Heavy neutral leptons searches from kaon experiments at CERN

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on behalf of the NA62 collaboration

Current trends in Flavor Physics

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Outline

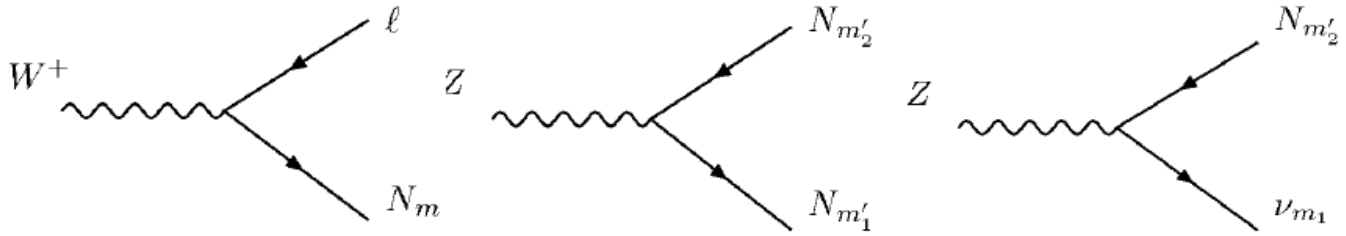
- **Majorana neutrinos in a nutshell**
- **North area experiments**
- **NA48/2 and NA62-R_K experimental setup**
- **NA48/2: heavy neutrino searches in $K^{\pm} \to \pi\mu\mu$**
- **NA62-R_K : heavy neutrino searches in $K^{+} \to \mu^{+}N$**
- **Conclusions**

Majorana neutrinos in a nutshell

Neutrino mass needs to be accomodated in the SM.
Asaka-Shaposhnikov model (νMSM) [*PLB 620 (2005) 17*] introduces three right-handed neutrinos N_i in the SM:

- **N_1 ($\mathcal{O}$(keV)) represents a Dark Matter candidate**
- **$N_{2,3}$ $\mathcal{O}$(100 MeV – few GeV) explain baryon asymmetry and produce low standard ν mass through seesaw mechanism**

Effective vertices with $W^{\pm}$, Z and SM leptons with U mixing matrix:



Production of $N_{2,3}$ in $K^{\pm}$ decays

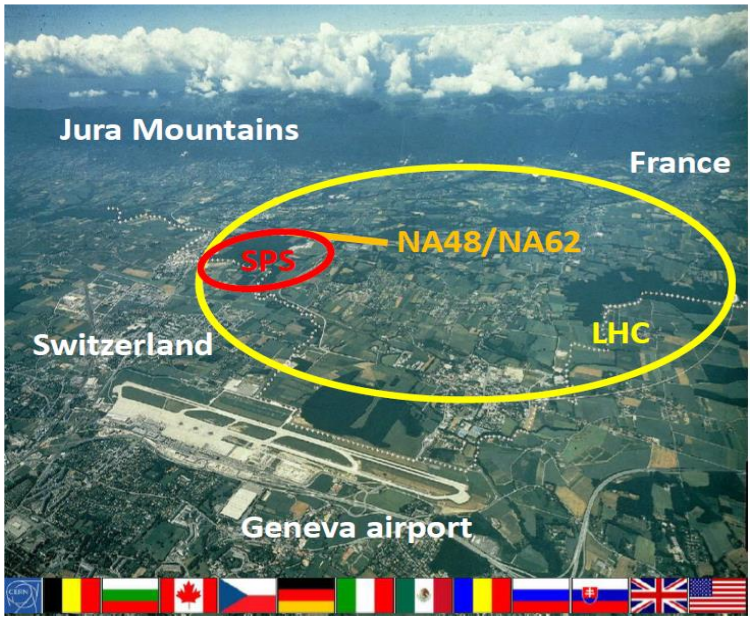
$K^{\pm} \to l^{\pm} N$, $K^{\pm} \to \pi^0 l^{\pm} N$, ...

Decay of $N_{2,3}$ for $m_{2,3} < m_K - m_\pi$

$N \to \pi^{\pm} l^{\mp}$, $N \to \pi^0 \nu$,
$N \to l_1^{\pm} l_2^{\mp} \nu_2$, $N \to \nu \bar{\nu} \nu_l$...

This talk with $l = \mu$

North Area experiments



Kaon Physics at CERN:

- ✓ **Fixed target experiments at CERN SPS**
- ✓ **Kaon decay-in-flight**

Currently in NA62:
~200 participants
29 institutions from 13 countries

NA48: K_L and K_S
ε'/ε and
Search for direct CPV
1997-2001

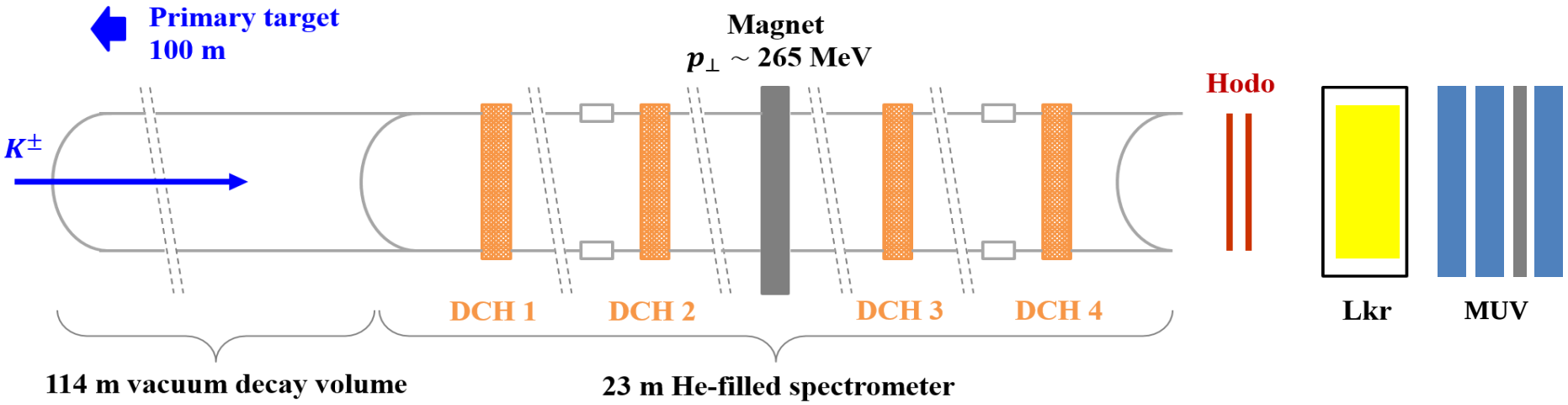
2002
NA48/1: K_S
K_s rare decay studies

2003-2004
NA48/2: K^+ and K^-
Search for direct CPV (charge asymmetry measurement), rare decays

