Early Experience with NuMI/MINOS

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Batavia, IL, USA
(presented by Stan Wojcicki, Stanford)

XI International Workshop on
Neutrino Telescopes
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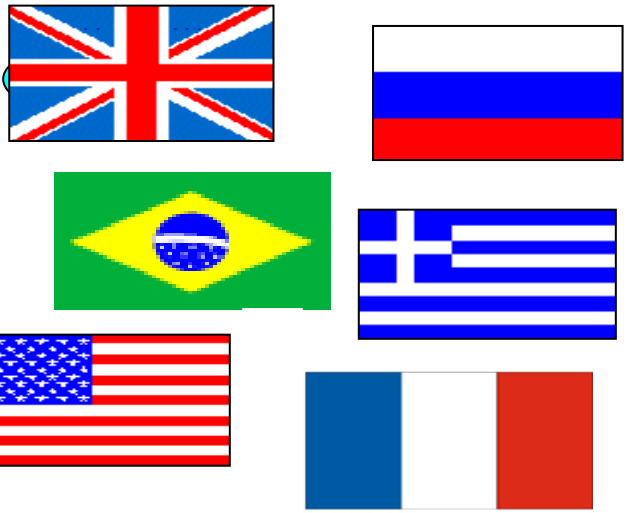
Venice

Outline of this Talk

- NuMI/MINOS Project and its Physics
- Beamlines and Instrumentation
- Soudan Laboratory and MINOS Far Detector
- MINOS Near Detector
- Commissioning activities and first neutrino events

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

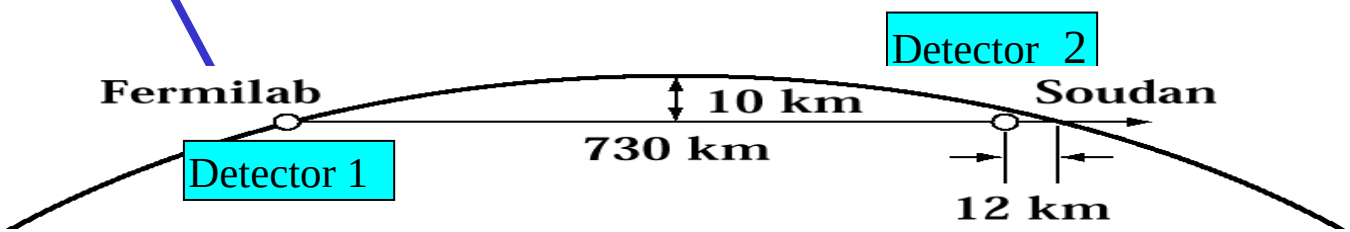
MINOS Collaboration members at Fermilab with the Near Detector surface bldg in the background (right)

MINOS Long-Baseline Experiment

Fermilab to Soudan, Minnesota

Far Detector: 5400 tons

Near Detector: 980 tons



MINOS Physics Goals

★ **Demonstrate oscillation behaviour**

- confirm flavour oscillations describe data
- provide high statistics discrimination against alternative models:
  decoherence, ν decay, extra dimensions, etc.

★ **Precise Measurement of Δm^2_{23}**

- ~10 %

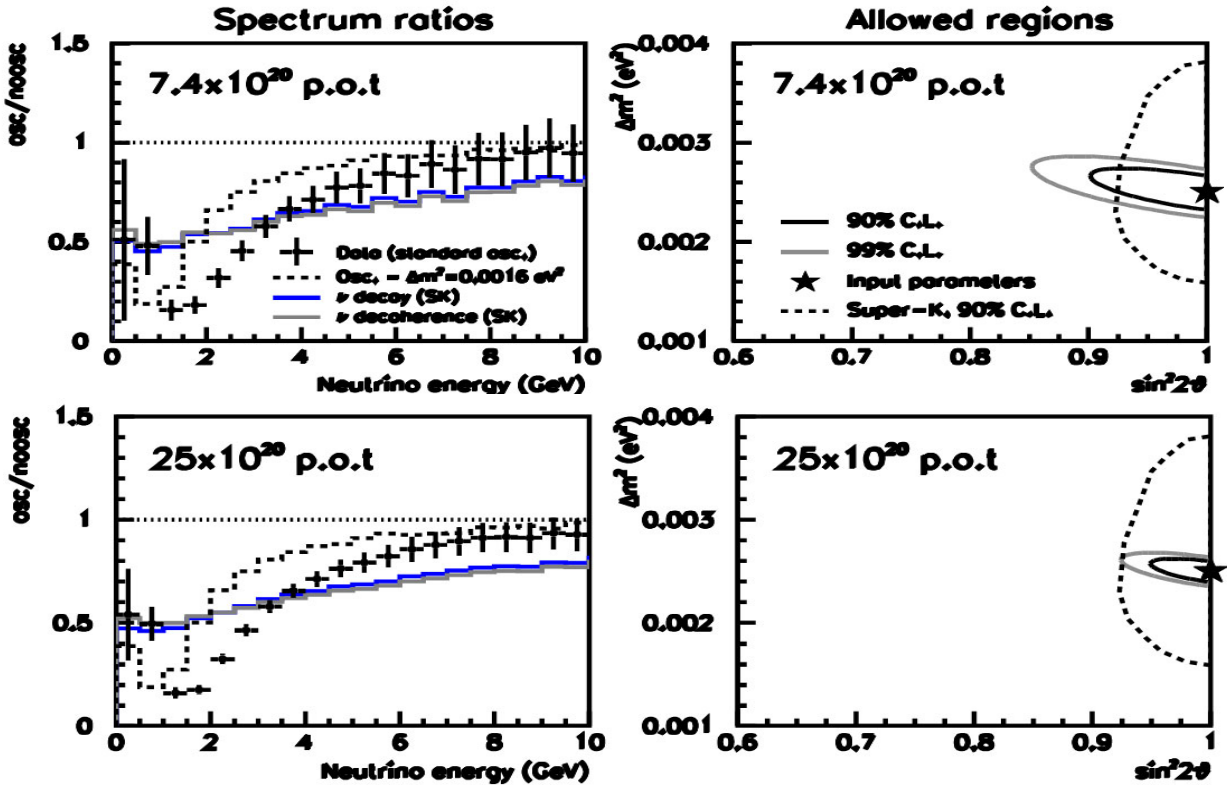
★ **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations**

- first measurements of θ_{13} ?

\+ **MINOS is the 1st large deep underground detector with a B-field**

- first direct measurements of ν vs $\bar{\nu}$ oscillations from atmospheric neutrino events

MINOS Sensitivity for Δm^2 and $\sin^2 2\theta$



Greatly improve existing measurement

Excellent test against alternative hypotheses

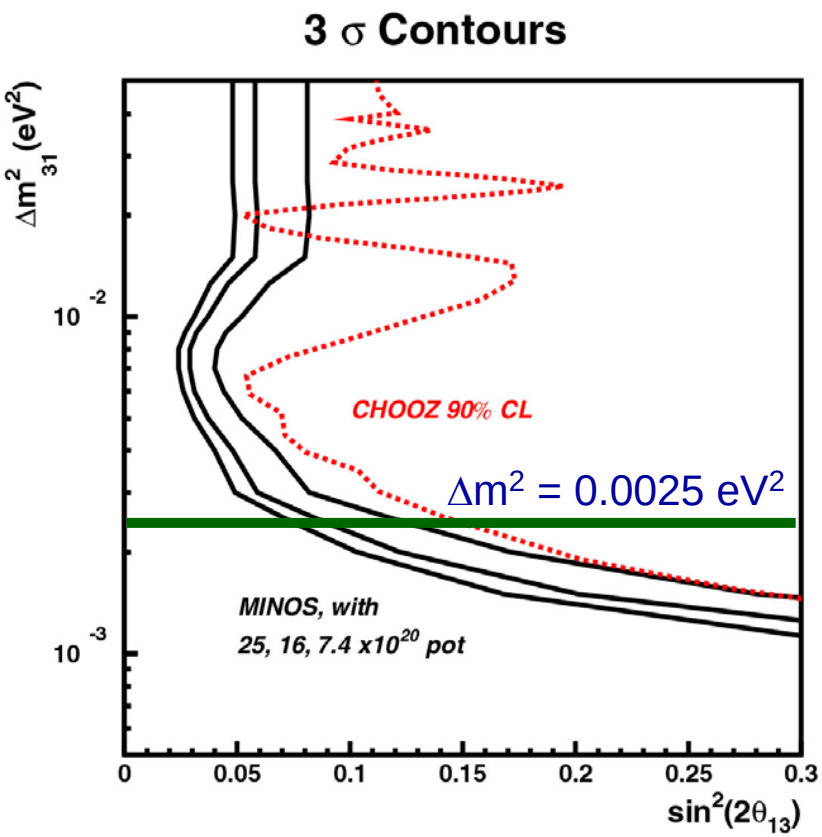
Continued improvement with additional protons

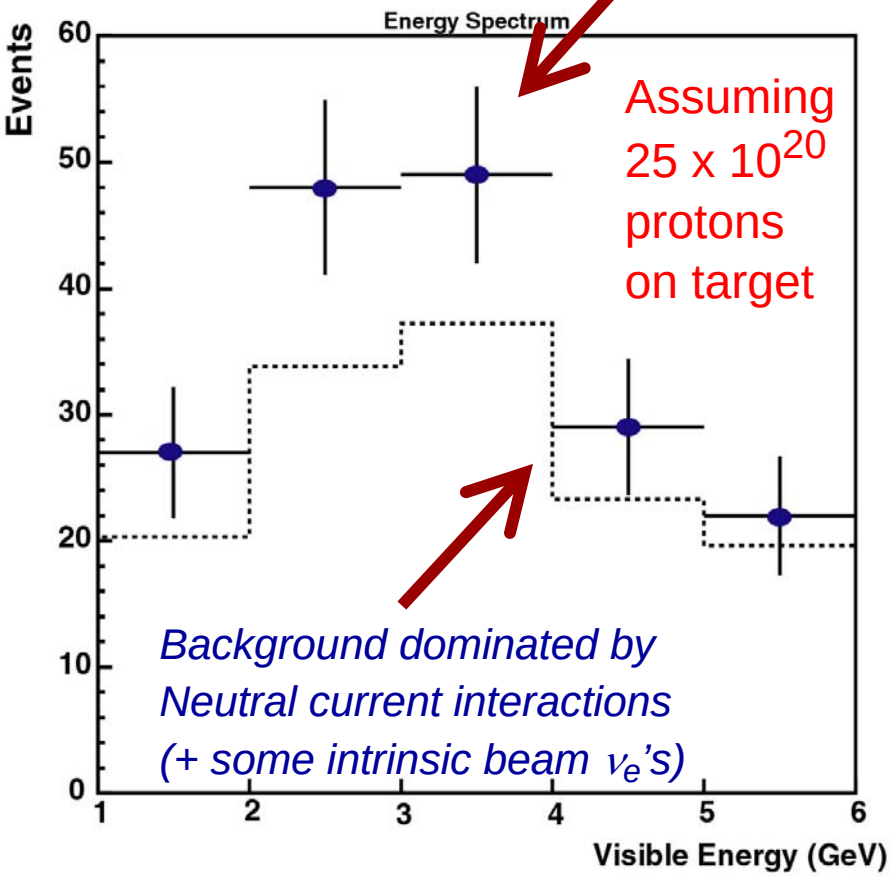
Sensitivity to ν_e appearance

detection of ν_e at Δm^2_{atm}

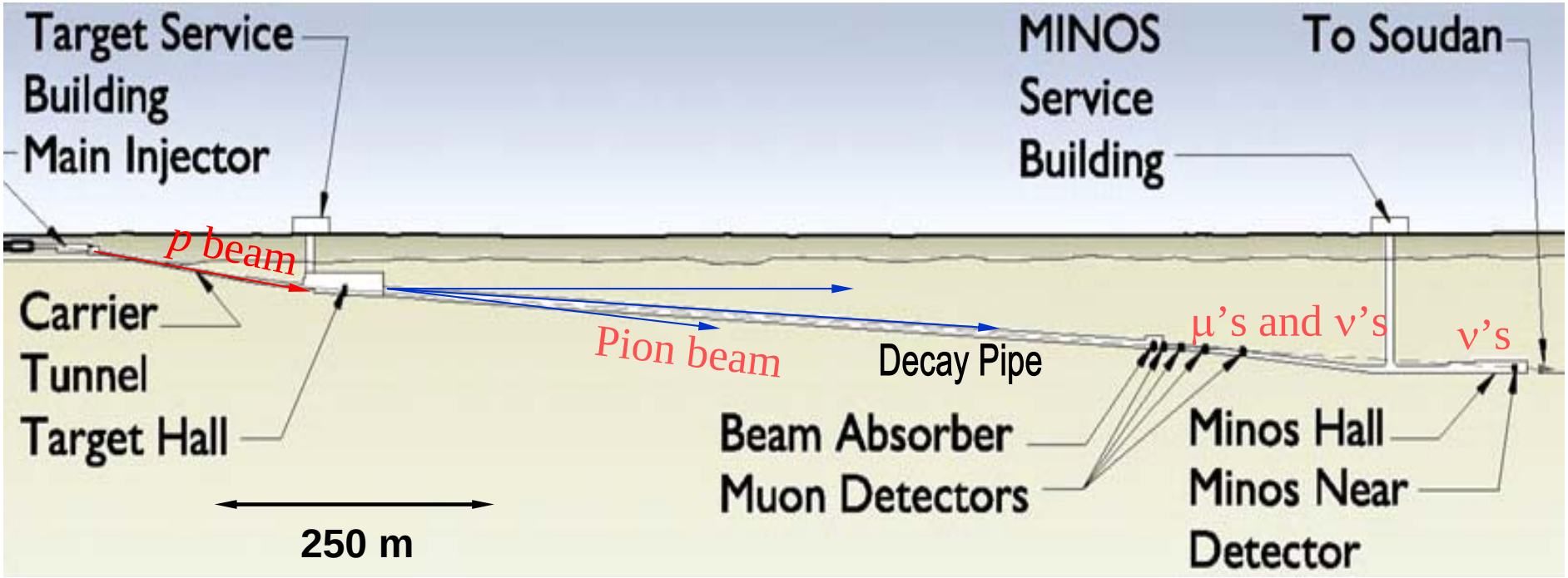
→ *evidence for non-zero θ_{13}*

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





NumI/MINOS Tunnel and Beamline



NuMI and Main Injector

Fermilab Main Injector:

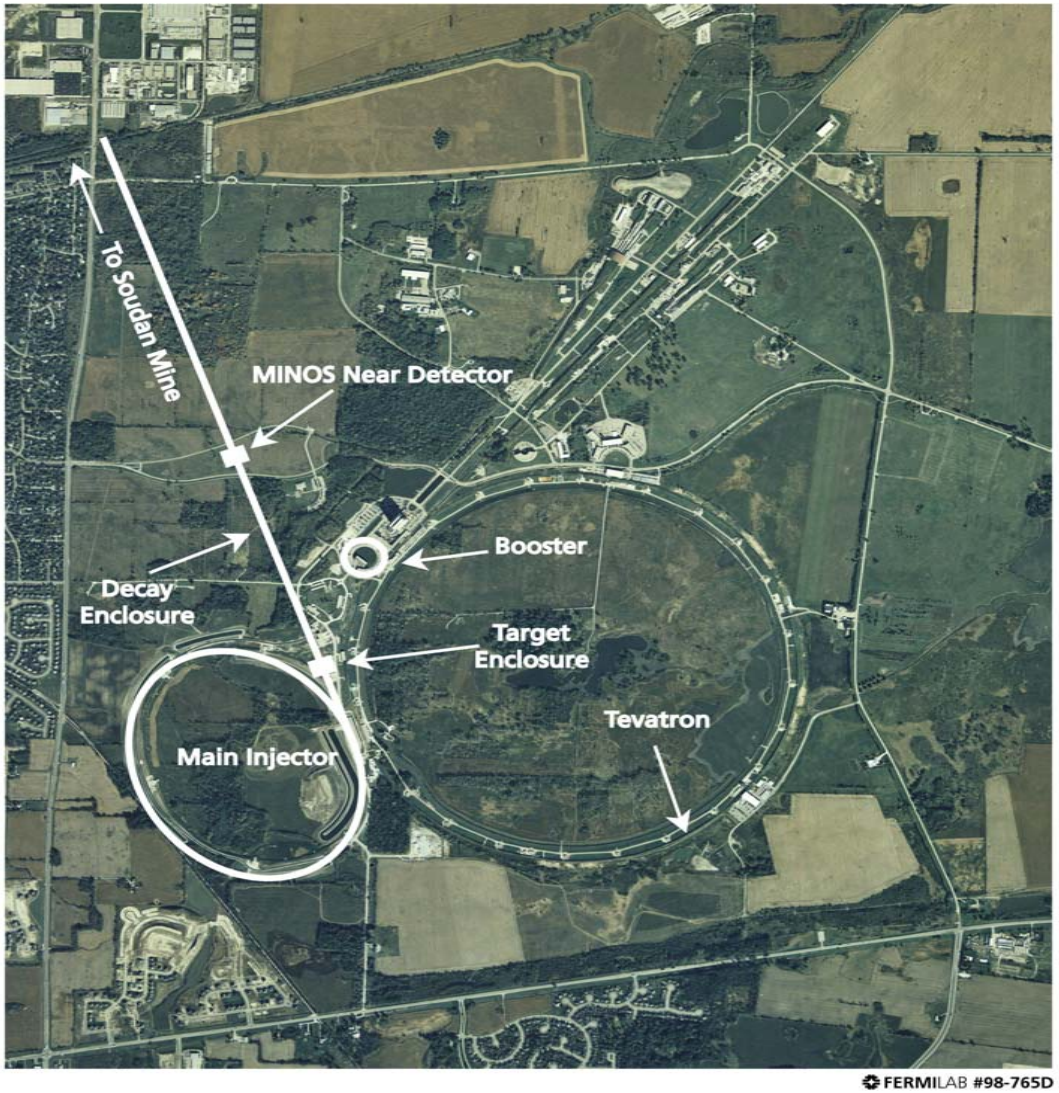
120 GeV protons
2.5 x 10^{13} protons/pulse
1.9 sec rep rate
(~8 μsec spill)
→ 0.25 MW

