Status of the MINOS Experiment

N. Saoulidou, Fermilab

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Outline

- Introduction
- Experiment Overview
- Neutrino Beam & MINOS Detectors
- Atmospheric neutrinos
- Beam Neutrino Data in :
  - Near Detector
  - Far Detector
- Physics Potential
- Summary

Introduction

- **Neutrinos** were invented in order to solve a **“mystery”** (energy non-conservation in beta decays)…

- Since their birth, they have created even more **mysteries** themselves ...

  - **Solar neutrino “problem”** (ν_e‘s from the Sun are less than expected)
  - **Atmospheric neutrino “problem”** (ν_μ‘s from the atmosphere are less than expected)

- The “problem” of missing neutrinos can be nicely explained if they posses non-degenerate masses, in which case they can **oscillate** between the different flavors:

  - **3 active (LEP/SLC)**
  - **n sterile (LSND result currently checked by MiniBoone, we will know soon!)**

3-Flavor Oscillation Formalism

• If neutrinos oscillate, then the interaction eigenstates (what we observe) can be expressed in terms of the mass eigenstates as follows:

$$\nu_{e(\mu)(\tau)} = \sum_{i=1}^{3} U^{*}_{e(\mu)(\tau)i}\,\nu_i$$

Atmospheric — Cross Mixing — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & -s_{23} \\ 0 & s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & -s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

Majorana phases

$$\begin{bmatrix} e^{ia_1/2} & 0 & 0 \\ 0 & e^{ia_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

0νββ decays

2-Flavor Neutrino Mixing

- In certain experimental situations only one q contributes, in which case one can write the oscillation probability as :

$$P = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2_{23} \cdot L}{E}\right)$$

Physics **Experiment**

•Different neutrino experiments , depending on what components of the mixing matrix they want to measure involve:

- Different baselines

- Different neutrino energies

- Different neutrino flavors

When the region of parameter space (Δm^2, $\sin^2 (2\theta)$) is ~ known then Δm^2 determines the L/E ratio for which the oscillation phenomenon will be maximum and therefore "easier" to observe (in reverse, L/E determines the experiment sensitivity).

SuperK , Atmospheric neutrinos

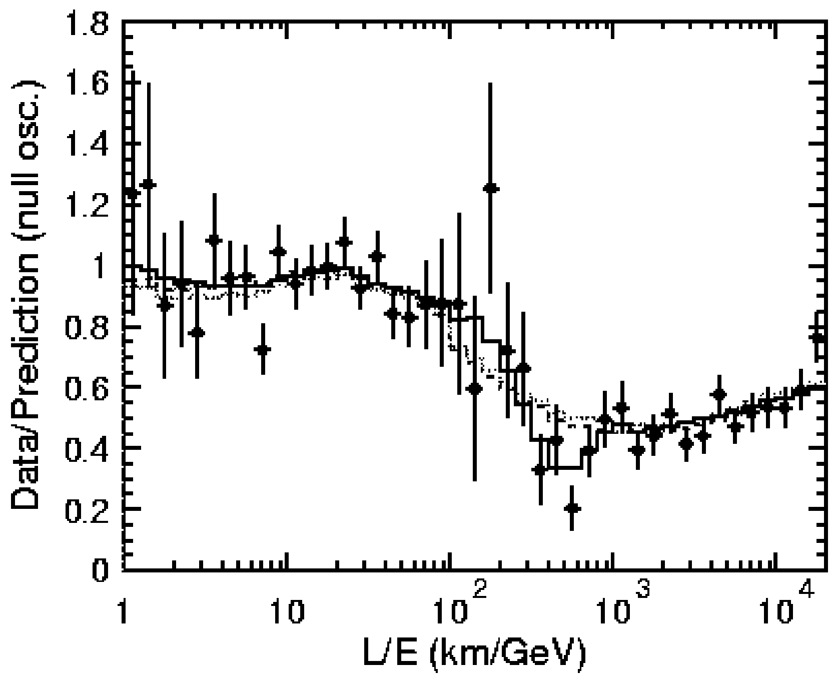
- Study muon and electron neutrinos produced in the upper atmosphere.
- Observation : fewer muon neutrinos than expected

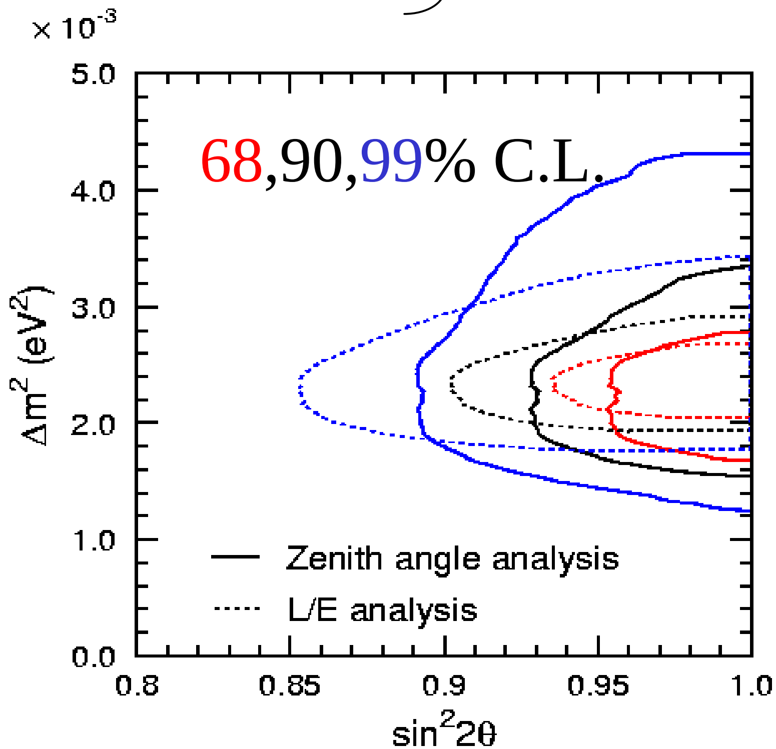
  : as many electron neutrinos as expected

  : as many NC interactions as expected

$\nu_\mu -> \nu_\tau$

Observed / Expected $\nu_\mu CC$ interactions



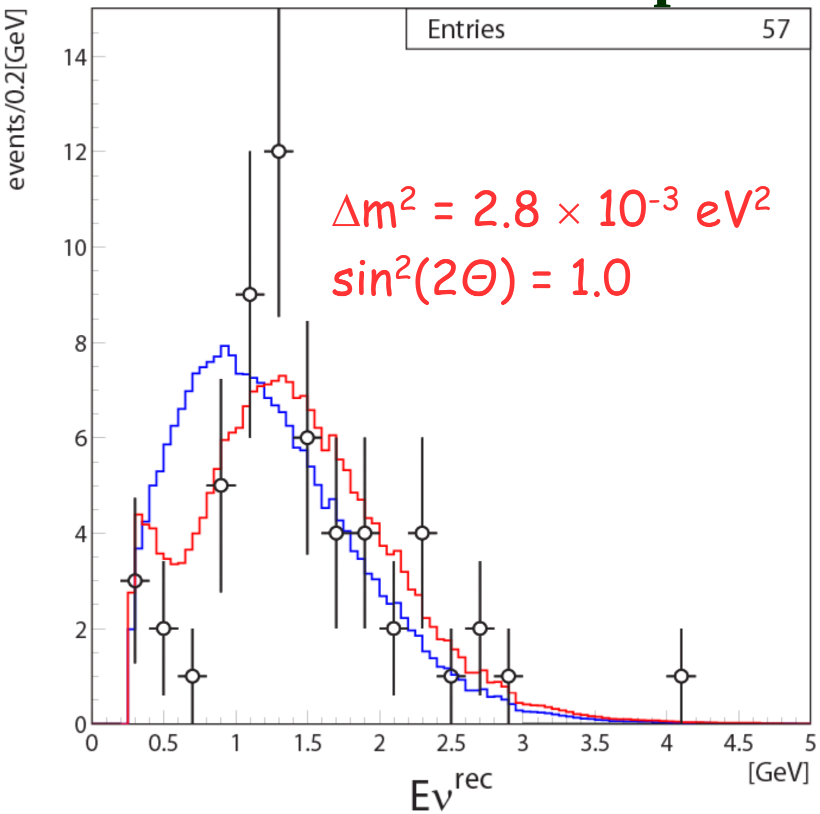


$sin^2(2\theta_{23})>0.92$ & $0.0015<\Delta m_{23}^2<0.0035$

K2K – the 1st Long-Baseline Accelerator-based Experiment

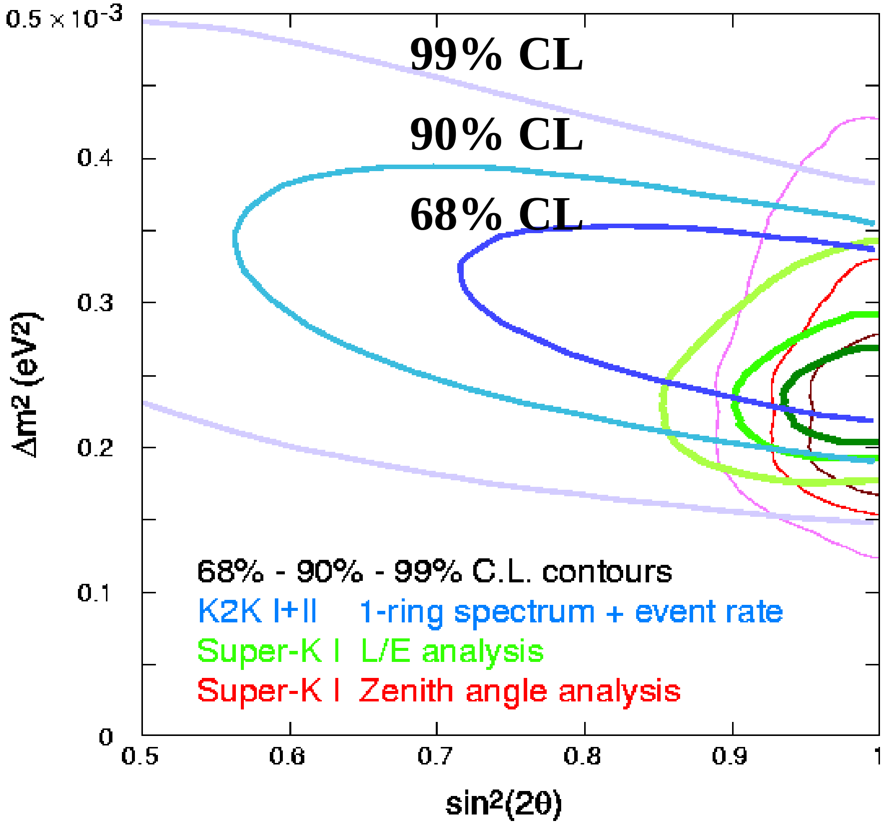
- **Goal was to confirm SK result with accelerator muon neutrinos**

107 Observed / 149.7 Expected



0.89×10^{20} p.o.t.

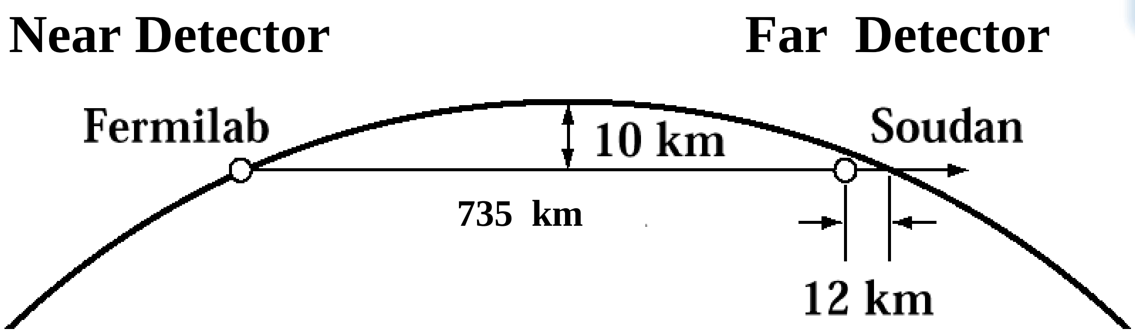
L=250Km



Plots courtesy C. Walter

MINOS Experiment

- **MINOS (Main Injector Neutrino Oscillation Search) is a two detector long baseline neutrino oscillation experiment.**
- ***Its goal is to study the region of parameter space indicated by atmospheric neutrino experiments and make precise measurement of the oscillation parameters Δm^2 & $\sin^2(2\theta)$***



Comparison between Near/Far measurements will establish the oscillation signal and characteristics

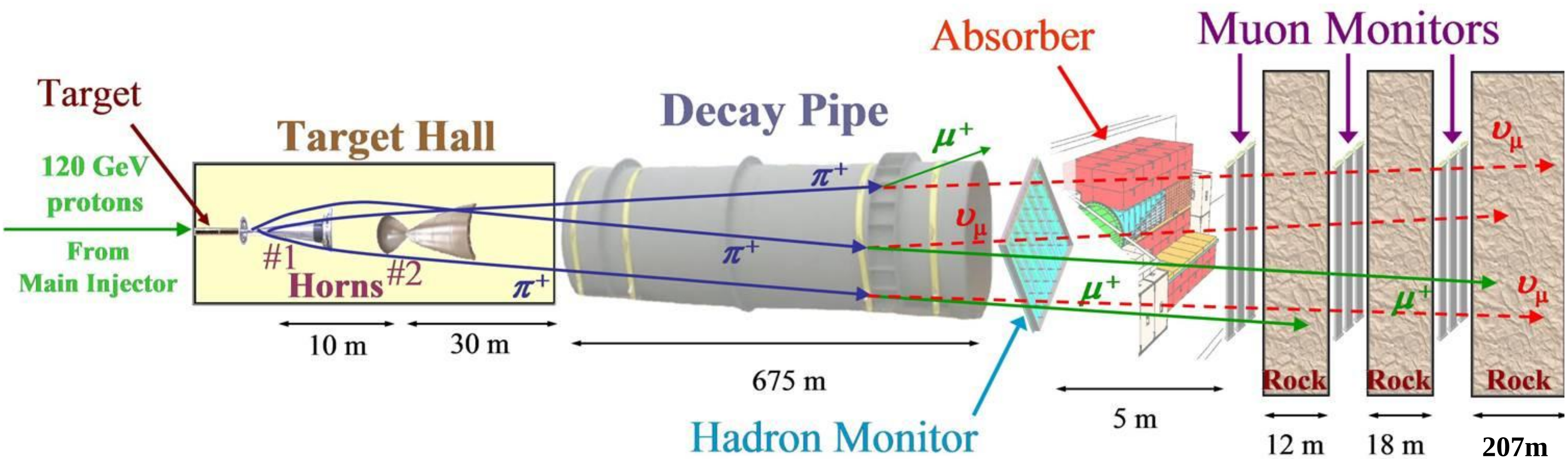
MINOS Collaboration

32 institutions
175 physicists

MINOS Near Detector Surface Building

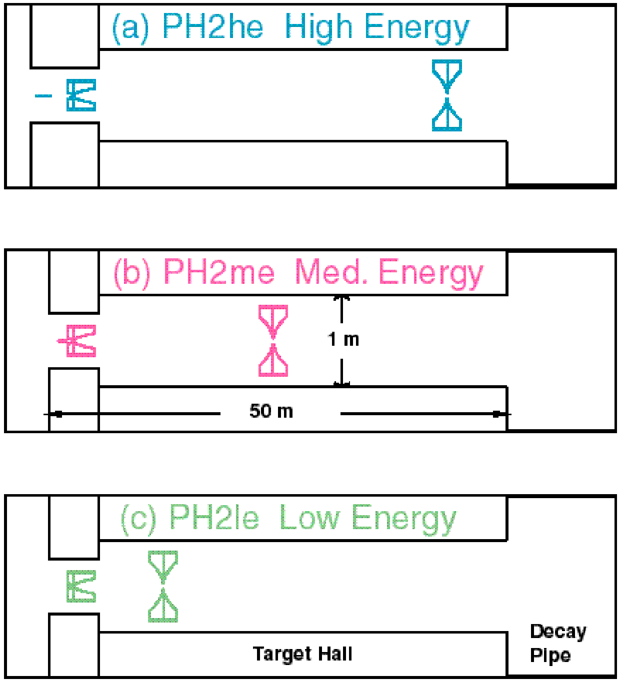
Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
College de France • Harvard • IIT • Indiana • ITEP-Moscow • Lebedev • Livermore
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Protvino • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Western Washington • William & Mary • Wisconsin

