Recent Results from MINOS

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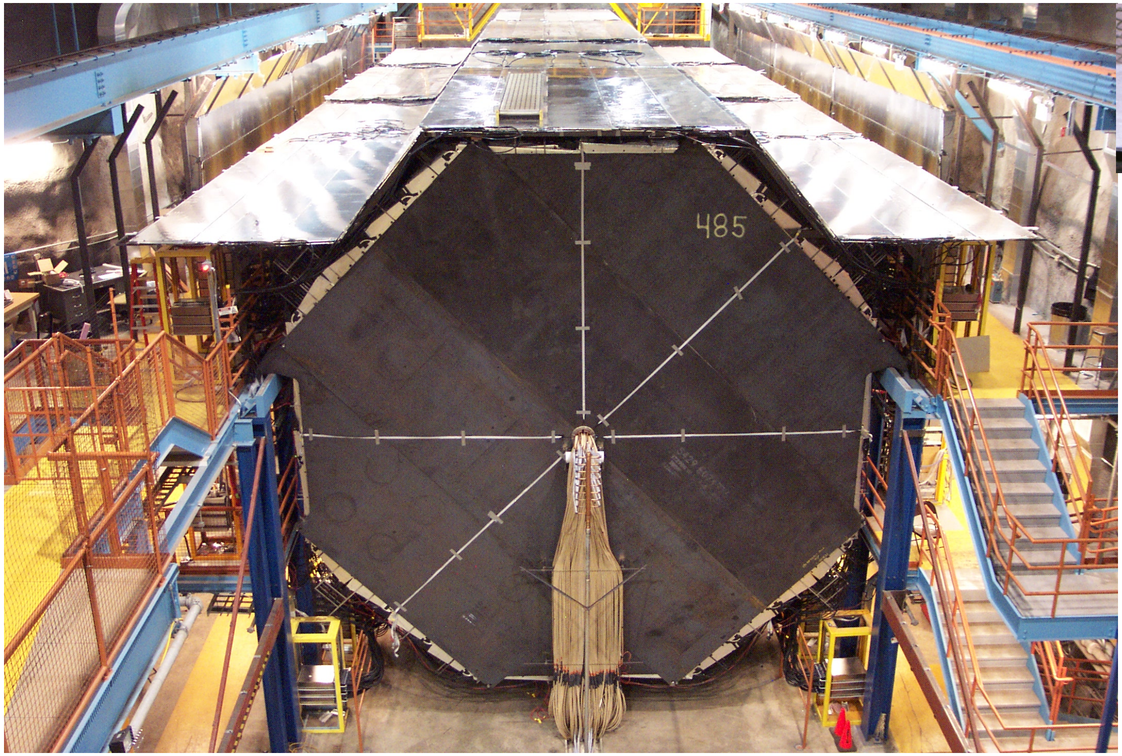



LEVEL NO. 27
2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL

This talk:

➊ Neutrinos: 1998 – 2008
➋ The MINOS Experiment
➌ The NuMI Beam
➍ The MINOS Detectors
➎ ν_μ Disappearance Results
➏ Other Results
➐ Future Prospects
➑ Summary

➊ Neutrinos: 1998 – 2008

10 years ago (PDG1998):

- ★ Standard Model : assumed massless ν
- ★ Fundamental states : ν_e , ν_μ , ν_τ
- ★ $m(\nu_e) < 3$ eV, ….

+ hints of Neutrino Oscillations:

- ★ Atmospheric neutrino oscillations
  - Statistically marginal + positive & negative results
- ★ Solar neutrino oscillations
  - Required faith in Astrophysics/Astrophysicists….!

January 2008:

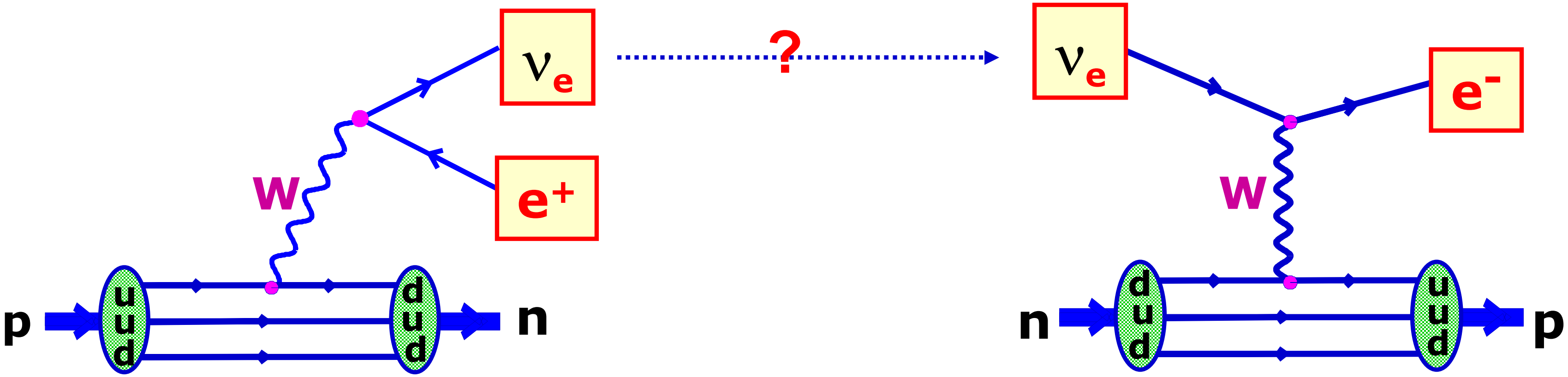
- ★ Standard Model : massive ν
- ★ Fundamental (mass) eigenstates : ν_1 , ν_2 , ν_3
- ★ Atmospheric neutrino oscillations
  - Compelling evidence : Super-Kamiokande
- ★ Solar neutrino oscillations
  - Compelling evidence : SNO + Super-Kamiokande
- ★ Reactor neutrino oscillations
  - Compelling evidence : KamLAND
- ★ Beam neutrino oscillations
  - Moving into the era of precision measurements: MINOS

Neutrino Flavours Revisited

★ Never **directly** observe neutrinos – can only detect them by their weak interactions hence by **definition** ν_e is the neutrino state produced along with an electron. Similarly, charged current weak interactions of the state ν_e produce an electron

$$\boxed{\nu_e, \nu_\mu, \nu_\tau \quad = \text{weak eigenstates}}$$

- For many years, assumed that ν_e, ν_μ, ν_τ were massless fundamental particles
- **Experimental evidence:** at short distances neutrinos produced along with an electron always produced an electron in CC Weak interactions, etc.

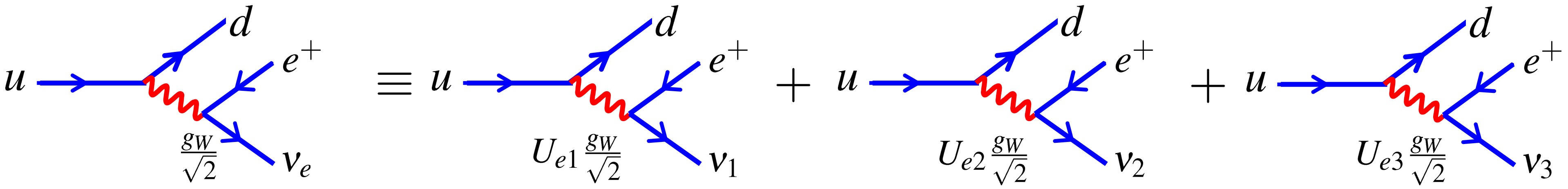


★ Now know that the weak eigenstates, ν_e, ν_μ, ν_τ, are linear combinations of the mass eigenstates

Neutrino Oscillations for Three Flavours

- Relate the weak eigenstates to the mass eigenstates via the Unitary **PMNS** Pontecorvo-Maki-Nakagawa-Sakata matrix.

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



- To calculate the oscillation probability, consider a state which is produced at $t=0$ as a $|\nu_e\rangle$

$$|\psi(t=0)\rangle = |\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

i.e. a coherent linear combination of the mass eigenstates

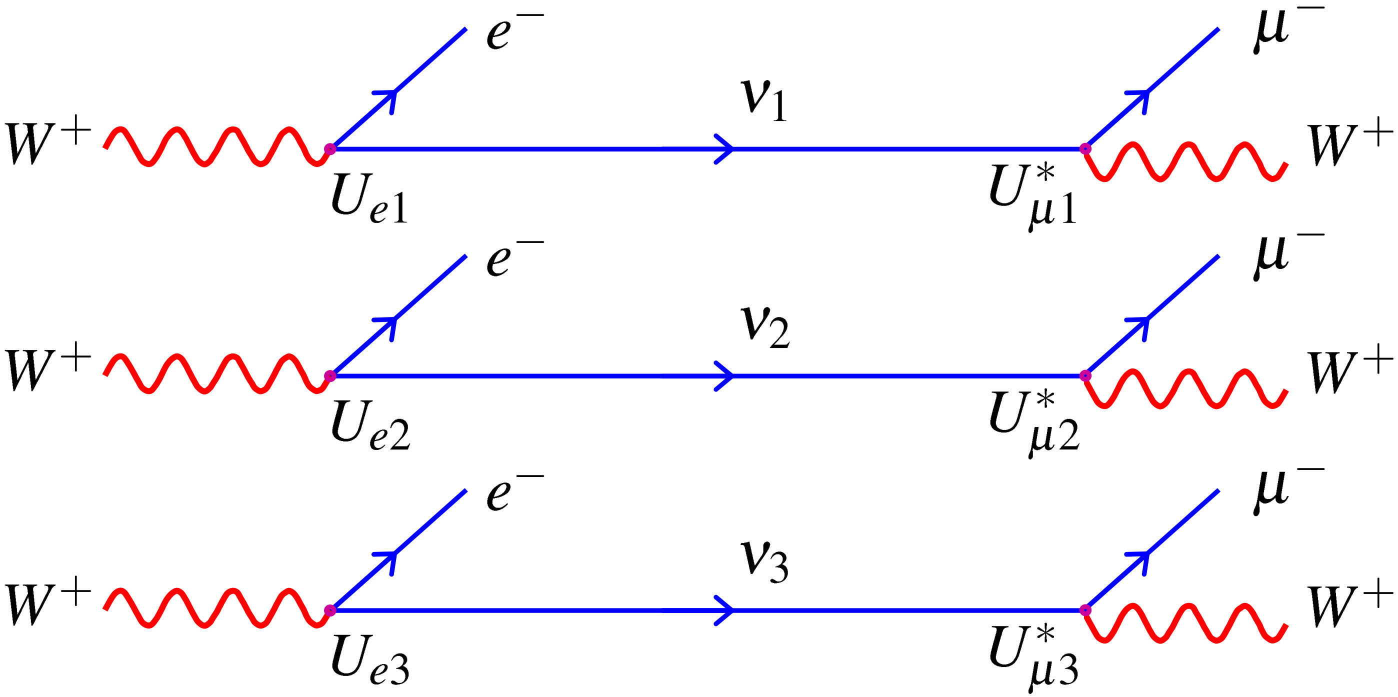
- From which we can calculate the oscillation probability

Phases from time evolution of mass eigenstates

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= |\langle \nu_\mu | \psi(L) \rangle|^2 \\ &= |U_{e1}U^*_{\mu 1}e^{-i\phi_1} + U_{e2}U^*_{\mu 2}e^{-i\phi_2} + U_{e3}U^*_{\mu 3}e^{-i\phi_3}|^2 \end{aligned}$$

$$P(\nu_e \to \nu_\mu) = |U_{e1}U^*_{\mu 1}e^{-i\phi_1} + U_{e2}U^*_{\mu 2}e^{-i\phi_2} + U_{e3}U^*_{\mu 3}e^{-i\phi_3}|^2$$

- The terms in this expression can be represented as:



- Because of the unitarity of the PMNS matrix:

$$U_{e1}U^*_{\mu 1} + U_{e2}U^*_{\mu 2} + U_{e3}U^*_{\mu 3} = 0$$

Consequently, unless the phases of the different components are different, the sum of these three diagrams is zero, i.e., require different neutrino masses for osc.

PMNS Matrix

★ The PMNS matrix is usually expressed in terms of 3 rotation angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a complex phase δ, using the notation $s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{“Atmospheric”}} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{“Solar”}}$$

Dominates:

- Writing this out in full:

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

★There are six **SM parameters** that can be measured in ν oscillation experiments

$\lvert\Delta m_{21}\rvert^2 = \lvert m_2^2 - m_1^2\rvert$	θ_{12}	Solar and reactor neutrino experiments
$\lvert\Delta m_{32}\rvert^2 = \lvert m_3^2 - m_2^2\rvert$	θ_{23}	Atmospheric and beam neutrino experiments
	θ_{13}	Reactor neutrino experiments + future beam
	δ	Future beam experiments (CP violation)

Neutrinos Today: What do we/don’t we know ?

“KNOWN”

★**Solar neutrino oscillations (mainly Super-K and SNO and KamLAND):**

$$|\Delta m^2_{21}| = 7.9^{+0.6}_{-0.5} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.40^{+0.1}_{-0.07}$$

★**Atmospheric neutrino oscillations (mainly Super-K):** **+ MINOS**

$$|\Delta m^2_{32}| \approx (2.5 \pm 0.5) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\theta_{23} > 0.92$$

Near maximal mixing

★**Reactor neutrino non-oscillations (CHOOZ):**

$$\sin^2\theta_{13} < 0.06$$

Small

UNKNOWN:

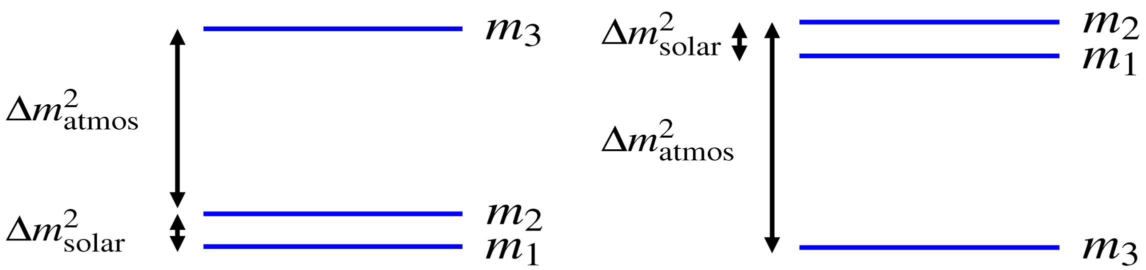
Mass

$$m_{\nu_e} < 2\,\mathrm{eV}$$

CP-Phase

$$\delta$$

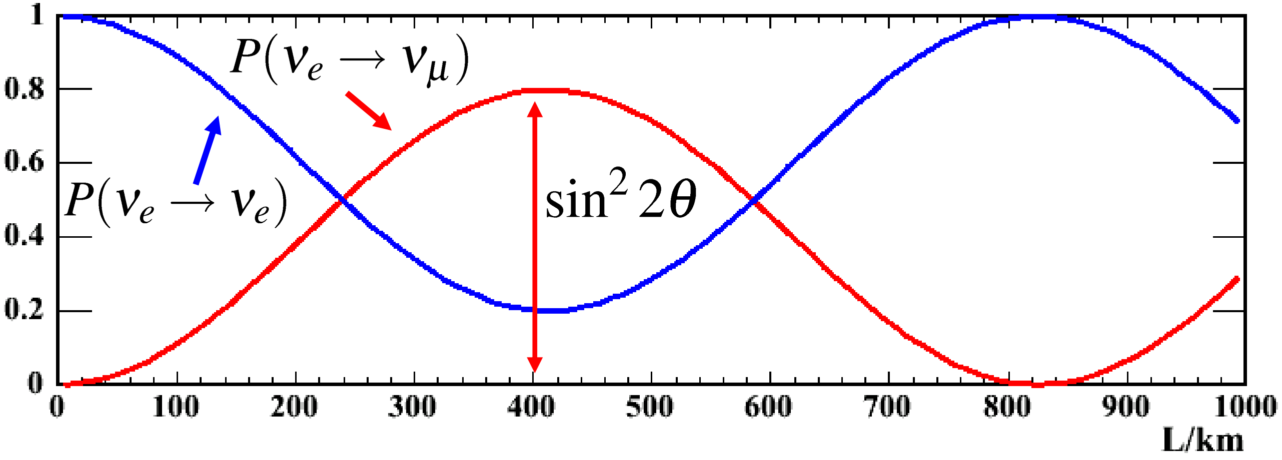
Mass Hierarchy



★ **Because θ_{13} is small, in many circumstances the two oscillation scales, $|\Delta m^2_{12}|,\ |\Delta m^2_{32}|$ decouple and can use the two flavour oscillation formula**

