Searches for Lepton Number Violation and Resonances in the $K^{\pm} \to \pi\mu\mu$

On behalf of the NA48/2 collaboration

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supported with a fellowship through GRK Symmetry Breaking (DFG/GRK 1581)

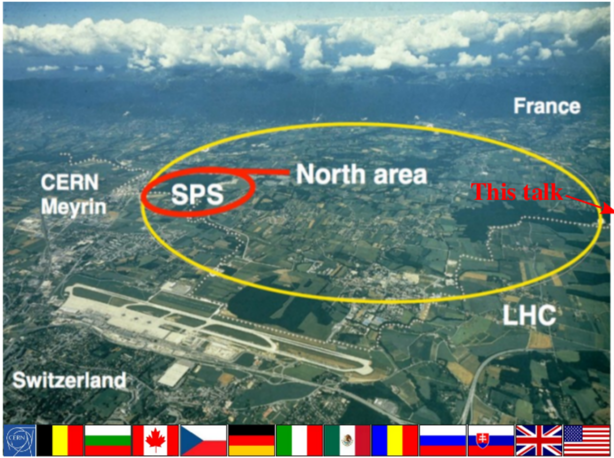
GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

April 14 2016

Deep Inelastic Scattering 2016, DESY, Hamburg

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



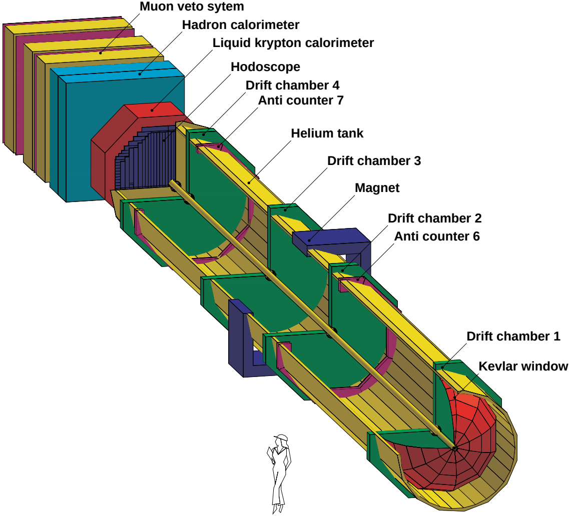
History of NA48/NA62 experiments		
97-01	NA48(K_S/K_L)	Re ϵ'/ϵ Discovery of direct CPV
02	NA48/1 (K_S/hyperons)	Rare K_S and hyperon decays
03-04	NA48/2 (K^+/K^-)	Direct CPV search in $K^\pm$
07-08	NA62-R$_K$ (K^+/K^-)	$R_K = K^\pm_{e2}/K^\pm_{\mu 2}$
15 -	NA62 (K^+)	$K^+ \to \pi^+\nu\bar{\nu}$, Rare $K^+$and π^0 decays

NA62: currently $\sim$ 200 collaborators, 29 institutions from 12 countries

Narrow $K^{\pm}$ momentum spread:
$P_K = 60$ GeV/c , $\delta P_K/P_K \sim 1\%$ (rms)
Nominal $K^{\pm}$ decay rate: ~ 100 kHz
Main triggers: 3-track vertex, $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$
Simultaneous K^+ and K^- beams

Sub-detectors

- **Spectrometer (4 DCH)**
  $\frac{\sigma_P}{P} = 0.480\% \oplus 0.009\% p(GeV)$
- **Scintillator Hodoscope**
  Fast trigger, time measurement $\sigma_t \sim 200$ ps
- **LKr EM Calorimeter**
  High-granularity
  $$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E(GeV)}} \oplus \frac{9\%}{\sqrt{E(GeV)}} \otimes 0.42\%$$
  $$\sigma_x = \sigma_y = \frac{4.2mm}{\sqrt{E(GeV)}} \oplus 0.6mm$$

