Searches for Lepton Number Violation and resonances in the $K^{\pm} \to \pi\mu\mu$ decays by NA48/2 at CERN

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on behalf of the NA48/2 Collaboration

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Outline:

- The NA48/2 experiment
- Theoretical Motivations
- Search for LNV $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay – Majorana neutrinos
- Search for resonances in $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ decays
- Prospects for the NA62 experiment

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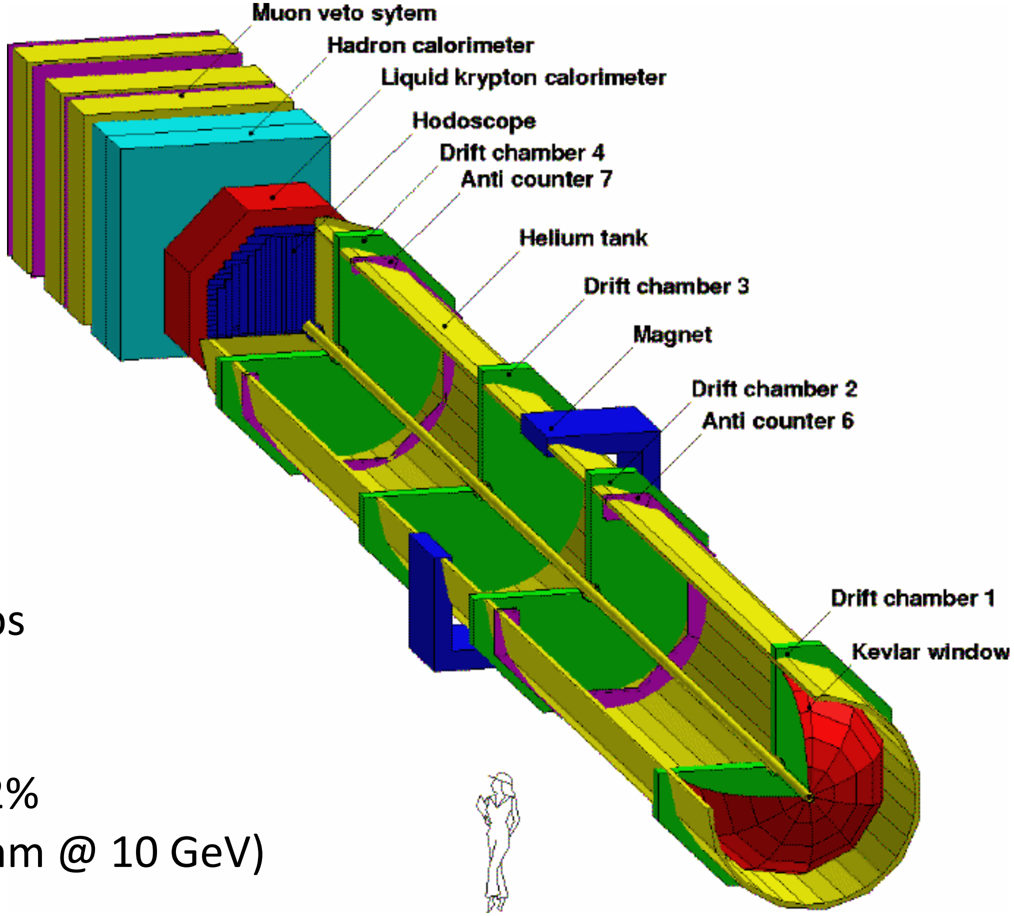
The NA48/2 detector

Narrow momentum band $K^{\pm}$ beams:
P_K = 60 GeV/c, $\delta P_K/P_K$ ~4% (rms)
Nominal $K^{\pm}$ decay rate: ~100 kHz
Main triggers: 3-track vertex $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$
Simultaneous K+/K– beams



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

- **Spectrometer (4 DCHs)**

$\sigma_p/p = 1.02\% \oplus 0.044\%\ p(\mathrm{GeV}/c)$
4 views/DCH: redundancy → efficiency

- **Scintillator Hodoscope**

Fast trigger, time measurement σ_t ~ 150 ps

- **LKr EM calorimeter**

High-granularity, quasi-homogeneous
$\sigma_E/E = 3.2\%/\sqrt{E(\mathrm{GeV})} \oplus 9\%/E(\mathrm{GeV}) \oplus 0.42\%$
$\sigma_x = \sigma_y = 4.2\mathrm{mm}/\sqrt{E(\mathrm{GeV})} \oplus 0.6\mathrm{mm}$ (1.5mm @ 10 GeV)

- **MUV:**

consisted of three 2:7 x 2:7 m^2 planes of plastic scintillator strips, each preceded by a 80 cm thick iron wall.

