Search for heavy neutral lepton production at the NA62 experiment

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Outline

1. Short introduction to Heavy Neutral Leptons and the NA62 experiment
2. Presentation of 2 NA62 papers, covering 4 world-leading results

Search for heavy neutral lepton production in K^+ decays to positrons

Phys. Lett. B 807 (2020) 135599

Search for K^+ decays to a muon and invisible particles

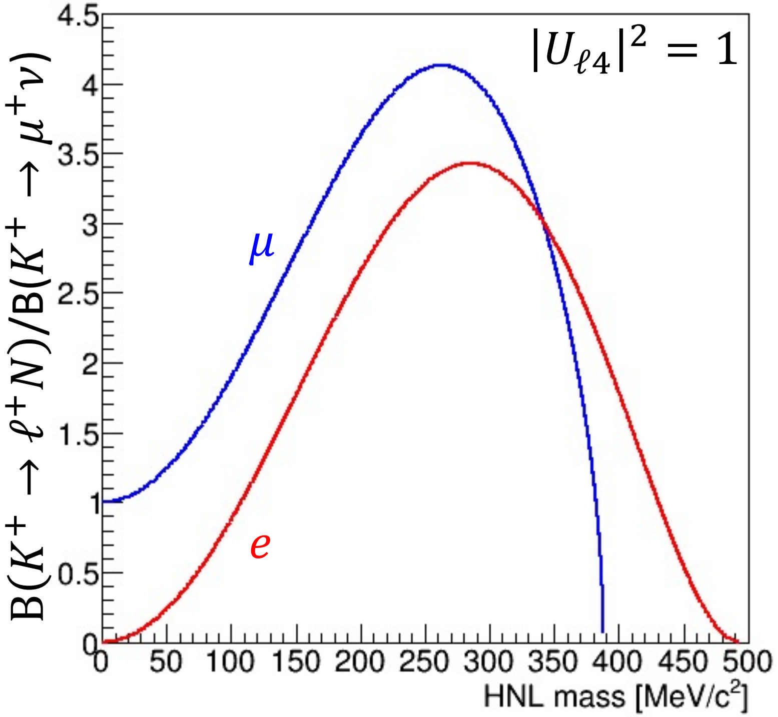
Phys. Lett. B 816 (2021) 136259

Heavy Neutral Leptons

- Neutrinos are massless in the Standard Model (SM), contrary to the well-established experimental observation of neutrino oscillations

- Including right-handed neutrinos (HNL) can generate neutrino masses via see-saw mechanism
  - Can achieve "low scale" see-saw with $O(100\mathrm{MeV})$ HNL masses
  - One popular example: Neutrino Minimal Standard Model ($\nu\mathrm{MSM}$) [1]

- HNL produced in $K^+ \to \ell^+ N$ ($\ell = e, \mu$) decays, with similar experimental signature to the SM decay $K^+ \to \ell^+ \nu$
  - Assumes HNL lifetime greater than 50ns i.e. "detector stable"



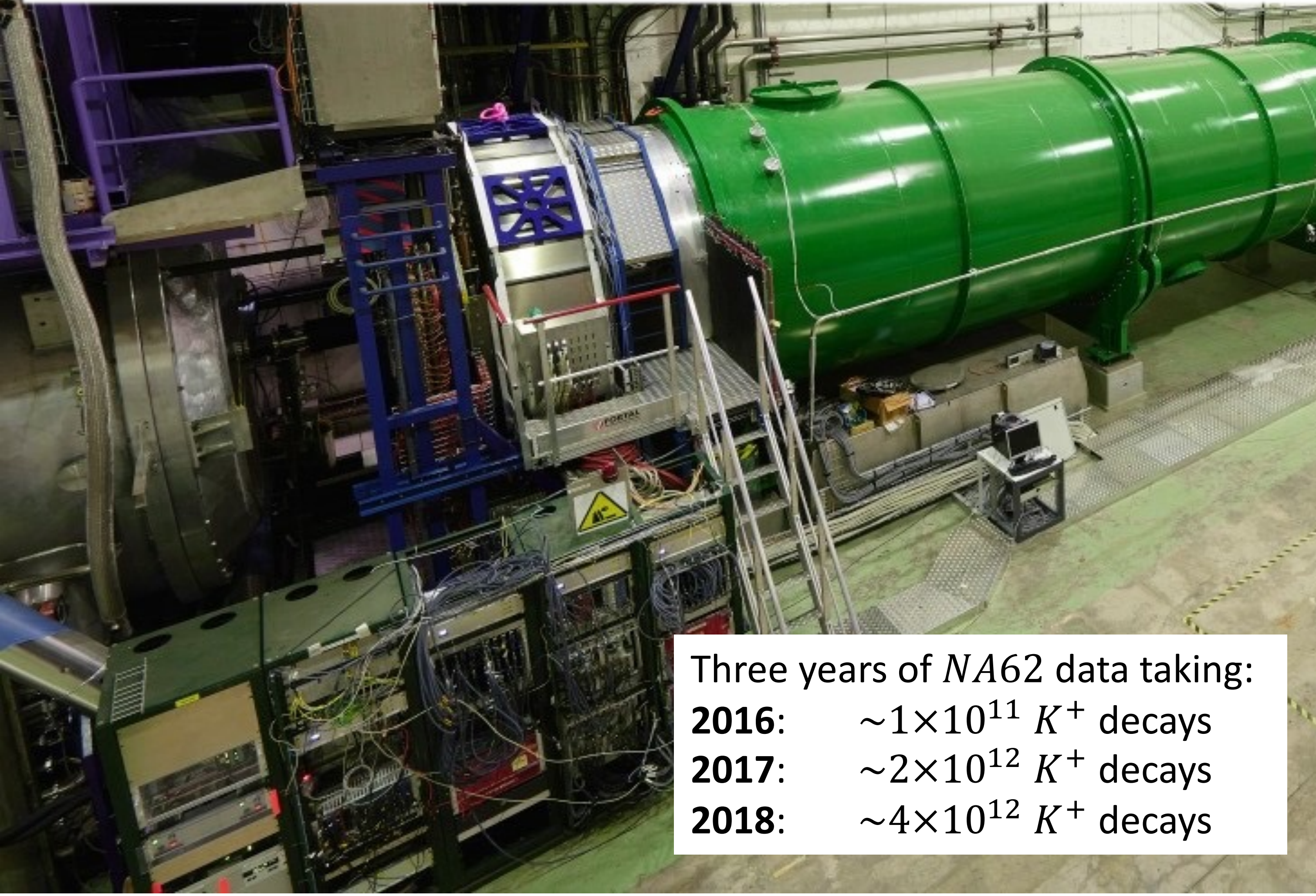
- The branching fraction is:

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

  where $\rho_\ell(m_N)$ is an $O(1)$ kinematic factor [2], and $|U_{\ell 4}|^2$ is the squared neutrino mixing parameter

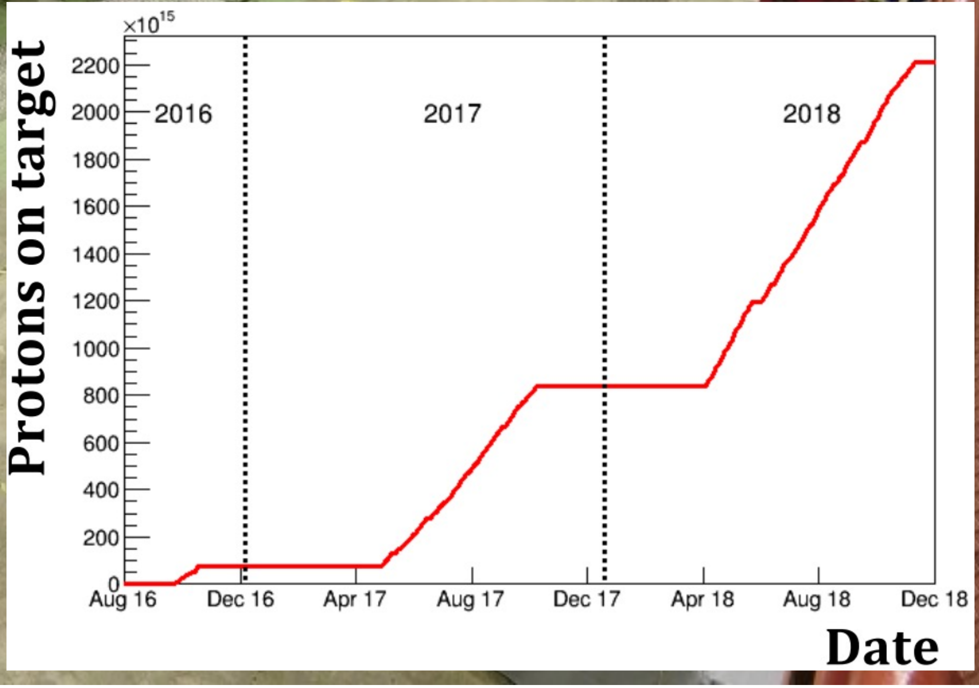
The NA62 experiment

NA62 is a kaon physics experiment based at the CERN North Area (NA)
It uses $400\ \mathrm{GeV}/c$ protons extracted from the CERN super-proton synchrotron (SPS)
to perform decay-in-flight measurements of (ultra) rare kaon decays



