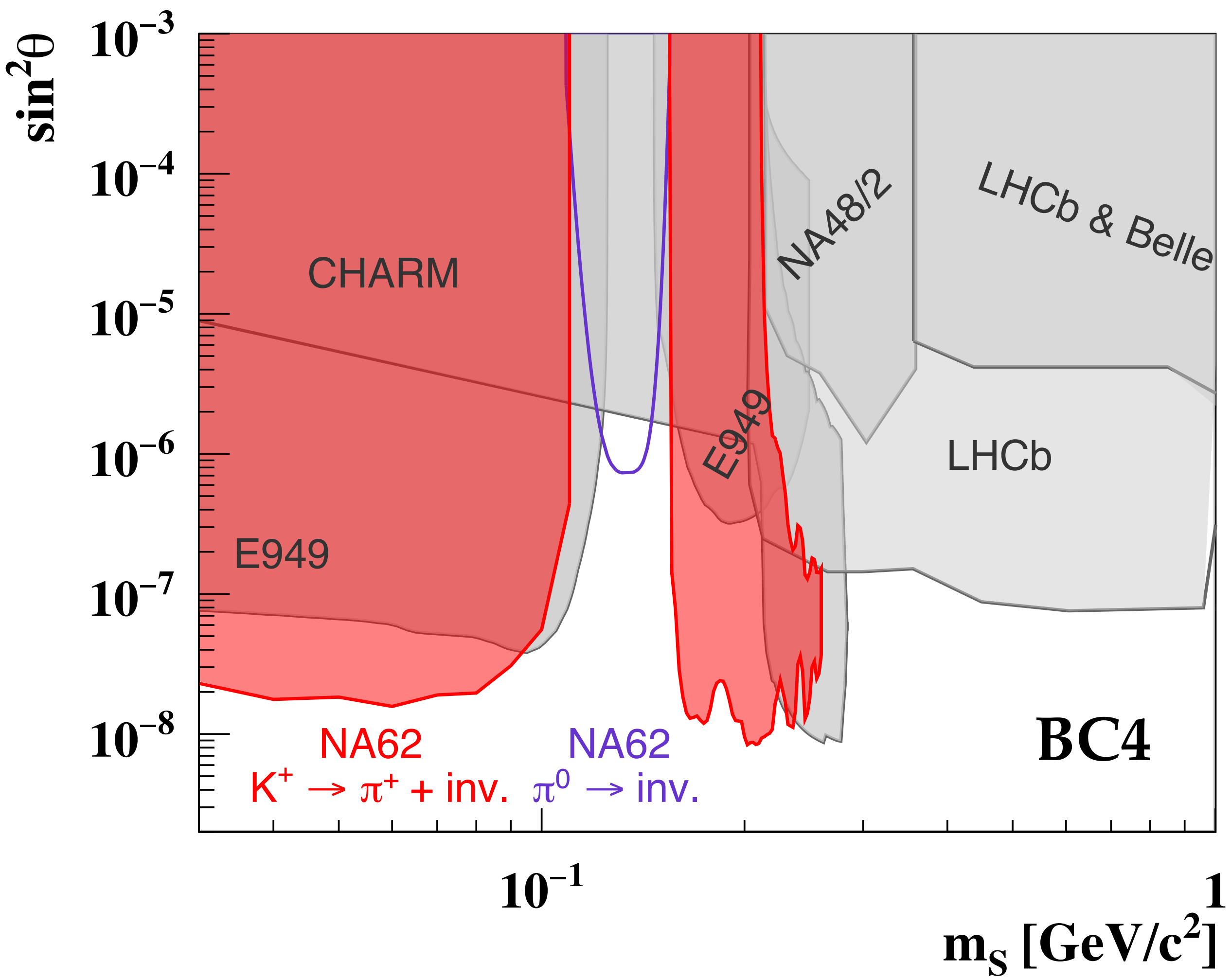
$K^+ \rightarrow \mu^+ \nu X$, X is scalar or vector