Majorana Neutrinos

AsakaShaposhnikov 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

- **N1** is the lightest O(keV) → Dark Matter candidate
- **N2, N3** are nearly degenerate (100 MeV to few GeV) to tune CPV-phases and extra-CKM sources of baryon asymmetry. N2, N3 produce standard neutrino masses through seesaw with a Yukawa coupling of ~ 10^{-8}

<u>Activesterile neutrino mixing (U-matrix):</u>

Effective vertices involving the sterile neutrinos N_i, the $W^{\pm}$, Z bosons and SM leptons

$$BR(K^{\pm} \longrightarrow \mu^{\pm} N_4) \times BR(N_4 \longrightarrow \pi^{\mp}\mu^{\pm}) \sim |U_{\mu 4}|^4$$

Inflatons

Shaposhnikov-Tkachev model [Shaposhnikov and Tkachev, PLB 639 (2006) 414]:
νMSM + a real scalar field (inflaton χ) with scale-invariant couplings
Explains Universe homogeneity and isotropy on large scales/structures on smaller scales

- χ-Higgs mixing with mixing angle θ
- χ-Higgs coupling → Universe reheating
- χ-is unstable: τ ~ (10^{-8}-10^{-12}) s

χ in Kaon decays [m_χ < 354 MeV/c2]

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

Basic principles of the searches:

- Fully reconstructed final states, 3-track vertex topology
- Similar topology to normalisation channel $K^\pm \to \pi^\pm\pi^+\pi^-$

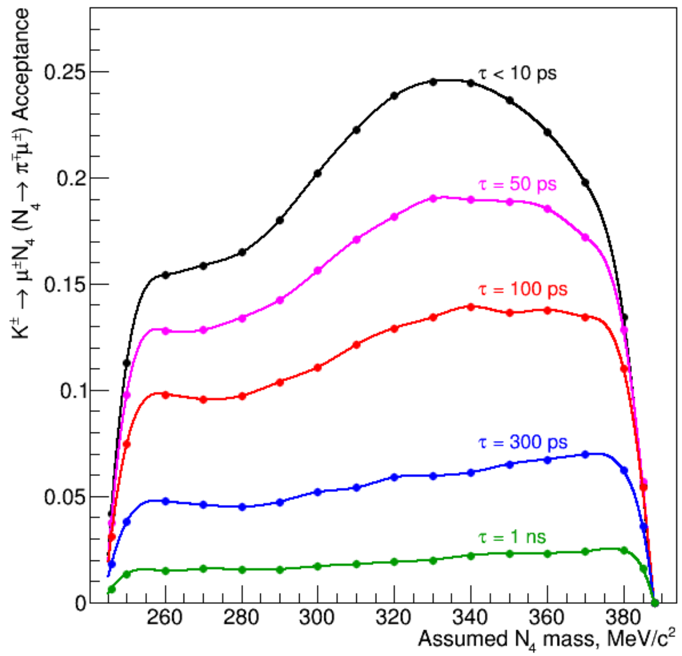
→ First-order cancellation of systematic effects (trigger inefficiency, etc)

- Method: exclusive search for the $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$ decay
- Main background: $K^\pm \to \pi^\pm\pi^+\pi^-$ with 2 $\pi^\pm \to \mu^\pm\nu$ decays (one within the Spectrometer)
- Sensitivity: UL on $BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm)$

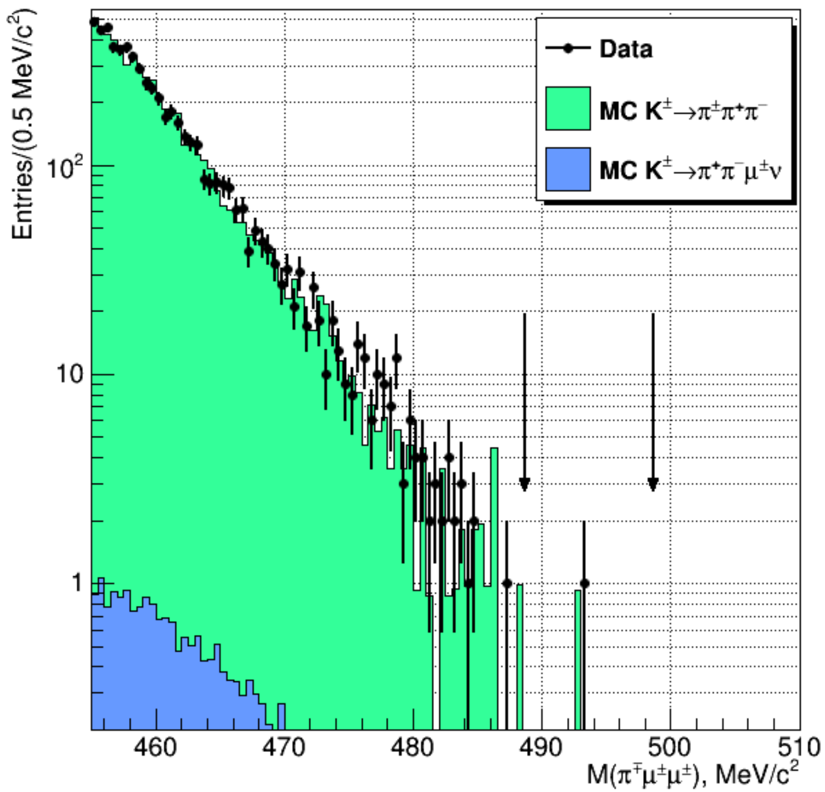
  UL on $BR(K^\pm \to \mu^\pm N_4) \times BR(N_4 \to \pi^\mp\mu^\pm)$

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

Mass and lifetime dependence of the signal acceptance from dedicated MC simulation of the signal



The same-sign muons selection (LNV)



