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

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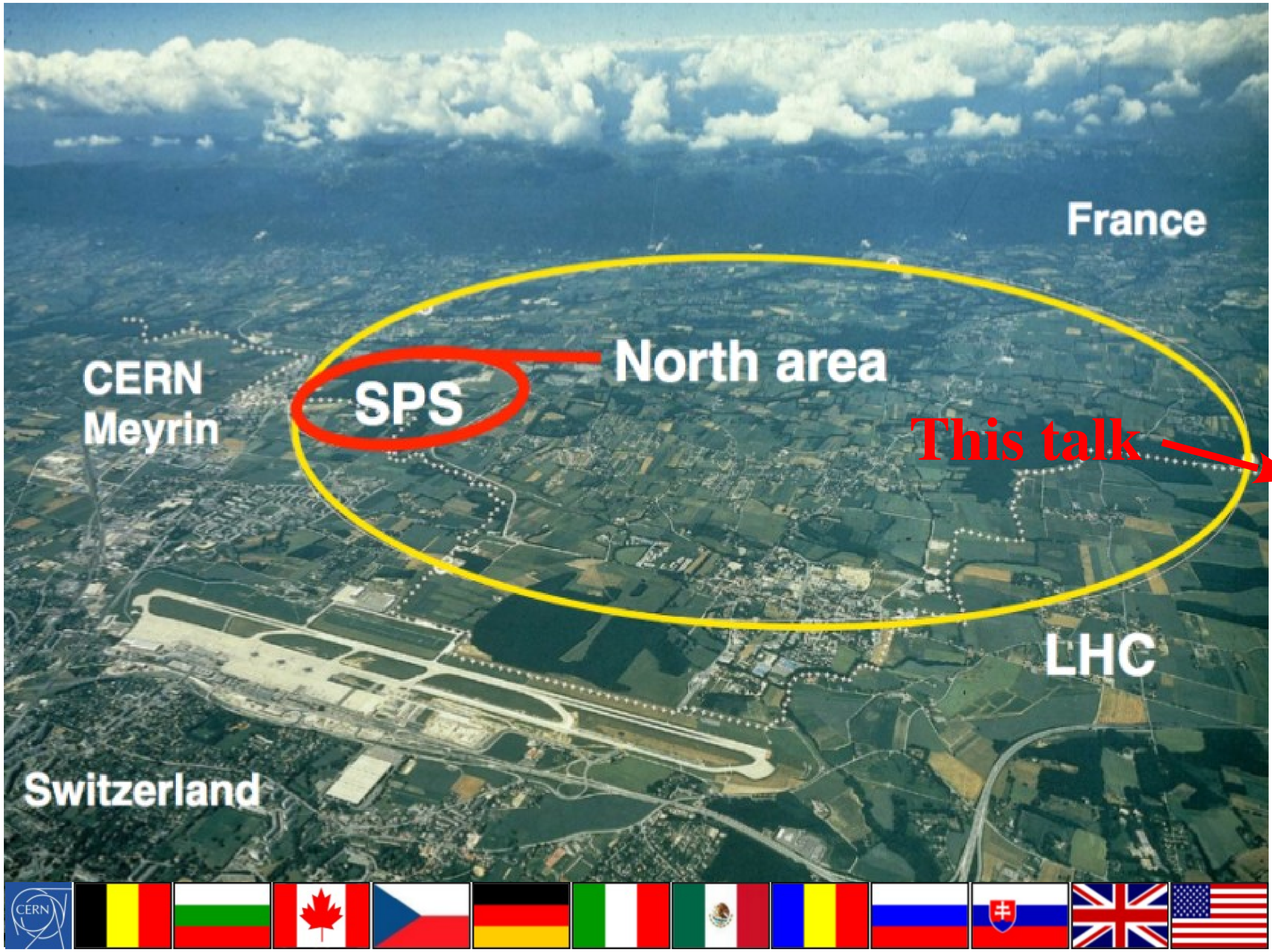
Outline:

- The NA48/2 experiment
- Theoretical Motivations
- 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
- Prospects for the NA62 experiment

1st Forum on Rare Kaon Decays – Edinburgh, UK – 22/02/2018

The NA48/NA62 experiments @ CERN



History of NA48/NA62 experiments		
1997 ↓ 2001	NA48 (K_S/K_L)	Re ε'/ε **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^-)	$R_K = K^{\pm}_{e2}/K^{\pm}_{\mu 2}$
2015 ↓ -	NA62 (K^+)	$K^+ \rightarrow \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays

Main NA48/2 physics goal: Search for direct CPV in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ and $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$ decays

Main triggers: 3-track vertex, $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\pi^{0}$

World largest $K^{\pm} \rightarrow$ 3-tracks sample: **Ideal environment for $K^{\pm} \rightarrow \pi \ell \ell$ studies**

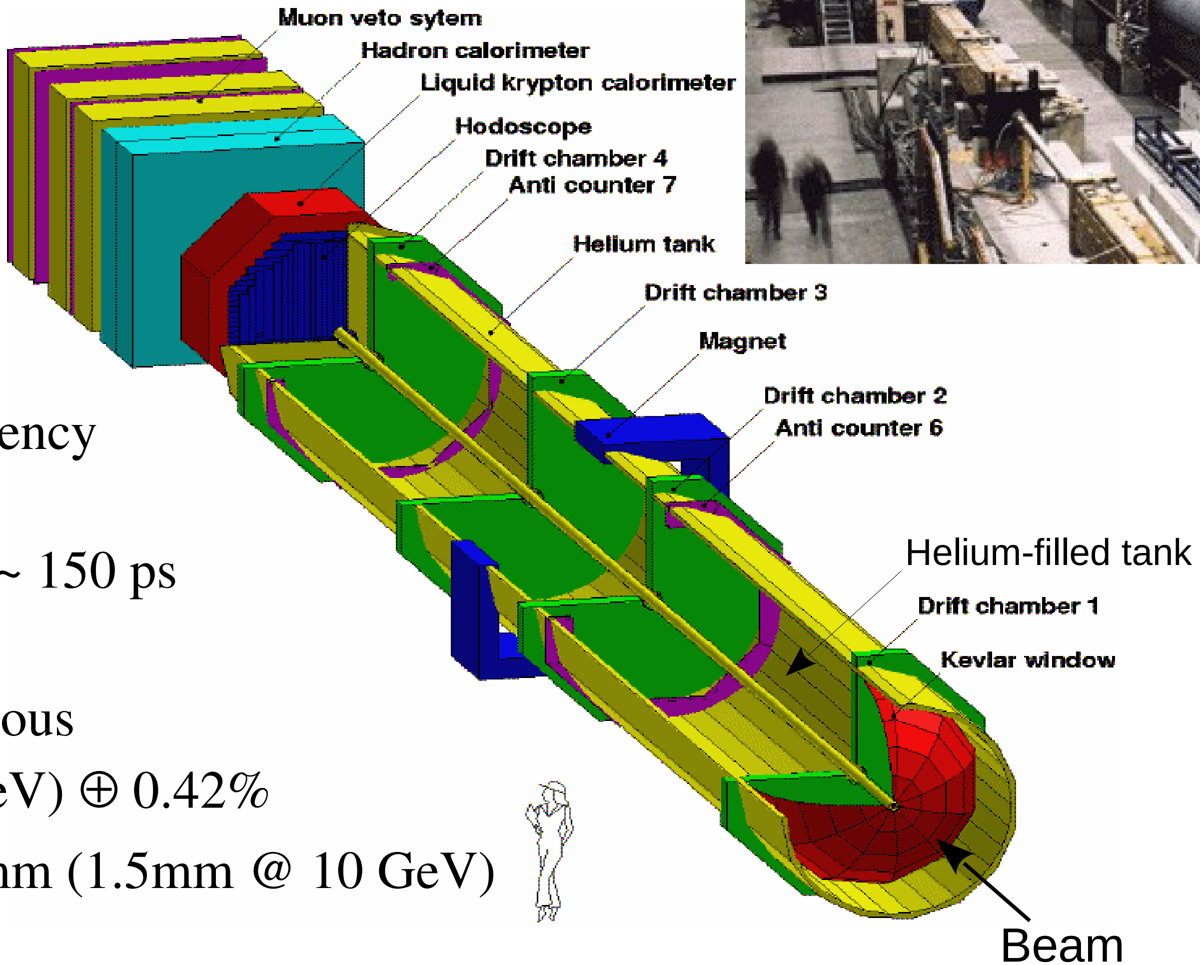
The NA48/2 detector

Narrow momentum band $K^{\pm}$ beams:
$P_K = 60$ GeV/c, $\delta P_K/P_K \sim 4\%$ (rms)
Nominal $K^{\pm}$ decay rate: ~ 100 kHz
Simultaneous K^+/K^- beams

22% of kaons decay in 114m-long vacuum tank upstream the detector

Principal sub-detectors:

- **Spectrometer (4 DCHs)**
  $\sigma_p/p = 1.02\% \oplus 0.044\%\ p(\text{GeV})$
  4 views/DCH: redundancy → efficiency
- **Scintillator Hodoscope**
  Fast trigger, time measurement $\sigma_t \sim 150$ ps
- **LKr EM calorimeter**
  High-granularity, quasi-homogeneous
  $\sigma_E/E = 3.2\%/\sqrt{E(\text{GeV})} \oplus 9\%/E(\text{GeV}) \oplus 0.42\%$
  $\sigma_x = \sigma_y = 4.2\text{mm}/\sqrt{E(\text{GeV})} \oplus 0.6\text{mm}$ (1.5mm @ 10 GeV)



