# New limits on heavy neutrino searches from recent Kaon experiments at CERN

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**Outline:**

- The NA48/2 and NA62-$R_K$ experiments
- Theoretical Motivations
- Search for heavy neutrino production in $K^+ \rightarrow \mu^+ N$ decays
- Search for heavy neutrino production + decay in $K^\pm \rightarrow \pi\mu\mu$ decays

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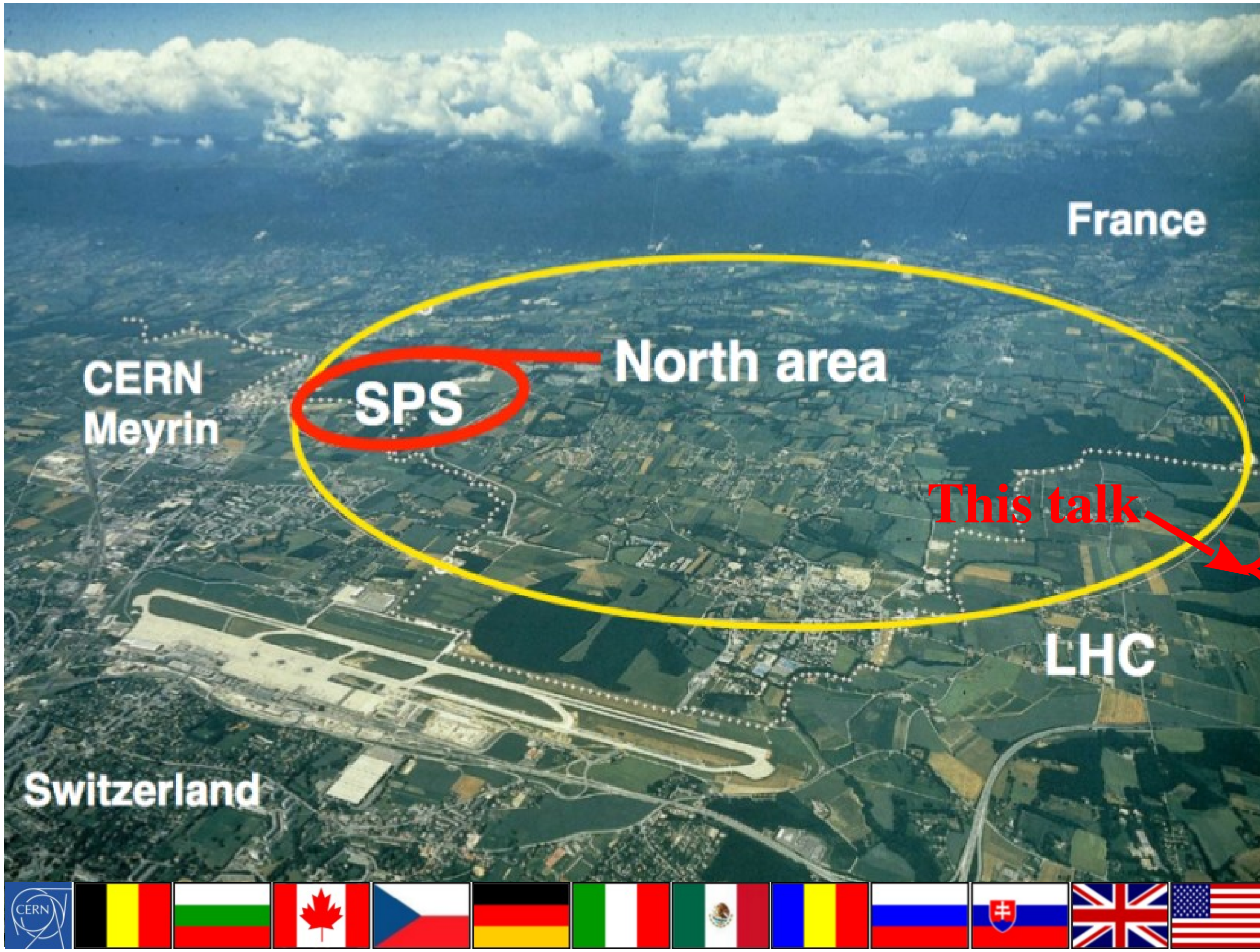
# The NA48/NA62 experiments @ CERN




| History of NA48/NA62 experiments | | |
|---|---|---|
| 1997 ↓ 2001 | NA48 ($K_S/K_L$) | Re $\varepsilon'/\varepsilon$ **Discovery of direct CPV** |
| 2002 | NA48/1 ($K_S$/hyperons) | Rare $K_S$ and hyperon decays |
| **2003 ↓ 2004** | **NA48/2 ($K^+/K^-$)** | Direct CPV, **Rare $K^+/K^-$ decays** |
| **2007 ↓ 2008** | **NA62-$R_K$ ($K^+/K^-$)** | $R_K = K^{\pm}_{e2}/K^{\pm}_{\mu 2}$, **Rare $K^+/K^-$ decays** |
| 2015 ↓ - | NA62 ($K^+$) | $K^+ \rightarrow \pi^+ \nu\bar{\nu}$, Rare $K^+$ and $\pi^0$ decays |

**NA62:** currently ~ 200 participants, 29 institutions from 12 countries

# The NA48/2 and NA62-$R_K$ detector

**Narrow momentum band $K^{\pm}$ beams:**

$P_K = 60$ GeV/c, $\delta P_K/P_K \sim 4$ % (rms) in NA48/2

$= 74$ GeV/c, $\delta P_K/P_K \sim 1$ % (rms) in NA62-$R_K$

**Nominal $K^{\pm}$ decay rate:** ~ 100 kHz

**Simultaneous $K^+/K^-$ beams**

**<u>Principal sub-detectors:</u>**

- **Spectrometer (4 DCHs)**

  $\sigma_p/p = 1.02\% \oplus 0.044\%$ p(GeV) in NA48/2

  $= 0.48\% \oplus 0.009\%$ p(GeV) in NA62-$R_K$

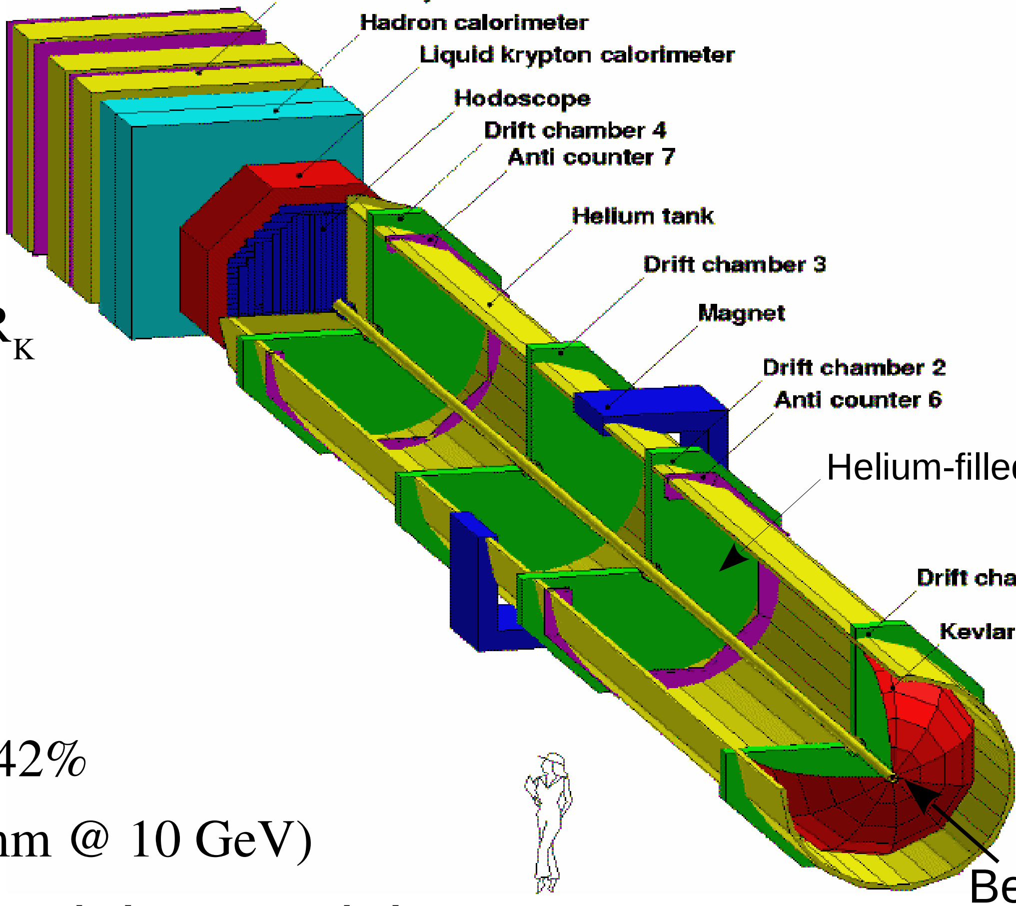
  4 views/DCH: redundancy → efficiency
- **Scintillator Hodoscope**