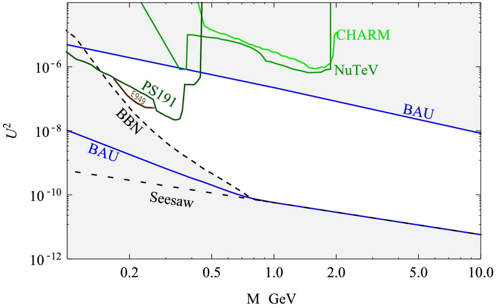


22 % of the kaons decay in 114m-long vacuum tank upstream the detector

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

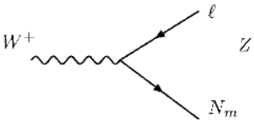
- N_1 - lightest $\mathcal{O}$(keV) $\rightarrow$ Dark Matter candidate
- N_2, N_3 - nearly degenerate (100 MeV - few GeV)
- **$N_{2,3}$ production in $K^{\pm}$ decays :**
  - $K^{\pm} \rightarrow l^{\pm} N(l = \mu$ this talk), $K^{\pm} \rightarrow \pi^0 l^{\pm} N, \cdots$
- **$N_{2,3}$ decays for $m_{2,3} < m_K - m_l$:**
  - $N \rightarrow \pi^{\pm} l^{\mp} (l = \mu$ this talk), $N \rightarrow \pi^0 \nu$
  - $N \rightarrow l_1^{\pm} l_2^{\mp} \nu_2$, $N \rightarrow l_1^{\pm} l_2^{\mp} \nu_1$

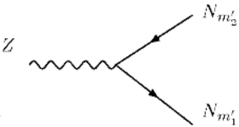
Gorbunov and Timiryasov, PLB 745 (2015) 29

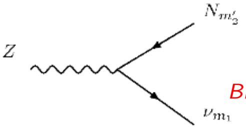


Active-sterile neutrino mixing $|U|^2$

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



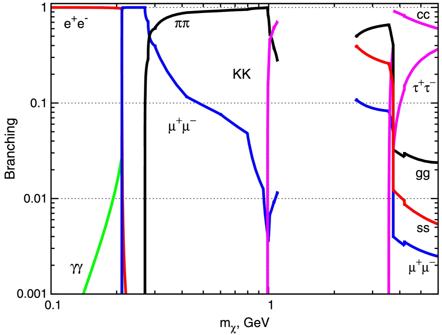


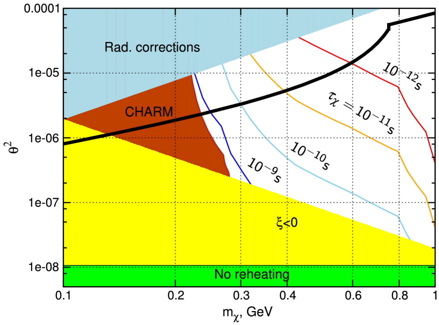


$BR(K^{\pm} \rightarrow \mu^{\pm} N) \times BR(N \rightarrow \pi^{\mp} \mu^{\pm}) \sim |U_{\mu 4}|^4$

Shaposhnikov-Tkachev model [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 $\rightarrow$ Universe reheating
- χ is unstable: $\tau \sim (10^{-8} - 10^{-12})$ s





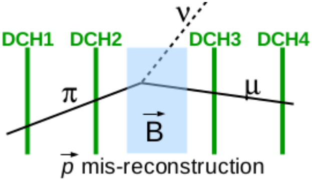
χ in Kaon decays [$m_\chi \leq 354$ MeV/c^2]

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

Basic principles of the searches

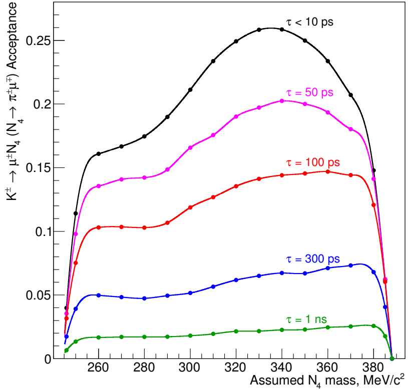
- Fully reconstructed final states, 3-track vertex topology
- Similar topology to normalization channel $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$

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



Exclusive search for the $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$

- Main background: $\boldsymbol{K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}}$ **with** $\boldsymbol{2\pi^{\pm} \to \mu^{\pm}\nu}$ decays (one within the spectrometer)
- Sensitivity $\sim \dfrac{1}{N_K \times Acceptance}$
  - 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:

