The MINOS experiment

Mark Dierckxsens

Brookhaven National Laboratory

BNL Particle Physics Seminar, 11/10/2005



Neutrino oscillations

- introduction
- experimental status

MINOS Experiment

- detectors & beamline
- physics sensitivities
- current status
- outlook & conclusions

Two Neutrino Oscillations

BROOKHAVEN NATIONAL LABORATORY

ν: produced/detected as WEAK eigenstates
propagates as MASS eigenstates

Quantum Mechanics: weak $\neq$ mass states

$\Rightarrow$ mixing:

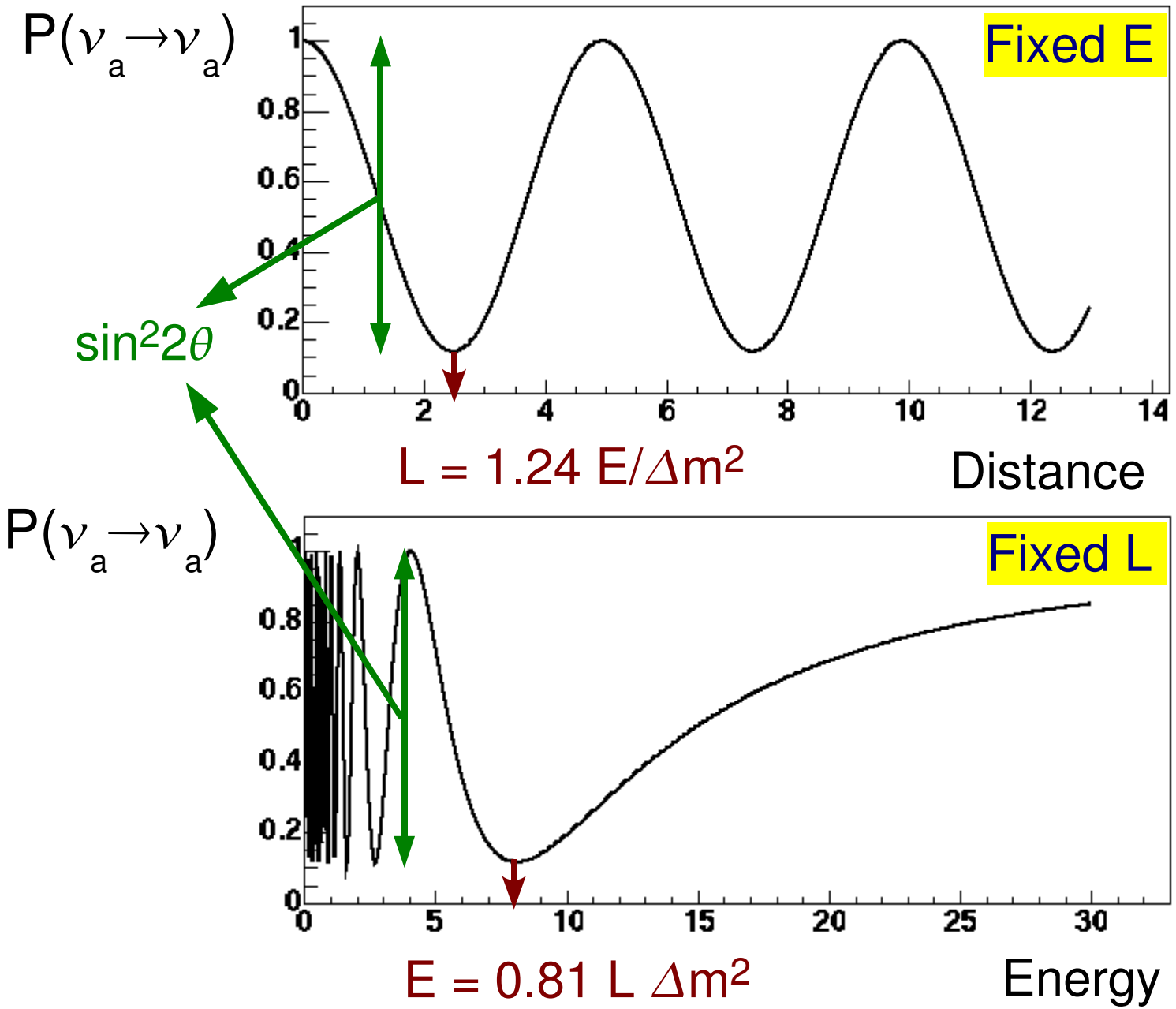
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} |\nu(0)\rangle &= |\nu_a\rangle \\ &= \cos\theta\ |\nu_1\rangle + \sin\theta\ |\nu_2\rangle \end{aligned}$$

survival prob: $P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\, L\, \Delta m^2_{21}}{E}\right)$

with L in km, E in GeV, $\Delta m^2_{21} = m_2^2 - m_1^2$ in eV^2

Two Neutrino Oscillations



Three Neutrino Oscillations

BROOKHAVEN NATIONAL LABORATORY

3 generation ν mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-
U: Nakagawa-Sakata
(PMNS) Matrix

⇨ 3 mixing angles
1 CP Phase

(+2 CP phases for Majorana ν)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

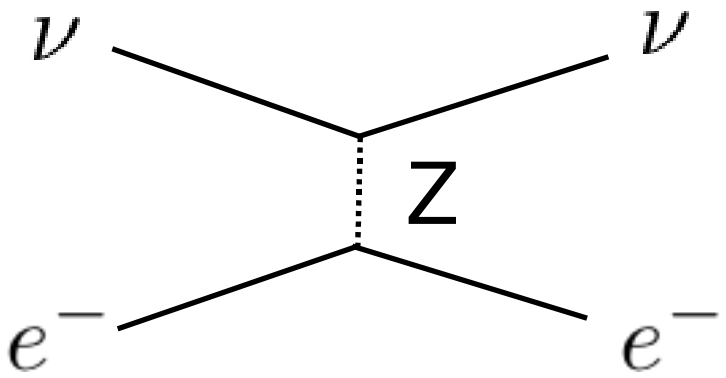
atmospheric — solar

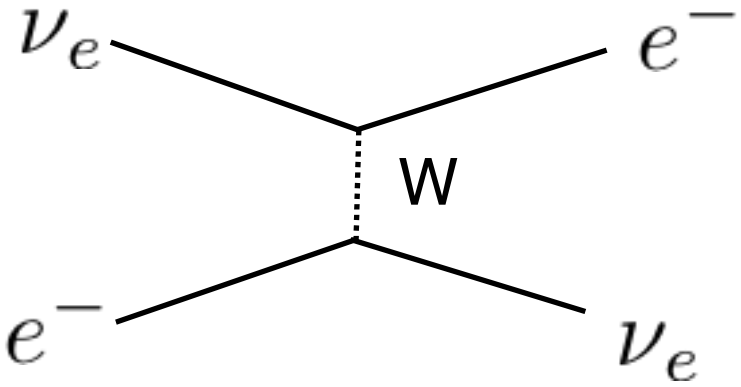
Neutrino oscillations described by 6 new parameters:

$\theta_{12}, \theta_{13}, \theta_{23}, \delta$
$\Delta m^2_{21}, \Delta m^2_{32}$

Matter Effects

Mikheyev-Smirnov-Wolfenstein (MSW) effect:
oscillation probabilities modified
in presence of matter





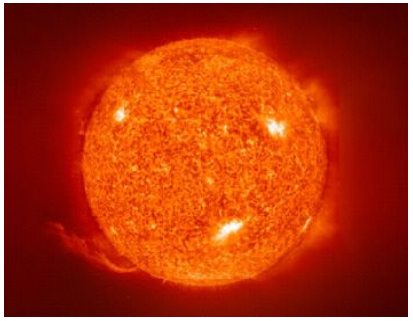
neutral current for
all type of neutrinos

charged current for
electron neutrinos only

extra potential for ν_e ($\overline{\nu}_e$): $\pm\sqrt{2}G_F N_e$

N_e: electron number density

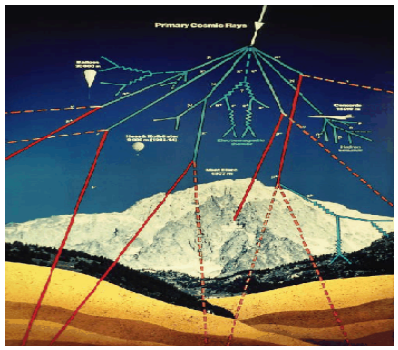
Current Results



SNO, KamLAND, Super-K,...

$$\Delta m^2_{21} = (8.0^{+0.6}_{-0.4})\,10^{-5}\,eV^2$$

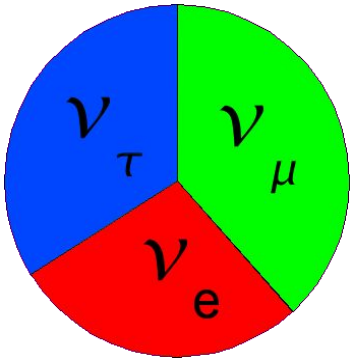
$$\sin^2 2\theta_{12} = 0.86^{+0.05}_{-0.06} \qquad (\theta_{12} \approx 34^o)$$



Super-K, K2K,...

$$|\Delta m^2_{32}| = (2.4^{+0.4}_{-0.3})\,10^{-3}\,eV^2 \qquad \text{sign?}$$

$$\sin^2 2\theta_{23} = 1.02 \pm 0.06 \qquad (\theta_{23} \approx 45^o)$$



Chooz,...

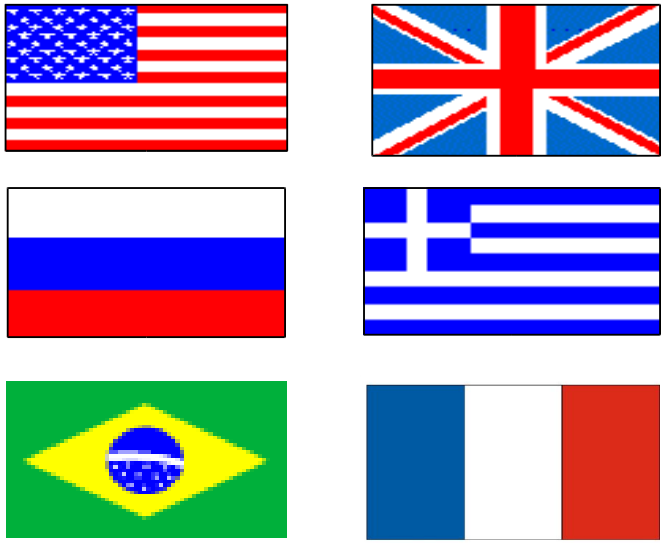
$$\sin^2 2\theta_{13} < 0.12 \qquad (99\%\ \text{C.L.})$$

$$\delta_{CP} = ???$$

LSND measured $\Delta m^2 \sim 1\ eV^2$

Main Injector Neutrino Oscillation Search

collaboration of
175 physicists
from 32 institutes
in 6 countries



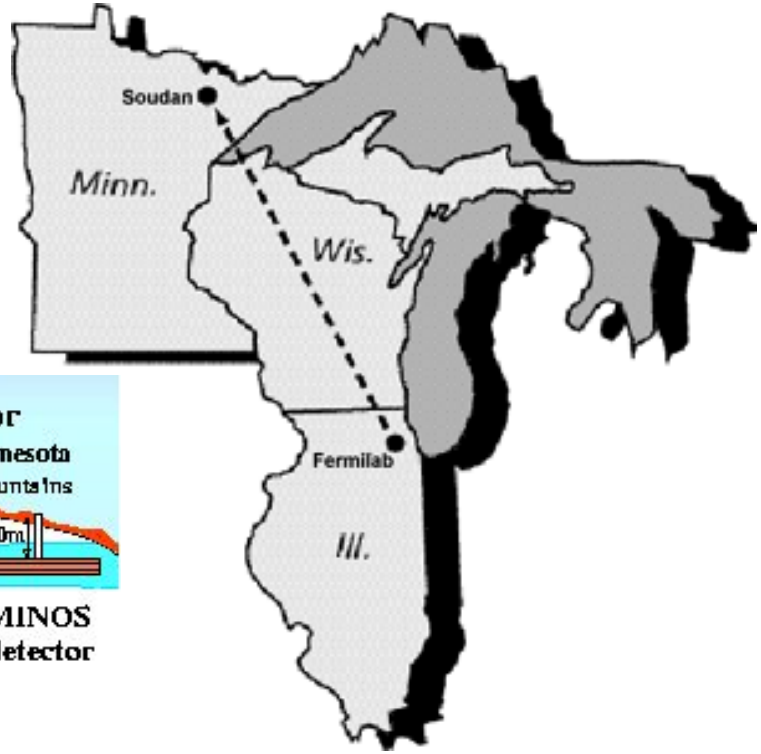


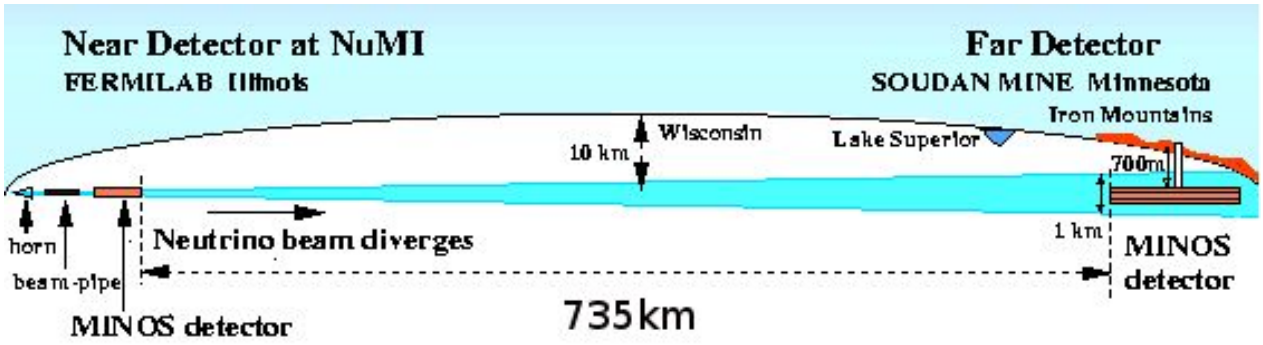
Argonne – Athens – Benedictine - Brookhaven – Caltech – Cambridge – Campinas – Fermilab – College de France – Harvard – IIT – Indiana – ITEP Moscow – Lebedev – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Protvino – Rutherford Appleton – Sao Paulo – South Carolina –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

NuMI/MINOS Concept

BROOKHAVEN NATIONAL LABORATORY

High intensity ν_μ beam from Fermilab to Soudan (MN)





compare spectrum: near (1kT) ⇔ far (5.4kT) det.

unoscillated ⇔ oscillated

- observe the oscillation dip
- measure Δm^2_{32} ~ 10%
- Look for evidence of $\nu_\mu \rightarrow \nu_e$