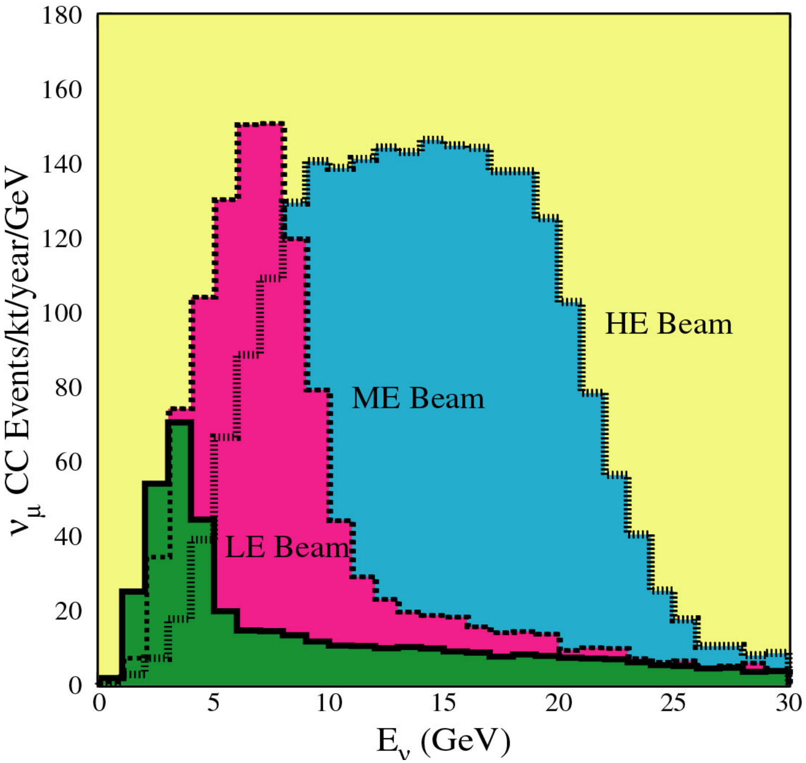
NuMI Neutrino Beam



- 120 GeV protons strike the graphite target
- Current intensity 1.5 x 10^{13} ppp every 2-4 sec
- Goal for the end of the year ~2.5 x 10^{13} ppp every 2 sec.
- (2008-9) expected rate ~ 3.4 x 10^{20} protons/year

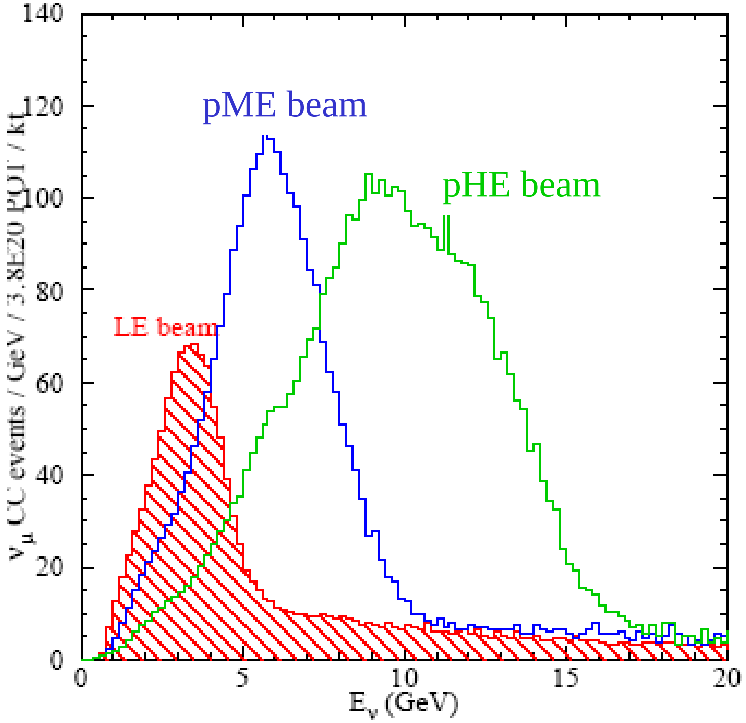
NuMI Target & Horns





- **Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn (provision is made for three different 2nd horn positions).**

NuMI Neutrino Beam configurations



Running in the LE configuration we expected 1300 ν_μ CC events for 2.5×10^{20}/year in the 5.4kt FAR detector (in the absence of oscillations).

•One can also obtain different neutrino spectra by just moving the target (fast, have taken data already for three different energy configurations).

• LE, pME and pHE data used to perform systematic studies in the Near Detector and tune our Monte Carlos (more about this later).

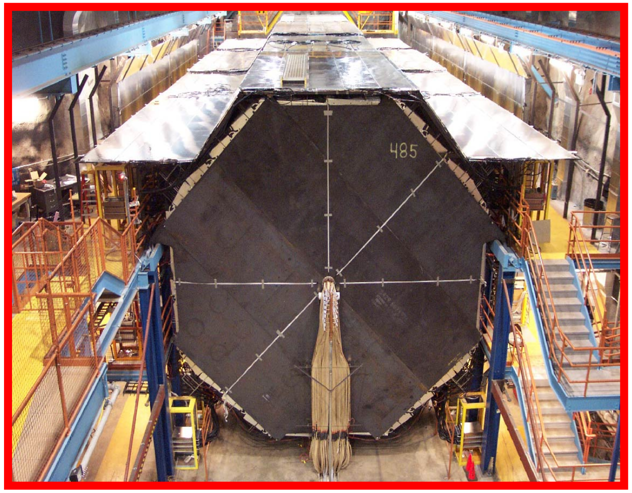
The MINOS Detectors

NEAR

0.98 kt

FAR

5.4kt

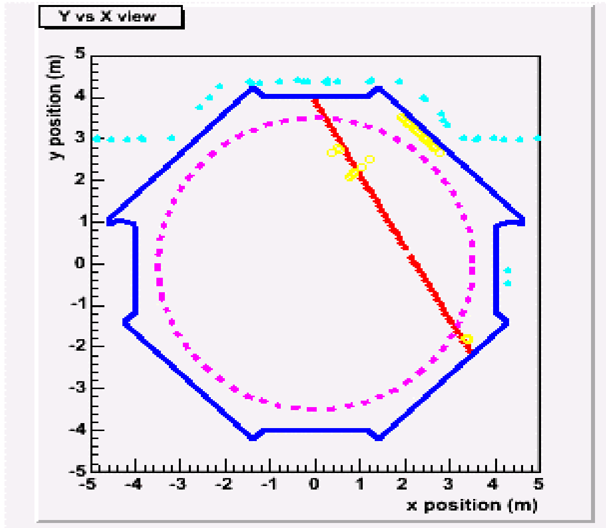


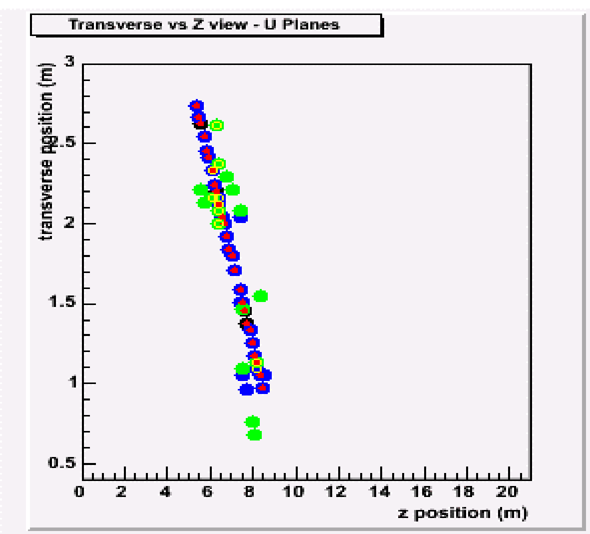
- **Basic Idea : Two detectors “identical” in all their important features.**

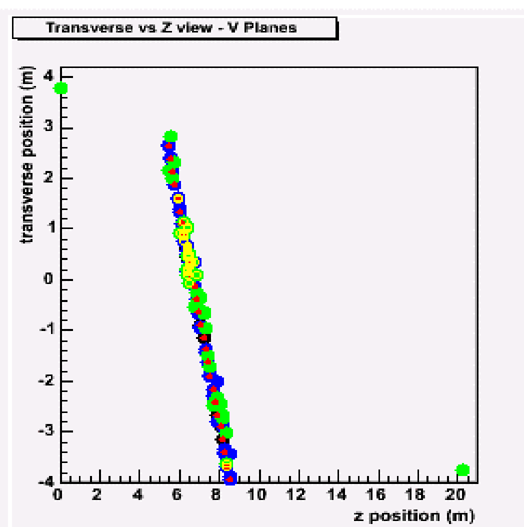
• Both detectors are tracking calorimeters composed of interleaved planes of steel and scintillator

- 2.54 cm thick steel planes
- 1 cm thick & 4.1 cm wide scintillator strips
- 1.5 T toroidal magnetic field.
- Multi-Anode Hamamatsu PMTs (M16 Far & M64 Near)
- Energy resolution: 55%/√E for hadrons, 23%/√E for electrons (measured with Calibration detector at Cern)
- Muon momentum resolution ~ 6 % from range (~ 12 % from curvature)

Far Detector Non Beam data
Typical events







- **In the Far detector we record events that satisfy either of the following trigger conditions:**

4/5 consecutive planes OR

Sum of ADC >1500 or 6 hits in any 4 consecutive plane window

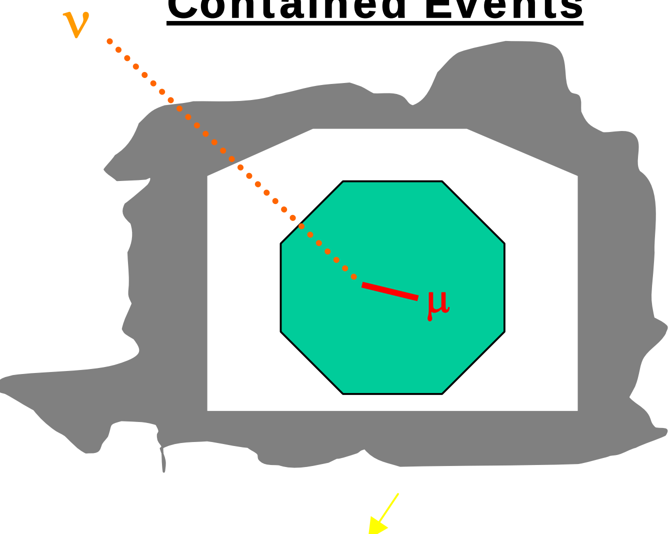
0R

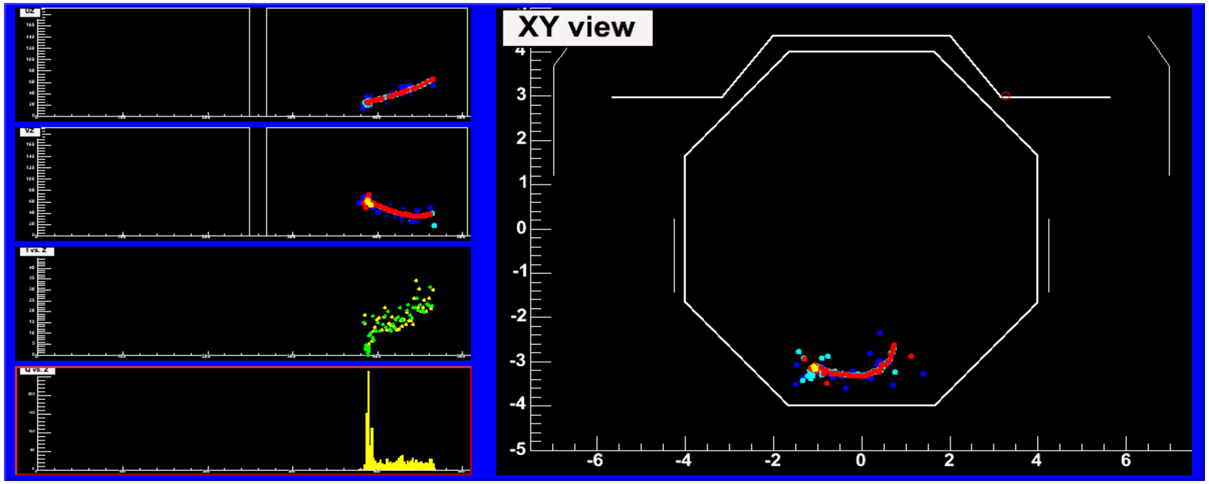
Events within +/-50 usec from a beam spill (beam data)

