Search for LNV and limits on Heavy Neutral Leptons by the CERN Kaon experiments

Cristina Biino * - INFN Torino

CIPANP – 13th Conference on the Intersections of Particle and Nuclear Physics

Palm Springs, *CA, 28 May – June 3, 2018*

* On behalf of the NA48/2 & NA62 Collaborations

Outline

- Heavy Neutral Leptons (HNL) searches - Theoretical motivations
- Kaon physics at CERN: the **NA48** & **NA62** experiments
- Search for HNL in **$K^+ \to \ell^+ N$ (ℓ=e,μ)** decays **@ NA62 (2007 & 2015 data)**

Phys.Lett. B772 (2017) 712-718

Phys.Lett. B778 (2018) 137-145

New

- Search for LNV and HNL decays in **$K^\pm \to \pi\ \mu\ \mu$** decays **@ NA48/2**

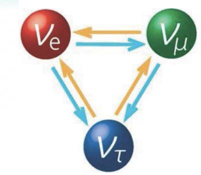
Phys.Lett. B769 (2017) 67-76

- Conclusions

Also at this conference: more NA62 results by Bob Velghe on $K^+ \to \pi^+ \nu\nu$ preliminary observation at CERN

Heavy Neutral Leptons

- **Observation of neutrino oscillations**
  - → **Neutrino masses need to be accomodated in the SM**
- **Heavy Neutrinos (HN): the neutrino minimal SM (νMSM)**
  - → **adding to the SM 3 right-handed sterile neutrinos N_i**

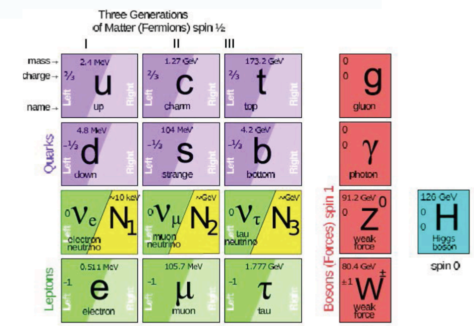


Asaka-Shaposhnikov - PLB 620 (2005) 17

- **N_1** is the lightest: $m_1 \sim O(10\ \text{KeV}/c^2)$ → **Dark Matter candidate**
- **N_2** and **N_3** : mass ~ $O(\text{MeV}/c^2$ to $\text{GeV}/c^2)$ introduce extra CPV-phases to account for Baryon Asymmetry of the Universe (BAU) and produce standard neutrino masses through See-Saw mechanism with a Yukawa coupling of $\sim 10^{-8}$

The model explains simultaneously:

- Neutrino oscillations and smallness of neutrino masses
- Cosmic Dark Matter (DM) candidate
- BAU: leptogenesis due to Majorana mass term



The branching fraction involving the HNL mass state

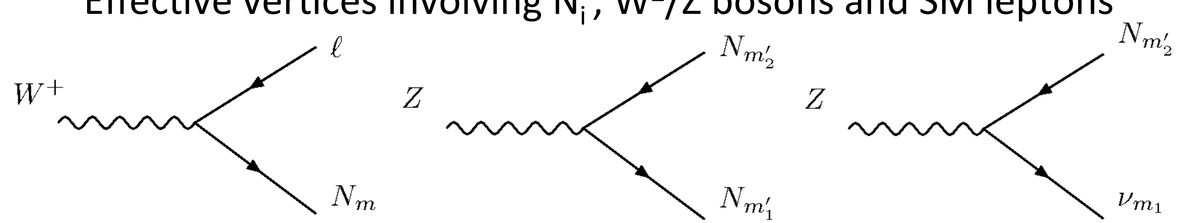
$$B(K^+ \to \ell^+ N) = B(K^+ \to \ell^+ \nu_\ell) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$$

where $|U_{\ell 4}|$ are elements of the extended neutrino mixing matrix between the SM flavour and HNL mass state:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Active-sterile neutrino N_i mixing with SM particles is described by the U-matrix

Effective vertices involving N_i, $W^\pm/Z$ bosons and SM leptons



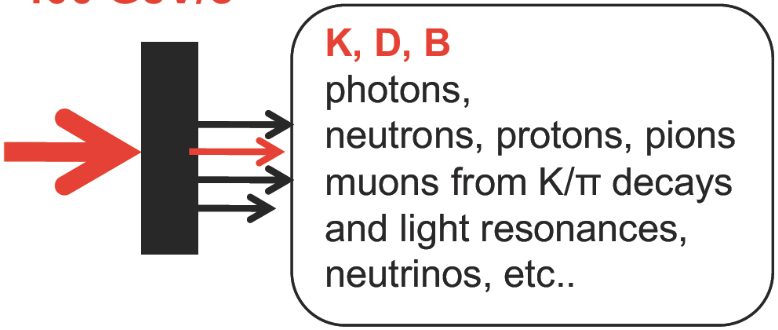
Heavy Neutral Leptons

- HNL can be produced in the decay of beauty, charm and strange hadrons and by photons originated in the interaction of protons of a target.
- HNL coupling to SM particles are very suppressed → production rates of 10^{-10} or less.
- Since charm and beauty cross sections increase with the energy, a high intensity, high energy proton beam is required to improve over the current results.
- HNL are expected to be long-lived.

The decays of HNL to SM particles can be detected by experiments with long decay volumes followed by a spectrometer with particle id capability.

In this talk I present searches for HNL at the CERN SPS with the Kaon experiments NA48/2 and NA62.

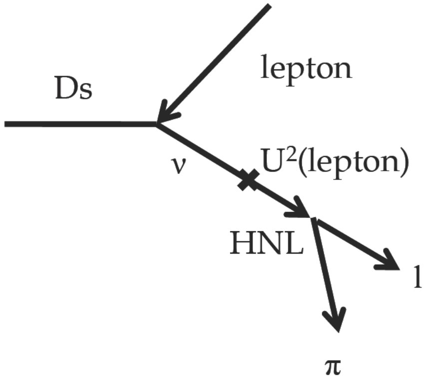
SPS protons
400 GeV/c



$\sigma(pp \rightarrow s\ \text{s-bar}\ X)/\sigma(pp \rightarrow X) \sim 0.15$
$\sigma(pp \rightarrow c\ \text{c-bar}\ X)/\sigma(pp \rightarrow X) \sim 2\ 10^{-3}$
$\sigma(pp \rightarrow b\ \text{b-bar}\ X)/\sigma(pp \rightarrow X) \sim 1.6\ 10^{-7}$

Production of HNL:

K, B, Bs, D, Ds → lepton + HN
K, B, Bs, D, Ds → semi-leptonic modes



HNL searches with Kaons

- If $m_N<(m_K-m_\ell)$ the HNL can be observed in kaon decays.

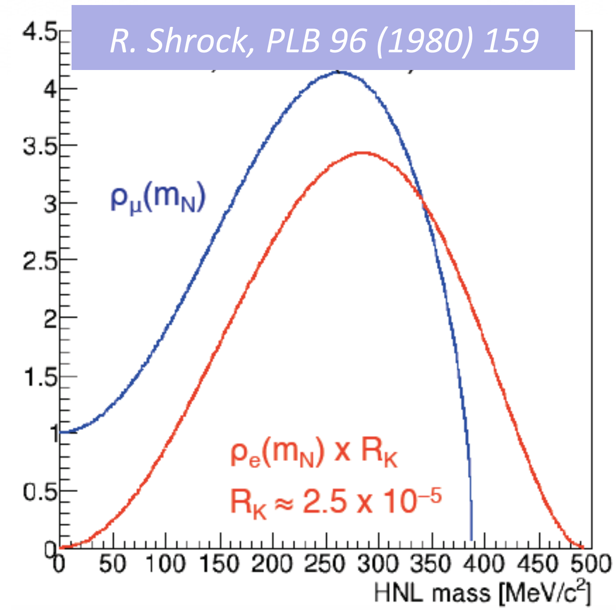
PRODUCTION: search for peaks in $\mathbf{m_N^2 = m_{miss}^2 = (p_K - p_\ell)^2}$

$$BR(K^+ \to \ell^+ N) = BR(K^+ \to \ell^+\nu_\ell) \times \rho_\ell(m_N) \times |U_{\ell 4}|^2$$

$$|U_{\ell 4}|^2 = \frac{BR(K^+ \to \ell^+ N)}{BR(K^+ \to \ell^+\nu_\ell) \times \rho_\ell(m_N)}$$

DECAY: HNL decay only into *SM particles* $\Gamma(N \to \textit{SM part}) \sim |U_{\ell 4}|^2 \times m_N^3$

- If $m_N < 500$ MeV/c² the main decays are:
  $N \to \pi^0 \nu$, $N \to \pi^\pm \ell^\mp$ ($\ell = e, \mu$), $N \to \nu\nu\nu$
- Assuming $|U_{\ell 4}|^2 < 10^{-4}$
  – mean free path of $K^+ \to \mu^+ N$ and $K^+ \to e^+ N$ > 10 Km in NA62
  – analysis possible in dump mode



Complementary searches in NA48/2 (2003 data), NA62-R_K (2007 data) and NA62 (2015 data)

NA48/2: HNL production + decay

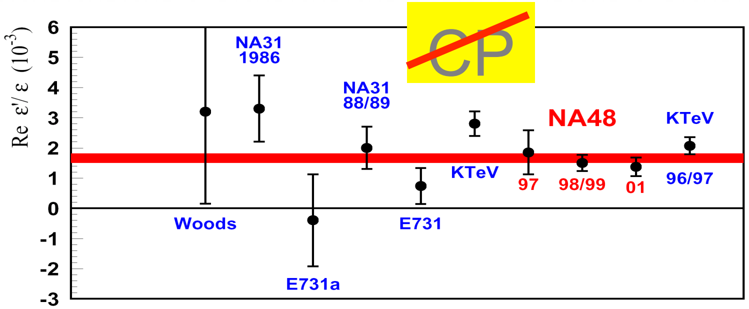
- Model dependent (HNL decay modes and lifetime)
- Sensitive to short-lived (unstable) HNL
- Sensitive to the Majorana/Dirac nature of HNL (|ΔL|=2 transitions)
- Search done on a sample of 3-track vertex events **(LNC & LNV): $K^\pm \to \mu^\pm N$ and $N \to \mu\pi$**

NA62: HNL production only

- Independent of HNL decay modes
- Sensitive to long-lived (or stable) HNLs
- Seeking peaks in the missing mass $m_{miss} = \sqrt{(p_K - p_{\ell+})^2}$ spectrum ($\ell^+ = e^+, \mu^+$)
- Search done on samples of minimum bias trigger events: **$K^+ \to \mu^+ N$ (2007); $K^+ \to e^+ N$, $\mu^+ N$ (2015)**

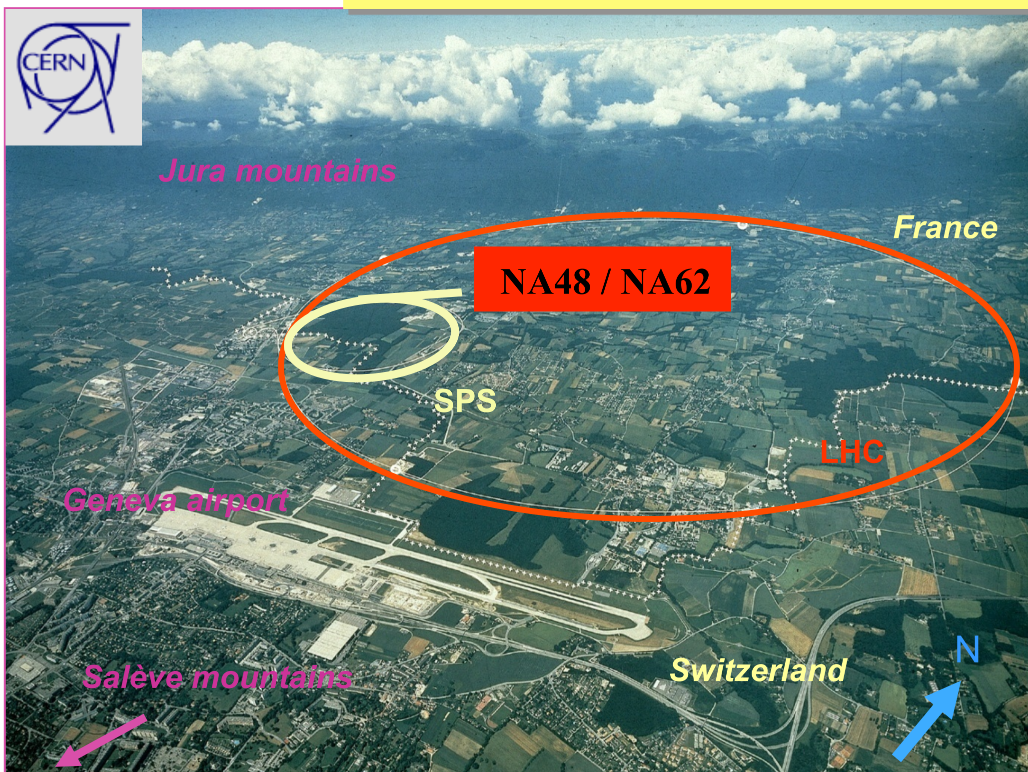
NA48 and NA62 experiments at CERN

A fixed target experiment at the CERN SPS dedicated to the study of CP violation and rare decays in the kaon sector….



Direct CP Viol. NA48 result:

$\varepsilon'/\varepsilon = (\,14.7 \pm 2.2\,)\,10^{-4}$



1997 1998 1999 2000 2001: **NA48 : $K_L + K_S$**
Search for direct CPV :
Measurement of ε'/ε

2002: **NA48/1 : K_S**
Rare K_S / Hyperon decays,
CPV tests

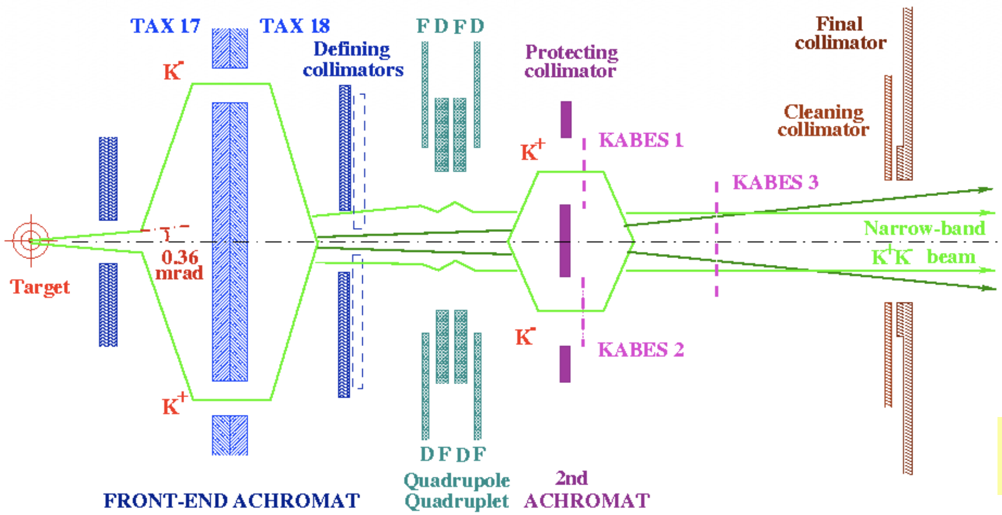
2003 2004 :: **NA48/2 : $K^+ + K^-$**
Search for direct CPV :
Charge asymmetry measurement

2007 2008 : 2015: **NA62-2007 : $K^+ + K^-$**
$R_K = \Gamma(K^{\pm}_{e2}) / \Gamma(K^{\pm}_{\mu 2})$
measurement (LFU)

2016 : 2018: **NA62 : K^+**
Measurement of the decay $K^+ \to \pi^+ \nu\bar{\nu}$

2020?

