Search for heavy neutrinos in kaon decays

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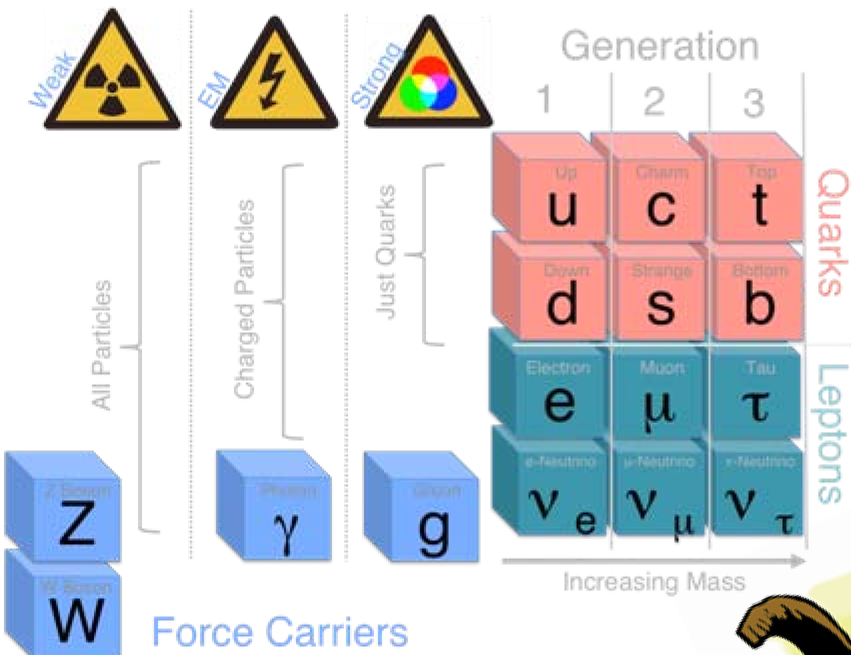
Outline

- Neutrino in the Standard Model and beyond
- Previous heavy neutrino searches
- Experiment BNL-E949
- Selection criteria
- Efficiency and background study
- Peak search method
- Results and conclusions

Standard Model neutrino



Standard Model neutrino
is massless particle

$$\nu_l = \sum U_{li} \nu_i, \; l = e, \mu, \tau; \; i = 1,2,3$$

Why do we need heavy neutrinos?

Although Standard Model has a huge success in explaining rich variety of experimental data (and with further credence from Higgs boson observation) it is known to be incomplete.

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

Neutrino mixing and oscillation

Dominance of matter over antimatter

Dark matter and dark energy

JHEP0808:008,2008
(arXiv:0804.4542v2 [hep-ph]),
Ann.Rev.Nucl.Part.Sci.59:191-214,2009D
(arXiv:0901.0011v2 [hep-ph])

νMSM

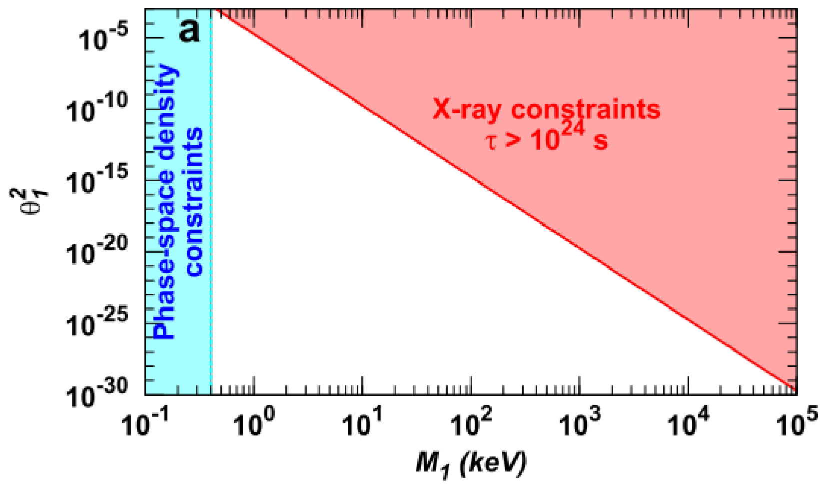
SM + 3 neutral right-handed heavy leptons

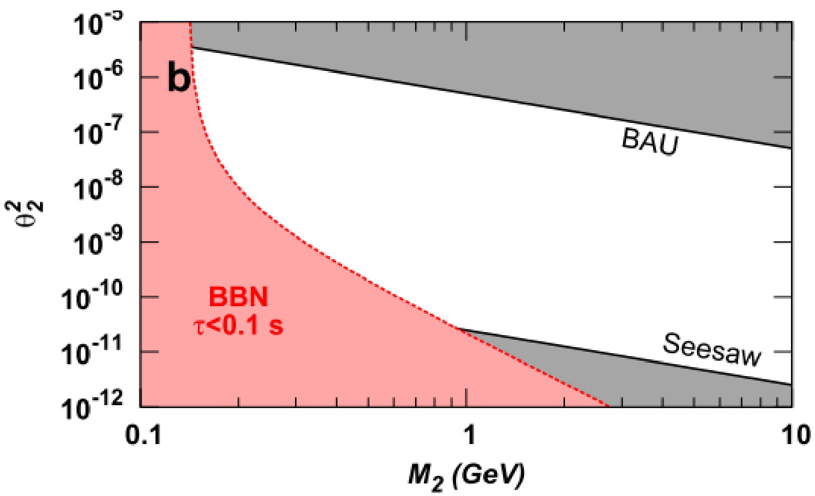
$M_{N_1} \in \mathrm{O}(10)$ keV

Dark matter

$M_{N2,3} \in \mathrm{O}(1)$ GeV

baryon asymmetry





θ_1 and θ_2 - mixing angels with SM particles

How to find heavy neutrino?