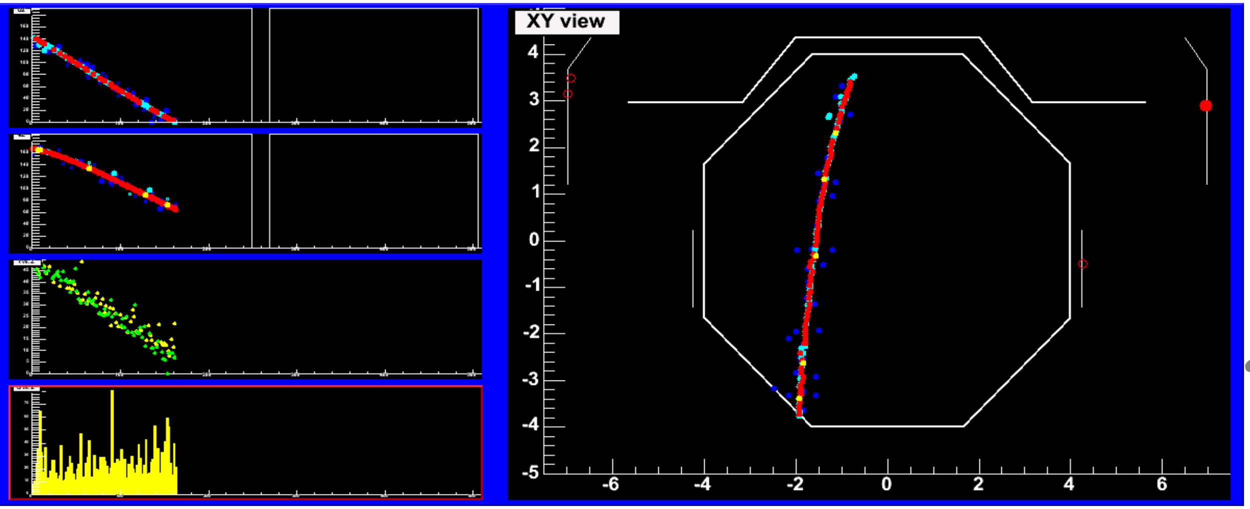
- **Mostly we record cosmic ray muons @ a rate of 0.5 Hz**

Far Detector Non Beam data
Atmospheric events

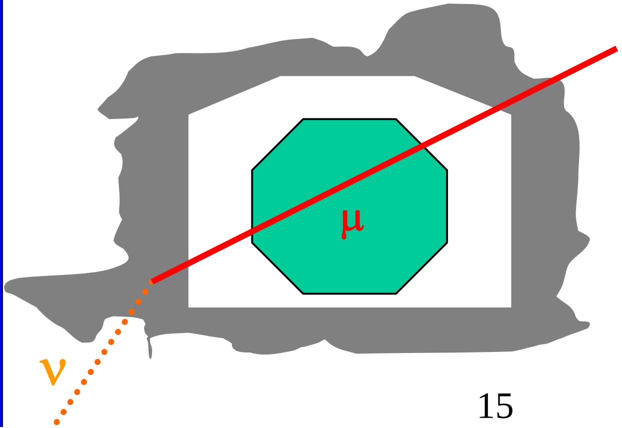
Contained Events





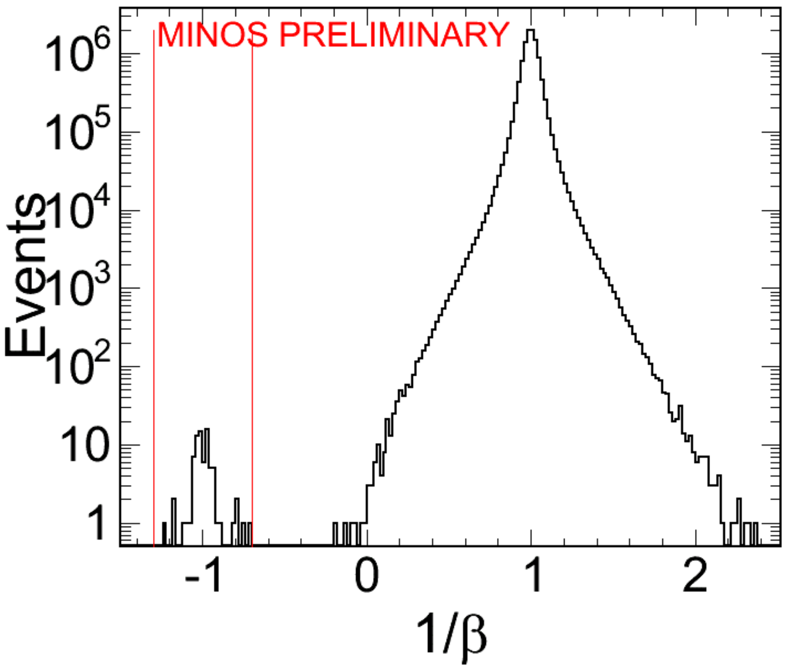


Upward-going muons



Far Detector Non Beam data

Atmospheric Events



Plotting: c dt / ds = 1 / β

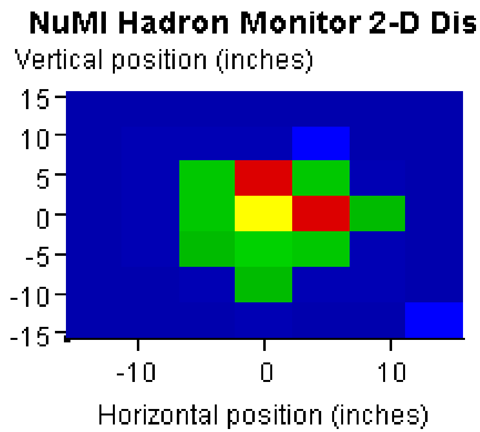
(*signed by dy/dt*)

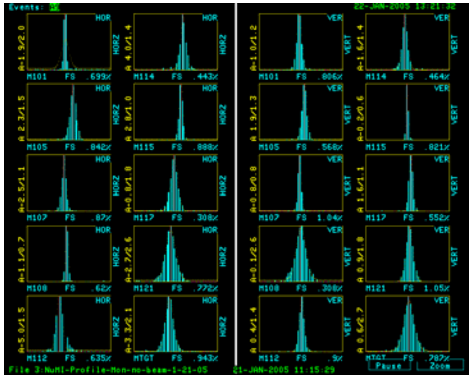
- **For ~440 live days we have 91 Upward-going (atmospheric neutrino induced) muons and 118 Contained atmospheric neutrino events.**
- **Analyses are converging, first results soon.**
- **We will continue to take atmospheric neutrino data throughout the MINOS run.**

Note: 2.4 ns single hit timing resolution !!

NuMI Starts!

- **December 3 - 4, 2004**
  - **Beam transported through the target hall & onto hadron absorber**
    - **Target out & decay pipe evacuated , no neutrinos expected (or seen)**
  - **Saw beautiful signal on profile monitors all the way down the beam line to the absorber and the hadron monitors on the 10^{th} pulse!**
  - **And then celebrated...**

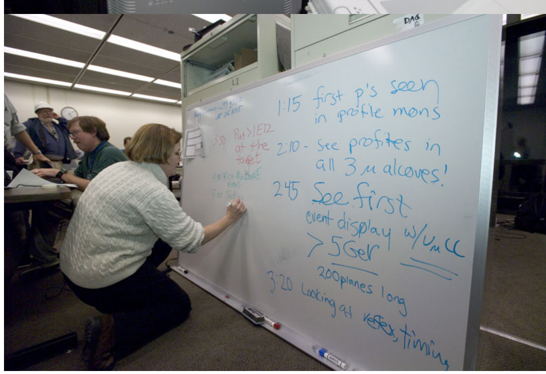


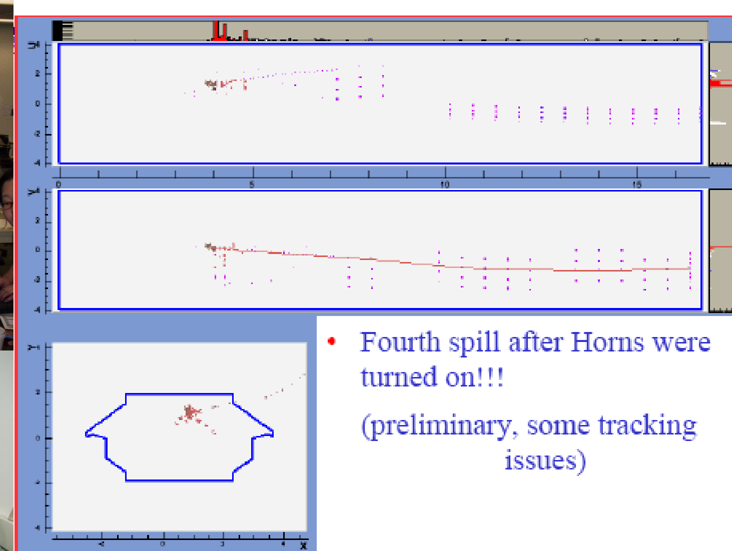


MINOS Starts!!

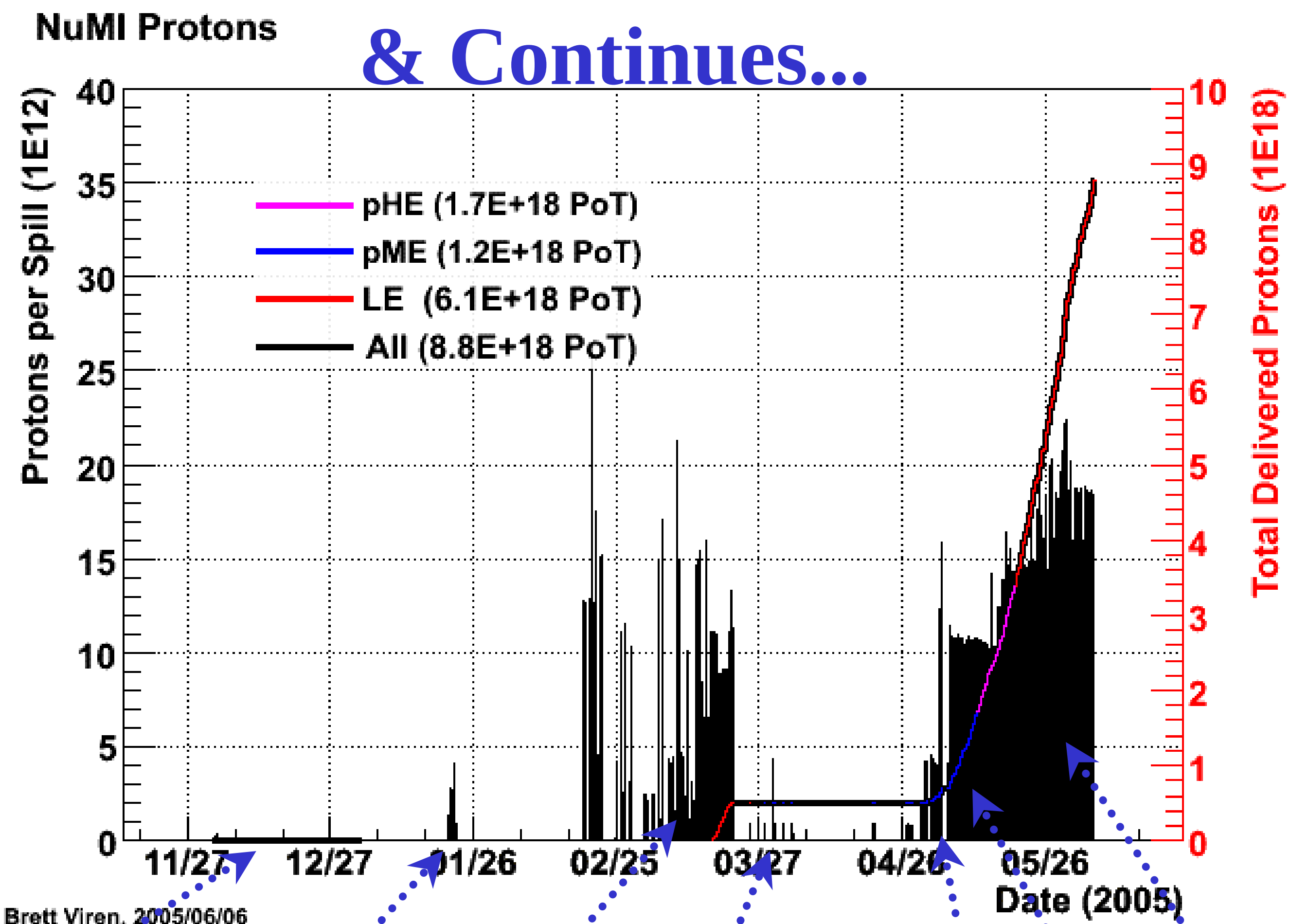
- **January 21 - 22, 2005**
  - First beam on target, Horns on, ME beam
  - On 4th!! horn pulse saw the first neutrino in the Near Detector ! (since then we have been seeing many many more!)
  - And then celebrated again...





& Continues...



First neutrino beam

First ND neutrino events

Completion of NuMI project

First FD neutrino events!

Target Leak, down for a month

Back up ME running

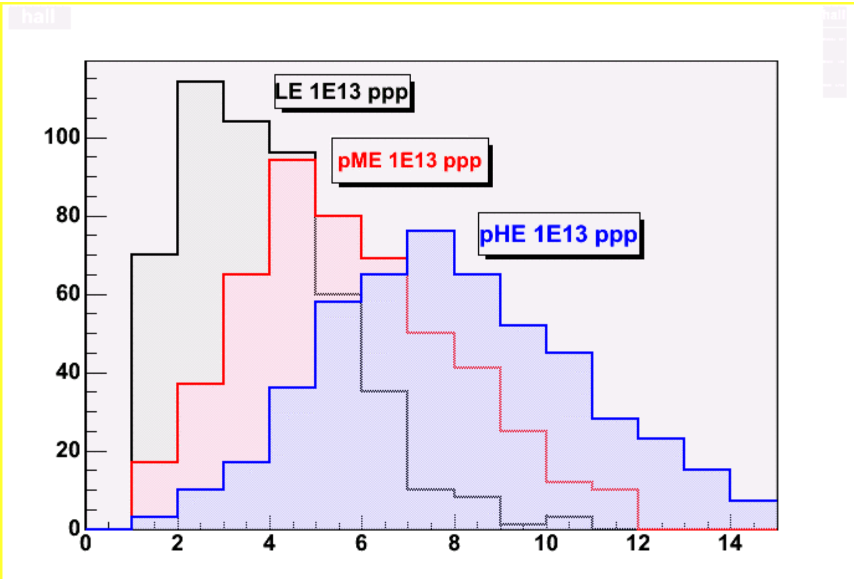
HE running

LE running

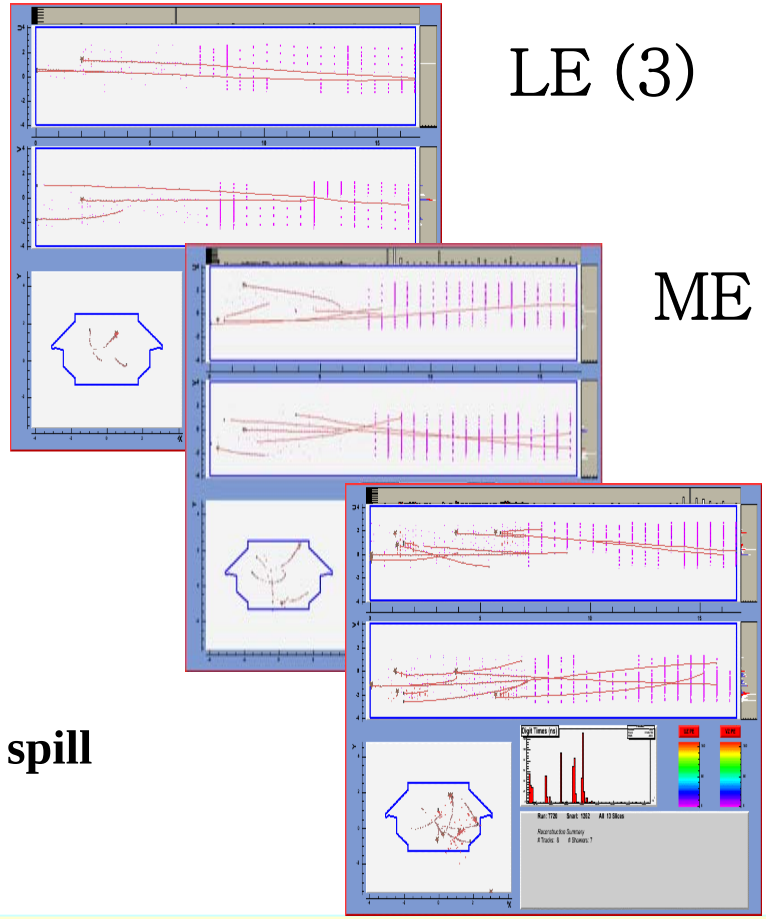
Neutrino Events per Spill

(rock muons & contained neutrino events)