NuMI Beam:

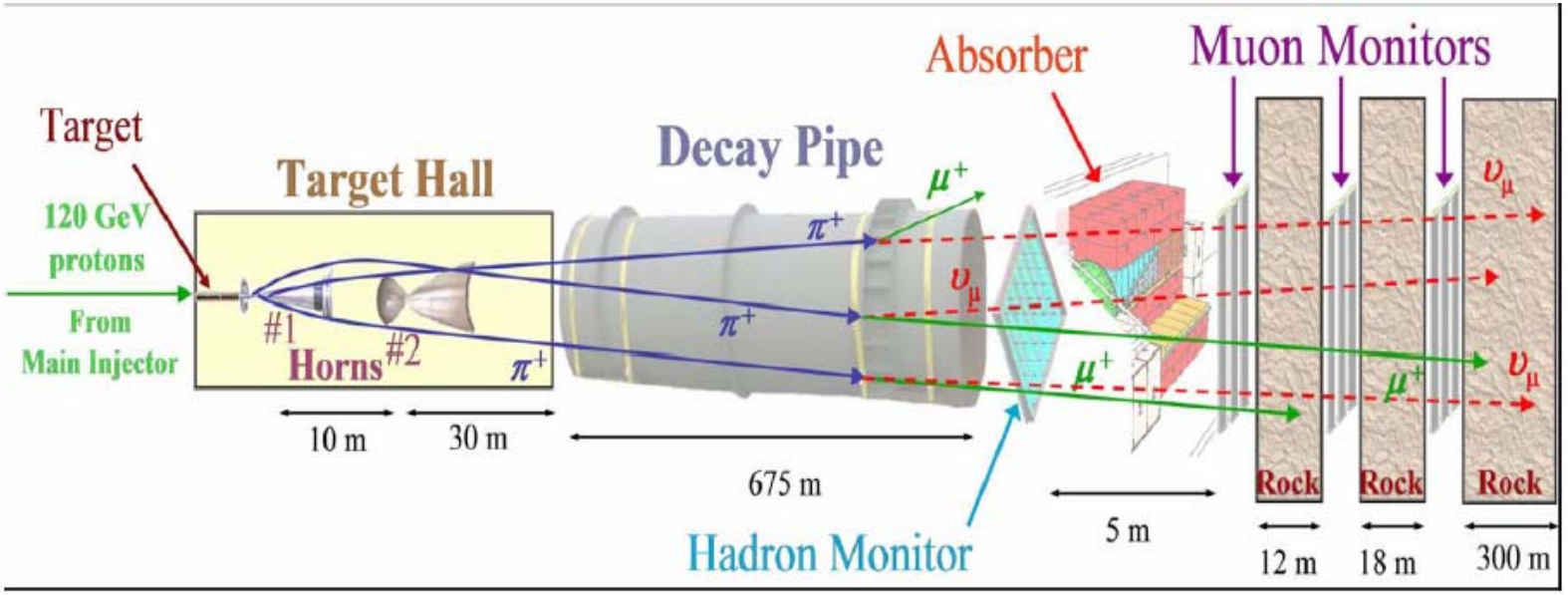
Graphite target
Two magnetic horns
675 m vacuum decay pipe
hadron absorber
designed for 4 x 10^{13} ppp

Beam Monitoring:

beam line monitors
muon detectors
hadron detectors
+ Near Detector !



Beamline and Focusing Layout



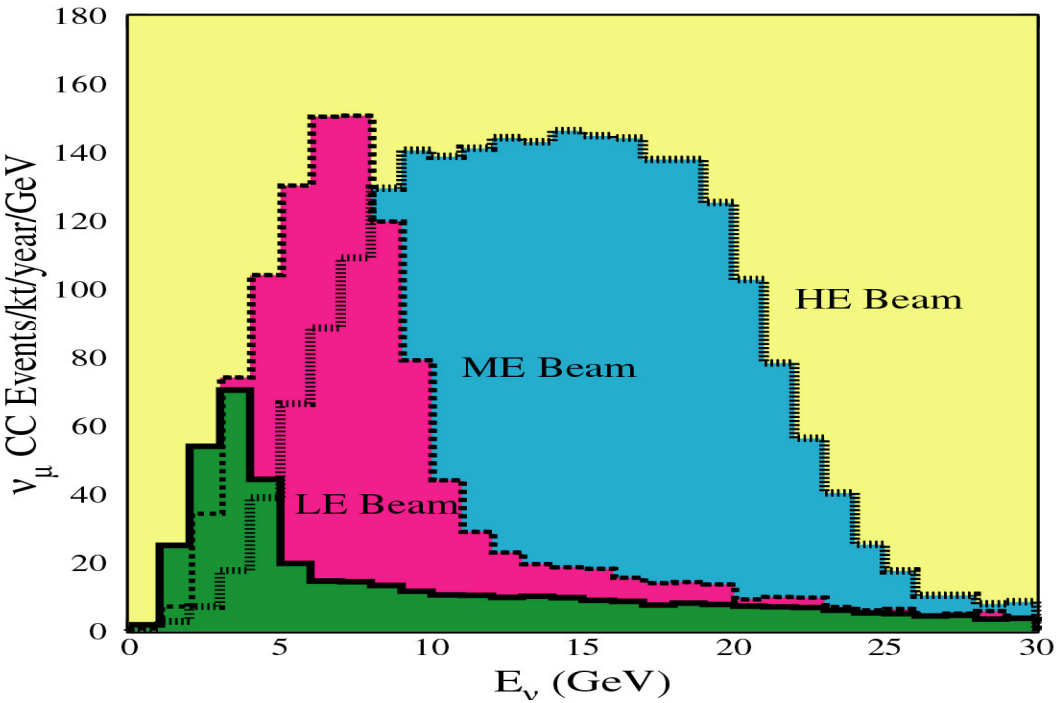
120 GeV primary Main Injector beam

Target readily movable in beam direction

2-horn beam adjusts for variable energy ranges

675 meter decay pipe for π decay

Beam Energy Variability



Example spectra from varying horn positions

Start with low energy beam to accommodate $\Delta m^2 \sim 0.002\ eV^2$

ν_μ CC Events in MINOS 5kt detector (2.5×10^{20} POT/yr)

Low	~ 1600/yr
Medium	~ 4300/yr
High	~ 9250/yr

Primary Beamline and Main Injector

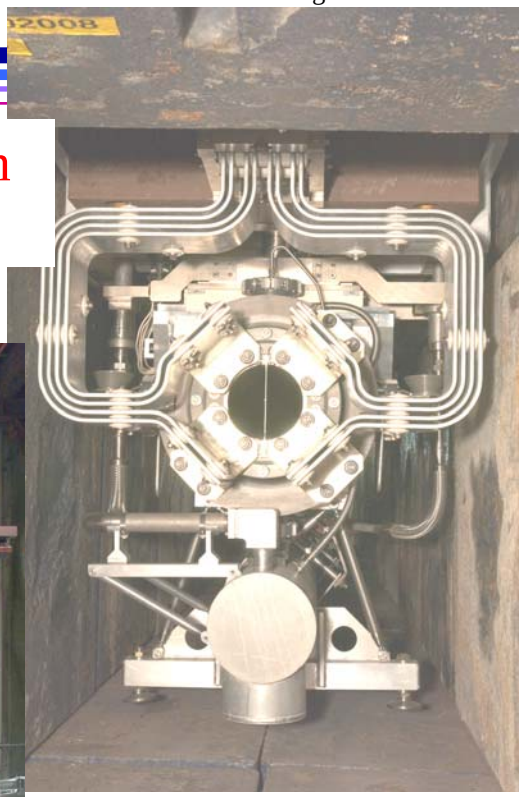
Main Injector showing NuMI beamline coming out and recycler overhead.

NuMI beamline descending towards pretarget

Target Hall Installation

Horn 2 Installation

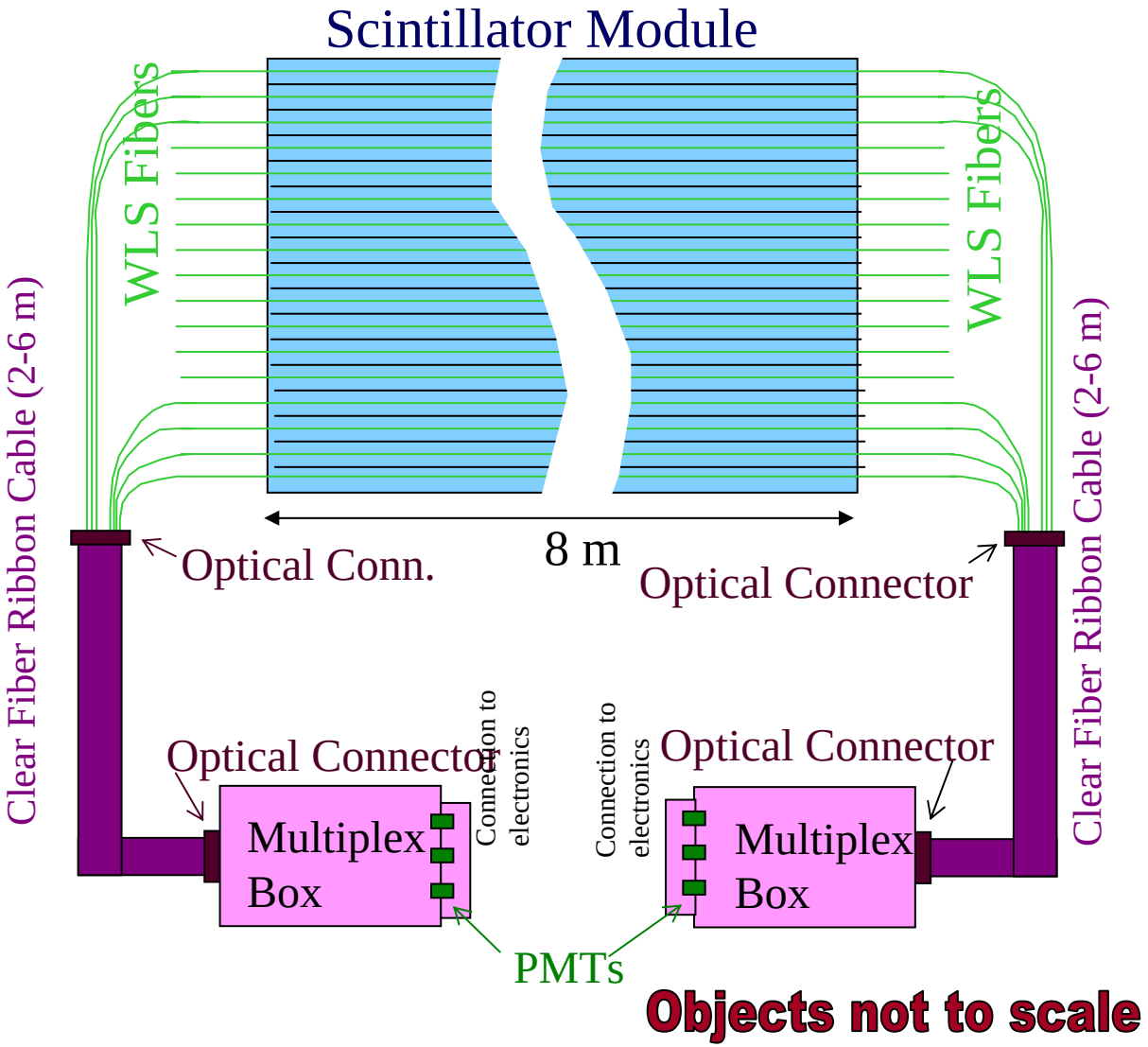
Horn 1 in position with stripline connections



Work Cell showing target carrier

Completion of Buildings, Shafts

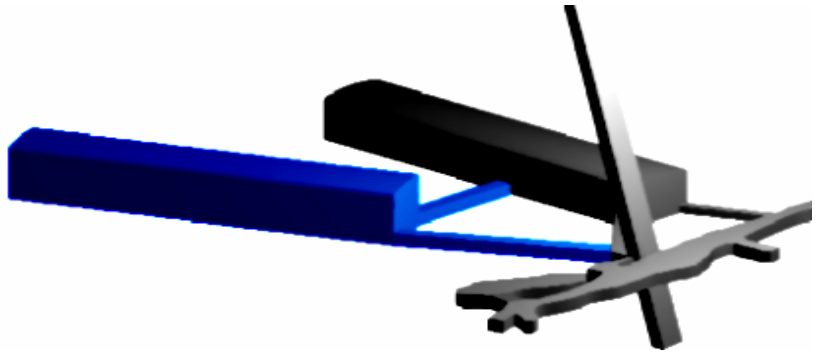
Detector Technology



MINOS Construction Challenge

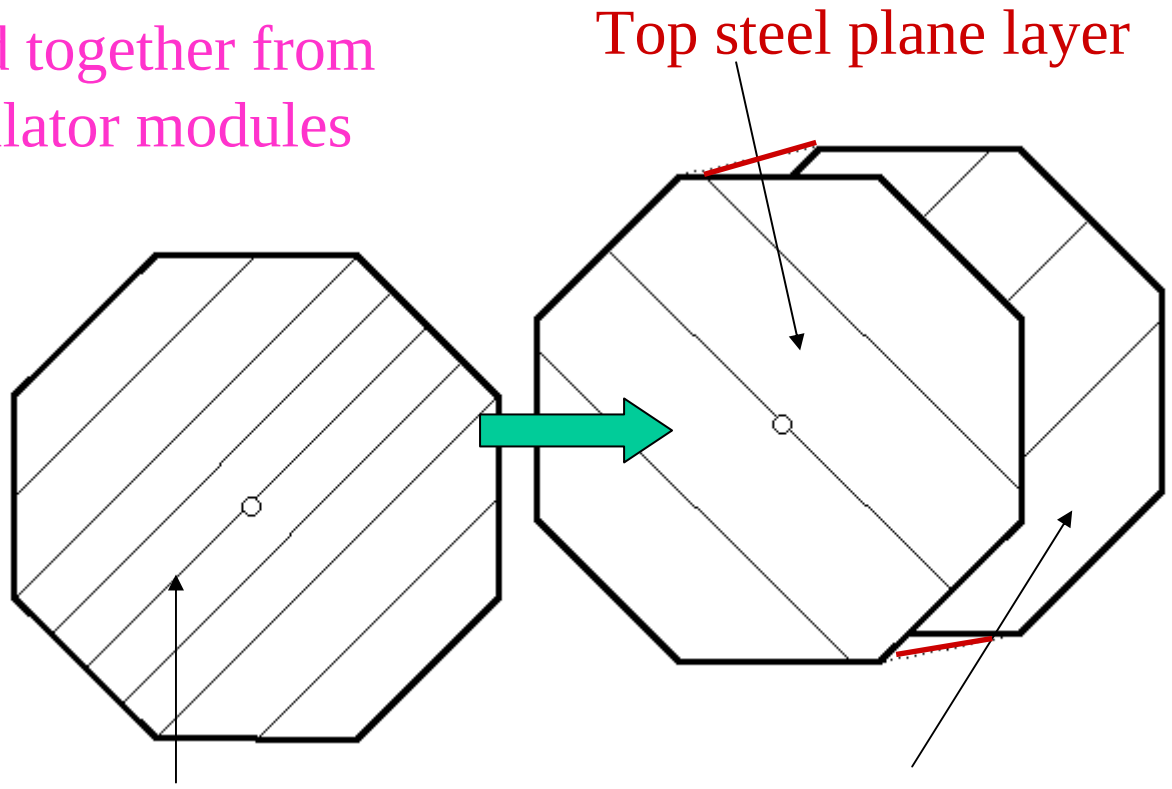
Soudan Underground Laboratory

- Operated by U. of Minn. and Minnesota Dept. of Natural Resources
- Soudan Mine - tourist attraction during summer months
- 1 elevator shaft limits loads to 1m x 2m x 9m



MINOS Far Detector Plane Schematic

Steel Layers welded together from plates, then 8 scintillator modules attached.