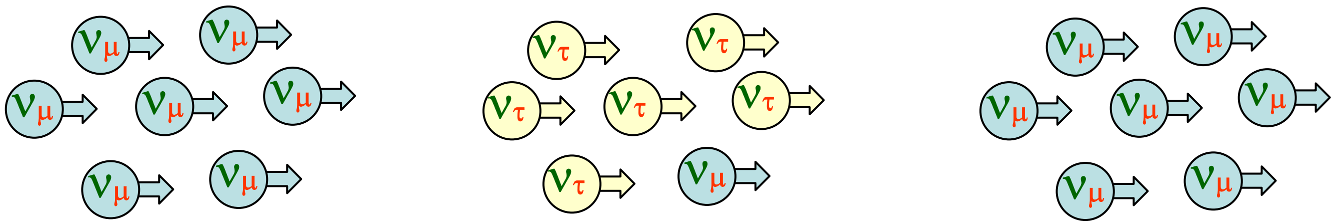
$$\boxed{P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)} \quad \textbf{with} \quad \boxed{\Delta m^2_{32} = m^2_3 - m^2_2}$$

- **e.g.** $\Delta m^2 = 0.003\,\mathrm{eV}^2, \qquad \sin^2 2\theta = 0.8, \qquad E_\nu = 1\,\mathrm{GeV}$



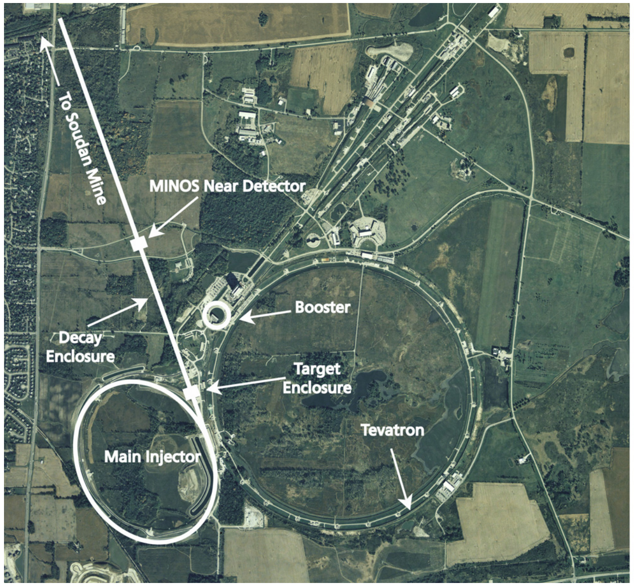
- **wavelength**

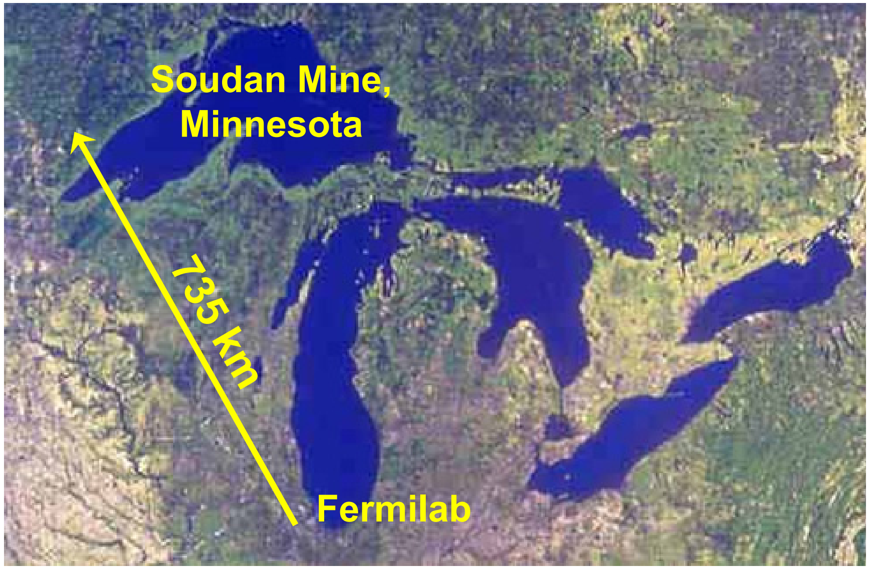
$$\boxed{\lambda_{\mathrm{osc}} = \frac{4\pi E}{\Delta m^2}}$$



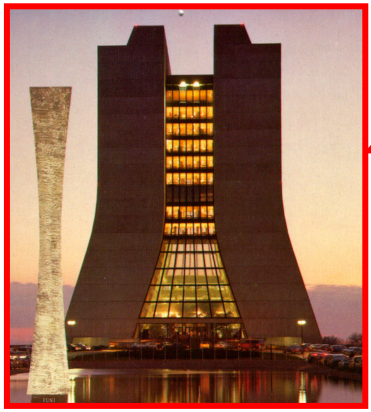
❷ The MINOS Experiment

- **120 GeV** protons extracted from the MAIN INJECTOR at Fermilab
- **2.5×10^{13}** protons per pulse hit target → very intense beam - **0.3 MW** on target





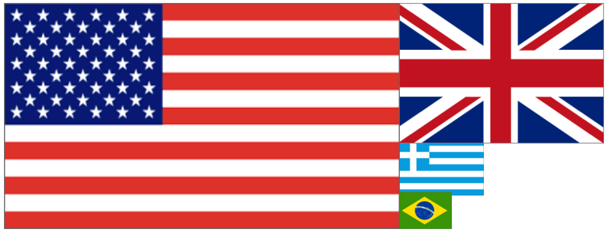
Two detectors:



★ 1000 ton, NEAR Detector at Fermilab: **1 km** from beam

★ 5400 ton FAR Detector, **720 m** underground in Soudan mine, N. Minnesota: **735 km** from beam

The MINOS Collaboration



27 institutions
175 scientists

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas
Fermilab • Harvard • IIT • Indiana
Minnesota-Twin Cities • Minnesota-Duluth • Oxford • Pittsburgh • Rutherford
Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • William & Mary

MINOS Physics Goals

☆ **Precise Measurement of “atmospheric” osc. parameters**

- < 10% measurement of Δm^2_{32}
- Test whether $\sin^2 2\theta_{23}$ is maximal

☆ **Demonstrate oscillation behaviour:**

- observe oscillatory dip and rise
- confirm neutrino flavour oscillations describe data
- test alternative scenarios (sterile, decay, decoherence)

☆ **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

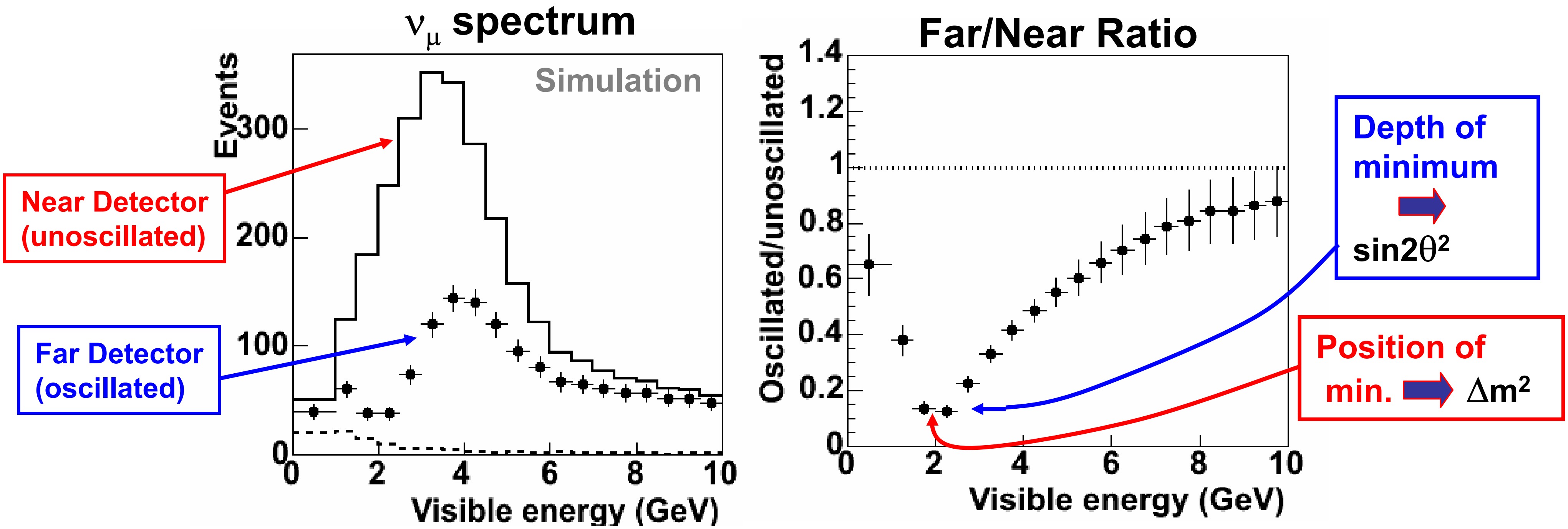
☆ **Test of CPT invariance in neutrino sector**

- first direct measurements of ν vs $\bar{\nu}$ oscillations from
  - atmospheric neutrino events
  - possibility of “reverse horn current” beam anti-ν run

☆ **Cosmic-ray physics**

MINOS in a Nutshell

- Intense neutrino beam: **0.2 MW**
- Two detectors: one close to beam the other 735 km away
- Measure ratio of the neutrino energy spectrum in far detector (oscillated) to that in the near detector (unoscillated)



Near Detector (unoscillated)

Far Detector (oscillated)

Depth of minimum → $\sin2\theta^2$

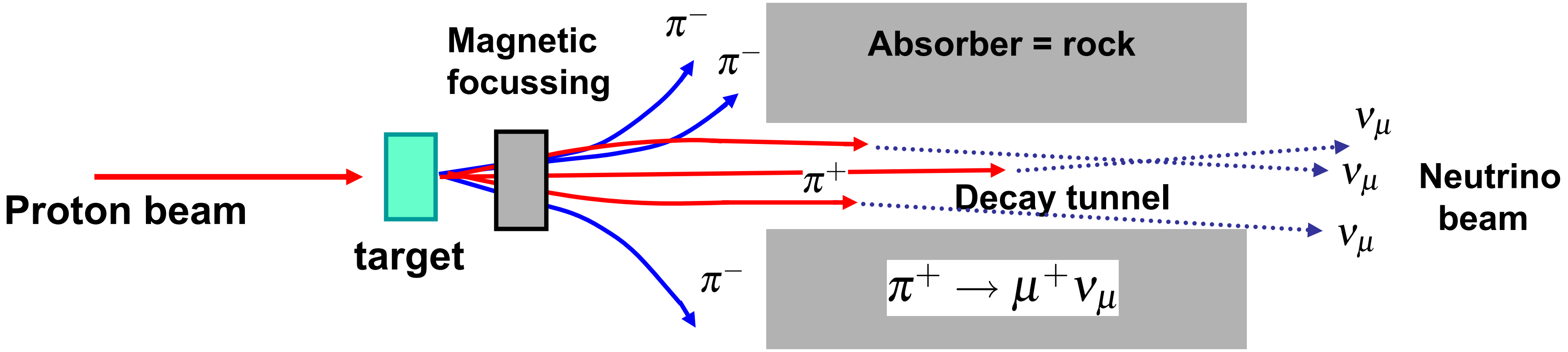
Position of min. → Δm^2

- Two detectors vital to understand beam → precise measurements
- Leads to a significant cancellation of systematic biases

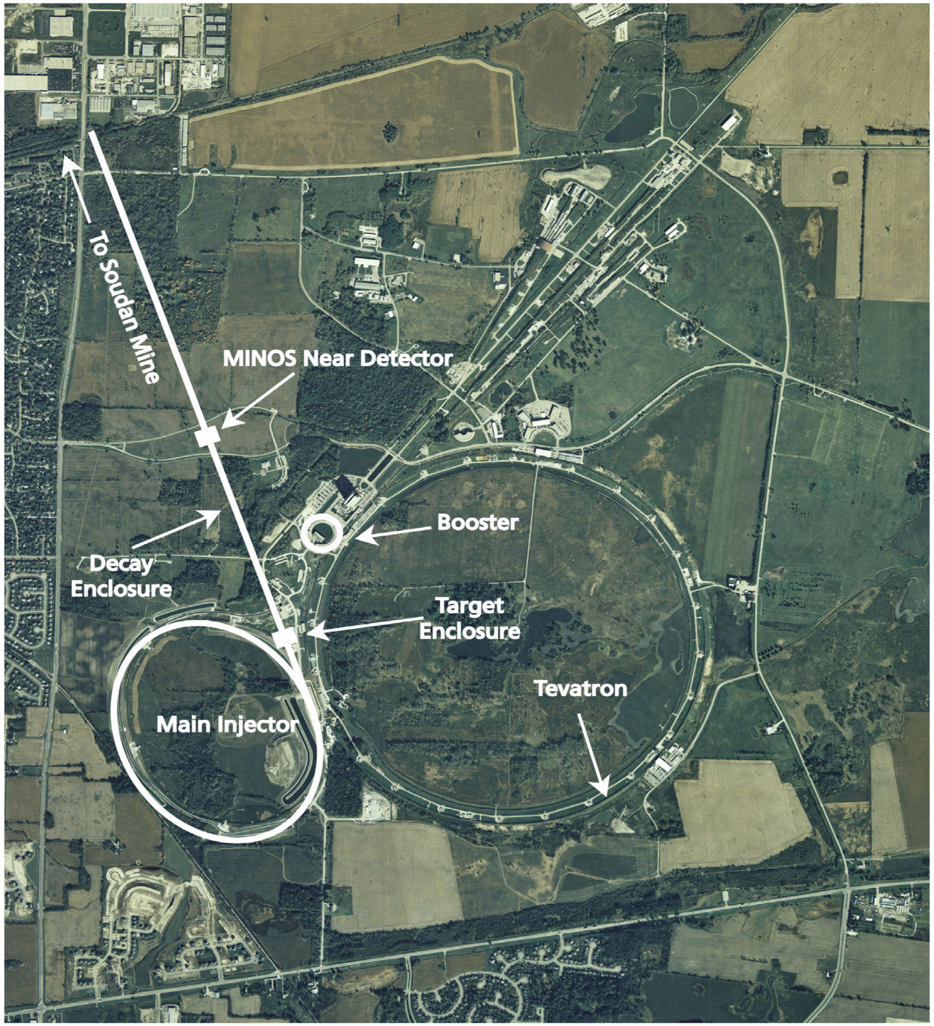
❸ The NuMI Neutrino Beam

★Neutrino Beams for beginners

- Smash high energy protons into a fixed target ➡ hadrons
- Focus positive pions/kaons
- Allow them to decay $\pi^+ \rightarrow \mu^+\nu_\mu$ + $K^+ \rightarrow \mu^+\nu_\mu$ $(BR \approx 64\,\%)$
- Gives a beam of "collimated" ν_μ
- Could focus negative pions/kaons to give beam of $\overline{\nu}_\mu$



The NuMI beam in more detail



FERMILAB #98-765D

Basic Design:

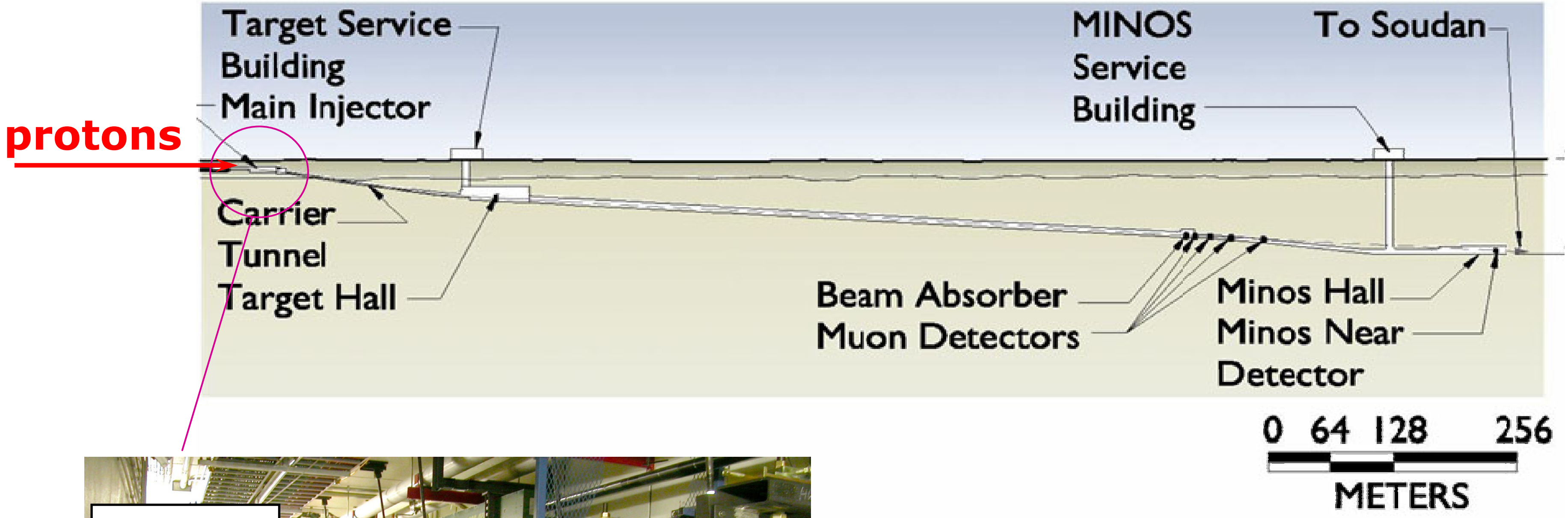
- ★ 120 GeV protons extracted from the MAIN INJECTOR in a single turn (8.7 μs)
- ★ 2.4 second cycle time
- ★ *i.e.* ν beam "on" for 8.7 μs every 2.4 seconds