- Blind analysis: $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection based on
  - o $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ MC simulation
    - – Uniform phasespace ($|M_{fi}|2 = 1$)
    - – Resonant Majorana neutrino model
  - o $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ MC simulation (10^{10} events)
- o Control Region: $M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 480$ MeV/c2
- Event selection:
  - o One wellreconstructed 3-track vertex
  - o 2 same-sign muons, 1 odd-sign pion
  - o Total P_T consistent with zero
  - o Signal Region: $|M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) - M_K| < 5$ MeV/c2
- 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 ⟶ $N_{obs} = 1$
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($K \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$) < 8.6 x 10^{-11} @ 90% CL**

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

Basic principles of the searches:

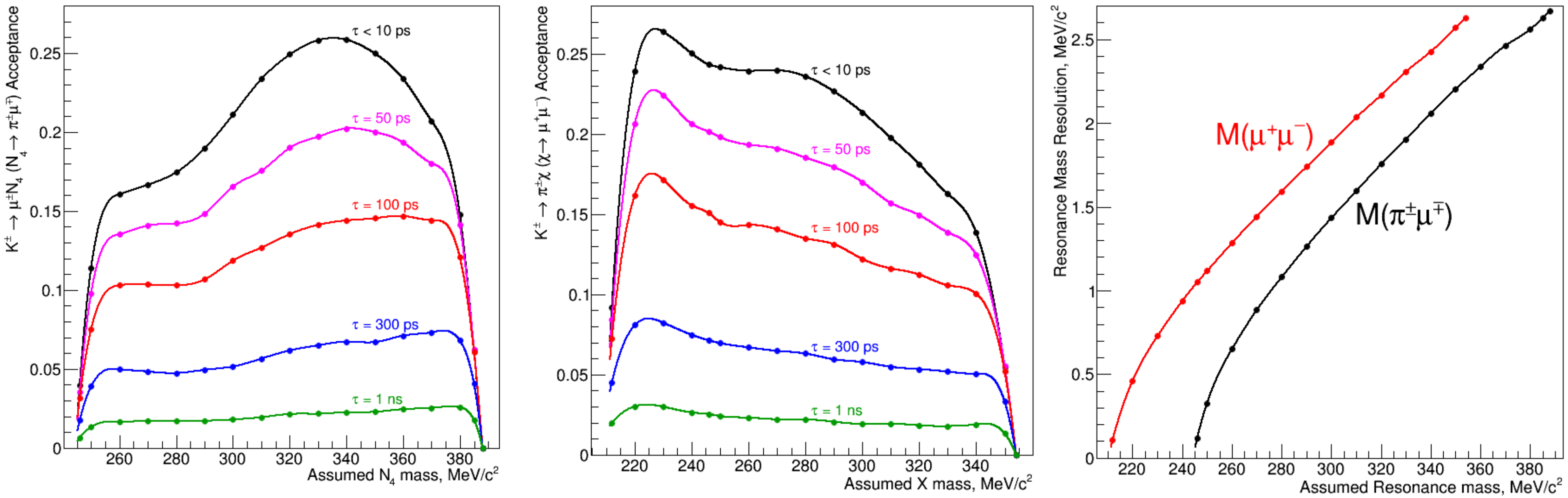
- Fully reconstructed final states, 3-track vertex topology
- Similar topology to normalisation channel $K^\pm \to \pi^\pm\pi^+\pi^-$

→ Firstorder cancellation of systematic effects (trigger inefficiency, etc)

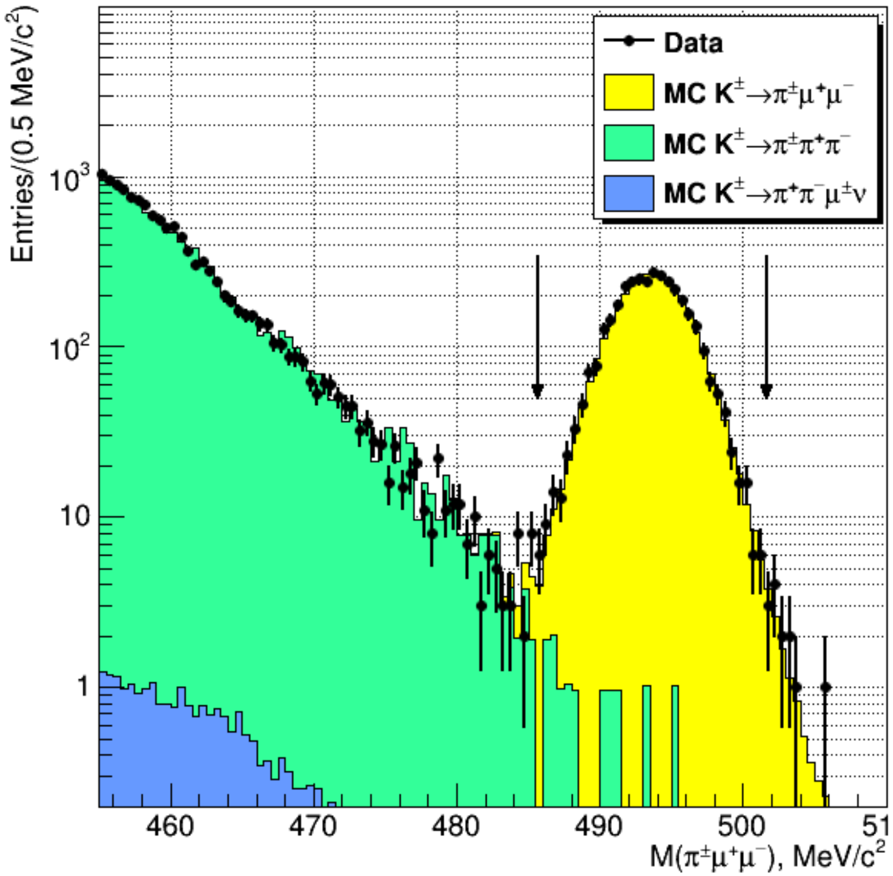
Search for resonances in $K^\pm \to \pi^\pm\mu^+\mu^-$ **– decays**

