Search for LNV and resonances in $K^{\pm} \rightarrow \pi\mu\mu$ decays at NA48/2

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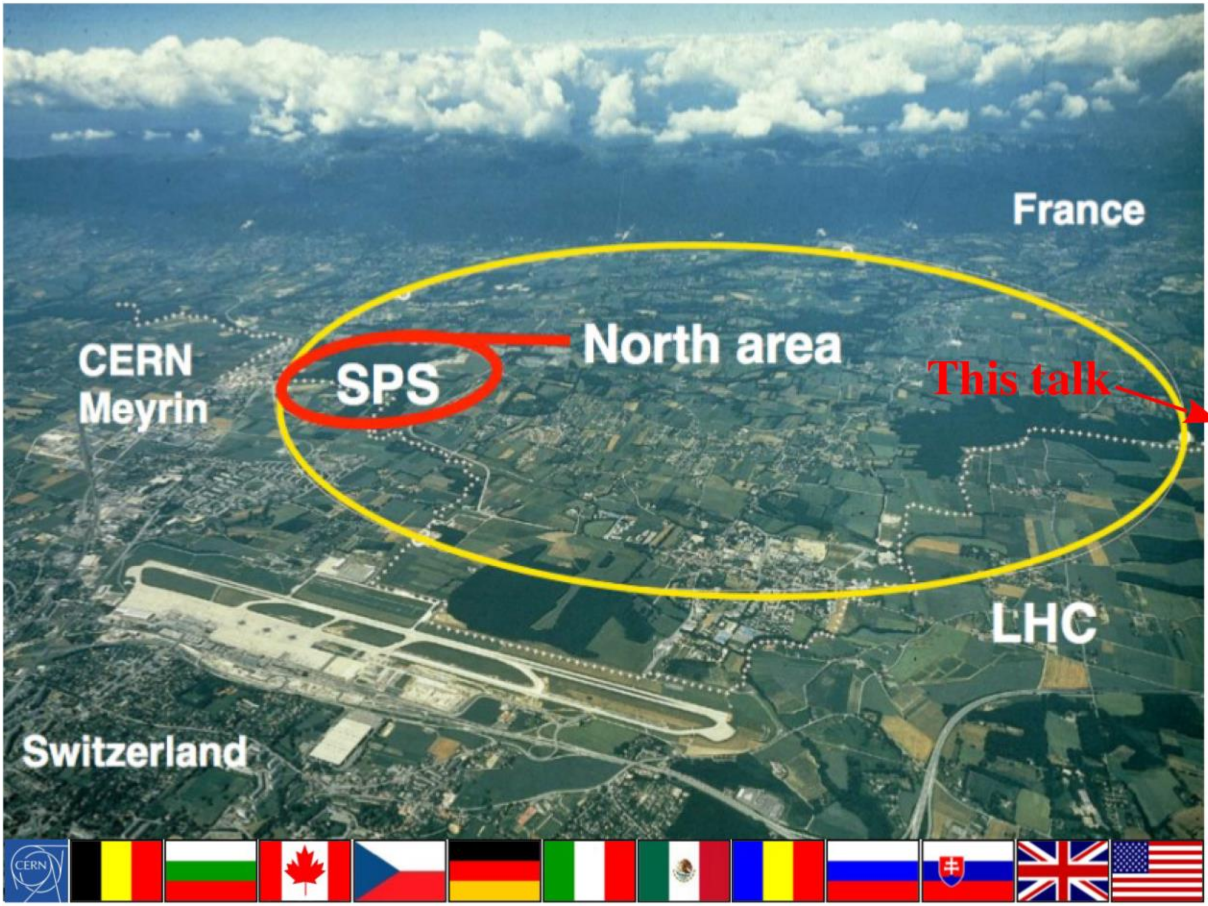
On behalf of the NA48/2 collaboration

Outline

- The NA48/2 beam and experiment
- Theoretical motivations:
    - Majorana Neutrinos
    - Inflatons
- Search for LNV $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay - Majorana neutrinos
- Search for resonances in the $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ decays
- Prospects for the NA62 experiment
- Conclusions

The NA48 and NA62 collaborations

NA62 is the last from a long tradition of fixed-target Kaon experiments in the CERN North Area



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^+)	$K^+ \to \pi^+ \nu\bar{\nu}$, Rare K^+ and π^0 decays