2007-2008
NA62-R_K: K^+ and K^-
Lepton universality: $K_{e2}/K_{\mu 2}$

2014-present
NA62: K^+
Main goal: BR($K^+ \to \pi^+ \nu\bar{\nu}$)

NA48/2 and NA62-R_K experimental setup



Narrow momentum band $K^\pm$ beam	P_K = 60 GeV, $\delta P_K/P_K$~4% (rms) P_K = 74 GeV, $\delta P_K/P_K$~1% (rms)	in NA48/2 in NA62-R_K
Drift chambers	σ_p/p = 1.02% $\oplus$ 0.044% p(GeV) σ_p/p = 0.48% $\oplus$ 0.009% p(GeV)	in NA48/2 in NA62-R_K
LKr EM calorimeters	σ_E/E = 3.2%/$\sqrt{E(\text{GeV})}$ $\oplus$ 9%/E(GeV) $\oplus$ 0.42% $\sigma_x = \sigma_y$ = 4.2 mm/$\sqrt{E(\text{GeV})}$ $\oplus$ 0.6 mm	
Hodoscope	Fast trigger, good time resolution σ_t ~150 ps	

NA48/2 and NA62-R_K strategies

NA48/2

Heavy Neutrino (HN) search in $K^{\pm} \to \mu^{\pm} N_4$ production + $N_4 \to \pi\mu$ decay [*PLB769 (2017), 67*] :

- **Model dependent (HN decay modes & lifetime)**
- **Sensitive to short-lived (unstable) HNs**
- **Sensitive to Majorana/Dirac nature of HNs**

Searching for a 3-tracks vertex topology events $K^{\pm} \to \mu^{\pm}\pi\mu$:

✓ **same sign muons sample $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ (LNV)**

✓ **opposite sign muons sample $K^{\pm} \to \pi^{\pm}\mu^{\pm}\mu^{\mp}$ (LNC)**

NA62-R_K

Heavy Neutrino (HN) search in $K^{\pm} \to \mu^{\pm} N_4$ production (paper in preparation):

- **Independent of HN decay modes**
- **Sensitive to long-lived (or stable) HN**

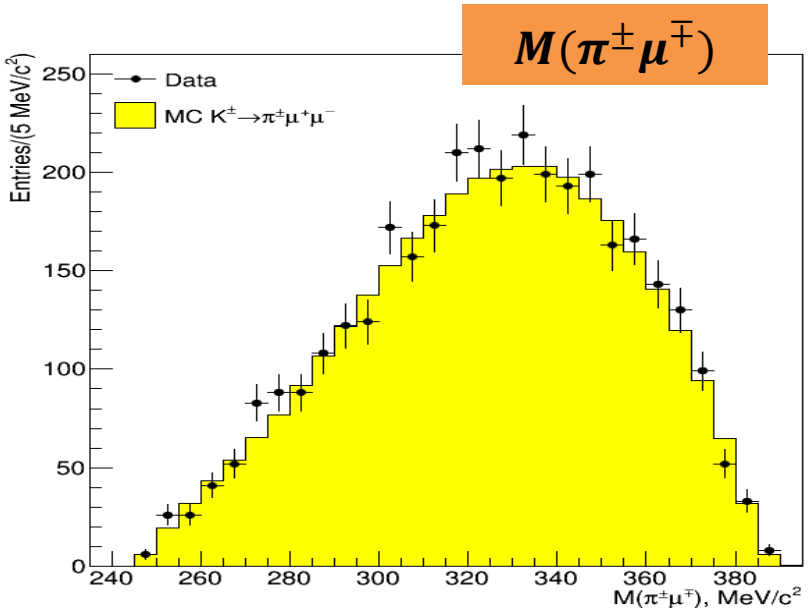
Searching for a peak in the $m_{miss} = \sqrt{(p_K - p_\mu)^2}$ spectrum

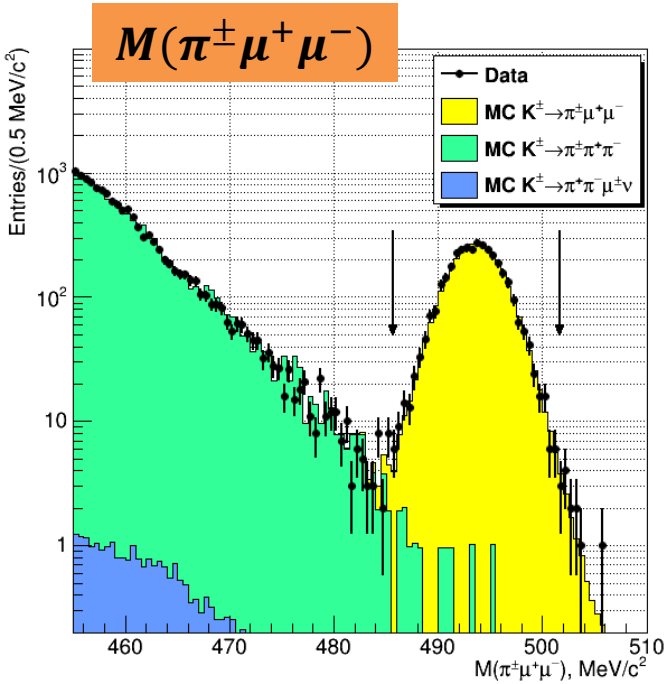
NA48/2: opposite sign muons sample (LNC)

Event selection:

- **Similar to same sign muons: 3-track vertex topology, 2 opposite-sign muons, 1 pion, P_T consistent with zero**
- **Signal region: $\left|M\left(\pi^{\mp}\mu^{+}\mu^{-}\right) - M_K\right| < 8$ MeV/c²**

