Search for heavy neutrinos in kaon decays

L. Littenberg
(work mainly done by
A.T.Shaikhiev INR RAS)

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Outline

- Motivation
- Previous heavy neutrino searches
- Experiment BNL-E949
- Selection criteria
- Efficiency and background study
- Peak search method
- Results and conclusions
- Something else?

Motivation

- We know the Standard Model is incomplete
  - It doesn't explain the baryon asymmetry of the universe
  - It doesn't explain dark matter or dark energy
  - It assumed massless neutrinos
- Massive, oscillating neutrinos suggest this sector might be a portal to BSM physics
  - A lot of work in progress measuring the 3-neutrino mixing parameters and searching for additional light (~eV) neutrinos
  - But it's also worth following up the 35-year old suggestion of Robert Shrock – to search for heavier ones
- <u>Of course, must first ask – are they ruled out by current phenomenology?</u>

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

Constraints in the νMSM

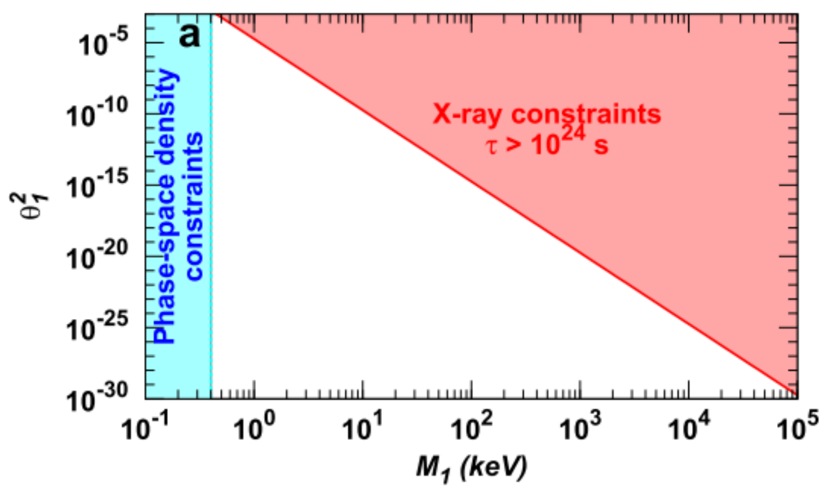
SM + 3 neutral right-handed heavy leptons

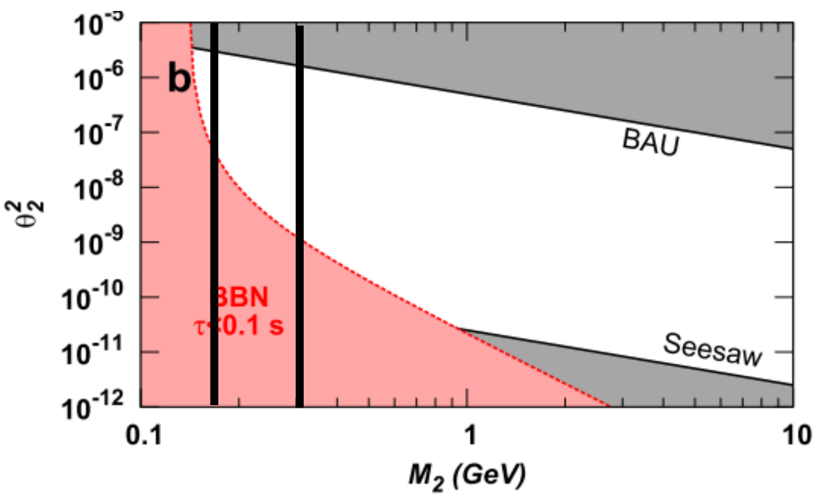
$M_{N_1} \in O(10)$ keV

Dark matter

$M_{N_{2,3}} \in O(1)$ GeV

baryon asymmetry



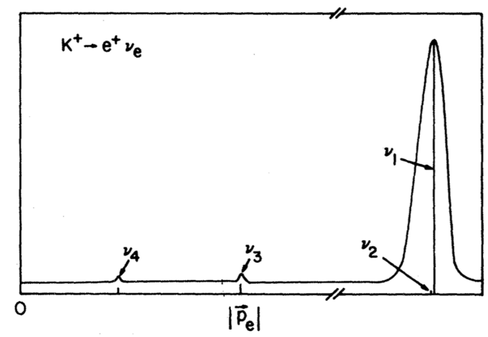


θ_1 and θ_2 - mixing angles with SM particles

How to find heavy neutrinos?

Meson decays

The search for additional peaks



R. Shrock
PRD 24 1232 (1981)

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

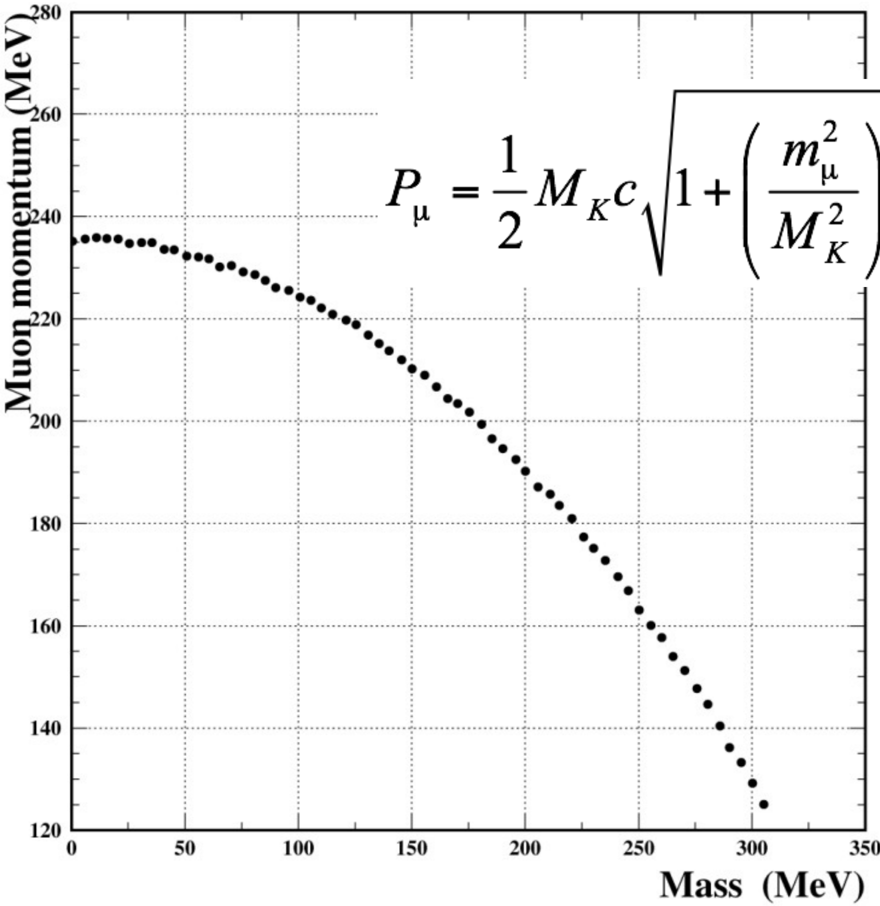
ρ is a kinematic factor

Heavy neutrino decays

"Nothing"→ leptons and hadrons

$\nu_H \to e^+ e^- \nu_\alpha,\ \mu^\pm e^\mp \nu_\alpha,\ \mu^+ \mu^- \nu_\alpha$
$\quad\to \pi^0 \nu,\ \pi e,\ \pi \mu,\ K e,\ K\mu,\ \ldots$