Three years of $NA62$ data taking:

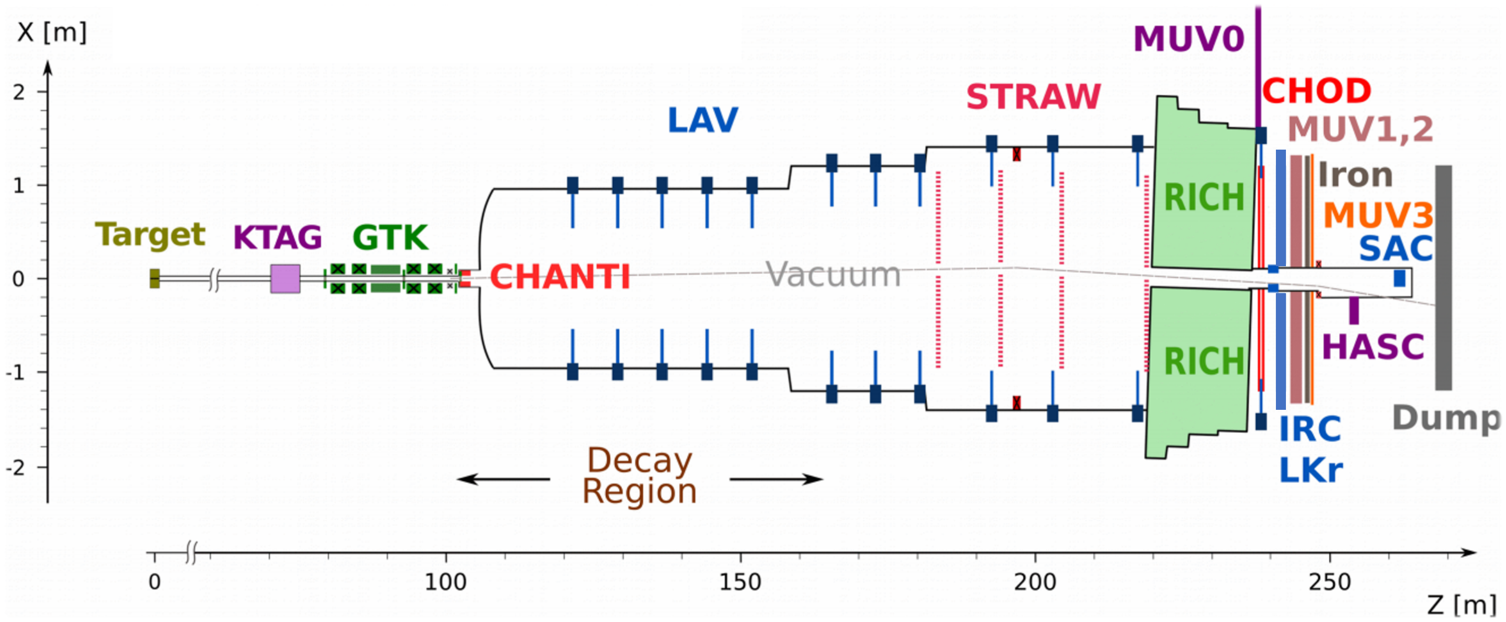
2016: $\sim 1\times 10^{11}\ K^+$ decays
2017: $\sim 2\times 10^{12}\ K^+$ decays
2018: $\sim 4\times 10^{12}\ K^+$ decays



The NA62 detector

400 GeV/c protons from CERN SPS

in 'spills' of 3s effective duration



- Proton-target interactions + achromatic selector forms secondary hadron beam with $p \approx 75\ GeV/c$
  - Nominally there are 750MHz of particles in the secondary beam; 6% are K^+ (45MHz)
- Measurement of all beam particles by kaon tagger **KTAG** and beam-particle tracker **GTK**
- About 15% of K^+ decay within the $\sim 75\text{m}$ vacuum **decay region**, which defines the experiments **fiducial volume**
- Measurement of K^+ decay products by the **STRAW** tracker and **CHOD** detectors
- Particle identification by the **RICH**, the **LKr** and **MUV** calorimeters, and the **MUV3** detector
- Hermetic photon veto provided by the **LAV, LKr, IRC, SAC** photon detectors

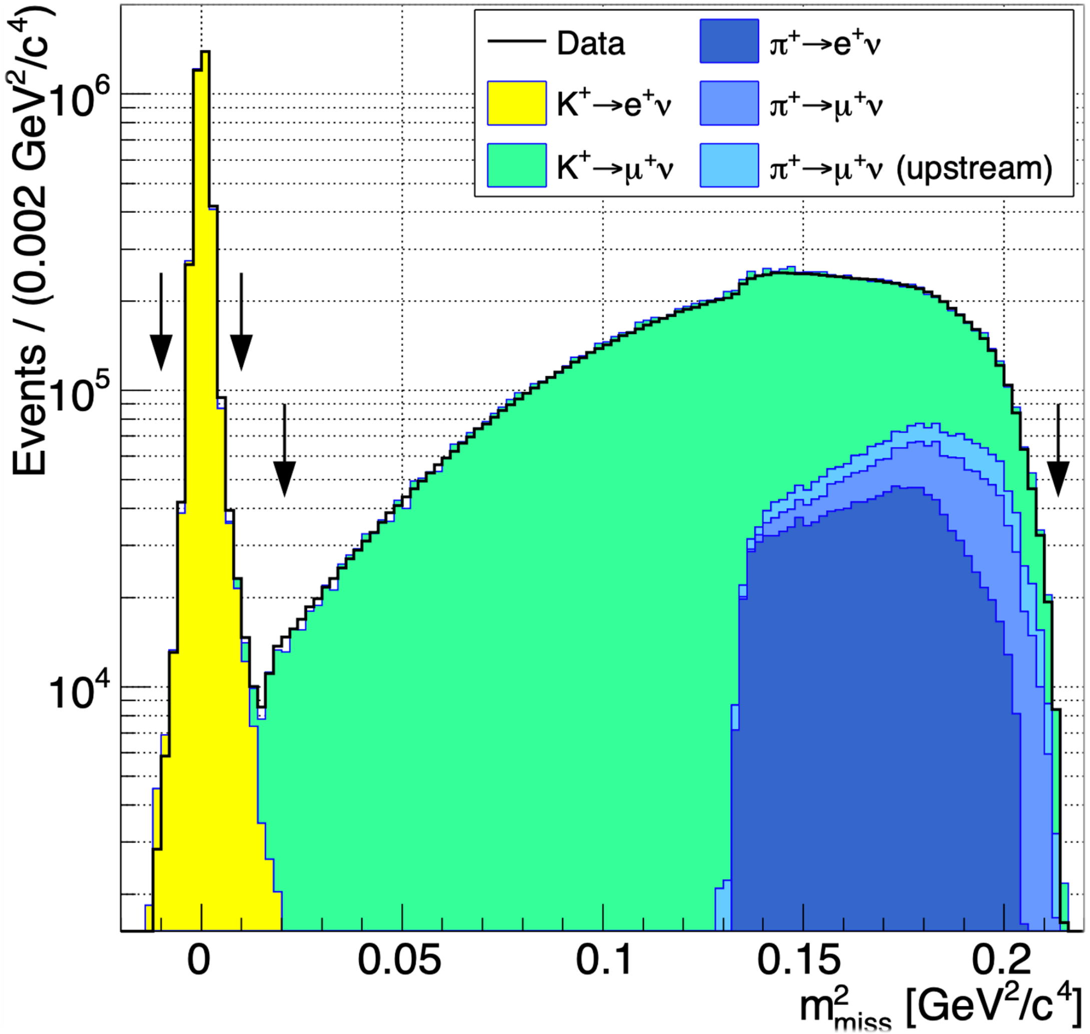
Search for heavy neutral lepton production in K^+ decays to positrons