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

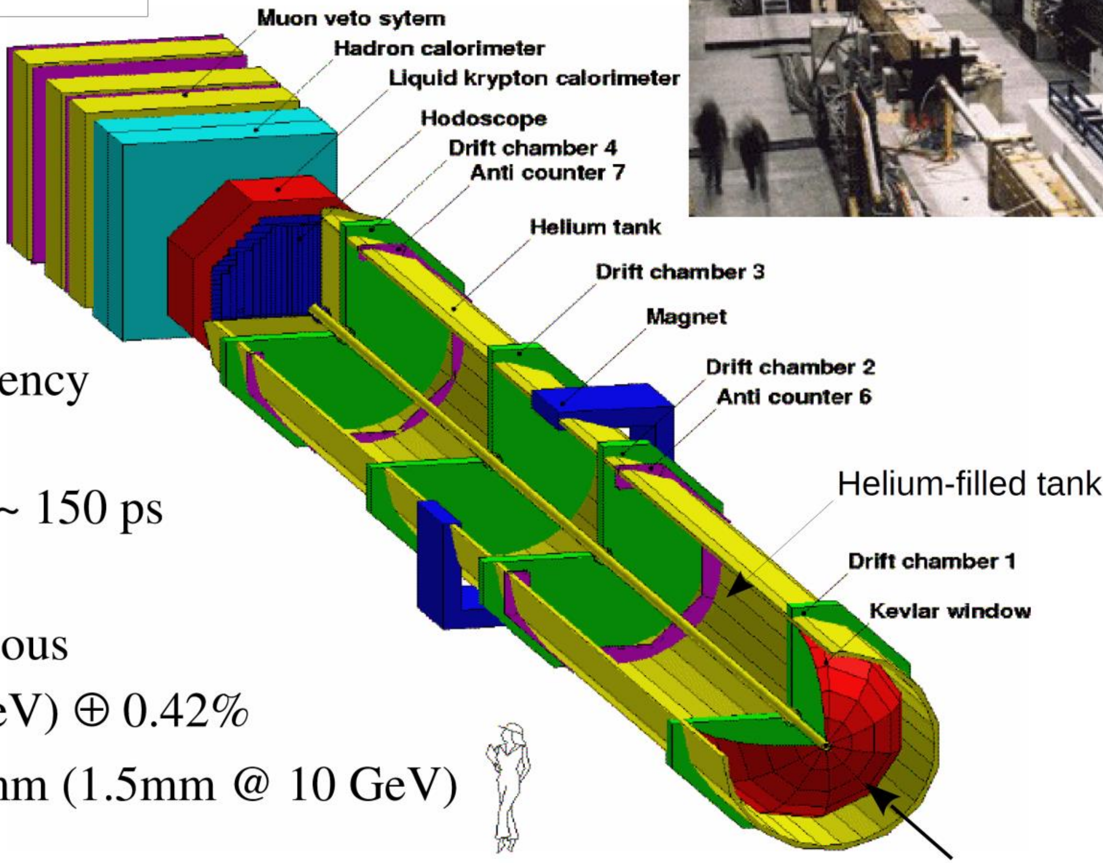
The NA48/2 beam and detector

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



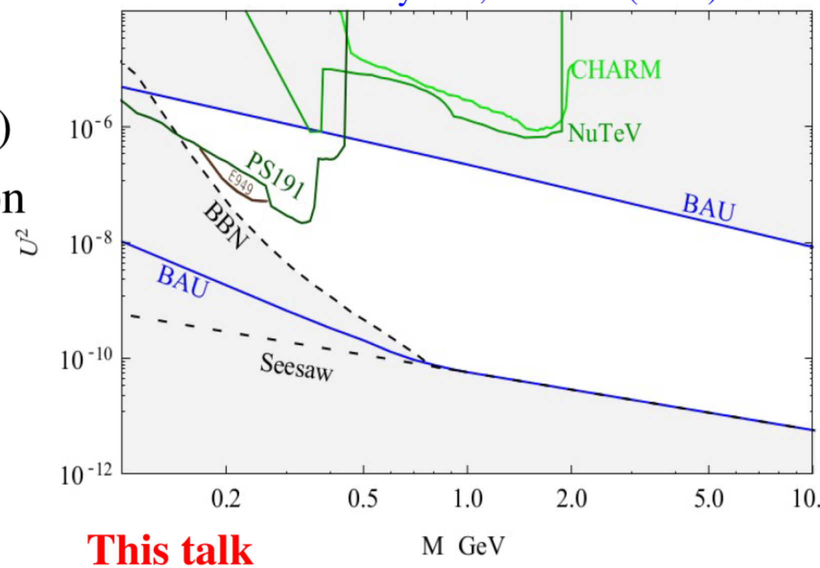
Majorana Neutrinos

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

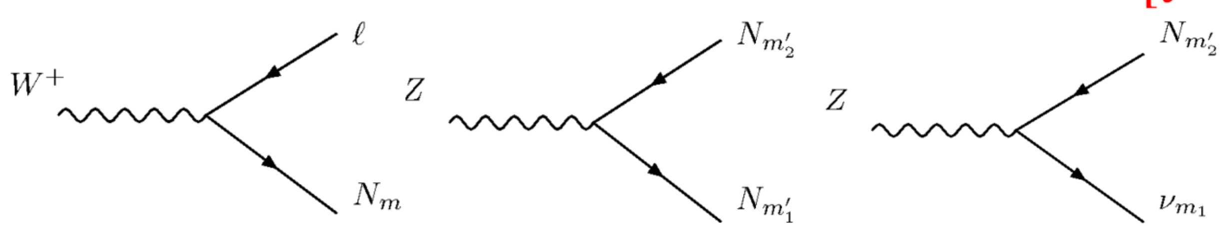
- $\mathbf{N_1}$ is the lightest O(keV) → Dark Matter candidate
- $\mathbf{N_2}$, $\mathbf{N_3}$ are nearly degenerate (100 MeV to few GeV)

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



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

This talk [$\ell = \mu$]

$N_{2,3}$ production in $K^\pm$ decays:
$K^\pm \to \ell^\pm N$, $K^\pm \to \pi^0 \ell N$, …

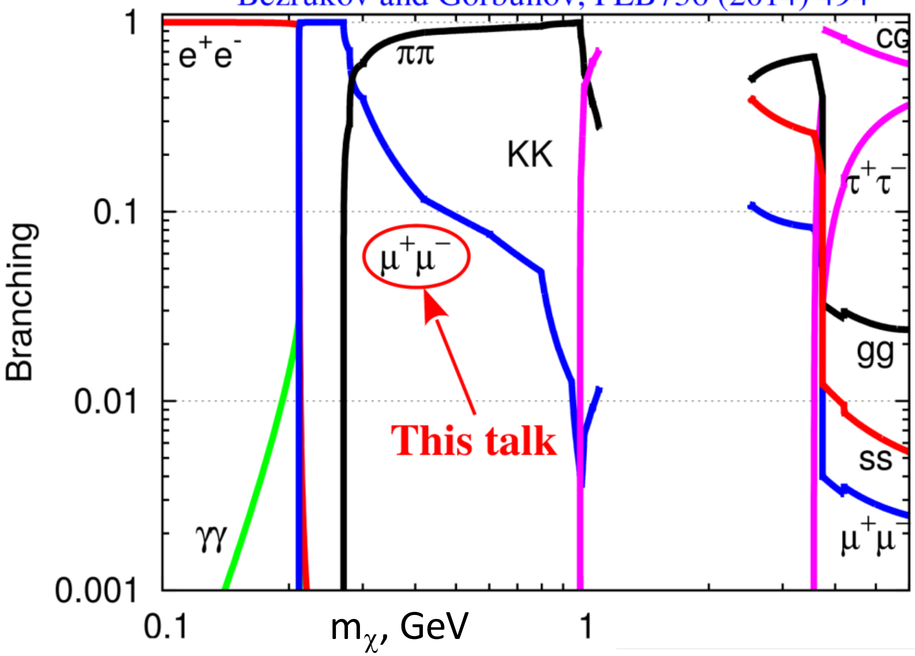
$N_{2,3}$ decays for $m_{2,3} < m_K - m_\ell$:
$N \to \pi^\pm \ell^\mp$, $N \to \pi^0 \nu$
$N \to \ell_1^\pm \ell_2^\mp \nu_2$, $N \to \nu_1 \ell_2^+ \ell_2^-$
$N \to \nu_\ell \nu \bar{\nu}$

Inflatons

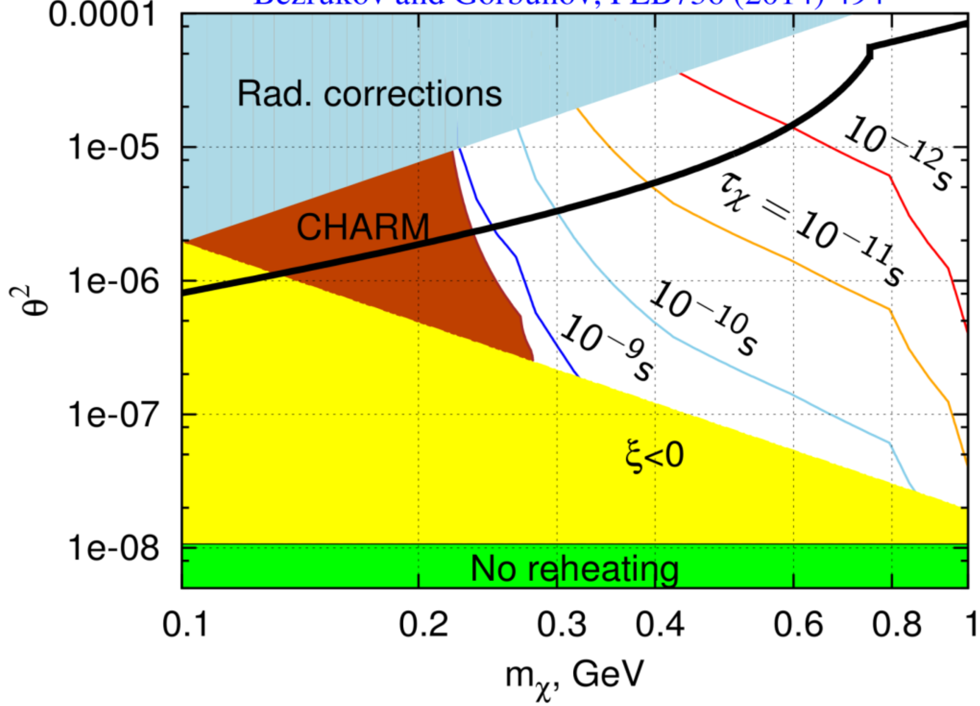
Shaposhnikov-Tkachev model [Shaposhnikov and Tkachev, PLB 639 (2006) 414]:
νMSM + a real scalar field (inflaton χ) with scale-invariant couplings
Explains Universe homogeneity and isotropy on large scales/structures on smaller scales

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

Bezrukov and Gorbunov, PLB736 (2014) 494



Bezrukov and Gorbunov, PLB736 (2014) 494



χ in Kaon decays [$m_\chi < 354$ MeV/c²]