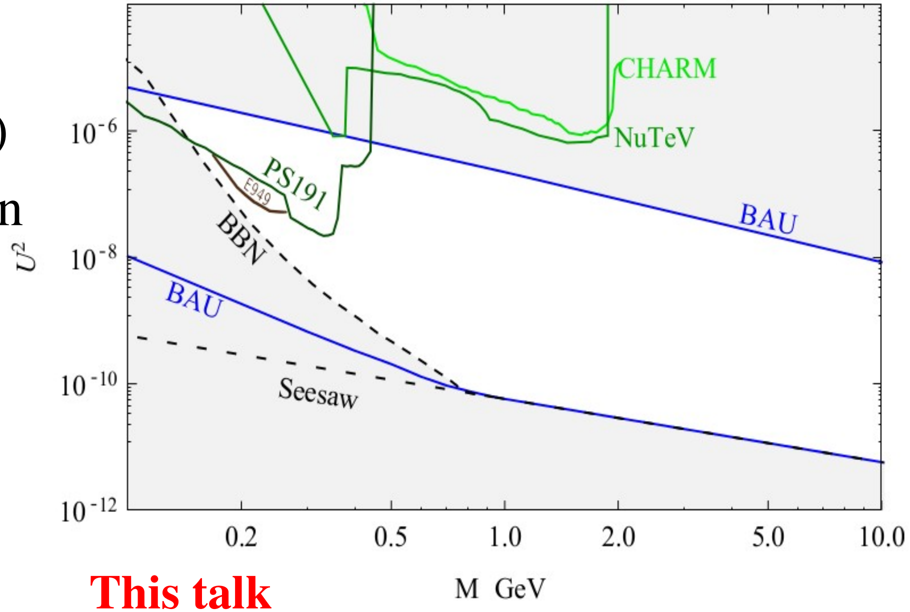
Majorana Neutrinos

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

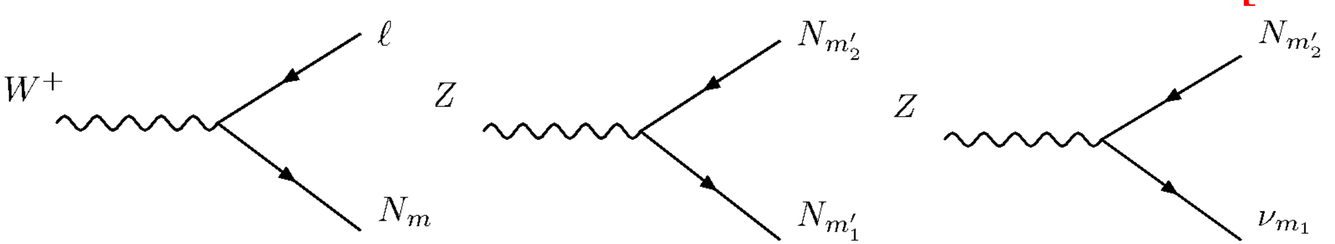
- N_1 is the lightest O(keV) → Dark Matter candidate
- N_2, N_3 are nearly degenerate (100 MeV to few GeV)

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



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



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

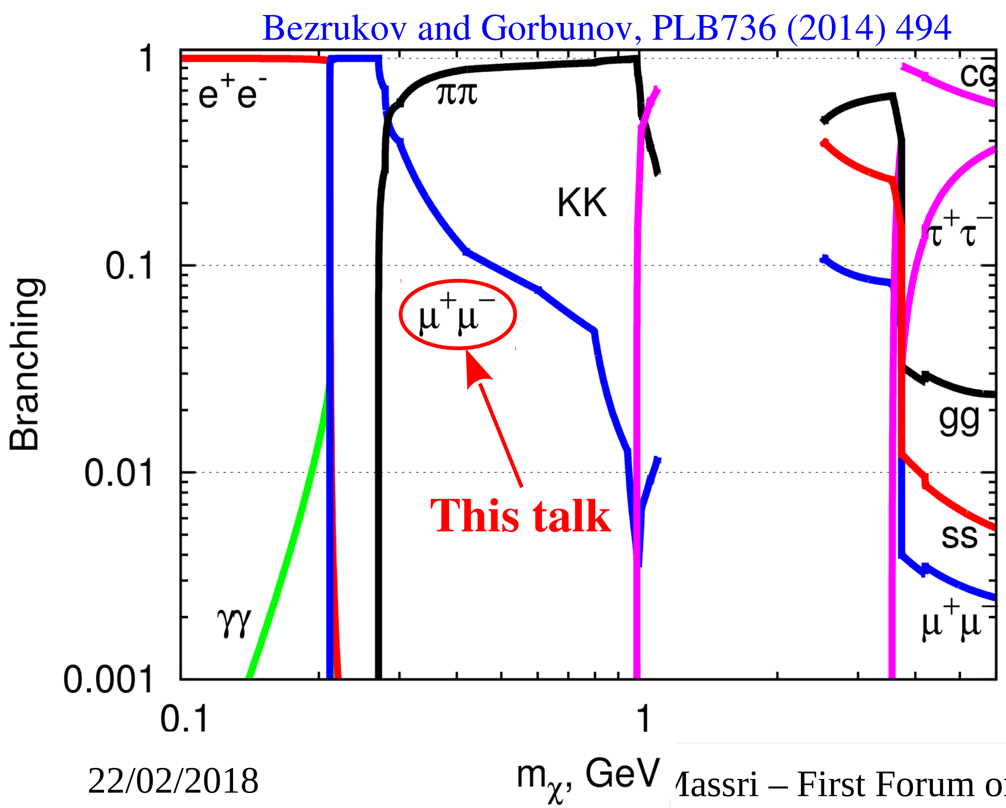
This talk
[$\ell = \mu$]

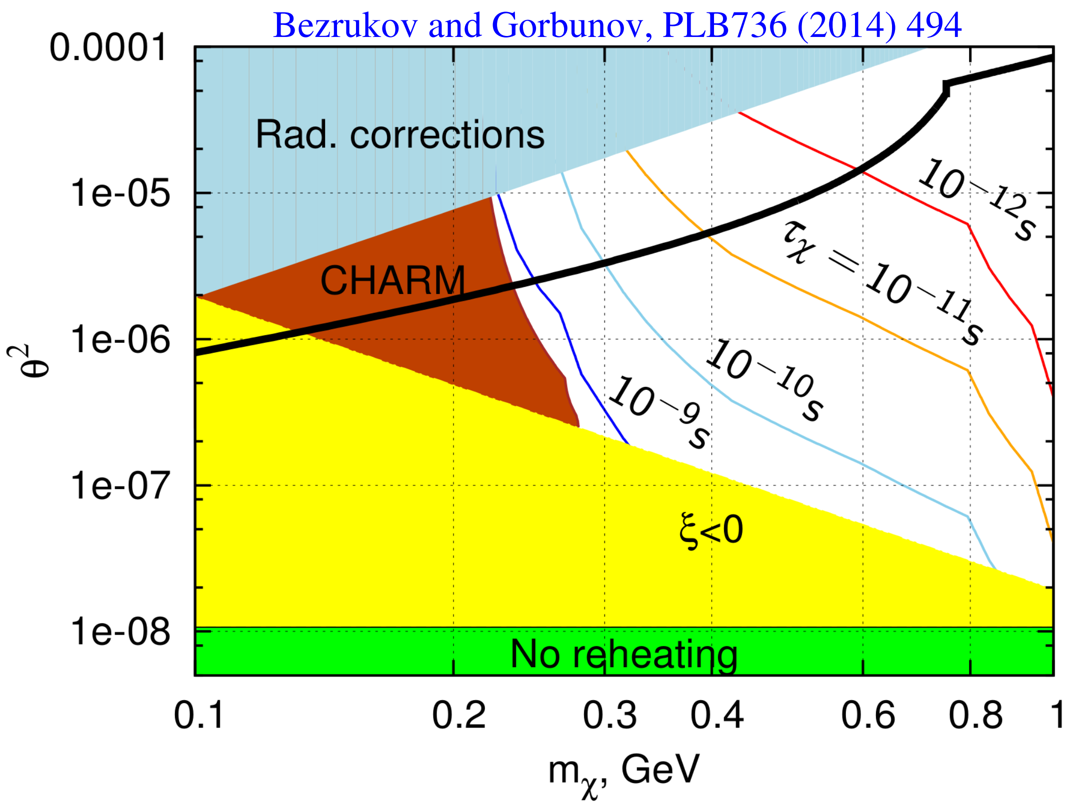
$N_{2,3}$ production in $K^\pm$ decays:
$K^\pm \to \ell^\pm N$, $K^\pm \to \pi^0 \ell N$, …
$N_{2,3}$ decays for $m_{2,3} < m_K - m_\ell$:
$N \to \pi^\pm \ell^\mp$, $N \to \pi^0 \nu$
$N \to \ell_1^\pm \ell_2^\mp \nu_2$, $N \to \nu_1 \ell_2^+ \ell_2^-$
$N \to \nu_\ell \nu \bar{\nu}$

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: $\tau \sim (10^{-8}\text{-}10^{-12})$ s





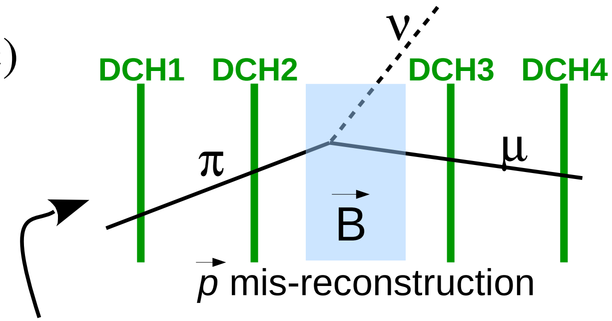
χ in Kaon decays [$m_\chi < 354$ MeV/c^2]

$$BR(K^\pm \to \pi^\pm \chi) = 1.3\times10^{-3}\left(\frac{2|\vec{p}_\chi|}{M_K}\right)\theta^2$$

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

<u>Basic principles of the searches:</u>

- 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)



