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

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on behalf of the NA48/2 Collaboration

New Trends in High-Energy Physics

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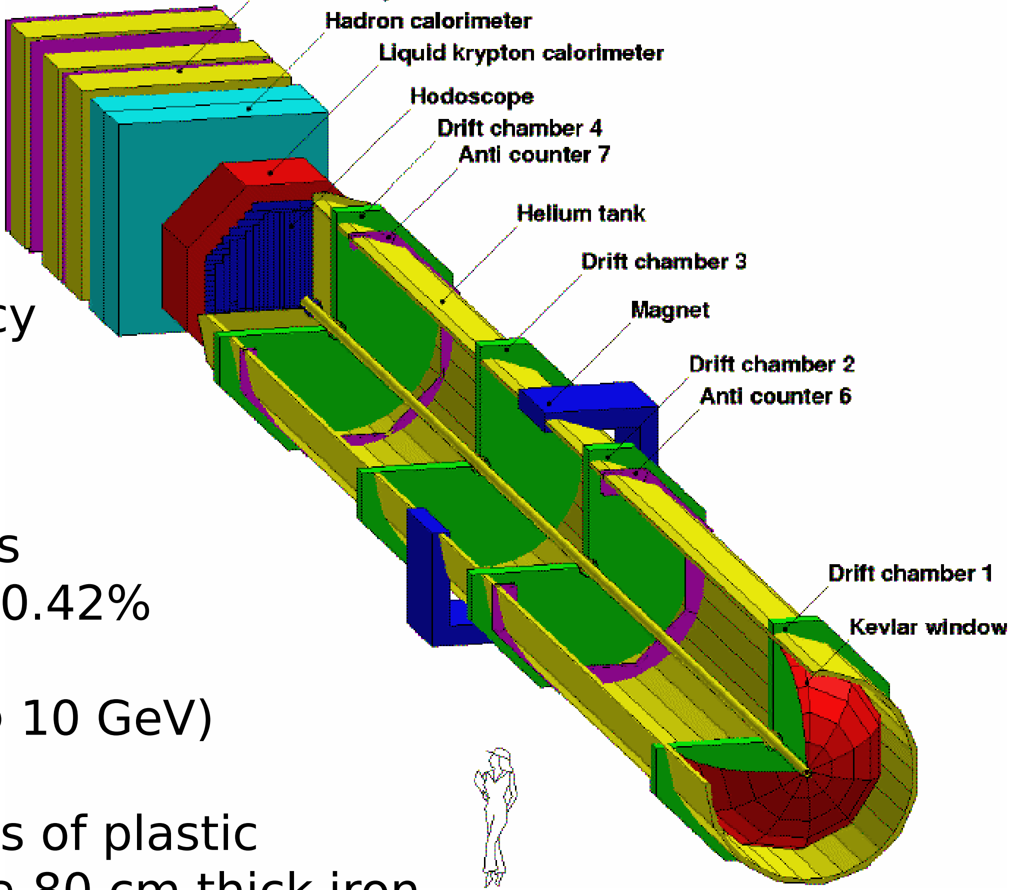
Outline:

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

NA48/2 (2003-2004)

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



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

- **Spectrometer (4 DCHs)**

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

- **Scintillator Hodoscope**

Fast trigger, time $\sigma \sim 150$ 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)

- **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.

Theoretical Motivation: ***neutrino physics development.***
neutrino oscillations → neutrino masses → right-handed neutrinos.
For example:

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 to the SM:

- One has a mass of O(KeV) – Dark Matter candidate.
- Two others have a mass of O(100 MeV – 1 GeV), tune CPV phases, provide an extra-CKM sources of baryon asymmetry and produce a standard neutrino masses through seesaw.

Active sterile neutrino mixing (U-matrix):
Effective vertices involving the sterile neutrinos N_i, the $W^{\pm}$, Z bosons and SM leptons,leading to LNV decays: $BR(K^{\pm} \rightarrow \mu^{\pm} N_4) \times BR(N_4 \rightarrow \pi^{\mp}\mu^{\pm}) \sim |U_{\mu 4}|^4$

More new particles in some models: **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 and structures on smaller scales (believed to be coming from inflation)

- χ-Higgs mixing with mixing angle θ
- χ-Higgs coupling → Universe reheating
- χ is unstable: $\tau \sim (10^{-8}\text{-}10^{-12})$ s

χ in Kaon decays
[may be $m\chi < 300\text{-}400\ \mathrm{MeV}/c^2$]

