The NuMI/MINOS Experimental Program

Status and Ongoing Prospects

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Presentation to HEPAP
12 October 2006

Neutrino physics with ν_μ beams

Studies of oscillations of $\nu_\mu \rightarrow \nu_\tau$ at atmospheric scale

$$P_{\nu_\mu \rightarrow \nu_\tau} = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2(\Delta_{13})$$

Search for and utilize $\nu_\mu \rightarrow \nu_e$ at atmospheric scale

$$\Delta_{13} = 1.27 \Delta m^2_{13} L / E_\nu$$

$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\Delta^2_{13}}{(\Delta_{13} \mp aL)^2} \sin^2(\Delta_{13} \mp aL)$$

MINOS Long-Baseline Experiment

Study the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis, by measuring precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$

Search for $\nu_\mu \rightarrow \nu_e$ oscillations

Constrain contributions of exotic phenomena

e.g Sterile ν or ν decay

Compare ν, $\bar{\nu}$ oscillations

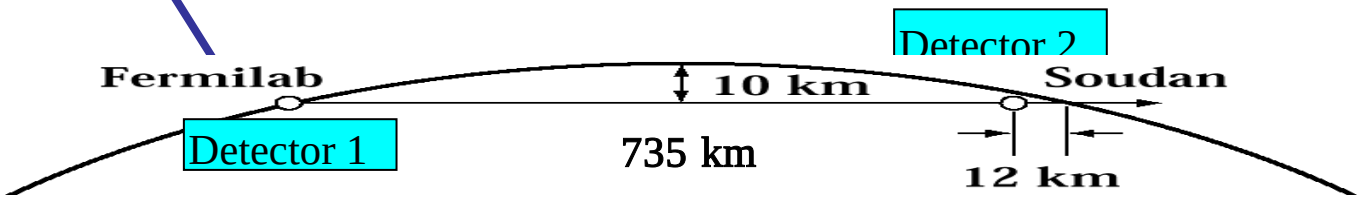
Test of CPT violation

Atmospheric neutrino oscillations

Phys. Rev. D73, 072002 (2006)

Far Detector: 5400 tons

Near Detector: 980 tons



NuMI Neutrino Beam

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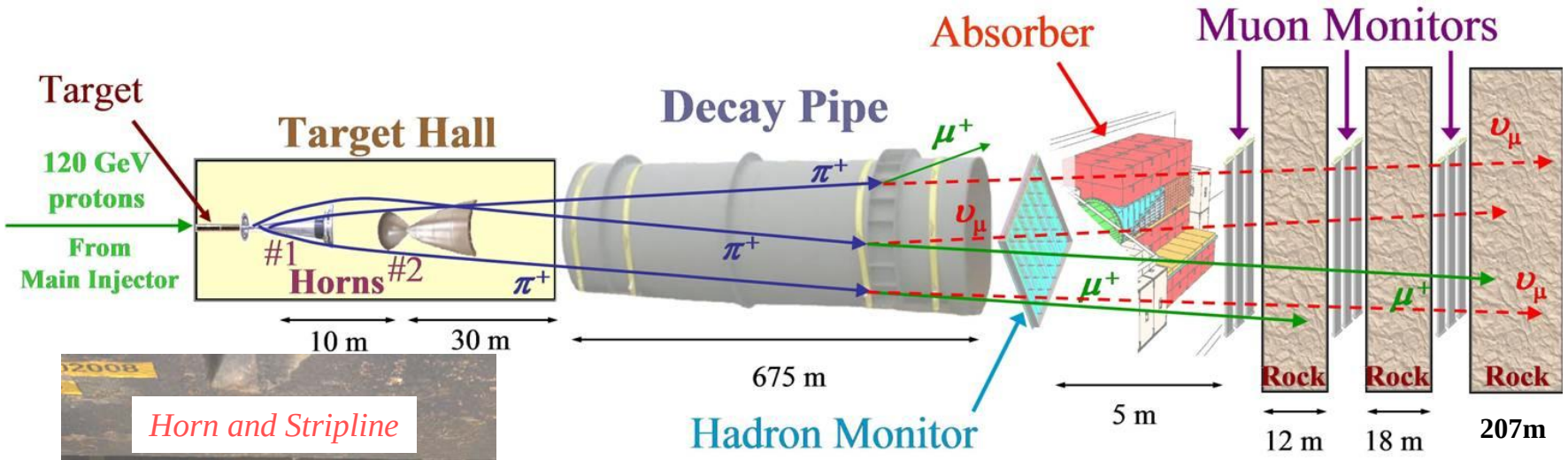

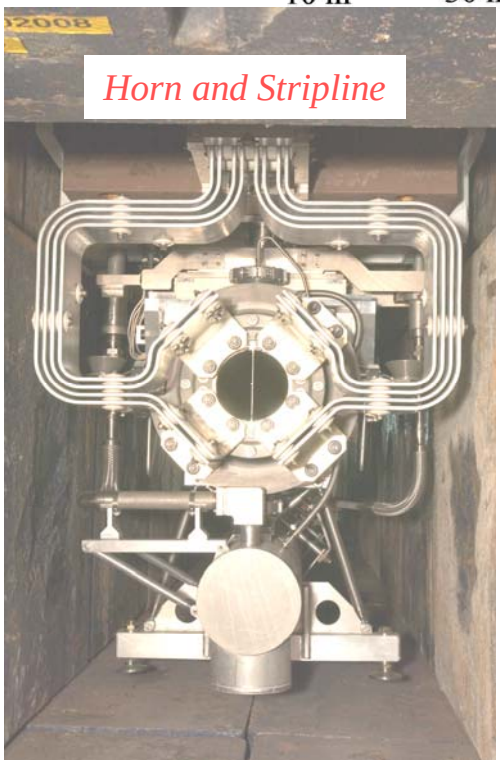

- **120 GeV protons strike the graphite target**
- **Nominal Intensity 2.4x10^{13} ppp with ~2 sec cycle time.**
- **Initial intensity ~2.5 x 10^{20} protons/year**
- **Ultimate intensity ~ 3.2 x 10^{20} protons/year (2008-9)**