- $N_K \sim 2 \times 10^{11}$
  - measured from $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Blind analysis:

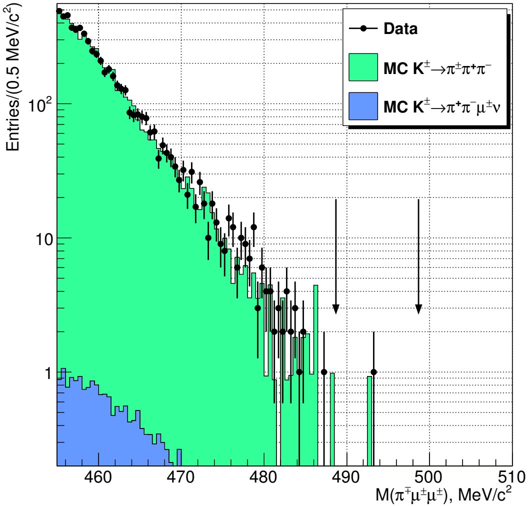
- $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ MC simulation
  - Uniform phase-space ($|M_{fi}|^2 = 1$)
  - Resonant Majorana neutrino model
- Control region: $M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 480$ MeV/c^2

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:

- $K^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ MC simulation (10^{10} events) used to evaluate number of expected $K^{\pm} \to \pi^{\pm}\pi^{-}\pi^{+}$ events in signal region



Event 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): $\mathbf{N_{exp} = 1.163 \pm 0.867_{stat} \pm 0.116_{syst} \pm 0.021_{ext}}$

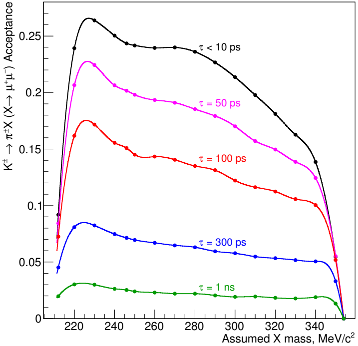
Rolke-Lopez method used to get UL(N_{sig}): $\mathbf{BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}}$ **@ 90% CL**

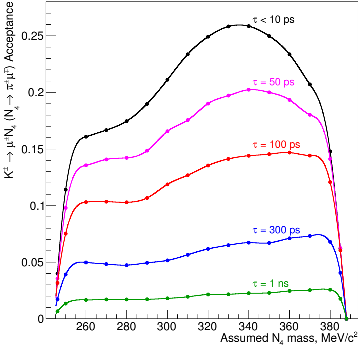
Basic principles of the searches

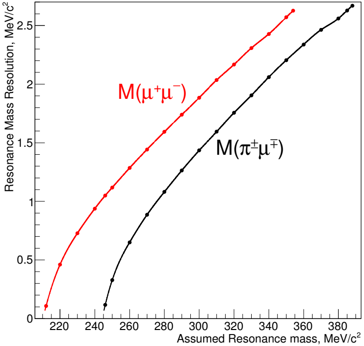
- Fully reconstructed final states, 3-track vertex topology
- Similar topology to normalization channel $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$
  $\to$ First-order cancellation of systematic effects (trigger efficiency, etc)

Exclusive search for the decays chains $K^{\pm} \to \pi^{\pm}X(X \to \mu^{+}\mu^{-}), K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\pm}\mu^{\mp})$

- Main background: $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ **(irreducible)** $\to$ Limited sensitivity
- Sensitivity $\sim \dfrac{\sqrt{BR(K^{\pm}\to\pi^{\pm}\mu^{+}\mu^{-})}}{\sqrt{N_K \times Acceptance}} \sqrt{\dfrac{\sigma(M_{res})}{m_K-(m_\pi+2m_\mu)}}$
  - UL on BR($K^{\pm} \to \pi^{\pm}X$)$\times$ BR(($X \to \mu^{+}\mu^{-}$))
  - UL on BR($K^{\pm} \to \mu^{\pm}N_4$)$\times$BR($N_4 \to \pi^{\pm}\mu^{\mp}$)