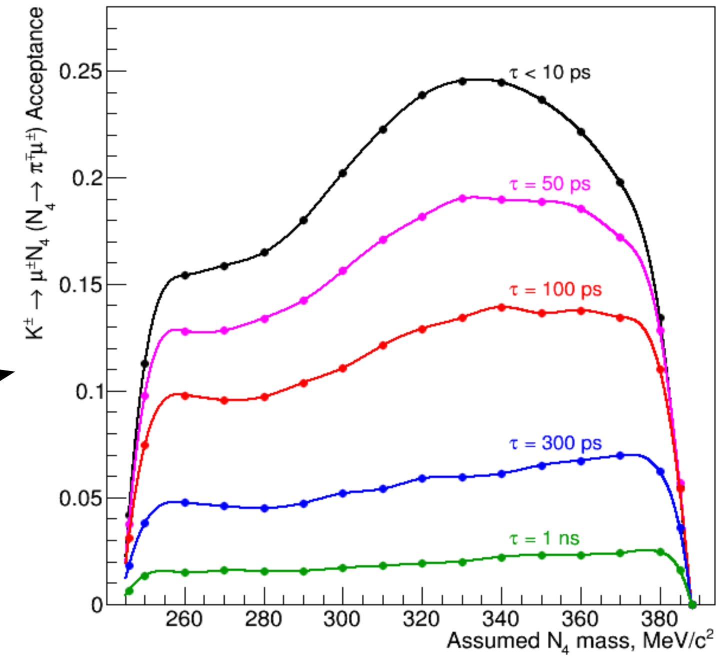
Search for Lepton Number Violation – Majorana neutrinos

- <u>Method:</u> exclusive search for the $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay
- <u>Main background:</u> $\mathbf{K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}}$ **with 2** $\mathbf{\pi^{\pm} \to \mu^{\pm}\nu}$ **decays** (one within the Spectrometer)

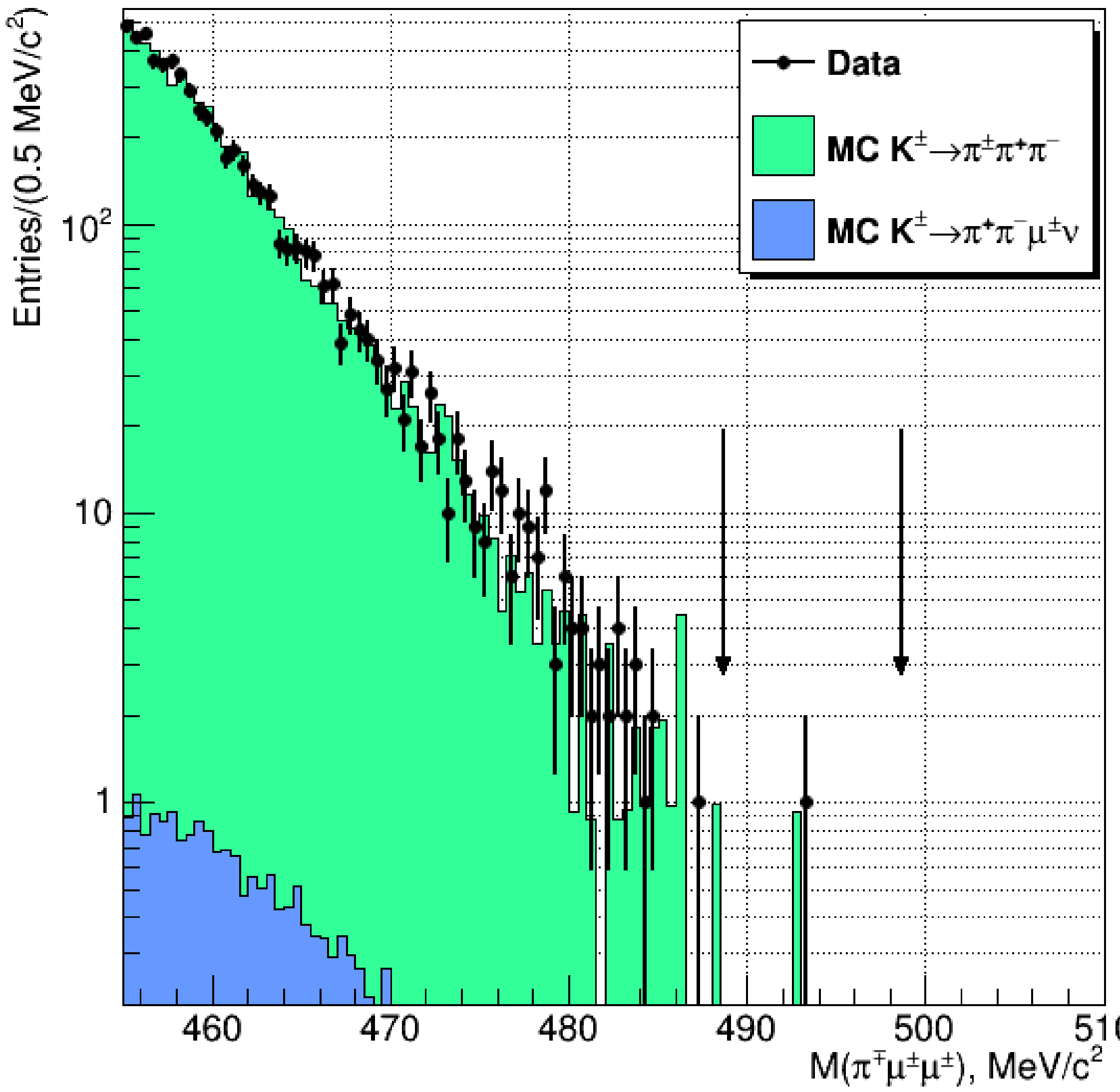
- <u>Sensitivity:</u>

$$\left.\begin{array}{l} \text{UL on BR}(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) \\ \text{UL on BR}(K^{\pm} \to \mu^{\pm}N_4) \times \text{BR}(N_4 \to \pi^{\mp}\mu^{\pm}) \end{array}\right\} \sim \frac{1}{N_K * Acceptance}$$

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
  - $K^{\pm}\to\pi^{\mp}\mu^{\pm}\mu^{\pm}$ MC simulation
    - Uniform phase-space ($|M_{fi}|^2 = 1$)
    - Resonant Majorana neutrino model
  - $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ MC simulation (10^{10} events)
  - Control Region:

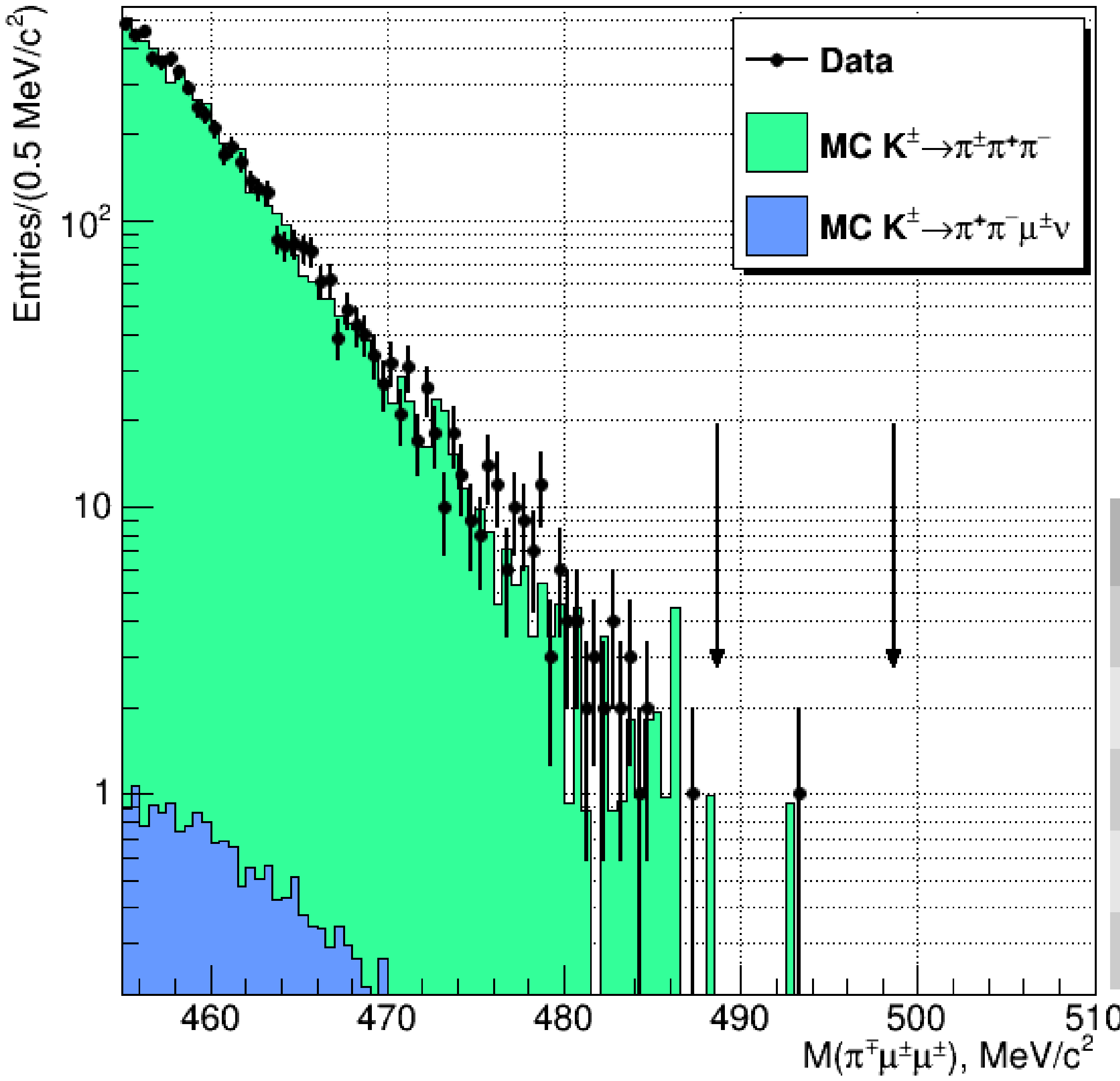
    $M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 480$ MeV/c^2

- **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

- **Expected background:** Additional $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ MC sample (10^{10} events) dedicated to evaluation of number of expected $K^{\pm}\to\pi^{\pm}\pi^{+}\pi^{-}$ events in Signal Region

Upper Limit on $BR(K^\pm \to \pi^\mp \mu^\pm \mu^\pm)$



- **Kaon decays in the fiducial volume:**

$N_K \sim 2\times10^{11}$

(from reconstructed $K^\pm \to \pi^\pm\pi^+\pi^-$ decays)