NA48/2 & NA62-R_K layout



- Simultaneous, unseparated, focused charged hadron beam; K~ 6%
- Kaon decays in the vacuum tank: 22%
- Flux ratio: K^+/K^- ~ 1.8
- Similar acceptance for K^+ and K^- decays
- p_K = (60 ± 3.0) GeV/c (NA48/2)
- p_K = (74 ± 1.4) GeV/c (NA62-R_K)

Decay region, in vacuum: 114 m

- **Liquid Krypton em calorimeter (LKr)**

  $\sigma_E/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV/)

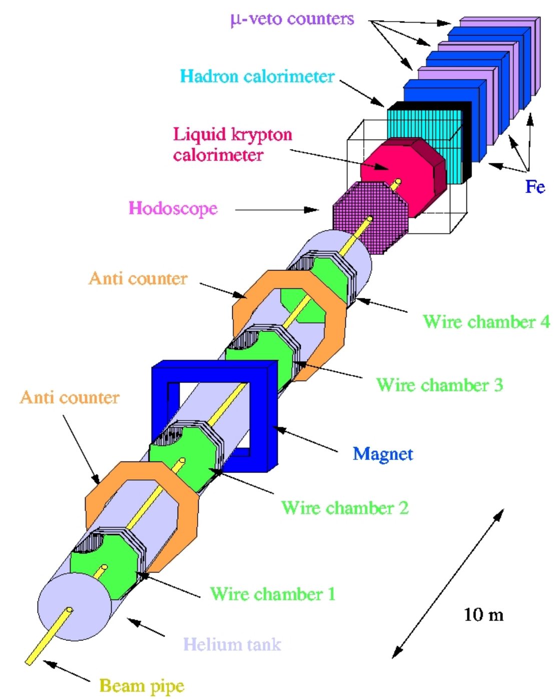
  $\sigma_x = \sigma_y = 4.2/E^{1/2} \oplus 0.6$ mm (E in GeV/)

- **Magnetic spectrometer (4 DCHs + dipole magnet)**

  $\sigma_p/p = (1.0 \oplus 0.044\, p)\%$ (p in GeV/c) NA48/2

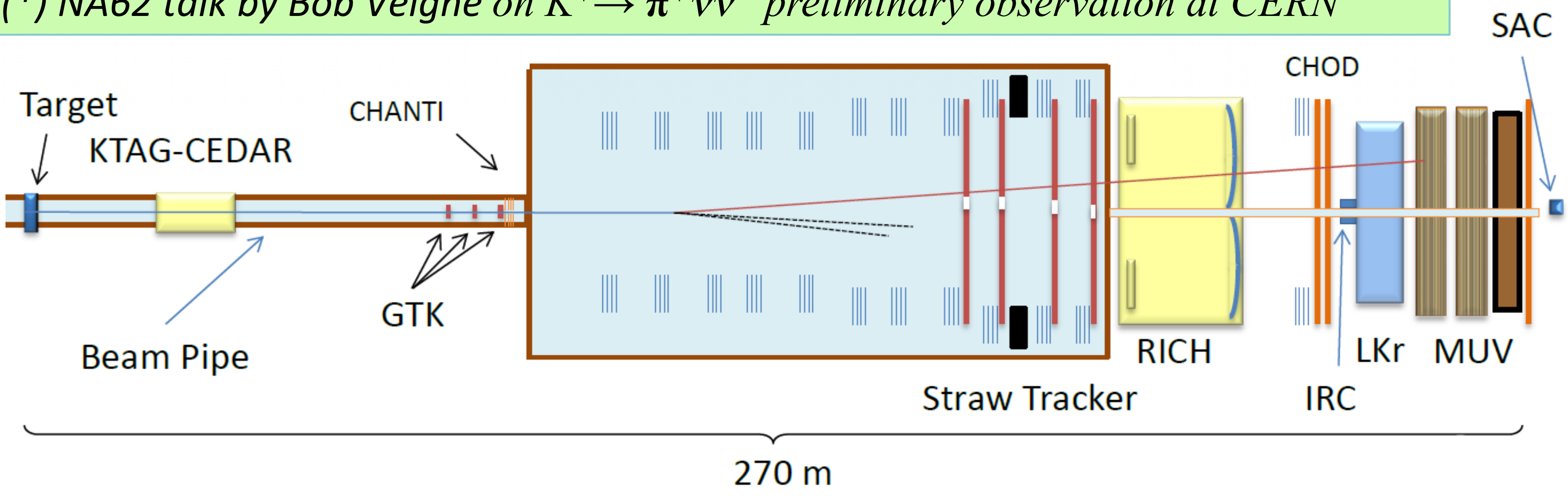
  $\sigma_p/p = (0.48 \oplus 0.009\, p)\%$ (p in GeV/c) NA62-R_K

- **Charged scintillator Hodoscope** σ_t = 150 ps
- **Muon counter**



The NA62 layout (*)

(*) NA62 talk by Bob Velghe on $K^+ \to \pi^+ \nu\nu$ preliminary observation at CERN



Primary beam: CERN SPS protons

- 3×10^{12} ppp, 3.4 s effective spill
- 750 MHz @GTK
- 400 GeV/c (x3 NA48/2)

Secondary beam:

- unseparated positive beam π/K/p
- K^+ ~ 6%, p_K = 75 GeV/c (Δp/p ~ 1.1%)
- K^+ decays/year = 4.5×10^{12} (×45 NA48/2)
- integrated average rate
- average K decay rate ≈ 10 MHz

Goal: measurement of BR($K^+ \to \pi^+ \nu \bar{\nu}$) @ 10% accuracy

Decay region

- ➔ Fiducial decay region 60 m
- ➔ Vacumm 10^{-6} mbar
- ➔ K^+ decay rate ~5MHz

Main detectors:

- **Tracking:** beam Si pixel tracker (GTK); Straw chambers in vacuum for decay products
- **PID:** beam Cherenkov for K^+ (KTAG); RICH + MUVs for π/μ/e
- **Hermetic veto:** calorimeters for γ/μ

★ Heavy Neutral Leptons search @ NA62
(from 2007 and 2015 data samples)

Phys.Lett. B772 (2017) 712-71

Phys.Lett. B778 (2018) 137-14

The NA62 single muon sample

Only K^+ beam data (43% of NA62-2007 sample) → higher muon halo rejection

Event selection

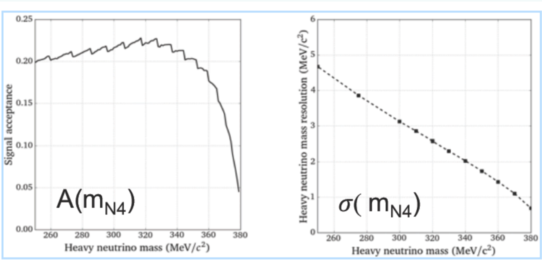
- One well reconstructed μ^+ track
- No extra clusters in LKr with E > 2 GeV
- Five-dimensional (z_{vertex}, ϑ, p, CDA, ϕ) kinematic suppression of muon halo

Data driven study of:

- Halo background
- Spectrometer resolution tails
- Trigger and μ-ID efficiencies

HNL detailed MC simulation for:

- Acceptance vs HNL mass: $A(m_{N4})$
- m_{miss} peak resolution vs HNL mass: $\sigma(m_{N4})$
- MC samples generated at 1 MeV/c^2 mass intervals

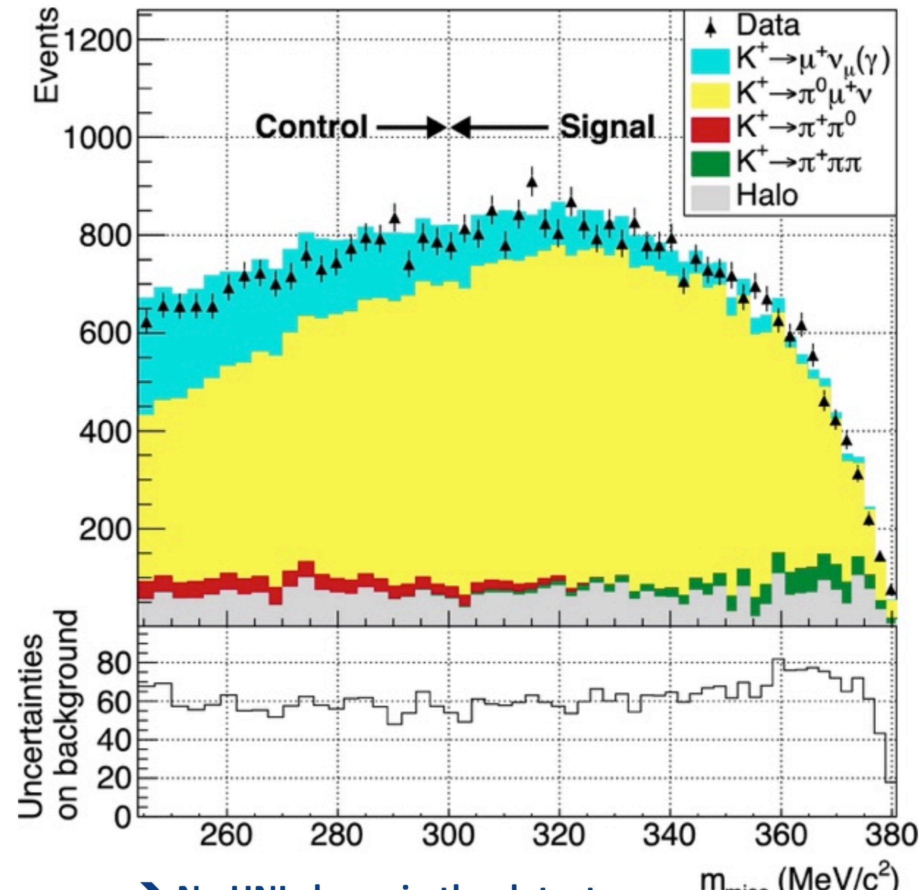


Kaon decays in the fiducial volume

• $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \to \mu^+\nu$)
(downscaling D=150 for the 1-track μ trigger)

$K^+ \to \mu^+ N$: **Search for peaks in $m_{miss} = \sqrt{(p_K - p_\mu)^2}$**

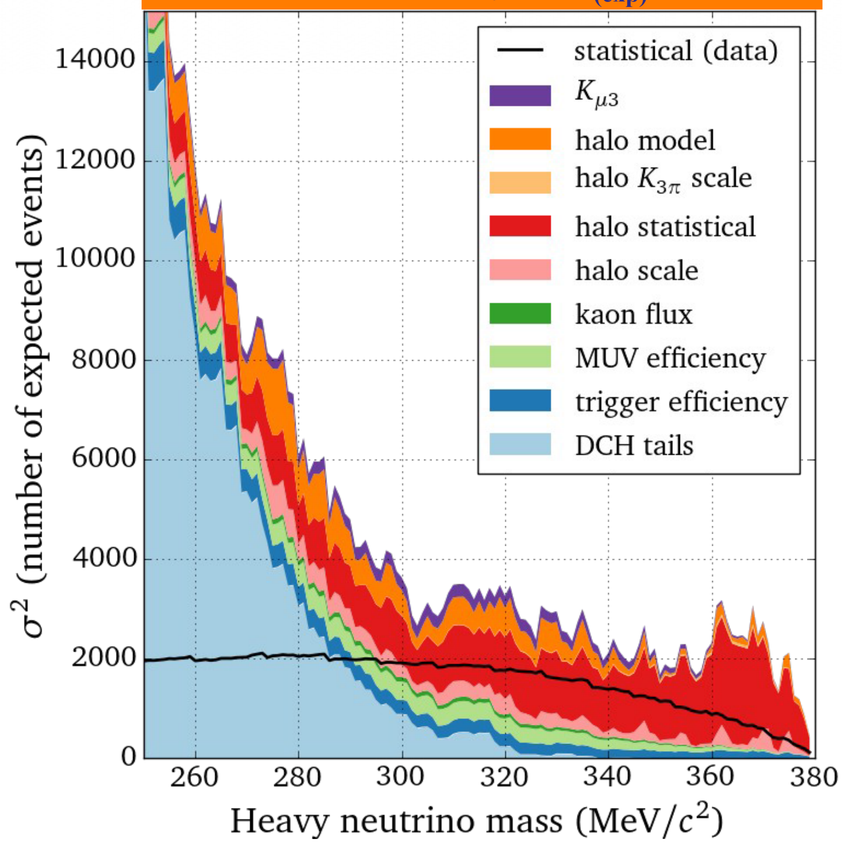
Signal region : $m_{miss}(\mu^+)$ in range [300 – 375] MeV/c^2



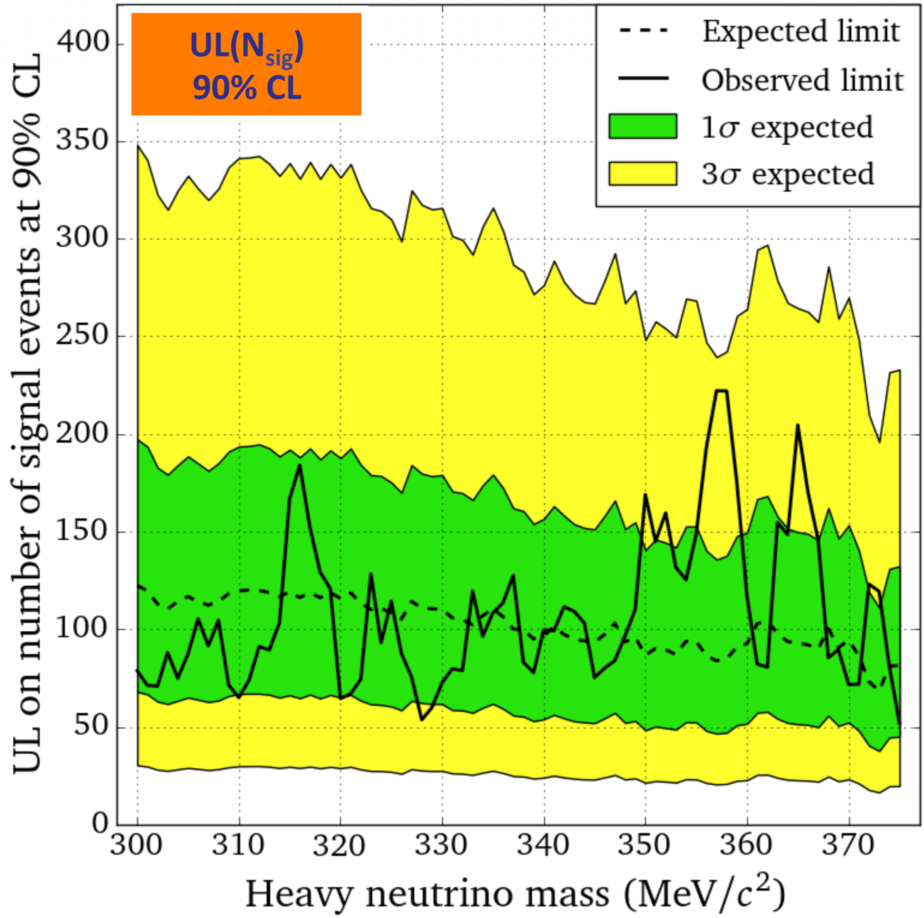
→ **No HNL decay in the detector**

HNL: search for $K^+ \longrightarrow \mu^+ N_4$

Uncertainty on $N_{(exp)}$



Upper Limits on Signal Events



Uncertainty on expected background:

- Muon halo background 5÷20%
- Statistical uncertainty on muon halo background dominates for HNL masses > 300 MeV/c²
- Kaon decays <1% (mainly $K_{\mu 3}$)