Same-sign muons sample (LNV)

- Fully reconstructed final states, 3-track vertex topology (50 cm Z resolution, lifetime < 10 ps is negligible)
- Similar topology of the normalisation channel $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

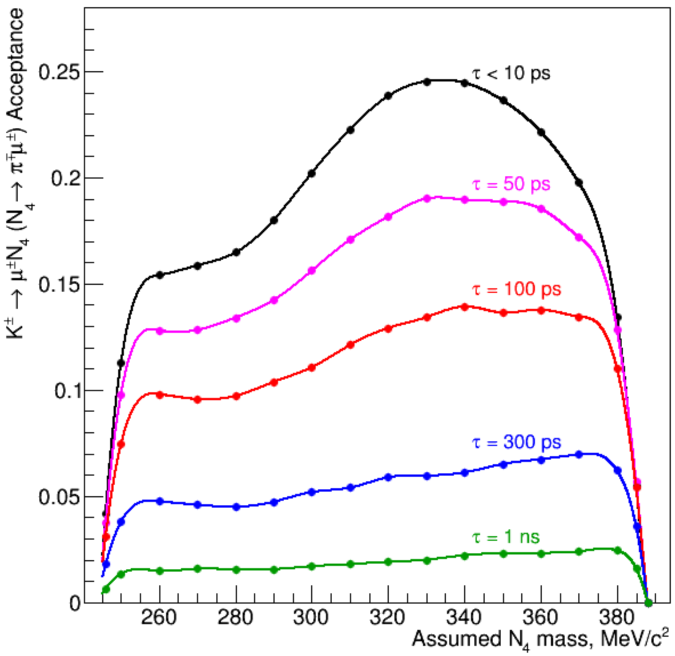
$\rightarrow$ First-order cancellation of systematic effects (trigger inefficiency, etc)

- Search for the LNV $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay
- Main background: $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ with 2 $\pi^{\pm} \rightarrow \mu^{\pm}\nu$ decays (one within the Spectrometer)

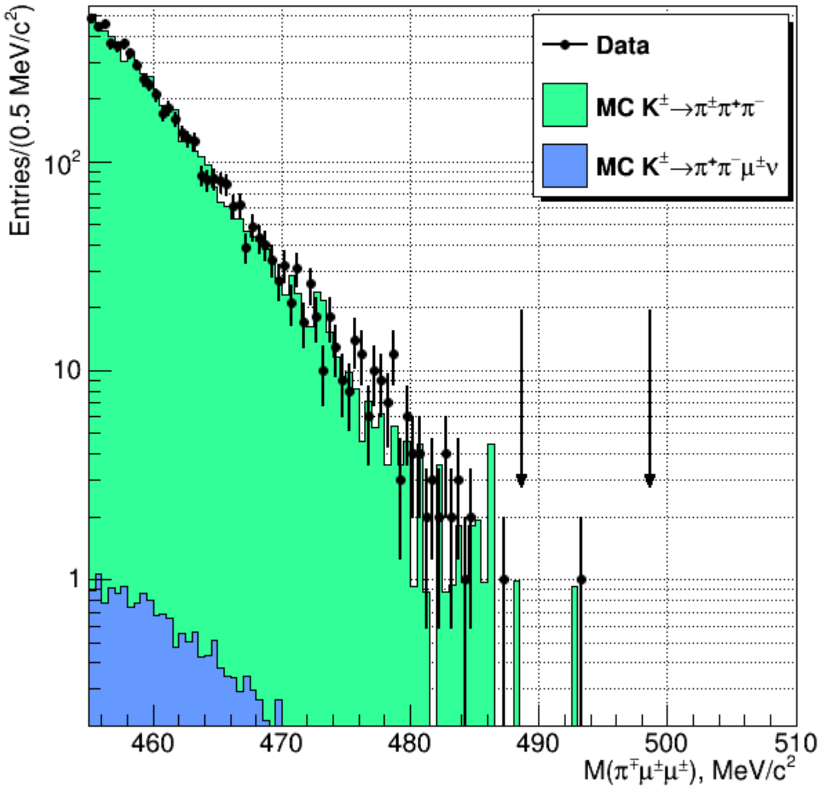
- UL on LNV $BR(K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm})$
- UL on resonant $BR(K^{\pm} \rightarrow \mu^{\pm}N_4) \times BR(N_4 \rightarrow \pi^{\mp}\mu^{\pm})$

~ 2×10^{11} $K^{\pm}$ decays in the fiducial volume (measured from $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$)

