BROOKHAVEN NATIONAL LABORATORY

SEARCH FOR THE RARE DECAYS $K^+ \to \mu^+ X$ IN E949 EXPERIMENT

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On behalf of the E949 collaboration

KAON2016
14–17 September, University of Birmingham, UK

OUTLINE

- Search for heavy neutrinos: $K^+ \rightarrow \mu^+ \nu_H$,
  Phys. Rev. D 91, 052001 (2015)

- Search for rare decay $K^+ \rightarrow \mu^+ \nu\nu\nu$,
  Phys. Rev. D 94, 032012 (2016)

INTRODUCTION

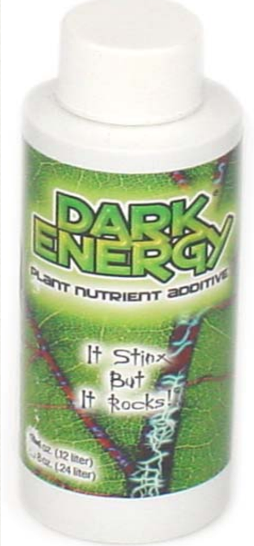
1. *Motivation*
2. *Experiment BNL — E949*
   - *The E949 detector*
   - *Data samples*

BEYOND THE STANDARD MODEL

Neutrino oscillation

Baryon asymmetry of the Universe

Dark matter and dark energy



νMSM: SM + 3 right-handed neutrinos

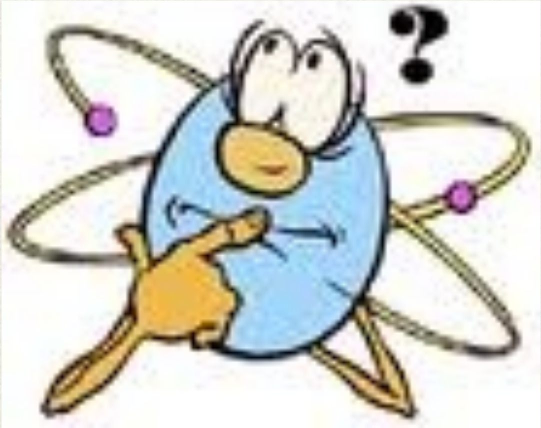
m_1 ~ 10 keV

$m_{2,3}$~ 100 MeV - 100 GeV

T. Asaka and M. Shaposhnikov

Phys. Lett. B620, 17 (2005).

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



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

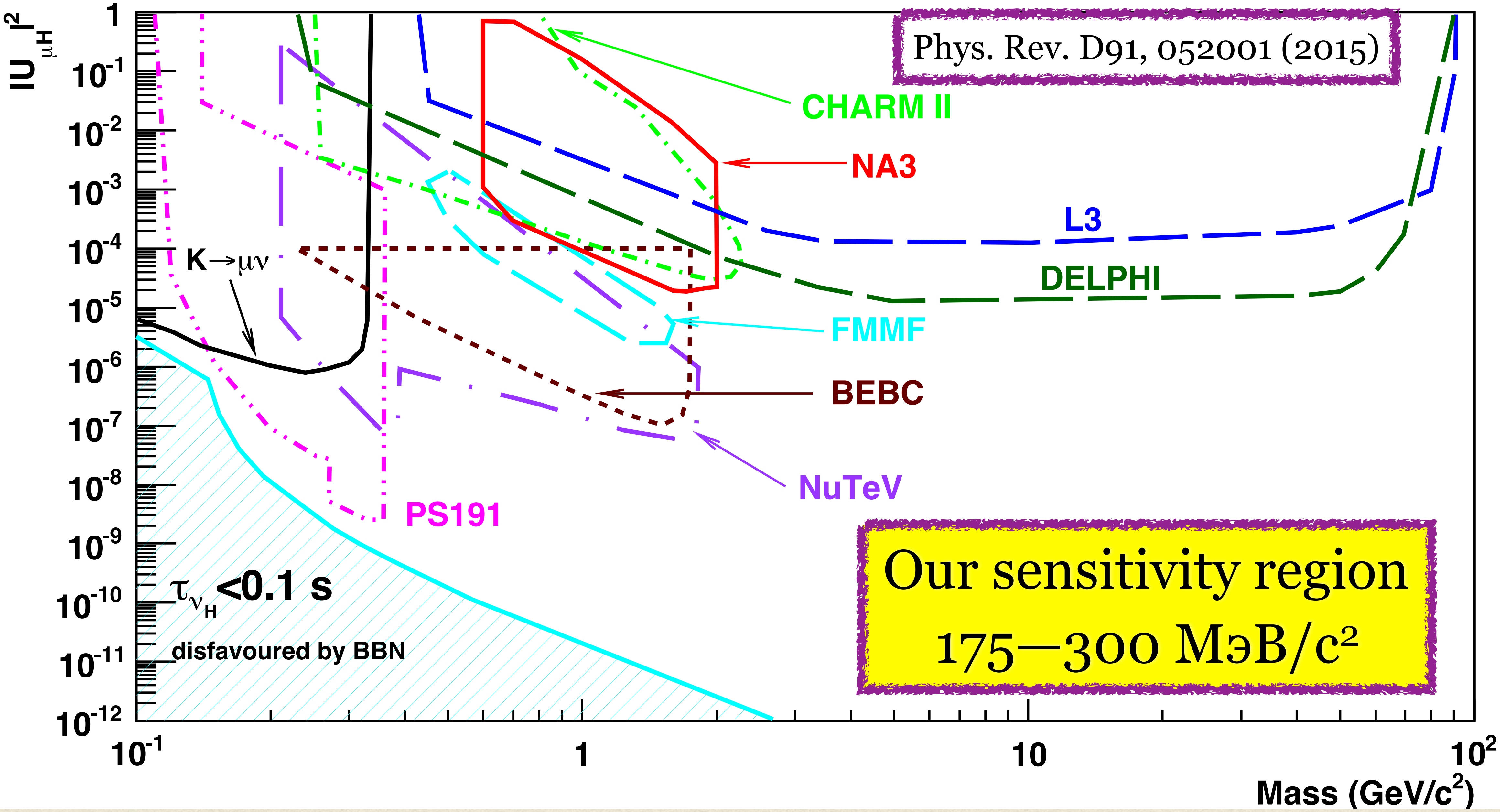
"Nothing" ➛ leptons and hadrons

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

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

CURRENT LIMITS(E949 RESULT IS OMITTED)

limits Belle, BaBaR, LHCb for heavy neutrino mass up to 5 GeV/c²
are not shown here (Nuclear Physics B Proceedings Supplement 00 (2014) 1–4, see also arXiv:1502.00477),
limits from CMS for mass 50—500 GeV/c² are also not shown (JHEP 04 (2016) 169)



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

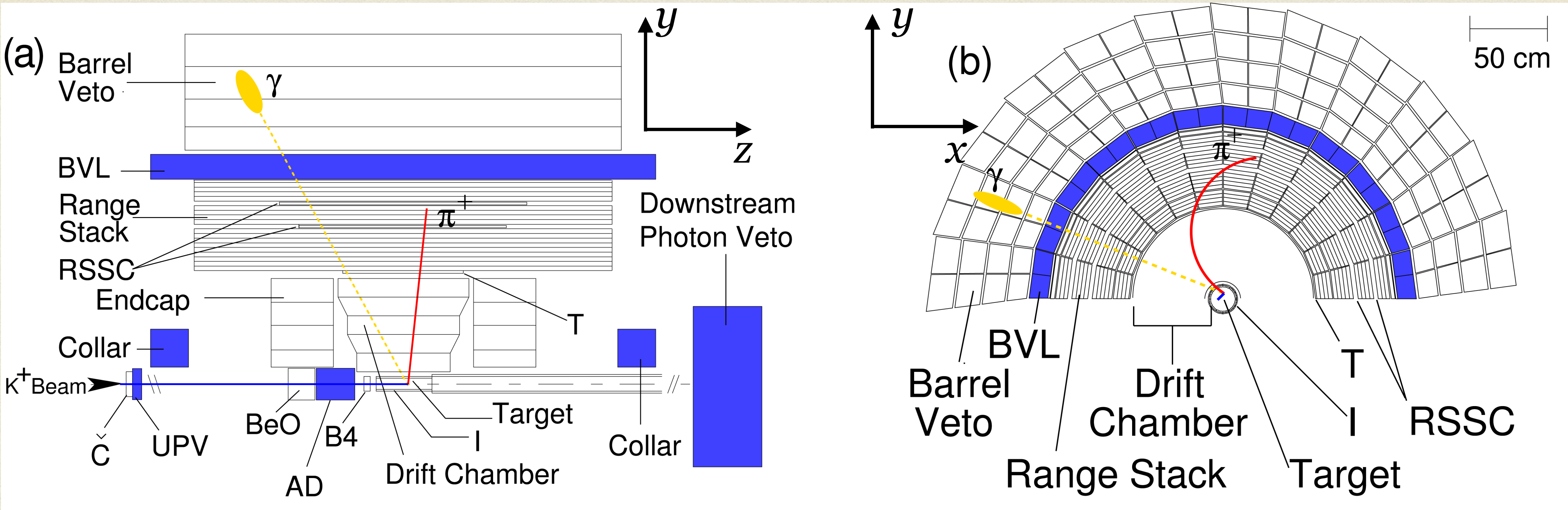
4+3(E787)=7 events

➜

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

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

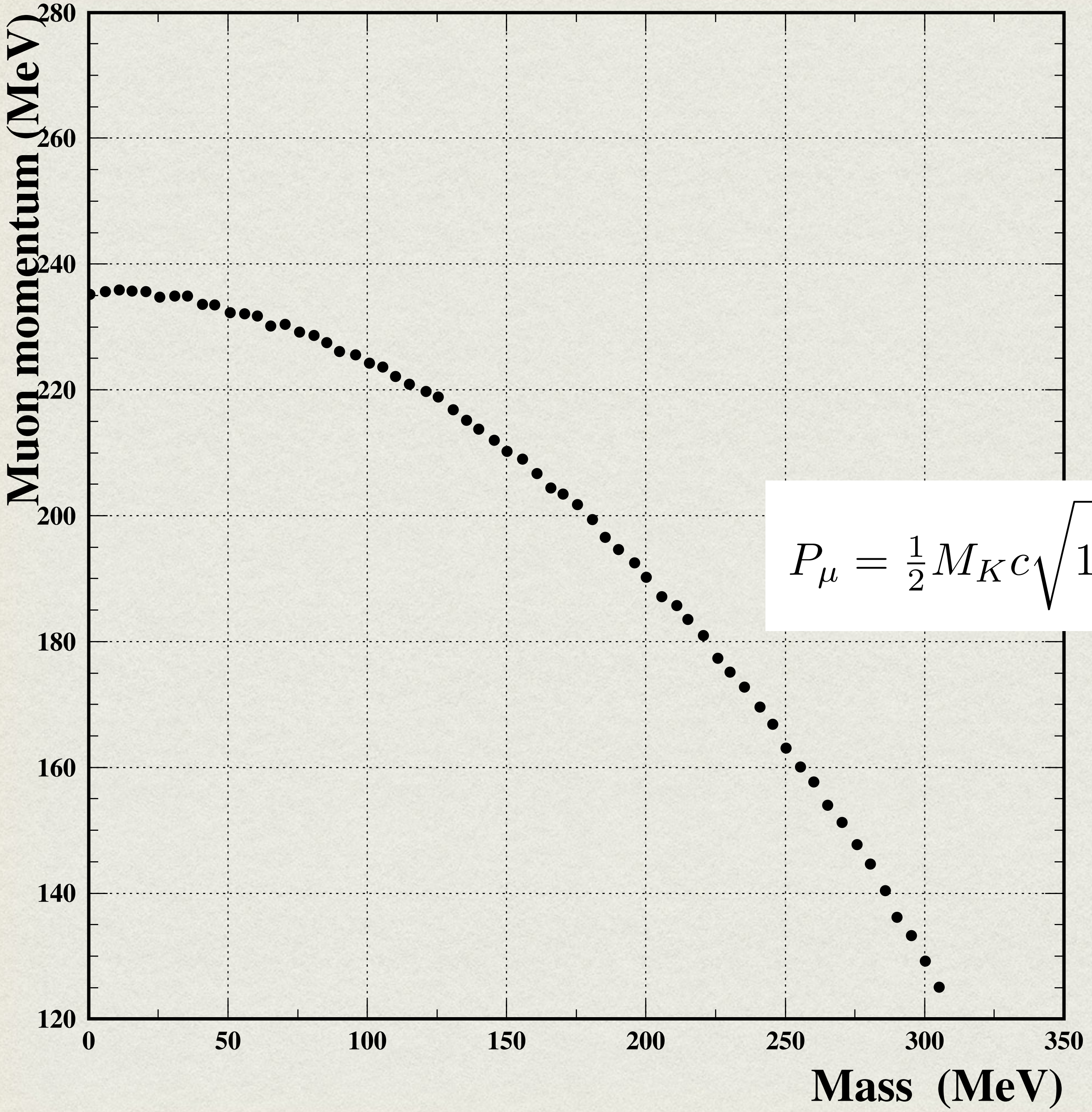
- The main trigger. Huge statistics: 1.70×10^{12} stopped kaons
  - Pros — signal decay $K^+ \to \mu^+ \nu_H$ is similar to $K^+ \to \pi^+ \nu\nu$: one single charge track and no other detector activity
  - Cons — it was designed to select pions from the $K^+ \to \pi^+ \nu\nu$, rejected muons
- Monitor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

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

DATA ANALYSIS

1. *Single muon selection criteria*
2. *Acceptance measurement*
3. *Study of the 1/20 data*
    - *Acceptance verification*
    - *Systematic uncertainties*
    - *Background study*
4. *Momentum resolution for the different muon momentum*
5. *Peak search method*

THE STRATEGY



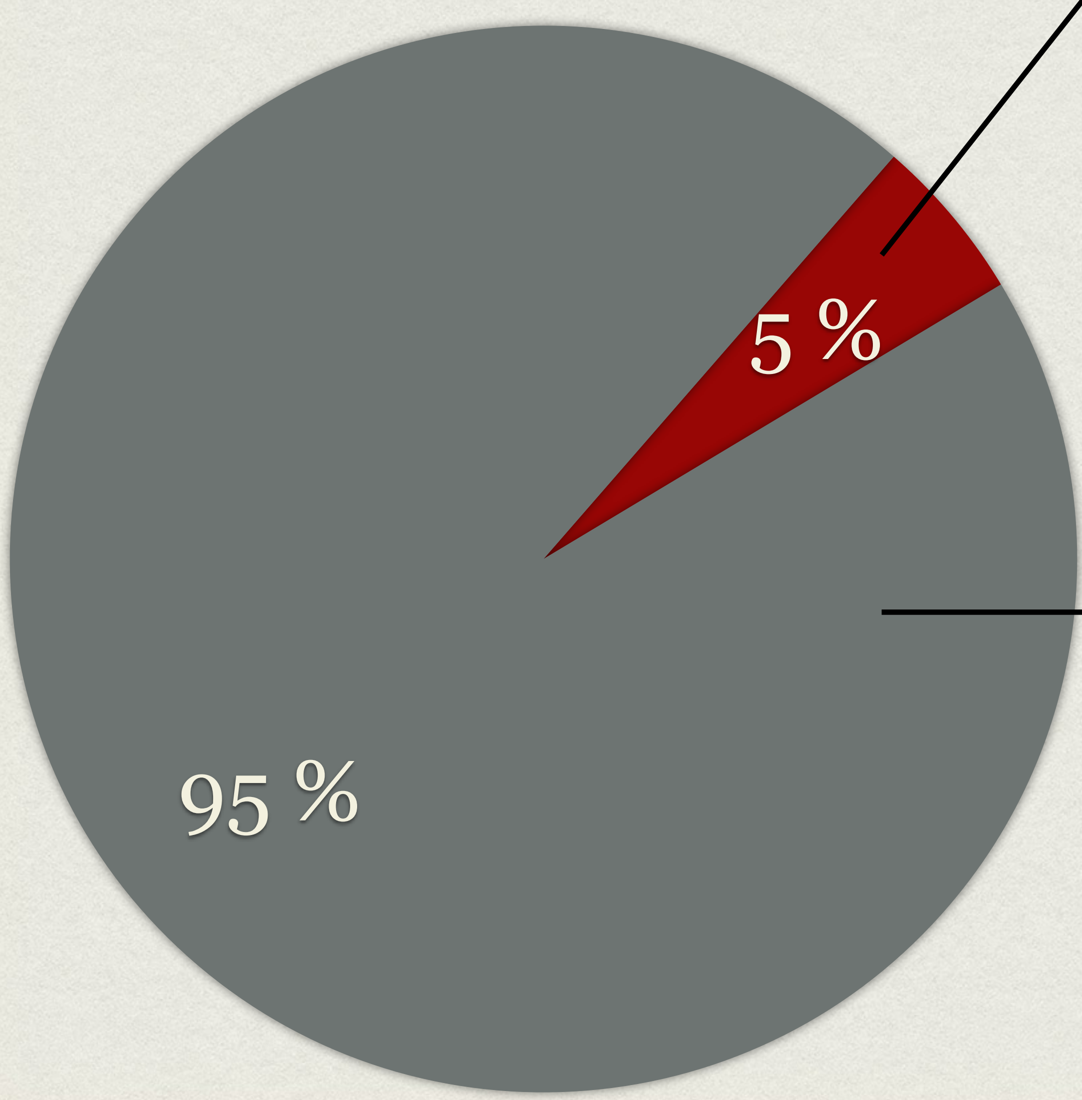
$K^+ \to \mu^+ \nu_H$ — two-body decay, the muon momentum is unambiguously defined by heavy neutrino mass