Upper Limit on $K^+ \rightarrow \mu^+ N_4$ signal events

- 1 MeV/c² mass steps
- Mass window size : $\pm(\sigma_{HN} = 12$ MeV/c² – $0.03 \times m_{HN})$
- Rolke-Lopez method to get UL(N_{sig})

No HNL signal above 3σ observed

HNL: NA62 results - (2007 data sample)

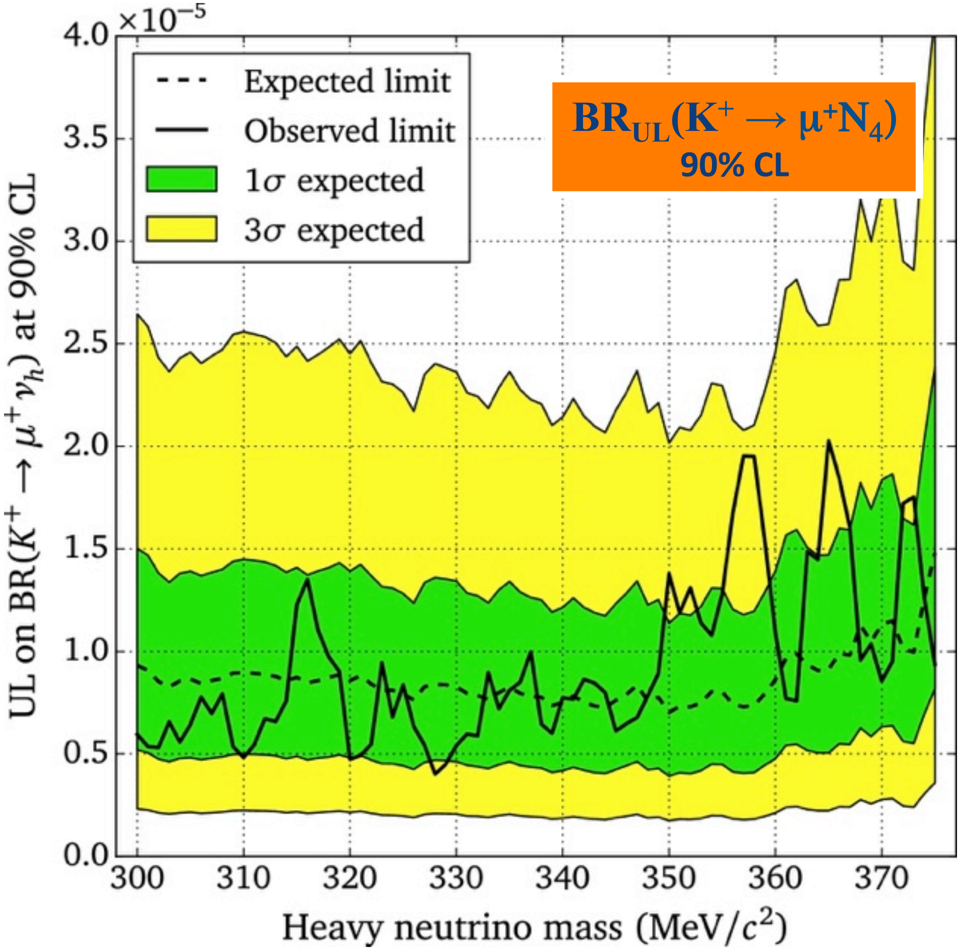
From N_{sig} to BR:

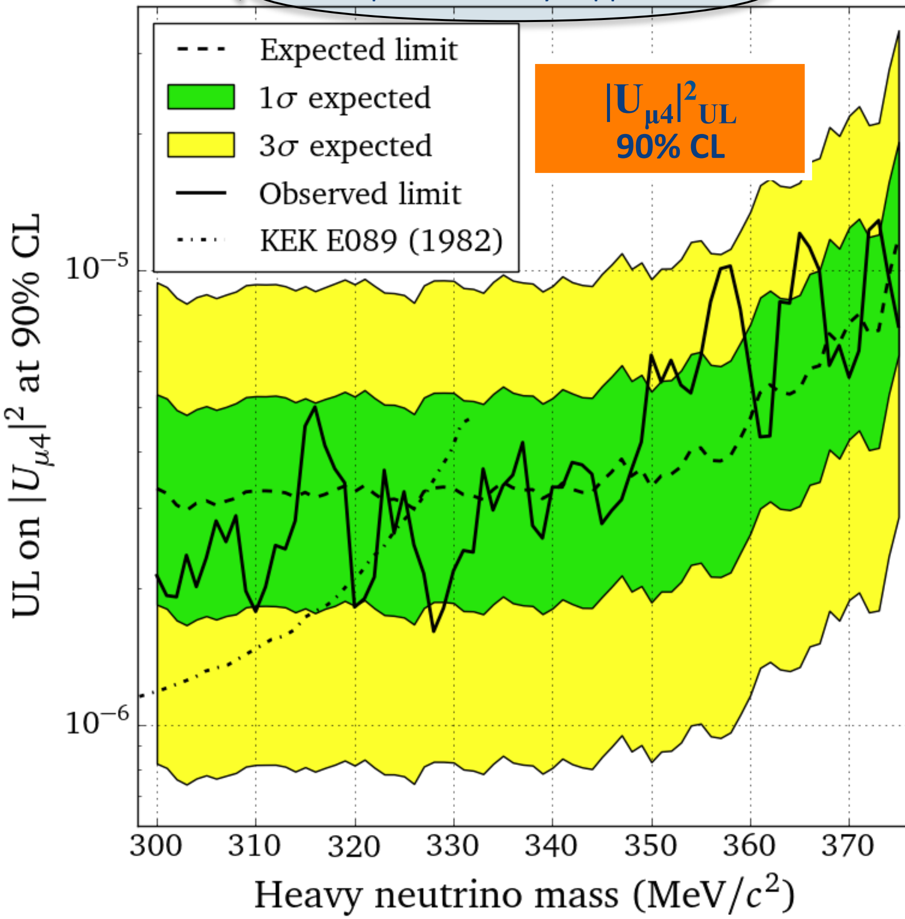
$$BR_{UL}(K^+ \rightarrow \mu^+ N_4) = \frac{UL(N_{sig})}{N_K \times \text{Acceptance}}$$

From BR to $|U_{\mu 4}|^2$:

$$|U_{\mu 4}|^2 \quad \frac{1}{f(m_{HN})} \times \frac{BR(K^+ \rightarrow \mu^+ N_4)}{BR(K^+ \rightarrow \mu^+ \nu_\mu)}$$

Phase Space + helicity suppression





Phys.Lett. B 772 (2017) 712-718

NA62 - Search for HNL production

- In **2015 NA62** collected 5 days of Min Bias data at 1% of nominal beam intensity
- No beam tracker: p_K given by beam average
- **Analysis of data shows: ~24M $K^+ \rightarrow \mu^+\nu_\mu$ (1767 $K^+ \rightarrow e^+\nu_e$)** decays with a back-ground level 100 times lower wrt NA62-2007 → Can set world most stringent limits on heavy neutrino production

Search for peaks in $m_{miss} = \sqrt{(p_K - p_{\ell+})2}$

Signal region : m_{miss} in range [170 – 448] and [250-373] MeV/c^2

Event selection for

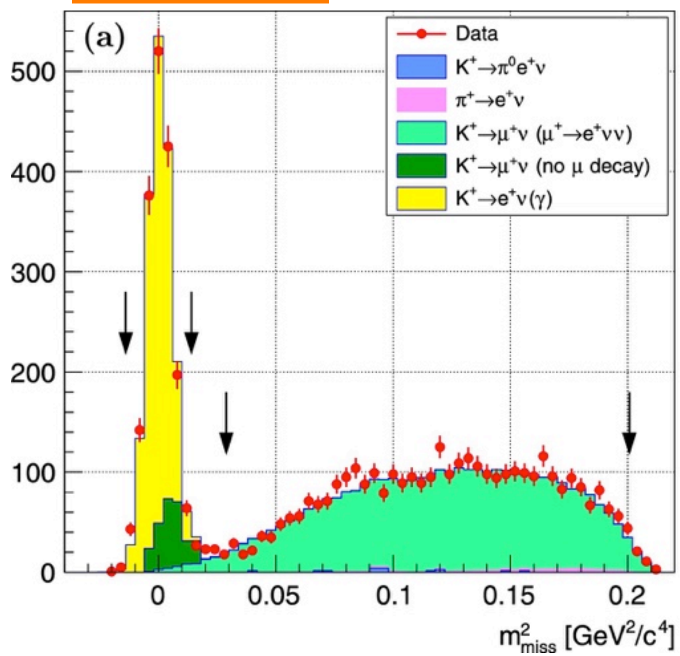
$K^+ \rightarrow e^+N$ and $K^+ \rightarrow \mu^+N$

- one positive charged track
- positrons and muons identified by the E/p ratio + MUV info and RICH up to 40 GeV
- one single electron clusters in the LKr calorimeter
- no photons in the photon-veto detector

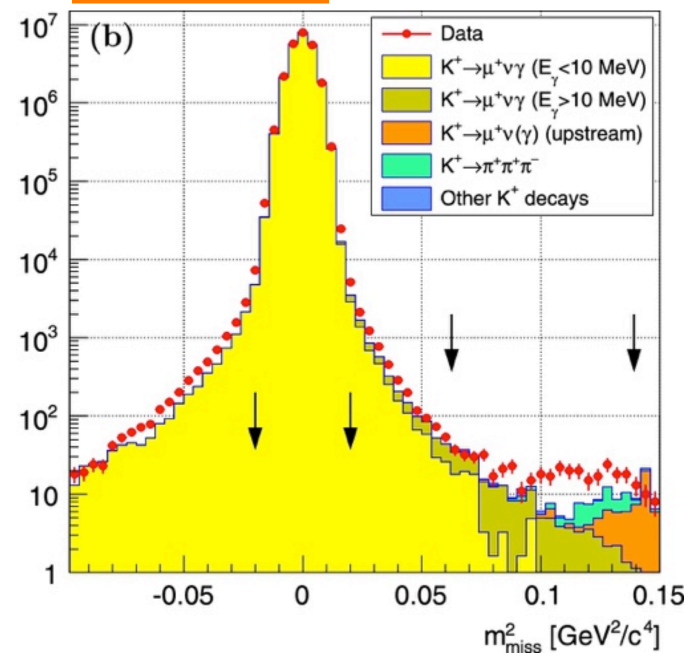
HNL detailed MC for:

- Acceptance vs HNL mass: $A(m_{N4})$
- m_{miss} peak resolution vs HNL mass: $\sigma(m_{N4})$

e^+ selection



μ^+ selection



NA62 - Search for HNL production

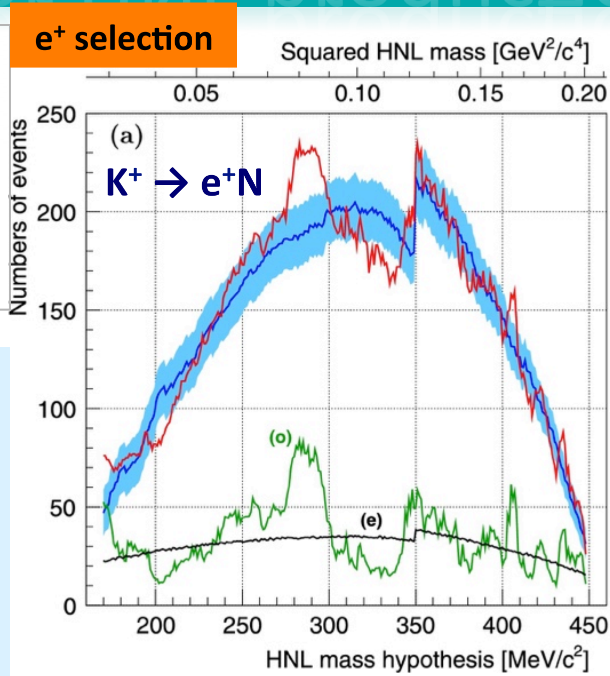
Upper limit on signal events
- 1 MeV/c² mass scan steps
- search window size for each mass hypothesis: ±1.5 $\sigma(m_N)$
- Rolke-Lopez method to get $UL(N_{sig})$

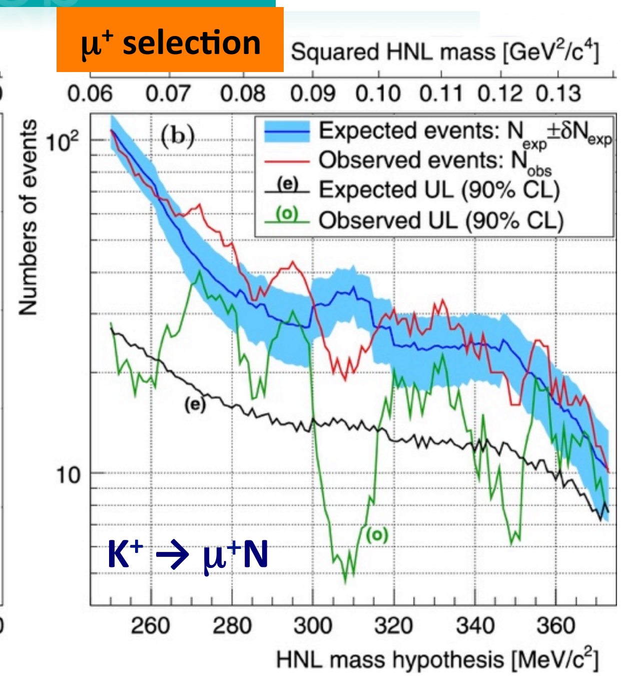
For each m_N hypothesis:
- numbers of expected (N_{exp}) and observed (N_{obs}) events, together with the uncertainty on N_{exp} (**δN_{exp}, as shown by the blue band)**
- obtained **expected** and **observed** upper limits at 90% CL on the numbers of **$K^+ \to \ell^+ N$ events**

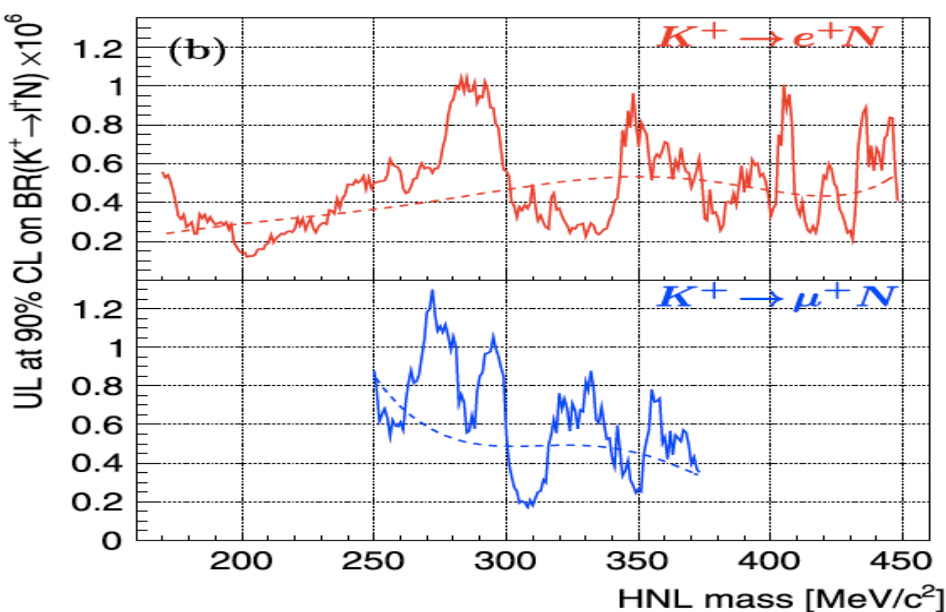
$$B_{SES}(K^+ \to \ell^+ N) = 1/[N_K \times A(K^+ \to \ell^+ N)]$$

$$|U_{\ell 4}|^2_{SES} = B_{SES}(K^+ \to \ell^+ N) / [B(K^+ \to \ell^+ \nu) \times \rho_\ell(m_N)]$$

