The MINOS Experiment:
Status & Report on
First Beam

Jon Urheim, Indiana University

Aspen Winter Conference,

17 February 2005

- Introduction
- MINOS Experiment Overview & Physics Reach
- Status of the MINOS Detectors & NuMI Beamline
- Report on Commissioning of NuMI Beam !

Introduction

- **MINOS is reaching a milestone today !!**
  - **DOE review of "Critical Decision 4" criteria…**

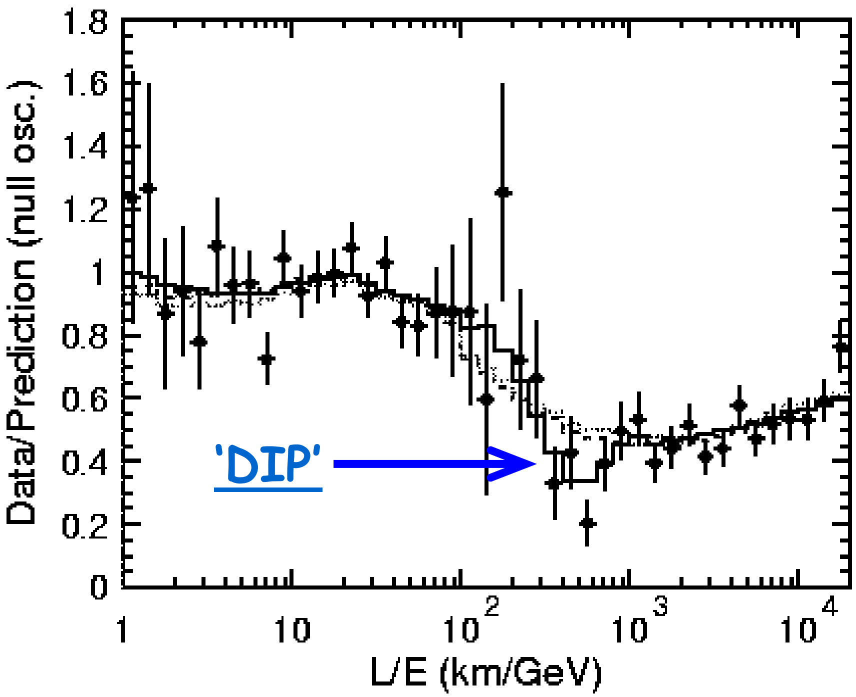
    includes:
    - observation of atmospheric neutrinos in MINOS Far Detector
    - observation of neutrinos from NuMI beam in Near Detector
    - achieve intensity of ***>1 x 10^{12}*** protons per spill on target
    - *I will talk about each of these here!*
  - **CD-4 marks transition to "operations" phase of expt.**
    - we are quite happy about this !
- **But first some background….**

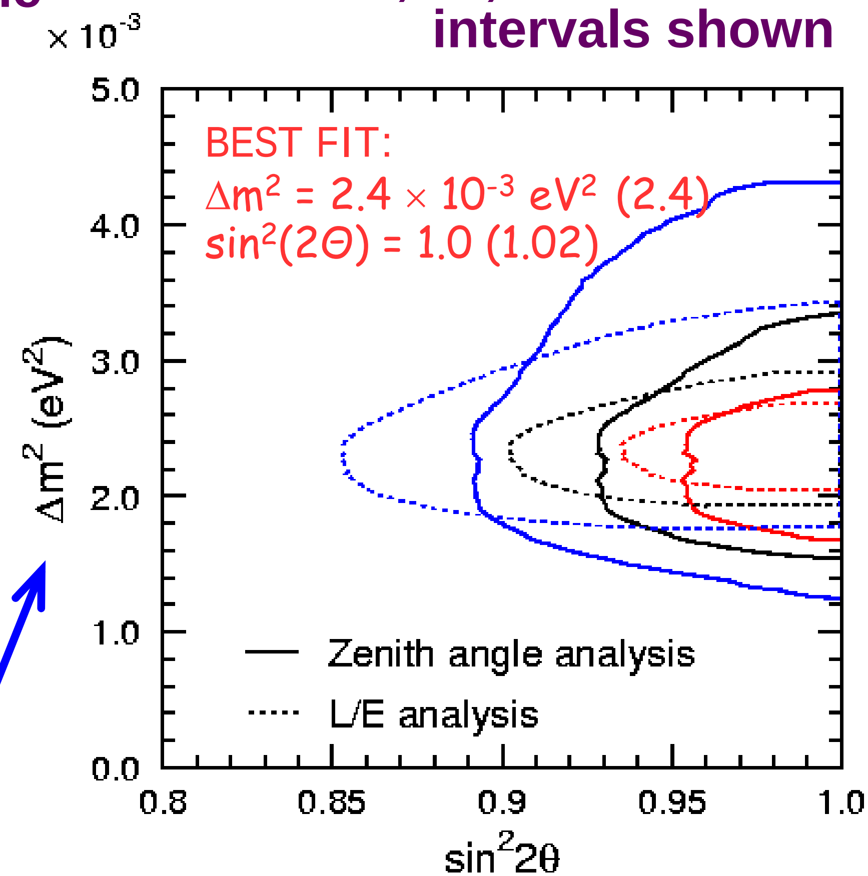
Atmospheric Neutrinos – SuperK

Latest new development:

- **selection of events w/ good resol'n in *L/E***
- **provides better sensitivity to Δm^2 !!**
- **can resolve characteristic dip in the L/E distribution at the ~3σ level.**

68, 90, 99% CL intervals shown

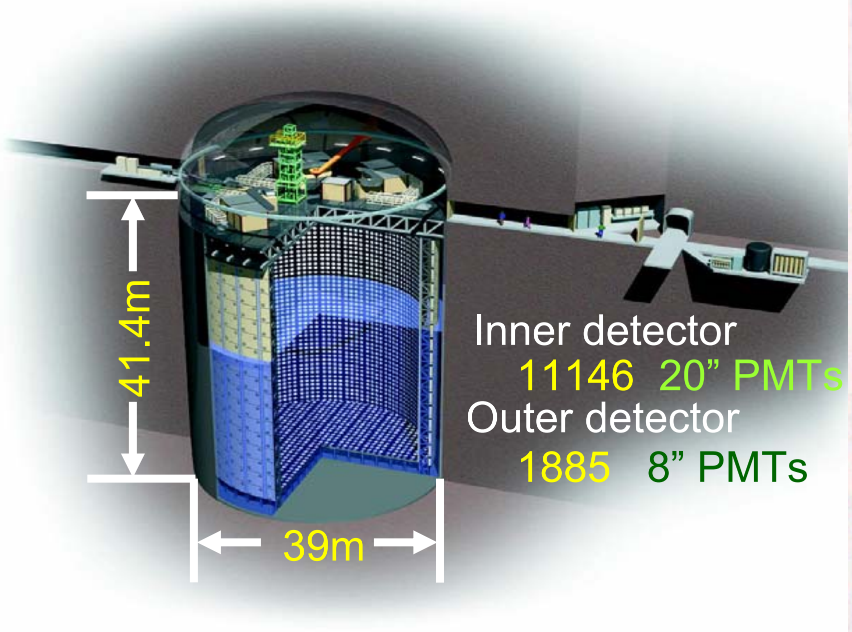


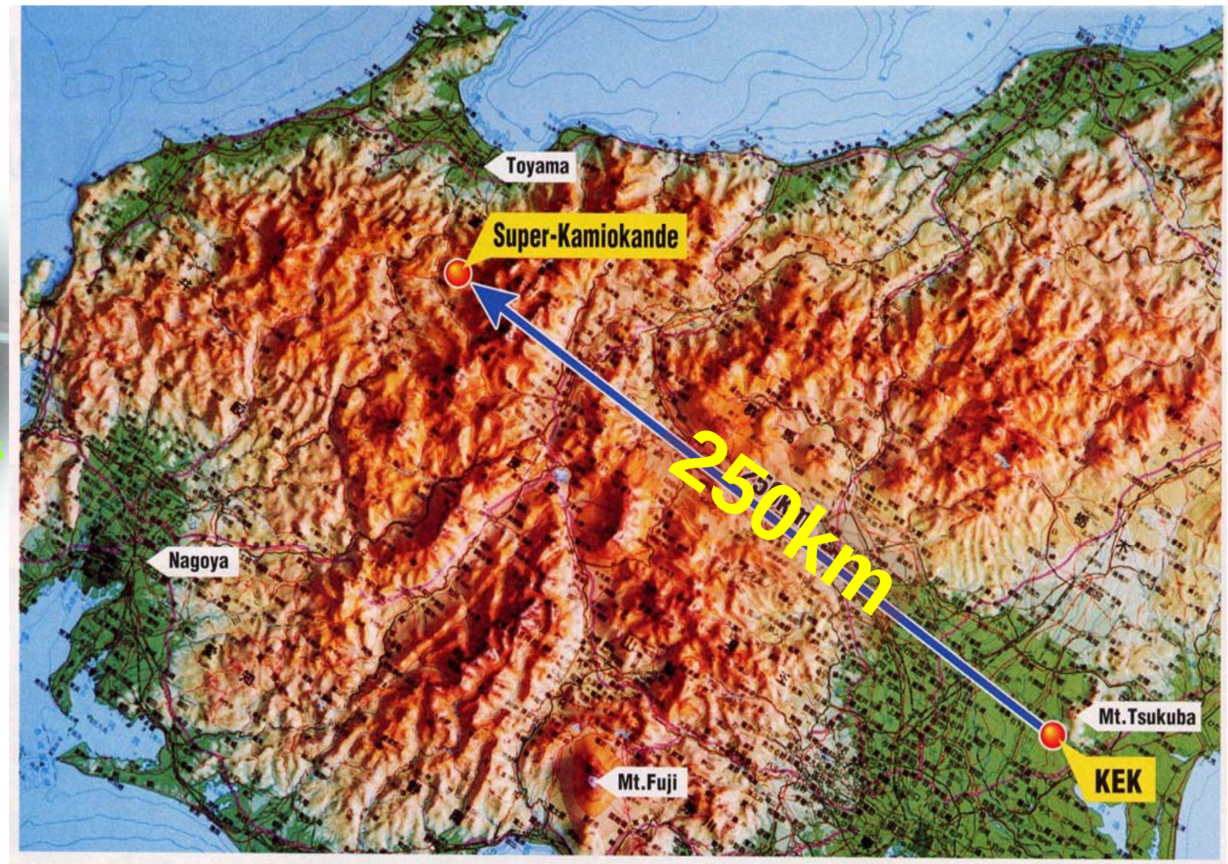


Note use of linear scale!

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

Super-Kamiokande I





Diagrams courtesy Y. Hayato

12GeV PS@KEK
ν beamline

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

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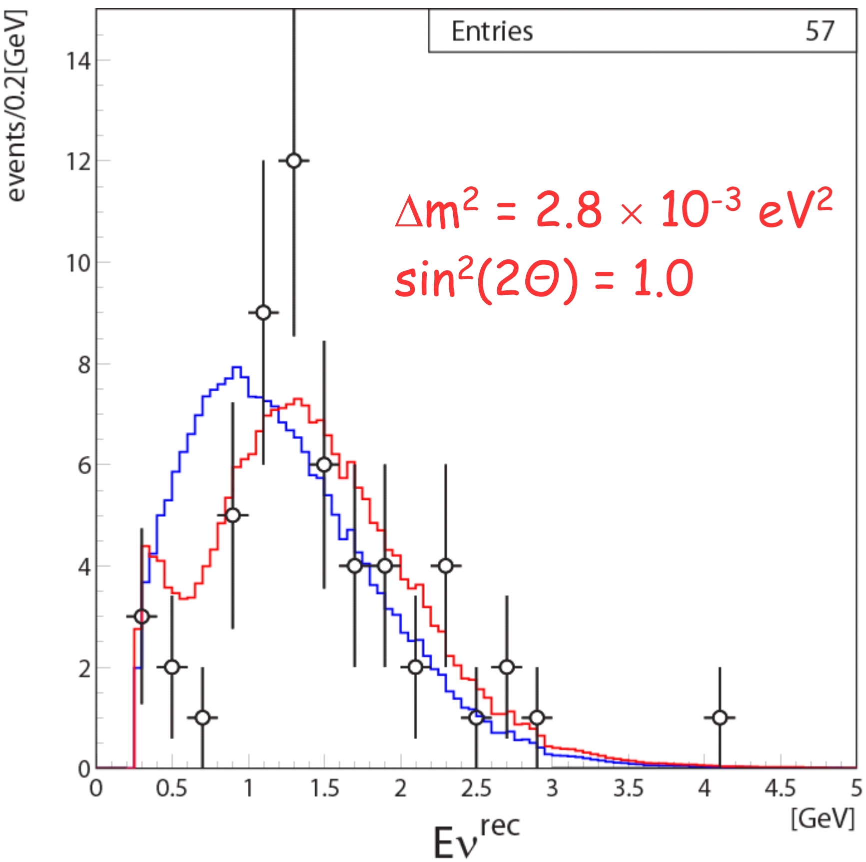
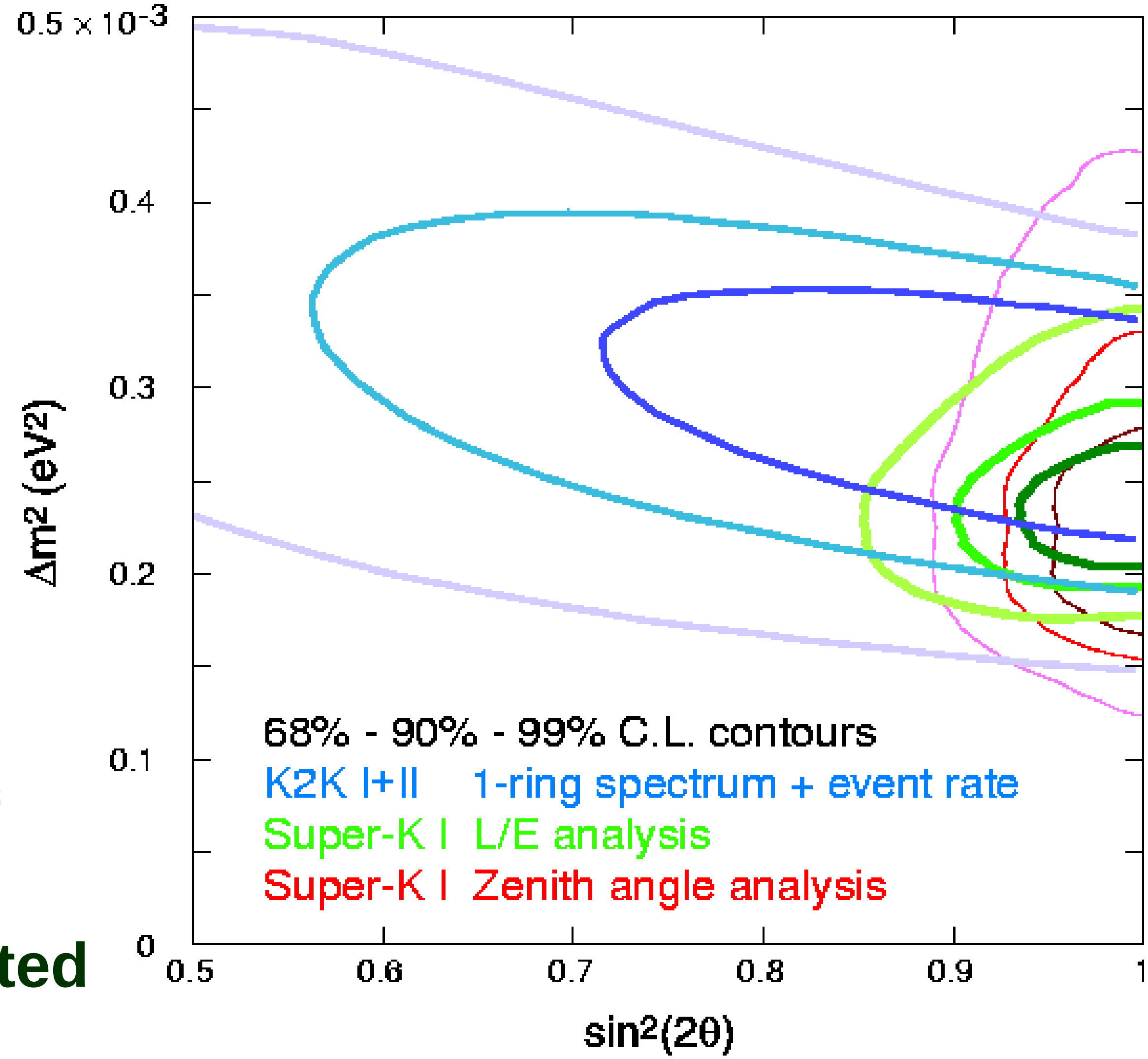
Based on 0.89 x 10^{20} p.o.t.





