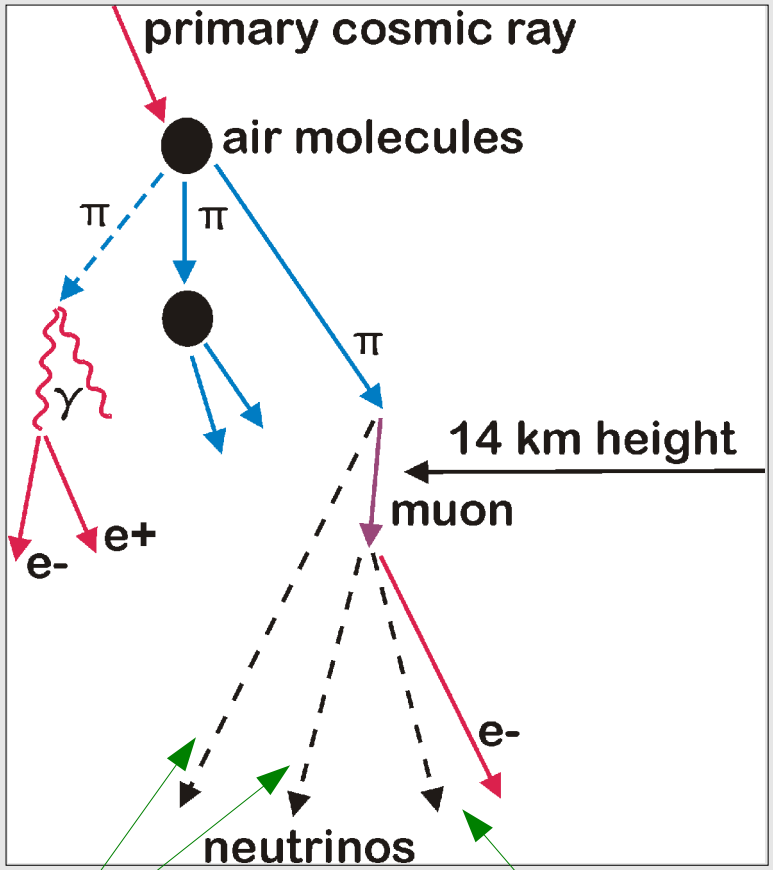
Using Quasi-Elastic Events to Estimate the Neutrino Flux of the MINOS Experiment

Mark Dorman

1st Year Talk, June '05

- Physics motivation for MINOS
- Physics capabilities of MINOS
- Events types and cross sections
- Quasi-elastic methodology
- Monte Carlo results
- Data/MC comparisons
- Future work

The Atmospheric Neutrino Anomaly and Pontecorvo's Idea



- Cosmic rays interact with molecules in the upper atmosphere producing cascades of secondary particles.
- The ratio of ν_μ(anti-ν_μ) : ν_e(anti-ν_e) arriving should be 2:1.
- Many experiments have seen a deficit in the numbers of muon neutrinos.
- The solution was proposed by Bruno Pontecorvo in 1967 – that the mass eigenstates of neutrinos are not the same as the weak eigenstates and that neutrinos have mass.

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Neutrino Oscillations

- A neutrino produced in a weak interaction will consist of a superposition of the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i \nu^*_{\alpha i} |\nu_i\rangle$$

- Consideration of the time evolution of this state in a situation where only two of the mass eigenstates are important results in the following oscillation equation:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left[1.27\, \Delta m^2(eV^2) \frac{L(km)}{E(GeV)}\right]$$

Oscillation probability

Mixing angle

Mass splitting

Neutrino energy

Distance traveled

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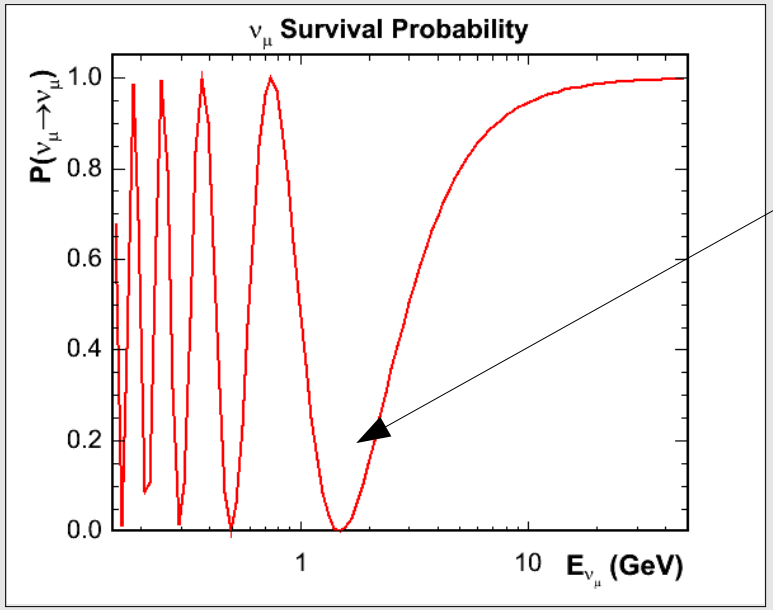
The MINOS Experiment

- MINOS is a long baseline experiment consisting of a beam of neutrinos produced at Fermilab whose path takes them through a Near Detector on-site at Fermilab and a Far Detector 735km away at the Soudan mine.
- Using this value for L, $sin^2 2\Theta = 1$ (maximal mixing) and $\triangle m^2 = 0.0025$ the survival probability of a muon neutrino looks as follows:



- MINOS is sensitive to the effects of this first dip (~1.5GeV).
- Depending on the exact values of the oscillation parameters this dip will move and so in MINOS the peak of the neutrino energy spectrum can be moved.

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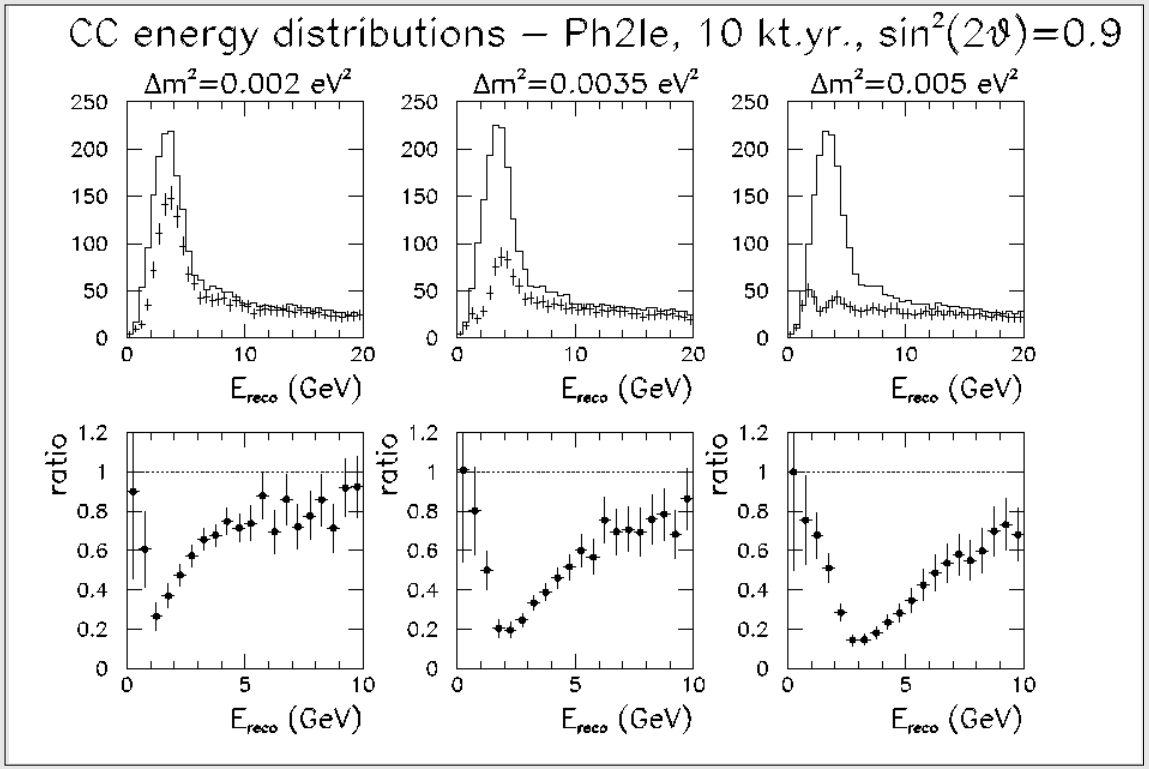
The MINOS Experiment

- The main physics goals for MINOS are to confirm the phenomena of neutrino oscillations and make a precision measurement of the parameters that govern these oscillations.
- The most sensitive method open to MINOS is a spectral comparison:



ND spectrum (data)

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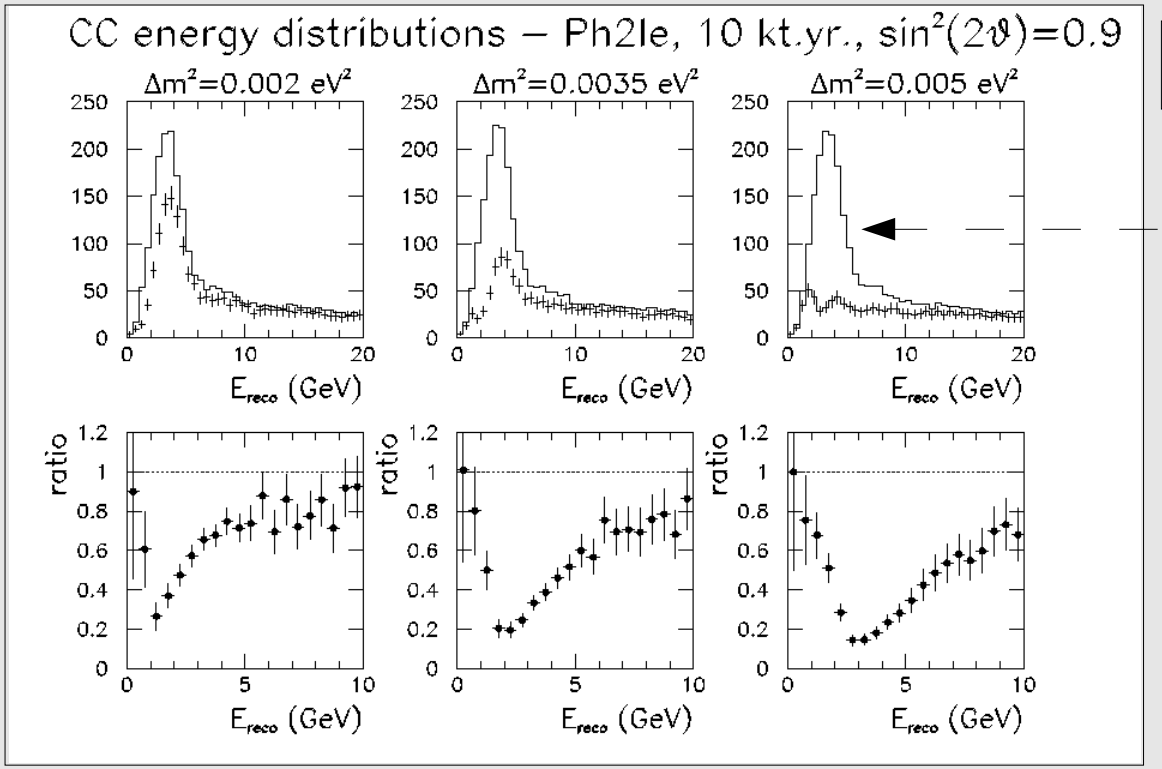