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



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
    - – 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 reconstructed 3-track vertex |Q|=1
  - o 2 same-sign muons, 1 odd-sign pion (E/p,MUV)
  - o Total P_T consistent with zero (<0.01 GeV/c)
  - o Signal Region: $|M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) - M_K| < 5$ MeV/c2
- Expected background: $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

MC sample (10^{10} events) used to evaluate number of expected $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ events in Signal Region

- 1 Event in Signal Region observed
- Expected background (from MC): $N_{exp} = 1.163 \pm 0.867_{stat} \pm 0.021_{ext} \pm 0.116_{syst}$

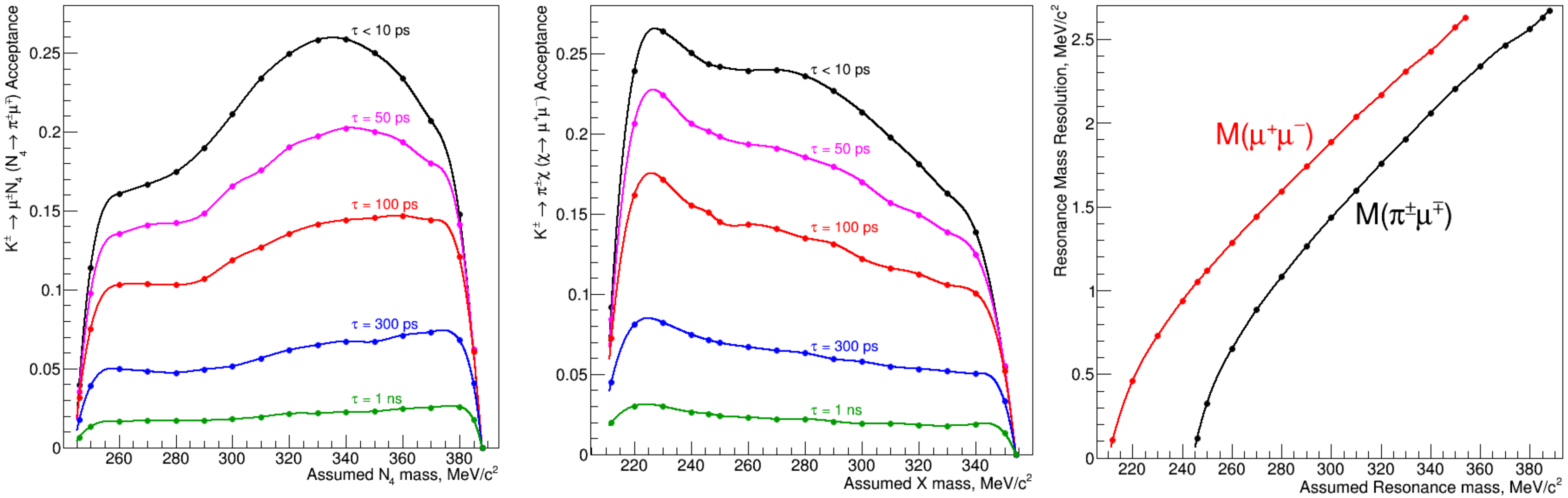
Rolke-Lopez statistical treatment to get UL(Nsig)→