3489 $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ candidates in signal region
$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ background: (0.32 ± 0.09)%





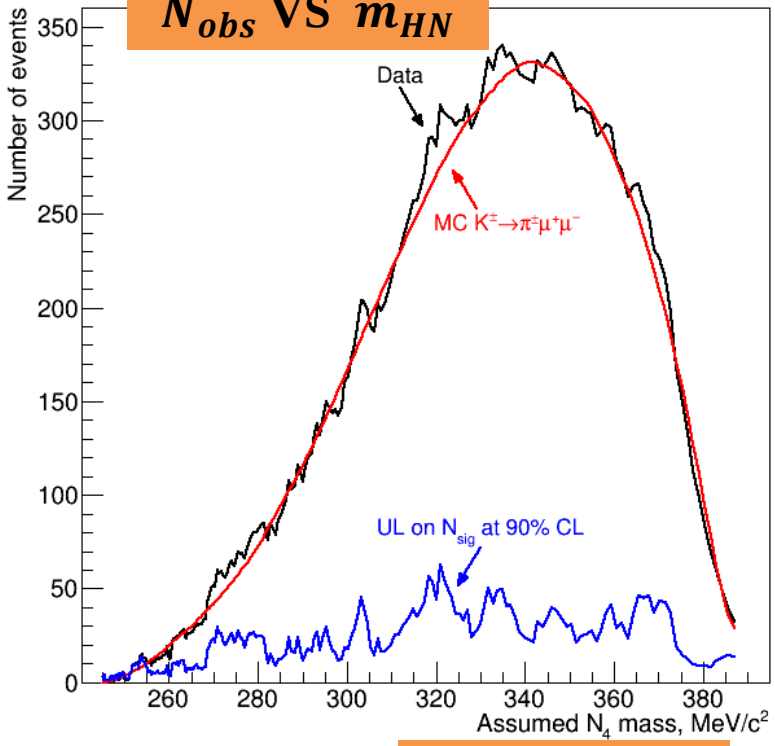
Search for resonances in $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ invariant masses; upper limit on the number of signal event N_{sig} using Rolke-Lopez from N_{obs} and N_{exp} for each hypothesis. Improved selection with respect to previous NA48/2 $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ analysis [*PLB 697(2011)107*]

Resonance searches in LNC sample

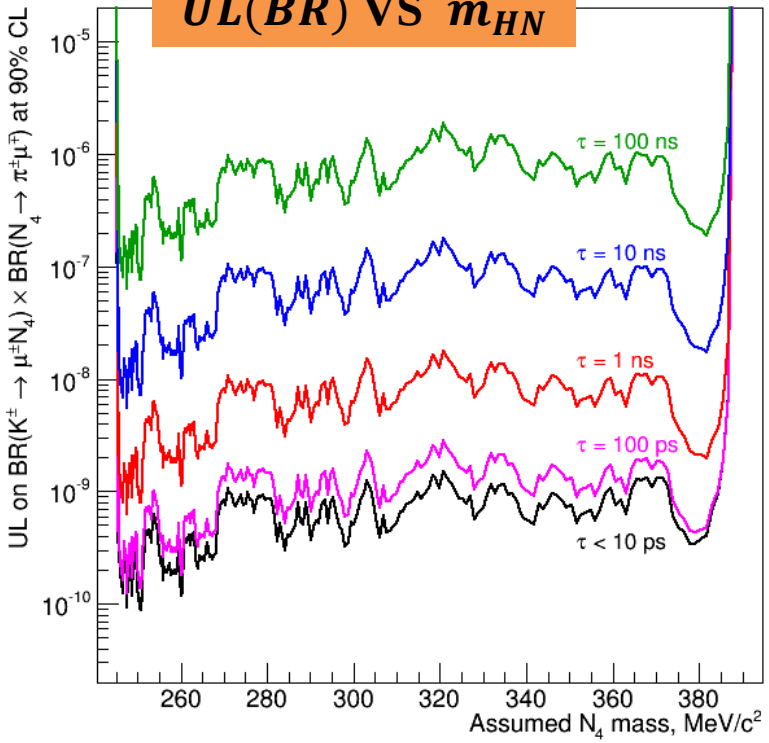
Search for $K^{\pm} \to \mu^{\pm} N_4$ $(N_4 \to \pi^{\pm}\mu^{\mp})$ decay.

Upper limits on N_{sig} and $BR(K^{\pm} \to \mu^{\pm} N_4)BR(N_4 \to \pi^{\pm}\mu^{\mp})) = \frac{N_{sig}}{N_K \cdot Acceptance}$

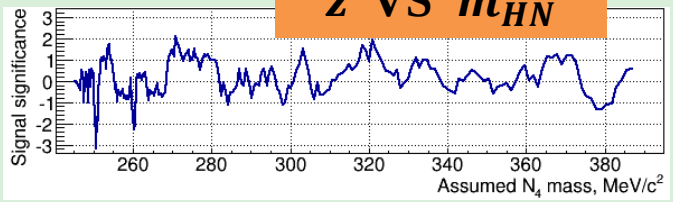
N_{obs} VS m_{HN}



$UL(BR)$ VS m_{HN}



z VS m_{HN}



Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

never exceeds 3σ: no signal observed

NA48/2: same sign muons sample (LNV)