ND spectrum (data)

Predicted un-oscillated FD spectrum (MC)

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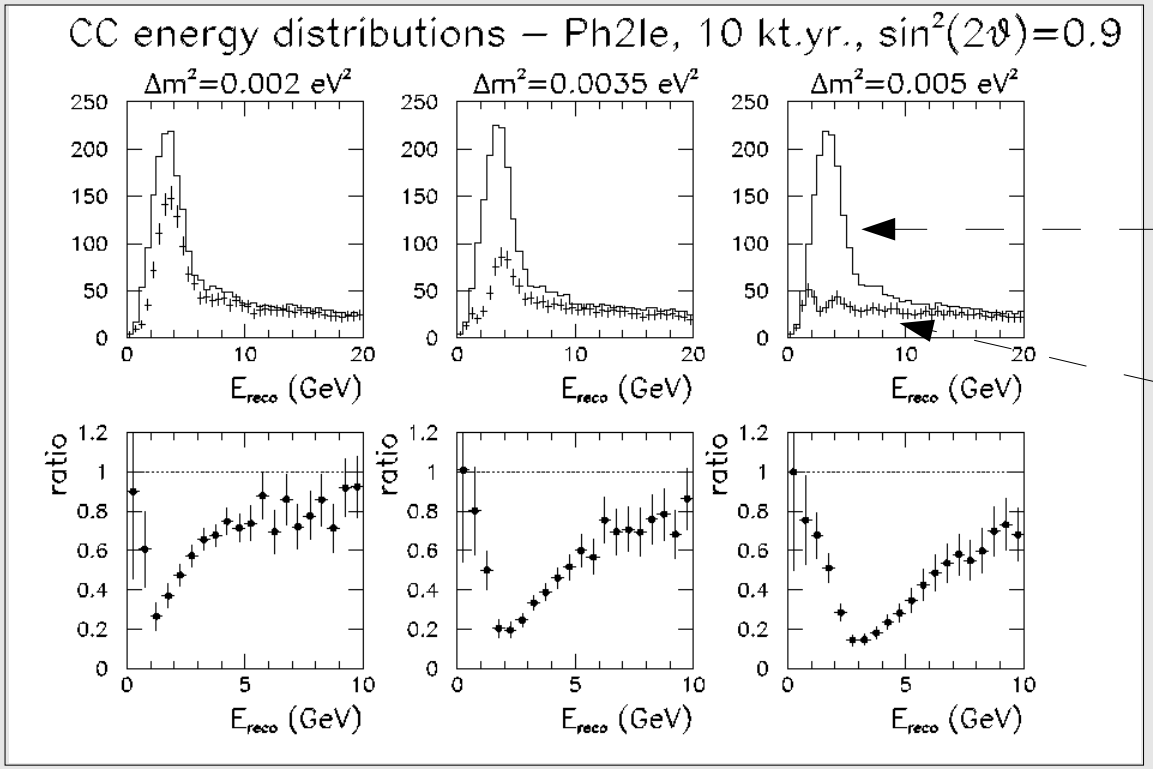

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FD spectrum (data)

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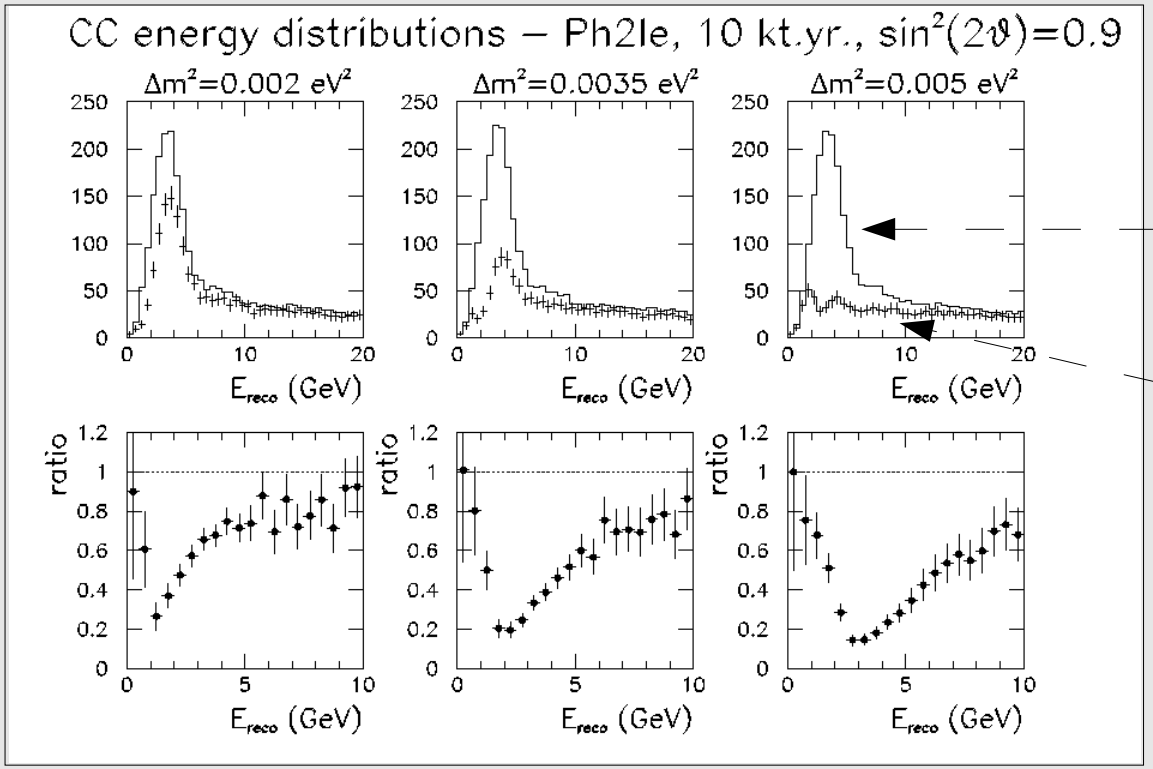

ND spectrum (data)

Predicted un-oscillated FD spectrum (MC)

FD spectrum (data)

Take ratio

- The dip depth and width are proportional to the oscillation parameters.

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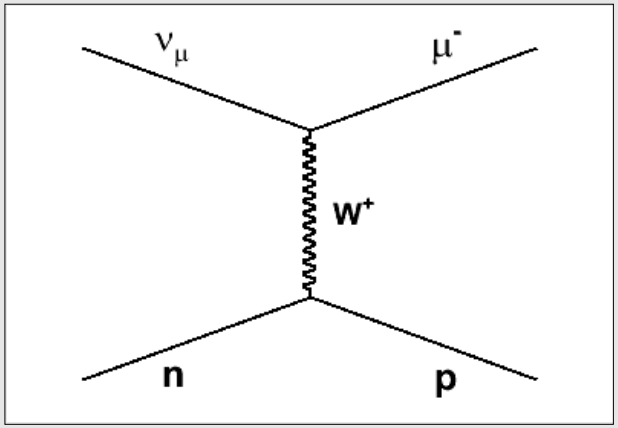
Events in MINOS

- MINOS will see both CC and NC events. The CC events may be further subdivided into several categories:



- Quasi-elastic (QE) – neutrino scatters off an entire nucleon. Target nucleus is modified but does not break up. Proton and muon observed in detectors.

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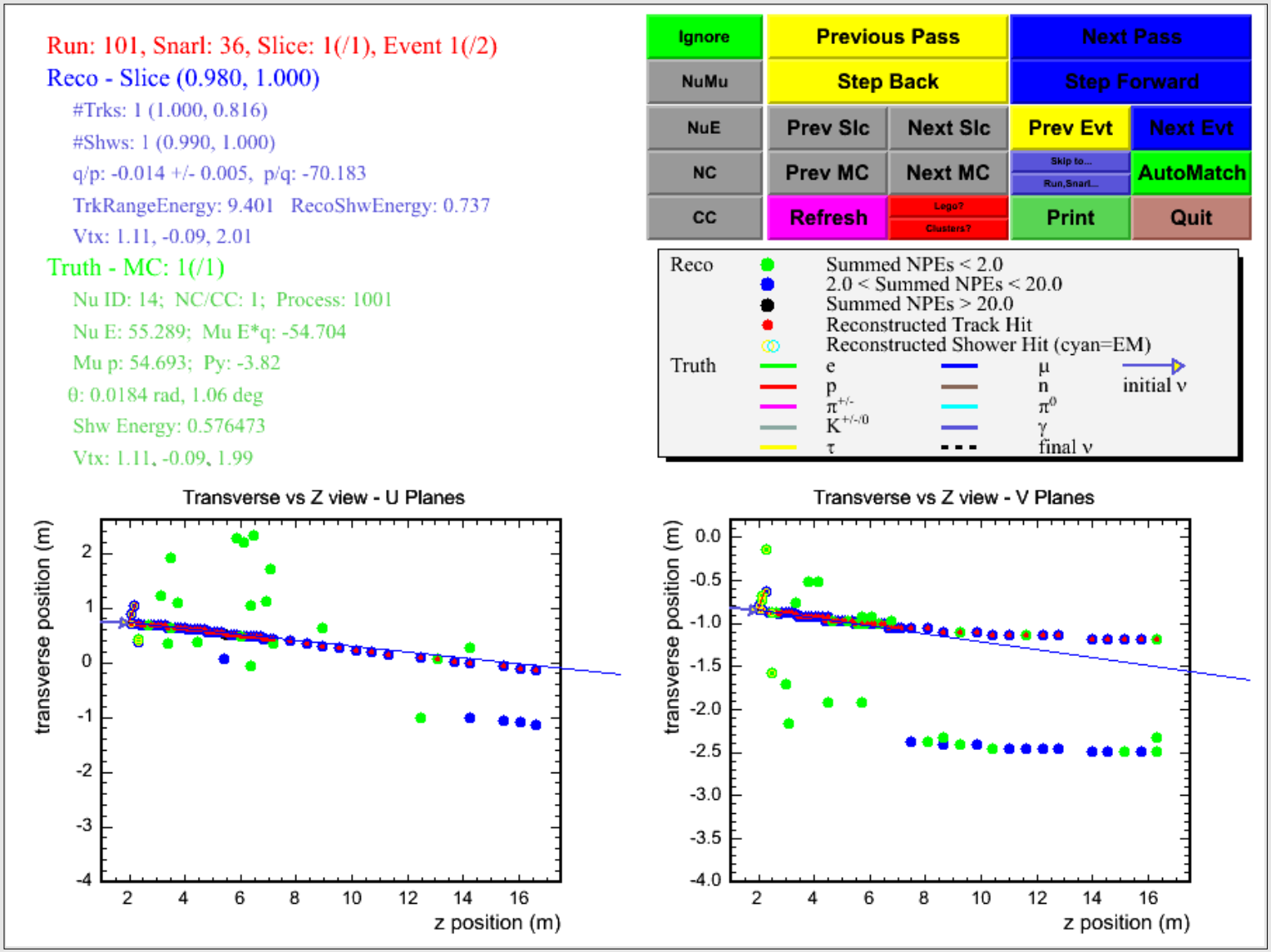