BR(K → π∓μ±μ±) < 8.6 x 10-11 @ 90% CL

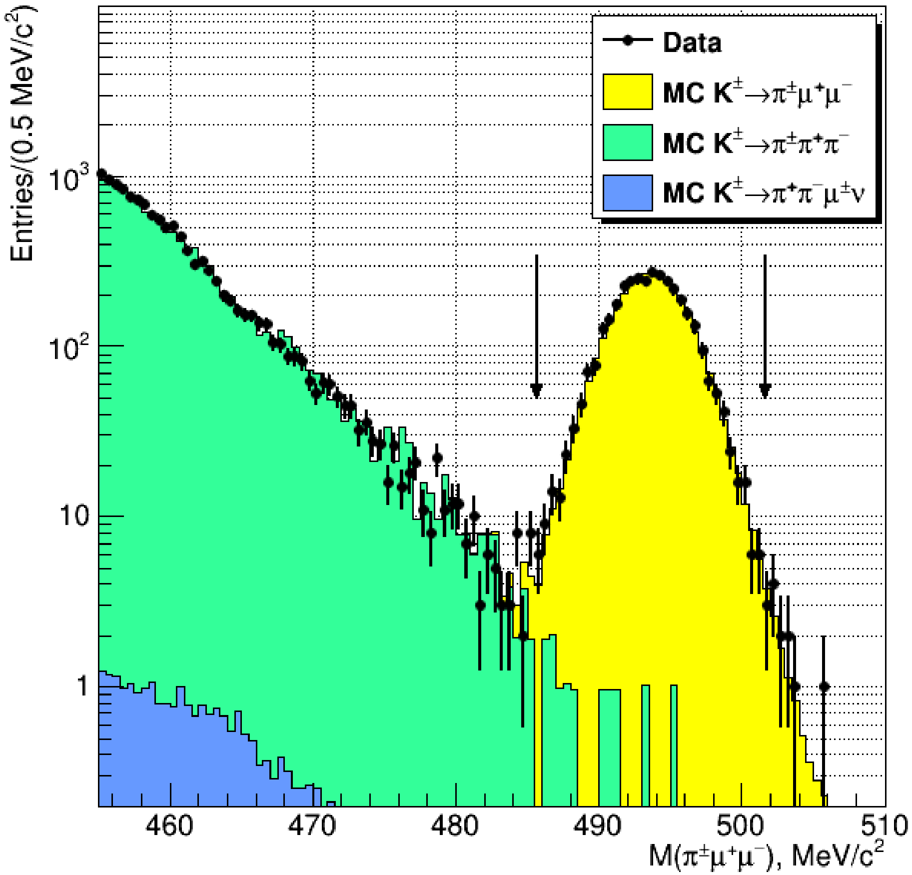
Opposite-sign muons sample (LNC)

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

- 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
- UL on BR($K^{\pm} \to \mu^{\pm}N^4$) x BR($N^4 \to \pi^{\pm}\mu^{\mp}$)
- UL on BR($K^{\pm} \to \pi^{\pm}X$) x BR($X \to \mu^{+}\mu^{-}$)



Opposite sign muons selection (LNC)



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

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

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

$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ background: (0.36±0.10)%

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

Two-body mass scans

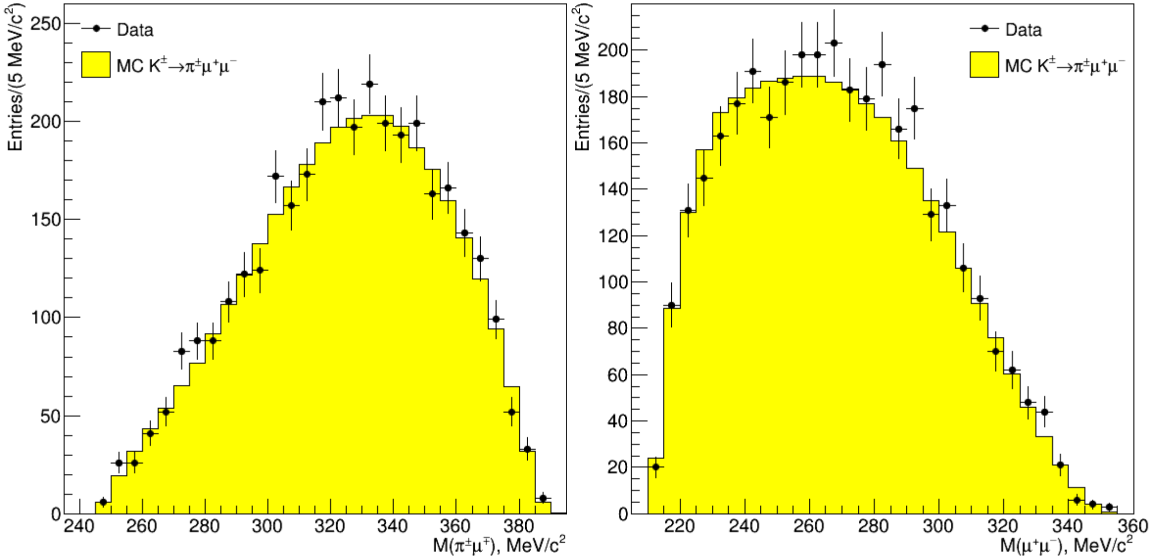
- Based on selected $K^{\pm} \to \pi^{\pm}\mu\mu$ candidates.
  Variable step = $0.5\sigma(M_{res})$ and window = $\pm 2\sigma(M_{res})$
- For each M_{res}:
  Observed events in data (N_{obs}) vs Expected events from MC (N_{exp}) → UL(N_{sig})
- Rolke-Lopez statistical treatment used in each mass hypothesis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