107 Observed / 149.7 Expected

Plots courtesy C. Walter

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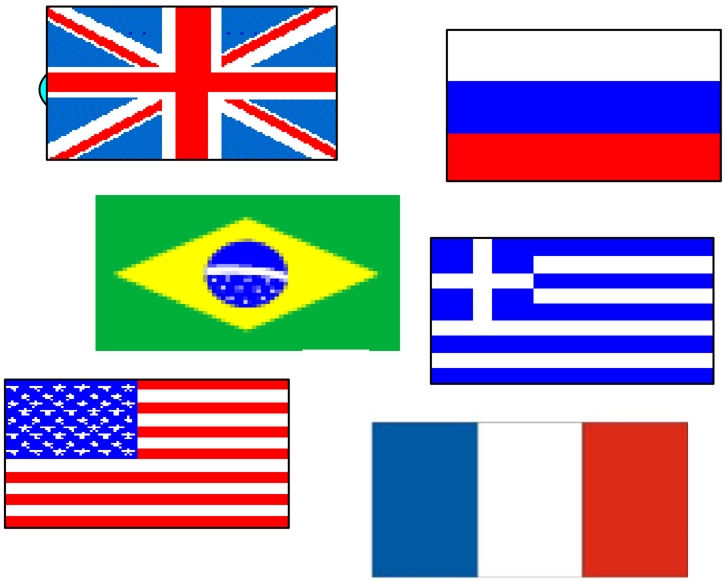
The MINOS Collaboration

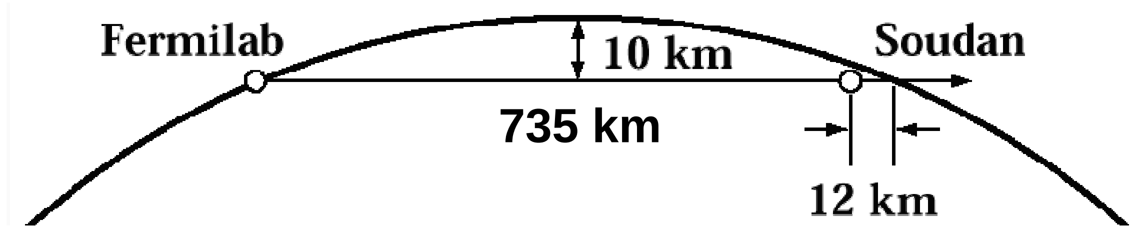
175 physicists from 32 institutes in 6 countries



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

Minos collaboration members at Fermilab with the Near Detector surface bldg in the background (right)

NuMI / MINOS Concept



ν_μ source: (NuMI)

120 GeV protons from FNAL Main Injector

detectors: (MINOS)

1) 'Far' detector:

5.4 kT magnetized iron/scintillator tracker/calorimeter in Soudan mine

2) 'Near' detector:

980 T version of far detector at FNAL

3) Also:
'Calibration' detector in test beams at CERN

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NuMI & The Main Injector

Fermilab Main Injector:

120 GeV protons

2.5 x 10^{13} protons/pulse

1.9 sec rep rate

(~8 μsec spill)

→ 0.25 MW

NuMI Beam:

Graphite target

Two magnetic horns

675 m. vac. decay pipe

hadron absorber

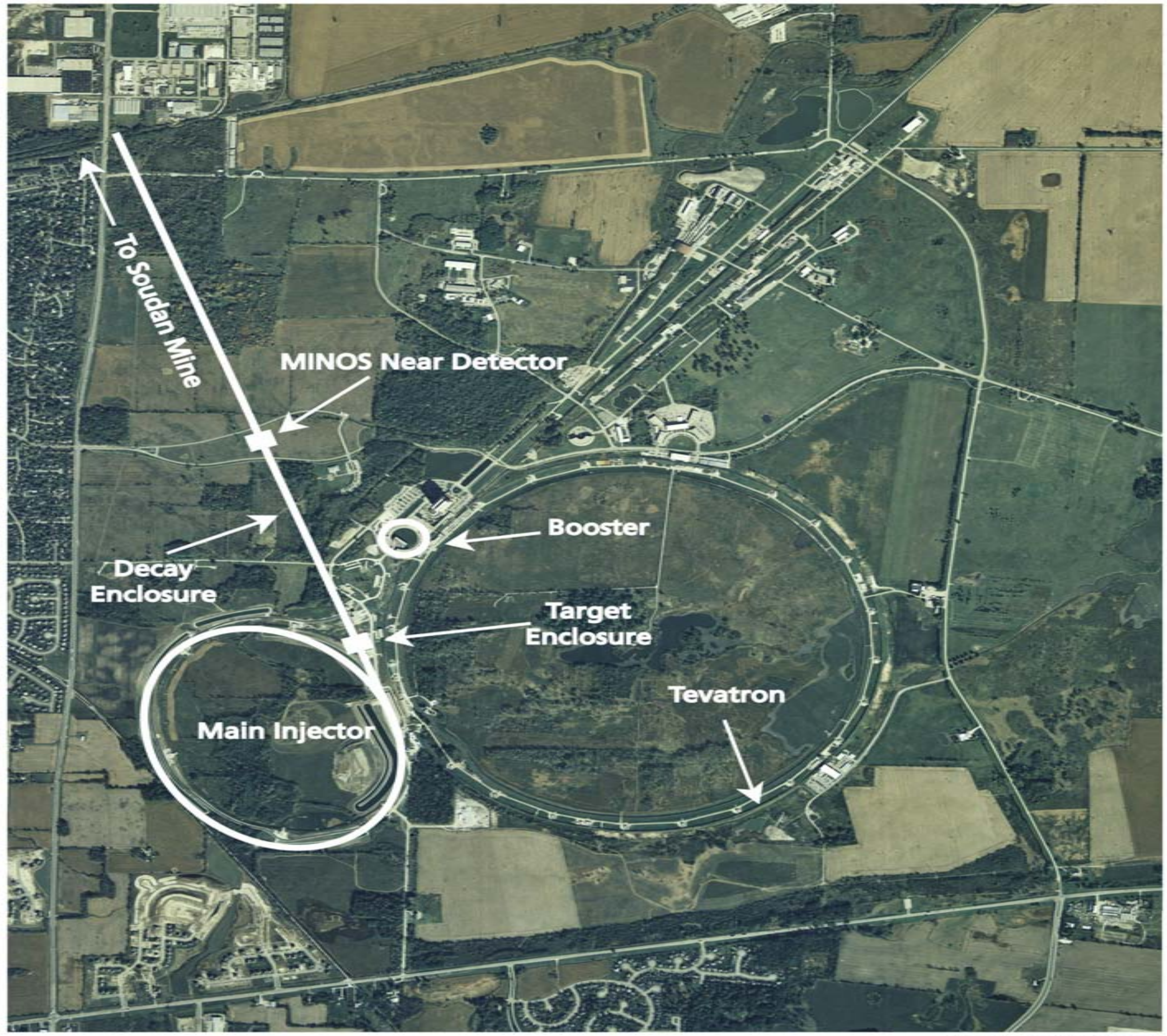
designed for 4 x 10^{13} ppp

Beam Monitoring:

muon detectors

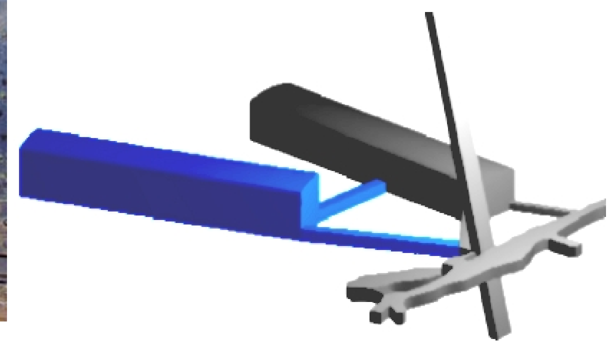
hadron detectors

+ Near Detector !



FERMILAB #98-765D

Soudan Underground Laboratory

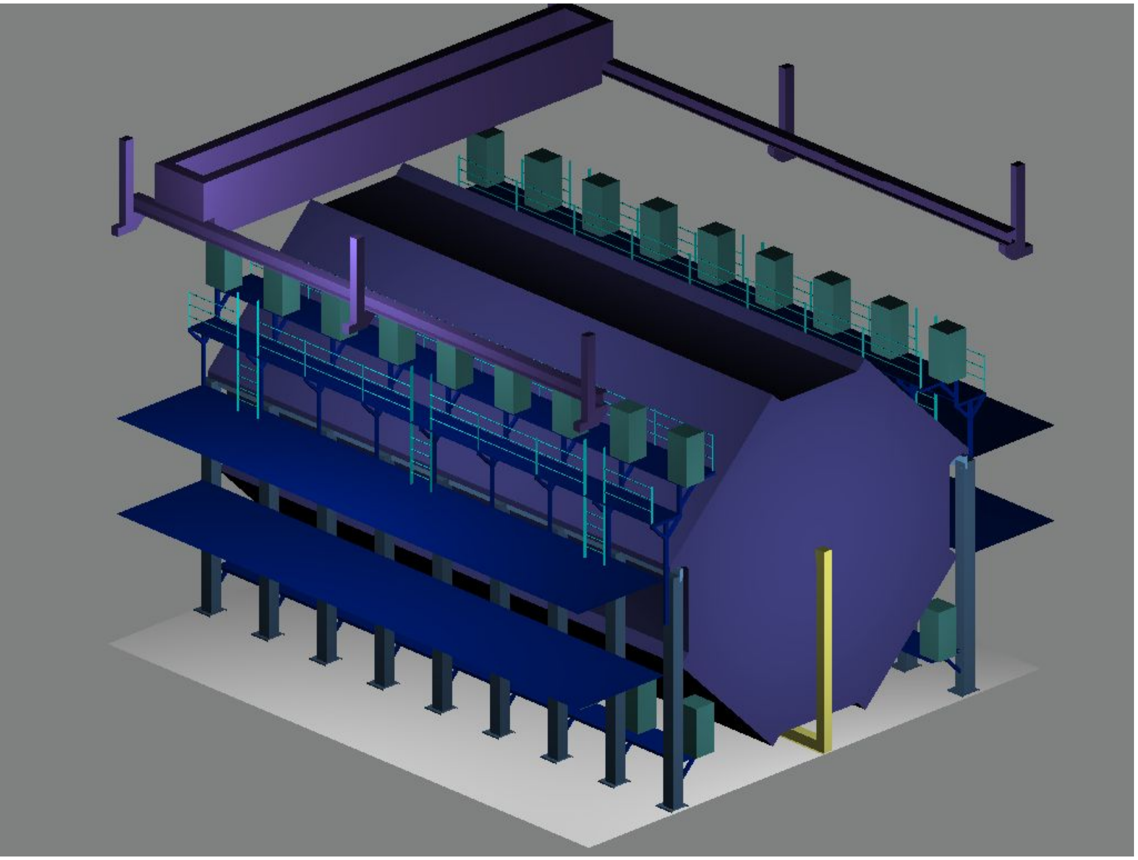


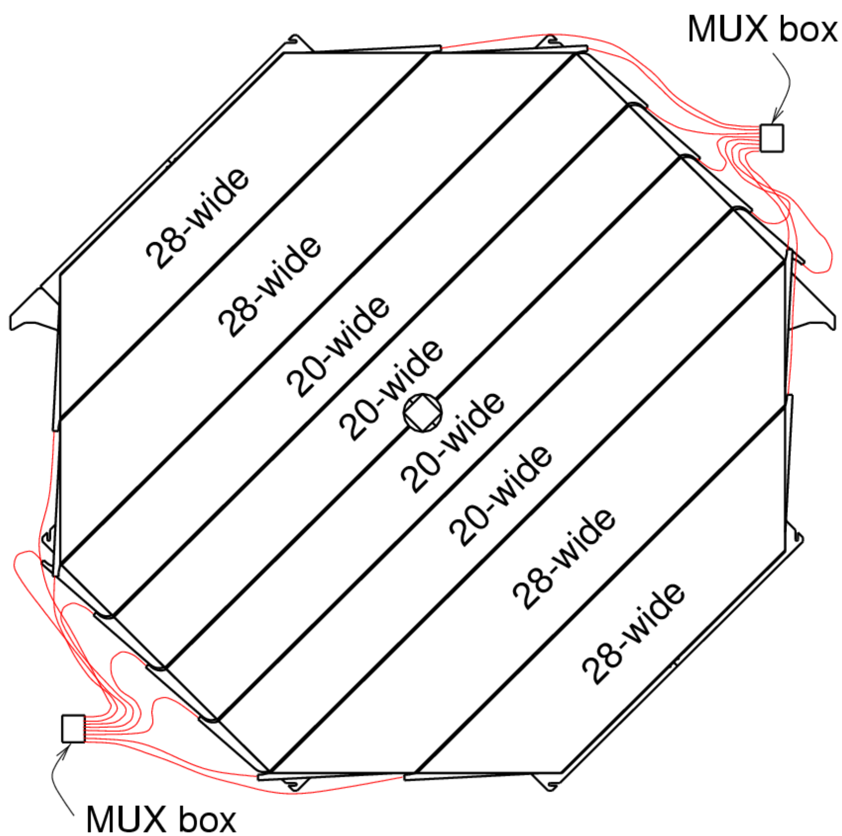
- **former iron mine, now a state park,**
  - **home of: Soudan-1 & 2 , CDMS-II , and MINOS expts**

Far Detector Module Layout

Shown here: 1 (of 2) super modules

- **248 planes: 8m x 8m x 15m !**





Steel / Scintillator :

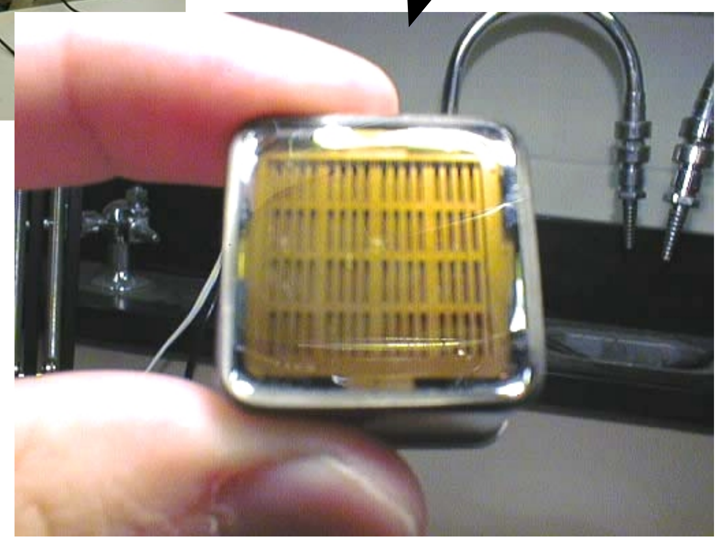
2.5 cm thick steel
4 cm x 1 cm polystyrene in Al cover
15,000 Amp-turn coil

486 Layers → 5.4 kTon !

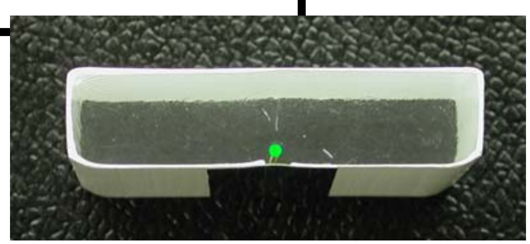
Scintillator Detectors & PMTs

Spool of 1.2 mm WLS fiber being glued into groove

Hamamatsu M16 16-channel PMT (8 fibers per pixel)



4.1 cm x 1 cm polystyrene strips
- coextruded with TiO_2 coating & groove for WLS fiber



View of Partially Constructed Far Detector

View as of April 2002.
This is less than half the full detector !

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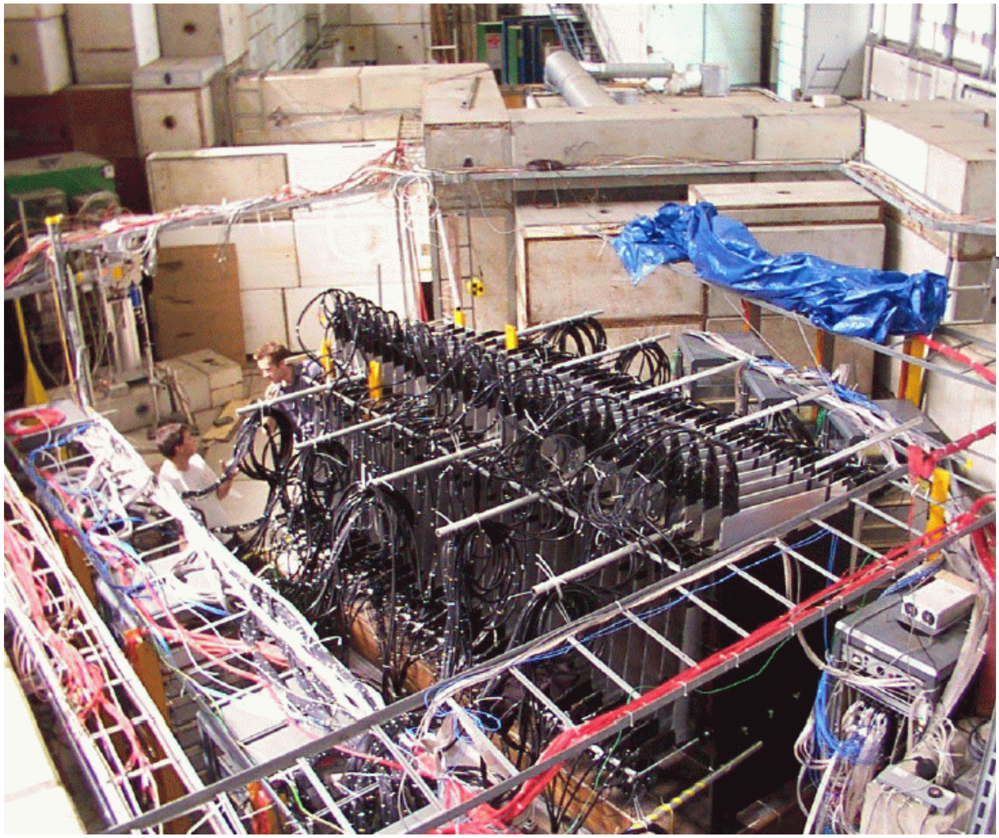
Far Detector Completed !!

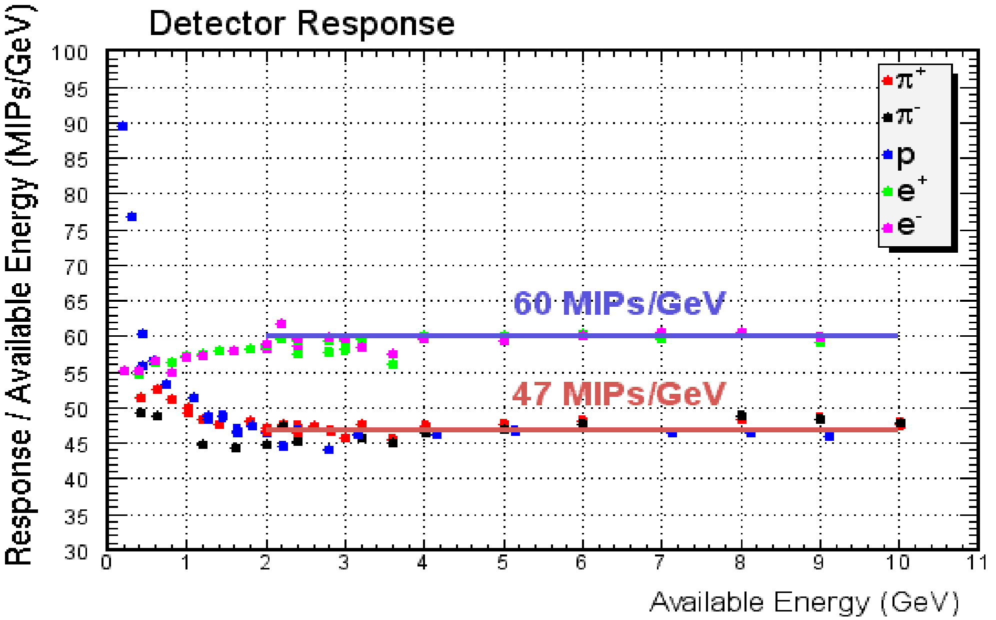
View as of July 2003, after energizing of SM2 coil

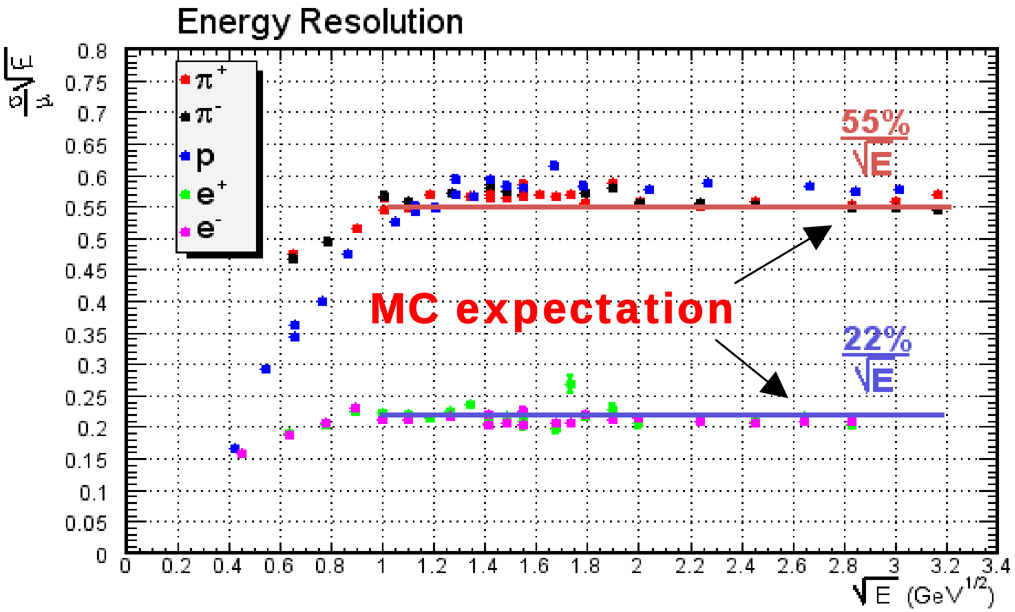
Calibration Detector

60-plane 'micro - MINOS'