- Method: exclusive search for the decay chains $K^\pm \to \mu^\pm N_4 (N_4 \to \pi^\pm \mu^\mp)$, $K^\pm \to \pi^\pm X (X \to \mu^+\mu^-)$
- Main background: $K^\pm \to \pi^\pm\mu^+\mu^-$ **– (irreducible)** → Limited sensitivity
- Sensitivity: UL on $BR(K^\pm \to \mu^\pm N_4) \times BR(N_4 \to \pi^\pm \mu^\mp)$

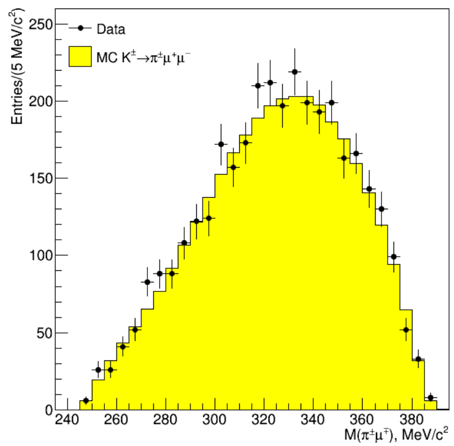
  UL on $BR(K^\pm \to \pi^\pm X) \times BR(X \to \mu^+\mu^-)$

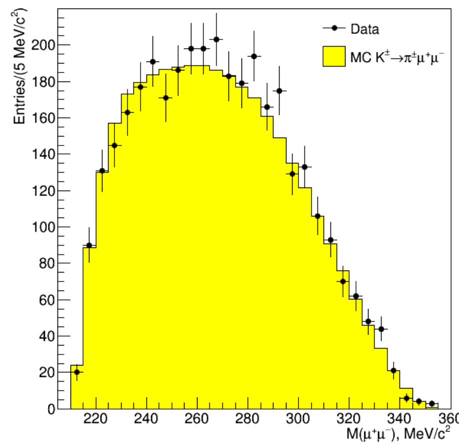


The opposite sign muons selection (LNC)



- Event selection:
  - o Minimal changes with respect to same-sign
  - o One well-reconstructed 3-track vertex
  - o 2 opposite-sign muons, 1 pion
  - o Total P_T consistent with zero
  - o Signal Region: $|M(\pi^{\pm}\mu^{+}\mu^{-}) - MK| < 8$ MeV/c2





3489 $K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-}$ candidates in Signal Region
$K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ background: (0.36 ± 0.10)%

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

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

The mass scan framework

Basic principles:

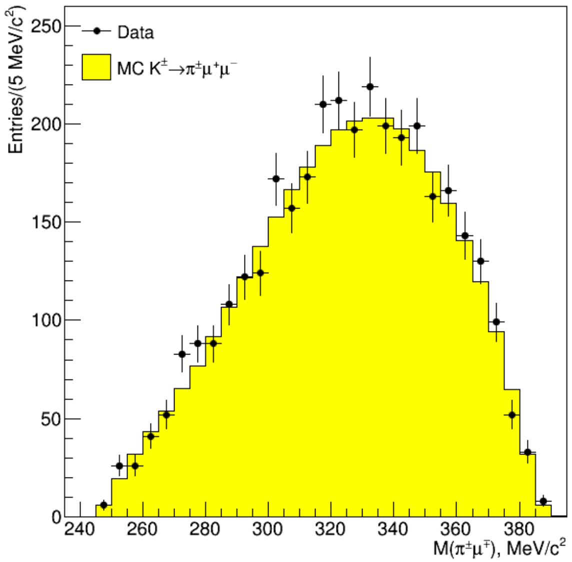
- Based on selected $K^{\pm} \to \pi^{\pm}\mu\mu$ candidates. Variable step = $0.5\sigma(M_{res})$ and window = $\pm 2\sigma(M_{res})$
- For each M_{res}: Observed events in data (N_{obs}) vs Expected events from MC (N_{exp}) → UL(N_{sig})
- Rolke-Lopez statistical treatment used in each mass hypothesis M_{res} to get UL(N_{sig})