Performance of NuMI

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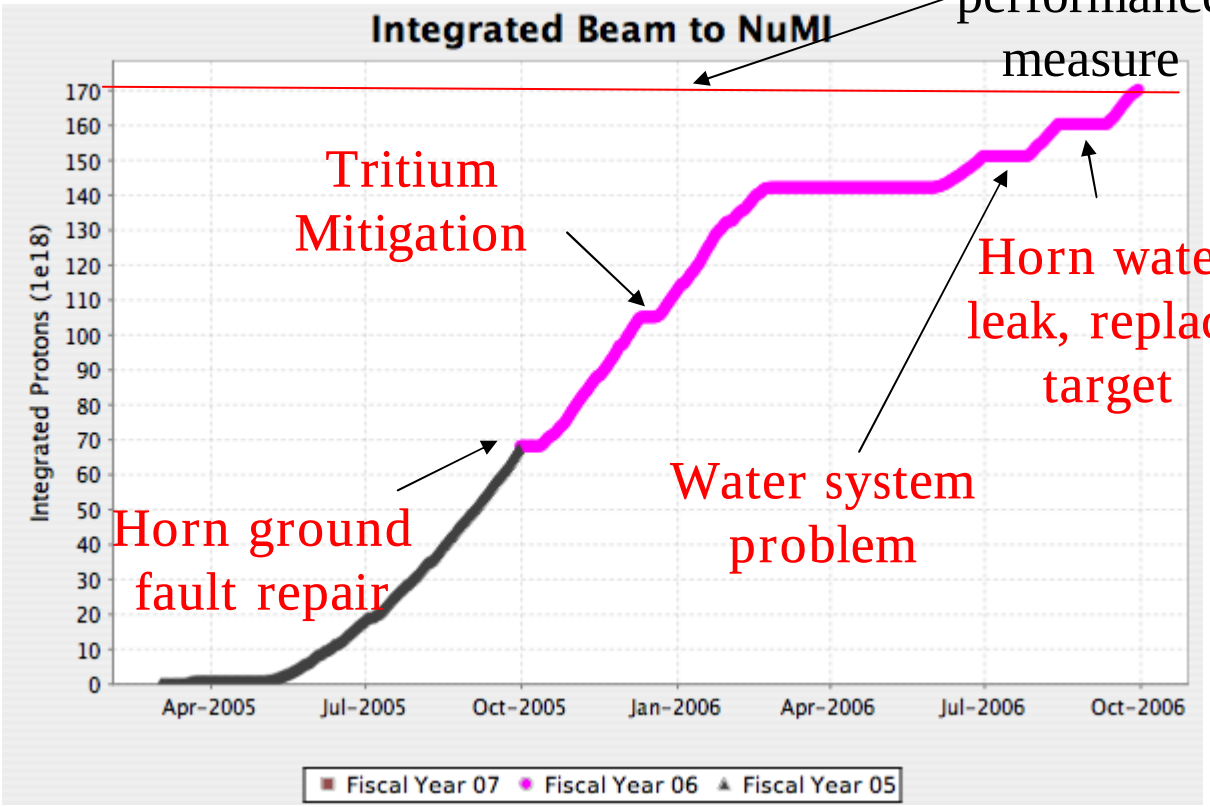
Excellent turn on and commissioning. FYO5 exceeded Fermilab expectations.

Beamline components have caused unscheduled downtime in FY06

Totals:

FY05 ~6.8 x 10^{20}

FY06 >1.0 x 10^{20}



Recent Performance of Main Injector for NuMI (10/2/06)

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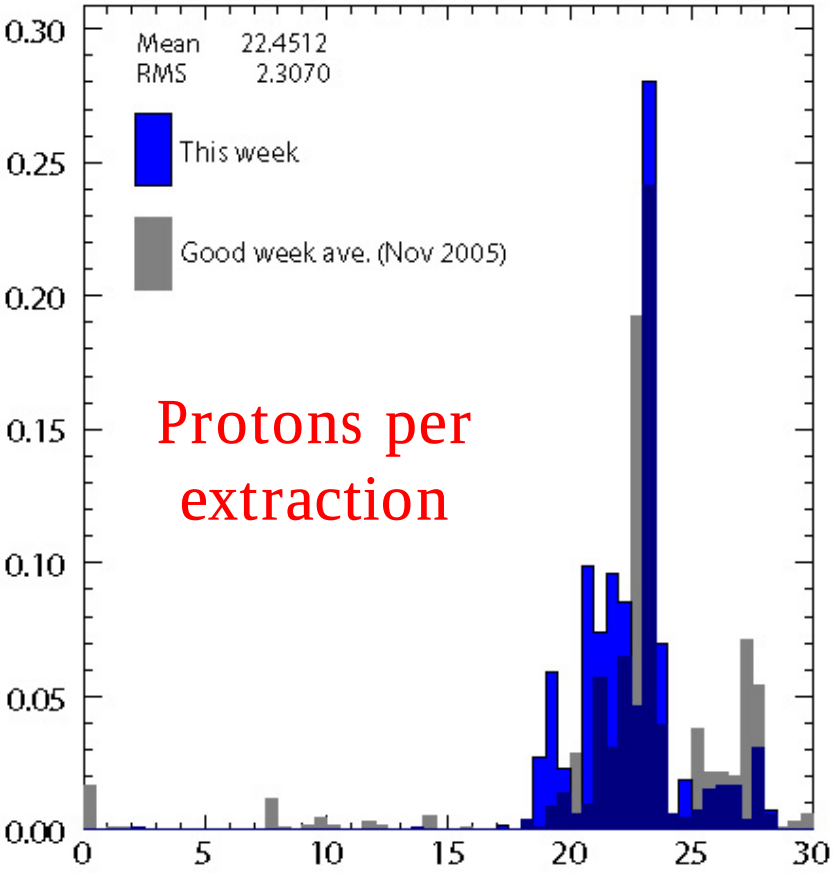

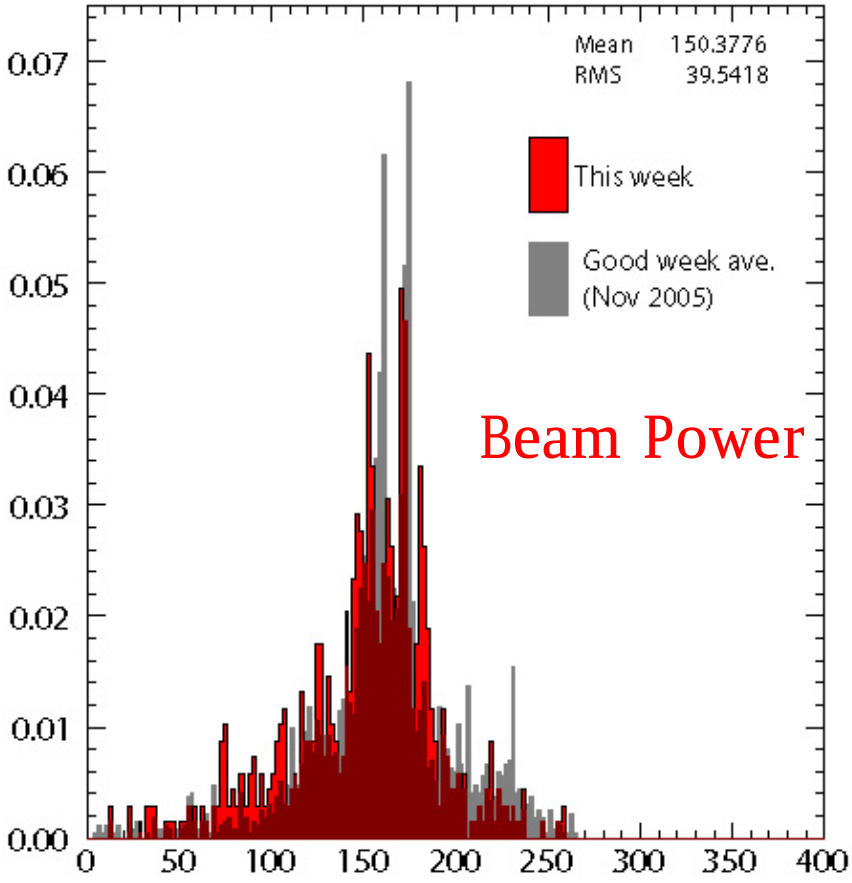

The MINOS Detectors

NEAR

0.98 Kton

MINOS Detector Hall, Fermilab

FAR

5.4 Kton

Soudan Underground Lab, Minnesota

Both detectors are tracking calorimeters composed of interleaved planes of steel and scintillator – uptimes routinely exceed 95-97%.