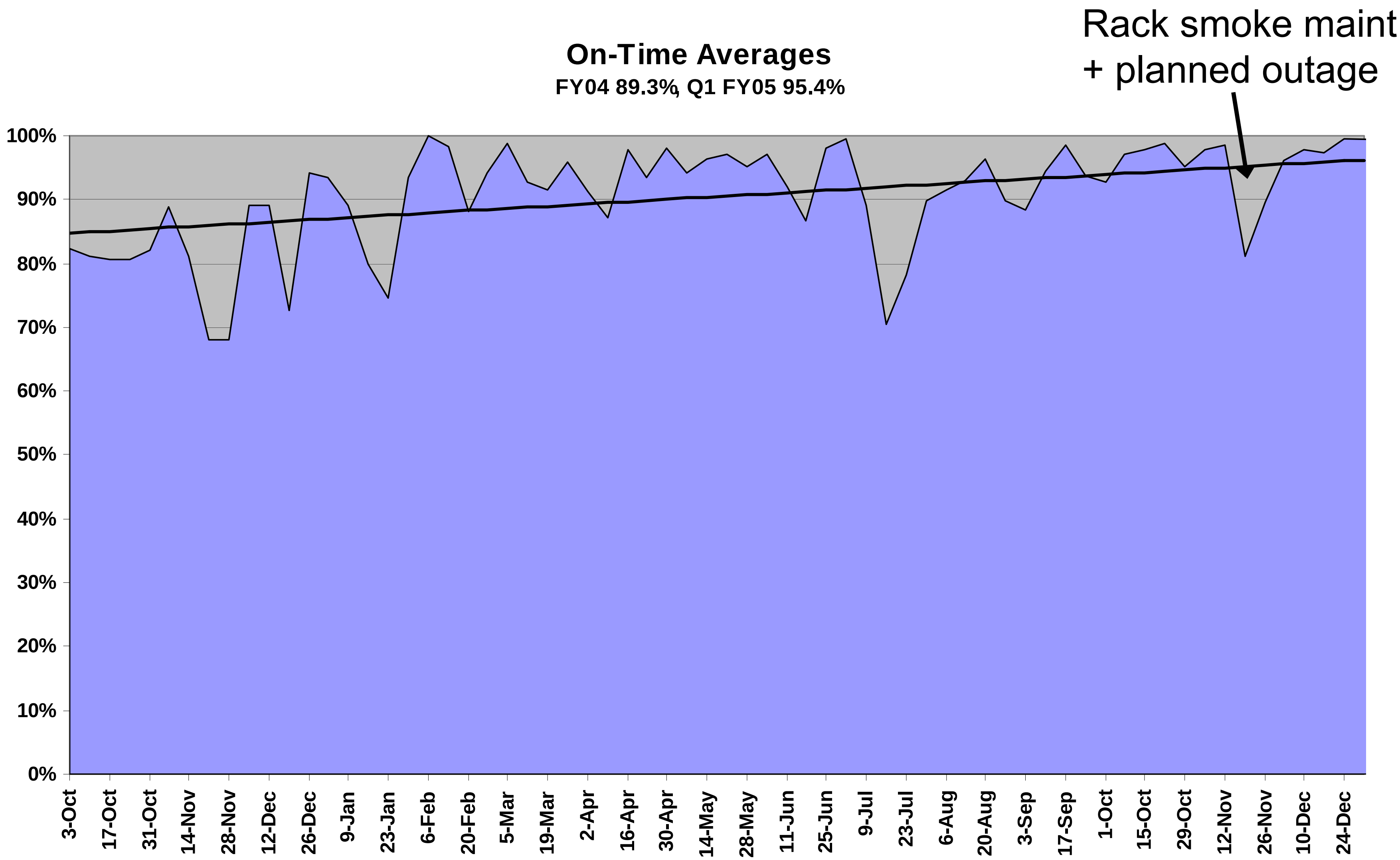
-- has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003







Far Detector Live Time 10/03 - 12/04



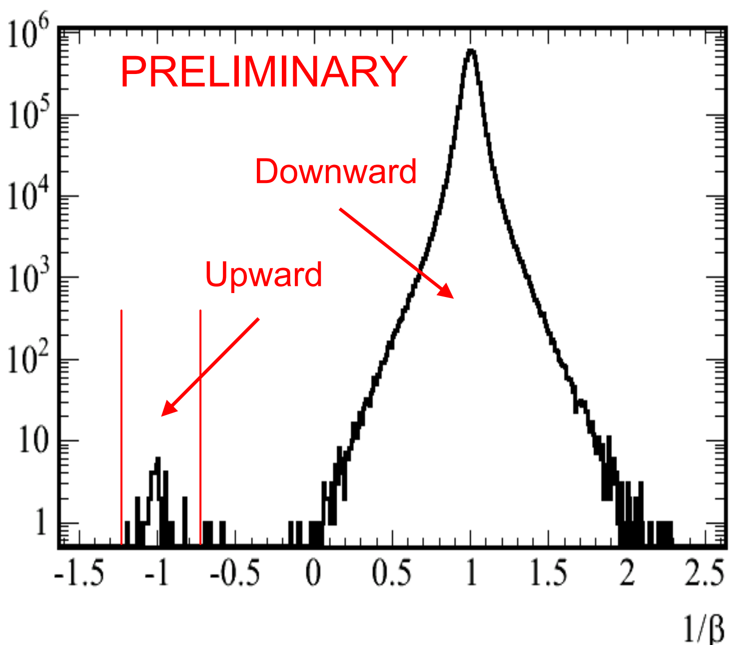
B. Speakman, A. Habig, B. Miller

Cosmic Ray Data in Far Detector

Upward-going muons (atmospheric neutrino-induced)

based on ~ 1 yr of data.

Plots: B. Rebel

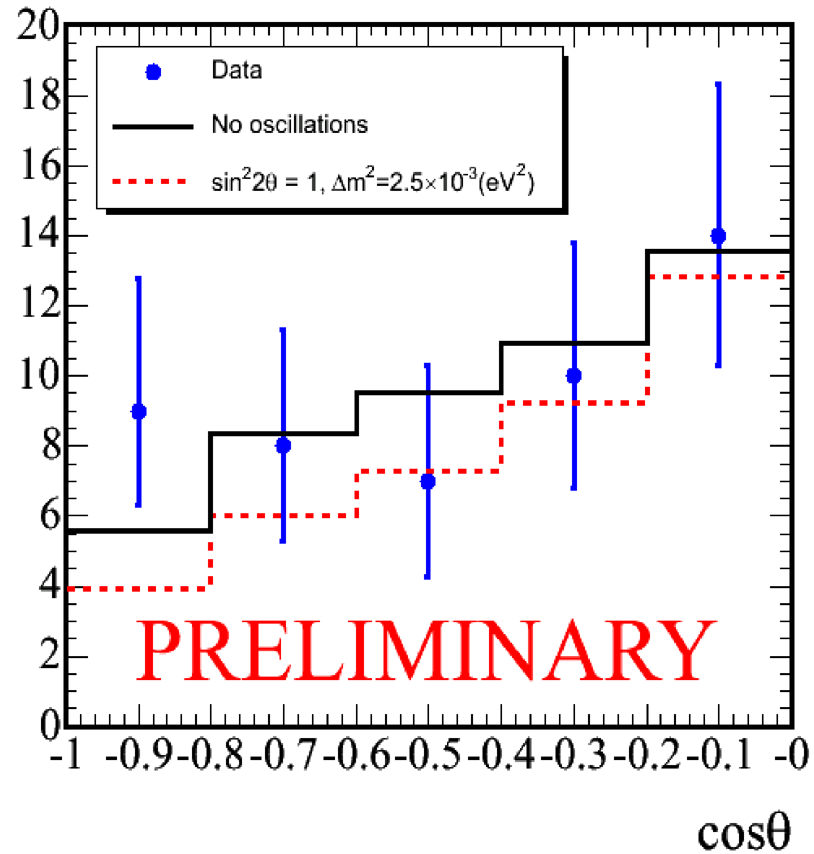


Plotting: c δt / δs = 1 / β

(signed by dy/dt)

Zenith angle distribution

MC: Nuance w/ Bartol '96 flux; no-osc'n dist. normalized to data



Note: 2.4 ns single hit timing resol'n !!

The MINOS Near Detector

1 kTon version of far det.

290 m d/s of hadron absorber
→ beam is small !

→ 4 regions:
'veto' + 'target' + 'shower'
+ 'spectrometer' (sparse)

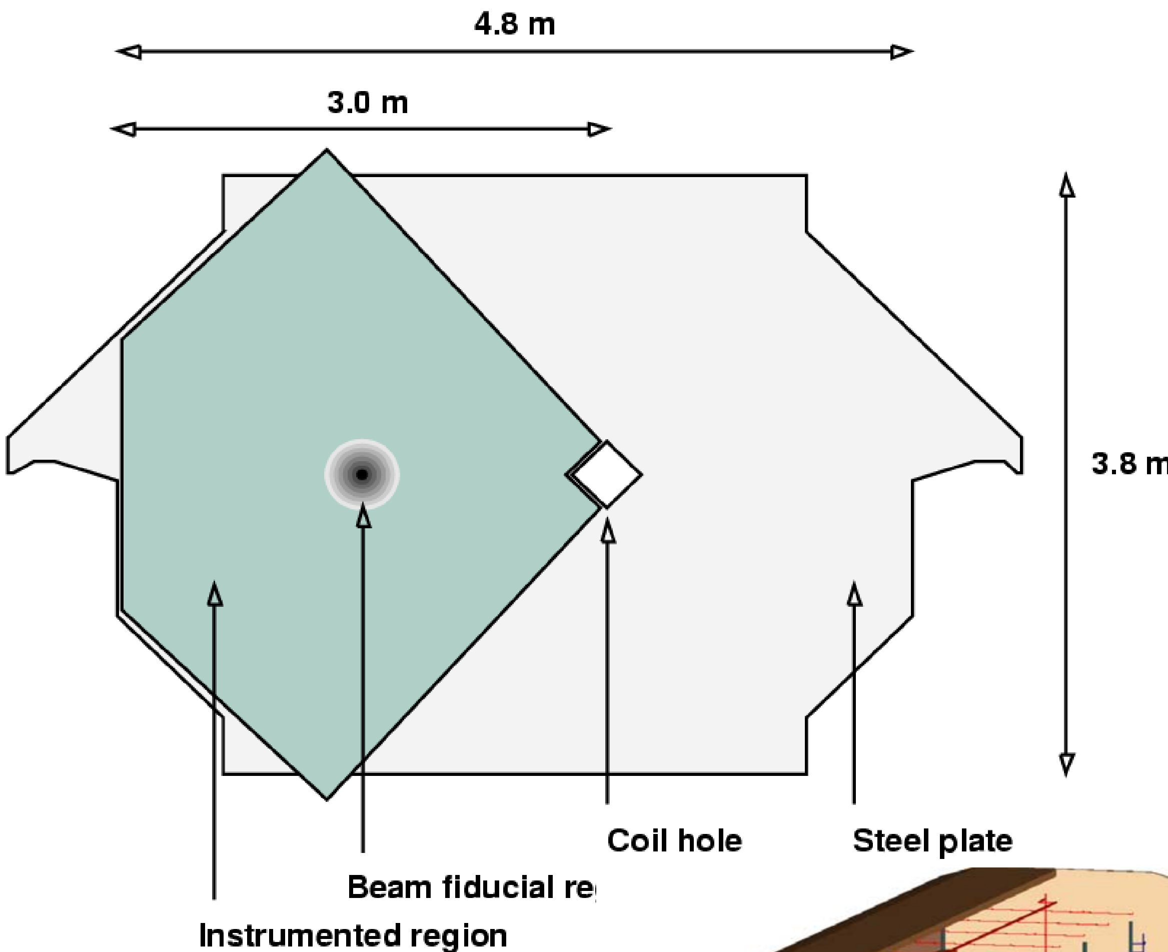
make as similar to
far detector as possible !

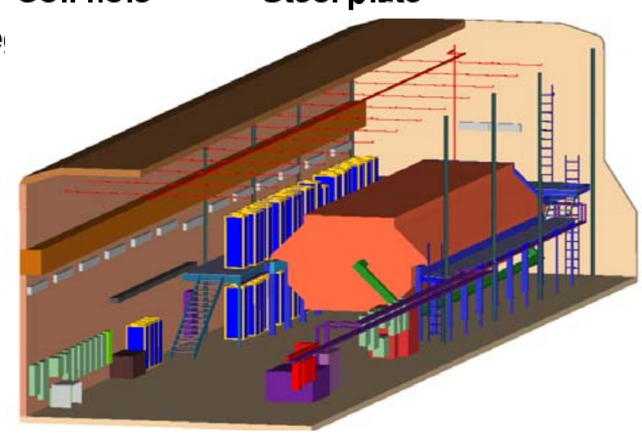
Readout:

Hamamatsu M64 pmt's

High instantaneous rates
(~20 ν events / 8 μsec spill)
→ fast front ends needed

→ use FNAL QIE chips





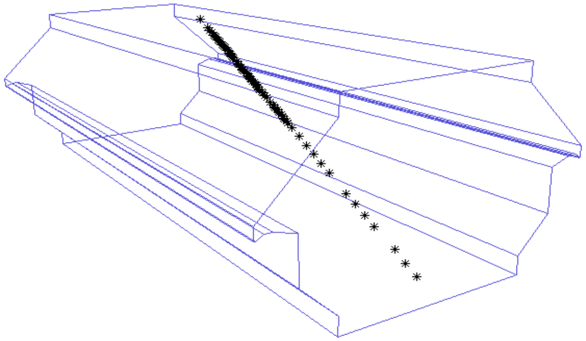
J. Urheim, IU, Aspen '05

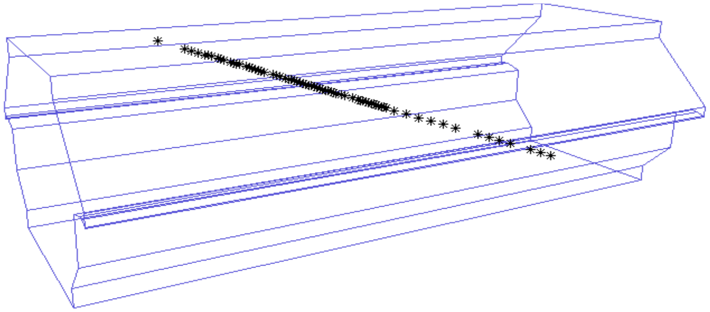
MINOS Near Detector

Plane construction complete in August 2004

Commissioned & calibrated w/ cosmic ray muons & light injection system

Magnet coil now installed & energized





View of Near Detector Hall nearing end of dectector construction

MINOS Physics Reach

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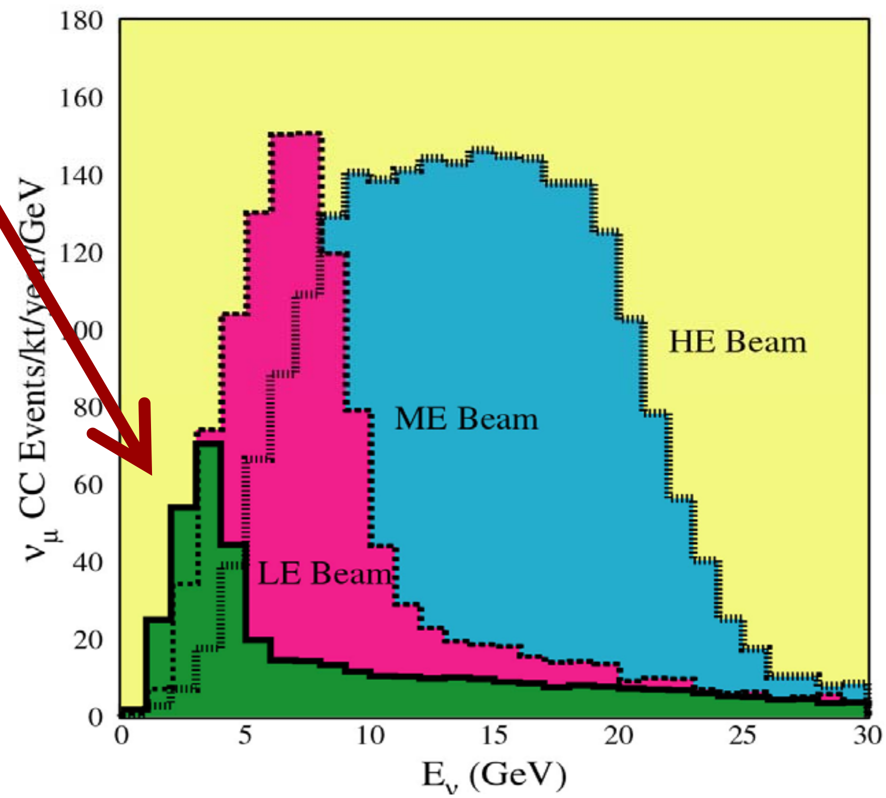
- **Intense ν_μ beam from FNAL**
  - **initially 2.5 x 10^{20} p.o.t./year,**
  (being commisioned now !!)
- **Measure un-oscillated E_ν spectrum in MINOS Near Det.**
- **Extrapolate spectrum to Far Det. Location 735 km away…**
  → **hope to use data from MIPP expt (FNAL E907) to enhance beam modeling capability**
- **Compare extrpolated spectrum with MINOS Far Det. Data**
  → **measure oscillation parameters**

Nominal Beam Configurations



ν_μ CC Events/year
(with no oscillations)

