Distinguishing Anti-Neutrinos in Super-Kamiokande IV Atmospheric Neutrino dataset using Neutron Tagging

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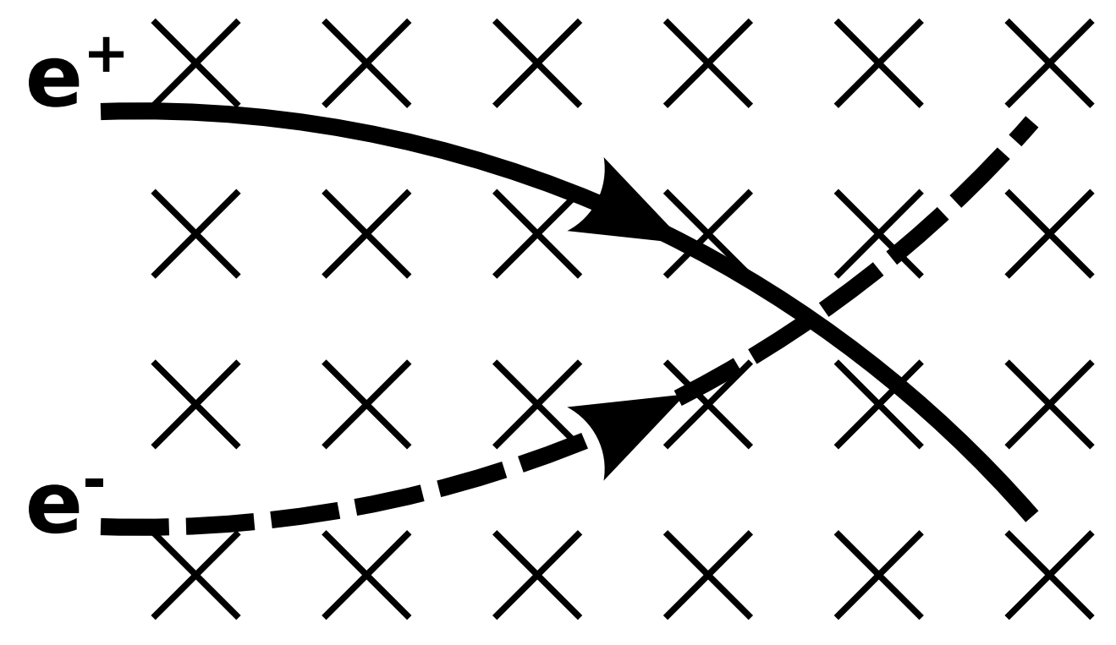
Why is it difficult to distinguish anti-neutrino from neutrino?

Neutrinos produce *negatively* charged leptons.
Anti-neutrinos produce *positively* charged leptons.

In most particle detectors these are distinguished using a magnetic field like so:



The magnetic field causes differently charged particles to curve in opposite directions.

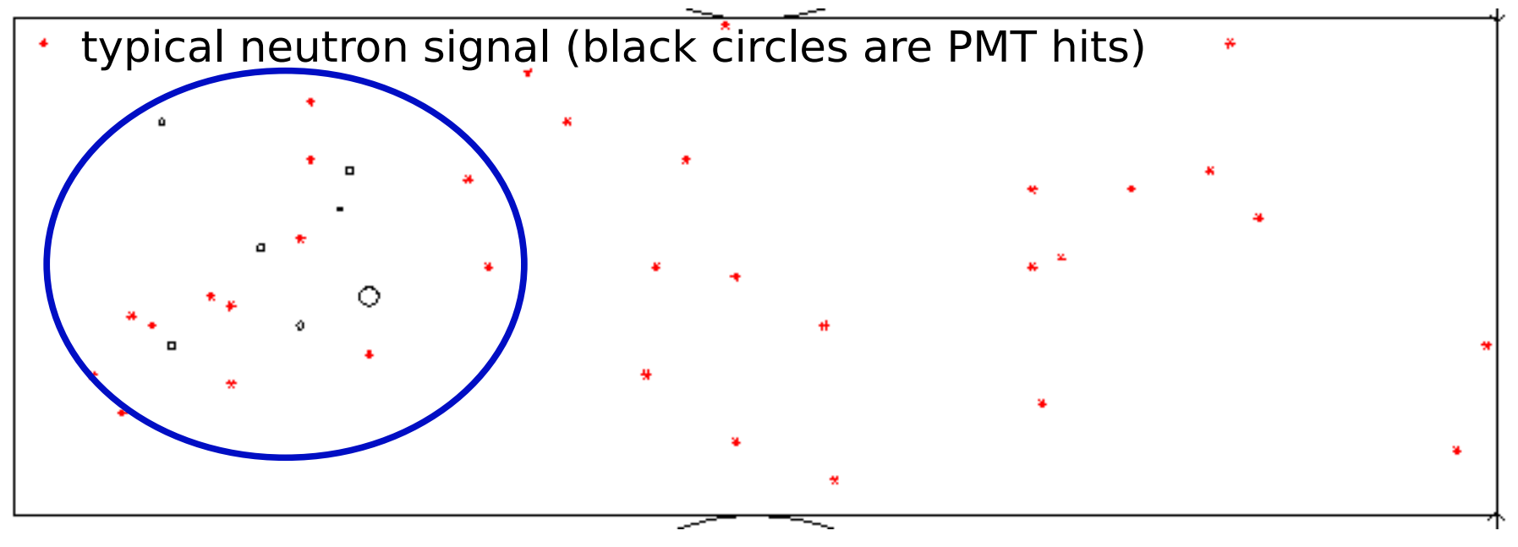
However, the photomultiplier tubes used in Super-Kamiokande are very sensitive to magnetic field, so we cannot apply this technique.

