Limits on heavy neutrinos at NA48 and NA62

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on behalf of the NA62 Collaboration

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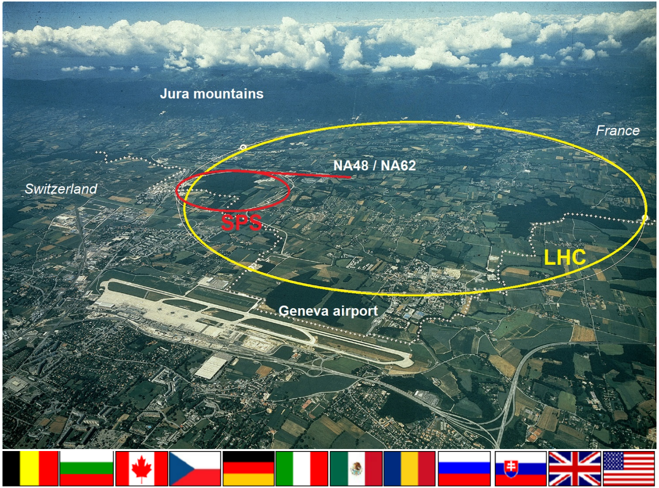
Kaon experiments at CERN

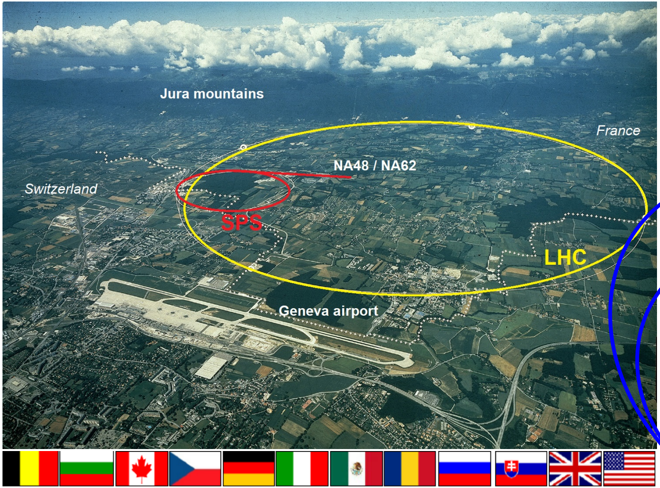


NA62: ~ 200 participants, ~ 30 institutes

- **NA48**: 1997–2001, *beam:* K_L/K_S
  - *Discovery of direct CPV*
- **NA48/1**: 2002, *beam:* K_S/hyperons
- **NA48/2**: 2003–2004, *beam:* K^+/K^-
  - $K^\pm \to \mu^\pm N_4$, $N_4 \to \mu\pi$
- **NA62-R$_K$**: 2007–2008, *beam:* K^+/K^-
  - $K^+ \to \mu^+ N_4$
- **NA62**: since 2014, *beam:* K^+
  2014: pilot run
  2015: commissioning run
  - $K^+ \to e^+ N_4$

  2016: $K^+ \to \pi^+ \nu\bar{\nu}$ run

Kaon experiments at CERN



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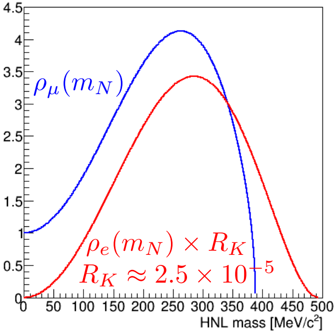
This talk

Heavy Neutrinos: Motivation

- **Neutrino oscillations** imply neutrinos are massive, **not accommodated in SM**
- **No SM Dark Matter** candidate and **Baryon Asymmetry** call for beyond SM physics
- Example of SM extension: **Neutrino Minimal SM (νMSM)** (*Asaka et al., PLB 620 (2005) 17*)
  - 3 right-handed sterile neutrinos N_i are added to SM, $m_1 \sim 10$ keV, $m_{2,3} \sim 1$ GeV
  - N_1 serves as **Dark Matter candidate**
  - $N_{2,3}$ introduce extra CPV phases to account for **Baryon Asymmetry** and are responsible for **SM neutrino masses** (**see-saw** mechanism)