Low	Medium	High
1,600	4300	9250

Beam spectra: M. Messier

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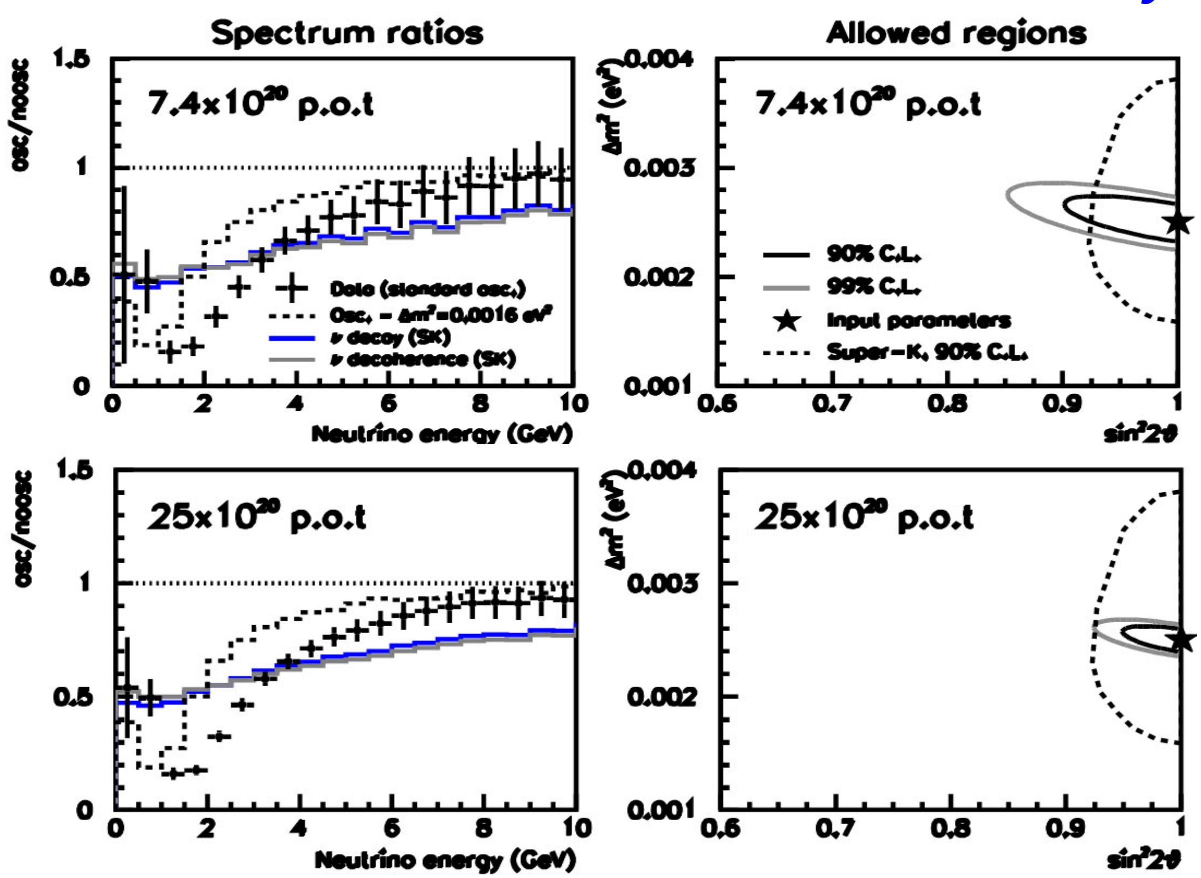
MINOS Physics Reach

D. Petyt

- **MINOS Sensitivity to ν_μ disappearance**
  (plotting ratio of yield at FarDet to expectation based on NearDet)



Assuming:

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

After:

3yrs at nom. intensity (top)

& w/ possible intensity upgrages (bottom)

- **Characteristic 'dip':** **location & depth yield δm^2 & $\sin^2 2\theta$.**

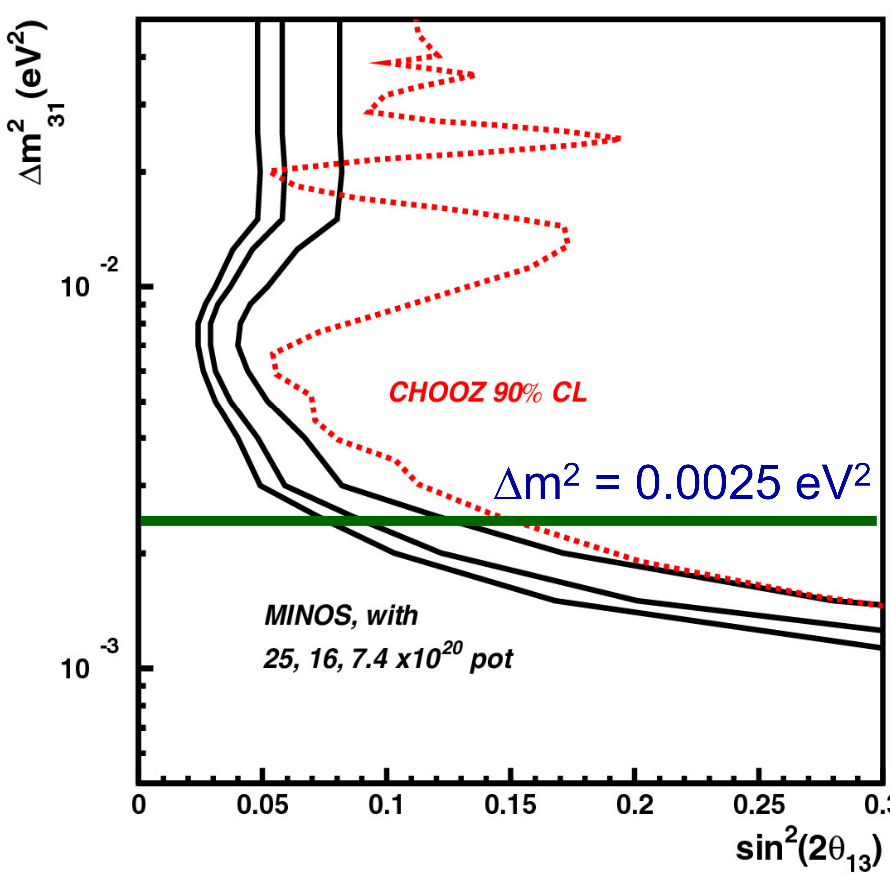
  → Will determine δm^2 to precision of < 10%,
  can also rule out exotic models of oscillations.

Sensitivity to ν_e appearance

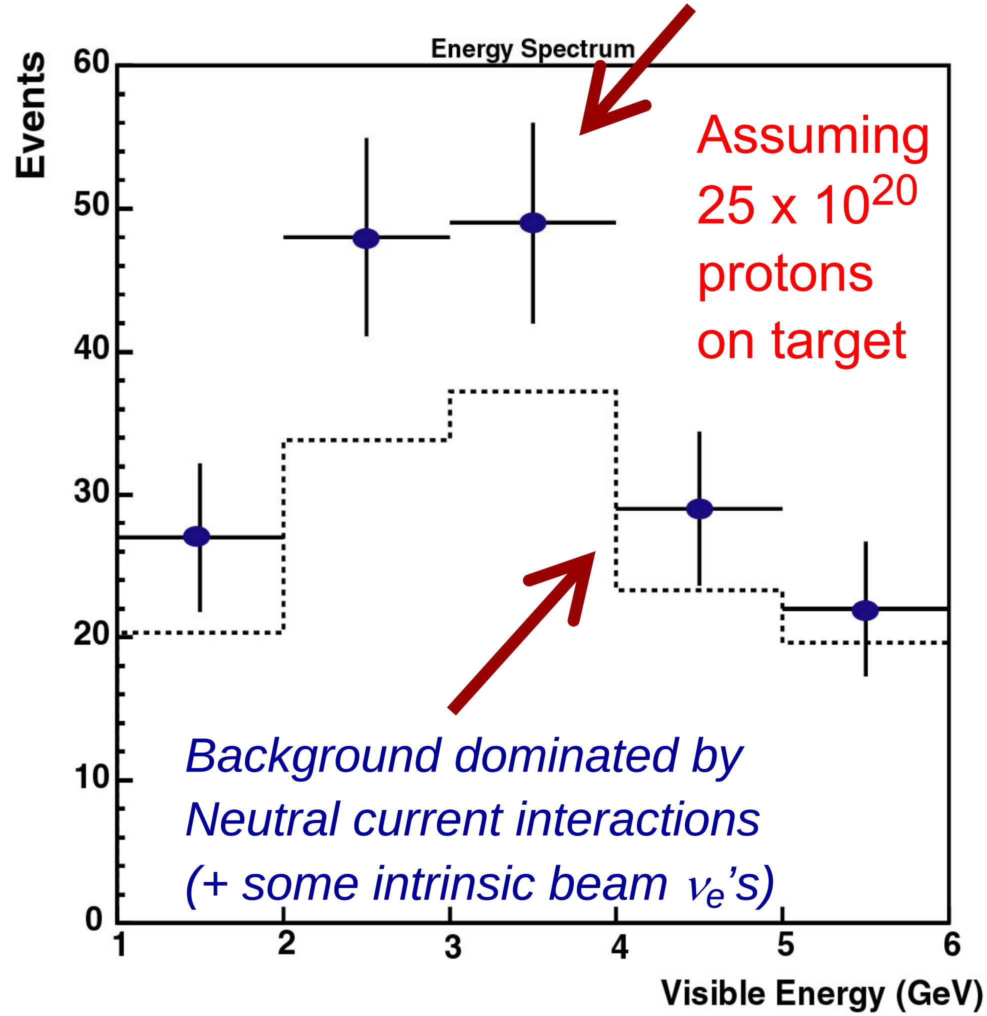
detection of ν_e at Δm^2_{atm}

→ *evidence for non-zero θ_{13}*

3 σ Contours



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



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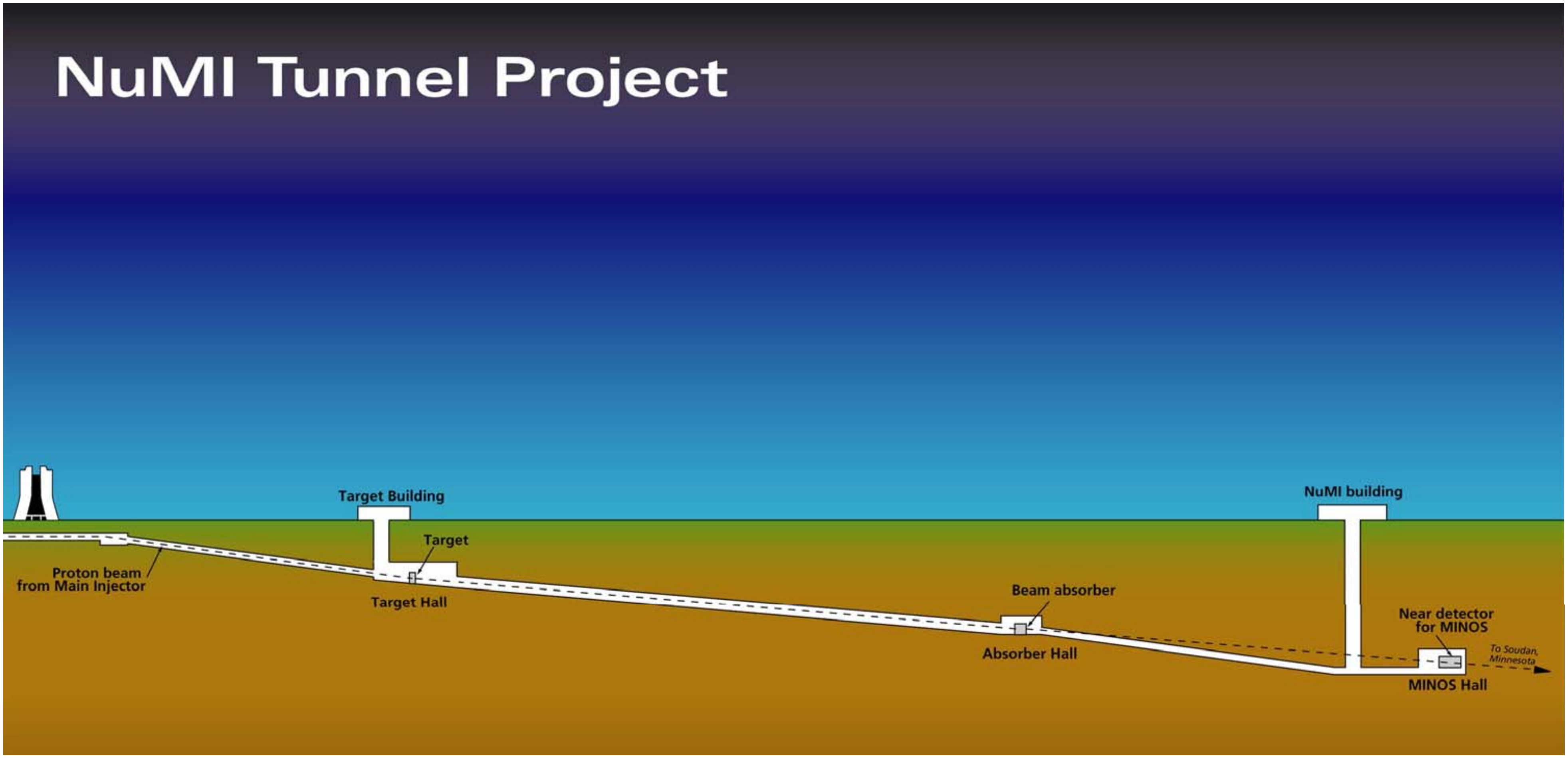
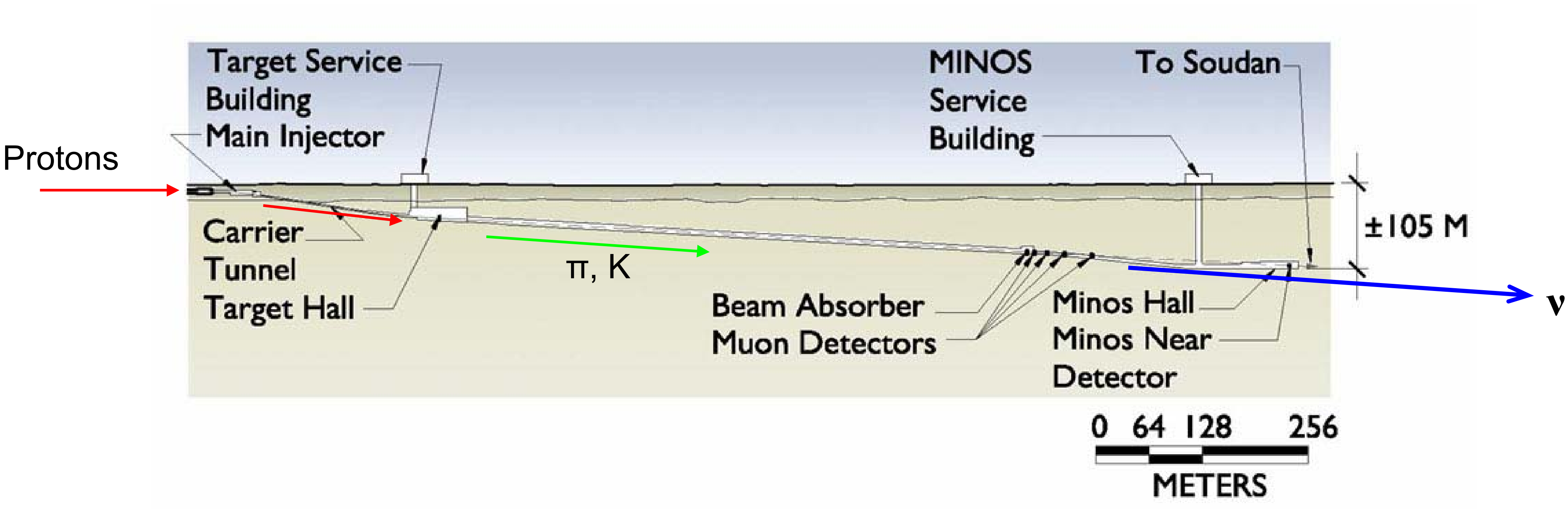
NuMI Beam Layout



NuMI Beam

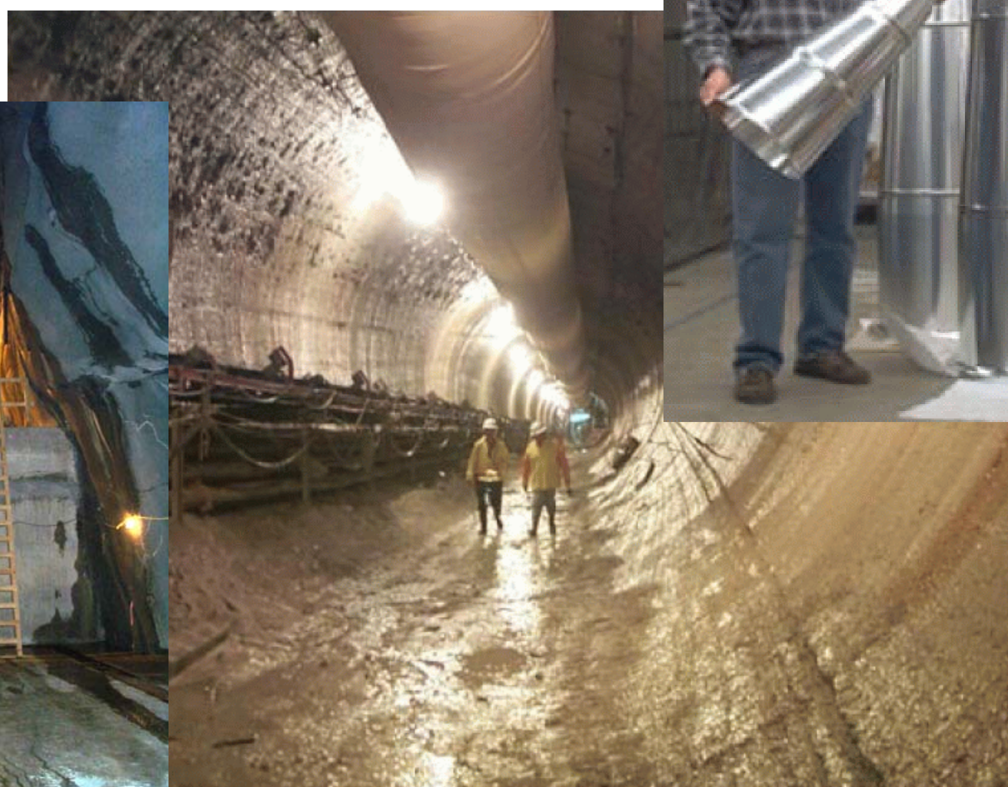


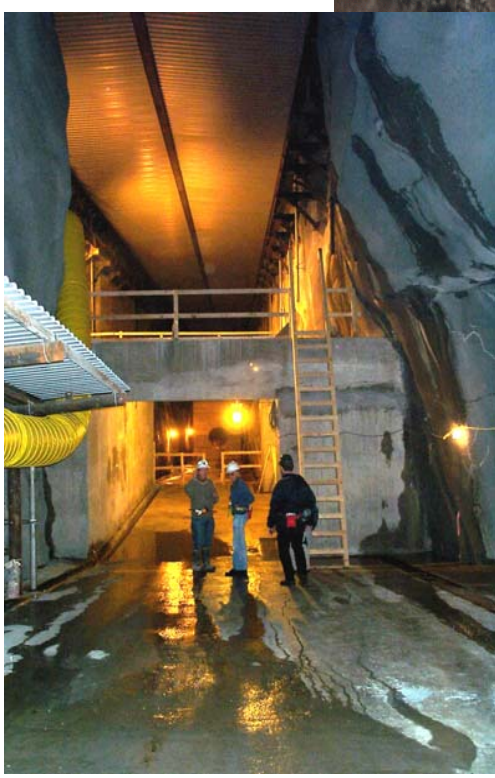
- 120 GeV protons extracted from MI into NuMI beam tunnel
- Pitched downwards @ 160 mrad (initially) then to 58 mrad – toward Soudan
- Incident on segmented graphite target
- Focus charged hadrons with two magnetic horns pulsed with 200kA
- 675m long steel decay pipe (0.5 Torr, encased in 2-3m concrete)
- Hadron absorber downstream of decay pipe
- 200m rock upstream of Near Detector for muon absorption

NuMI Construction - now completed!

