Neutron detection and distinguishing high energy anti-neutrinos at Super-Kamiokande

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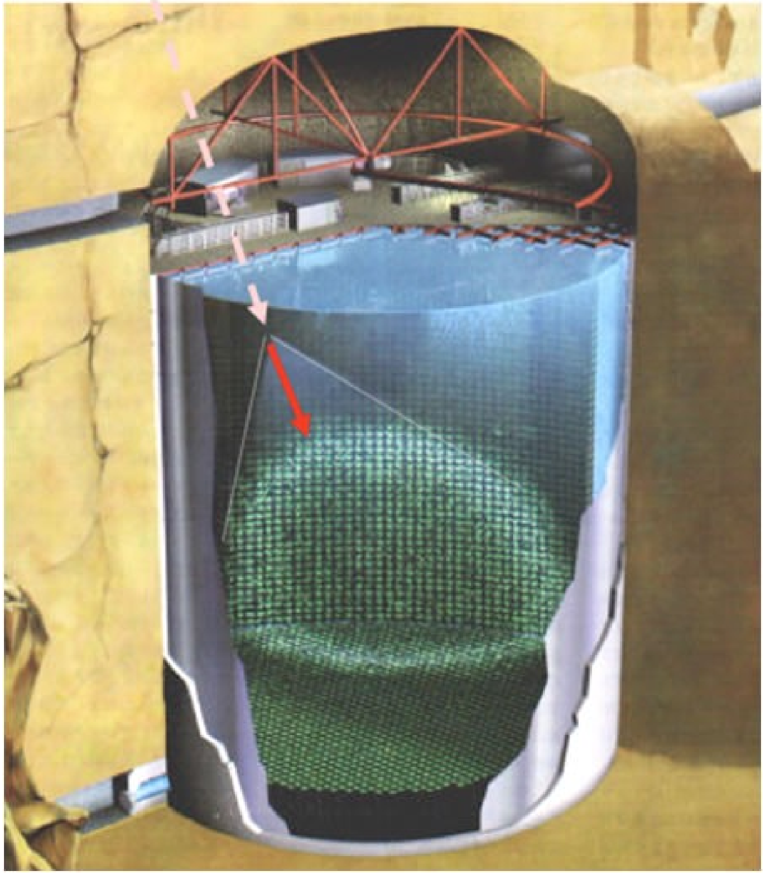
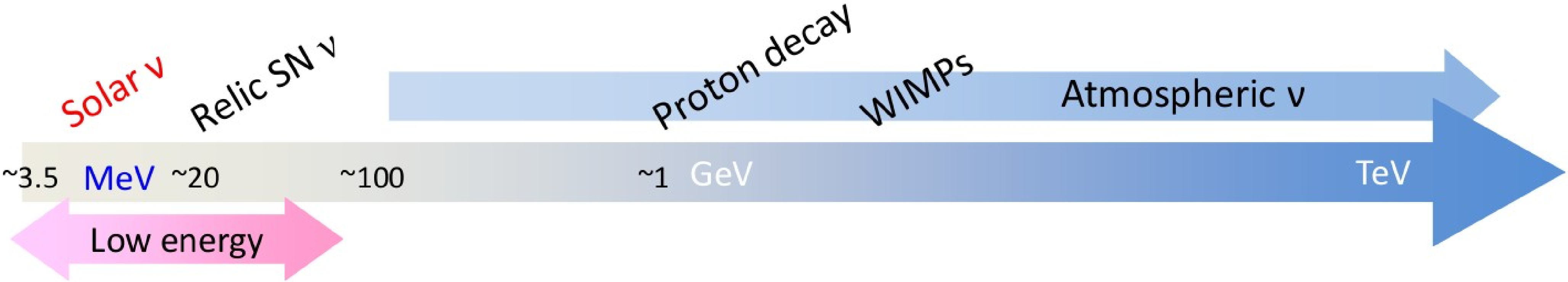
Super Kamiokande

- Water Cerenkov particle detector, buried 1000m below Mt. Ikenoyama in Gifu-ken.
- 50,000 tons of pure water, ~13,000 PMTs.
- Observe ~8 atmospheric neutrino events in fiducial volume / day.
- Able to study a variety of physics at different energy ranges