Mesons decays

The search for additional peak

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

Heavy neutrino decays

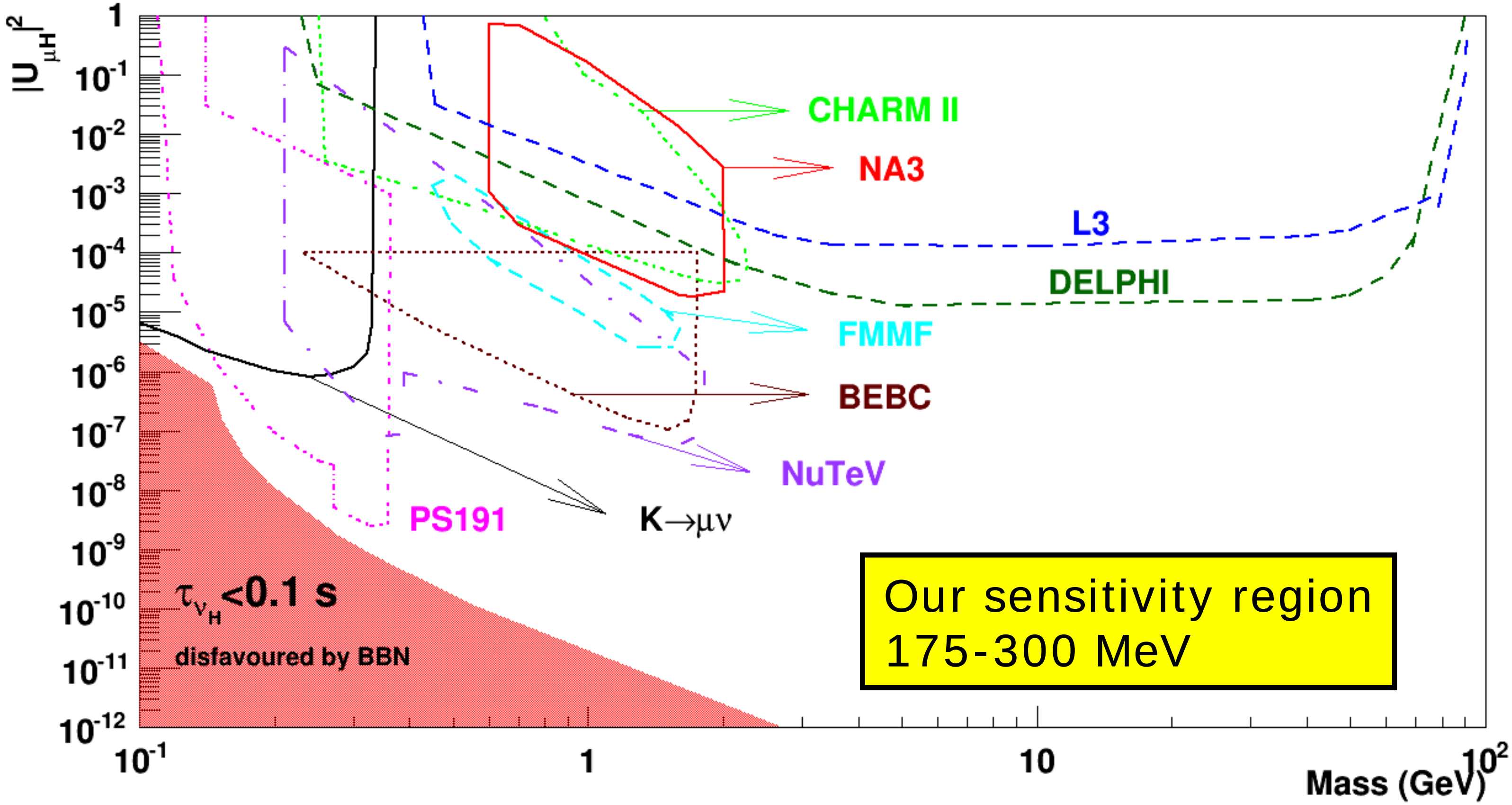
"Nothing"$\to$ leptons and hadrons

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

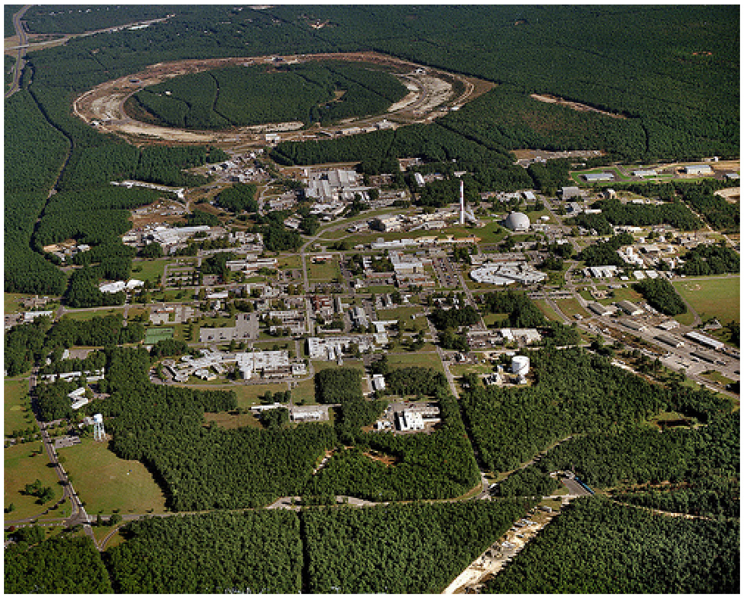
$$N \to \pi^0 \nu, \pi e, \pi \mu, Ke, K\mu ...$$

Current limits

plot from
JHEP0710:015,2007
(arXiv:0705.1729v1 [hep-ph]),
JHEP 0905:030,2009
(arXiv:0901.3589v2 [hep-ph])



Experiment BNL E949



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

Phys. Rev. D 79, 092004 (2009)

SM expectation

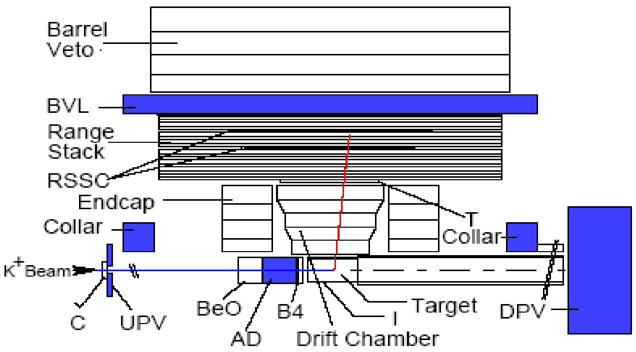
$$\mathcal{B}_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$$