- 2.54 cm thick steel planes
- 4.1 cm wide scintillator strips
- 1.5 T toroidal magnetic field.
- Multi-Anode Hamamatsu PMTs (M16 Far & M64 Near)
- Near electronics optimized for high occupancy (~20) during 10 μs spill
- Energy resolution: 55%/√E for hadrons, 23%/√E for electrons
- Muon momentum resolution ~ 6 % from range (~ 12 % from curvature)

Large event rate in near detector

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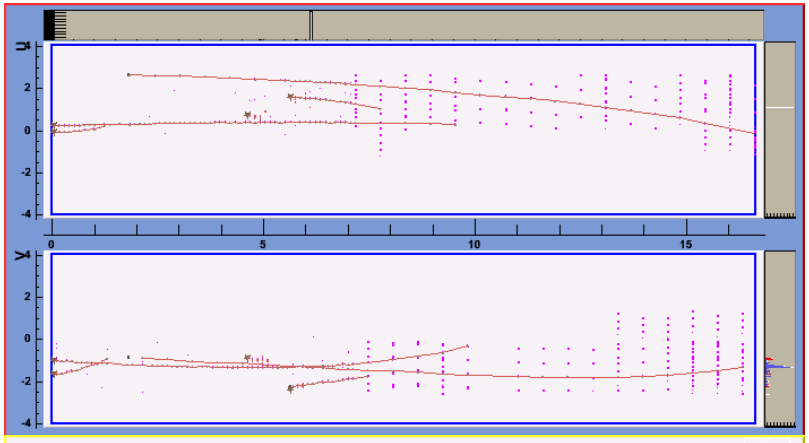
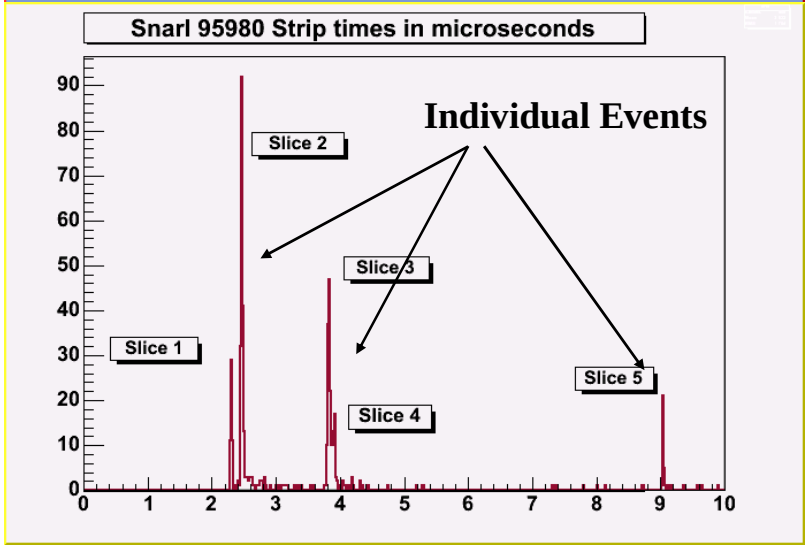
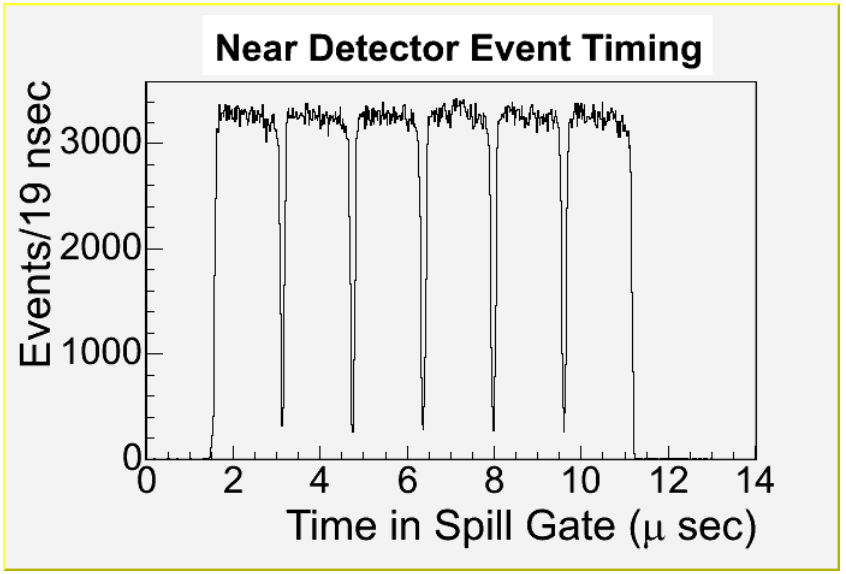
A spill (10 μs) in near detector







Beam arrives in 10 μs batches

Multiple events separated by timing, topology.

Relative timing greatly simplifies event identification at far detector

Near Detector Distributions

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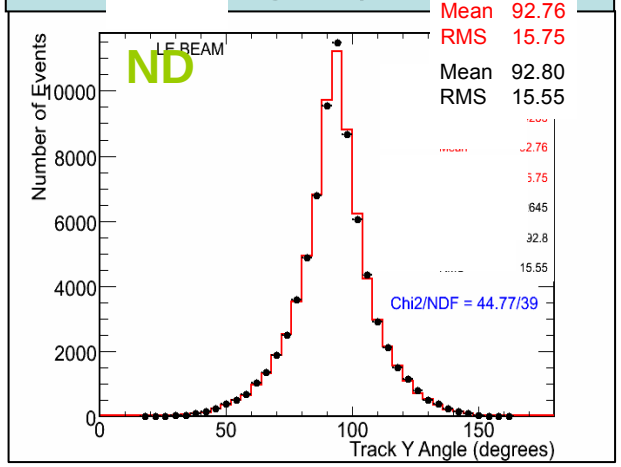
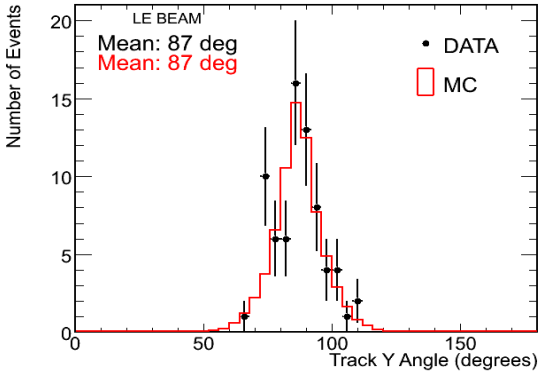
- Acceptance well reproduced by simulation
- Track angle w.r.t. vertical exhibits characteristic -3° to Soudan

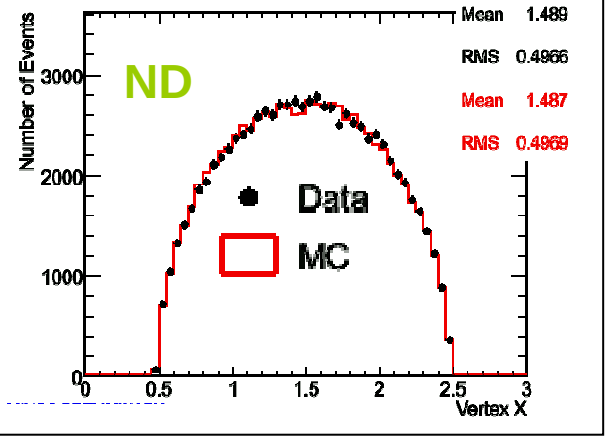
Track Angle (wrt vert.)