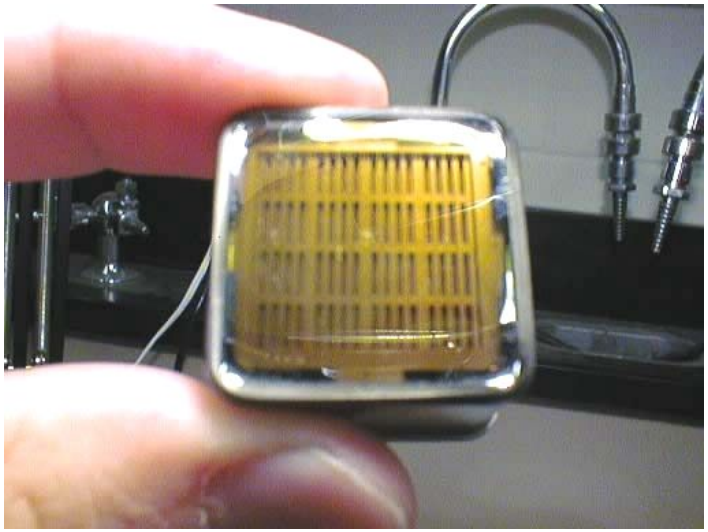
MINOS detectors

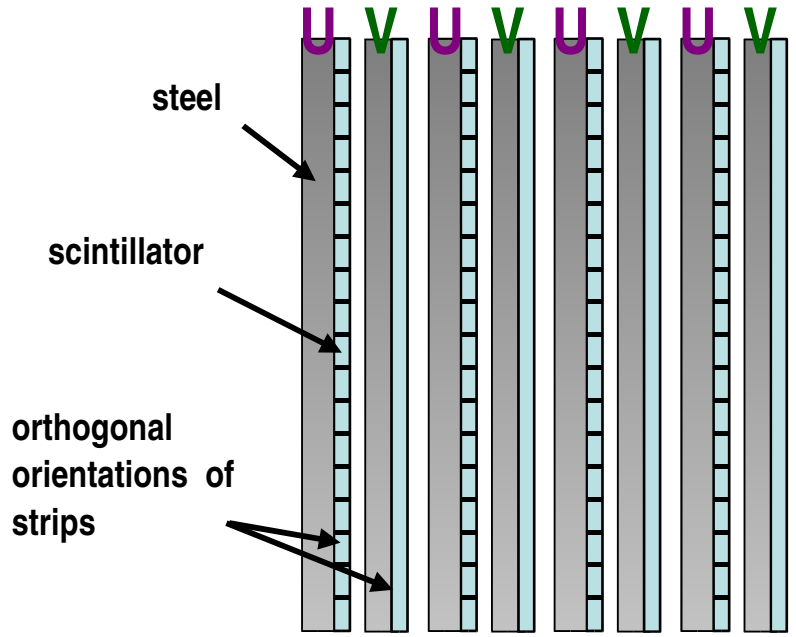
BROOKHAVEN NATIONAL LABORATORY

Magnetized iron scintillator sampling calorimeter:

- 1 inch steel for showering
- 4.1x1cm^2 thick scintillator strips
- 1.2mm wavelength shifting fiber
- Hamamatsu multi-channel PMT's
- consecutive planes have orthogonal strips







Far Detector (FD)

- Located in the SOUDAN underground lab
- home of Soudan-1 & 2, CDMS-II and MINOS
- former iron mine







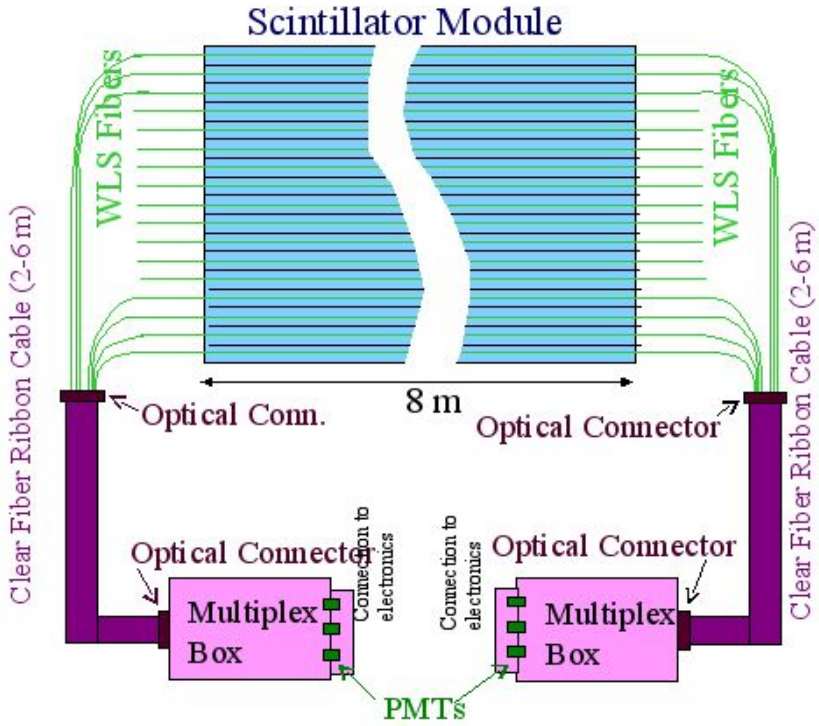


Far Detector

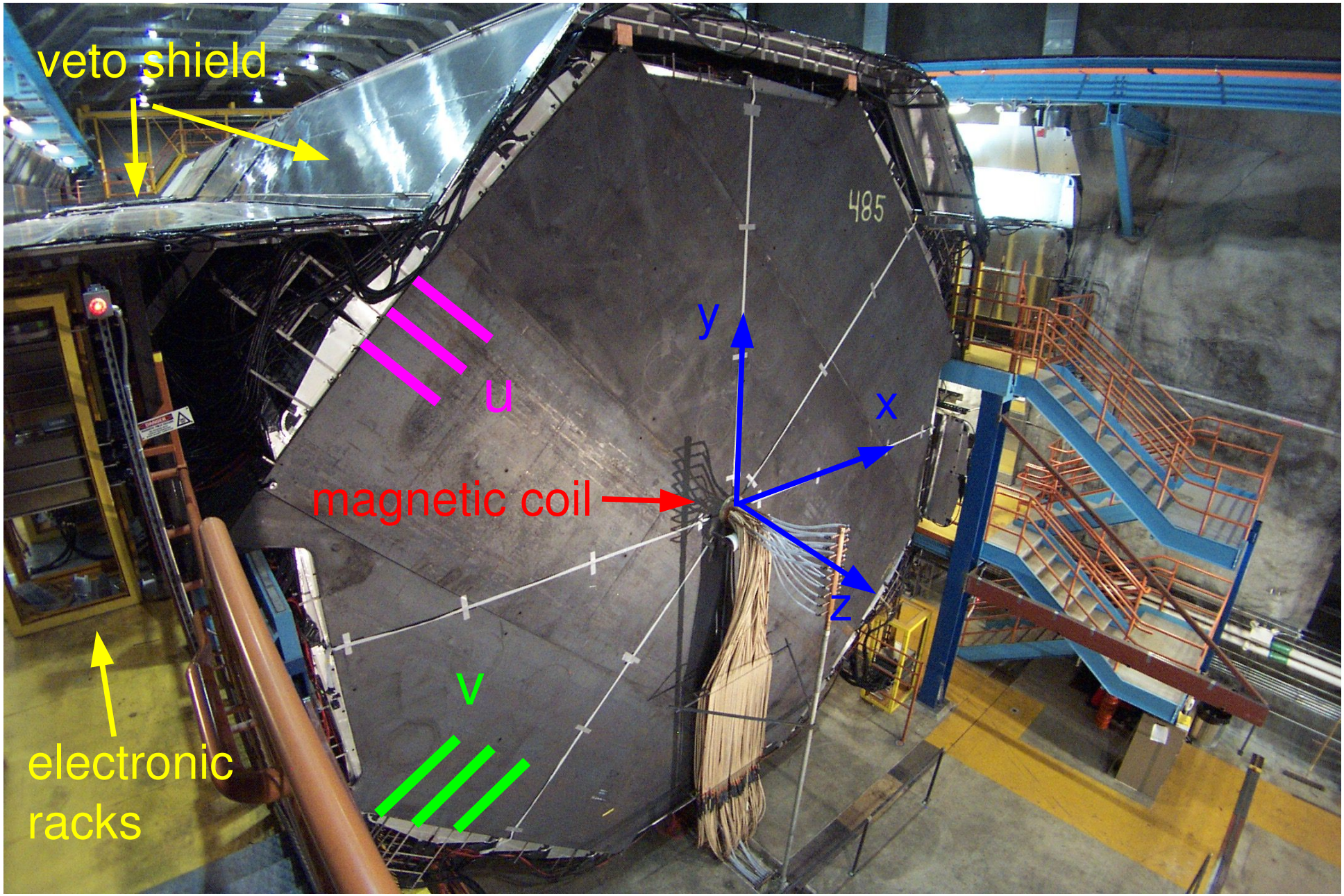
- 8m octagonal steel plates
- 486 planes in total ⇒ 5.4 kton
- Toroidal B-field 1.5T
- Strips read out from both sides
- 8 fiber to 1 channel multiplexed
- Completed July 2003







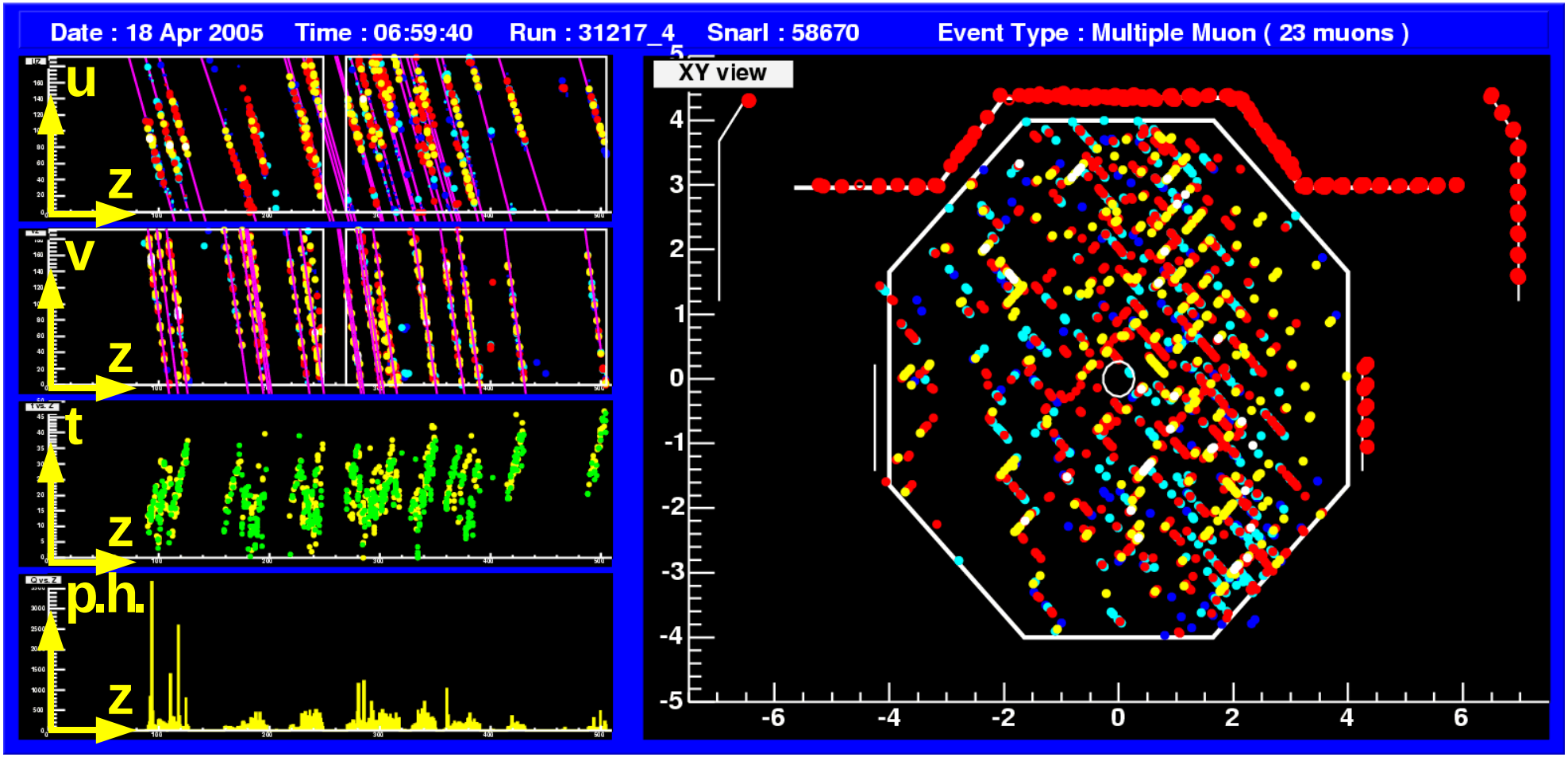
Far Detector



FD cosmic muons

BROOKHAVEN NATIONAL LABORATORY

very high multiplicity cosmic muon event



online event display:
http://farweb.minos-soudan.org/events/LiveEvent.html

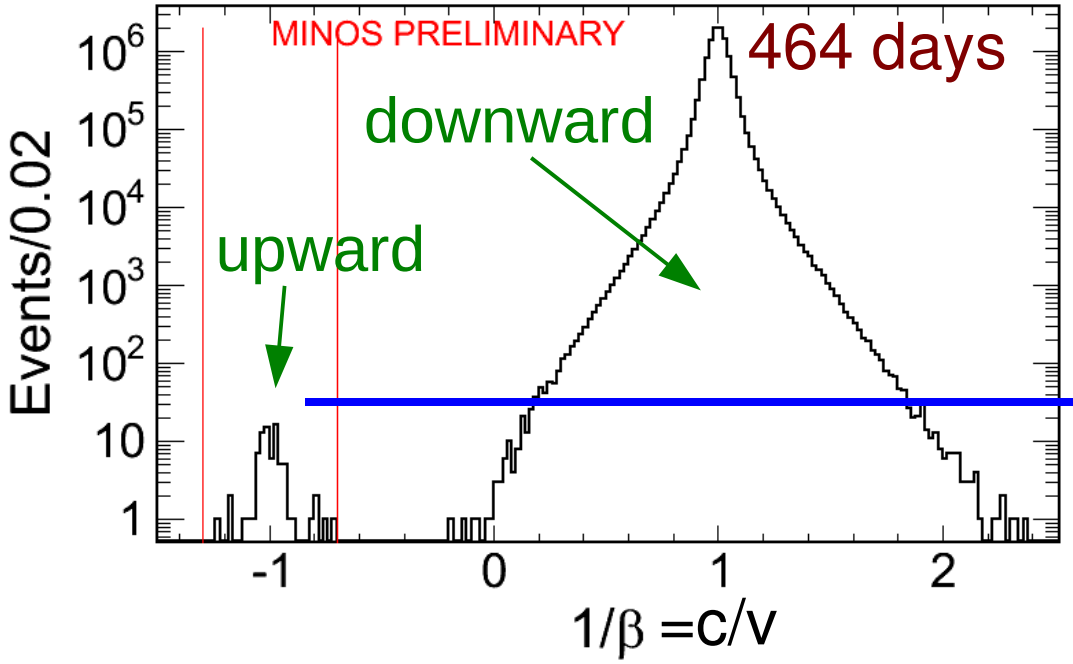
FD atm. neutrinos

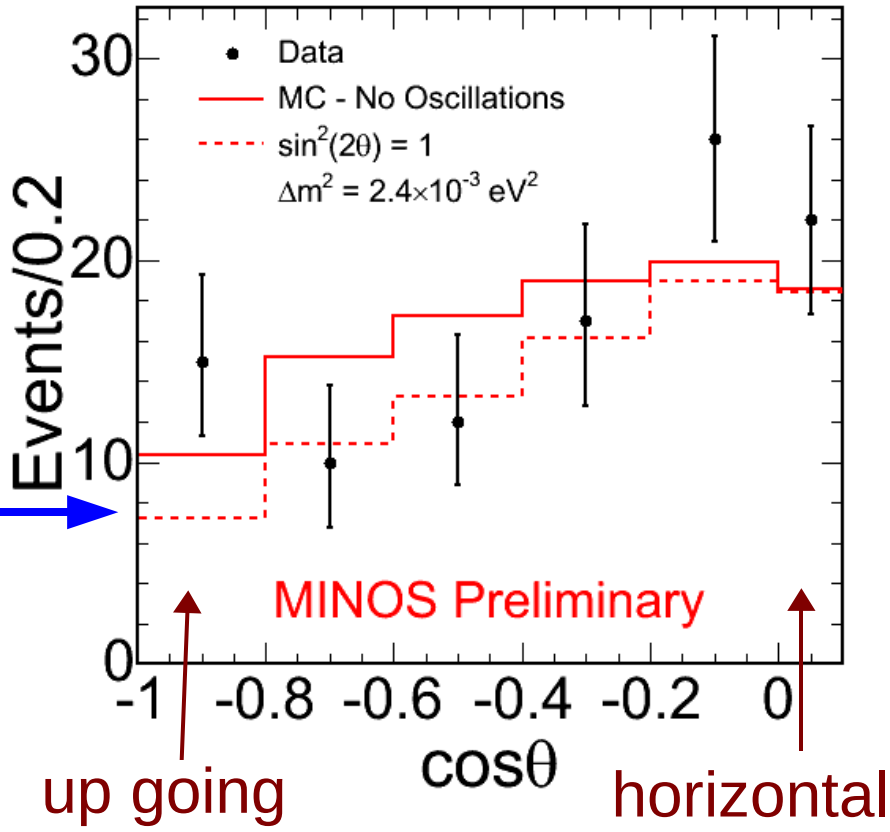
BROOKHAVEN NATIONAL LABORATORY

2 types of atmospheric neutrino analyses:

- (partially) contained μ's: interaction in detector
- neutrino-induced μ's: interaction in rock

Upwards going muons



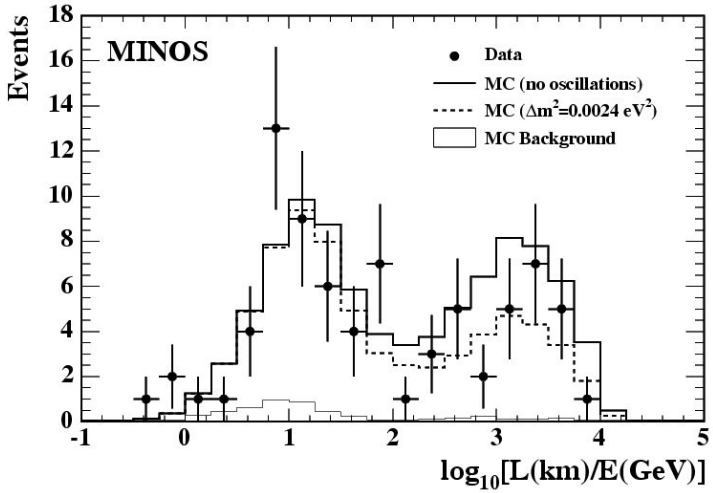


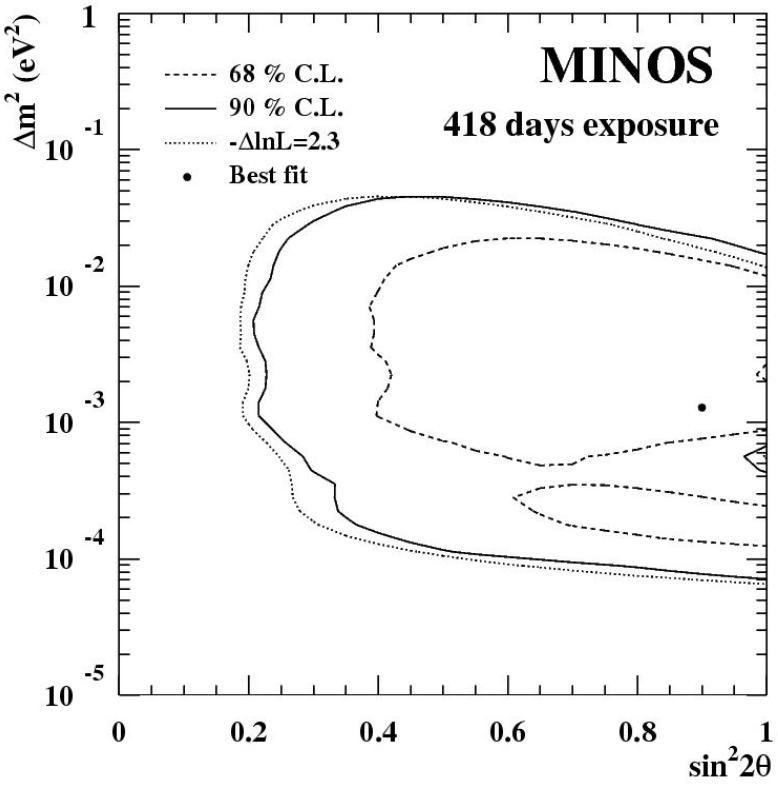
FD atm. neutrinos

BROOKHAVEN NATIONAL LABORATORY

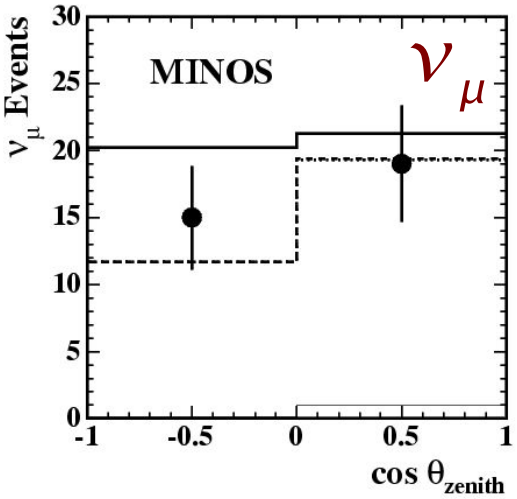
(Partially) Contained Events

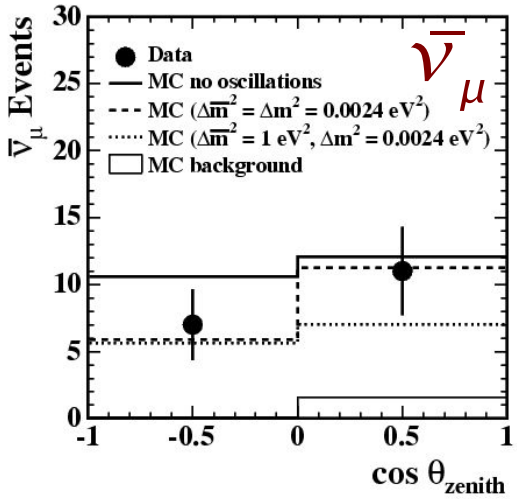
- Oscillation fit:





- First $\nu \Leftrightarrow$ anti-ν separation:





$$R = \frac{\bar{\nu}}{\bar{\nu} + \nu}$$

assume equal oscillations for MC

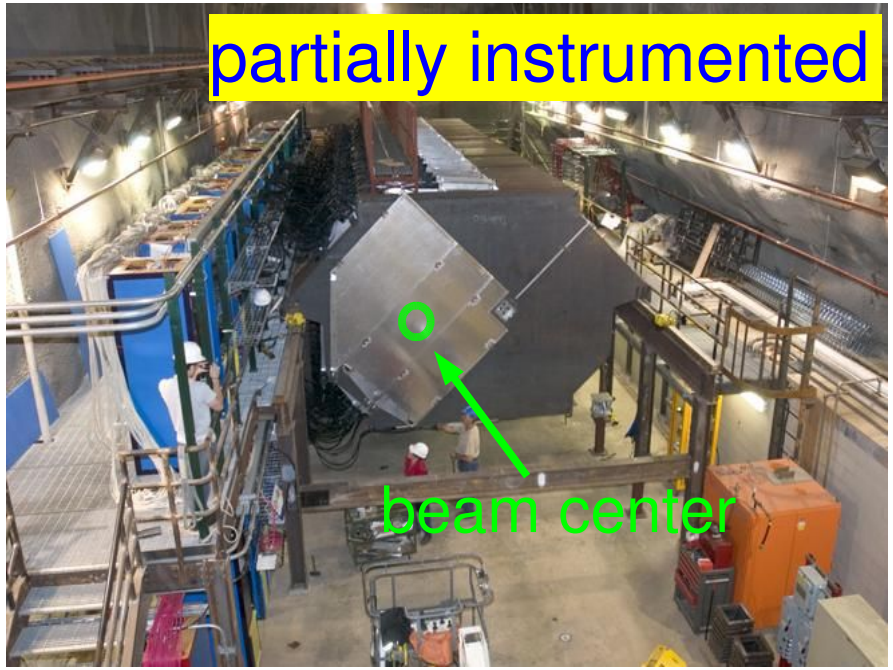
$$\frac{R^{data}}{R^{MC}} = 0.98 \pm 0.20$$

Publication will be submitted soon

Near Detector (ND)

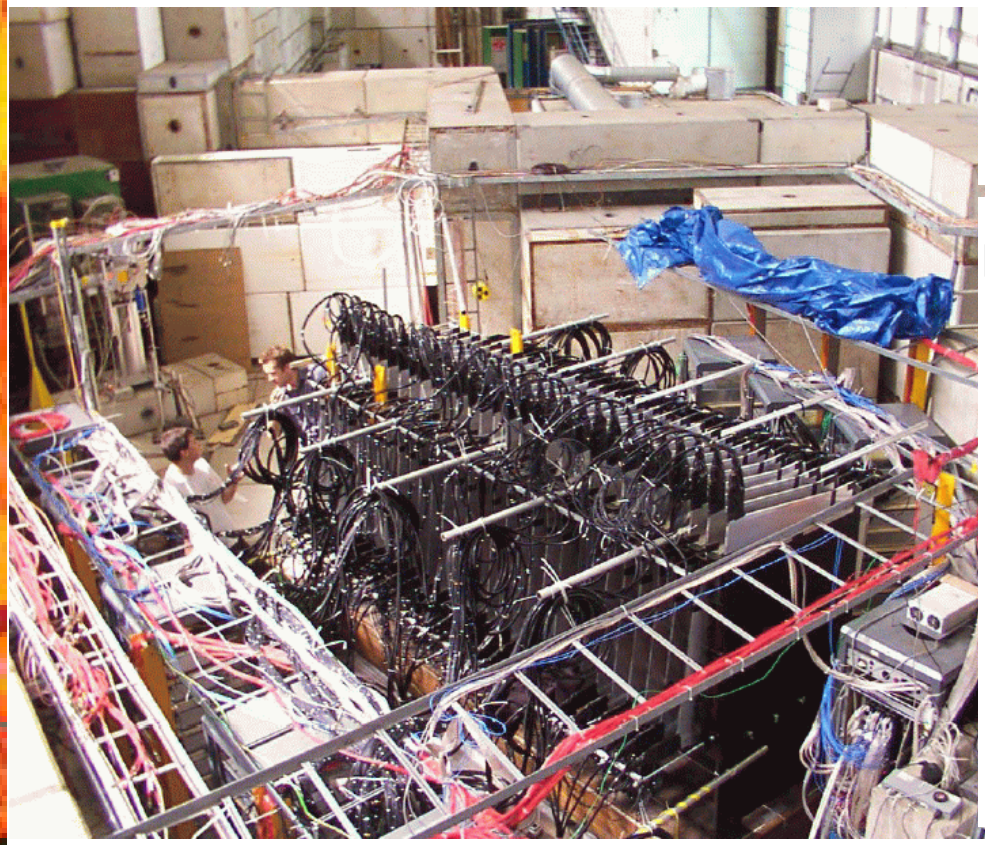
- Same basic design as far det.
- Located 100m underground at 1km from target
- 282 planes: 0.98 kT
  - calorimeter region:
    total of 120 planes
    4 part. + 1 fully instrum.
  - spectrometer region:
    total of 162 planes
    only every 5th instrumented
  - strips read out from one side
  - only spectrometer multiplexed
  - fast 'QIE' electronics:
    continuous digitization during spills: 19ns time slices

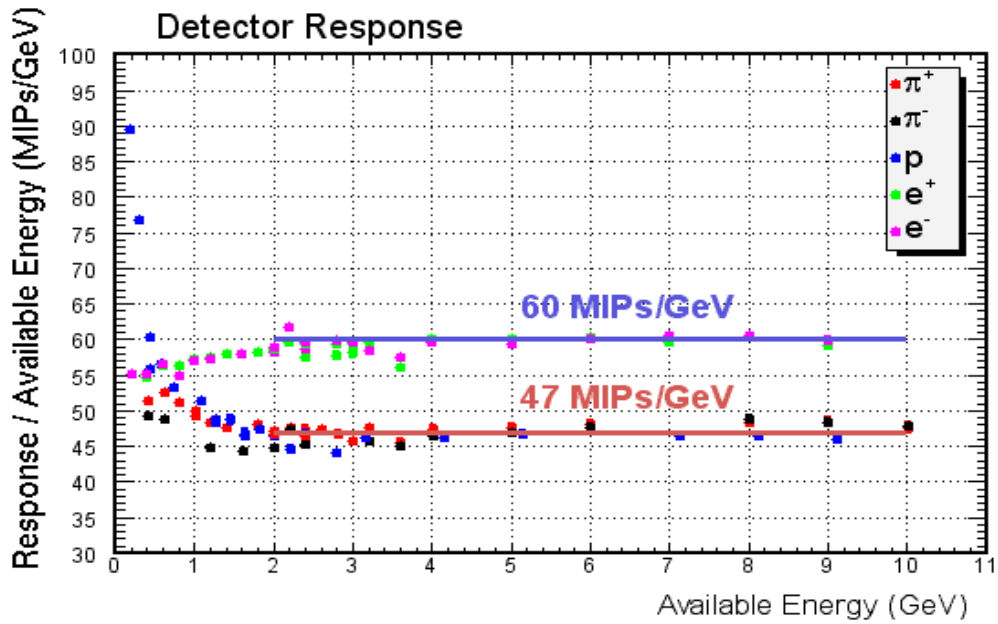


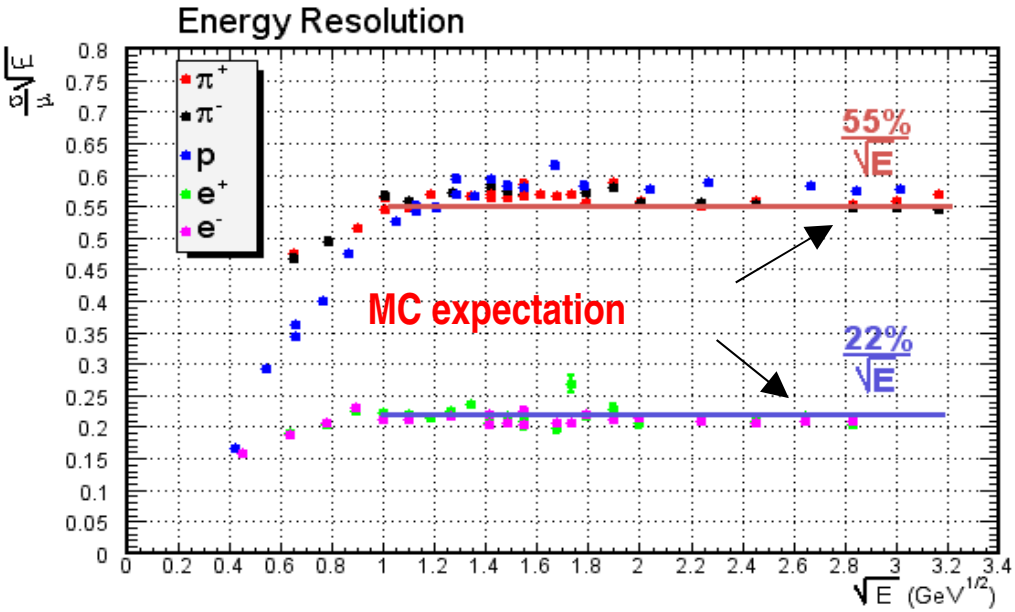


Calibration Detector

- 60-plane 'mini-MINOS'
- taken data at T7 & T11 test beam lines at CERN during 2001-2003