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

Search for additional peaks in muon momentum spectrum

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

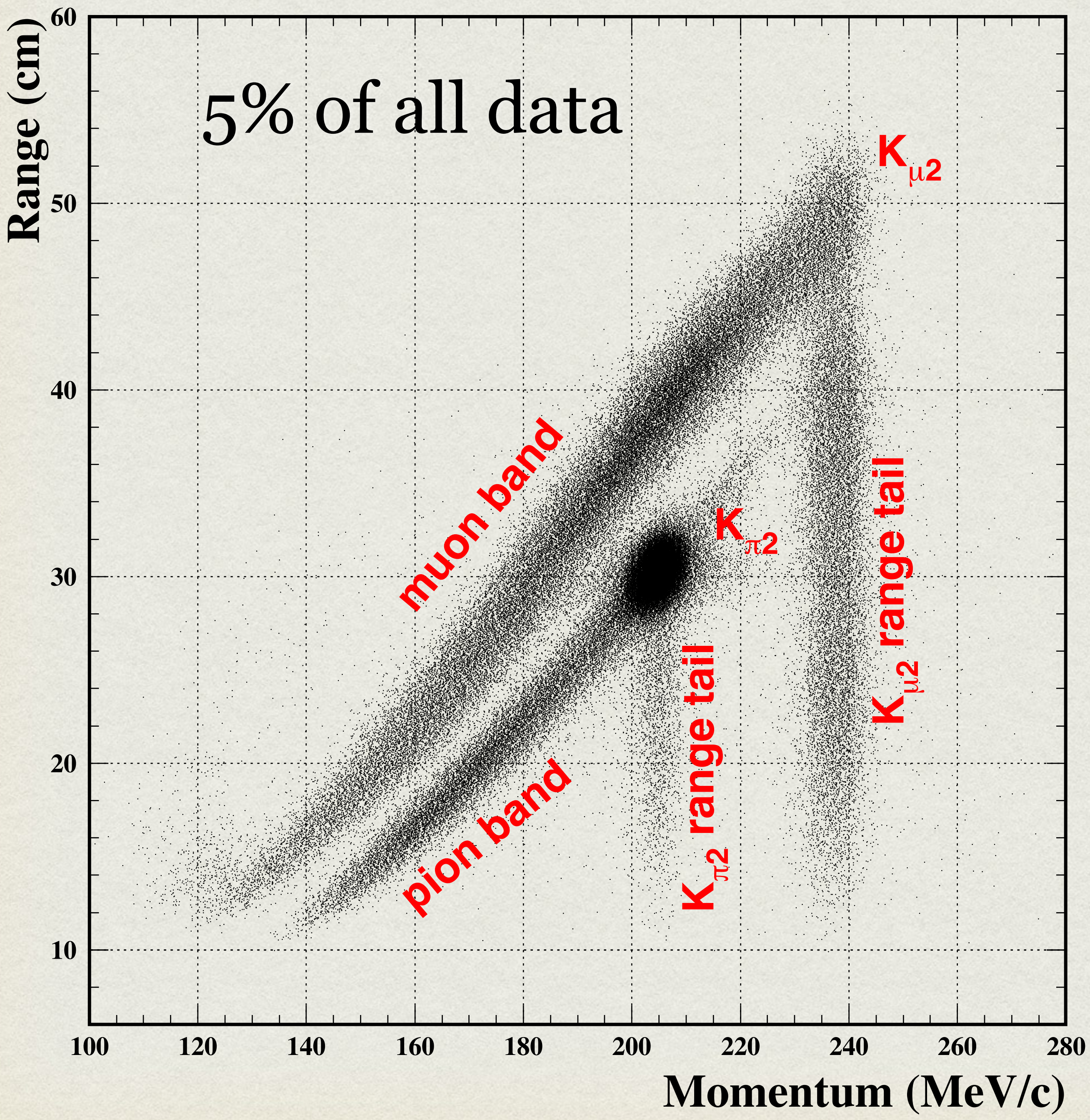
Trigger

- 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)

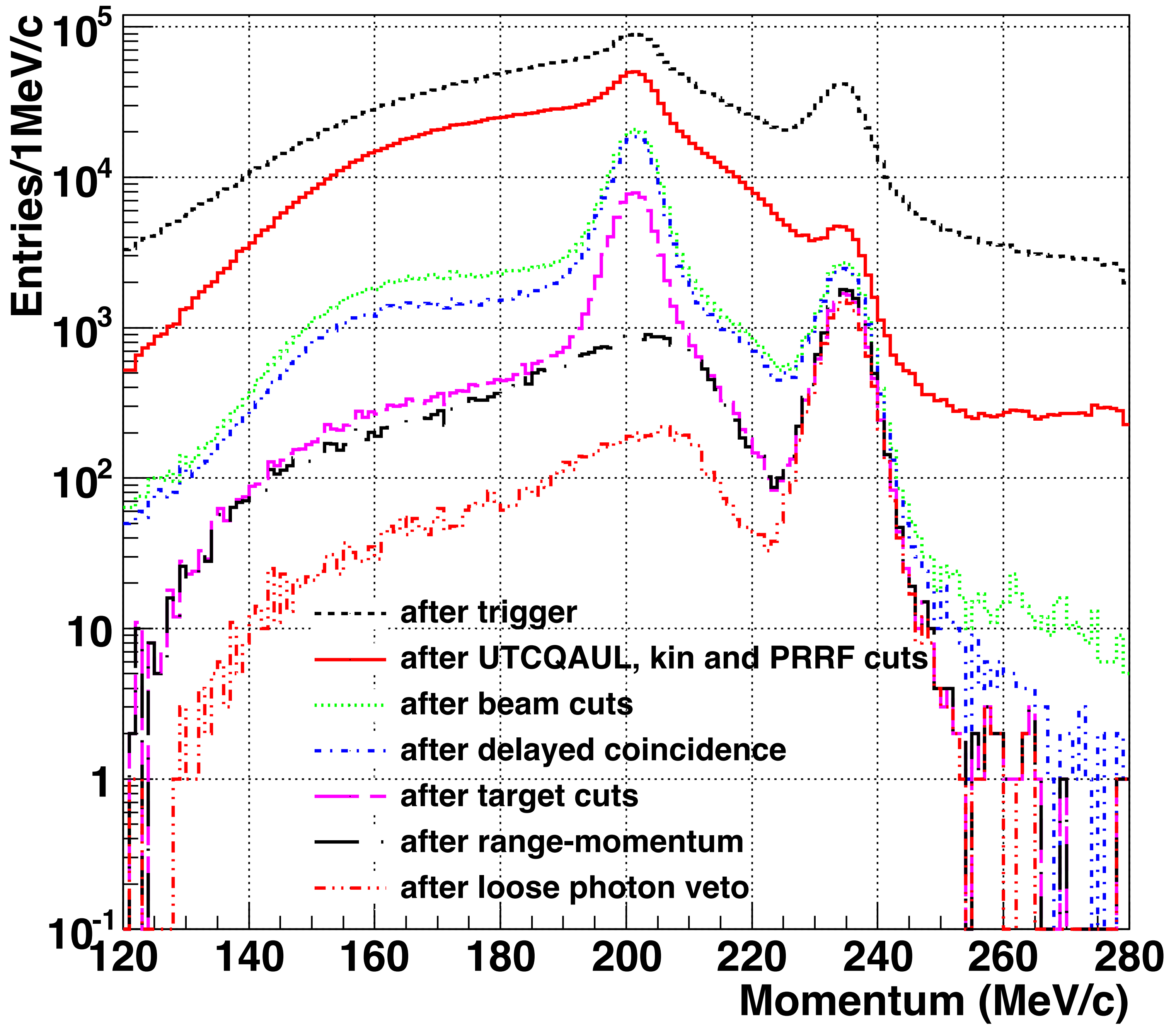
THE MAIN TRIGGER DATA



- Selected by choosing every 20th event (included all runs)
- Muon band: muons from $K_{\mu\nu\gamma}$ and $K_{\mu 3}$ decays
- Pion band: pions from $K_{\pi 2\gamma}$ decay and from $K_{\pi 2}$ decay in which the pions scattered in the target or Range Stack and beam pions that scattered in the target
- Both $K_{\mu 2}$ and $K_{\pi 2}$ range tails — elastic or inelastic scattering in the Range Stack

SELECTION CRITERIA

5% of all data

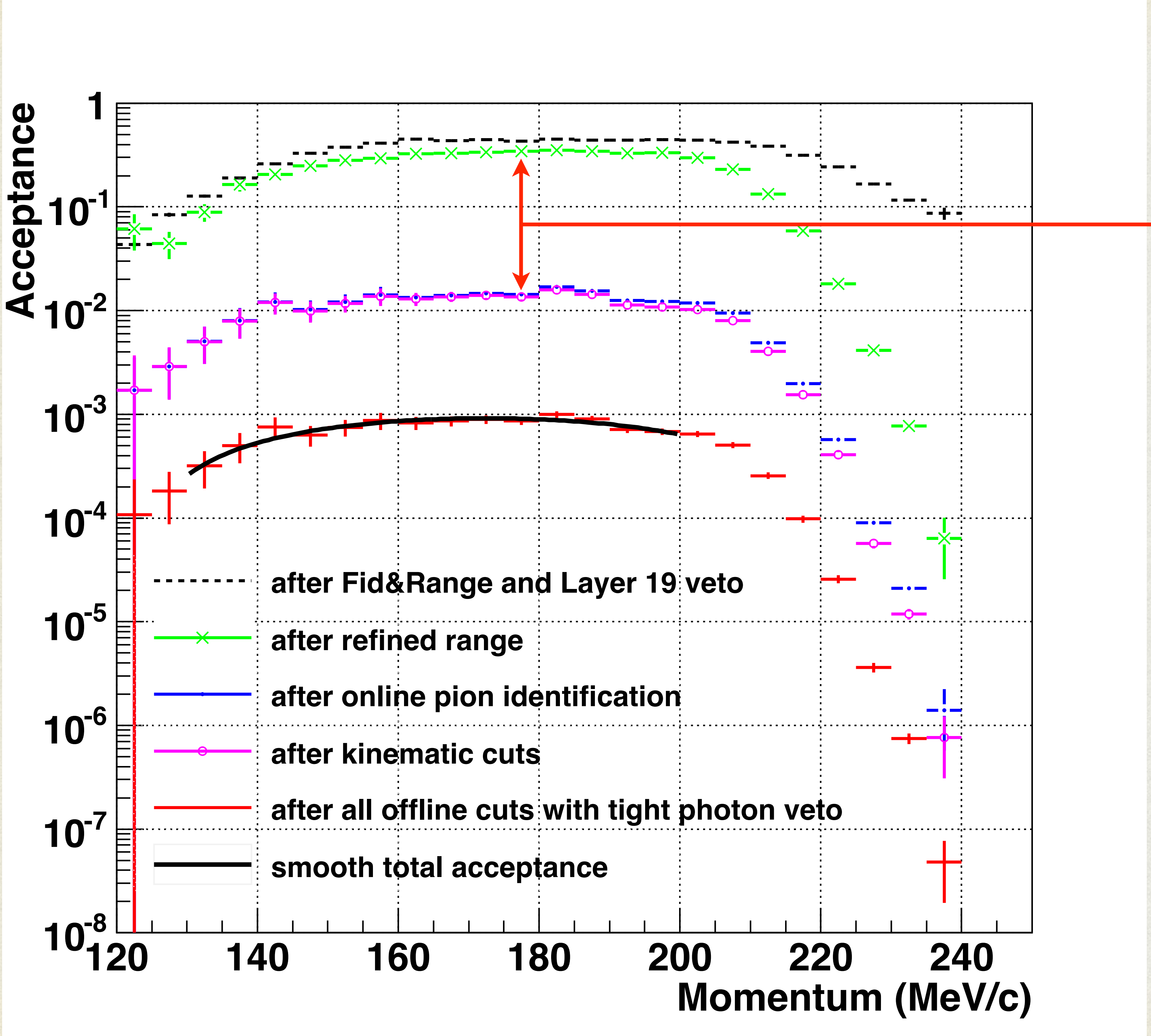


ACCEPTANCE MEASUREMENT

Total: 73 selection criteria

- Muons from $K^+ \to \mu^+ \nu_\mu$ and $K^+ \to \mu^+ \nu_\mu \gamma$ decays. Used monitor triggers (63 selection criteria)
- Monte-Carlo simulation of the $K^+ \to \mu^+ \nu_H$ decay (fiducial volume) (6 selection criteria)
- Used values from the main E949 analysis ($K^+ \to \pi^+ \nu \bar{\nu}$ decay) (4 selection criteria)

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:

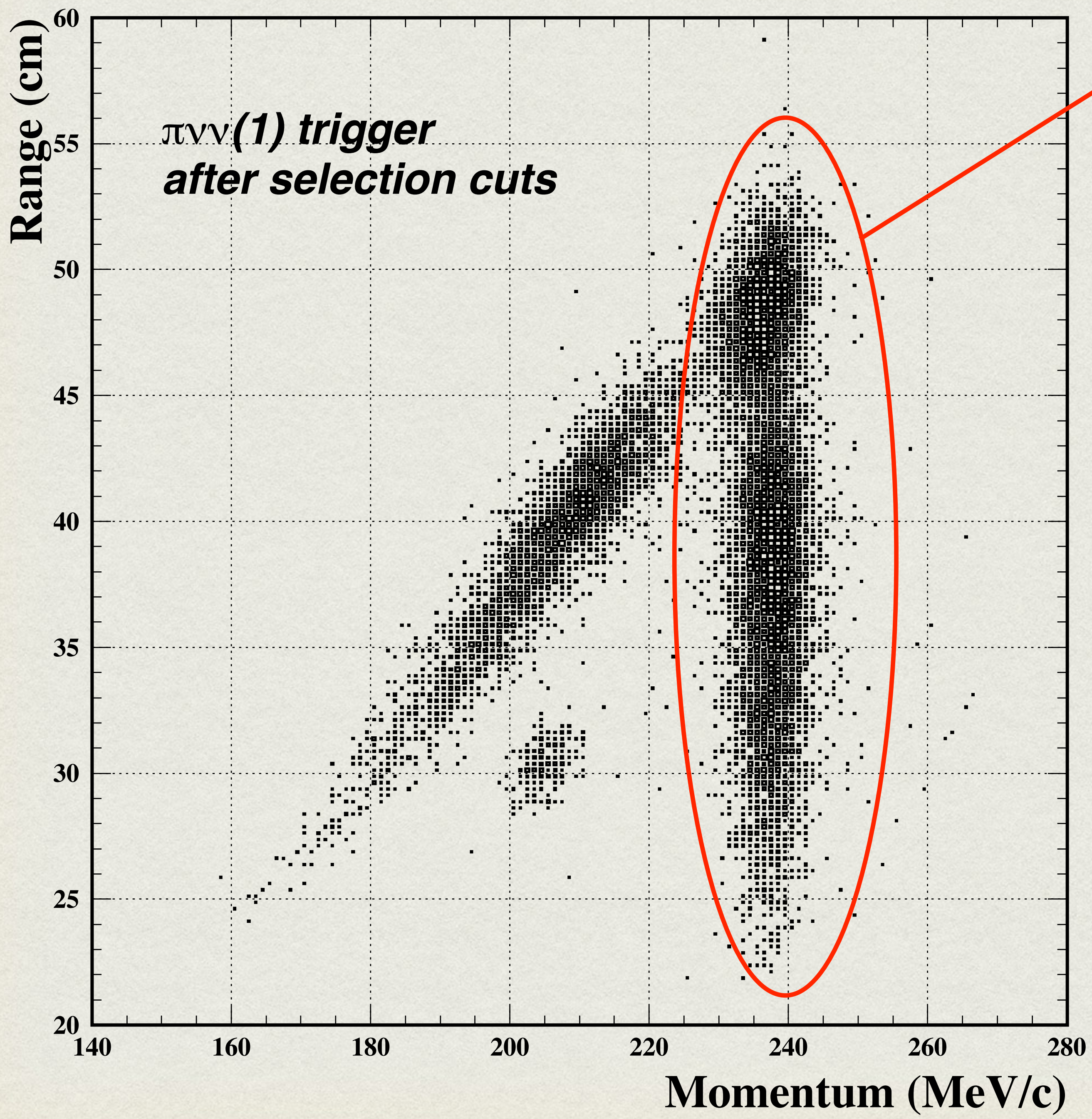
$$S.E.S = \frac{1}{KBlive \times Acc} =$$

$$7.35 \times 10^{-10}$$

ACCEPTANCE VERIFICATION

- The $K^+ \to \mu^+ \nu_\mu$ branching ratio measurement, 5% of all data was used
- The $K^+ \to \mu^+ \nu_\mu \gamma$ branching ratio measurement ($140 < p_\mu < 200$ MeV/c), 5% of all data was used

