BROOKHAVEN NATIONAL LABORATORY

SEARCH FOR EXOTIC PROCESSES IN KAON DECAYS IN THE E949 EXPERIMENT

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On behalf of the E949 collaboration

ICPPA 2016
10–14 October, MEPhI, Moscow, Russia

OUTLINE

- Search for heavy neutrinos: $K^+ \to \mu^+ \nu_H$,
  Phys. Rev. D 91, 052001 (2015), presented on many conferences
- Search for rare decay $K^+ \to \mu^+ \nu\nu\nu$,
  Phys. Rev. D 94, 032012 (2016)

BEYOND THE STANDARD MODEL

Neutrino oscillation	Baryon asymmetry of the Universe	Dark matter and dark energy
		 

There is new physics beyond the Standard Model, but we don't know exactly what is it

νMSM: SM + 3 right-handed neutrinos

$m_1 \sim 10$ keV

$m_{2,3} \sim 100$ MeV - 100 GeV

T. Asaka and M. Shaposhnikov

Phys. Lett. B620, 17 (2005).

HOW TO FIND HEAVY NEUTRINOS?

- Meson decays ✓

Search for extra peaks in lepton distributions (momentum, energy, missing mass, ...)

$$\Gamma(M^+ \to l^+ \nu_H) = \rho \times \Gamma(M^+ \to l^+ \nu_l) \times |U_{lH}|^2$$

R.E. Shrock, Phys. Rev. D24, 1232 (1981)

- Heavy neutrino decays

"Nothing" ➛ leptons and hadrons

$$\nu_H \to e^+ e^- \nu_\alpha, \nu_H \to \mu^\pm e^\mp \nu_\alpha, \nu_H \to \mu^+ \mu^- \nu_\alpha,$$

$$\nu_H \to \pi^0 \nu, \pi e, \pi \mu, K e, K \mu, \ldots$$

$K^+ \to \mu^+ X$ DECAY

- X is invisible set of neutral particles
- We are able to set a limit on any decay with a single muon
- For example, the $K^+ \to \mu^+ \nu\nu\nu$ decay, which hasn't been probed since 1973
  - BR ~10^{-16} in SM (recent calculation, arXiv:1605.08077). Any signal — clear evidence of New Physics
  - Can provide information on two effects: neutrino-neutrino interaction (Phys. Lett. B32, 121–124 (1970), arXiv:hep-ph/9908272) and six fermion interaction (Phys. Rev. 133, B130–B131 (1964))
  - PDG value 6.0×10^{-6} based on neutrino-neutrino interaction model (1973!)

EXPERIMENT BNL—E949

Search for ultra-rare decay

$K^+ \to \pi^+ \nu \bar{\nu}$

Stopped kaons were used

$$BR_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) =$$
$$(9.11 \pm 0.72) \times 10^{-11}$$

Buras, A.J., Buttazzo, D. & Knegjens, R., JHEP 1511 (2015) 166

E949+E787

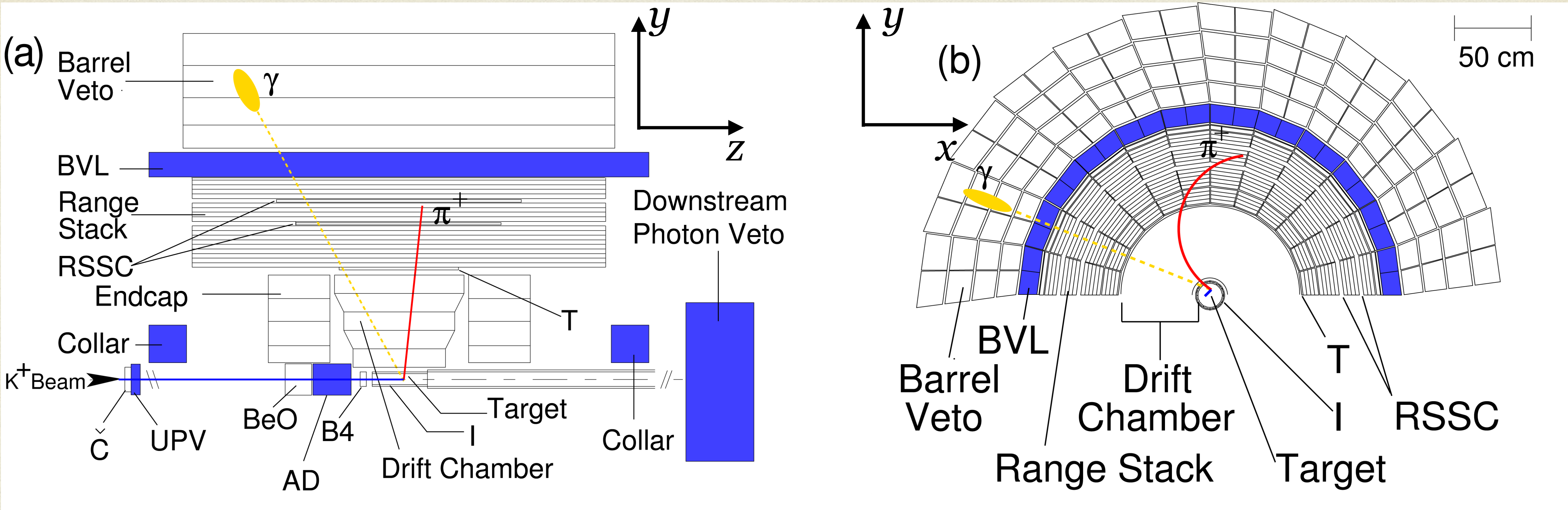
4+3(E787)=7 events

➜

$$BR(K^+ \to \pi^+ \nu \bar{\nu}) =$$
$$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