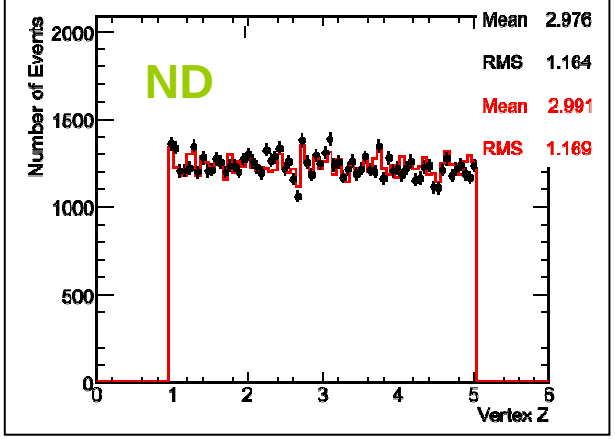
Sneak Preview – Far Detector CC events going upward



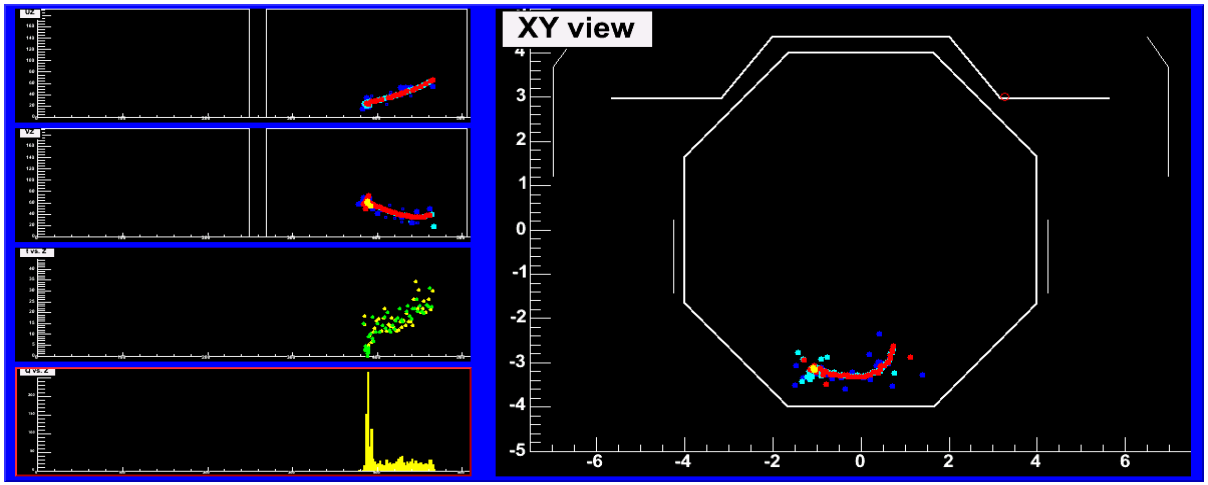
X Vertex



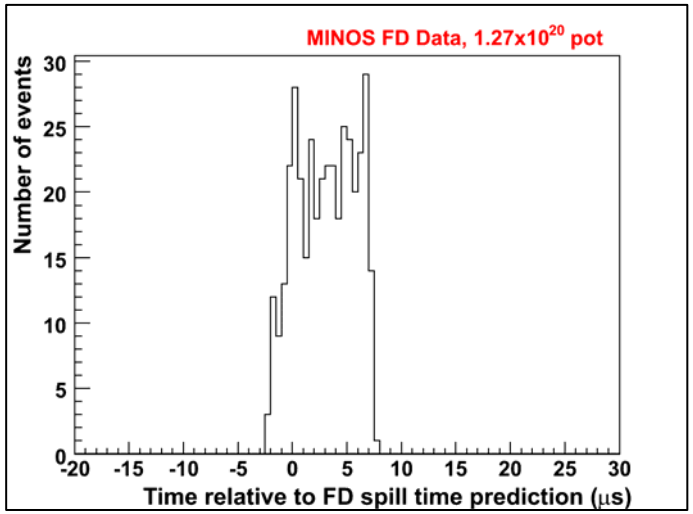
Z Vertex



Minos Far Detector Events



Contained CC event
Expected rate ~3/day



Far Detector triggers on spill time (50 μs window), also activity triggers

Further require fiducial, angle cuts

Estimate ~9% NC background, <1 cosmic event

Selection of FD events and prediction of Spectrum

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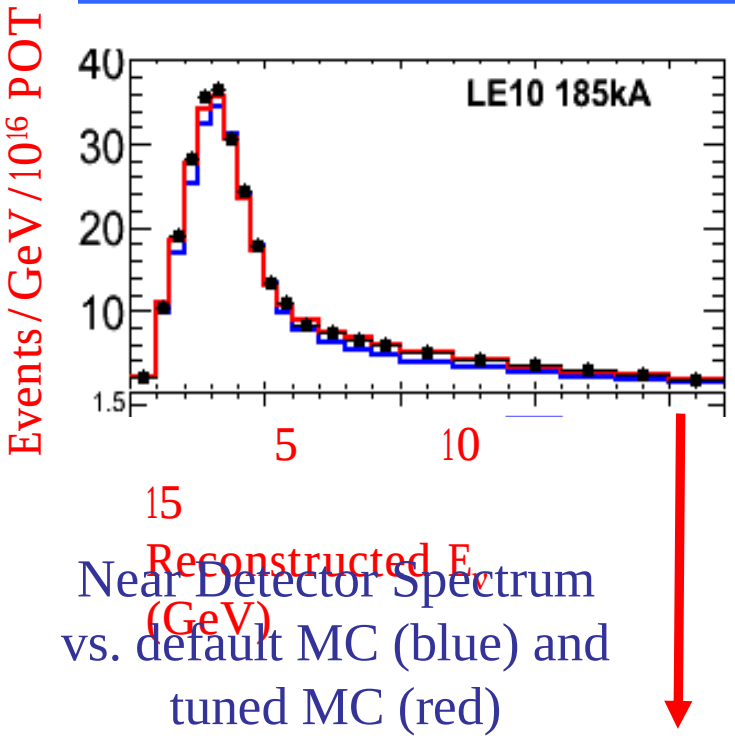
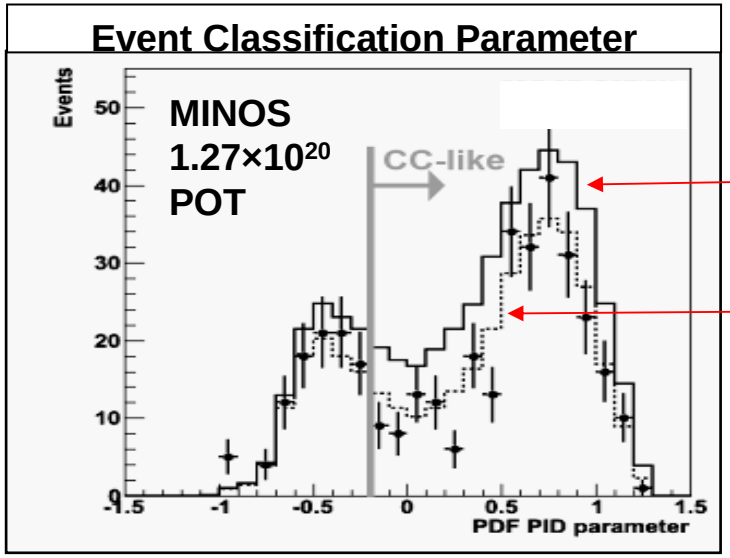