  Fast trigger, time measurement $\sigma_t \sim 150$ ps
- **LKr EM calorimeter**

  High-granularity, quasi-homogeneous

  $\sigma_E/E = 3.2\%/\sqrt{E(GeV)} \oplus 9\%/E(GeV) \oplus 0.42\%$

  $\sigma_x = \sigma_y = 4.2mm/\sqrt{E(GeV)} \oplus 0.6mm$ (1.5mm @ 10 GeV)



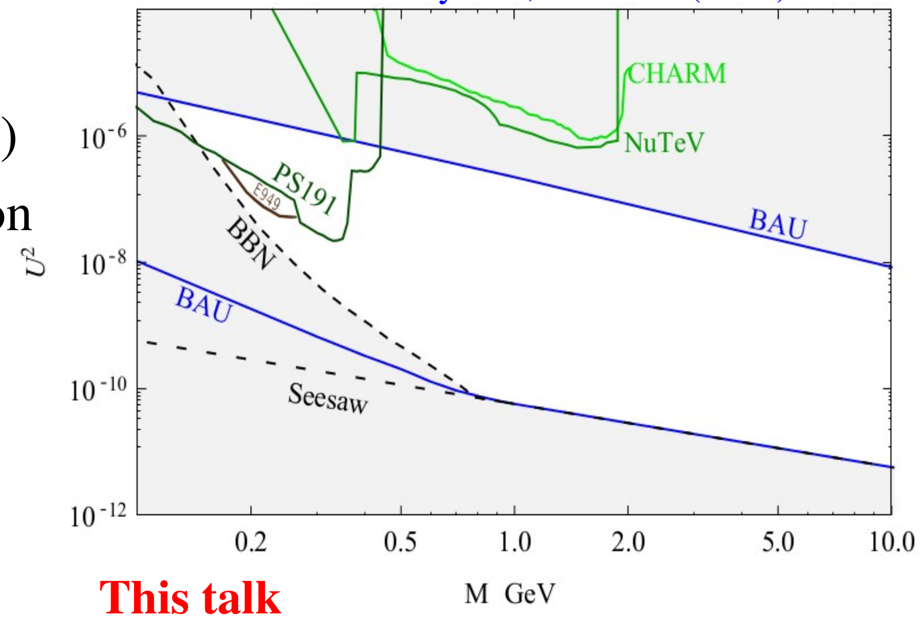
# Majorana Neutrinos

**Asaka-Shaposhnikov** model (νMSM) [Asaka and Shaposhnikov, PLB 620 (2005) 17]:
Dark Matter + Baryon Asymmetry of the Universe (BAU) + low mass of SM ν can be explained by adding three sterile Majorana neutrinos $N_i$ to the SM

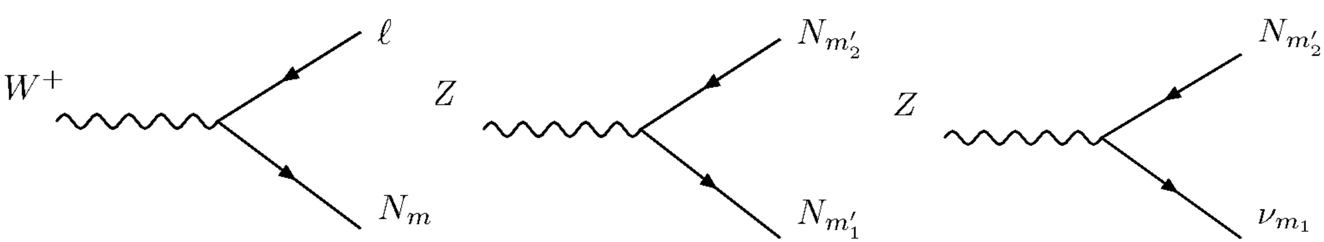
- $N_1$ is the lightest O(keV) → Dark Matter candidate
- $N_2$, $N_3$ are nearly degenerate (100 MeV to few GeV)

to tune CPV-phases and extra-CKM sources of baryon asymmetry. $N_2$, $N_3$ produce standard neutrino masses through seesaw with a Yukawa coupling of ~ $10^{-8}$

Gorbunov & Timiryasov, PLB 745 (2015) 29




<u>Active-sterile neutrino mixing (U-matrix):</u>
Effective vertices involving the sterile neutrinos $N_i$, the $W^{\pm}$, Z bosons and SM leptons




**This talk [$\ell = \mu$]**

**$N_{2,3}$ production in $K^{\pm}$ decays:**
$K^{\pm} \to \ell^{\pm} N$, $K^{\pm} \to \pi^0 \ell N$, …
**$N_{2,3}$ decays for $m_{2,3} < m_K - m_\ell$:**
$N \to \pi^{\pm}\ell^{\mp}$, $N \to \pi^0 \nu$
$N \to \ell_1^{\pm}\ell_2^{\mp}\nu_2$, $N \to \nu_1 \ell_2^{+}\ell_2^{-}$
$N \to \nu_\ell \nu\bar{\nu}$