It it difficult to distinguish what charge the lepton has, or what type of neutrino we started with

Detecting Neutrons

Neutrons get captured by hydrogen (capture lifetime 204μs), and emit 2.2MeV γ-ray ~100% of the time.

These gamma rays typically produce only ~8 hits on PMTs, so they are difficult to distinguish from background noise.



typical neutron signal (black circles are PMT hits)

These 2.2MeV γ-rays can be identified using 3 characteristics:

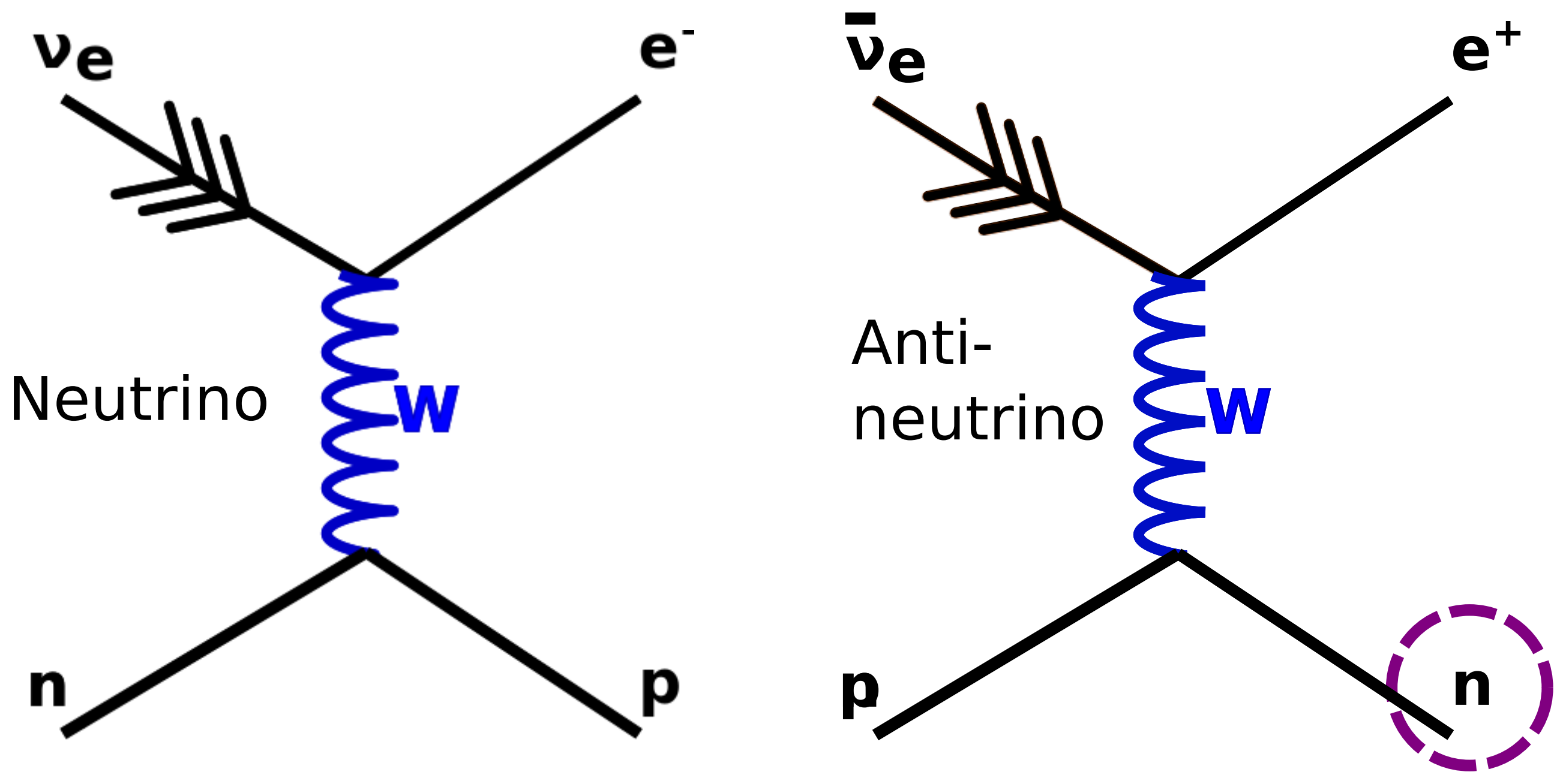
Position of the hits - the hit pattern should be in a cerenkov cone, and correspond to a position in the tank close to the neutrino interaction vertex.
Timing of the hits - As the hits originate from just one particle, they should have a tight timing distribution.
Energy of the hits - The corresponding energy of the hits should be close to 2.2MeV.