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



Events for the $K_{\mu 2}$ branching ratio measurement

For the given muon momentum some acceptance factors should be corrected

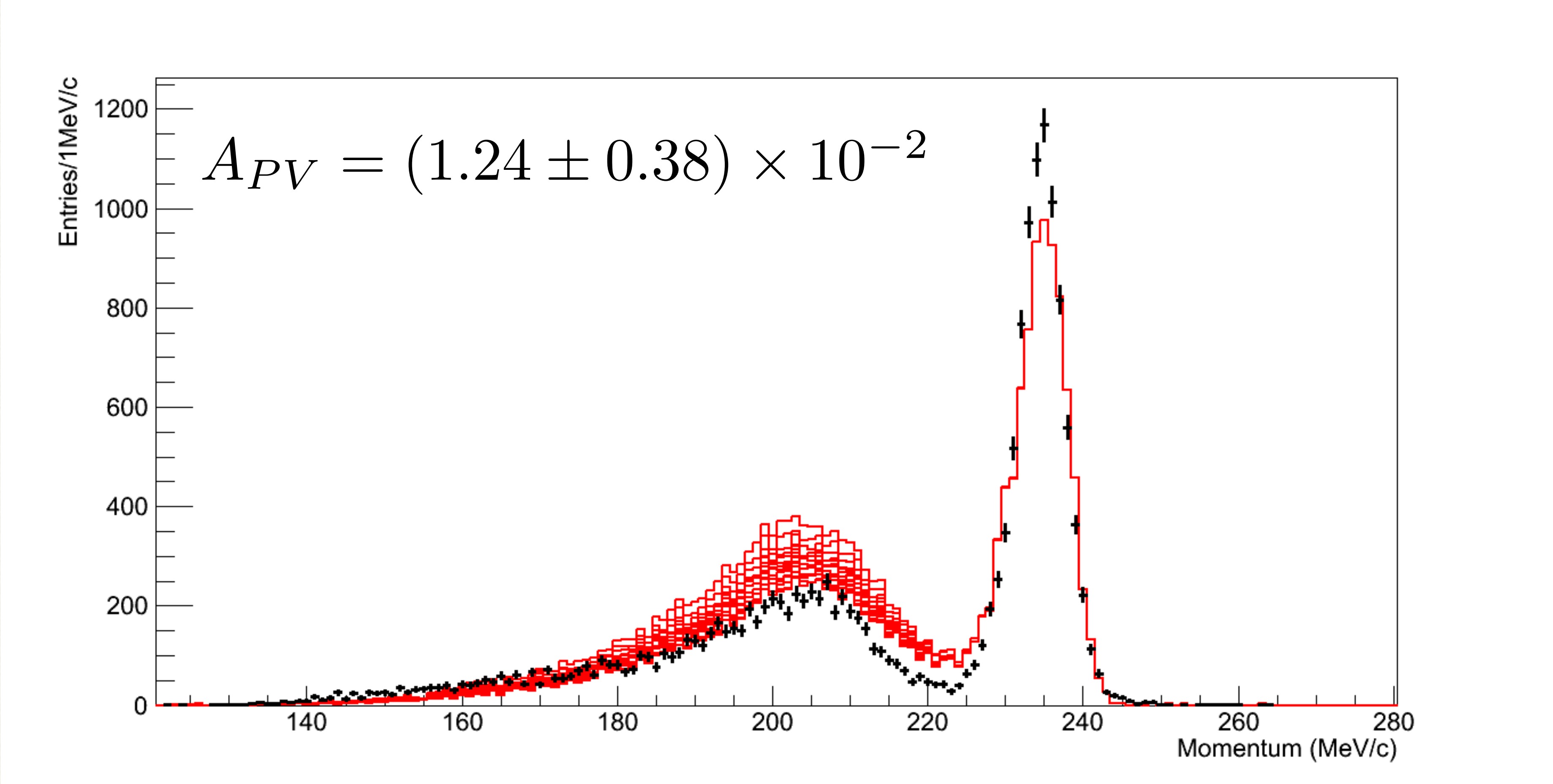
$$BR(K_{\mu 2}) = 0.54 \pm 0.15$$

$$BR^{PDG}(K_{\mu 2}) = 0.6355 \pm 0.0011$$

$K^+ \to \mu^+ \nu_\mu \gamma$ DECAY

Branching ratio measurement in the muon momentum region $140 < p_\mu < 200$ MeV/c. We measured all acceptance factors, except the photon veto (one photon in the final state)

Used MC simulation and single photon inefficiency table.



Varied photon veto detectors thresholds from zero to the nominal values. The photon veto acceptance (A_{PV}) — the mean acceptance of all red histograms.

$K^+ \rightarrow \mu^+ \nu_\mu \gamma$ DECAY

The branching ratio for the muon momentum $140 < p_\mu < 200$ MeV/c was measured to be:

$$BR(K_{\mu\nu\gamma}) = (1.3 \pm 0.4) \times 10^{-3}$$

The measured uncertainty is the systematic uncertainty for the acceptance of the $K^+ \rightarrow \mu^+ \nu_H$ decay.

$$BR^{PDG}(K_{\mu\nu\gamma}) = (6.2 \pm 0.8) \times 10^{-3}, p_\mu < 231.5 \text{ MeV/c}$$

Used MC simulation to determine branching ratio in the selected muon momentum region:

$$BR^{PDG}(K_{\mu\nu\gamma}) = (1.4 \pm 0.2) \times 10^{-3}$$

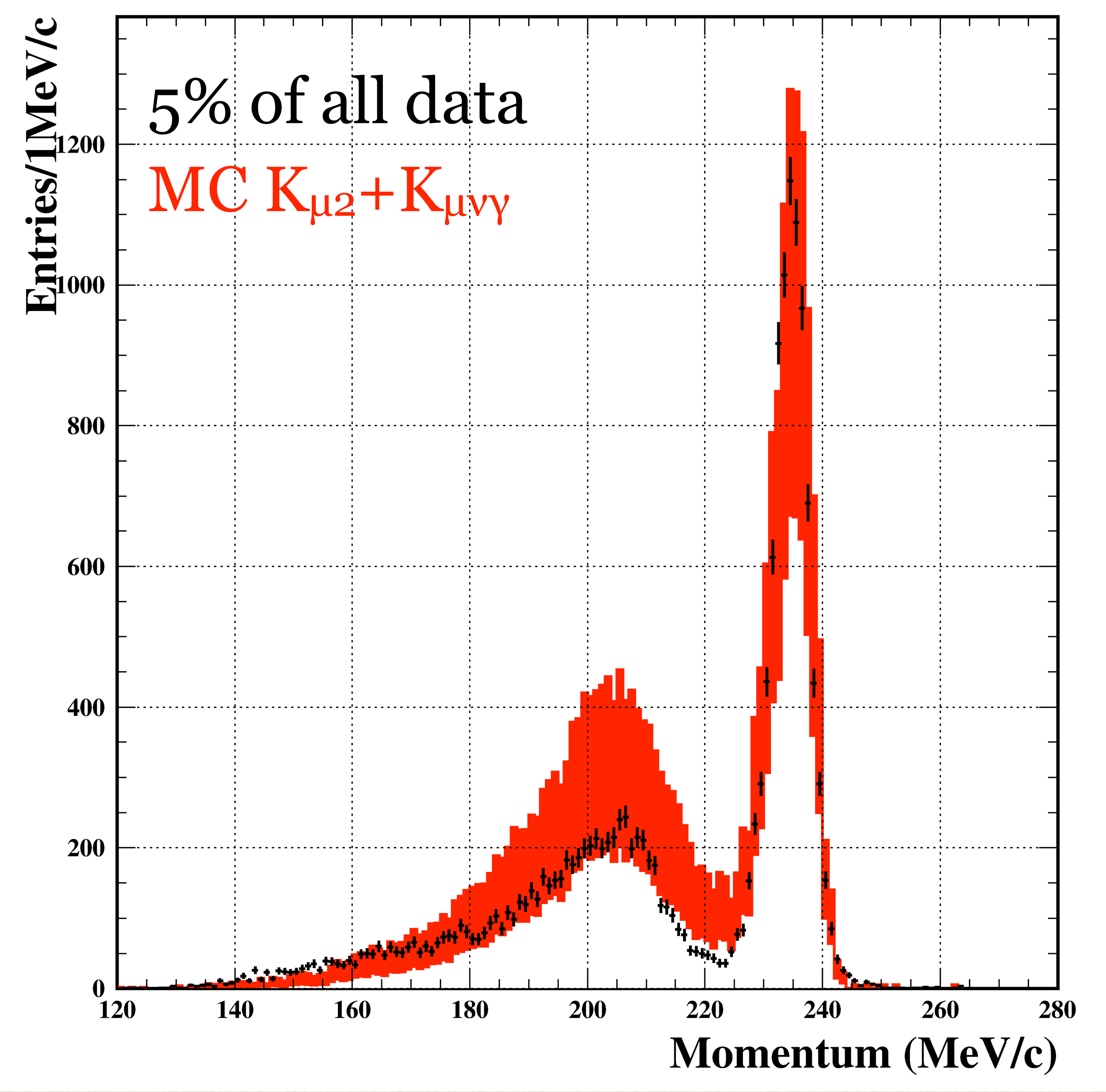
BACKGROUND PROCESSES

Process	Trigger+cuts rej	BR	Total rejection
$K_{\mu\nu\gamma}$	$\sim 10^4$	6.2×10^{-3}	$\sim 10^7$
$K_{\mu 3}$	$\sim 10^7$	3.35×10^{-2}	$\sim 10^9$
Only $\pi\nu\nu(1+2)$ trigger			
$K_{\pi 2\gamma}$	$\sim 5 \times 10^4$	2.75×10^{-4}	$\sim 2 \times 10^9$

Used MC simulation . The $K_{\pi 2\gamma}$ decay was ignored due to three photons in the final state and large pion rejection (removed pion band).

The $K_{\mu\nu\gamma}$ decay is dominant background source.

BACKGROUND SHAPE

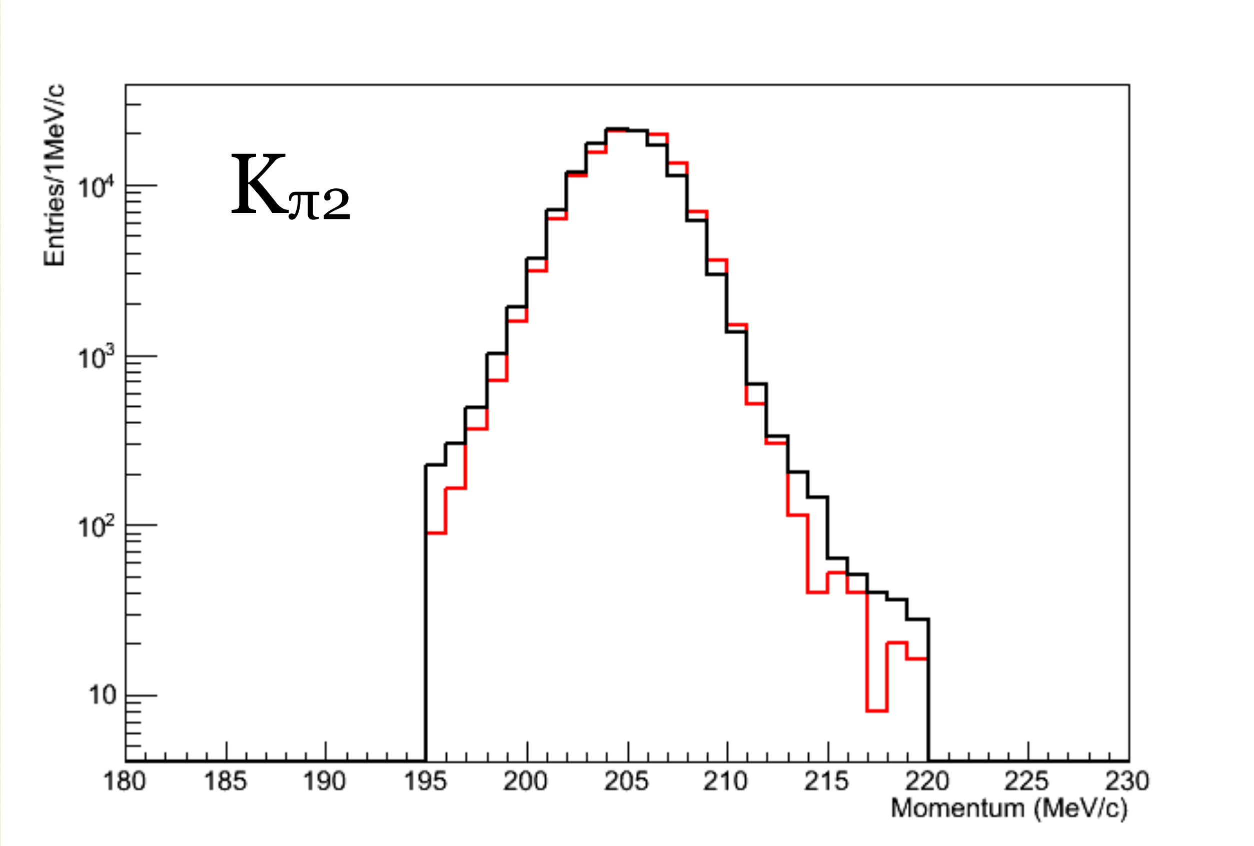


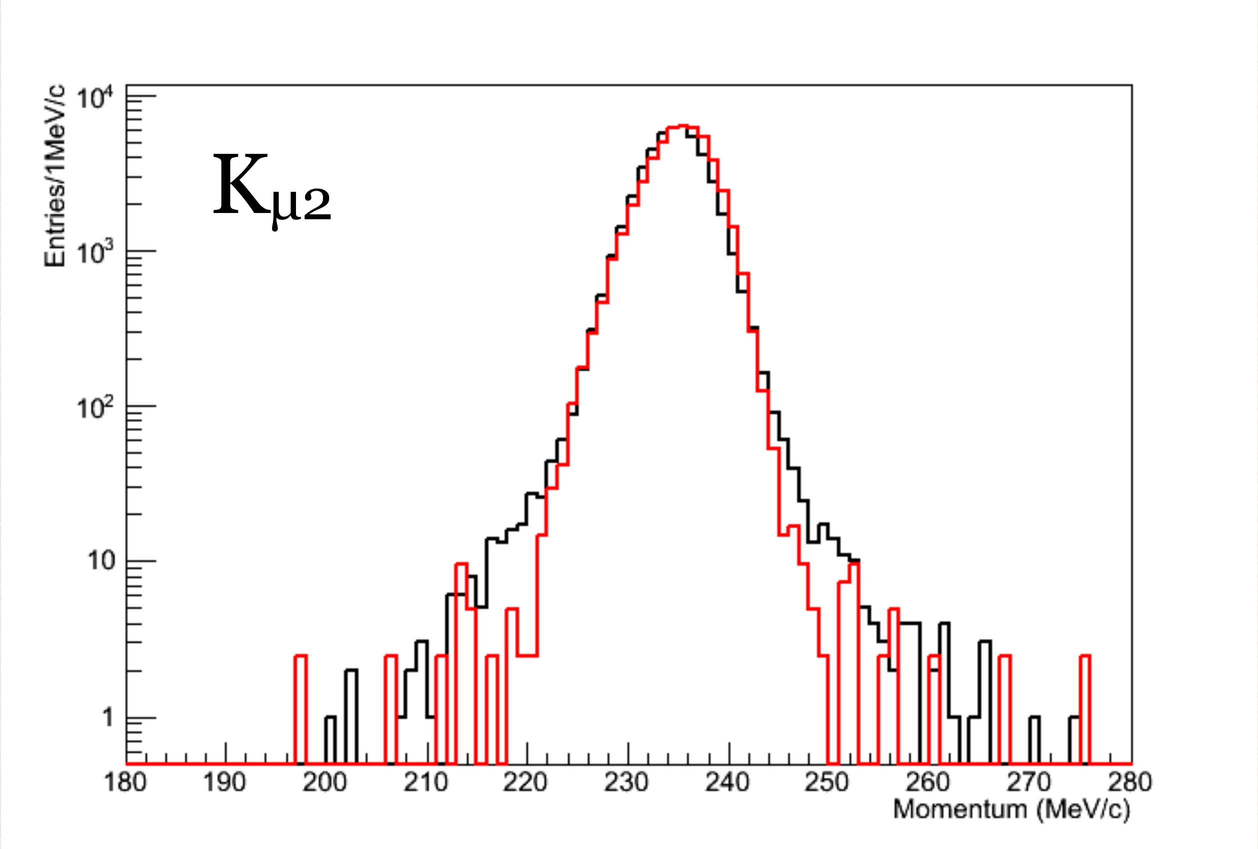
$$k_{K_{\mu2}} = \frac{(KBlive)_{1/20}}{N_{sim,K_{\mu2}}} \times \frac{A^{Exp}_{K_{\mu2}}}{A^{MC}_{K_{\mu2}}} \times BR(K_{\mu2})$$

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

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.