R. Shrock PLB96 (1980) 159

- If $m_N < M_{K^\pm} - m_{l^\pm}$, heavy neutrinos are observable via **production** in processes

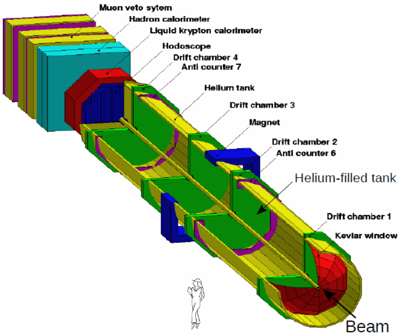
$$\Gamma(K^\pm \to l^\pm N) = \Gamma(K^\pm \to l^\pm \nu_l)\rho_l(m_N)|U_{l4}|^2$$

Kinematic enhancement factor

Mixing matrix element

- **Short-lived neutrino decays** can be observed as **resonances** in spectra of certain $K^\pm$ decays, such as $K^\pm \to \mu^\pm N$, $N \to \pi\mu$

NA48/2 and NA62-R$_K$: Beam and Detector



Main goals

- **NA48/2:** several K$^{\pm}$ decay parameters, *see NA48/2 website*
- **NA62-R$_K$:** $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ *Phys. Lett. B719 (2013) 326*

Beam parameters

- **Narrow momentum bands:**
  - **NA48/2:** $P_K = 60$ GeV/c, $\delta P_K/P_K \sim 4\%$ (rms)
  - **NA62-R$_K$:** $P_K = 74$ GeV/c, $\delta P_K/P_K \sim 1\%$ (rms)
- **Availability of K$^+$ and/or K$^-$ beams**

Main subdetectors

- **Spectrometer (4 DCHs):**
  - **NA48/2:** $\sigma_p/p = 1.02\% \bigoplus 0.044\% \cdot p$[GeV]
  - **NA62-R$_K$:** $\sigma_p/p = 0.48\% \bigoplus 0.009\% \cdot p$[GeV]
- **Scintillator hodoscope:** $\sigma_t \sim 150$ ps
- **LKr EM callorimeter**
  $\sigma_E/E = 3.2\%/\sqrt{E[\text{GeV}]} \bigoplus 9\%/E[\text{GeV}] \bigoplus 0.42\%$
  $\sigma_x = \sigma_y =$
  4.2 mm$/\sqrt{E[\text{GeV}]} \bigoplus 0.6$ mm $(1.5$ mm @ 10 GeV$)$
- **Muon veto system**

NA48/2 and NA62-R_K: HN searches

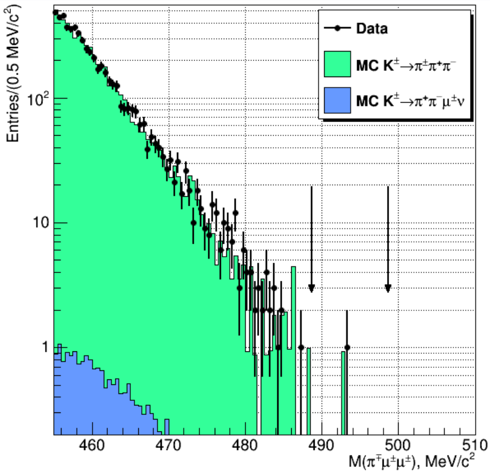
NA48/2: HN production + decay

- Model-dependent (HN decay modes & lifetime)
- Sensitive to short-lived (unstable) HNs
- Sensitive to Majorana/Dirac nature of HNs
- Search done on 3-track vertex sample $K^{\pm} \to \mu^{\pm} N_4$, $N_4 \to \pi\mu$ (LNC & LNV)
  Phys. Lett. B769 (2017) 67-76