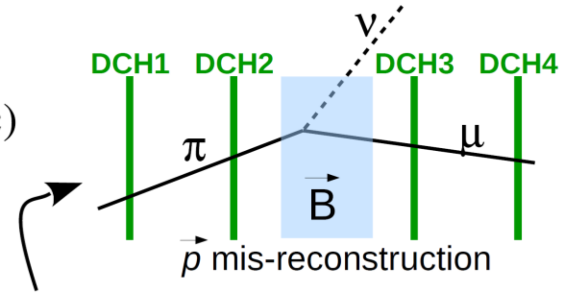
$$BR(K^\pm \to \pi^\pm \chi) = 1.3\times 10^{-3}\left(\frac{2|\vec{p}_\chi|}{M_K}\right)\theta^2$$

The same-sign muons sample (LNV)

Basic principles of the searches:

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

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



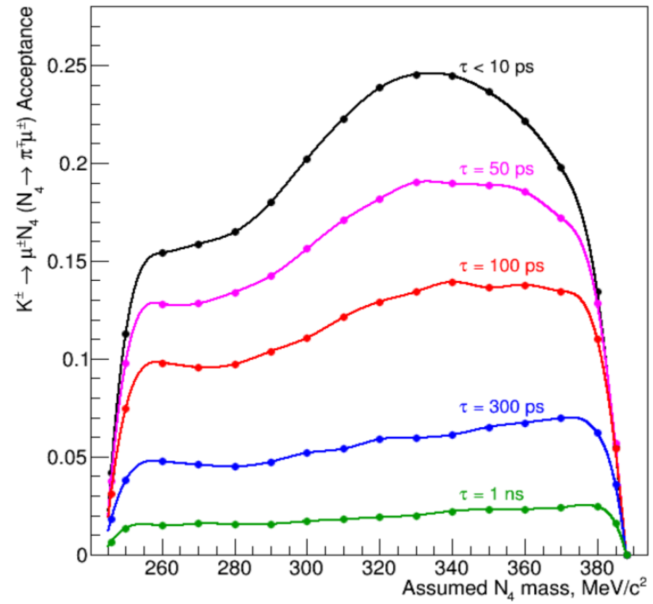
Search for Lepton Number Violation – Majorana neutrinos

- 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 $BR(K^\pm \to \pi^\mp\mu^\pm\mu^\pm)$

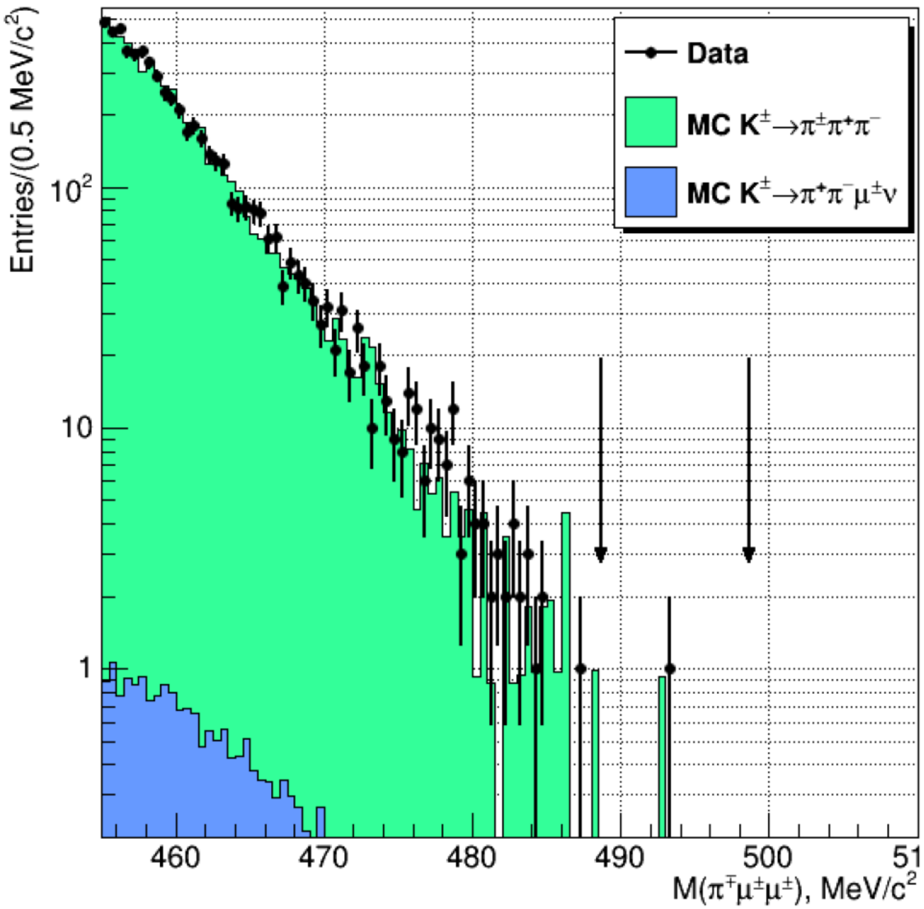
  UL on $BR(K^\pm \to \mu^\pm N_4) \times BR(N_4 \to \pi^\mp\mu^\pm)$ $\Big\} \sim \dfrac{1}{N_K * Acceptance}$

$K^\pm$ 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



- **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) 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 × 10^{-11} @ 90% CL**

$K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ background

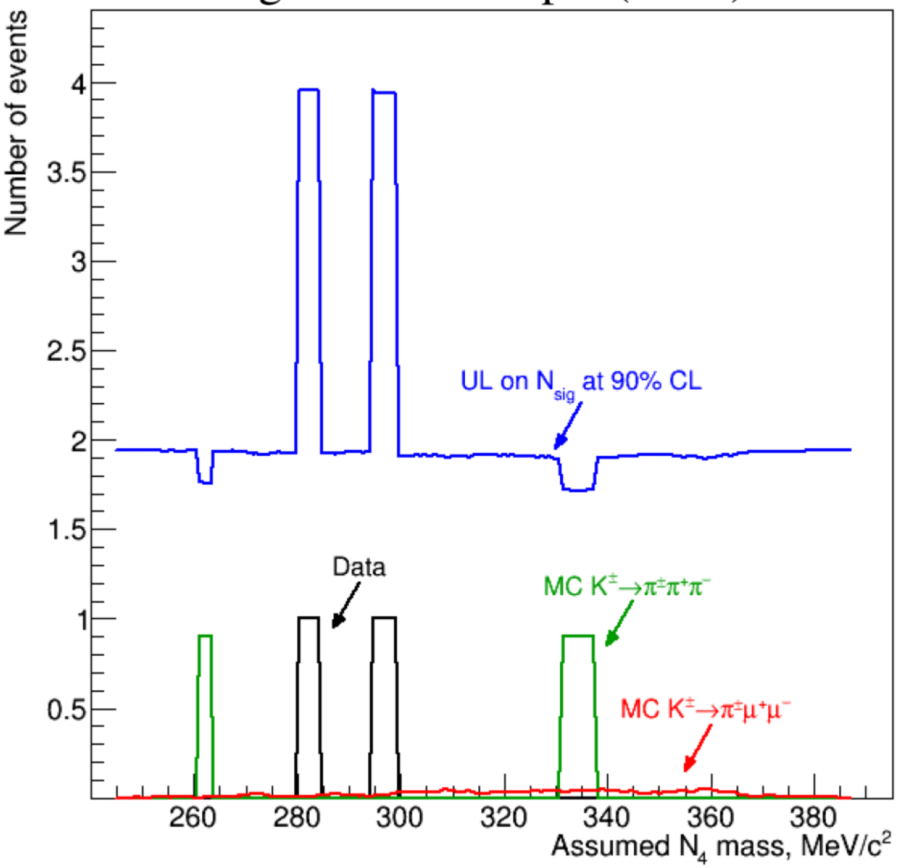
Size of MC sample compared to the data:

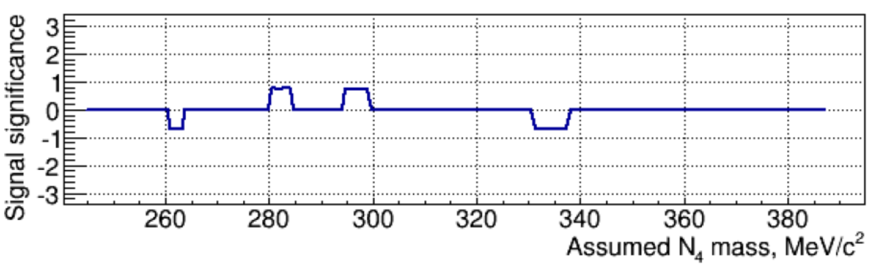
$$\rho = \frac{N_{GEN}}{N_K \times BR}$$

Decay channel	Branching fraction	ρ	$N_{\text{exp}}^{\text{LNV}} \pm \sigma_{\text{stat}}^{N} \pm \sigma_{\text{ext}}^{N}$
$K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$	$(5.59 \pm 0.04) \times 10^{-2}$	1.15	$0.867 \pm 0.867 \pm 0.009$
$K^{\pm} \rightarrow \pi^{+}\pi^{-}\mu^{\pm}\nu$	$(4.5 \pm 0.2) \times 10^{-6}$ (expected)	119.4	$0.027 \pm 0.015 \pm 0.001$
$K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$	$(9.4 \pm 0.6) \times 10^{-8}$	571.7	$0.257 \pm 0.021 \pm 0.016$
$K^{\pm} \rightarrow \mu^{+}\mu^{-}\mu^{\pm}\nu$	1.35×10^{-8} (expected)	3981	0.012 ± 0.001
Total	–	–	$1.163 \pm 0.867 \pm 0.018$

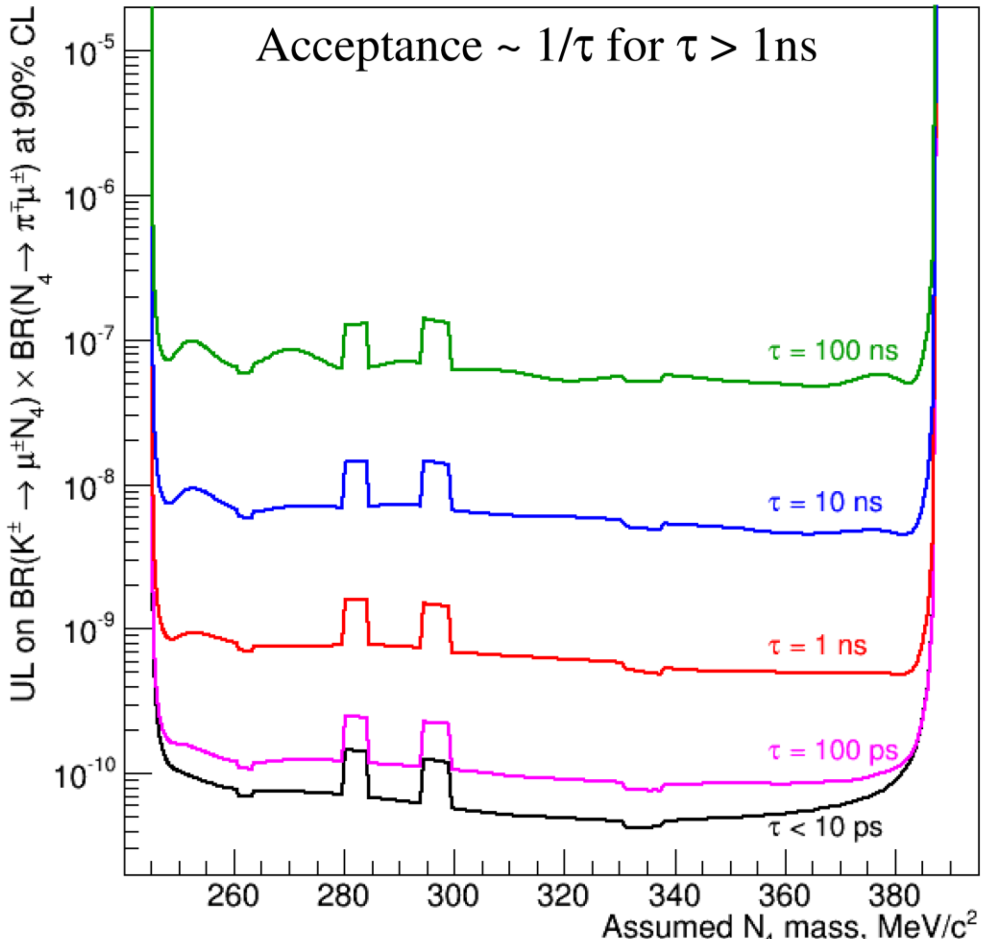
Search for $K^{\pm}\rightarrow\mu^{\pm}N_4(N_4\rightarrow\pi^{\mp}\mu^{\pm})$ decays

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**

The opposite-sign muons sample (LNC)

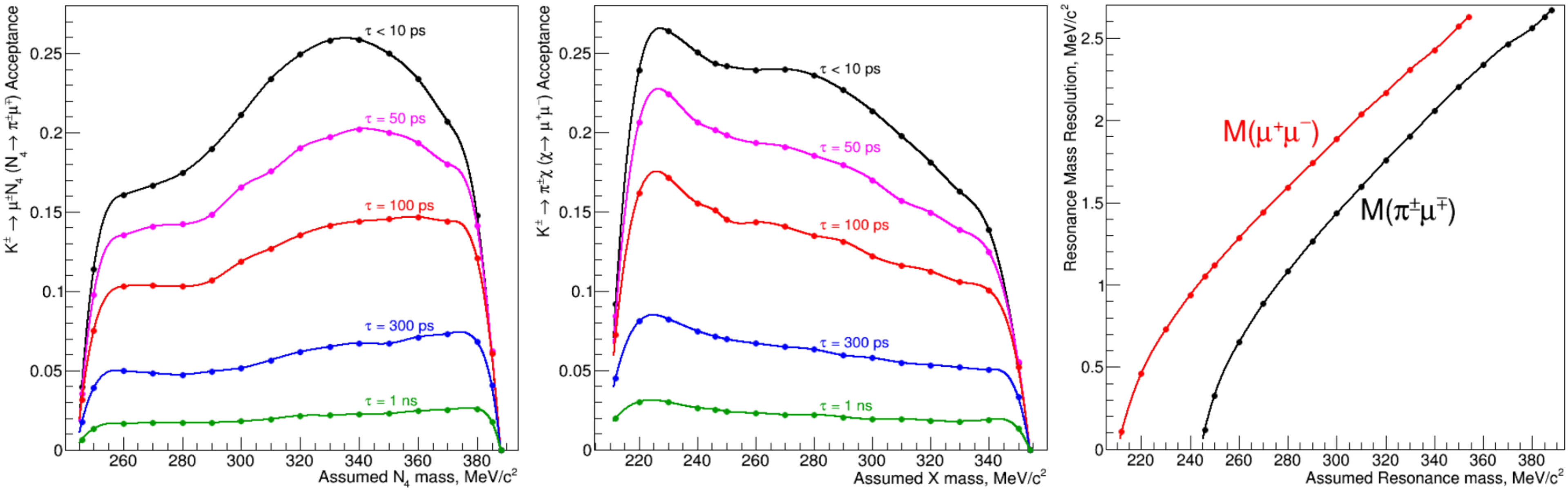
Basic principles of the searches:

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

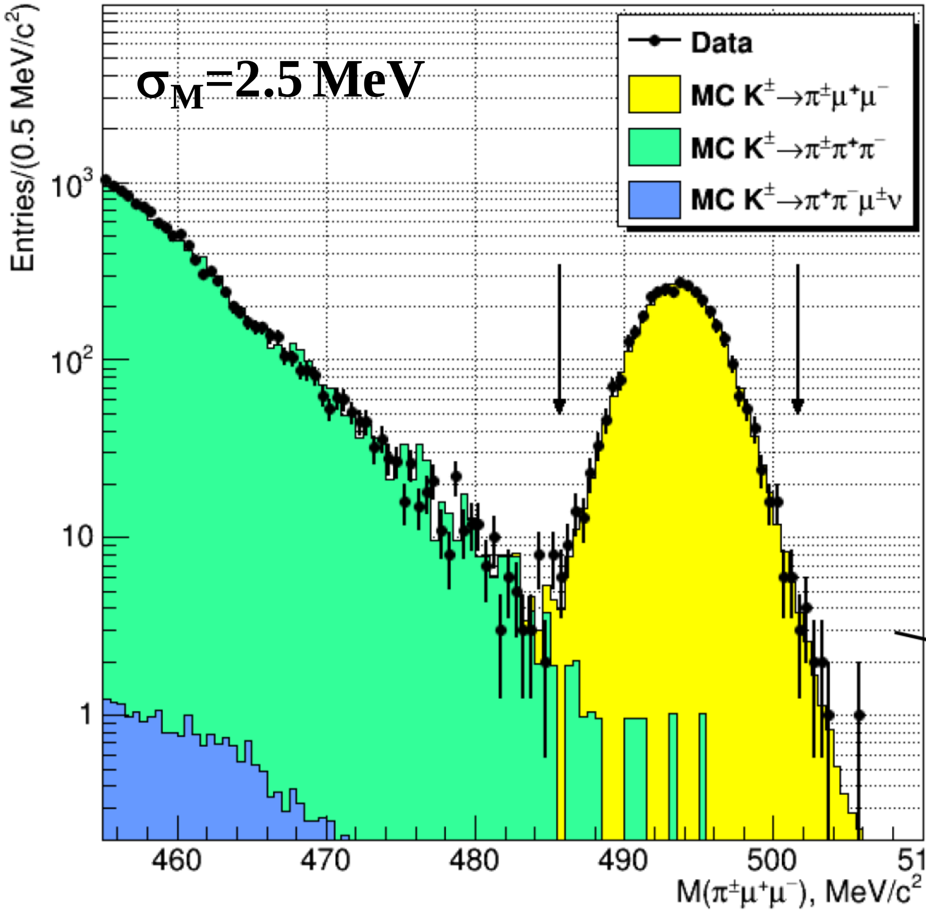
  $\to$ First-order cancellation of systematic effects (trigger inefficiency, etc)

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

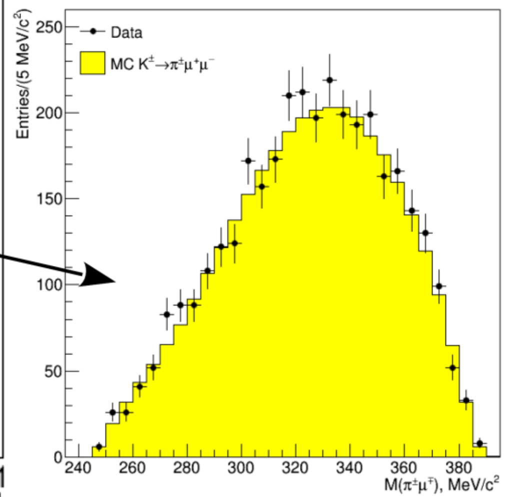
- Method: exclusive search for the decay chains $K^\pm \to \mu^\pm N_4 (N_4 \to \pi^\pm\mu^\mp)$, $K^\pm \to \pi^\pm X (X \to \mu^+\mu^-)$
- Main background: **$K^\pm \to \pi^\pm\mu^+\mu^-$ (irreducible)** $\to$ Limited sensitivity
- Sensitivity: UL on $BR(K^\pm \to \mu^\pm N_4) \times BR(N_4 \to \pi^\pm\mu^\mp)$, UL on $BR(K^\pm \to \pi^\pm X) \times BR(X \to \mu^+\mu^-)$ $\sim \frac{\sqrt{BR(K^\pm \to \pi^\pm\mu^+\mu^-)}}{\sqrt{N_K * Acceptance}} \sqrt{\frac{\sigma(M_{res})}{m_K - (m_\pi + 2m_\mu)}}$

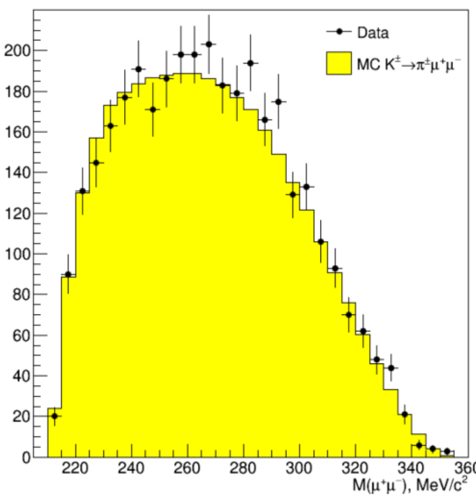


The opposite-sign muons selection



- **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





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

→ 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 method

Basic principles:

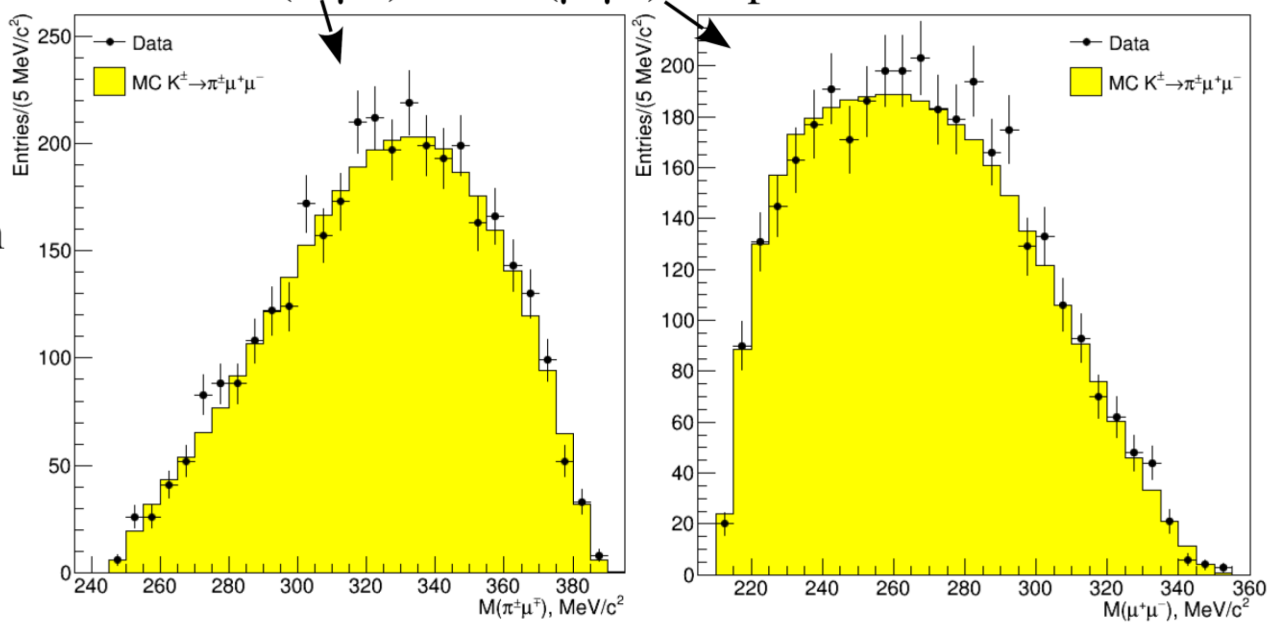
- Based on selected $K^{\pm} \rightarrow \pi\mu\mu$ candidates. Variable step = $0.5\sigma(M_{res})$ and window = $\pm\, 2\sigma(M_{res})$
- For each M_{res}: Observed events in data (N_{obs}) vs Expected events from MC (N_{exp}) → UL(N_{sig})
- Rolke-Lopez statistical treatment used in each mass hypothesis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