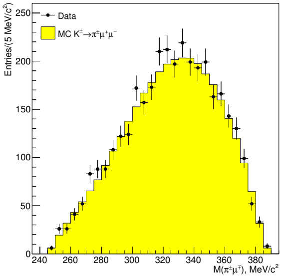




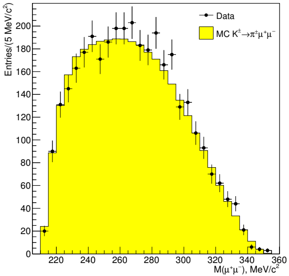


Event selection:

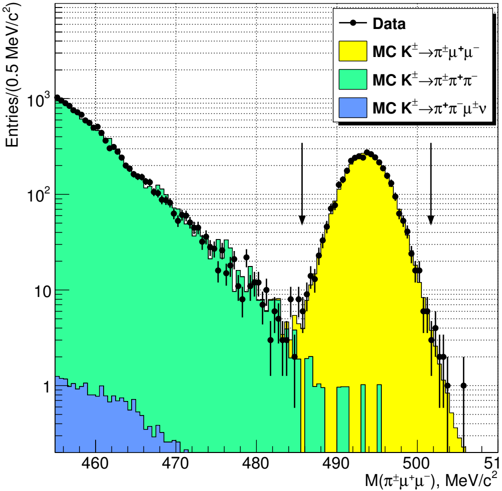
- One well-reconstructed 3-track vertex
- 2 opposite-sign muons, 1 odd-sign pion
- Total P_T consistent with zero
- Signal region: $|M(\pi^{\pm}\mu^{+}\mu^{-}) - M_K| < 8$ MeV/c^2



$M(\pi^{\pm}\mu^{\mp})$



$M(\mu^{+}\mu^{-})$



Scanning performed to search for peaks in $M(\pi^{\pm}\mu^{\mp})$ and $M(\mu^{+}\mu^{-})$ invariant mass distributions

3489 $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ candidates in the signal region

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

Procedure

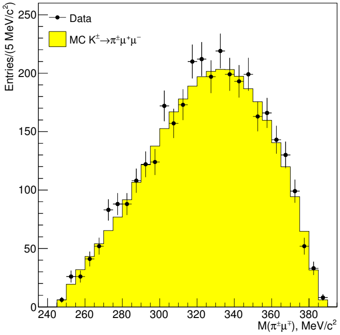
- Variable scanning step $= 0.5\sigma(M_{res})$ and window $= \pm 2\sigma(M_{res})$
- For each M_{res}: Observed events in data(N_{obs}) vs expected events from MC(N_{exp}) $\to$ UL(N_{sig})
- Rolke-Lopez statistical treatment used in each mass hypothesis M_{res} to get UL(N_{sig})

Search for $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ decays (LNV) - Majorana neutrinos

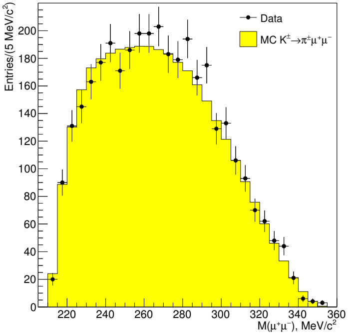
- 2 possibilities in building $M(\pi^{\mp}\mu^{\pm})$ [same sign muons]
  - Only the closest to the invariant mass to M_{res} considered
- 284 mass hypotheses M_{res} tested

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

- 267 hypotheses for $M(\pi^{\pm}\mu^{\mp})$
- 280 hypotheses for $M(\mu^{-}\mu^{+})$