ν_h Mass vs μ Momentum



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

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

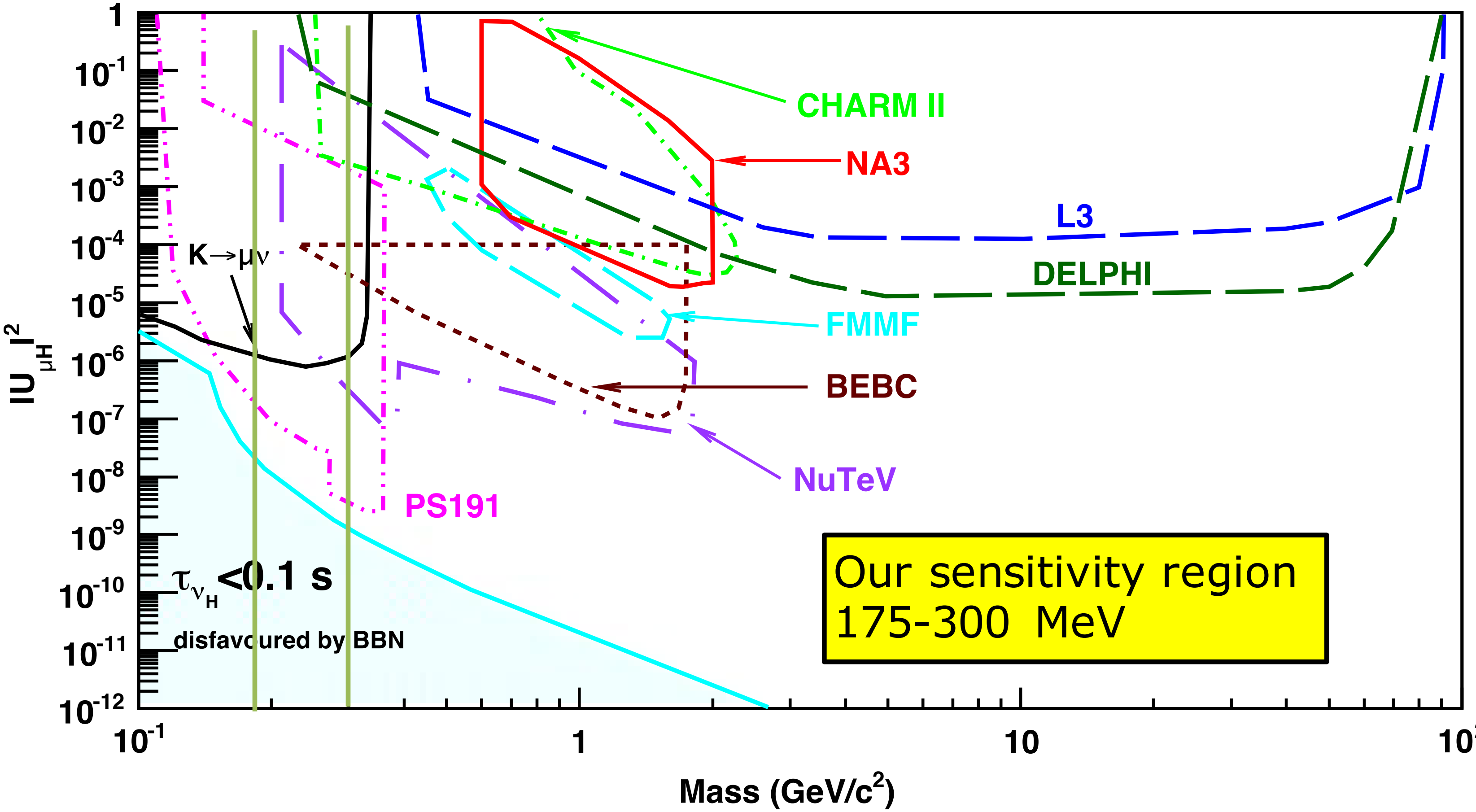
M_K - kaon mass

m_μ - muon mass

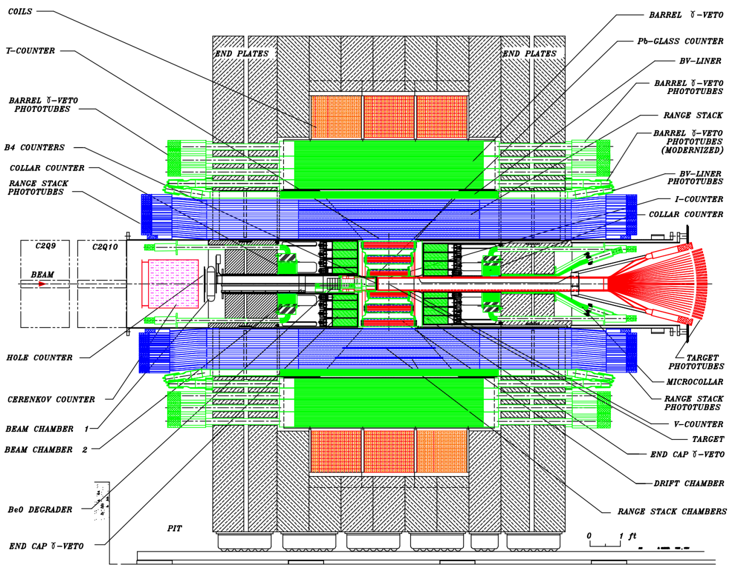
m_ν - heavy neutrino mass

plot from
PRD91, 052001 (2015)

Current limits



Experiment BNL E949



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

Phys. Rev. D 79, 092004 (2009)