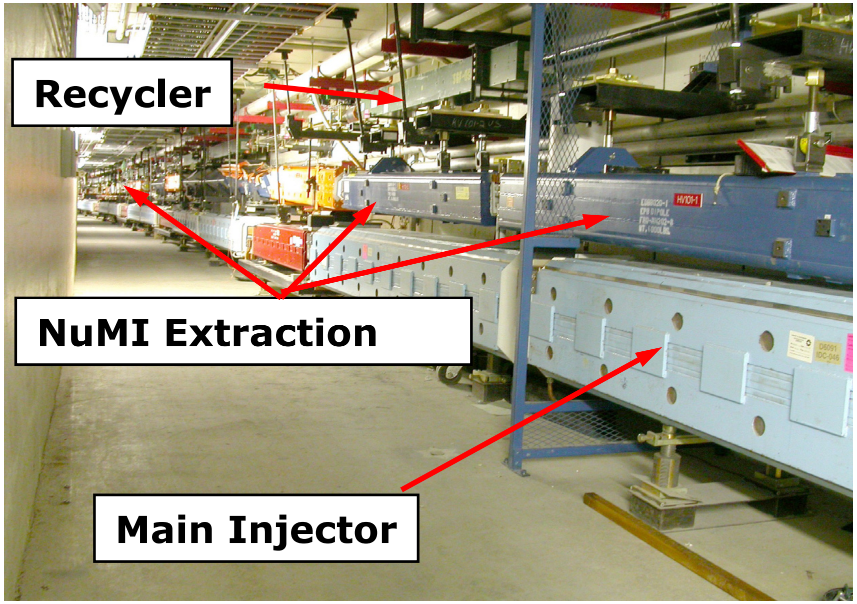
Beam Performance (2007):

- ★ 2.4x10^{13} protons/pulse
- ★ 0.2 MW on target !
- ★ Integrated intensity

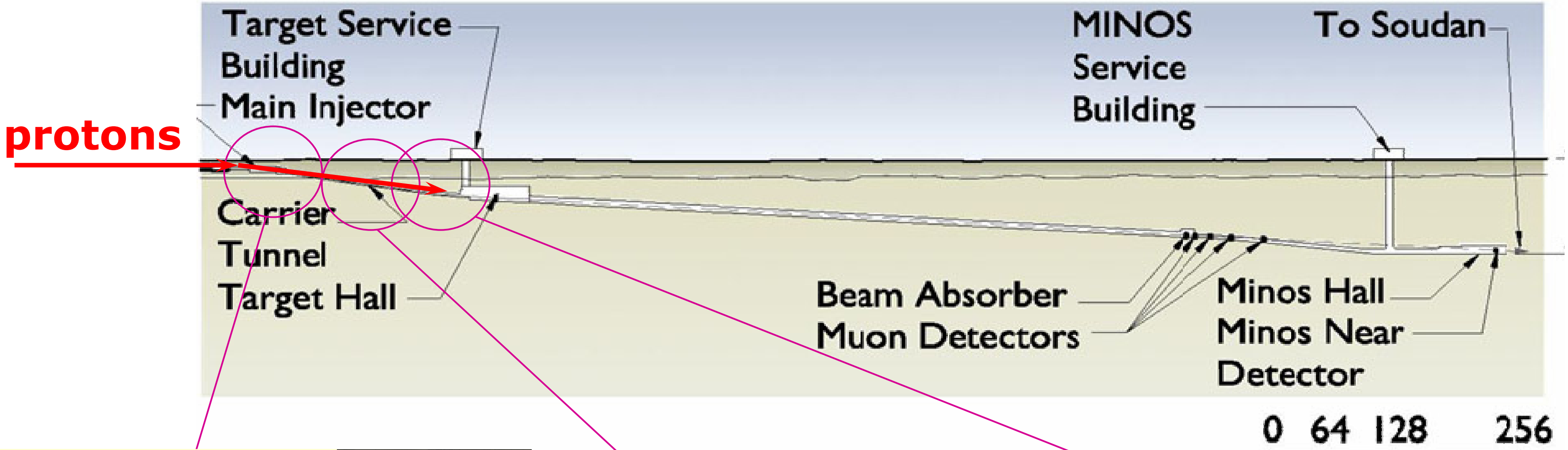
  2.5x10^{20} protons/year

The NuMI ν beam : I





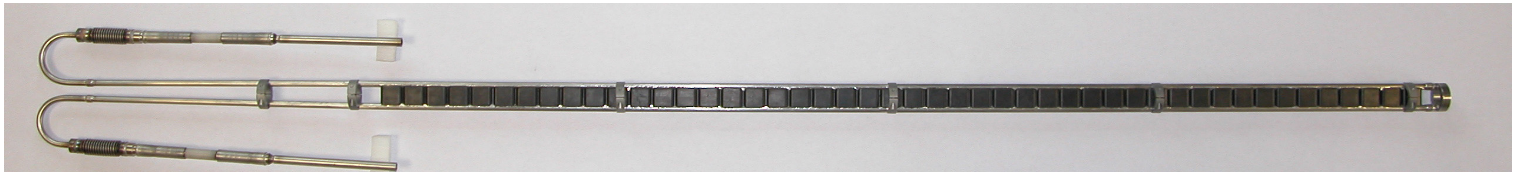
The NuMI ν beam : II



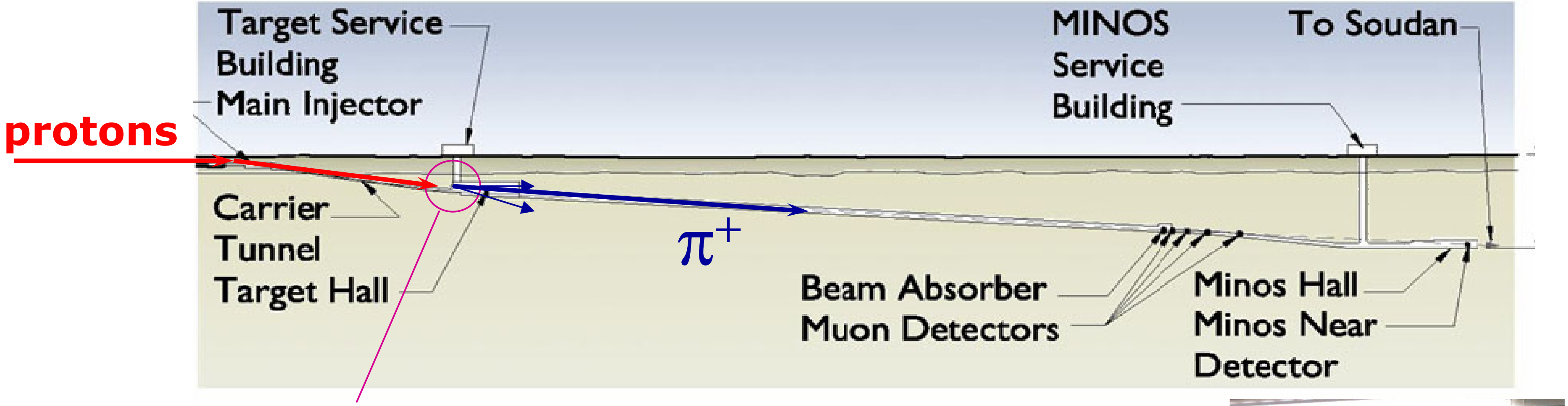

Steep incline


Carrier tunnel

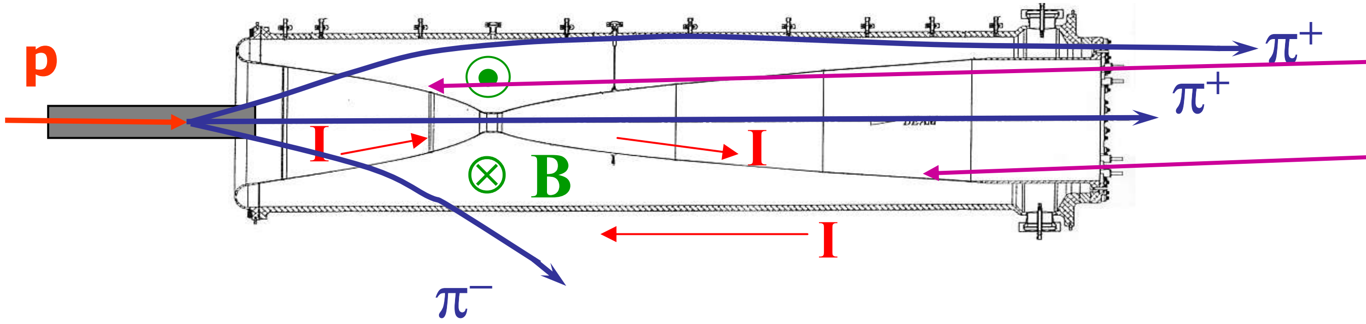

Pre-target


NuMI segmented graphite target with water cooling lines

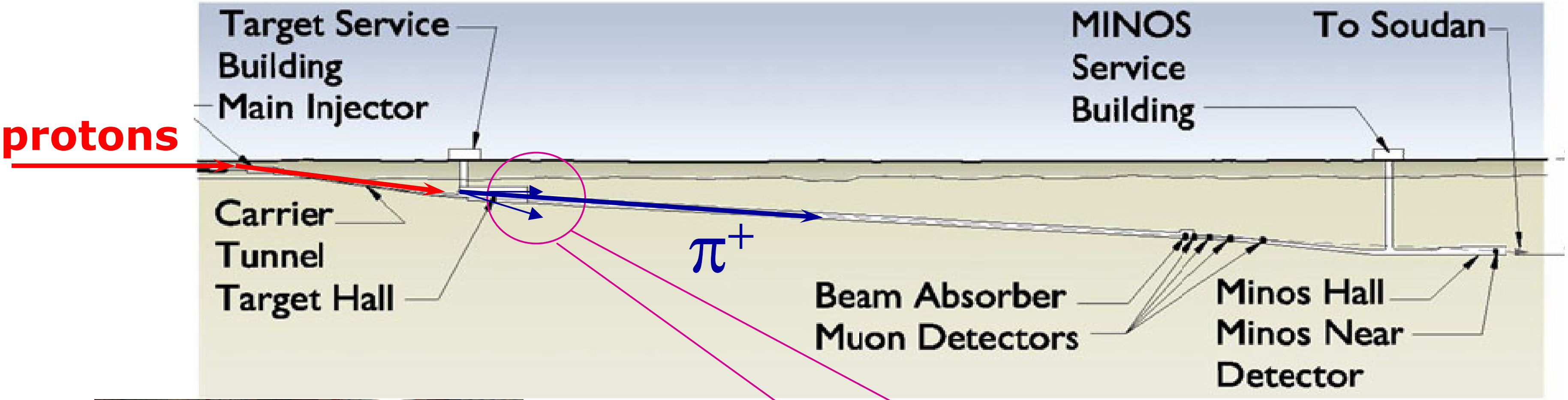
The NuMI ν beam : III



- **Two focusing horns pulsed with 200 kA**
- **Toroidal Magnetic field *B* ~ I/*r* between the inner and outer conductors**
- **Maximum field – 3 T**