Motivation

Measure anti-neutrino flux from cosmic sources.
Reduce proton decay background.
Look for CPT violation in neutrino sector.
At E > 1GeV, distinguishing between ν and $\bar{\nu}$ is necessary for calculating neutrino mass hierarchy.

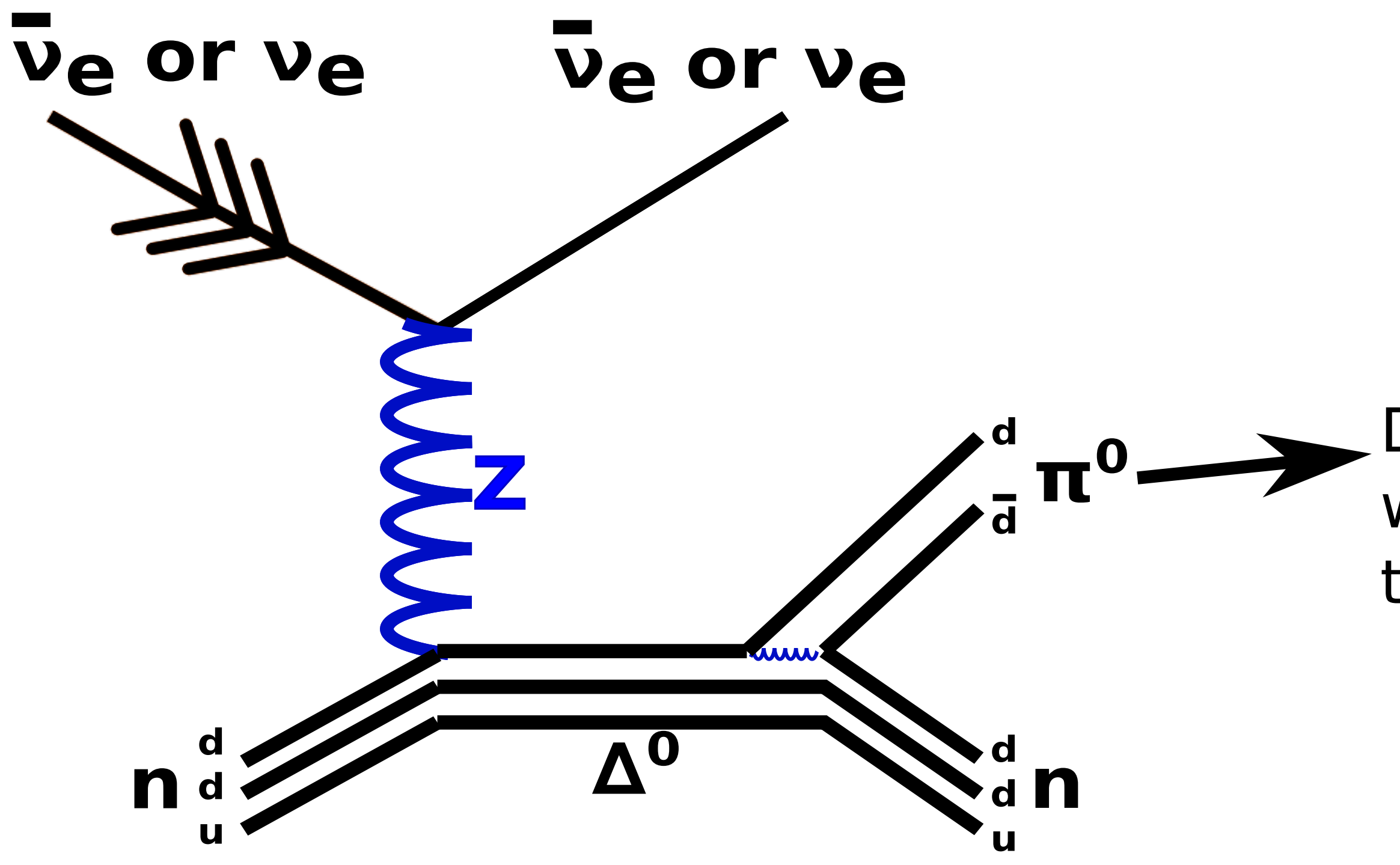
How can we use neutrons to detect anti-neutrinos?