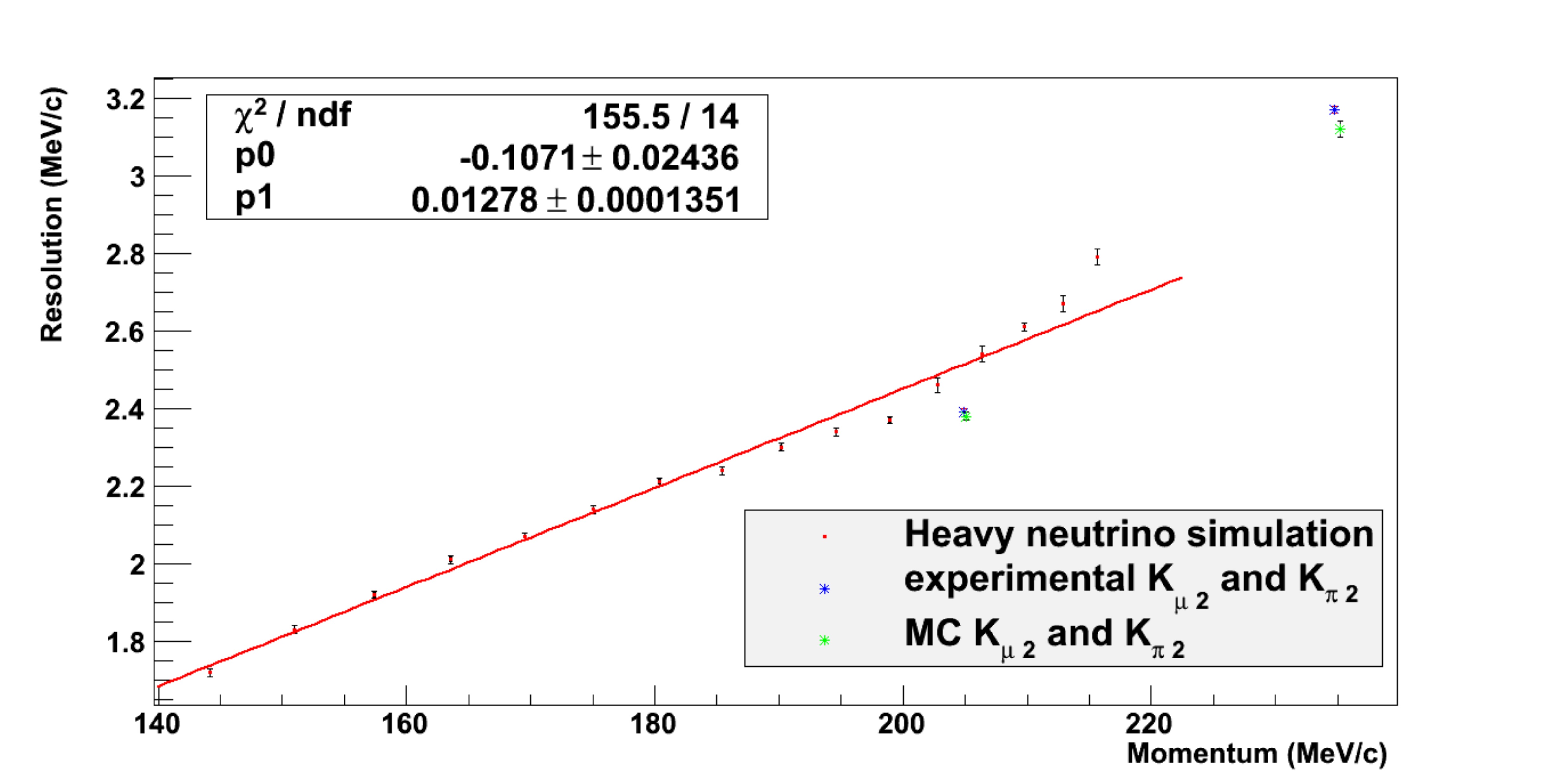
MOMENTUM RESOLUTION





MC simulation was consistent with data, so we used the $K^+ \rightarrow \mu^+ \nu_H$ simulation to measure muon momentum resolution

MOMENTUM RESOLUTION



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

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 (σ is momentum resolution for the selected point) 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)

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, θ=1, μ is signal strength parameter;

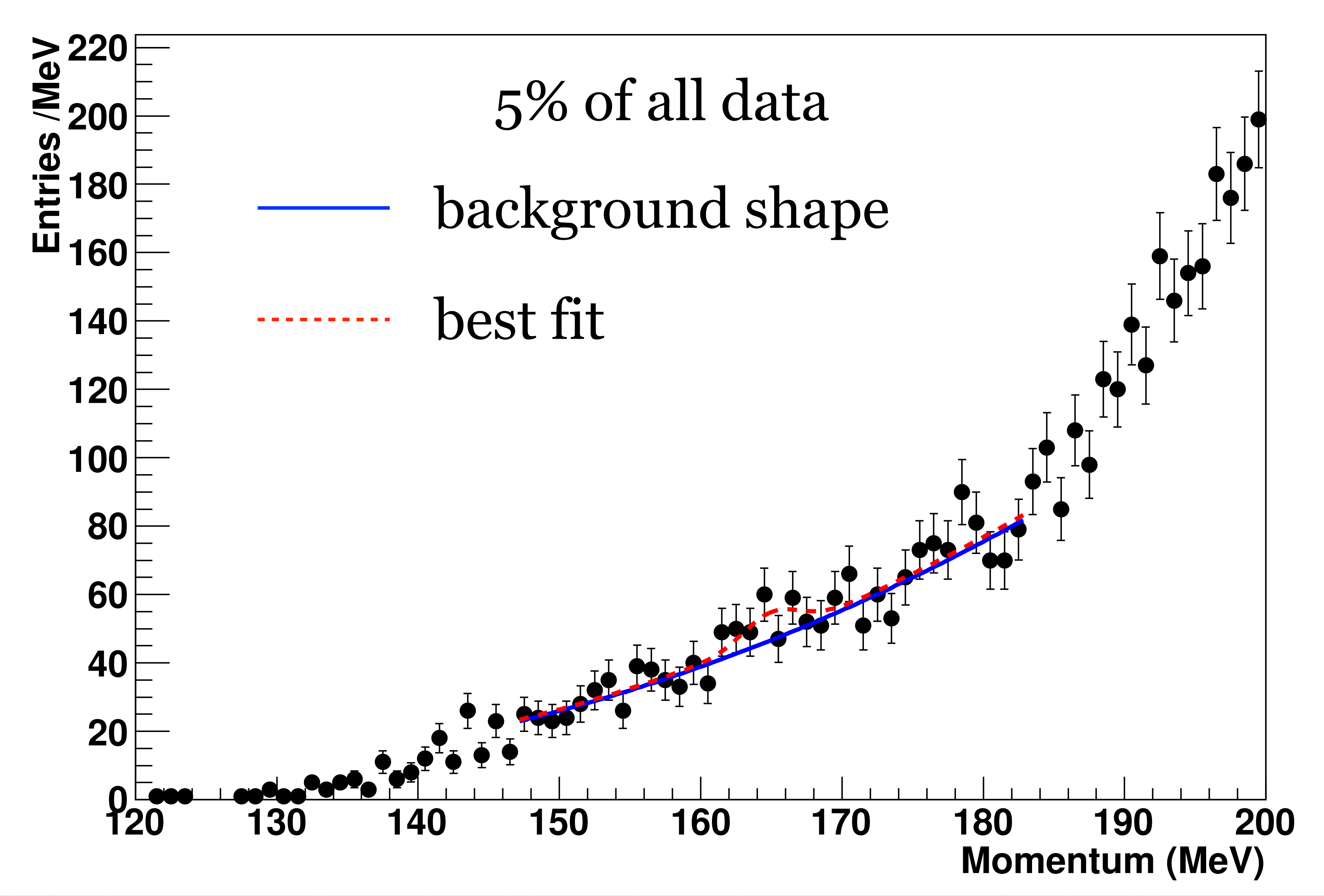
s – gauss. n_i – number of observed events in each bin;

β takes into account acceptance of the point of interest (β_{peak}) and its total error (σ_β)

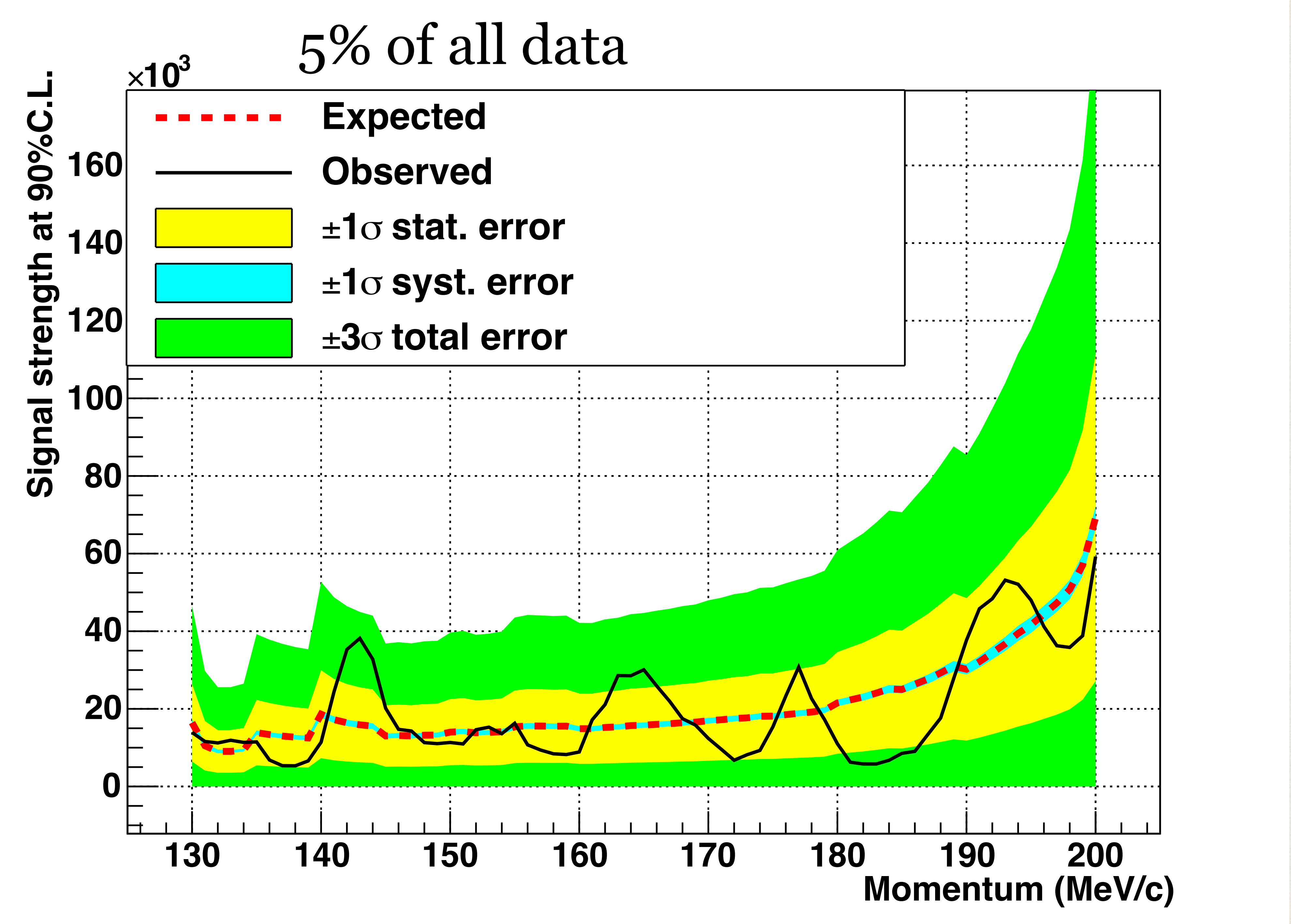
PEAK SEARCH METHOD

- "Asimov" data set based on background shape was generated to calculate expected upper limit (background only hypothesis) at 90%C.L.
- Use the same upper limit calculation method but with experimental data to get observed upper limit at 90%C.L.

PEAK SEARCH METHOD

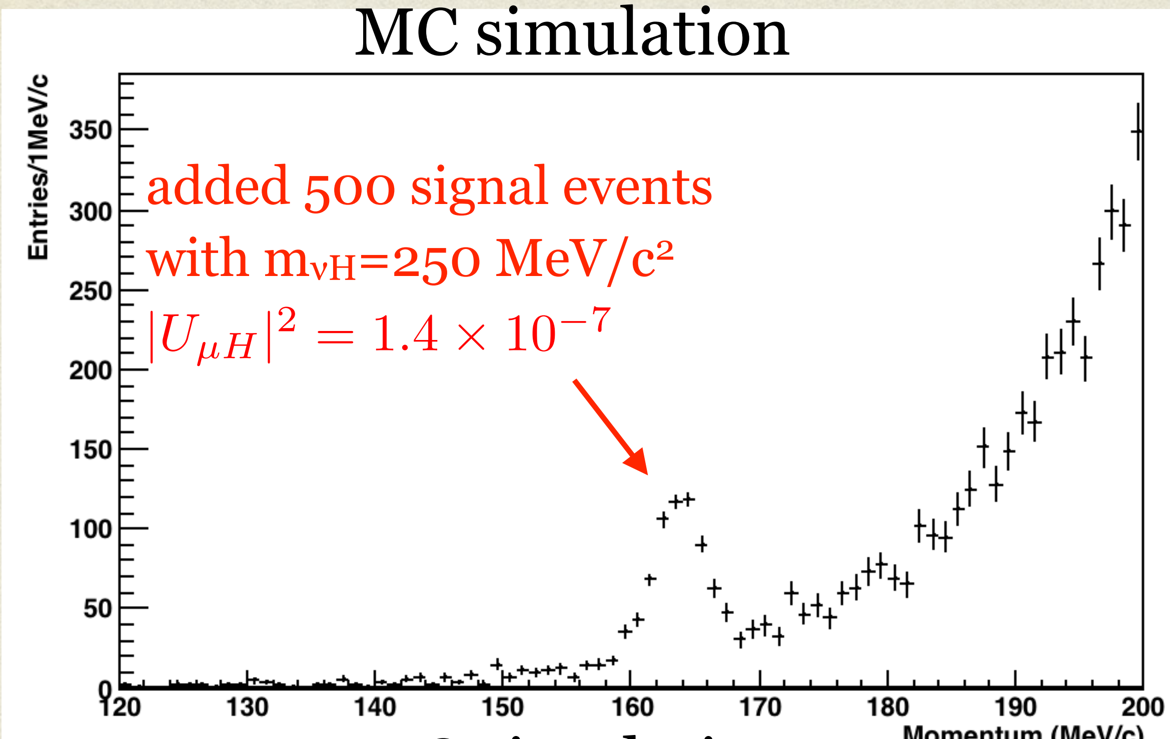


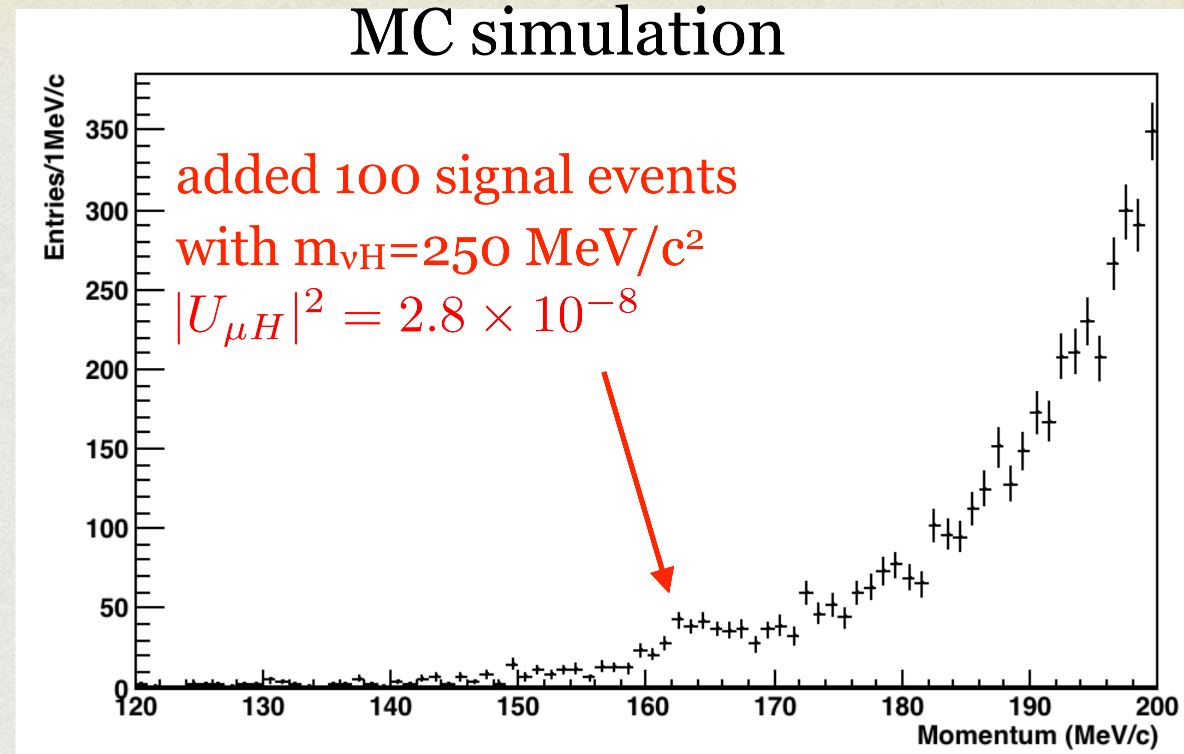
PEAK SEARCH METHOD

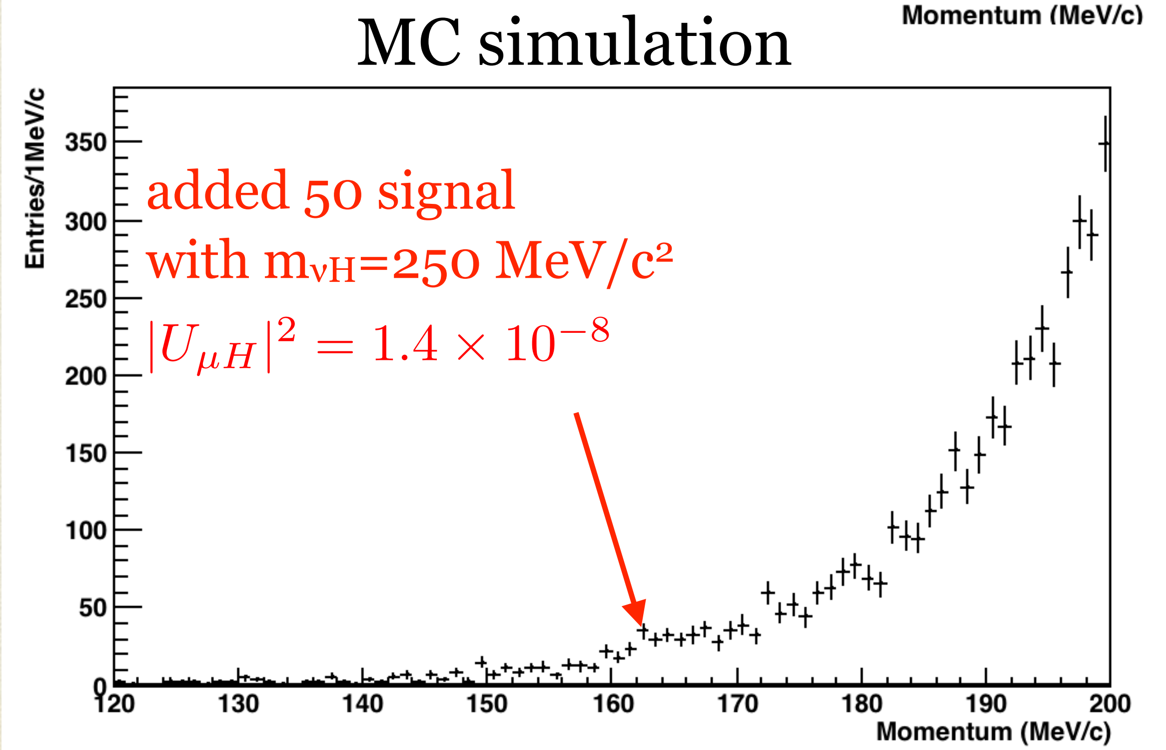


SIGNAL ILLUSTRATION

THERE ARE NO REAL DATA POINTS!!!