The NuMI ν beam : IV

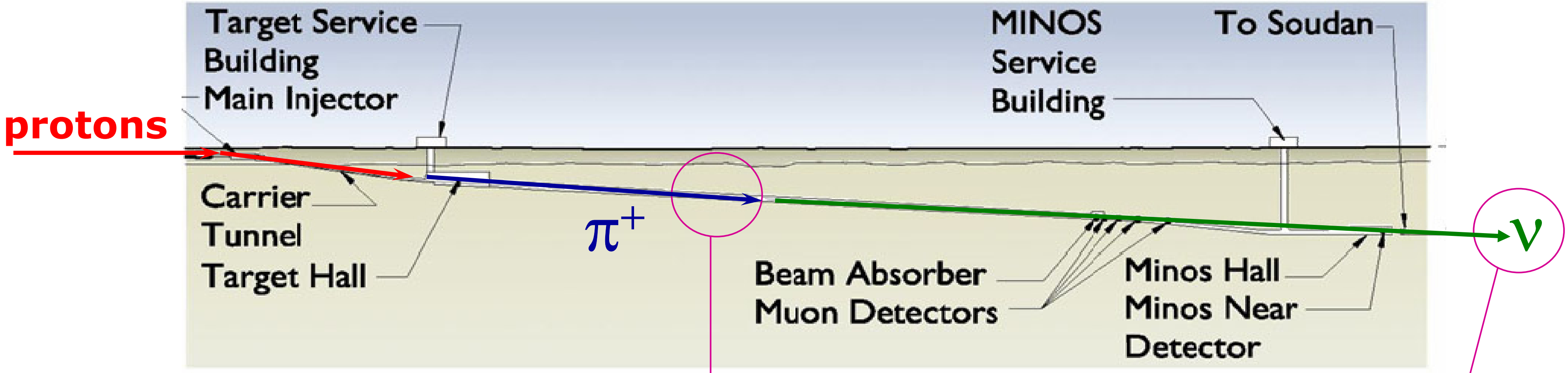



Horn on mounting


Target Hall before shielding


After shielding installation

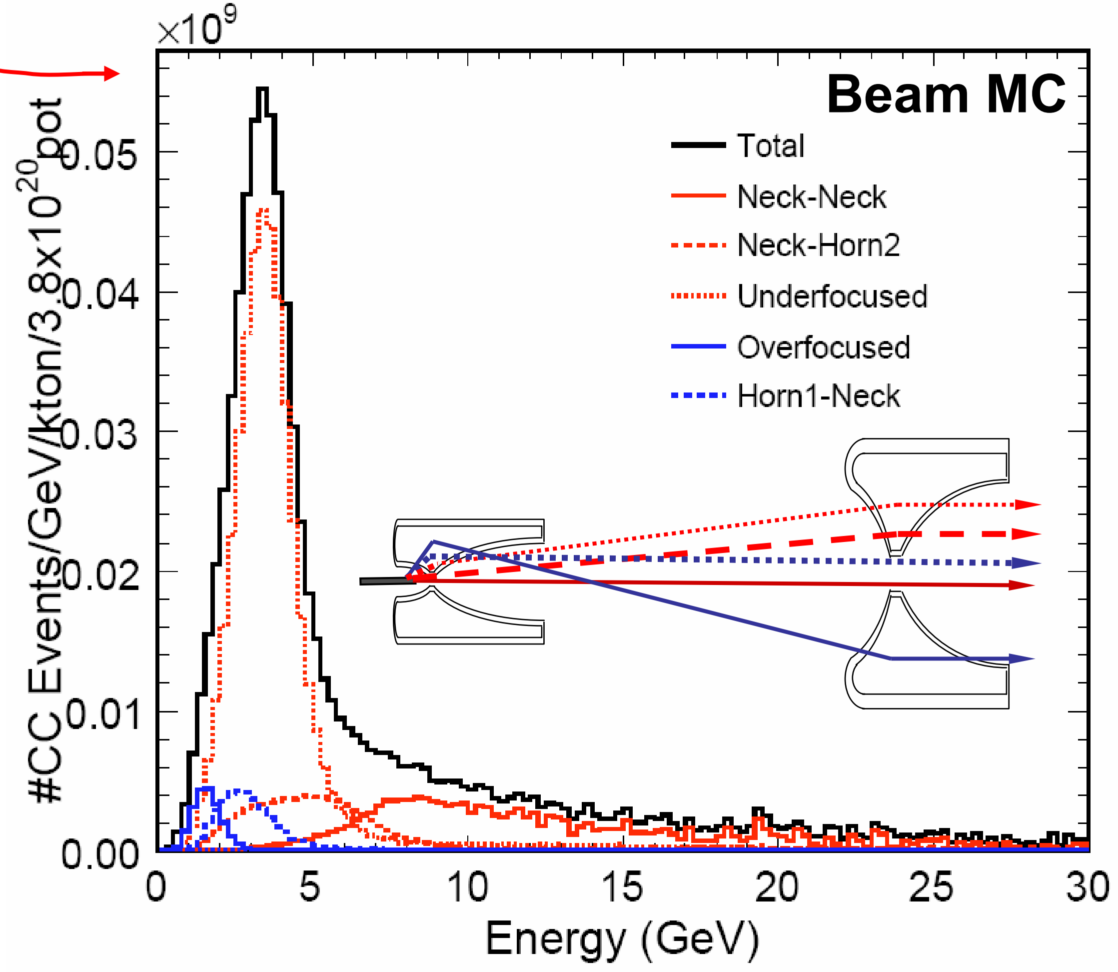
The NuMI ν beam : V

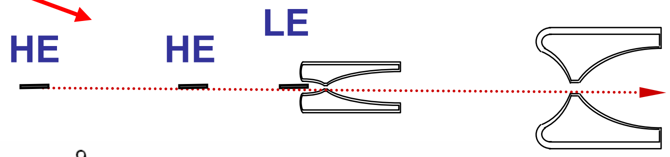


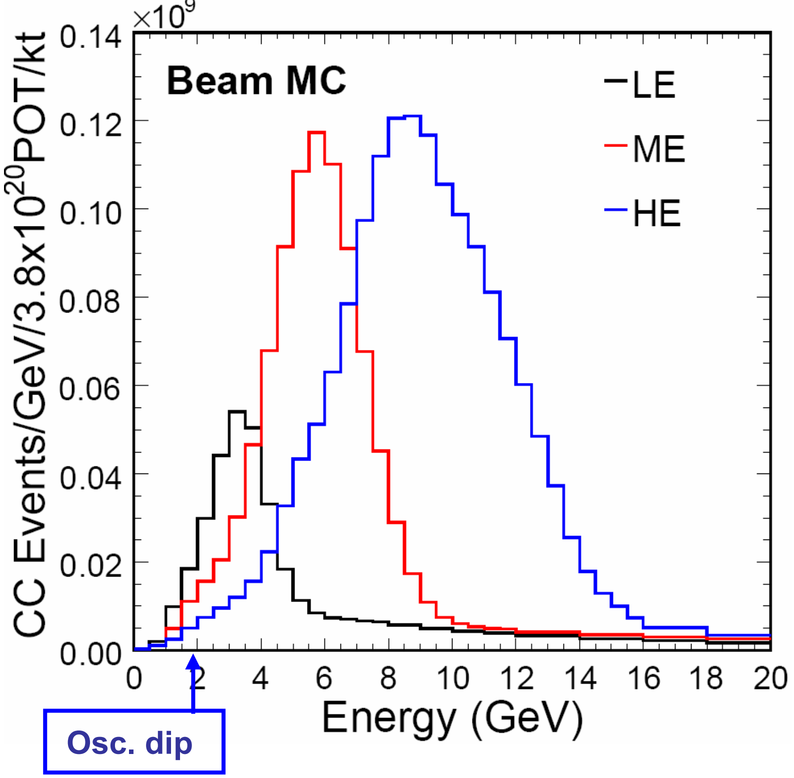
675 m long decay pipe

- ★ Need long decay pipe:
  for a 5 GeV π^+
  $\gamma ct \sim 200$ m
- ★ Evacuated to 1.5 Torr
- ★ Steel decay pipe installed and encased in 2-3 m of concrete to protect ground water

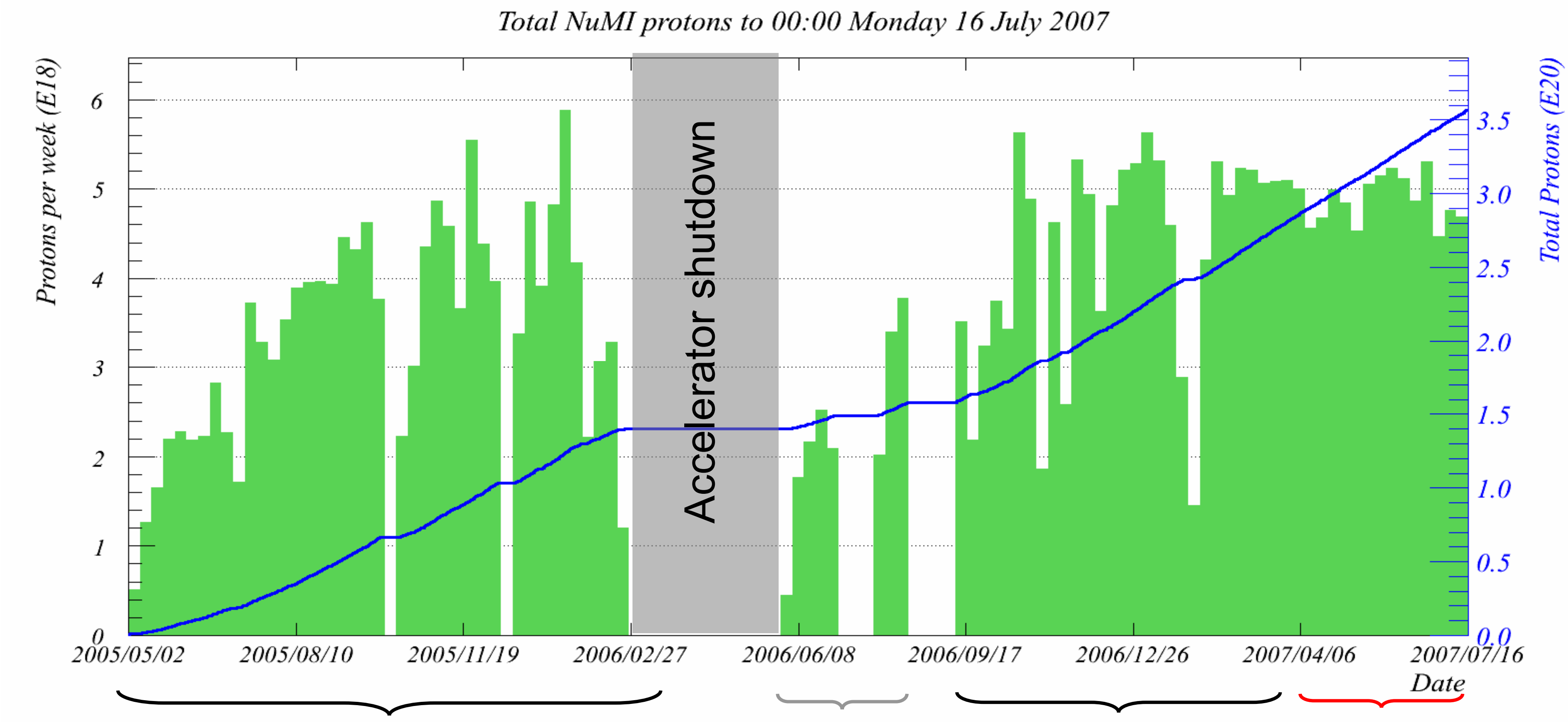
- **Focussing is achieved with a two horn system**
- **Behaves like a pair of (achromatic) lenses**
- **By moving target position can vary energy spectrum (default = LE)**







NuMI Performance



RUN I -
$1.27\text{x}10^{20}$ POT
(published in PRL)

Higher energy beam running

RUN IIa -
$1.23\text{x}10^{20}$ POT
(arXiv:0711.0769)

RUN IIb - $0.8\text{x}10^{20}$ POT
(Analysis in progress)

Results presented here: Run I + Run IIa - 2.5×10^{20} POT

❹ The MINOS Detectors

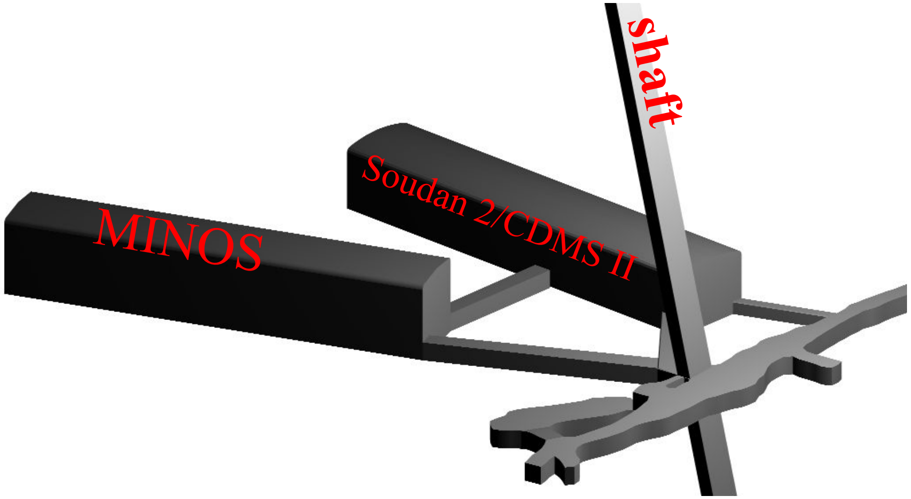
Far Detector in deepest darkest Minnesota – nearest main town Ely, MN

Photo by Jerry Meier

LEVEL NO. 27

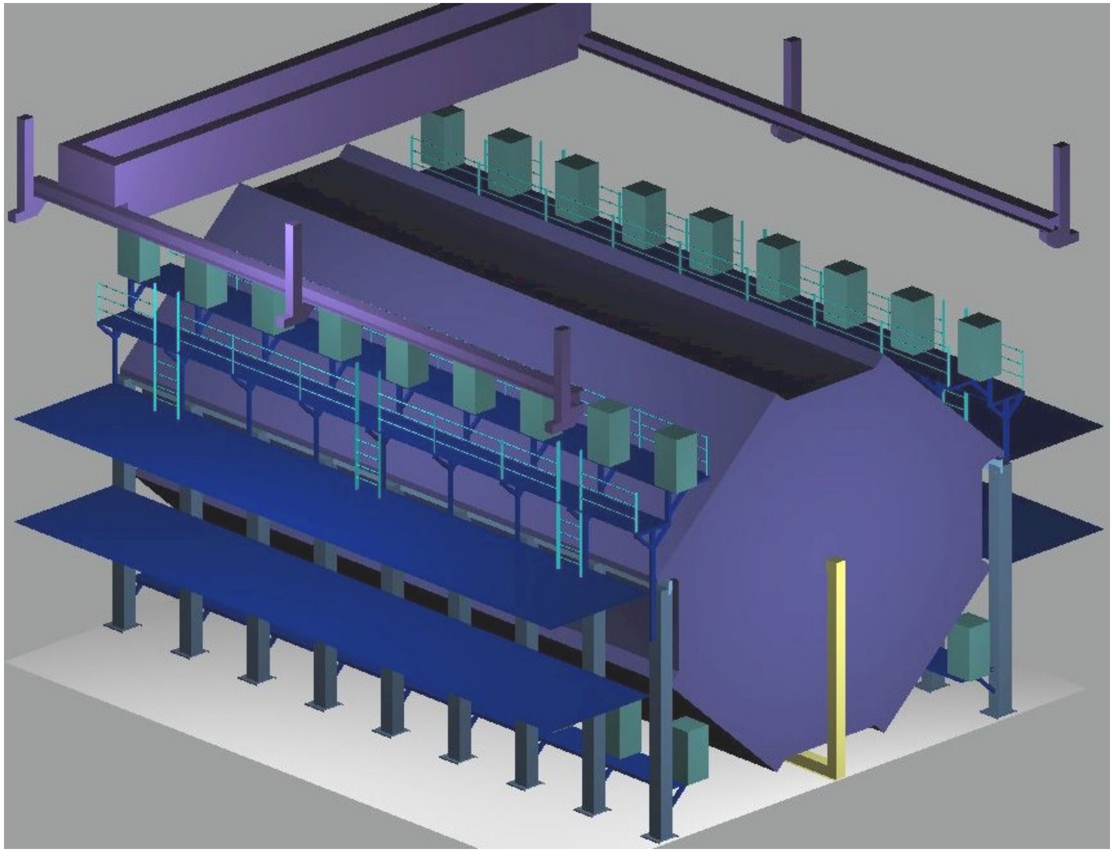
2341 FEET BELOW THE SURFACE
689 FEET BELOW SEA LEVEL

2070 mwe



MINOS Far Detector

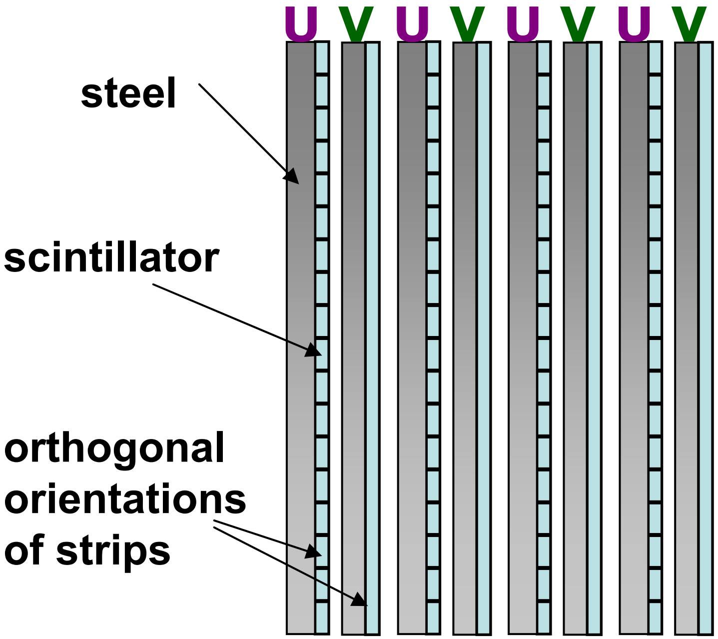
- 8m octagonal steel & scintillator tracking calorimeter
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.2 T)
- 484 planes of scintillator

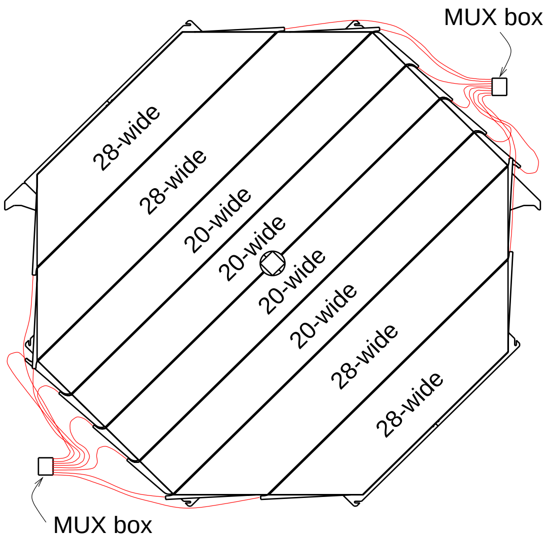


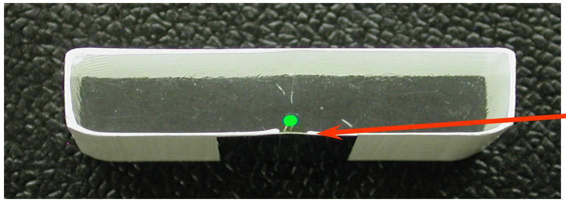
One Supermodule of the Far Detector…
Two Supermodules total.