Phys. Rev. D79, 092004 (2009)

THE E949 DETECTOR



- Incoming 710 MeV/c kaons were identified by Čerenkov counter and slowed down by degraders.
- Kaons came to rest in the centre of the target, which was made of 413 5 mm square scintillating fibres.
- The whole spectrometer was in a 1 Tl magnetic field. Daughter particle momentum was measured in the Drift Chamber, energy and range — in the Range Stack.
- Hermetic system of photon veto detectors.

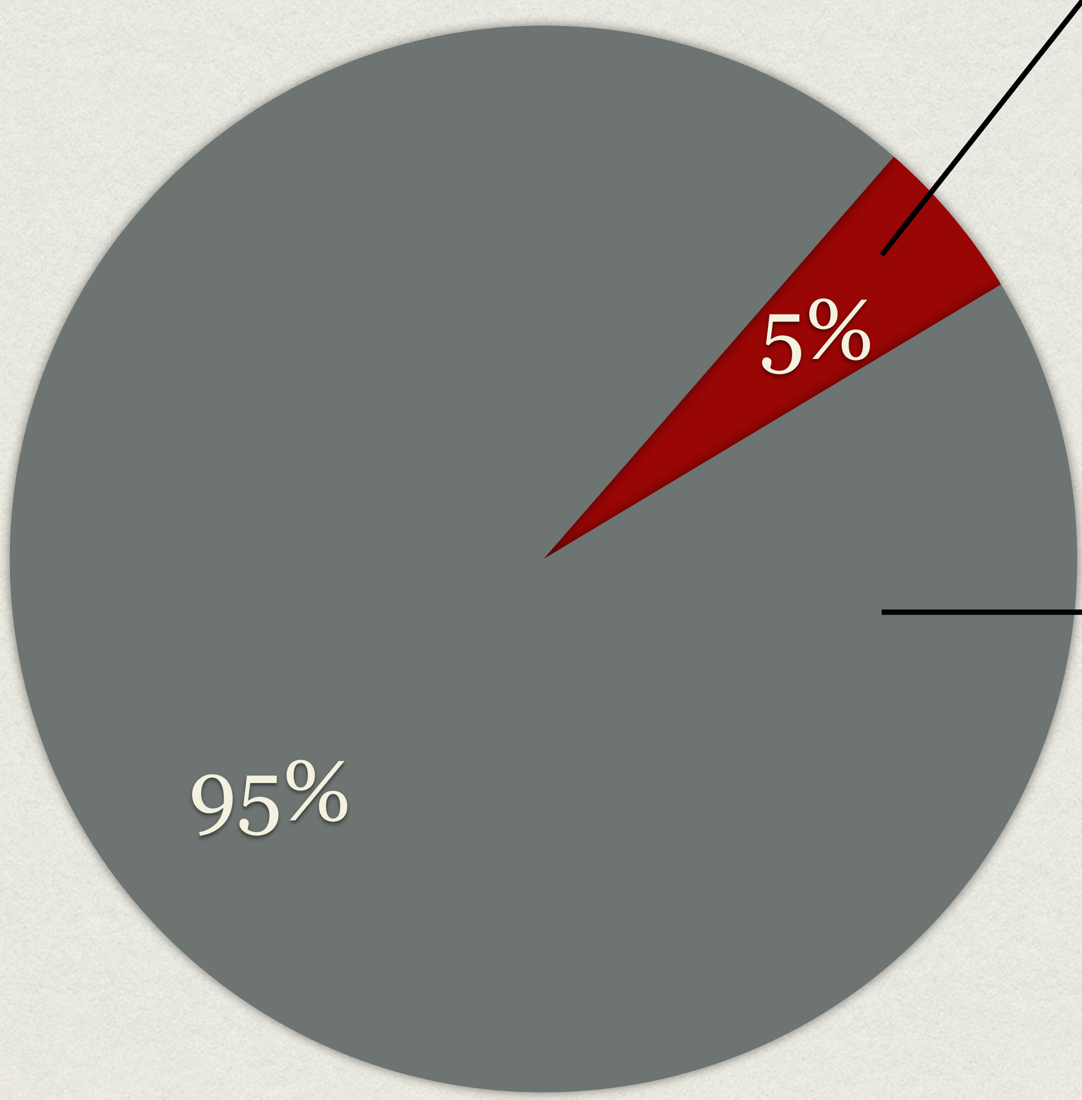
DATA SAMPLES

- The main trigger. Huge statistics: 1.70×10^{12} stopped kaons
  - ☑ Pros — signal decay $K^+\rightarrow\mu^+\nu_H$ is similar to $K^+\rightarrow\pi^+\nu\nu$: one single charge track and no other detector activity
  - ☐ Cons — it was designed to select pions from the $K^+\rightarrow\pi^+\nu\nu$, rejected muons
- Monitor triggers
  - ☑ Pros — simple selection, no muons rejection
  - ☐ Cons — much less stopped kaons ($\sim10^7$)

Used for data quality assessment, calibrations of the detector subsystems and acceptance measurement for the $K^+\rightarrow\mu^+\nu_H$ decay.