# NA48/2 + NA62-$R_K$: a complementary study

**Heavy Neutrino Production:**

- Independent of HN decay modes
- Sensitive to long-living (or stable) HNs

**Heavy Neutrino Production + Decay:**

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

**Main trigger streams**

**NA48/2:** **3-track vertex**, $K^\pm \to \pi^\pm \pi^0 \pi^0$

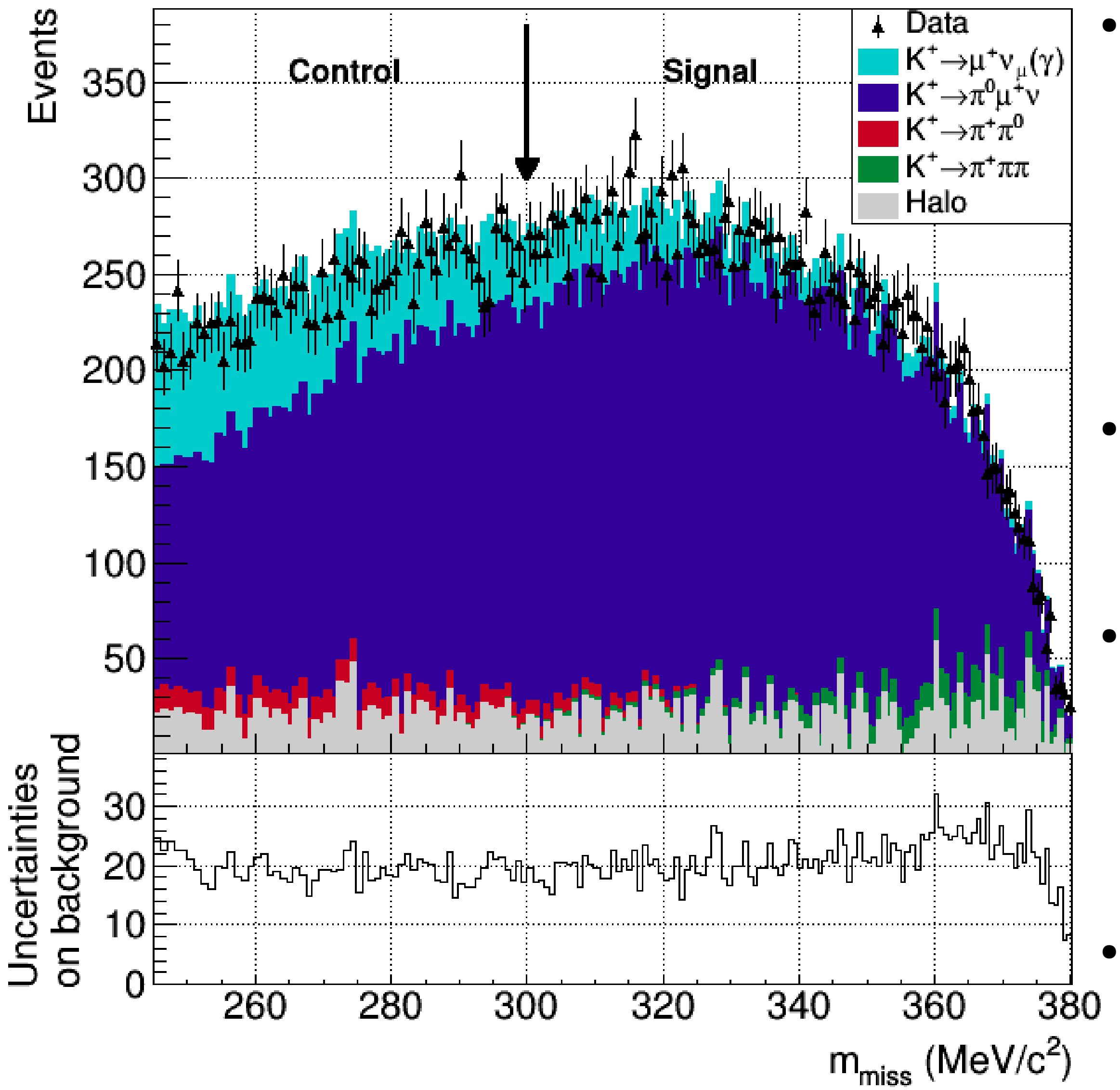
**NA62-$R_K$:** 1-track ($e^\pm$), **min-bias**

NA48/2: $\mathbf{K^\pm \to \mu^\pm N_4 (N_4 \to \pi\mu)}$
HN Production + Decay
[arXiv:1612.04723]

NA62-$R_K$: $\mathbf{K^+ \to \mu^+ N_4}$
HN Production
[*Paper in preparation*]

# The NA62-$R_K$ single-muon sample

Only $K^+$ period (43% of NA62-$R_K$ sample) due to higher muon halo rejection



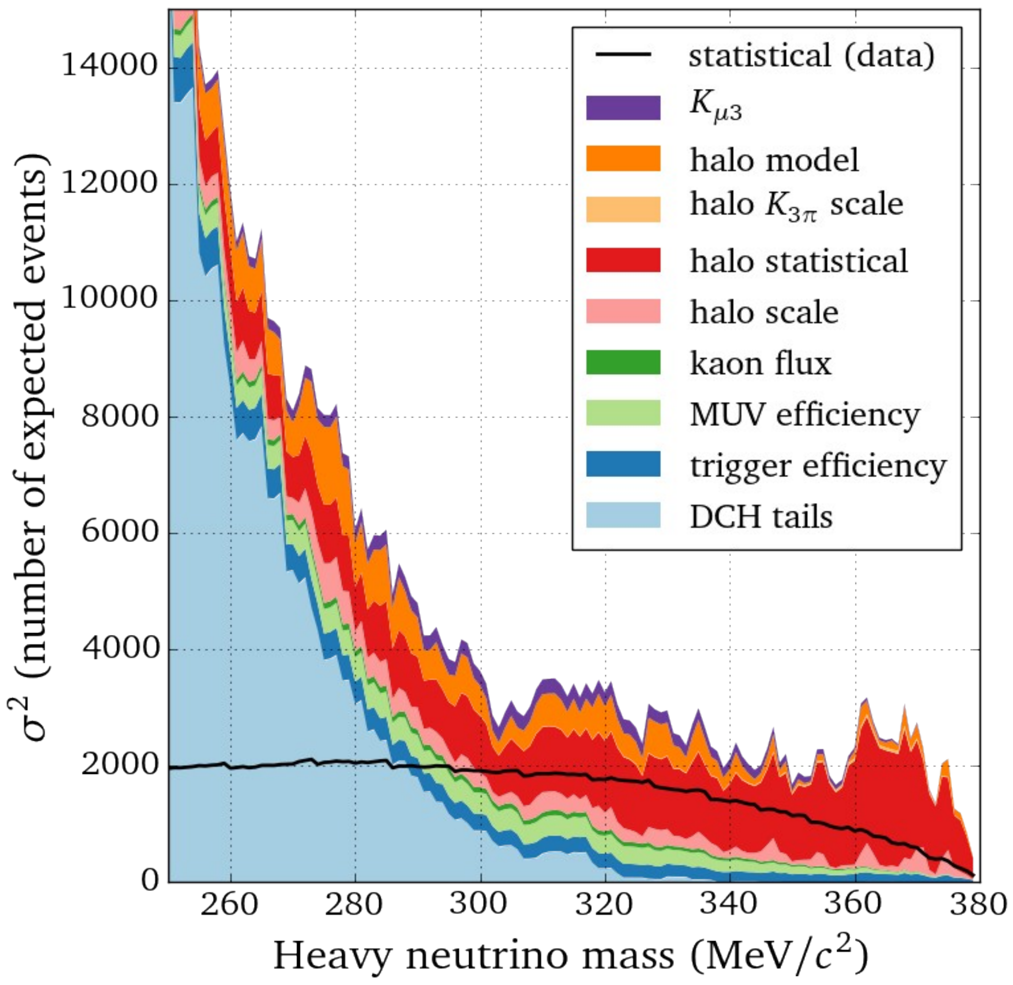

- **Event selection:**
  - One well-reconstructed $\mu^+$ track
  - No clusters in LKr with E > 2 GeV, if not associated to the track
  - Cuts on $z\theta$ plane to suppress muon halo
  - Signal Region: $M_{miss}(\mu^+) > 300$ MeV/$c^2$
- **Kaon decays in the fiducial volume:**

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

  [Downscale D = 150 of min-bias trigger]
- **Data-driven study of:**
  - Halo background
  - Spectrometer resolution tail
  - Trigger efficiency
  - Muon ID efficiency
- **Dedicated MC simulation for:**
  - Acceptance vs HN mass
  - HN Peak resolution vs HN mass