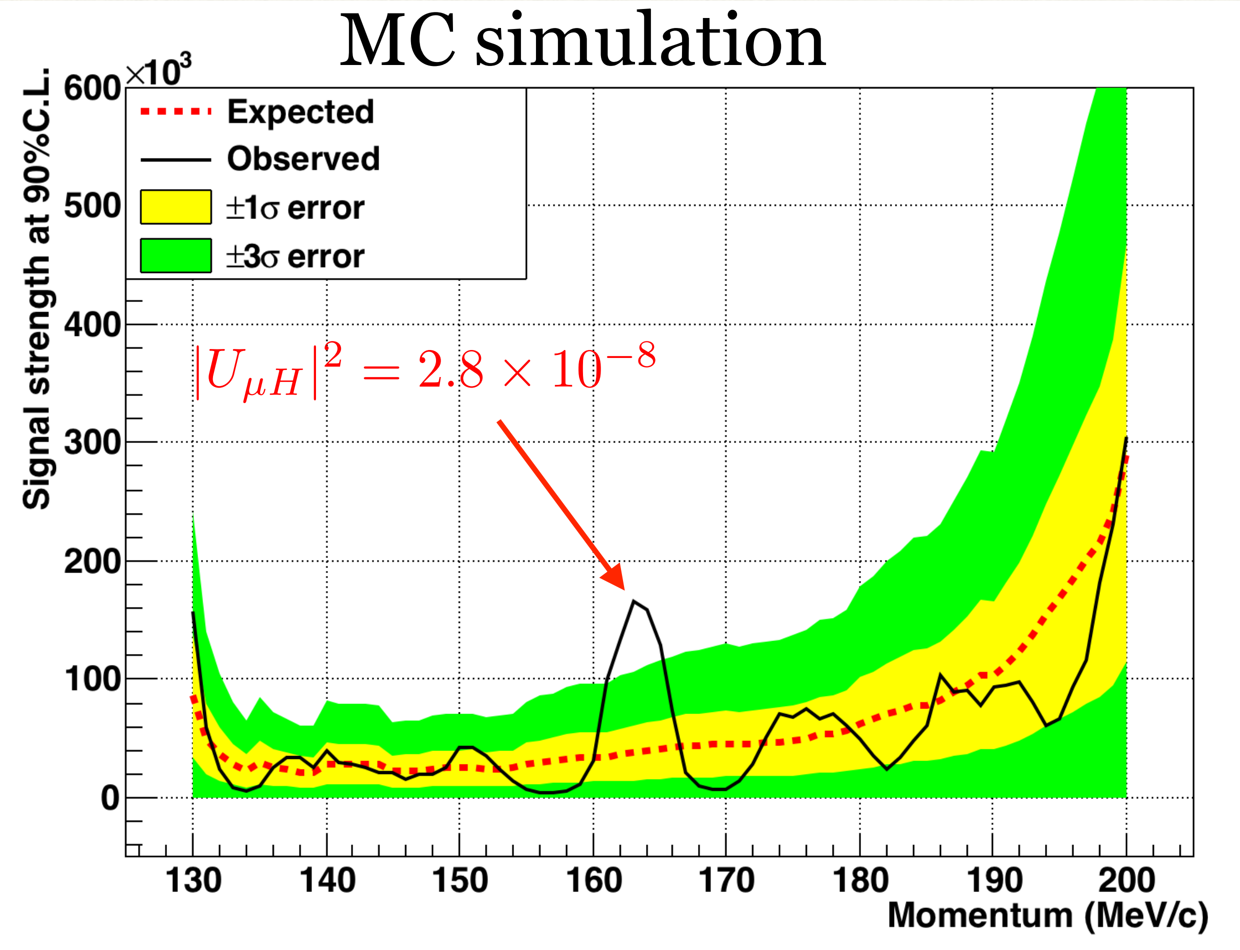


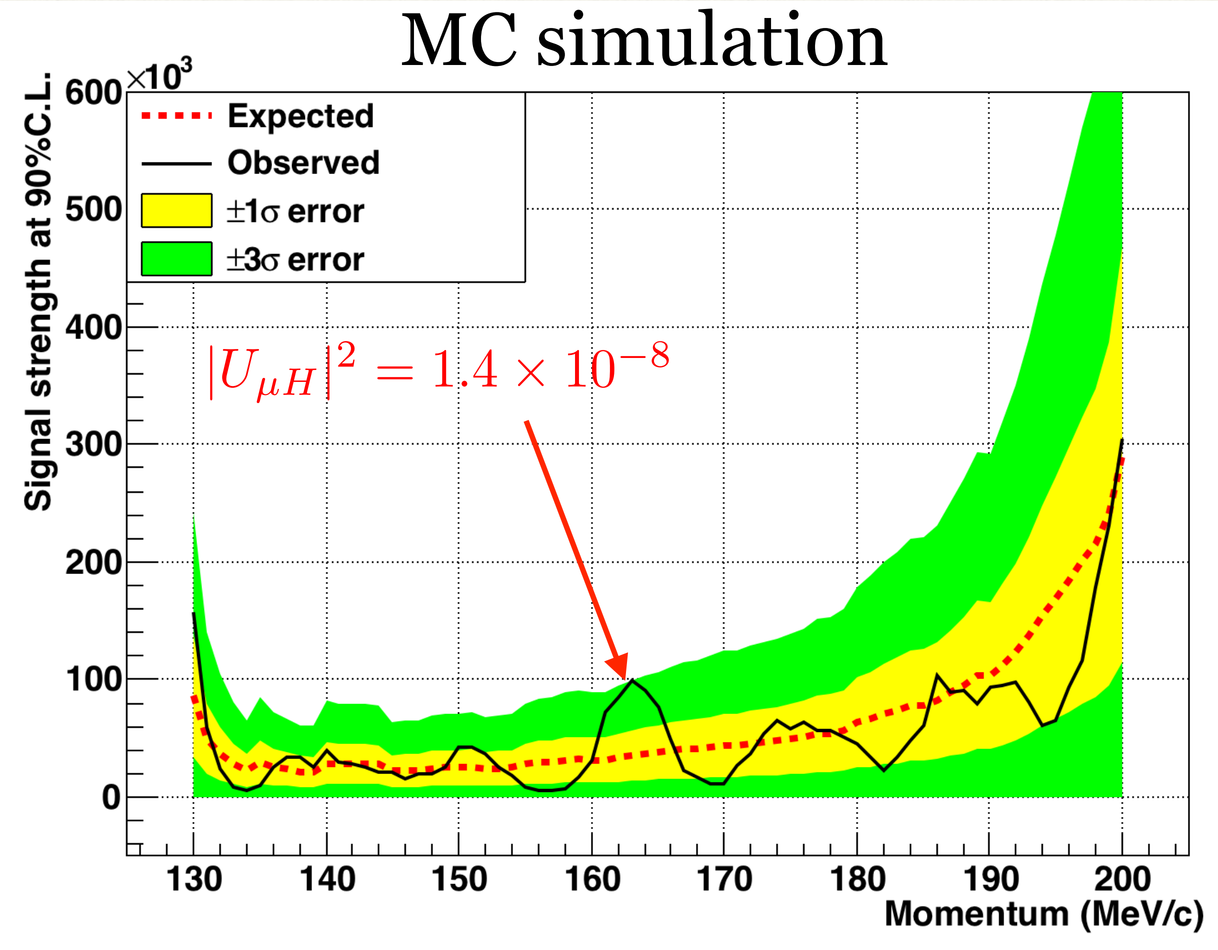


The 5% of all data was fitted by exponent in the momentum region 120—200 MeV/c. The background was generated in ROOT by using the fit parameters. The signal events were added to the generated background

SIGNAL ILLUSTRATION

THERE ARE NO REAL DATA POINTS!!!





Yes! We found the peak at 5.6σ

added 100 signal events
with $m_{\nu H}$=250 MeV/c²

We are not able to find the peak

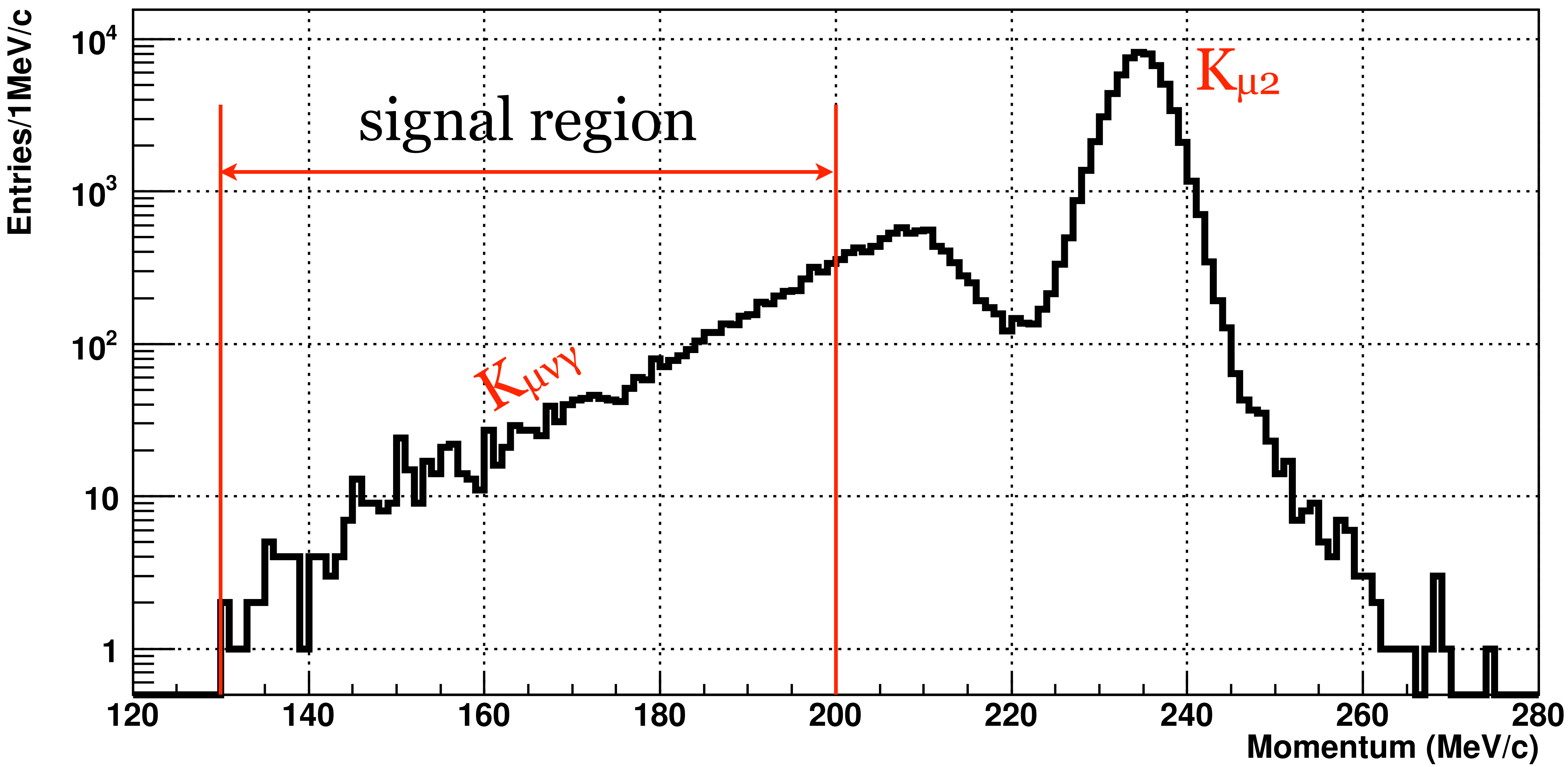
added 50 signal events
with $m_{\nu H}$=250 MeV/c²

RESULTS

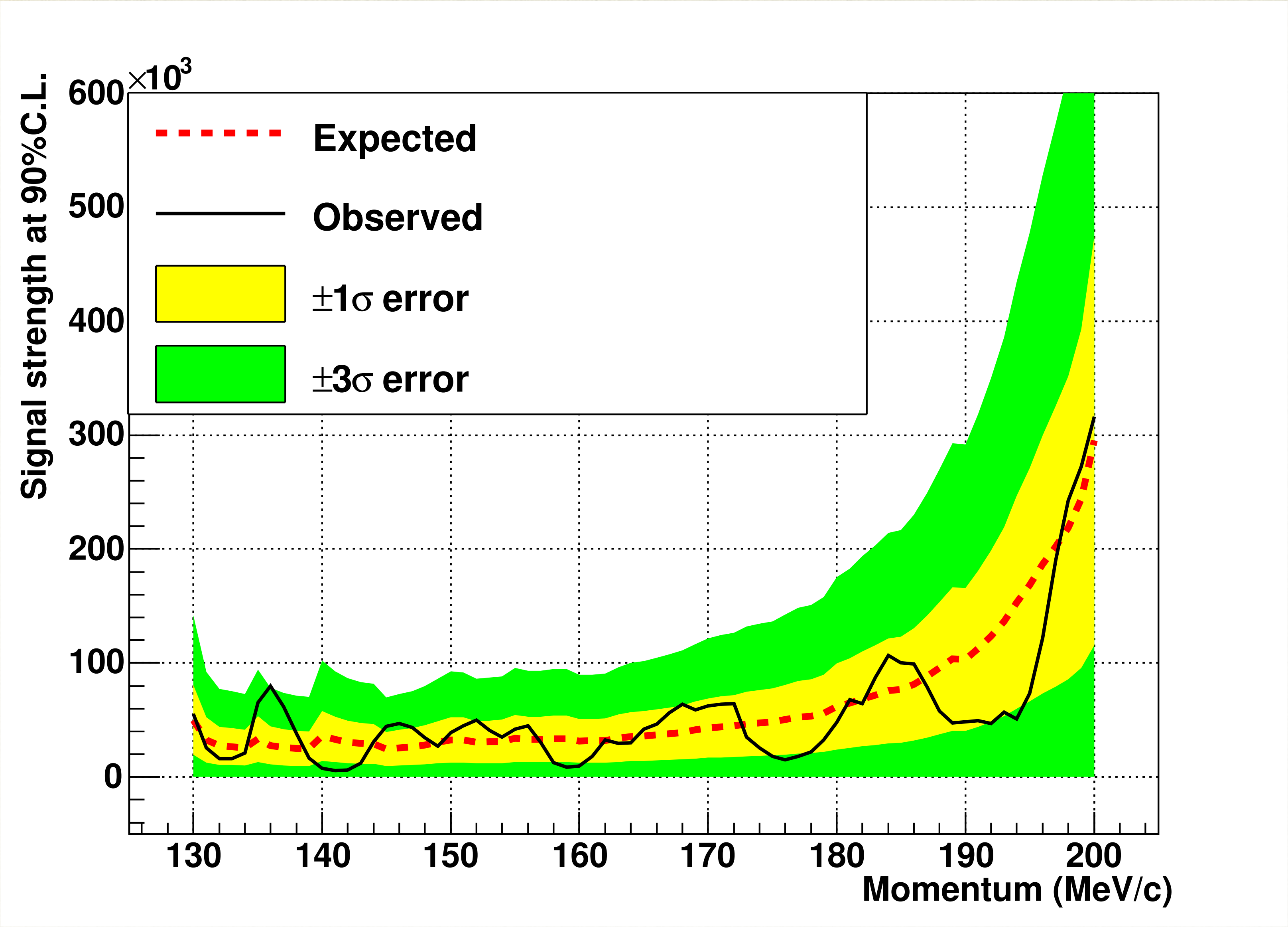
1. *Full data analysis*
2. *Interpretations*
3. *Conclusions*

FULL DATA SAMPLE

after all selection criteria (100% of data)