Event Selection

- Exploit the precise tracking and powerful PID to reconstruct both the K^+ and e^+, then match the two tracks together
- Exploit the $O(100\text{ps})$ time resolution to veto any other in-time activity

- $N_{SM} = 3.495 \times 10^6$ $K^+ \rightarrow e^+\nu$ candidates
- $N_K = (3.52 \pm 0.02) \times 10^{12}$
  (analysis-dependent sample size)

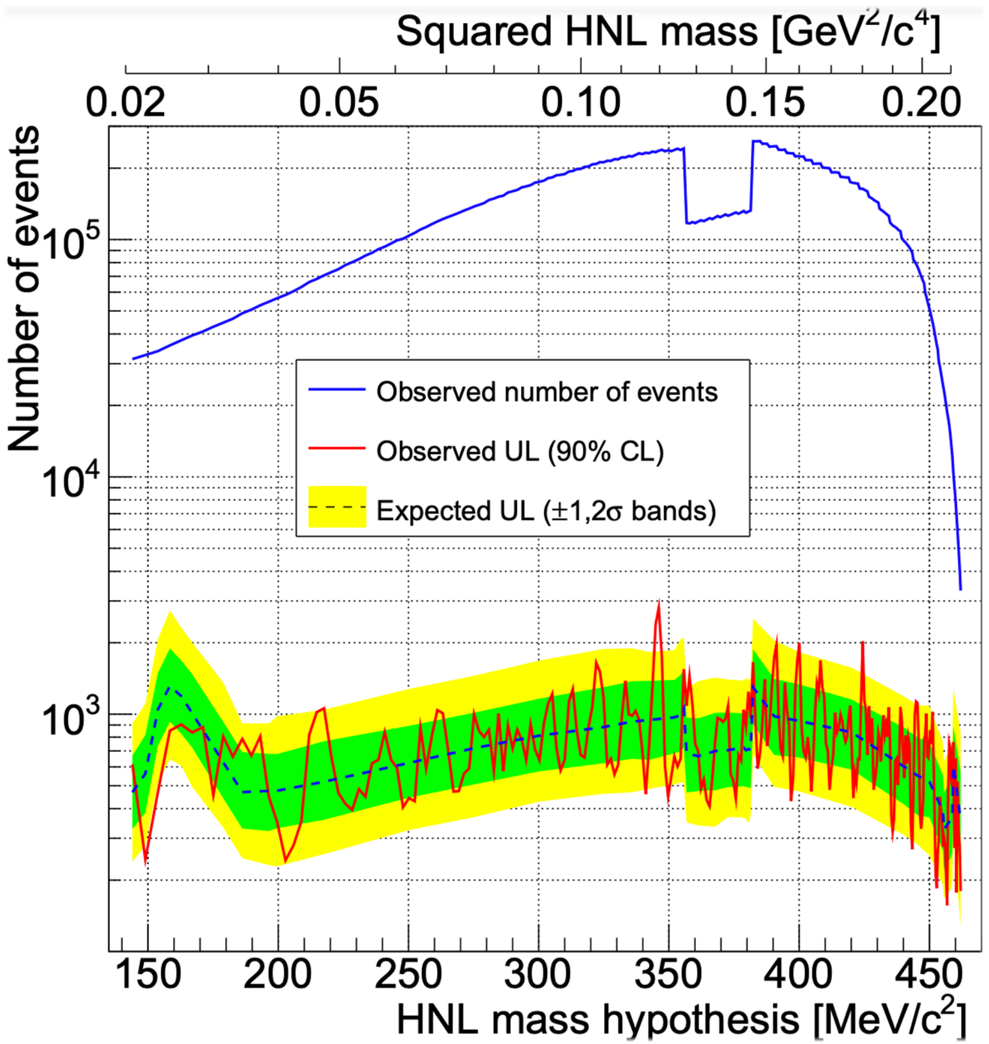
- $K^+ \rightarrow eN$ decays appear as a sharp bump in the positive m^2_{miss} sideband of candidate $K^+ \rightarrow e^+\nu$ decays



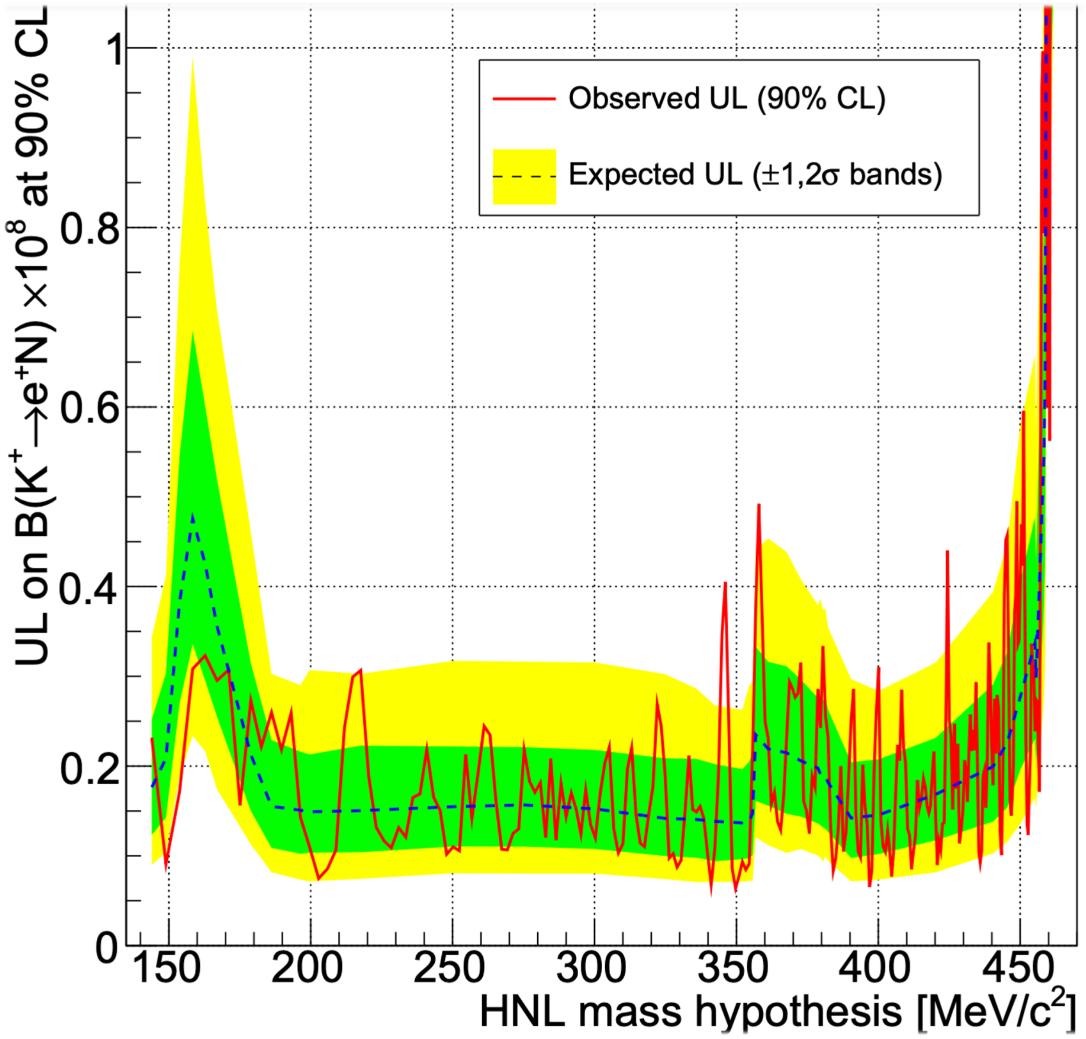
Search for heavy neutral lepton production in K^+ decays to positrons