Solar ν

Relic SN ν

Proton decay

WIMPs

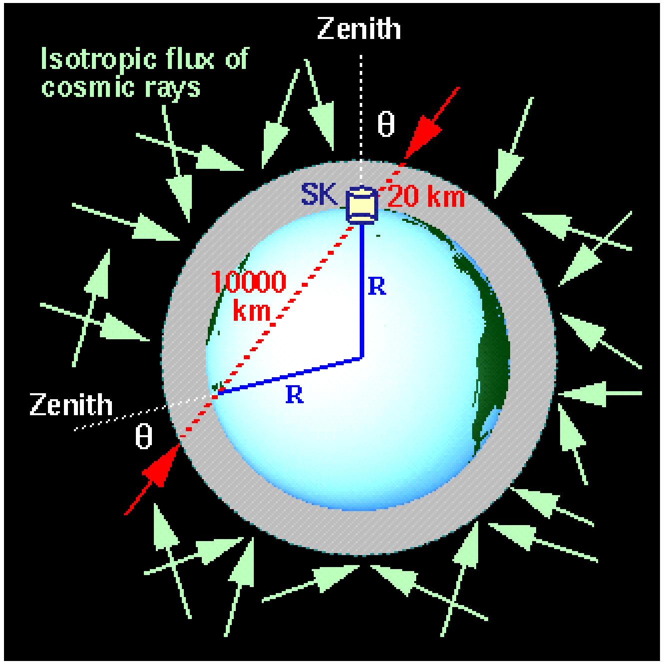
Atmospheric ν

~3.5 MeV ~20 ~100 ~1 GeV TeV

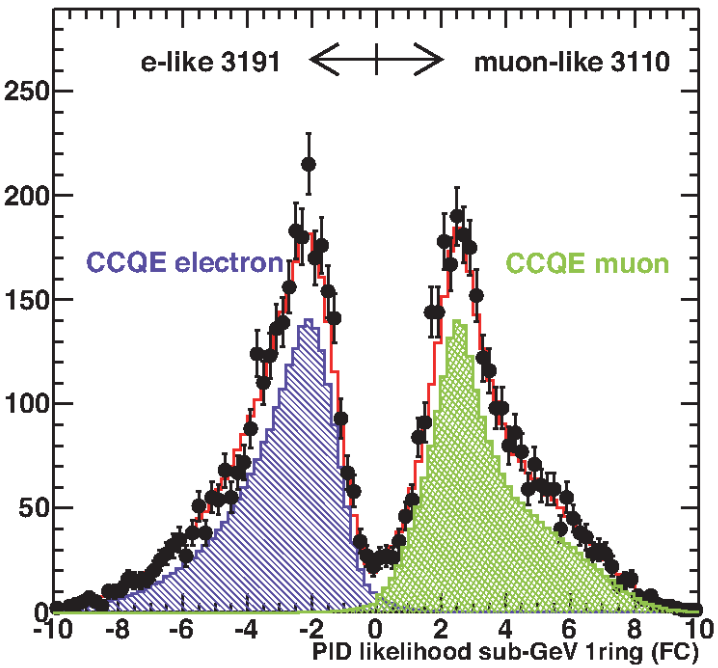
Low energy

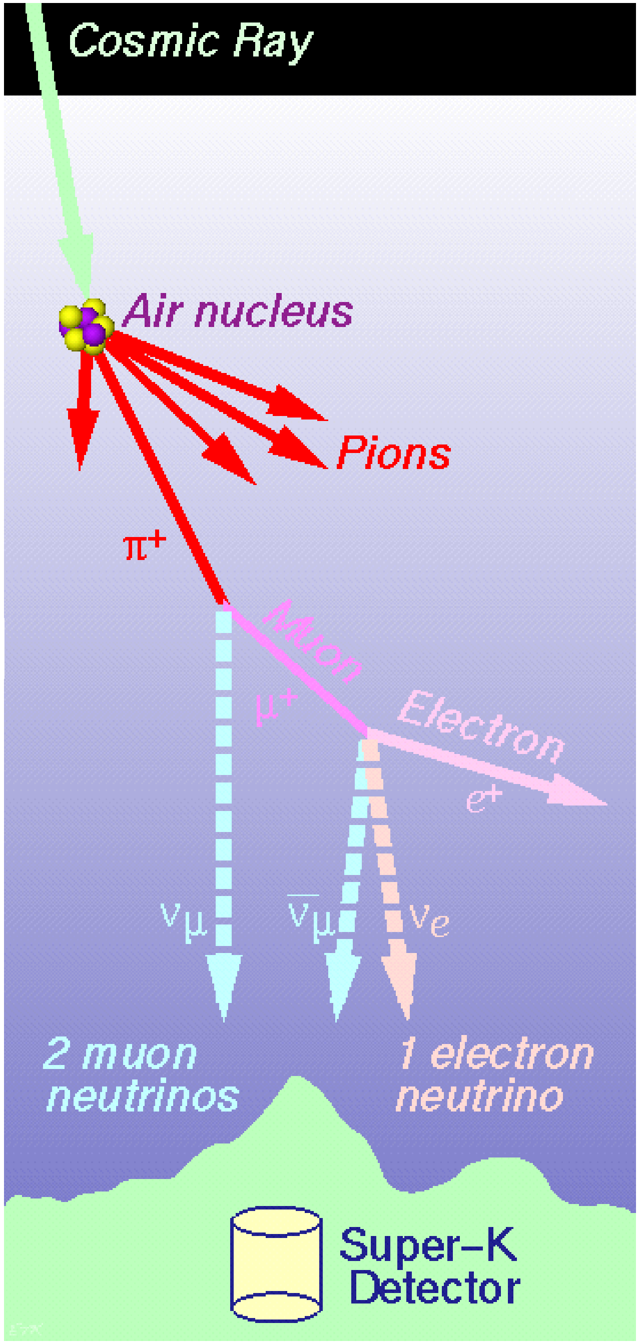
Atmospheric Neutrinos

- Electron and Muon neutrinos are produced in the atmosphere after cosmic ray impacts.
- We are able to distinguish electron and muon neutrinos by looking at cerenkov ring pattern.
- It is more difficult to distinguish neutrino from anti-neutrino.

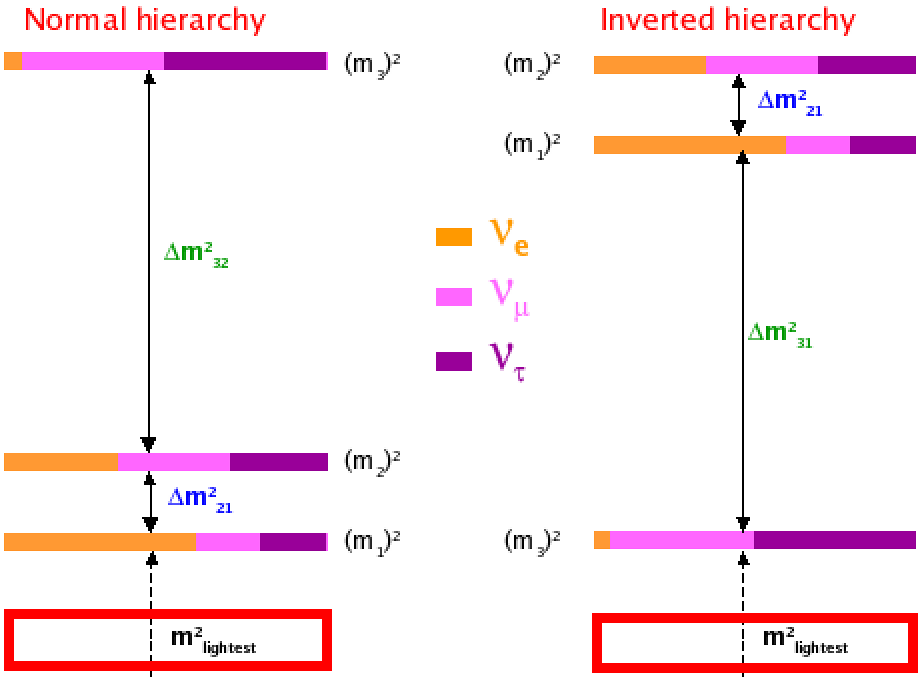


Muon vs Electron neutrino identification

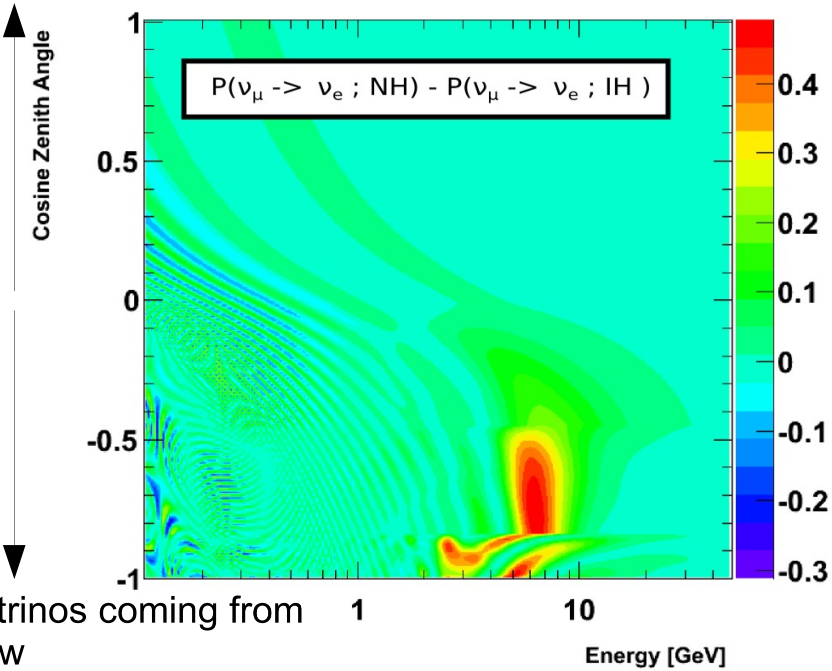




Motivation: Mass Hierarchy



Neutrinos coming from above



Neutrinos coming from below

- We know the difference in neutrino mass, we do not know which mass state is the lightest.
- As neutrinos pass through the earth, the matter effect will enhance either electron neutrino, or electron anti-neutrino signal, depending on which hierarchy is true.
- So the more we can distinguish neutrino and anti-neutrino, the better sensitivity we have to neutrino mass hierarchy.

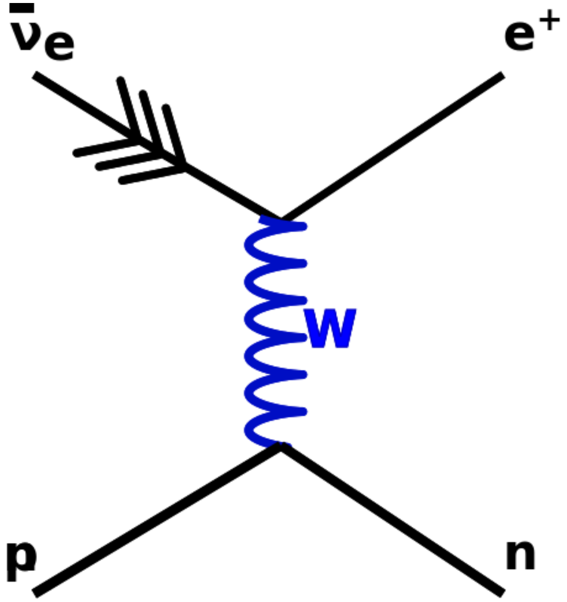
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - {A_{CC}}/{\Delta m_{31}^2}\right)^2 + \sin^2 2\theta_{13}}$$