Horn 2 inner conductor →

NuMI 675-meter decay tunnel prior to vacuum pipe install’n





Horn on mounting

NuMI Beam Commissioning

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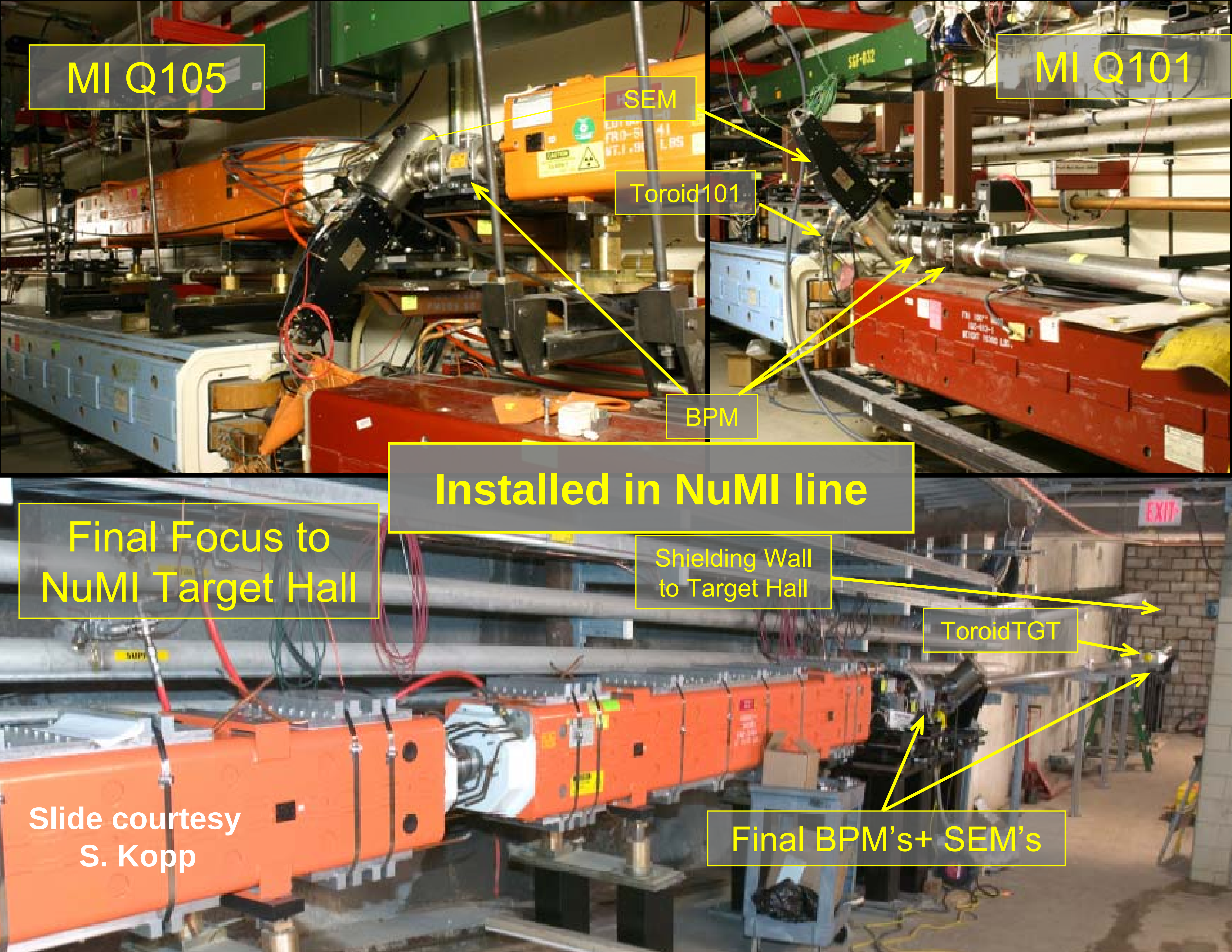
- **December 3 - 4, 2004**
  - **beam transported to target hall & onto hadron absorber**
    - target out -- so no neutrinos
    - small number of carefully planned pulses (to limit radiation)
- **January 21 - 22, 2005**
  - **first beam on target !!**
    - horns powered
    - target at z= -1 m from nominal → "pseudo-medium energy beam"
    - MI operating w/ single Booster batch *(nominally 5 or 6)*
    - 864 spills at 60-180 second intervals *(nominally 2 seconds)*
    - typical (max) intensity: 2.6e12 (4.1e12) protons per spill
      (note: already near initial goal for multi-batch: 2.5e13 ppp !!)
  - **yes, we saw some neutrinos in the Near detector…**


MI Q105
SEM
MI Q101
Toroid101
BPM
Installed in NuMI line
Final Focus to
NuMI Target Hall
Shielding Wall
to Target Hall
ToroidTGT
Final BPM's+ SEM's
Slide courtesy
S. Kopp

Beam monitoring instrumentation

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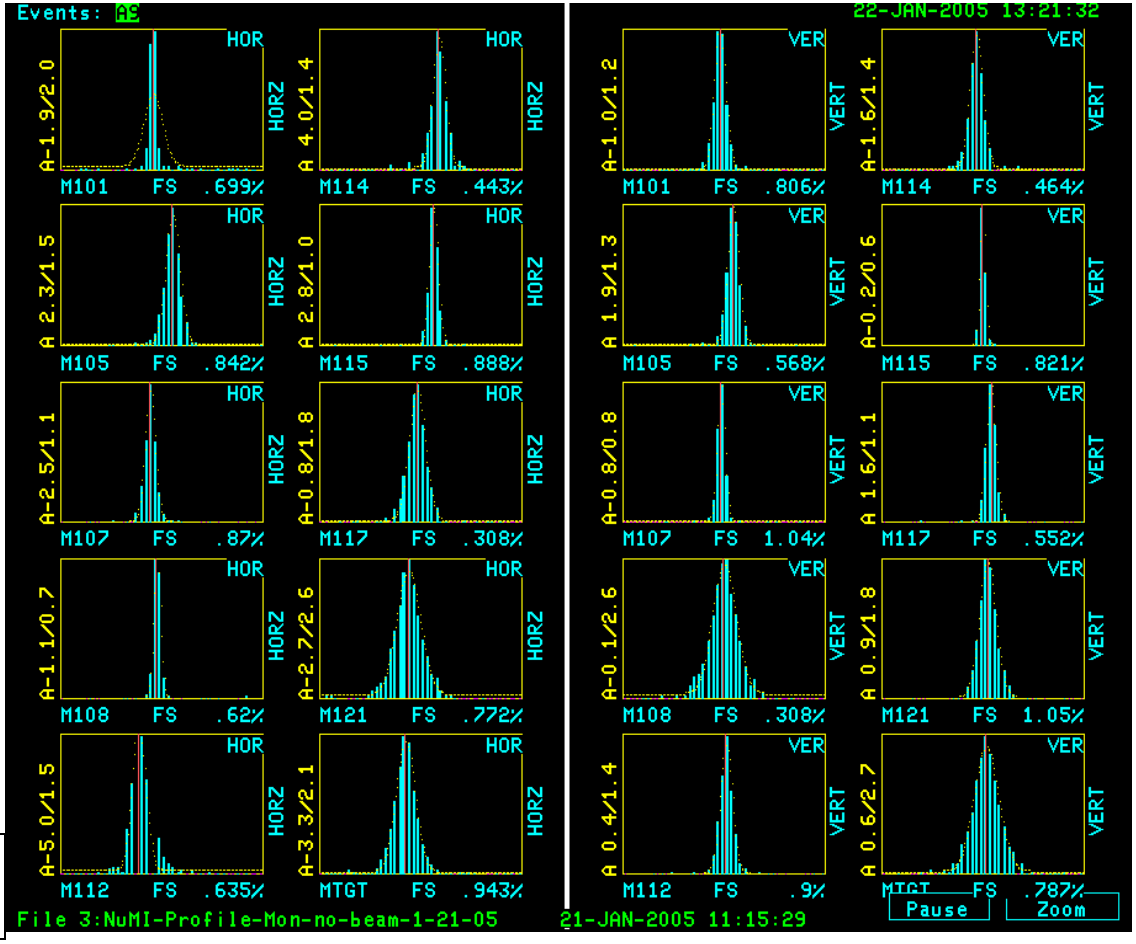
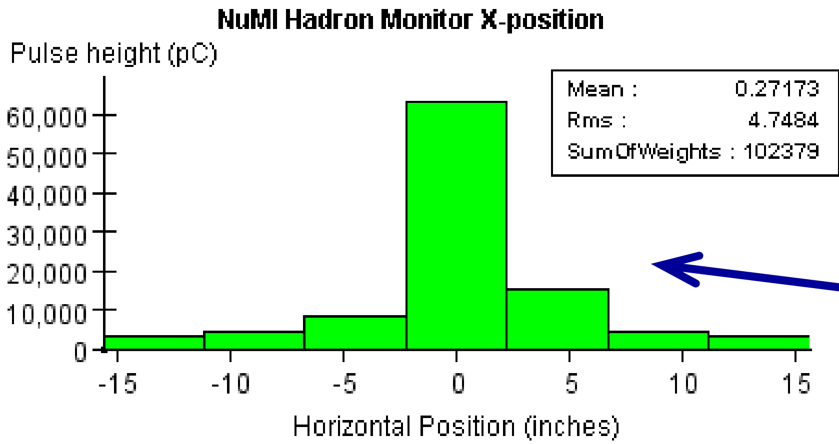
Beam profiles from secondary emission monitors (SEMs) along NuMI beamline from January 21 beam test



Transport down the entire beamline was achieved with only 12 beam pulses during the December test…



Profile from hadron monitor system, downstream from decay pipe.

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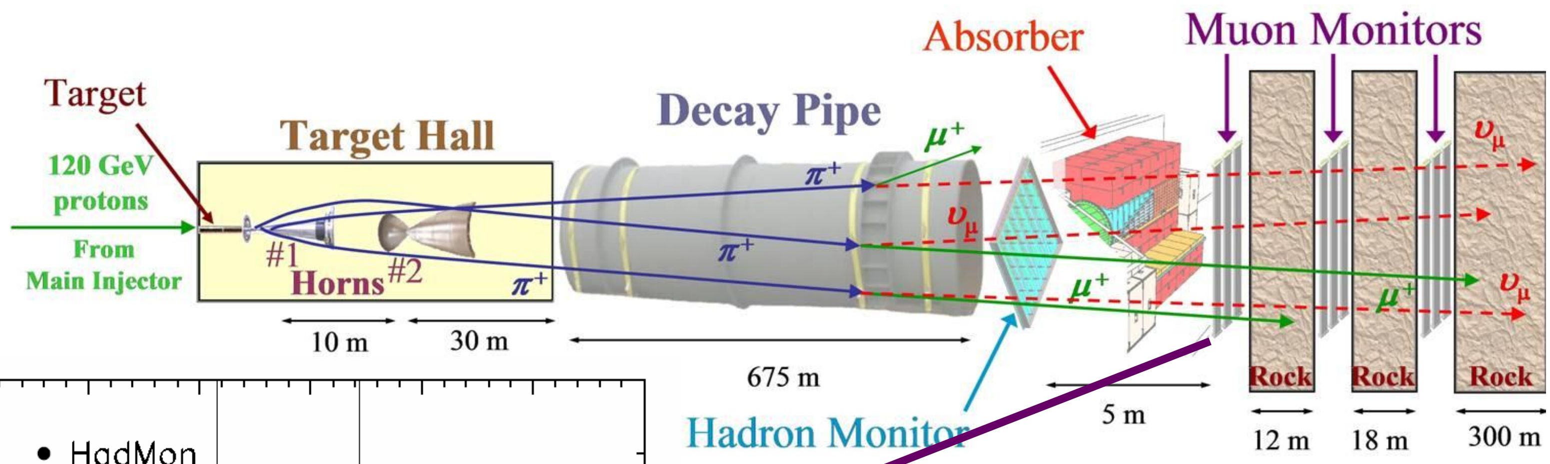
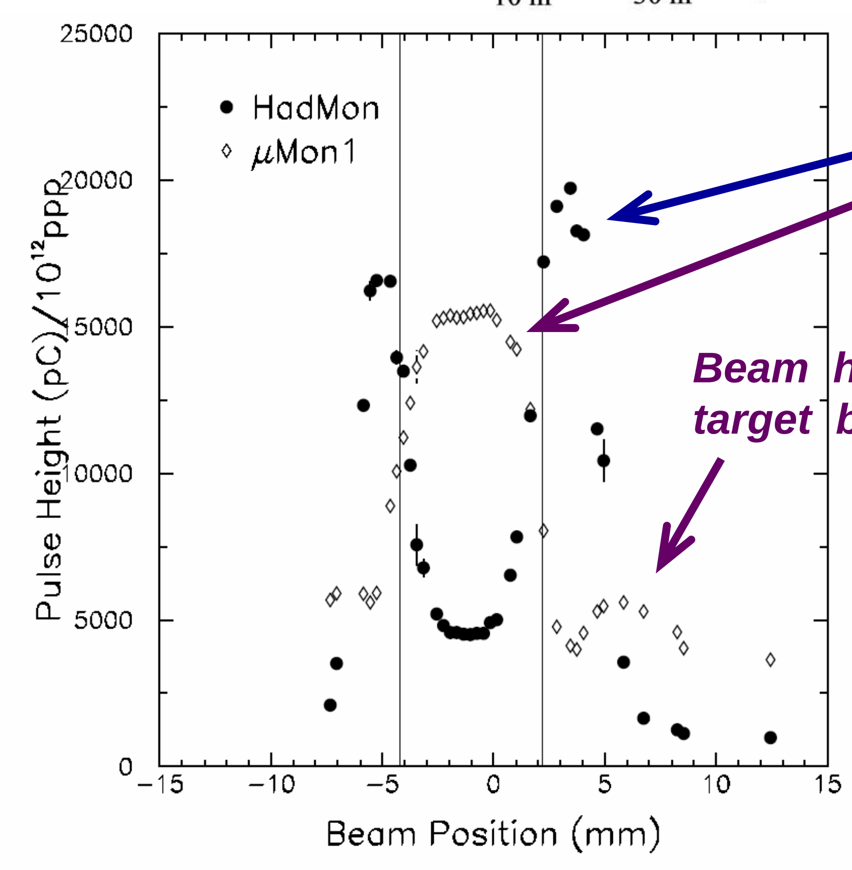
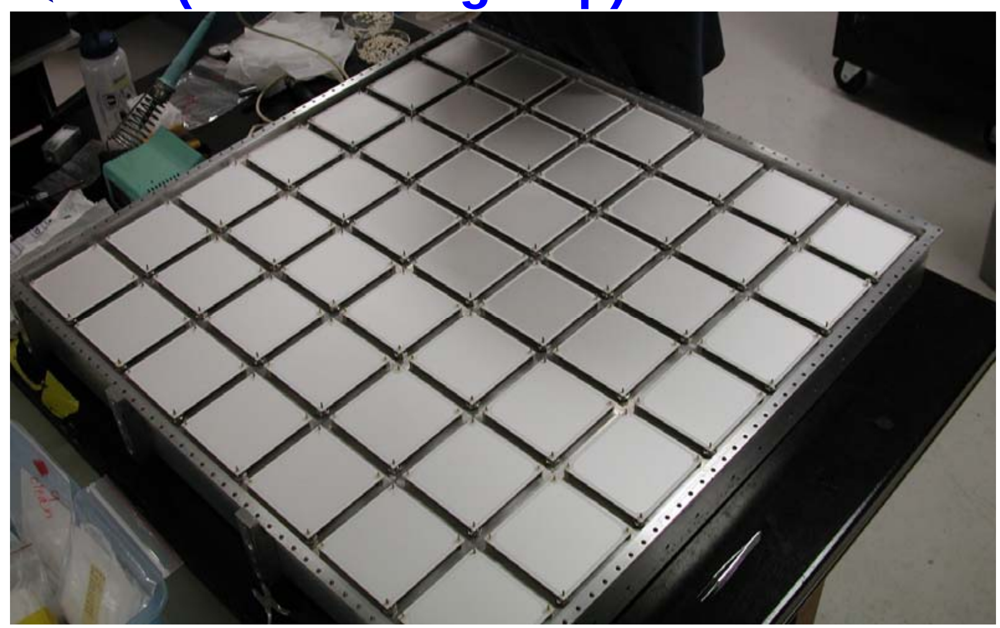
Imaging the Target via Hadron & Muon Monitors





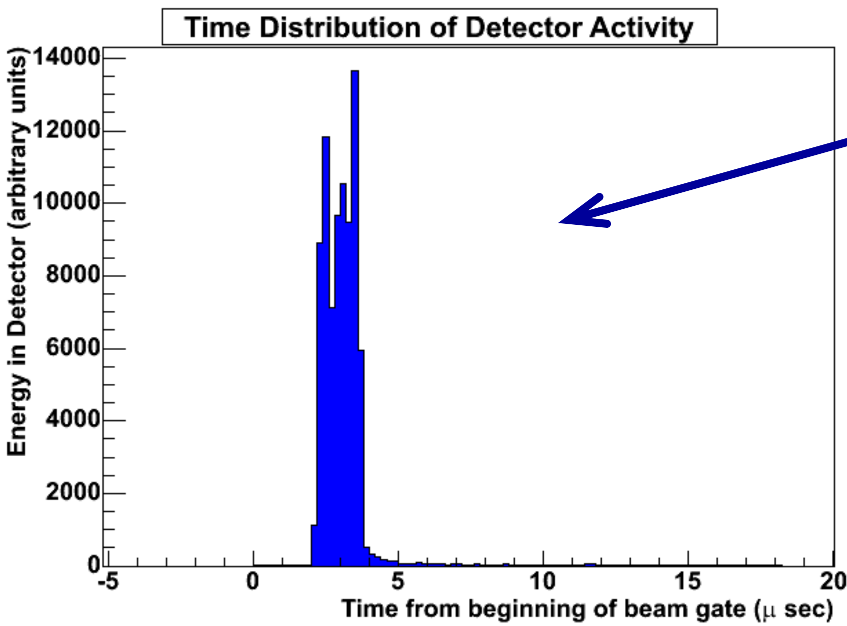
Beam hitting target baffle

Parallel plate ionization chambers (UT Austin group)



Analysis by Texas & BNL groups

Distributions in the Near Detector

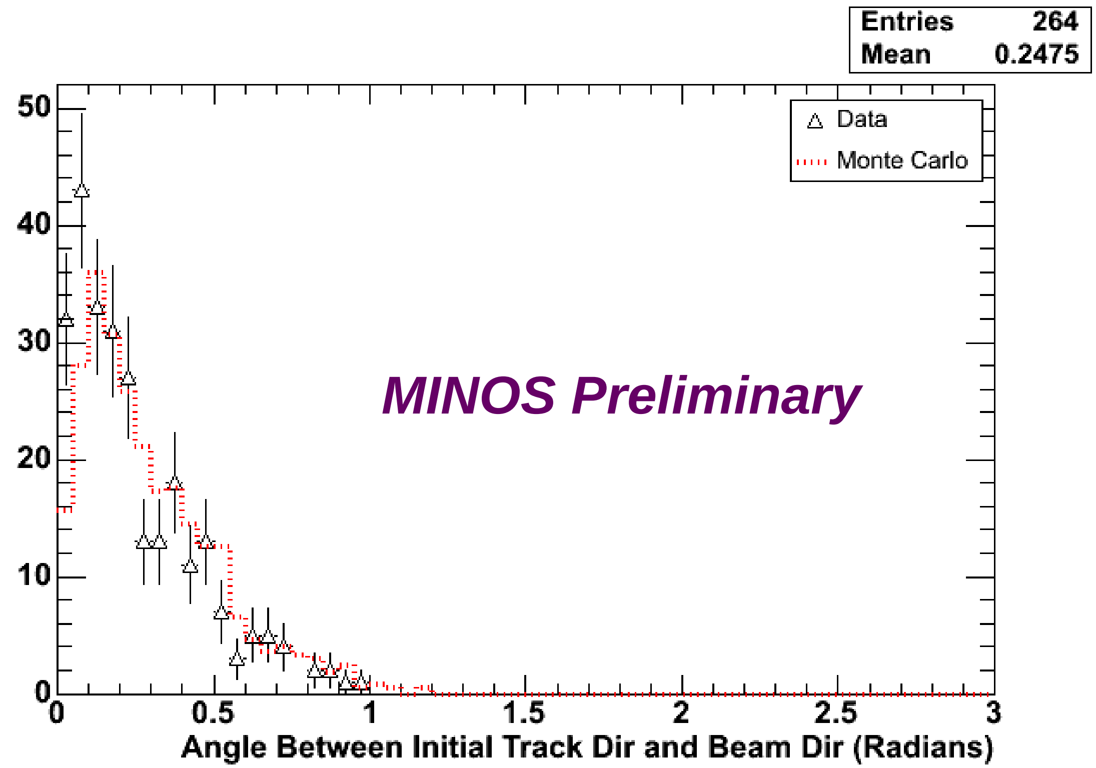


Time distribution of energy deposited in the Near Detector:

Beam gate open 2 μs before start of beam spill; open for 18 μs.