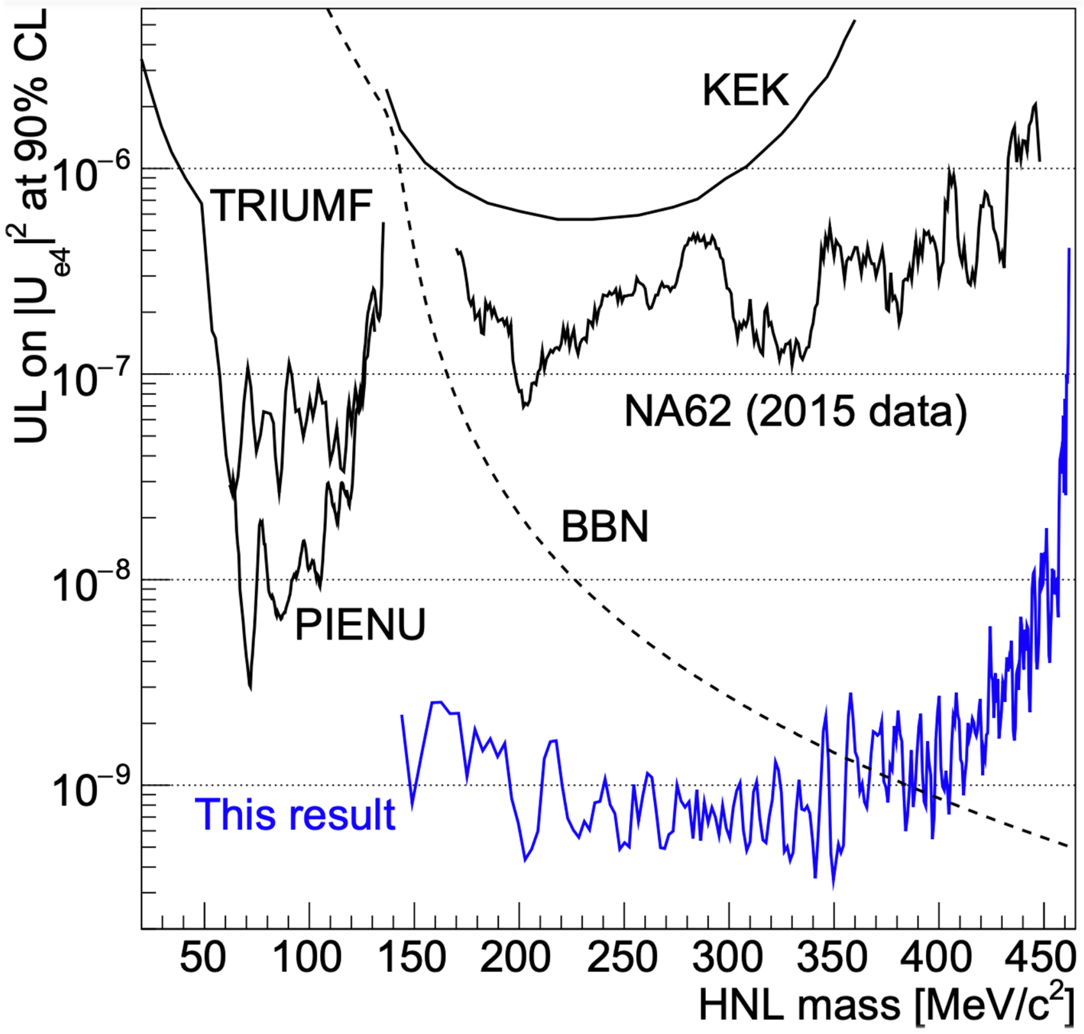
Limit-setting procedure

- Scan across m^2_{miss} in steps defined by the $O(1\text{MeV}/c^2)$ mass resolution on m_N
- Count expected and observed events in a $\pm 1.5\sigma$ window at each step
- Expected number of events estimated using 2nd order polynomial fits to the data
- Close to kinetmatic edge of π^+ decays $(356 - 382\ \text{MeV}/c^2)$ use stricter selection to shift π^+ backgrounds to higher m^2_{miss}
  - Less stringent limits in this region!
- Set limits on the number of $K^+ \to eN$ decays using the CLs method