If Anti-neutrino: $A_{cc} \rightarrow -A_{cc}$

If inverted hierarchy: $\Delta m^2 \rightarrow -\Delta m^2$

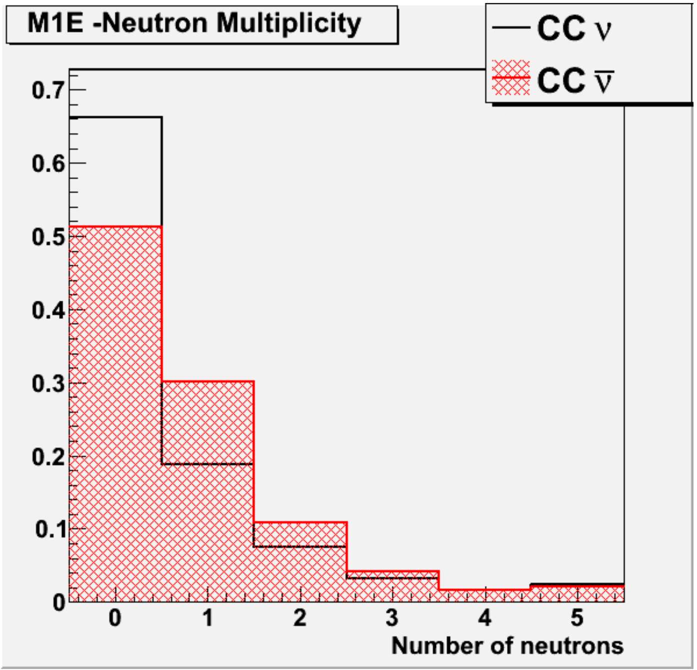
To determine which hierarchy is correct, we fit assuming normal hierarchy, and separately inverted hierarchy, and then look at ΔX2 between the two. Currently ΔX2 = 1.5, favouring inverted hierarchy.

Neutrons and Anti-neutrinos



- In a simple charged current quasi-elastic interaction, an anti-neutrino will produce a neutron, but a neutrino will not.
- Therefore if we can detect neutrons, we have some sensitivity to neutrino type.
- However, in high energy interactions, many secondary neutrons are produced for all neutrinos, so the separation is not perfect.

For >1GeV, electron-like neutrinos, the predicted number of neutrons detected for **Neutrino (black)** and **Anti-neutrino (red)**

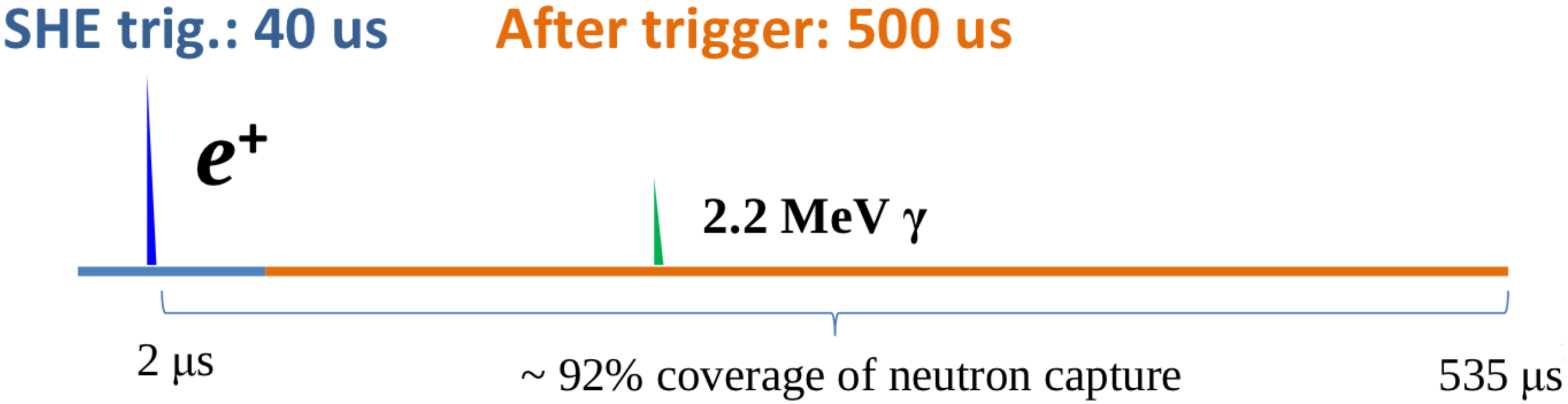


Detecting neutrons

- Almost 100% of neutrons are captured by hydrogen, and release 2.2MeV gamma ray.

$$n+p\rightarrow d+\gamma\left(2.2\text{MeV}\right);\mathit{capture\ lifetime}=206.3\mu\text{s}$$

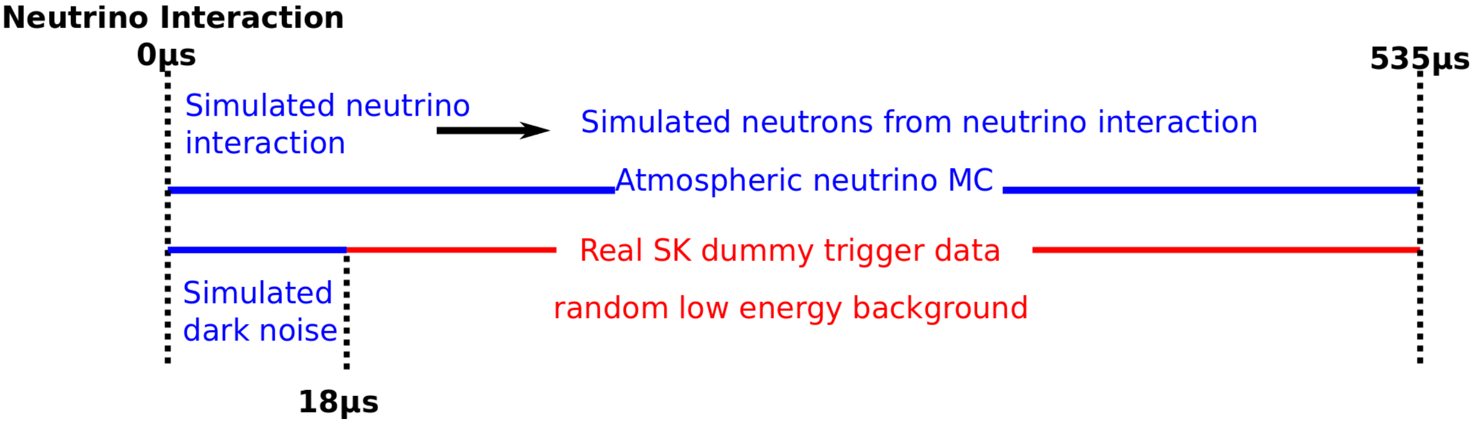
- A forced trigger period of 500µs was added after the initial high energy neutrino trigger.



- 2.2MeV signal is still difficult to detect at SK – usually seen as ~5-8 photomultiplier (PMT) hits.

Neutron MC

Random low energy events are not well simulated by our MC, so I used a hybrid Neutrino MC (for neutrino interaction + neutron signal), with real dummy trigger data applied over it (for low energy backgrounds).