For Weak Charged Current Elastic Interactions, an anti-neutrino will always produce a neutron, whereas a neutrino usually does not.



This is due to conservation of
1). Charge
2). Lepton number

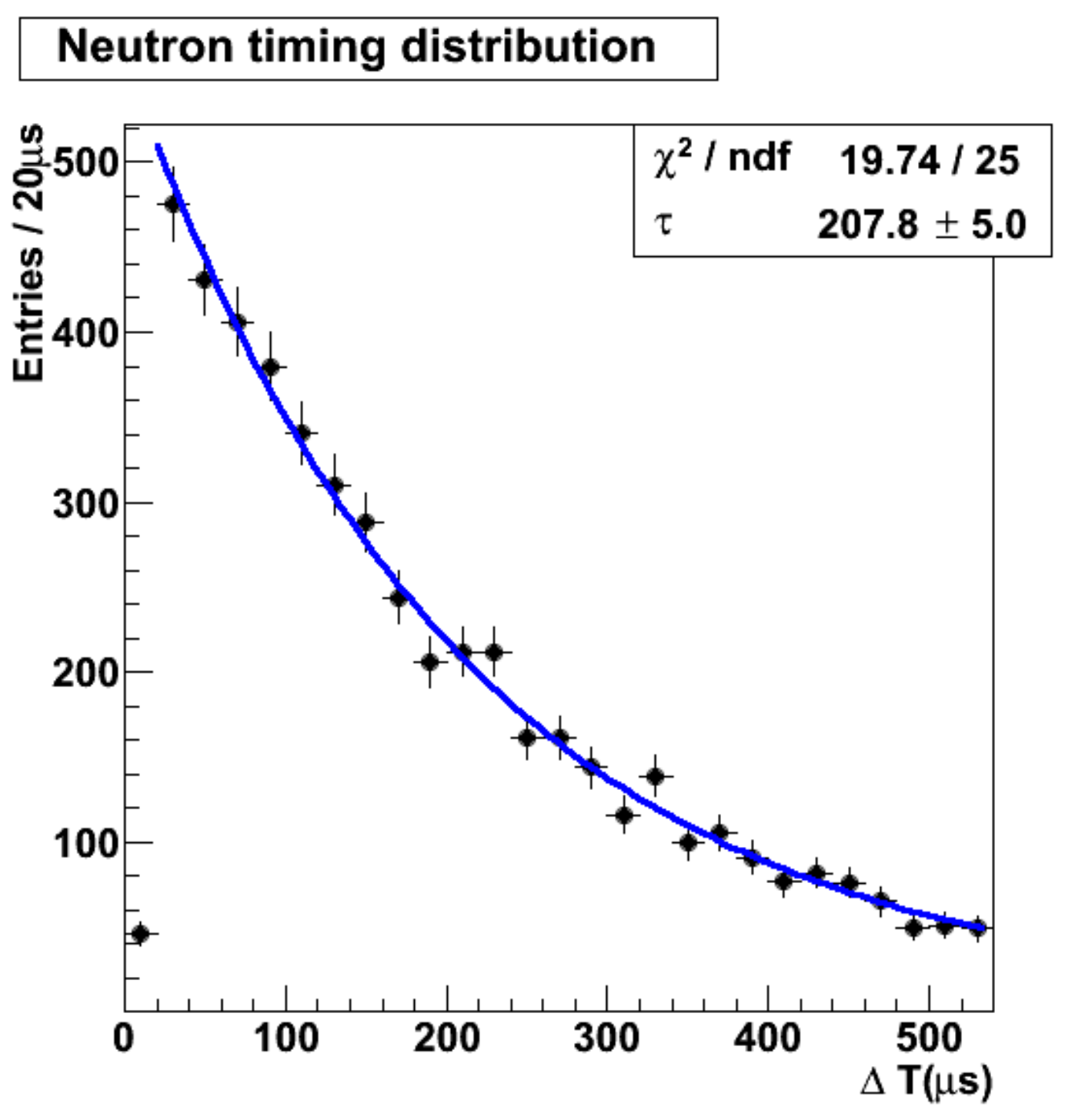
Unfortunately, there are higher order interactions in which even neutrinos can produce neutrons, so this method is not perfect.