Search for heavy neutral lepton production in K^+ decays to positrons



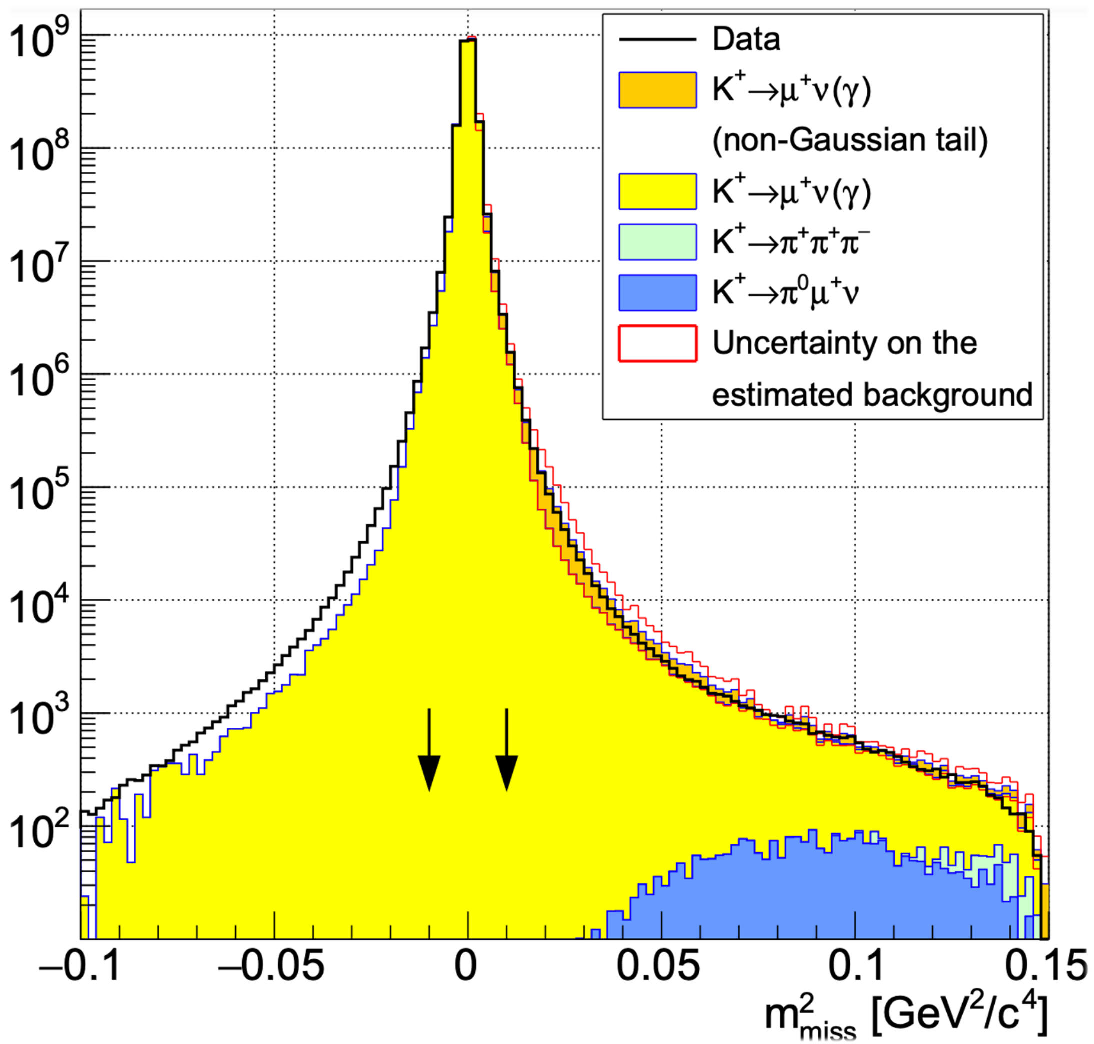


Search for K^+ decays to a muon and invisible particles

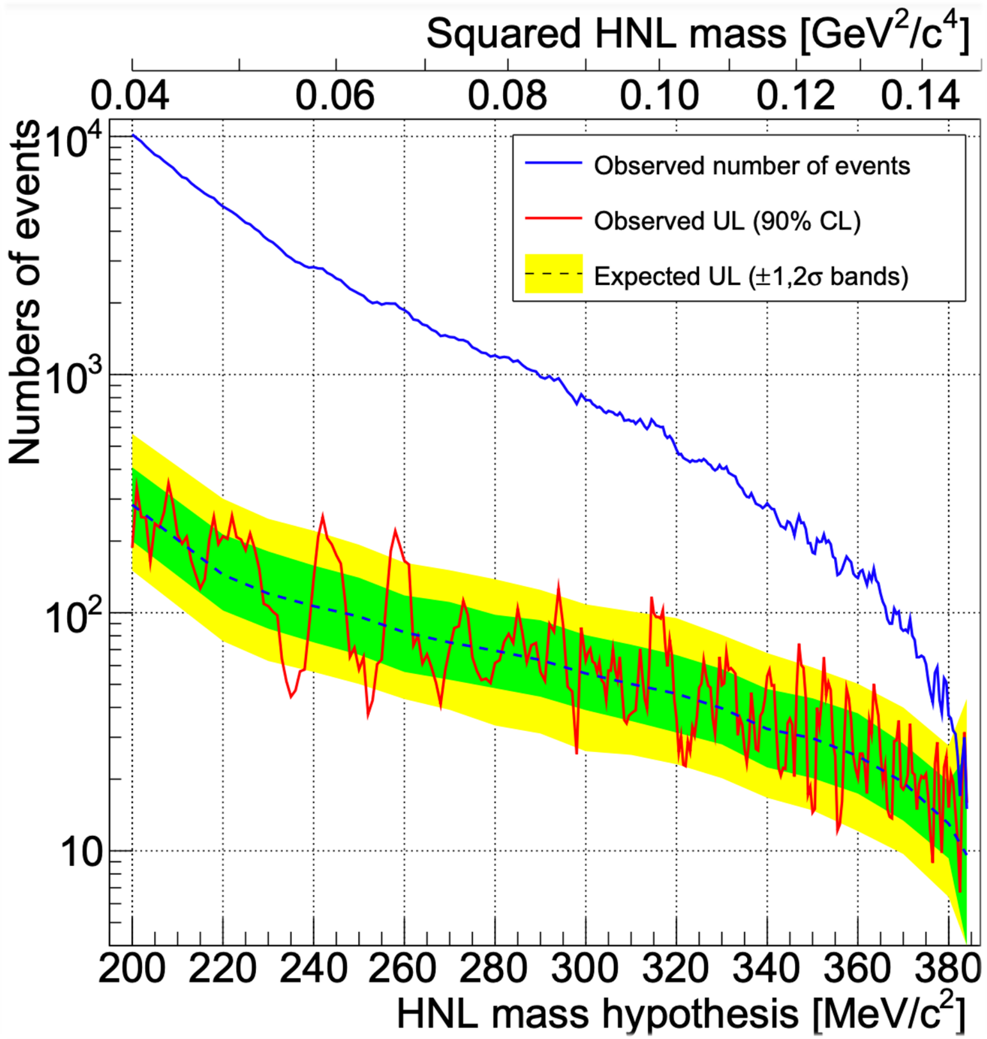
- Similar event selection techniques applied to select $K^+ \to \mu^+ \nu$ candidates
- π^+ decays negligible in this case
- Simulation of beam-particle pileup and GTK inefficiency causes deficit of simulated events in non-gaussian tails of m^2_{miss}
  - Assume tail is symmetric around 0; assign a 100% systematic uncertainty

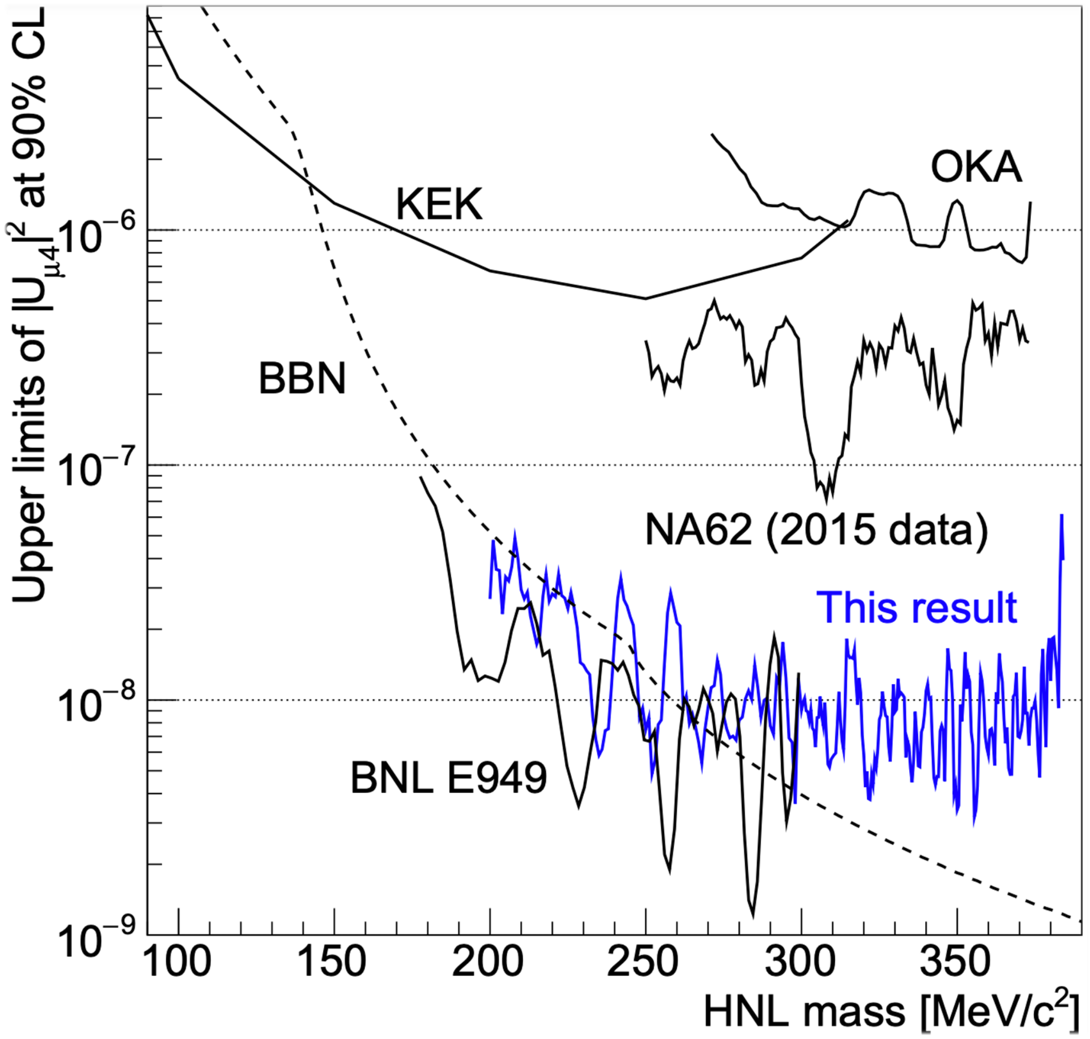
- $N_{SM} = 2.19 \times 10^9\ K^+ \to \mu^+ \nu$ candidates
- $N_K = (1.14 \pm 0.02) \times 10^{10}$
  - N_K smaller than in the electron mode due ~ 400 trigger downscale