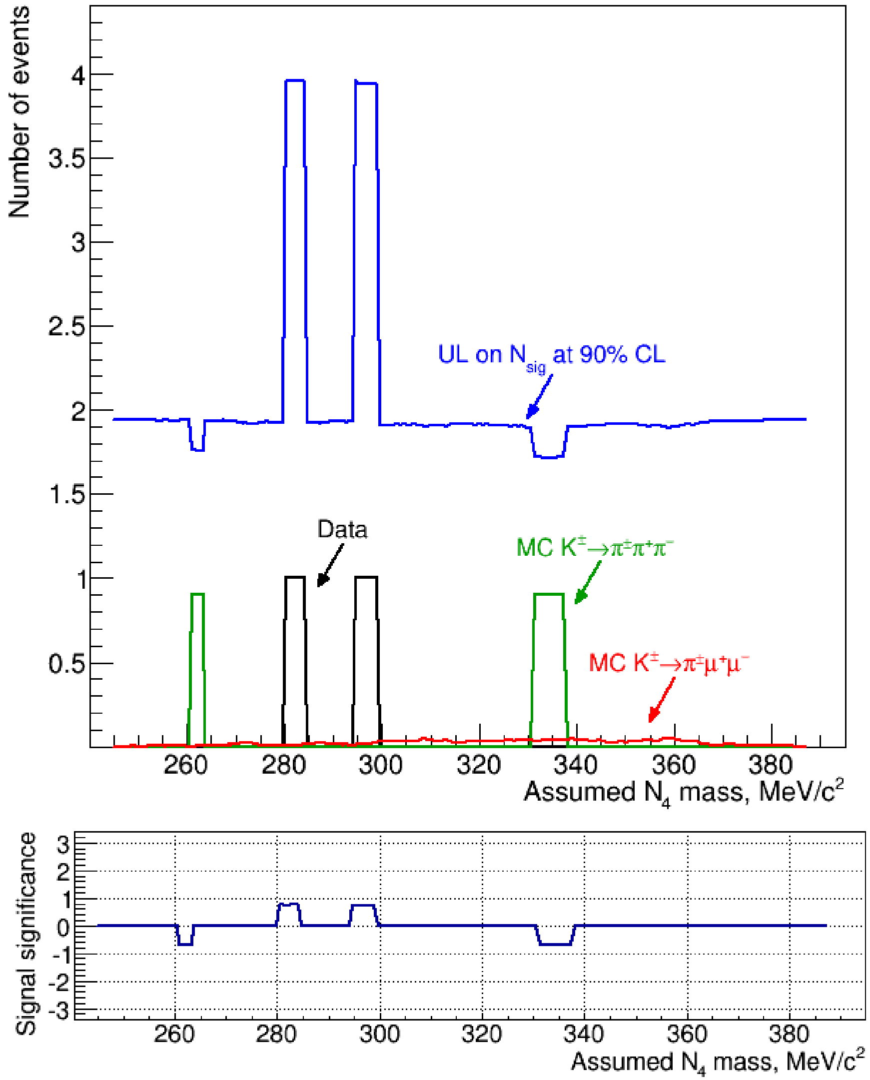
Search for resonances in LNC $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ - decays