NA62-R_K: HN production only

- Independent of HN decay modes
- Sensitive to long-lived (or stable) HNs
- Search done on minimum bias sample $K^+ \to \mu^+ N_4$
  Phys. Lett. B772 (2017) 712-718

NA48/2 same-sign muons sample (LNV)



Blind analysis, $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection based on

- $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ MC simulations
- Control region: $M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 480$ MeV/c^2

Event selection

- One well-reconstructed 3-track vertex
- 2 same-sign muons, one odd-sign pion
- Total p_T consistent with zero
- Signal Region: $|M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) - M_K| < 5$ MeV/c^2

Kaon decays in the fiducial volume

- $N_K \sim 2 \times 10^{11}$ (from reconstructed $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$)

Expected background in the Signal Region

- Estimated using $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ MC sample

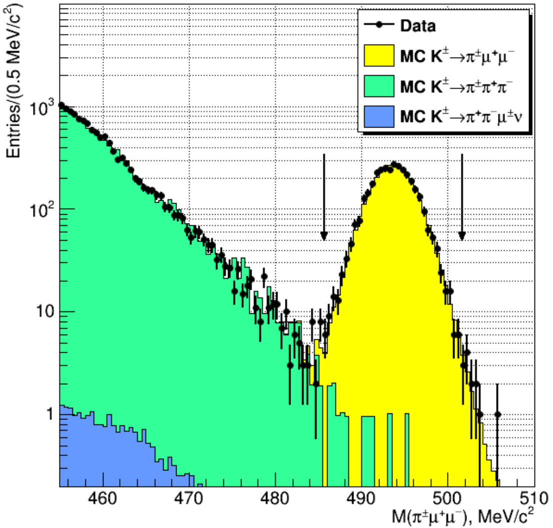
Number of events left in the signal region after finalizing the selection: $N_{\text{obs.}} = 1$

Expected background from MC simulation: $N_{\text{exp.}} = 1.163 \pm 0.867_{\text{stat.}} \pm 0.021_{\text{ext.}} \pm 0.116_{\text{syst.}}$

Rolke-Lopez method used to determine $UL(N_{\text{sig.}})$, resulting in UL on $\mathcal{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm})$:

$$\mathcal{B}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11} @ 90\% \text{CL}$$

NA48/2 opposite-sign muons sample (LNC)

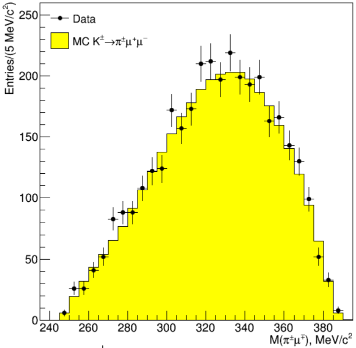


3489 $K^+ \to \pi^\pm\mu^+\mu^-$ candidates in Signal Region

$K^+ \to \pi^\pm\mu^+\mu^-$ background: $(0.32 \pm 0.09\%)$

Event selection

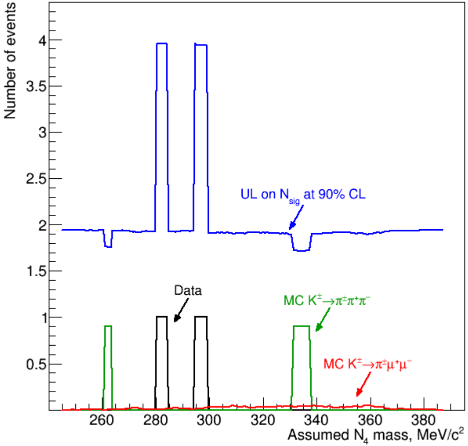
- Almost identical to same-sign
- 2 opposite-sign muons, one pion
- Signal Region: $|M(\pi^\pm\mu^+\mu^-) - M_K| < 8$ MeV/c^2