Number of spills



Number of reconstructed neutrino events per spill



LE (3)

ME (5)

HE (7)

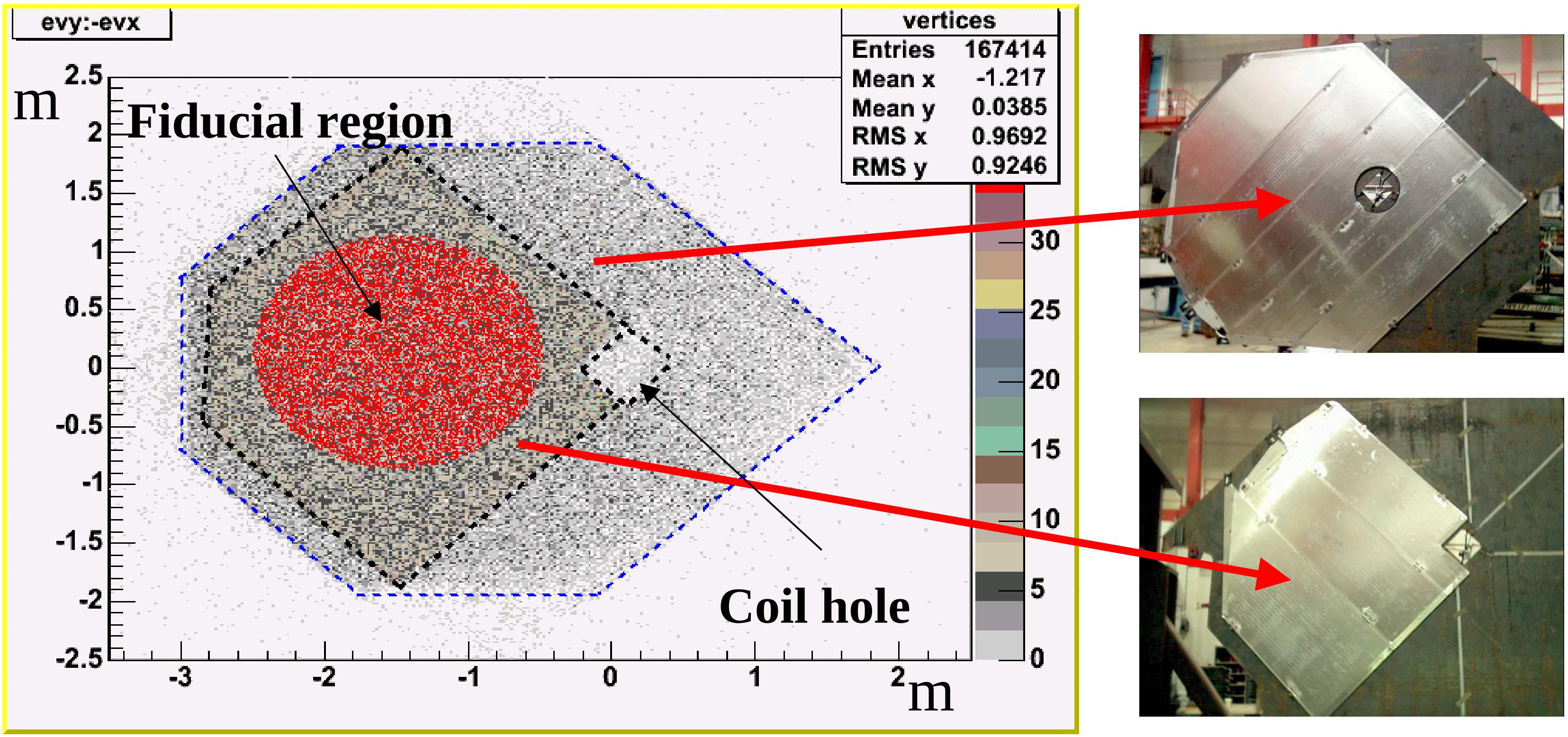
- For the same beam intensity the number of neutrino events scales with neutrino energy (scaling factor as expected from MC).
- Very reassuring as far as detector performance is concerned.

Event Vertices & Fiducial Region

- **Near Detector**

-2.5x10^{13} POT every 2 sec (2.5x10^{20} per year)-> 1,000,000 ν's in a cylindrical fiducial region of 1 m radius and 4 m length.

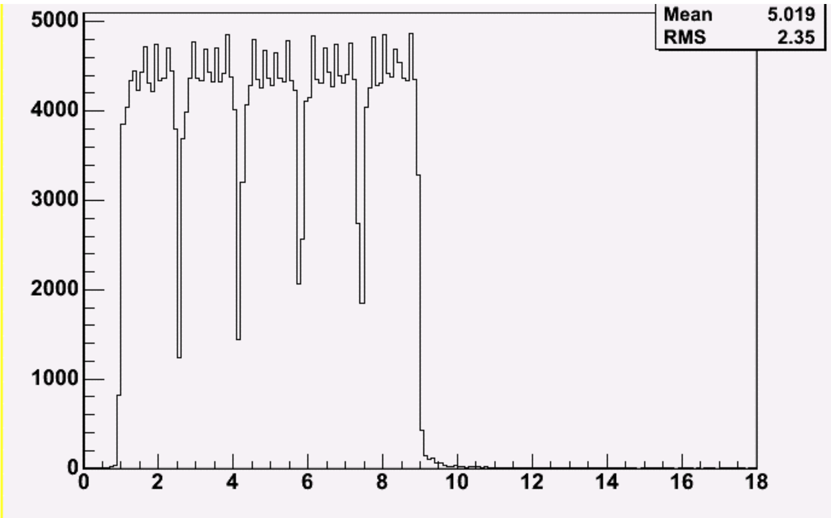
-Enough statistics already to be able to "see" detector details...



Near Detector Timing

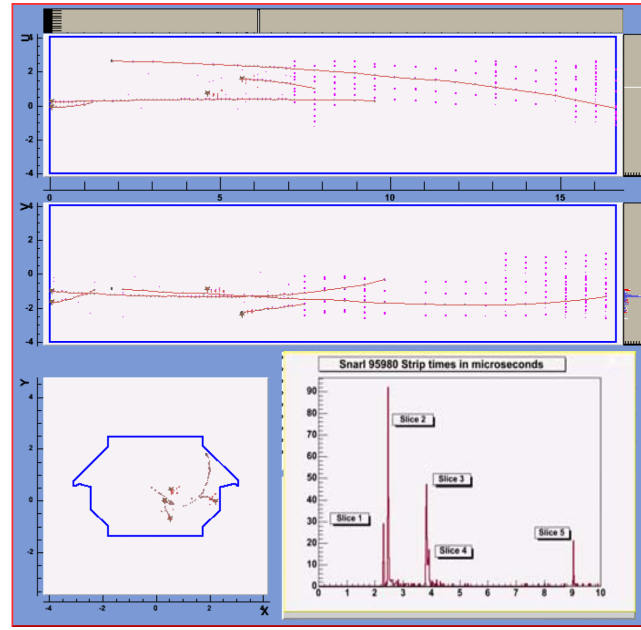
Detector activity

Starting time of Events with respect to the Spill Gate



usec

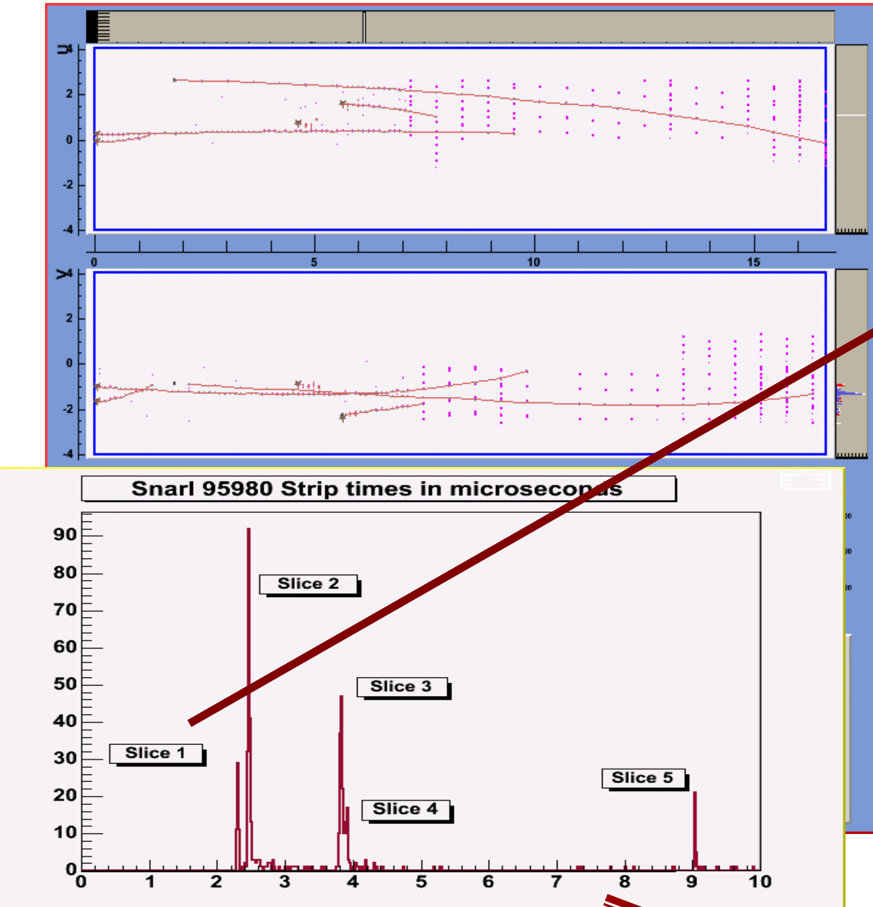
One Spill



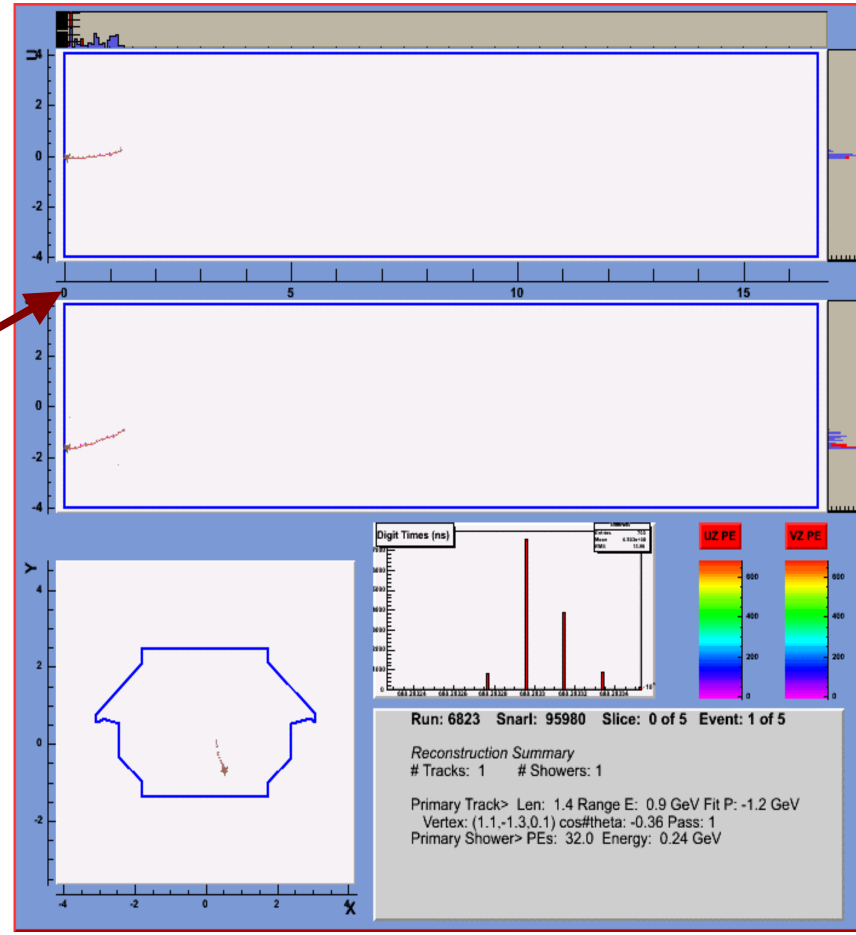
- 8 –10 usec spill of 5-6 "batches" each of ~ 1.6 usec length.
- Events recorded within a 18 micro sec window.
- Many neutrino interactions per spill , time and space used to "slice" = separate individual events (timing resolution : 18.9 nsec)

Event Timing

One Spill



"Rock muon"