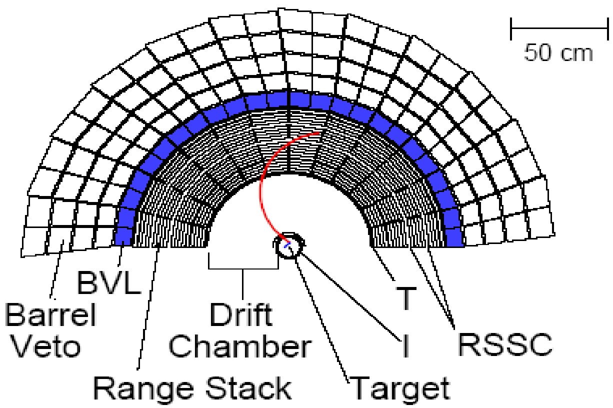
E949 + E787

4 + 3 (from E787) = 7

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

The Detector





- ~700 MeV/c kaon beam is slowed down by degraders.
- K^+ stops and decays in scintillating fiber target
- Measure π^+ momentum in drift chamber, energy and range in target and Range Stack (RS)
- π^+ stops and decays in RS – observe $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain
- Set of photon veto detectors

Heavy neutrino trigger

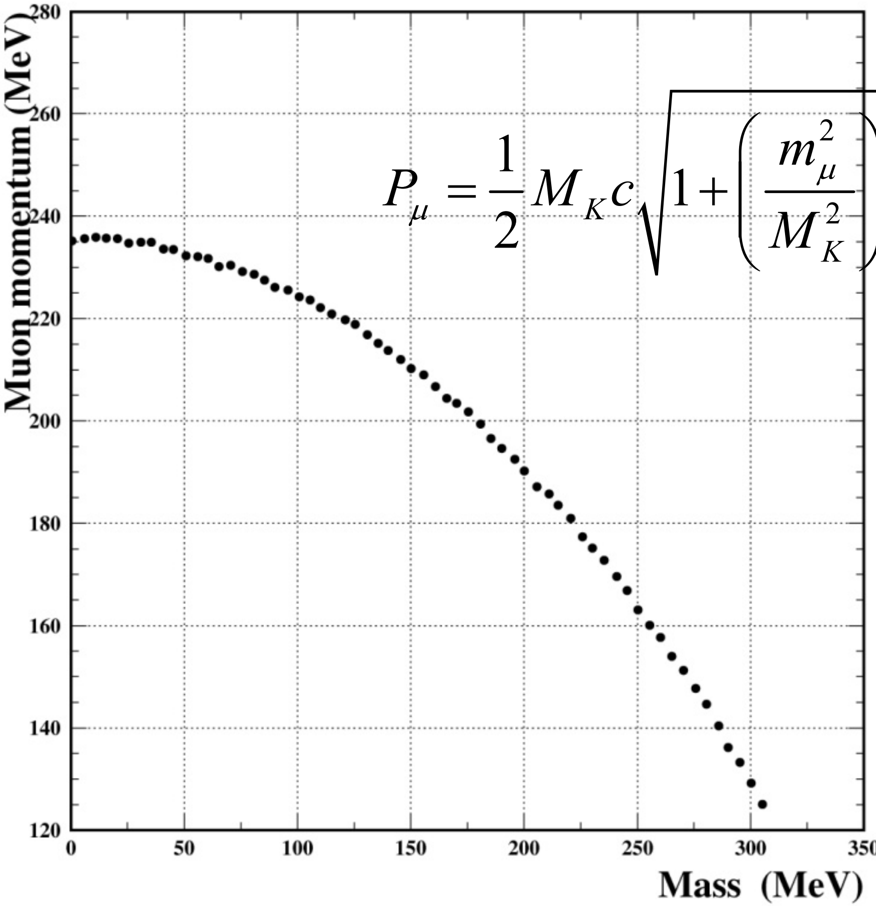
$K^+ \to \mu^+ \nu_H$ has the same experimental signature as $K^+ \to \pi^+ \nu \bar{\nu}$

single charged particle + “nothing” → use standard E949 trigger

- Wait at least 2 ns for K^+ decay
- Stopping layer in RS between 6 and 18, layer 19 veto
- Additional refined requirements of the charged track range taking into account number of the target fiber hits and track’s downstream position (refined range)
- π^+ identification: online check $\pi^+ \to \mu^+$ decay chain in the stopping counter
- Photon veto: no showers in RS, Barrel,…

Additional monitor triggers and Monte Carlo simulation were used to measure efficiency of these requirements.

Strategy



$$K^+ \rightarrow \mu^+ \nu_H$$ two body decay

$$P_\mu = \frac{1}{2} M_K c \sqrt{1 + \left(\frac{m_\mu^2}{M_K^2}\right)^2 + \left(\frac{m_\nu^2}{M_K^2}\right)^2 - 2\left(\frac{m_\mu^2}{M_K^2} + \frac{m_\nu^2}{M_K^2} + \frac{m_\mu^2}{M_K^2}\frac{m_\nu^2}{M_K^2}\right)}$$