Neutrino Interaction

0μs

535μs

Simulated neutrino interaction

Simulated neutrons from neutrino interaction

Atmospheric neutrino MC

Real SK dummy trigger data

Simulated dark noise

random low energy background

18μs

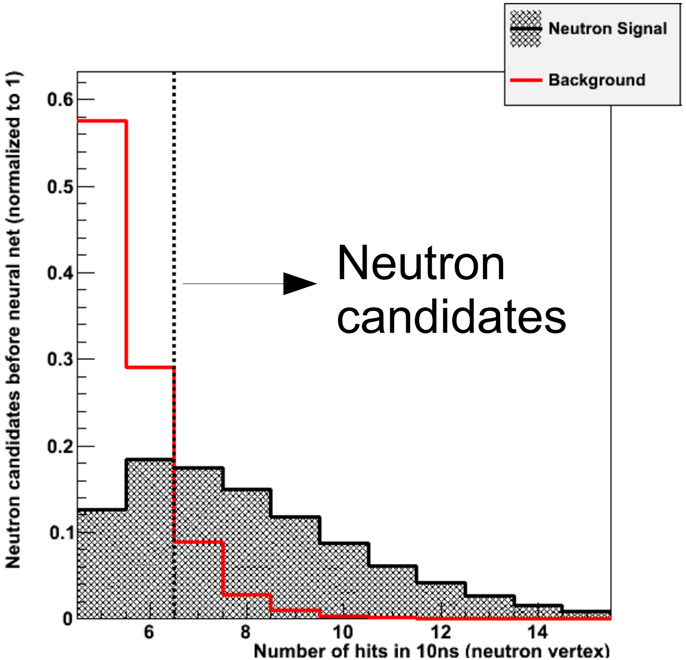
- Simulated dark noise is kept up until 18μs.
  - This is to keep all other Atmospheric neutrino analysis mostly unaffected.
  - <0.1% of muons remain after 18μs, so a small amount of decay electron are affected.
  - There is an electronic after-pulse that can occur in photo-multiplier tubes up till 18μs after the neutrino interaction, which causes significant background to neutron tagging. Therefore it was decided to only search for neutrons after 18μs.

Selecting neutrons (1)

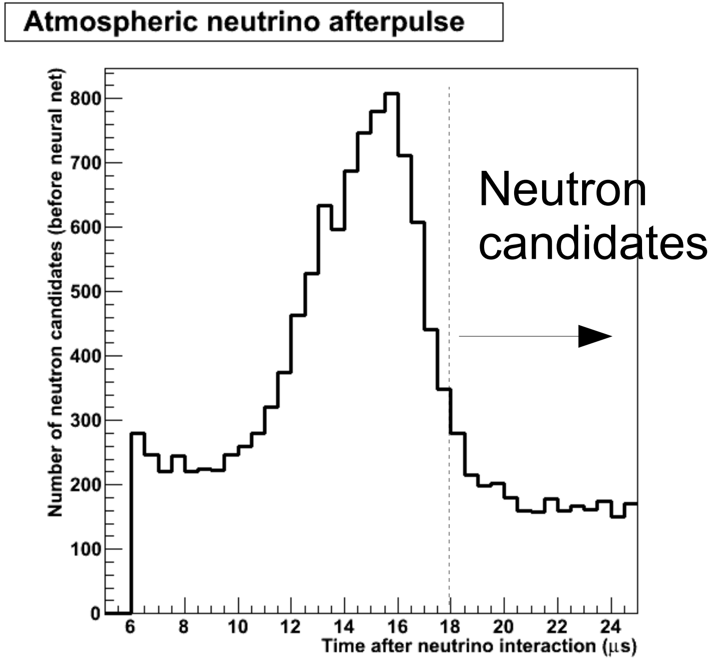
- To find neutrons, we search for peaks of hits, clustered in 10ns (N10 = number of hits in 10ns).
- Initially we must time of flight correct hits to the neutrino vertex, and find initial candidates.
- However, in high energy atmospheric neutrino interactions, the neutron may travel >1m from the neutrino interaction vertex.
- So after the initial selection, we search for an improved vertex, recalculate N10 using this, and then select the final candidates

	Remaining neutrons	BG / Event
Candidate Selection	41%	2.7

Cut all candidates < 18μs, to remove background from neutrino interaction



Neutron candidates

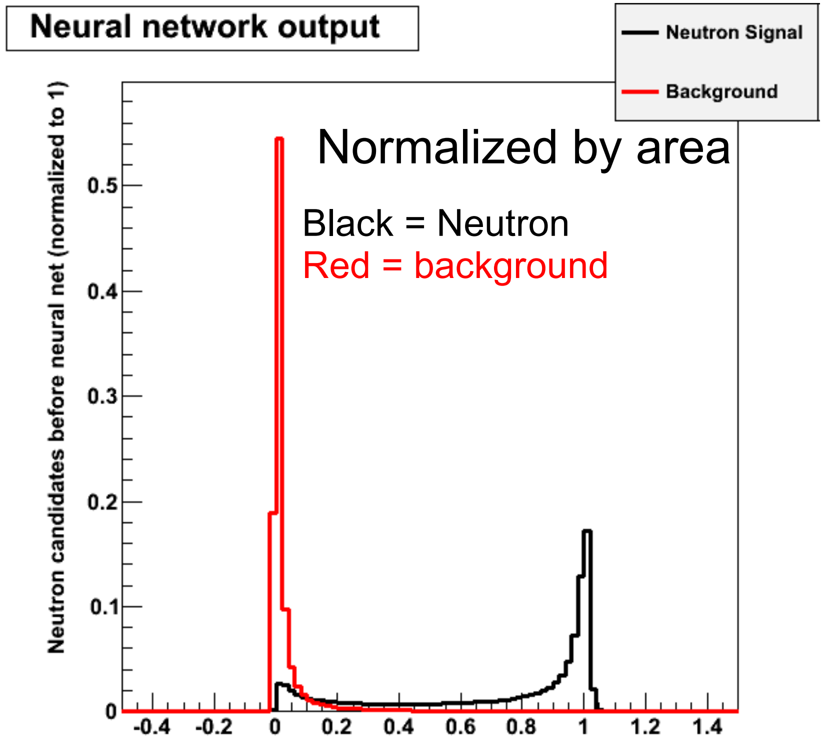


Atmospheric neutrino afterpulse

Neutron candidates

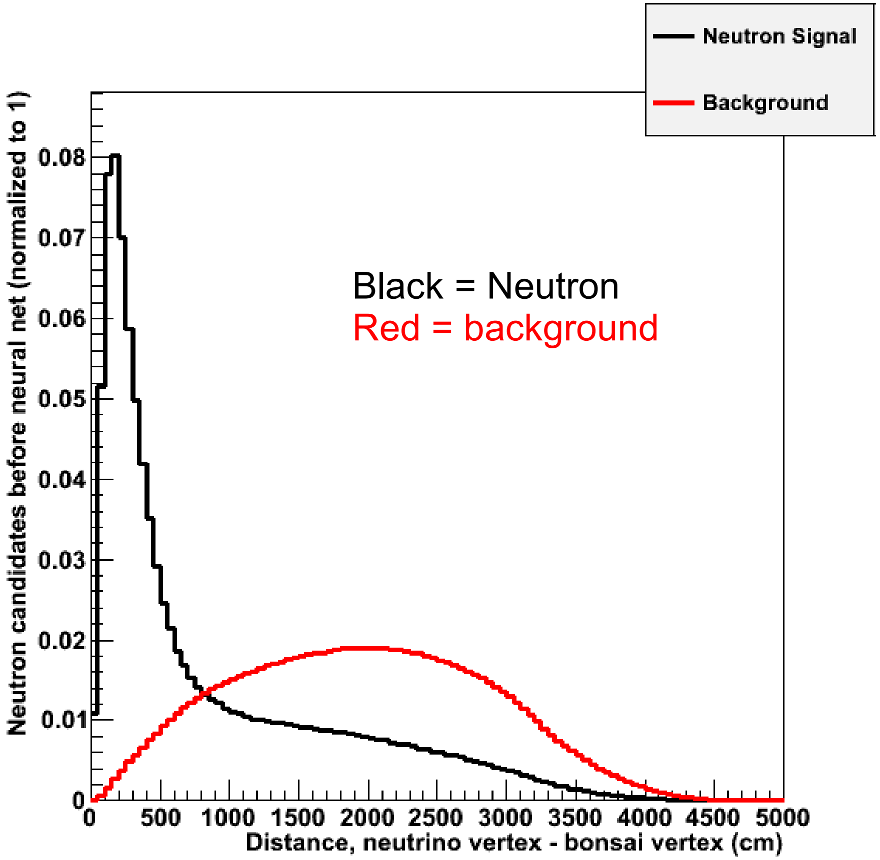
Selecting neutrons (2)

- After candidate selection, 28 variables are fed into a neural net to select final neutrons. Some important variables are:
  - Distance between fitted neutrino vertex and fitted candidate vertex.
  - Reconstructed energy of candidate.
  - T-rms of the candidate hits.