- Similar limit-setting procedure as earlier, but each step has a fixed size



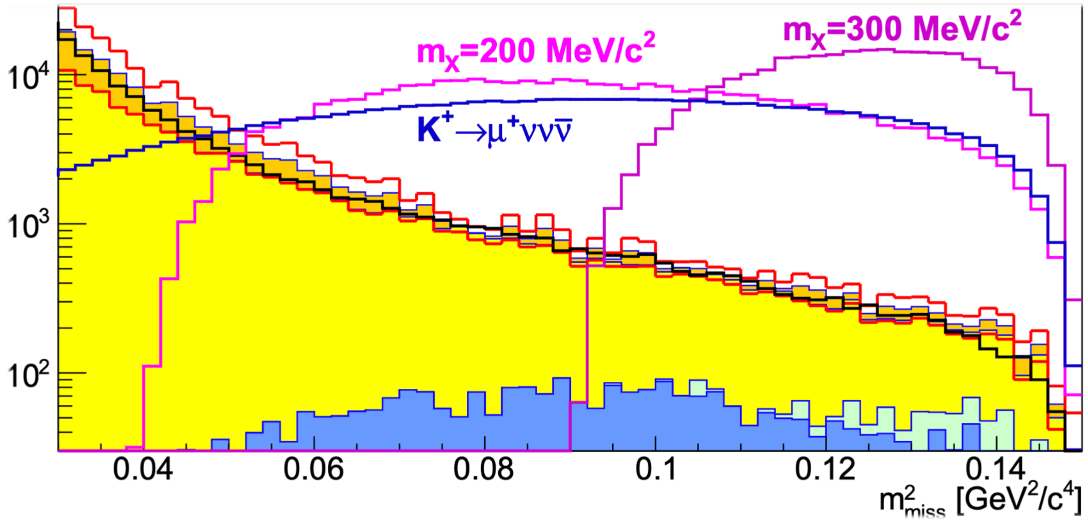
Search for K^+ decays to a muon and invisible particles



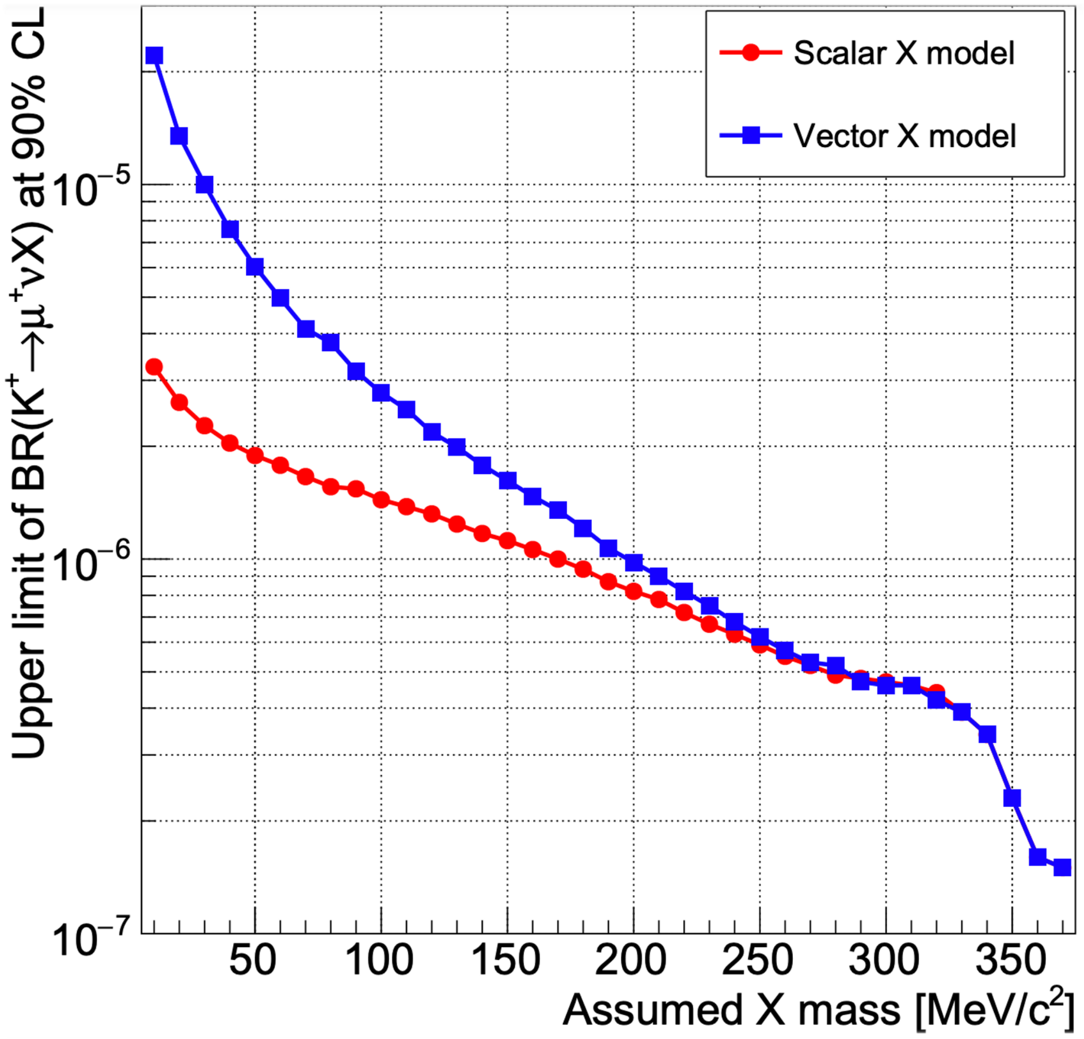


Search for K^+ decays to a muon and invisible particles

- While studying the $K^+ \to \mu^+\nu$ missing-mass spectrum, also check for $K^+ \to \mu^+\nu X$ and $K^+ \to \mu^+\nu\nu\nu$ decays



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



Summary

- Four recent results from NA62 were presented:

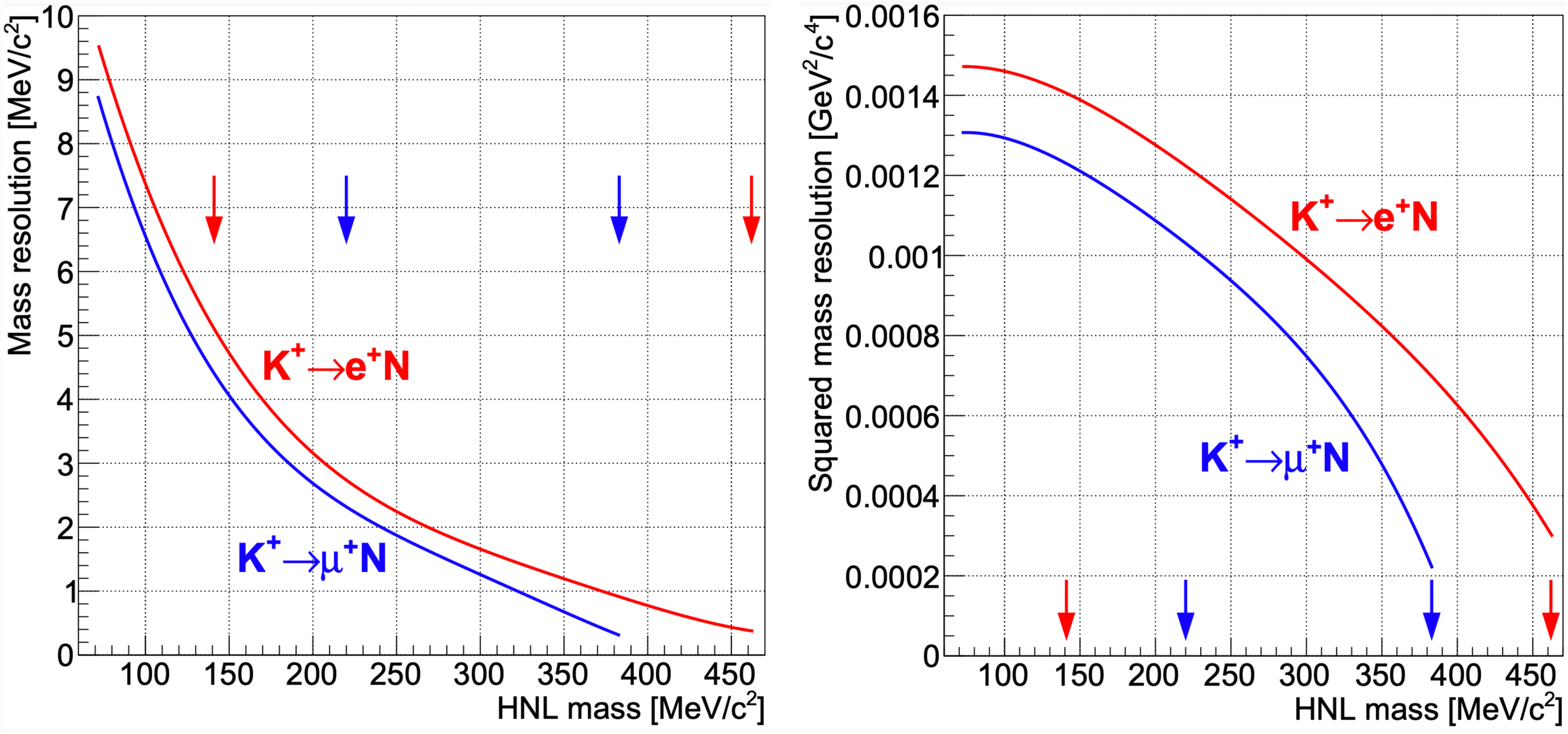
1. Set limits on $|U_{e4}|^2$, at the level of 10^{-9} in the $144 - 462\ \mathrm{MeV}/c^2$ mass range
    - Worlds best limits across this mass range
    - Region favoured by Big Bang Nucleosynthesis excluded up to about $340\ \mathrm{MeV}/c^2$
2. Set limits on $\left|U_{\mu 4}\right|^2$, at the level of 10^{-8} in the $200 - 384\ \mathrm{MeV}/c^2$ mass range
    - Worlds best limits above $\sim 300\mathrm{MeV}/c^2$
3. Worlds first limits on the $K^+ \to \mu^+ \nu X$ decay, with X being a scalar or vector mediator decaying to an invisible final state with X masses in the $10 - 370\ \mathrm{MeV}/c^2$ mass range
4. Worlds best limit of 1.0×10^{-6} on the $K^+ \to \mu^+ \nu\nu\nu$ branching fraction