Near Detector Spectrum vs. default MC (blue) and tuned MC (red)



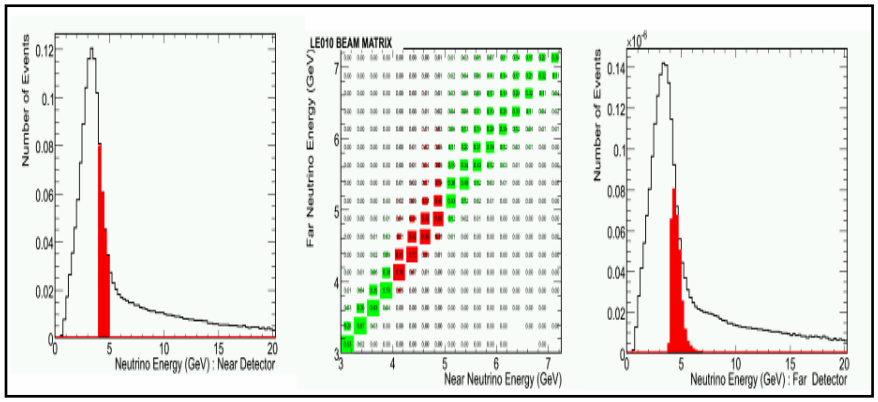
No oscillations

Best fit

Likelihood based on event length, pulse height in track

Use near detector data, beam kinematics to predict far spectrum

Also use bin-to-bin ratios, direct fitting to simulation, results stable.



MINOS Best-Fit Spectrum

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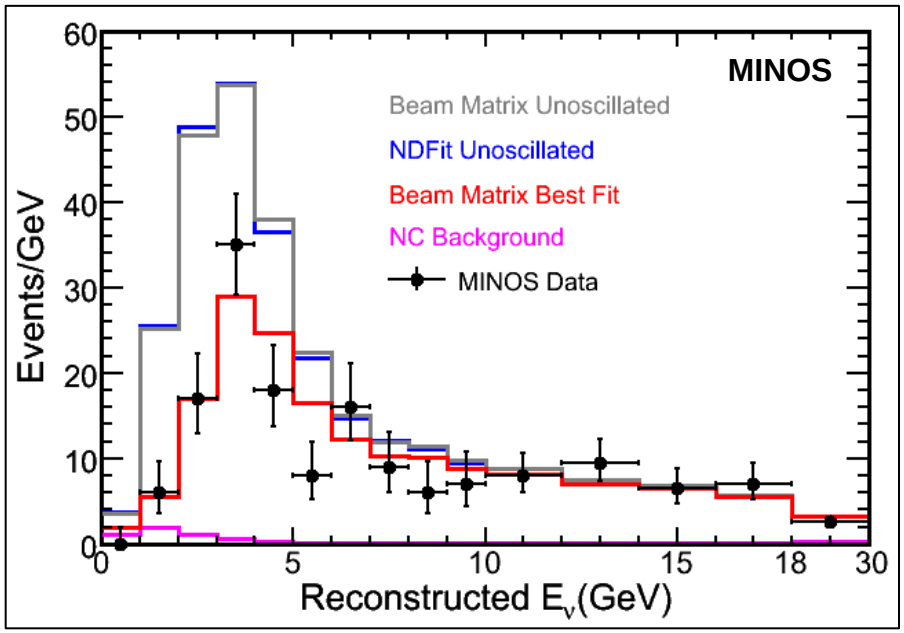
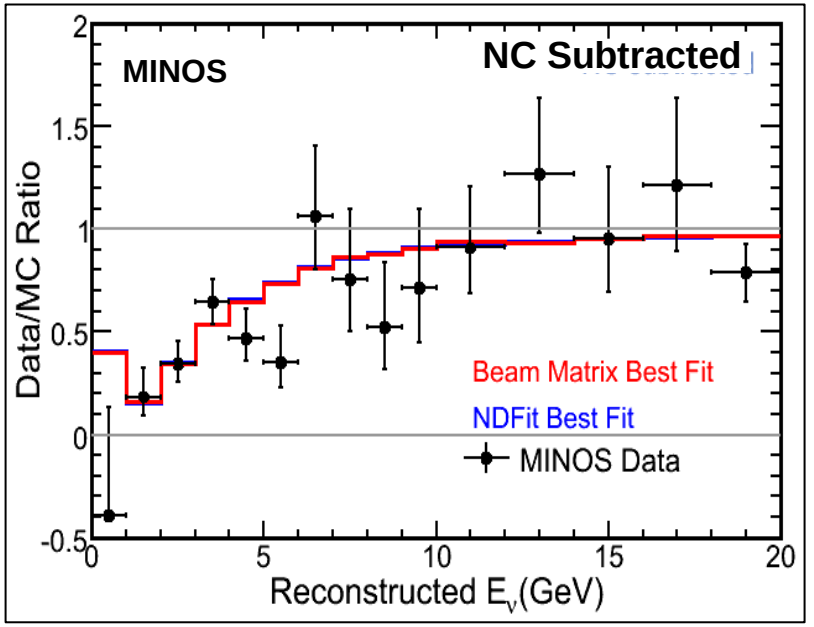
FD neutrino spectrum and ratios





Data Sample	FD Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)
ν_μ (<30 GeV)	215	336.0±14.4	0.64±0.05
ν_μ (<10 GeV)	122	238.7±10.7	0.51±0.05
ν_μ (<5 GeV)	76	168.4±8.8	0.45±0.06