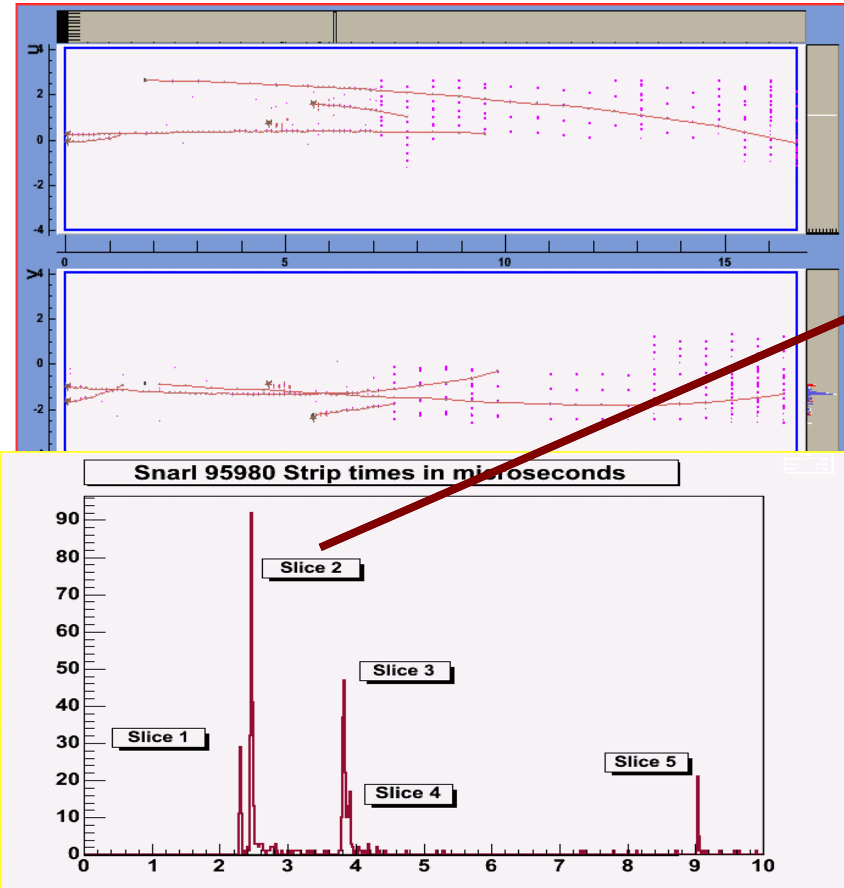


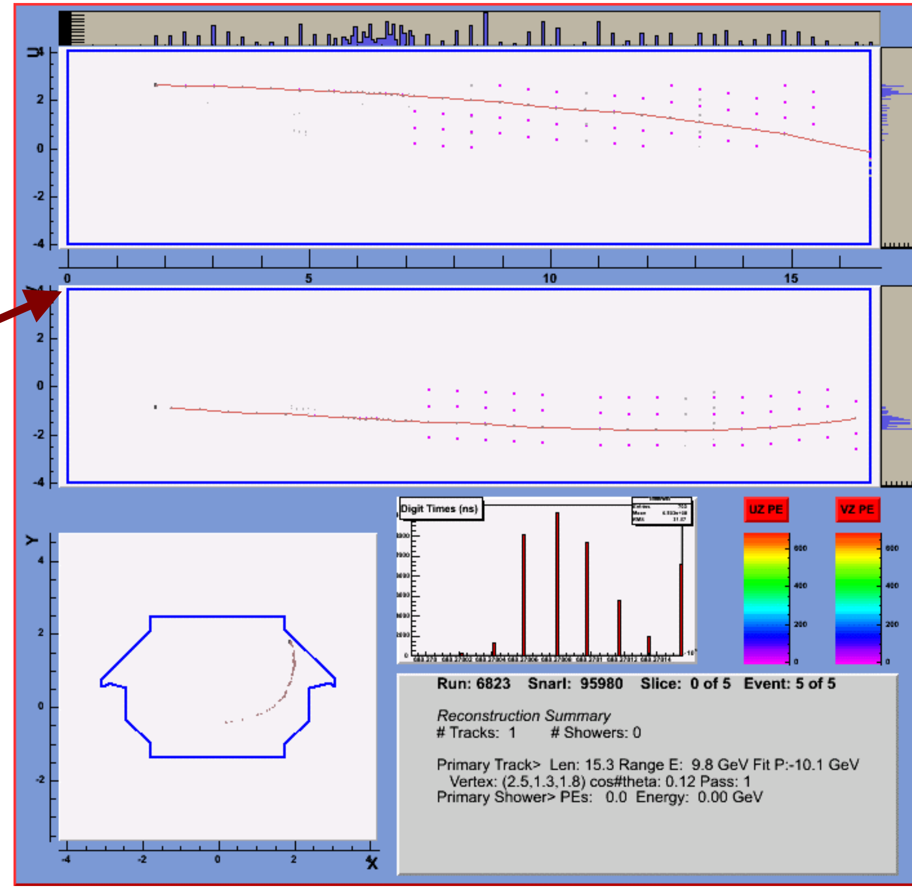
5 time slices -> 5 events

Event Timing

One Spill

Rock Muon

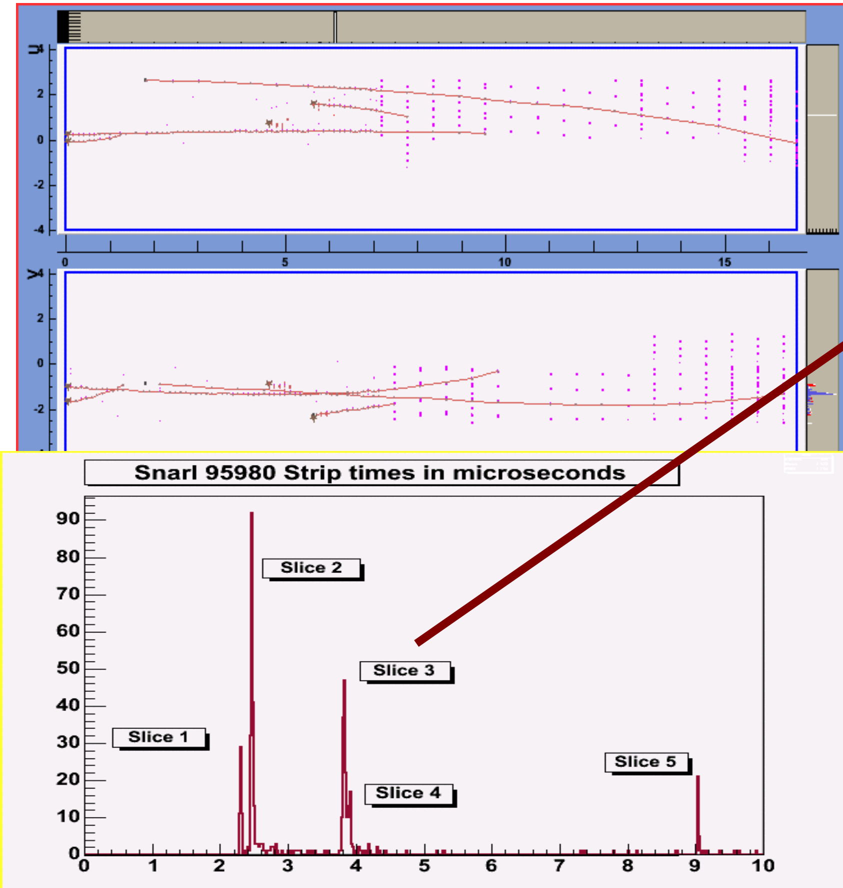




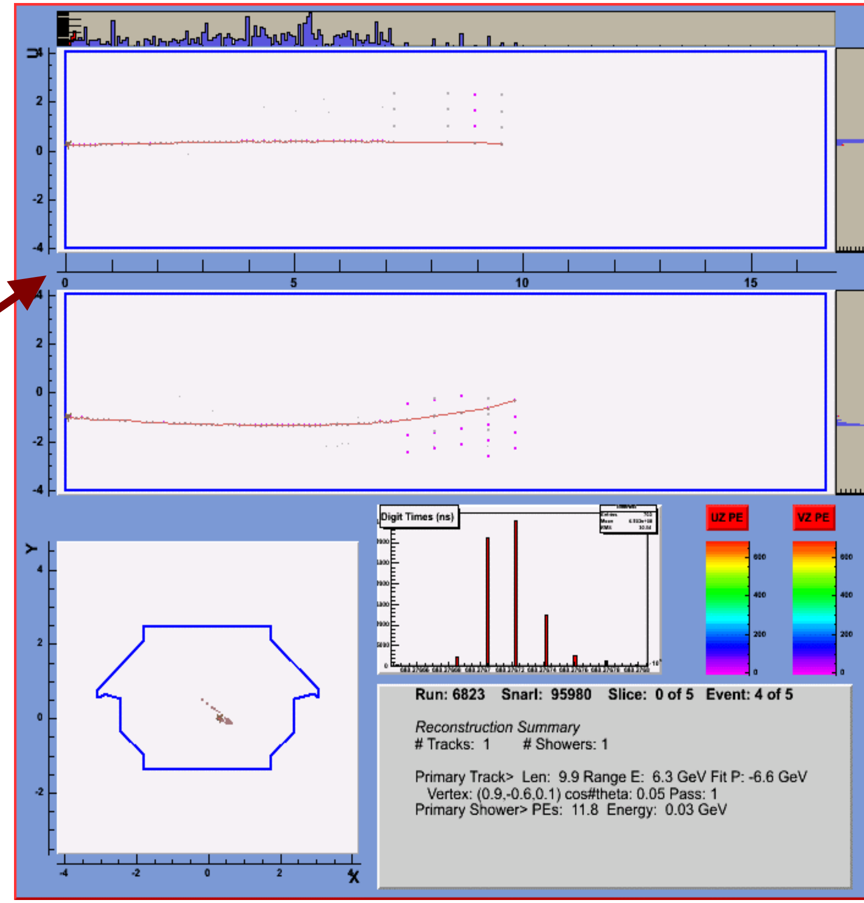
5 time slices -> 5 events

Event Timing

One Spill



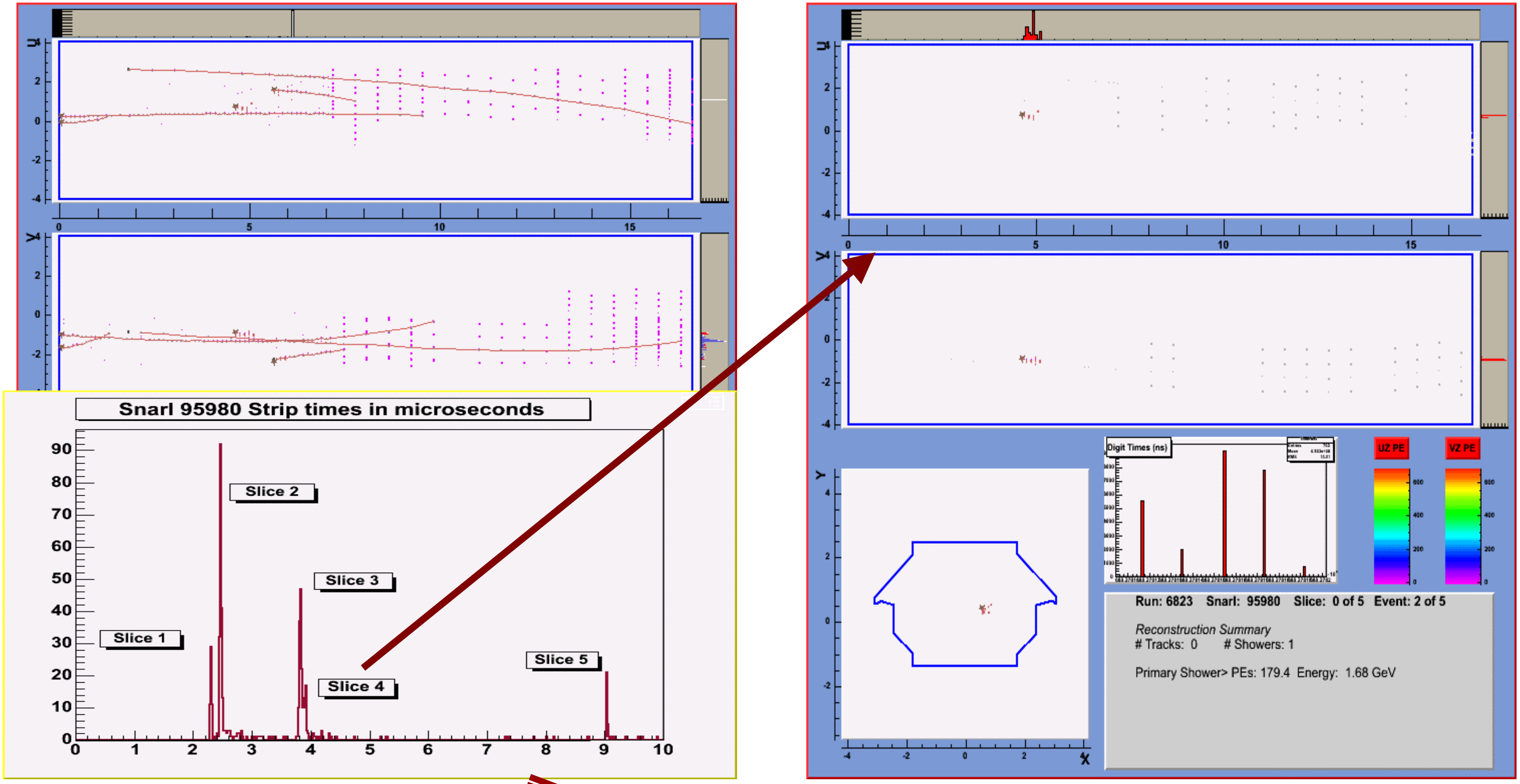
Rock Muon



5 time slices -> 5 events

Event Timing

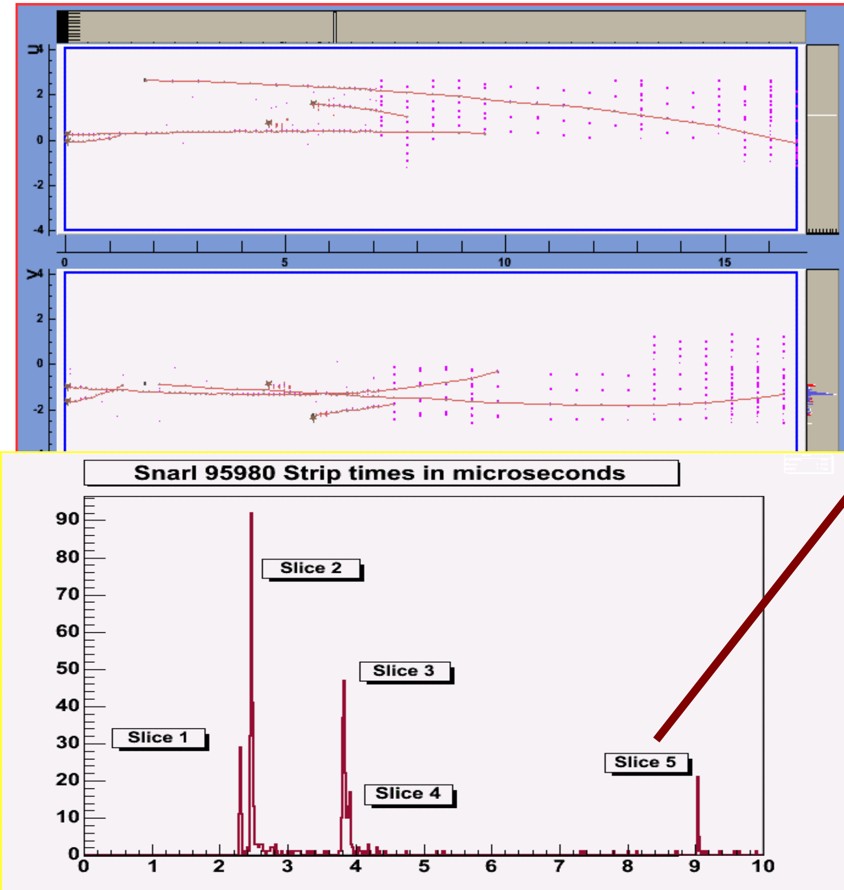
One Spill **Contained event**



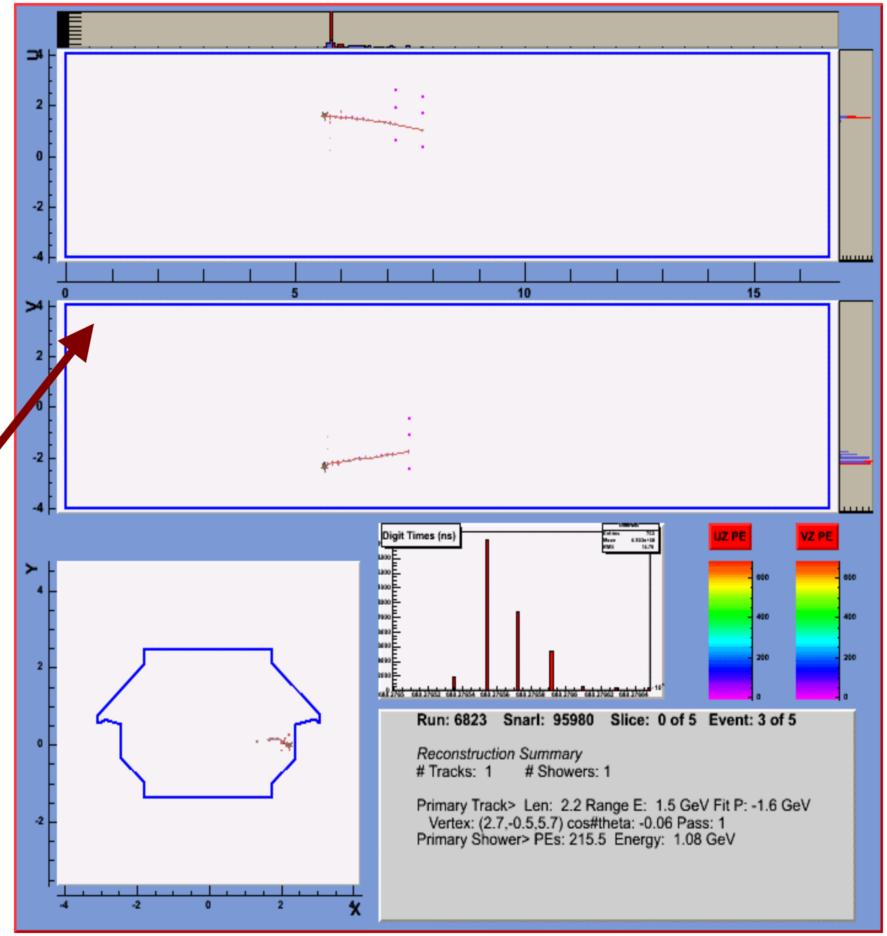
5 time slices -> 5 events

Event Timing

One Spill



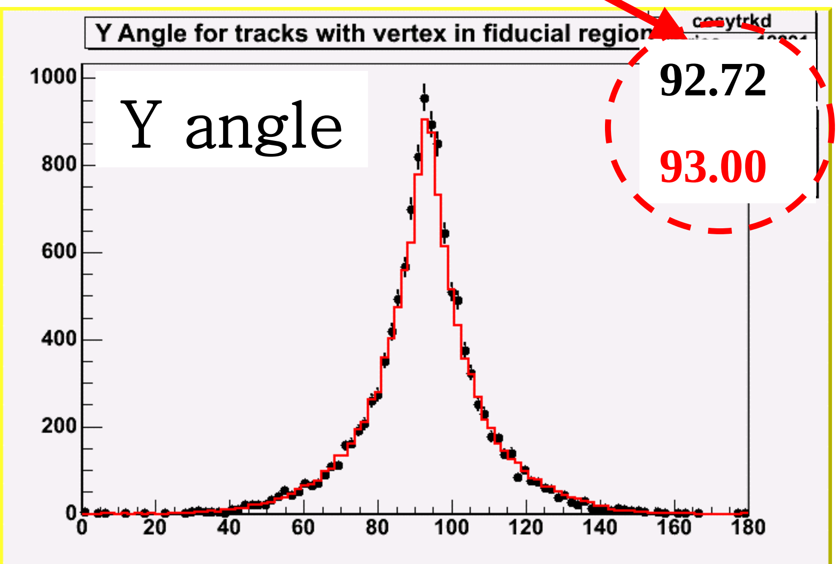
Contained event



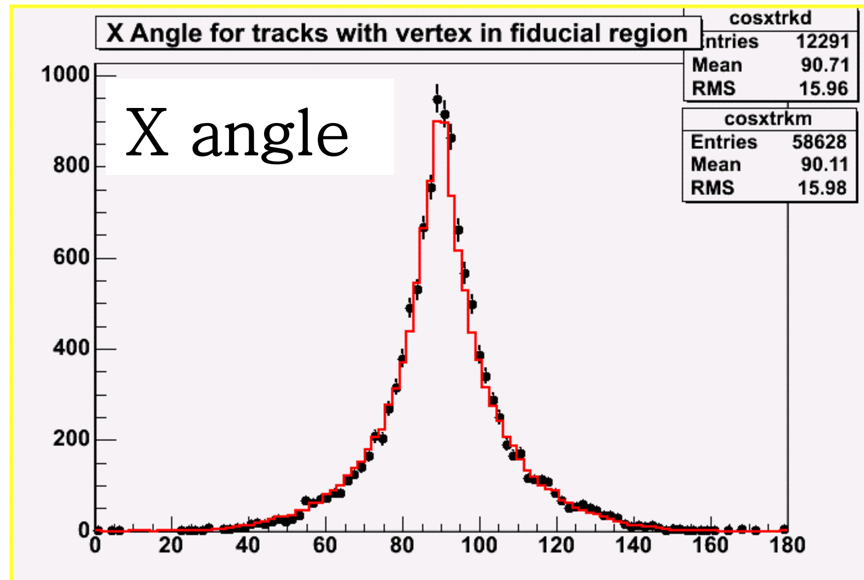
5 time slices -> 5 events

Track Angles (events in fiducial region)

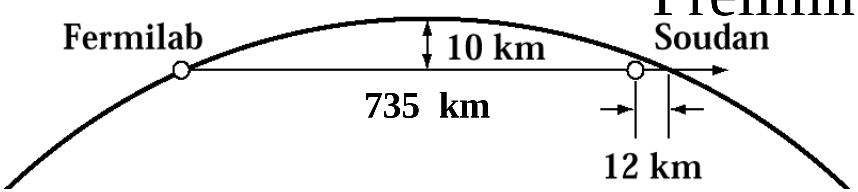
In order for the neutrino beam to "reach" MINOS FAR detector it has to be pointing 3 degrees down in Y...(note: plots show muon track direction, not neutrino direction)

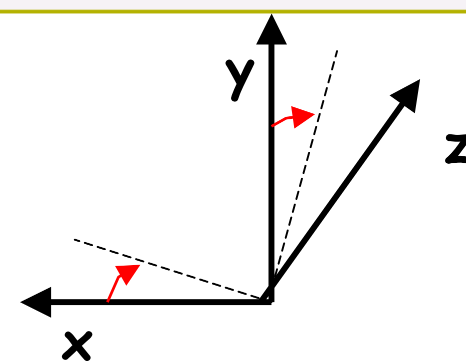


Data Black MC Red

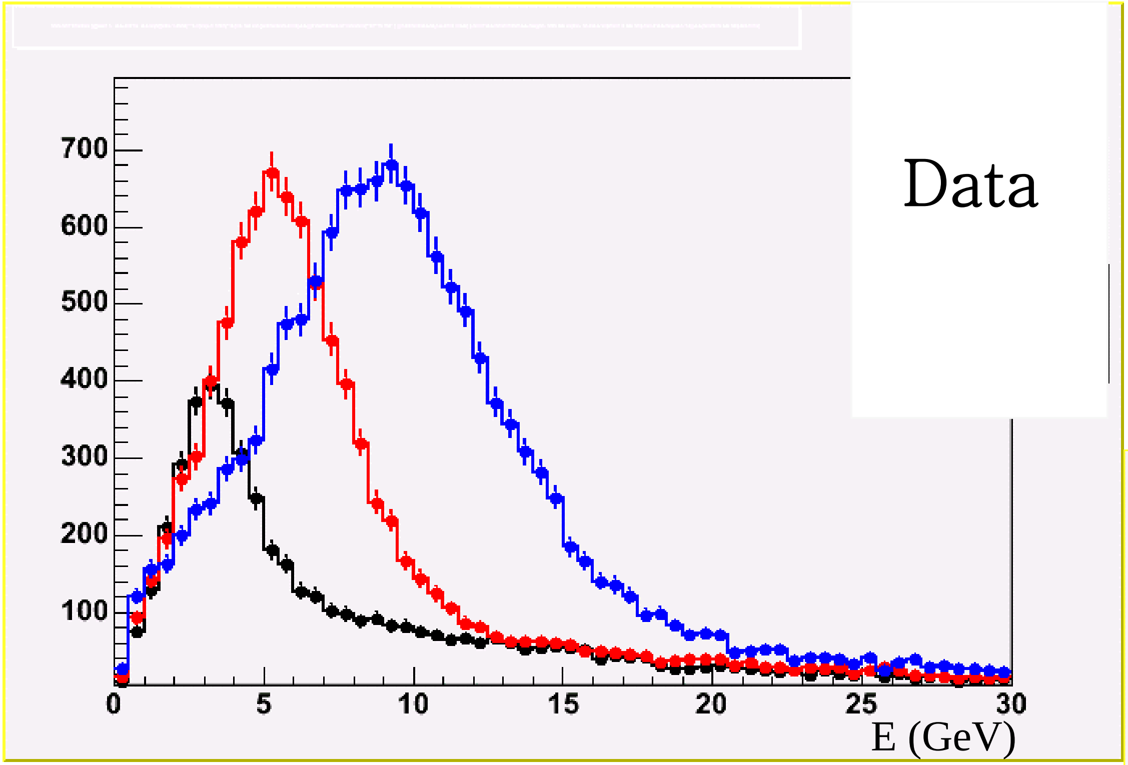


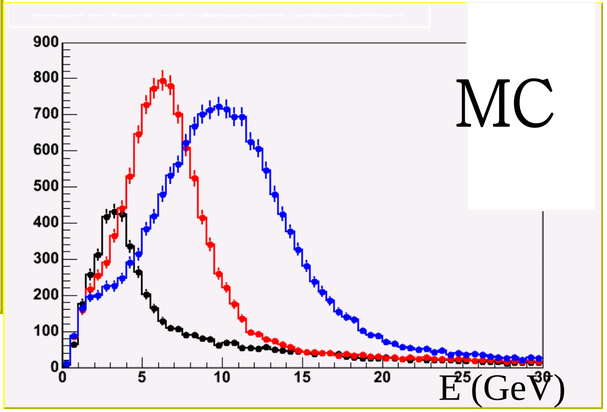
Preliminary





Near Detector Data from Energy Scan