For spills containing reconstructed (muon) tracks:

Angle between initial track direction and beam direction



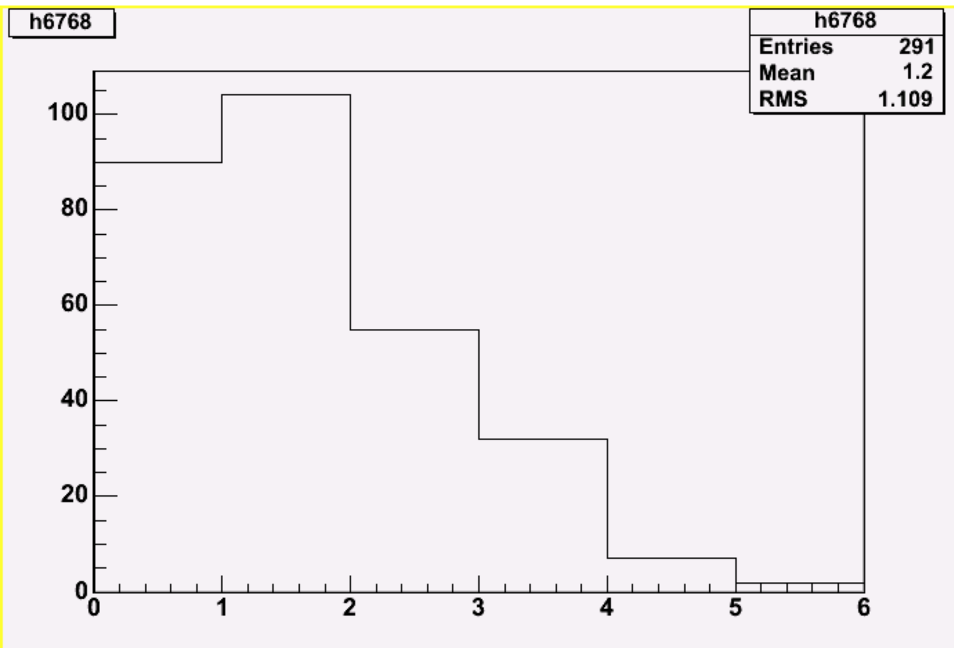
A. Marino

Event Yields

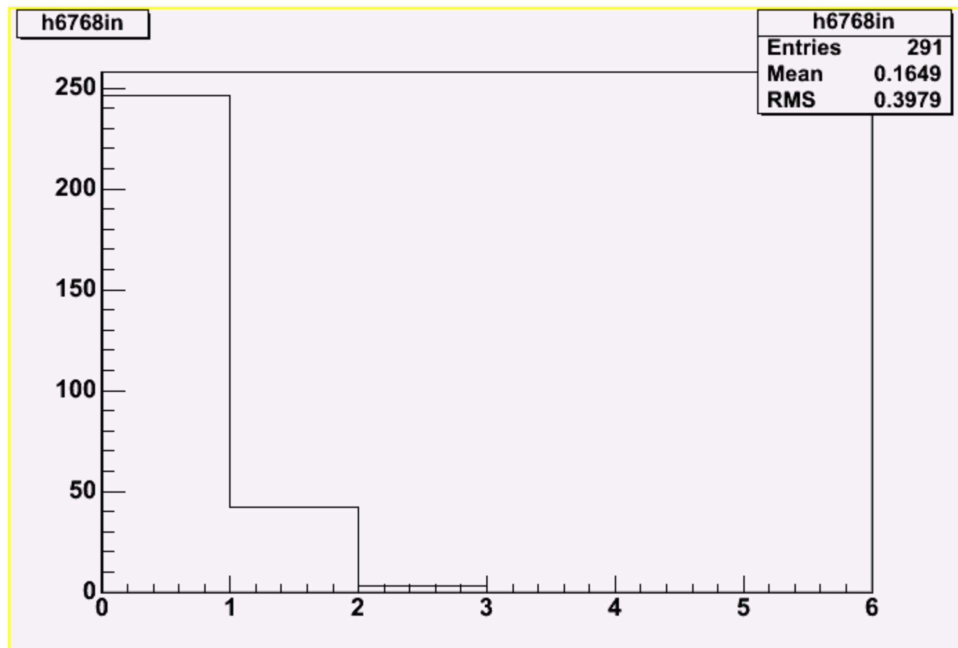
Observed 354 "Events" in 291 spills analyzed.

of these, 48 satisfy track & fiducial (containment) requirements

Both consistent w/ expectations (accounting for "rock" muons)



Total events per spill



Total events per spill satisfying track and fiducial cuts

Spill data in the Near Detector

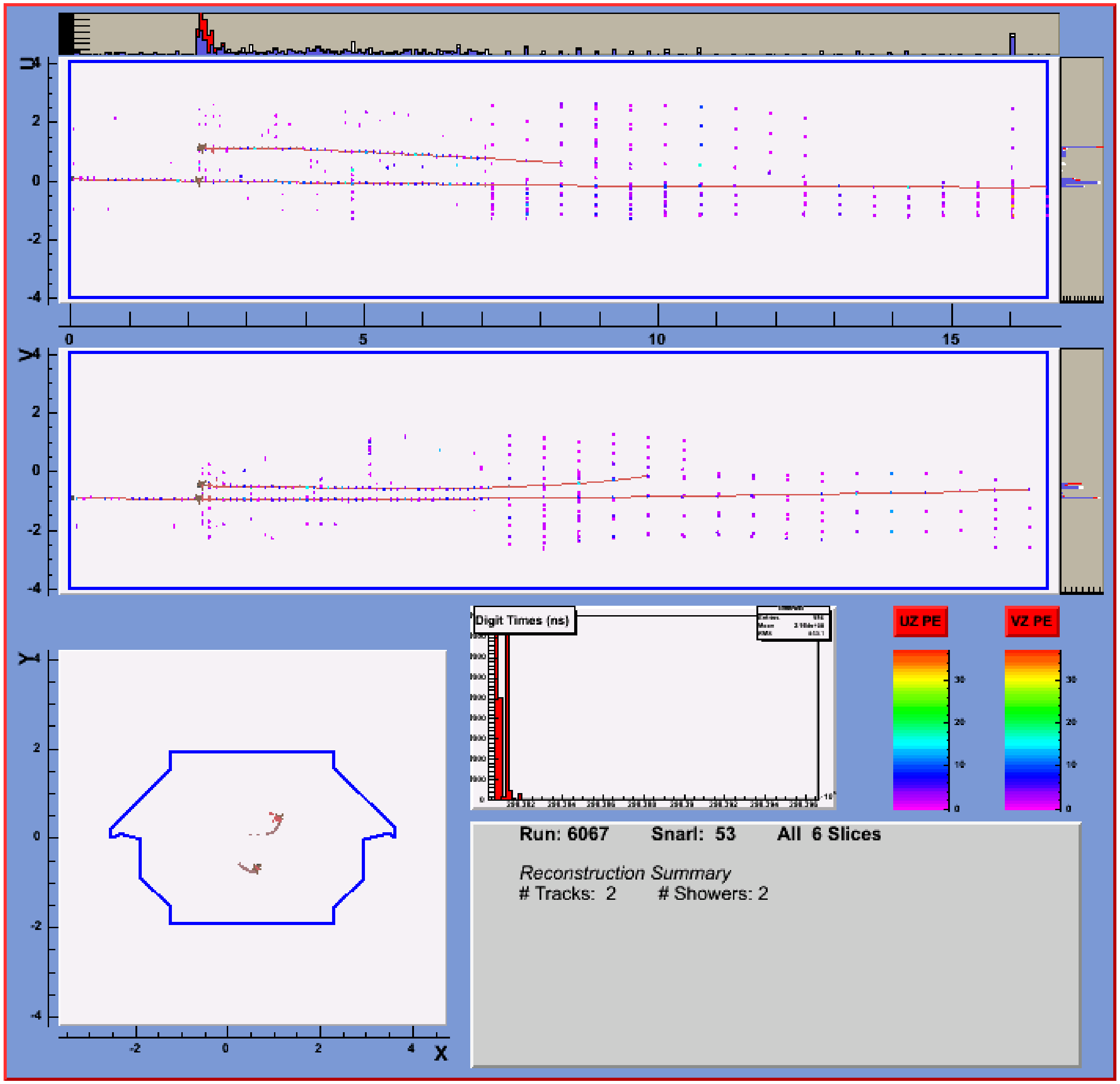
Two separate neutrino interactions here:

1) "Rock muon" from ν interaction upstream of near detector

2) Fully-contained interaction in the near detector

Note: this is one entire (1.6 μs) spill's worth of data!

- 19 ns timing on readout allows separation of interactions

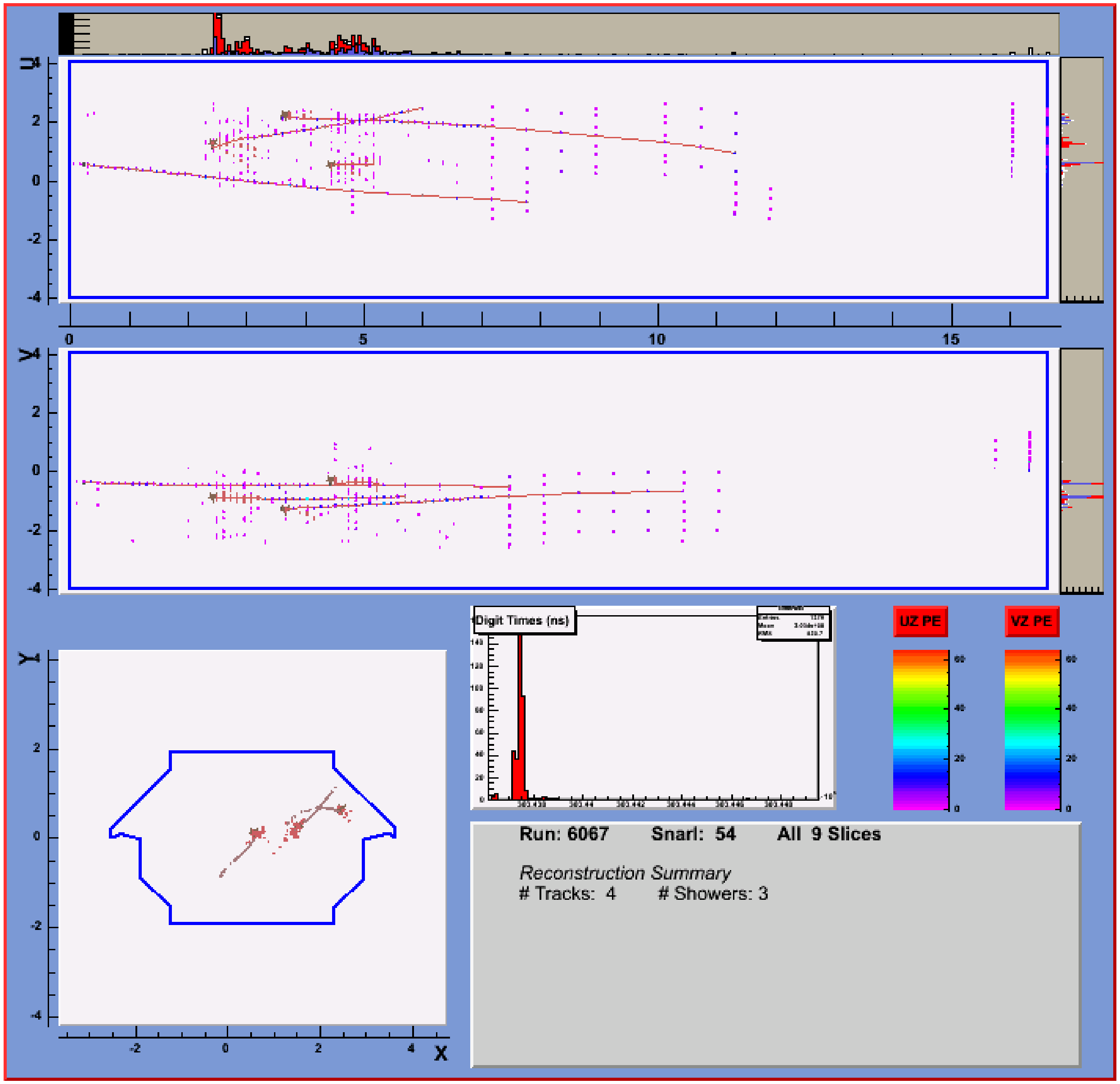


Spill data in the Near Detector

This spill contained 4 neutrino interactions !

Again, this is NOT a problem !

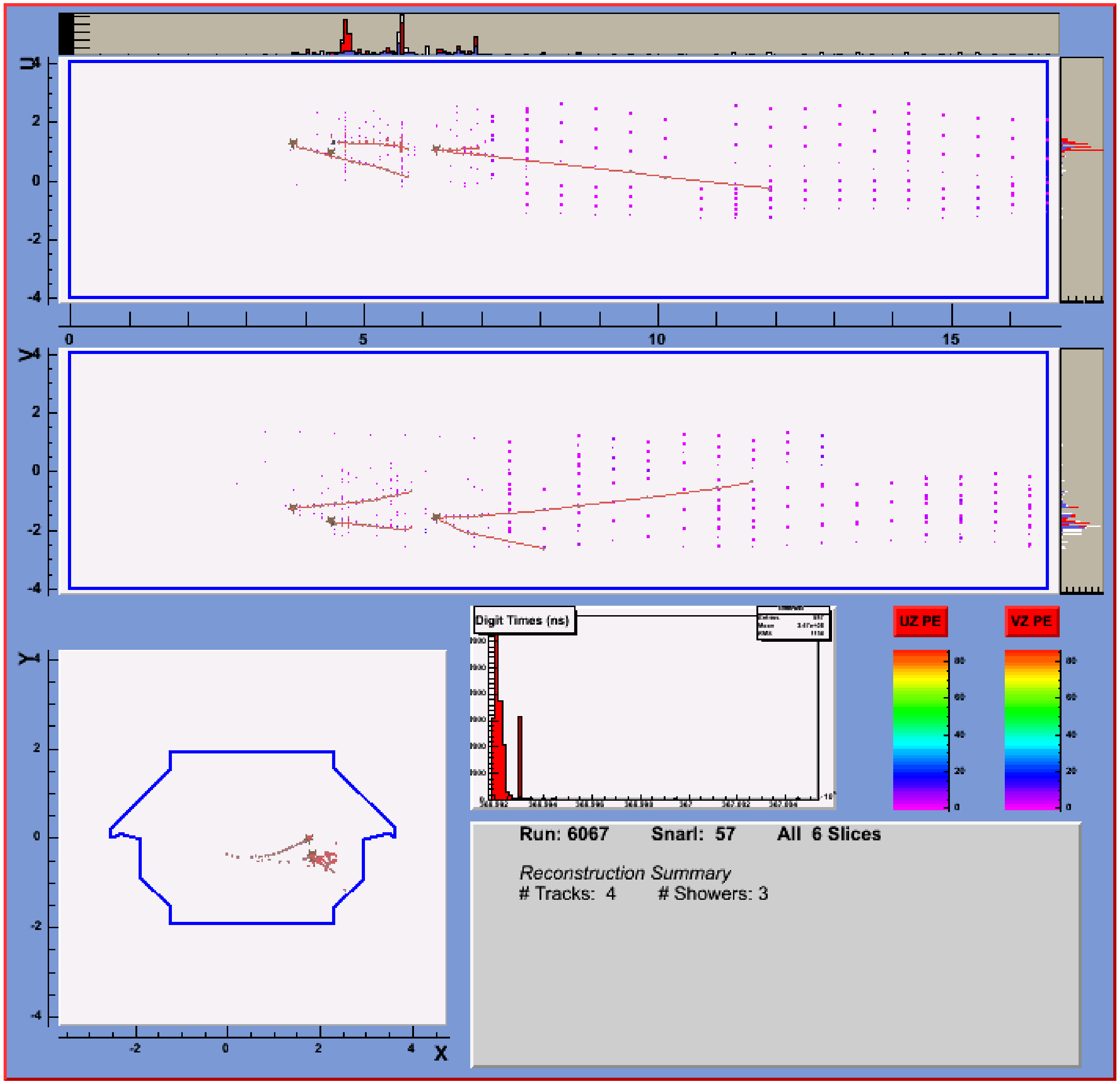
Individual events can be easily separated according to the 19 ns time bucket in which they occur.



Spill data in the Near Detector

This spill contained
3 neutrino interactions,

one with a second track !



Summary of MINOS

– **Data-taking w/ NuMI beam is "under way"**
  - **Both detectors are 100% complete**
    (very stable: < 1 ns timing drifts, ~ 1% pulseheight drifts)
  - **Calibration detector data analysis is complete**
  - **Now the main effort is to understand the beam!**

– **By 2007, will have precise measurements:**
  - **osc'n parameters for ν_μ disappearance**; (NC/CC ratio for mode id)
  - **search for subdominant $\nu_\mu \rightarrow \nu_e$**

– **Will also have ~ 24 kiloton-year exposure to atm. ν's**
  - **energy, direction resol'n → Minos competitive on ν_μ disappear.**
  - **1st direct search for CPT non-cons.** ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ vs $\nu_\mu \rightarrow \nu_\mu$)

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Backup Slides

Introduction

- **picture emerging from existing data**
  - **Large effect at "atmospheric" Δm^2**
    - oscillation hypothesis very strong **[Super K]**
    - effect now seen at accelerator expt. **[K2K]**
    - dominant mode likely to be $\nu_\mu \rightarrow \nu_\tau$ **[Super K]**
  - **Also large effect at "solar" Δm^2** **[Davis]**
    - LMA solution confirmed !! **[Ga + SNO + SK + KamLAND]**
  - **Questions:**
    - two angles large, what about the third, θ_{13} ?
    - complex phase in MNS matrix → CPV ?
    - what about mass hierarchy ?
    - where does LSND fit ? CPT ? sterile neutrinos ?
    - Extra dimensions ?