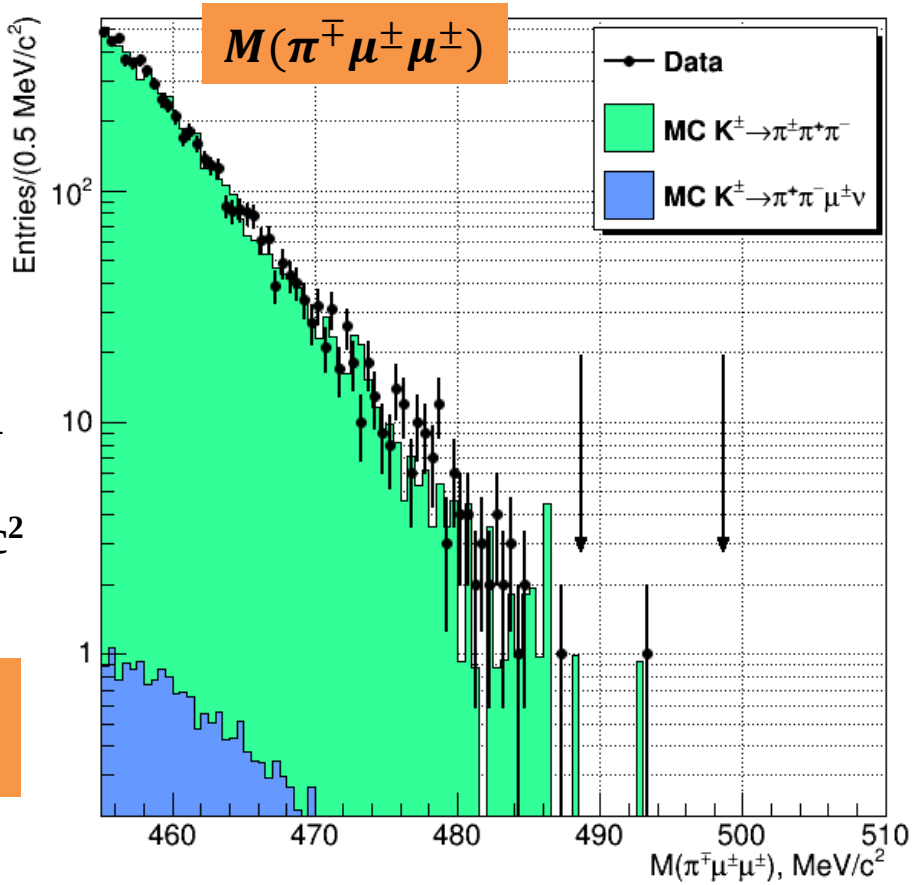
Blind analysis:

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

Event selection:

- 3-track vertex topology, 2 same-sign muons, 1 odd-sign pion, P_T consistent with zero
- Signal region: $\left|M\left(\pi^{\mp}\mu^{\pm}\mu^{\pm}\right) - M_K\right| < 5$ MeV/c^2

Kaon decays in the fiducial volume: $N_K \sim 2\times10^{11}$ (from reconstructed $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$)



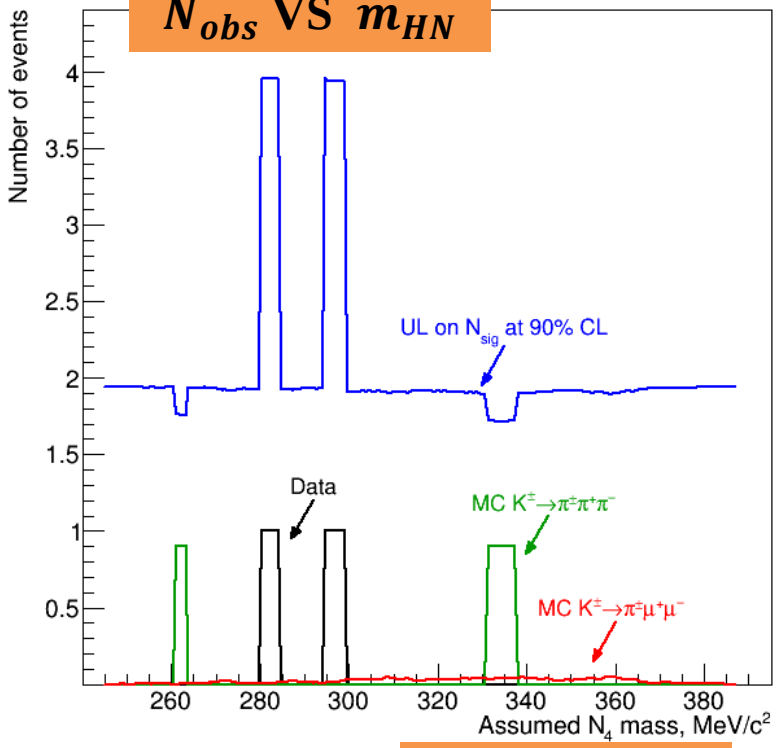
Events in Signal Region observed after $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection: $N_{obs} = 1$
Expected background (from MC): $N_{exp} = 1.163 \pm 0.867_{stat} \pm 0.021_{ext} \pm 0.116_{syst}$
From Rolke-Lopez statistical method: $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90% CL

Resonance searches in LNV sample

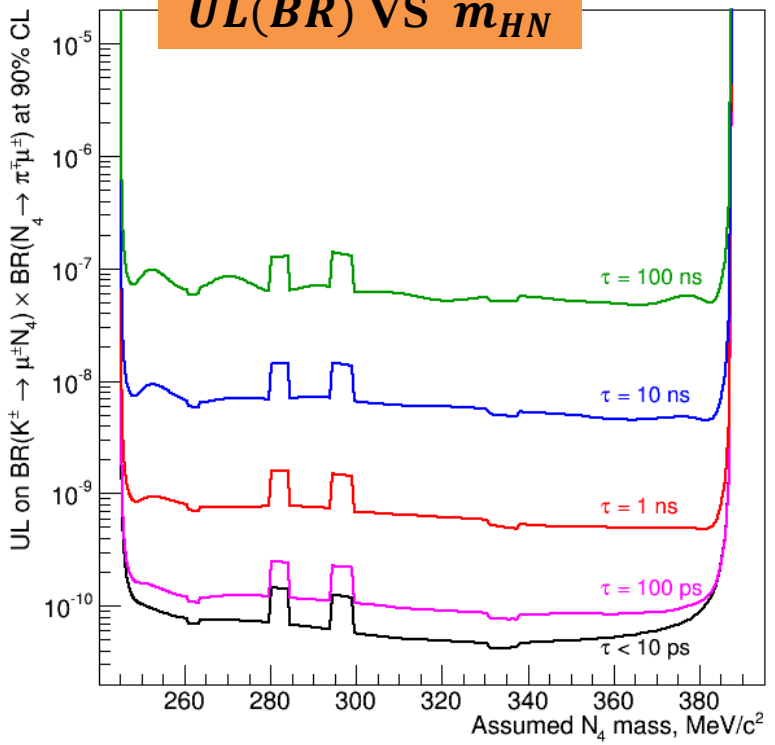
Search for $K^{\pm} \to \mu^{\pm} N_4$ $(N_4 \to \pi^{\mp}\mu^{\pm})$ decay.