Scintillator plane

Orientations alternate ±90^{o}
in successive planes

Assembly and Mounting at Soudan

MINOS Far Detector Features

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm magnetized Fe plates
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readou
- Veto shield against entering cosmic ray muons
- Completed June 2003

Detector during construction

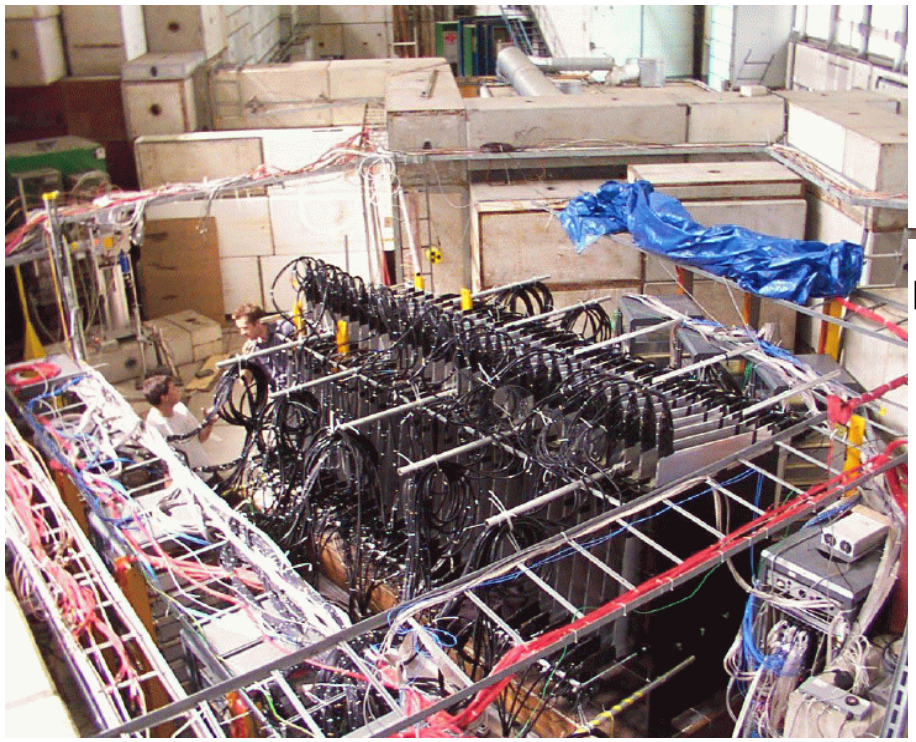
282 out of 486 layers up

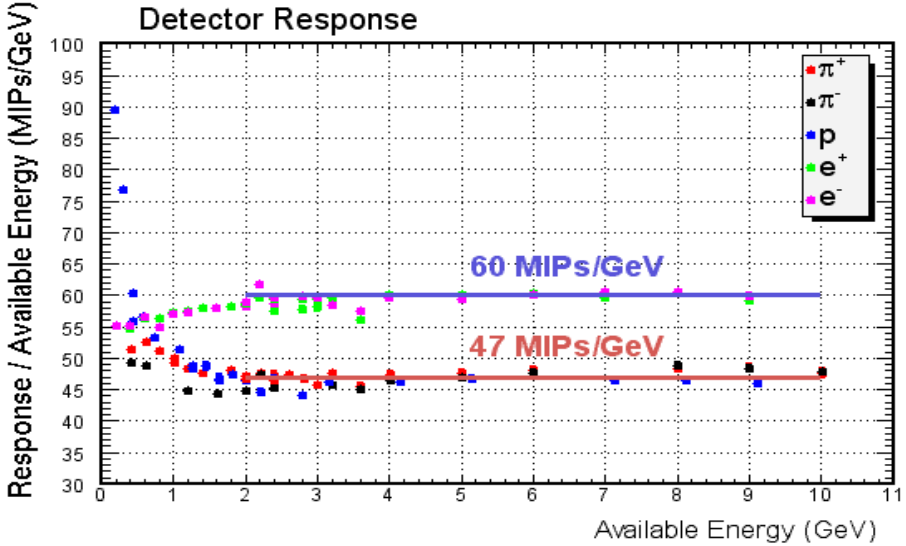
Calibration Detector

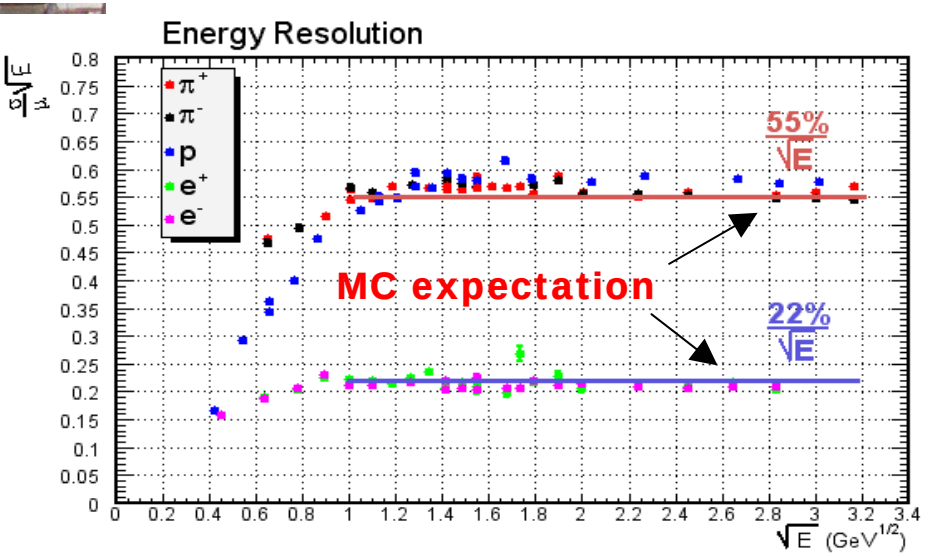
(how well such a detector measures energy?)

60-plane 'micro - MINOS'

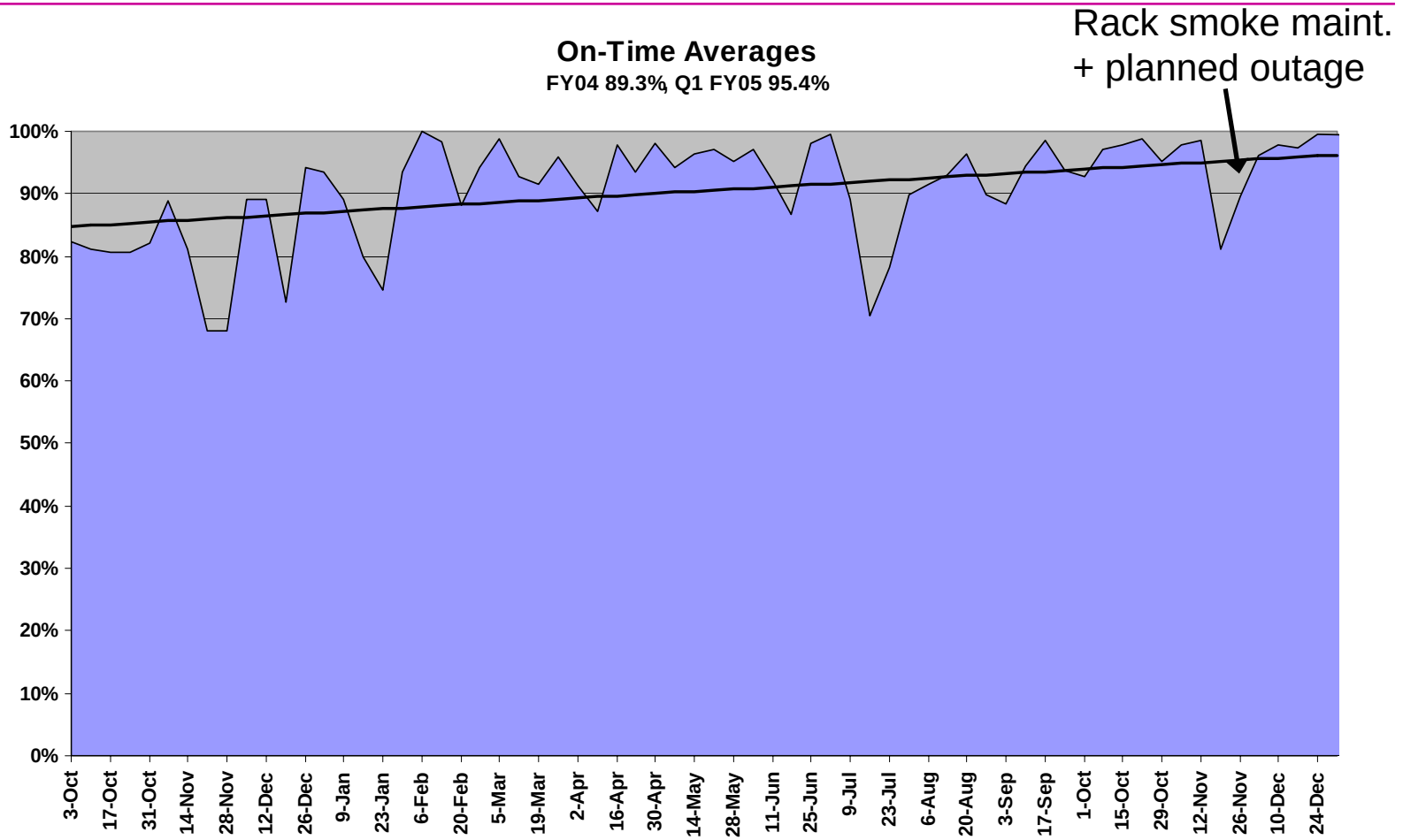
-- has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003