- **Events in Signal Region observed:**

$N_{obs} = 1$

- **Expected background:** (from MC)

Decay	BR	N_{exp} (LNV)
$K^\pm \to \pi^\pm\pi^+\pi^-$	$(5.583 \pm 0.024)\%$	0.864 ± 0.864
$K^\pm \to \pi^+\pi^-\mu^\pm\nu$	$(4.5 \pm 0.2)\times10^{-6}$	0.027 ± 0.015
$K^\pm \to \pi^\pm\mu^+\mu^-$	$(9.4 \pm 0.6)\times10^{-8}$	0.257 ± 0.027
$K^\pm \to \mu^\pm\mu^+\mu^-\nu$	1.35×10^{-8}	0.012 ± 0.001
Total	–	1.160 ± 0.865

$\text{Acceptance}(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) = (20.62 \pm 0.01)\%$

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

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

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

Basic principles of the searches:

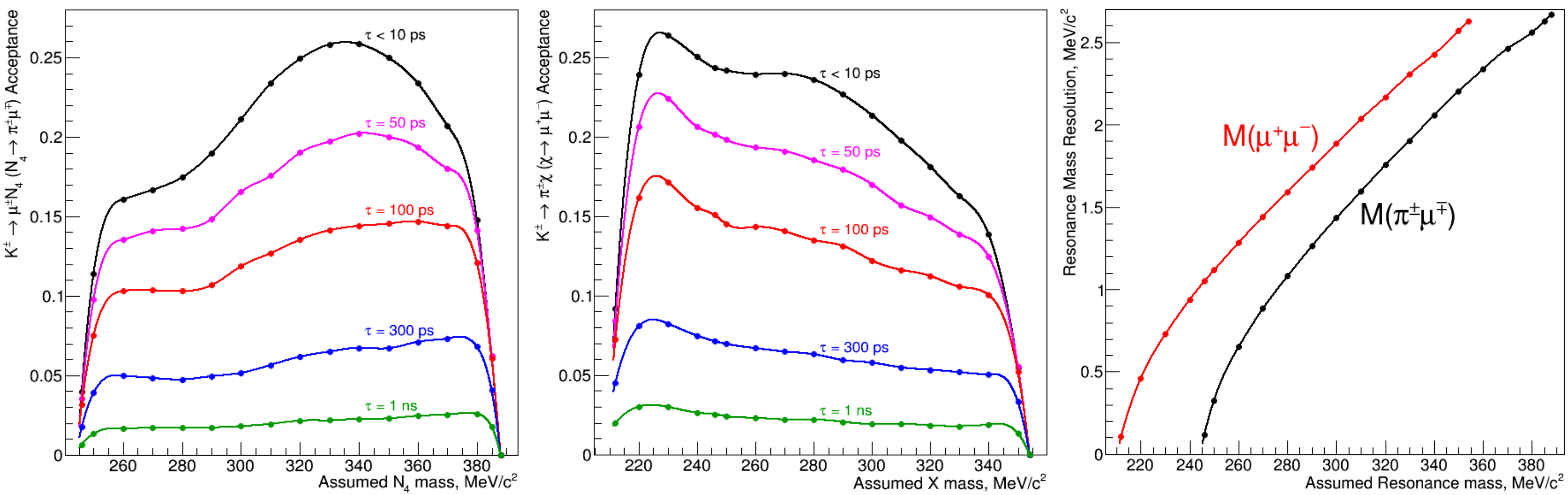
- Fully reconstructed final states, 3-track vertex topology
- Similar topology to normalisation channel $K^\pm \to \pi^\pm\pi^+\pi^-$

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

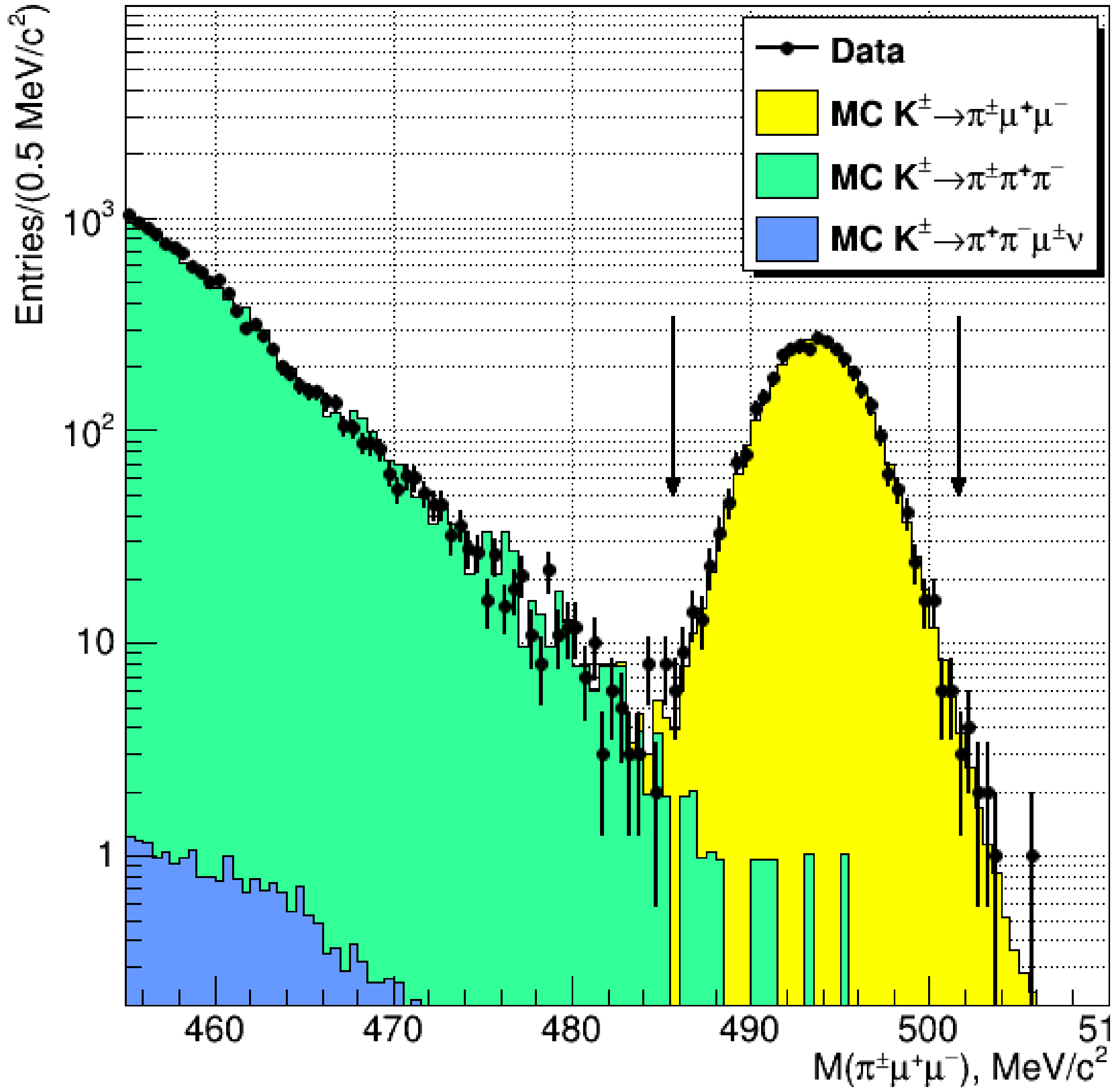
Search for resonances in $K^\pm \to \pi^\pm\mu^+\mu^-$ decays

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

$$\sim \frac{\sqrt{BR(K^\pm \to \pi^\pm\mu^+\mu^-)}}{\sqrt{N_K * Acceptance}} \sqrt{\frac{\sigma(M_{res})}{m_K - (m_\pi + 2m_\mu)}}$$



The opposite-sign muons selection (LNC)



- **Event selection:**
  - Minimal changes wrt LNV selection
  - One well-reconstructed 3-track vertex
  - 2 opposite-sign muons, 1 pion
  - Total P_T consistent with zero
  - Signal Region:

$$|M(\pi^{\pm}\mu^{+}\mu^{-}) - M_K| < 8\ \mathrm{MeV}/c^2$$

- **Expected background:** (from MC)

Decay	BR	N_{exp} (LNC)
$K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$	$(5.583 \pm 0.024)\%$	10.85 ± 3.06
$K^{\pm} \to \pi^{+}\pi^{-}\mu^{\pm}\nu$	$(4.5 \pm 0.2)\times10^{-6}$	0.018 ± 0.012
$K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$	$(9.4 \pm 0.6)\times10^{-8}$	3422 ± 219
$K^{\pm} \to \mu^{\pm}\mu^{+}\mu^{-}\nu$	1.35×10^{-8}	0.037 ± 0.003
Total	–	3433 ± 219

3489 $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ candidates in Signal Region* ⟶ To be scanned searching for peaks in $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ invariant masses

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

The mass scan framework

Basic principles:

- Based on selected $K^{\pm} \rightarrow \pi\mu\mu$ 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})

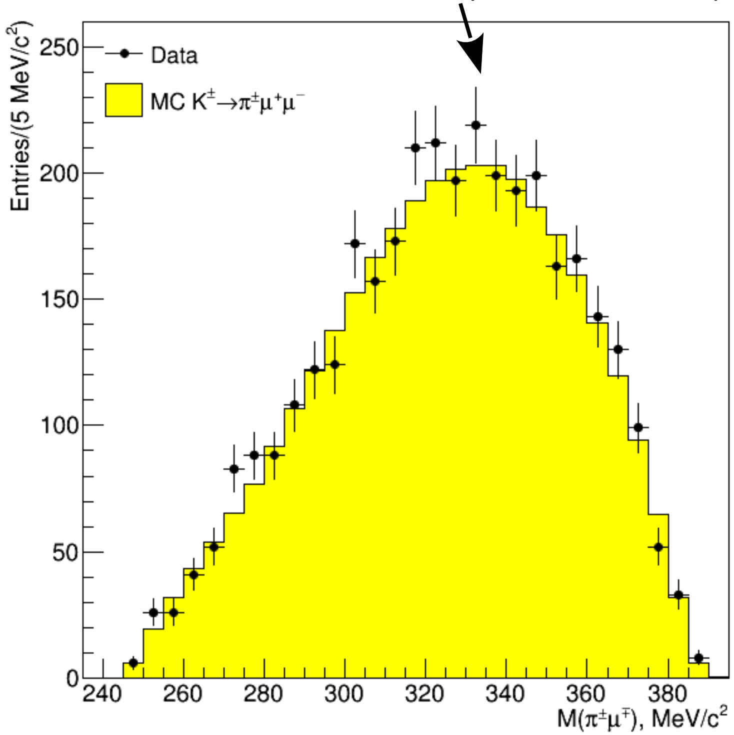
Search for Lepton Number Violation/Majorana neutrinos [284 mass hypotheses M_{res} tested]