M_K - kaon mass

m_μ - muon mass

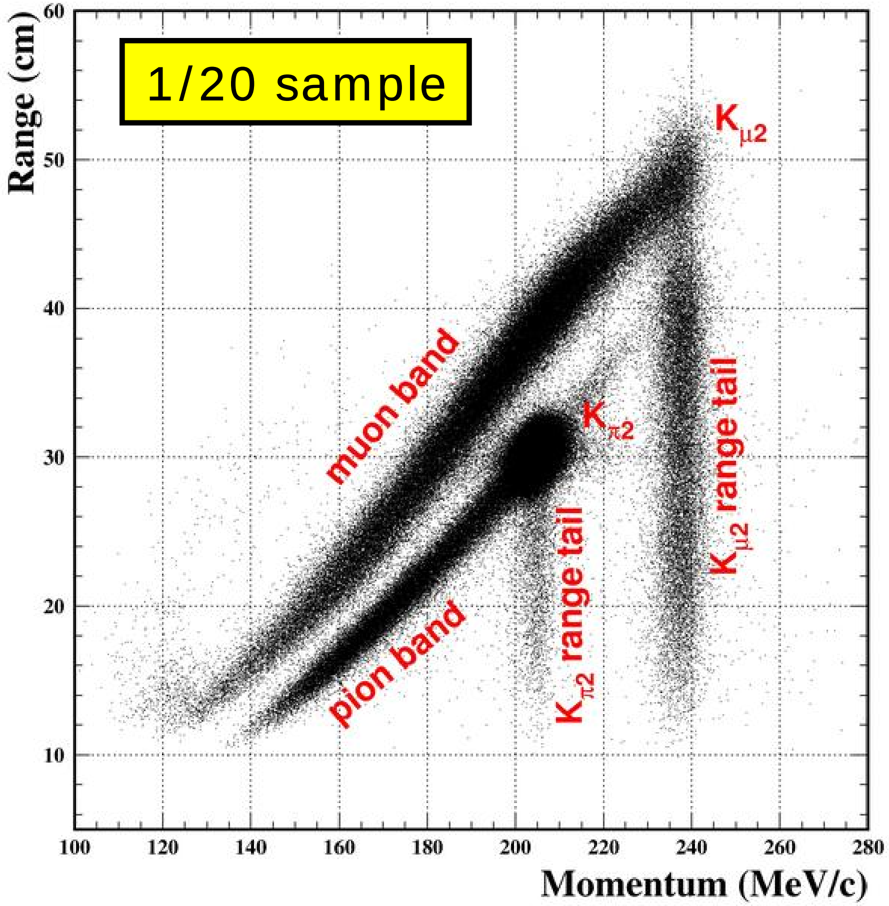
m_ν - heavy neutrino mass

Strategy

Search for additional peak below $K_{\mu2}$ peak.

- Split full sample into 1/20 and 19/20. 1/20 – acceptance verification, background study; 19/20 – blinded sample
- Measure $K^+ \rightarrow \mu^+ \nu_H$ acceptance using monitor samples. No photons in final state
- Use $K_{\mu2}$ and $K_{\mu\nu\gamma}$ decays to verify total acceptance measurement. Study the main background shape ($K_{\mu\nu\gamma}$)
- Measure momentum resolution for the signal region
- Analyze full data sample

Data sample



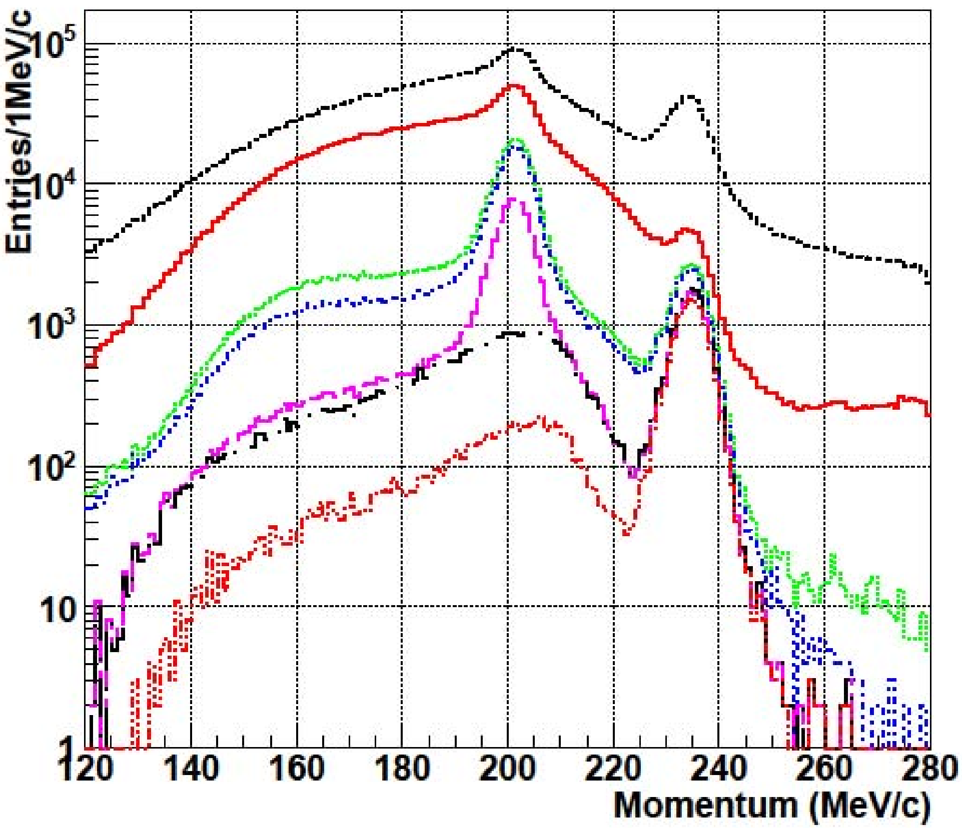
✓ Data were taken for 12 week from March to June 2002
✓ Total number of stopped kaons is equal to 1.70×10^{12}
✓ Every 20th event of full sample was selected to form 1/20 sample

- Muon band: generally $K_{\mu2\gamma}$, $K_{\mu3}$ decays
- Pion band: $K_{\pi2\gamma}$, $K_{\pi2}$ in which pion scattered in the target or RS and beam pion

Additional selection criteria

- Kinematic cuts. To select events in the detector fiducial volume
- Beam cuts. To identify the incoming particle as a kaon and suppress extra beam particles at the track time
- Delay coincidence. To suppress kaon decays-in-flight
- Target cuts. Numerous requirement were placed in on the activity in the target to suppress background and ensure reliable determination of the kinematic properties of the charged muon
- Range-momentum cut was changed to select muon band (pion band was selected in the main E949 analysis)
- Photon veto cuts. To suppress photon activity in the detector. Loose – for background study, tight – for full sample