Goals of 1st generation of Long Baseline Experiments

Confront emerging picture with precision data

- confirm deficit of ν_μ in accelerator-based exp't
- confirm oscillation hypothesis:

  must measure/know E & L precisely to see osc'ns in L/E
  pin down oscillation parameters

- demonstrate $\nu_\mu \rightarrow \nu_\tau$ is dominant mode:

  Tau appearance ! (CNGS → direct, MINOS → NC/CC)

Look for new phenomena

- evidence for non-zero θ_{13} : → detection of ν_e
- test for possible CPT violation ?
- etc….

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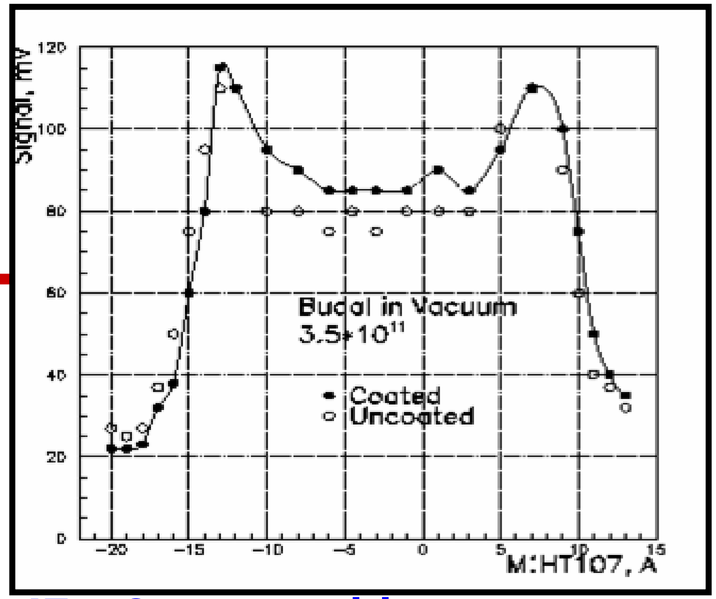
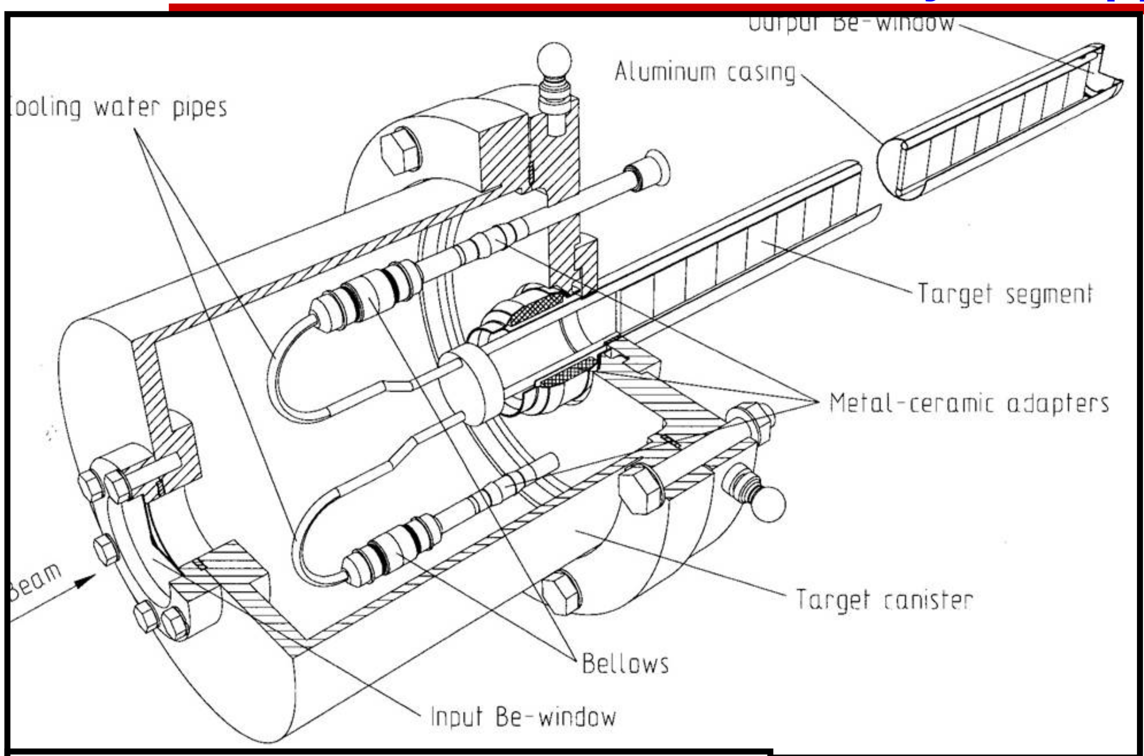
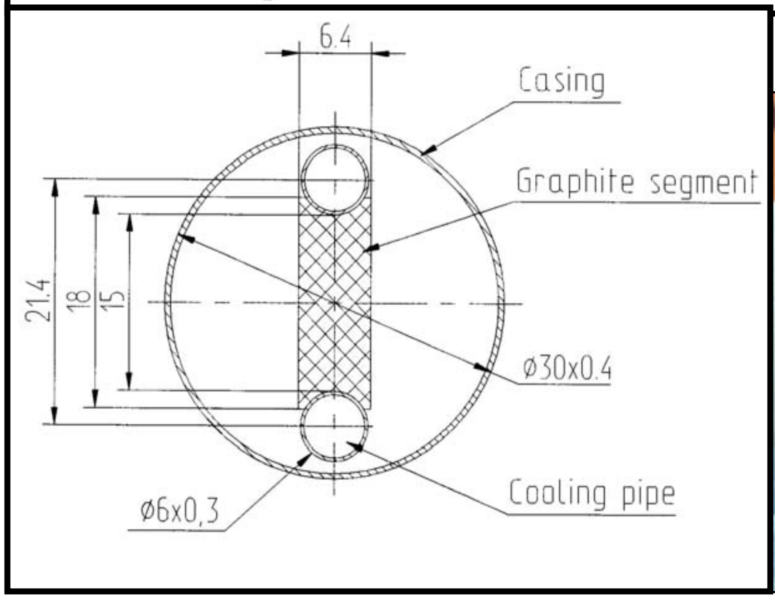
NuMI Target

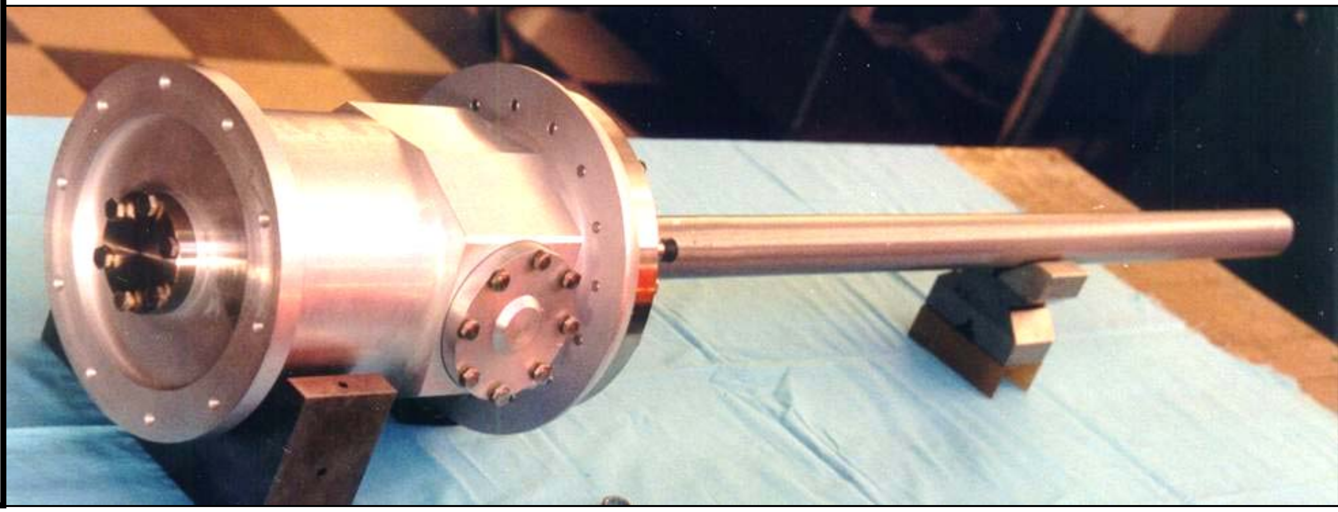
Slide courtesy S. Kopp







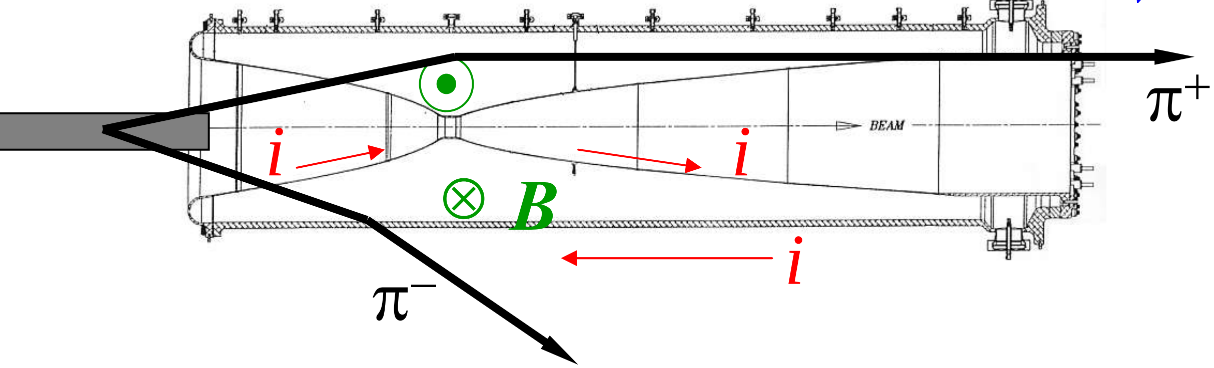
- **47 × 2 cm graphite segments**
  - **6.4 × 28 mm² profile**
  - **Beam is 1 mm radius**
  - **1.9 interaction lengths**
- **Water cooled**
  - **4 kW deposited beam power**
- **Could survive 1MW if 2mm spot size**

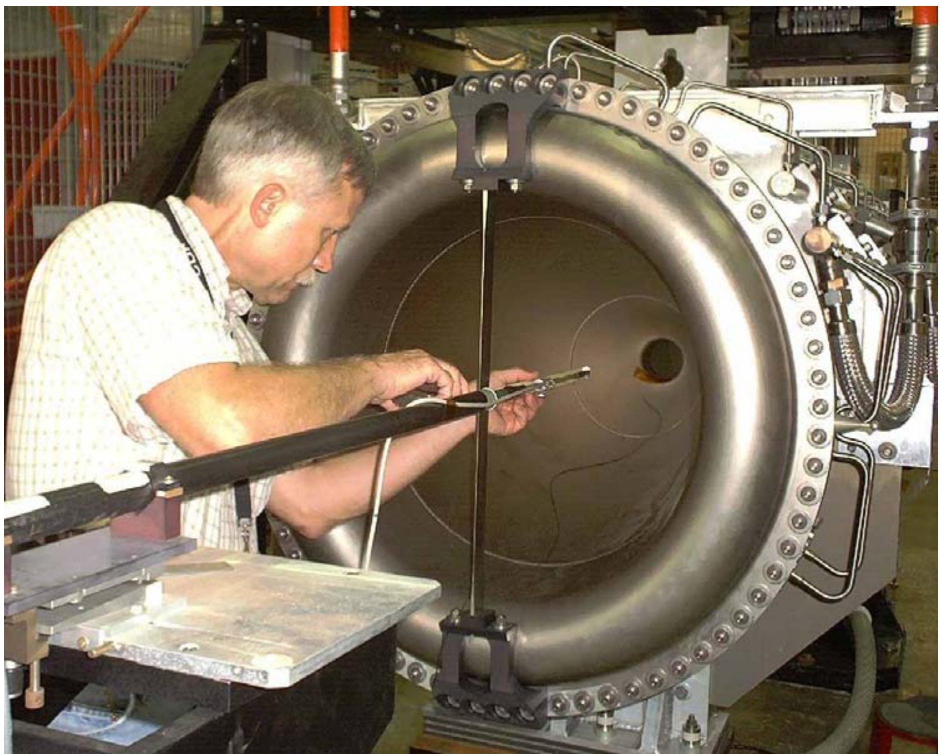


The “Magnetic Horns”

Slide courtesy S. Kopp

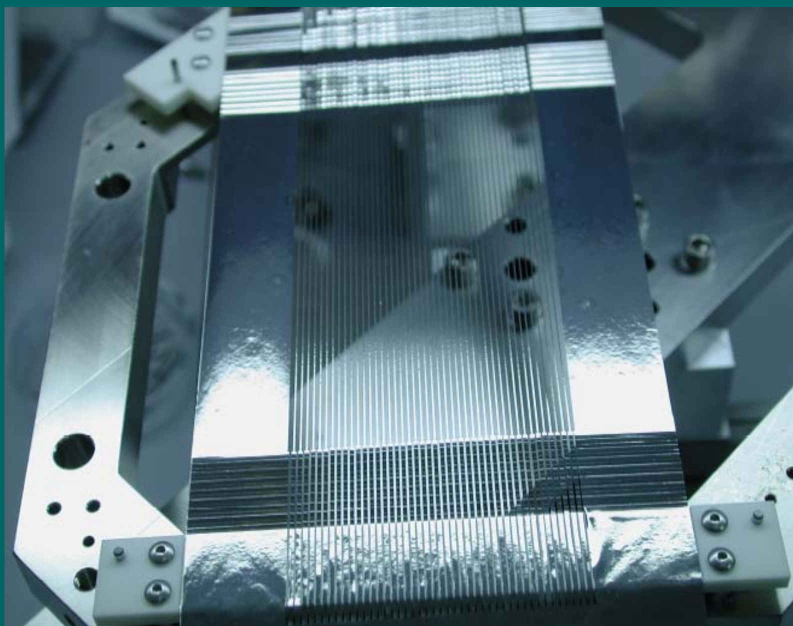
- **Toroidal Magnet $B \sim 1/r$**
- **p_T kick of $\Delta p_T \propto \int B d\ell \propto r \propto p_\pi \propto E_\nu$**





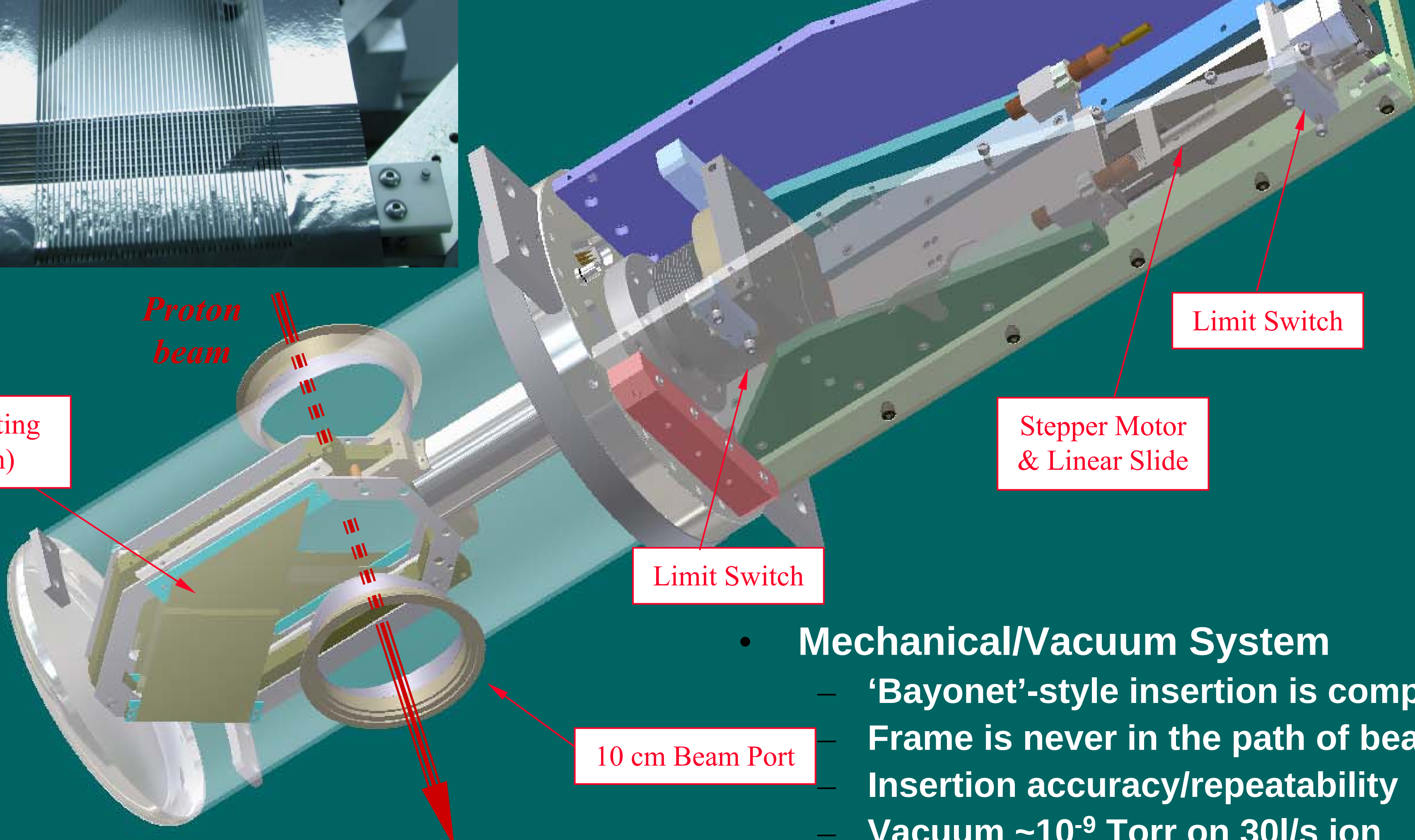
Slide courtesy
S. Kopp

Segmented Foil SEM's



Foil Secondary Emission Monitors

- Beam profile + halo measurement
- Very low mass (5 μm Ti)
- Reduced Beam Heating problems
- Ti signal lasts longer in the beam