SM expectation

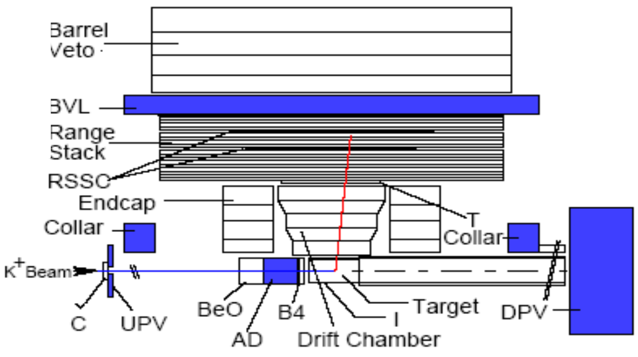
$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$$

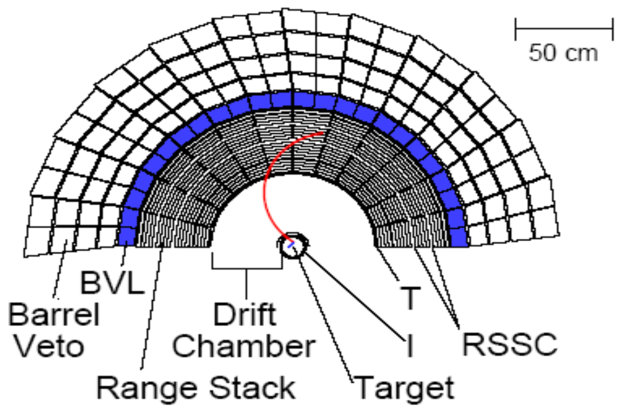
E949 + E787

4 + 3 (from E787) = 7

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

The Detector





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

For the heavy ν search, only μ that somehow pass the online decay chain cut are available

Heavy neutrino trigger

$K^+ \rightarrow \mu^+ \nu_H$ has a similar experimental signature to $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

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

- Wait at least 2 ns for K^+ to decay
- Photon veto: no showers in RS, Barrel,…
- 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 the track’s downstream position (refined range)
- π^+ identification: online check $\pi^+ \rightarrow \mu^+$ decay chain in the stopping counter

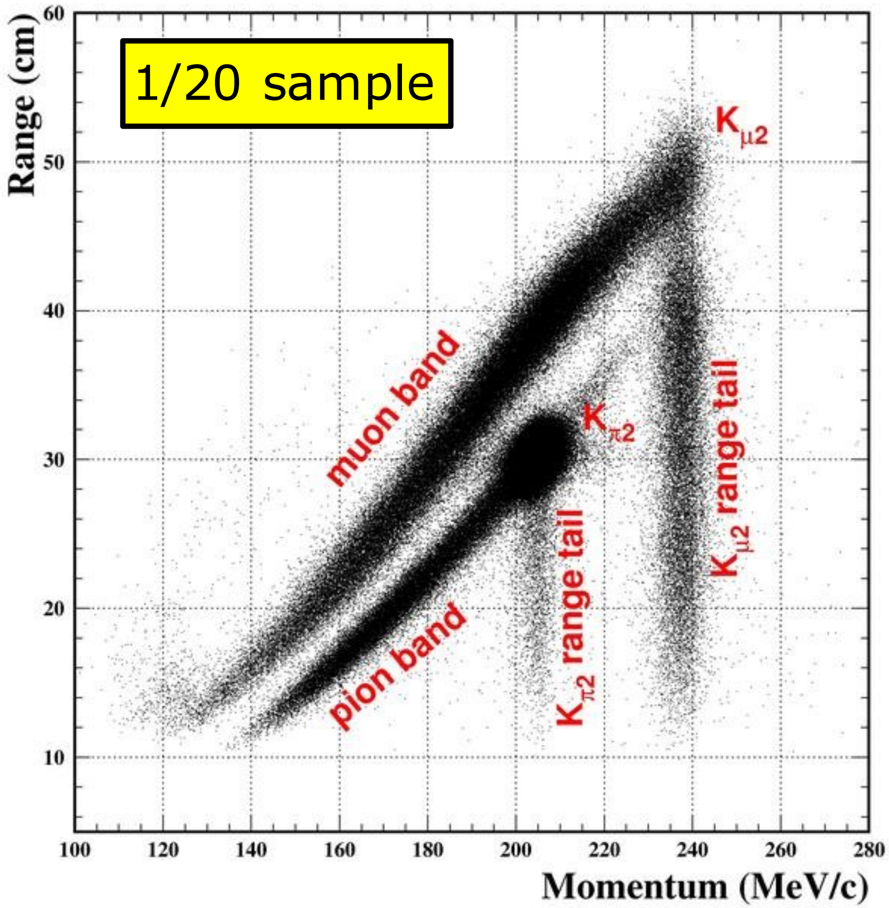
Additional monitor triggers and Monte Carlo simulation were used to measure efficiency of these requirements.

Strategy

Search for an additional peak in the muon spectrum below the $K_{\mu 2}$.

- Split full sample into 1/20 and 19/20. 1/20 – acceptance verification, background study; 19/20 – blinded sample
- Measure $K^+ \to \mu^+ \nu_H$ acceptance using monitor samples.
- Use $K_{\mu 2}$ and $K_{\mu\nu\gamma}$ decays to verify the total acceptance measurement.
- Study the main background shape ($K_{\mu\nu\gamma}$)
- Measure the momentum resolution for the signal region
- Analyze full data sample

Data sample



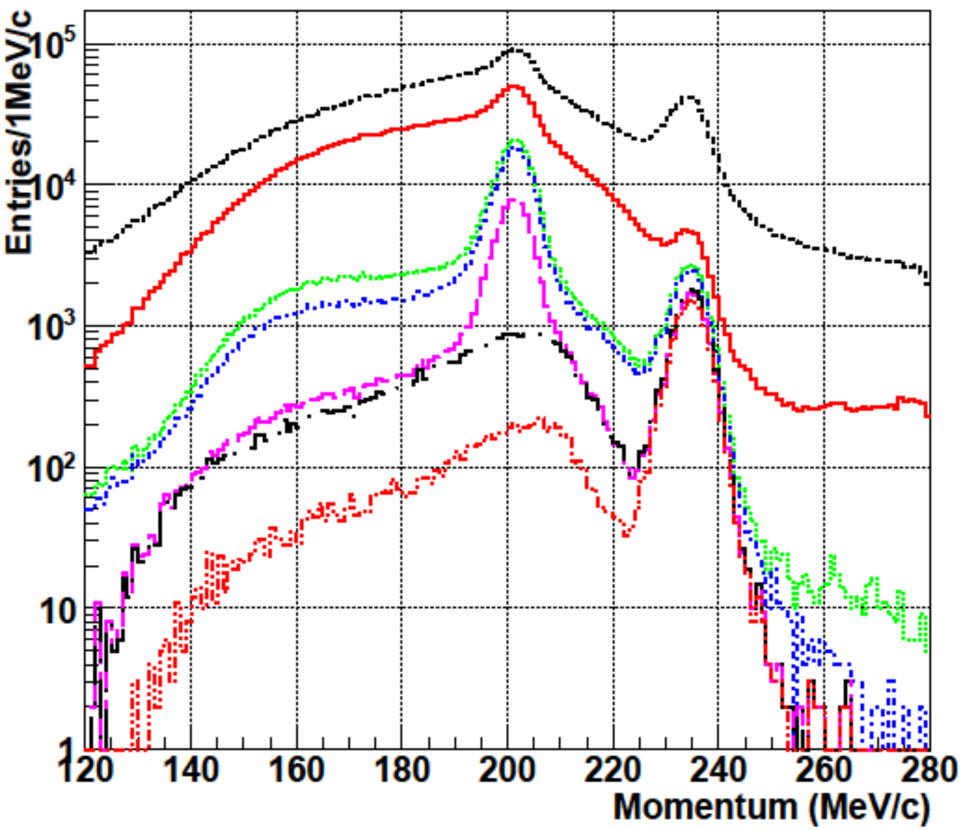
✓ Data were taken for 12 weeks from March to June 2002
✓ Total number of stopped kaons - $1.70 \cdot 10^{12}$
✓ Every 20th event of full sample was selected to form 1/20 sample