1/20 Data Sample



after trigger

after kinematics

after beam

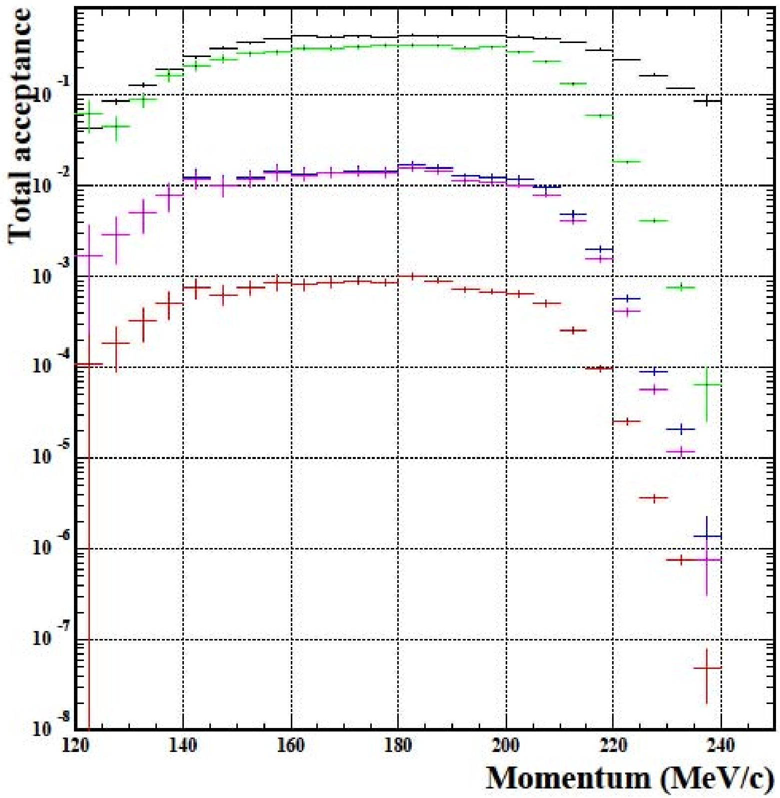
after delay coincidence

after target

after range-momentum

after loose photon veto

Total acceptance



after trigger

after refined range

after pion identification online

after kinematic cuts

after all other cuts tight photon veto applied

Singe event sensitivity (S.E.S.) for heavy neutrino with mass m=250 MeV that corresponds muon momentum p=163.6 MeV/c

$$S.E.S = \frac{1}{Acc \times N_K} = 7.15 \times 10^{-10}$$

Total acceptance verification

The $K_{\mu 2}$ branching ratio measurement

High trigger rejection by
- ✓ Layer 19 veto
- ✓ Refined range requirement
- ✓ Online pion identification

because these cuts were designed to suppress $K_{\mu 2}$ decay

Not enough statistics to measure acceptance for this decay with high precision: $A^{tot}_{K_{\mu 2}} = (1.60 \pm 0.45) \times 10^{-7}$

$$\boxed{\begin{aligned} BR(K_{\mu 2}) &= 0.5425 \pm 0.1513 \\ BR^{PDG}(K_{\mu 2}) &= 0.6355 \pm 0.0011 \end{aligned}}$$

The $K_{\mu\nu\gamma}$ branching ratio measurement

High trigger rejection by photon veto requirement due to one photon in the final state

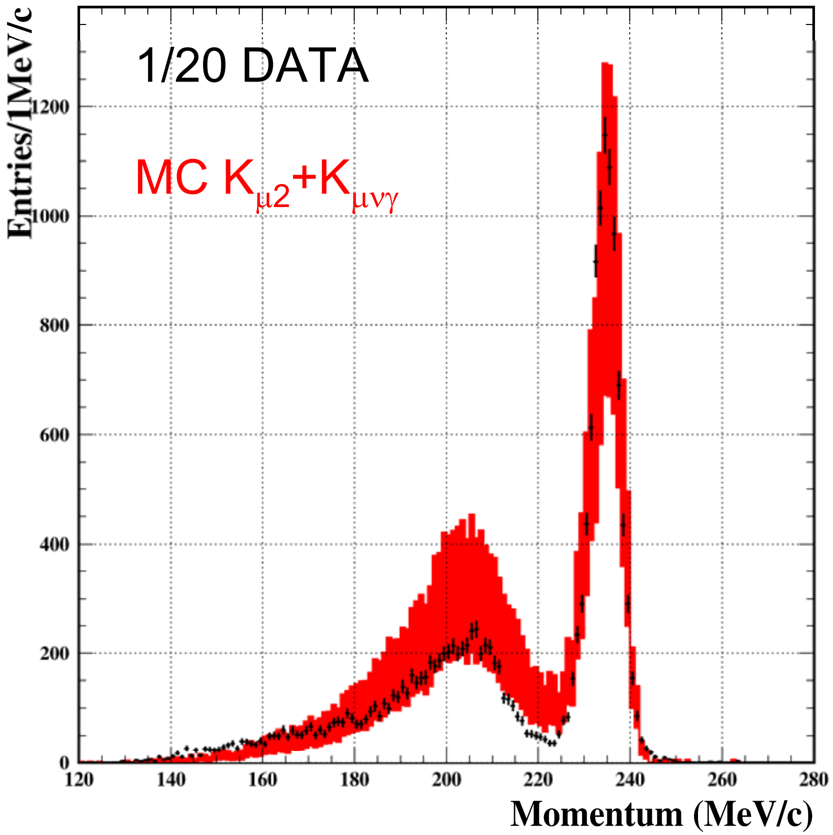
Use Monte Carlo simulation to study acceptance. Photon detectors thresholds ~1 MeV for data. Noise is not implemented to MC

$A^{tot}_{K_{\mu\nu\gamma}} = (3.60 \pm 1.11) \times 10^{-5}$

$$\boxed{\begin{aligned} BR(K_{\mu\nu\gamma}) &= (1.3 \pm 0.4) \times 10^{-3} \\ BR^{PDG}(K_{\mu\nu\gamma}) &= (1.4 \pm 0.2) \times 10^{-3} \end{aligned}}$$

$140 < p_{\mu} < 200$ MeV/c

Background study.



MC includes all errors

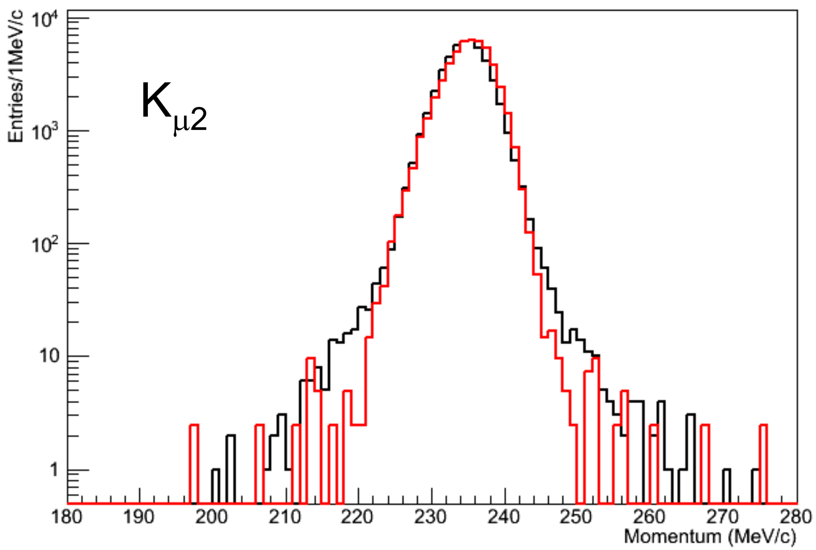
$$k_{K_{\mu2}} = \frac{(N_K)_{1/20}}{N^{MC}_{K_{\mu2}}} \times \frac{A^{Exp}_{K_{\mu2}}}{A^{MC}_{K_{\mu2}}} \times BR(K_{\mu2}) = 2.96$$