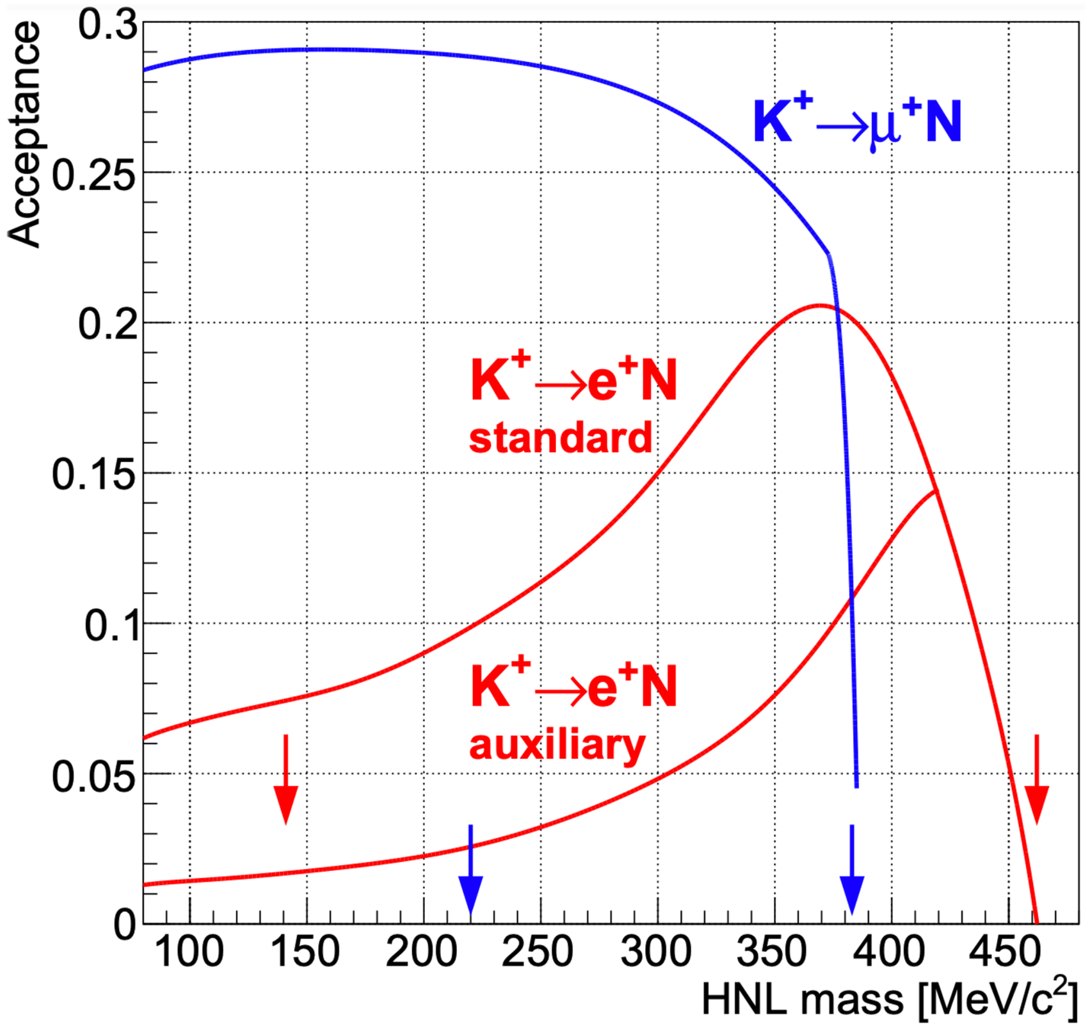
- This month, NA62 started a new data-taking period covering the full extent of LHC run 3
    - Expectation to run at 30% higher beam intensity and collect $O(10^{13})\ K^+$ decays
    - Expect to collect 10^{18} protons-on-target in “dump mode” to further probe Heavy Neutral Lepton parameters, with new muon tagger to reduce muon backgrounds from the target