# Search for $K^+ \to \mu^+ N_4$ decays

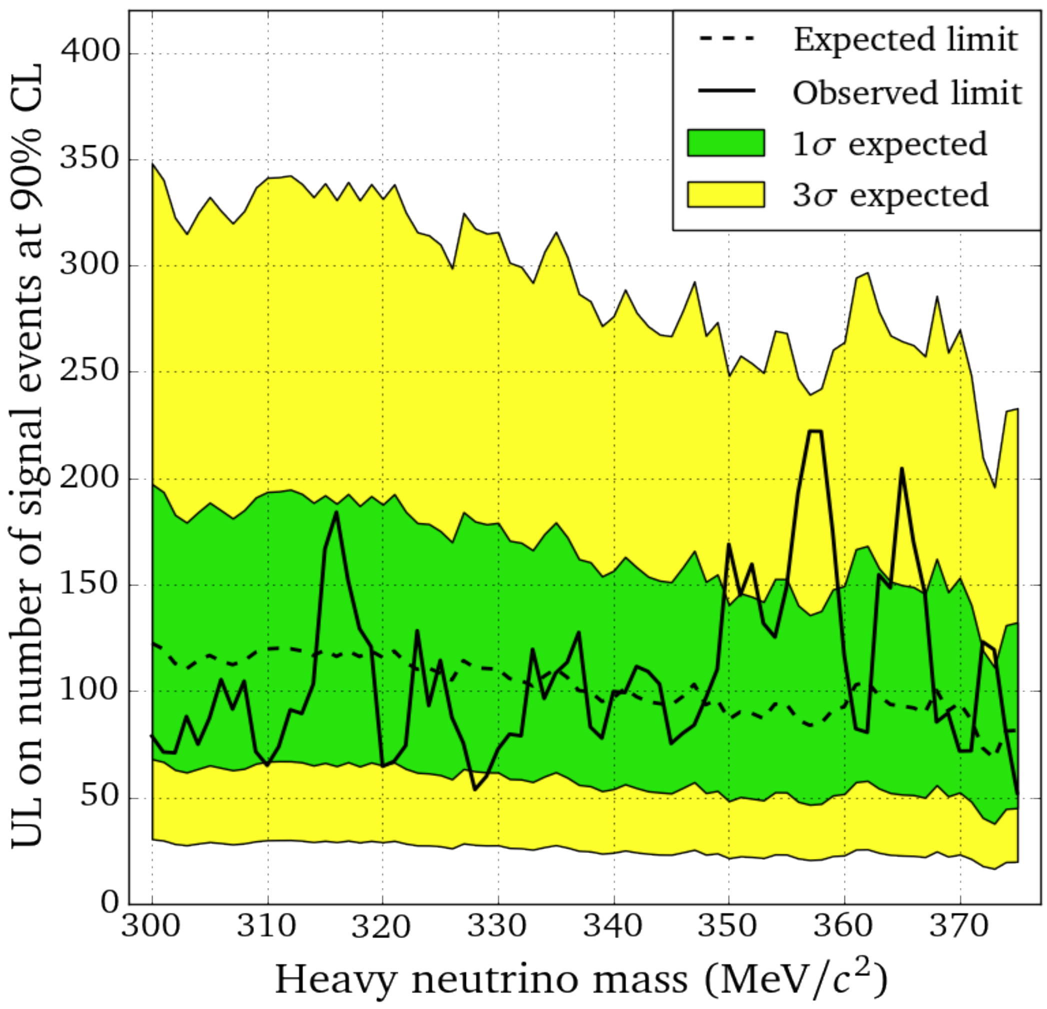
## Error budget vs HN mass:




Statistical uncertainty on halo background dominates for HN masses > 300 MeV/c²

Peak search in missing mass $M_{miss} = \sqrt{(P_K - P_\mu)^2}$

Rolke-Lopez statistical treatment to get $UL(N_{sig})$



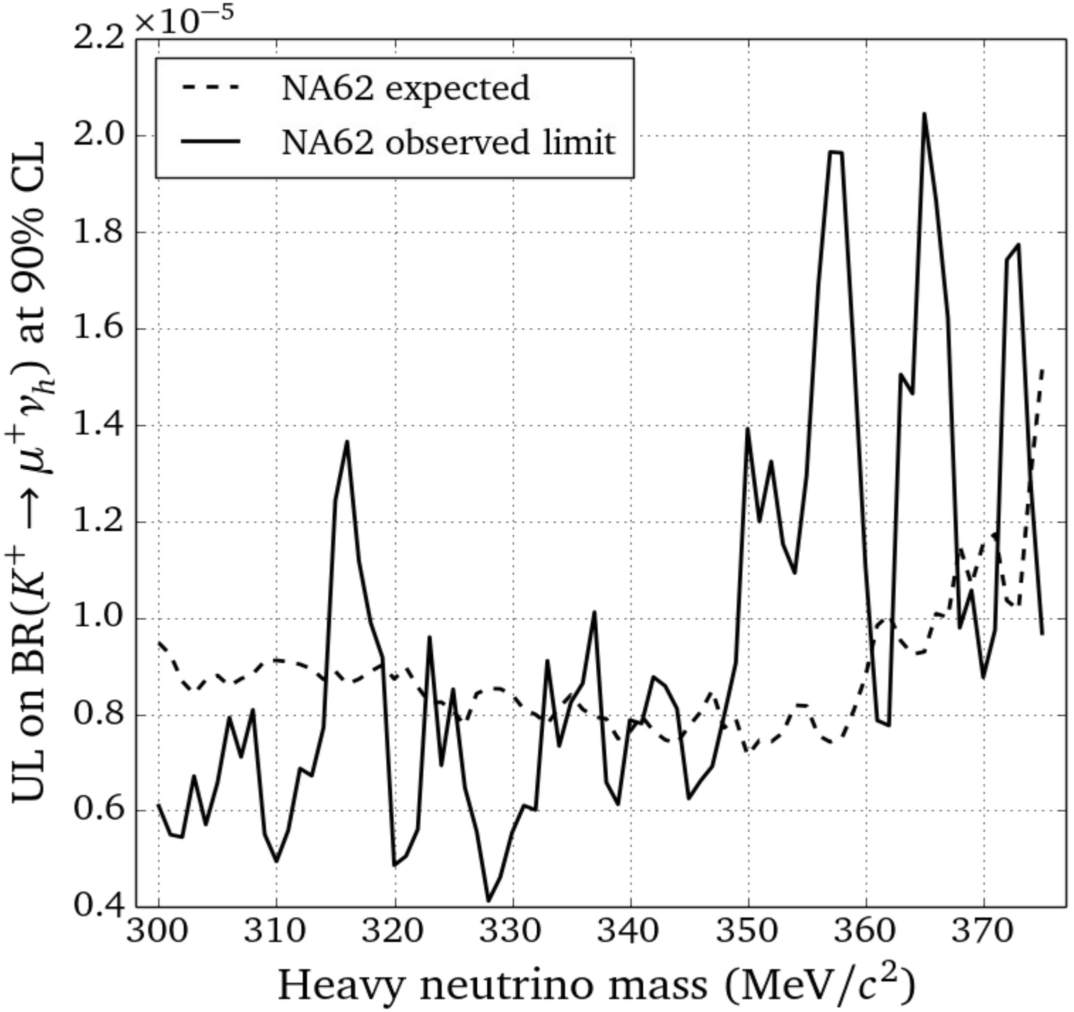
# Constraints on $|U_{\mu4}|^2$ from NA62-$R_K$

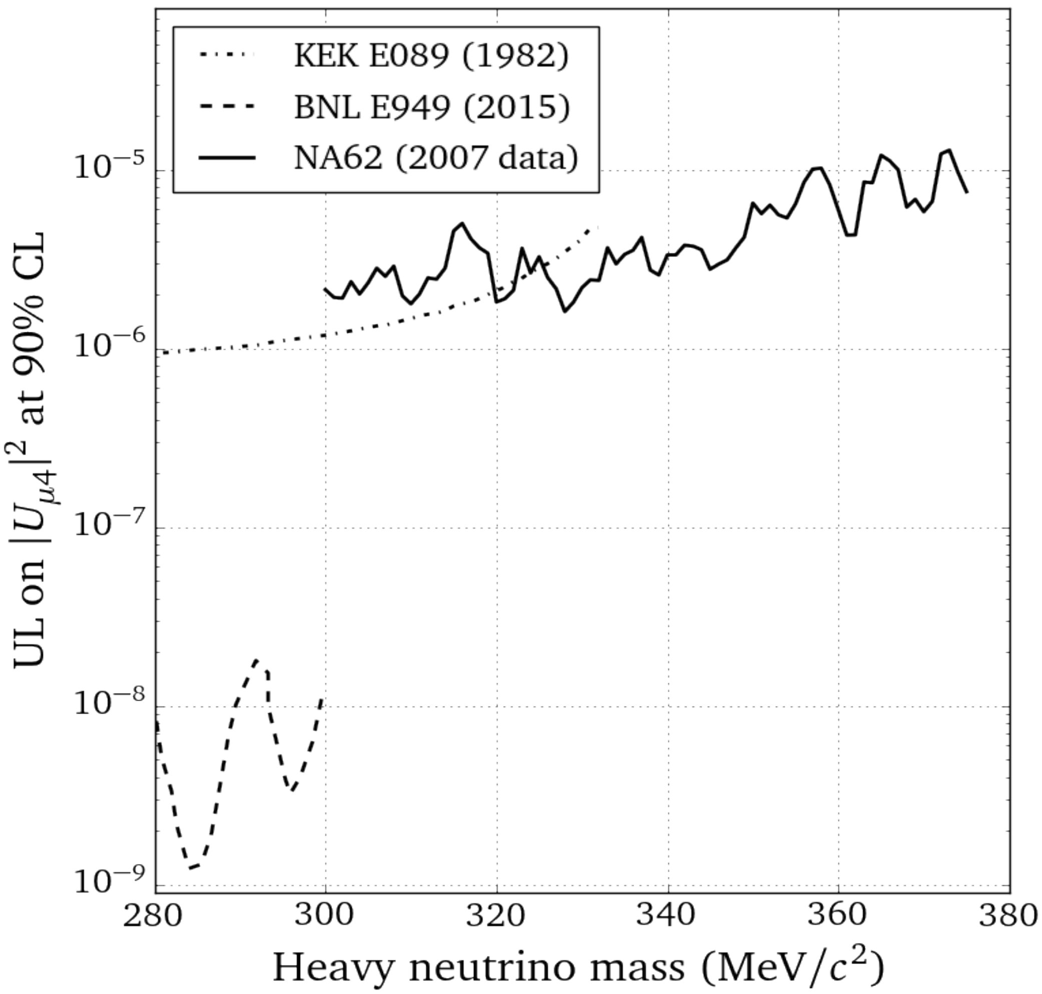
**From $N_{sig}$ to BR:**

$$UL(\mathcal{B}(K^+ \to \mu^+ N_4)) = \frac{UL(N_{\rm sig})}{N_K * Acceptance}$$