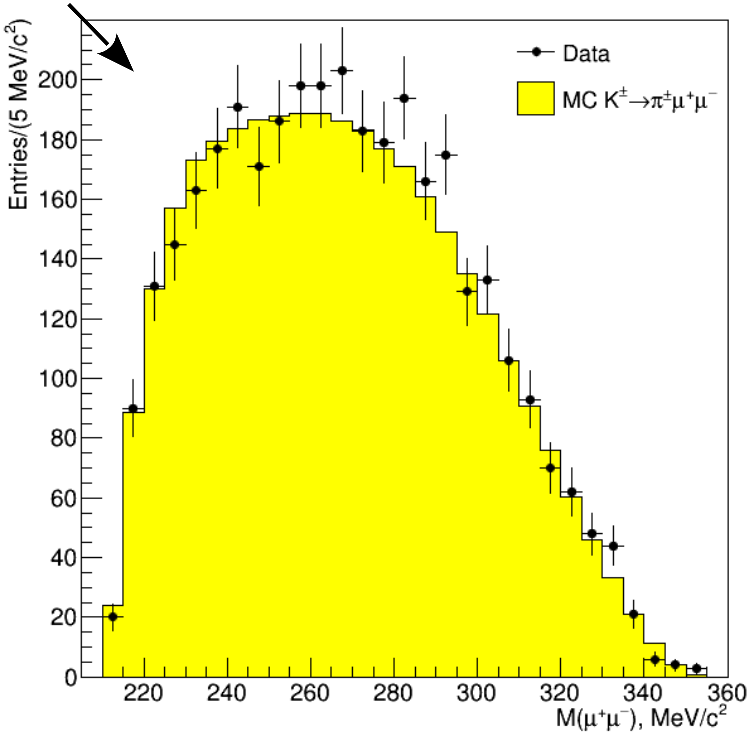
- 2 possibilities in building $M(\pi^{\mp}\mu^{\pm})$ [same-sign μs]: closest invariant mass to M_{res} considered

Search for resonances in $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ decays [267 hypotheses for $M(\pi^{\pm}\mu^{\mp})$, 280 for $M(\mu^{+}\mu^{-})$]

- The distributions of both invariant masses $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ are probed

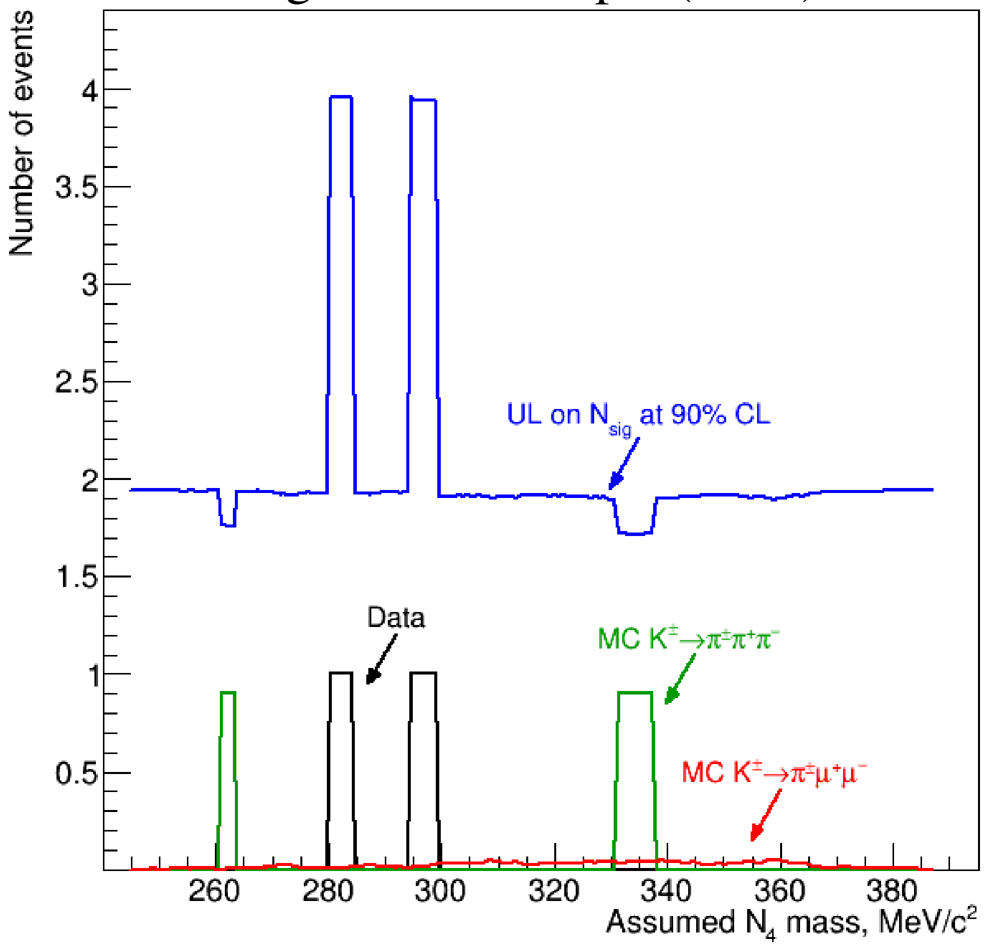
$K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ MC uses form factors extracted from the selected data sample to obtain best data/MC agreement

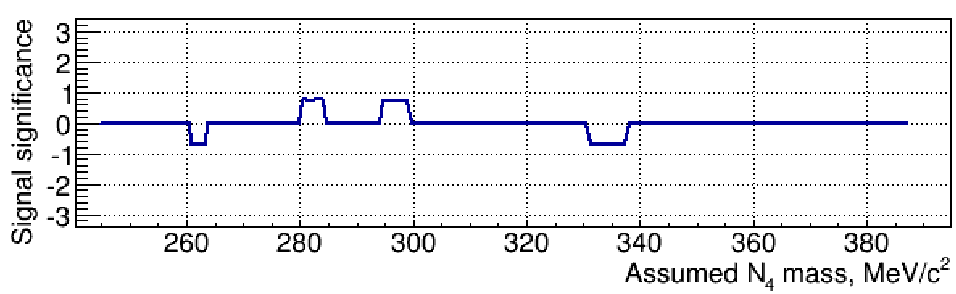




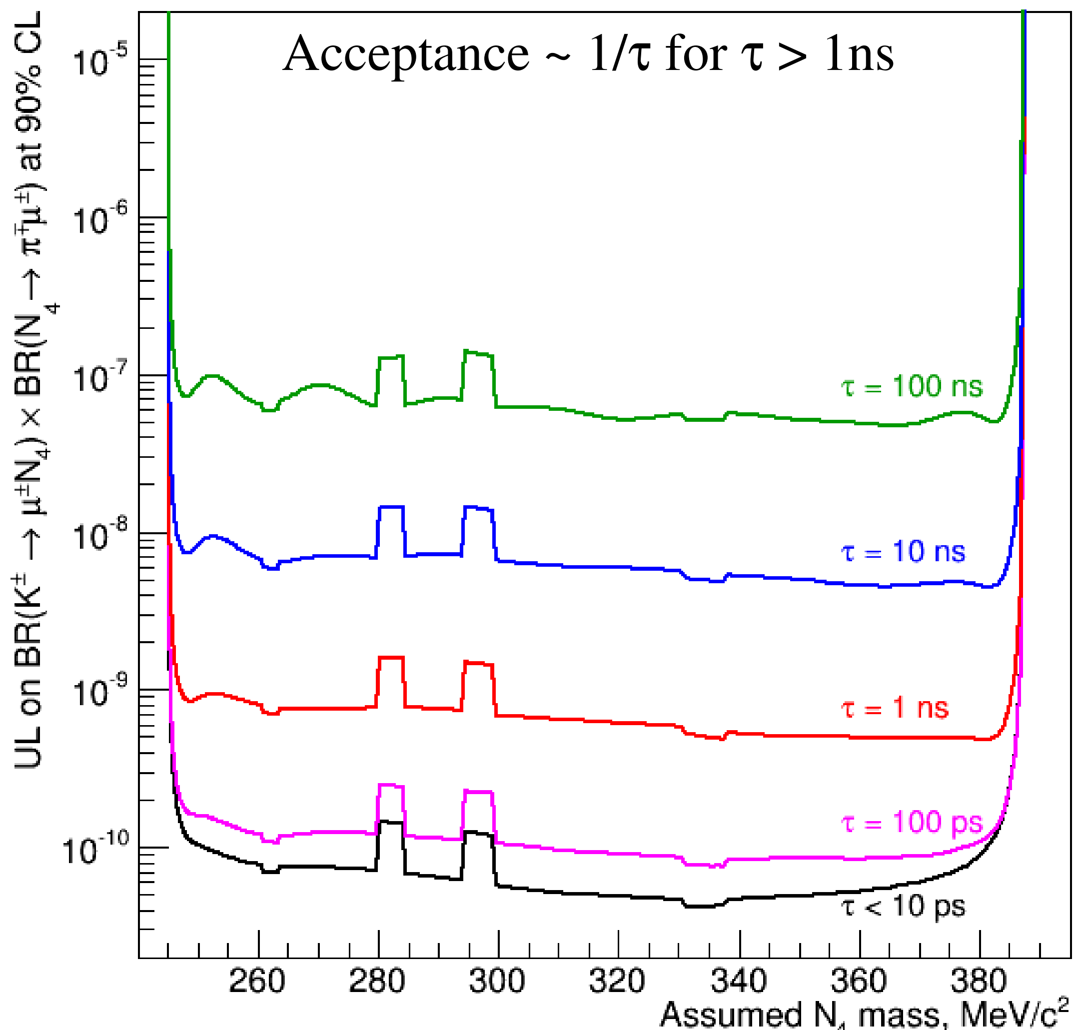
Search for $K^{\pm} \rightarrow \mu^{\pm} N_4 (N_4 \rightarrow \pi^{\mp}\mu^{\pm})$ decays