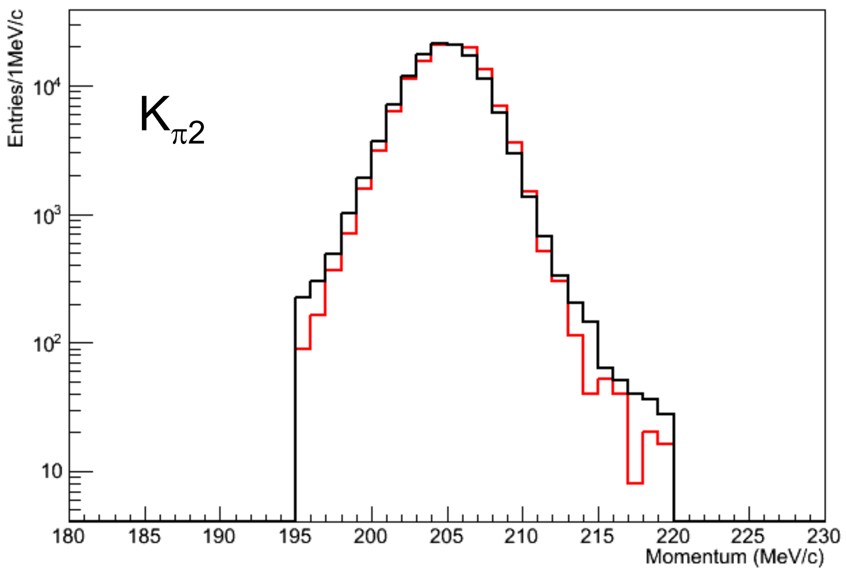
$$k_{K_{\mu\nu\gamma}} = \frac{(N_K)_{1/20}}{N^{MC}_{K_{\mu\nu\gamma},140<p<200}} \times \frac{A^{Exp}_{K_{\mu\nu\gamma}}}{A^{MC}_{K_{\mu\nu\gamma}}} \times BR(K_{\mu\nu\gamma}) = 0.72$$

Monte Carlo and experimental spectra are consistent. MC shape doesn't have obvious bumps or valleys, so we may conclude that experimental background shape should have smooth behavior, but we don't know exact background shape.

$K_{\mu 2}$ / $K_{\pi 2}$ resolution

Data
MC

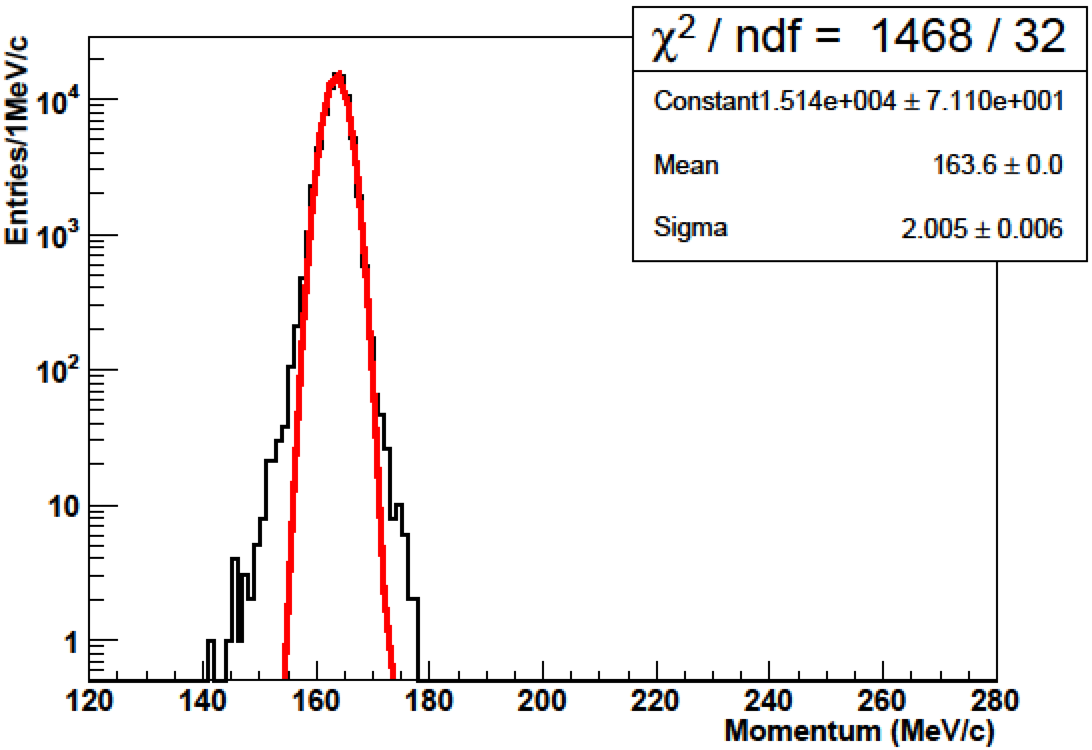




MC simulation of the $K\mu 2$/$K\pi 2$ decays is consistent with data. We may use MC to study detector resolution

Signal resolution

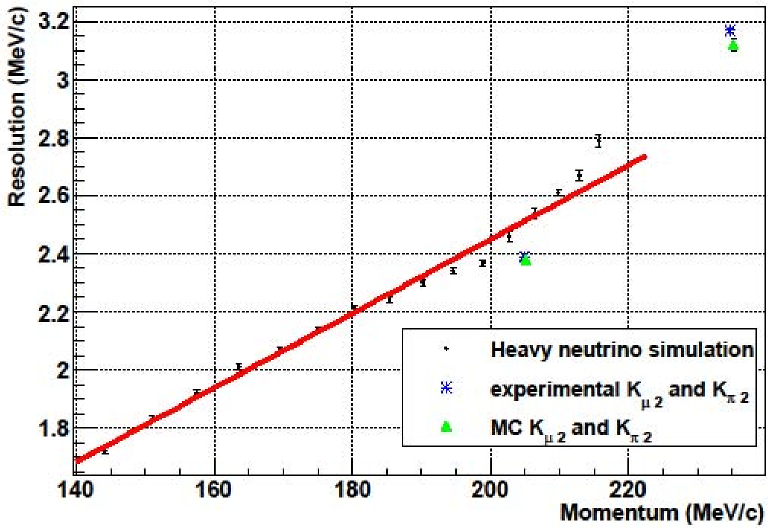
MC simulation of the $K^+ \to \mu^+ \nu_H$ decay with $m_{\nu_H} = 250\ \mathrm{MeV/c^2}$