Preliminary

- **Took data in LE, pME and pHE configuration.**
- **Reconstructed neutrino energy spectra already looks very close to what is expected!**
- **Detailed analyses of these data underway...**

Far Detector Beam Data !

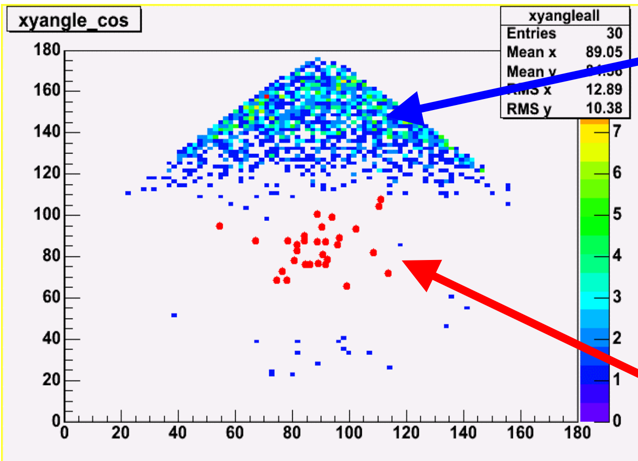
- Before you get too excited, I am NOT going to show events from the Low Energy running ("oscillation" data).
- I am going to show events from the High Energy running (Mean energy at 10 GeV).
- In this one week of data ~150000 spills were recorded in the FAR detector and less than 100 had detector activity (that survived basic cuts).
- We selected FAR detector CC-like event candidates based on timing (Far Spill Events) and requiring that they contain a track.

Preliminary

- Then we visually scanned all candidates and categorized them and found :
  - Contained CC-like Events (21)
  - Rock muons (9)
  - Cosmics (6) (expect 7)

Far Detector Beam Data con't

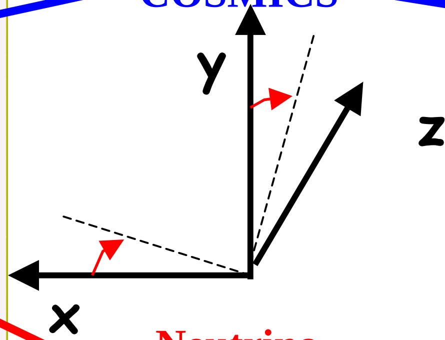
Beam neutrino candidates have quite a distinct topology



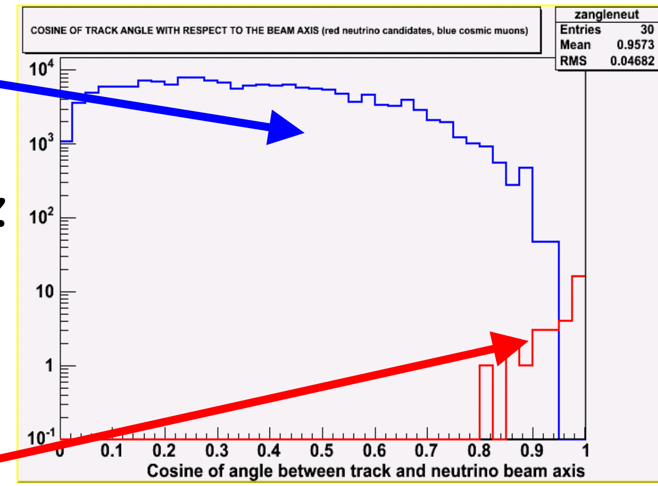
Y angle (vert.)

X angle (horz.)