Upper limits on N_{sig} and $BR(K^{\pm} \to \mu^{\pm} N_4)BR(N_4 \to \pi^{\mp}\mu^{\pm}) = \frac{N_{sig}}{N_K \cdot Acceptance}$

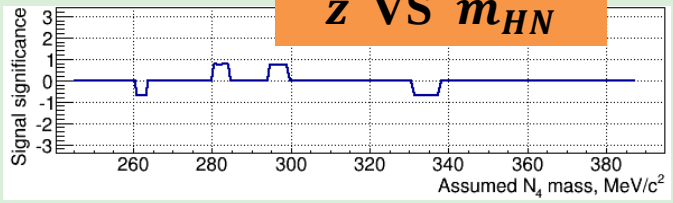
N_{obs} VS m_{HN}



$UL(BR)$ VS m_{HN}



z VS m_{HN}



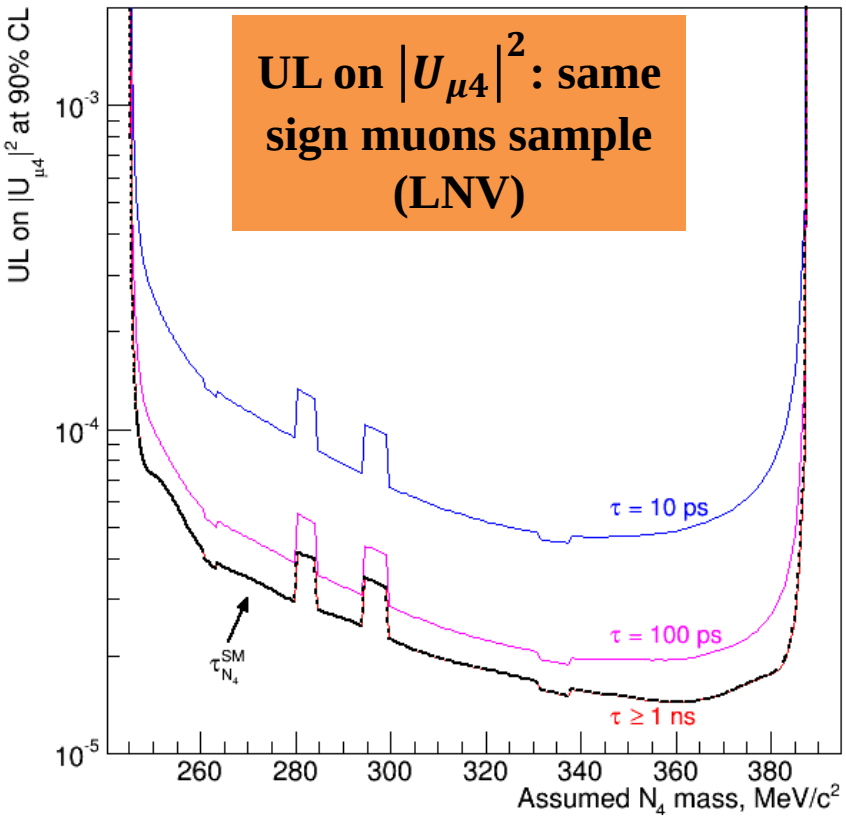
Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

never exceeds 3σ: no signal observed

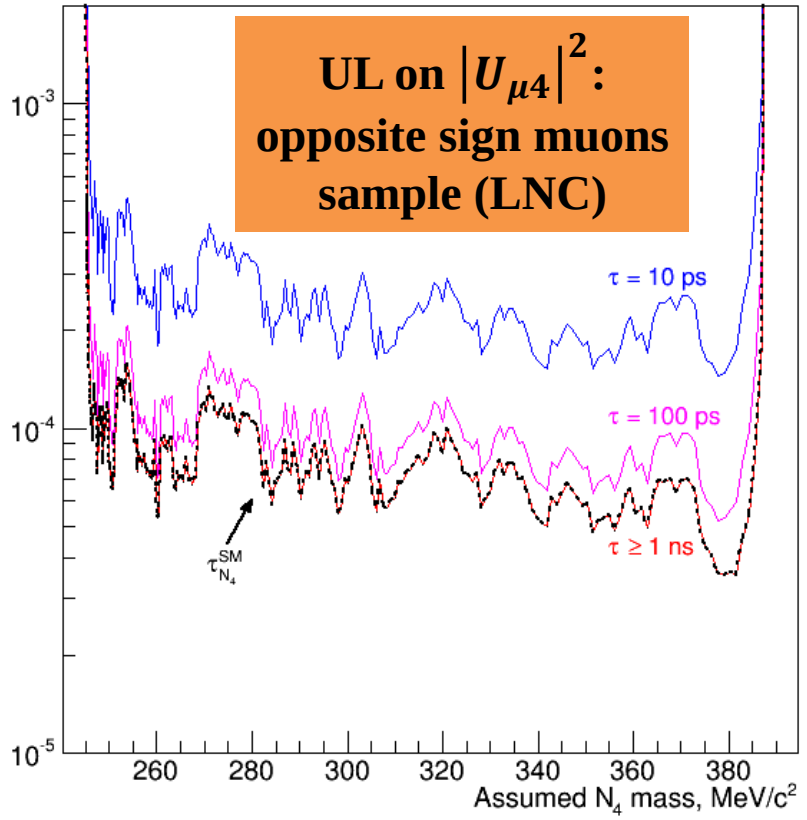
Constraints on $|U_{\mu 4}|^2$

From UL on *BR* to UL on $|U_{\mu 4}|^2$:

$$|U_{\mu 4}|^2 = \frac{8\sqrt{2}\pi\hbar}{G_F^2\sqrt{M_K\tau_K}f_K f_\pi |V_{us}V_{ud}|}\sqrt{\frac{\mathcal{B}(K^\pm \to \mu^\pm N_4)\mathcal{B}(N_4 \to \pi\mu)}{\tau_{N_4} M_{N_4}^5 \lambda^{\frac{1}{2}}(1, r_\mu^2, r_{N_4}^2)\lambda^{\frac{1}{2}}\left(1, \rho_\pi^2, \rho_\mu^2\right)\chi_{\mu\mu}}}$$



UL on $|U_{\mu 4}|^2$: same sign muons sample (LNV)



UL on $|U_{\mu 4}|^2$: opposite sign muons sample (LNC)