- Muon band: generally $K_{\mu 2\gamma}$, $K_{\mu 3}$ decays
- Pion band: $K_{\pi 2\gamma}$, $K_{\pi 2}$ in which pion scatters in the target or RS and scattered beam pions

Additional selection criteria

- Fiducial cuts. To select events in the detector fiducial volume
- Beam cuts. To identify the incoming particle as a kaon & suppress extra beam particles at track time
- Delayed coincidence. To suppress kaon decays in flight
- Target cuts. Numerous requirements were placed on the activity in the target to suppress background and ensure reliable determination of the kinematic properties of the μ
- Range-momentum cut selected muon band (*c.f.* 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 fiducial volume

after beam cuts

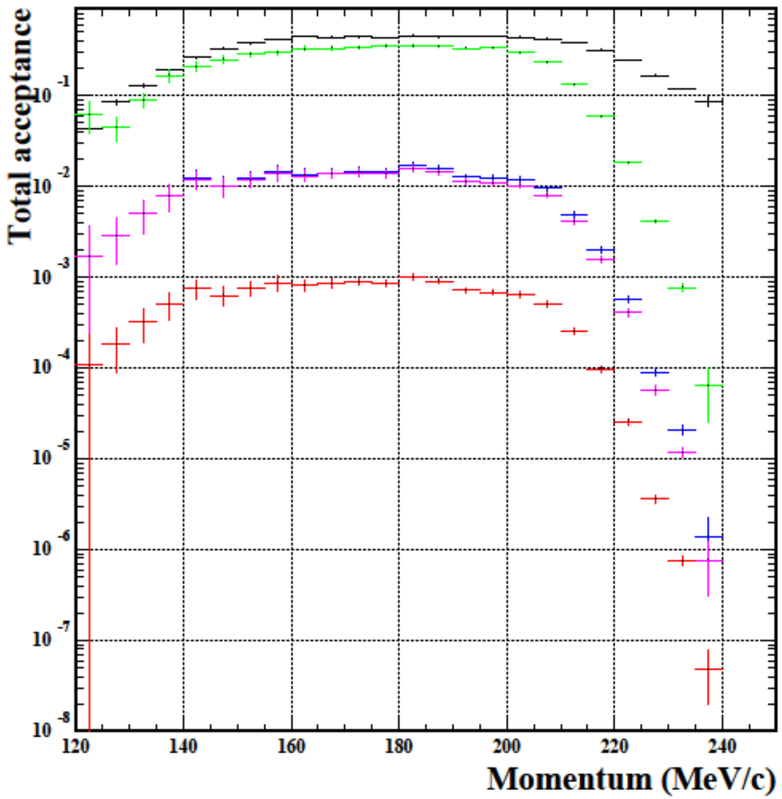
after delayed coinc.

after target cuts

after range-momentum

after loose γ veto

Total acceptance



after fiducial cuts

after refined range

after pion identification online

after kinematic cuts

after all other cuts tight photon veto applied

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

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

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

Insufficient 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

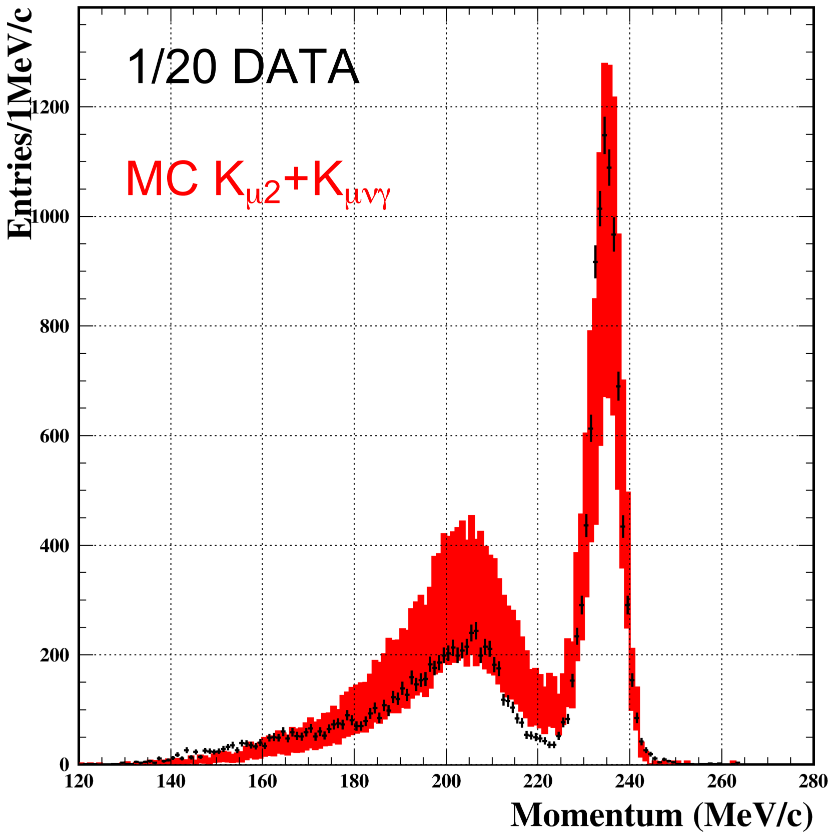
Use Monte Carlo simulation to study acceptance. Photon detector thresholds ~1 MeV for data. Noise is not implemented in MC

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

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

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

Background study.