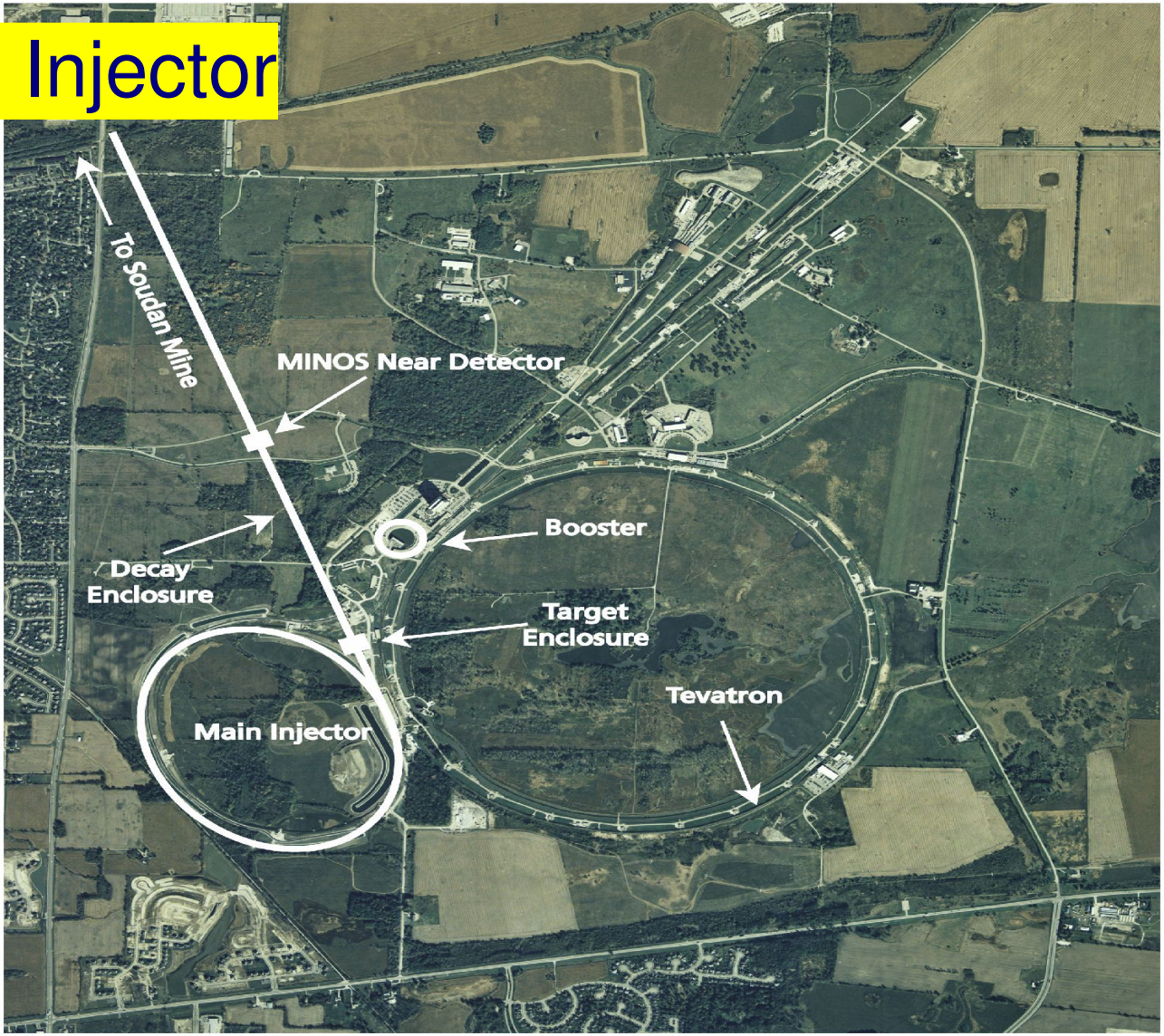
NuMI Beamline

BROOKHAVEN NATIONAL LABORATORY

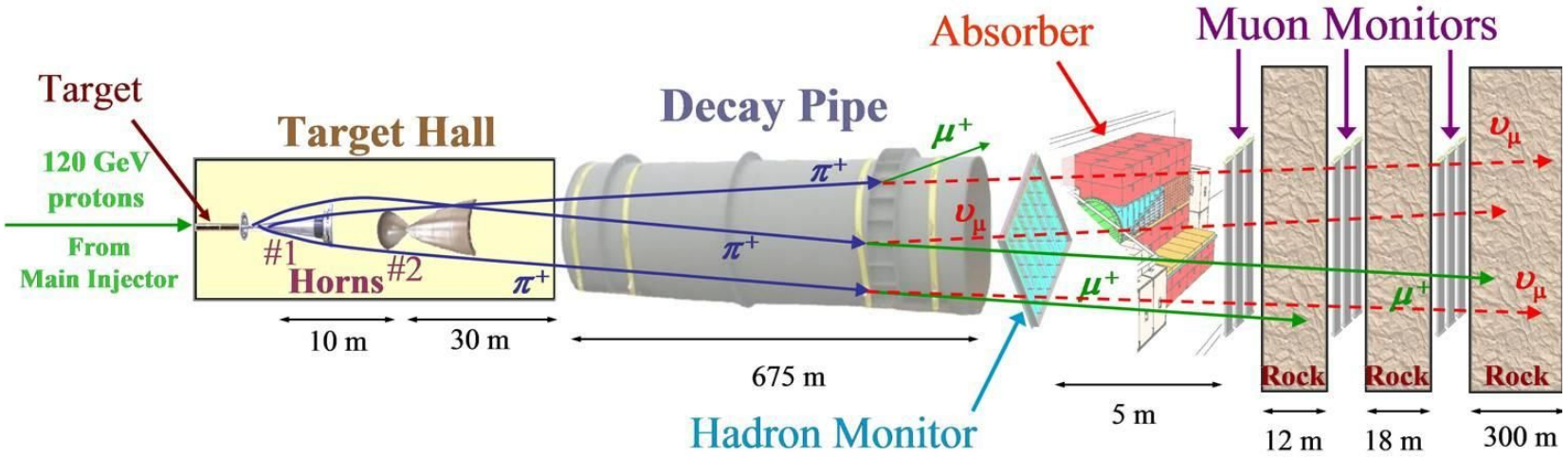
Fermilab Main Injector

- 120 GeV protons
- 2.5 10^{13} p/spill
- 1.9s rep. rate
- ~8 μs spill

⇒ 250 kW



NuMI Beamline



NuMI Beam

- pitched down 58 mrad
- incident on graphite target
- 2 magn. horns to focus hadrons
- 675m long steel decay pipe
- hadron absorber downstream
- 200m rock for μ absorption

Beam Monitoring

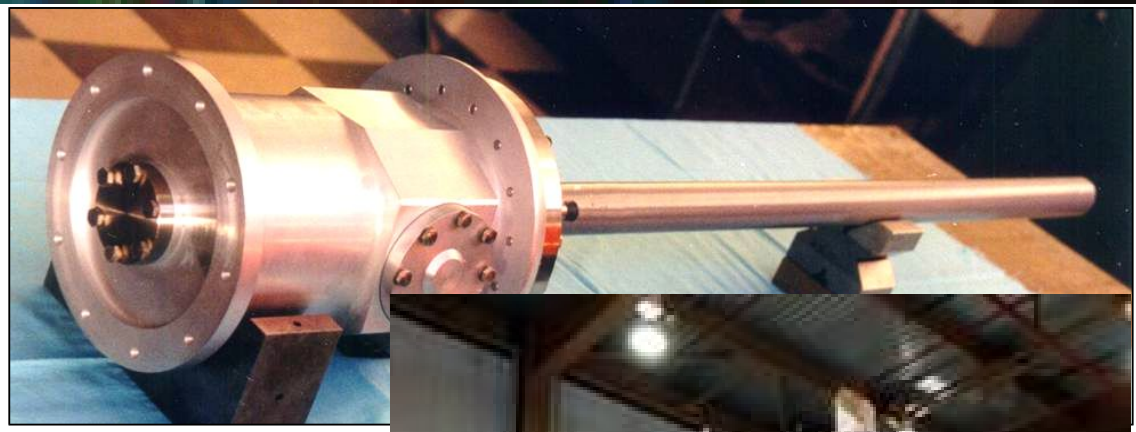
- pre-target:
  - secondary emission mon.
  - beam position monitors
  - toroids, loss monitors,...
- post-target:
  - hadron monitor
  - 3 muon monitors

Target & Horns

BROOKHAVEN NATIONAL LABORATORY

Graphite Target

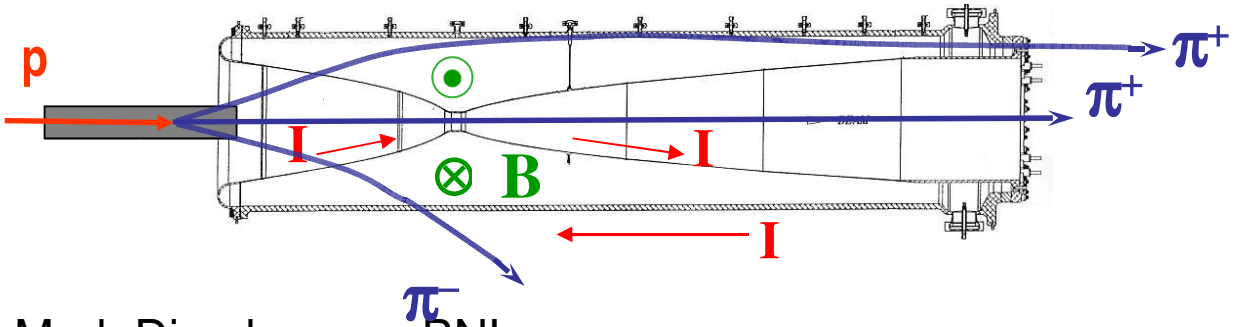
- 6.4 x 28 mm² profile (1mm beam size)
- two 47cm segments
- beam is 1 mm radius
- water cooled (4 kW beam power)





Horns

- pulsed with 200kA
- toroidal B-field ~I/r between inner & outer conductor



Beam Spectrum

BROOKHAVEN NATIONAL LABORATORY

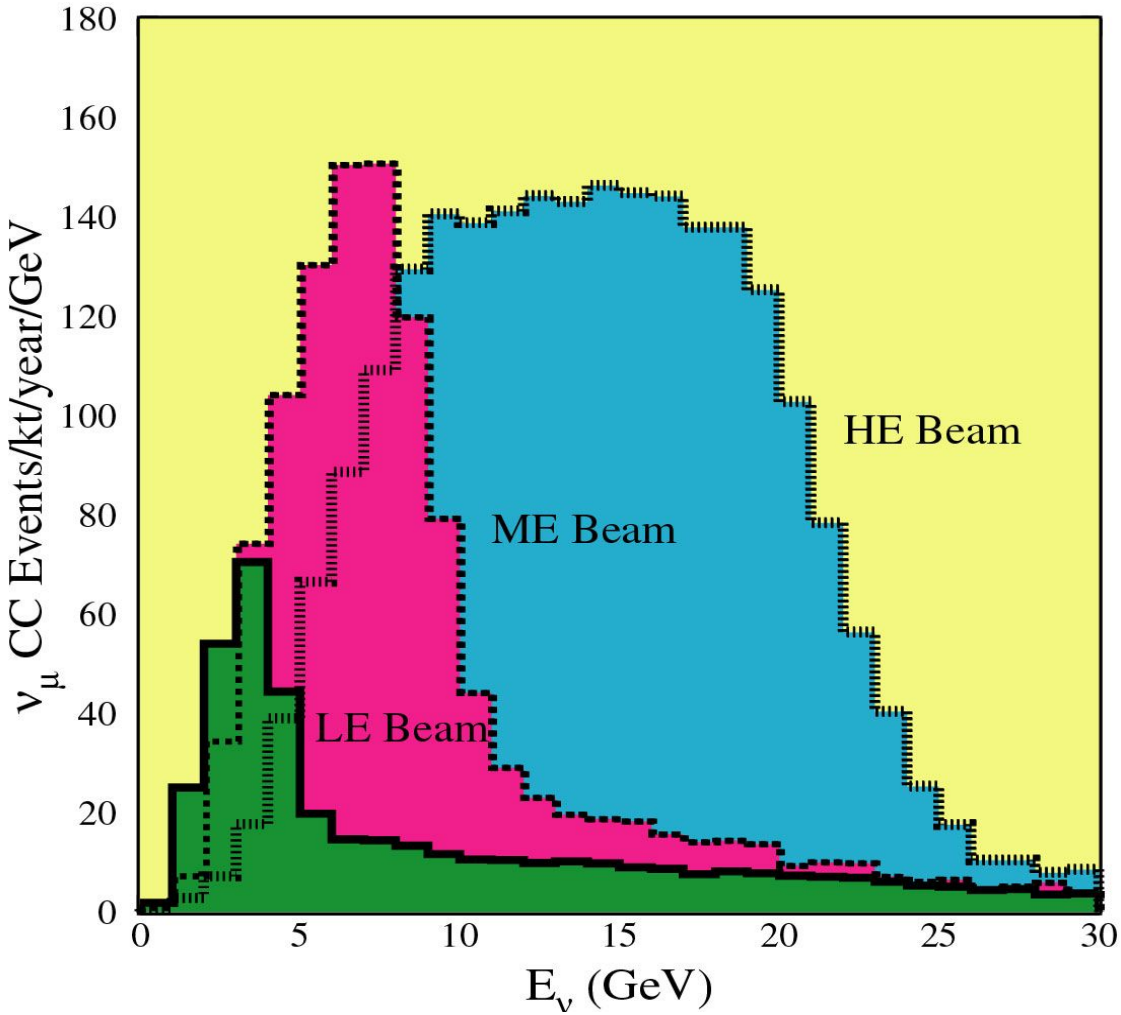
Beam spectrum can be adjusted by changing target and horn positions

ν_μ CC Events/year

(with no oscillations)

Low	Medium	High
1,600	4300	9250

preferred for current value of Δm^2_{32}



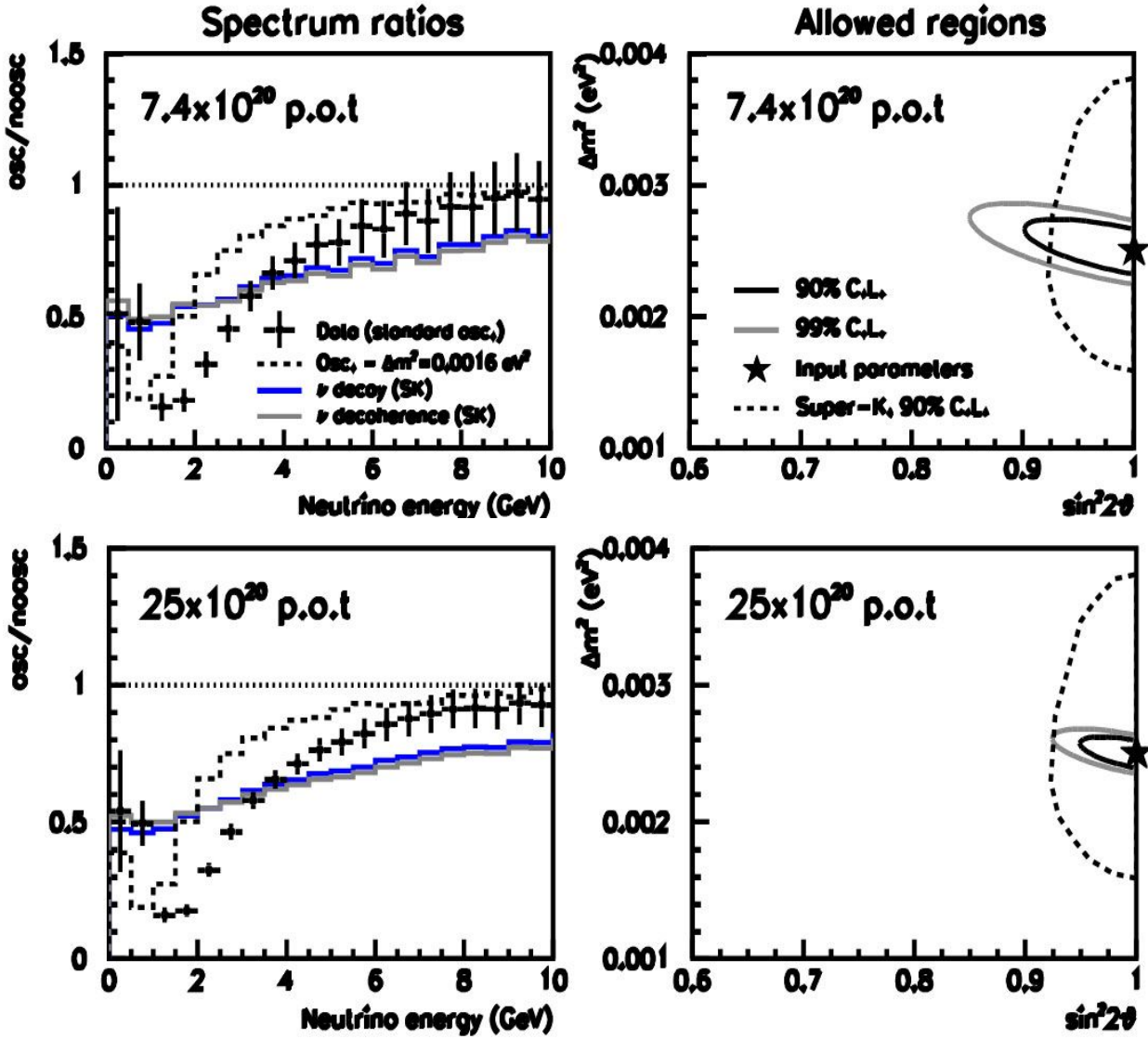
Physics Reach

BROOKHAVEN NATIONAL LABORATORY

ν_μ disappearance

- Ratio of yield at far det. to expected based on near det.
- location and depth of dip give Δm^2_{32} and $\sin^2 2\theta_{23}$