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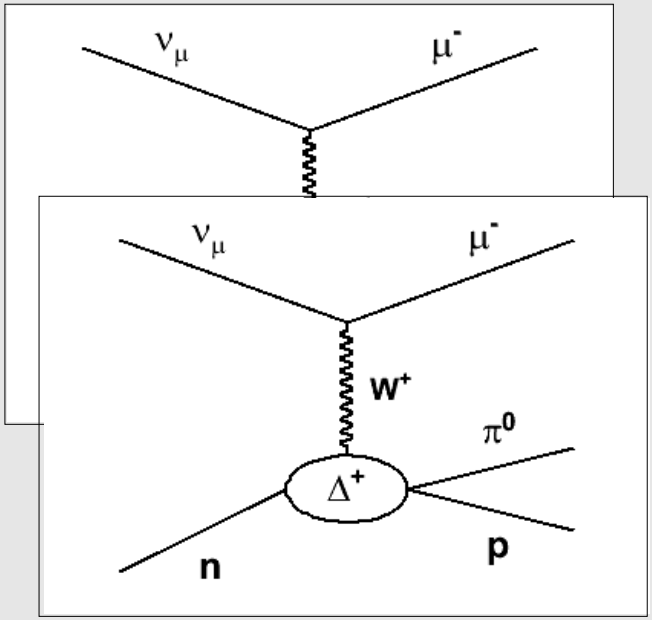

- Quasi-elastic (QE) – neutrino scatters off an entire nucleon. Target nucleus is modified but does not break up. Proton and muon observed in detectors.
- Resonance (RES) – target nucleus does not break up but a resonance is formed that subsequently decays to a proton and pion which are observable in the detectors.

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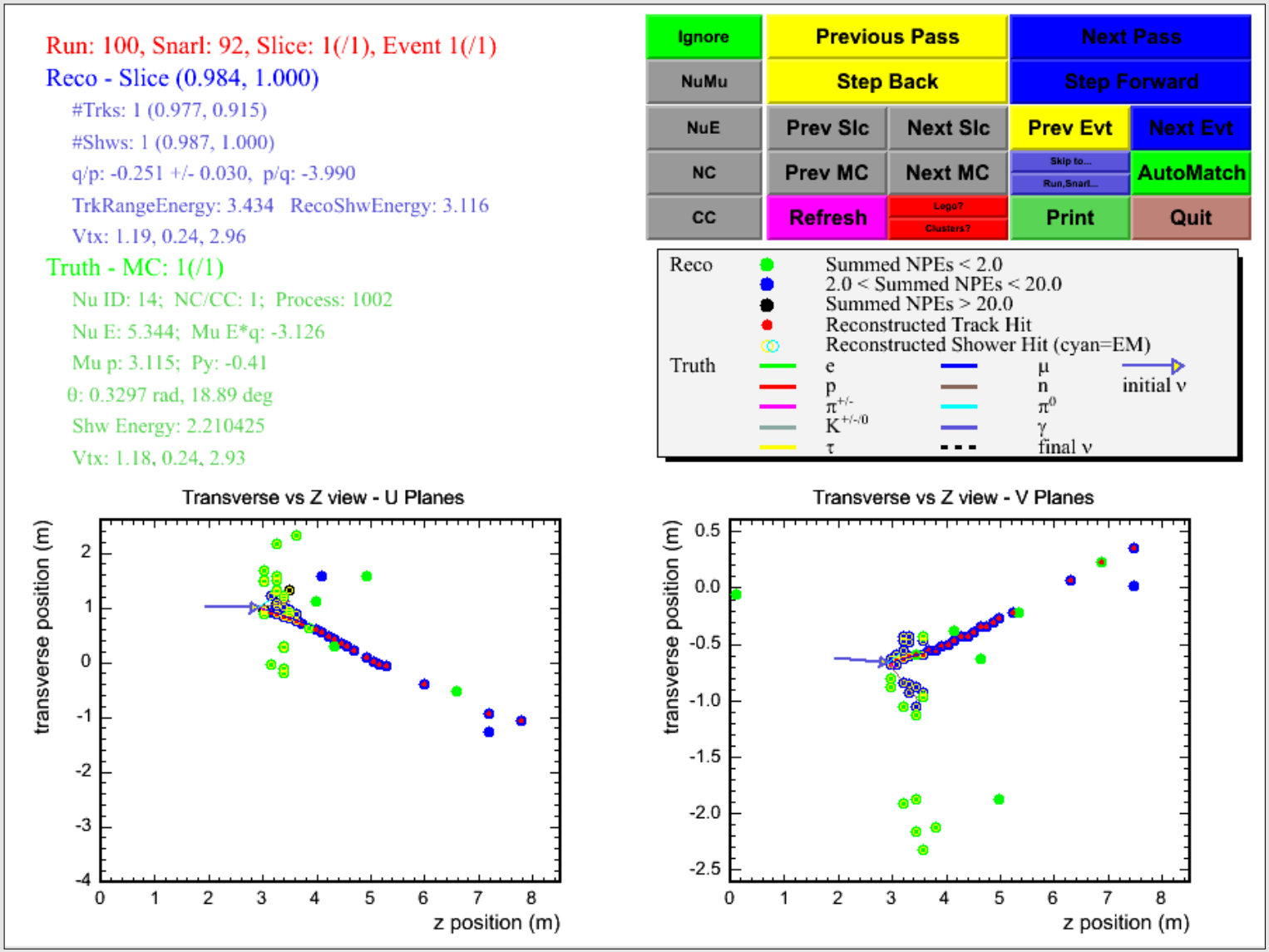

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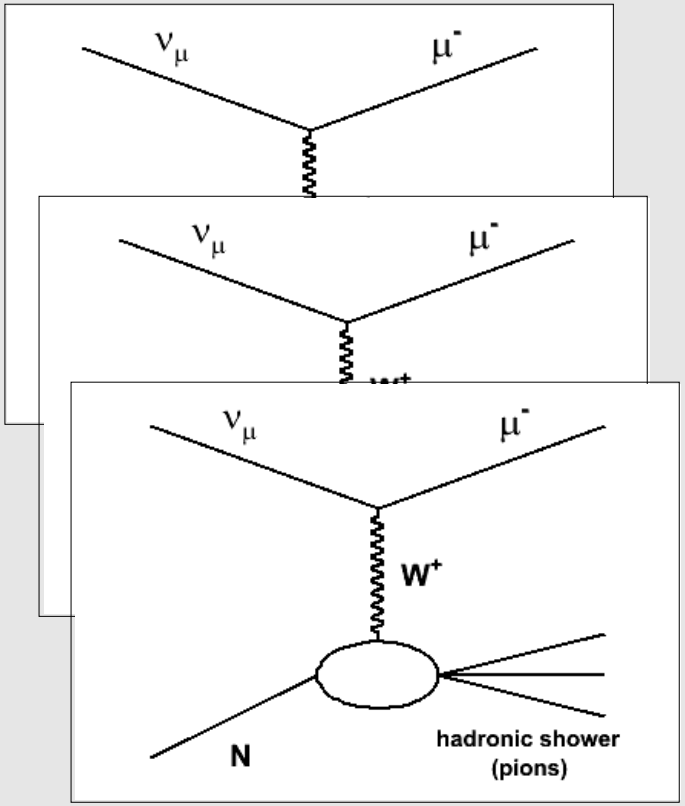


- Quasi-elastic (QE) – neutrino scatters off an entire nucleon. Target nucleon is modified but does not break up. Proton and muon observed in detectors.
- Resonance (RES) – target nucleon does not break up but a resonance is formed that subsequently decays to a proton and pion which are observable in the detectors.
- Deep inelastic scattering (DIS) – large momentum transfers and the target nucleon breaks up giving rise to a hadronic shower of pions.

Run: 100, Snarl: 2, Slice: 1(/1), Event 1(/1)

Reco - Slice (0.990, 0.996)

#Trks: 1 (0.968, 0.906)

#Shws: 2 (0.901, 0.005) (0.992, 0.986)

q/p: -0.044 +/- 0.010, p/q: -22.782

TrkRangeEnergy: 7.432 RecoShwEnergy: 23.436

Vtx: 1.47, -0.30, 2.67

Truth - MC: 1(/1)

Nu ID: 14; NC/CC: 1; Process: 1003

Nu E: 42.495; Mu E*q: -19.007

Mu p: 18.996; Py: -2.70

θ: 0.1113 rad, 6.38 deg

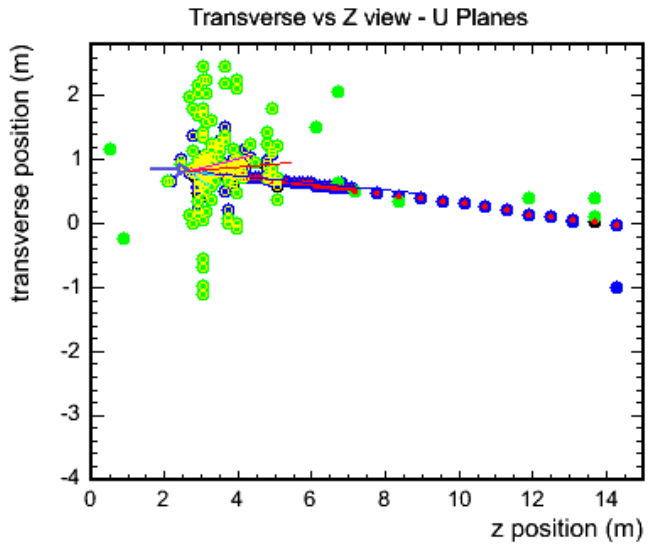
Shw Energy: 23.481712

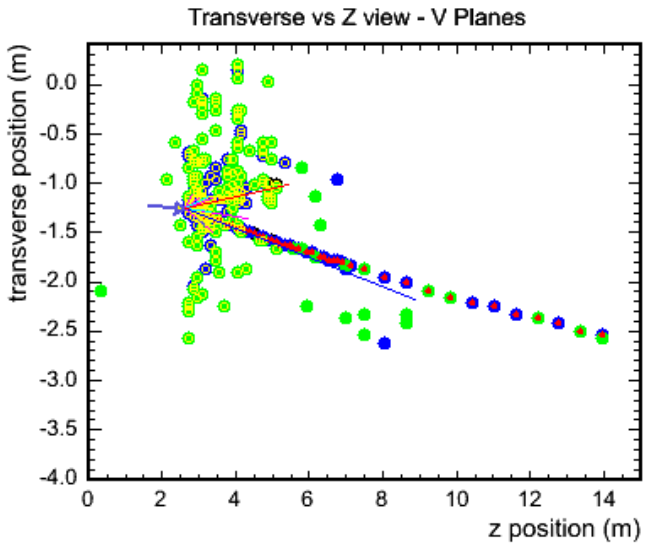
Vtx: 1.48, -0.30, 2.62

Ignore	Previous Pass		Next Pass	
NuMu	Step Back		Step Forward	
NuE	Prev Slc	Next Slc	Prev Evt	Next Evt
NC	Prev MC	Next MC	Skip to... / Run,Snarl...	AutoMatch
CC	Refresh	Lego? / Clusters?	Print	Quit