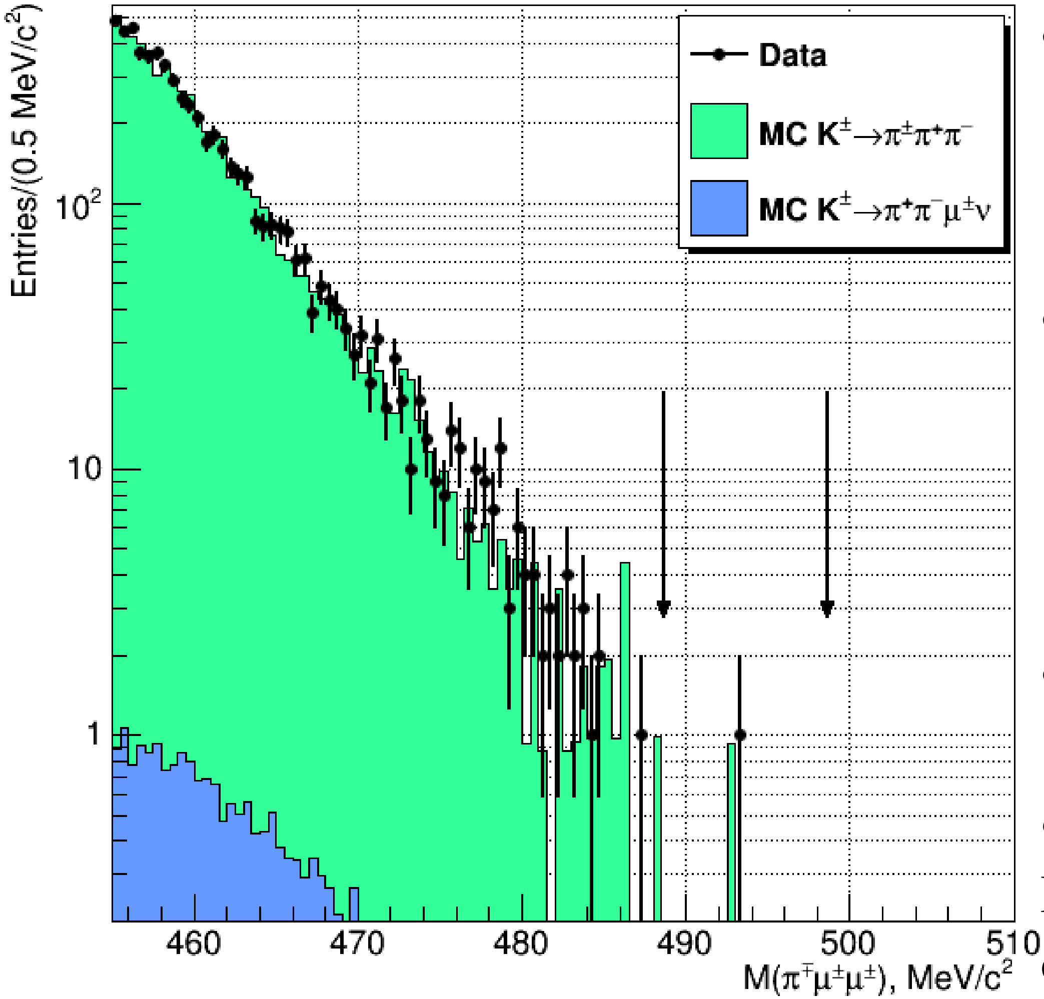
**From BR to $|U_{\mu4}|^2$:**

$$|U_{\mu4}|^2 = \frac{1}{\rho(M_{N_4})} \frac{\mathcal{B}(K^+ \to \mu^+ N_4)}{\mathcal{B}(K^+ \to \mu^+ \nu)}$$



# The NA48/2 same-sign muons sample (LNV)




- **Blind analysis:** $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ selection based on
  - $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ MC simulation
  - $K^\pm \to \pi^\pm\pi^+\pi^-$ MC simulation ($10^{10}$ events)
  - 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, 1 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:**

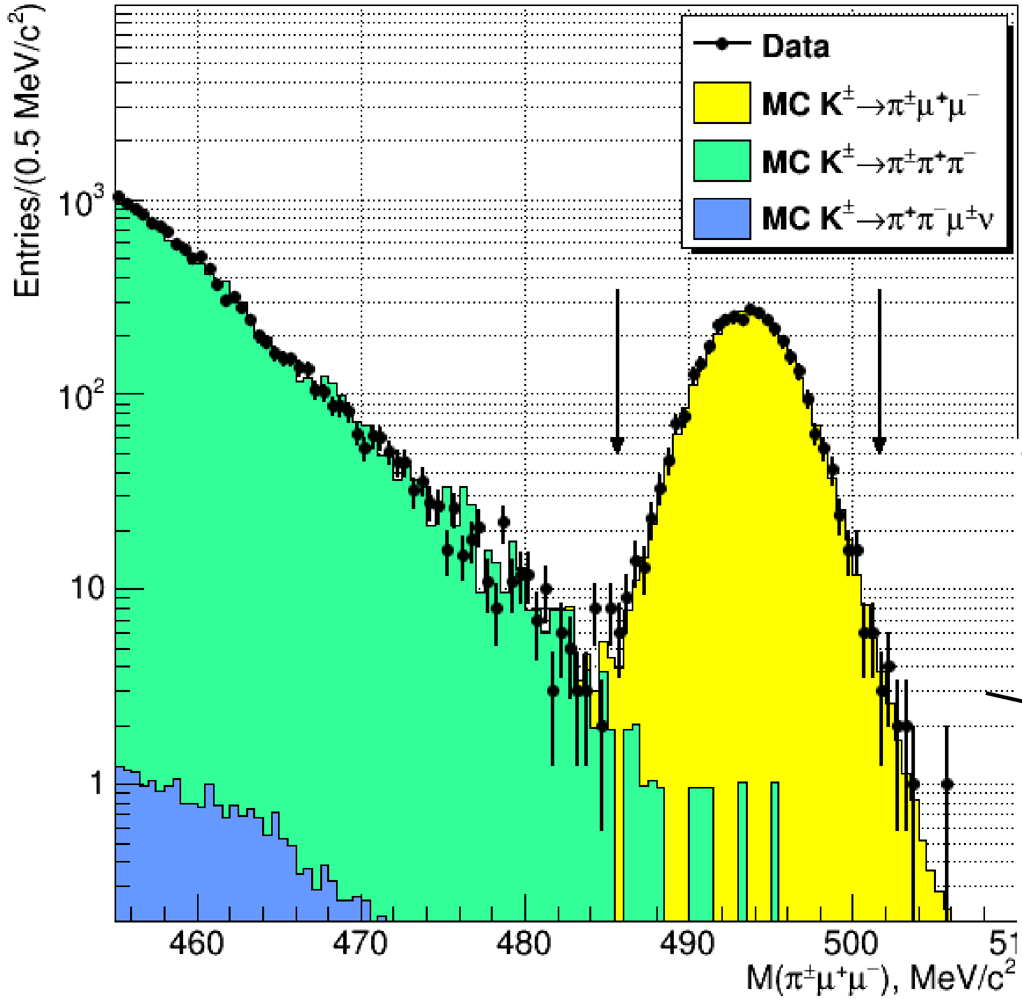
  $N_K \sim 2\times10^{11}$ (from reconstructed $K^\pm \to \pi^\pm\pi^+\pi^-$)
- **Expected background:** Additional $K^\pm \to \pi^\pm\pi^+\pi^-$ MC sample ($10^{10}$ events) used to evaluate number of expected $K^\pm \to \pi^\pm\pi^+\pi^-$ events in Signal Region