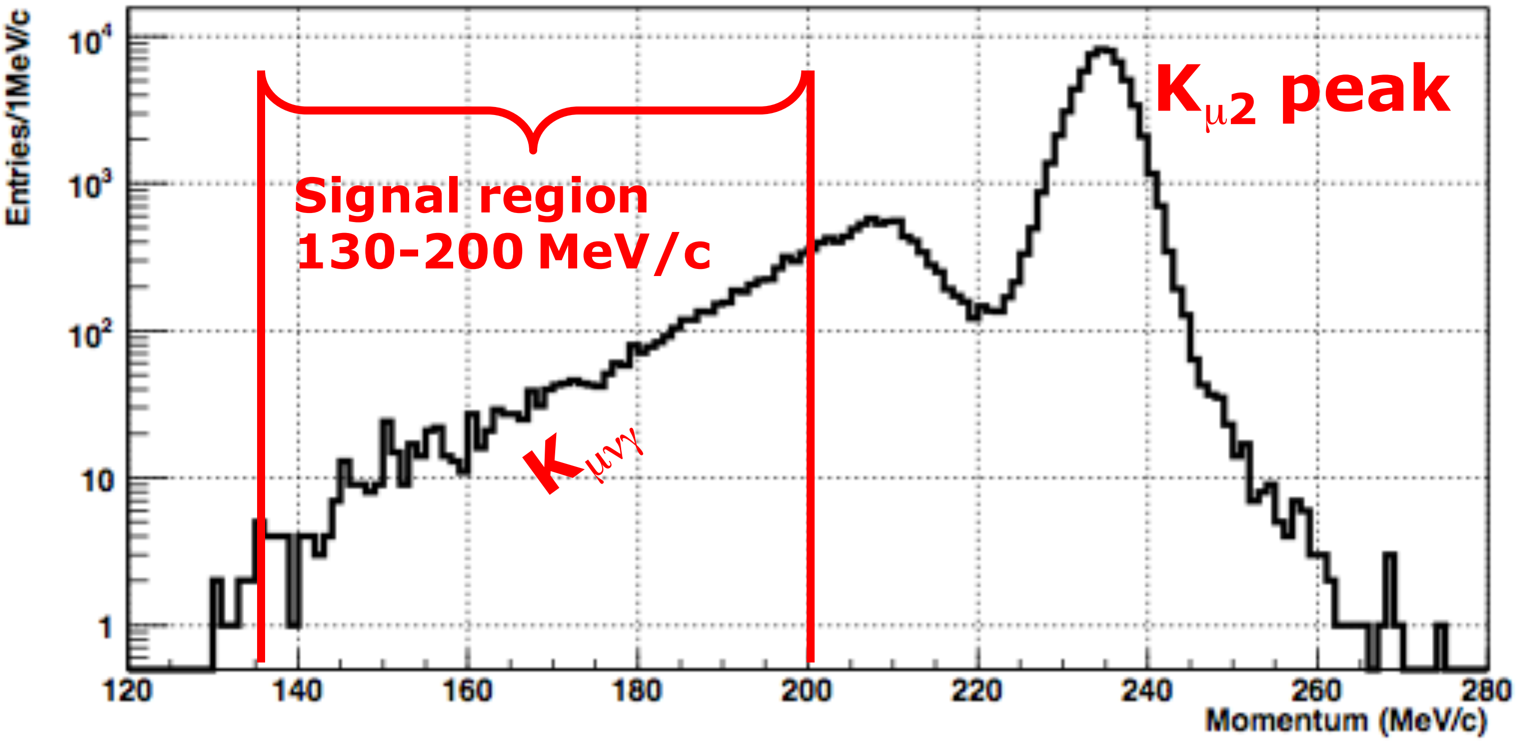
MC includes all errors

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

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

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.

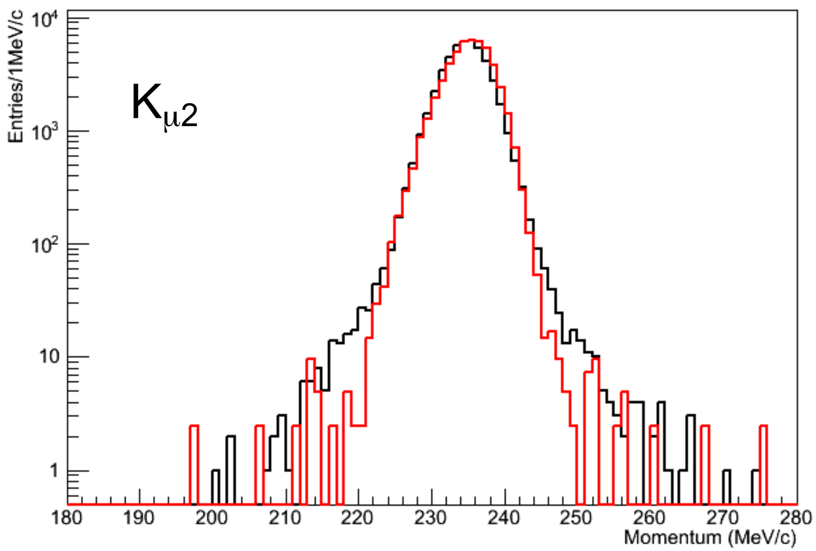
Analyze full data sample

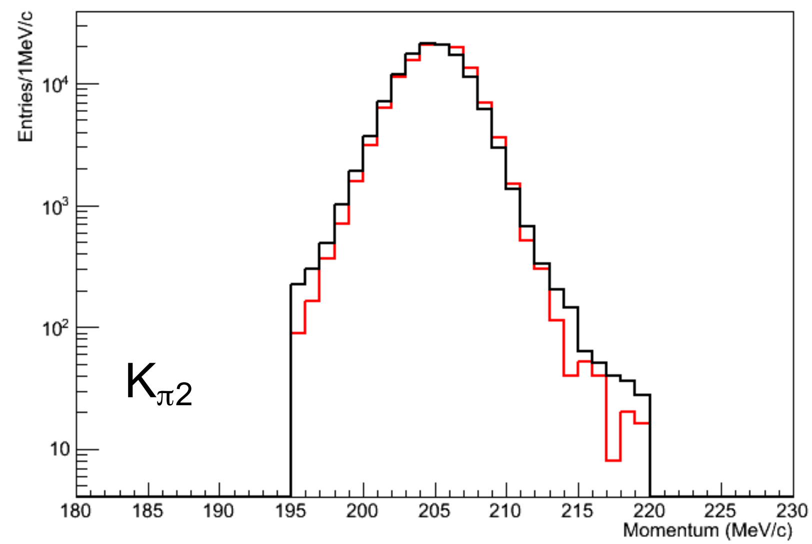


Muon momentum spectrum after opening the box. All cuts applied

$K_{\mu2}/K_{\pi2}$ resolution

Data MC





MC simulation of the $K_{\mu2}/K_{\pi2}$ decays is consistent with data. Thus we may use MC to study the detector resolution for a possible ν_{Heavy} signal.