THE STRATEGY

The main trigger data



Selected by choosing every 20th event (included all runs)

- Acceptance verification
- Systematic uncertainties
- Background shape

Not accessed until all cuts were determined. Used only to extract final result

SELECTION CRITERIA

The $K^+ \to \mu^+ \nu_H$ signature — single muon track

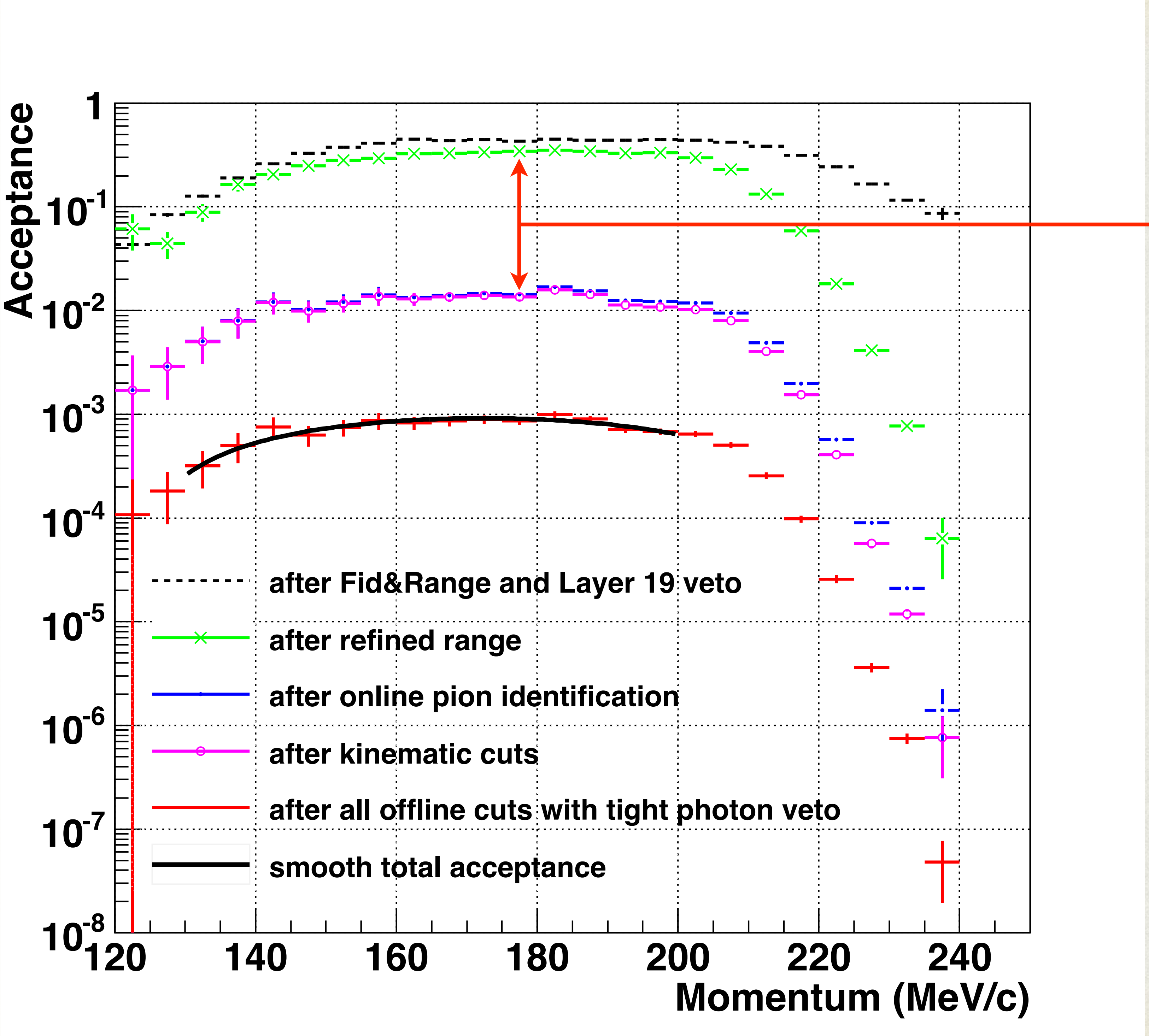
Trigger

- Kaon stopped in target
- Charged track in the fiducial volume(1)
- Delay coincidence (rejected kaon decays-in-flight)
- Rejected long track
- Photon veto
- Pion identification in the stopping counter: requested decay chain $\pi \to \mu$

Offline

- Track was reconstructed in the drift chamber
- Charged track in the fiducial volume(2)
- Rejected kaon decays-in-flight
- Rejected extra beam particles
- Good track in the target and Range Stack (numerous requirements)
- Muon identification
- Photon veto (loose or tight)