Events in Signal Region observed after finalising $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ selection → $\mathbf{N_{obs} = 1}$

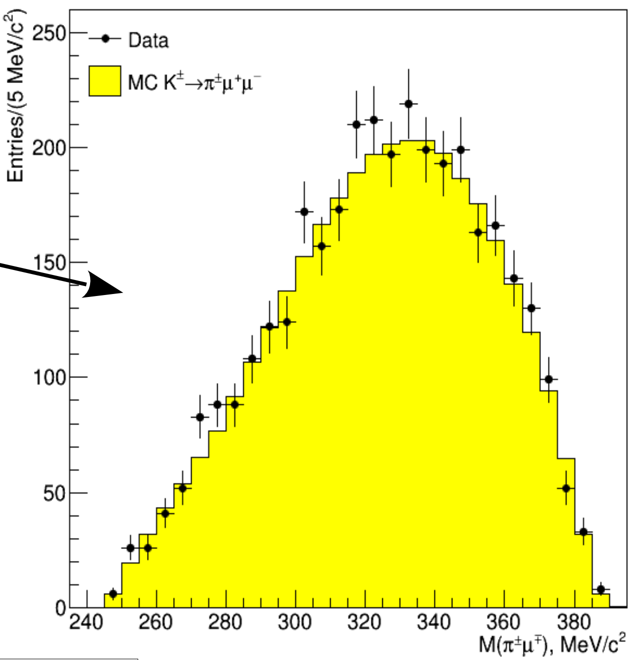
Expected background (from MC simulation): $N_{exp} = 1.163 \pm 0.867_{stat} \pm 0.021_{ext} \pm 0.116_{syst}$

Rolke-Lopez statistical treatment to get UL($N_{sig}$) → **$BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) < 8.6 \times 10^{-11}$ @ 90% CL**

# The NA48/2 opposite-sign muons sample (LNC)




- **Event selection:**
  - Minimal changes with respect to same-sign
  - One well-reconstructed 3-track vertex
  - 2 opposite-sign muons, 1 pion
  - Total $P_T$ consistent with zero
  - Signal Region: $|M(\pi^{\pm}\mu^{+}\mu^{-}) - M_K| < 8$ MeV/c$^2$



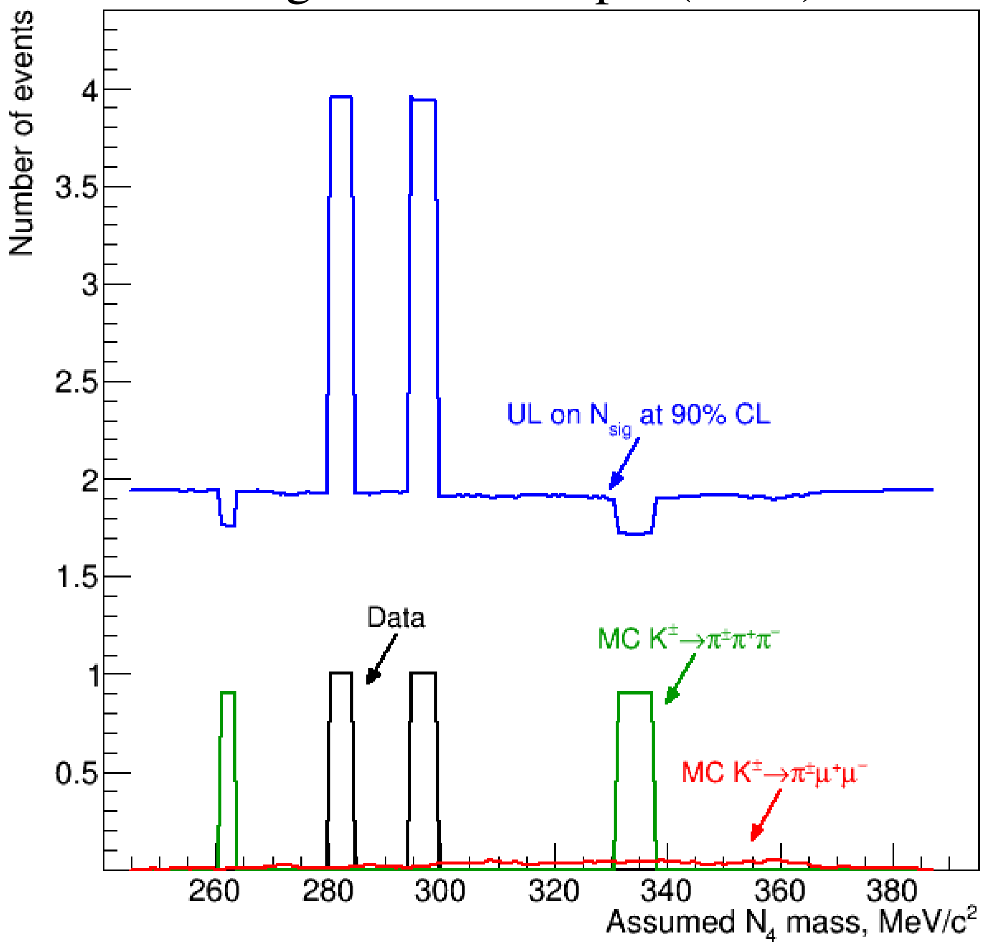

Improved selection with respect to previous NA48/2 $K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$ analysis [PLB 697(2011)107]

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

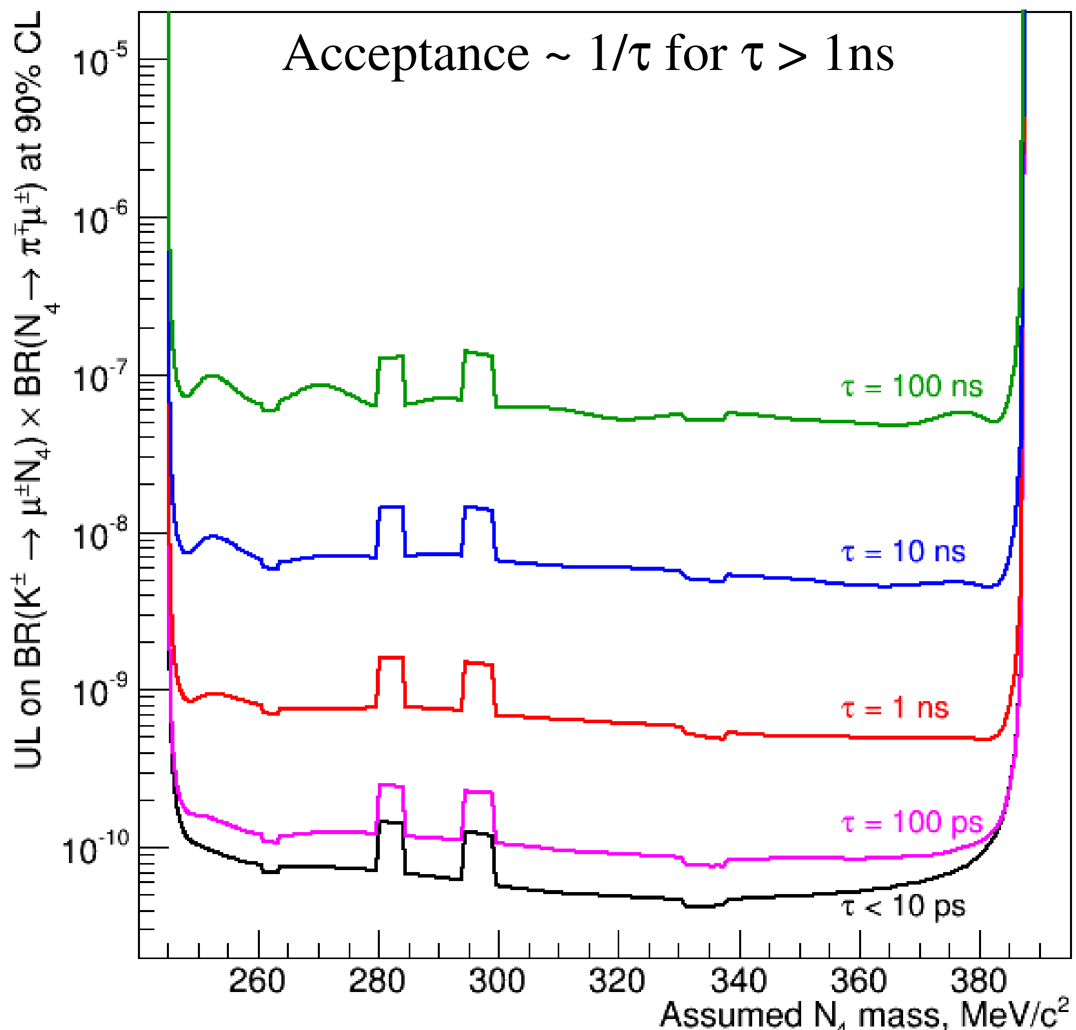
To be scanned searching for peaks in $M(\pi^{\pm}\mu^{\mp})$ invariant mass