No HNL signal observed above 3σ significance

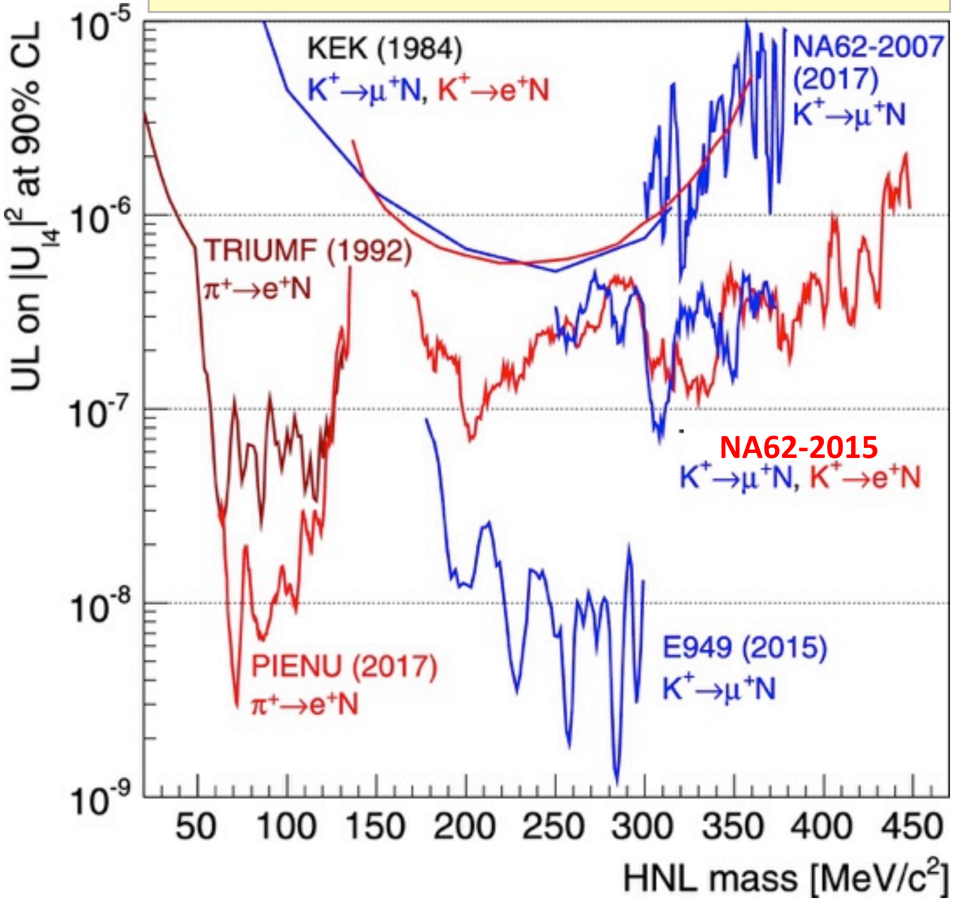






Current results on HNL searches: $|U_{\ell 4}|^2$

Latest results on limits from production searches



$|U_{\ell 4}|^2 = BR(K^+ \to \ell^+ N) / [BR(K^+ \to \ell^+ \nu) \times \rho_\ell (m_N)]$

$K^+ \to \mu^+ N$ **NA62 (2007) data**

About 60 billion K^+ decays

Improved limits in $300 \le m_N \le 375$ MeV/c^2

Phys.Lett. B772 (2017) 712-718

$K^+ \to e^+ N$ **NA62 (2015) data**

About 300 billion K^+ decays

New limits $O(10^{-6 \div -7})$ in $170 \le m_N \le 448$ MeV/c^2

Phys.Lett. B778 (2018) 137-145

$K^+ \to \mu^+ N$ **NA62 (2015) data**

About 100 billion K^+ decays

New limits $O(10^{-6 \div -7})$ in $250 \le m_N \le 373$ MeV/c^2

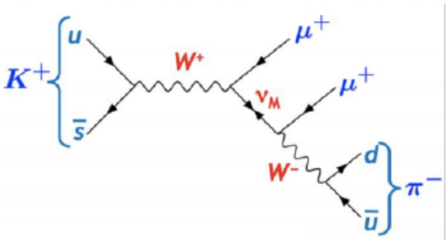
Phys.Lett. B778 (2018) 137-145

Prospects → **NA62-2016 data**: **$K^+ \to e^+ N$** analysis quite advanced, improvements due to higher beam intensity, commissioned beam tracker → higher sensitivity → **$|U_{e4}|^2$** limit expected to decrease by 1-2 order of magnitude.

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

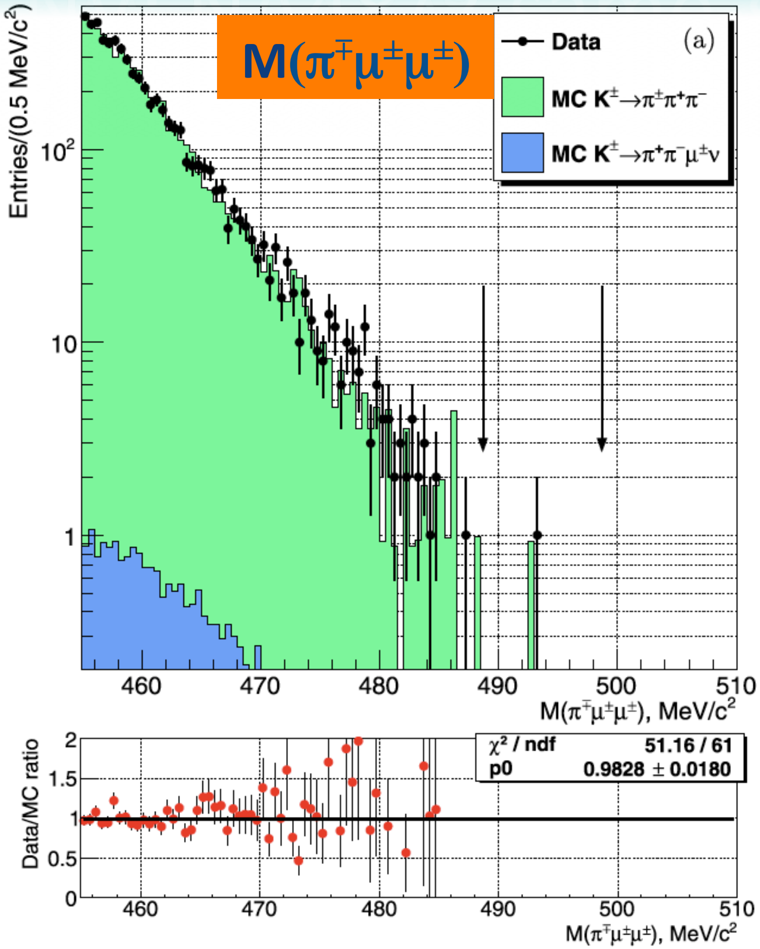
Two different samples:

- same-sign muons sample LNV decay
- opposite sign muons sample LNC decay



Phys.Lett. B769 (2017) 67-76

LNV: NA48/2 same-sign muon sample



Search for $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm} \to |\Delta L|=2$ transitions mediated by Majorana neutrino exchange

Blind analysis:

- Selection based on MC simulation of $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ and $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$
- Additional $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ MC sample for background estimation
- Control region $M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) < 480\ \mathrm{MeV}/c^2$

Event selection:

- One well reconstructed 3-track vertex
- **2 same-sign muons, 1odd sign pion**
- Total P_t consistent with zero
- Signal region $|M(\pi^{\mp}\mu^{\pm}\mu^{\pm}) - M_k| < 5\ \mathrm{MeV}/c^2$

Kaon decays in the fiducial volume

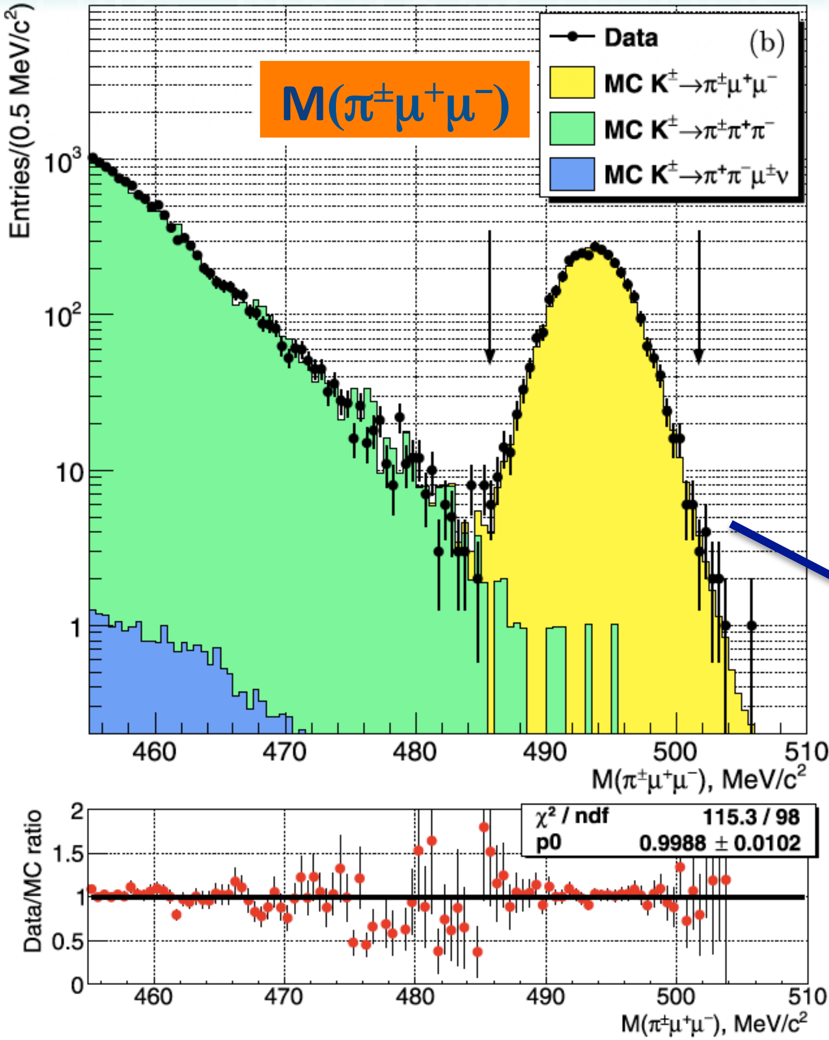
$N_K \sim 2 \times 10^{11}$ (from reconstructed $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$)

- Events in Signal Region observed after $K^{\pm} \to \pi^{\mp}\mu^{\pm}\mu^{\pm}$ selection: $N_{obs} = 1$
- Expected background (from MC): $N_{exp} = 1.160 \pm 0.865$
- Rolke-Lopez method to get $UL(N_{signal})$

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

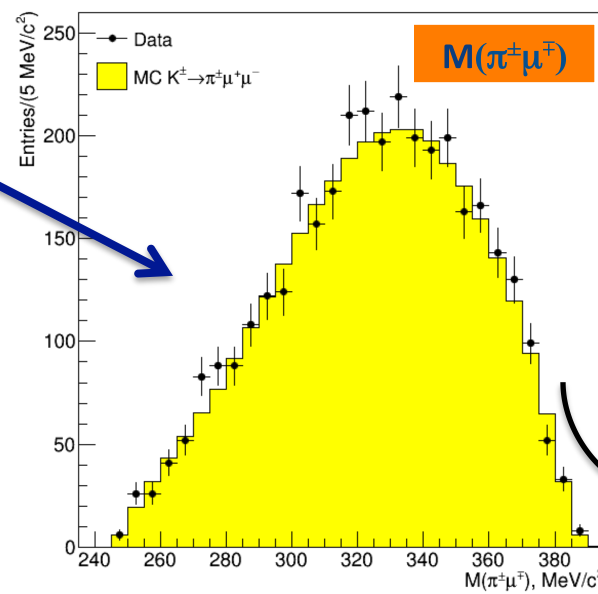
world best limit

LNC: NA48/2 opposite-sign μ sample



Event selection:

- Similar to same-sign muon sample
- One well reconstructed 3-track vertex
- 2 opposite-sign muons, 1same-sign pion
- Total P_t consistent with zero
- Signal region $|M(\pi^{\pm}\mu^{+}\mu^{-}) - M_k| < 8\ MeV/c^2$



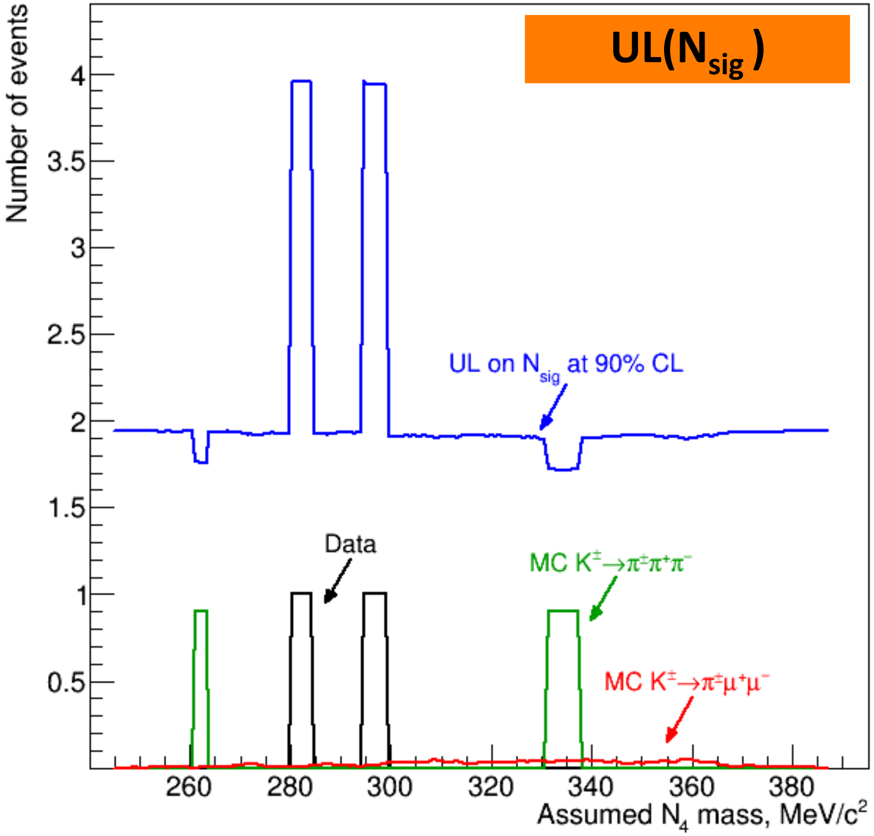
Improved selection wrt previous NA48/2 $K^{\pm}\rightarrow\pi^{\pm}\mu^{+}\mu^{-}$ analysis *[PLB 697(2011)107]*