ACCEPTANCE MEASUREMENT

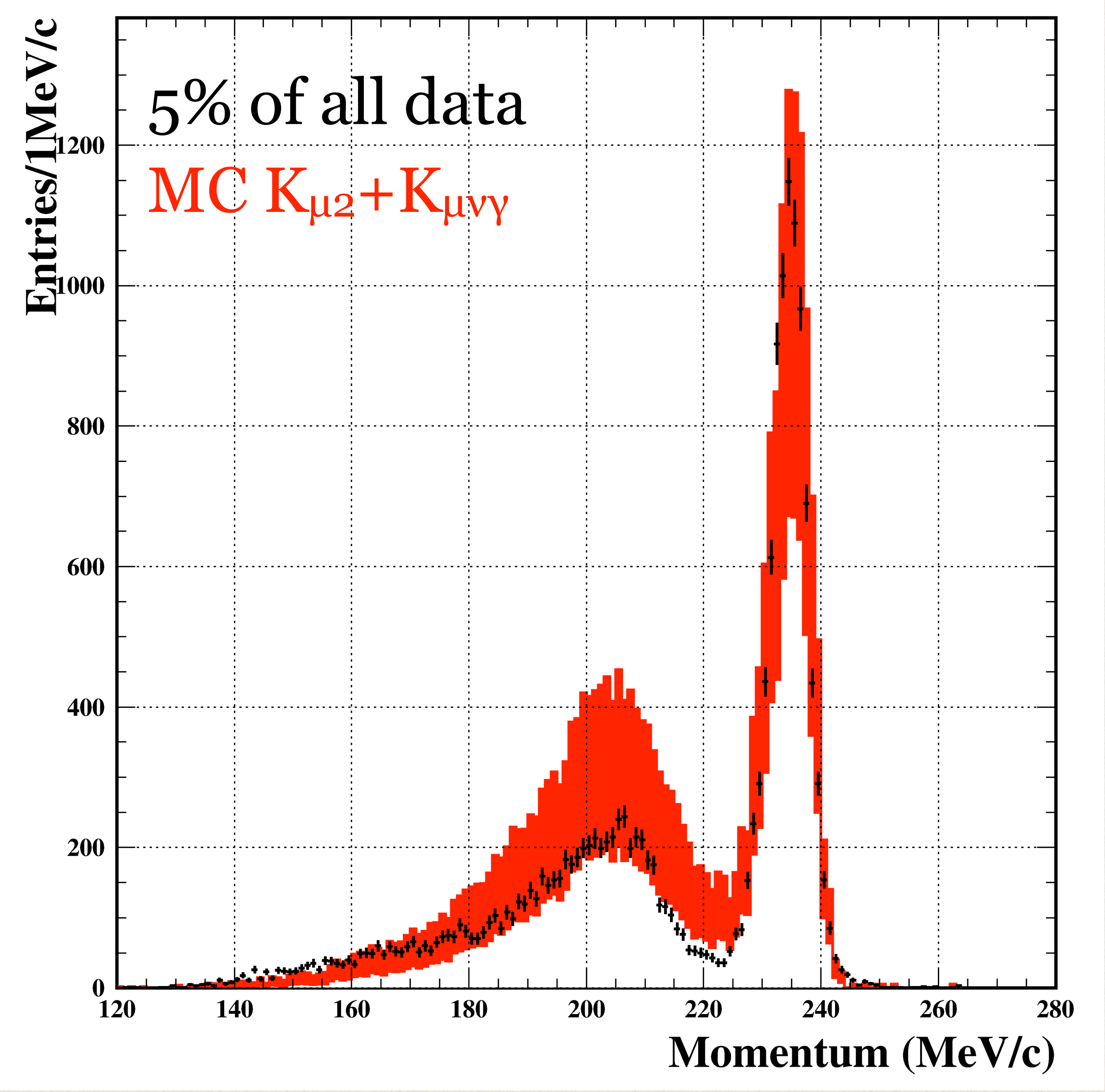


The largest acceptance lost was due to pion identification online (~20). It was implemented in the trigger, cannot be turned off

Single events sensitivity for the $K^+ \to \mu^+ \nu_H$ decay:

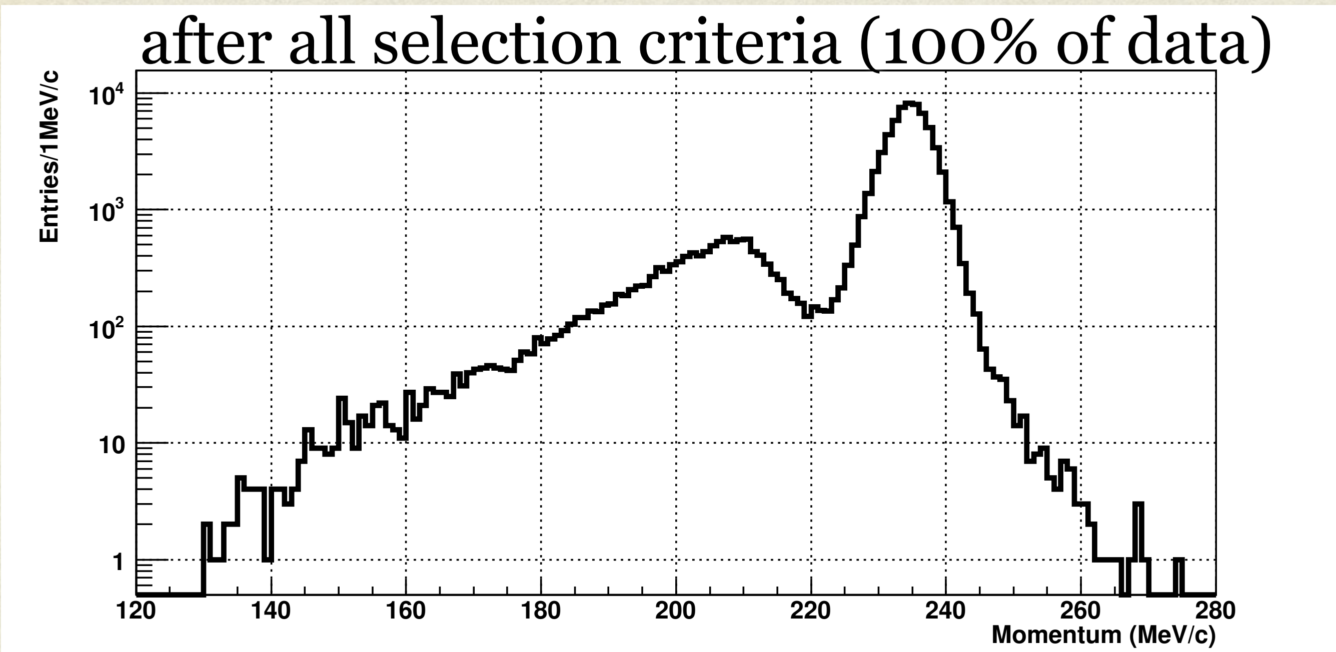
$$S.E.S = \frac{1}{KBlive \times Acc} = 7.35 \times 10^{-10}$$

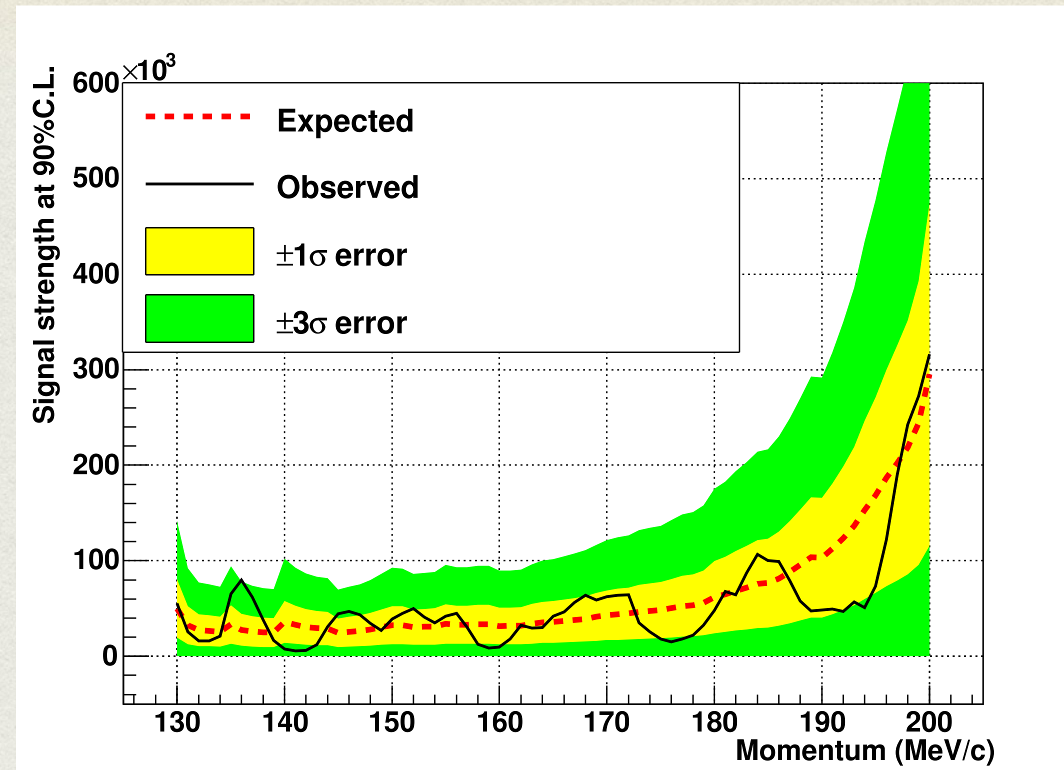
BACKGROUND SHAPE



Obviously, MC is not the best fit of data, but we are not going to use the simulated background shape in the further analysis. MC shape does not have obvious bumps or valleys, so the only conclusion from simulation is to assume that experimental background shape also should be smooth, but we do not know exact background shape.