Decays to two photons, which look very similar to an electron in SK

Are we able to see neutrons?

Using the above method, I am able to detect 19.0% of neutrons produced by high energy neutrinos, with a background of 1.67 / 100 neutrinos.

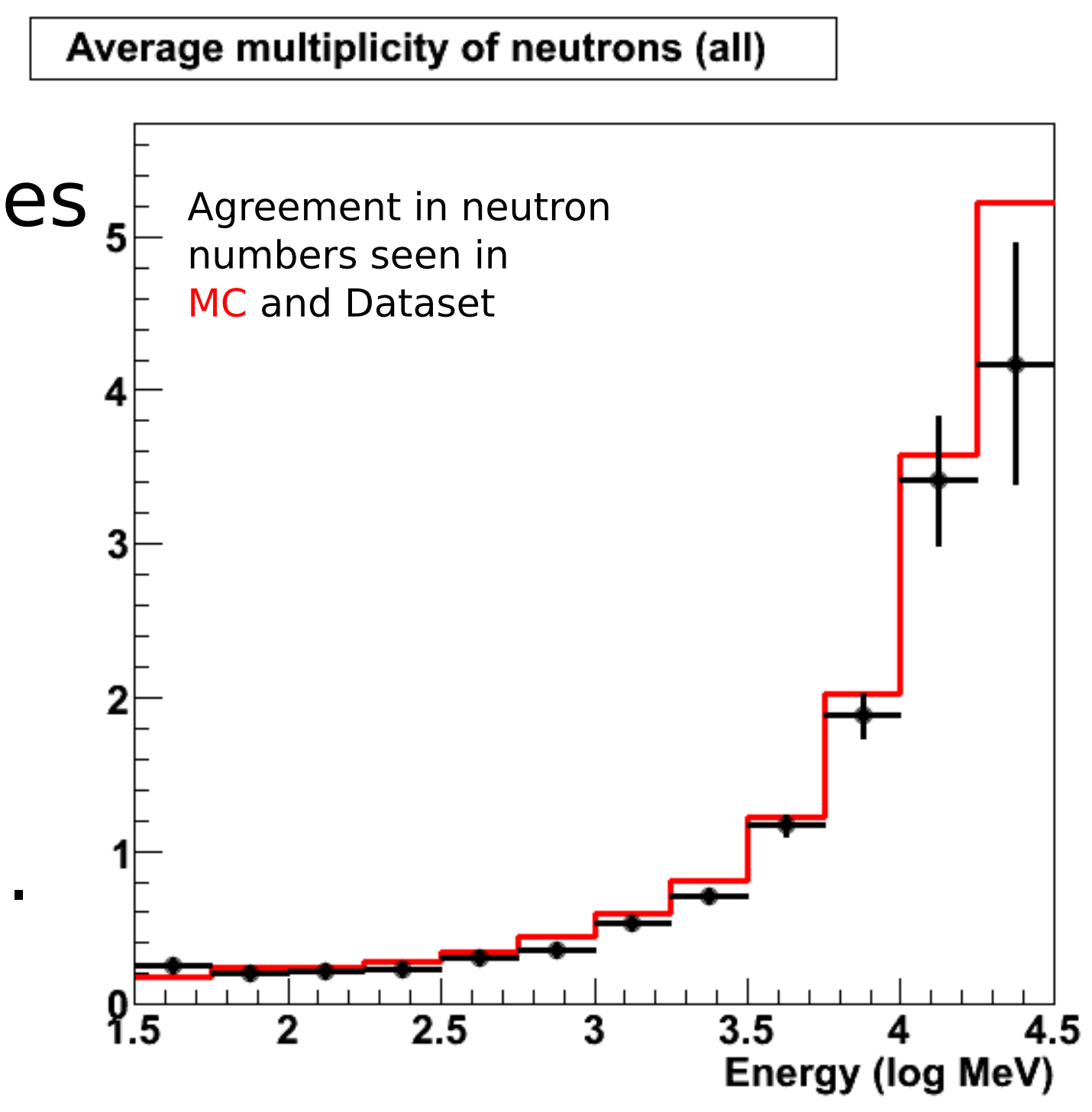