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

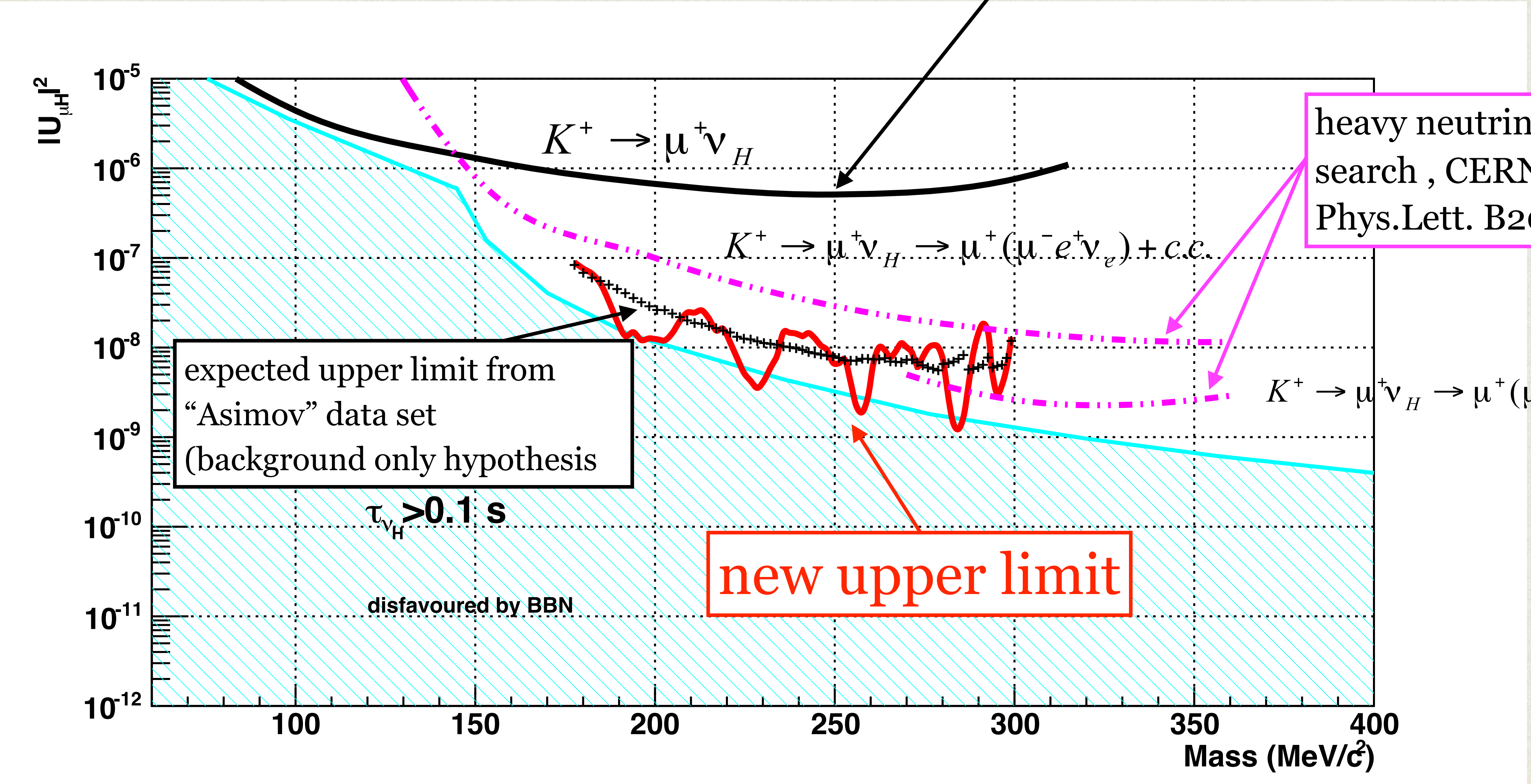
MIXING MATRIX ELEMENT

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

$N_{candidates}$ → μ

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

heavy neutrino decay search , CERN PS191
Phys.Lett. B203, 332(1988)

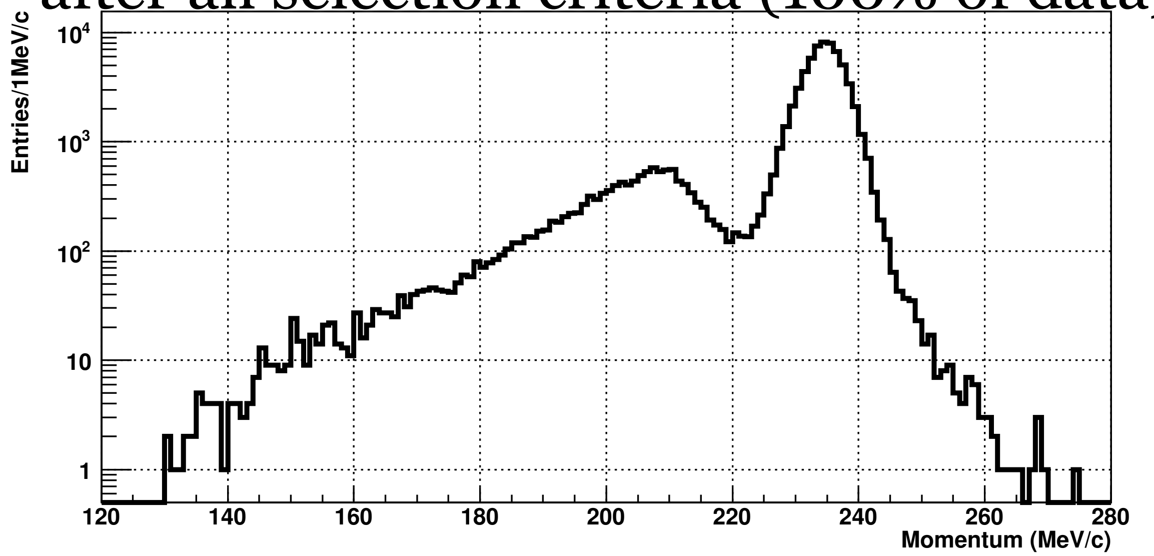


$K^+ \to \mu^+ X$ DECAY

- 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)
  - 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!)

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

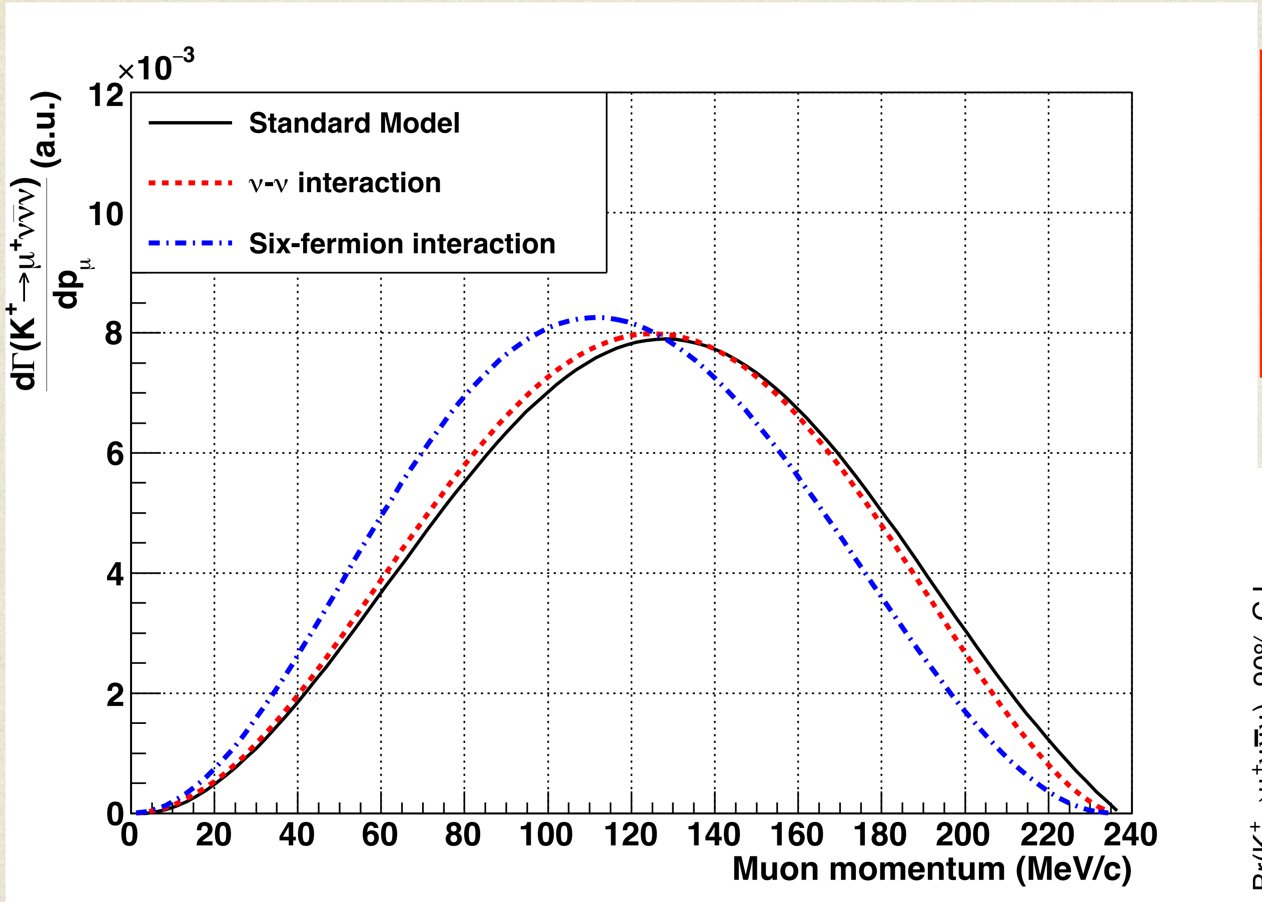
$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} = 7.5 \times 10^{-7} \times \frac{\int_0^{p_\mu^{max}} (d\Gamma/dp_\mu) dp_\mu}{\int_{130}^{175} (d\Gamma/dp_\mu) dp_\mu}$$

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:

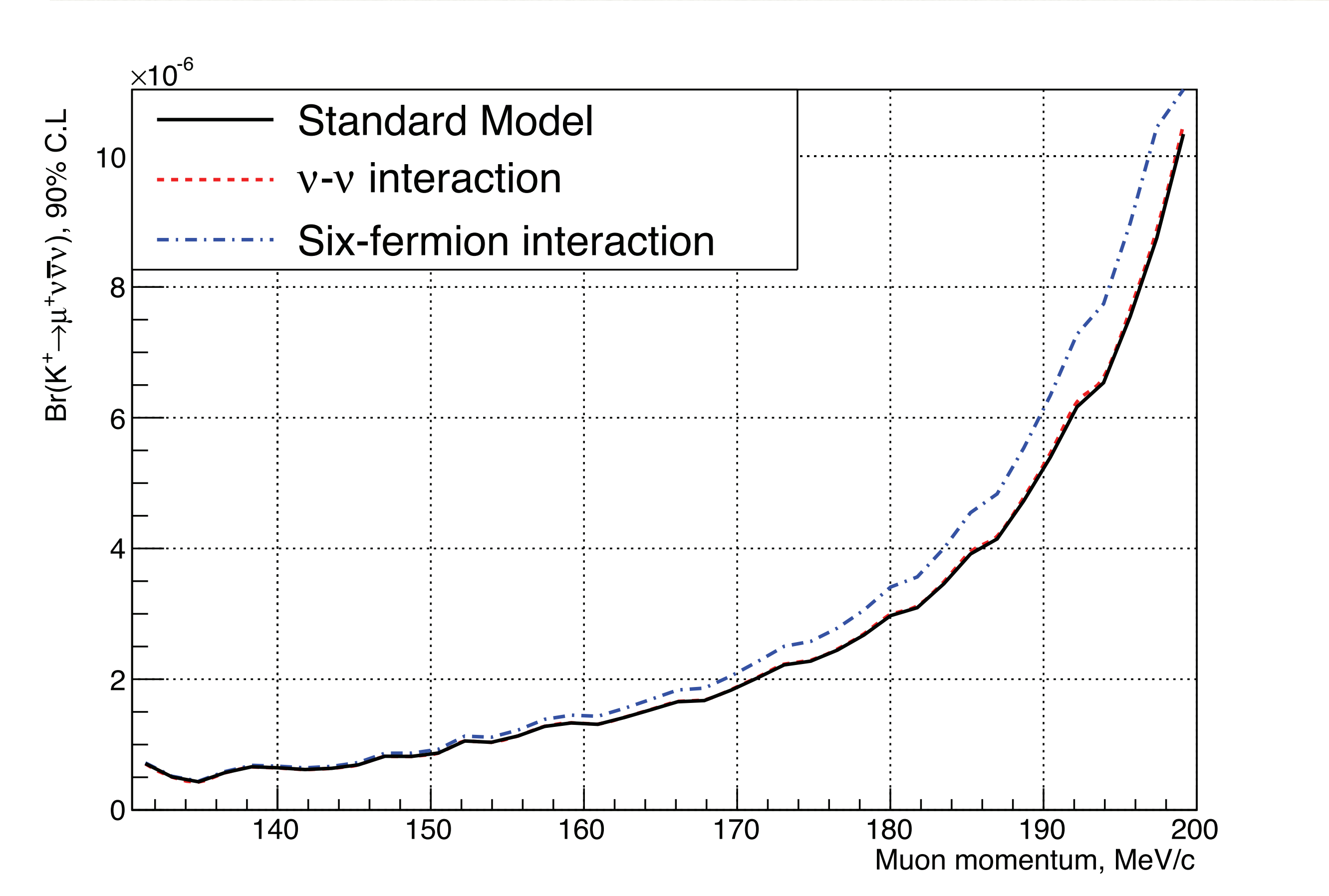
$$\frac{\Gamma(K^+ \to \mu^+ \nu\bar{\nu}\nu)}{\Gamma(K^+ \to \text{all})} = BR_P(K^+ \to \mu^+ + X) \times \times \frac{\int_0^{p_\mu^{max}} (d\Gamma/dp_\mu) dp_\mu}{\int_{130}^{P} (d\Gamma/dp_\mu) dp_\mu}$$

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

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

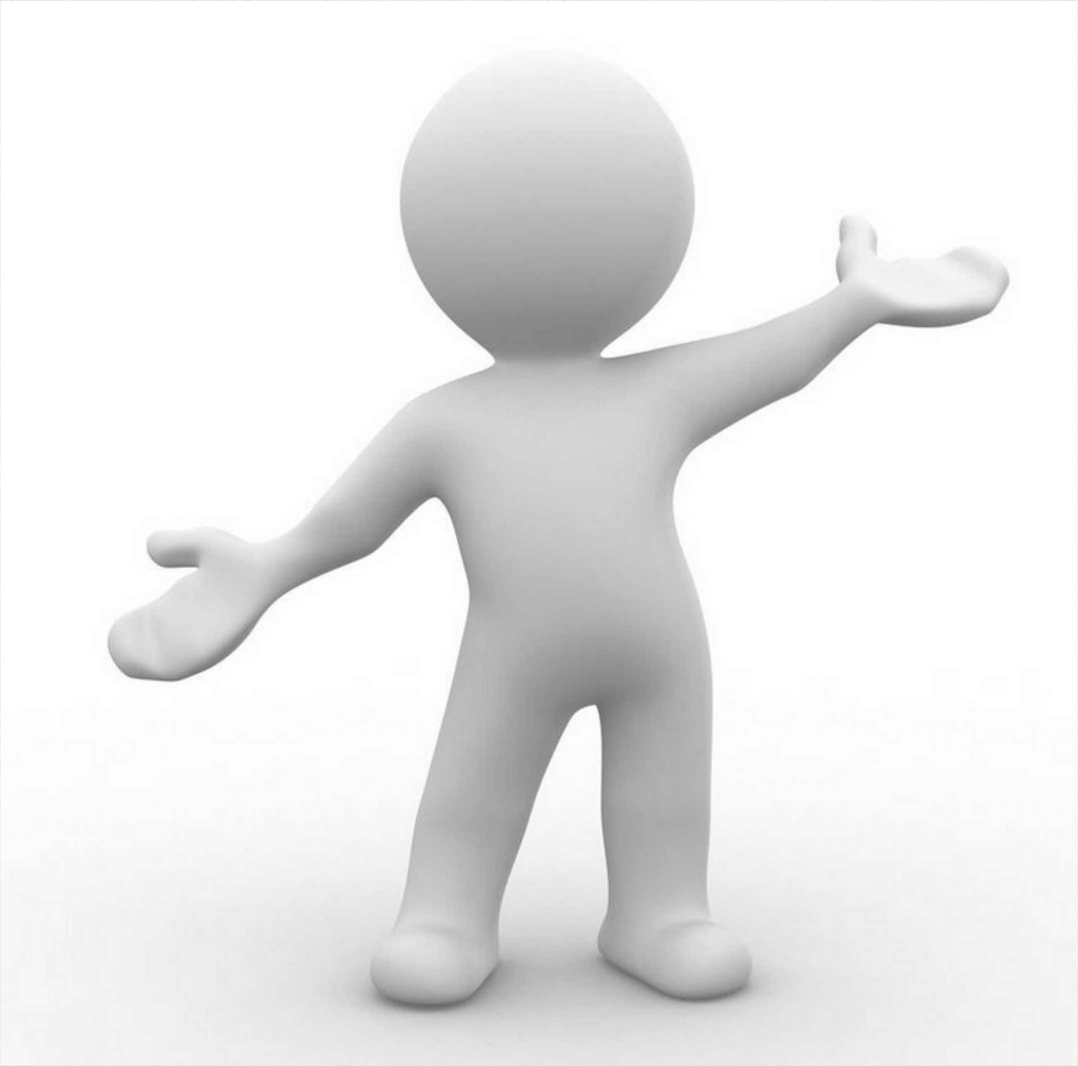
3. Six-fermion interaction:

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

CONCLUSIONS

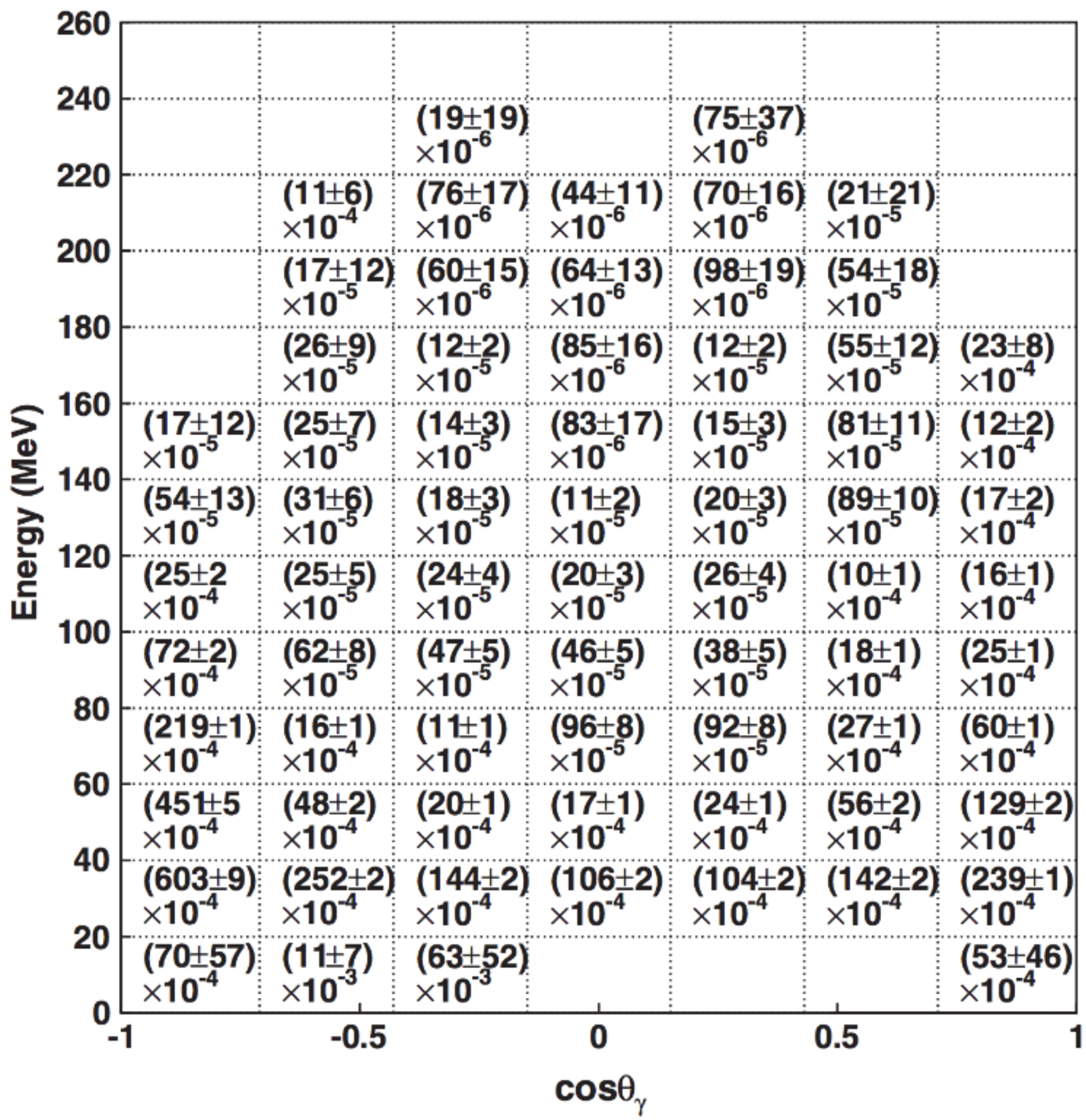
- The heavy neutrino existence in the mass region 175-300 MeV/c^2 was tested using E949 experimental data set
- No evidence was found
- Previous best constraints from CERN PS191 were improved by order of magnitude
- New mixing matrix element $|U_{\mu H}|^2$ upper limit is varying between 10^{-9} and 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!



EXTRA SLIDES

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.

MUON SAMPLES

MC simulation

Roles		$K^+ \to \mu^+\nu_\mu$	$K^+ \to \mu^+\nu_\mu\gamma$	$K^+ \to \mu^+\nu_H$
Acceptance measurement for the $K^+ \to \mu^+\nu_H$ decay	trigger			✓
	L1n		✓	
	Refined Range		✓	
	kin			✓
	beam&target	✓		
	RNGMOM		✓	
	PV	✓		
Background study			✓	
Resolution		✓		✓

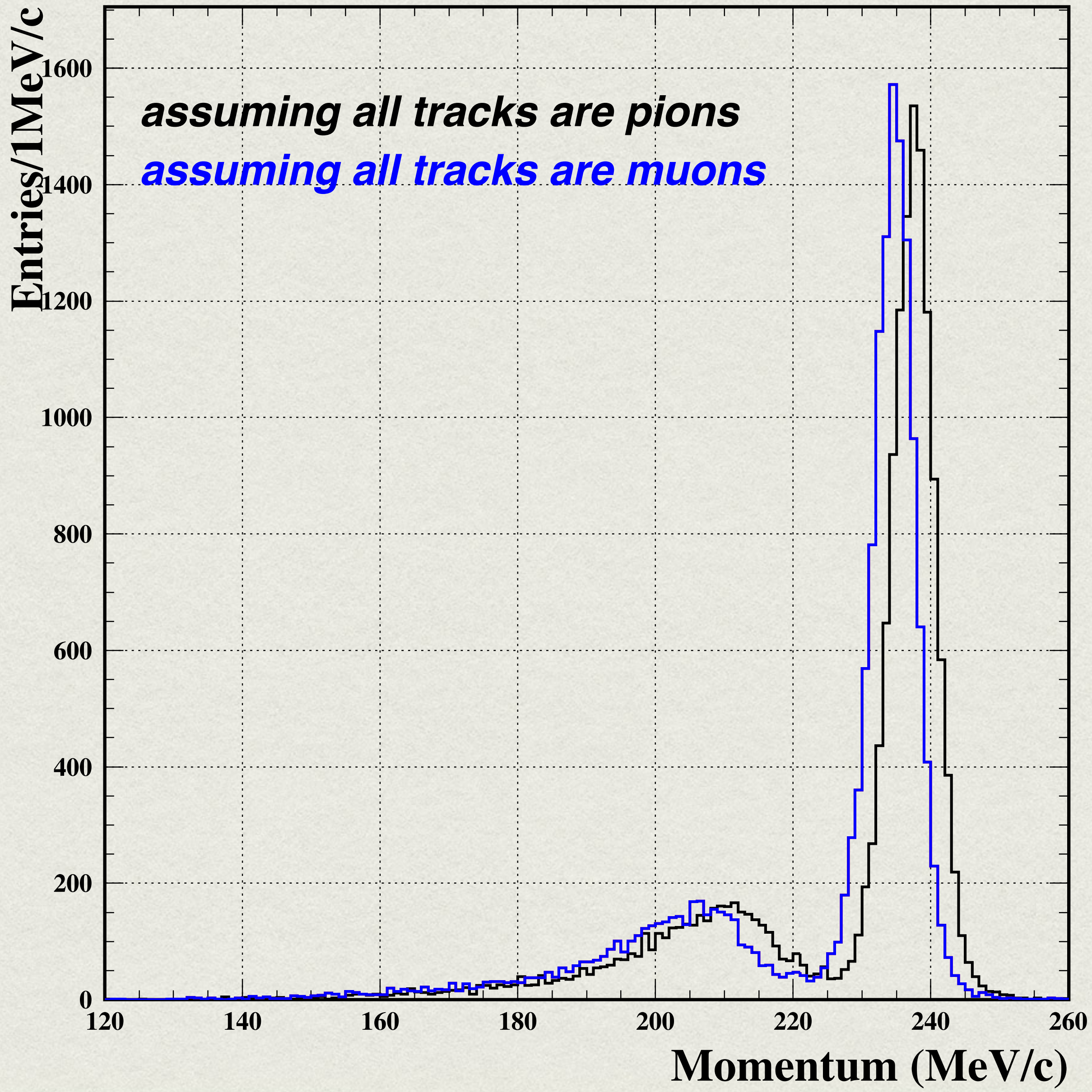
We used muons from the $K_{\mu 2}$ decay to measure the acceptance, in general. Muons from this decay have certain momentum. To study acceptance vs momentum we used $K_{\mu\nu\gamma}$ decay.

ACCEPTANCE MEASUREMENT

<table>
<tr><th colspan="2">Acceptance factors</th><th>$K^+ \to \mu^+ \nu_H$</th><th>$K^+ \to \mu^+ \nu_\mu \gamma$</th><th>$K^+ \to \mu^+ \nu_\mu$</th></tr>
<tr><td colspan="2">f_s</td><td colspan="2">Kπ2(1)</td><td rowspan="2"></td></tr>
<tr><td colspan="2">A_{PRRF}</td><td colspan="2" rowspan="2">π_{scat}</td></tr>
<tr><td colspan="2">$A_{UTCQUAL}$</td><td></td></tr>
<tr><td colspan="2">$\epsilon_{T\bullet 2}$</td><td colspan="3">$Kbeam$</td></tr>
<tr><td colspan="2">$A_{Fid\&Range}$</td><td colspan="2" rowspan="4">MC</td><td rowspan="2"></td></tr>
<tr><td colspan="2">$A_{Kinematic}$</td></tr>
<tr><td colspan="2">$A_{\overline{19_{ct}}}$</td><td>Kμ2</td></tr>
<tr><td colspan="2">$A_{RefinedRange}$</td><td rowspan="2">Kπ2(1)</td></tr>
<tr><td colspan="2">$A_{\pi\to\mu}$</td><td colspan="2" rowspan="2">Kπ2(1)</td></tr>
<tr><td colspan="2">A_{RNGMOM}</td><td>not applied</td></tr>
<tr><td colspan="2">$A_{Beam\&Target}$</td><td colspan="2" rowspan="2">Kμ2</td><td rowspan="3"></td></tr>
<tr><td colspan="2">A_{DELC}</td></tr>
<tr><td rowspan="2">A_{PV}</td><td>Loose</td><td>not applied</td><td>MC</td></tr>
<tr><td>Tight</td><td>Kμ2</td><td>not applied</td><td>not applied</td></tr>
</table>

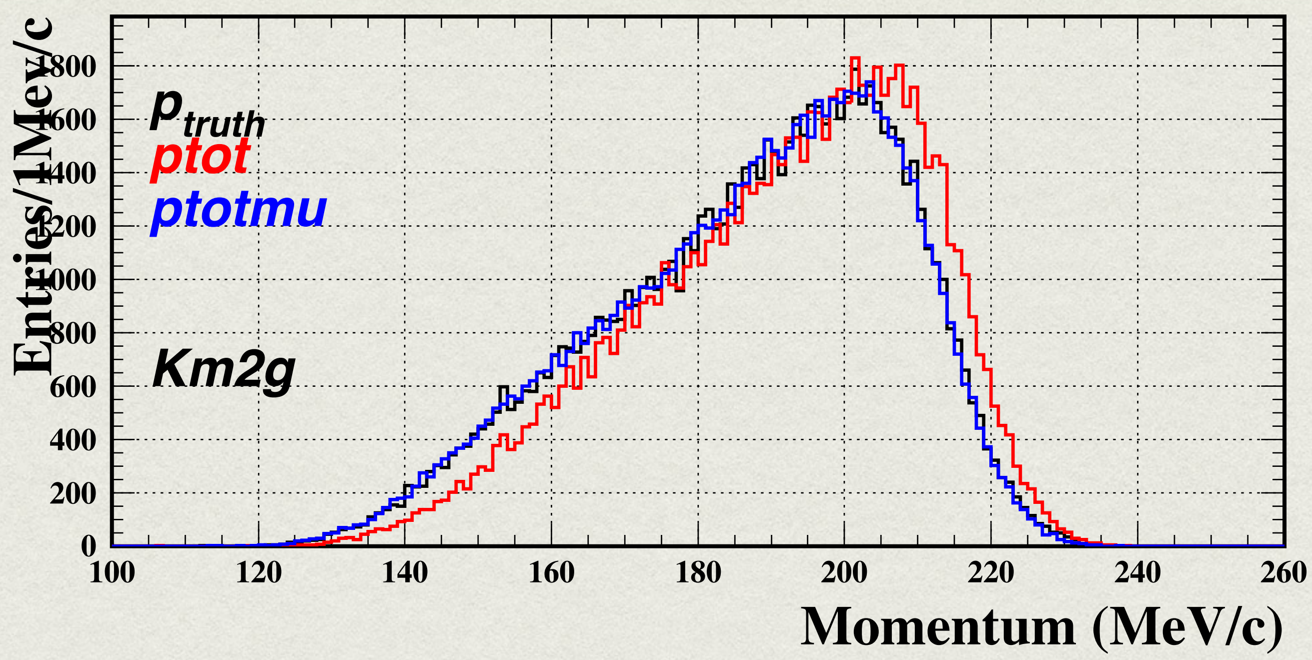
MOMENTUM MEASUREMENT

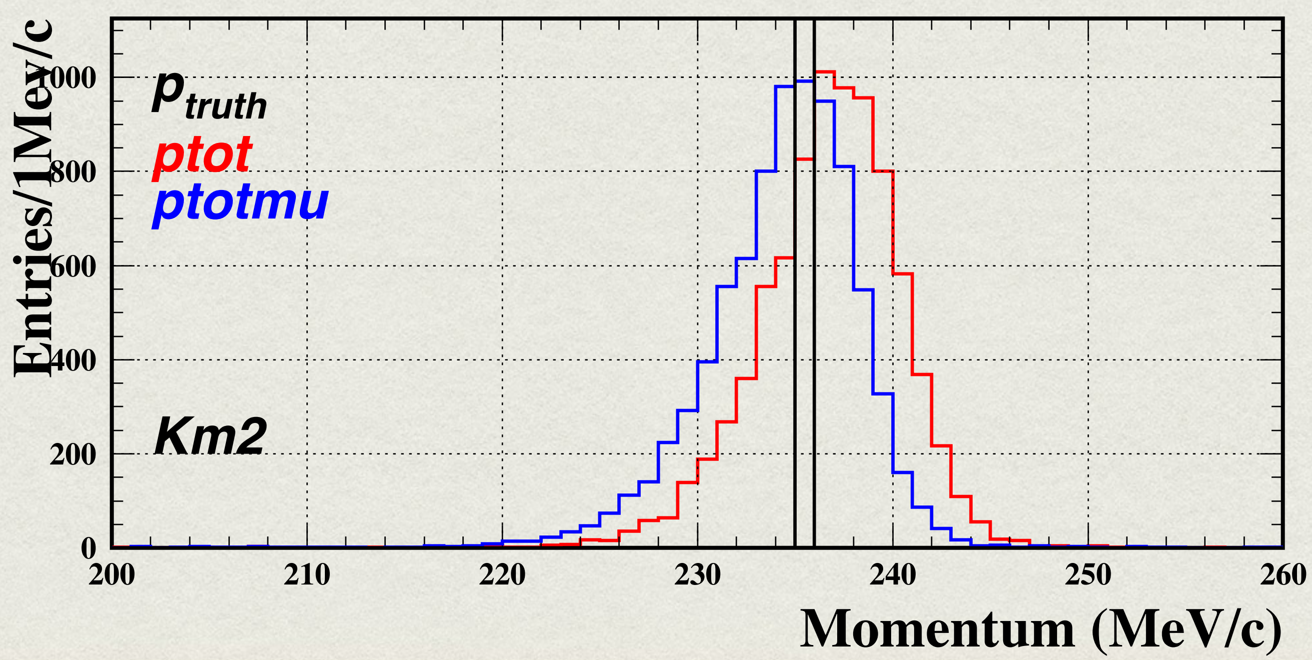
$P = P_{UTC}$ + CORRECTION (energy losses in target, drift chamber)



Muon sample (5% of all data)