PEAK SEARCH





No peaks were found

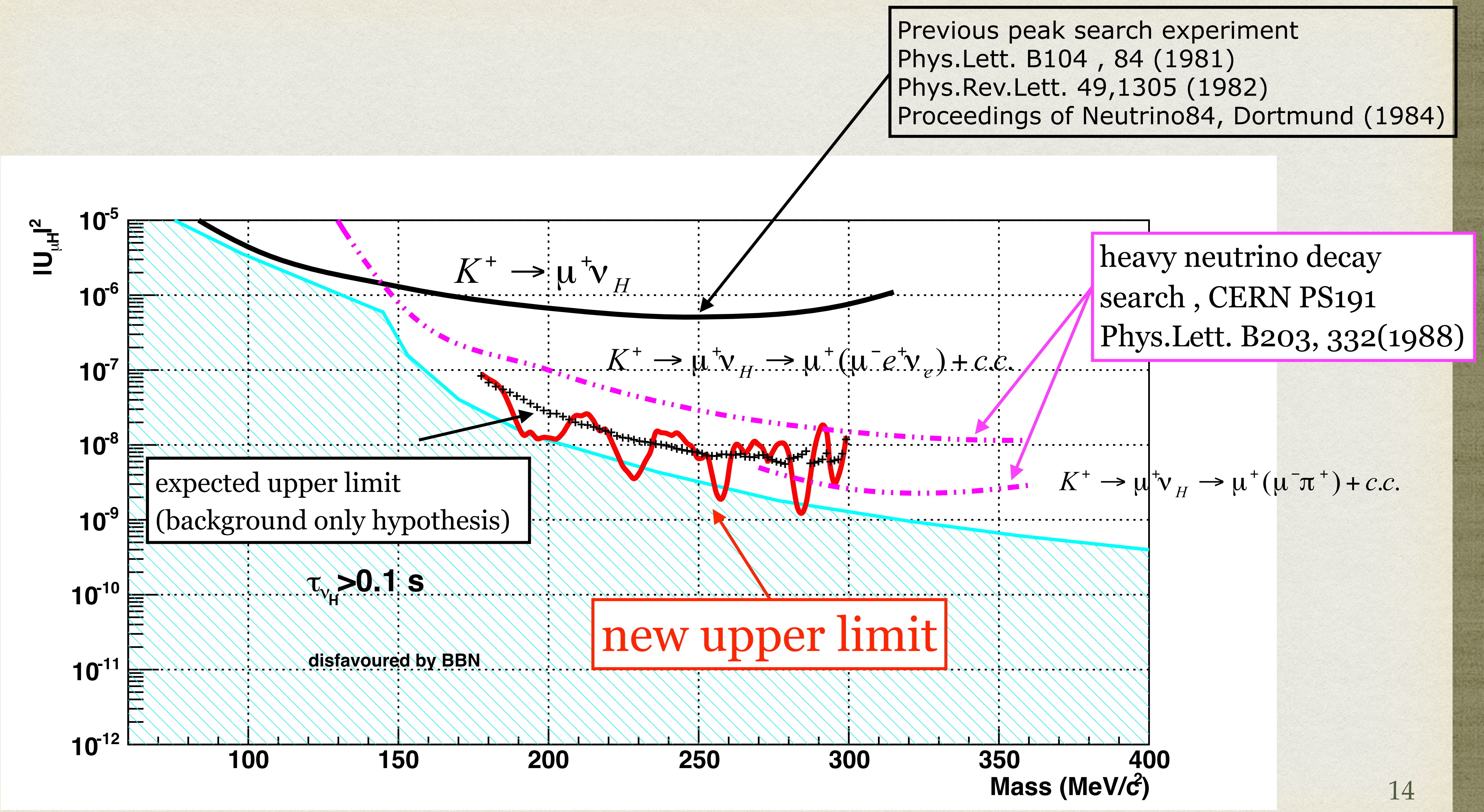
↓

No evidence for the heavy neutrino signal

→

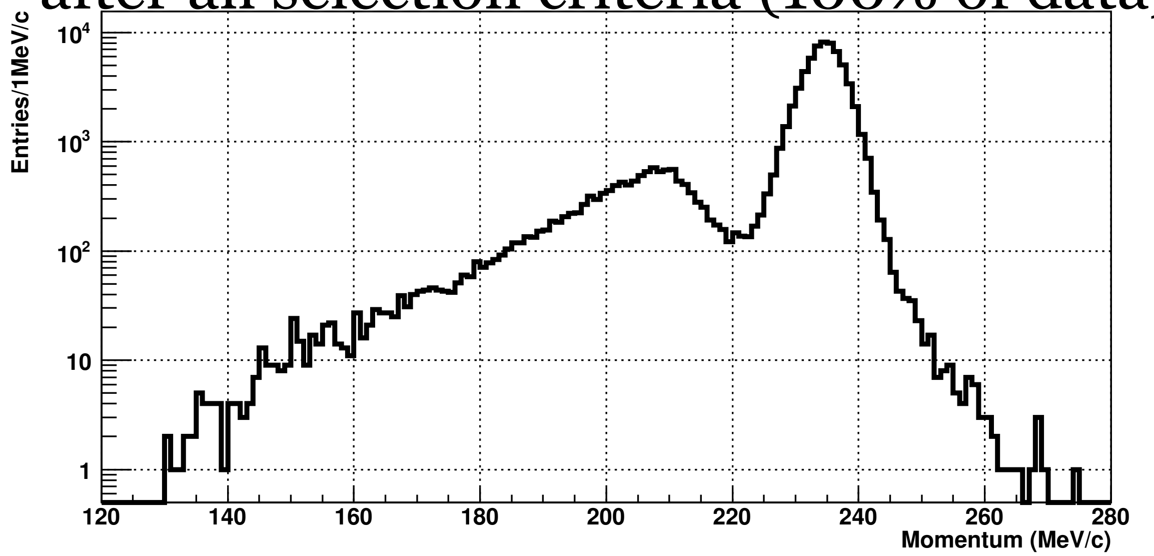
Set upper limit on the mixing matrix element between muon and heavy neutrino