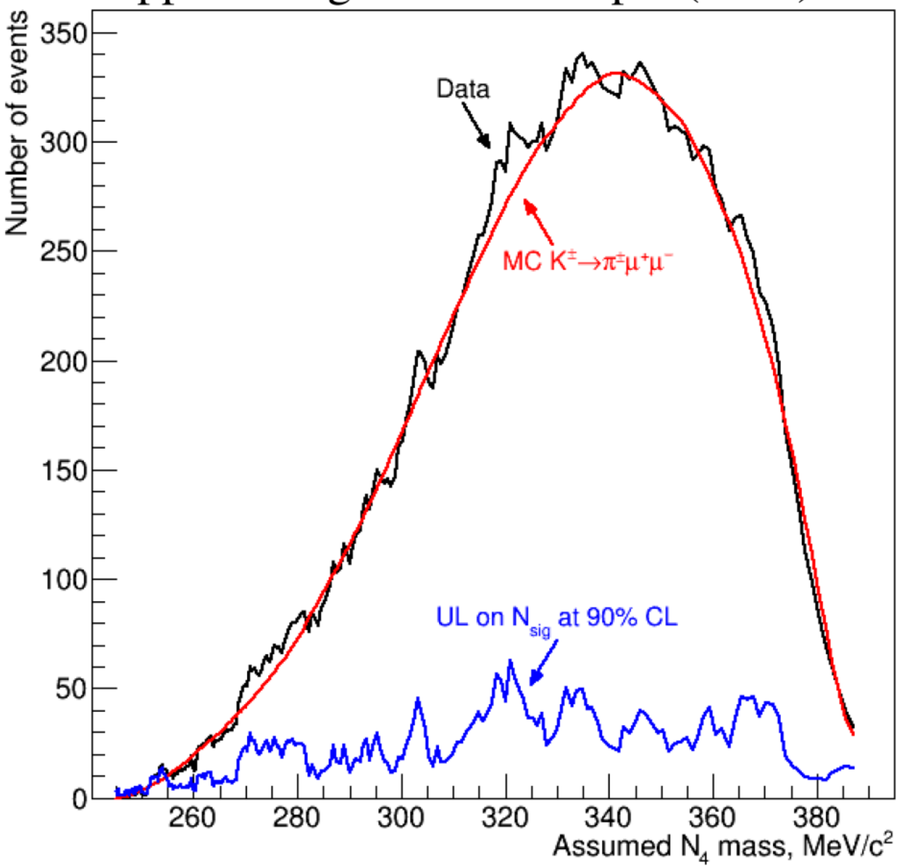
Search for resonances in $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ decays

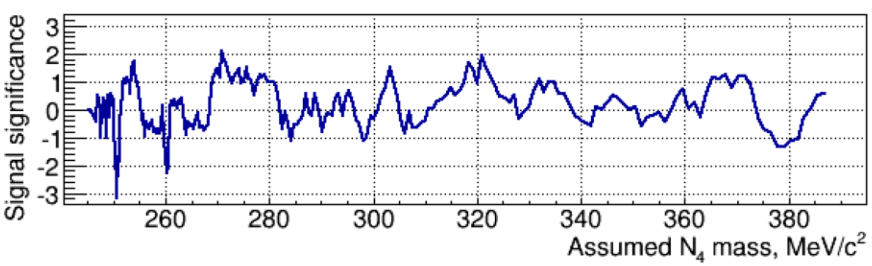
- The distributions of both invariant masses $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ are probed
- 267 hypotheses for $M(\pi^{\pm}\mu^{\mp})$
- 280 hypotheses for $M(\mu^{+}\mu^{-})$
- $K^{\pm} \rightarrow \pi^{\pm}\mu^{+}\mu^{-}$ MC simulation uses form factors extracted from the selected data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



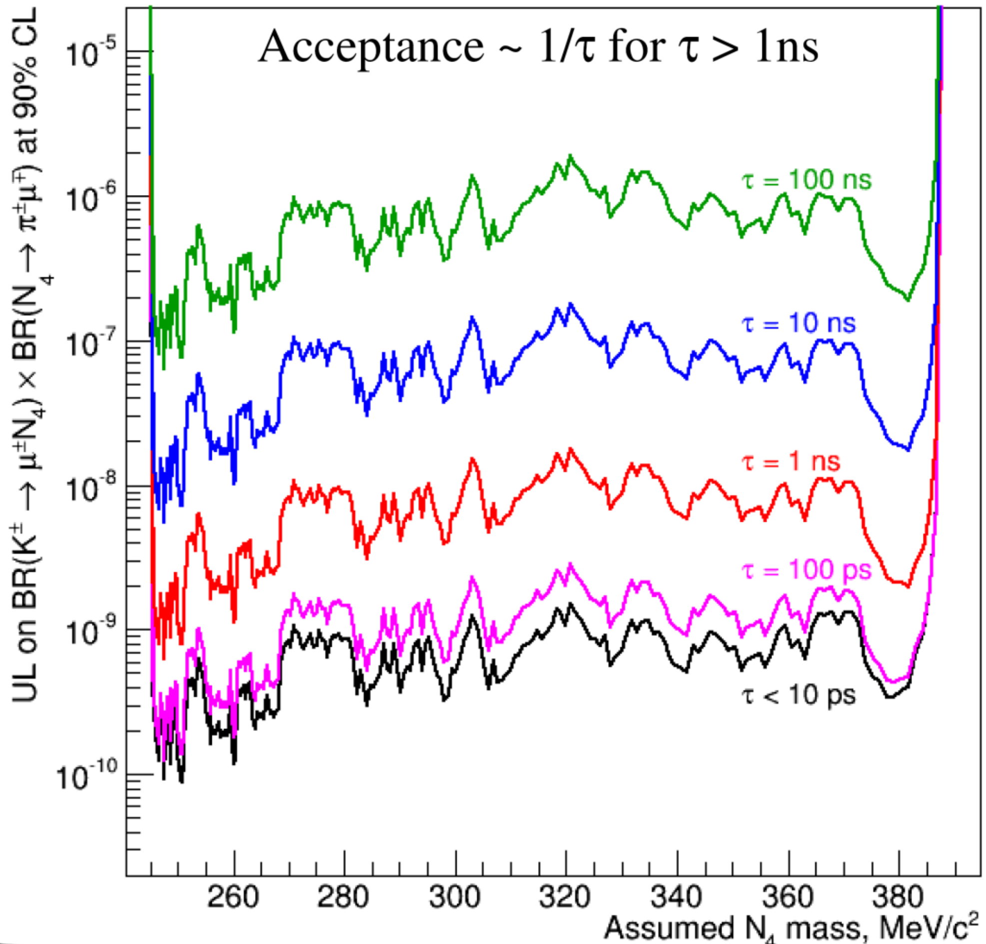
Search for $K^{\pm}\rightarrow\mu^{\pm}N_4(N_4\rightarrow\pi^{\pm}\mu^{\mp})$ decays

Opposite-sign muons sample (LNC)