The Left plot shows the timing distribution of all detected neutrons following high energy neutrino interactions.

The blue curve is an exponential fit for the lifetime.

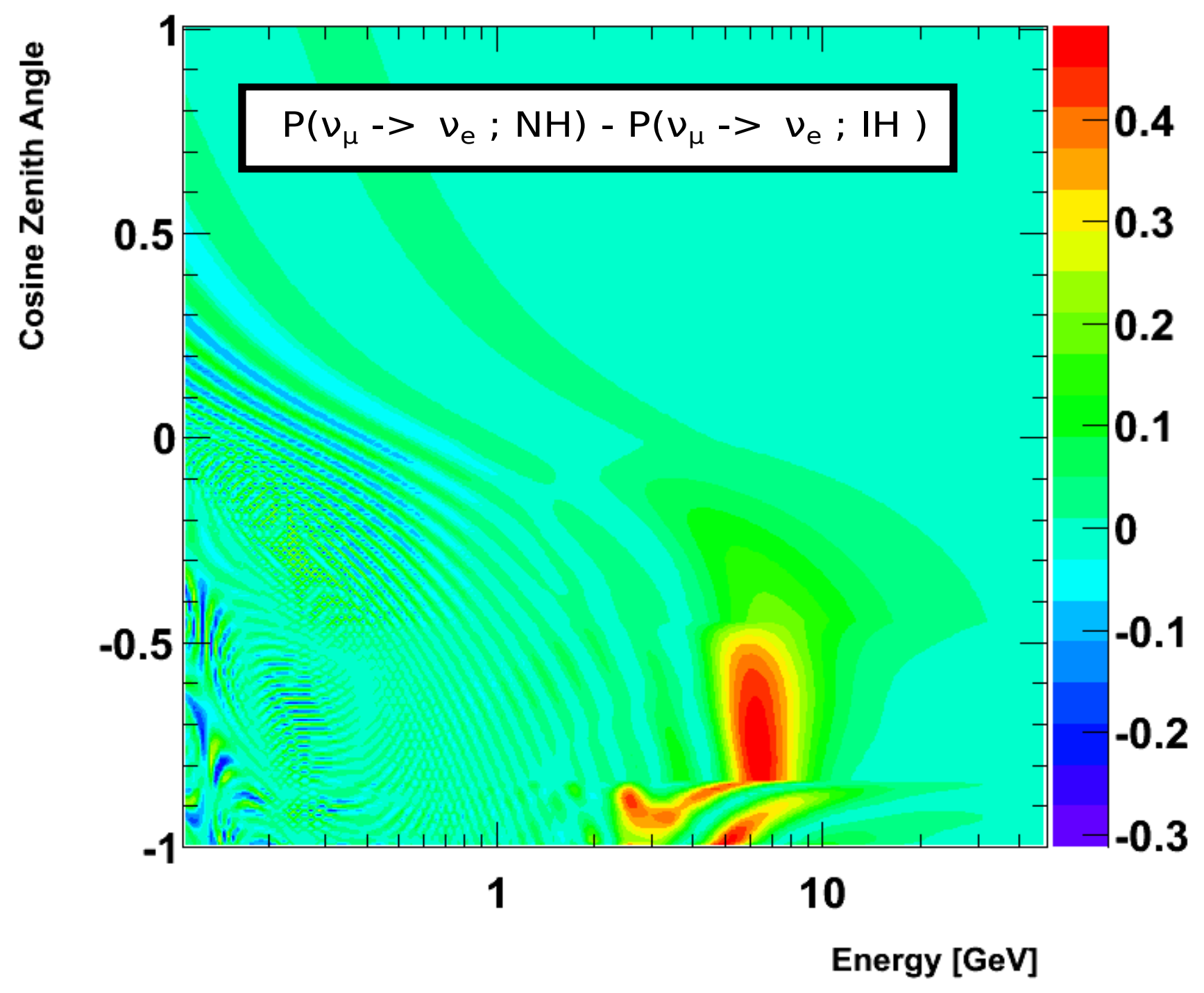
Lifetime 207.8±5μs is consistent with neutron capture lifetime 204μs, verifying that neutrons are correctly being identified.