COSMICS

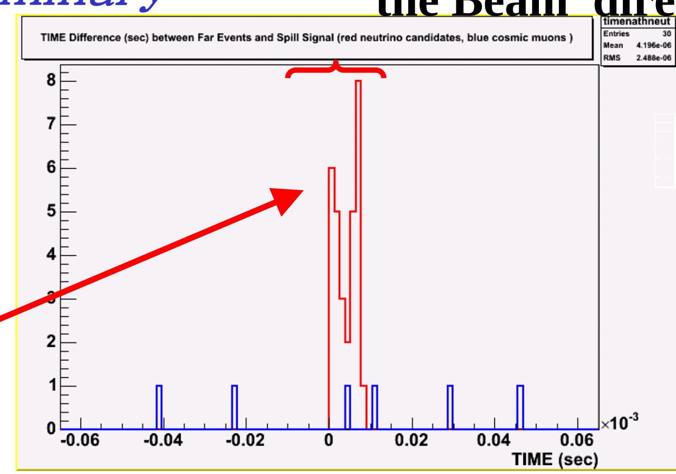


Neutrino Candidates



Track angle with respect to the Beam direction

Preliminary

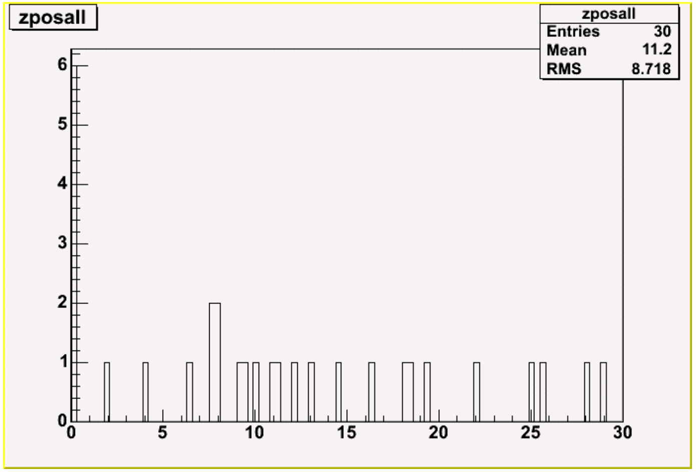


Time difference (in sec) between neutrino candidates and far spill signal in the +/-50 usec window.

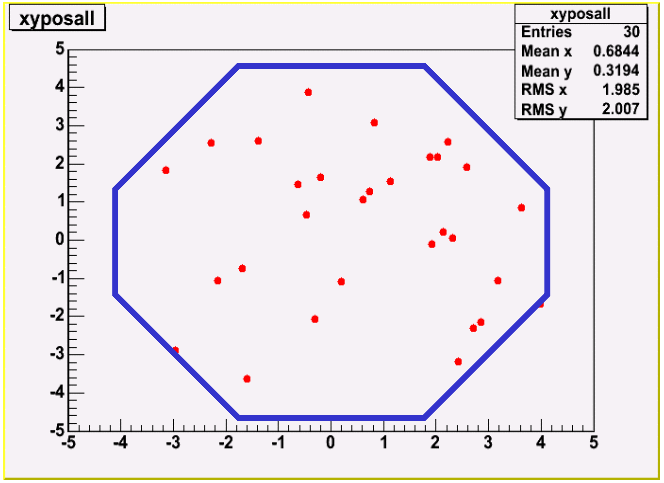
Beam neutrino candidates are within a 10 usec time interval, as expected for the 10usec width of NuMI beam.

Far Detector Beam Data con't

Preliminary



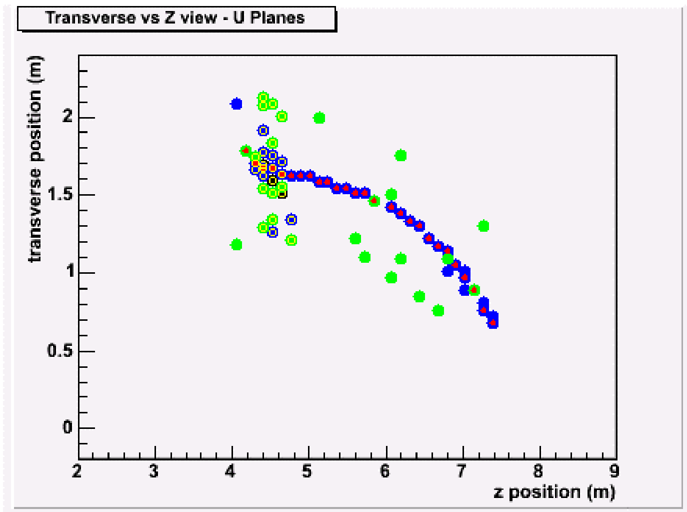
Z vertex (m)

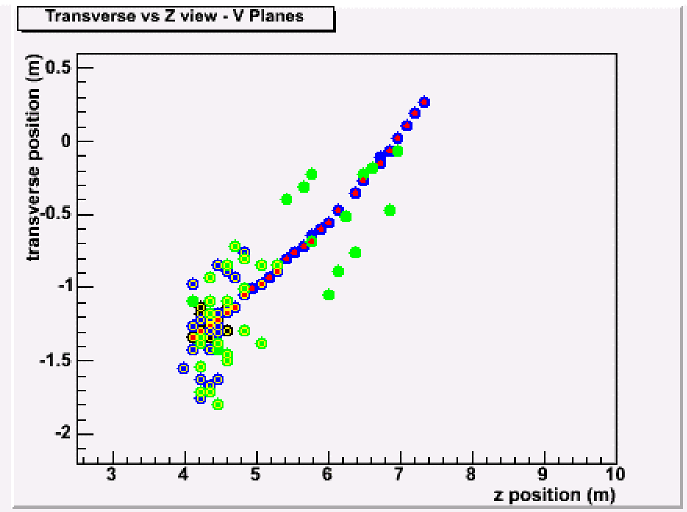


X-Y vertex (m)

- Timing and topological characteristics of beam neutrino event candidates in agreement with expectations, event rate in the right range.

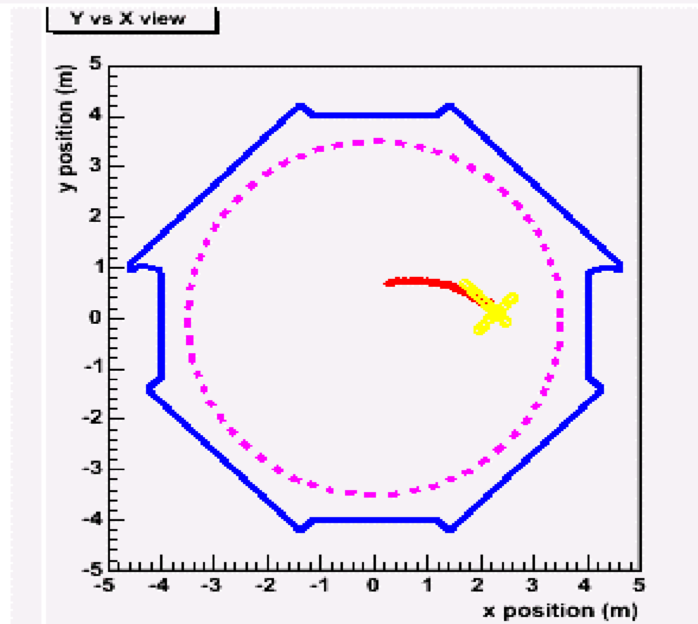
Far Detector Neutrino Events





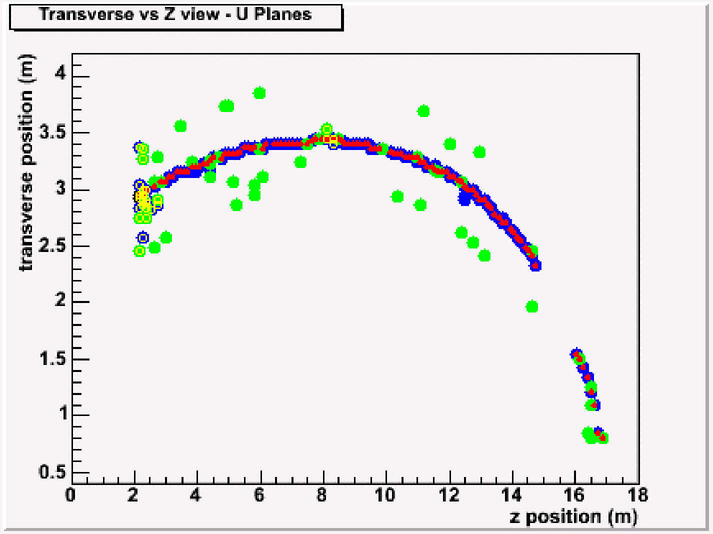
TrkRangeEnergy: 2.481 RecoShwEnergy: 4.754

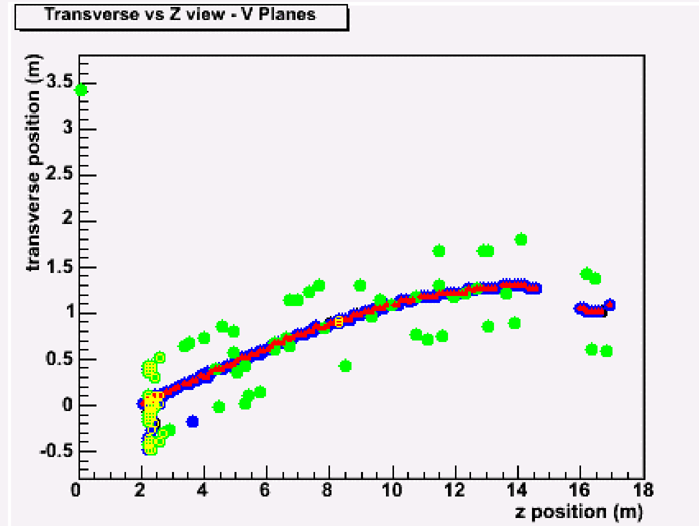
Vtx: 2.18, 0.29, 4.11



Preliminary

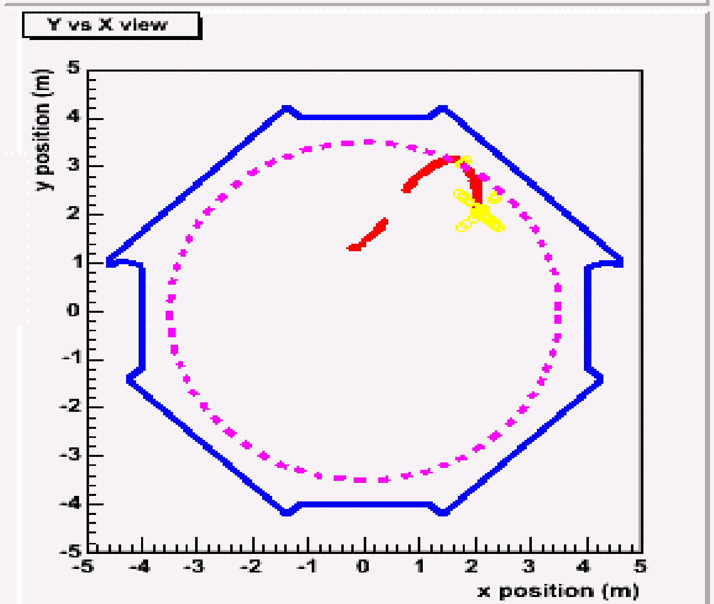
Far Detector Neutrino Events





TrkRangeEnergy: 9.596   RecoShwEnergy: 5.108

Vtx: 2.07, 2.11, 2.09



Preliminary

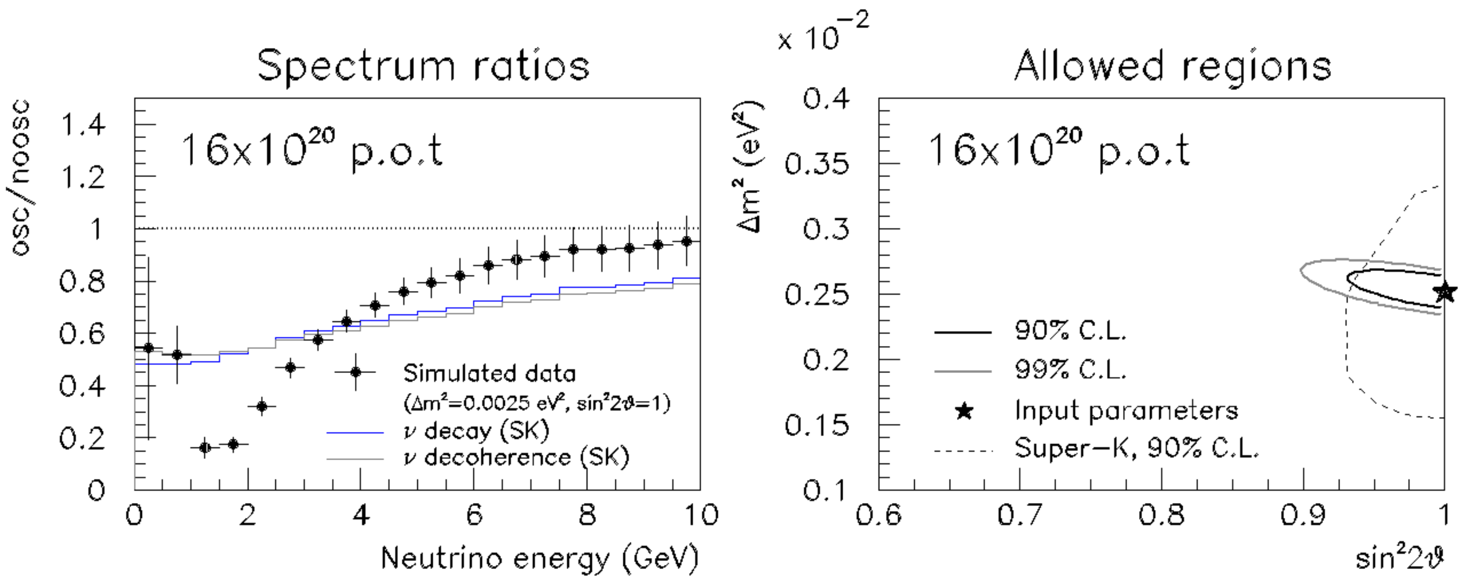
MINOS Physics Goals : $\nu_\mu \not\to \nu_\mu$

- **The study and comparison of ν_μ CC interactions between the NEAR and FAR detector will allow us to:**

  -Confirm oscillation hypothesis with accelerator muon neutrinos (ν_μ disappearing from the beam)