Reco
- Summed NPEs < 2.0
- 2.0 < Summed NPEs < 20.0
- Summed NPEs > 20.0
- Reconstructed Track Hit
- Reconstructed Shower Hit (cyan=EM)

Truth
- e, μ, initial ν
- p, n
- $\pi^{+/-}$, π^{0}
- $K^{+/-/0}$, γ
- τ, final ν





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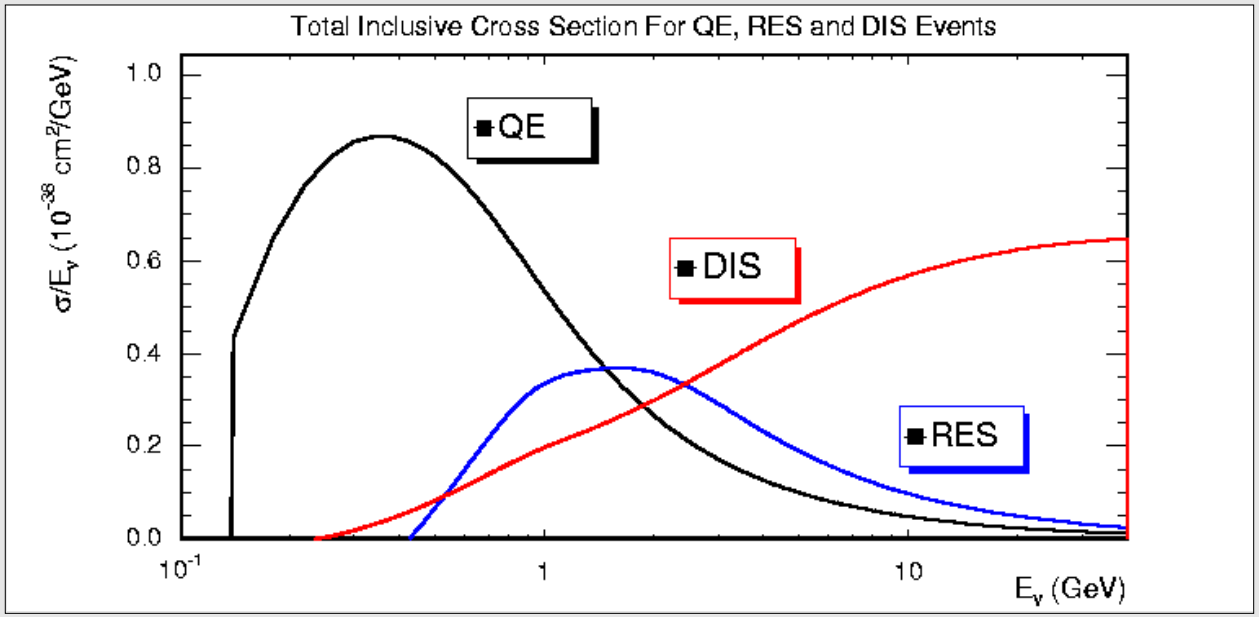
Process Cross Sections

- The following diagram shows the cross sections for QE, RES and DIS events:



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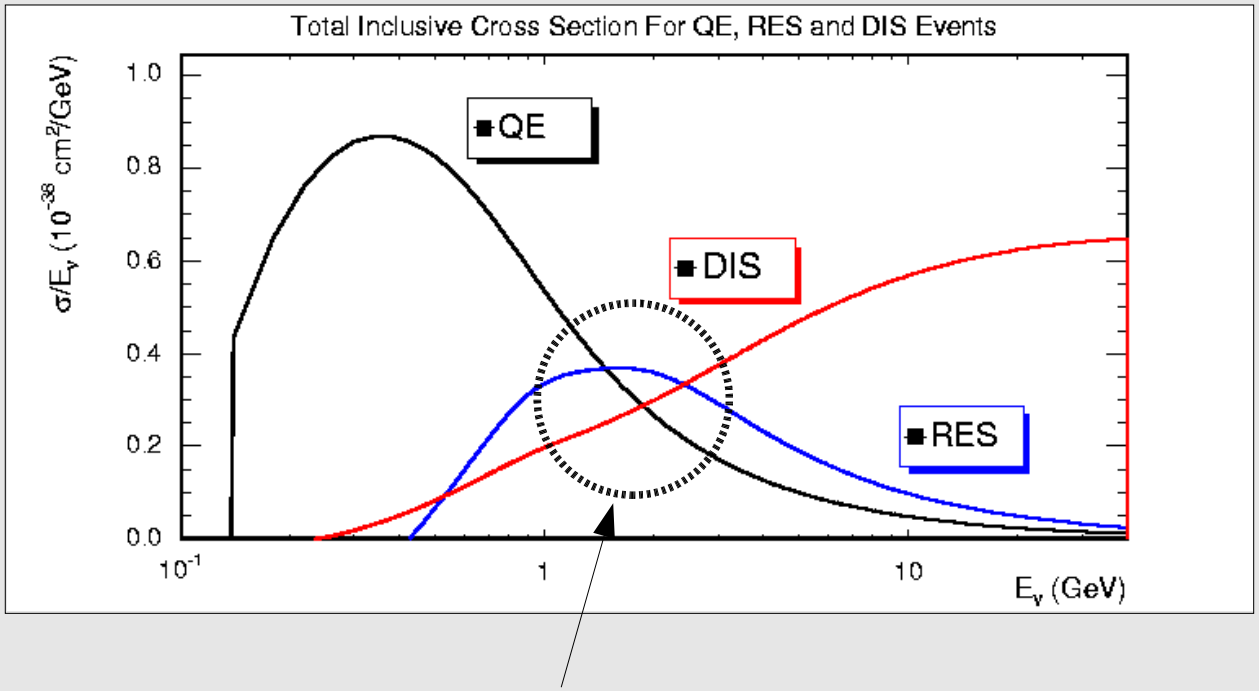

To be sensitive to the region of parameter space suggested by SuperK MINOS must have a neutrino energy spectrum peaked at a few GeV. In this regime all the processes will contribute significantly to the observed events.

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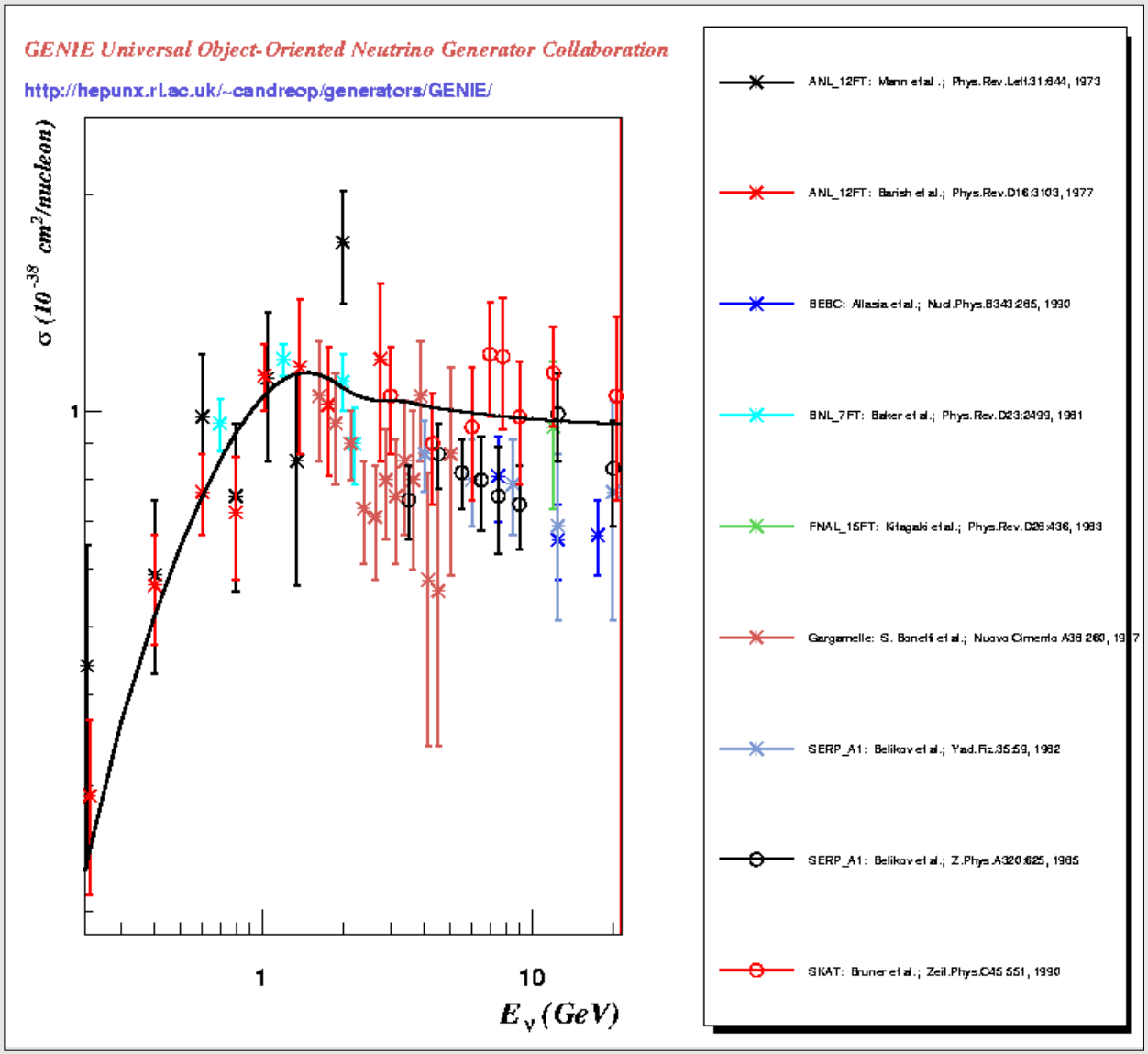
Using QE Events for a Flux Estimate



Shape well known.

Normalisation not so well known.