- 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

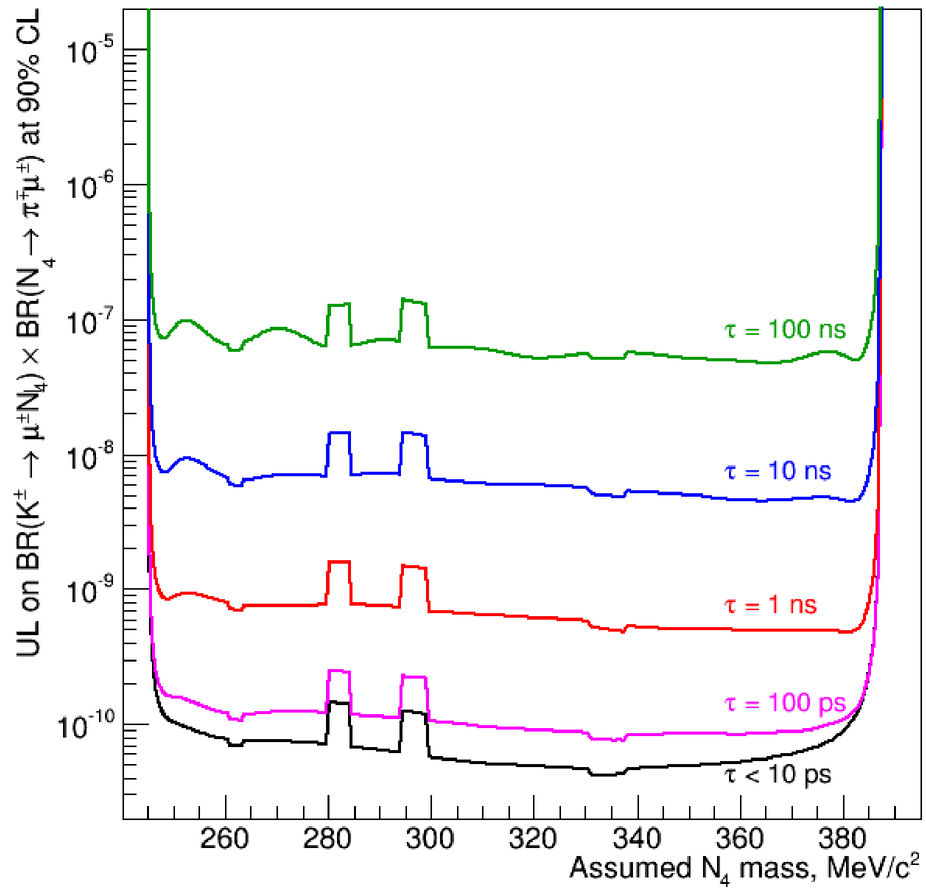


Search for $K^{\pm} \to \mu^{\pm} N_4 (N_4 \to \pi^{\mp} \mu^{\pm})$ decays

Same-sign muons sample

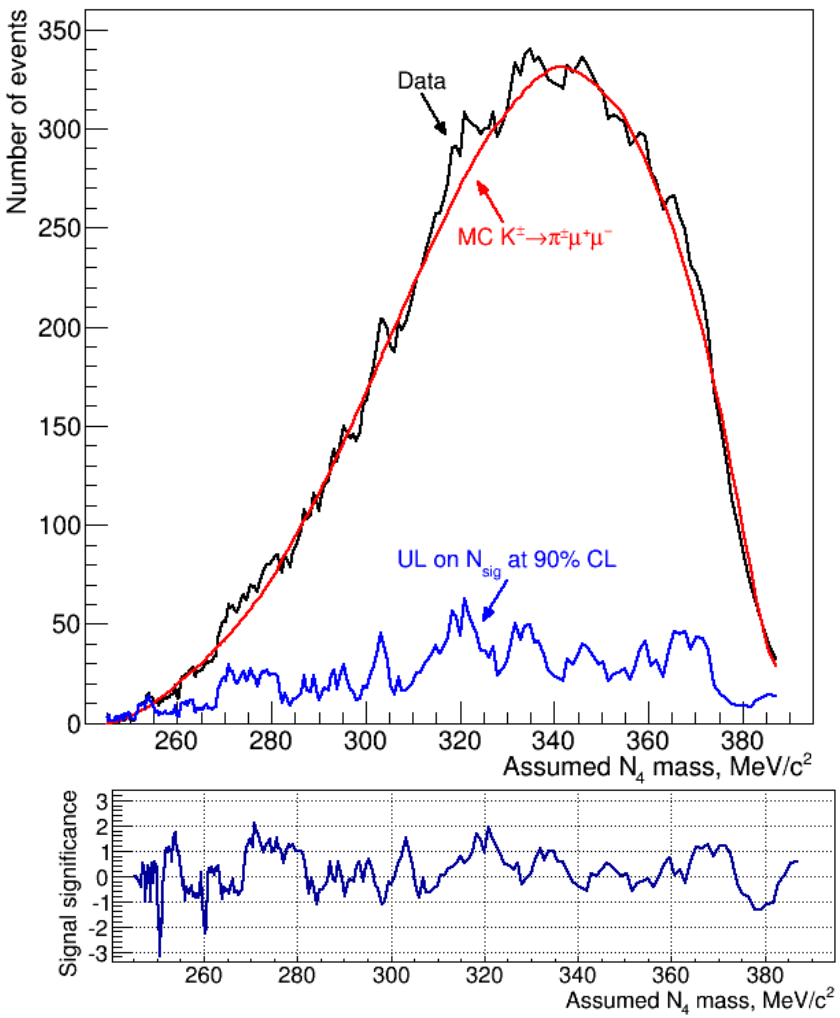


$UL(BR(K^{\pm} \to \mu^{\pm} N_4) BR(N_4 \to \pi^{\mp}\mu^{\pm}))=$

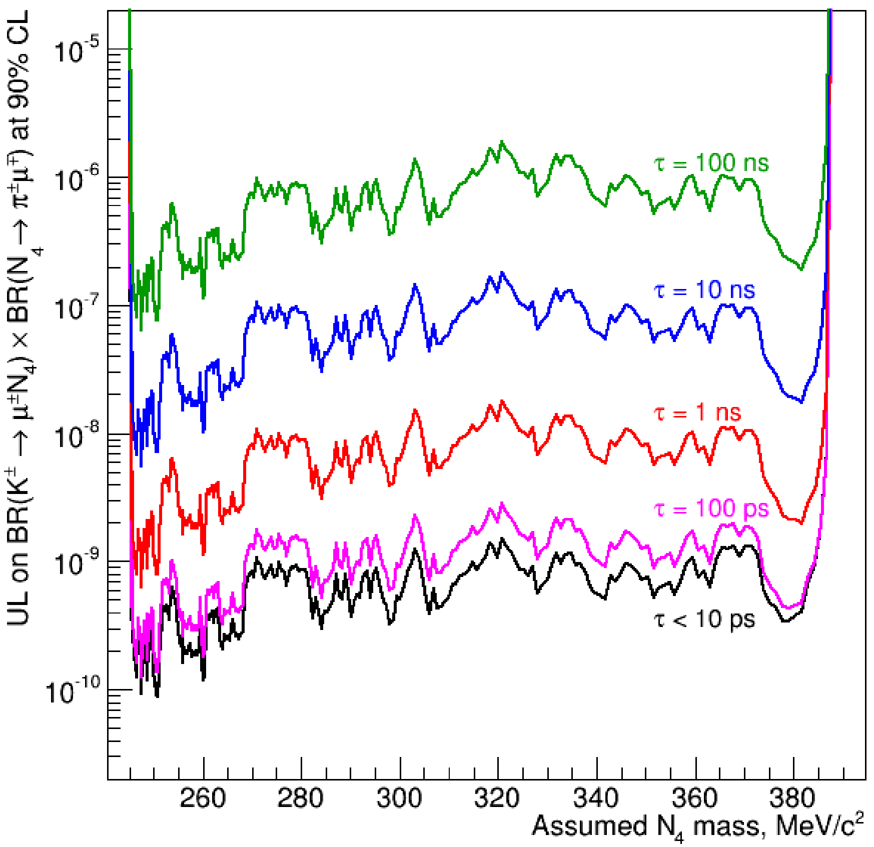


Statistical significance never exceeds +3σ: no signal observed

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



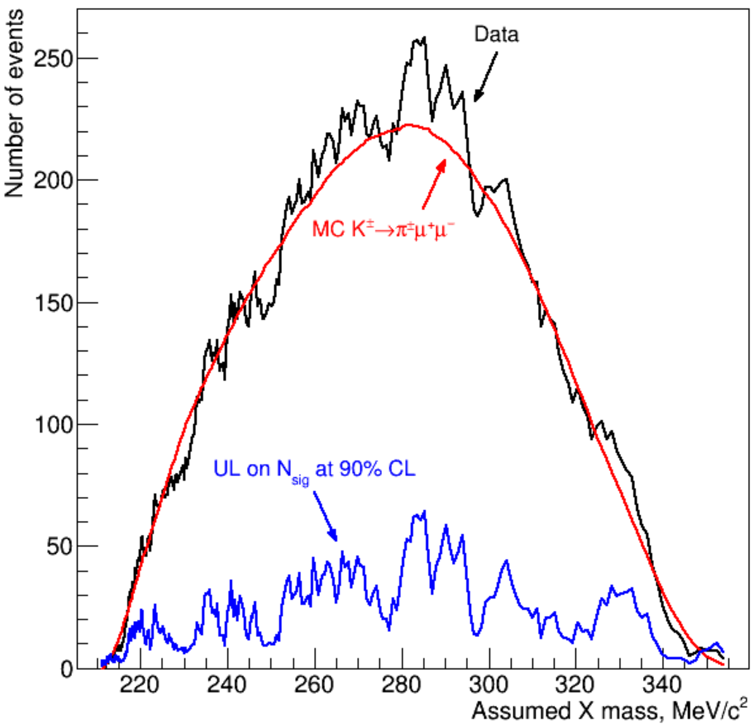
UL(BR(K±→μ± N₄)BR(N₄→π±μ∓))=

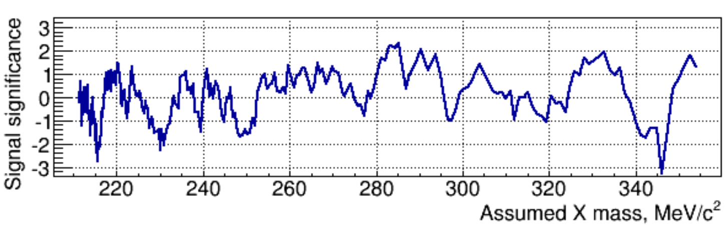