Result: $\sigma(p) \sim (-0.107 + 0.0128p) \pm 0.14 \pm 0.05$ (*i.e.* ~1.2%)

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 $\pm 6\sigma$ region around the point of interest and fit it with a 2^{nd} order polynomial
- Use Gaussian with known sigma as a signal
- Use likelihood approach a la Higgs search to get upper limit (Eur.Phys.J.C71:1554,2011 (arXiv:1007.1727 [physics.data-an]))

Peak search method

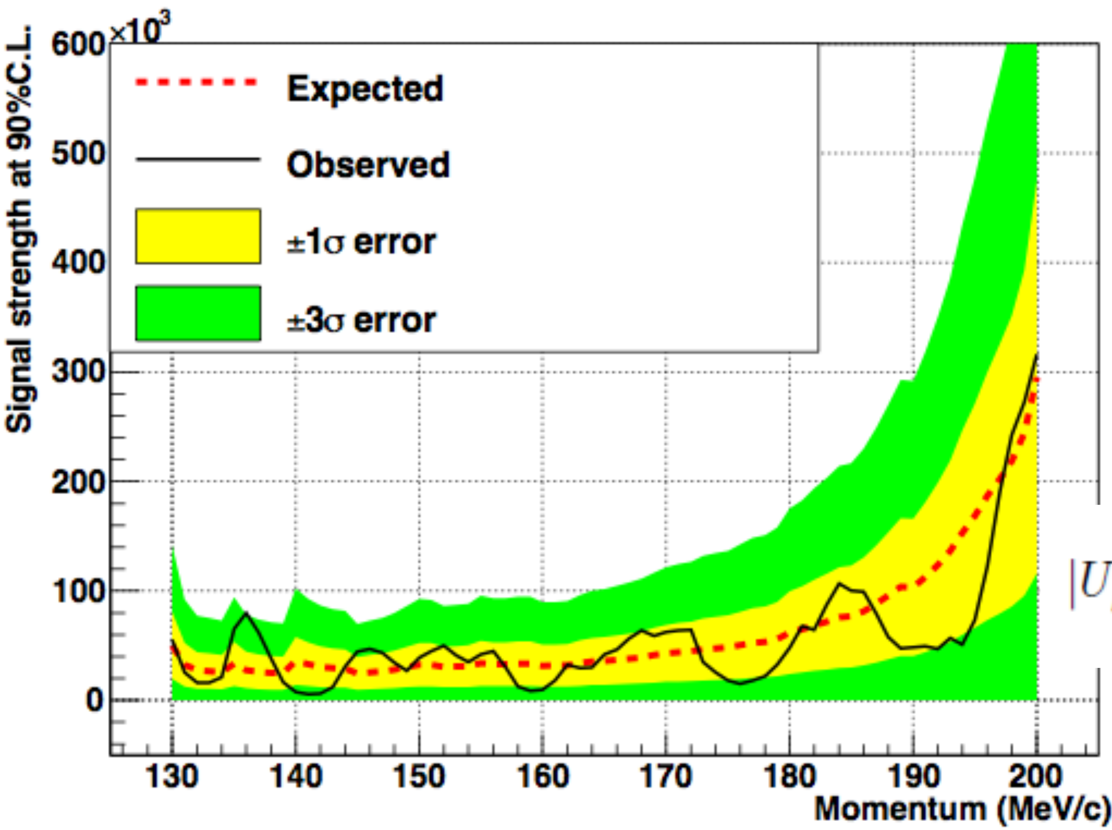
- Construct the following likelihood function

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

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

s and *b* – signal and background distributions. Since background distribution is taken from data fit, $\theta=1$, μ is signal strength parameter; *s* – gaussian 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)

Results



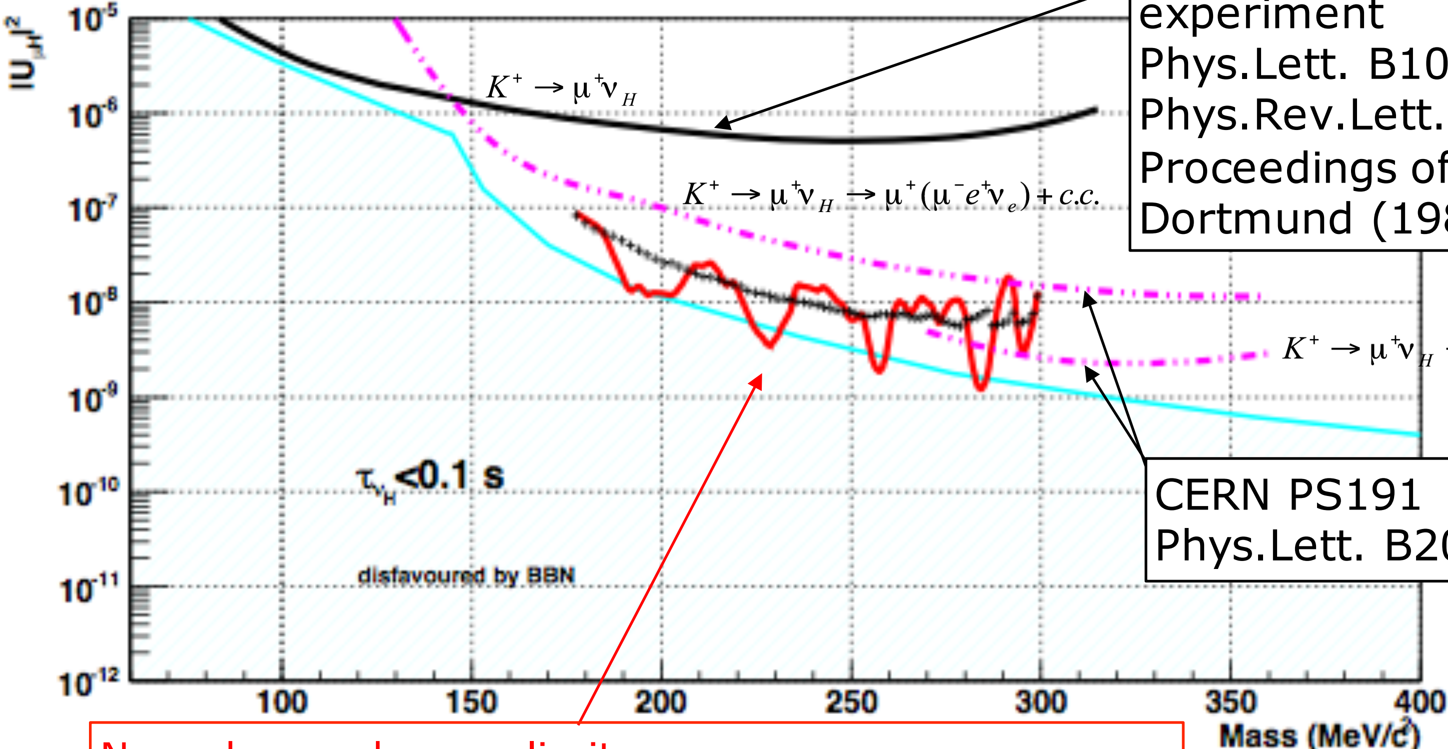
No evidence for heavy neutrino existence was observed in mass region 175-300 MeV/c²