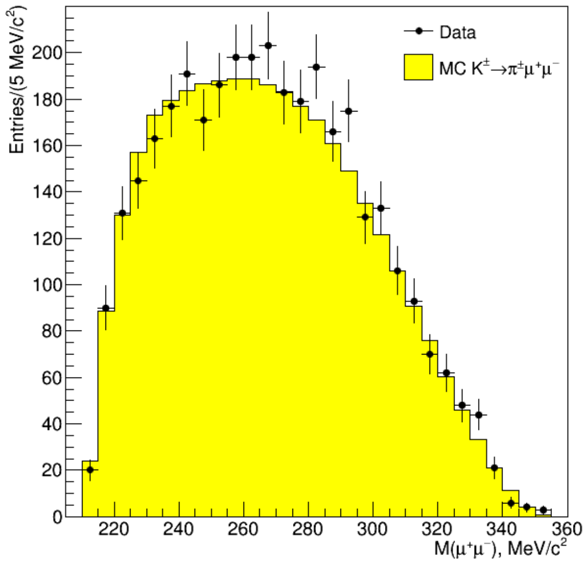
Search for Lepton Number Violation – Majorana neutrinos

- 284 mass hypotheses M_{res} tested
- 2 possibilities in building $M(\pi^{\mp}\mu^{\pm})$ [same-sign μs]: closest invariant mass to M_{res} considered

Search for resonances in $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ – decays

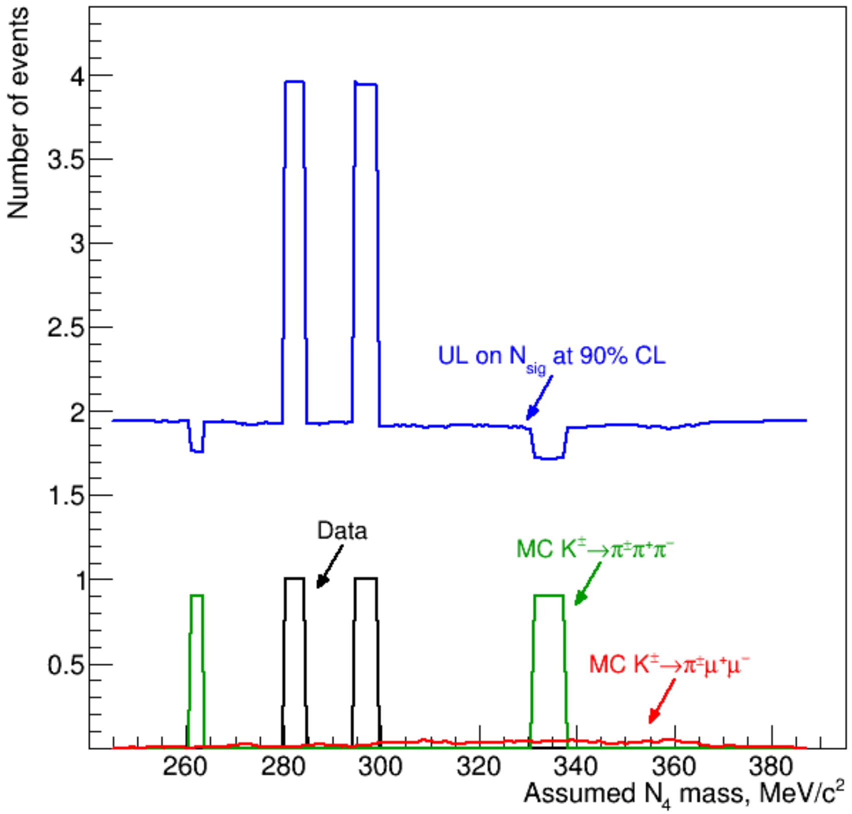
- The distributions of both invariant masses $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ are probed
- 267 hypotheses for $M(\pi^{\pm}\mu^{\mp})$
- 280 hypotheses for $M(\mu^{+}\mu^{-})$
- $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ – MC simulation uses form factors extracted from the selected data sample to obtain best data/MC agreement