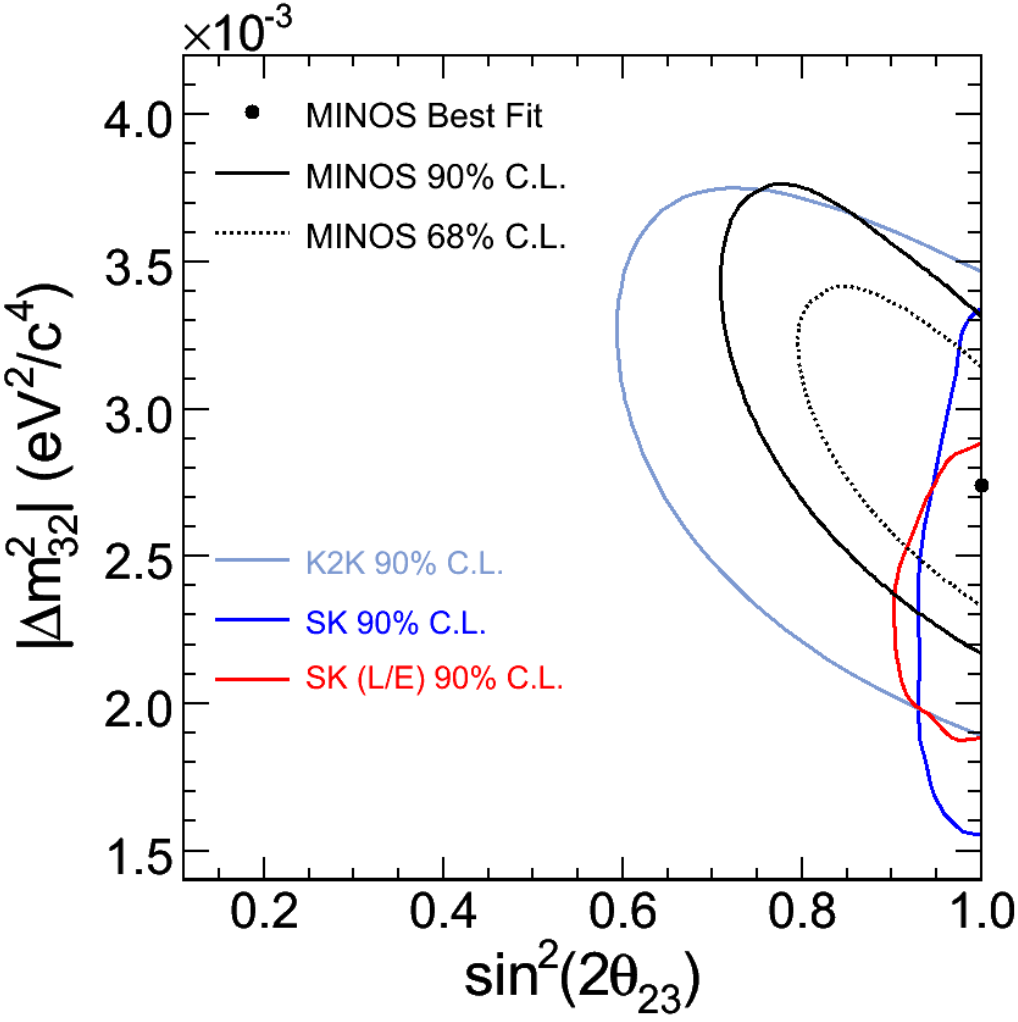
FD Event totals

Allowed Region

- Fit includes penalty terms for three main systematic uncertainties
  - Near/Far Normalization
  - Hadronic E scale
  - NC contamination
- Fit is constrained to physical region: $\sin^2(2\theta_{23}) \leq 1$

$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$



Fermilab Proton Plan for NuMI Beamline

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Currently, 5 booster batches for NuMI is main running mode

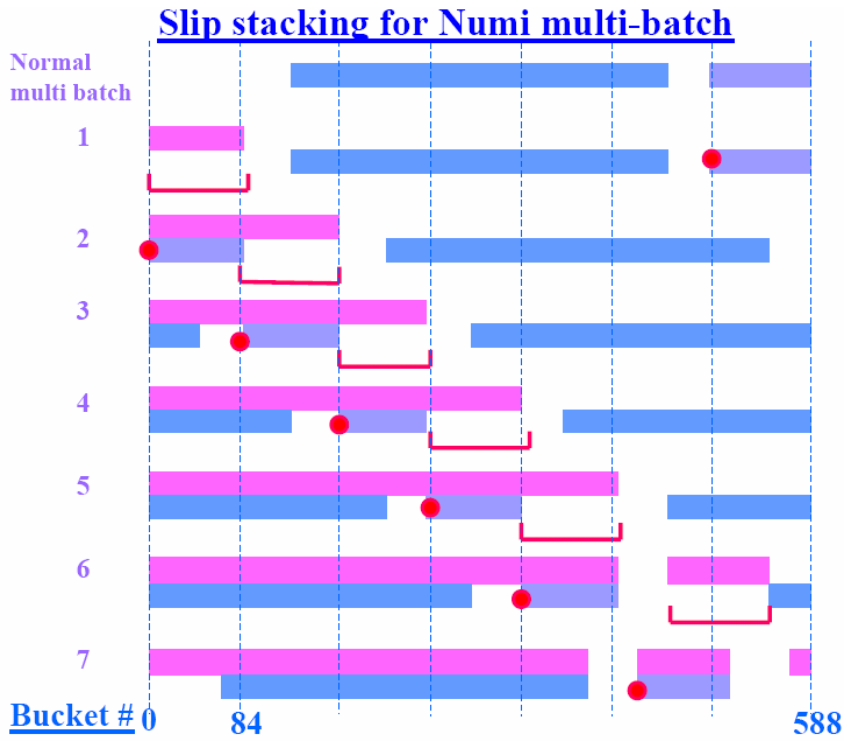
Expansion of “slip-stacking” scheme will allow 9 batch running.

Move from current values to ~400 kW.

Within booster capability

Expect Main Injector collimators (control losses) and some RF changes required for high intensities

Proton plan has realistic shutdowns, efficiencies, turn-on curves.