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

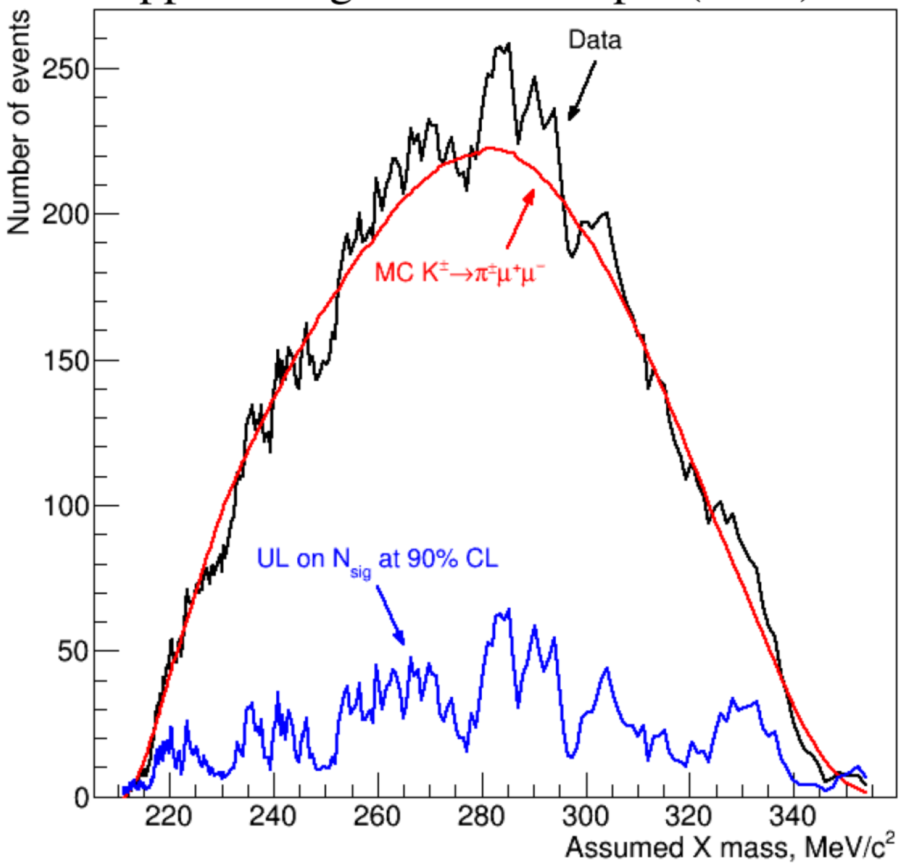


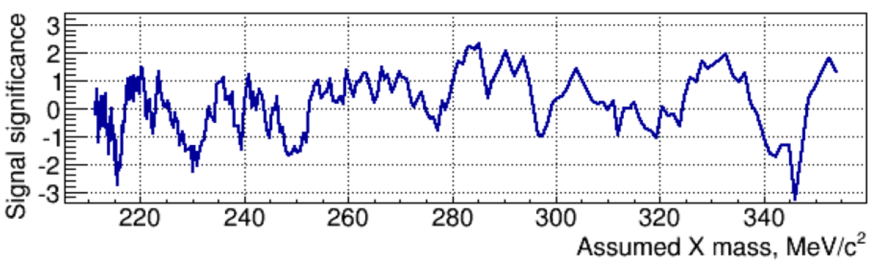
Statistical significance $z=\frac{N_{obs}-N_{exp}}{\sigma(N_{obs})\oplus\sigma(N_{exp})}$

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

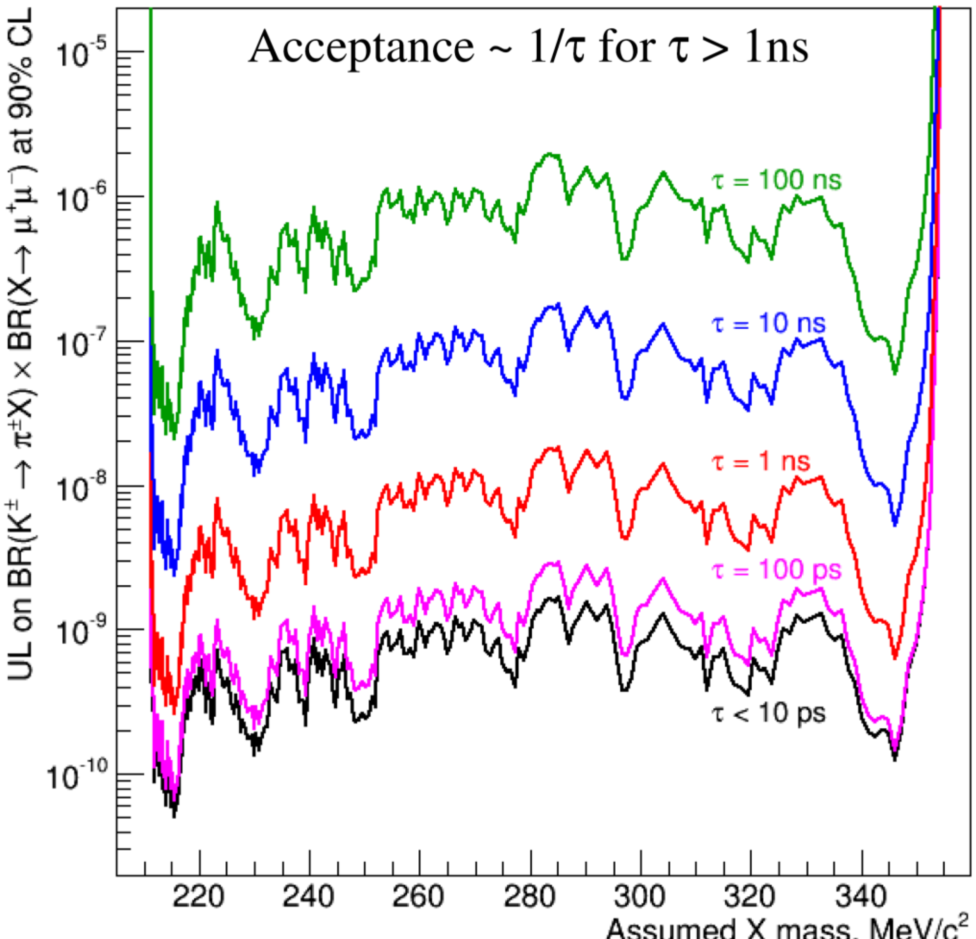
Search for $K^{\pm}\to\pi^{\pm}X(X\to\mu^{+}\mu^{-})$ decays

Opposite-sign muons sample (LNC)





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

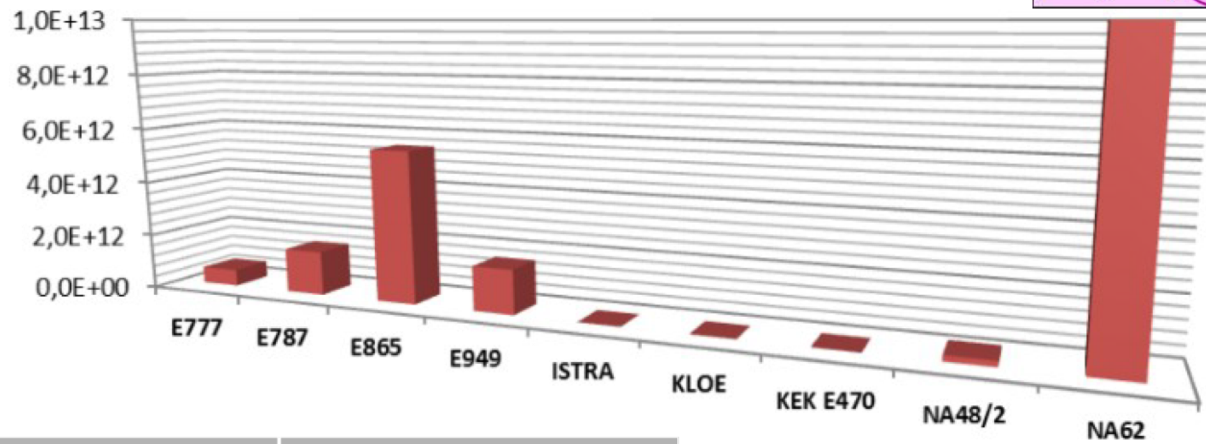


Statistical significance $z=\frac{N_{obs}-N_{exp}}{\sigma(N_{obs})\oplus\sigma(N_{exp})}$

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

Prospects for the 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%
$\pi^0 \to \mu^- e^+$			

This talk

* From fast MC with flat phase-space distribution.