Determine Δm^2_{32} to 10% and rule out exotic models



3 years of running at nominal intensity (top) & with upgrade (bottom)

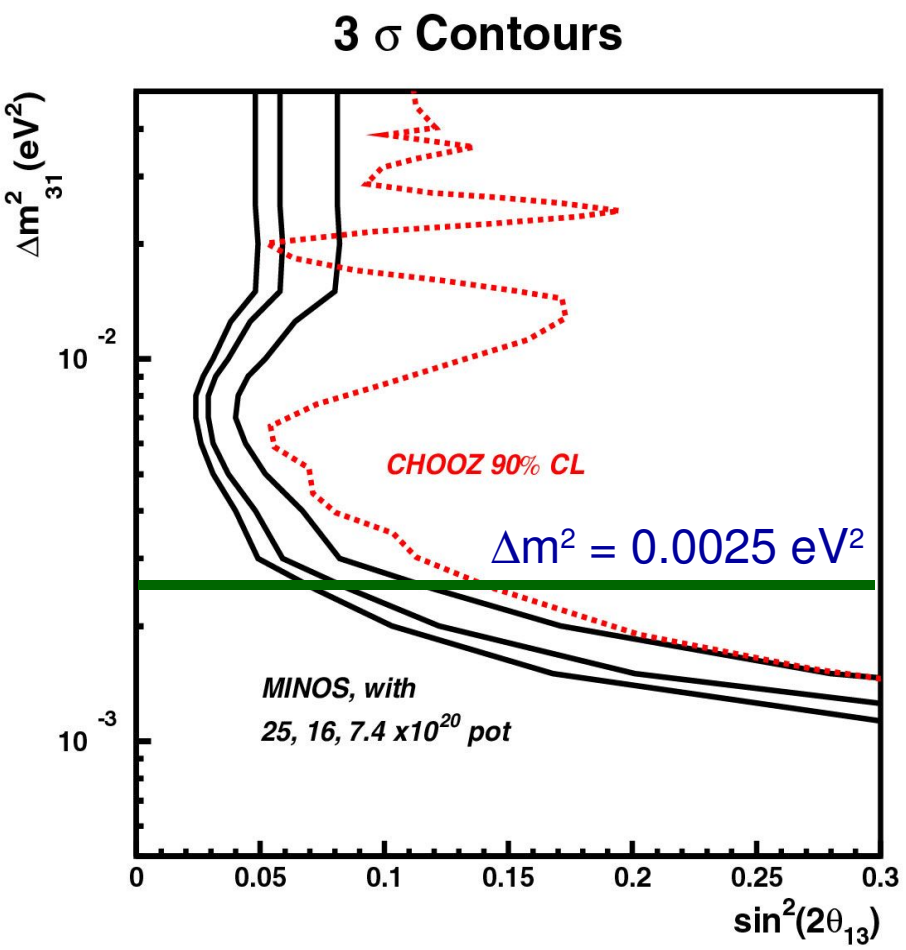
Physics Reach

BROOKHAVEN NATIONAL LABORATORY

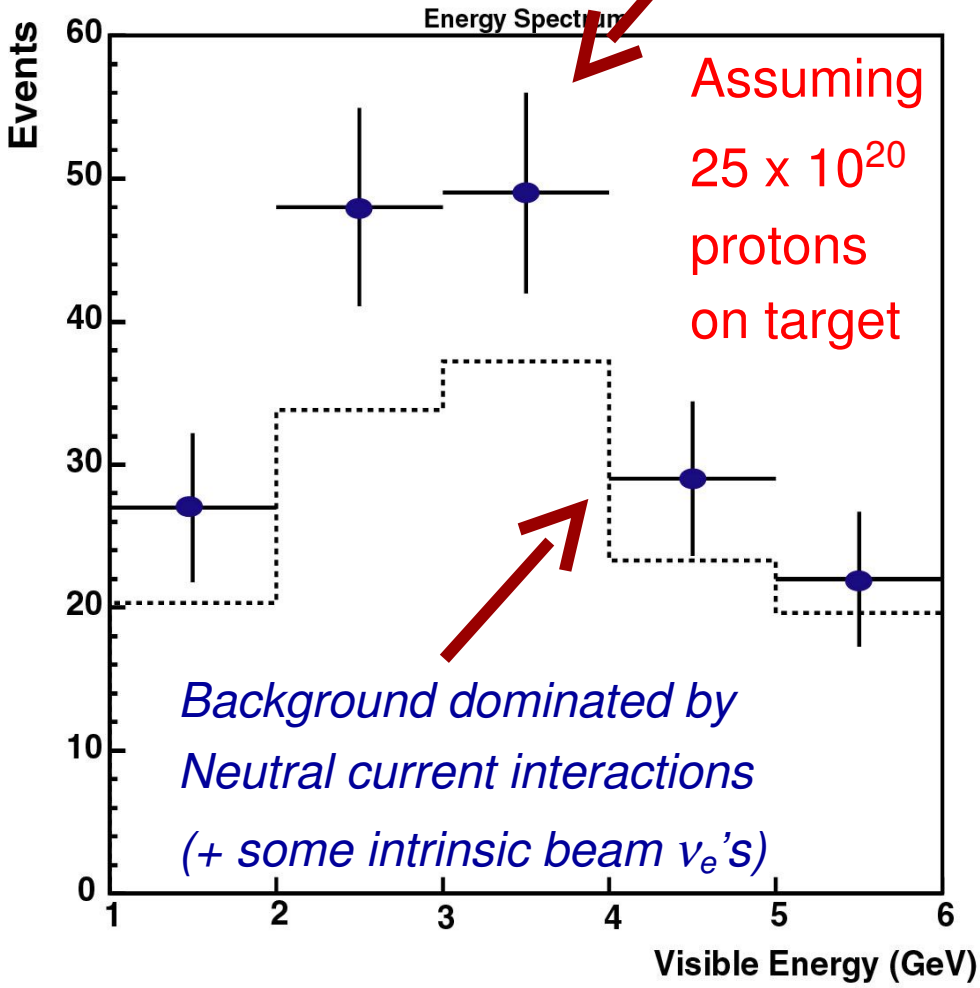
ν_e appearance

↓

evidence for non-zero θ_{13}

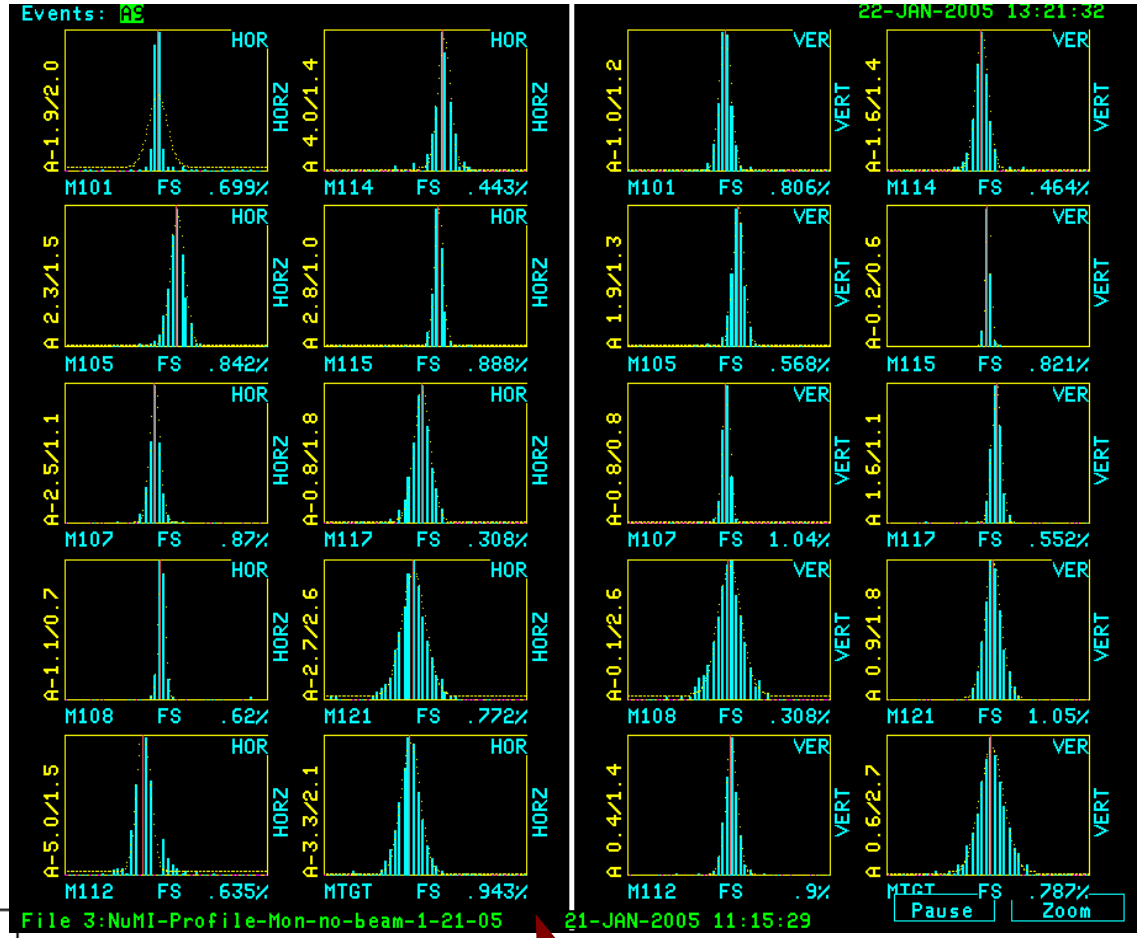


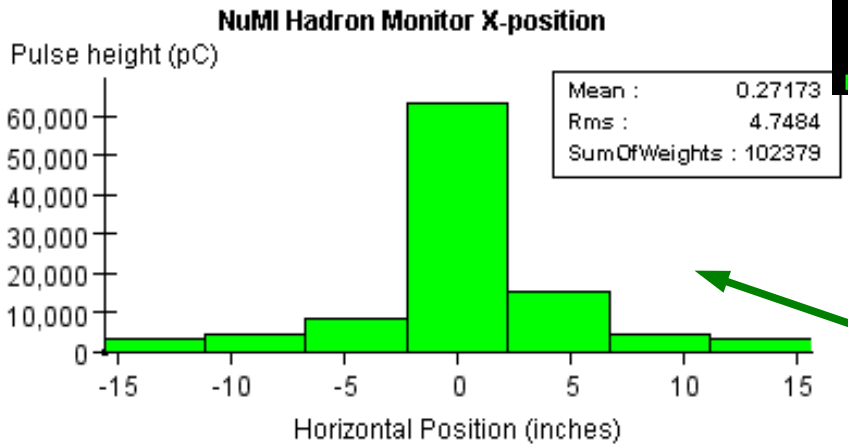
For Δm^2 = 0.0025 eV^2, $\sin^2 2\theta_{13}$= 0.067



First Beam in NuMI

- Transport down entire beamline was achieved on 12th beam pulse during December tests
- Target was out and horns were off