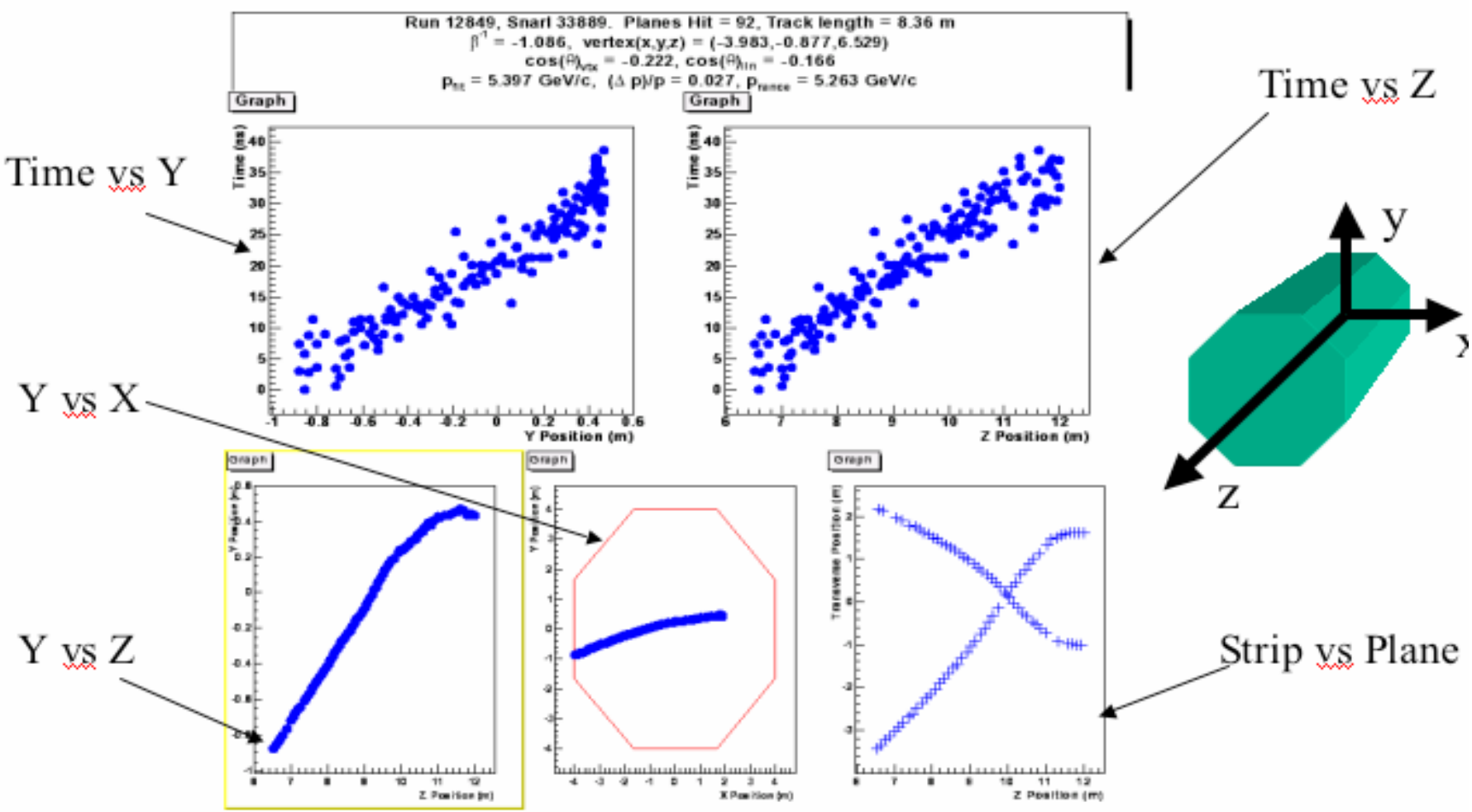
Far Detector Live Time



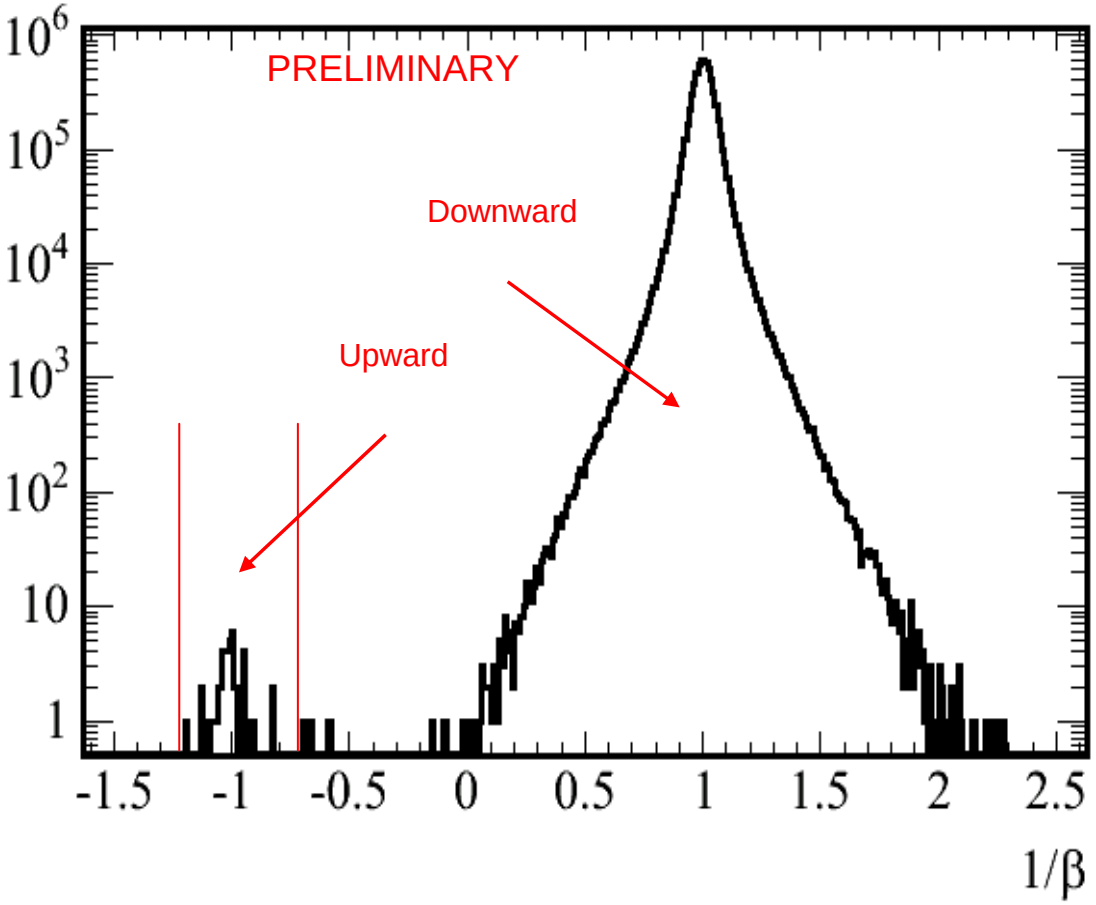
B. Speakman, A. Habig, B. Miller

A "typical" event

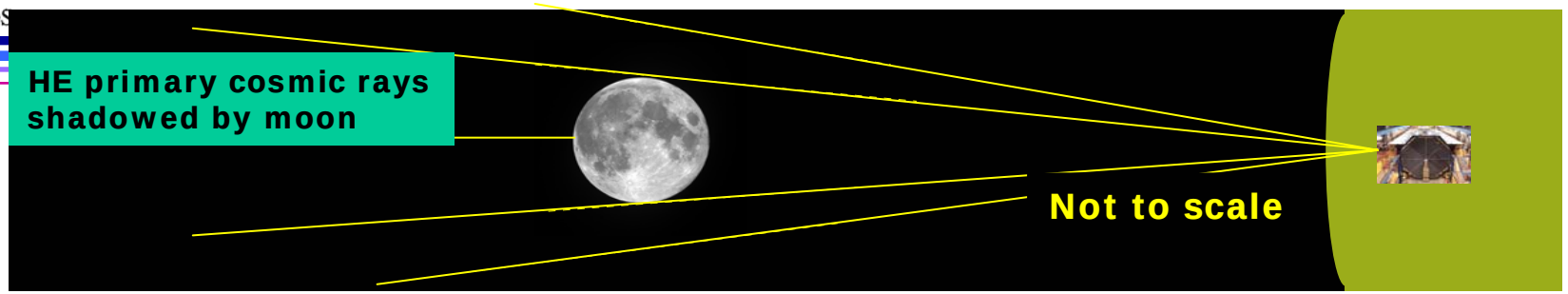
Upward going, stopping, through the coil-hole



Upward going muons - 1/β plot

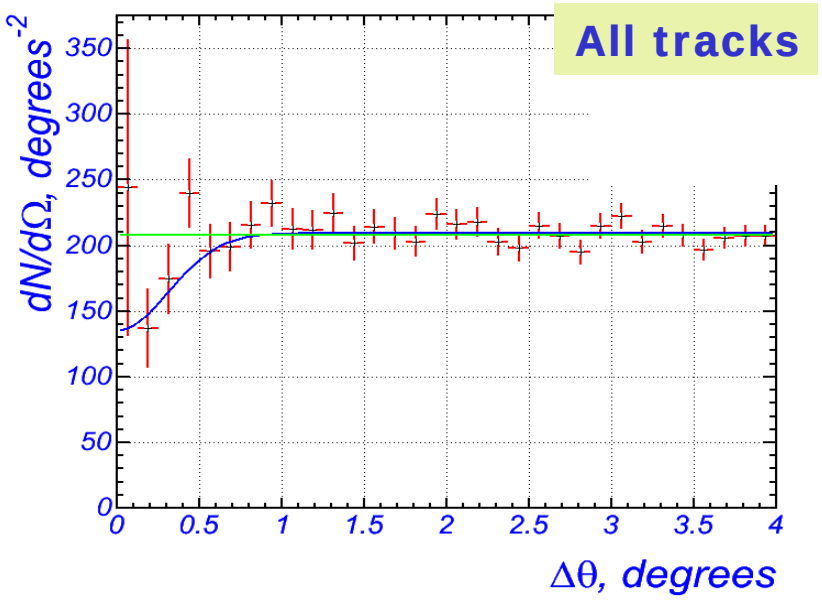


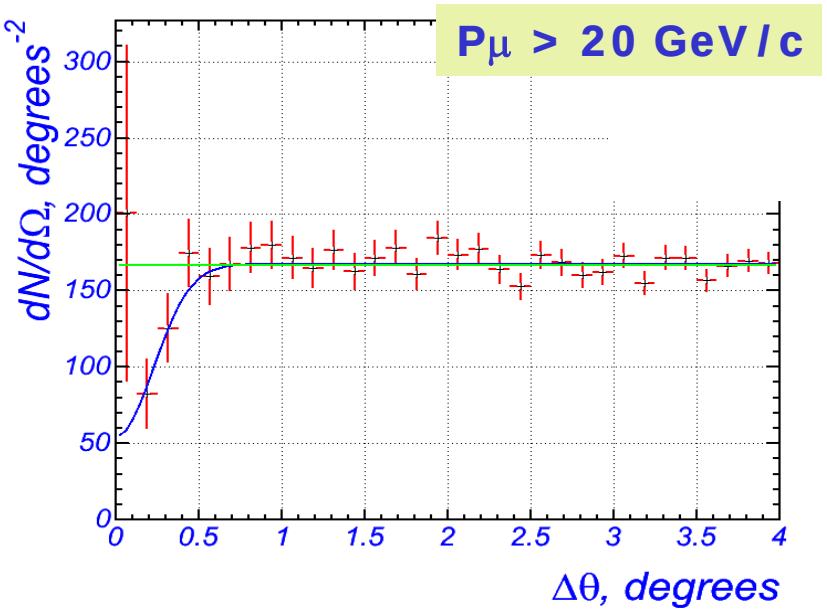
Seeing the moon underground



★ **Have recorded 10 M cosmic muons**
observed shadow of moon

★ **Angular res. improved by selecting high momenta muons**





MINOS Near Detector Architecture

In cavern 90 m below ground

Cavern is 46 m long, 10 m high

Access is by 6.5 m diameter shaft

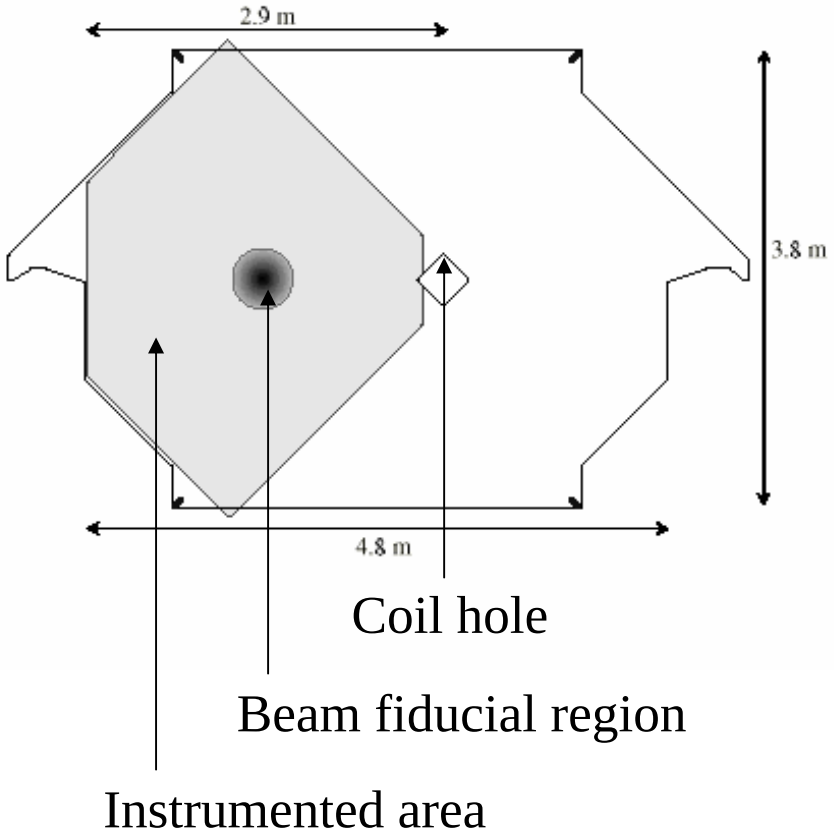
280 single steel plates, shorter modules

Calorimeter (1st 3/7 - logically Veto, Target, Hadron Absorber) is partially instrumented except for 1/5 of planes with full coverage

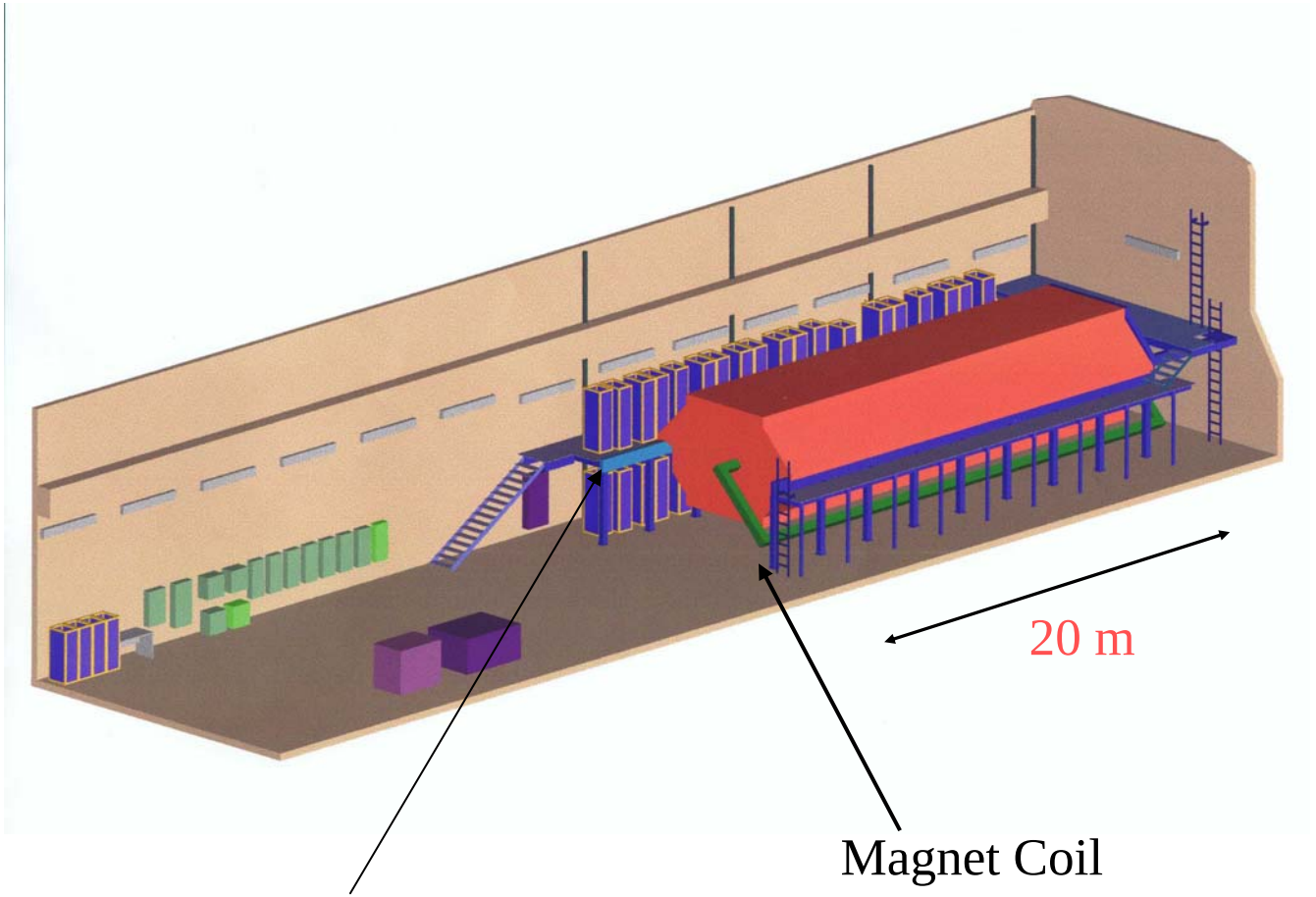
Muon Spectrometer section has only every 5th plane instrumented

Magnet coil provides <B> ~ 1.3 T

980 tons



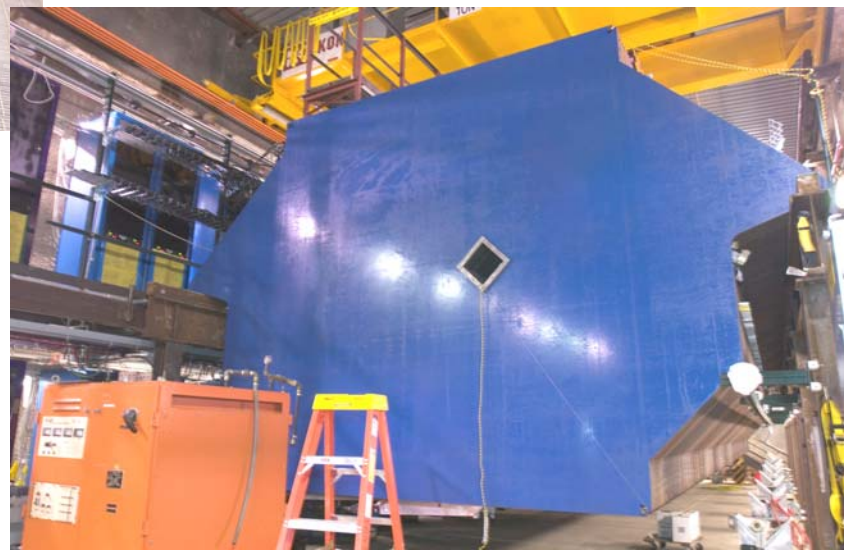
Layout View of MINOS Near Detector



Near Detector Assembly

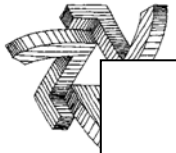
Completed planes delivered underground 3-5 each day

Readout commissioned immediately.