Search for 2-body resonances in the $M(\pi^{\pm}\mu^{\mp})$ invariant mass

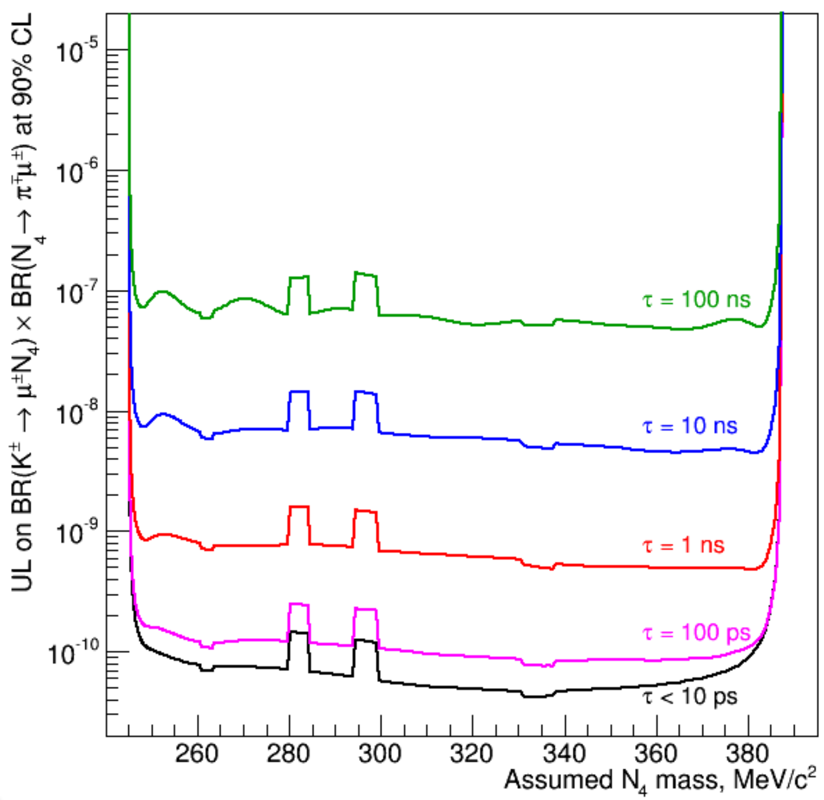
- **3489** $K^{\pm}\rightarrow\pi^{\pm}\mu^{+}\mu^{-}$ candidates in Signal Region
- $K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$ Background: **(0.32 ± 0.09)%**

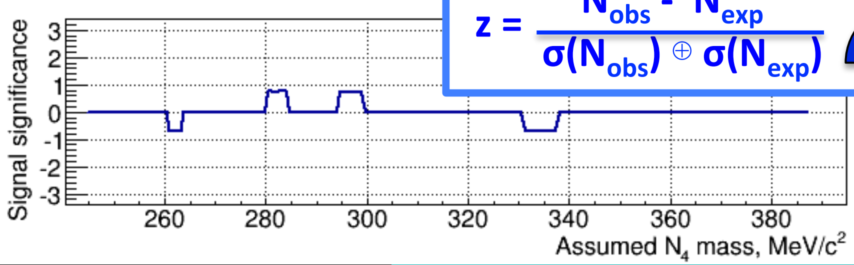
HN resonance search in LNV sample

Same-sign μ sample: search for $K^{\pm} \rightarrow \mu^{\pm} N_4$ ($N_4 \rightarrow \pi^{\mp}\mu^{\pm}$)



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





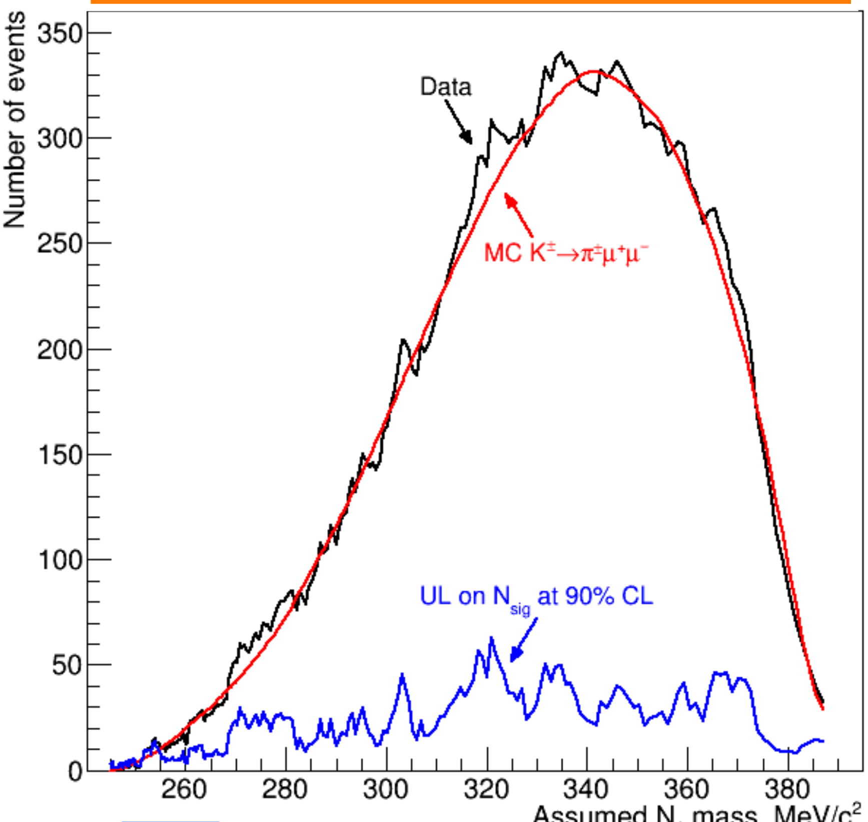
$$z = \frac{N_{obs} - N_{exp}}{\sigma(N_{obs}) \oplus \sigma(N_{exp})}$$

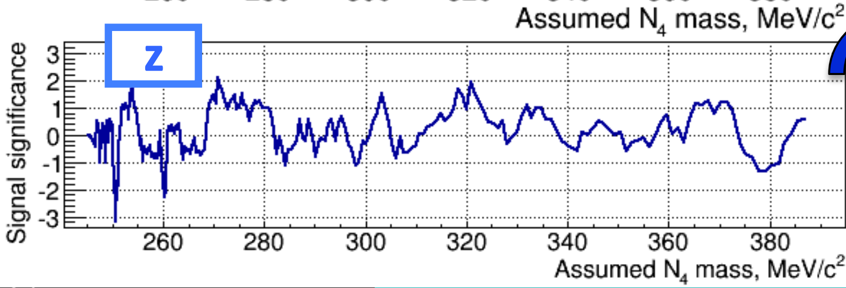
Statistical significance never exceed 3σ:
no signal observed

HN resonance search in LNC sample

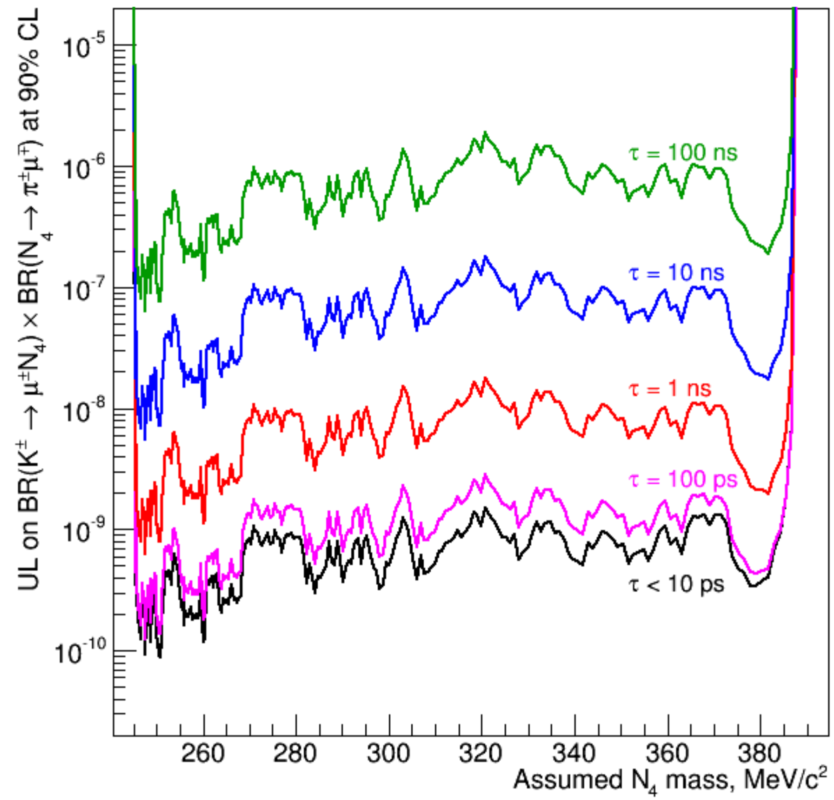
Opposite-sign μ sample: search for $K^{\pm} \rightarrow \mu^{\pm} N_4$ ($N_4 \rightarrow \pi^{\pm}\mu^{\mp}$)

$UL(N_{sig})$





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



Statistical significance never exceed 3σ:

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

no signal observed

Summary & Future

NA48/2 and NA62 are Kaon experiments at CERN with a broad physics program that includes studies of the neutrino sector.

❖ **NA48/2: HNL Production + Decay** *Phys.Lett.B 769 (2017) 67-76*

→ **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 10 improvement wrt previous best limit *(1.1×10^{-9} @ 90% CL)*

→ **Search for $K^\pm \to \mu^\pm N_4$ ($N_4 \to \pi^\pm\mu^\mp$) (LNC Heavy neutrino)**

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

→ **Search for $K^\pm \to \mu^\pm N_4$ ($N_4 \to \pi^\mp\mu^\pm$) (LNV Majorana neutrino)**

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

❖ **NA62-2007: HNL Production in $K^+ \to \mu^+ N_4$ decays** *Phys.Lett. B772 (2017) 712-718*

→ Limits on **$BR(K^+ \to \mu^+ N_4) \sim 10^{-5}$**

→ Limits on **$|U_{\mu 4}|^2 \sim 10^{-5}$** for **$m_{HN} > 300$ MeV/c^2**

❖ **NA62-2015: HNL Production in $K^+ \to \ell^+ N_4$ (ℓ=e,μ)** *Phys.Lett. B778 (2018) 137-145*

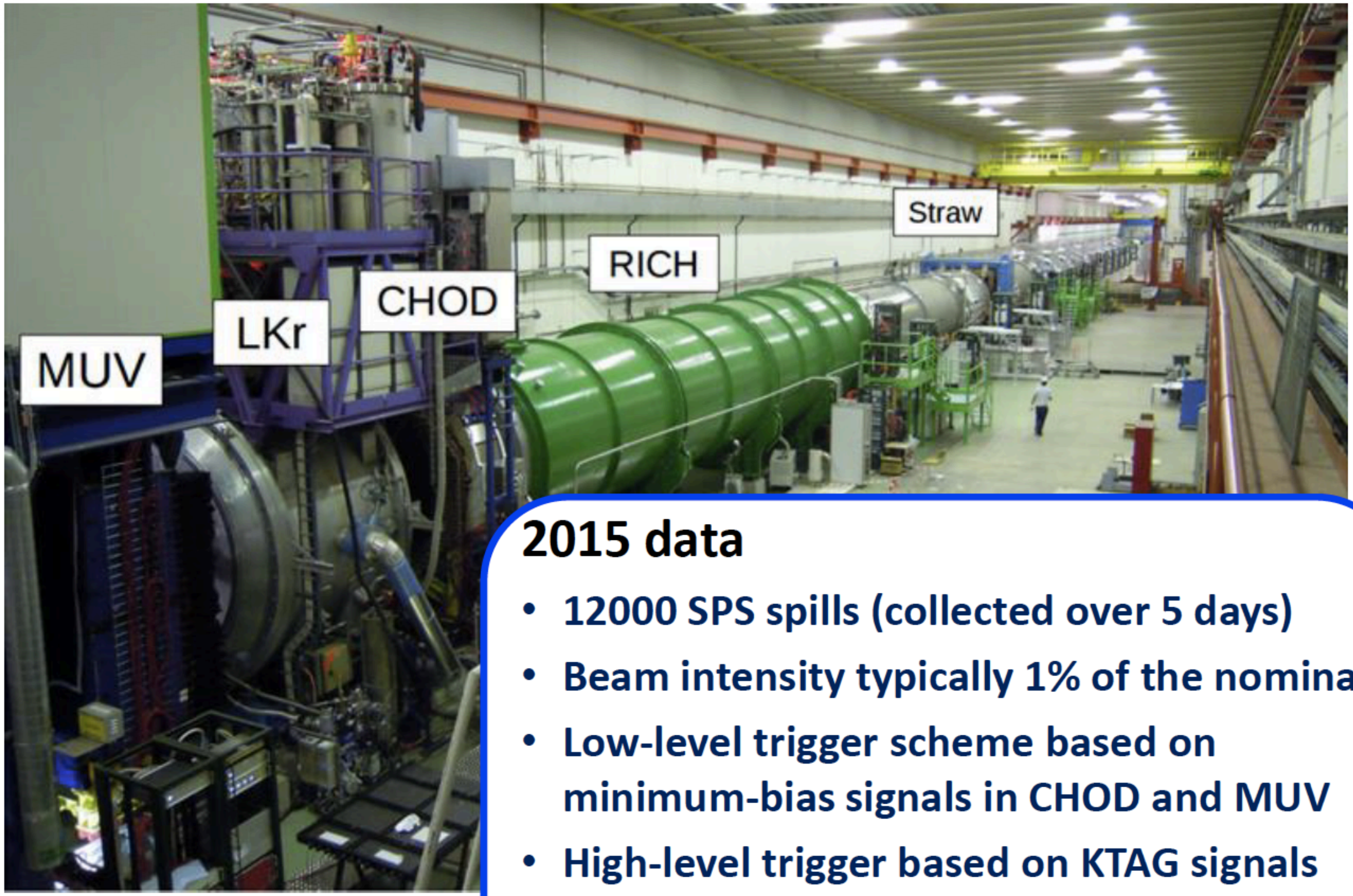
→ Limits on **$|U_{\ell 4}|^2 \sim 10^{-7\div-6}$** for **$m_{HN}$ [170÷448] and [250÷ 373] MeV/c^2 respectively**

❖ **NA62 perspectives:** 2016-2018 data set: **$K^+ \to \ell^+ N$** event yield expected to be larger with improved mass resolution and much lower bkg

→also improved results from $K^+ \to \pi\ell\ell$ expected in the coming years

SPARES

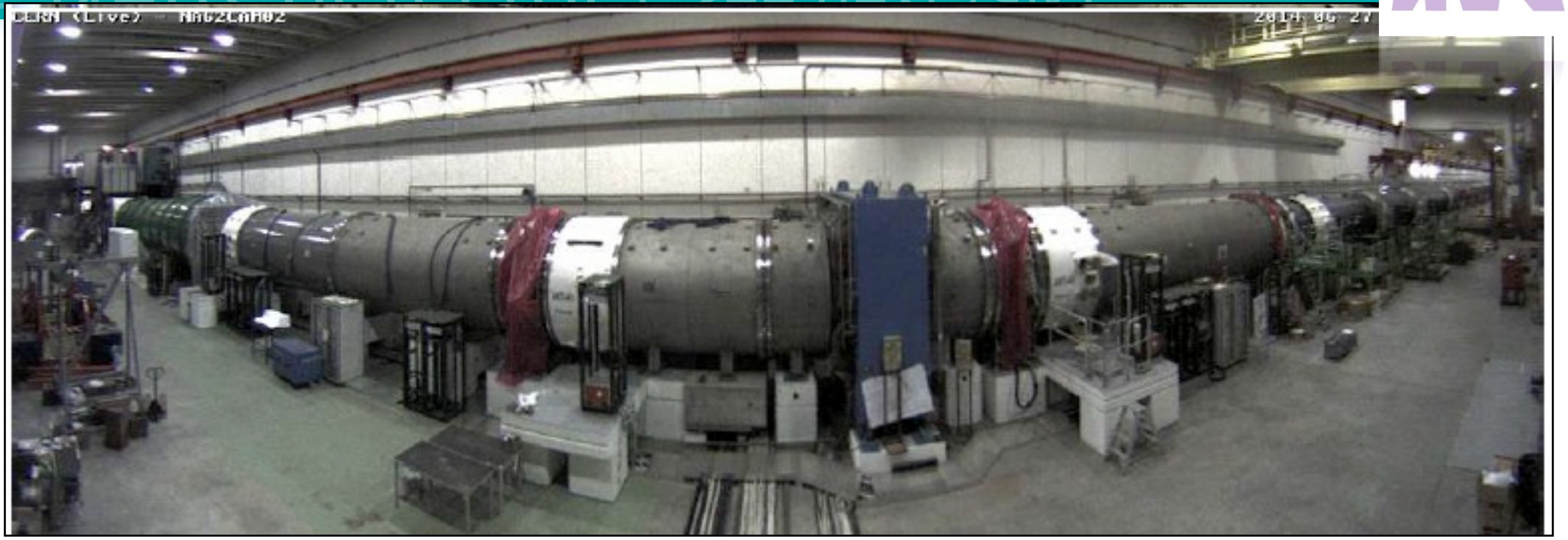
NA62 data sample



2015 data

- 12000 SPS spills (collected over 5 days)
- Beam intensity typically 1% of the nominal
- Low-level trigger scheme based on minimum-bias signals in CHOD and MUV
- High-level trigger based on KTAG signals
- GTK under commissioning (not used)