Statistical significance never exceeds +3σ: no signal observed

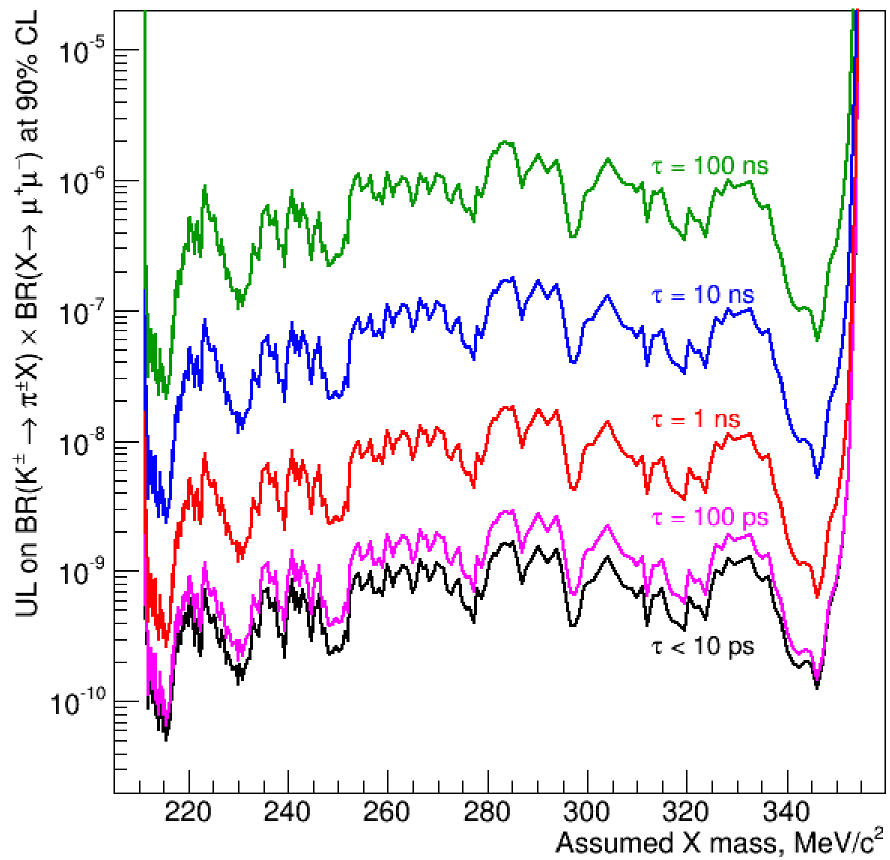
Search for $K^{\pm} \to \pi^{\pm}X(X \to \mu^{+}\mu^{-})$ decays

Opposite sign muons sample (LNC)





UL(BR($K^{\pm}\to\pi^{\pm}$ X)BR($X\to\mu^{+}\mu^{-}$))=



Statistical significance never exceeds +3σ: no signal observed

Conclusion

New NA48/2 results presented:

− 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}]

− Search for $K^{\pm} \to \mu^{\pm}N4$ ($N4 \to \pi^{\mp} \mu^{\pm}$) **decays [Majorana neutrinos]**

- Limits on BR products of the order of 10^{-10} for neutrino lifetimes < 100 ps

− Search for $K^{\pm} \to \mu\pm N4(N4 \to \pi^{\pm} \mu^{\mp})$ **decays [LNC heavy neutrinos]**

- Limits on BR products of the order of 10^{-9} for neutrino lifetimes < 100 ps

− Search for $K^{\pm} \to \pi^{\pm}X$ ($X \to \mu^{+}\mu^{-}$) **decays [Inflatons, …]**

- Limits on BR products of the order of 10^{-9} for resonance lifetimes < 100 ps

Prospects for the new NA62 experiment

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.

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