Completed Near Detector Planes

NUMI



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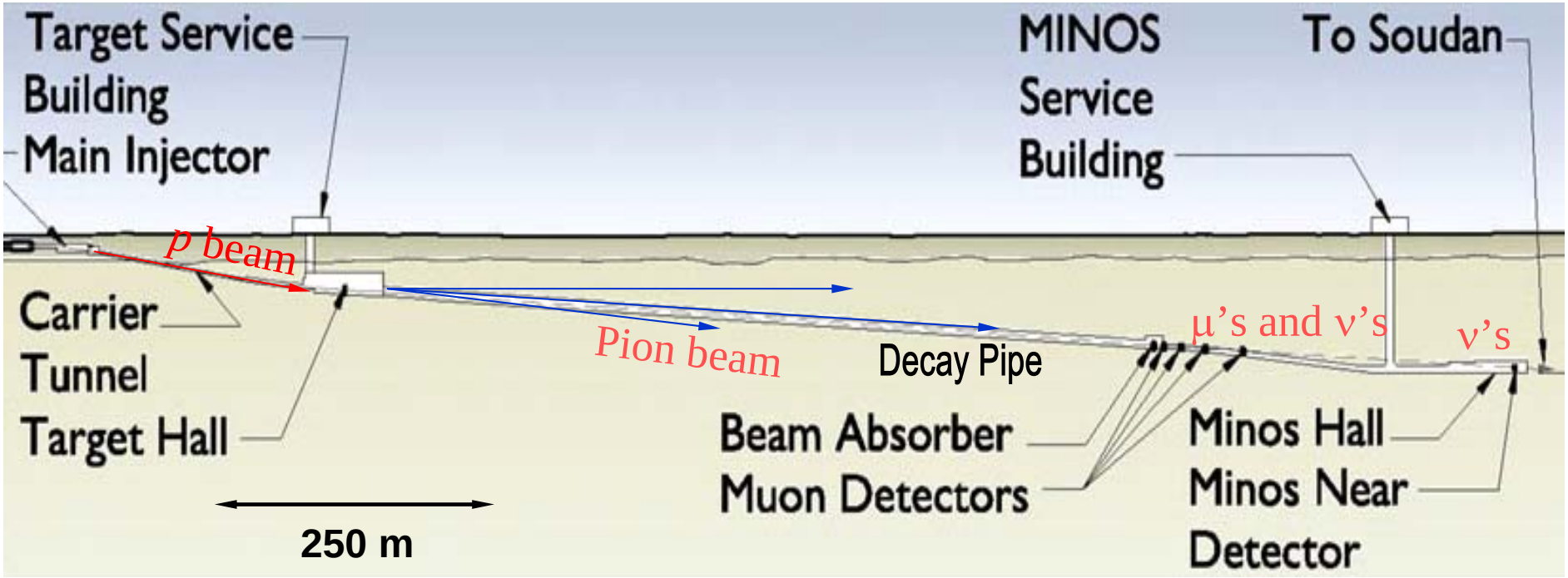
Near Detector Cosmics

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

NumI/MINOS Tunnel and Beamline

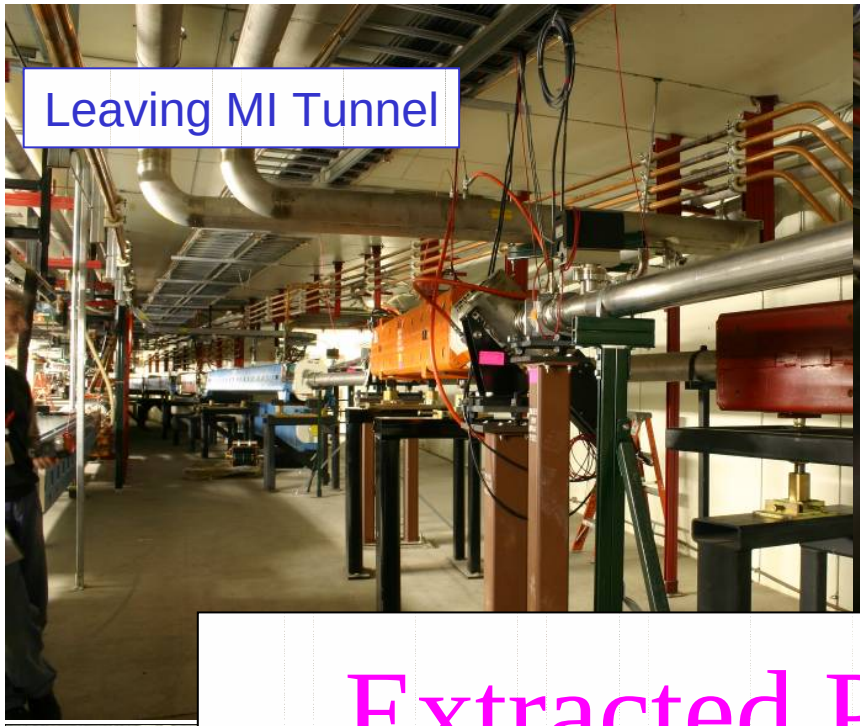


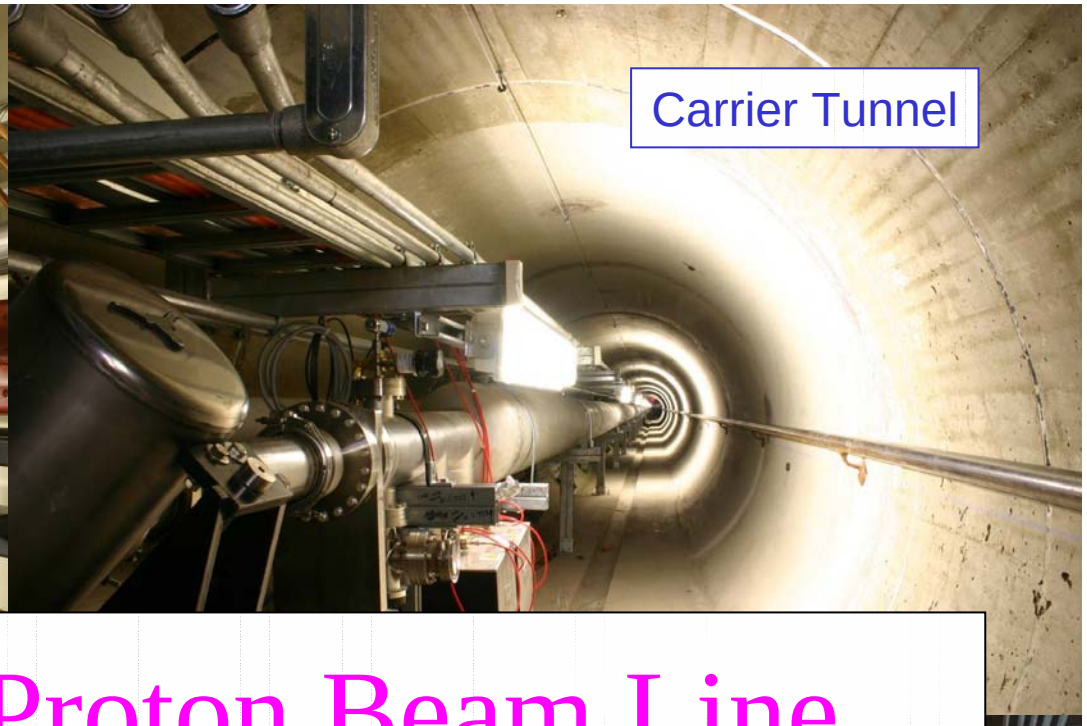
NuMI Beam Commissioning

- December 3 - 4, 2004
  - beam transported to target hall & onto hadron absorber
    - target out -- so no neutrinos; goal is beam line commissioning
    - 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 !!)

- February 18 - , 2005
  - Nominal intensity running (5 Booster batches, ~1.2e13 ppp and more??)





Extracted Proton Beam Line

Primary Beamline Instrumentation

Thin-foil SEM's developed at U. Texas

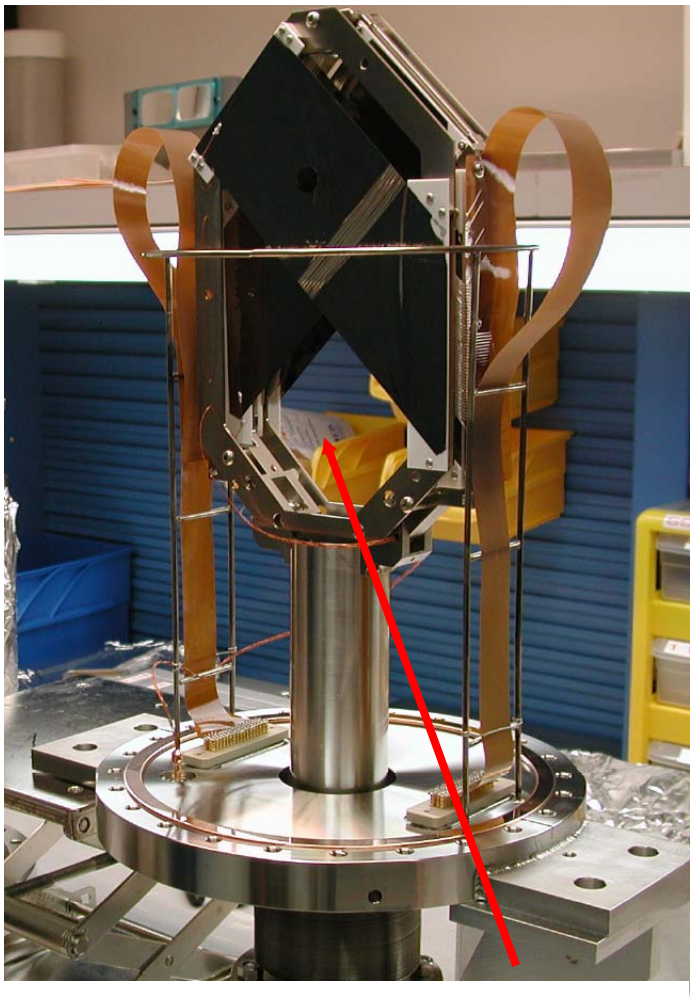
5 micron Titanium foils

Pitch 1 mm (8 units) or 0.5 mm (2 units)

2 Beam Toroids,
24 Beam Position Monitors

54 Loss monitors to ensure clean beam conditions.

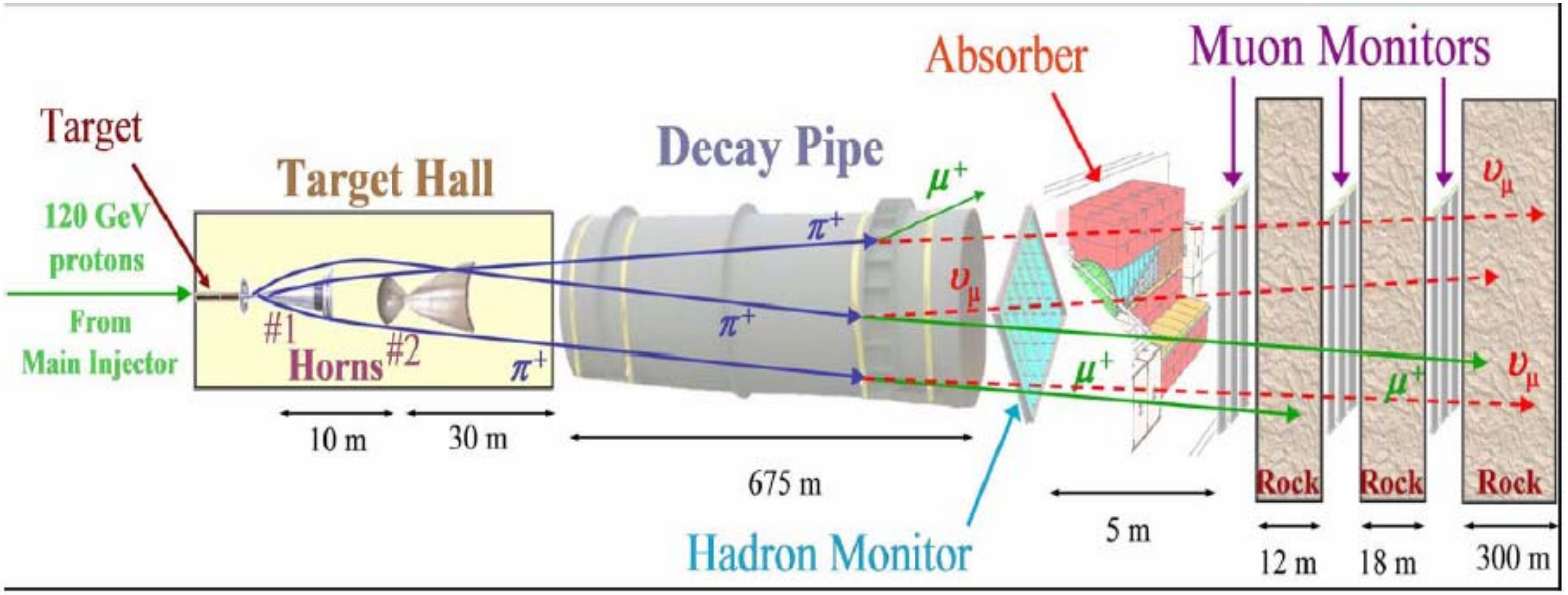
Our goal is $<10^{-5}$ lost beam fraction.



Beam hole for "detector out" position

Photo S. Kopp

Beamline and Focusing Layout

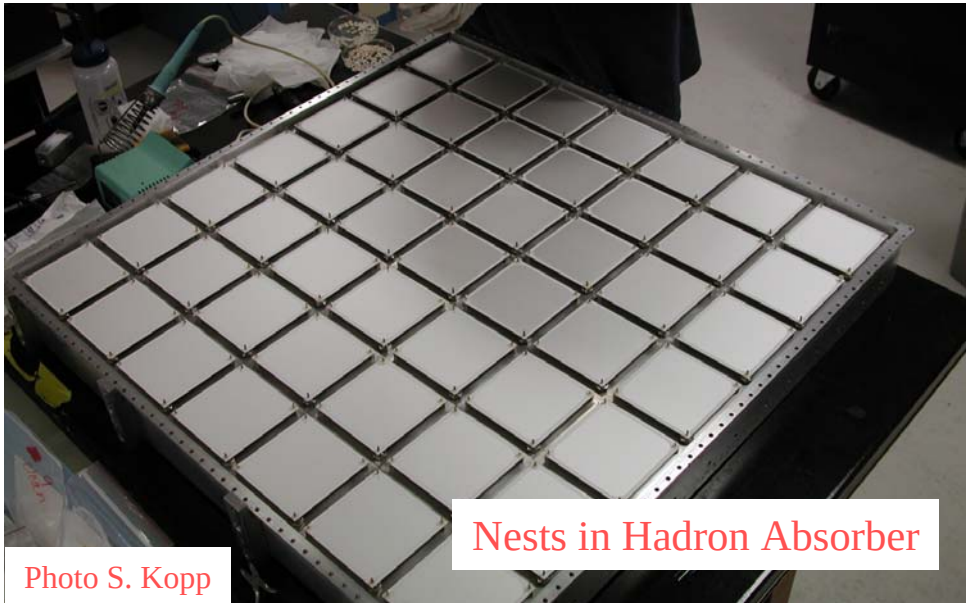


120 GeV primary Main Injector beam

2-horn beam adjusts for variable energy ranges

675 meter decay pipe for π decay

Secondary Hadron and Muon Instrumentation



Hadron Monitor under construction (U. Texas)

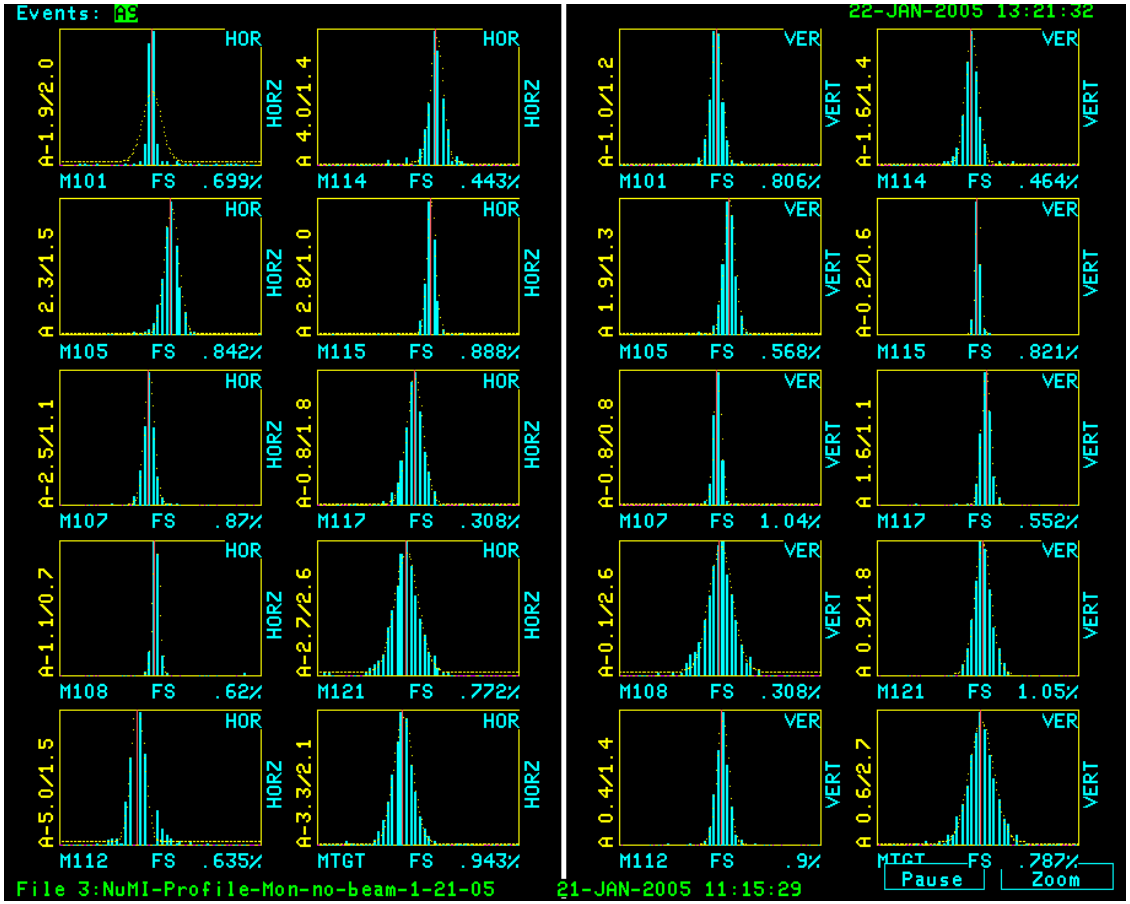
Plated ceramic pads prop. chambers (He).