The NA62 detector (*see next talk)



Primary beam: CERN SPS protons

- 3×10^{12} ppp,
- 400 GeV/c (x3 NA48/2)

Secondary beam:

- unseparated positive beam π/K/p
- K^+ ~ 6%, p_K = 75 GeV/c (Δp/p ~ 1.1%)
- K^+ decays/year = 4.5×10^{12} (×45 NA48/2)
- integrated average rate = 750 MHz
- average K decay rate ≈ 10 MHz

Goal: measurement of BR($K^+\rightarrow \pi^+ \nu \bar{\nu}$) @ 10% accuracy

➔ O(20) SM events/year

➔ 2014: detector commissioning

➔ 2015: Trigger and high intensity beam line commissioning, detector quality studies

➔ 2016: High level trigger and full beam tracker commissioning, physics analysis (ongoing)

➔ Data samples

- 2015: Low intensity beam, minimum bias trigger
- 2016-2018: Stable conditions up to 40% of nominal intensity

The NA62 single muon sample

Only K^+ beam data (43% of NA62-2007 sample) → higher muon halo rejection

Event selection

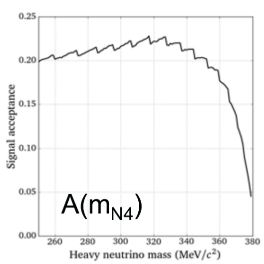
- One well reconstructed μ^+ track
- No extra clusters in LKr with E > 2 GeV
- Five-dimensional (z_{vertex}, ϑ, p, CDA, ϕ) kinematic suppression of muon halo

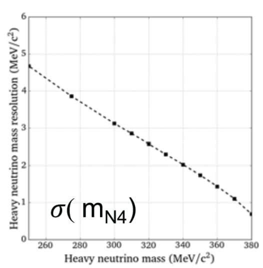
Data driven study of:

- Halo background
- Spectrometer resolution tails
- Trigger and μ-ID efficiencies

HNL detailed MC simulation for:

- Acceptance vs HN mass: $A(m_{N4})$
- m_{miss} peak resolution vs HN mass: $\sigma(m_{N4})$
- 1 MeV/c^2 mass intervals



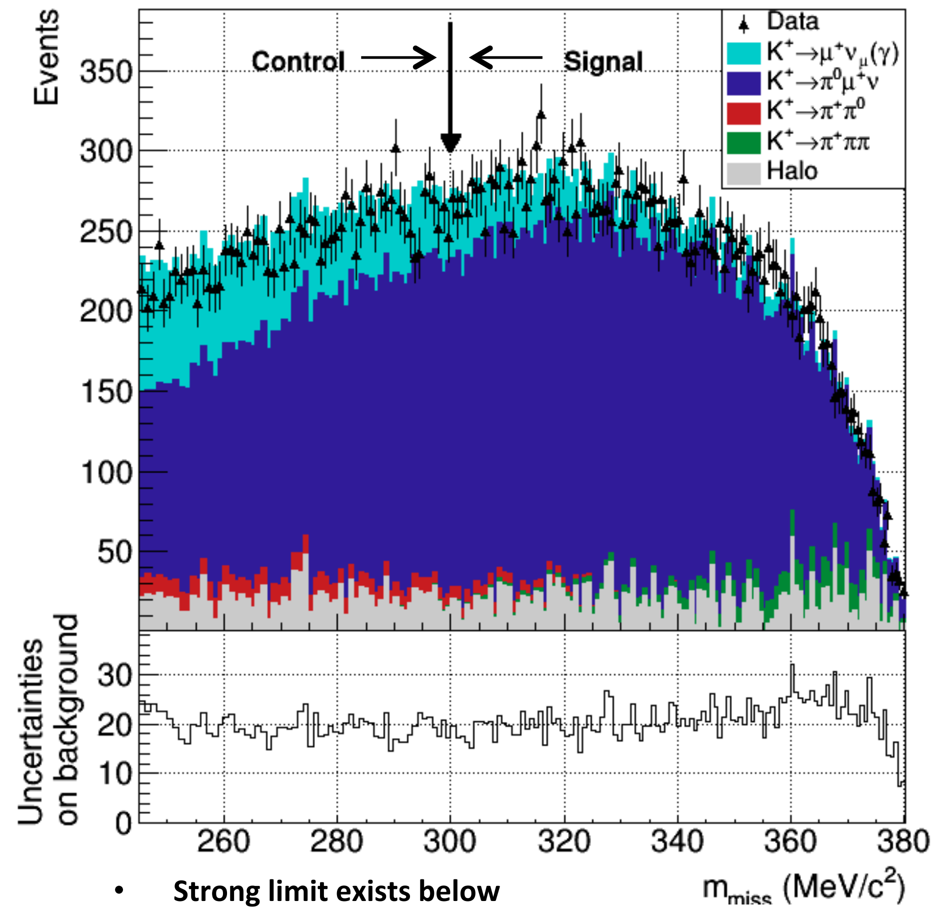


Kaon decays in the fiducial volume

- $N_K \sim 6 \times 10^7$ (from reconstructed $K^+ \to \mu^+\nu$) (downscaling D=150 for the 1-track μ trigger)

Search for peaks in $m_{miss} = \sqrt{(p_K - p_\mu)^2}$

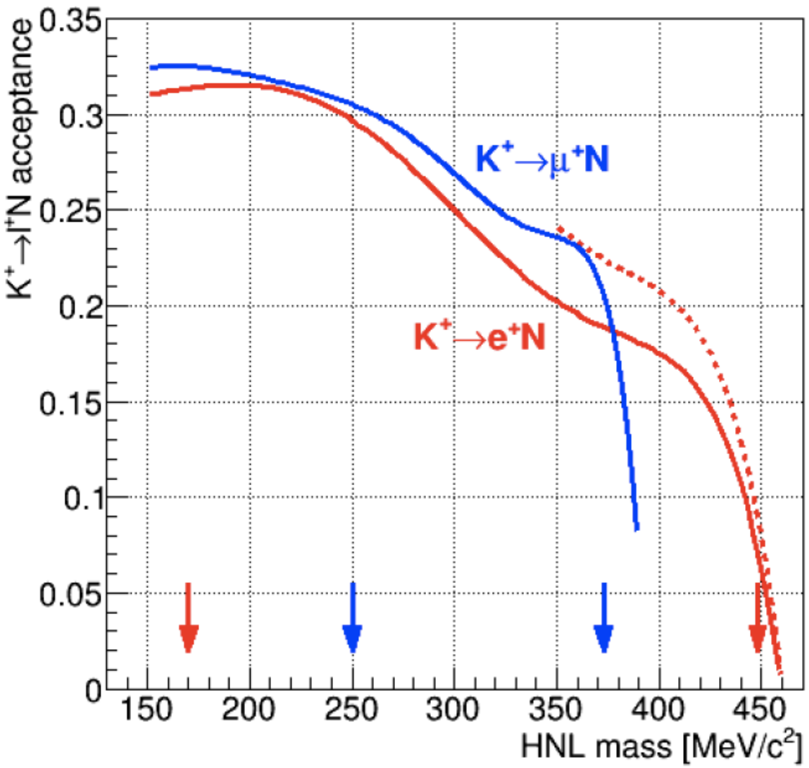
Signal region : $m_{miss}(\mu^+)$ in range [300 – 375] MeV/c^2

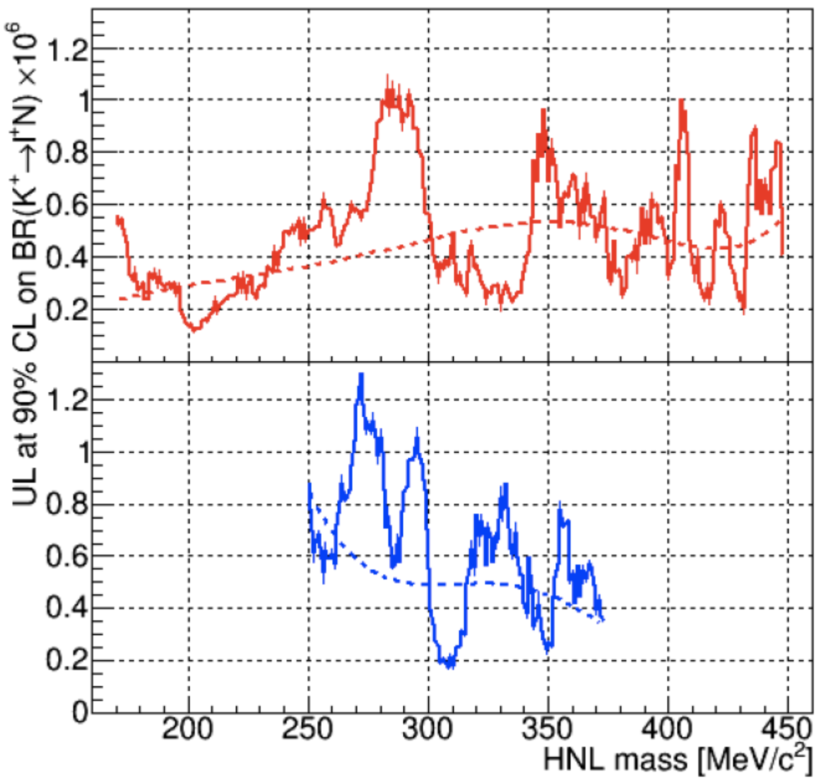


- **Strong limit exists below**
- **No acceptance above**

Limits on HNL Branching Fraction

- The limits on $\mathbf{n_{UL}}$ are converted into limits on the branching fractions $B(K^+ \to e^+ N)$ and $B(K^+ \to \mu^+ N)$ via $B(K^+ \to \ell^+ N) = \frac{n^\ell_{UL}}{N^\ell_K \bullet A^\ell_N(m_N)}$ which depends on the HNL acceptance $A^\ell_N(m_N)$

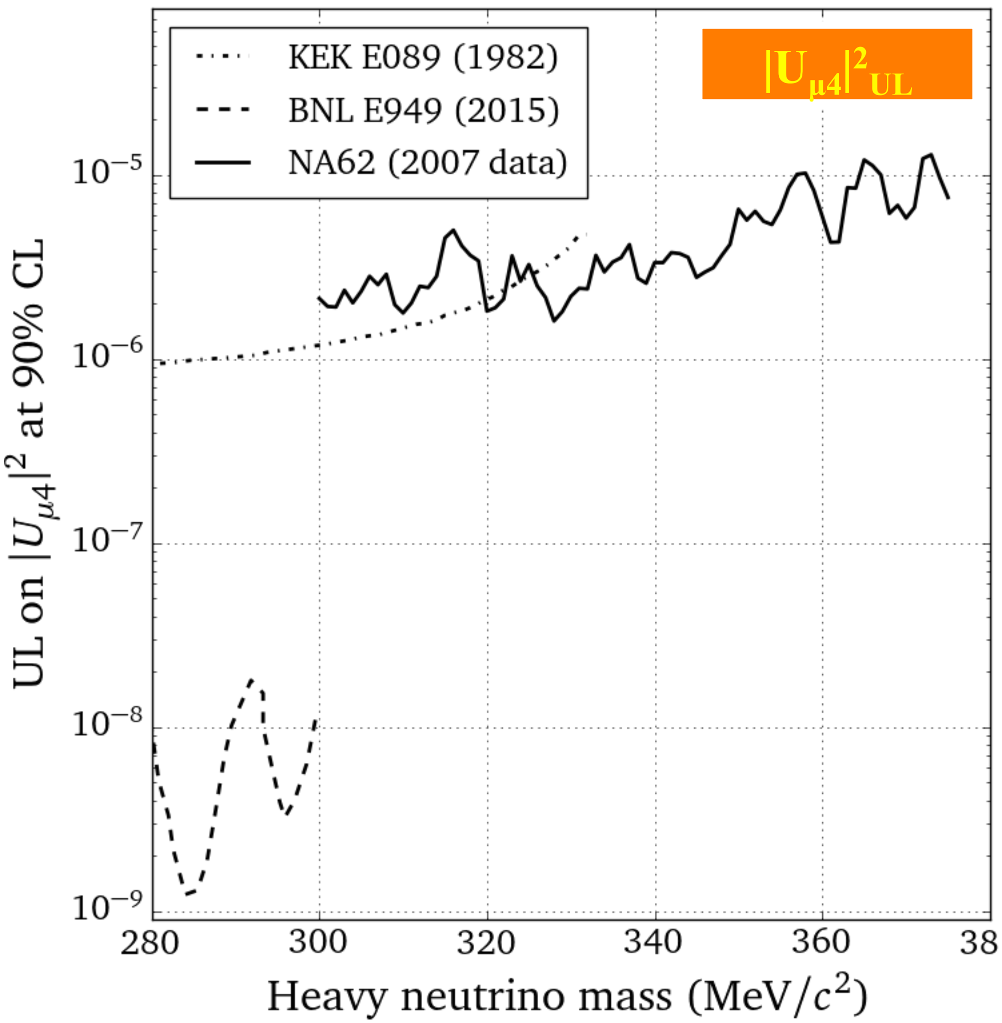




HN: results comparison

HN: results comparison

Comparison to existing peak search measurements



$$|U_{\mu 4}|^2 = \frac{1}{f(m_{HN})} \cdot \frac{BR(K^+ \to \mu^+ N_4)}{BR(K^+ \to \mu^+ \nu_\mu)}$$

f(mh) accounts for the phase space factor and the helicity suppression, and varies in the range 1.5–4.0 for m_{HN} in the region 300–375MeV/*c*2 considered in the present analysis.