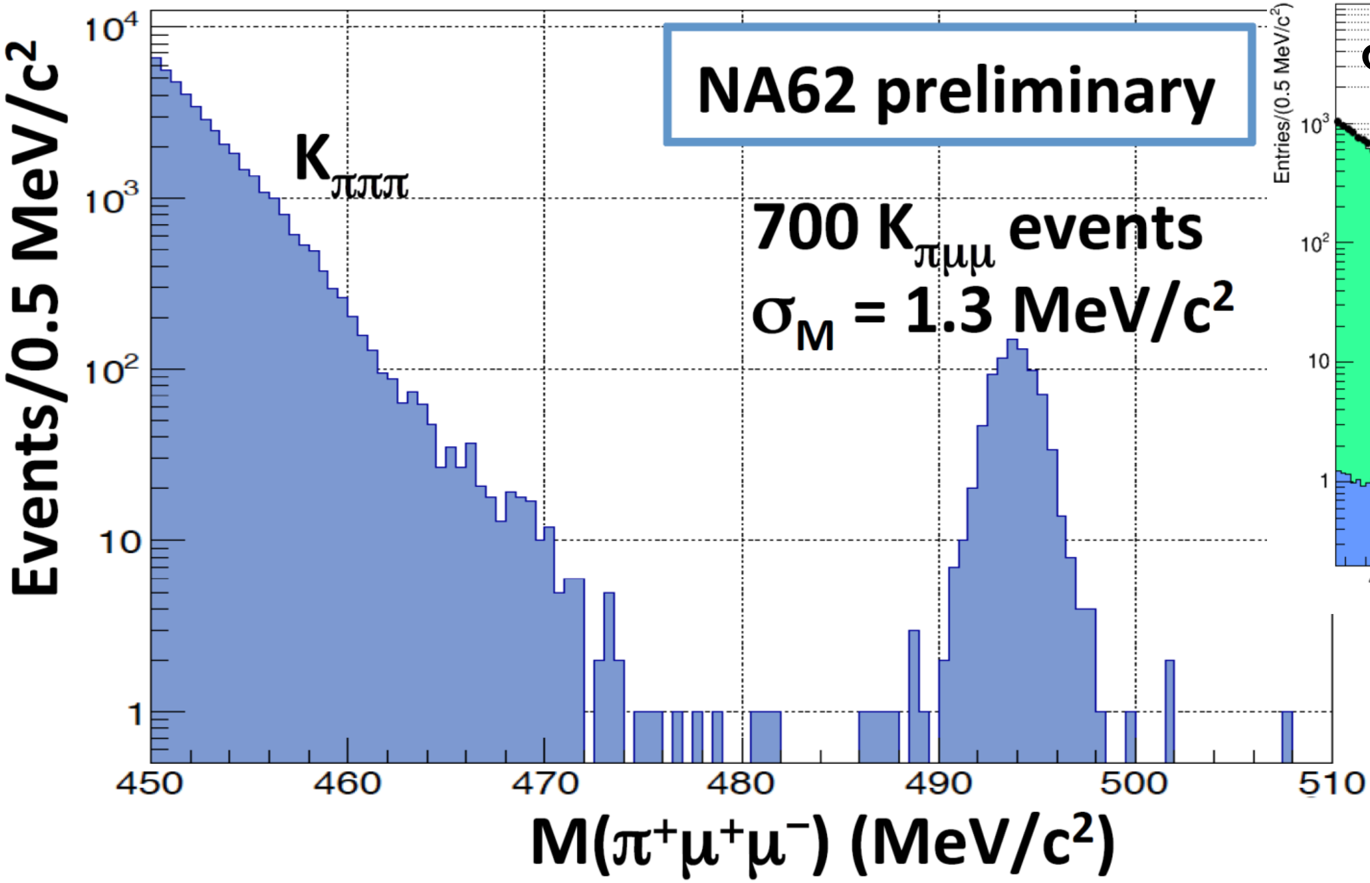
Single-event sensitivity: $1/(N_K \times \text{acceptance})$

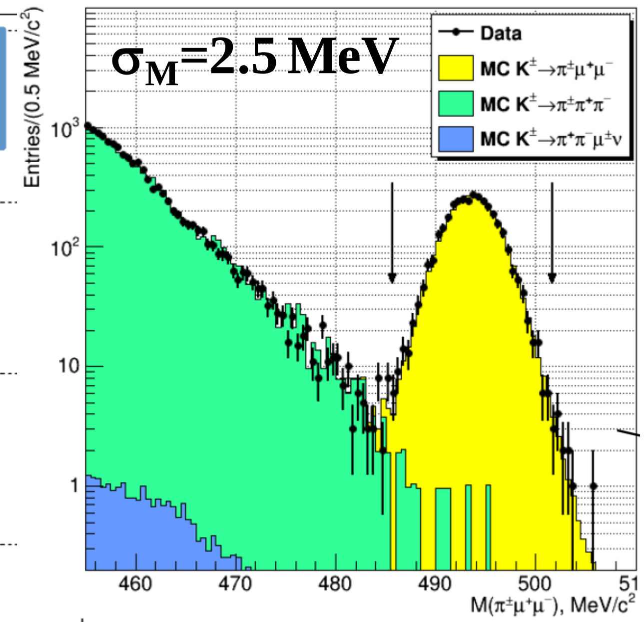
NA62 Sensitivities:
~10^{-12} for K^+ decays
~10^{-11} for π^0 decays

NA62: first look to 2016 data

First look to 2016 data, dedicated 2μ trigger included in the DAQ:

~60K burst (~2 week equivalent) at 18% of nominal NA62 intensity





Mass resolution better by a factor ~2 with respect to NA48/2

Conclusions

The NA48/2 experiment was exposed to $\sim 2\times10^{11}$ $K^{\pm}$ decays in 2003-2004

- **<u>New and preliminary NA48/2 results presented in this talk:</u>**
  - **Search for LFN $K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decay:**
    - **<u>BR(</u>$K^{\pm} \rightarrow \pi^{\mp}\mu^{\pm}\mu^{\pm}$) $< 8.6 \times 10^{-11}$ @ 90% CL [World Best Limit]**
    - Factor of 10 improvement with respect to previous best limit [1.1×10^{-9} @ 90% CL]
  - **Search for $K^{\pm} \rightarrow \mu^{\pm}N_4(N_4 \rightarrow \pi^{\mp}\mu^{\pm})$ decays [Majorana neutrinos]**
    - Limits on BR products of the order of **10^{-10}** for neutrino lifetime < 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 lifetime < 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 lifetime < 100 ps

- **<u>Prospectd for the NA62 Experiment:</u>**
  - Major beam and detectors upgrade for $K^{+} \rightarrow \pi^{+}\nu\bar{\nu}$ ➡ improved performances
  - NA62 will collect the world-largest K^{+} sample ($\sim 10^{13}$ in three years)
  - Potential sensitivities $\sim 10^{-12}$ on K decays and $\sim 10^{-11}$ on π^{0} decays