Normalized by area

Black = Neutron
Red = background



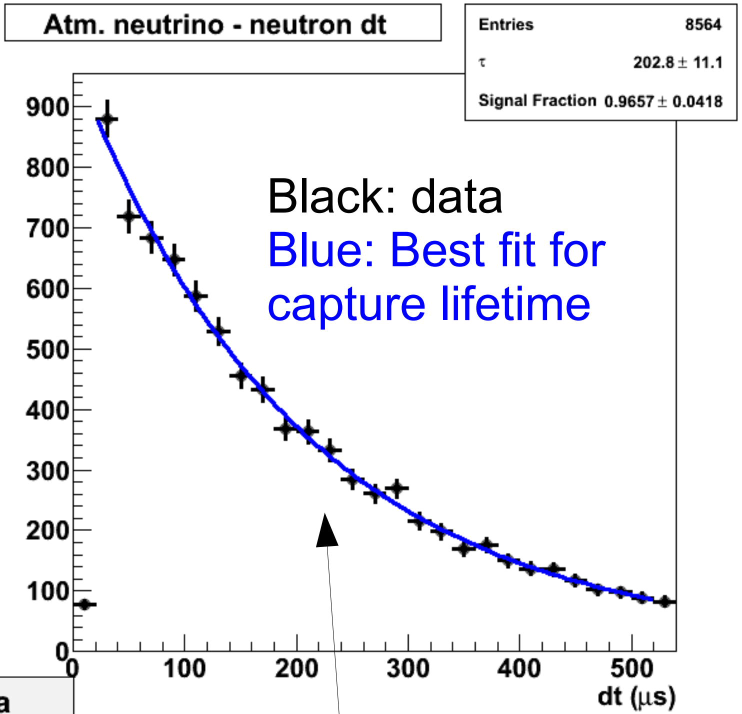
Black = Neutron
Red = background

	Detection Efficiency	BG / Event
Final Selection	**28.1%**	0.02

Neutrons from Atmospheric Neutrinos

- Atmospheric neutrino SK4 dataset was used for this study (From November 2008) -1608.9 days of data.

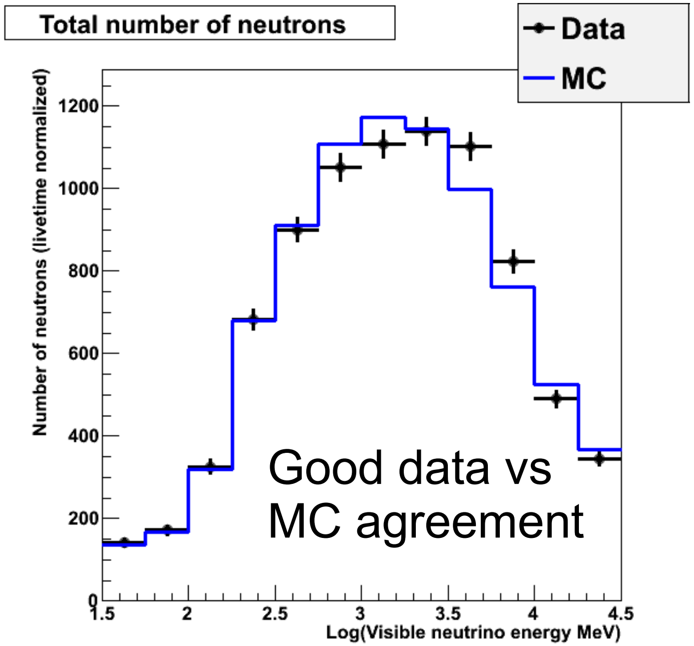
Visible energy 31MeV < 31GeV	Data	MC
Total Neutrons	8284	8293.7
Total Events with any neutron	4382	4203.2



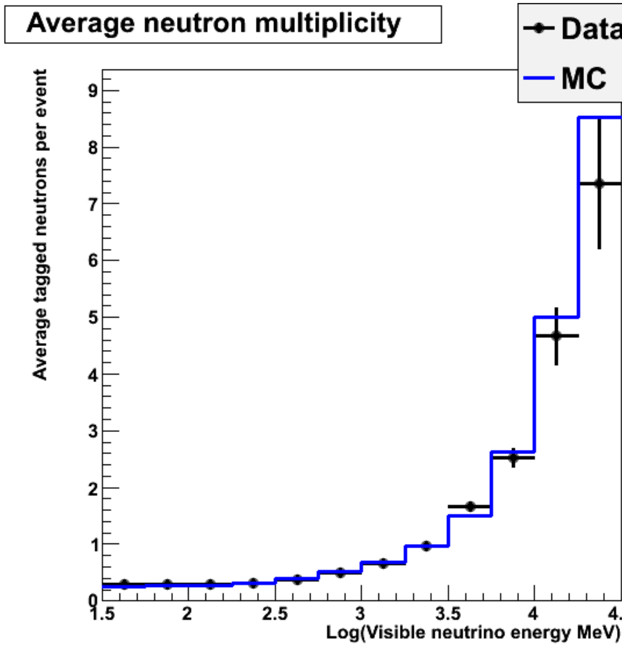
Black: data
Blue: Best fit for capture lifetime

Neutron capture lifetime fits to 202.8±11.1μs.

Good agreement with previous measurement at 206.3±5.1μs
(Stooksberry, Crouch, Phys Rev 114 no.6 1561-1563)