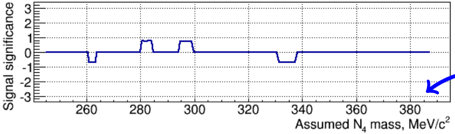


$M(\pi^\pm\mu^\mp)$ scanned for peaks

Search for HN in LNV mode

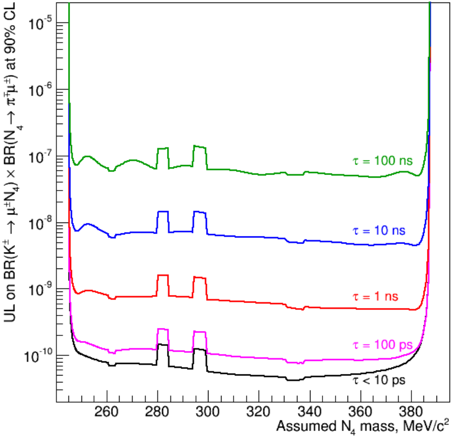
Same-sign muon sample





$$\frac{1}{N_K \cdot A(m_{N_4})}$$

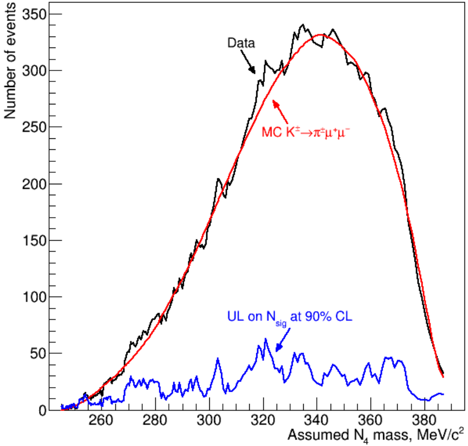
$UL(\mathcal{B}(\mathrm{K}^{\pm} \to \mu^{\pm} N_4)\mathcal{B}(N_4 \to \pi^{\mp}\mu^{\pm}))$

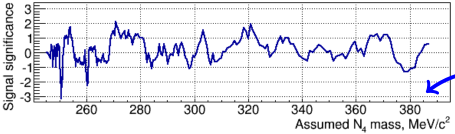


- Statistical significance never exceeds 3σ
  No signal observed

Search for HN in LNC mode

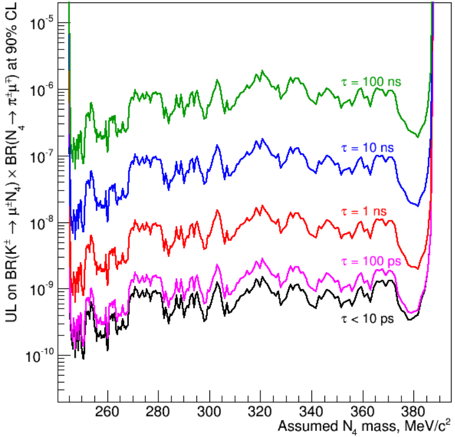
Opposite-sign muon sample





$$\frac{1}{N_K \cdot A(m_{N_4})}$$

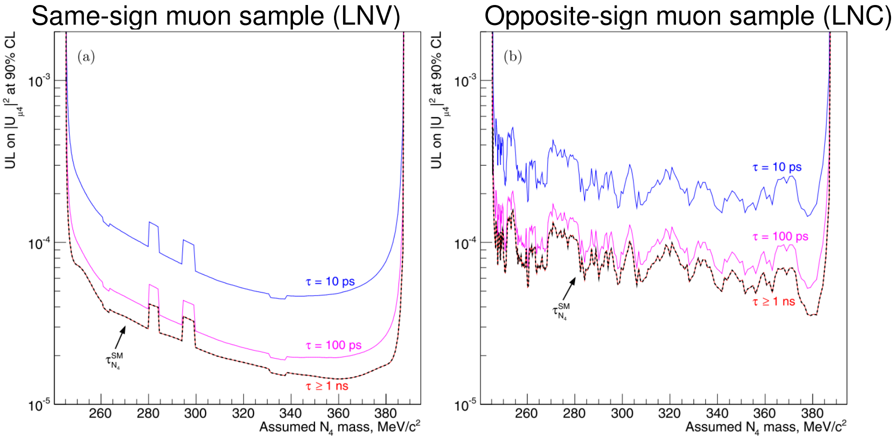
$UL(\mathcal{B}(K^{\pm} \to \mu^{\pm} N_4)\mathcal{B}(N_4 \to \pi^{\pm}\mu^{\mp}))$