MIXING MATRIX ELEMENT



$K^+ \to \mu^+ X$ DECAY

after all selection criteria (100% of data)



$$BR_P(K^+ \to \mu^+ + X) < \frac{1}{N_K} \sum_{i=130}^{P} \frac{N_i}{Acc_i} + 1.28\sigma,$$

Acceptance for single muon selection is already known

$$BR(K^+ \to \mu^+ + X, 130 < p_\mu < 175 \text{ MeV/c}) <$$
$$< 7.5 \times 10^{-7}$$

To get total decay rate we need to know the signal shape

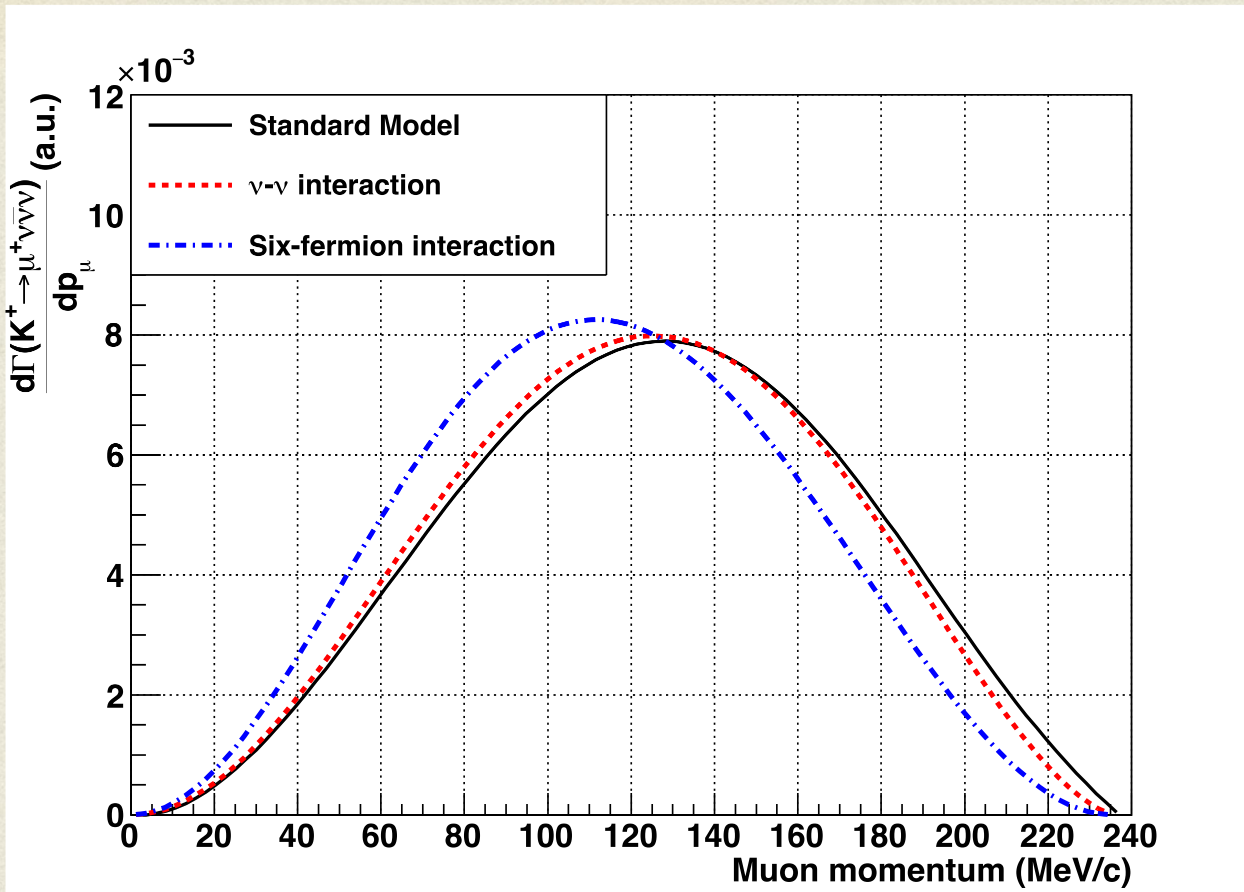
$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} = 7.5 \times 10^{-7} \times \frac{\int_0^{p_\mu^{max}} (d\Gamma/dp_\mu) dp_\mu}{\int_{130}^{175} (d\Gamma/dp_\mu) dp_\mu}$$

here can be any set of neutral particles which are invisible in the detector

More general, if you do not like 130—175 MeV/c region:

$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} = BR_P(K^+ \to \mu^+ + X) \times$$
$$\times \frac{\int_0^{p_\mu^{max}} (d\Gamma/dp_\mu) dp_\mu}{\int_{130}^{P} (d\Gamma/dp_\mu) dp_\mu}$$

$K^+ \to \mu^+ \nu\nu\nu$ DECAY



1. Standard Model.

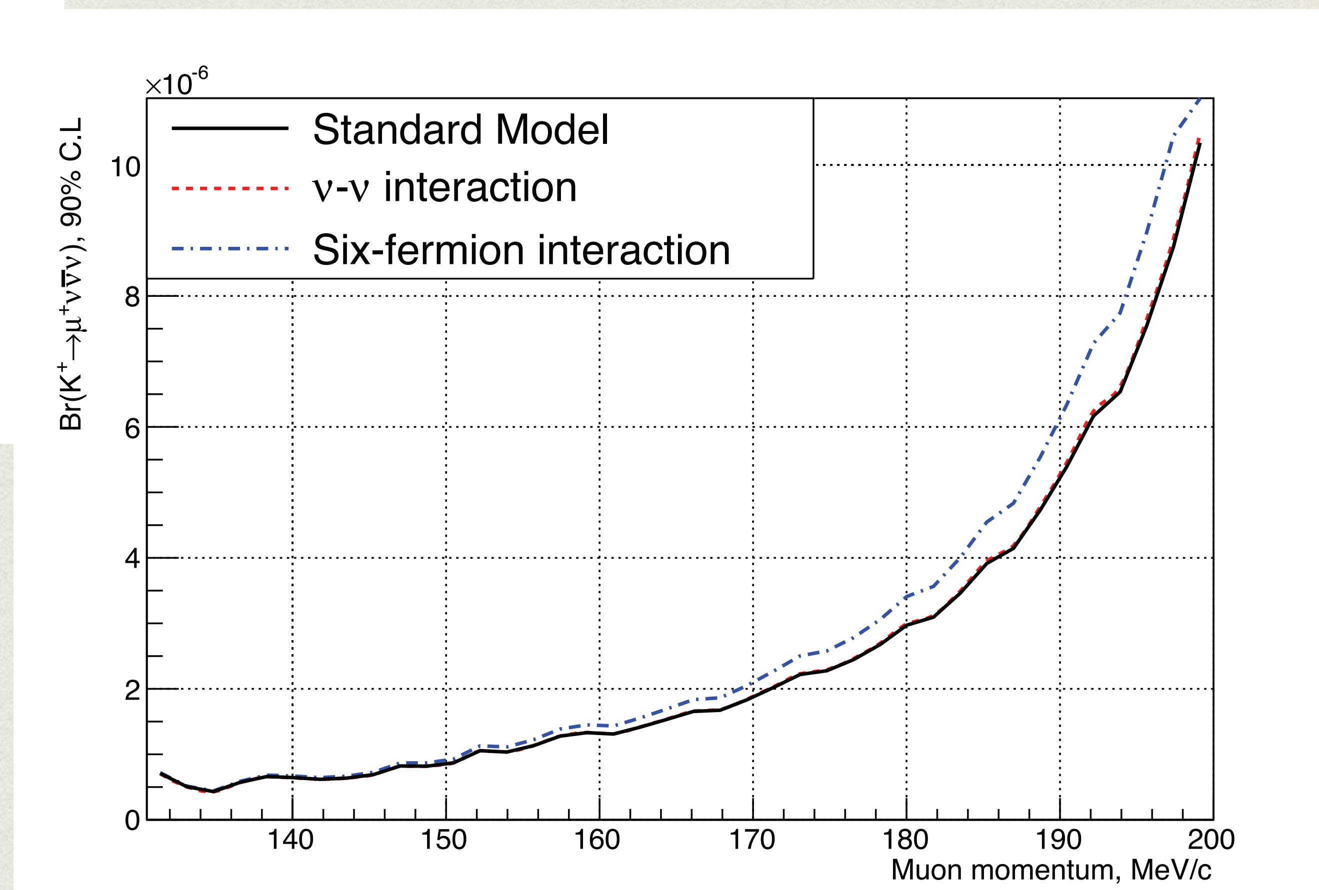
$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} < 2.4 \times 10^{-6}$$

2. Neutrino-neutrino interaction.

$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} < 2.4 \times 10^{-6}$$

3. Six-fermion interaction:

$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} < 2.7 \times 10^{-6}$$



CONCLUSIONS

- The heavy neutrino existence in the mass region 175-300 MeV/c^2 was tested using E949 experimental data set
- No evidence was found
- Previous best constraints from CERN PS191 were improved by order of magnitude
- New mixing matrix element $|U_{\mu H}|^2$ upper limit is varying between 10^{-9} and 10^{-8}
- In contrast to CERN PS191 or BBN lower limit our result is model-independent.
- No evidence for $K^+ \to \mu^+ \nu\nu\nu$ decay was found
- Improved the current limit by factor ~3. For the first time limit is presented in the framework of the standard model
- Presented procedure to calculate upper limit on any possible kaon decay to muon and invisible set of neutral particles for any assumed muon momentum spectrum

THANK YOU!