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 = $N_{candidates}/Acc$

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)

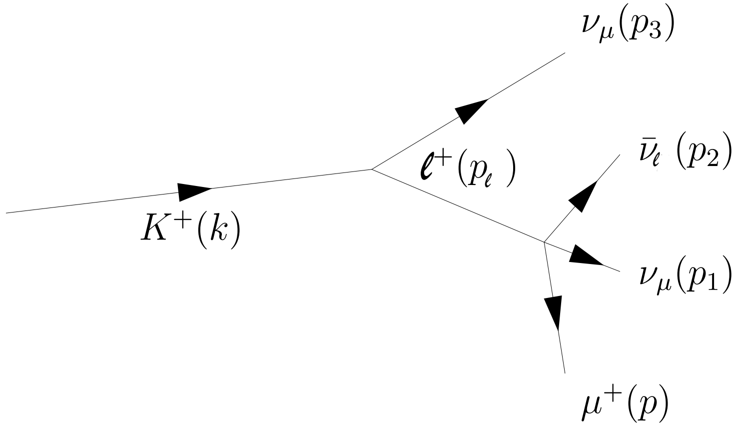
New observed upper limit
Black crosses are expected upper limit based on background fit shape

Conclusion

- The existence of heavy neutrinos in the mass region 175-300 MeV/c^2 was probed using the E949 experimental data set
- No evidence was found for them
- The previous best constraints from CERN PS191 were improved by a factor 5-10.
- New mixing matrix element $|U_{\mu H}|^2$ upper limit varies between 10^{-9} and 10^{-8}
- In contrast to CERN PS191 or BBN lower limit our result is model-independent.

What else is this data good for?

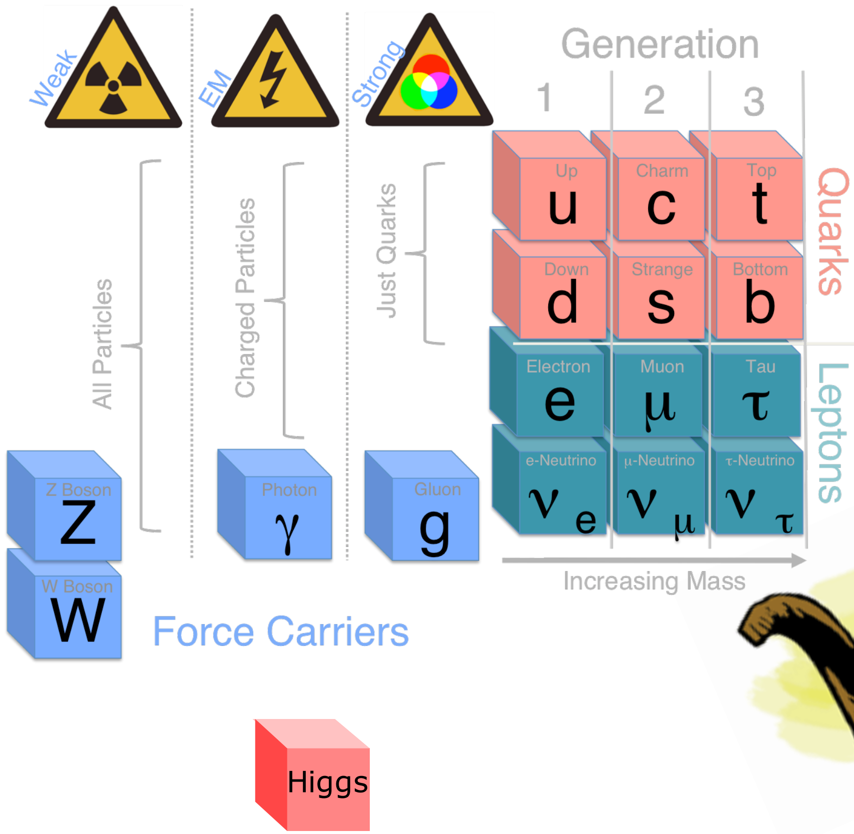
- Could look for >2 body decays where one daughter is a muon and the other bodies are invisible
- E.g. $K^+ \rightarrow \mu^+\nu\nu\nu$, which hasn't been probed since 1973
- There is a SM contribution, mediated by diagrams like



- Gives a BR ~ 10^{-16}
- So any practical observation will indicate BSM physics.

More of Artur's Slides

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?

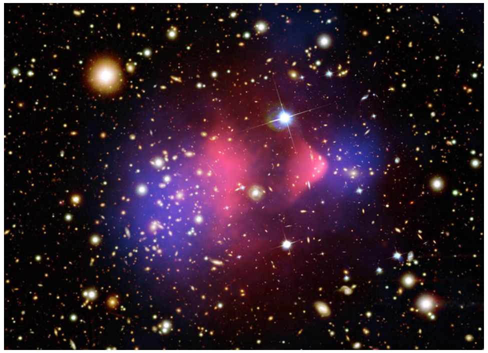
Although the Standard Model has been hugely successful in explaining a rich variety of experimental data (gaining further credence from the Higgs boson observation) it is known to be incomplete.