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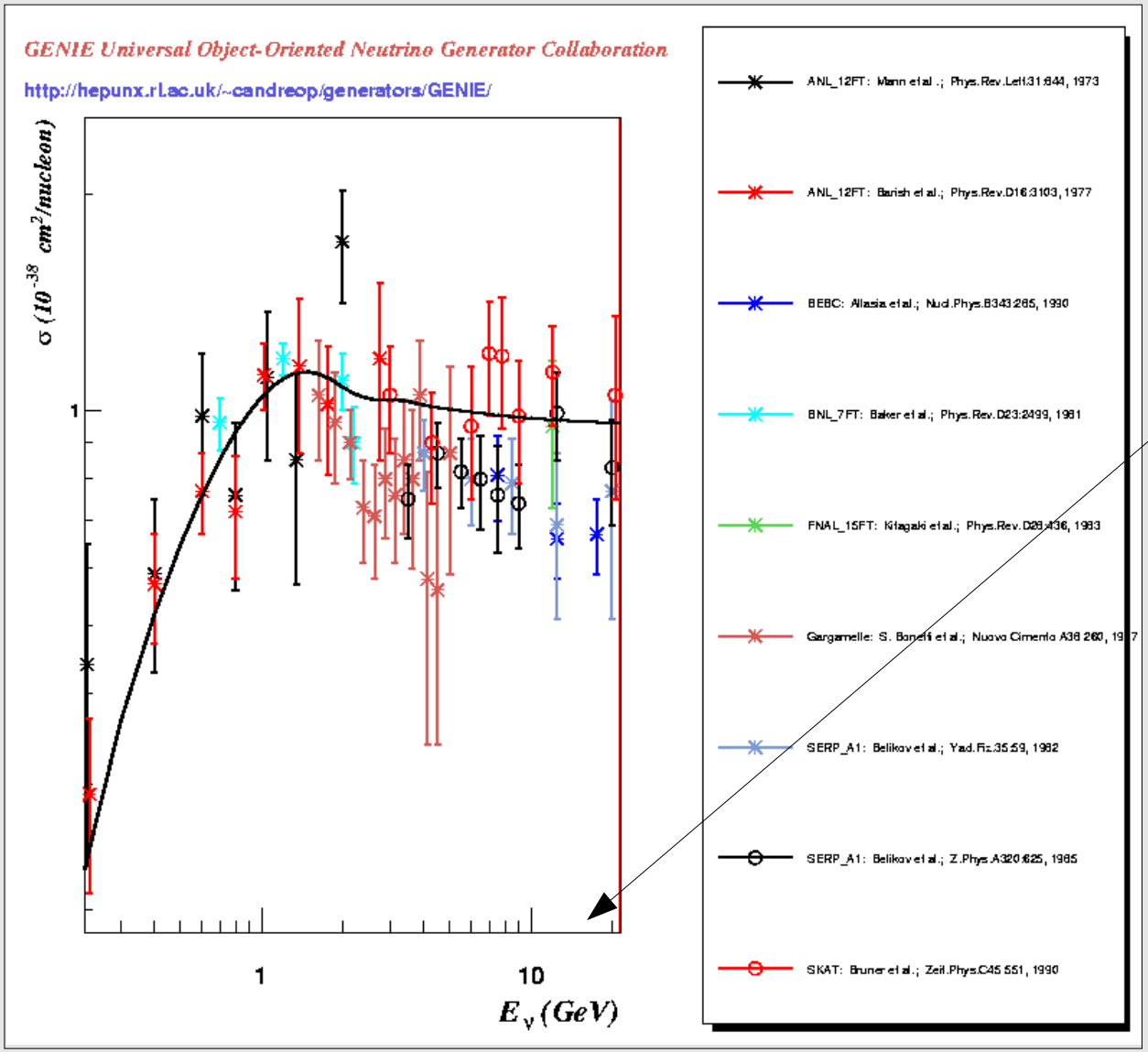

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DIS x-sec is well known here.

'Divide out' DIS x-sec from a DIS sample at ~20GeV to get flux.

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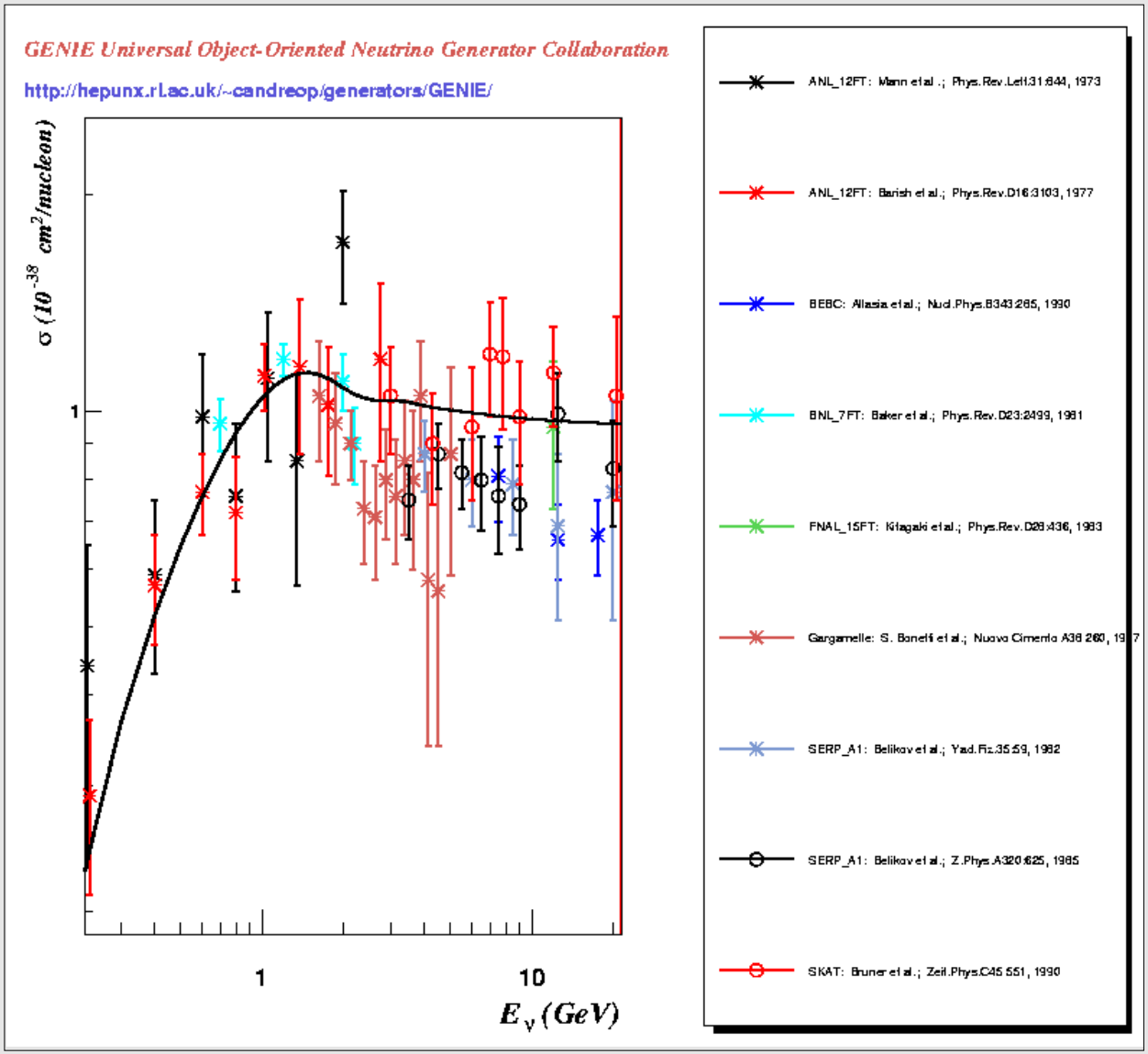

Shape well known.

Normalisation not so well known.

DIS x-sec is well known here.

'Divide out' DIS x-sec from a DIS sample at ~20GeV to get flux.

Use this to 'pin' the normalisation of QE x-sec.

'Divide out' QE x-sec from QE samples to get flux as f(E).

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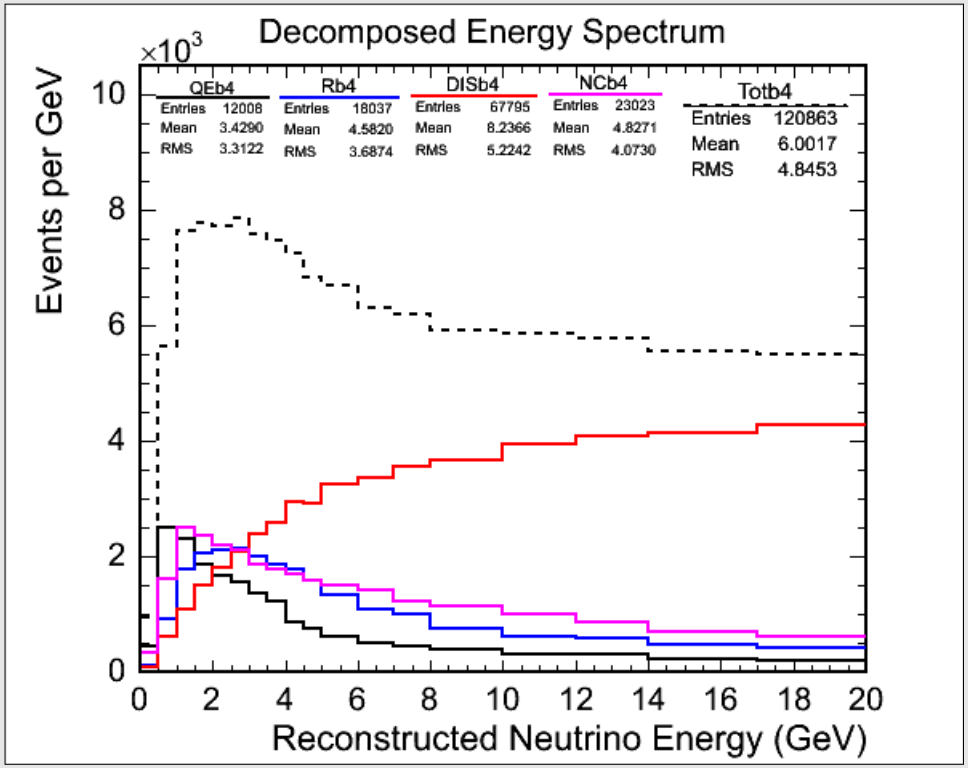
QE Sample Selection

- The method relies on selecting a relatively pure QE sample with backgrounds that are understood and can be corrected for.
- I searched for variables that could be used to discriminate between QE events and RES/DIS/NC events. The plots to follow will all correspond to the following decomposed energy spectrum (from large MC event set):



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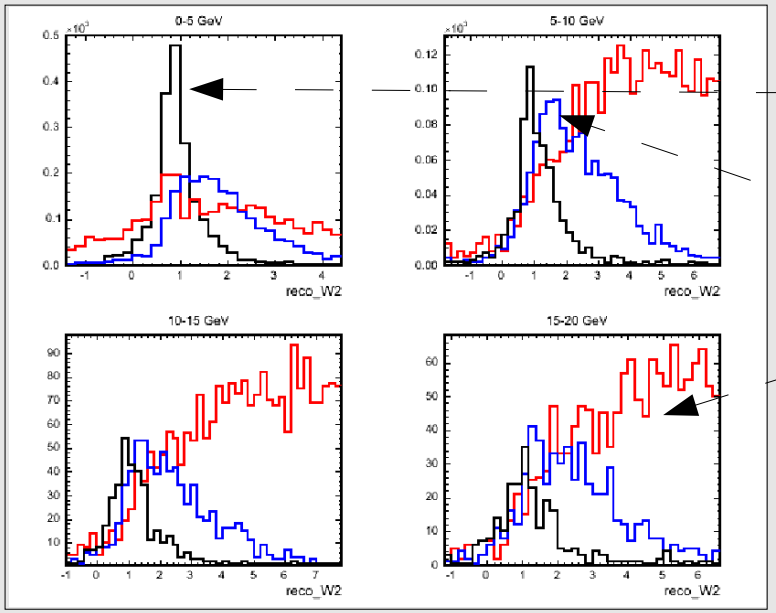
Discriminating Variables

- The first 3 variables I found useful are reconstructed quantities that are added to all MINOS physics ntuples - the numbers of showers and tracks in an event and the reconstructed invariant mass squared:



QE – peak at ~mass of proton ^{2}

RES – peak at ~mass of delta(1232) ^{2}

DIS – spread out as depends on the number of pions produced

- I then decided to try to use the hit topology and energy distributions near to the event vertex to derive some discriminating variables.