Basic Detector Elements

- ★ Steel-Scintillator sandwich : **SAMPLING CALORIMETER**
- ★ Each plane consists of a **2.54 cm** steel **+1 cm** scintillator
- ★ Each scintillator plane divided into **192 x 4cm** wide strips
- ★ Alternate planes have **orthogonal** strip orientations (U and V)

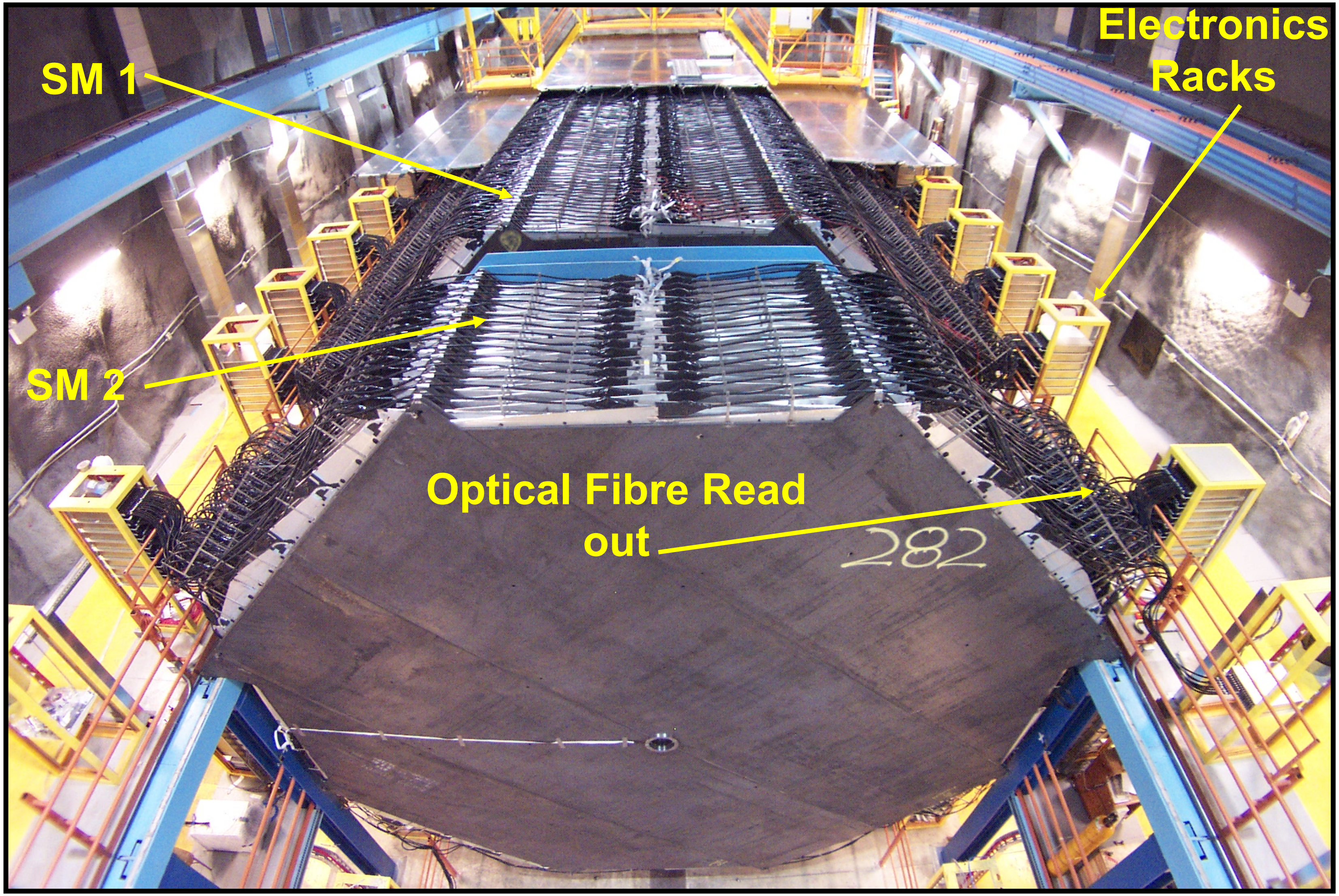




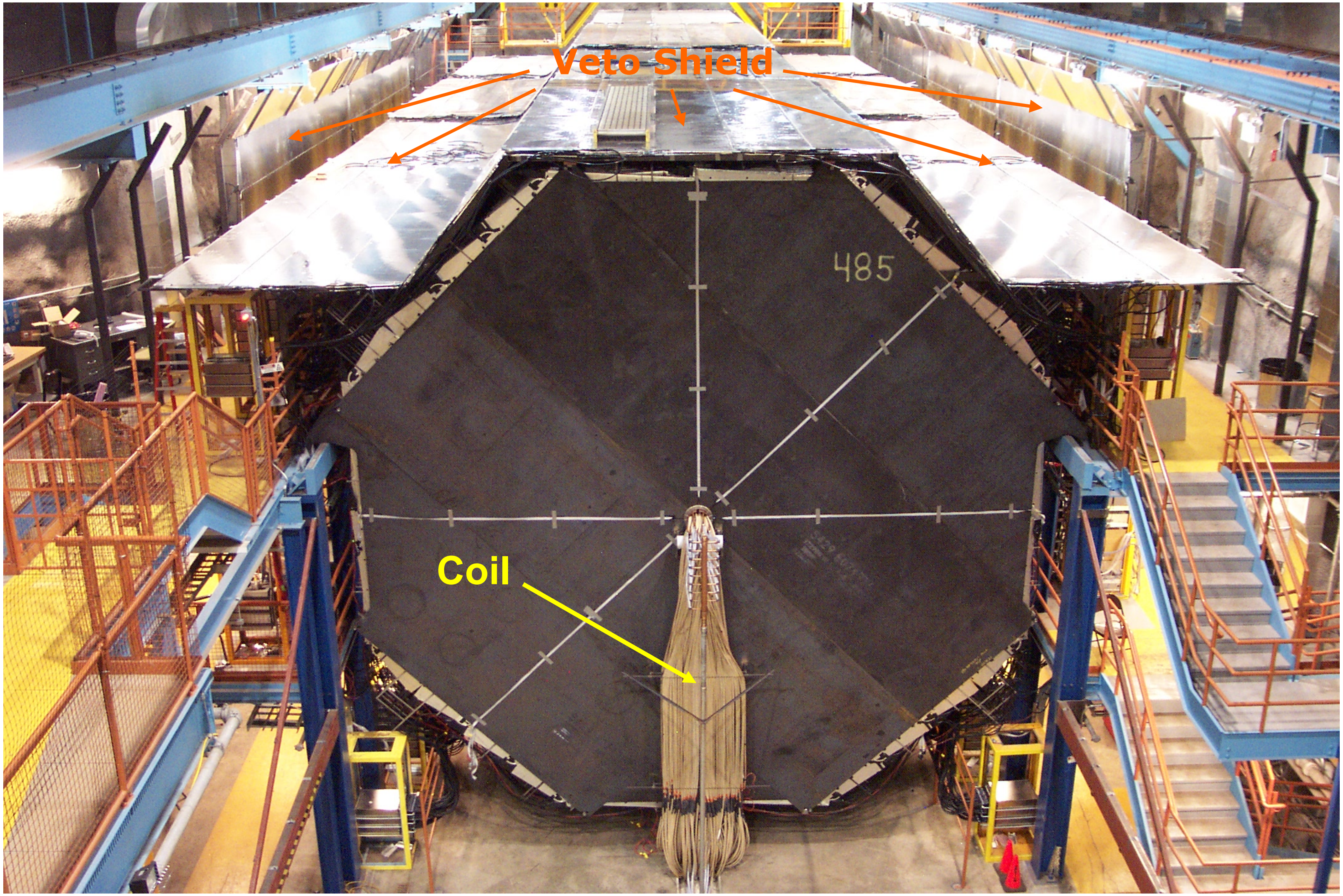


- ✦ Scintillation light collected by WLS fibre glued into groove
- ✦ Readout by multi-pixel PMTs

MINOS Far Detector during installation

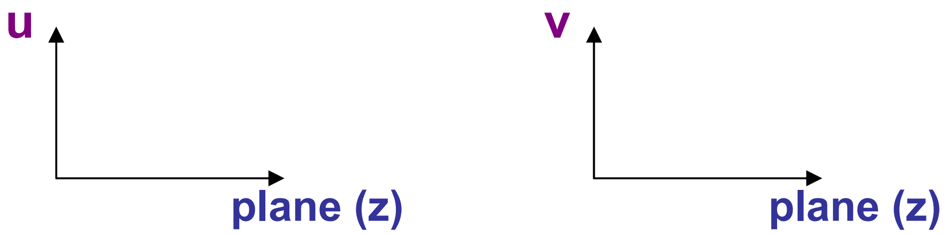


Far Detector : fully operational since July 2003



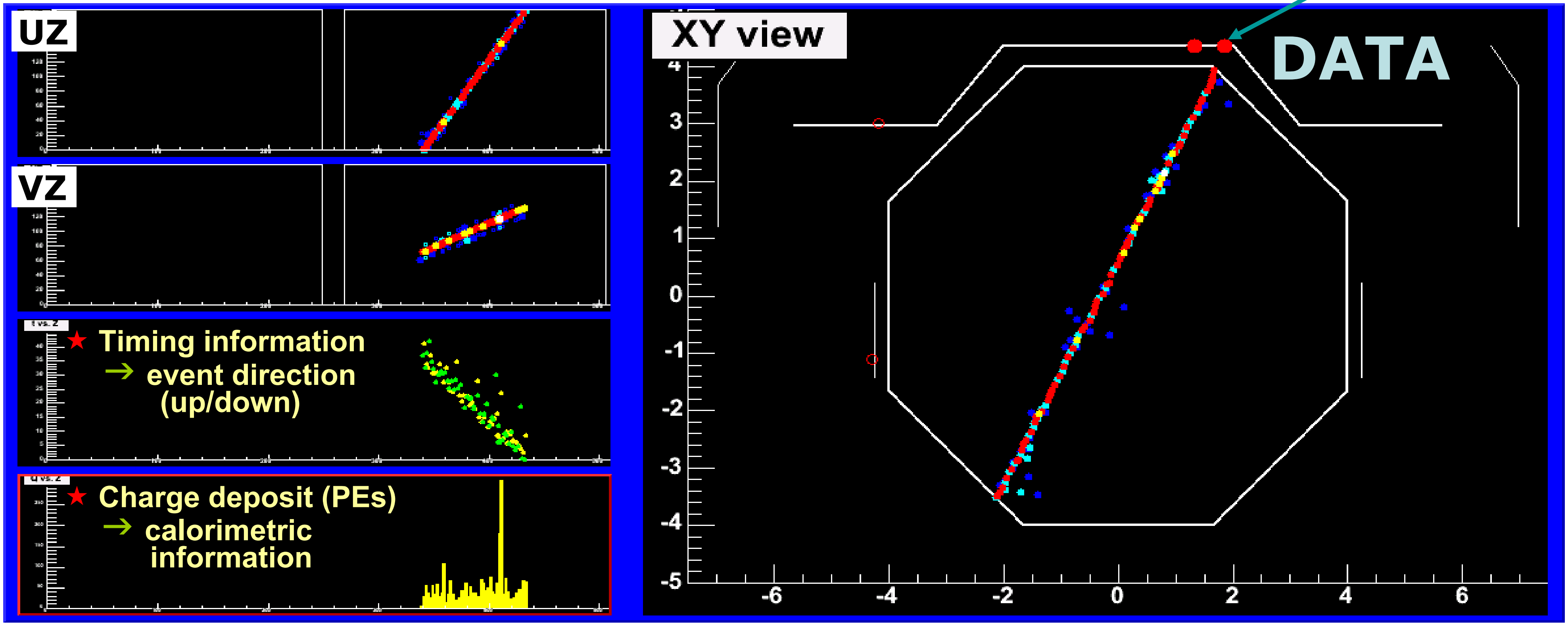
Event Information

- ★ Two 2D views of event



- ★ Software combination to get `3D' event

Veto shield hit



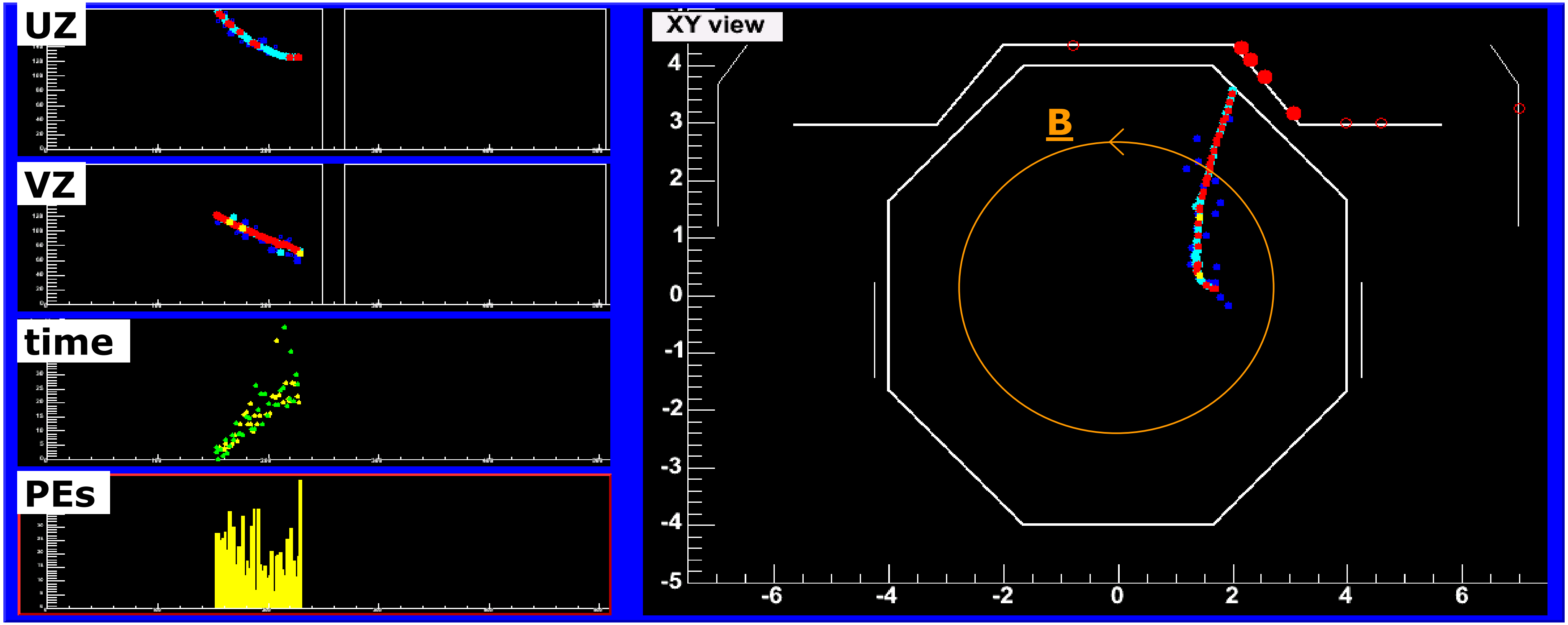
★ Timing information
→ event direction (up/down)

★ Charge deposit (PEs)
→ calorimetric information

B-Field

~1.3 T Magnetic Field

- ★ Charge separation
- ★ Momentum measurement from curvature



Single hit timing res. : 2.5 ns

Stopping cosmic-ray muon:

P_{range} = 3.86 GeV/c

$P_{curvature}$ = 4.03 GeV/c

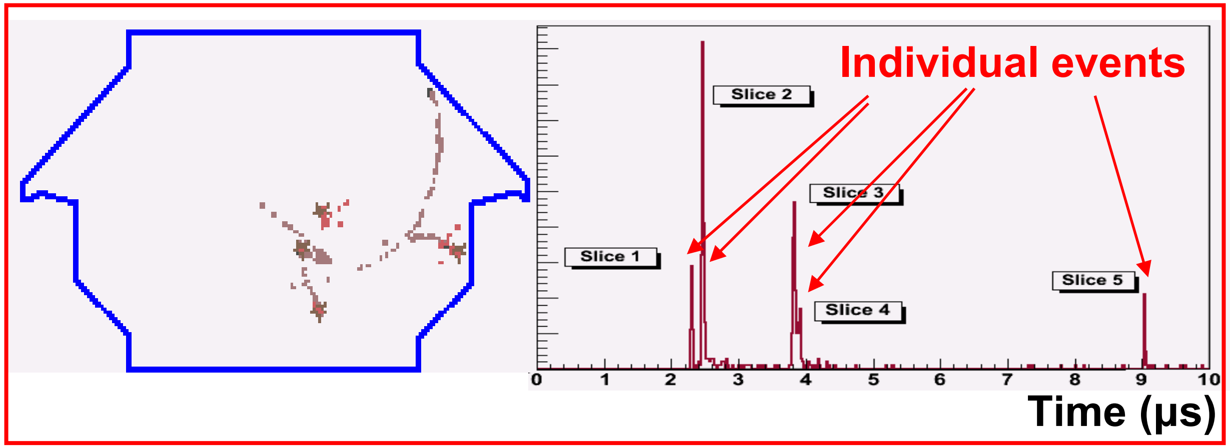
MINOS Near Detector

- ★ 1 km from beam
- ★ 1 kton total mass
- ★ Same basic design as Far Detector
  steel, scintillator, etc
- ★ **But some differences:**
  - ♦ Faster electronics
  - ♦ Different PMTs (M64 vs M16)
  - ♦ Different triggering
  - ♦ Only partially instrumented
    - ♦ **282** planes of steel
    - ♦ **153** planes of scintillator
    - ♦ (Rear part only used to track muons)

- ★ But the main difference is

EVENT RATE

- ★ Multiple event interactions per beam spill
- ★ Separated using timing + spatial information