Same-sign muons sample (LNV)





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

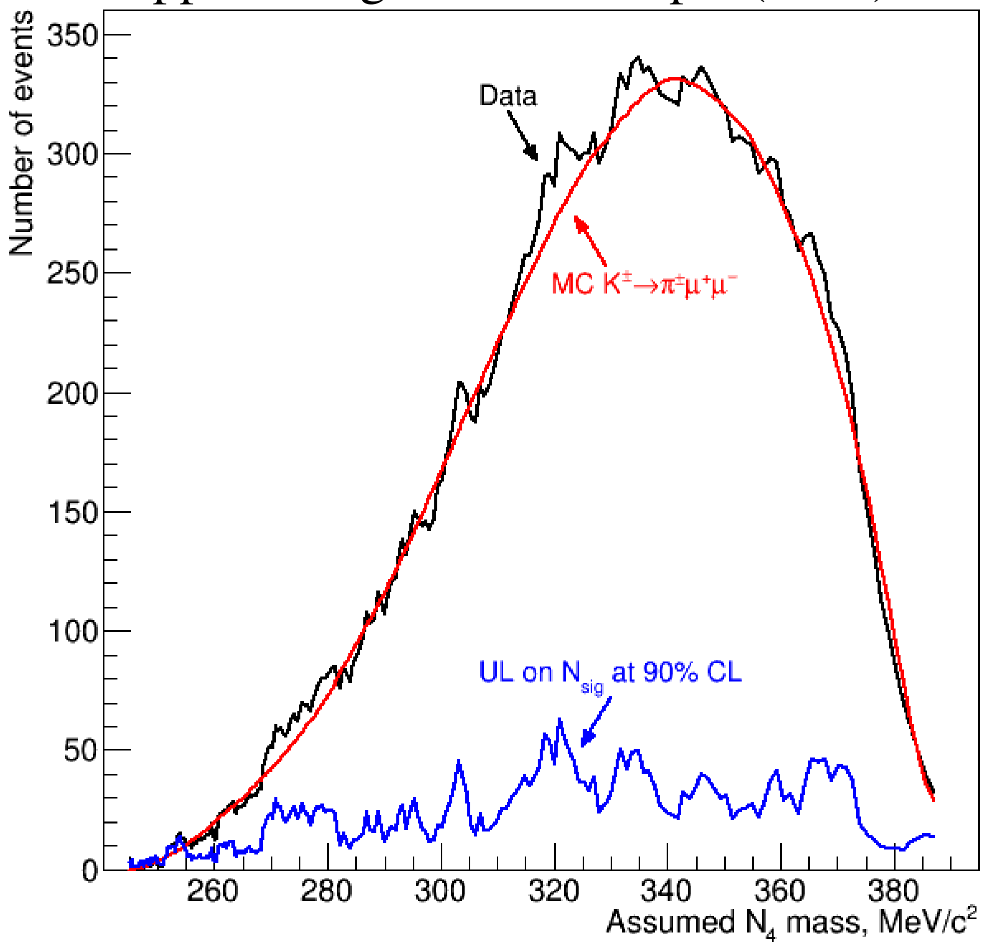


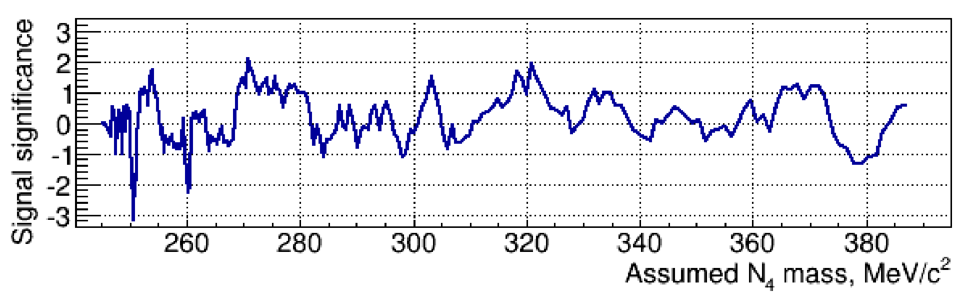
Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

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

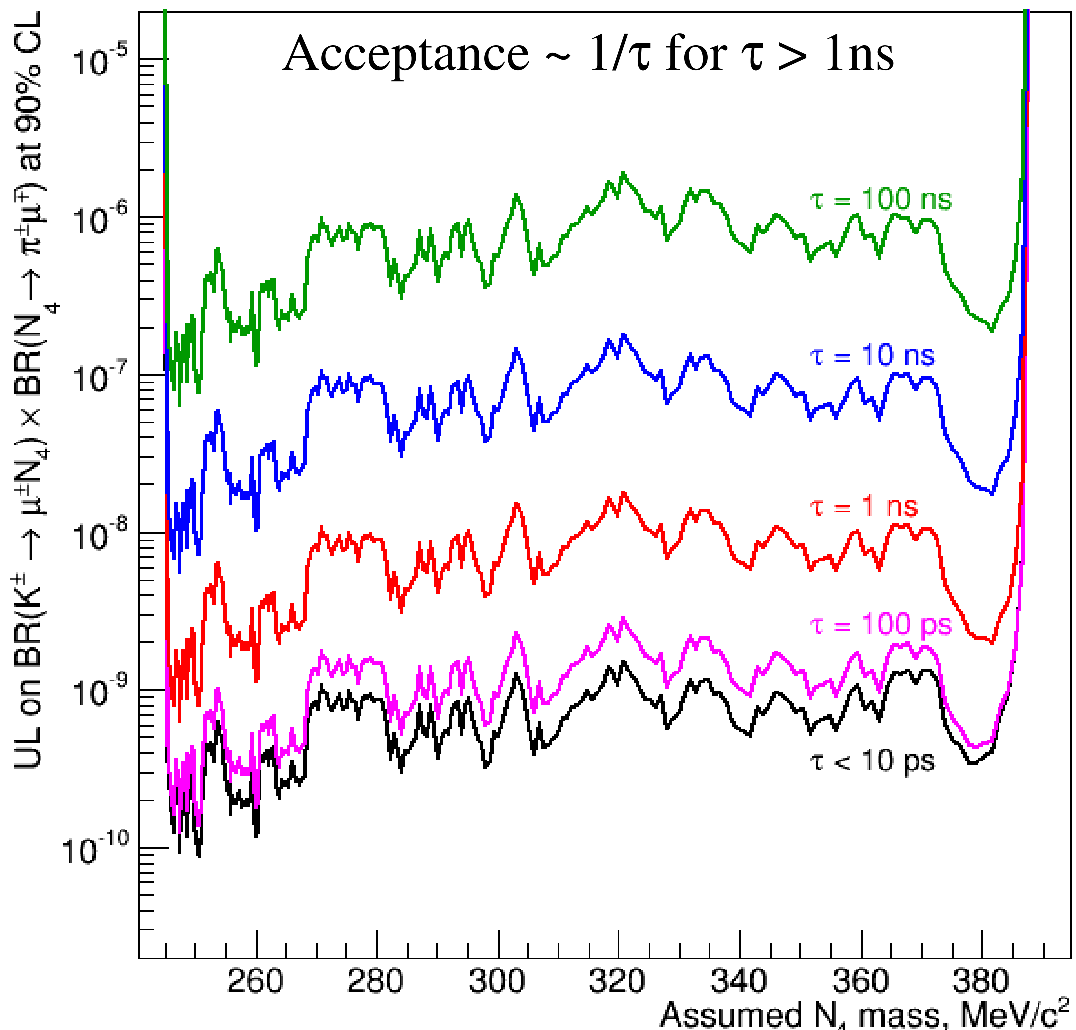
Search for $K^{\pm} \rightarrow \mu^{\pm} N_4 (N_4 \rightarrow \pi^{\pm} \mu^{\mp})$ decays

Opposite-sign muons sample (LNC)