The right plot demonstrates the agreement between average number of neutrons generated per neutrino in a Monte-Carlo simulation (Red line), and the same measured in real data (black circles).

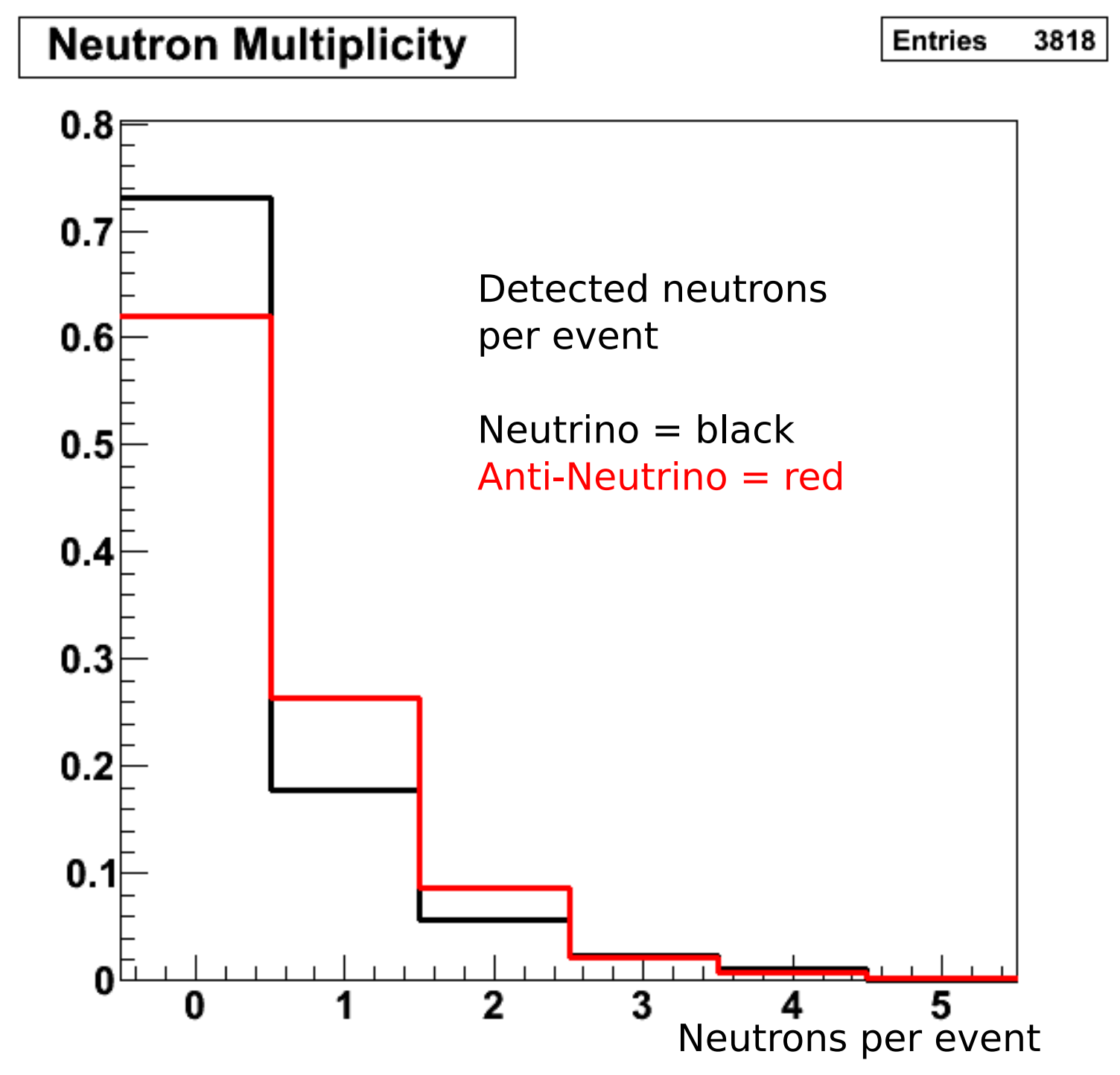


Is this useful for finding anti-neutrinos (and mass hierarchy)?