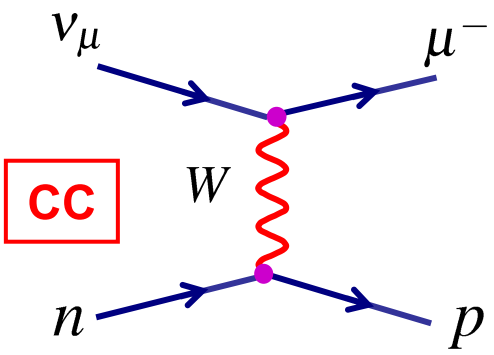


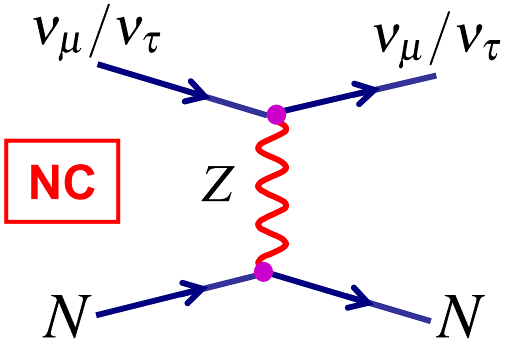
❺ ν_μ Oscillation Analysis

- ★ MINOS neutrino beam is 93 % ν_μ, 6 % $\overline{\nu}_\mu$, 1 % ν_e, and 0.1 % $\overline{\nu}_e$
- ★ For values of Δm^2_{32} from atmospheric neutrinos oscillation minimum at **~2 GeV**
- ★ In region where oscillations occur – predominantly ν_μ
- ★ Oscillations expected to be predominantly $\nu_\mu \rightarrow \nu_\tau$ (see later for ν_e)
- ★ However threshold for Charged Current (CC) ν_τ interactions is

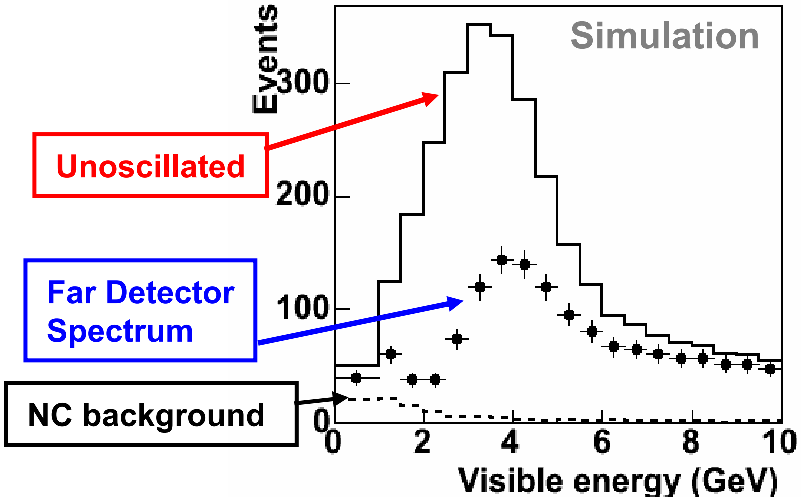
$$E_{\nu_\tau} > 2m_N m_\tau \sim 3.5\,\mathrm{GeV}$$

- ★ Oscillated $\nu_\mu \rightarrow \nu_\tau$ mostly below/close to CC threshold – effectively disappear
- ★ Analysis strategy:
  - Identify CC ν_μ interactions (i.e. reject NC interactions)
  - Reconstruct neutrino energy
  - Compare Far Detector Spectrum to expectation





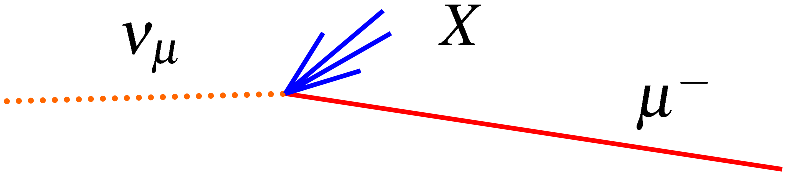
ν_μ CC spectrum



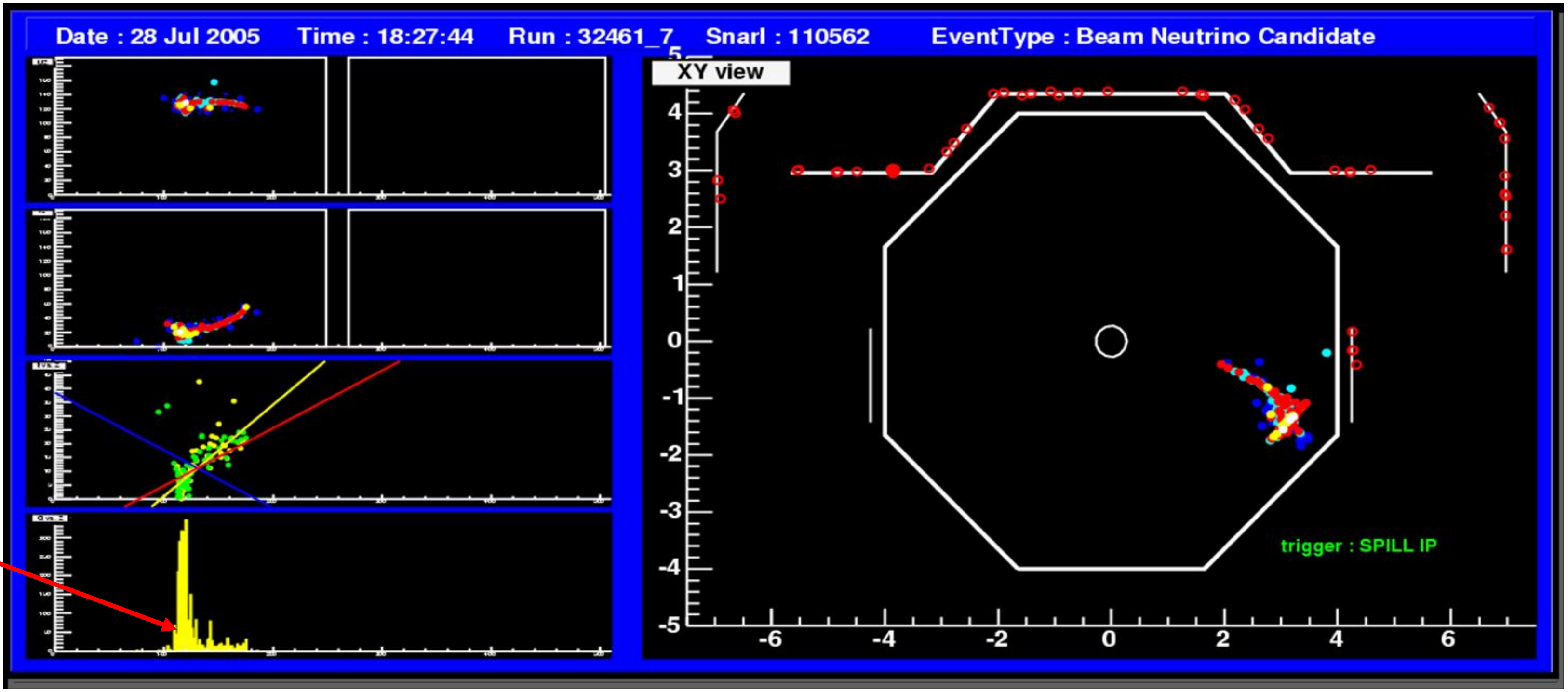
Event reconstruction

- Neutrino detection via CC interactions on nucleon (~5/day in FD)

$$\nu_\mu + N \rightarrow \mu^- + X$$



Example event:


Date : 28 Jul 2005 Time : 18:27:44 Run : 32461_7 Snarl : 110562 EventType : Beam Neutrino Candidate

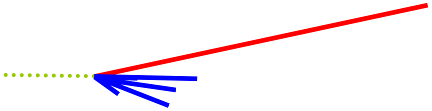
Signal from hadronic shower

- Reconstruct muon momentum + energy of hadronic system

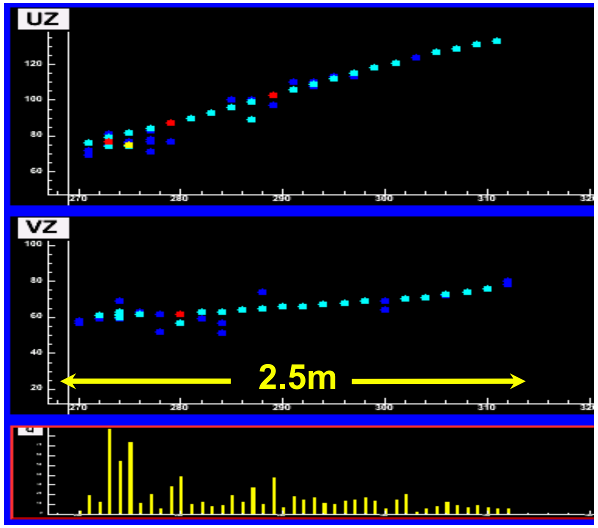
$$\boxed{E_\nu = E_\mu + E_X} \qquad \boxed{y = E_X/(E_\mu + E_X)}$$

Event Identification

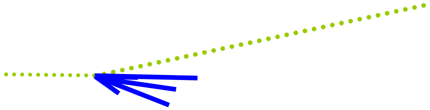
★ Different Neutrino interactions have very different event topologies



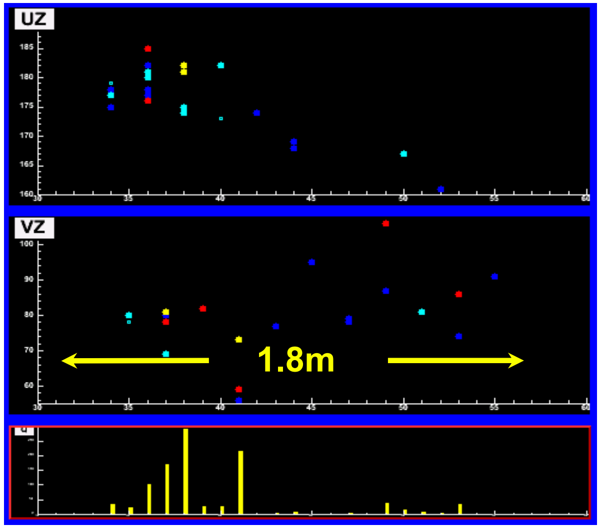
$\nu_\mu \mathrm{CC}$



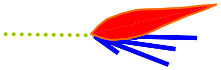
- ♦ **Clear muon track**
- ♦ **Hadronic activity at interaction vertex**



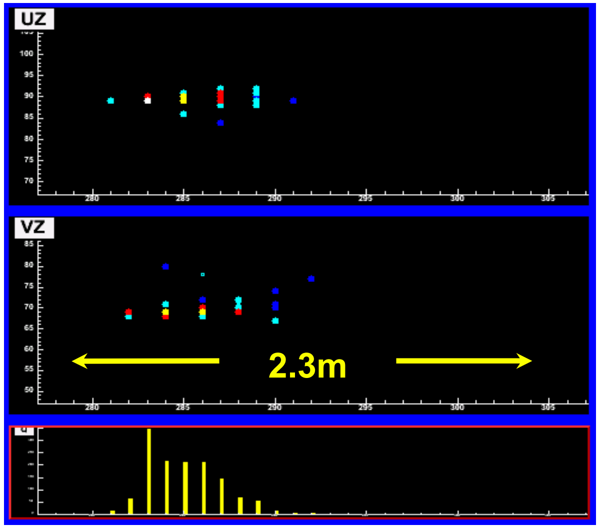
NC



- ♦ **Short**
- ♦ **Diffuse**



$\nu_e \mathrm{CC}$

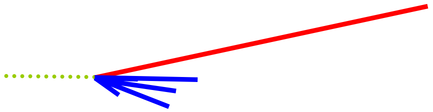


- ♦ **Compact EM shower**
- ♦ **+Hadronic activity**

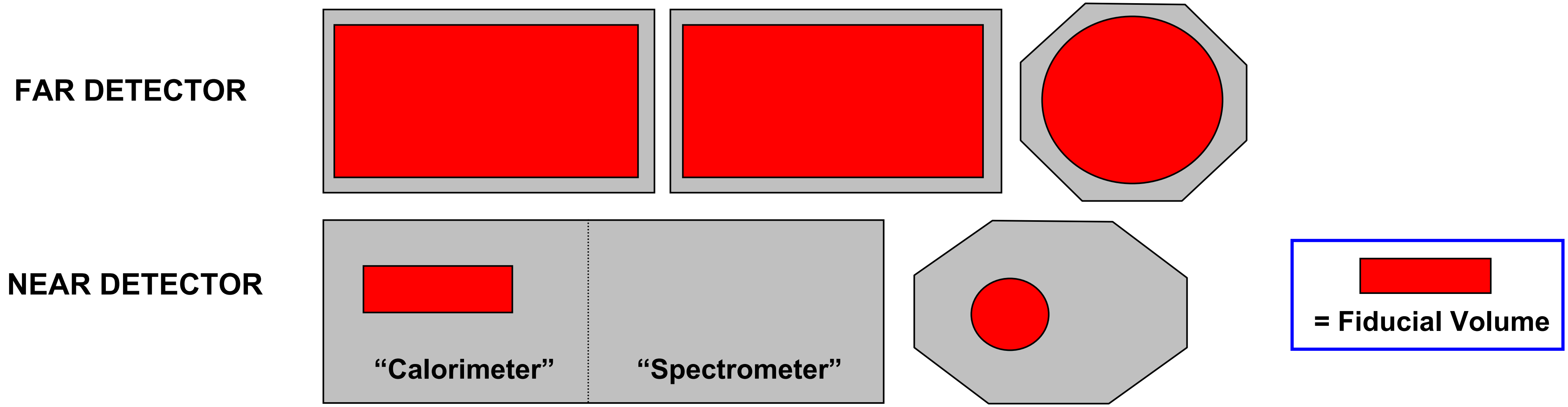
Monte Carlo

★ Use multivariate likelihood method to select $\nu_\mu \mathrm{CC}$ events in **NEAR** and **FAR** detectors

Event selection cuts : Near and Far



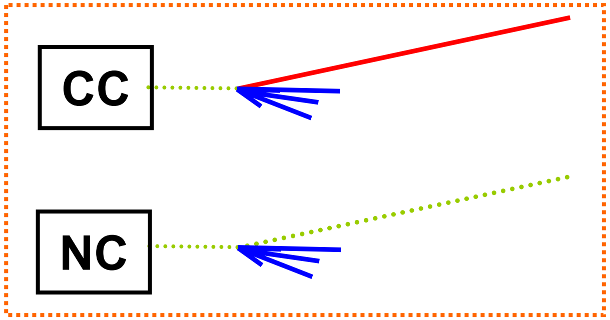
- ★ $\nu_\mu \mathrm{CC}$ candidate events are selected by requiring:
  - The event must have a good reconstructed track
  - The reconstructed track vertex must lie in the detector fiducial volume (avoid edges and less well understood regions of detector)



- ★ Likelihood selection to separate CC and NC events using **7 reconstructed quantities**

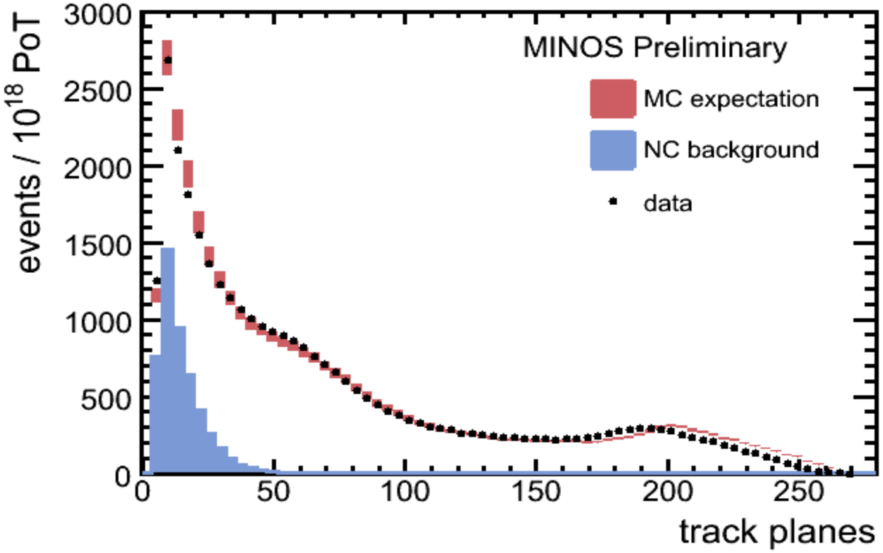
Track Topology Variables:
- ♦ Track Pulse Height Per Plane
- ♦ Number of Track-Like Planes
- ♦ Number of Planes
- ♦ Goodness of Muon Track Fit
- ♦ Reconstructed Track Charge

Event Variables:
- ♦ Neutrino Energy
- ♦ y

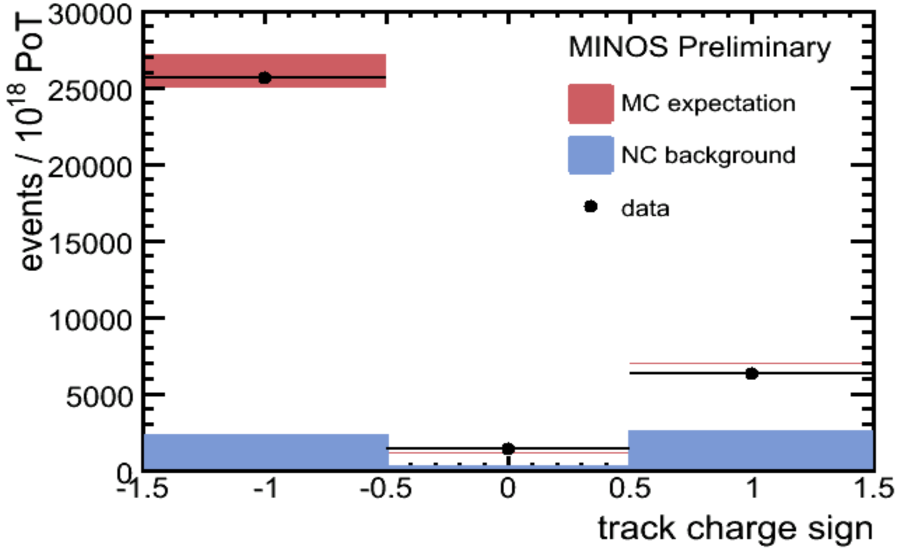


Near detector Data/MC comparisons: PID inputs

e.g.