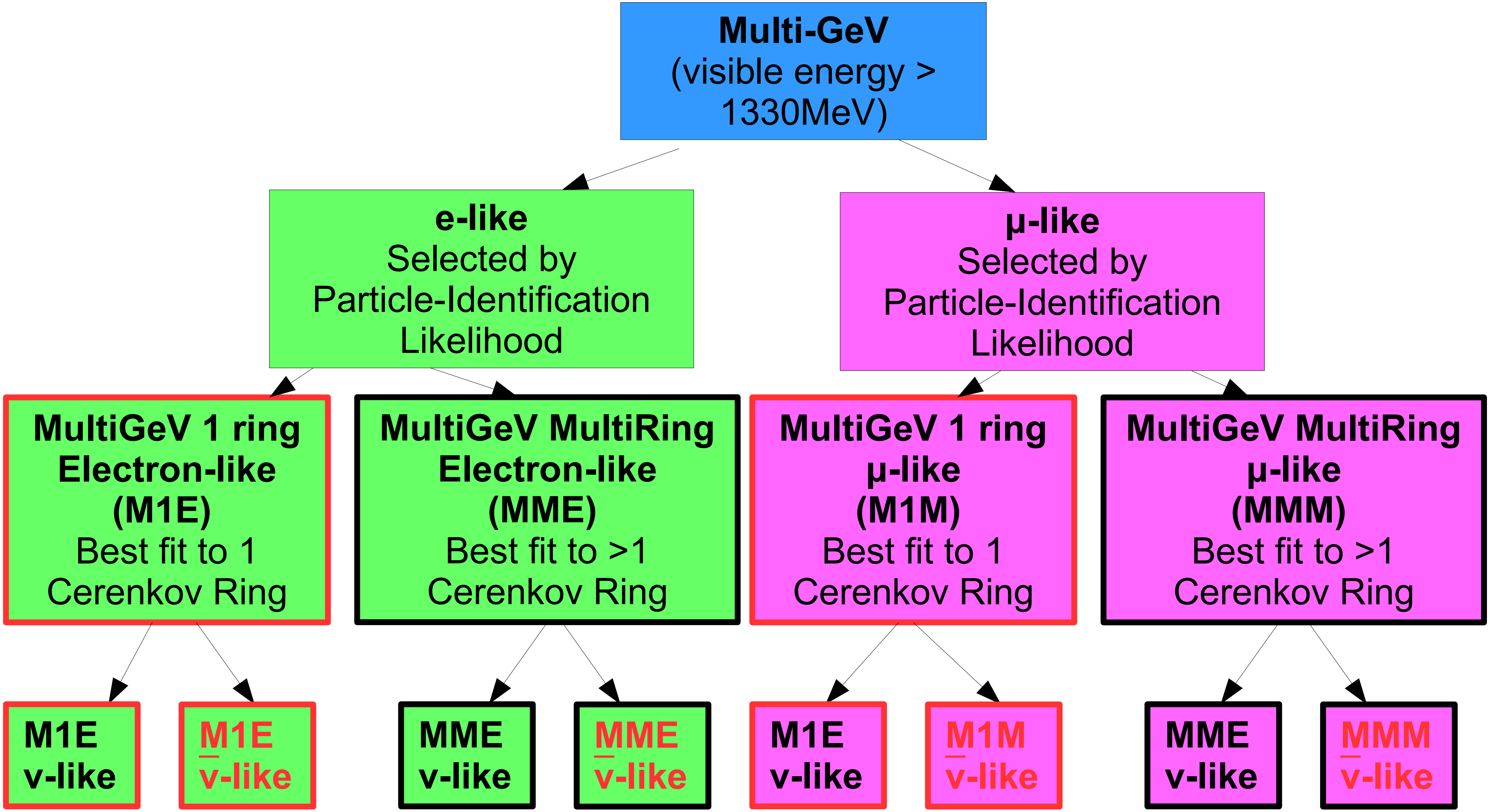


Good data vs MC agreement



Anti-Neutrino Separation

- Multi-GeV samples in Super-Kamiokande are split up into 4 sub-samples, by whether they are electron/muon, and whether they have 1 or >1 Cerenkov rings



Multi-GeV
(visible energy > 1330MeV)

e-like
Selected by Particle-Identification Likelihood

μ-like
Selected by Particle-Identification Likelihood

MultiGeV 1 ring Electron-like (M1E)
Best fit to 1 Cerenkov Ring

MultiGeV MultiRing Electron-like (MME)
Best fit to >1 Cerenkov Ring

MultiGeV 1 ring μ-like (M1M)
Best fit to 1 Cerenkov Ring

MultiGeV MultiRing μ-like (MMM)
Best fit to >1 Cerenkov Ring

M1E ν-like

M1E ν̄-like

MME ν-like

MME ν̄-like

M1E ν-like

M1M ν̄-like

MME ν-like

MMM ν̄-like

- I am concentrating on improving the final selection – splitting into **ν-like** and **ν̄-like**, for each of the 4 samples.

How to Distinguish Anti-neutrino

For CC ν_e:

$\nu_e + n \rightarrow e^- + N' +$ pions (Total charge for the N' and pion system is +1)

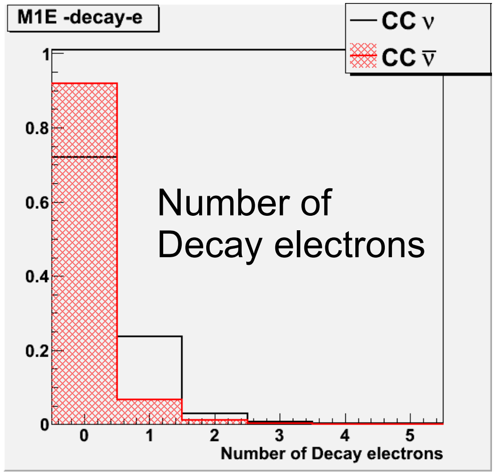
$\nu_e + p \rightarrow e^- + N' +$ pions (Total charge for the N' and pion system is +2)

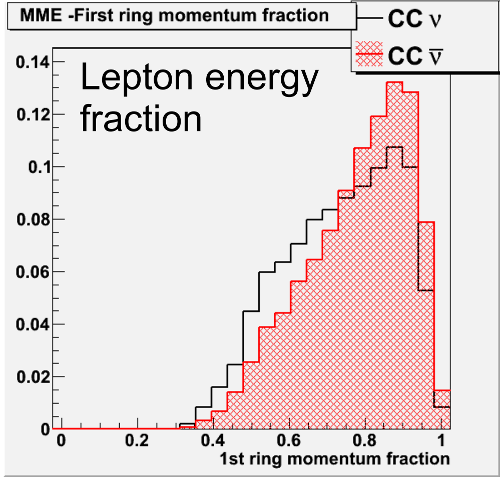
For CC$\overline{\nu}_e$:

$\bar{\nu}_e + p \rightarrow e^+ + N' +$ pions (Total charge for the N' and pion system is 0)

$\bar{\nu}_e + n \rightarrow e^+ + N' +$ pions (Total charge for the N' and pion system is -1)

- So we may expect more hadrons, and specifically charged pions, from neutrino interactions. This leads to...
  - More decay electrons
  - Smaller energy fraction in primary lepton.
  - Decay electron from μ will be closer to neutrino interaction
  - Less well defined first ring (Particle Identification)
- Also, specifically to muons, μ- may be captured by O16, but not μ+.
  - The time decay electrons are observed will be typically shorter for neutrino events.
- And of course, number of neutrons.

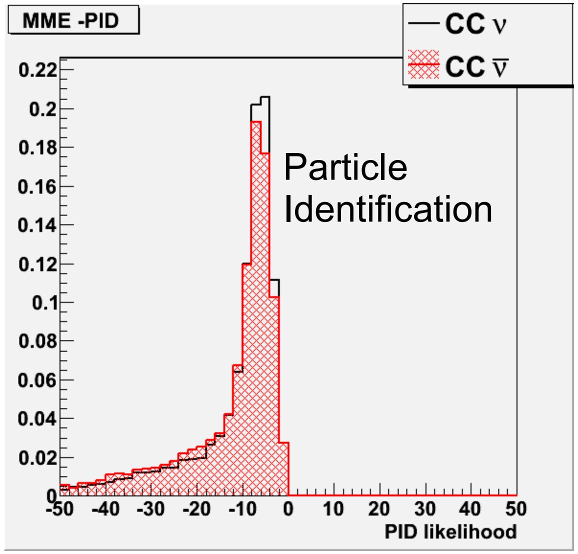


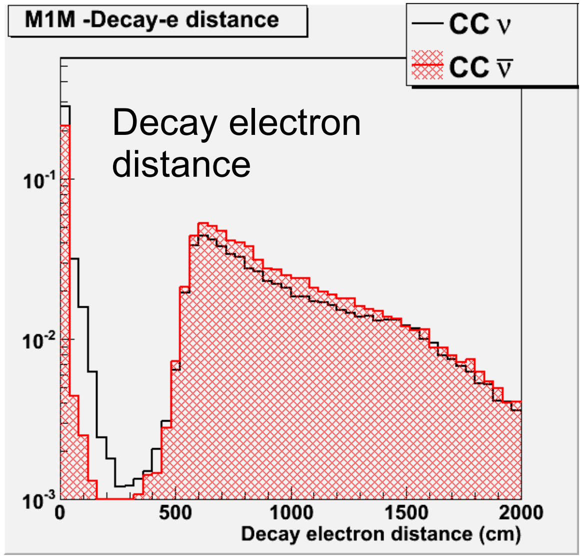


How to distinguish anti-neutrino (2)

Less well defined first ring in neutrino sample.