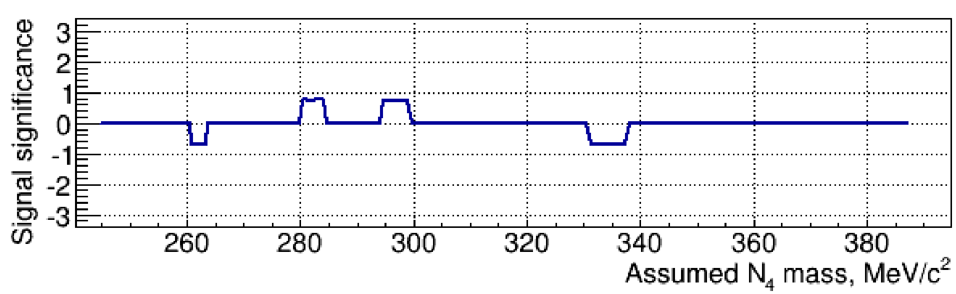
# Search for $K^{\pm} \rightarrow \mu^{\pm} N_4 (N_4 \rightarrow \pi^{\mp} \mu^{\pm})$ decays

Same-sign muons sample (LNV)




$$UL(BR(K^{\pm} \rightarrow \mu^{\pm} N_4) BR(N_4 \rightarrow \pi^{\mp} \mu^{\pm})) = \frac{UL(N_{sig})}{N_K * Acceptance}$$