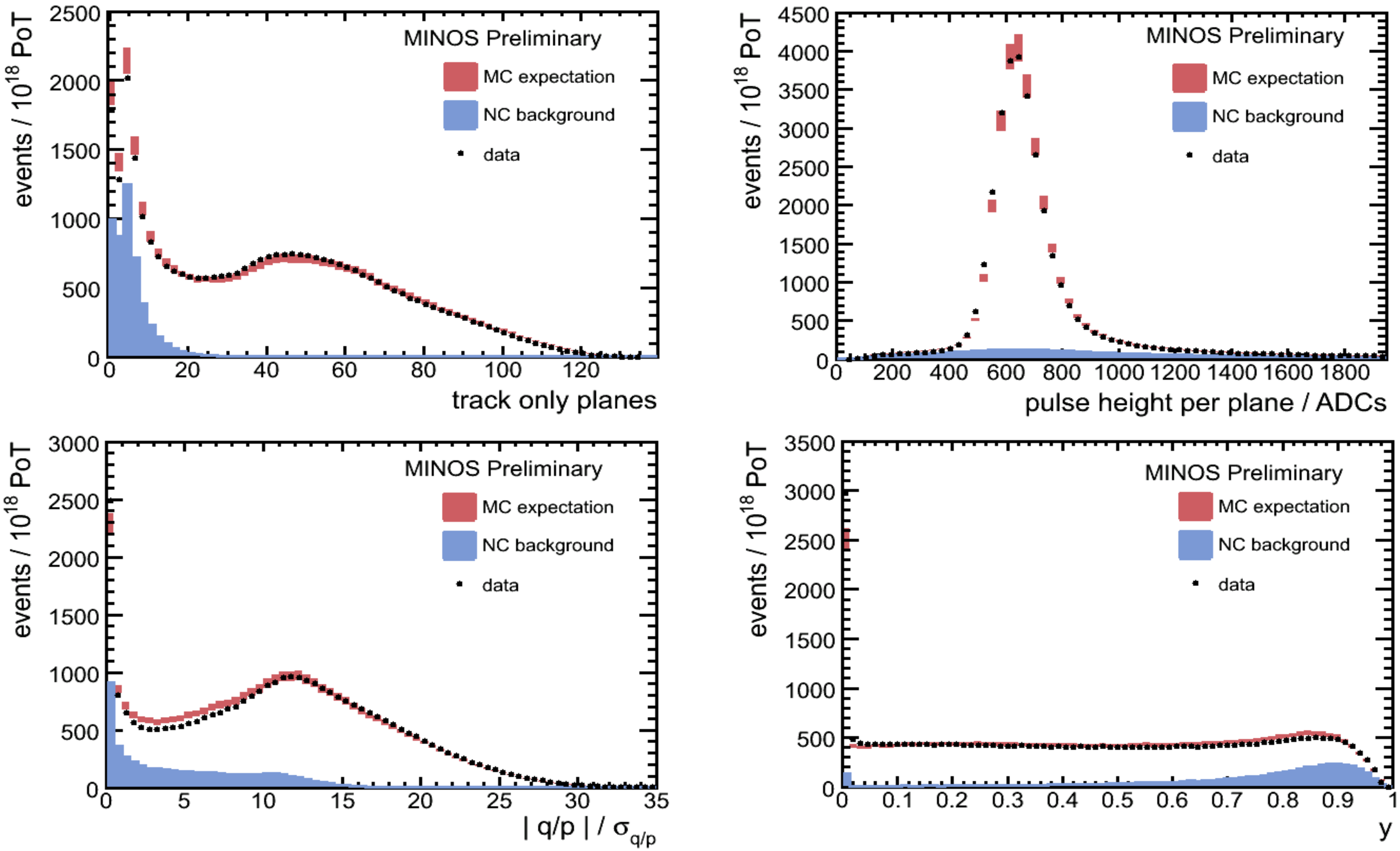


★ **Track Planes** (essentially event length)
  - CC events much longer due to presence of muon track



★ **Track charge sign** (from curvature)
  - ν_μ CC events produce a μ^-
  - Track in NC events usually a $\pi^\pm$ from hadronic system or a fake track
  - In either case equally likely to be ±

Near detector Data/MC comparisons: PID inputs, cont.



★ **High statistics Near Detector data demonstrates that all variables are reasonably well modelled !**

Combine into Likelihood discriminant

- ★ Use MC to create **NC** and **CC** probability density functions (pdfs) for each variable
- ★ Using pdfs calculate probability that an event is consistent with being **NC** and **CC**

$$\boxed{\mathrm{P_{CC}} = \prod_{i=1,7} P_i(x_i|\mathrm{CC}) = P(x_1|\mathrm{CC}).P(x_2|\mathrm{CC})\ldots}$$

$$\boxed{\mathrm{P_{NC}} = \prod_{i=1,7} P_i(x_i|\mathrm{NC})}$$

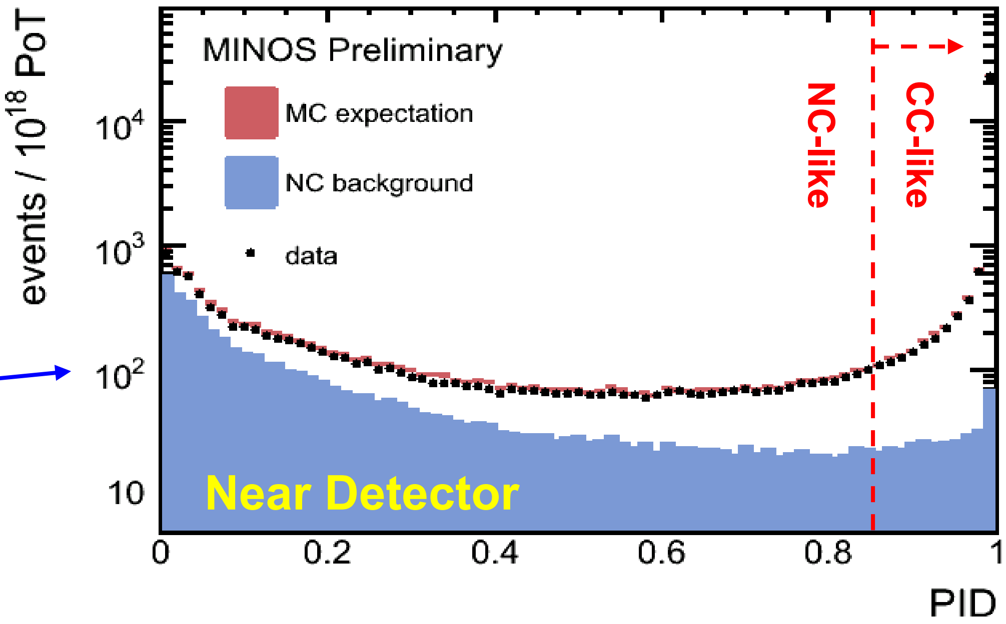
from CC PDFs for individual variables

- ★ Combine in to event "particle" identification variable "PID"

$$\boxed{\mathrm{PID} = \frac{\mathrm{P_{CC}}}{\mathrm{P_{CC}} + \mathrm{P_{NC}}}}$$

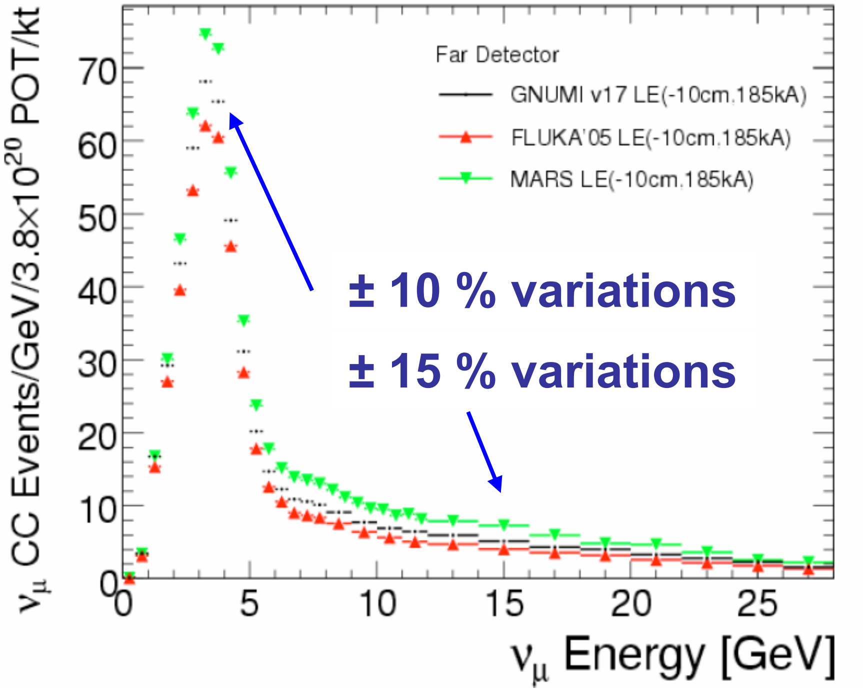
- ★ Require $\boxed{\mathrm{PID} > 0.85}$

- ★ PID variable well-modelled in **Near Detector data**



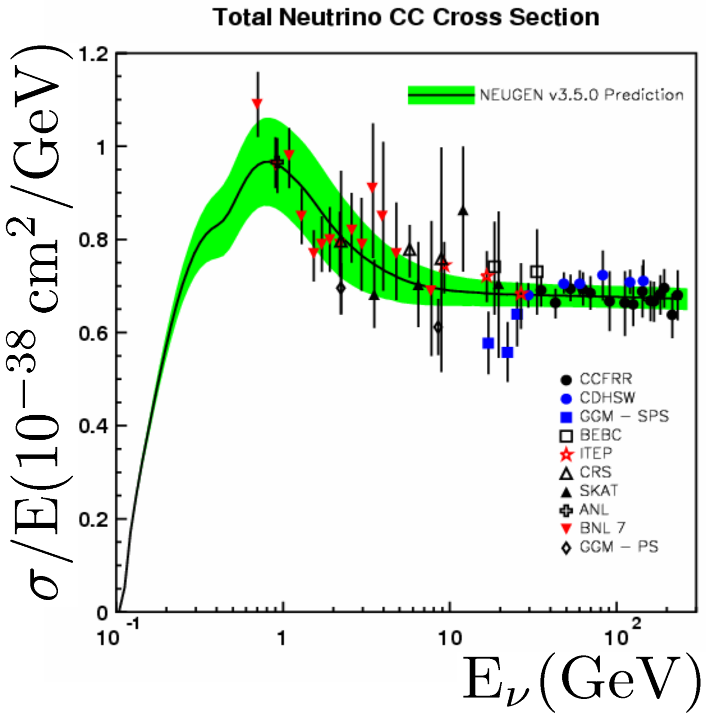
Neutrino Energy Spectrum

- ★ **We've covered the easy part** – i.e. selecting CC like neutrino interactions
- ★ Now want to compare CC neutrino energy spectrum in Far Detector to Monte Carlo expectation with and without oscillations, and fit etc.
- ★ To do this need to be able to accurately predict expected event rate
- ★ Require:
  - ▪ accurate simulation of neutrino flux from **120 GeV protons** hitting target
  - ▪ accurate simulation of (low energy) neutrino cross sections
- ★ NEITHER EXIST – due to lack of appropriate data !



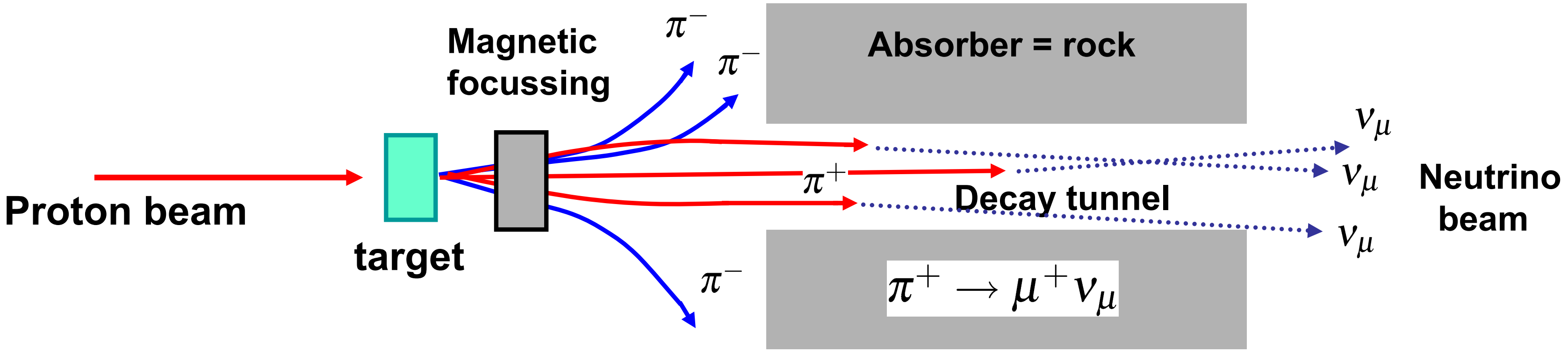
± 10 % variations

± 15 % variations

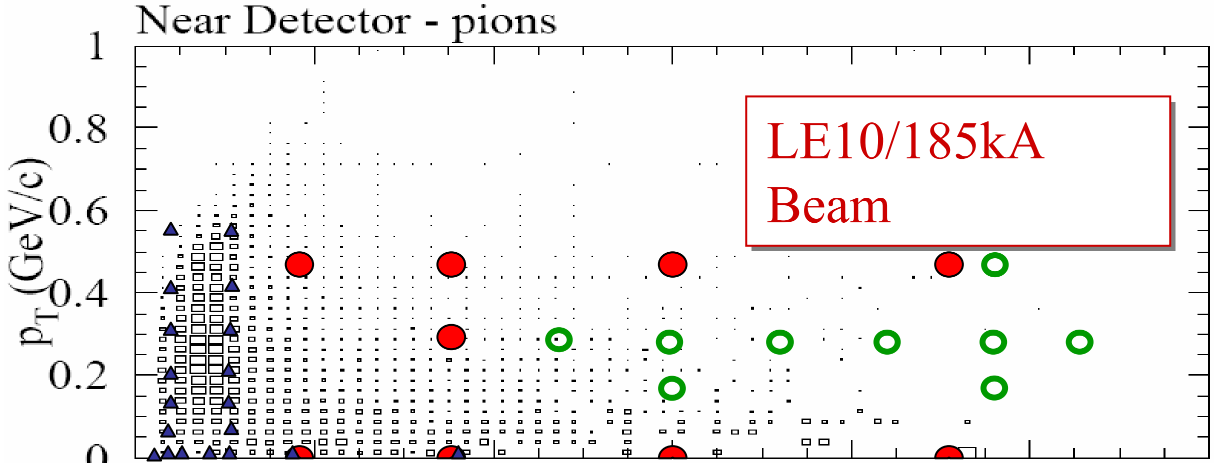


Hadron Production…

- ★ Perhaps the hardest part is predicting the neutrino flux
- ★ To do this need to know **energy** and $\mathbf{p_T}$ spectrum of meson from target