- **Mechanical/Vacuum System**
  - 'Bayonet'-style insertion is compact
  - Frame is never in the path of beam
  - Insertion accuracy/repeatability
  - Vacuum ~10^{-9} Torr on 30l/s ion pump

www.hep.utexas.edu/~kopp/minos/sem/

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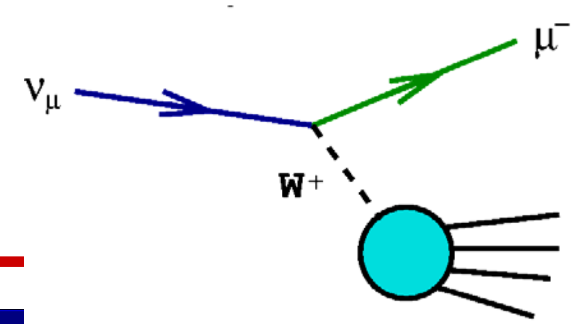
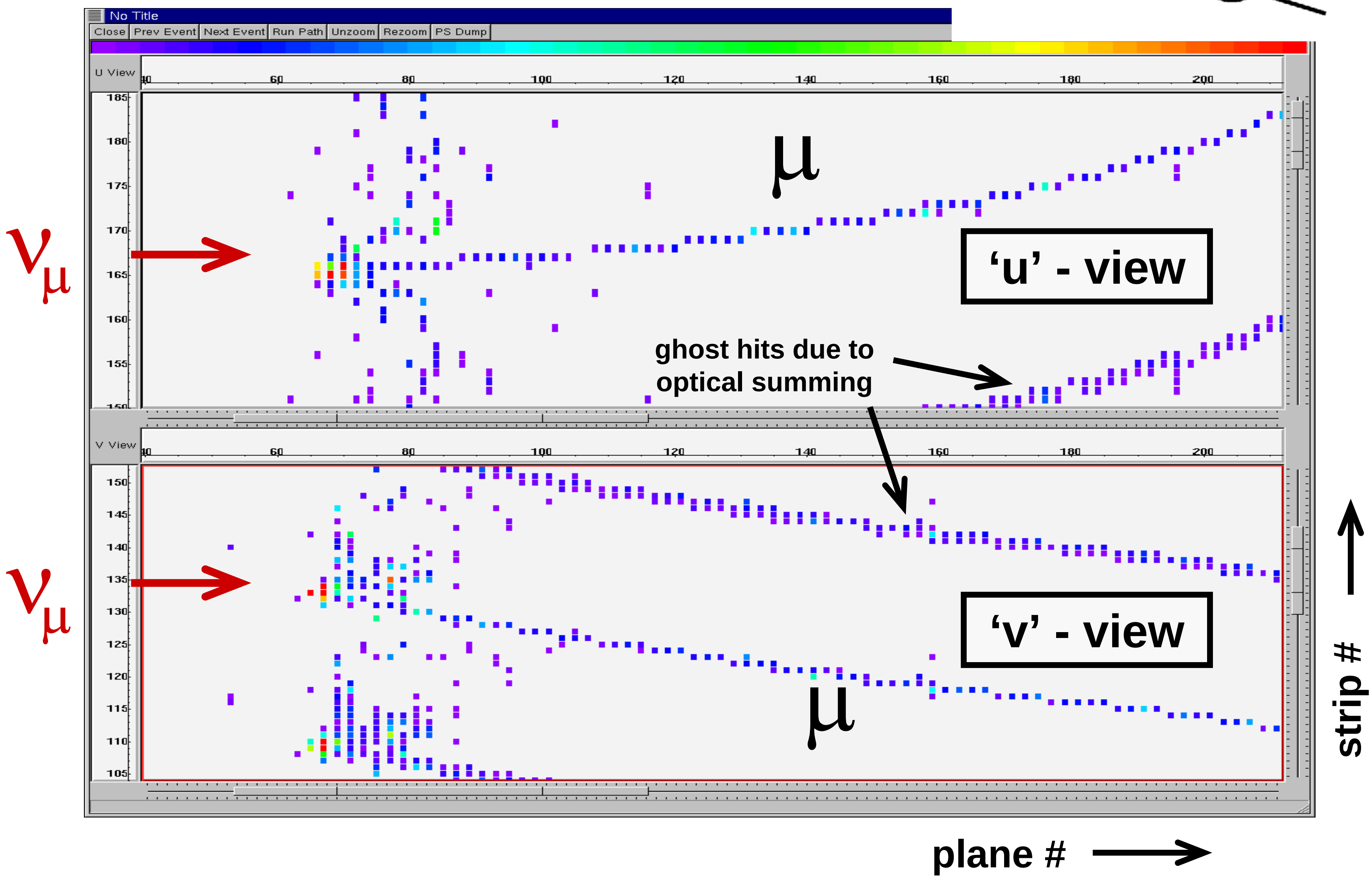
Simulated Neutrino Interaction





Beam Intensity During Jan 21-22

Beam Intensity as measured by downstream NuMI toroid

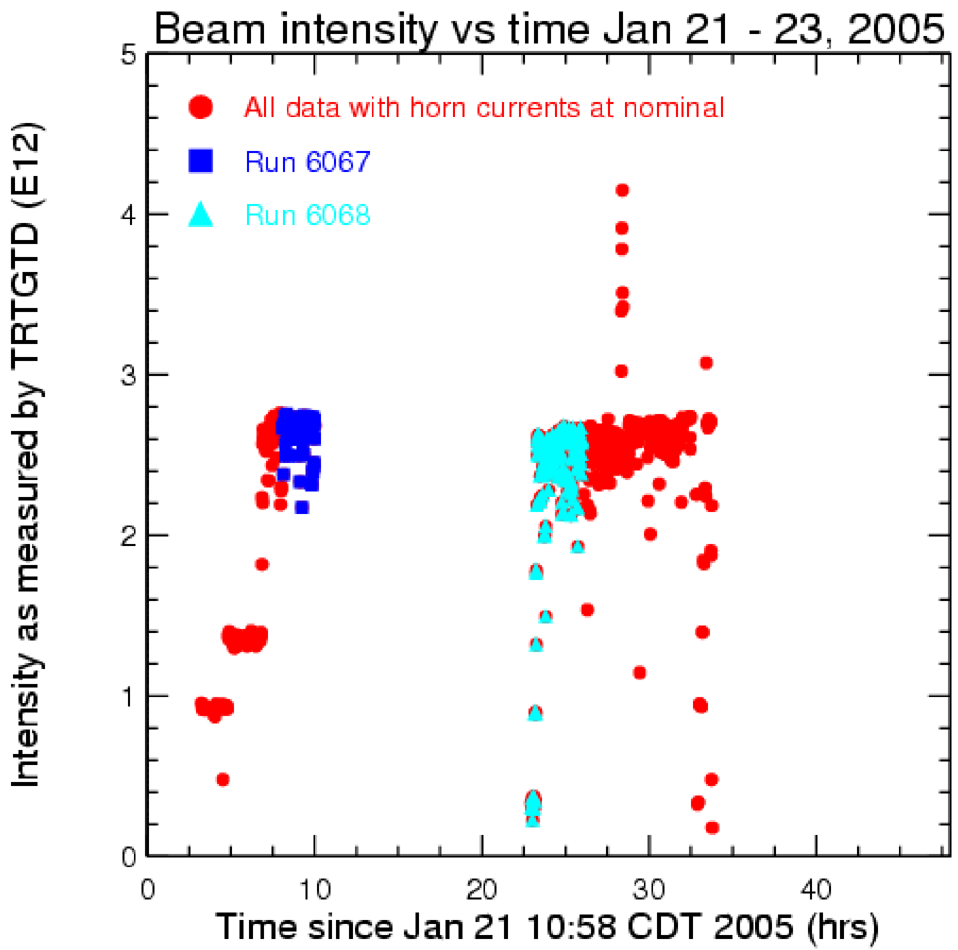
2.5e12 **protons/pulse was typical.**
Intensity scan up to *4.1e12 ppp* !!

Recall CD-4 criterion: *1.0e12 ppp*.

Simple extrapolation to multi-batch operations:
4.1e12 ppp x 5 = 2.1e13 ppp

c.f. intensity goal: 2.5e13 ppp

Note - this is just one of > 300 beam instrumentation devices being read out & available for offline analysis!



M. Bishai

Distributions of events in Near Det

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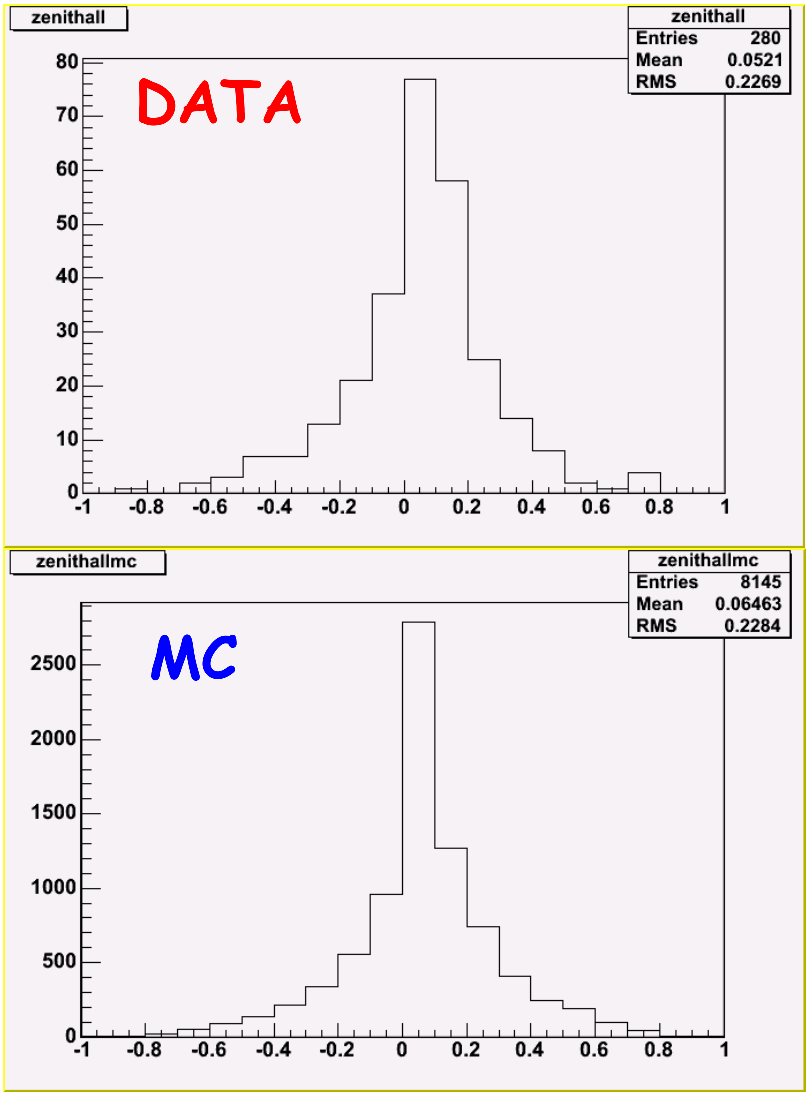
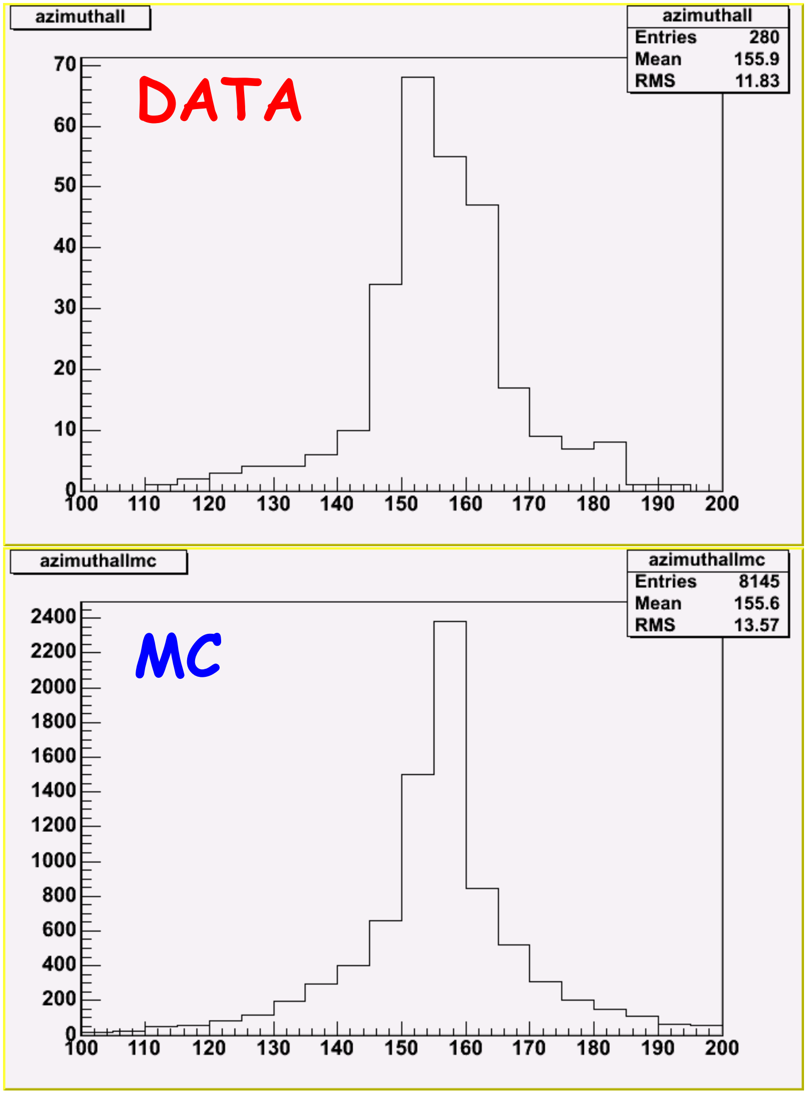
Cosine zenith angle: All tracks



Azimuth angle All tracks



N. Saoulidou

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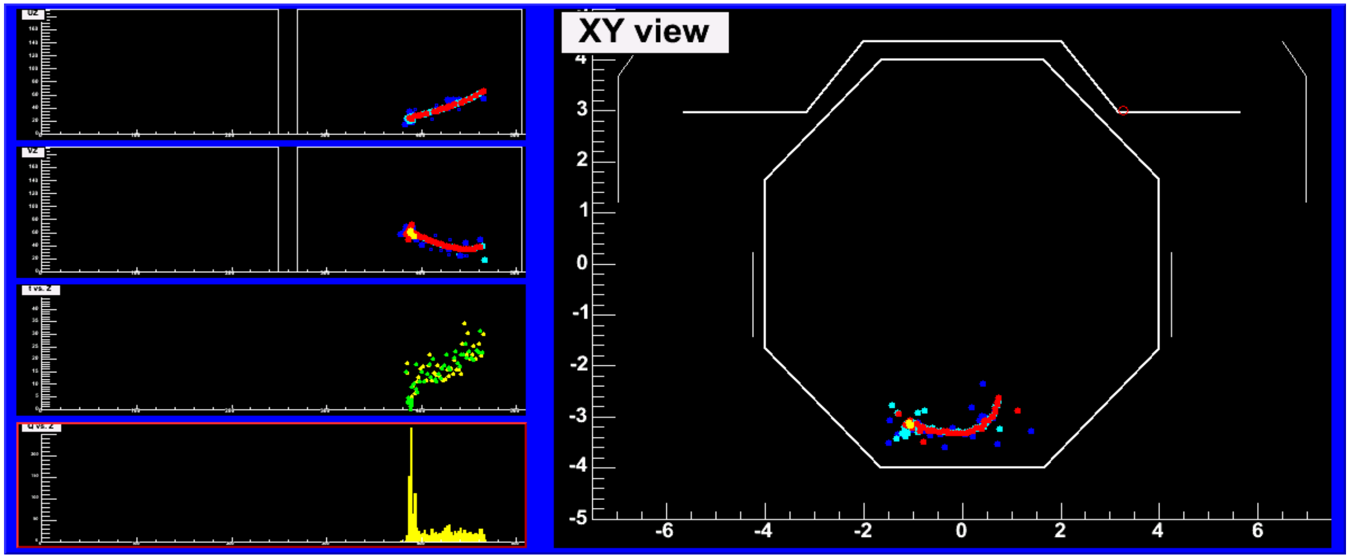
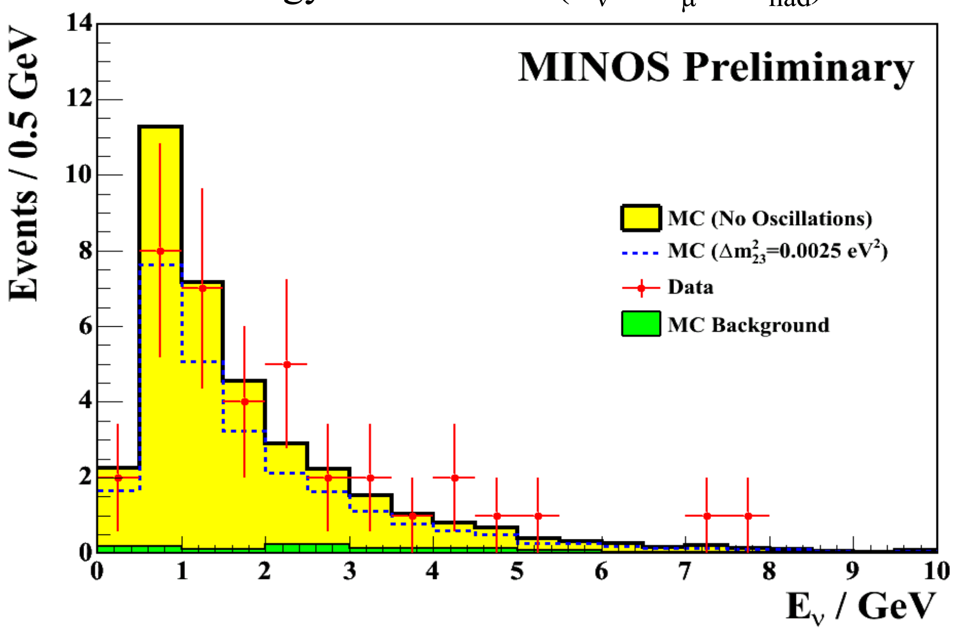
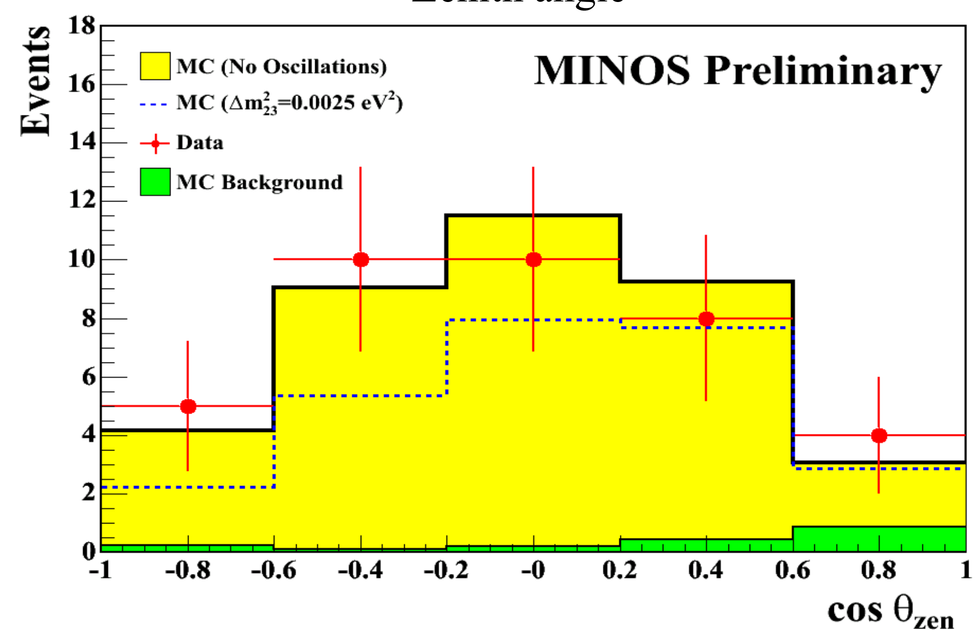
Fully contained atmospheric ν_μ CC events in Far Detector



Energy distribution ($E_\nu = E_\mu + E_{had}$)



Zenith angle



Plots: C. Howcroft & M. Thomson