Heavy neutrino in NA62-R_K: strategy

HN search in $K^+ \to \mu^+ N_4$:

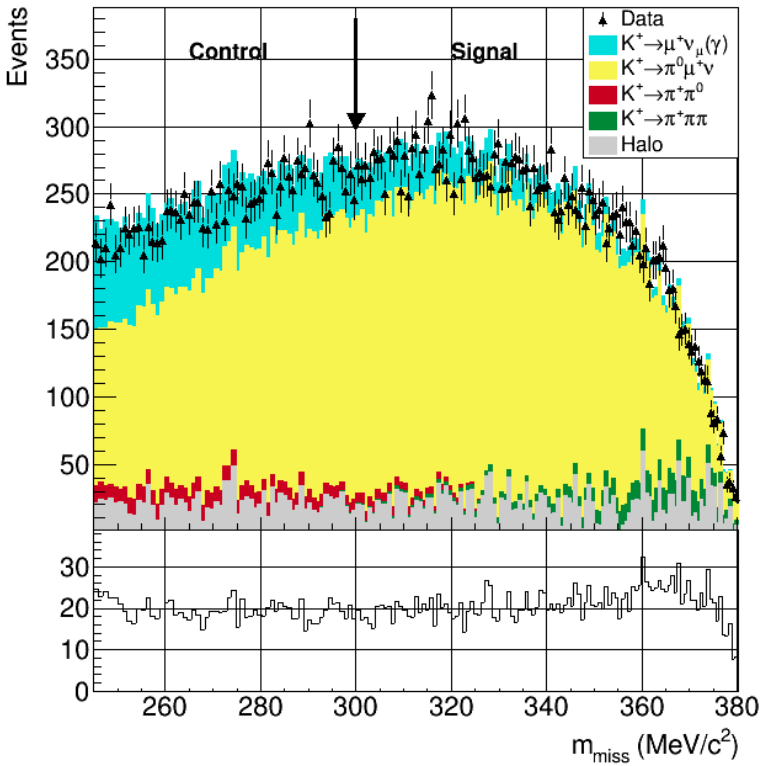
- **Independent of HN decay modes**
- **Sensitive to long-lived (or stable) HN**

Strategy:

- **Search for peaks in**

$$m_{miss} = \sqrt{(p_K - p_\mu)^2}$$ **spectrum**

- **Dedicated HN MC simulation for acceptance and resolution as a function of HN's mass at 1 MeV/c² intervals**



Event selection:

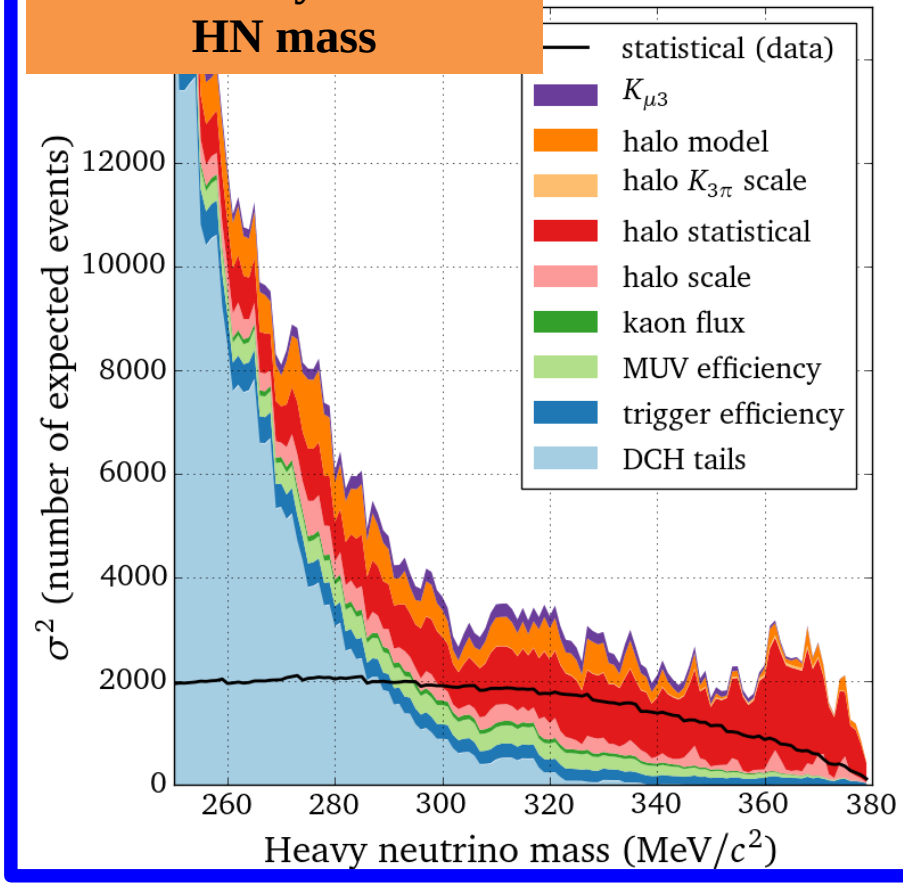
- **One positively charged muon track**
- **No clusters in LKr with E > 2 GeV not associated to the track**
- **Multi-dimensional cuts in ($z_{vtx}, \theta, p, CDA, \phi$) to suppress muon halo**
- **Signal Region: 300 MeV/c² <m_{miss}< 375 MeV/c²**

Kaon decays in the fiducial volume: $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \to \mu^+ \nu_\mu$)
[Downscale D = 150 of one track trigger]

Heavy neutrino in NA62-R_K: results

Data-driven study of halo background, spectrometer resolution tail, trigger efficiency, muon ID efficiency