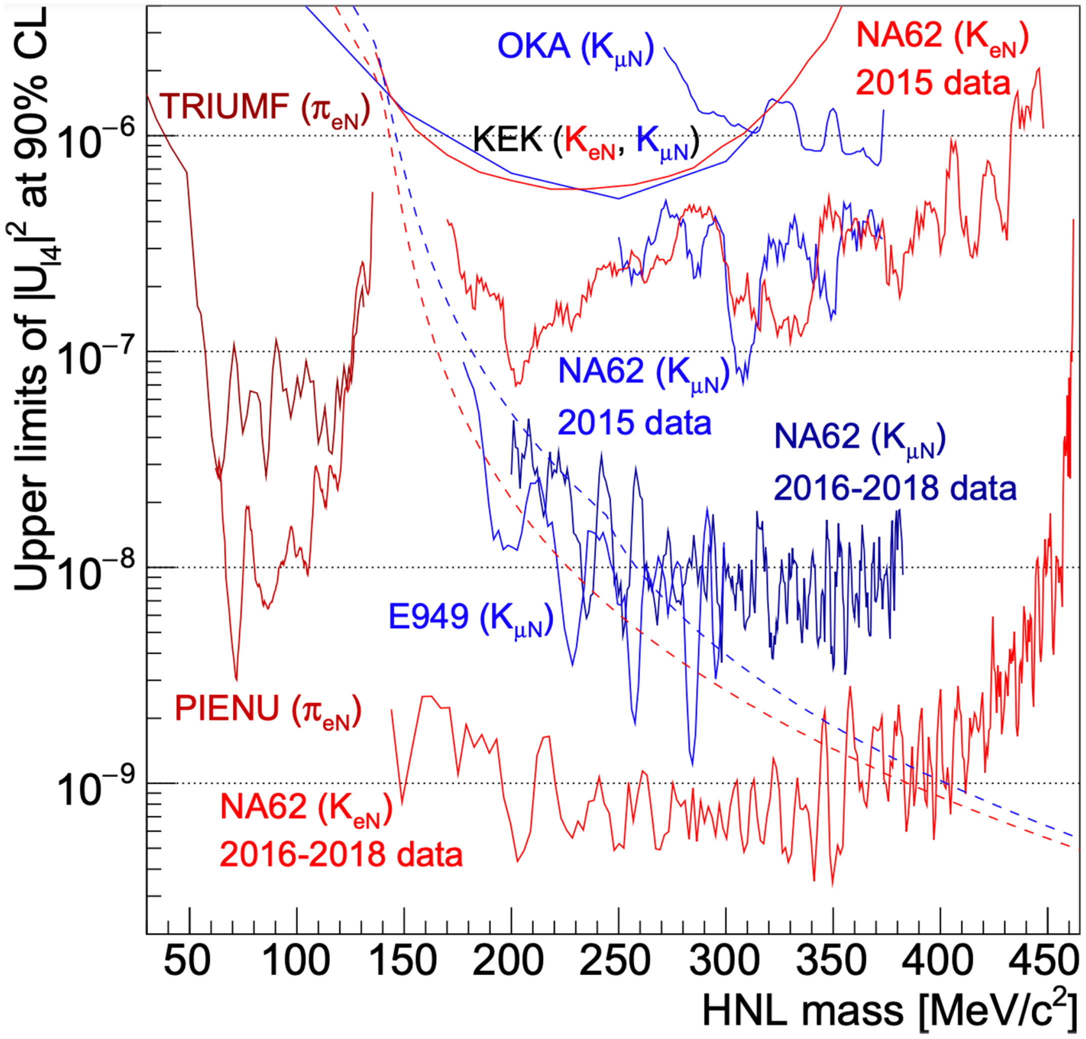
References

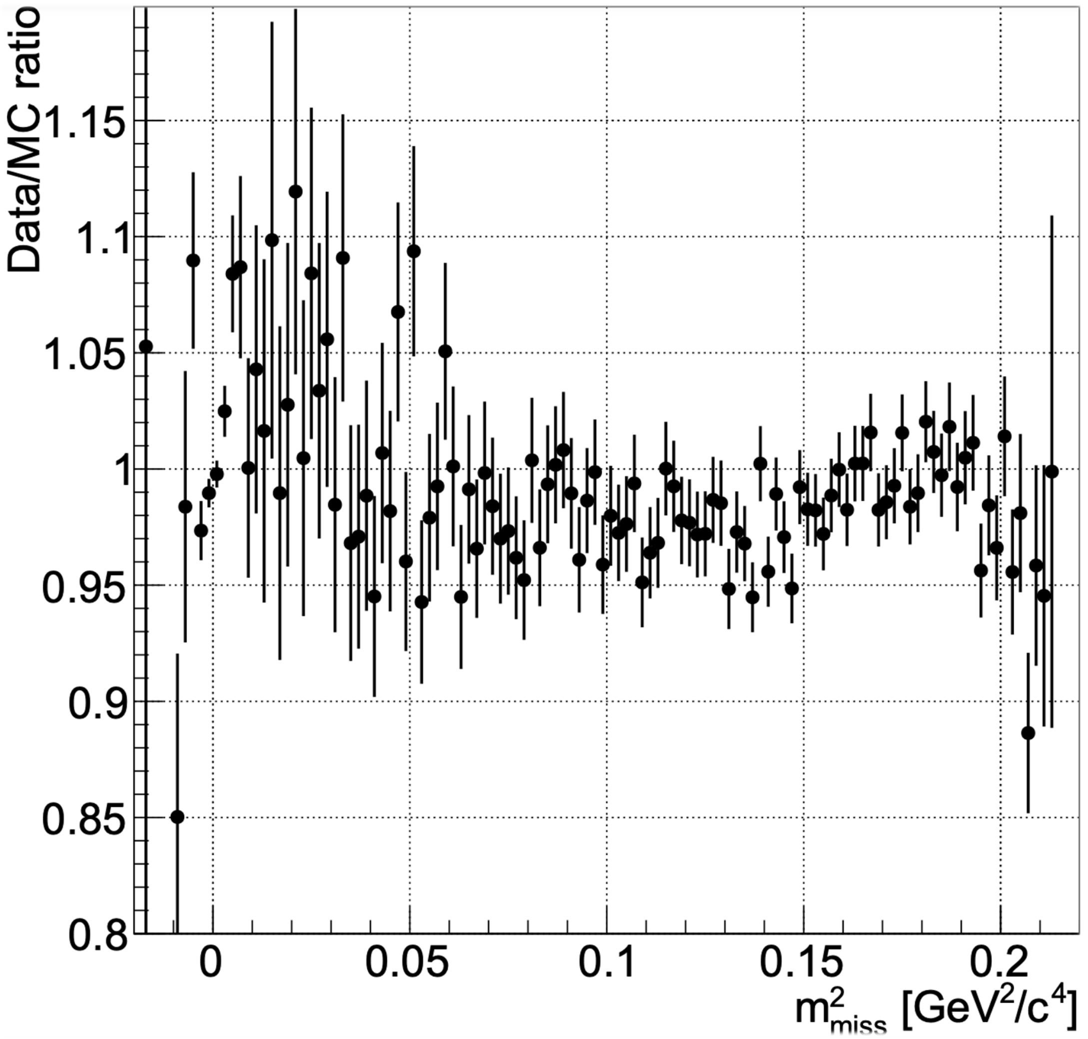
1. T. Asaka, M. Shaposhnikov, Phys. Lett. B 620 (2005) 17
2. R. Shrock, Phys. Lett. B 96 (1980) 159; Phys. Rev. D 24 (1981) 1232

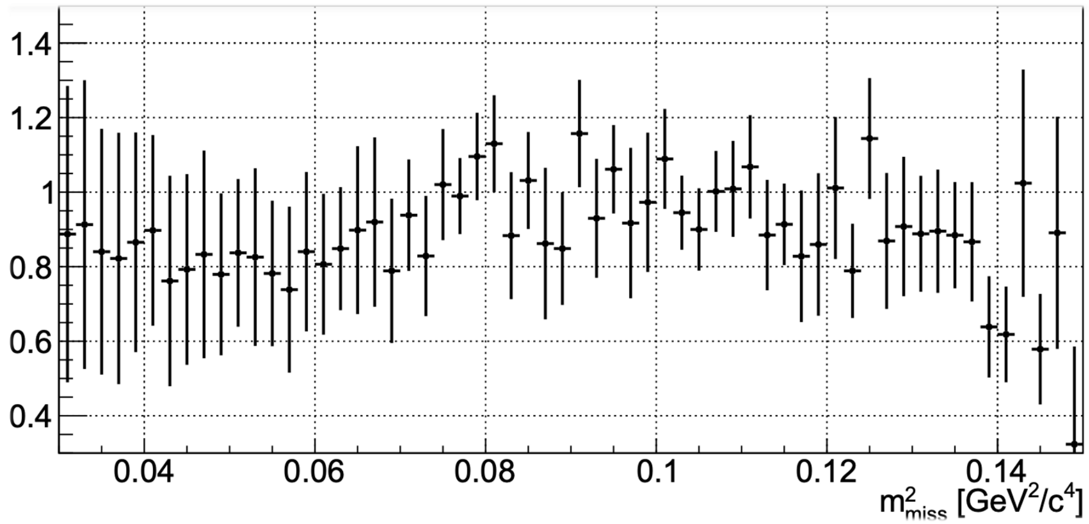
Backup


Mass resolution [MeV/c2]
0
1
2
3
4
5
6
7
8
9
10
100
150
200
250
300
350
400
450
HNL mass [MeV/c2]
K+→e+N
K+→μ+N
Squared mass resolution [GeV2/c4]
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
100
150
200
250
300
350
400
450
HNL mass [MeV/c2]
K+→e+N
K+→μ+N


Acceptance
0.3
0.25
0.2
0.15
0.1
0.05
0
$K^+ \to \mu^+ N$
$K^+ \to e^+ N$
standard
$K^+ \to e^+ N$
auxiliary
100 150 200 250 300 350 400 450
HNL mass [MeV/c^2]


Upper limits of $|U_{l4}|^2$ at 90% CL
10^{-6}
10^{-7}
10^{-8}
10^{-9}
TRIUMF (π_{eN})
OKA ($K_{\mu N}$)
KEK (K_{eN}, $K_{\mu N}$)
NA62 (K_{eN})
2015 data
NA62 ($K_{\mu N}$)
2015 data
NA62 ($K_{\mu N}$)
2016-2018 data
E949 ($K_{\mu N}$)
PIENU (π_{eN})
NA62 (K_{eN})
2016-2018 data
50 100 150 200 250 300 350 400 450
HNL mass [MeV/c^2]


Data/MC ratio
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0
0.05
0.1
0.15
0.2
m^2_{miss} [GeV^2/c^4]


1.4
1.2
1
0.8
0.6
0.4
0.04
0.06
0.08
0.1
0.12
0.14
m^2_{miss} [GeV^2/c^4]