Slip-stacking graphically
First batches blue
Second batches purple

Proton Plan Expectation for NuMI Beam

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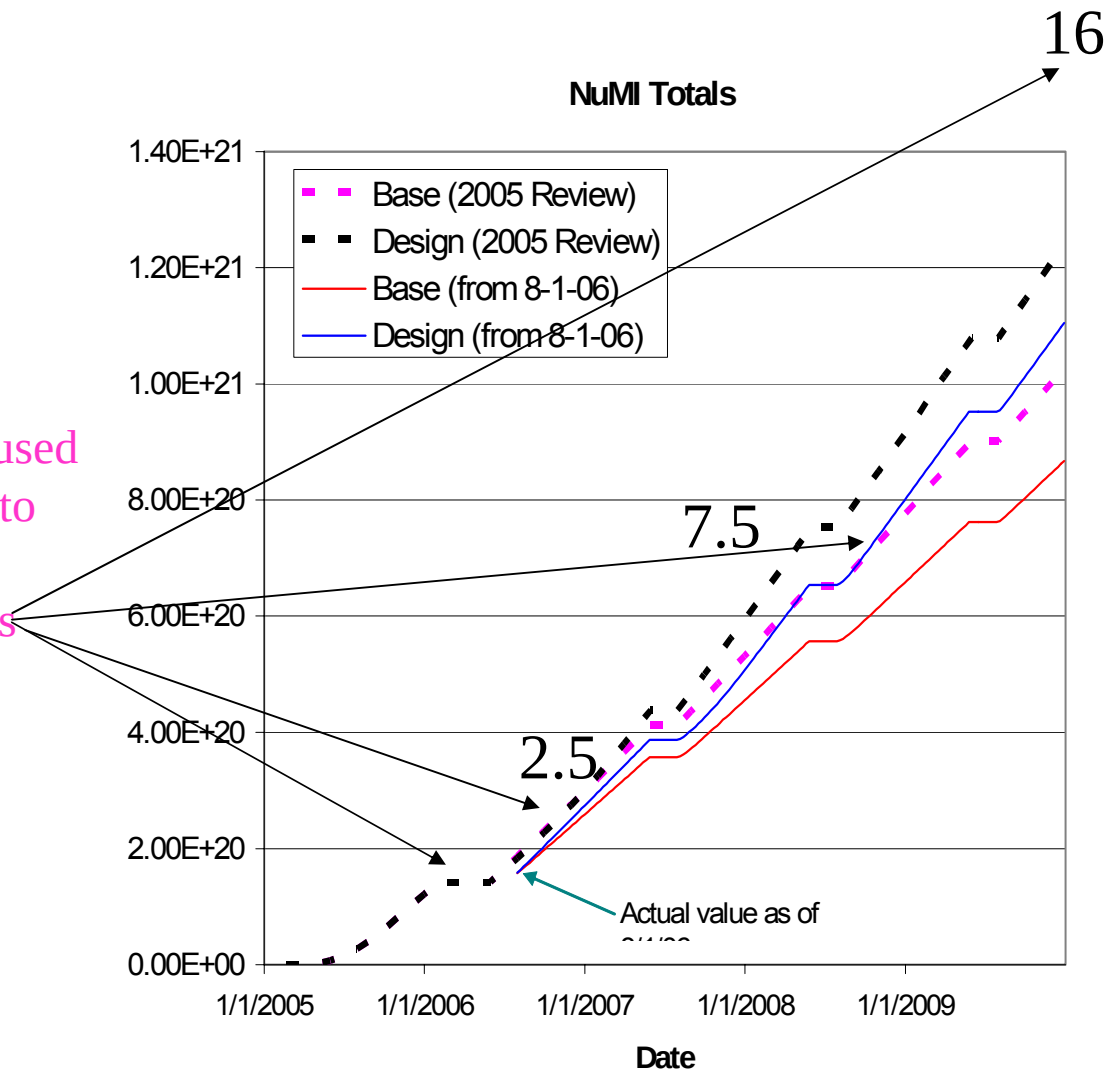
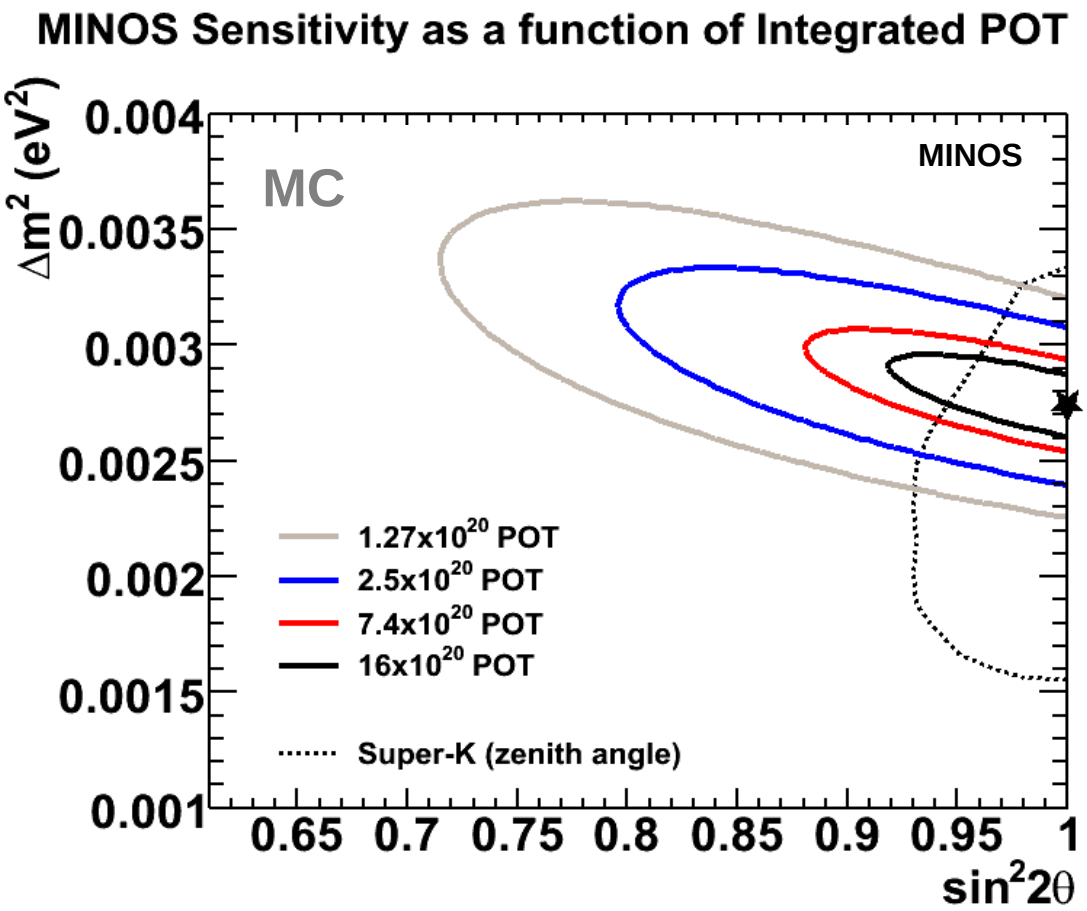
These values used by MINOS to compute sensitivities



Projected MINOS Sensitivity

ν_μ Disappearance



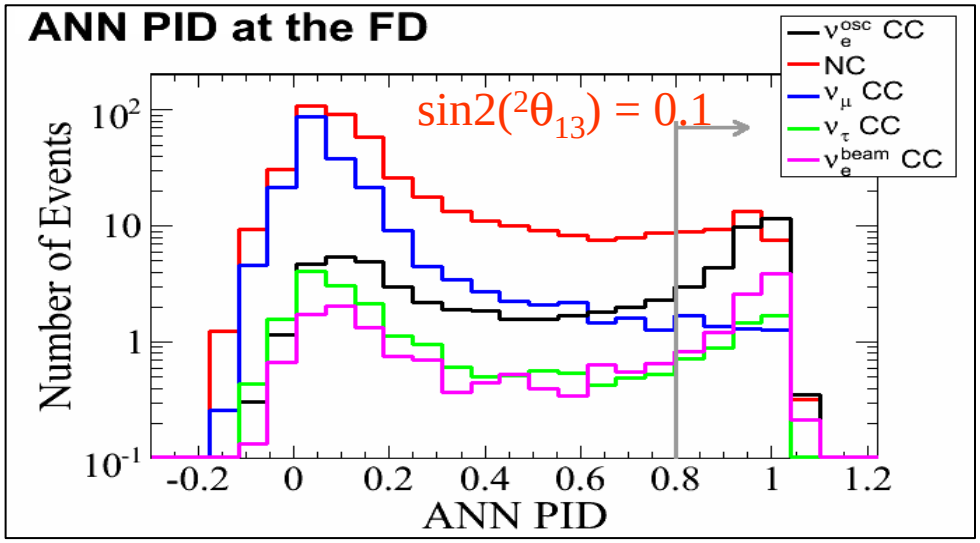
- MINOS sensitivity for different POT
- Current best values used as input:
  $\Delta m^2_{32}=2.74\times10^{-3}$eV^2
  $\sin^2 2\theta_{23}=1.00$
- Contours are 90% C.L. statistical errors only

Potential for Electron Identification

Challenging because of detector granularity – typical electron is 8 planes long, 4 strips wide.