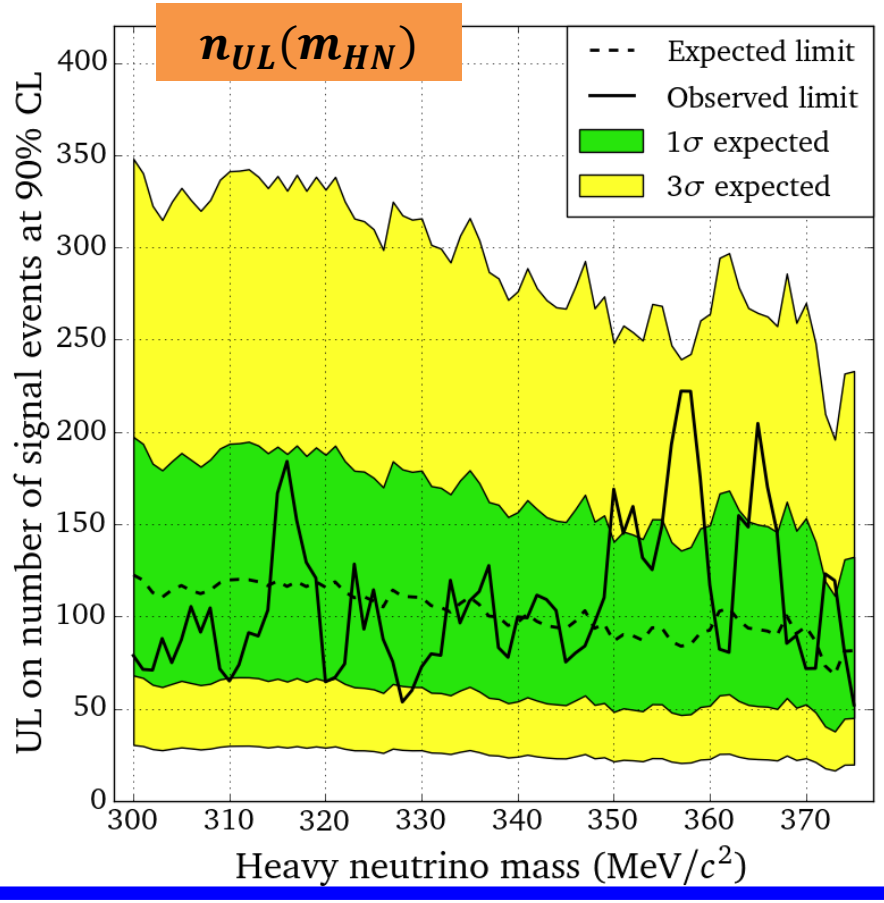
Uncertainty for each HN mass



Rolke-Lopez method to obtain n_{UL} on m_{HN} from n_{obs}, n_{exp} and uncertainty on n_{exp} for each tested mass

No excess above 3 σ observed

$n_{UL}(m_{HN})$

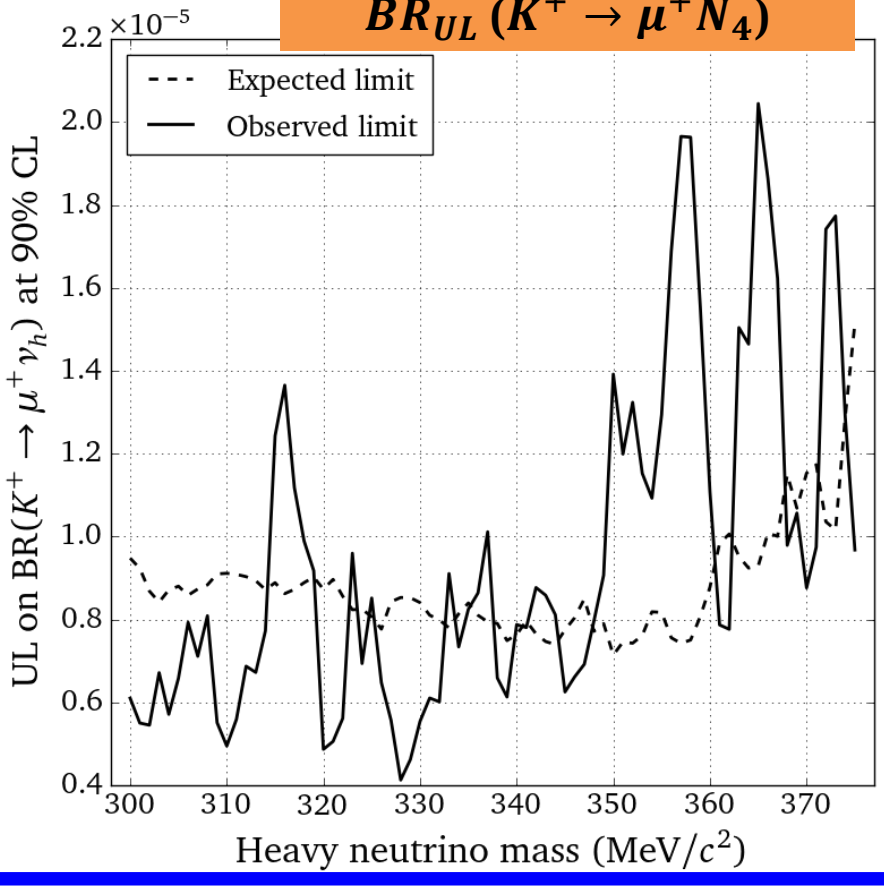


Heavy neutrino in NA62-R_K: results

From n_{UL} to the BR_{UL} :