Hadron monitor 1mm, Muon monitor 3mm gap.

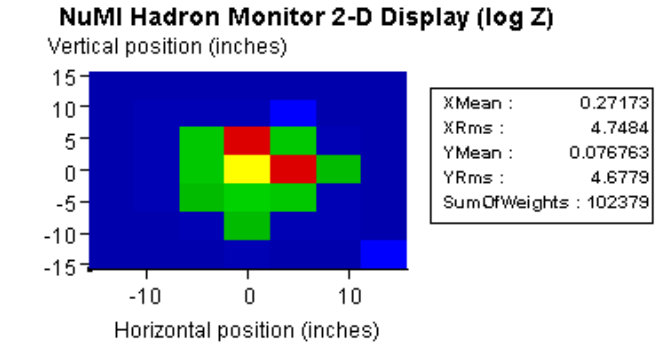
A muon monitor station

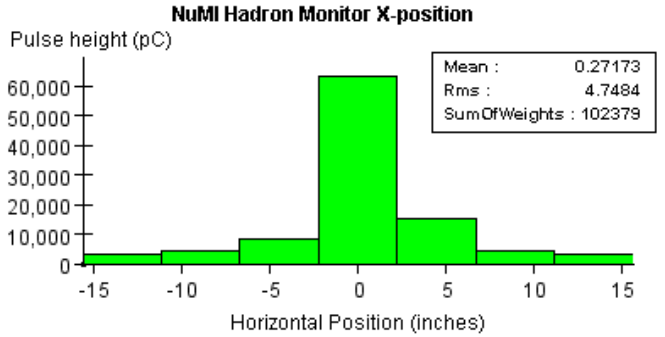
Beam Extraction - After 12 Pulses

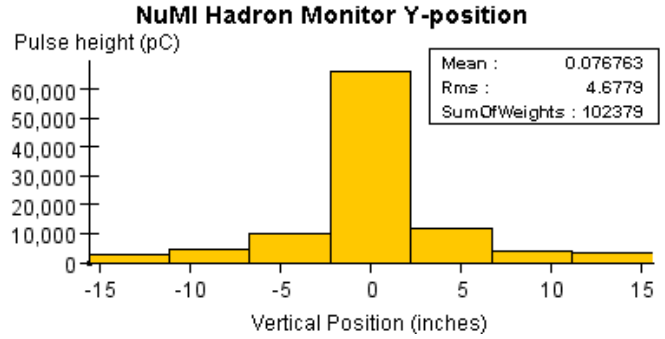
December 3-4, 2004



Profile monitor output along the beamline (few pulses later)
(from the extraction up to the target - ~ 400 m distance)







Conclusions from first run

- Extraction from Main Injector OK
- Beamline instrumentation works well
- All magnets in right polarity
- Hadron and muon monitors work well
- Beam points in the right direction to <.01mr
- All goals accomplished in 1 day

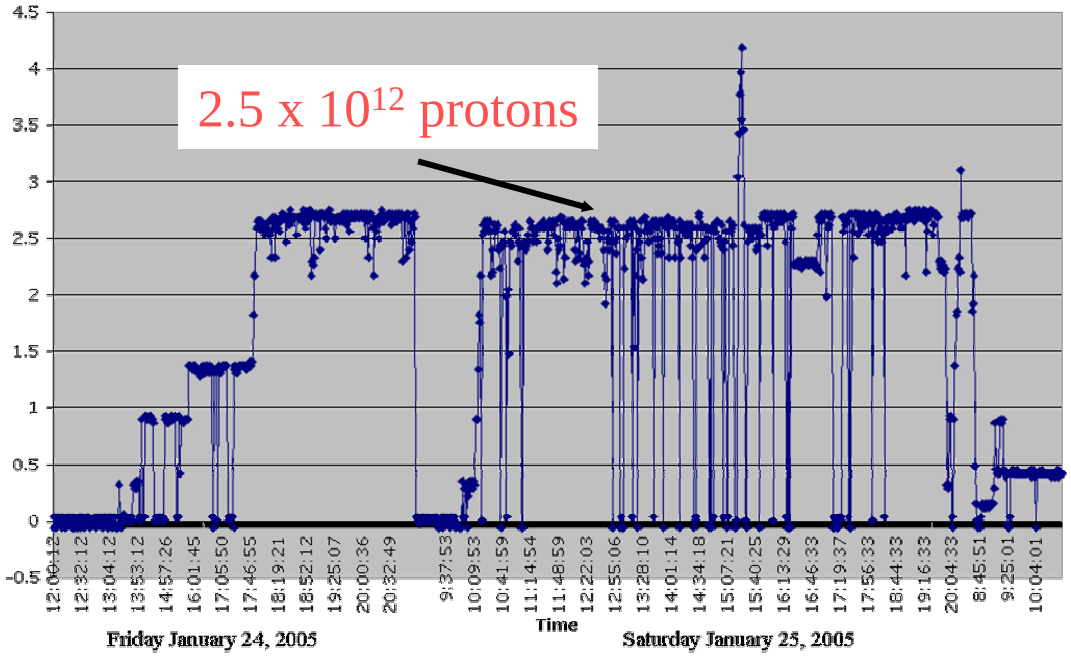
First NuMI/MINOS Commissioning Running (with target)

January 21-23, 2005

About 1 hour to establish beam

Pulses once per minute

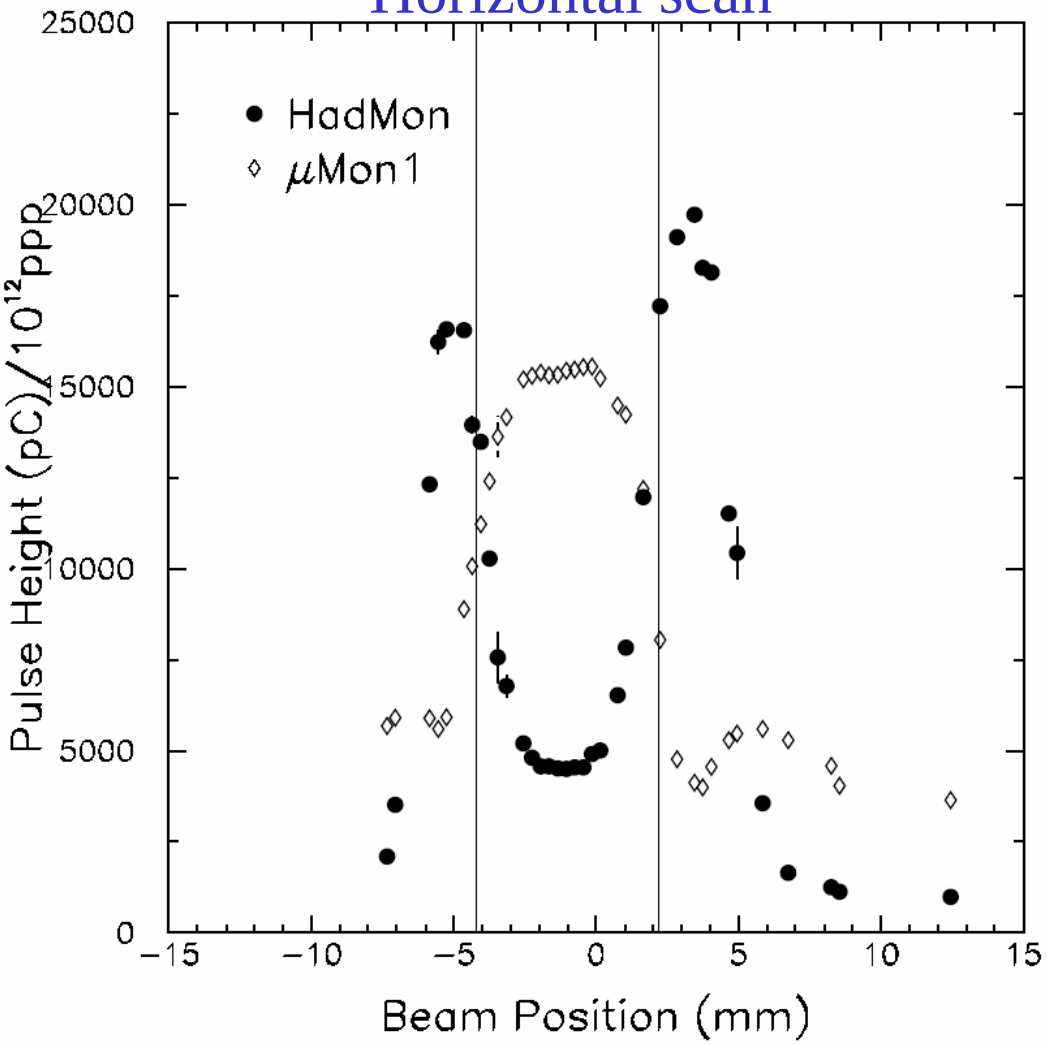
Instantaneous rate comparable to planned initial operating conditions (but only one batch instead of 5)



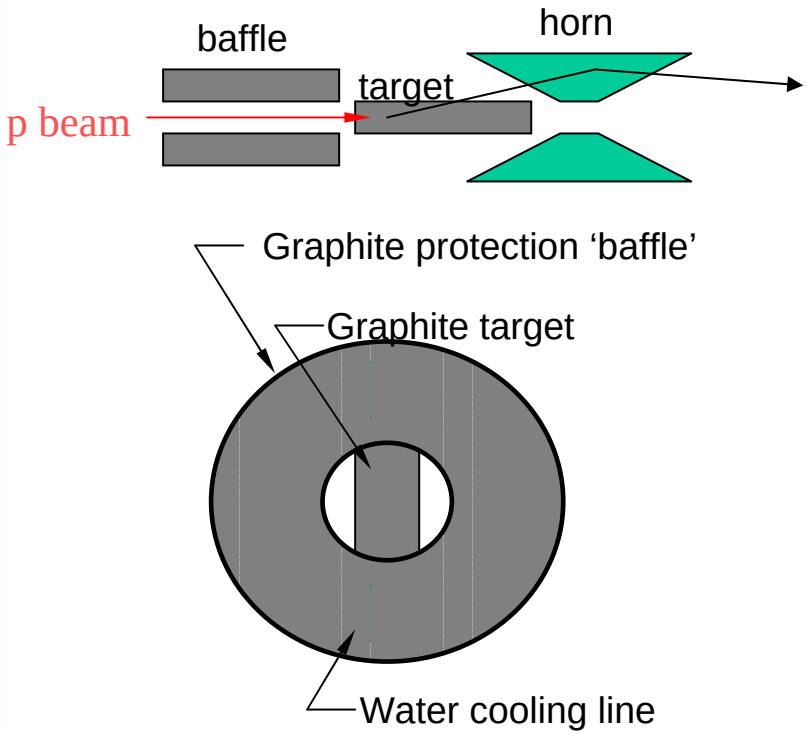
Approx. 2 x 10^{15} POT, of which 50% was usable for detector commissioning

Beam Scans - with Target Hadron and Muon Monitors

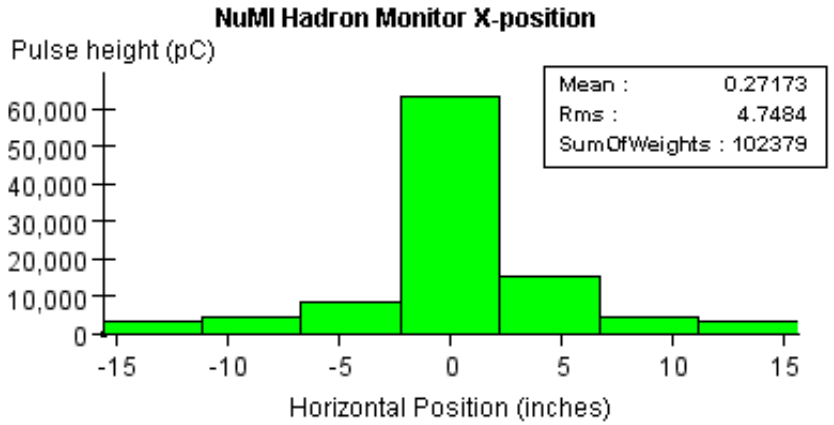
Horizontal scan



Baffle, target, horn geometry

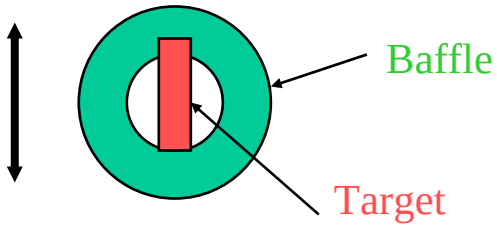


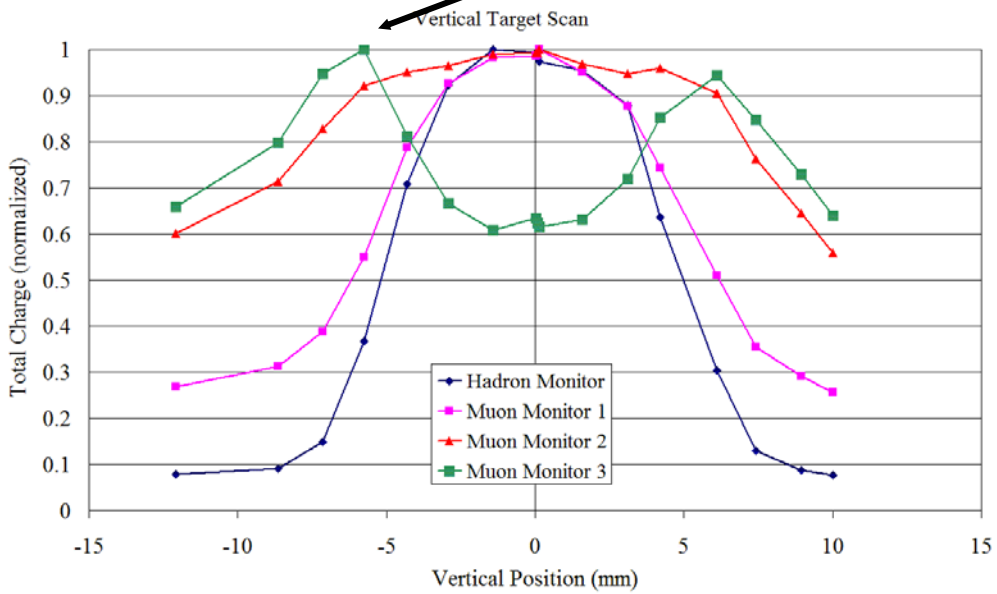
Hadron and Muon Monitor Performance - Vertical Scan