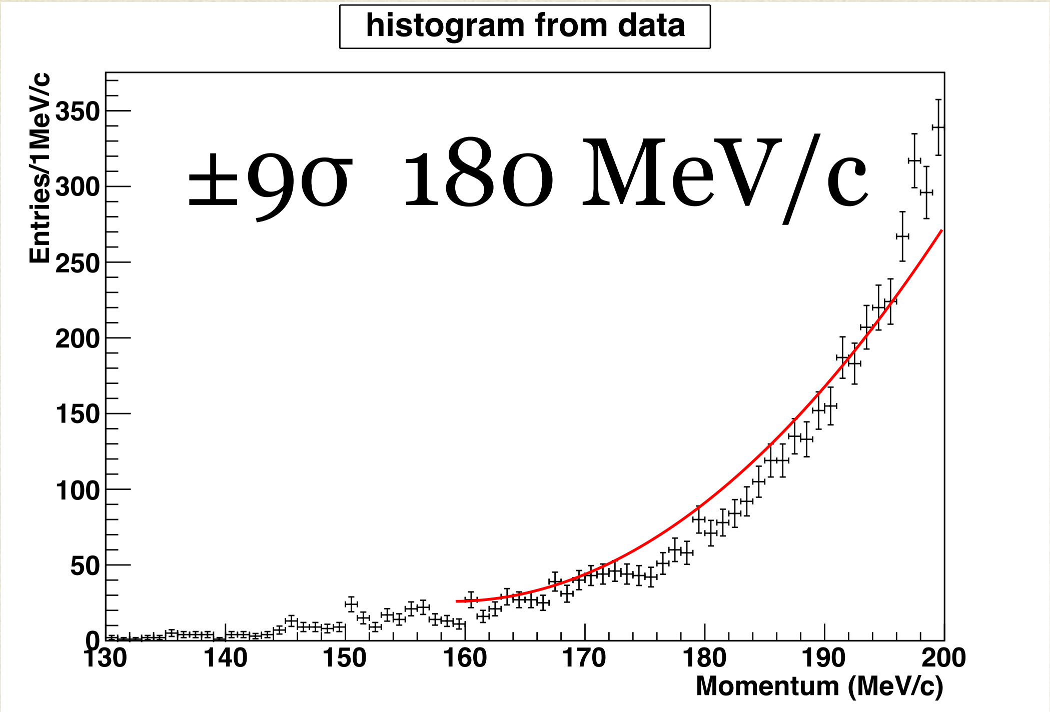
MOMENTUM MEASUREMENT

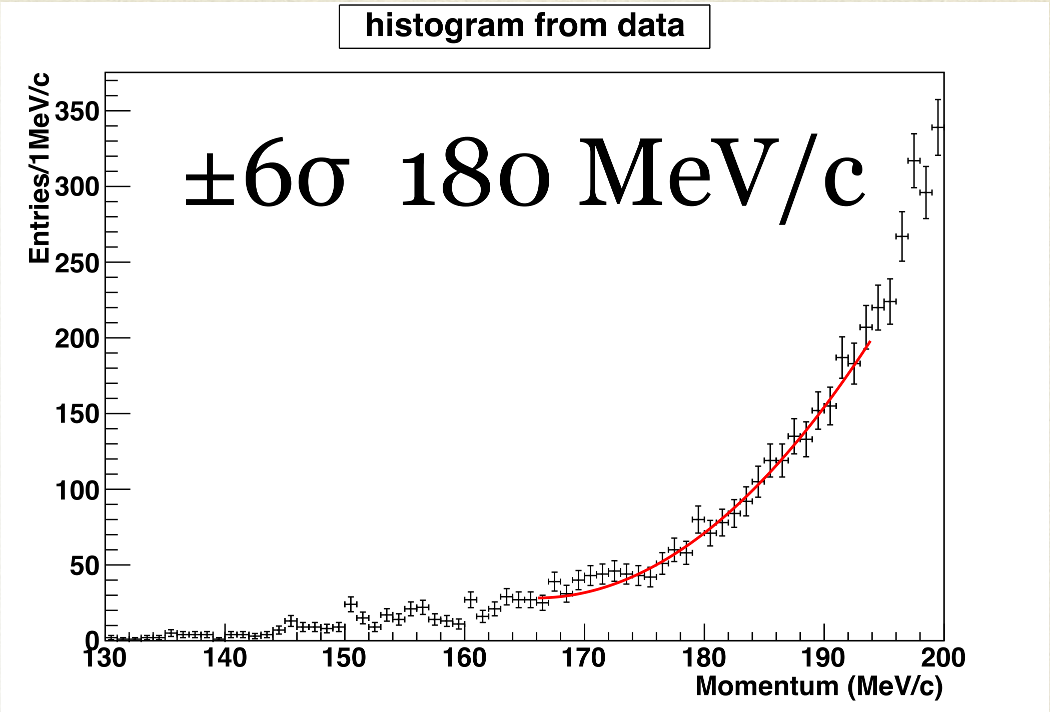


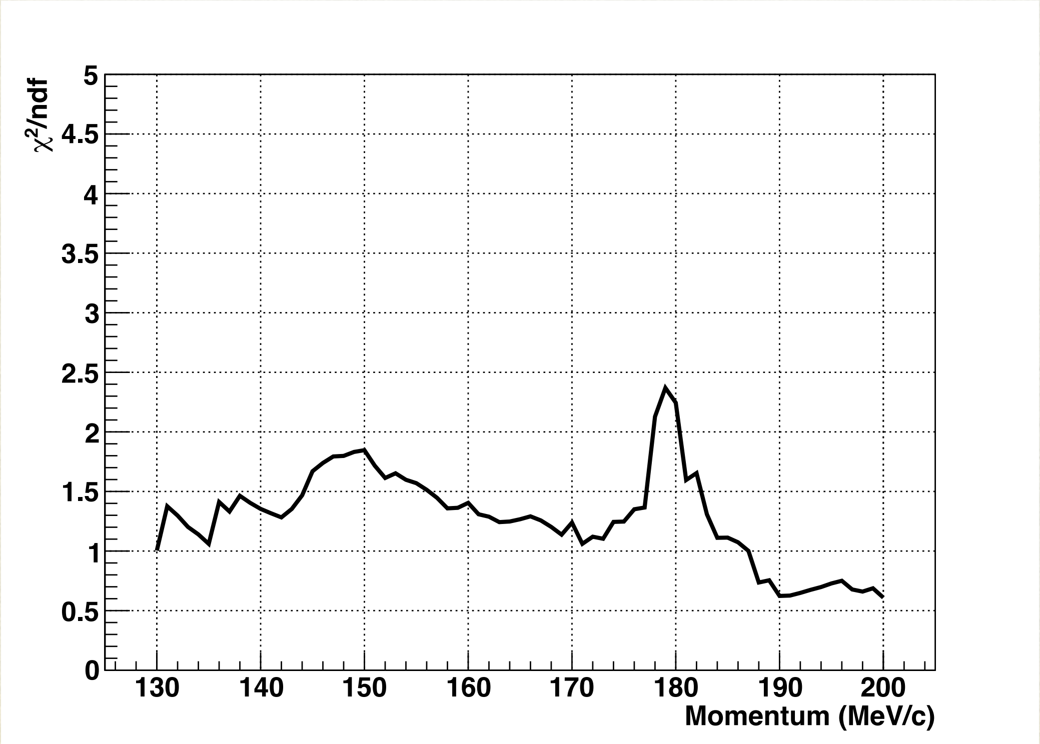


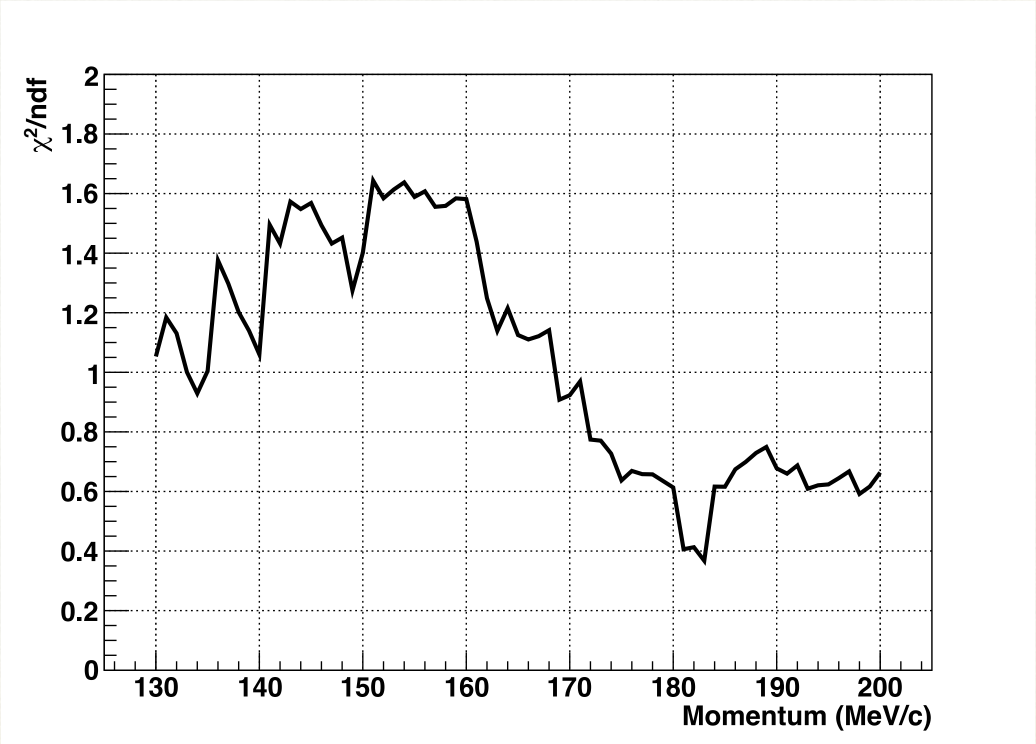
MC simulation

±9σ→ ±6σ


histogram from data
±9σ 180 MeV/c
Entries/1MeV/c
Momentum (MeV/c)


histogram from data
±6σ 180 MeV/c
Entries/1MeV/c
Momentum (MeV/c)

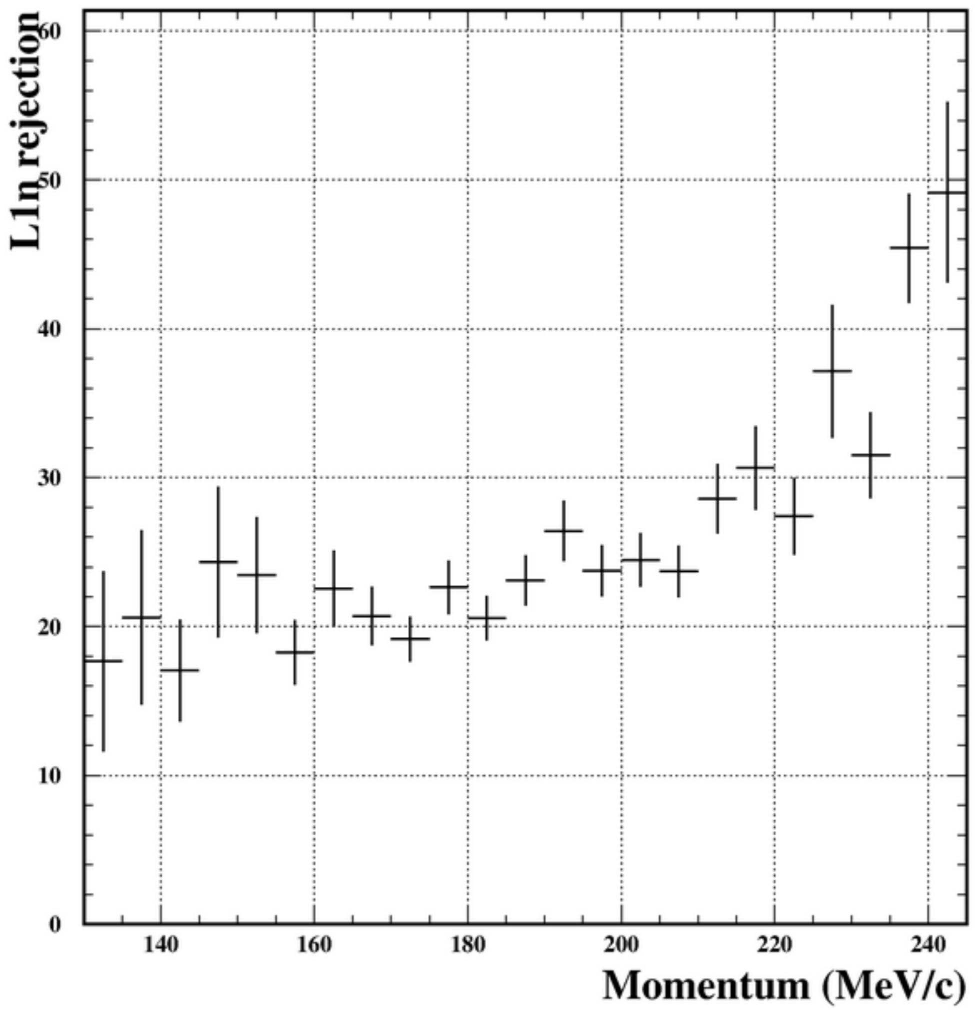

χ^2/ndf
Momentum (MeV/c)


χ^2/ndf
Momentum (MeV/c)

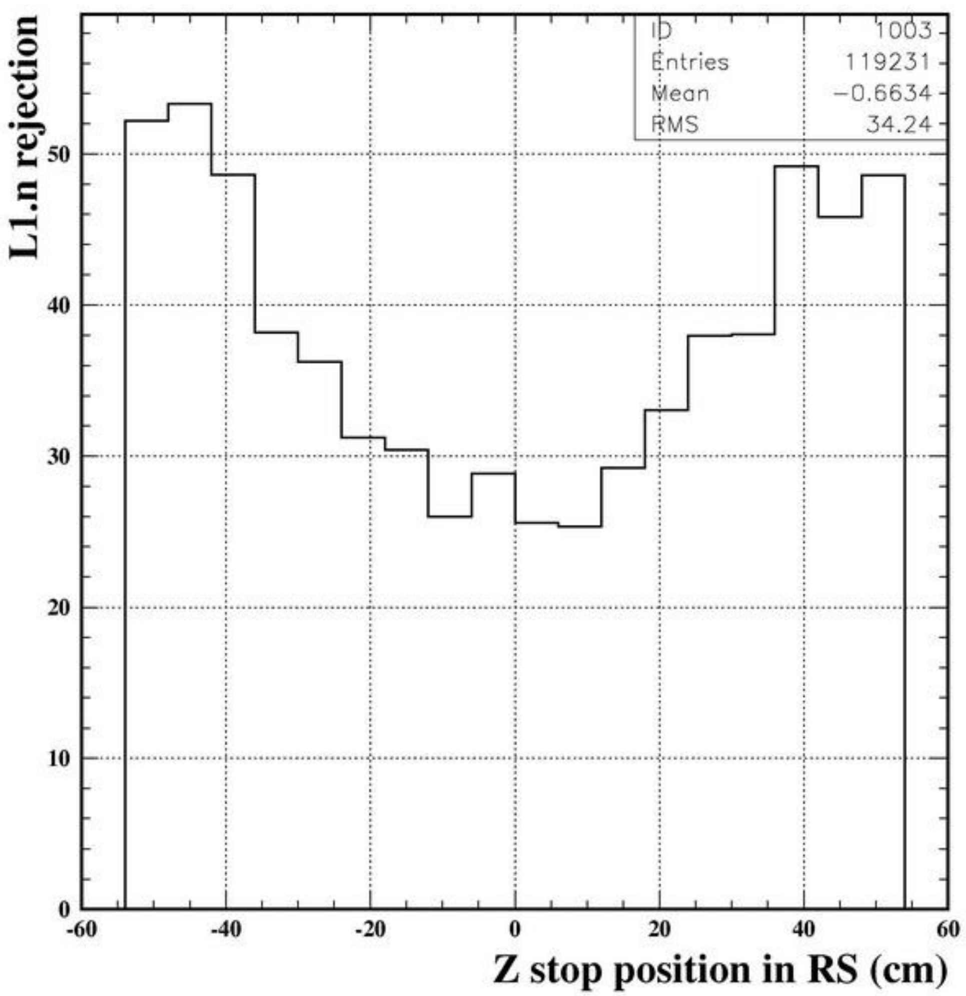
ONLINE PION IDENTIFICATION (L1N)

- Online $\pi \to \mu$ decay requirement:
  - The pulse height (PH) and the area (PA) of the pulse(s) recorded by TDs in the stopping counter are compared. The ratio PH/PA would be smaller for double pulses than for a single pulse
- Requirements for stopping counter finding:
  - Events are rejected if coincident hits are detected in a RS near the stopping counter
  - Events are rejected if one of two adjacent hextant hits is not due to a charged track

ONLINE PION IDENTIFICATION (L1N)

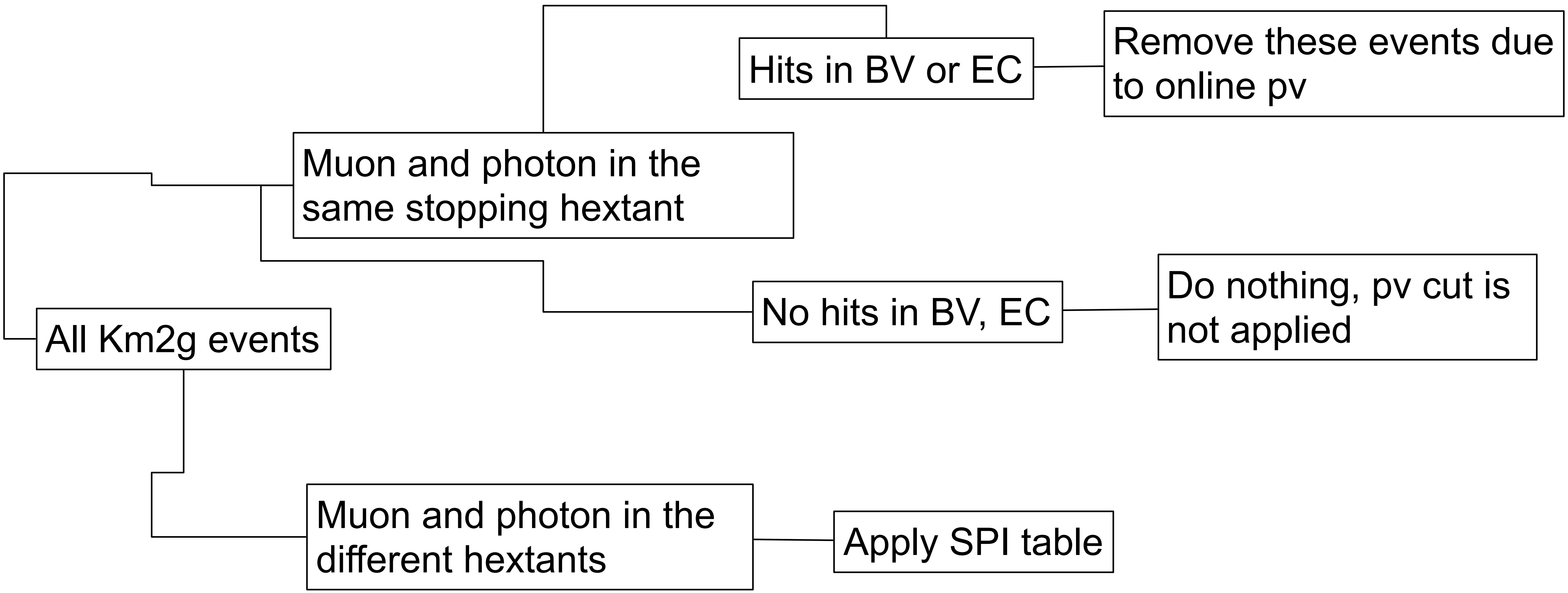


Use monitor trigger (KP21) and some offline cuts to select pure muon sample: KP21, UTCQUAL, COS3D, ZFRF, ZUTOUT, PRRF, B4DEDX, PV90, RNGMOM. No TD cuts



We use Z-dependence of L1n cut to emulate it in MC

PV acceptance measurement



Use MC simulation of the Km2g decay within pnn1 or pnn2 or pnn12 trigger w/o online photon veto

Thresholds in BV and EC are 5 MeV and 20 MeV respectively. For 140<ptotmu<200 MeV/c gamma energy E>20 MeV