Leads to particle identification likelihood becoming less certain of result (closer to 0)



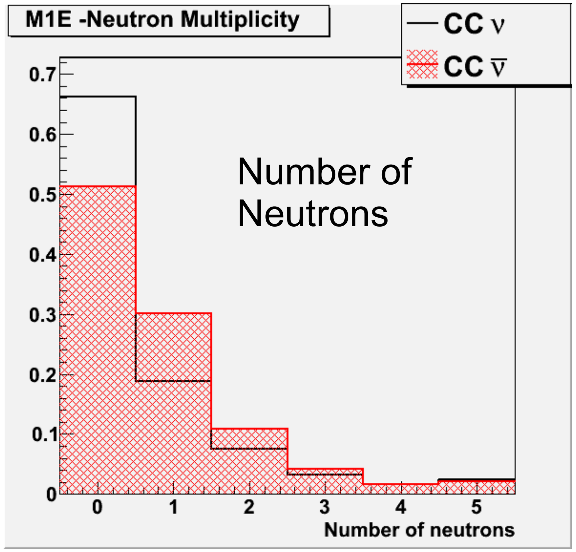


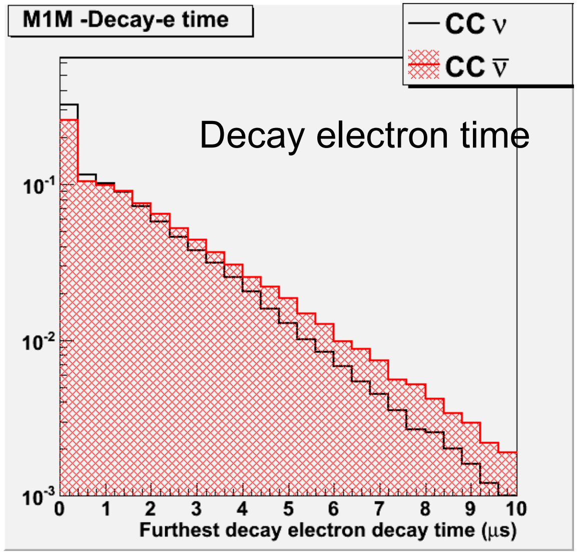
The primary lepton has less energy, due to larger number of hadron production. If the primary lepton is a muon, it will decay to an electron after some distance.

If the muon has less momentum (e.g. in neutrino interaction, the decay electron will be found closer to the neutrino interaction.

In charged current quasi-elastic interactions, a neutron is produced by an anti-neutrino, however a proton is produced by a neutrino.

Therefore we expect to see an excess of neutrons in anti-neutrino interactions



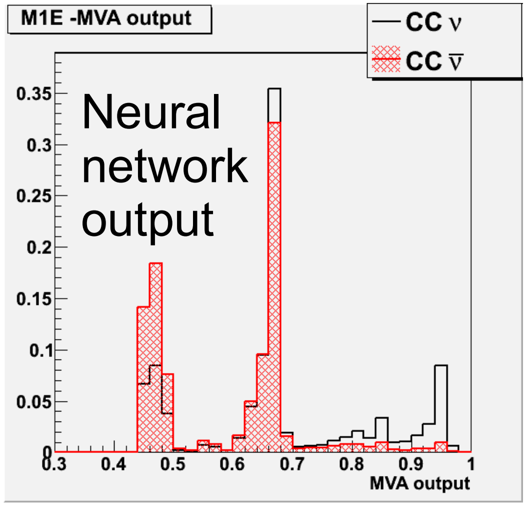


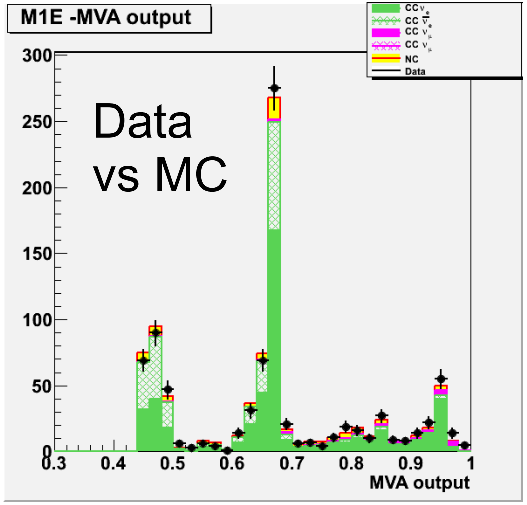
A μ- (produced by neutrino), may be captured by O16, however μ+ (produced by anti-neutrino), may not.

This leads to an apparent reduction in decay electron time for neutrino events.

Results (e-like)

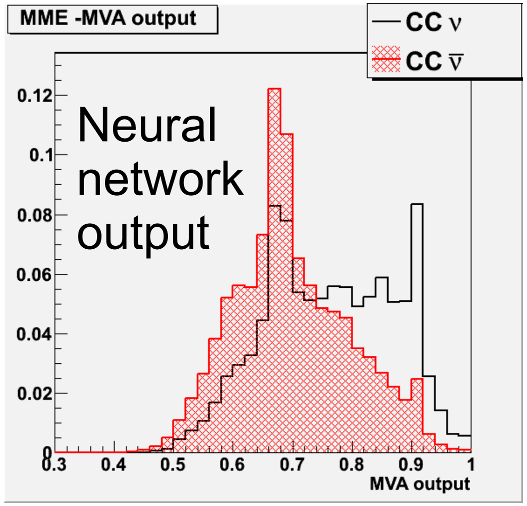
Electron-like 1 ring

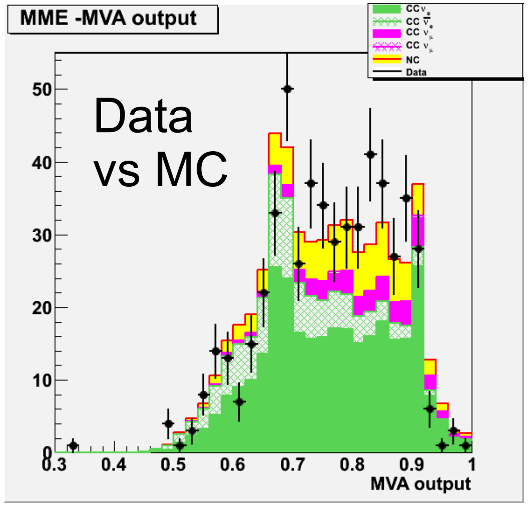




- These distributions are combined using a neural network which outputs distributions with the best possible separation of neutrino type.
- Cut position is chosen based on the optimal Efficiency * Purity of both samples.
- The discontinuities in the distributions are due to the dominant effect of the discreet variables, number of decay-electron and number of neutrons.

Electron-like Multi-ring



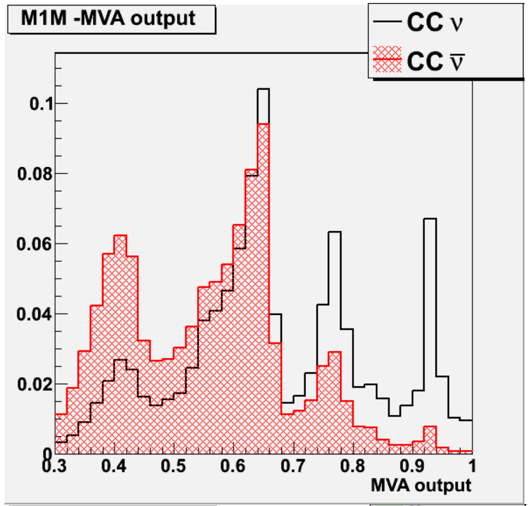


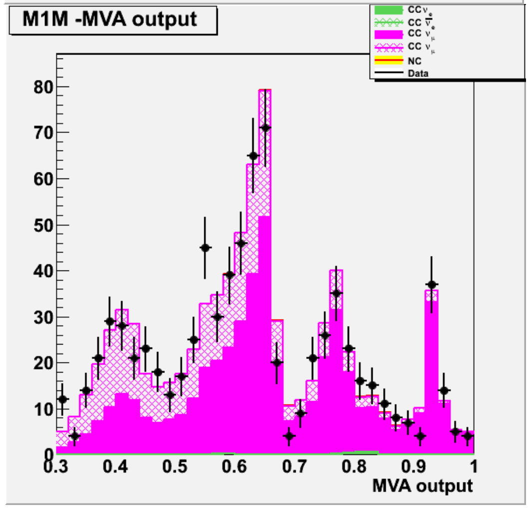
M1E	**ν-like**	**ν̄-like**
Purity	0.607	0.450
Efficiency	0.739	0.492