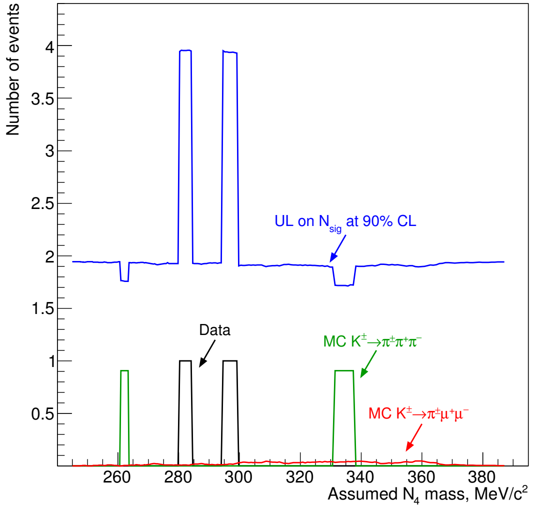


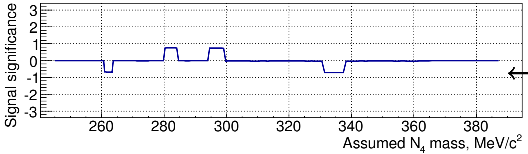
$M(\pi^{\pm}\mu^{\mp})$



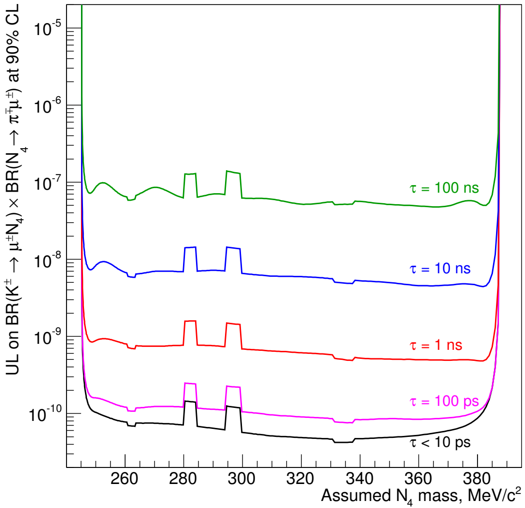
$M(\mu^{+}\mu^{-})$

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



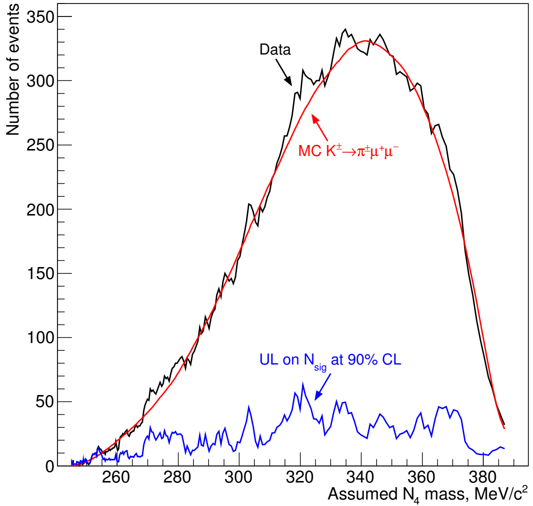


$$\mathrm{UL}(\mathrm{BR}(K^{\pm} \to \mu^{\pm} N_4) \times \mathrm{BR}(N_4 \to \pi^{\mp} \mu^{\pm})) = \frac{UL(N_{sig})}{N_K \times Acc}$$

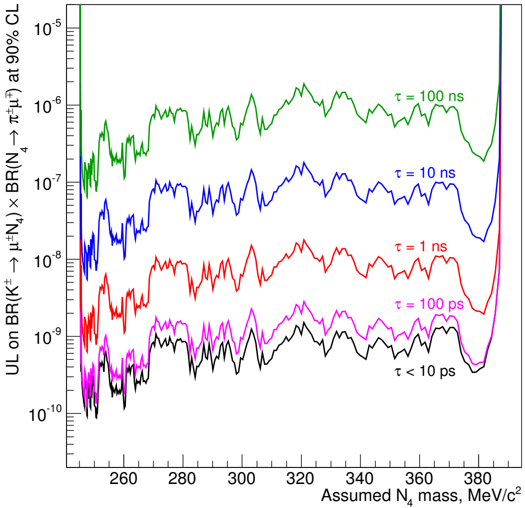


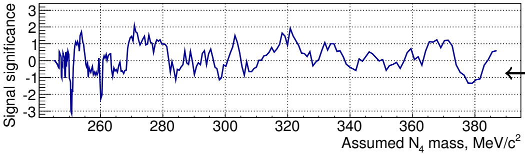
Statistical significance $z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \otimes \sigma(N_{gen})}$