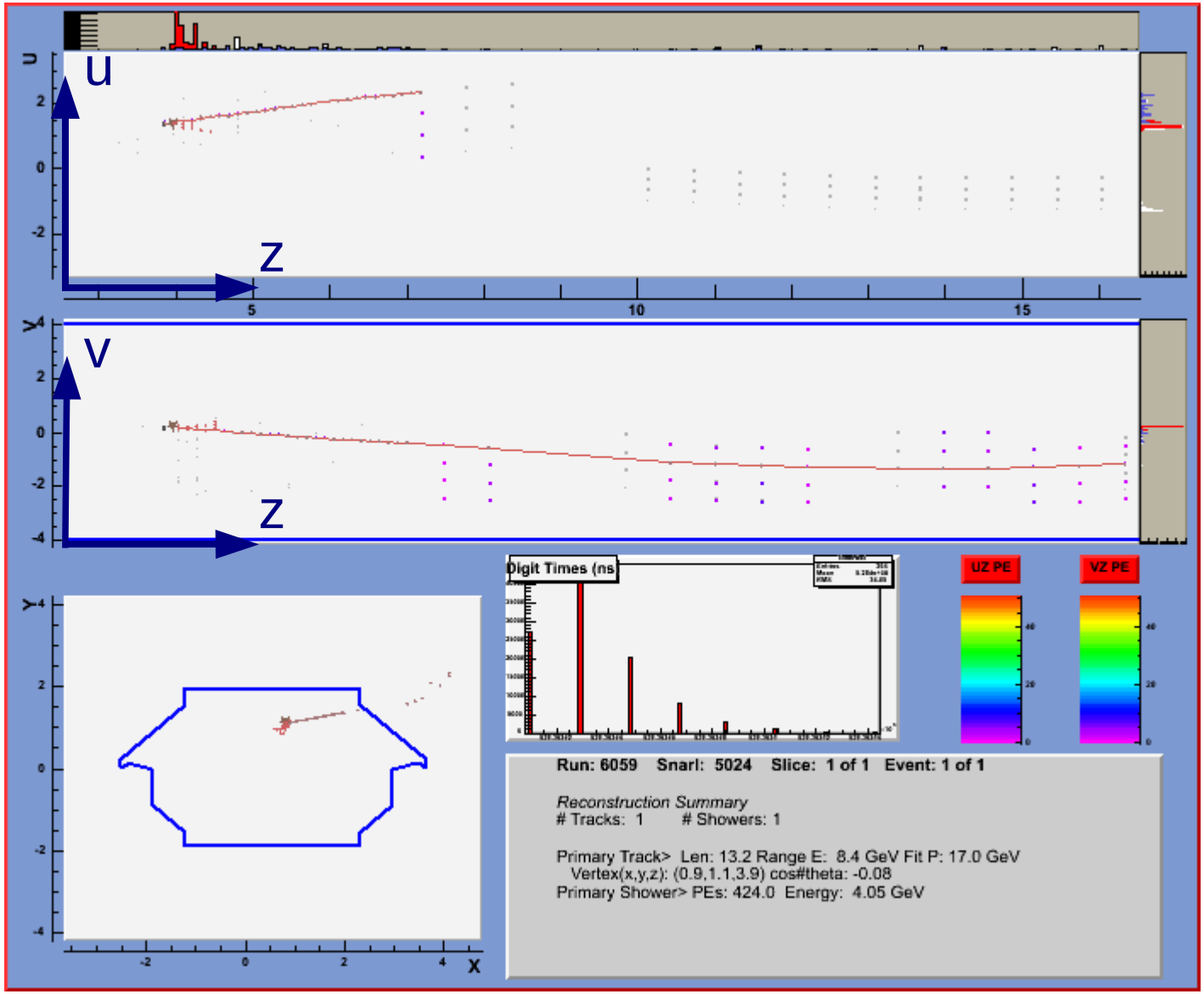
Beam profiles from SEMs

Profile from hadron monitor

First ND Beam Neutrinos

Target put in ME position and horns on for Jan. beam tests

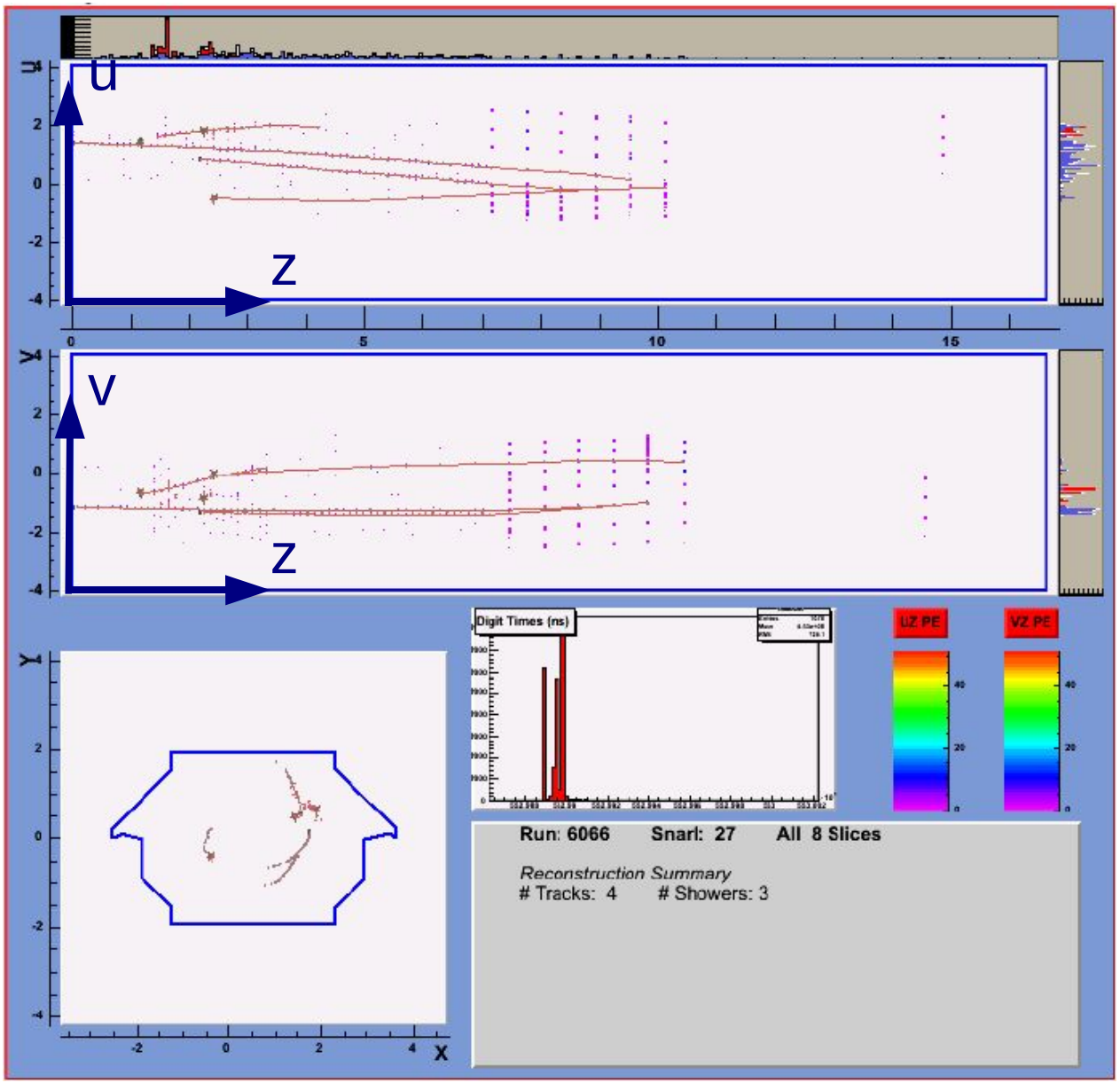
Observed our first neutrino from the beam in the near det. on Jan 21, 2005

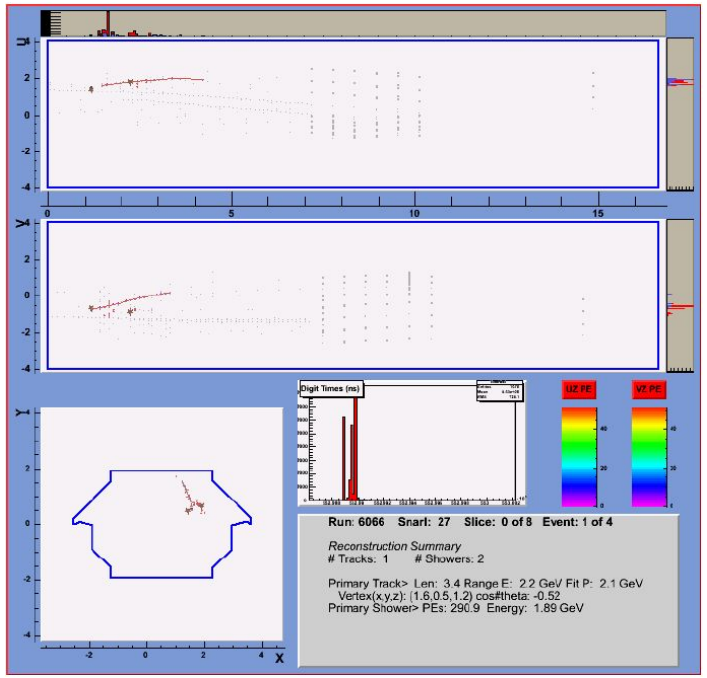


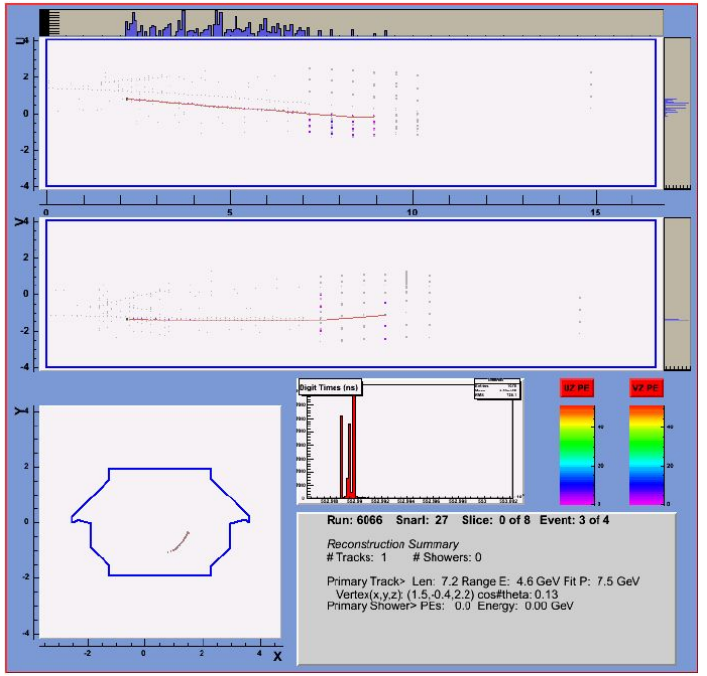
First ND Beam Neutrinos

BROOKHAVEN NATIONAL LABORATORY

multiple ν interactions during a spill







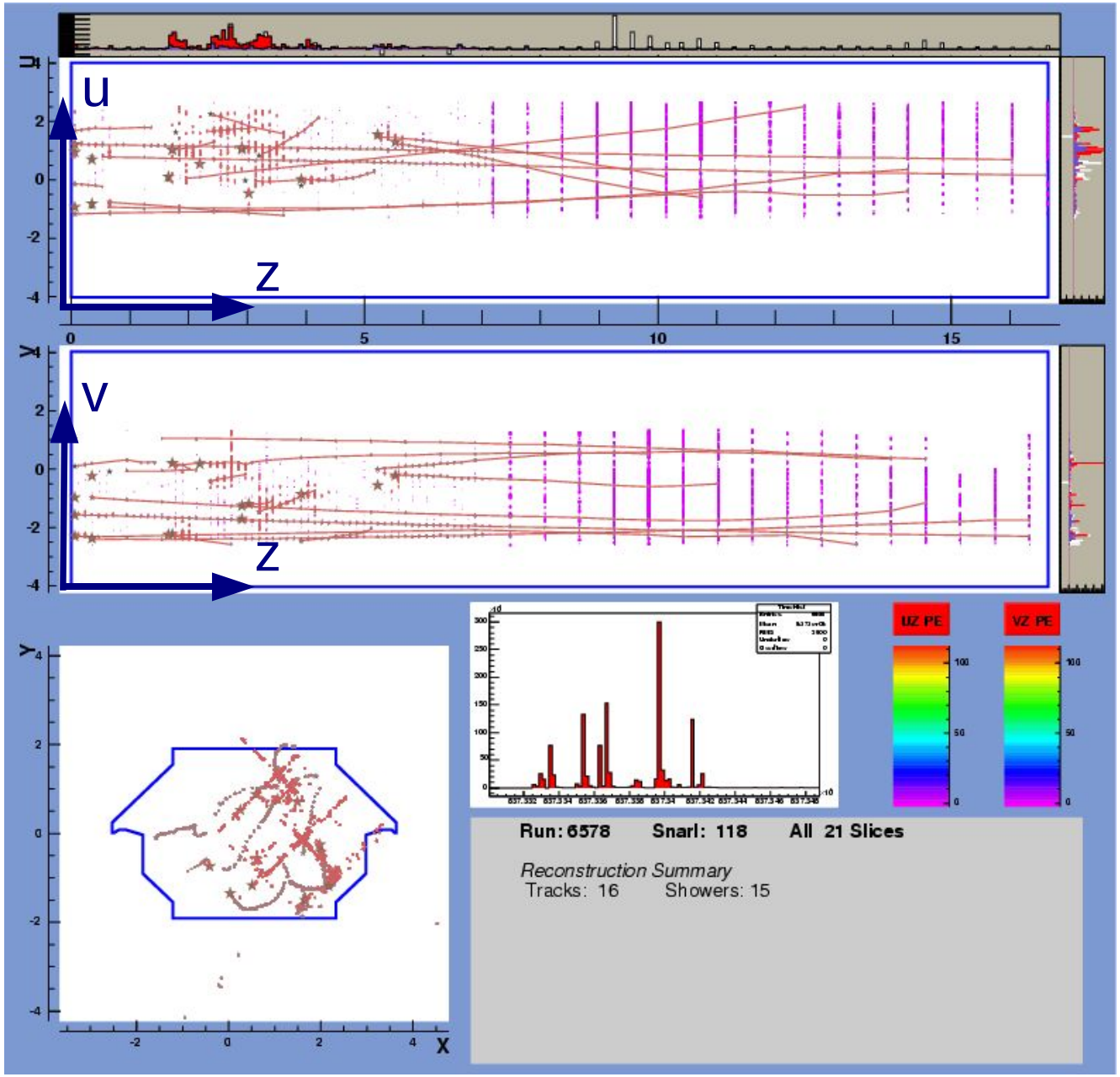
Mark Dierckxsens, BNL

First ND Beam Neutrinos

BROOKHAVEN NATIONAL LABORATORY

2.5 10^{13} p/spill

target is in ME position

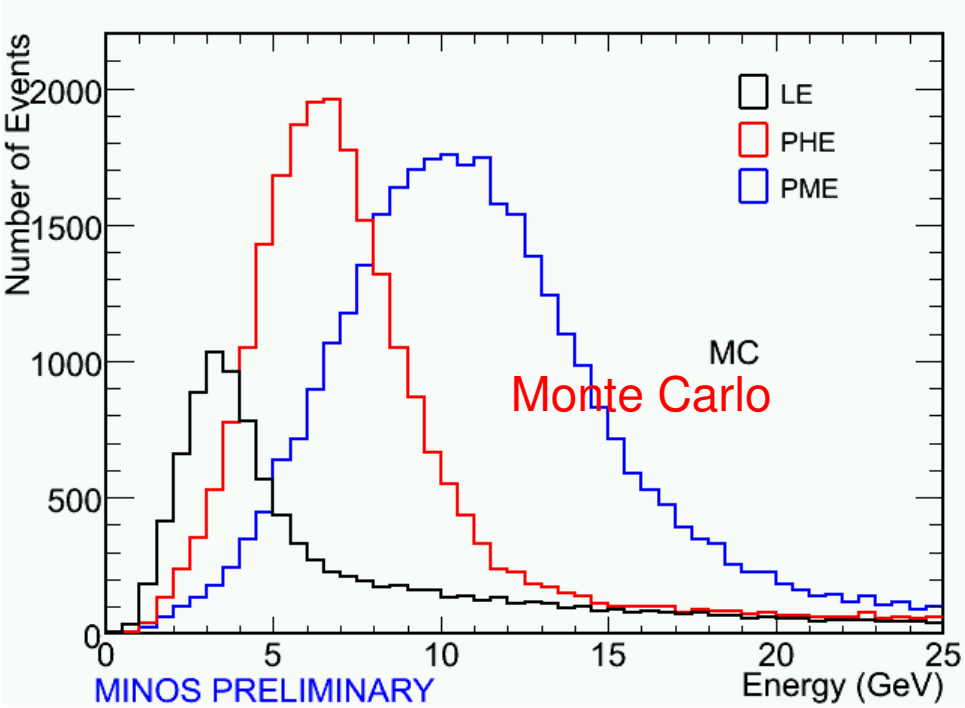


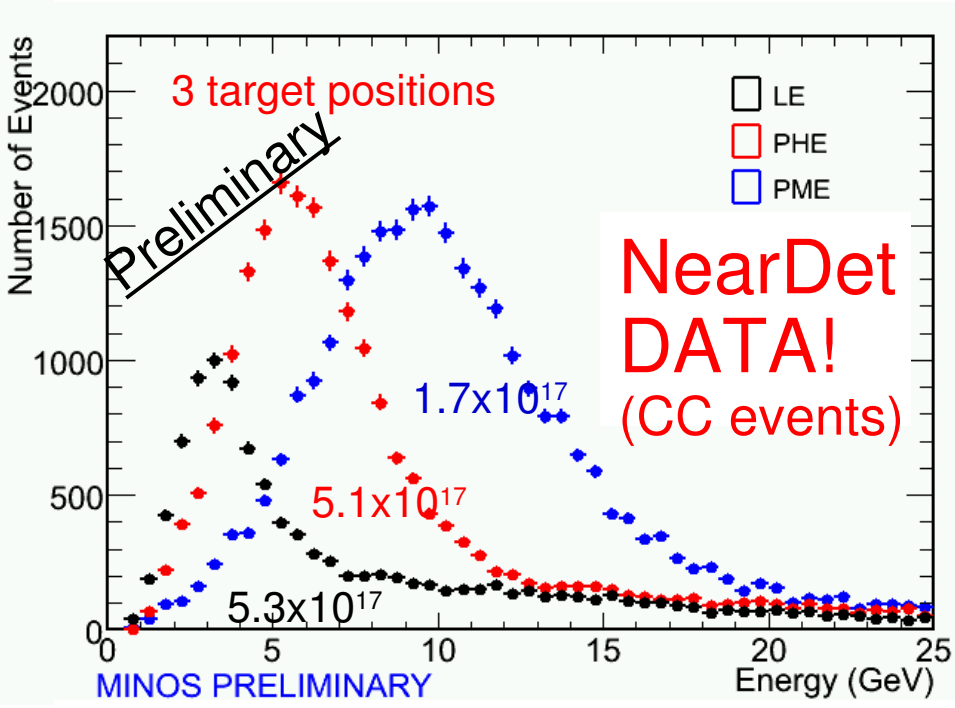
At nominal running:
- near: 11K evts/day
- far: few evts/day