MME	**ν-like**	**ν̄-like**
Purity	0.559	0.295
Efficiency	0.617	0.627

Results (μ-like)

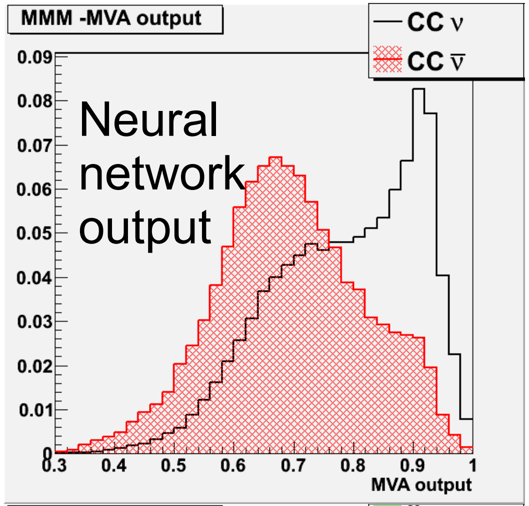
Muon-like 1 ring



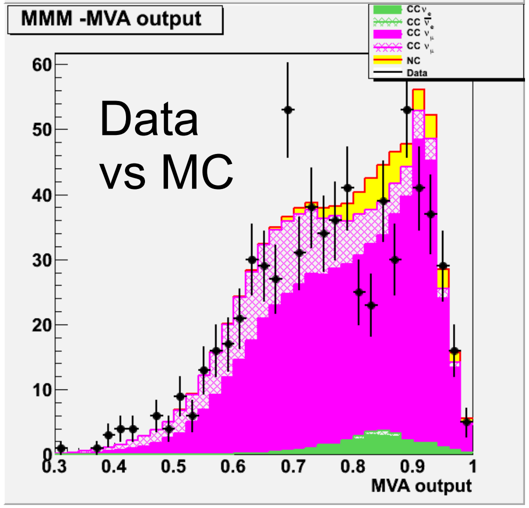


M1M	ν-like	$\bar{\nu}$-like
Purity	0.729	0.528
Efficiency	0.692	0.579

Muon-like Multi-ring



Neural network output

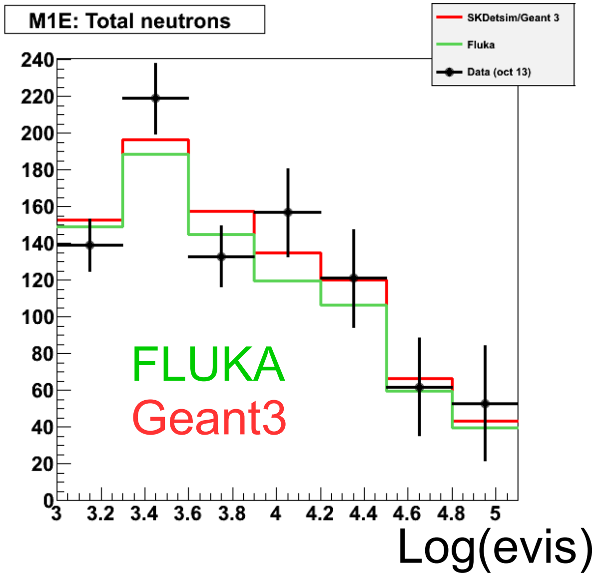


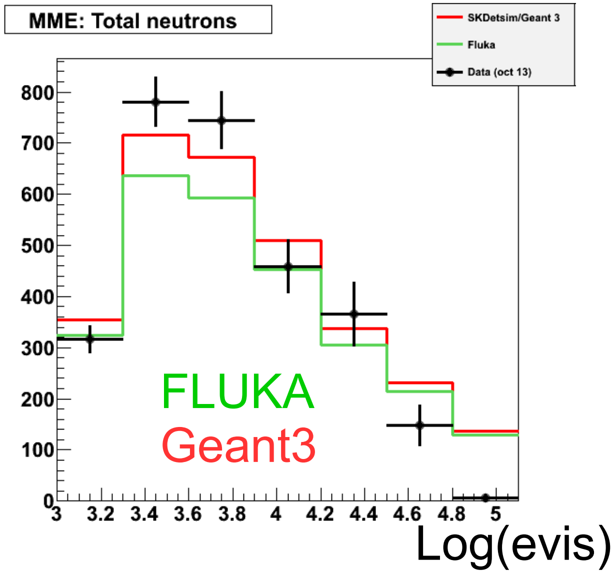
Data vs MC

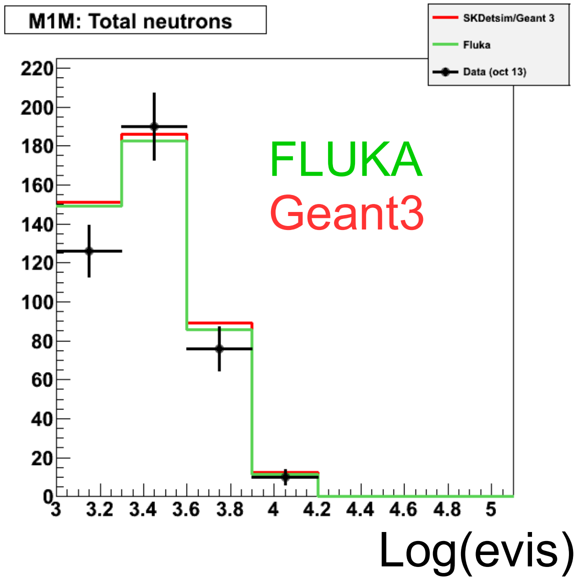
MMM	ν-like	$\bar{\nu}$-like
Purity	0.771	0.373
Efficiency	0.702	0.597

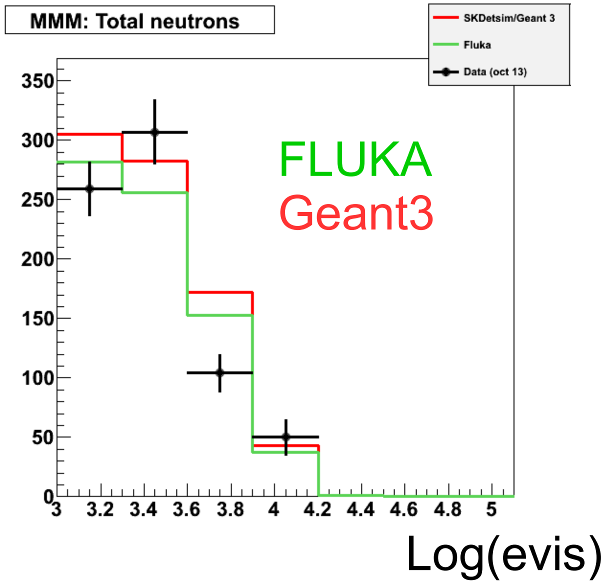
Systematic Error

- There is much uncertainty about specific hadronic interaction cross sections and processes involved in secondary hadronic production.
- I calculate systematic error by comparing the SK Monte-Carlo (geant3 + Skdetsim) to an external model – FLUKA Standalone package.
- Particle guns for proton, neutron and charged pion were created, and recorded neutron captures were compared between the two simulation packages.
- Difference in neutron captures is used to weight final neutrino events.
- Energy dependent systematic error is taken as the difference between FLUKA and Geant3 for each sample.









Summary

- Successfully able to identify 28.2% of neutron capture events on Hydrogen in Super-Kamiokande IV, with a background of 2% per neutrino event.
- This can be combined with other relevant information, to separate neutrino and anti-neutrino events.
- Oscillation analysis and mass hierarchy sensitivity will be prepared soon...