$$BR_{UL}(K^+ \to \mu^+ N_4) = \frac{n_{UL}}{N_K \cdot Acceptance}$$

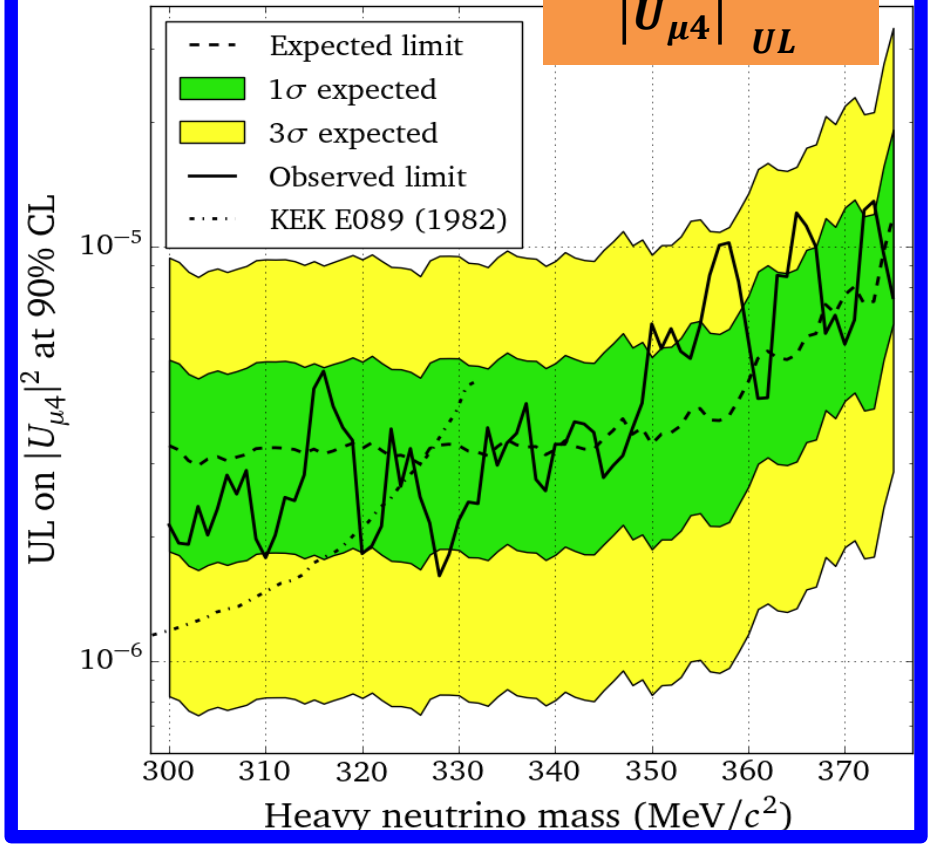
$BR_{UL}(K^+ \to \mu^+ N_4)$



From BR_{UL} to $|U_{\mu 4}|^2_{UL}$:

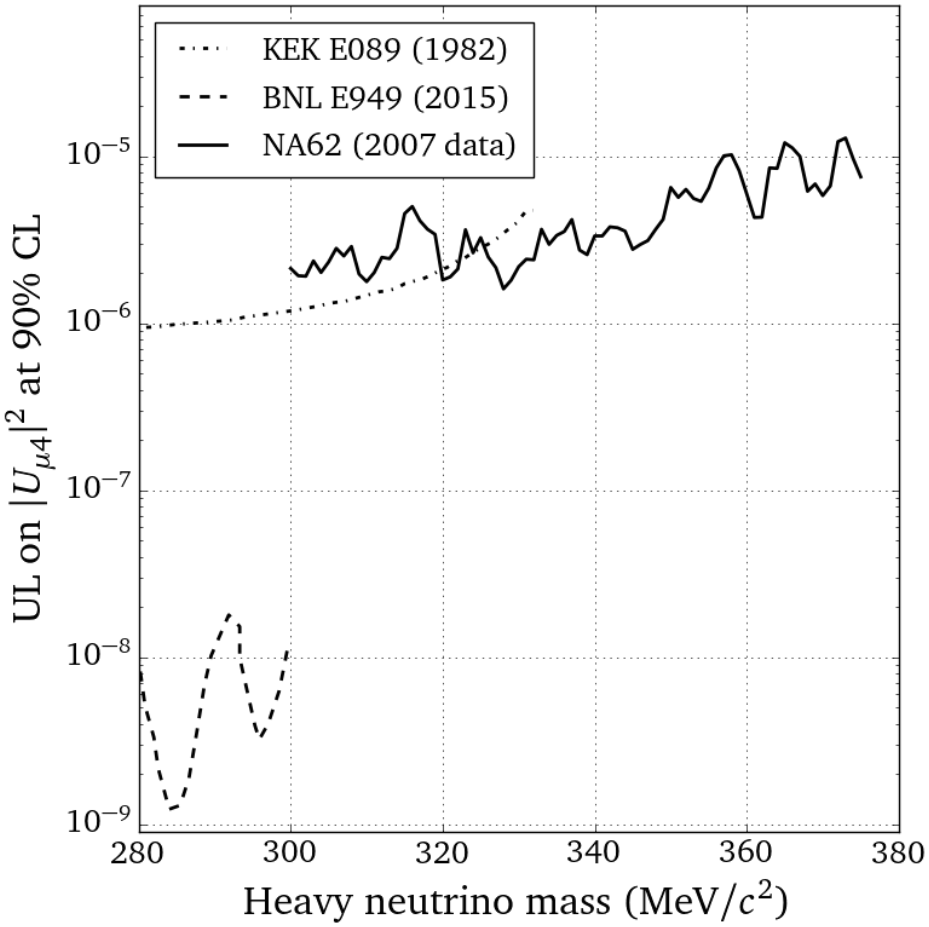
$$|U_{\mu 4}|^2 = \frac{1}{f(m_{HN})} \times \frac{BR(K^+ \to \mu^+ N_4)}{BR(K^+ \to \mu^+ \nu_\mu)}$$

$|U_{\mu 4}|^2_{UL}$



Comparison with existing measurements

NA62 (2007) sets the world's most stringent limit on heavy neutrino production in the mass region $325 < M_{HN} < 375$ MeV/c^2



Conclusions

The NA48/2 and NA62-R_K experiments at CERN were exposed to ~2×10^{11} and ~2×10^{10} $K^{\pm}$ decays respectively

NA48/2 results on HN production and decay [*PLB769 (2017), 67*] :

- ✓ **Search for LNV $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay:**
  - **$BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90% CL [World Best Limit]**
  - **Factor of 10 improvement with respect to previous best limit [1.1×10^{-9} @ 90% CL]**
- ✓ **Search for $K^{\pm} \to \mu^{\pm}N_4$ ($N_4 \to \pi^{\mp}\mu^{\pm}$) decays [Majorana neutrinos]**
  - **Limits on BR products of the order of 10^{-10} for neutrino lifetimes < 100 ps**
- ✓ **Search for $K^{\pm} \to \mu^{\pm}N_4$ ($N_4 \to \pi^{\pm}\mu^{\mp}$) decays [LNC heavy neutrinos]**
  - **Limits on BR products of the order of 10^{-9} for neutrino lifetimes < 100 ps**

NA62-R_K results on $K^+ \to \mu^+ N_4$ decays research [*Paper in preparation*] :

- ✓ **Limits on BR($K^+ \to \mu^+ N_4$) ~ 10^{-5}, limits on $|U_{\mu 4}|^2$ ~10^{-5} for M_{HN}>300 MeV/c^2**