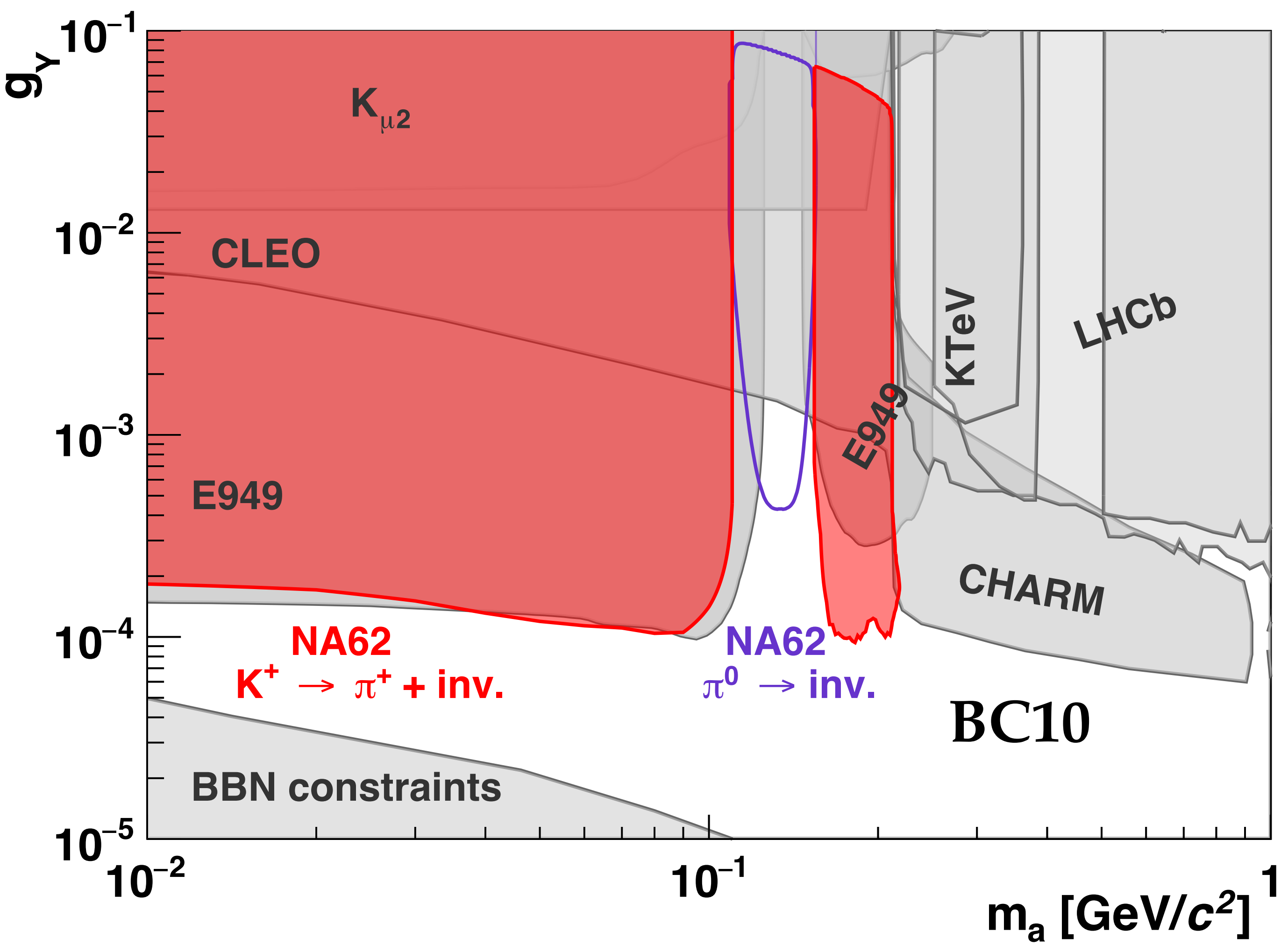
- No signal observed
- The limits obtained in the scalar model are stronger than those in the vector model due to larger mean m^2_{miss} value.

PLB816 (2021) 136259

Dark Scalar, Axion-like-particle

Interpretation of the $K^+ \to \pi^+ X$ searches (two analyses: $K^+ \to \pi^+ \nu\nu$ and $\pi^0 \to inv$) in the dark scalar with Higgs mixing (BC4) framework or axion-like-particle with fermionic coupling (BC10) framework.