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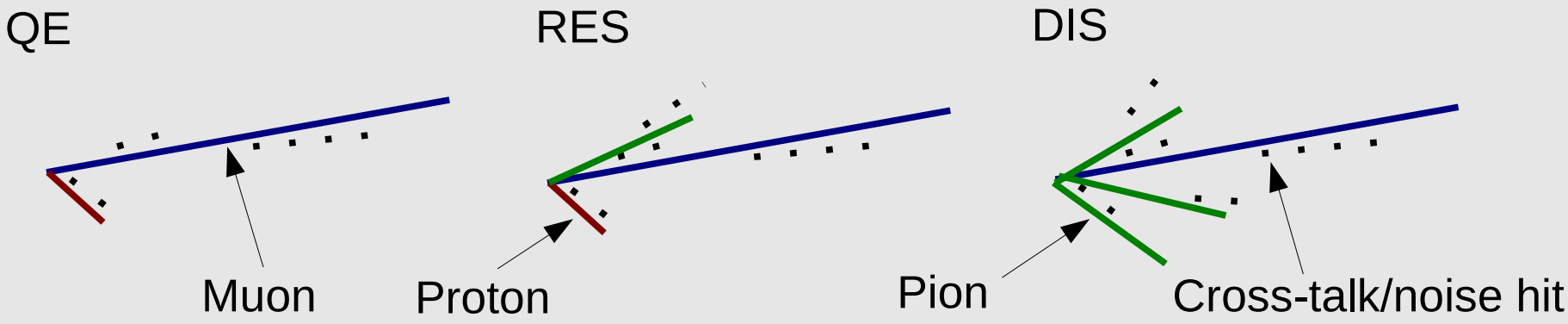
Discriminating Variables



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- Finally I try to remove cross-talk and noise hits using a simple pulse height (hit energy) cut.

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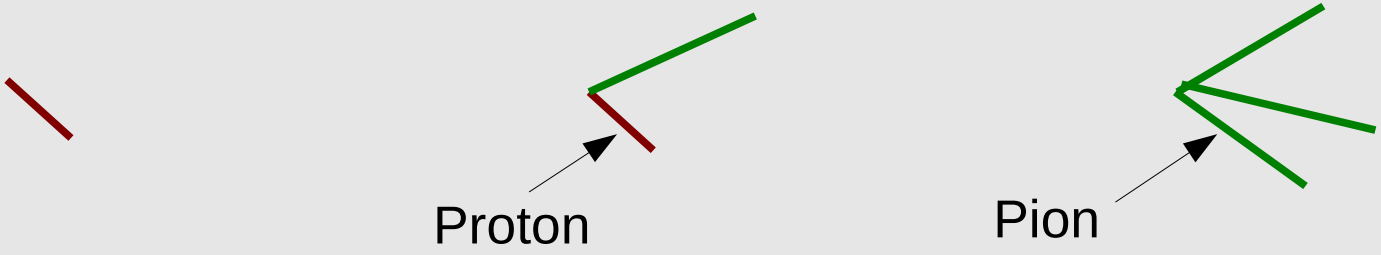
Discriminating Variables

QE

RES

DIS



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Now quite different topologies.

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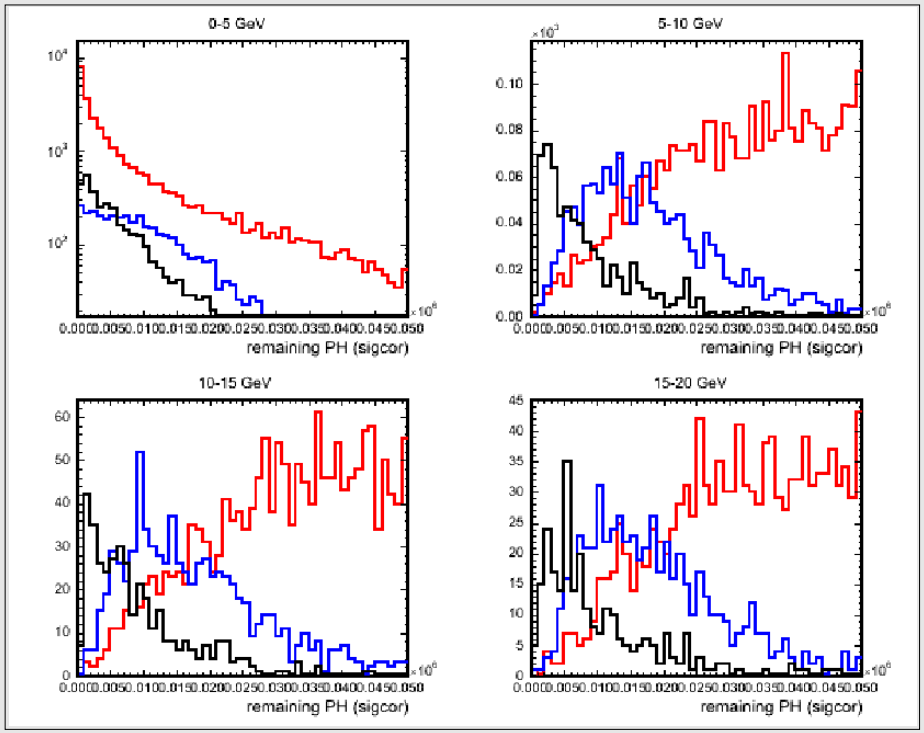
Discriminating Variables

- I define some variables based upon the properties of the remaining hits in an event:
  - The total PH remaining.



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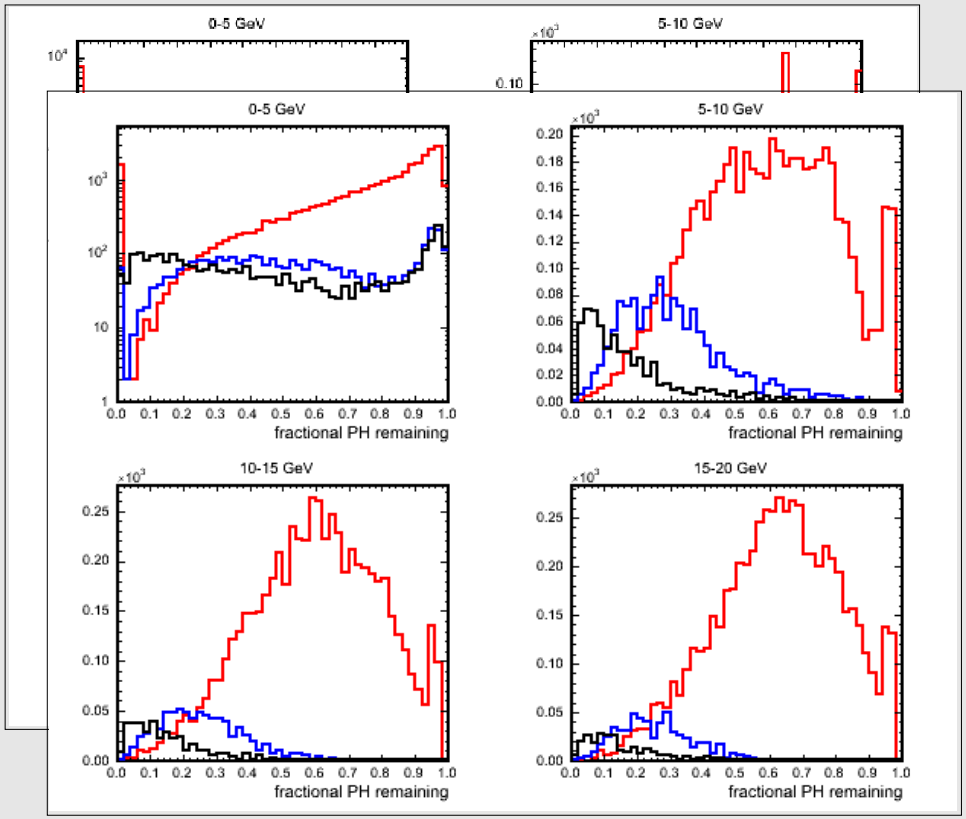

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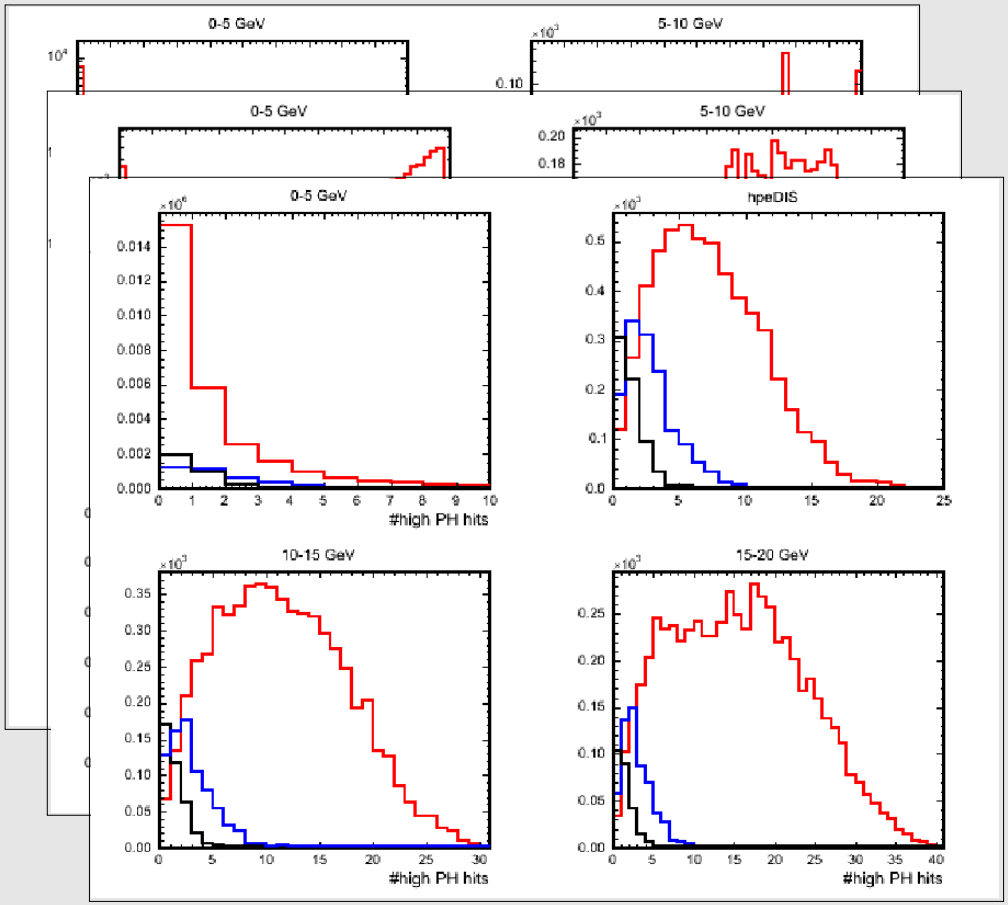