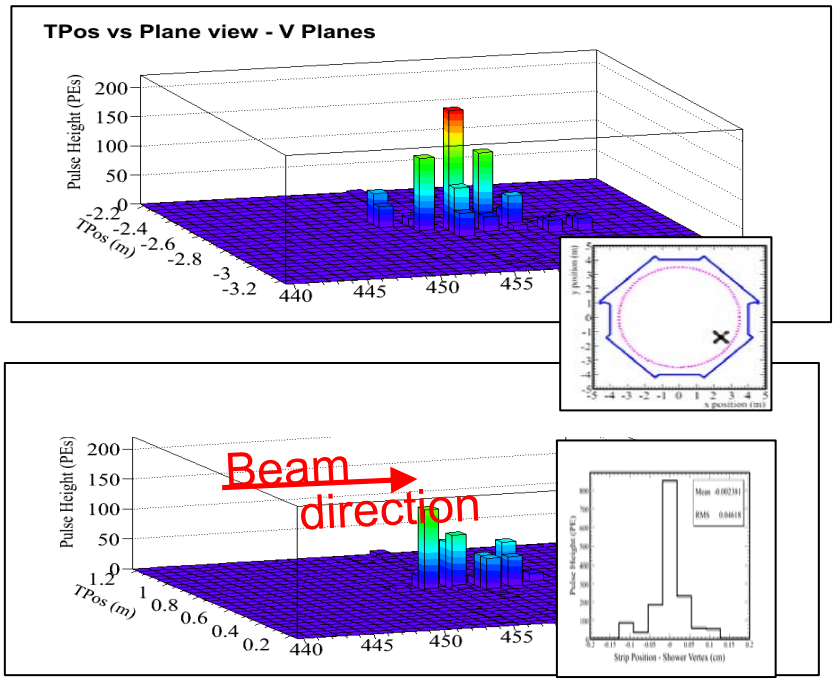
Background high – especially misidentified NC.

Several algorithms under study



ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total	ν_e^{osc}
5.6	39.0	8.7	4.7	58.0	29.1

Background composition from MC (16 x 10^{20} POT)



8.7 GeV electron candidate from data

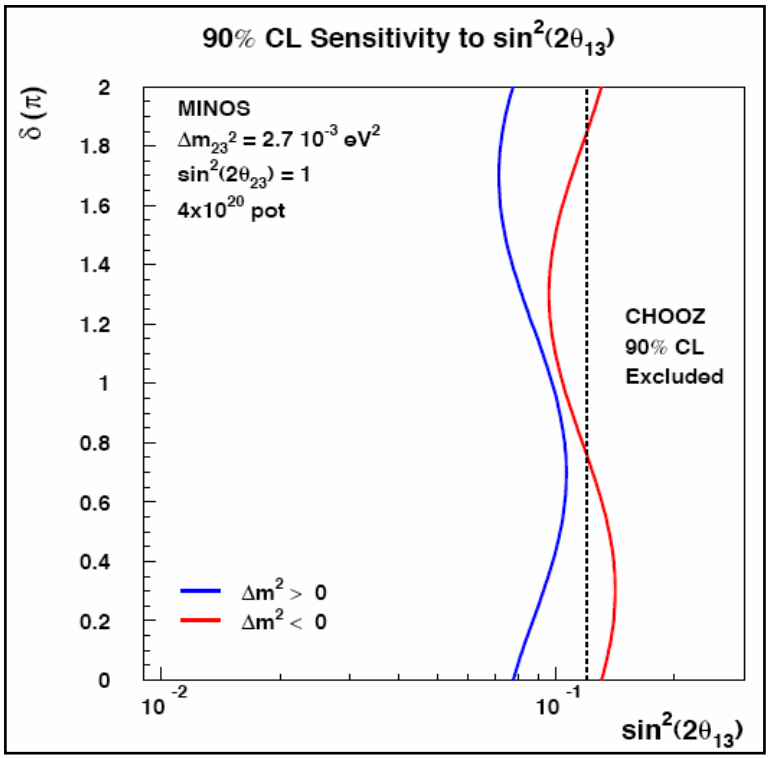
Exclusion and Discovery Potential

Result presented as function of mass hierarchy, CP-violating phase δ.

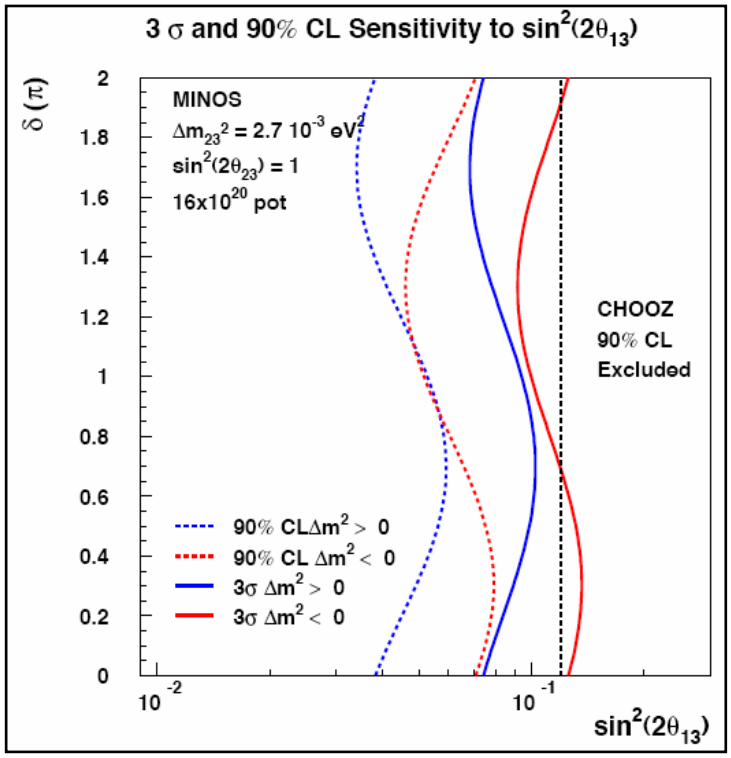
e.g mass hierarchy ±30% effect on rate.

MINOS can improve significantly on CHOOZ limit.

Full program of running with proton plan strengthens MINOS capabilities.



4 x 10^{20} POT



16 x 10^{20} POT

Conclusions and Expectations

- The MINOS experiment and NuMI beam have had a successful first running period.
  - Two publications accepted, atmospheric and beam oscillation papers
  - 3 more in pipeline.
- Operational difficulties with the NuMI beam have been repaired
  - Tritium mitigation, horn and target problems
  - Remarkable effort by Fermilab Accelerator Division
  - "Industrialization" effort for spares underway
- MINOS has active short and long-term physics program
  - Short term includes improved CC analysis, first ND physics, special topics.
- Fermilab proton plan provides a well-defined path forward in proton Intensity
- MINOS program has developed a robust scientific culture
  - Strong involvement by all segments of the collaboration in the CC PRL
  - Commitment to young people in positions of importance (32 postdocs, ~40 students)