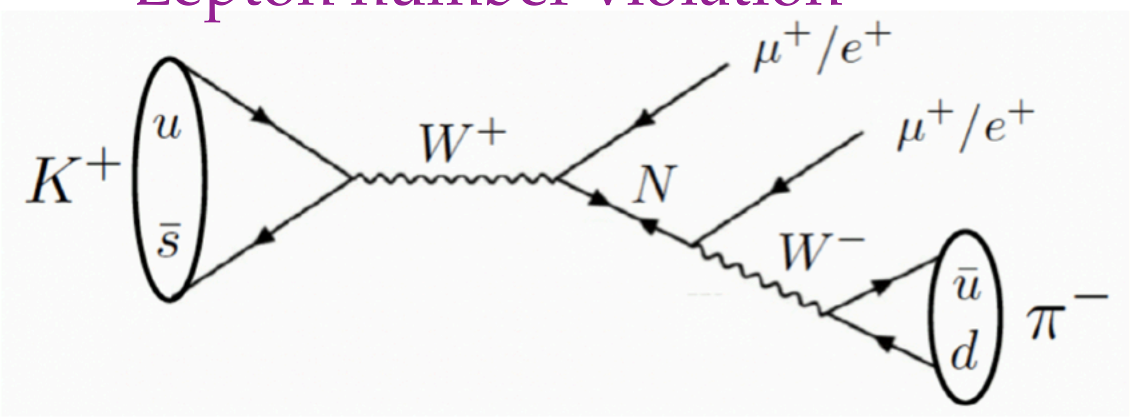
JHEP06 (2021) 093

JHEP03 (2021) 058

Lepton Number/Flavour Violation

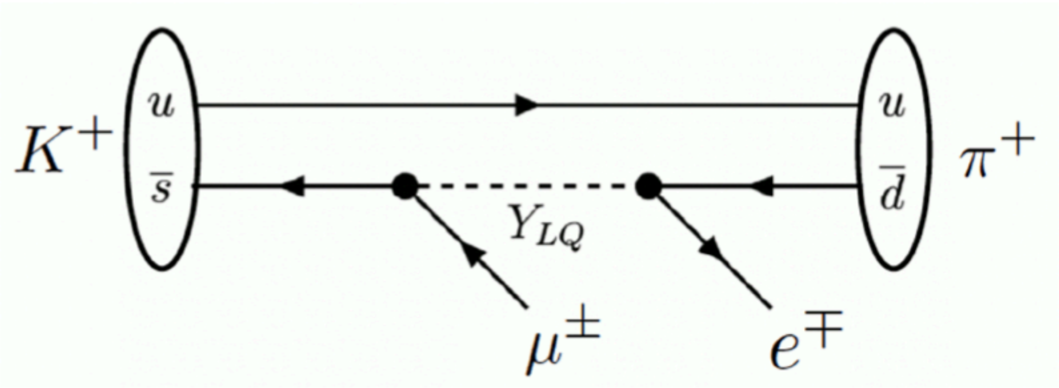
- Lepton number (L) and lepton flavour (L_e,L_μ,L_τ) are conserved quantities in the Standard Model
- Violation of these quantities is a clear indication of Physics Beyond the Standard Model

Lepton number violation



Seesaw mechanism provides a source of LNV through the exchange of Majorana neutrinos as in 0νββ decay [JHEP 0905 (2009) 030]

Lepton flavour violation



LFV processes can occur via the exchange of leptoquarks, of a Z′boson, or in SM extensions with light pseudoscalar bosons [JHEP 10 (2018) 148, Rev. Mod. Phys. 81, 1199 (2009), JHEP 01 (2020)158]

NA62 LNV/LNF summary

	Previous UL PDG 2019	NA62 UL at 90% CL	
$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0×10^{-10}	BR < 4.2×10^{-11}	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2×10^{-10}	BR < 6.6×10^{-11}	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	BR < 3.4×10^{-9}	BR < 3.2×10^{-10}	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	BR < 8.6×10^{-11}	BR < 4.2×10^{-11}	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	BR < 6.4×10^{-10}	BR < 5.3×10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	BR < 8.5×10^{-10}	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	N/A	BR < 8.1×10^{-11}	PLB 838 (2022) 137679

Summary

- The NA62 experiment is a powerful laboratory to make searches for exotic particles/processes
- World best upper limits on HNL, Dark scalar, ALP mixing parameters have been set
- World best upper limit on BR($K^+ \to \mu^+ \nu\nu\nu$) has been set
- World best upper limits on LNV/LNF kaon decays have been set
- NA62 will continue to take data until LongShutdown3(LS3) — resumed in 2021