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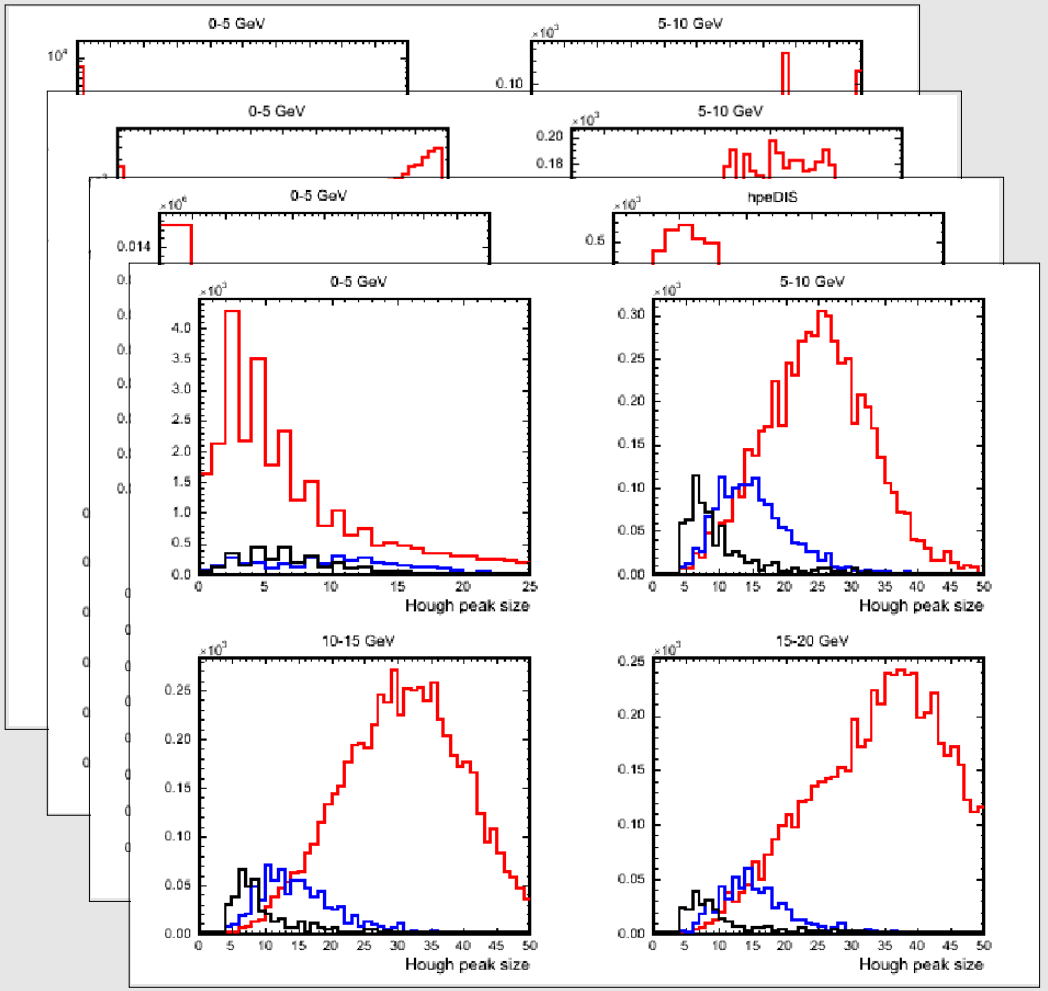
  - The number of high PH hits remaining.
  - The size of the peak in Hough space when a Hough transform is applied to the remaining hits.



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Maximum Likelihood Based Event ID

- I decided to combine these variables into a maximum likelihood analysis and use the individual histograms for each event type and variable as pdfs.
- All variables will scale with energy with some functional form and so I decided to perform an independent likelihood analysis in a number of bins of reconstructed neutrino energy.
- The bins range from 0-20GeV but are asymmetric – they get larger with energy in accordance with the energy resolution of the detectors.
- I define a ID parameter for an event as:

$$P_{PID} = -\,sqrt(-logP_{QE}) + sqrt(-logP_{bg})$$

Compound probability to be a QE event.

Compound probability to be a background event.

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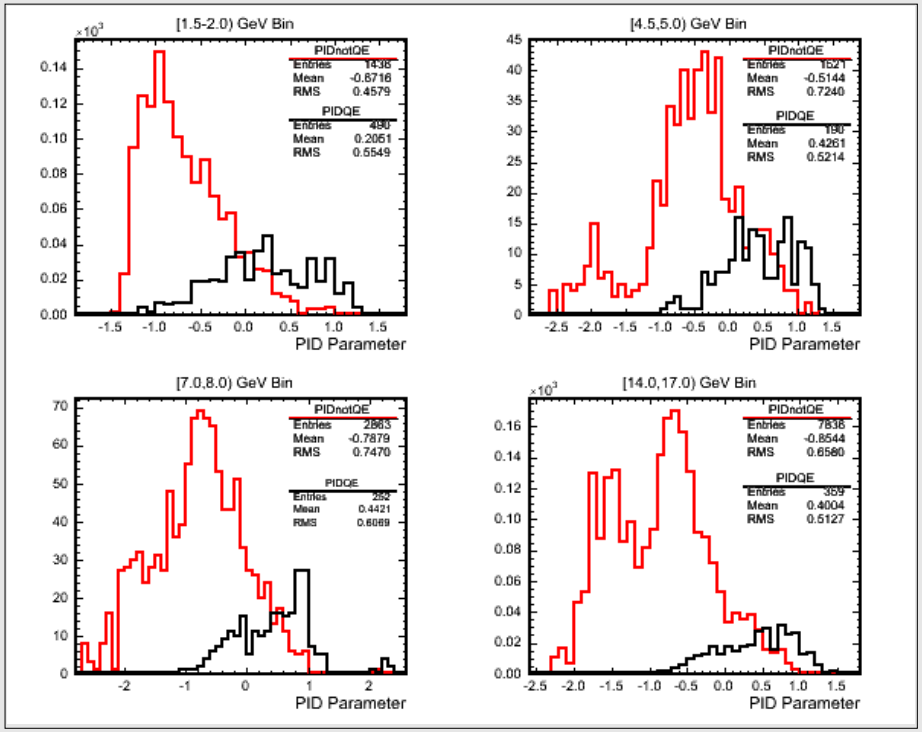
Results for the MC Sample

- I used half of the MC sample shown before to fill the pdfs and then ran the second half of the events though the likelihood analysis.
- The following figure shows some examples of the distributions of the ID parameter for true QE (black) and true RES+DIS+NC (red) events:



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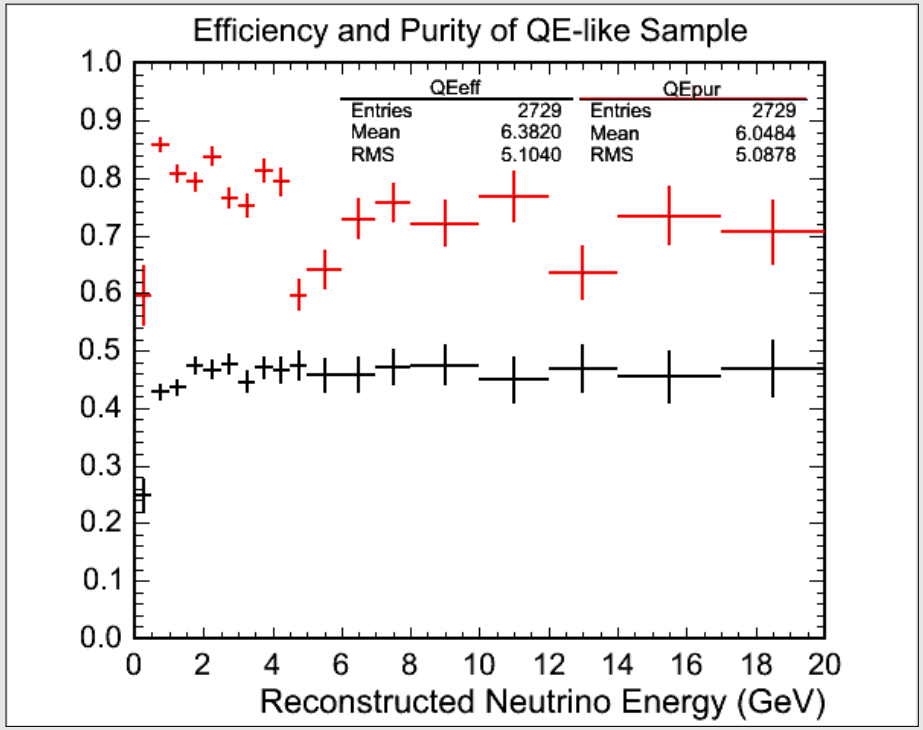
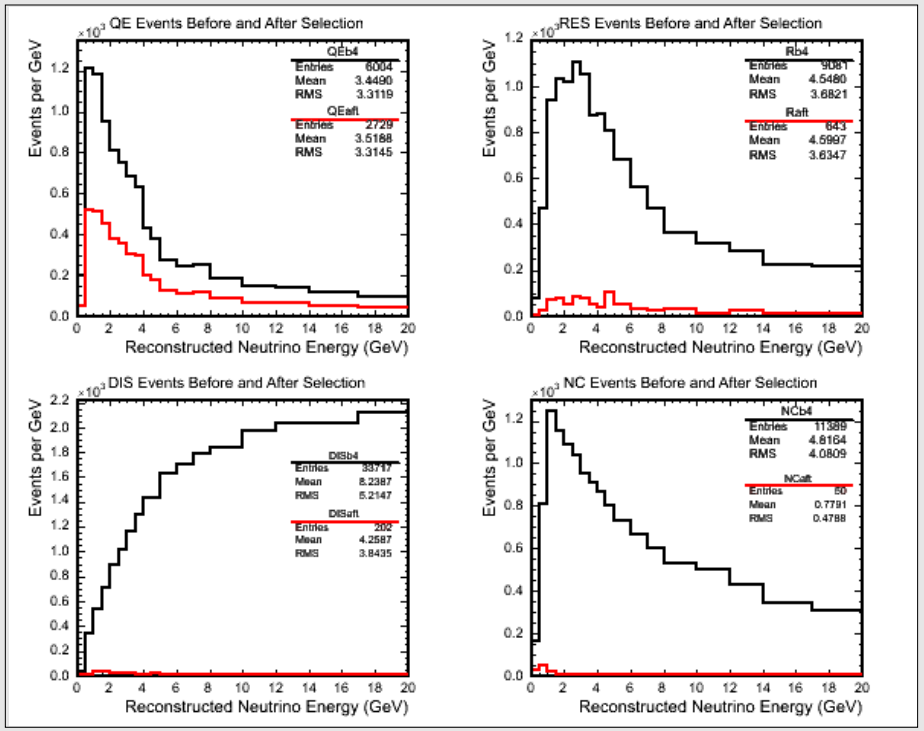
Results for the MC Sample

- A cut was applied to the ID parameter in each energy bin and these cuts were tuned to give a flattened efficiency for selecting QE events.
- The following figures show the efficiency and purity of the QE-like sample and the numbers of QE,RES,DIS and NC events that pass the cuts:





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Flux Extraction

- One possible way of unfolding the flux from this QE sample is to construct an estimator for the number of true QE events in each reconstructed energy bin *i* according to:

$$\hat{n}_i = C_i (m_i - b_i)$$

Number of events in bin *i* (from data).

Expected number of background events in bin *i* (from MC).