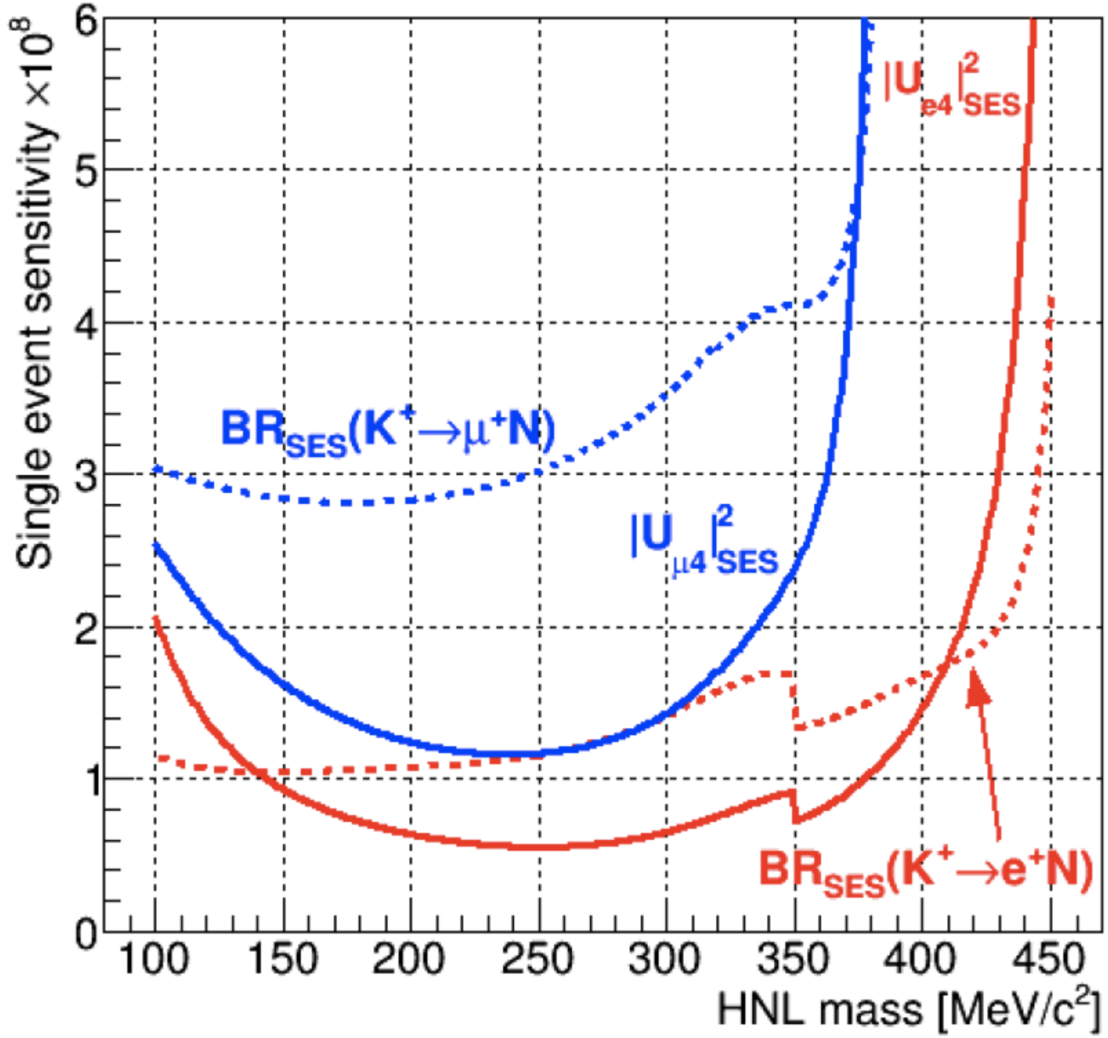
- **NA62-2007 result extends the mass range for UL on $|U_{\mu 4}|^2$ in HN production search experiments**
- **Most stringent limit on HN production in the mass region 300 < m_{HN} < 375 MeV/c^2**

Phys.Lett. B772 (2017) 712-718

NA62 - Search for HNL production

$B_{SES}(K^+ \rightarrow \ell^+ N) = 1/[N_K \times A(K^+ \rightarrow \ell^+ N)]$

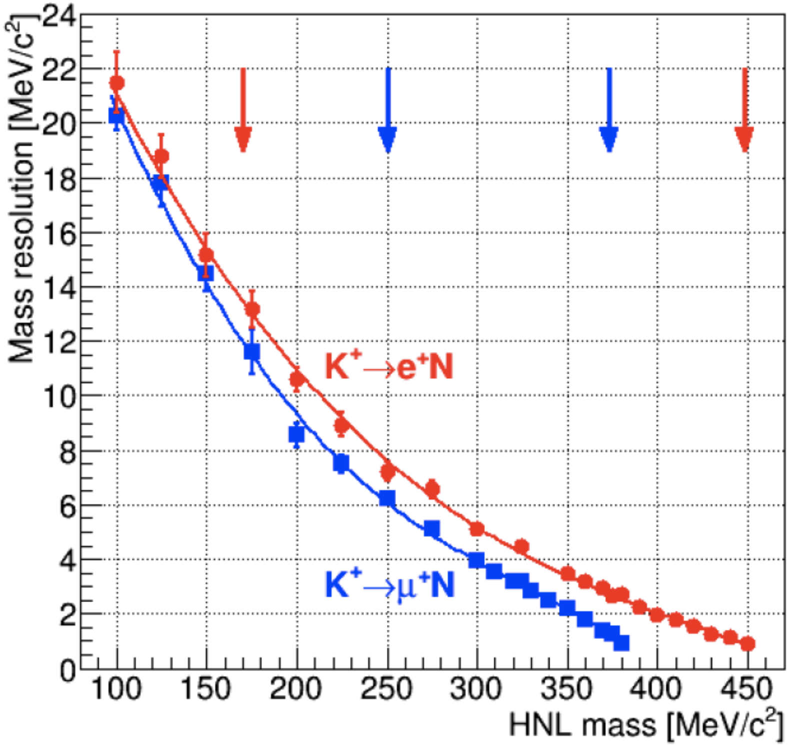
$|U_{\ell 4}|^2_{SES} = B_{SES}(K^+ \rightarrow \ell^+ N) / [B(K^+ \rightarrow \ell^+ \nu) \times \rho_\ell(m_N)]$



Limit setting procedure

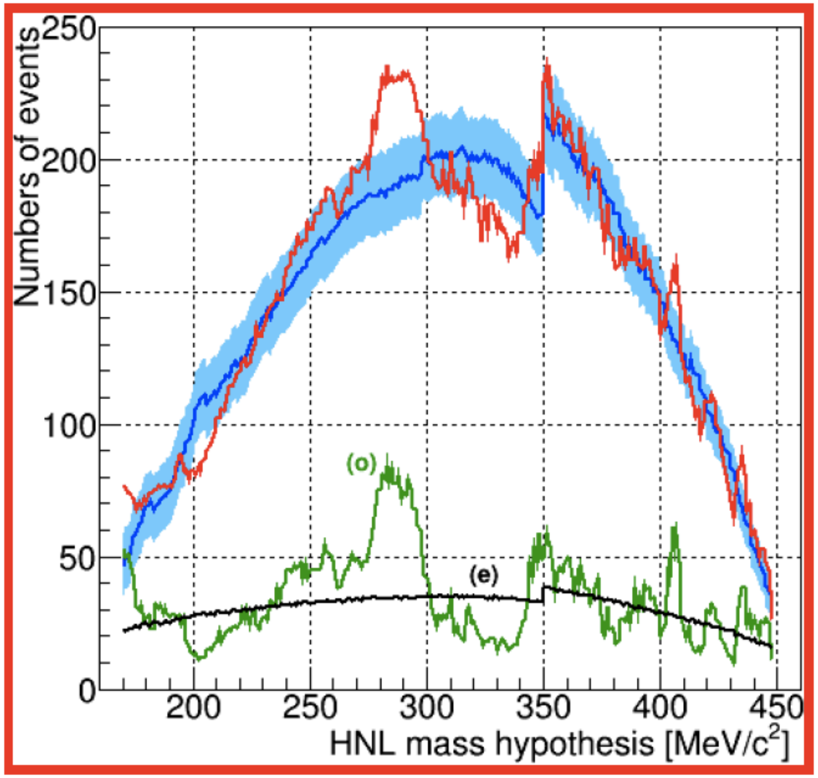
- Set limits on the number of HNL decays $\mathbf{n_{UL}}$ using **Rolke-Lopez** method [4]
- The limit is computed based on number of observed $\mathbf{n_{obs}}$ events, the number of expected events $\mathbf{n_{exp}}$, and the uncertainty on $\mathbf{n_{exp}}$

- Limit computed in steps of **1MeV/c²** across the **HNL mass** range
- $\mathbf{n_{obs}}$ determined by counting events in a “search window” of $\mathbf{1.5\sigma_m}$ at each HNL mass step
- $\mathbf{n_{exp}}$ estimated by fitting data events outside of the search window

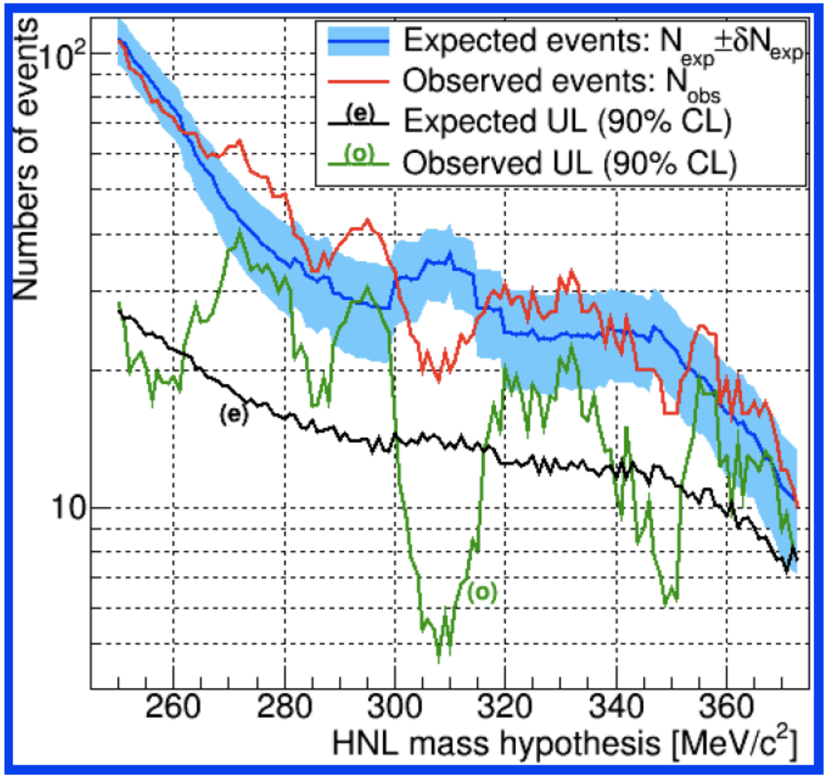


Limits on number of HNL decays

$K^+ \rightarrow e^+ N$



$K^+ \rightarrow \mu^+ N$



- Limits on the number of $K^+ \rightarrow e^+ N$ are set at the level of **O(30)** events
- Limits on the number of $K^+ \rightarrow \mu^+ N$ are set at the level of **O(20)** events

Search for resonances: Acceptance

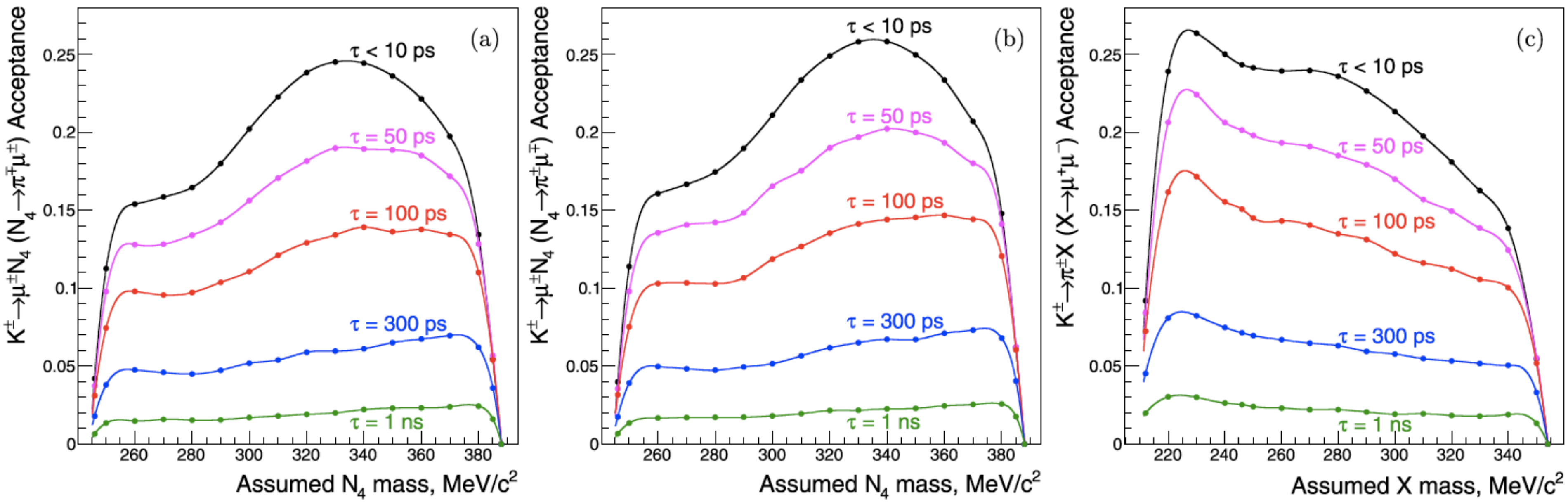
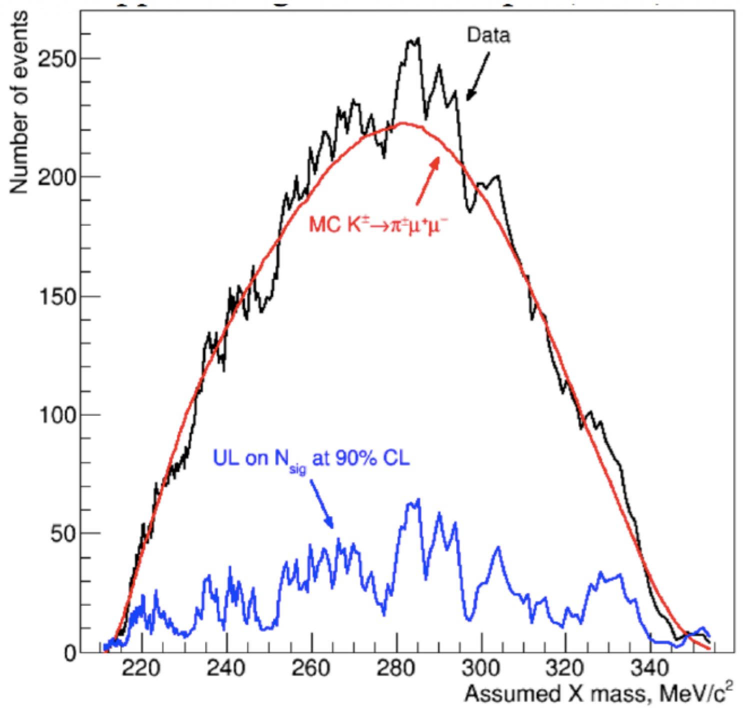
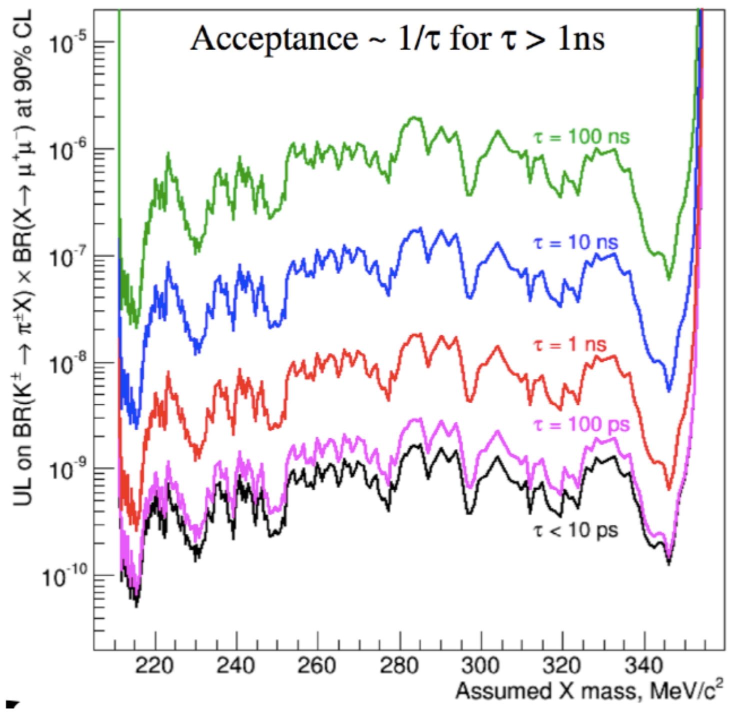


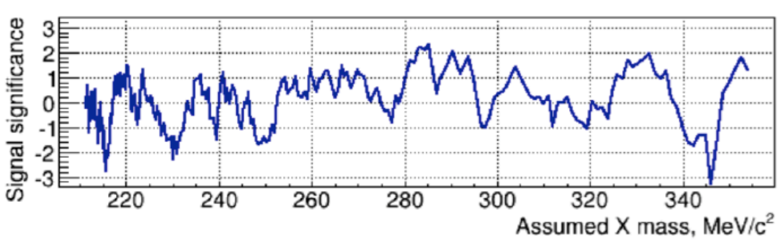
Fig. 2. Acceptances as functions of the assumed resonance mass and lifetime of: (a) the $K_{\pi\mu\mu}^{\mathrm{LNV}}$ selection for $K^\pm \to \mu^\pm N_4$, $N_4 \to \pi^\mp\mu^\pm$ decays; (b) the $K_{\pi\mu\mu}^{\mathrm{LNC}}$ selection for $K^\pm \to \mu^\pm N_4$, $N_4 \to \pi^\pm\mu^\mp$ decays; (c) the $K_{\pi\mu\mu}^{\mathrm{LNC}}$ selection for $K^\pm \to \pi^\pm X$, $X \to \mu^+\mu^-$ decays. For resonance lifetimes $\tau > 1$ ns the acceptances scale as $1/\tau$ due to the required three-track vertex topology of the selected events. In the LNV selection, the tighter $M_{\pi\mu\mu}$ cut leads to a 5% smaller acceptance. The mass dependence in case (c) differs from the others due to the $p > 15$ GeV/c pion momentum cut, not applied to muons (Sec. 2).