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



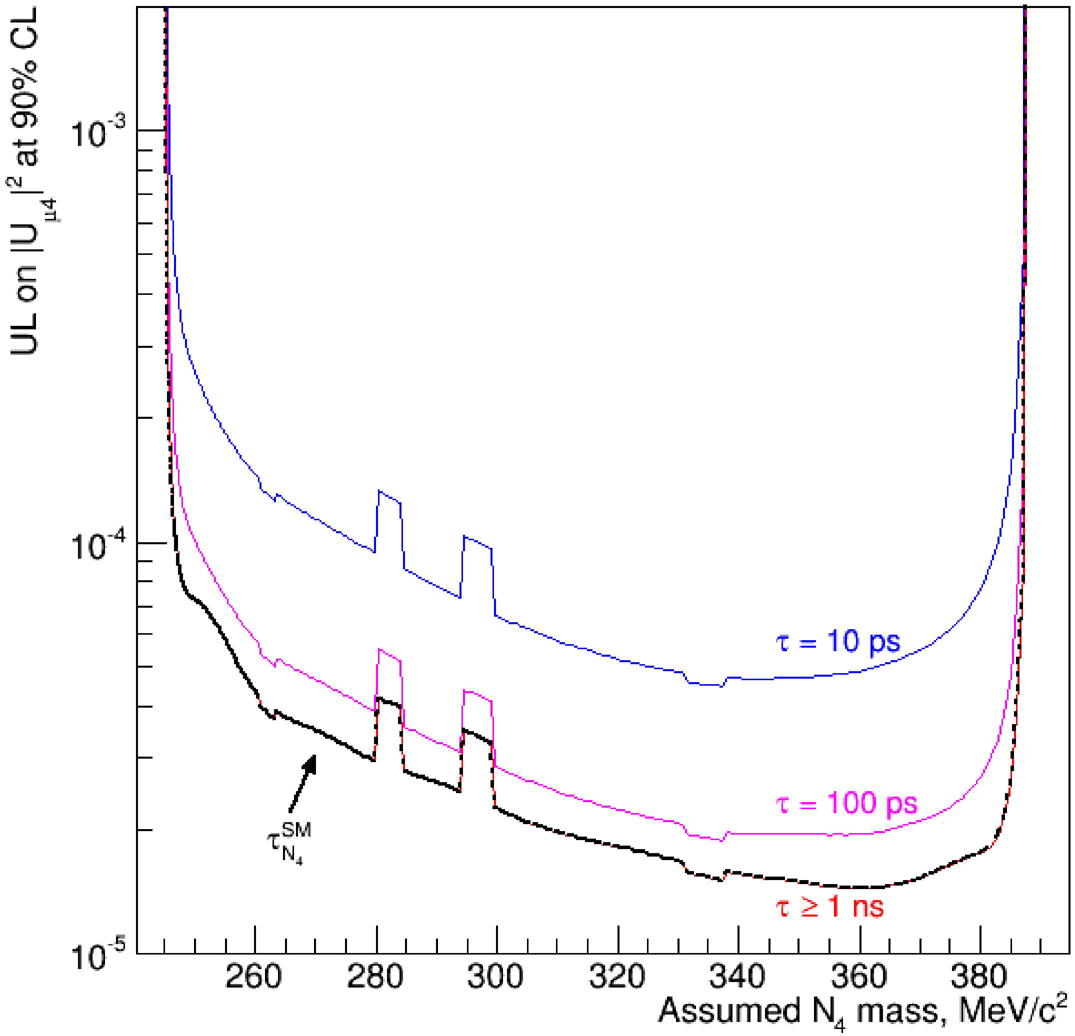
Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

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

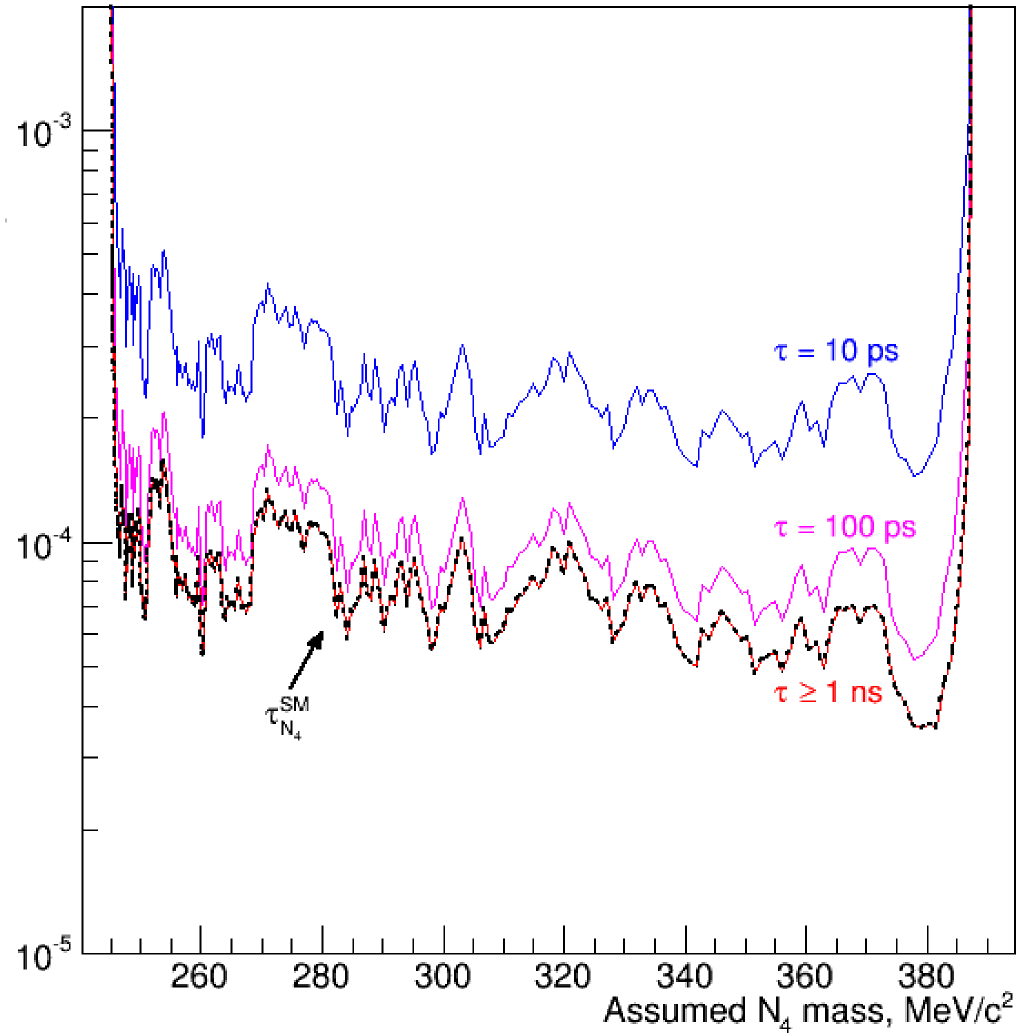
Limits on $|U_{\mu4}|^2$ from $K^\pm \to \mu^\pm N_4 (N_4 \to \pi\mu)$

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

Same-sign muons sample (LNV)

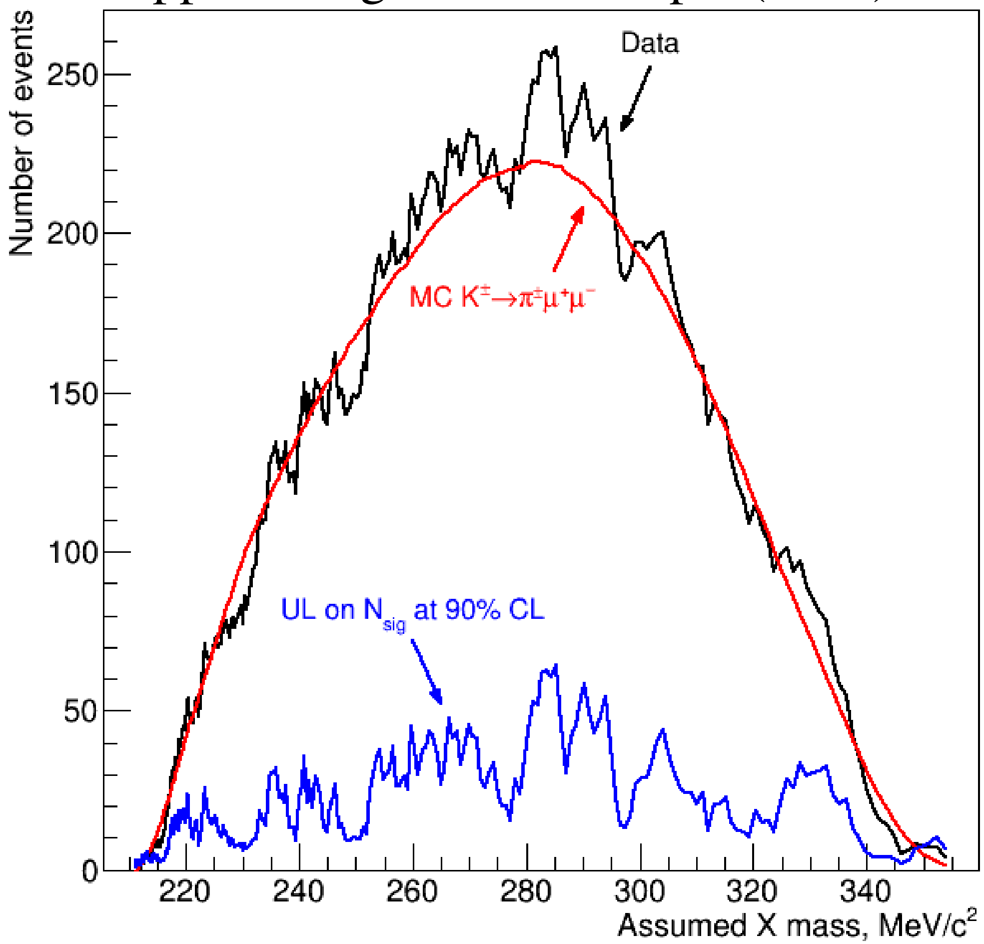


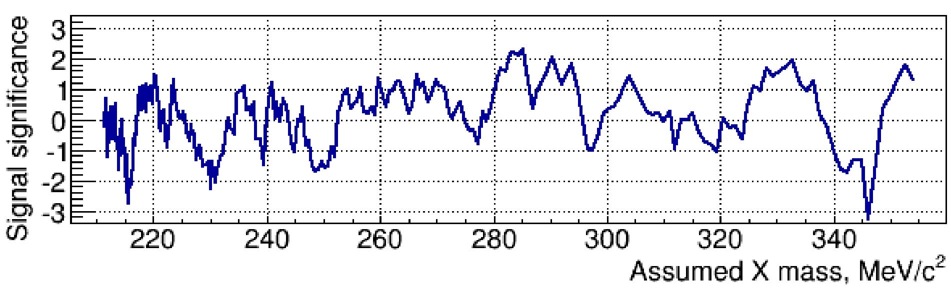
Opposite-sign muons sample (LNC)