ND Beam Energy Scan

3 energy spectra by varying target position w.r.t. horn 1:

- LE: target in horn 1
- pME: target 1m from horn 1
- pHE: target 2.5m from horn 1

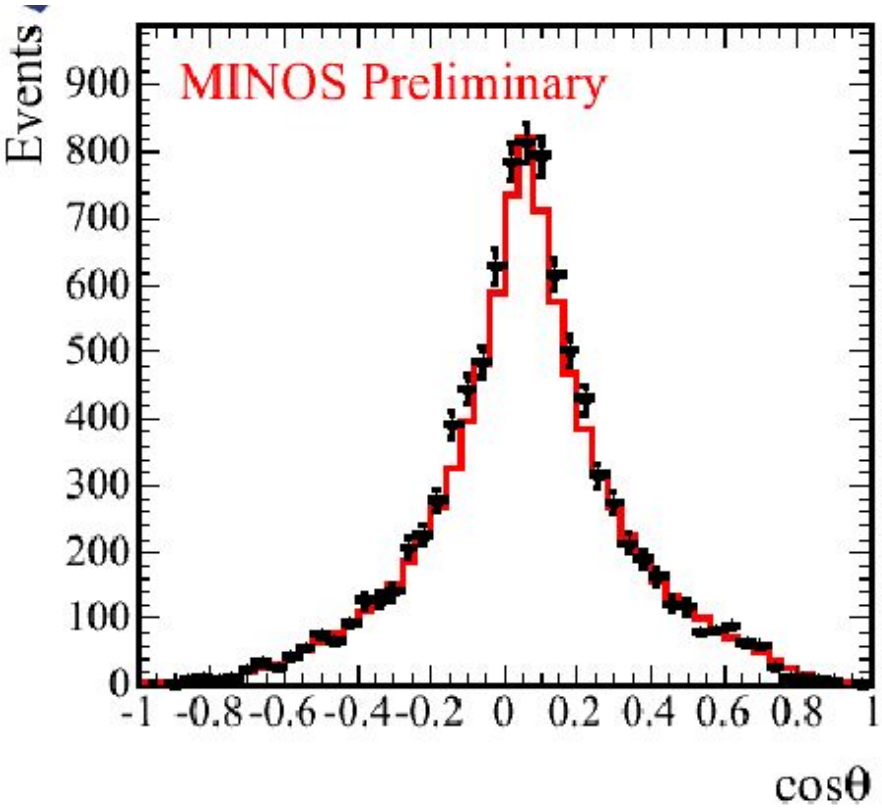


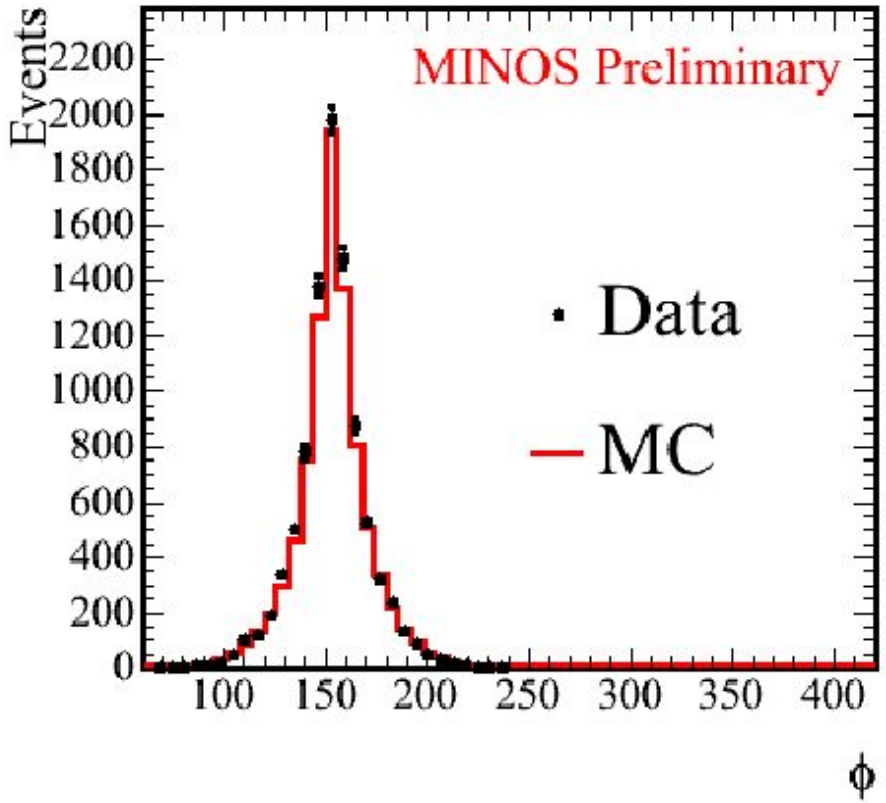


Very preliminary: agreement data - MC

Neutrino Beam Direction

Another check with the near detector data:
is the neutrino beam pointing in the right direction?





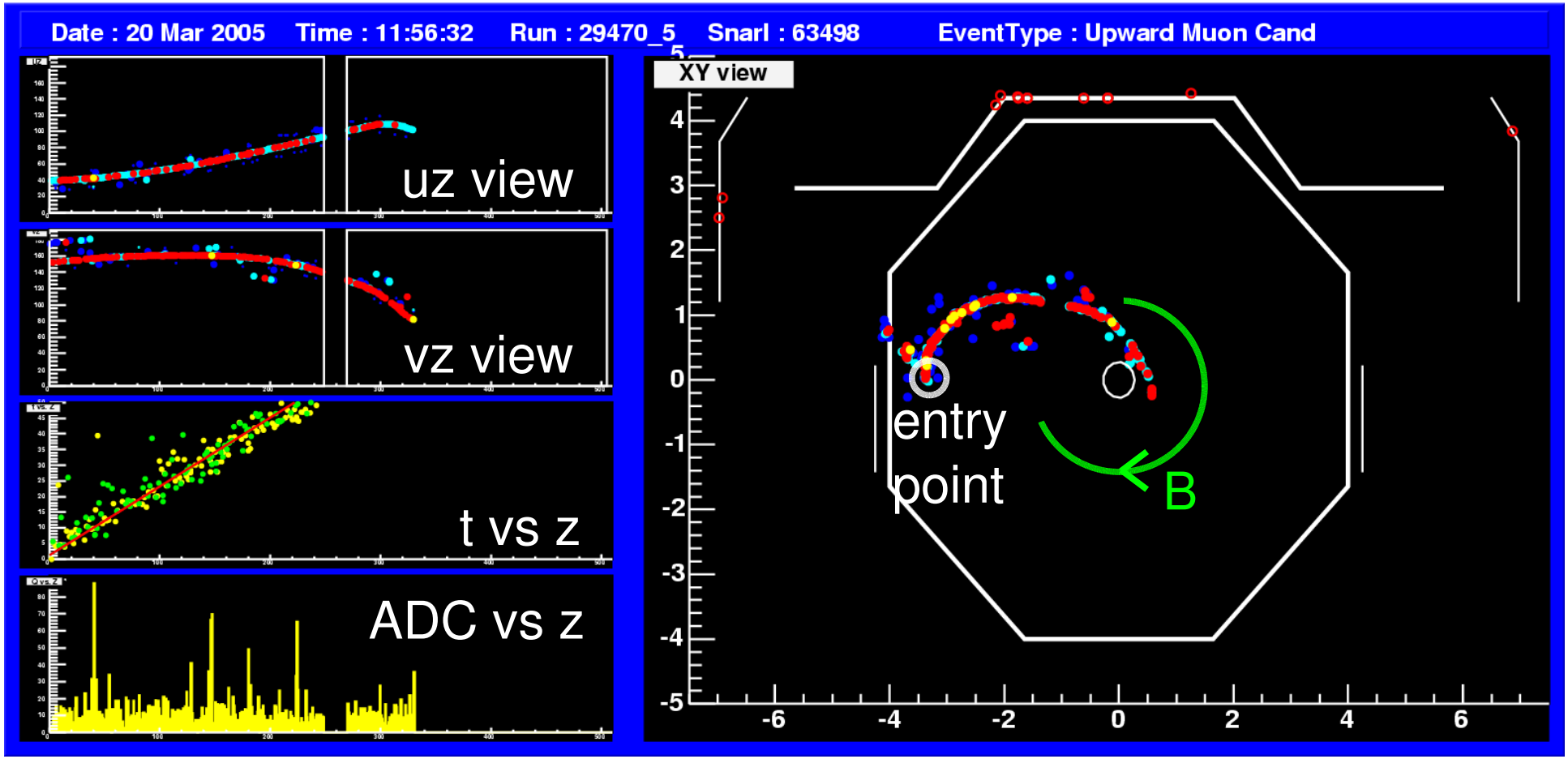
⇒ ν beam pointing towards Soudan mine

⇒ should observe ν's from beam in far detector

First FD Beam Neutrinos

BROOKHAVEN NATIONAL LABORATORY

First reported beam candidate: a “rock” muon



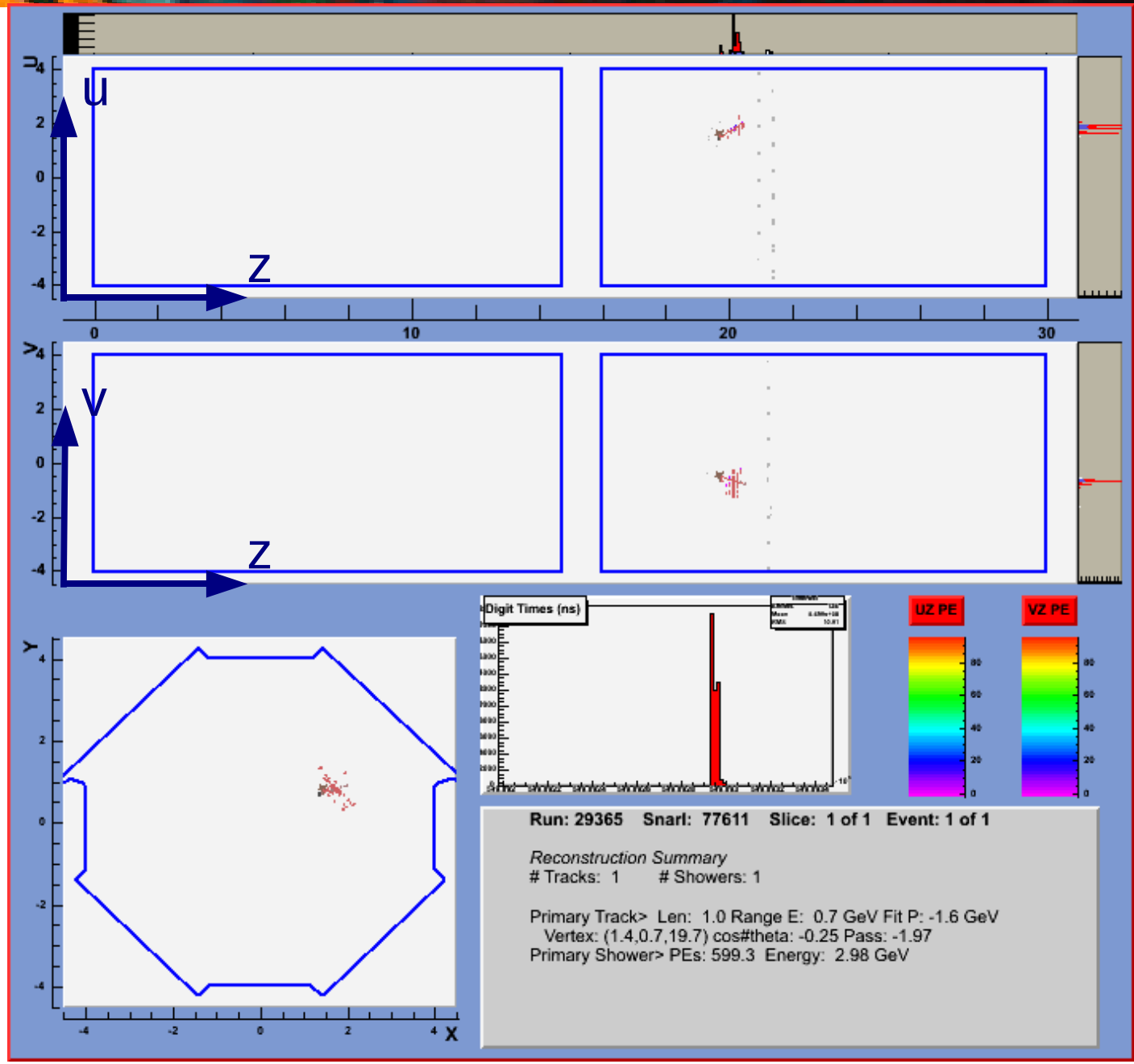
- timing and direction consistent with beam neutrino
- tracking indicates a 12 GeV μ^-

First FD Beam Neutrinos

BROOKHAVEN NATIONAL LABORATORY

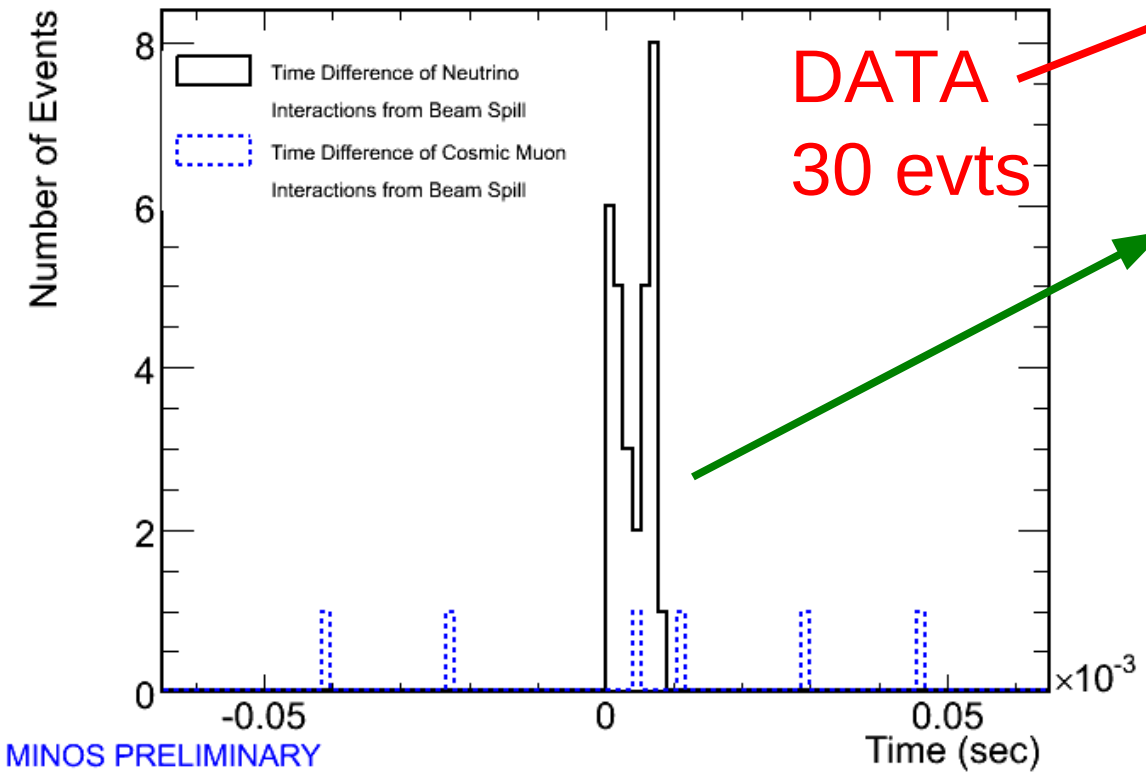
First contained event with interaction vertex inside fiducial volume

neutral current candidate



FD beam ν properties

- blind approach: unknown fraction FD beam data blinded



for June-Sept data, 5.1 10^{19} p.o.t.:

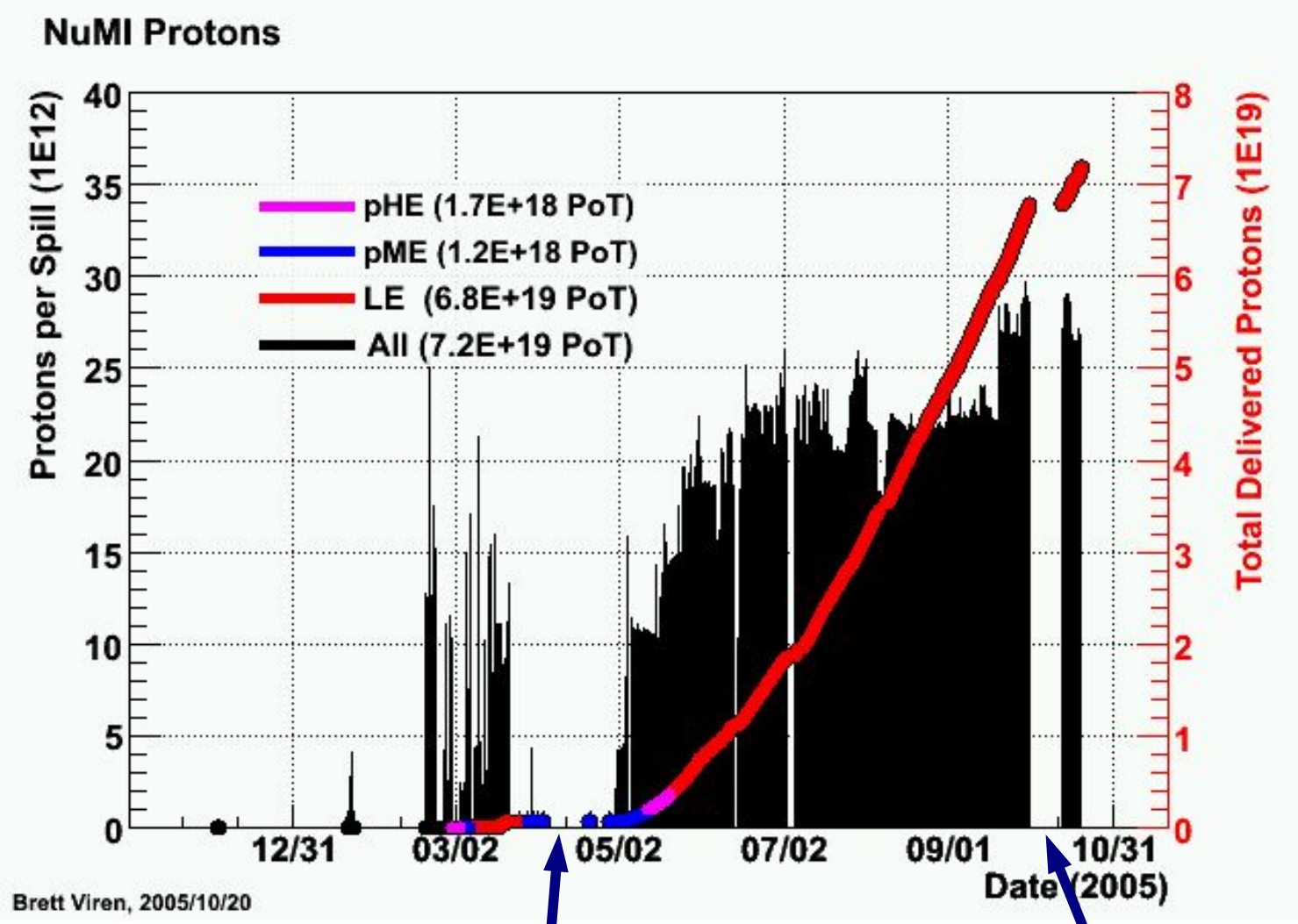
139 ν events

(no fiducial cuts)

- cosmic μ bkg reduced to 0.03 evts/month by cuts on timing, angle w.r.t. beam, fiducial volume

$\Rightarrow$ acceptance beam ν: 64%

Protons Delivered

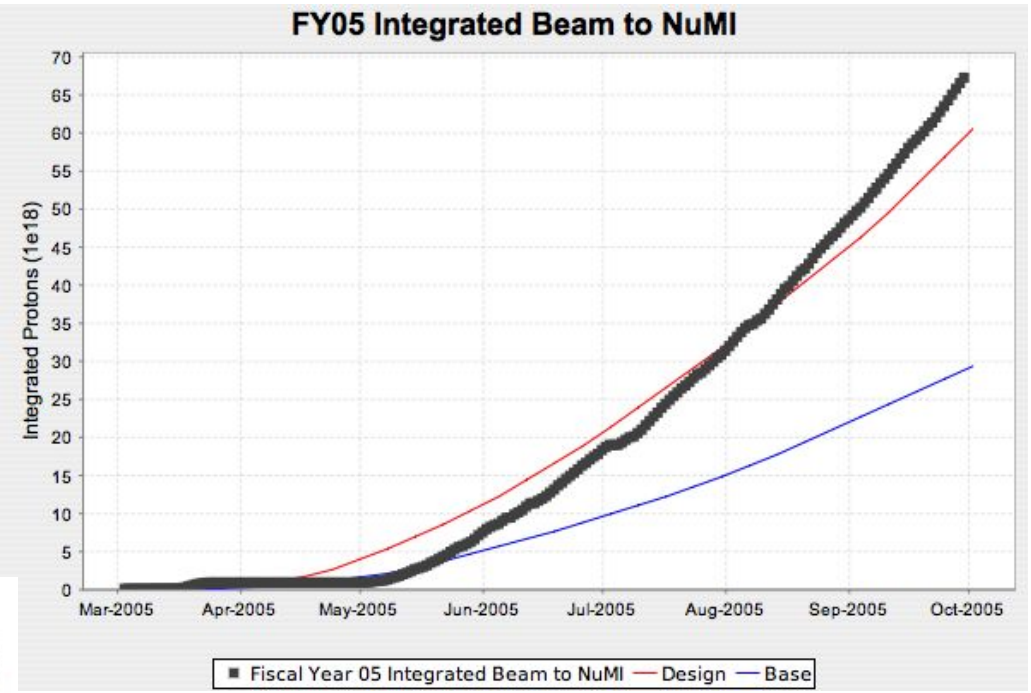


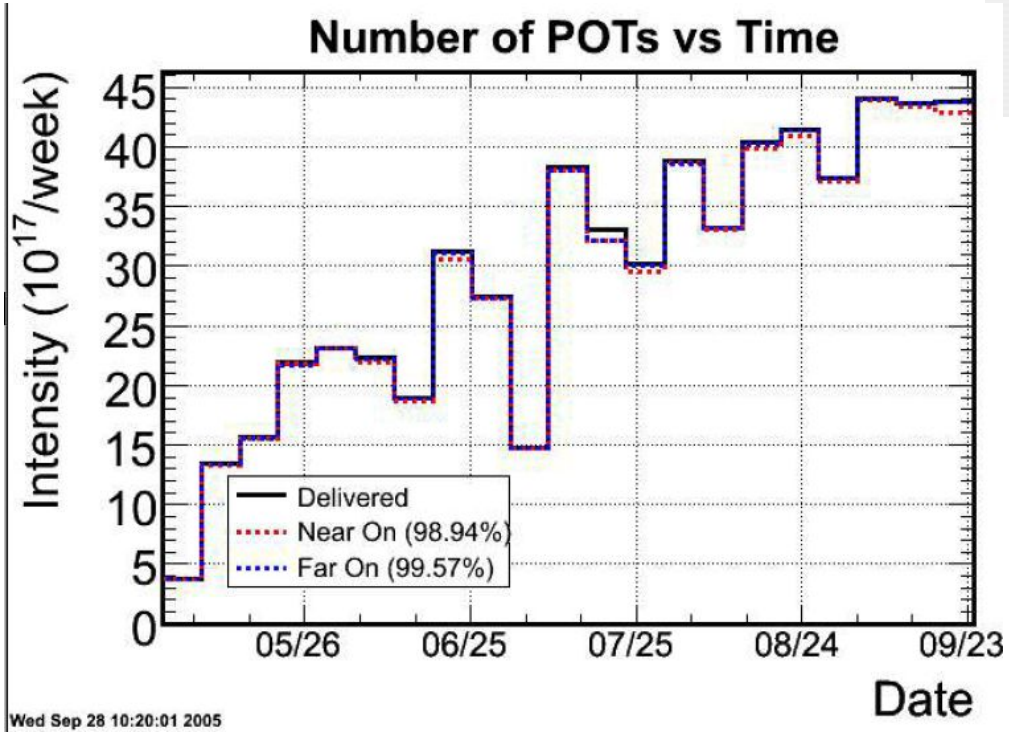
water leak in target vessel

horn 2 short

Protons Delivered

- Protons delivered to date: 8.5 10^{19}
- Maximum beam power achieved: 270 kW





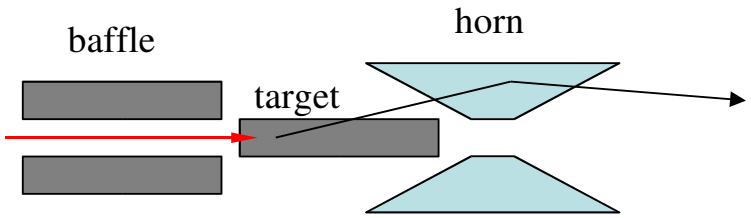
Live-time detectors since May:

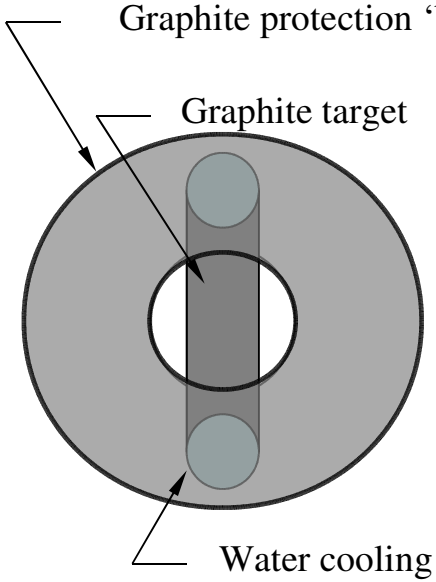
Near: 98.9%

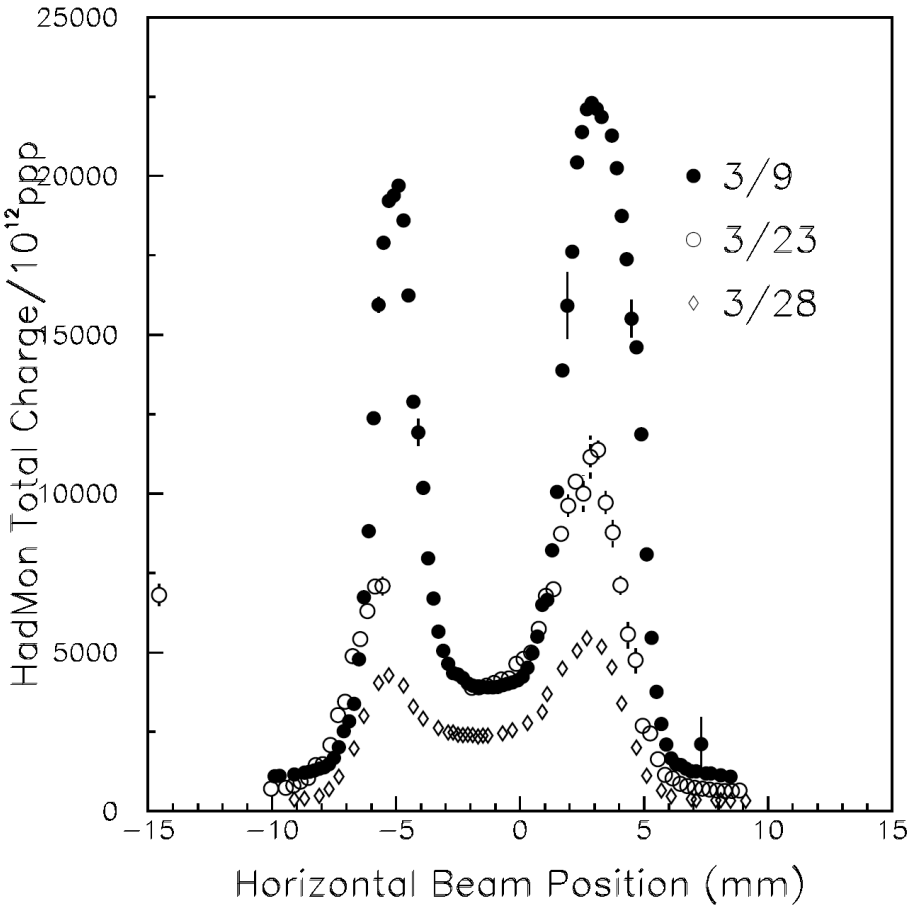
Far: 99.6%

Water Leak in Target

- On March 23, indications of leak in water cooling system
- confirmed by target scans





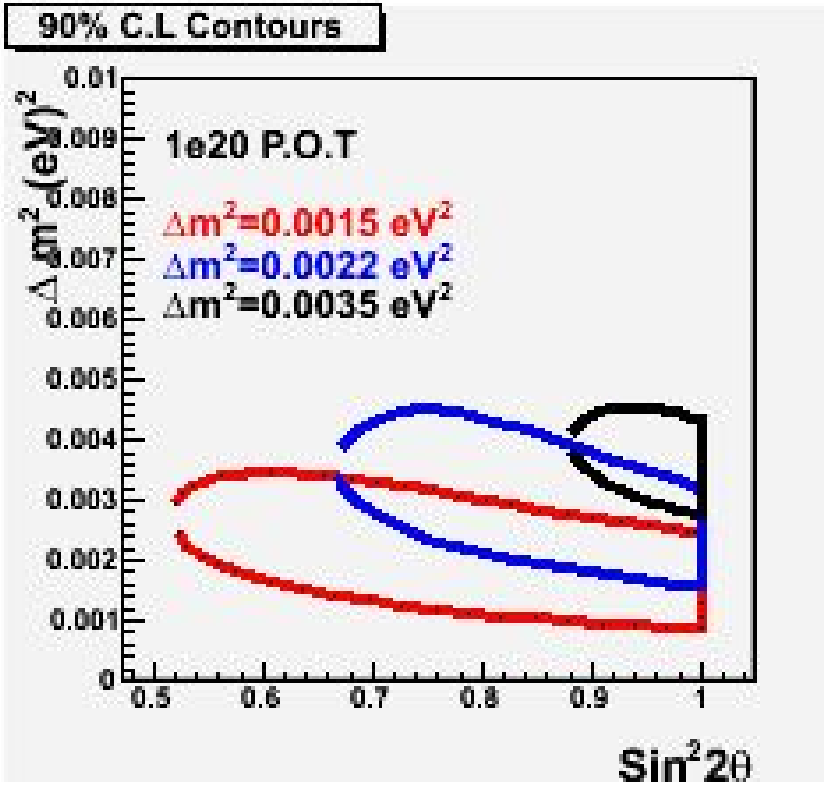


- target was taken out and investigated
- canister back-pressured solved the problem
- A spare target & carrier is available

Near Term Future

- Unblind data early January
- ~ $1x10^{20}$ protons on target
- assess beam energy

ν_μ disappearance



ν_e appearance

$\sin^2 2\theta_{23} = 1.0$

$\Delta m^2_{32} = 0.0025\ eV^2$

$\sin^2 2\theta_{13} = 0.12$

2.0 signal events

3.4 background

Conclusions

- MINOS expects to measure Δm^2 to 10%
- MINOS will improve limits on ν_e appearance
- MINOS is taking data since end of February
- Detectors are running very smoothly
- Far detector operational since July 2003
  publication of atmospheric neutrinos soon
- Initial design goals of 2.5 10^{13} protons/pulse
  and 2s rep rate achieved.
- Unblind data and publish results after first 10^{20} p.o.t.