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



$$UL(BR(K^{\pm} \to \mu^{\pm} N_4) \times BR(N_4 \to \pi^{\pm}\mu^{\mp})) = \frac{UL(N_{sig})}{N_K \times Acc}$$





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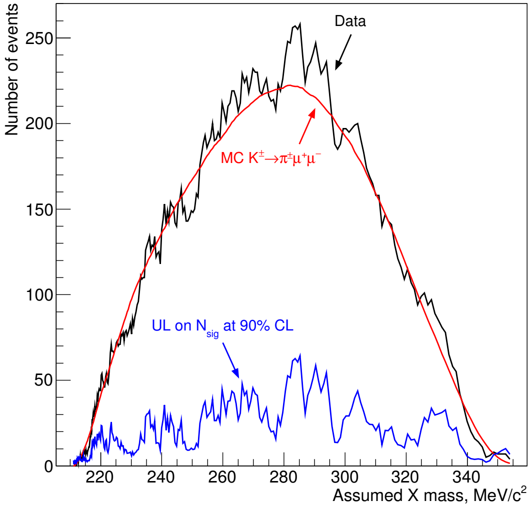
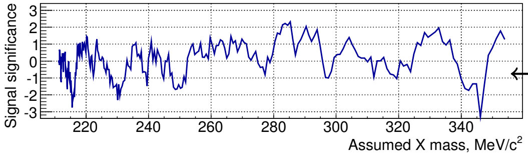
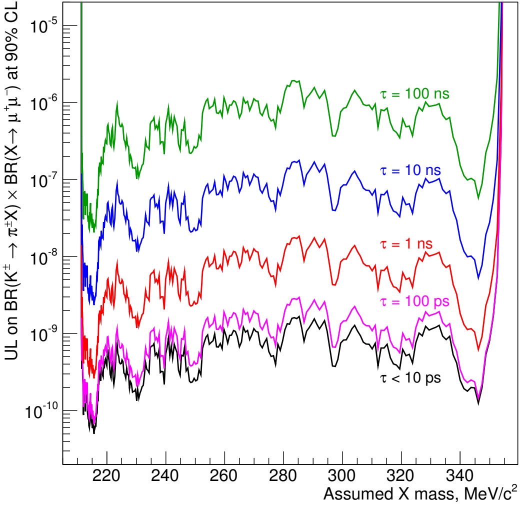




$$\mathrm{UL}(\mathrm{BR}(K^{\pm} \to \mu^{\pm} X) \times \mathrm{BR}(X \to \mu^+ \mu^-)) = \frac{UL(N_{sig})}{N_K \times Acc}$$



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

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

Conclusions

$\sim 2 \times 10^{11} K^{\pm}$ decays recorded by NA48/2 in 2003-2004

New NA48/2 results

1. **Search for LNV $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$**
   - $BR(K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}) < 8.6 \times 10^{-11}$ @ 90% CL [World best limit]
   - Factor of 10 improvement with respect to previous best limit [1.1×10^{-9} @ 90 %CL]
2. **Search $K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\mp}\mu^{\pm})$ decays [Majorana neutrinos]**
   - Limits of the order of 10^{-10} for $\tau < 100$ ps
3. **Search $K^{\pm} \to \mu^{\pm}N_4(N_4 \to \pi^{\pm}\mu^{\mp})$ decays [LNC heavy neutrinos]**
   - Limits of the order of 10^{-9} for $\tau < 100$ ps
4. **Search $K^{\pm} \to \pi^{\pm}X(X \to \mu^{+}\mu^{-})$ decays [Inflatons,...]**
   - Limits of the order of 10^{-9} for $\tau < 100$ ps

Prospects for the new NA62 experiment

1. The new NA62 detector is optimised for $K^{\pm} \to \pi^{+}\nu\overline{\nu}$
2. NA62 will collect the world-largest K^{+} decay sample ($\sim 10^{13}$) in 3 years of data taking
3. Potential sensitivities 10^{-12} for K decays, 10^{-11} for π^{0} decays