Beam scans with target
Hadron and muon monitors

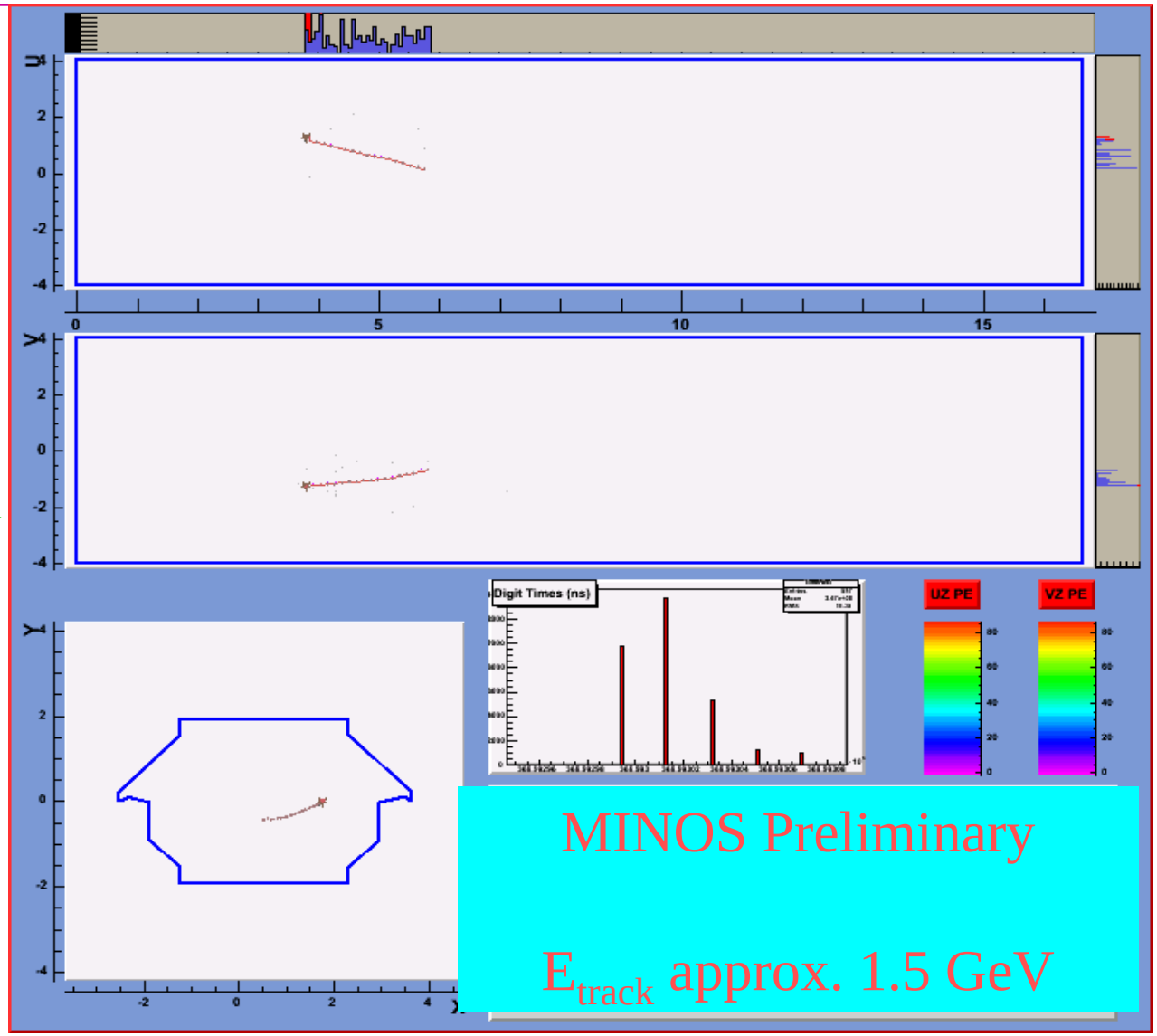
Increased focusing energy due to beam hitting upstream baffle.





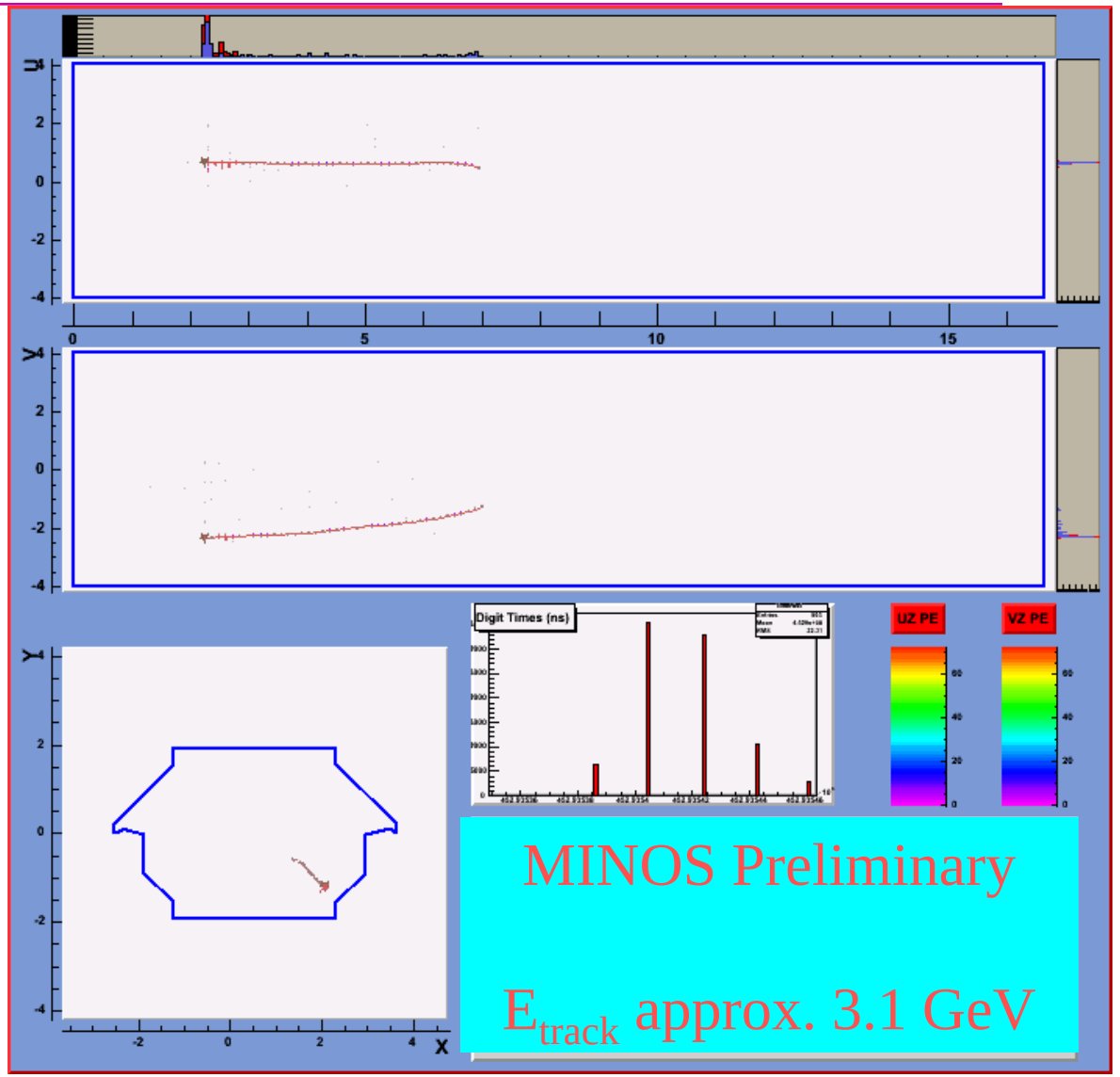
Near Detector Event

Low-energy track from fiducial region



Additional Near Detector Events

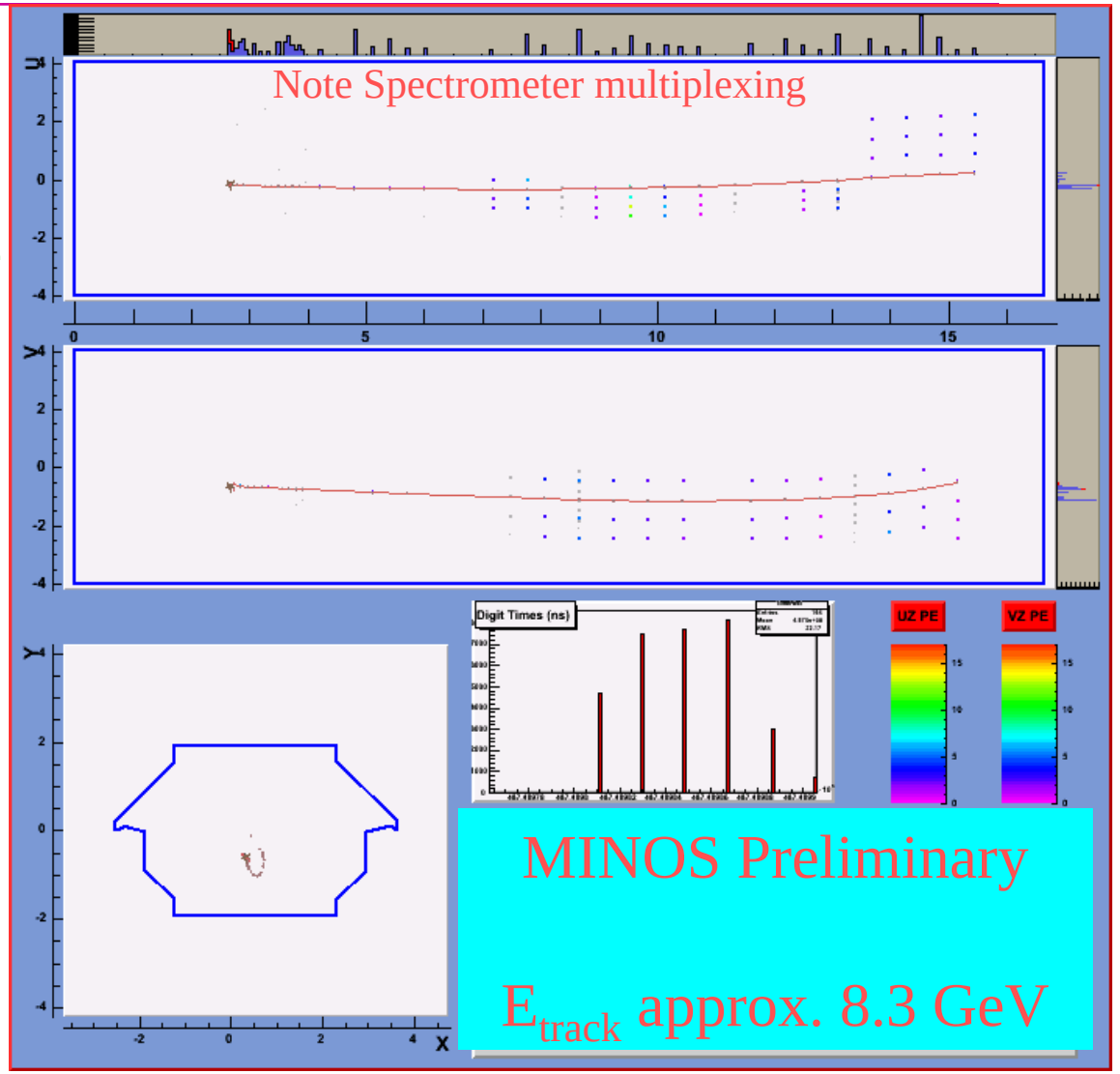
Medium energy track from near peak in "pseudo-medium" beam



Additional Near Detector Events

High-energy track, possible partial containment

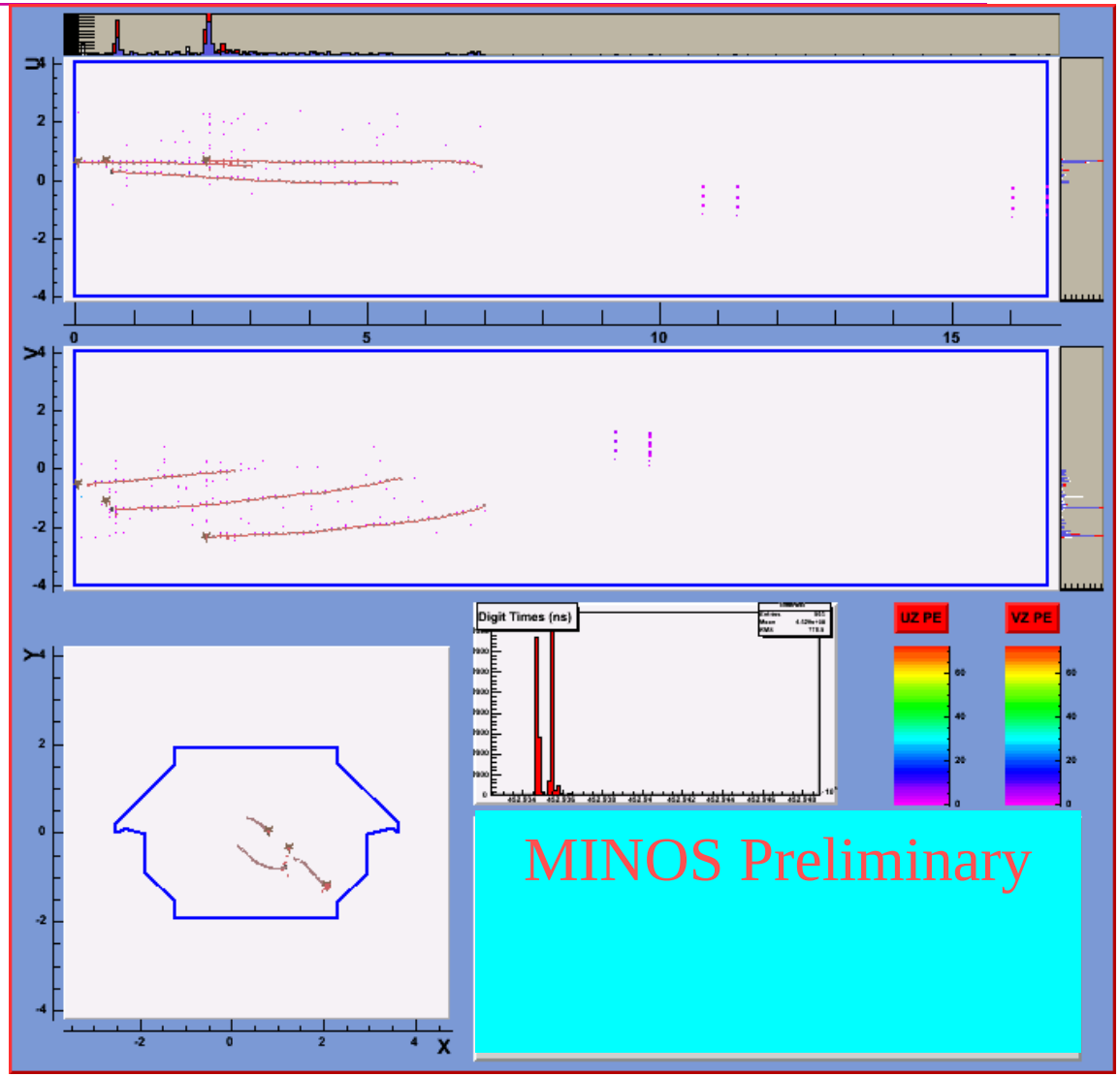
Bending in residual steel magnetic field, although current not on.



Additional Near Detector Events

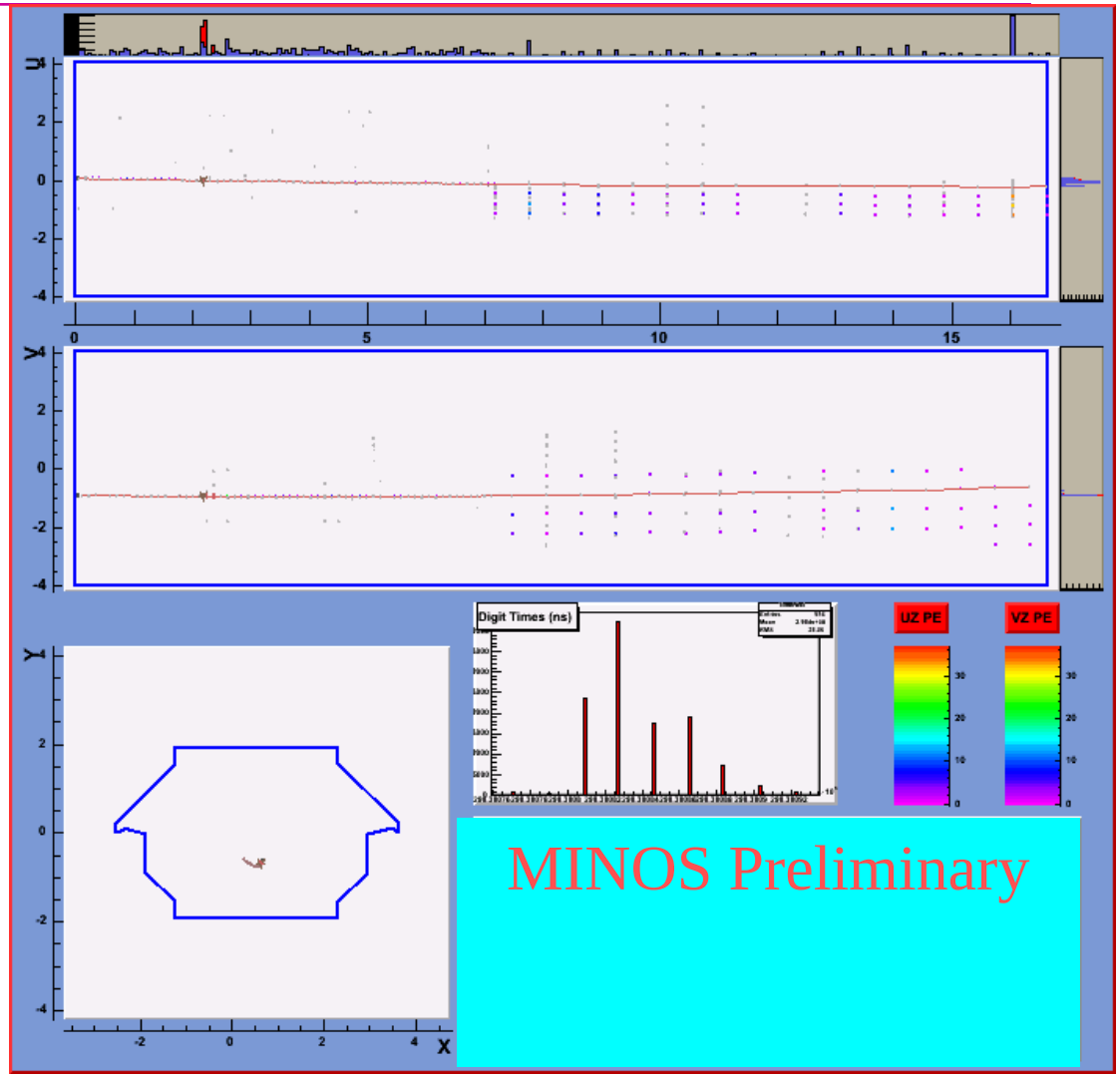
One “snarl” (beam pulse) in near detector, showing multiple events.