Search for $K^\pm \rightarrow \pi^\pm X$ ($X \rightarrow \mu^+\mu^-$) decay



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





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

Statistical significance never exceeds $+3\sigma$

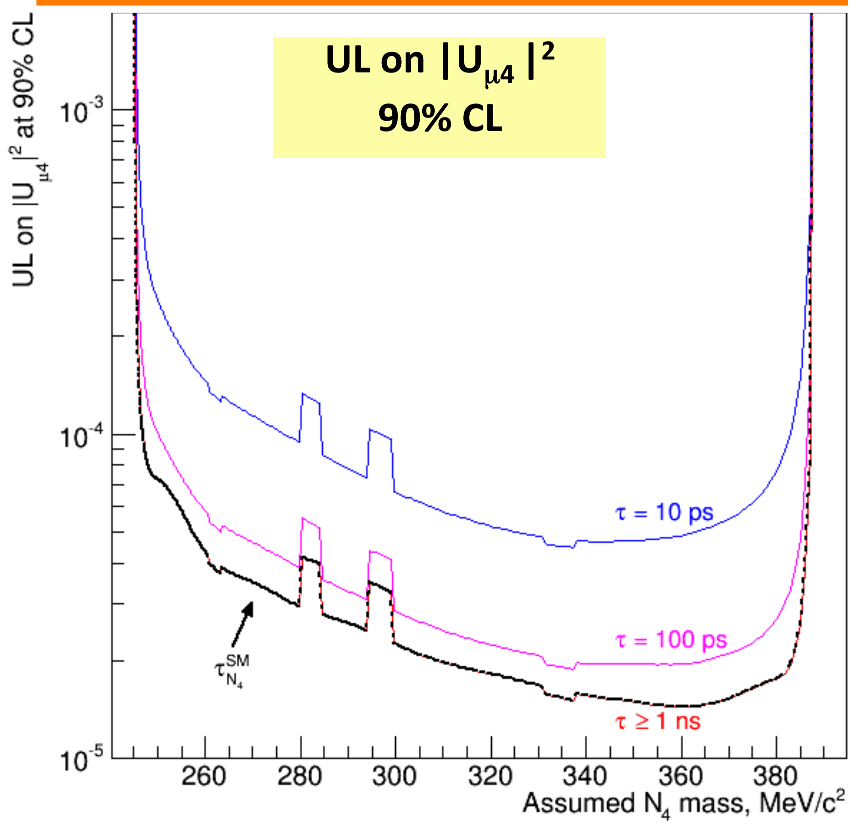
No signal observed!

NA48/2 Constraints on $|U_{\mu4}|^2$

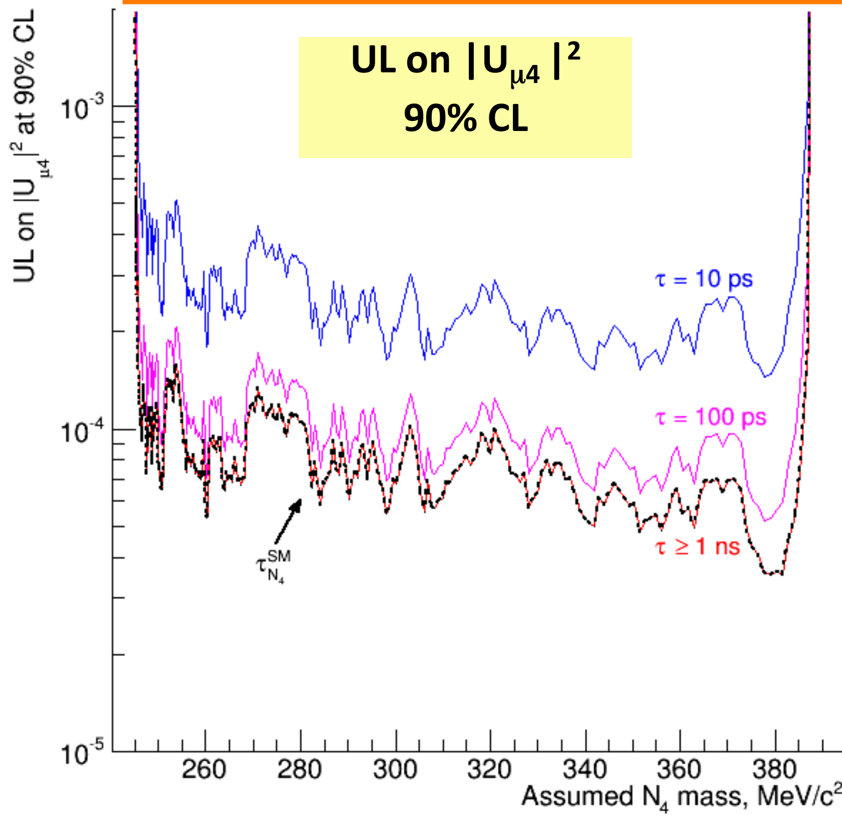
From UL on BR to UL on $|U_{\mu4}|^2$:

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

Same sign μ sample (LNV)

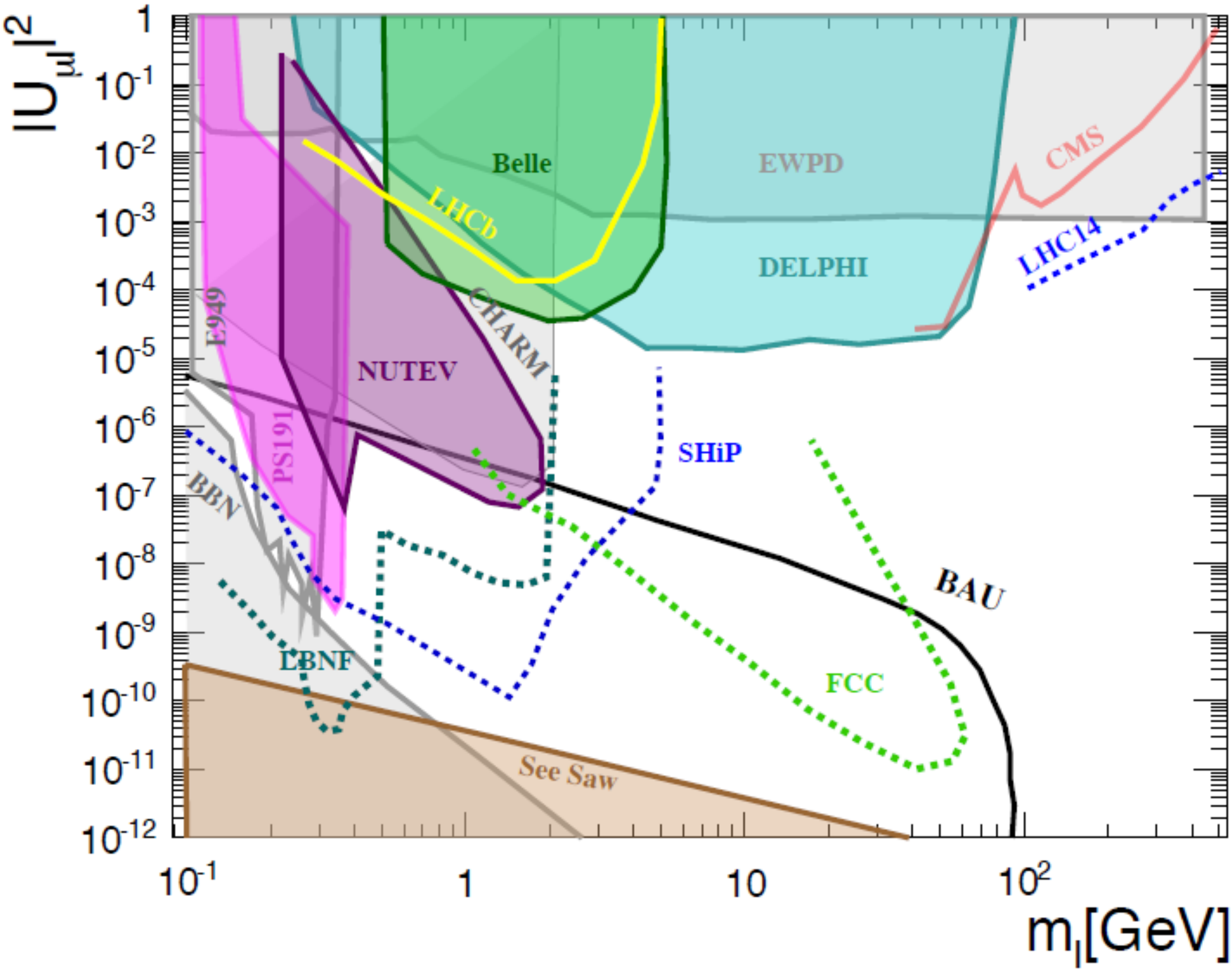


Opposite-sign μ sample (LNC)



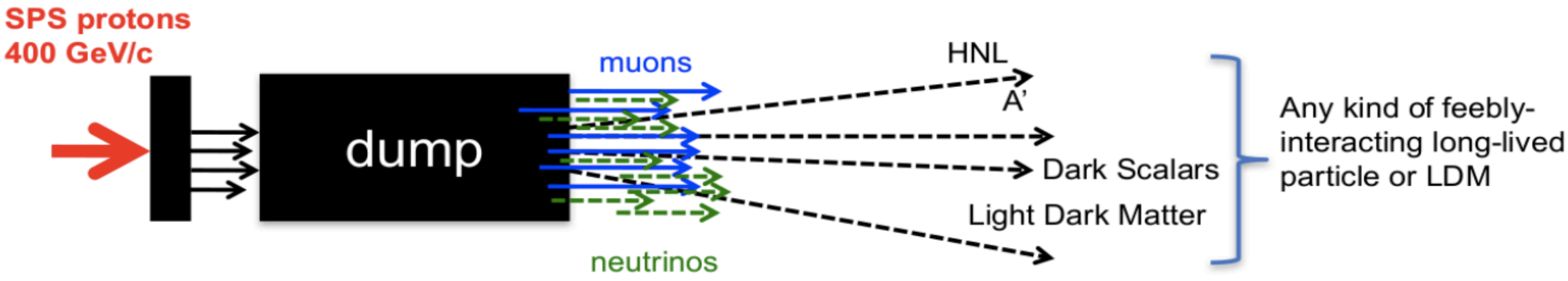
❖ **NA48/2 limits on $|U_{\mu4}|^2$ only applies to short lived HN (τ < 100 ps)**

Limits on $|U_{\mu 4}|^2$



NA62 in dump mode

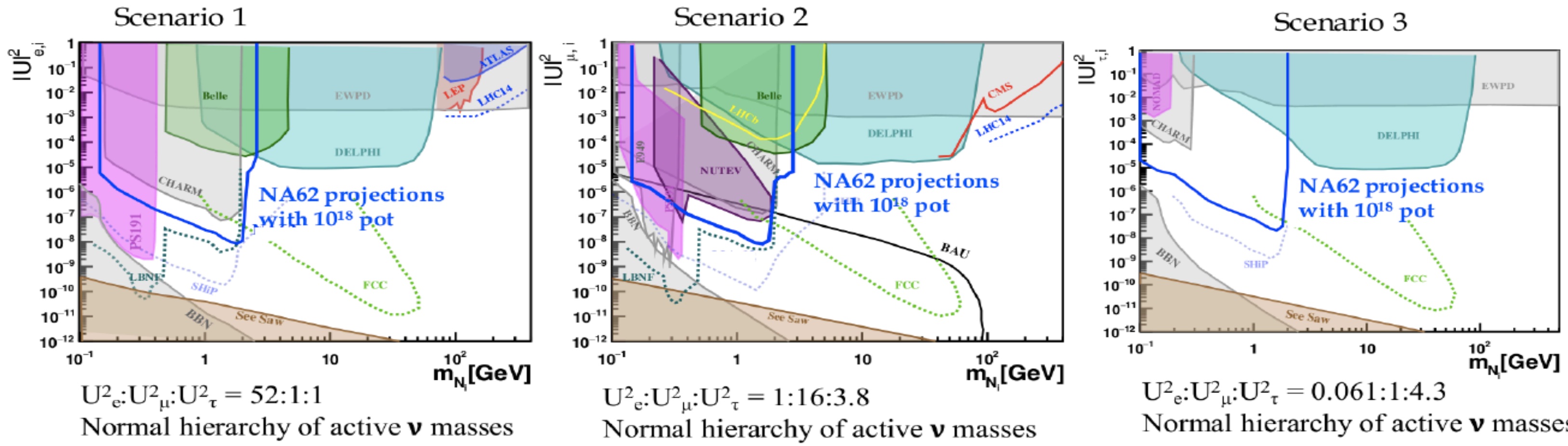
A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:



NA62: Muon halo & neutrino halo

- Muons produce inelastic interactions and combinatorial background
  - In beam mode about ∼5 MHz of μ^+ and 150 kHz μ^- present due to early decays in flight of K and π in the beam
  - In dump mode the muon halo is reduced by 2 orders of magnitudes (2016 data)
- Neutrinos produce inelastic interactions in the material surrounding the Fiducial Volume
  - In dump mode about ∼10 GHz of active neutrinos are expected at nominal condition

NA62 in dump mode - prospects



Assume to detect all 2-track final states, including open channels, and zero background.

Zero background for charged particle final states has been proven at $\sim 4 \times 10^{15}$ POT and fully reconstructed final states

The current NA62 run will be exploited to evaluate background rejection up to $\sim 10^{16} - 10^{17}$ POT's

- optimise the detector design for future beam-dump mode: improvements in the setup are under study
- potentially achieve first results on the dark sector searches

- Possible running in dump-mode after LS2 to colllect 10^{18} PoT (80 days @ full intensity) to search for hidden particles from charm/ beauty decays