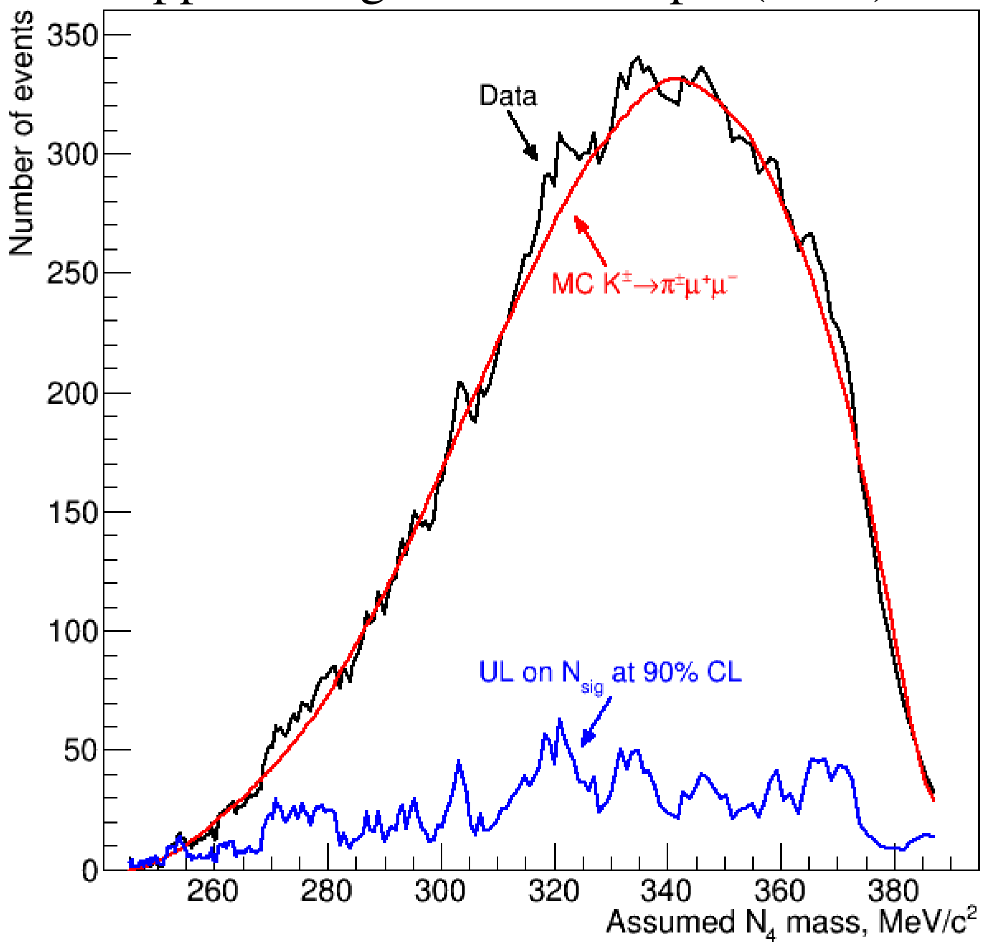



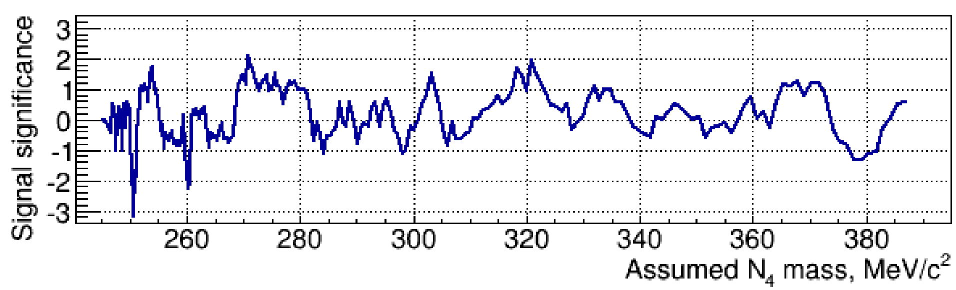

Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

never exceeds $+3\sigma$: **no signal observed**

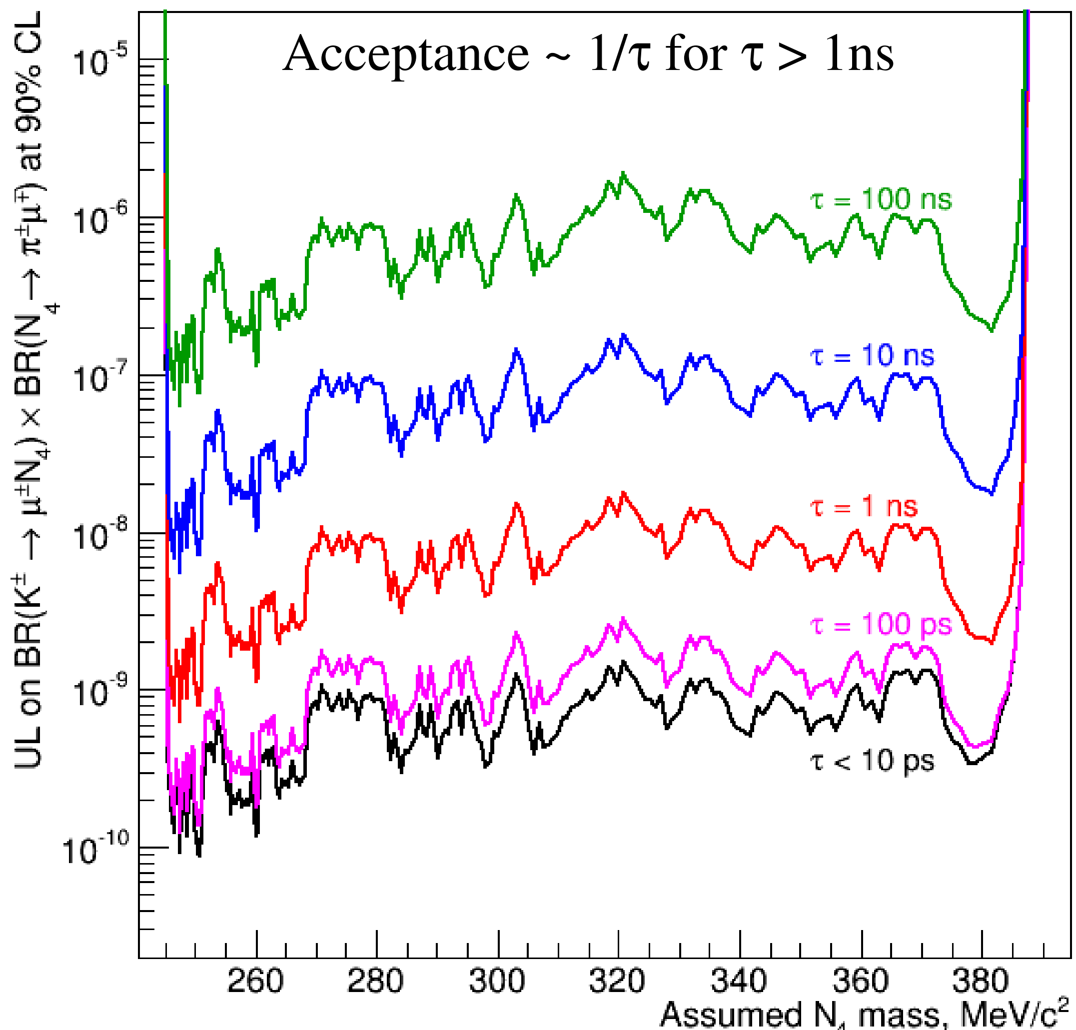
# Search for $K^{\pm} \rightarrow \mu^{\pm} N_4 (N_4 \rightarrow \pi^{\pm} \mu^{\mp})$ decays

Opposite-sign muons sample (LNC)




$$UL(BR(K^{\pm} \rightarrow \mu^{\pm} N_4) BR(N_4 \rightarrow \pi^{\pm} \mu^{\mp})) = \frac{UL(N_{sig})}{N_K * Acceptance}$$



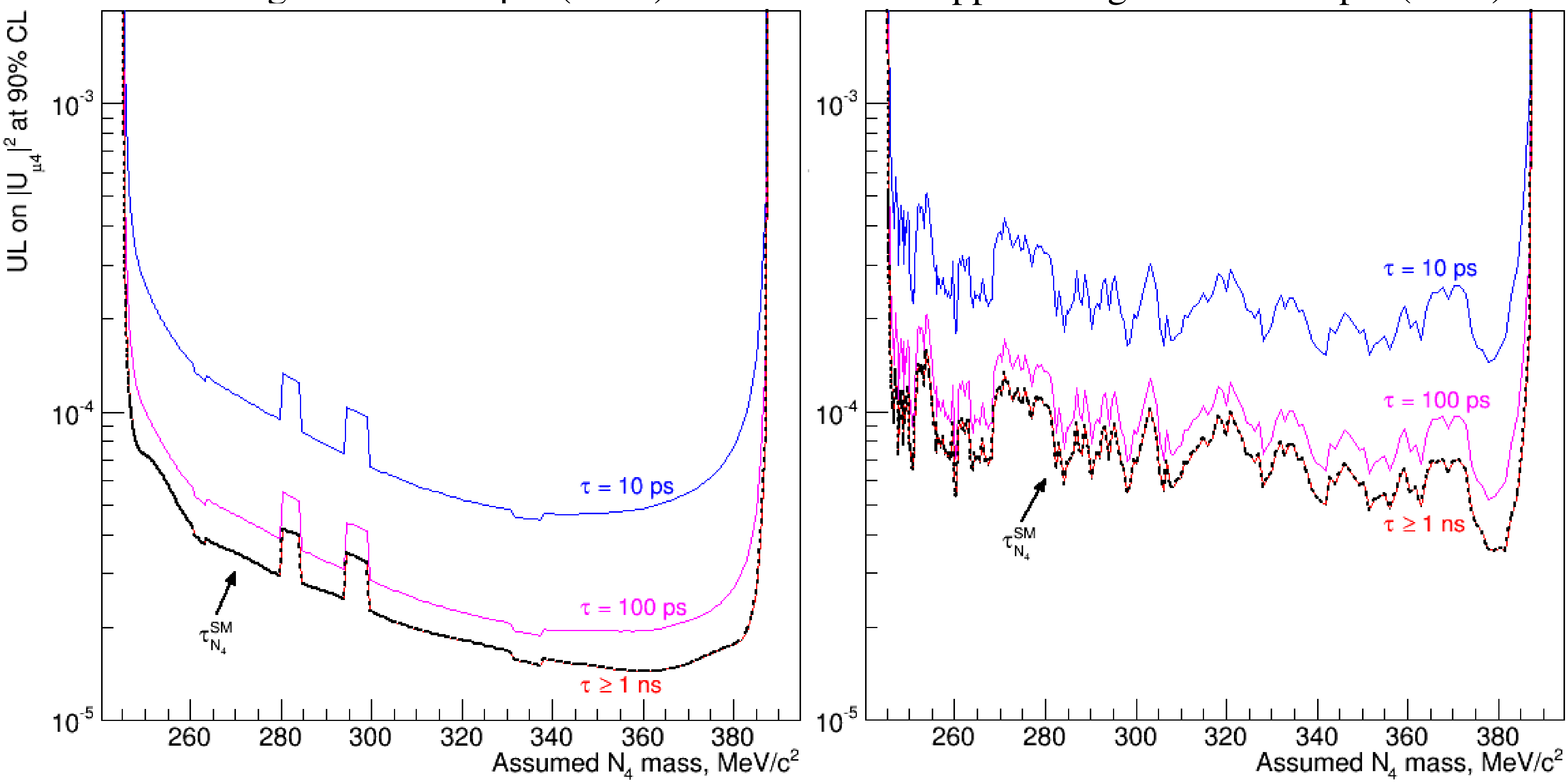

Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

never exceeds $+3\sigma$: **no signal observed**

# Constraints on $|U_{\mu4}|^2$ from NA48/2

$$|U_{\mu4}|^2 = \frac{8\sqrt{2}\pi\hbar}{G_F^2\sqrt{M_K\tau_K}f_K f_\pi |V_{us}V_{ud}|}\sqrt{\frac{\mathcal{B}(K^\pm \to \mu^\pm N_4)\mathcal{B}(N_4 \to \pi\mu)}{\tau_{N_4} M_{N_4}^5 \lambda^{\frac{1}{2}}(1, r_\mu^2, r_{N_4}^2)\lambda^{\frac{1}{2}}(1, \rho_\pi^2, \rho_\mu^2)\,\chi_{\mu\mu}}}$$

Same-sign muons sample (LNV) | Opposite-sign muons sample (LNC)



# Conclusions

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

Heavy Neutrino searches presented today:

- **Search for $K^+ \to \mu^+ N_4$ decays** [HN production]
  - Limits on $BR(K^+ \to \mu^+ N_4) \sim 10^{-5}$, limits on $|U_{\mu 4}|^2 \sim 10^{-5}$ for $M_N > 300$ MeV/$c^2$
- **Search for LNV $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay** [Production and 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 [$1.1 \times 10^{-9}$ @ 90% CL]
- **Search for $K^{\pm} \to \mu^{\pm} N_4 (N_4 \to \pi^{\mp}\mu^{\pm})$ decay**s [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