SK is sensitive to neutrino mass hierarchy in energy of ~2-10GeV.



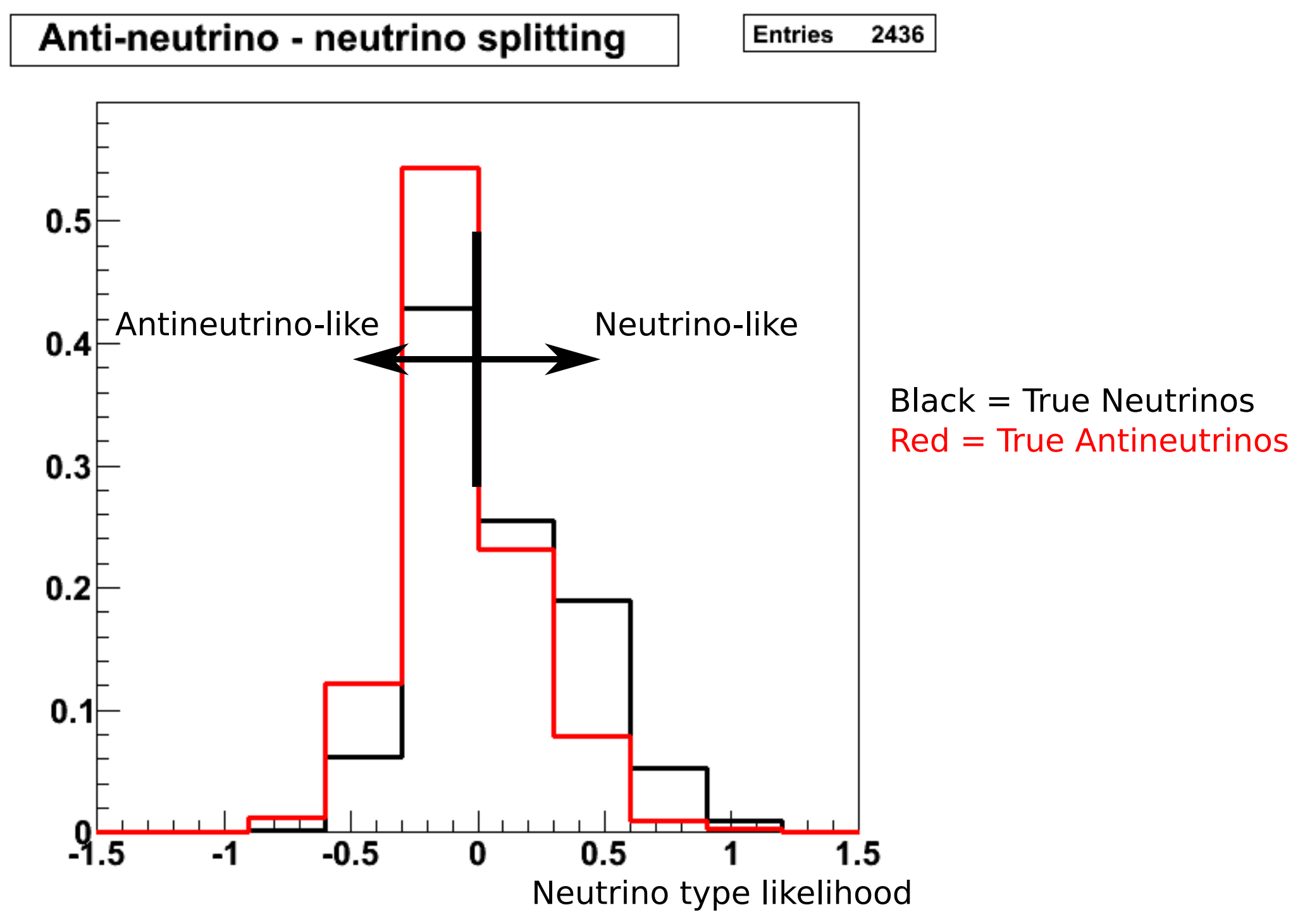
The below plot shows the number of neutrons produced per event in this energy range, for neutrinos and anti-neutrinos.



It is also known that more π^+ are expected to be produced by neutrino, than anti-neutrino interactions.

It is hard to directly count π^+, but an excess implies differences in the following variables:

- Number of decay electrons
- Distance between neutrino and decay electrons
- Energy fraction of the initial lepton
- The total number of cerenkov rings seen in an event



I used this information to create a likelihood distribution which is able to distinguish between neutrino and anti-neutrino.