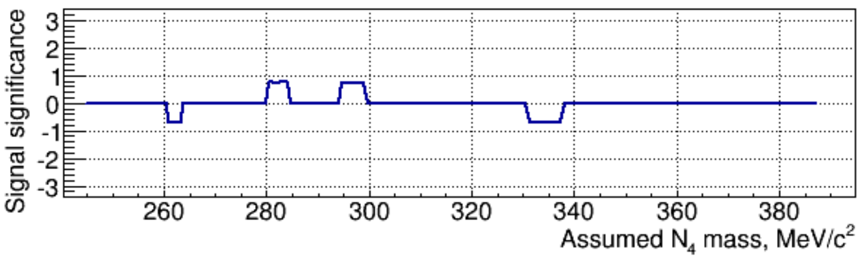




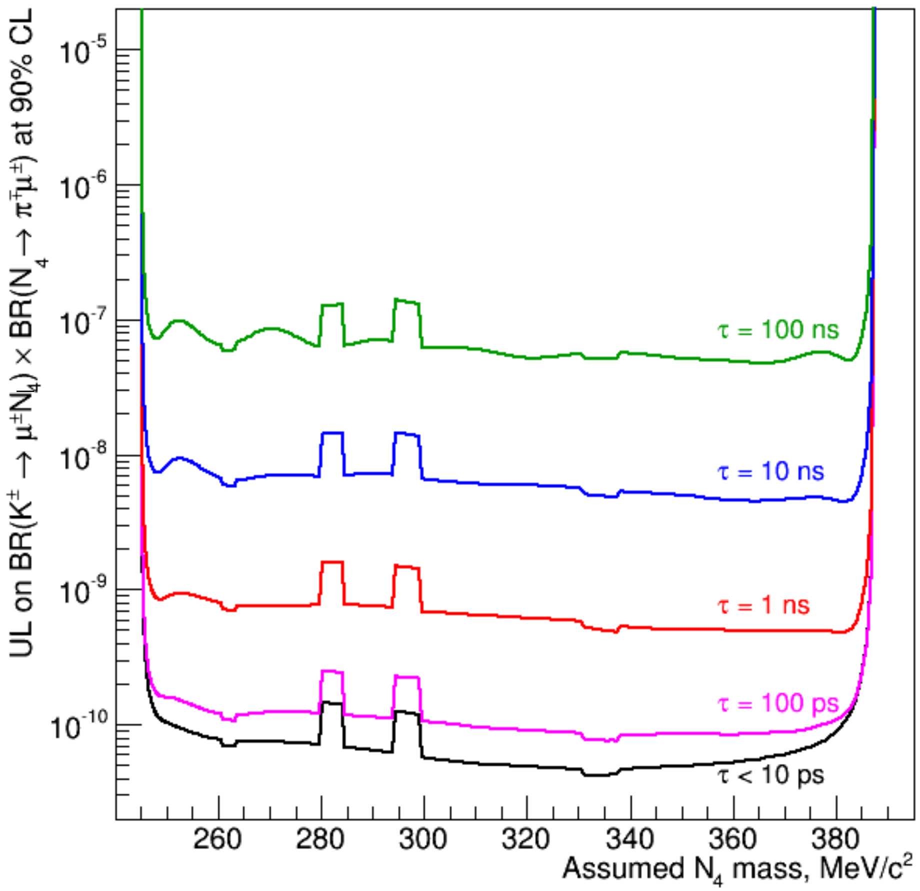
Search for $K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\mp}\mu^{\pm})$ decays

Same-sign muons sample (LNV)