- Statistical significance never exceeds 3σ
  No signal observed

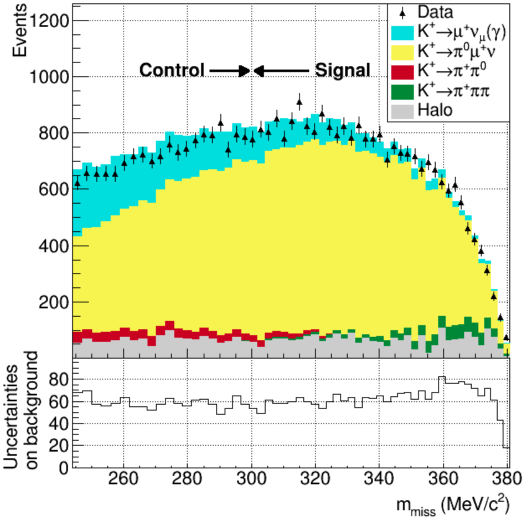
Upper limits on $|U_{\mu4}|^2$ from NA48/2

$$|U_{\mu4}|^2 = \frac{\mathcal{B}(K^\pm \to \mu^\pm N_4)}{\mathcal{B}(K^\pm \to \mu^\pm \nu_\mu)\rho_\mu(m_{N_4})}$$



Unlike NA62-R$_K$ and NA62 2015 results in the following slides, NA48/2 ULs on $|U_{\mu4}|^2$ are applicable for short-lived HNs.

Search for HN at NA62-R_K, single-muon sample



Kaon decays in the fiducial volume

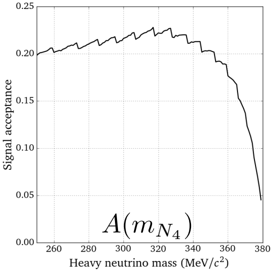
- $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \to \mu^+ \nu$)

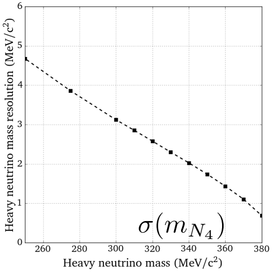
Analysis outline

- Analysis done on K^+ sample only
- Peak search performed in Missing Mass: $M_{miss} = \sqrt{(P_K - P_\mu)^2}$
- Signal Region: $M_{miss} \in (300, 375)$ MeV/c^2

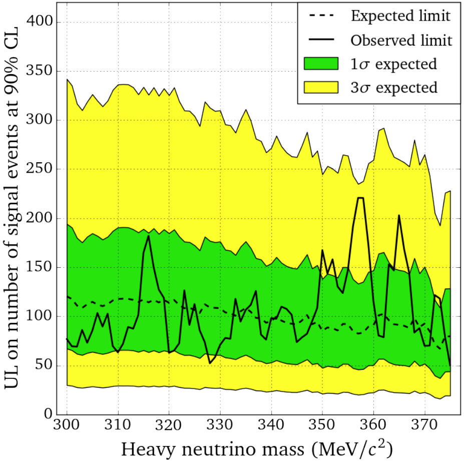
HN MC simulation

- Acceptance vs. HN mass: $A(m_{N_4})$
- M_{miss} resolution vs. HN mass: $\sigma(m_{N_4})$

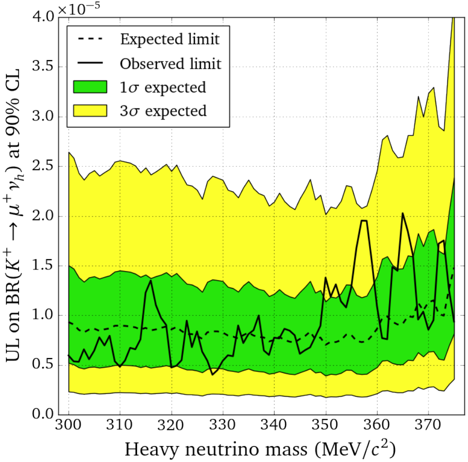




Search for HN at NA62-R_K, ULs on $N_{\text{sig.}}$ and $\mathcal{B}(K^+ \to \mu^+ N_4)$