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

Neutrino mixing and oscillation

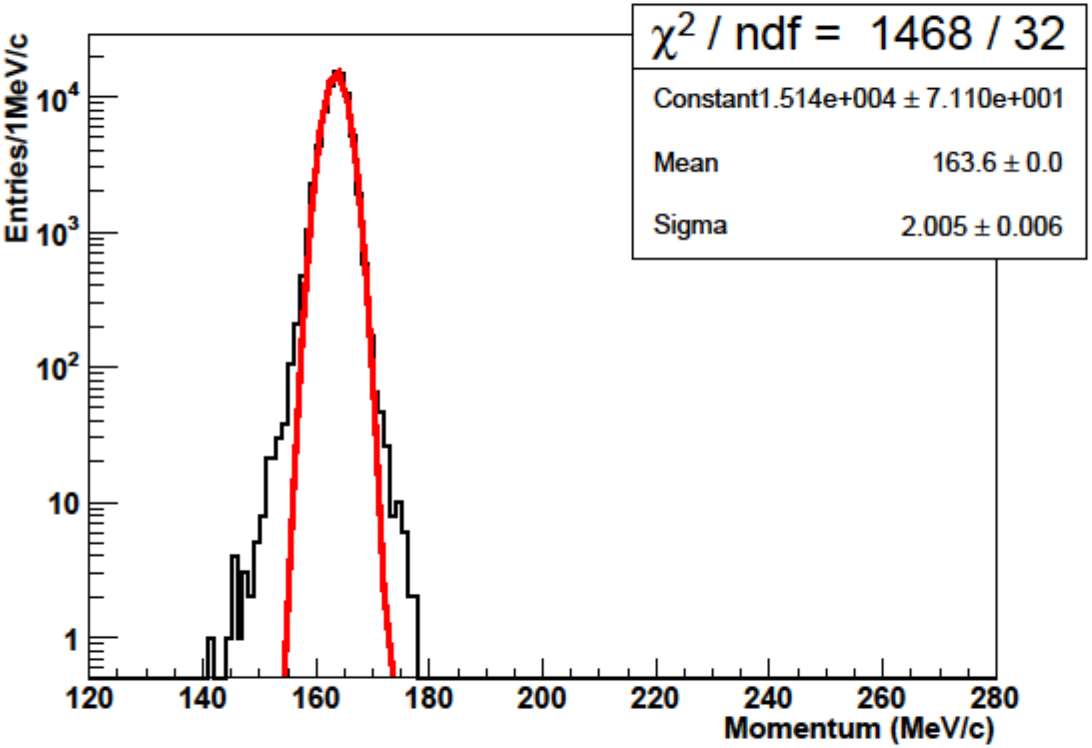
Dominance of matter over antimatter

Dark matter and dark energy



Signal resolution

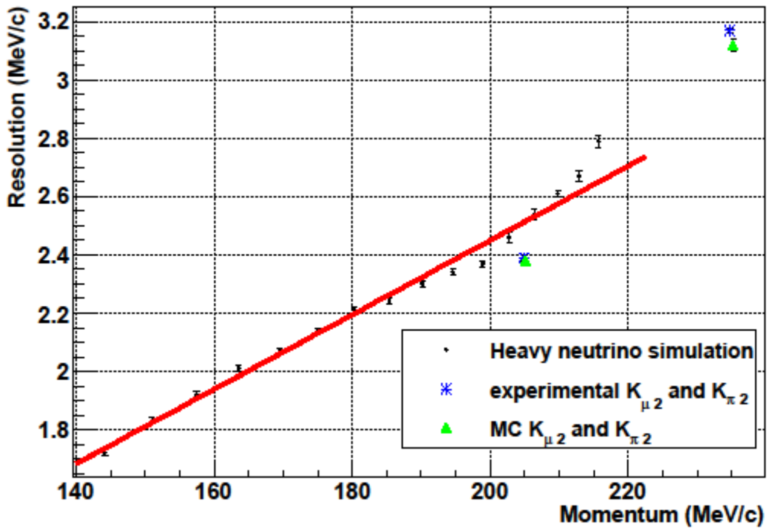
MC simulation of the $K^+ \to \mu^+ \nu_H$ decay with $m_{\nu_H} = 250\ \mathrm{MeV/c^2}$



All cuts applied

Signal distribution looks Gaussian at least in ±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

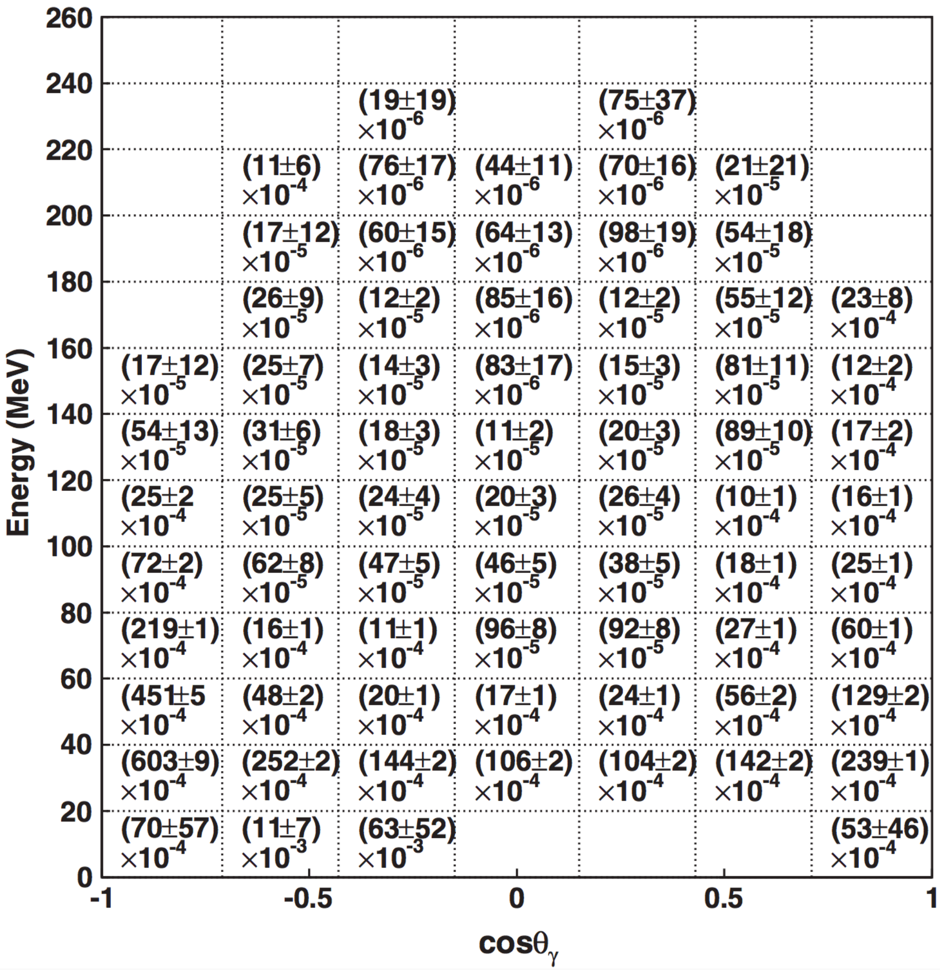
Peak search method

- “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

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.

Photon inefficiency



Obtained ned by fitting $K^+ \to \pi^+\pi^0 \to \pi^+\gamma\gamma$ where the π^+ and one γ are measure. This determines the second γ's energy and direction.