All cuts applied

Signal distribution looks like Gaus at least at ±3σ region

Resolution. MC simulation



Signal resolution is measured within main trigger.

$$\sigma(p) = (-0.1071 + 0.01278 \times p) \pm 0.14 \pm 0.05$$

Maximum difference between MC heavy neutrino points and fitted line

MC and data difference by comparing $K_{\mu 2}/K_{\pi 2}$ points

Peak search method

- We don’t know exact background shape due to very low acceptance for background. But it is not really necessary because the background fitting is data-driven
- Define shape locally: choose ±6σ region around the point of interest and fit it by 2 order polynomial function
- Use Gaussian with well known sigma as a signal
- Use likelihood approach which is approved by Higgs search to get upper limit (Eur.Phys.J.C71:1554,2011 (arXiv:1007.1727 [physics.data-an]))

Peak search method

- Construct the following likelihood function

$$L(\mu,\theta)=\{\prod_{i=1}^{Nbins}\frac{(\mu\cdot\beta s_i+\theta b_i)^n}{n!}e^{-(\mu\cdot\beta s_i+\theta b_i)}\}\times$$

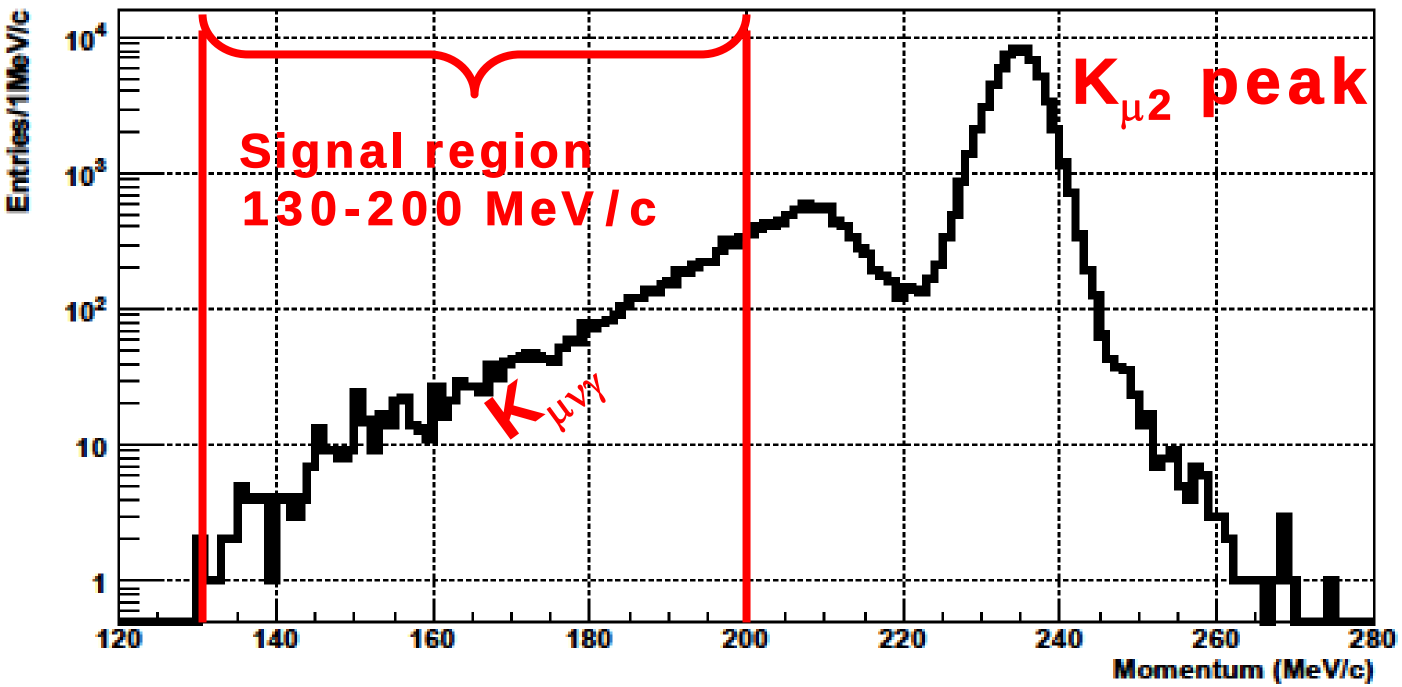
$$\times Gauss(\beta;\beta_{peak},\sigma_{\beta_{peak}})$$

s and b – signal and background distributions. Since background distribution is taken from data fit, $\theta=1$, μ is signal strength parameter; s – gauss. n_i – number of observed events in each bin.
β takes into account acceptance of the point of interest (β_{peak}) and its total error (σ_β)

Peak search method

- “Asimov” data set based on background shape was generated to calculate expected upper limit (background only hypothesis)
- Use the same upper limit calculation method but with experimental data to get observed upper limit