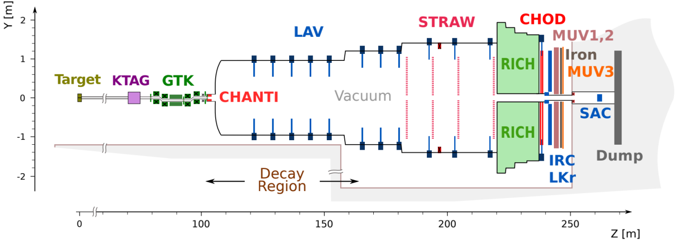


$$\xrightarrow{\dfrac{1}{N_K \cdot A(m_{N_4})}}$$



- Rolke-Lopez method used to determine UL on $N_{\text{sig.}}$
- Heavy neutrino mass step: 1 MeV/c^2
- Search window determined according to $\sigma(m_{N_4})$
- Statistical significance never exceeds 3σ: **No signal observed**

NA62: Beam and Detector



NA62 collaboration, JINST 12 (2017) P05025

Main goal

- **10% precision measurement of** $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu})$

Beam parameters

- **Beam momentum:** 75 GeV/c $(\pm 1\%)$
- **Positive beam:** $\sim 6\%$ K^+

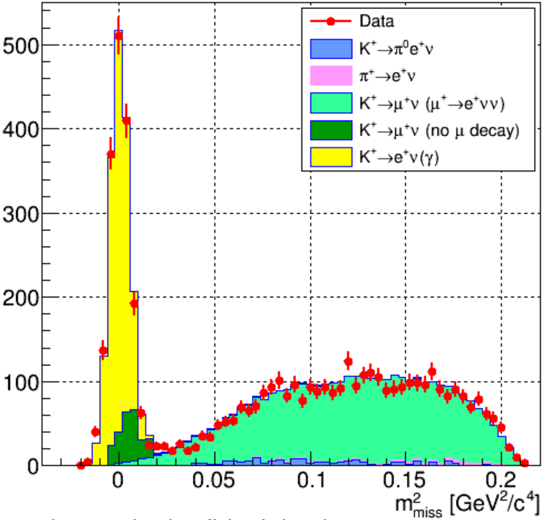
Main subdetectors

- **Trackers:** beam (GTK), $\pi/\mu/e$ (STRAW)
- **Hermetic veto detectors:**
  - Photon vetoes (LAV, LKr, IRC, SAC)
  - Muon vetoes (MUV)
- **Particle identification:**
  - Beam kaons (KTAG)
  - $\pi/\mu/e$ (RICH, LKr, MUV)

Data taking conditions in 2015

- **Minimum bias data:** taken at 1% of design beam intensity
- **Beam tracker not available:** kaon momentum estimated as beam average

Search for HN at NA62, single-track sample



Kaon decays in the fiducial volume

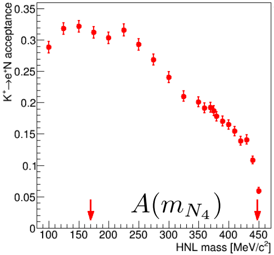
- $N_K = (3.01 \pm 0.11) \times 10^8$

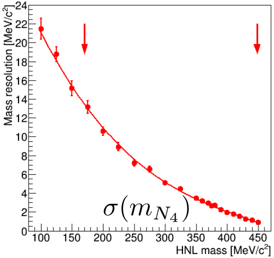
Analysis outline

- Peak search performed in Missing Mass: $M_{\text{miss}} = \sqrt{(P_K - P_e)^2}$
- Signal Region: $M_{\text{miss}} \in (170, 448)$ MeV/c^2