- Where C_i is the correction factor (or generalised efficiency) and can be expressed as:

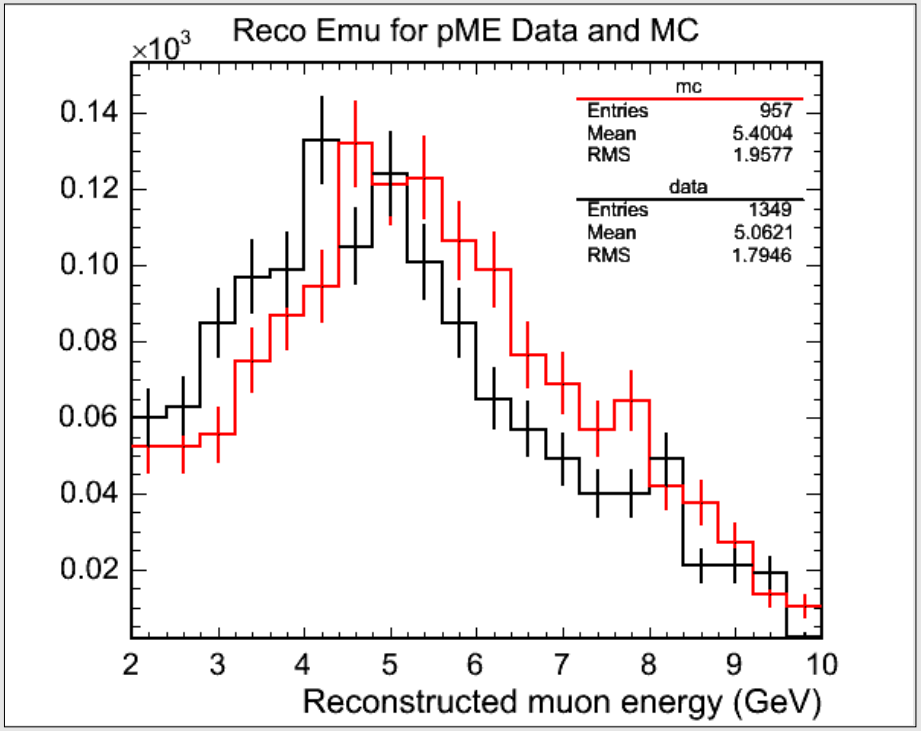
$$C_i = (n_i / r_i)$$

Number of true QE events in the true energy bin *i* (from MC).

Number of QE-like events in reco'd energy bin *i* (from MC).

Data and MC Comparisons

- Very exciting time for MINOS – the data is flowing fast! Does our ND MC describe our ND data?
- I have taken MC and data for the MINOS medium energy beam (peak at ~5GeV) and run them through the QE sample selection. I have then compared physics quantities for the data and MC QE-like samples using the number of protons hitting the NuMI target as a normalisation.



Small offset with ND MC a little higher than the data. This is a comparable effect to that seen by others in the collaboration.

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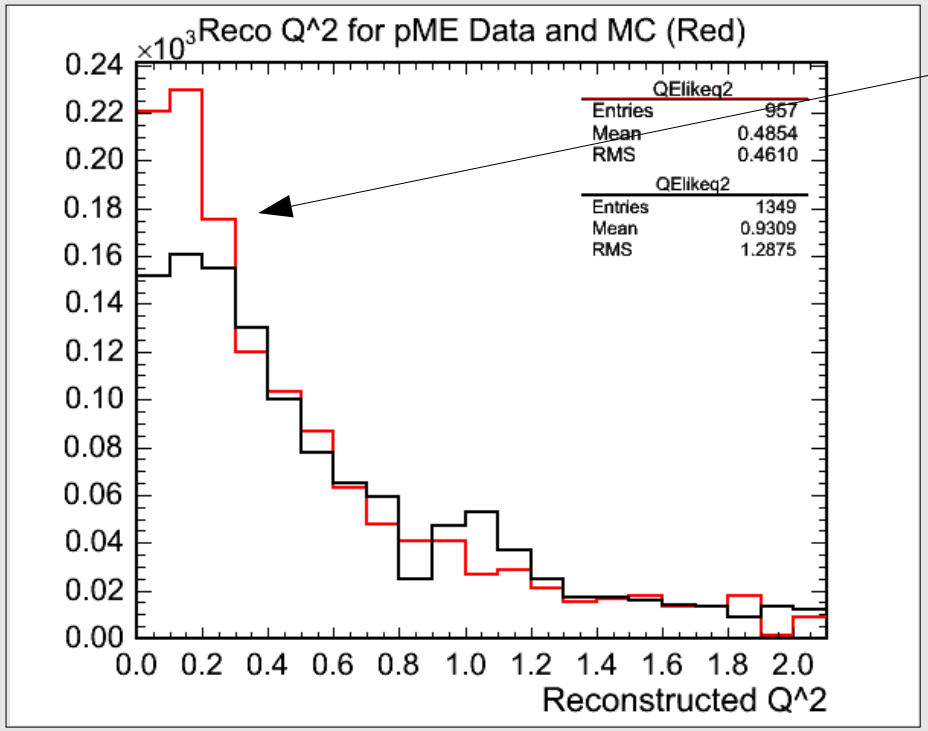
Data and MC Comparisons

- The only other quantity that I shall show here is a plot of the reconstructed Q^2 for data (black) and MC (red).



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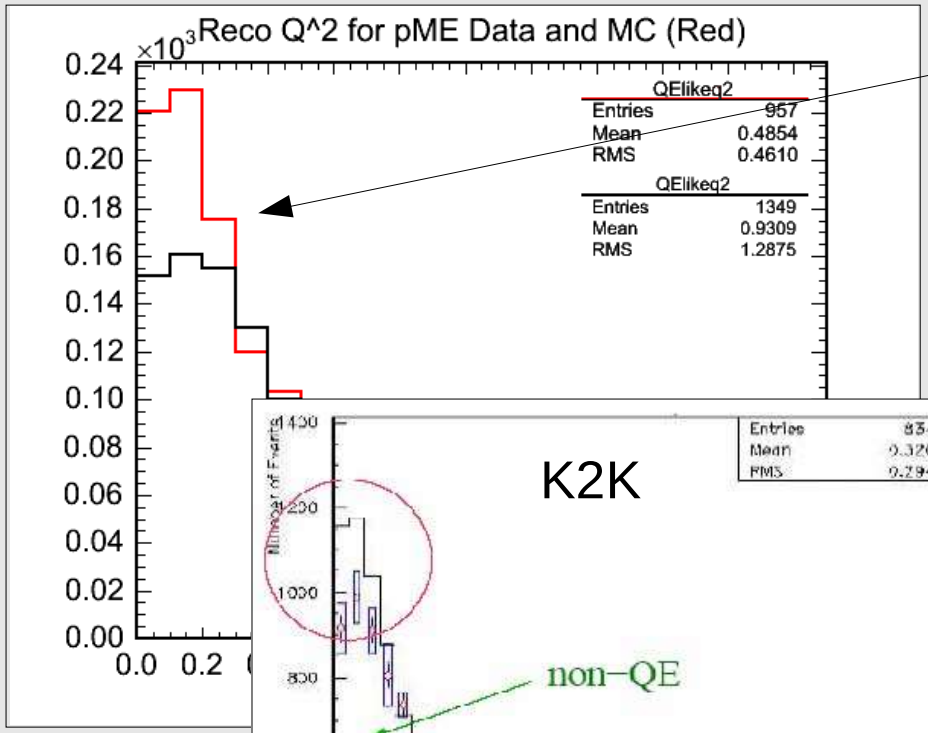
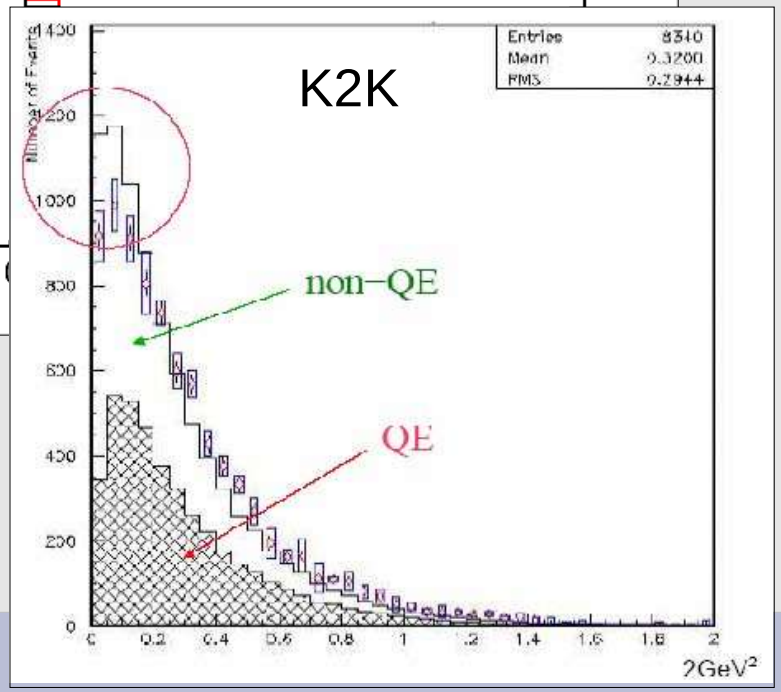
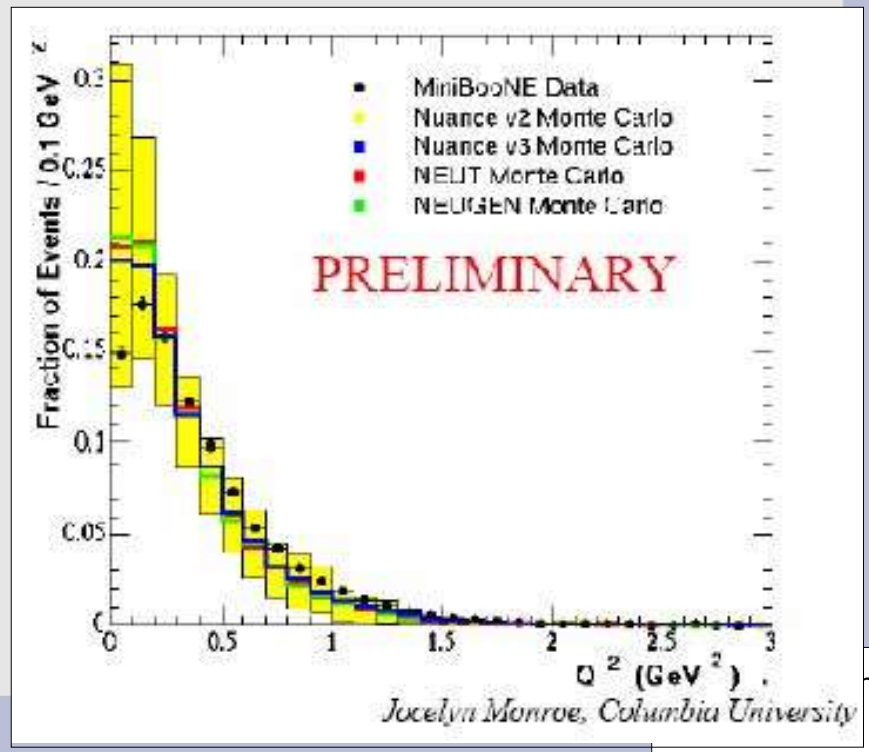


Possible suppresion at low Q^2?

- This has been seen by both K2K and MiniBooNE:





And what about the thesis...

- This is a very exciting time to be a PhD student on MINOS and one of my tasks for the near future will be to continue to look at comparisons between ND data and MC and to investigate any discrepancies.
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Any questions?