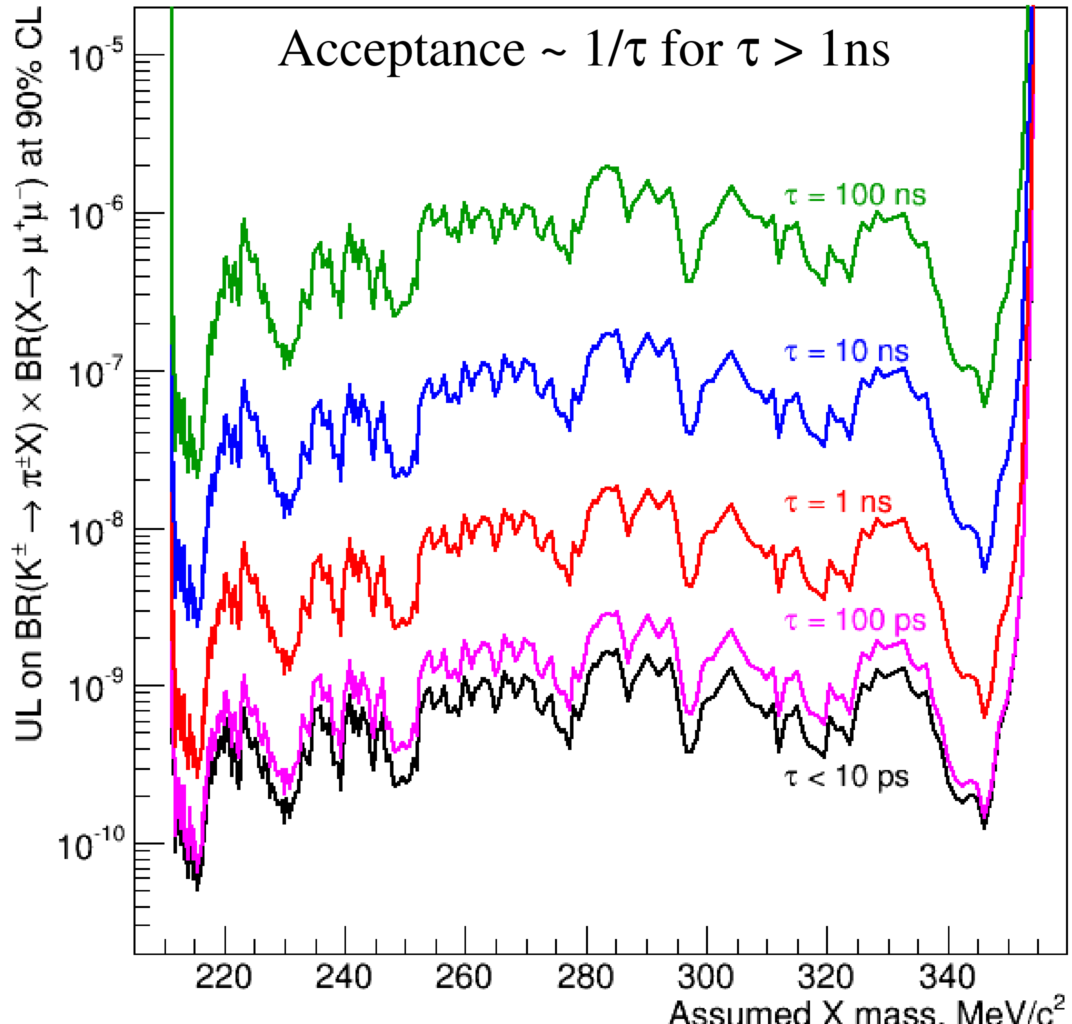
Search for K → $\pi^{\pm}$X(X → $\mu^+\mu^-$) decays

Opposite-sign muons sample (LNC)





$$UL(BR(K^{\pm} \to \pi^{\pm} X) BR(X \to \mu^+\mu^-)) = \frac{UL(N_{sig})}{N_K * Acceptance}$$

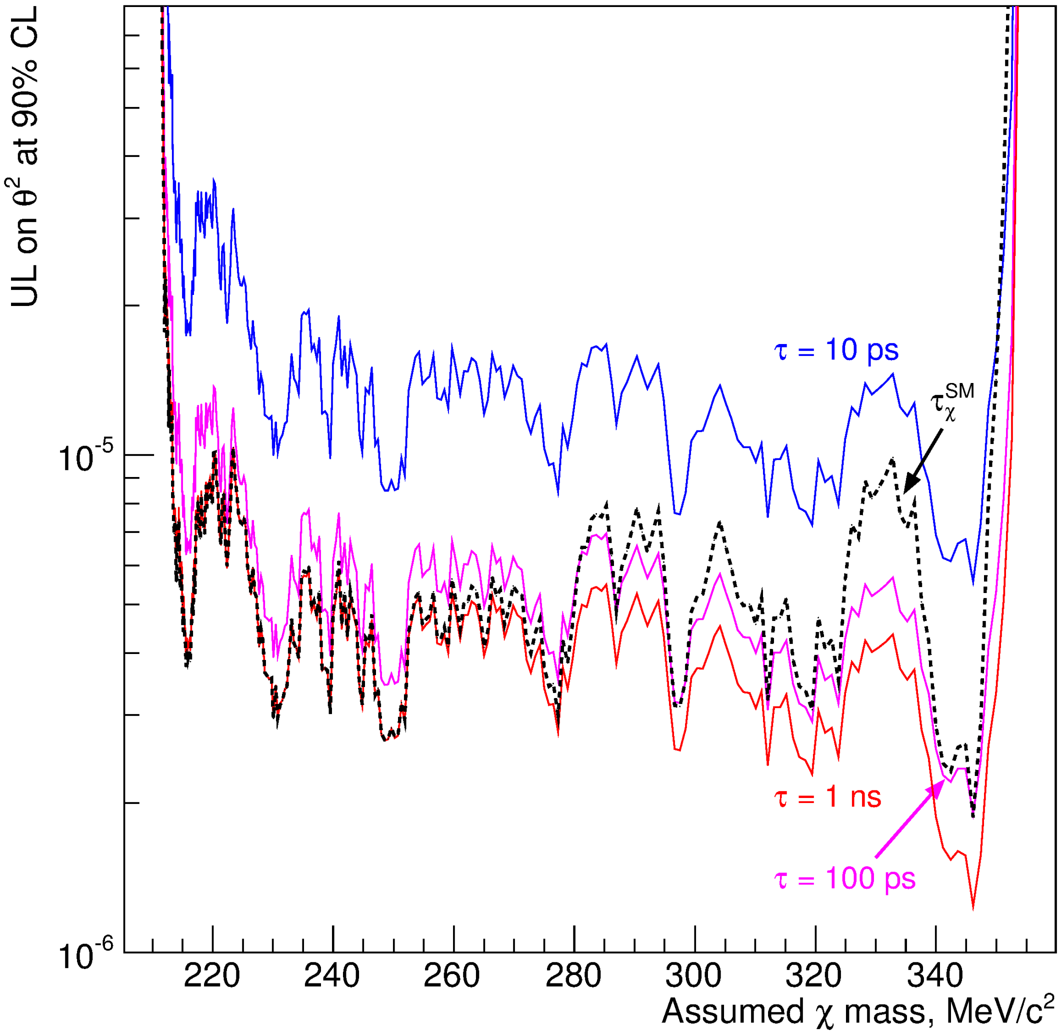


Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$

never exceeds +3σ: **no signal observed**

Limits on θ² from $K^{\pm}\to\pi^{\pm}X(X\to\mu^{+}\mu^{-})$

$$\theta^2 = \sqrt{\frac{8\pi\hbar v^2}{\alpha_\chi}}\sqrt{\frac{\mathcal{B}(K^\pm\to\pi^\pm\chi)\mathcal{B}(\chi\to\mu^+\mu^-)}{\tau_\chi M_\chi^3\lambda^{\frac{1}{2}}(1,r_\pi^2,r_\chi^2)\lambda^{\frac{1}{2}}\left(1,\tilde{\rho}_\mu^2,\tilde{\rho}_\mu^2\right)\tilde{\chi}_{\mu\mu}}}$$



Prospects for the NA62 experiment

Search for Lepton Number Violation – Majorana neutrinos

- Main background: **$K^\pm \to \pi^\pm\pi^+\pi^-$ with 2 $\pi^\pm \to \mu^\pm\nu$ decays** (one within the Spectrometer)
- Sensitivity:

$$\left.\begin{array}{l}\text{UL on } BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm) \\ \text{UL on } BR(K^\pm \to \mu^\pm N_4)\times BR(N_4 \to \pi^\mp\mu^\pm)\end{array}\right\} \sim \frac{1}{N_K * Acceptance}$$

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

- Main background: **$K^\pm \to \pi^\pm\mu^+\mu^-$ (irreducible)** → Limited sensitivity
- Sensitivity:

$$\left.\begin{array}{l}\text{UL on } BR(K^\pm \to \mu^\pm N_4)\times BR(N_4 \to \pi^\pm\mu^\mp) \\ \text{UL on } BR(K^\pm \to \pi^\pm X)\times BR(X \to \mu^+\mu^-)\end{array}\right\} \sim \frac{\sqrt{BR(K^\pm \to \pi^\pm\mu^+\mu^-)}}{\sqrt{N_K * Acceptance}}\sqrt{\frac{\sigma(M_{res})}{m_K-(m_\pi+2m_\mu)}}$$

NA62 expectations (from C. Parkinson numbers):

- $N_{NA62}(K_{\pi\mu\mu}) \sim 7\times N_{NA48/2}(K_{\pi\mu\mu})$
- $Acc_{NA62}(K_{\pi\mu\mu}) \sim 0.8\times Acc_{NA48/2}(K_{\pi\mu\mu})$
- $\sigma_{NA62}(M_{\pi\mu\mu}) \sim 0.5\times\sigma_{NA48/2}(M_{\pi\mu\mu})$

} →

$SES_{NA62}(LNV) \sim 0.2\times SES_{NA48/2}(LNV)$

$SES_{NA62}(LNC) \sim 0.3\times SES_{NA48/2}(LNC)$

Conclusions

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

- **NA48/2 results presented:** **[Batley et al., PLB 769 (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
  - **Search for $K \to \pi^\pm X (X \to \mu^+\mu^-)$ decays [Inflatons, …]**
    - Limits on BR products of the order of **10^{-9}** for resonance lifetimes < 100 ps

- **Prospects for the new NA62 experiment (See next talk by C. Parkinson):**
  - NA62 will collect the world-largest K^+ decay sample (~ 10^{13}) in 3 years of data taking
  - Major beam and detector upgrades for $K^+ \to \pi^+ \nu\bar{\nu}$: improved performances
  - Possible improvements to the present limits by a factor ~ × 3–5