Analyze full data sample

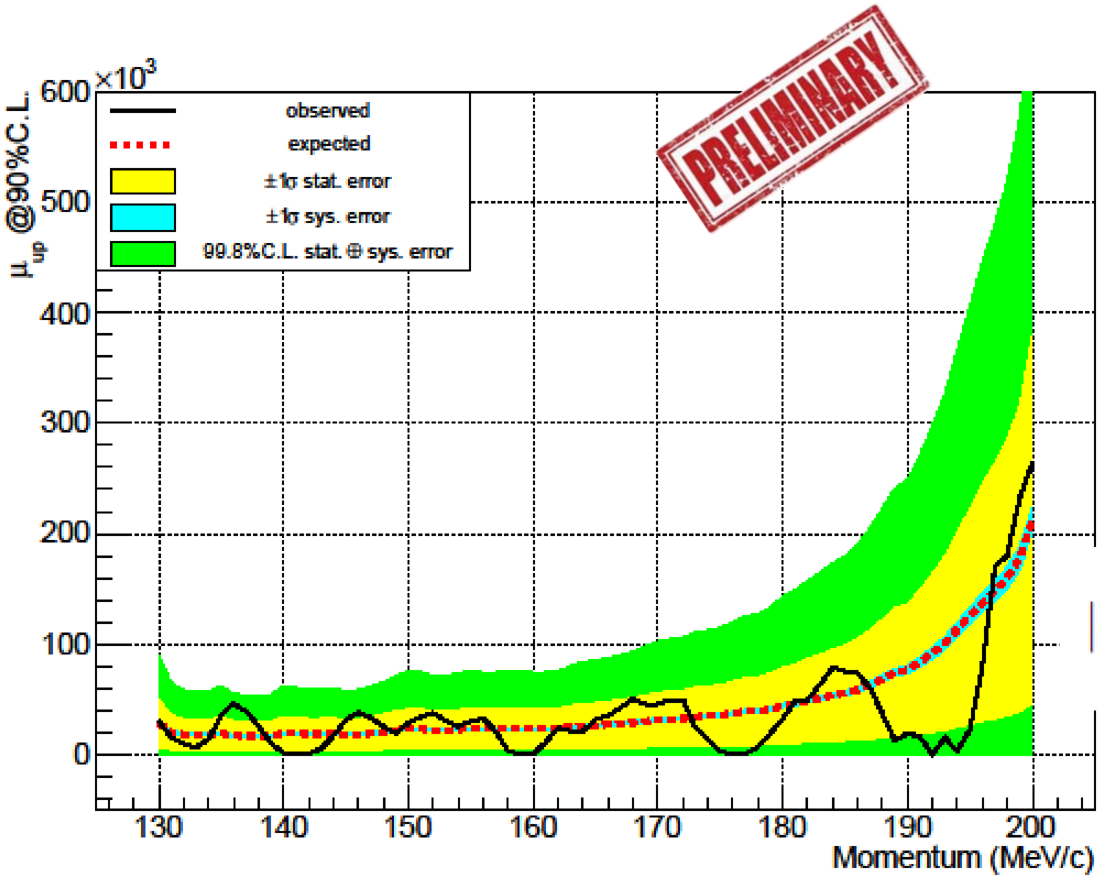


Muon momentum spectrum after open the box. All cuts applied

Changes after unblinding data

- By default we used χ^2 method to define background shape locally, but it does not work well for low statistics in low momentum region. So, we changed to log-likelihood method for the background definition
- The $\pm 9\sigma$ region is not suitable for high momentum region to define background shape, $\pm 6\sigma$ is enough for that purpose.

Results

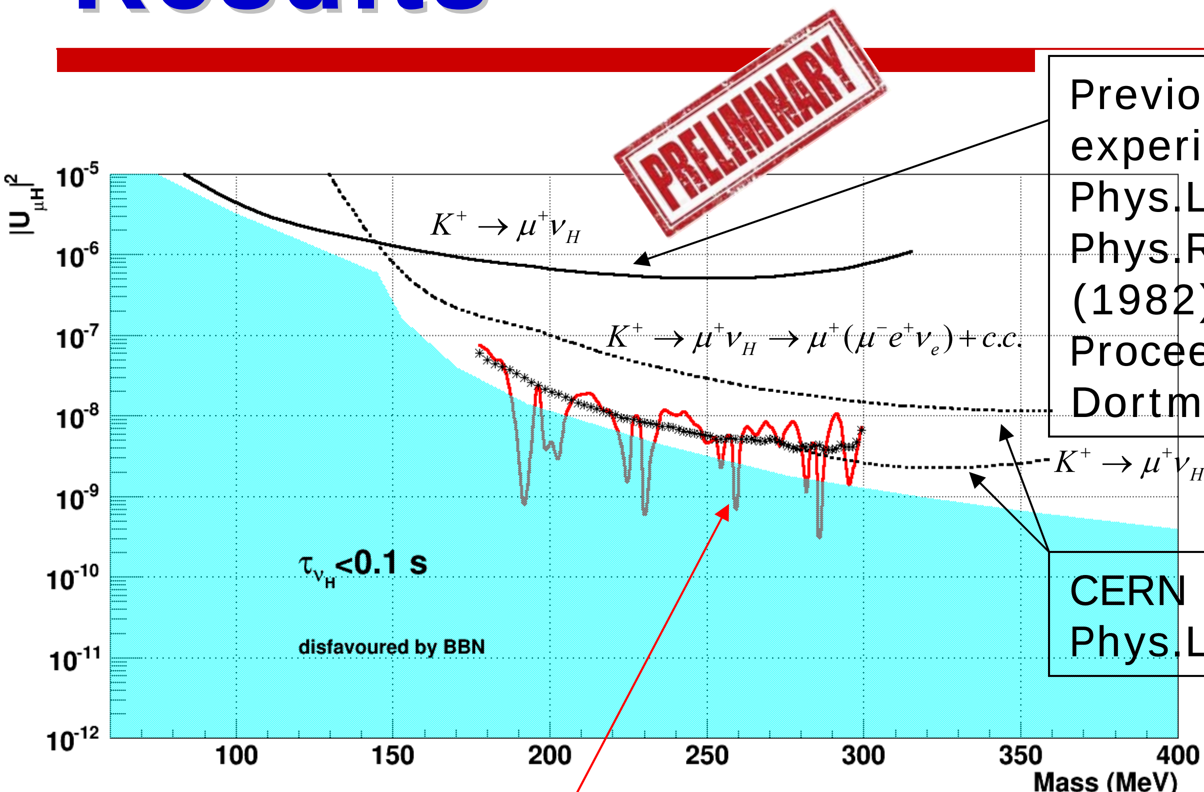


No evidence for heavy neutrino existence was observed in mass region 175-300 MeV/c^2
Using this plot it is possible to calculate mixing matrix element upper limit

$$|U_{\mu H}|^2 = \frac{N_{candidates}}{Acc \times N_K \times \rho \times BR(K_{\mu 2})}$$

Y-axis $\mu_{up} = N_{candidates}/Acc$

Results



Previous peak search experiment
Phys.Lett. B104 , 84 (1981)
Phys.Rev.Lett. 49,1305 (1982)
Proceedings of Neutrino84, Dortmund (1984)

CERN PS191
Phys.Lett. B203, 332 (1988)

New observed upper limit
Black stars are expected upper limit based on background fit shape

Conclusion

- 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.

THANK YOU