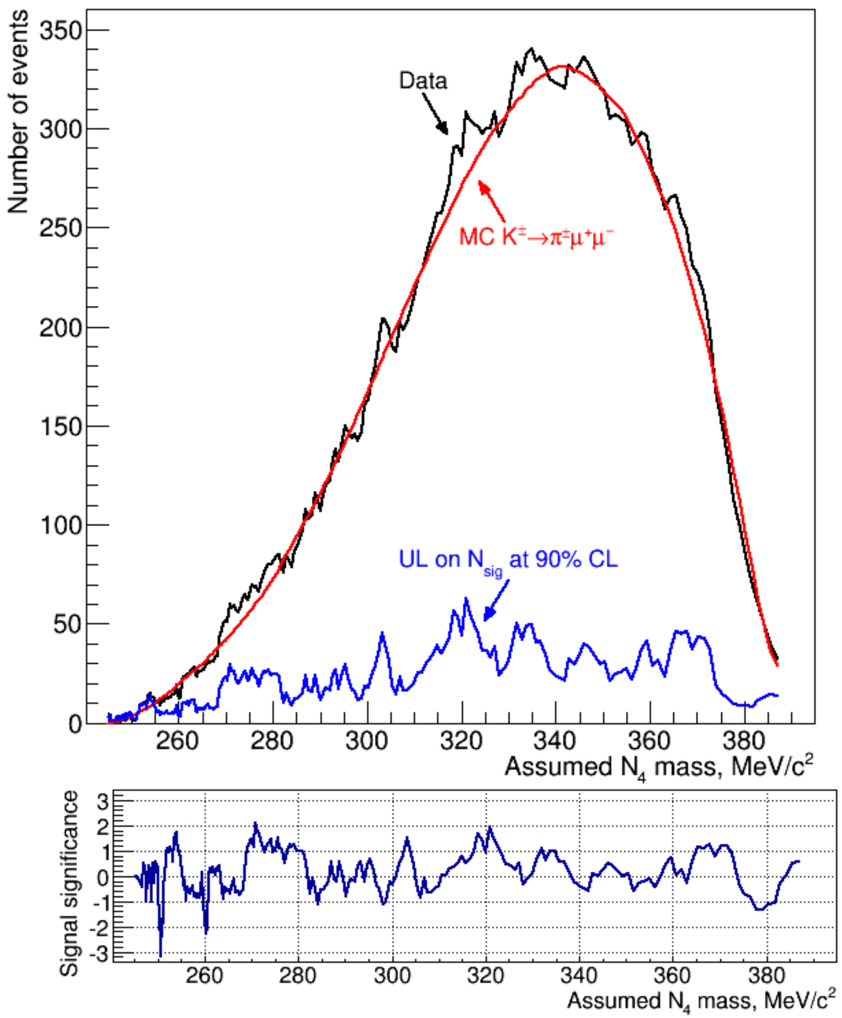


UL(BR(K±→μ± N₄)BR(N₄→π∓μ±))=

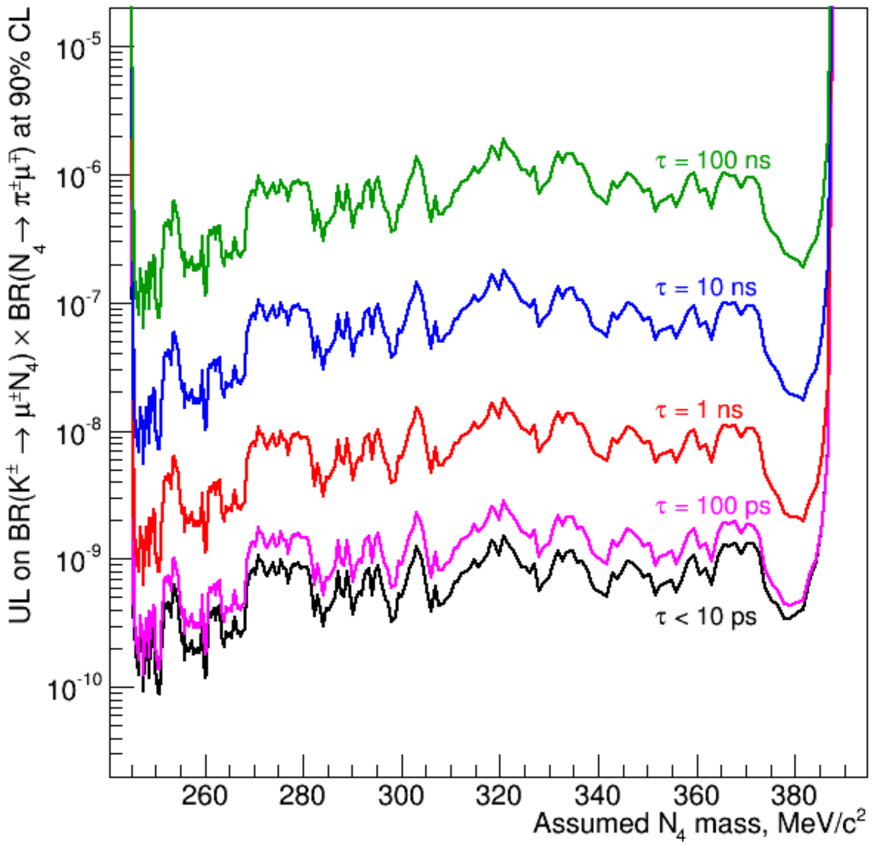


Statistical significance
never exceeds +3σ: no signal observed

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



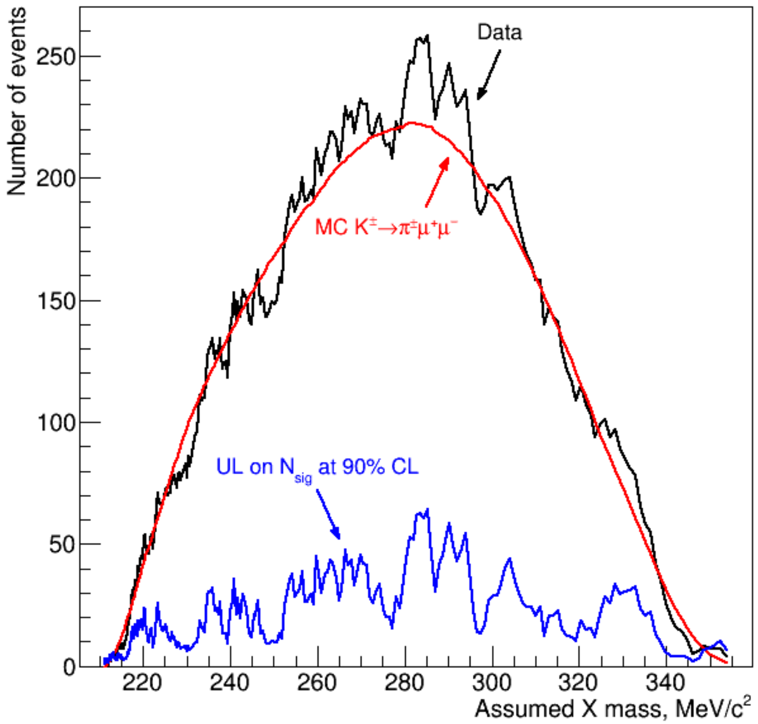
UL(BR(K±→μ± N4)BR(N4→π±μ∓))=

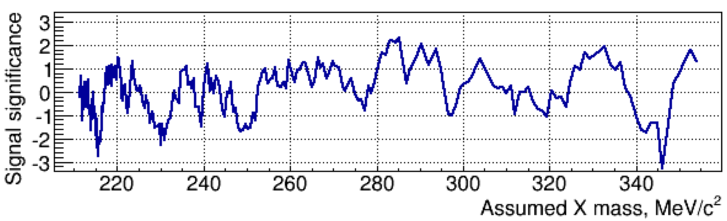


Statistical significance
never exceeds +3σ: no signal observed

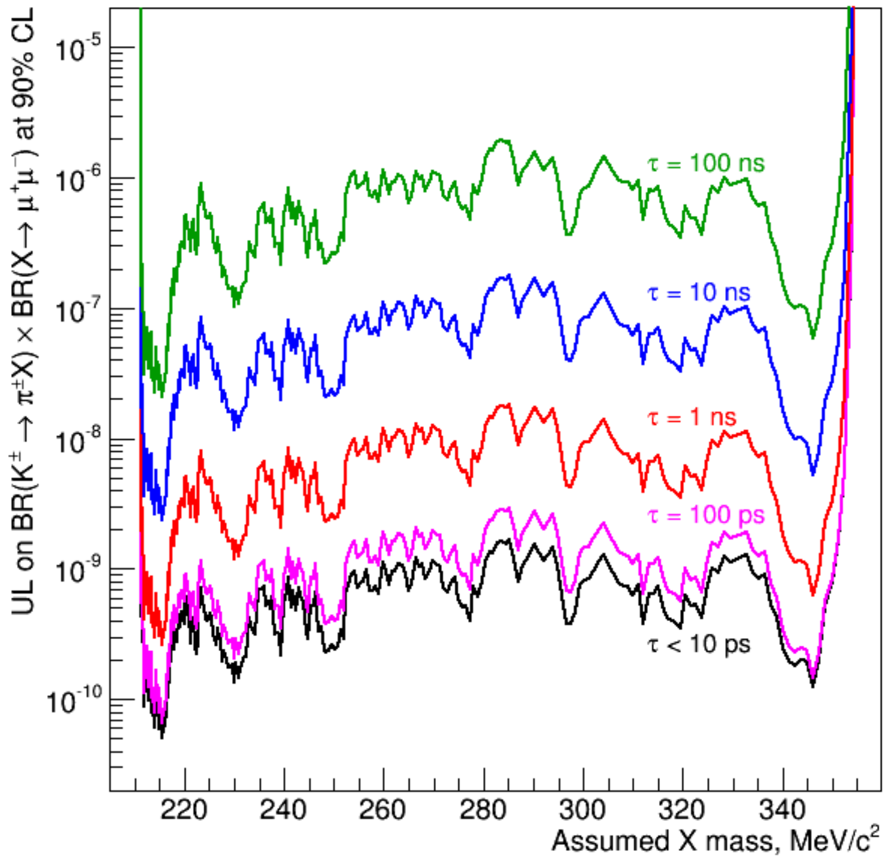
Search for K± → π±X(X → μ⁺μ⁻) decays

Oppositesign muons sample (LNC)





UL(BR(K±→π± X)BR(X→μ⁺μ⁻))=



Statistical significance
never exceeds +3σ: no signal observed

Prospects for the new NA62 experiment

NA62 will collect the world-largest K+ decay sample: ~ 10^{13} decays in 3 years of data taking (~ 50 times more than NA48/2)

Kaon and π^0 LNFV decays

Mode	UL at 90% CL	Experiment	NA62 acceptance*
$K^+ \to \pi^+ \mu^+ e^-$	1.3×10^{-11}	BNL 777/865	~ 10%
$K^+ \to \pi^+ \mu^- e^+$	5.2×10^{-10}	BNL 865	~ 10%
$K^+ \to \pi^- \mu^+ e^+$	5.0×10^{-10}	BNL 865	~ 10%
$K^+ \to \pi^- e^+ e^+$	6.4×10^{-10}	BNL 865	~ 5%
$K^+ \to \pi^- \mu^+ \mu^+$	**8.6×10^{-11}**	**NA48/2**	**~ 20%**
$K^+ \to \mu^- \nu e^+ e^+$	2.0×10^{-8}	Geneva Saclay	~ 2%
$K^+ \to e^- \nu \mu^+ \mu^+$	no data		~ 10%
$\pi^0 \to \mu^+ e^-$	3.6×10^{-6}	KTeV	~2%
$\pi^0 \to \mu^- e^+$			

* From fast MC with flat phase-space distribution.

Single-event sensitivity:

NA62 Sensitivities:
~10^{-12} for K^+ decays
~10^{-11} for π^0 decays

Conclusions

The NA48/2 experiment at CERN was exposed to ~2×10^{11} $K^{\pm}$ decays in 2003-2004

- New NA48/2 results presented for the first time today:
  - Search for LNV $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ **decay:**
    - BR($K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ **) < 8.6×10^{-11}** @ 90% CL [World Best Limit]
    - Factor of 10 improvement with respect to previous best limit [1.1×10^{-9} @ 90% CL]
  - Search for $K^{\pm} \rightarrow \mu^{\pm}N_4(N_4 \rightarrow \pi^{\mp}\mu^{\pm})$ **decays [Majorana neutrinos]**
    - Limits on BR products of the order of 10^{-10} for neutrino lifetimes < 100 ps
  - Search for $K^{\pm} \rightarrow \mu^{\pm}N_4(N_4 \rightarrow \pi^{\pm}\mu^{\mp})$ **decays [LNC heavy neutrinos]**
    - Limits on BR products of the order of 10^{-9} for neutrino lifetimes < 100 ps
  - Search for $K^{\pm} \rightarrow \pi^{\pm}X(X \rightarrow \mu^{+}\mu^{-})$ **decays [Inflatons, …]**
    - Limits on BR products of the order of 10^{-9} for resonance lifetimes < 100 ps
- Prospects for the new NA62 experiment:
  - Major beam and detector upgrades for $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$: improved performances
  - NA62 will collect the world-largest K^{+} decay sample (~10^{13}) in 3 years of data taking
  - Potential sensitivities ~ 10^{-12} for K decays, ~ 10^{-11} for π^{0} decays