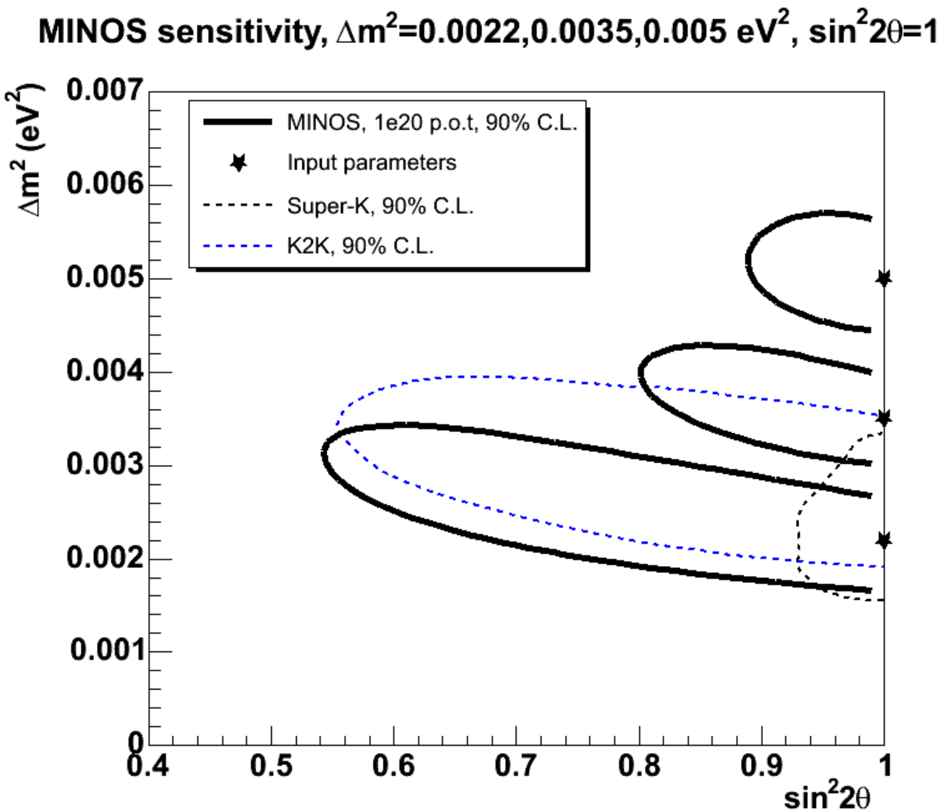
  - Obtain precise measurements of the oscillation parameters, (Δm_{23} <10%) and $\sin^2 2\Theta_{23}$

$$\Delta m^2 = 0.0025 eV^2, \sin^2 2\theta = 1.0$$

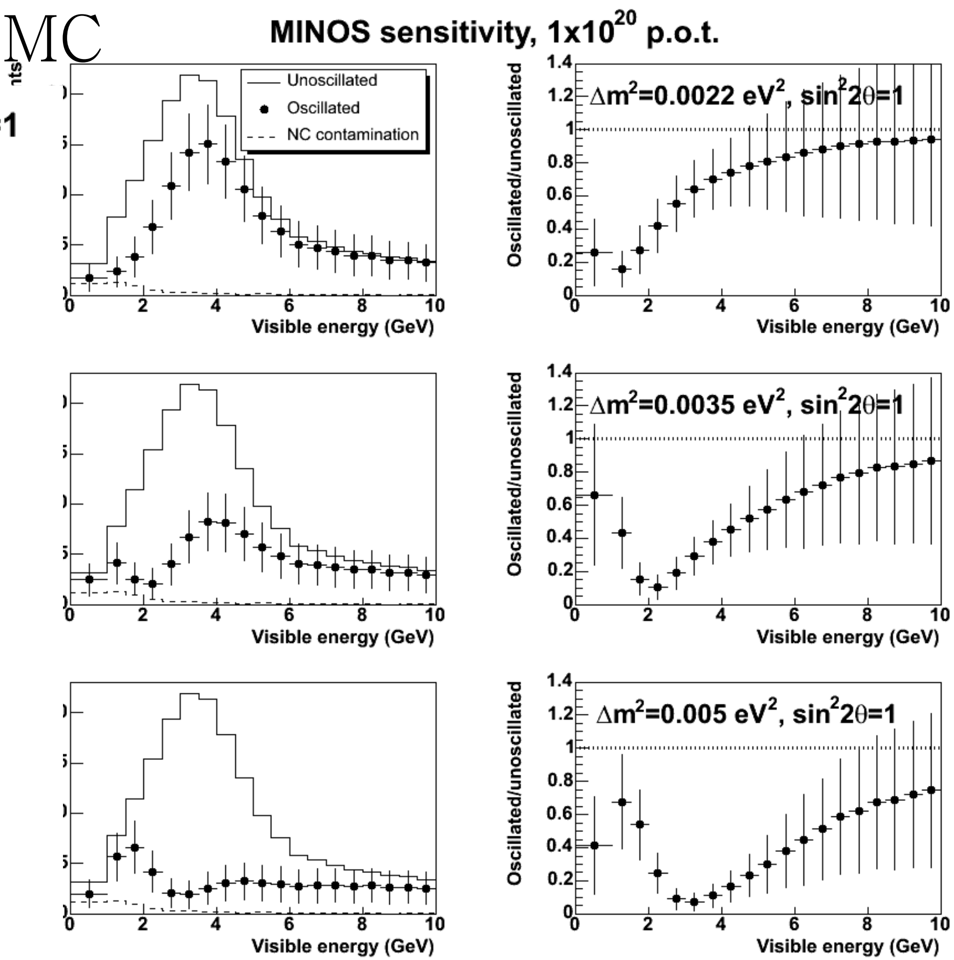


MINOS Physics Goals : $\nu_\mu \not\to \nu_\mu$

- What can we do in a few months where we will have ~ 1 x 10^{20} POTs...
- Check that we are running with the right beam energy!!

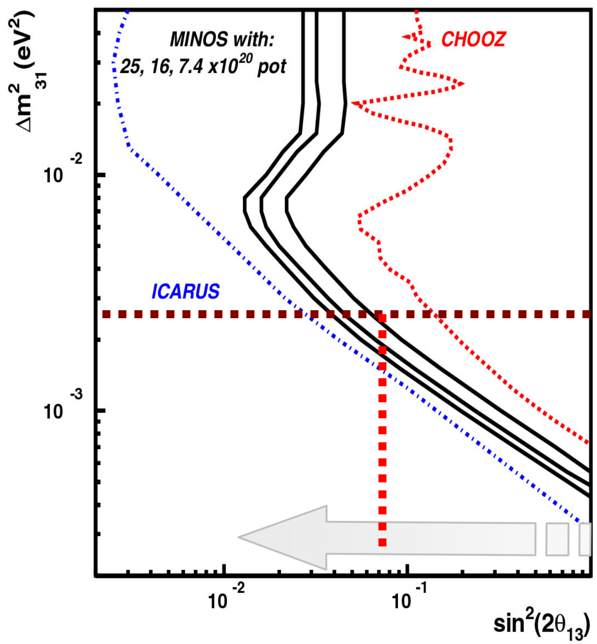


MC

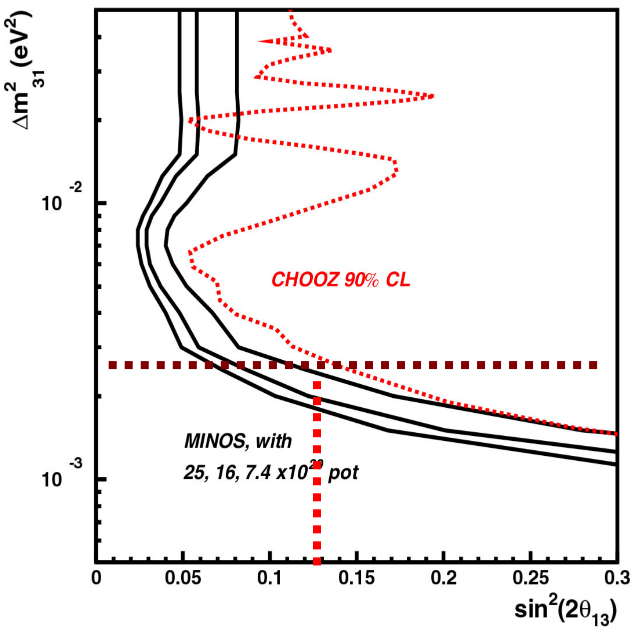


MINOS Physics Goals : $\nu_\mu \rightarrow \nu_e$

90 % CL exclusion plot



3σ sensitivity plot



- **Measuring θ_{13} is currently one of the most "hot" issues in neutrino physics.**
- **Trying to do so with the MINOS detector and the current LE beam is very challenging but we will try!**
- **If θ_{13} is close to the CHOOZ limit, we will see a >3 σ effect in ~3 years of running.**
- **Otherwise we will be able to improve the current limit by a factor of 2 or 3.**

Summary & Conclusions

- MINOS Near and Far detectors are running and collecting Beam Neutrino Data!
- Plethora of neutrino data in the Near Detector already, systematic studies and physics analysis underway!
- Tools in place to perform Far Detector oscillation analysis when we accumulate reasonable statistics (although we are spoiled by the Near Detector, up there we need to be patient...)
- Getting used to having at our “disposal” the most intense neutrino beam!

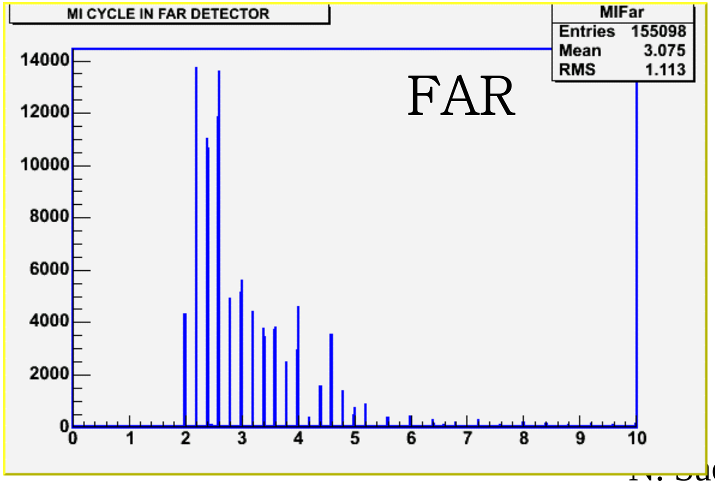
Finally…

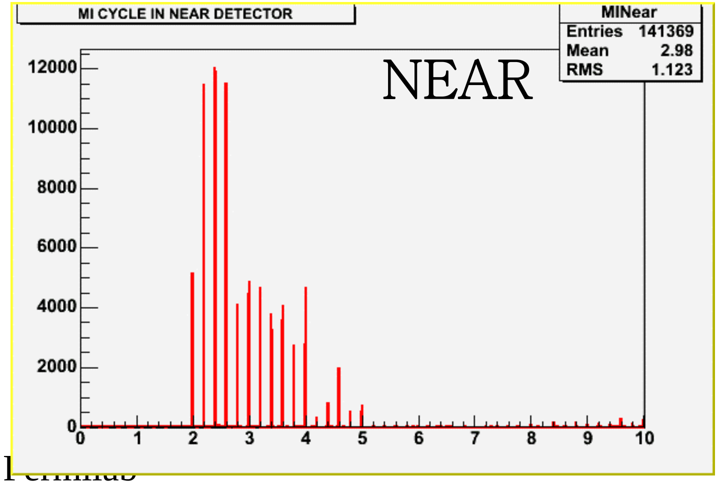
On behalf of the MINOS collaboration we would like to extend our sincere thanks to all of the many people and organizations who contributed to the realization and success of the NuMI facility and the MINOS experiment.

Palace of King MINOS ,Throne Room
Knossos Late 15th century B.C.

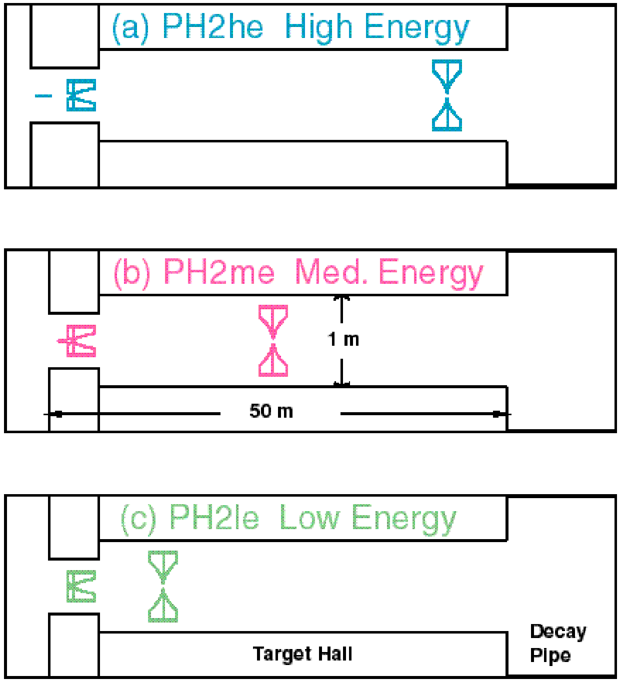
NuMI Beam at the Far Detector

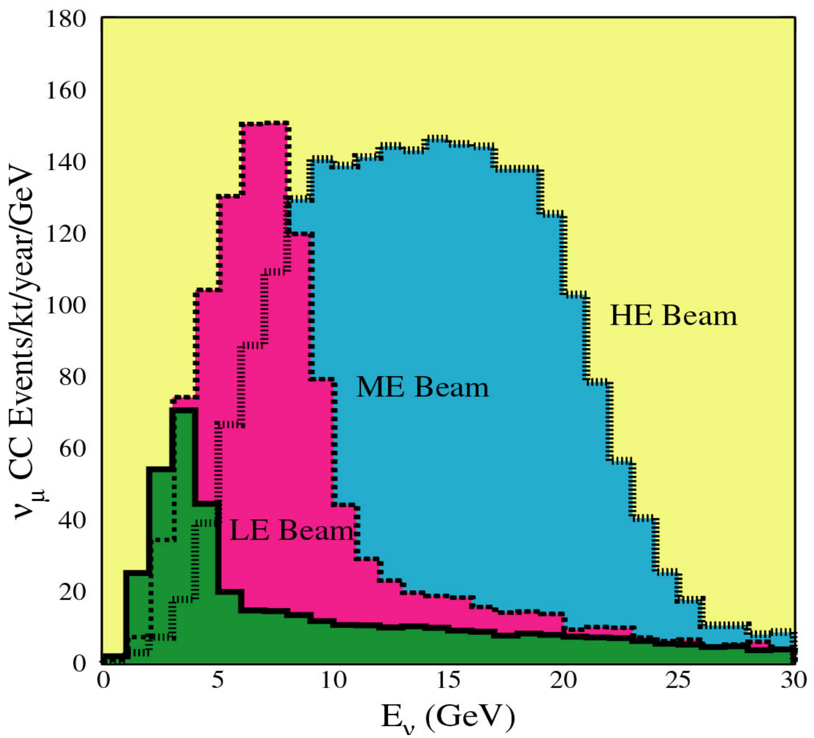
- The way we record "spill" events in the Far detector is the following :
  - There are GPS timing modules at both Near and Far detectors
  - $A74 : Kicker pre-fire initiates a sequence of timing events to send a spill signal from Fermilab to Soudan using the network.
  - Once spill timing data arrives at the Far detector, events which occurred in a +/- 50usec window around the spill time are recorded and tagged as "spill" events.
- The difference of adjacent spills in the Far & Near detector represents the MI cycle time :





NuMI Target & Horns





· Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn (provision is made for three different 2nd horn positions).