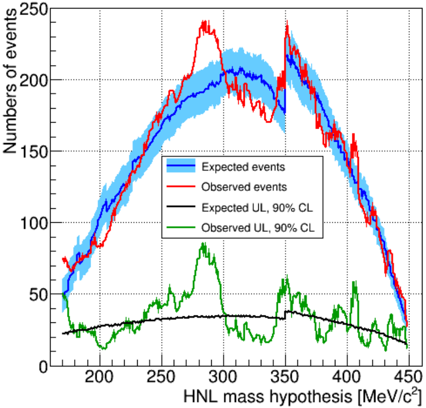
HN MC simulation

- Acceptance vs. HN mass: $A(m_{N_4})$
- M_{miss} resolution vs. HN mass: $\sigma(m_{N_4})$

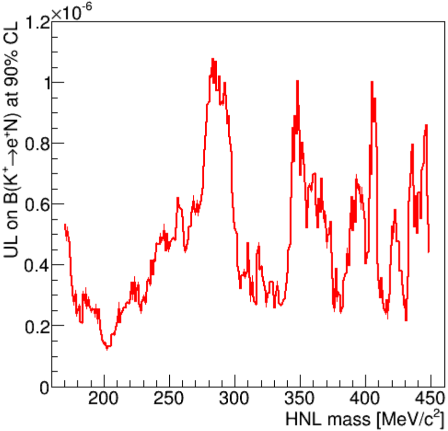




Search for HN at NA62, ULs on $N_{\text{sig.}}$ and $\mathcal{B}(\mathrm{K}^+ \to \mu^+ N_4)$



$$\xrightarrow{\dfrac{1}{N_K \cdot A(m_{N_4})}}$$

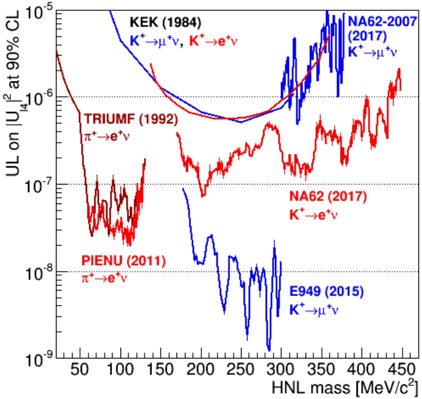


- Rolke-Lopez method used to determine UL on $N_{\text{sig.}}$
- Heavy neutrino mass step: 1 MeV/c^2
- Search window chosen to be $\pm 1.5\sigma(m_{N_4})$
- Statistical significance never exceeds 3σ: **No signal observed**

Summary and Outlook

NA48/2 and NA62 HN production (and decay) searches in $K^{\pm}$ decays were presented:

No HN signal has been observed



$$|U_{l4}|^2 = \frac{\mathcal{B}(K^{\pm} \to l^{\pm} N_4)}{\mathcal{B}(K^{\pm} \to l^{\pm}\nu_{\mu})\rho_l(m_{N_4})}$$

Analysis of NA48/2 2004 Data (*Phys. Lett. B769 (2017) 67*)

- About 200 billion $K^{\pm}$ decays in the fiducial volume
- Reached $\mathcal{O}(10^{-4})$ limit on $|U_{\mu 4}|^2$ for $m_{N_4} \in (245, 390)$ MeV/c^2 (also short-lived HNs)

Analysis of NA62-R_K 2007 Data (*Phys. Lett. B772 (2017) 712*)

- About 60 million K^+ decays in the fiducial volume
- Improved limits on $|U_{\mu 4}|^2$ for $m_{N_4} \in (300, 375)$ MeV/c^2

Analysis of NA62 2015 Data (*paper in preparation*)

- About 300 million K^+ decays in the fiducial volume
- New limits on $|U_{e4}|^2$ reaching $10^{-6} - 10^{-7}$ for $m_{N_4} \in (170, 448)$ MeV/c^2

Future prospects

- Major analysis improvements with NA62 2016 high intensity data (fully working beam tracker)