Detector read out in 19 ns buckets, allowing event separation.

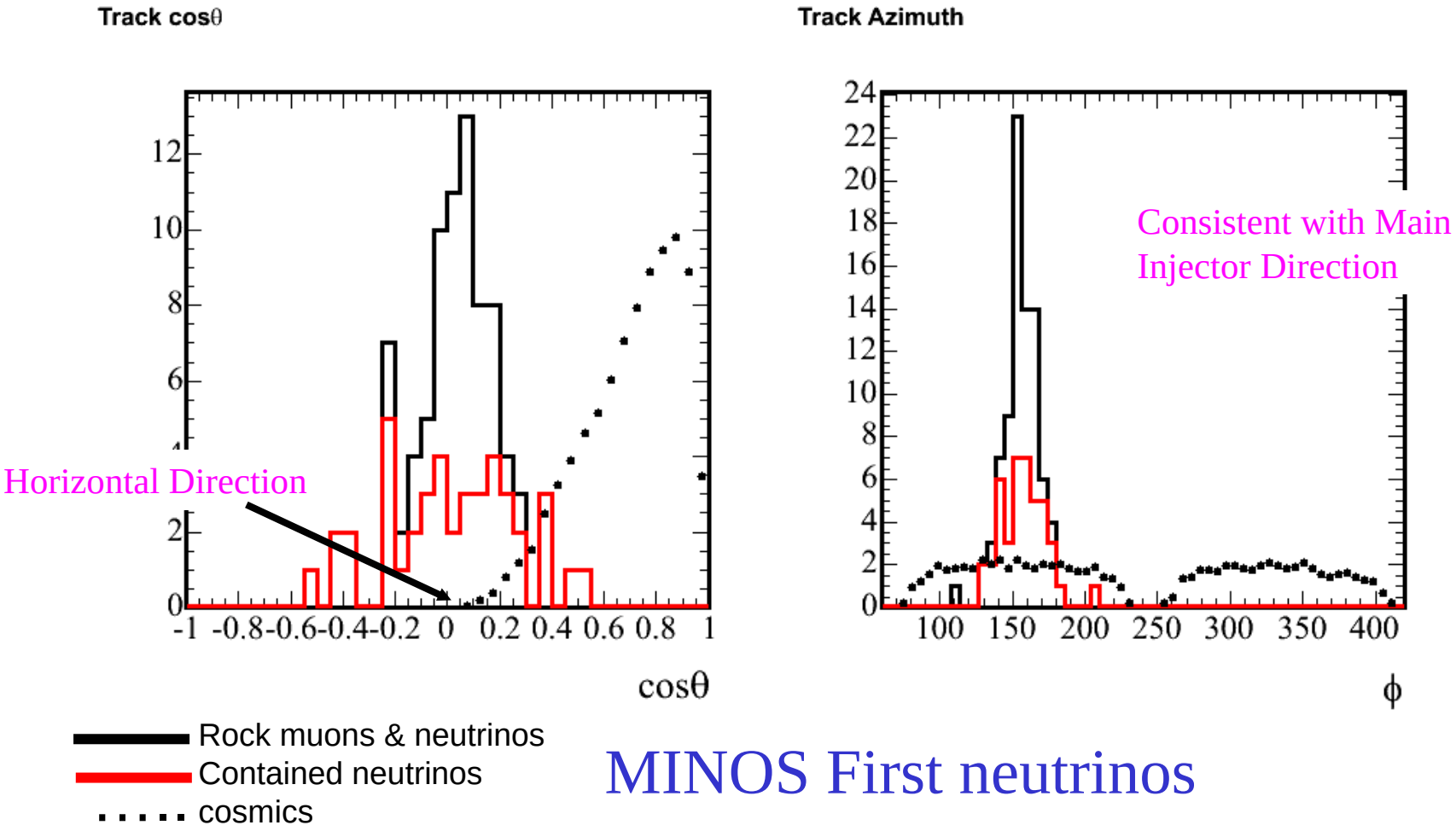


Muons from Rock Interactions

Probable through-going muon generated in rock.



Neutrino Event Angular Distributions



MINOS First neutrinos

Conclusions from 2nd run

- No serious misalignments of baffle, target, horns
- Hadron and muon monitors perform as expected
- Neutrino events in Near Detector cleanly identified; no background
- Multiple events (in one spill) easily identified and separated (at 50% intensity in pseudo-medium energy beam)
- Ready for next stage (full intensity, more statistics)

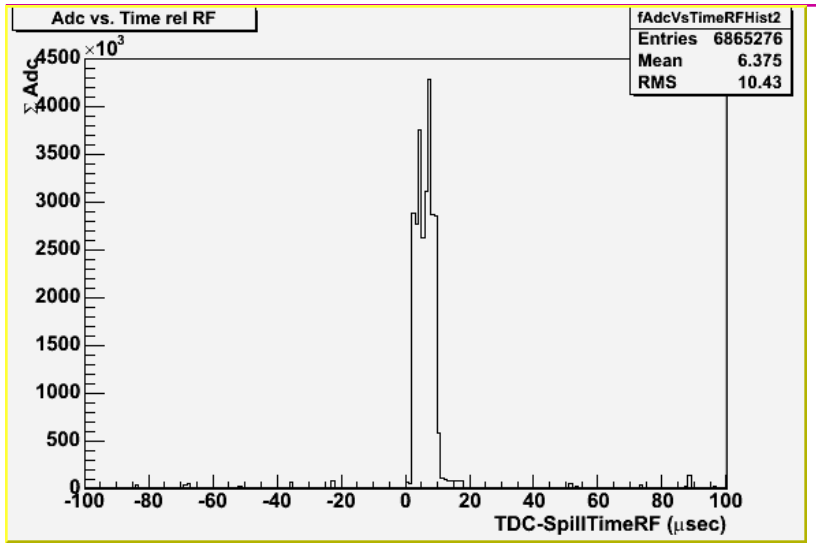
The Latest Happenings (as we speak)

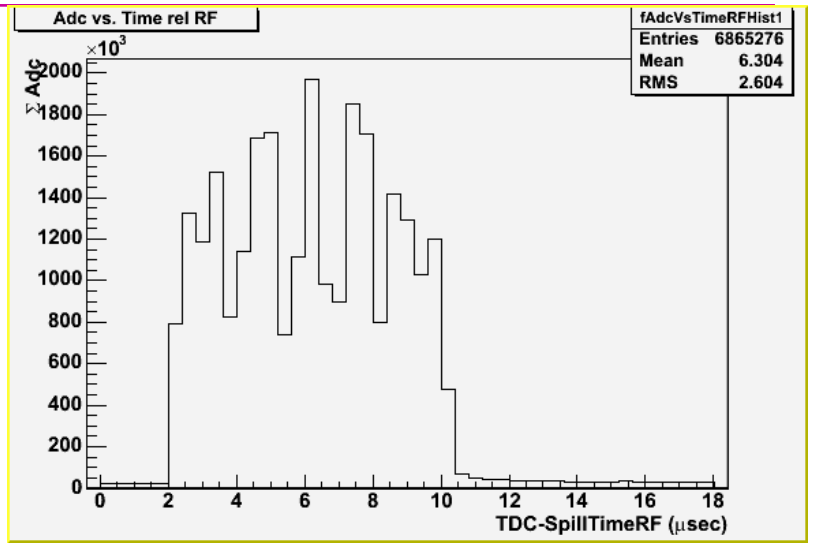
5 batches injected and accelerated

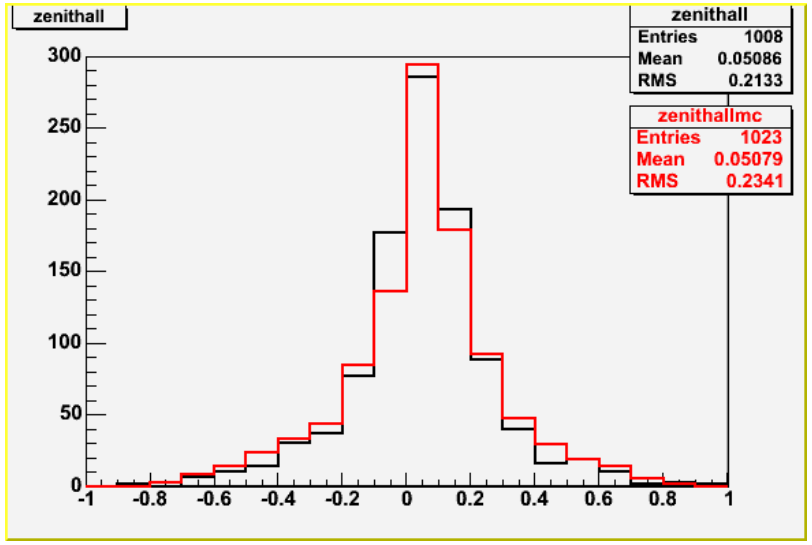
Trying to reach nominal beam intensity (2.5×10^{13})

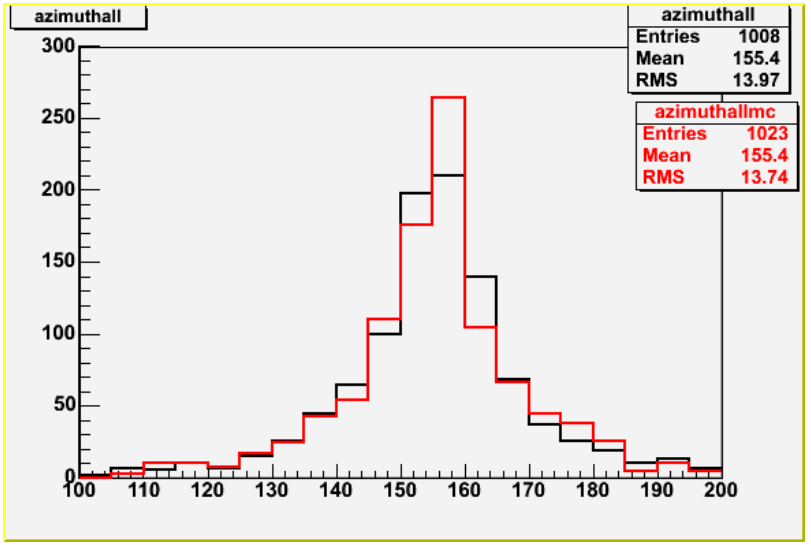
1.9×10^{13} achieved in one pulse Sunday morning

Sunday Run - yes, these are neutrinos



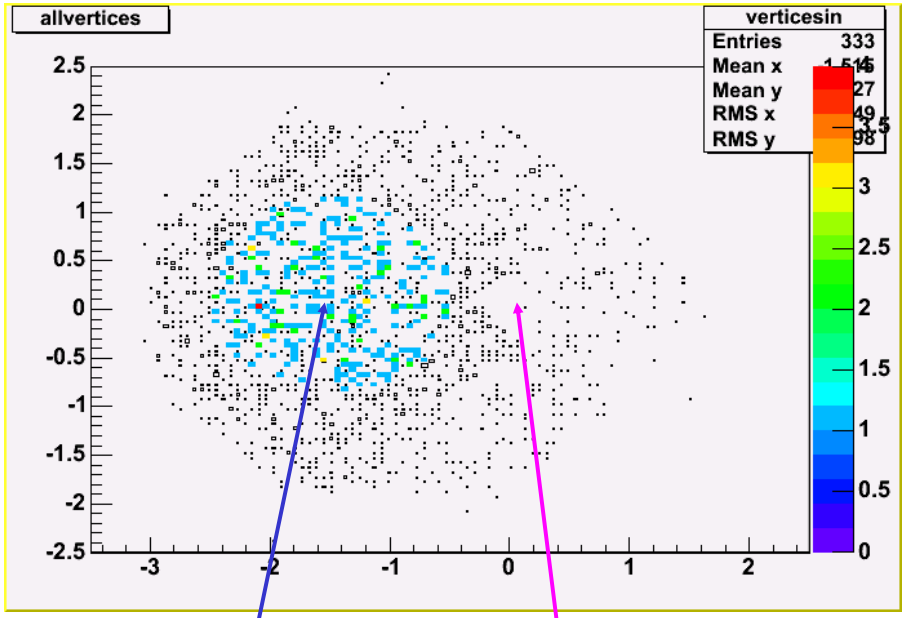




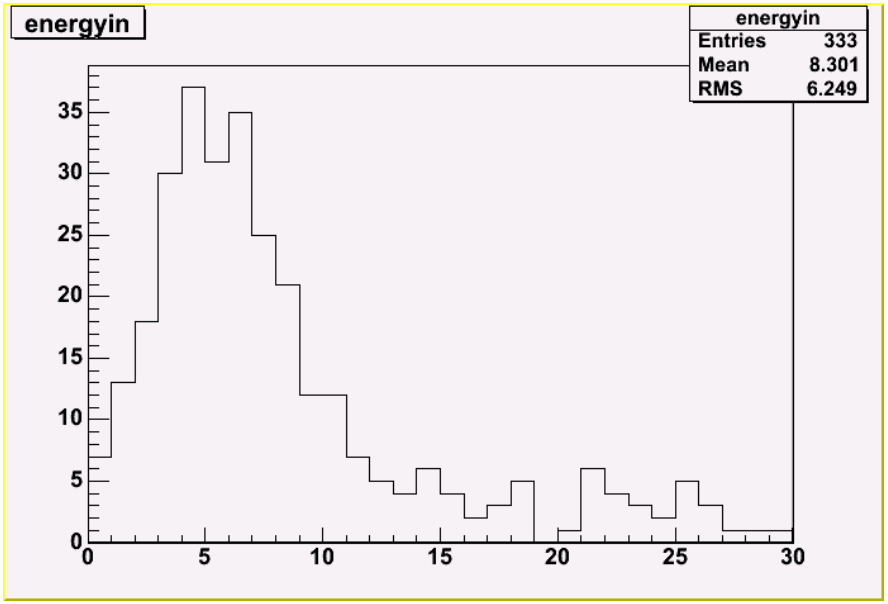


More neutrino distributions

x-y distribution of vertices



Fiducial region Coil hole



neutrino "energy" distribution
(for contained events only)
Caveat: No B field, residual field only

Roughly 1 day's data at 1 pulse/minute (rather than 1/2 sec) at ~1.3 x 10^{12} ppp

Conclusions

- NuMI/MINOS construction project successfully concluded
- Far and near detectors working extremely well
- Initial beamline commissioning proceeding rapidly and better than expected
- Expect beam-generated neutrino interactions in Far Detector very soon (~10^{17} pot/nteraction)
- Almost ready to start transitioning to data taking
- All that has been made possible by the dedicated, intense and ingenious work of **my MINOS collaborators** (young and old). It has been a real pleasure working with them.