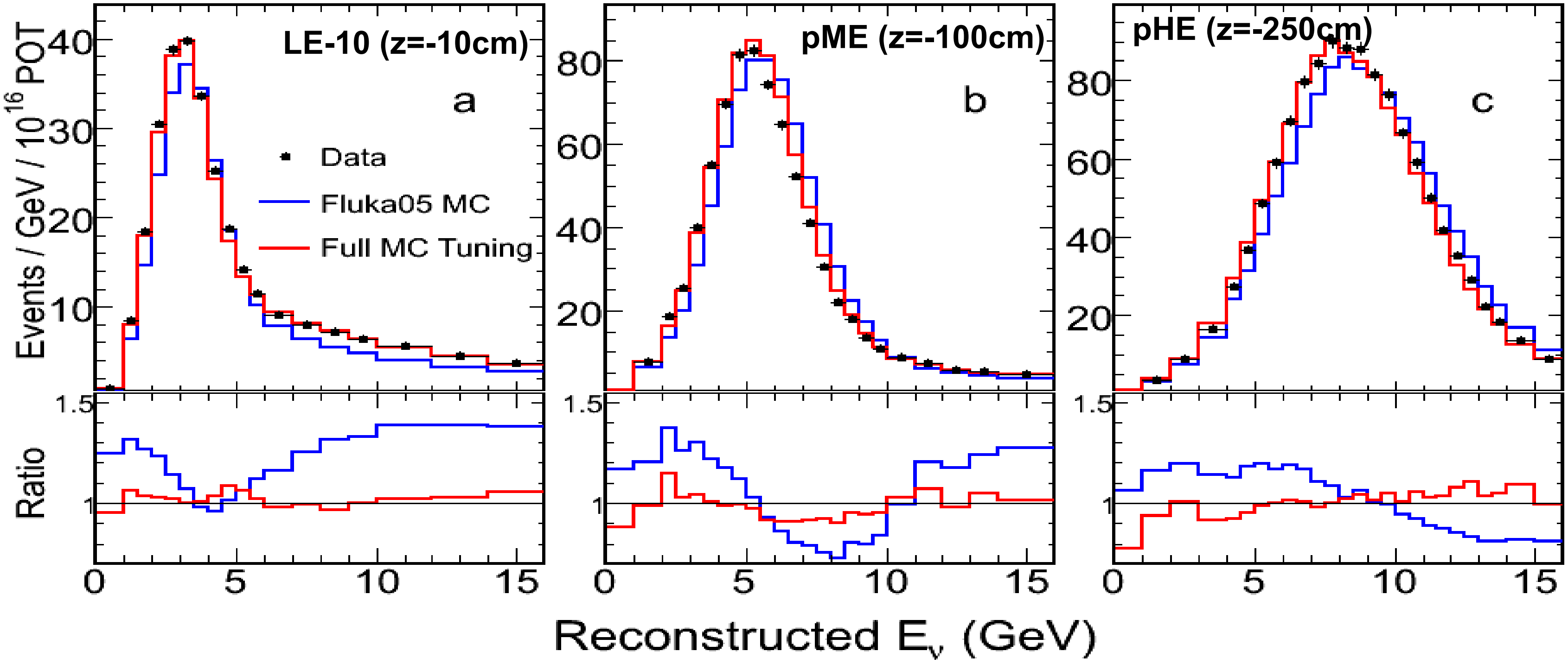
- ★ Hadron cascade models (e.g. GEANT, Fluka, MARS) all tuned to data
- ★ But data in relevant $\mathbf{p_T}$, $\mathbf{x_F}$ region is relatively sparse



- ★ Situation will improve with data from MIPP experiment at Fermilab

The Near Detector to the Rescue

- ★ **Want the expected Far Detector (FD) energy spectrum for selected CC events**
- ★ **Use the measured Near Detector (ND) energy spectrum**
- ★ **First "tune" Monte Carlo using ND data recorded in 7 different beam settings, e.g.**



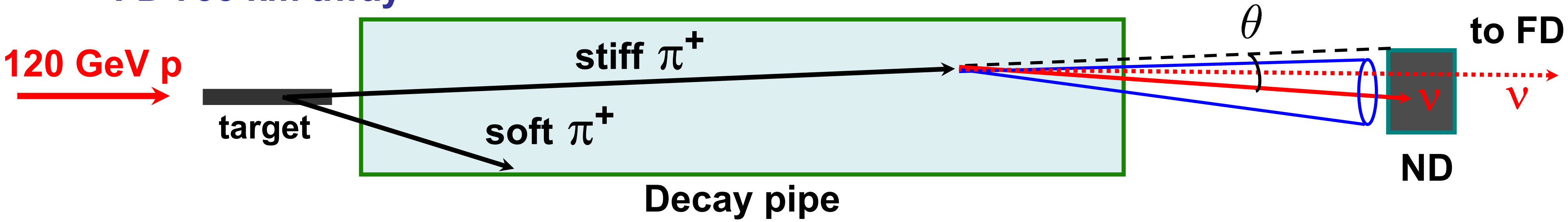
- **Discrepancy between data and nominal (FLUKA05) MC changes with beam setting**
- **Suggestive that discrepancy is mainly due to flux rather than cross-section model**
- **Tune MC to ND data using a function that varies smoothly with hadronic x_F and p_T**
- **Tuned MC gives better agreement with data in all beam configurations**

Extrapolating to the Far Detector

- ★ BUT: even in the absence of oscillations the NEAR and FAR detector neutrino spectra are different !

<u>**Easy to understand…**</u>

- ★ Consider a pion decaying in the decay pipe
- ★ Neutrino can intersect the ND for a relatively wide range of decay angles
- ★ For far detector only decays in a very small range of angles will cross the FD 735 km away

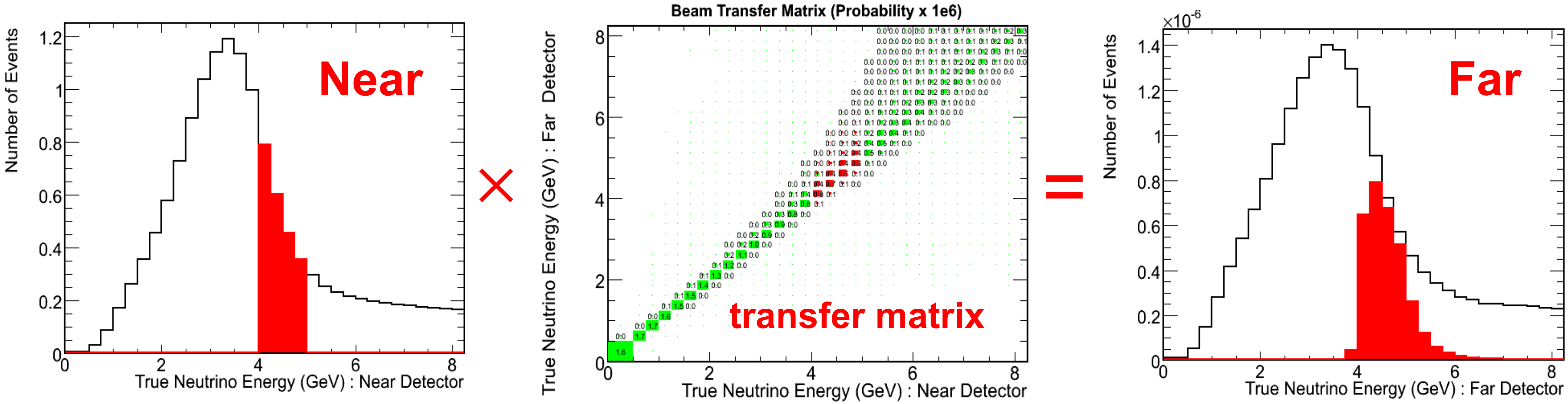


- ★ From simple relativistic kinematics for pion decay – neutrino energy depends on decay angle relative to pion line of flight

$$\boxed{E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}}$$

- ★ Decays with neutrinos pointing towards the FD tend to have smaller θ and hence have slightly higher energy
- ★ Difference is just kinematics, i.e. well understood !

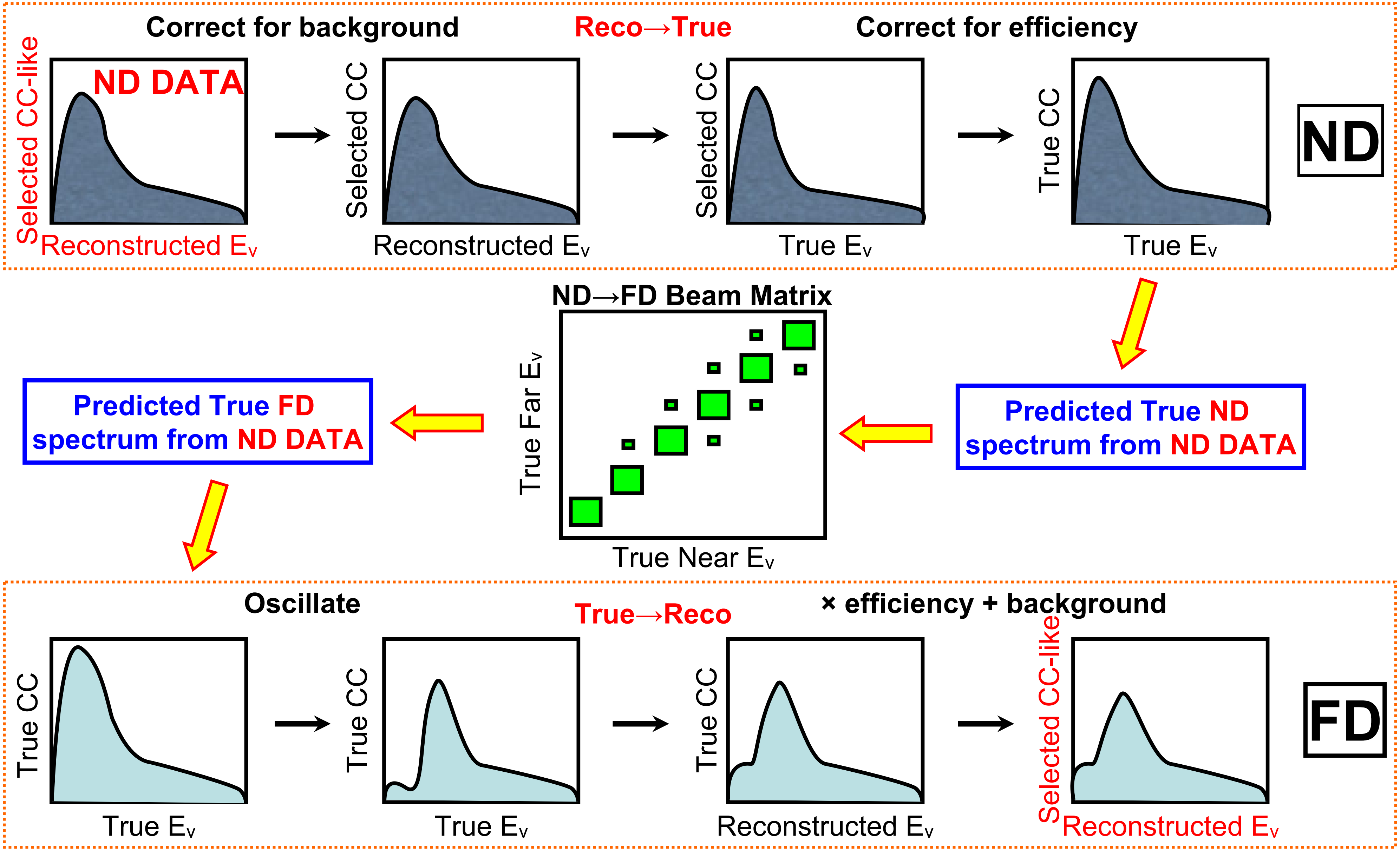
The Beam Transfer Matrix



Beam Transfer Matrix:

- Encapsulates knowledge of 2-body pion decay and geometry
- Provides a simple way of relating near and far detector energy spectra
- Beam matrix determined from MC but does not depend strongly on details; kinematics & geometry dominate
- Near detector data “directly” determines predicted Far Detector spectrum

Details of matrix Near → Far beam extrapolation



Correct for background **Reco→True** **Correct for efficiency**

ND DATA

ND

ND→FD Beam Matrix

Predicted True ND spectrum from ND DATA

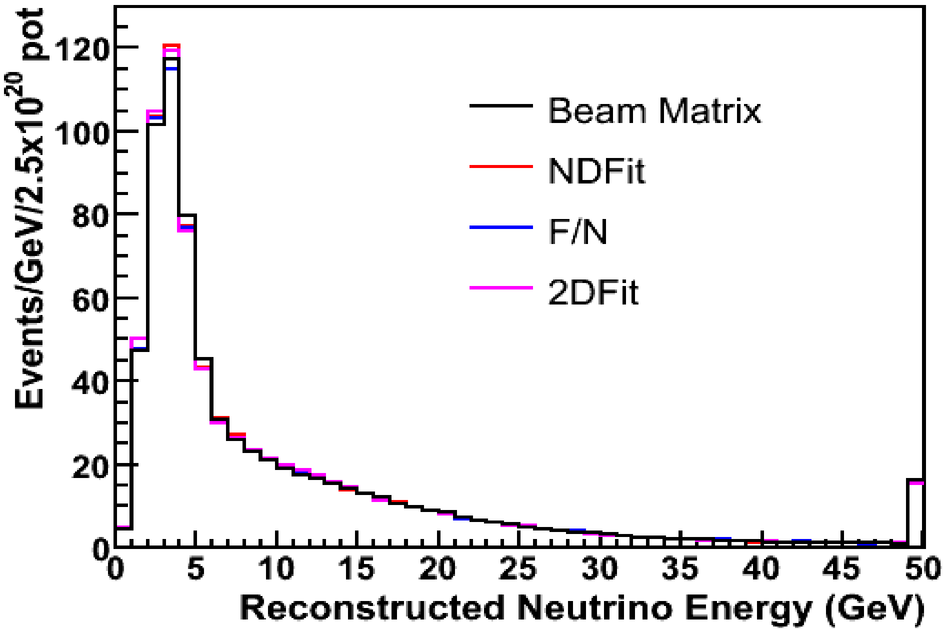
Predicted True FD spectrum from ND DATA

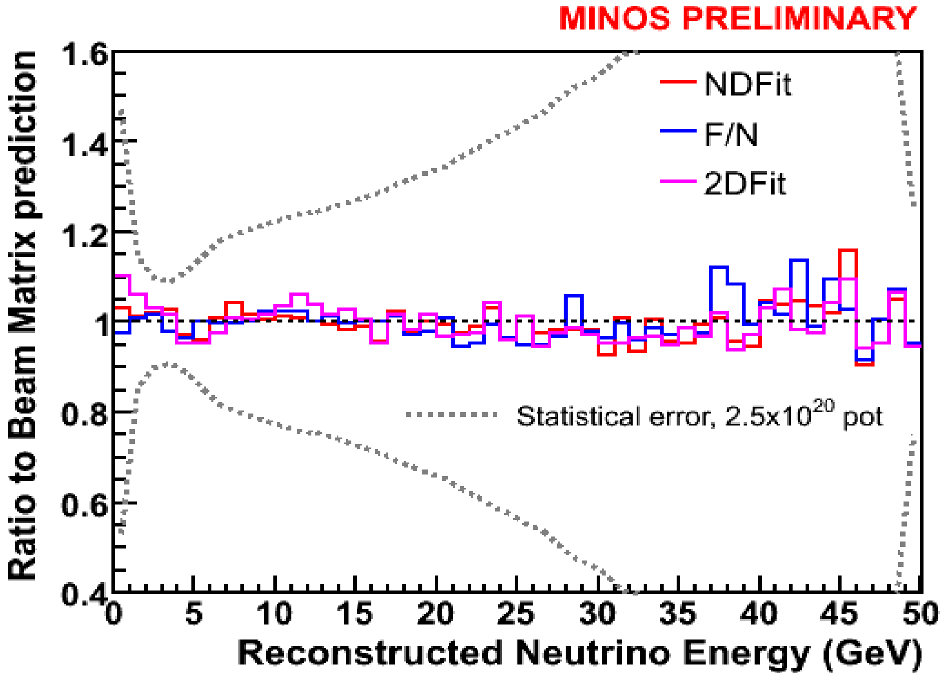
Oscillate **True→Reco** **× efficiency + background**

FD

Cross-checks of the extrapolated spectrum

- ★ In addition to Beam Matrix Method have 3 cross-check methods to extrapolate ND energy spectrum:
  - Data-driven : **Far/Near ratio** “simple ID version of beam matrix”
  - Fit-based Methods : **NDFIT** and **2DFit**





- ★ Predicted Far Detector energy spectra agree with ±4 %
- ★ **Much better than expected statistical error**
- ★ **Confident in far detector expectation…**
- ★ **LOOK AT FAR DETECTOR DATA (blind analysis)**

Far Detector beam events

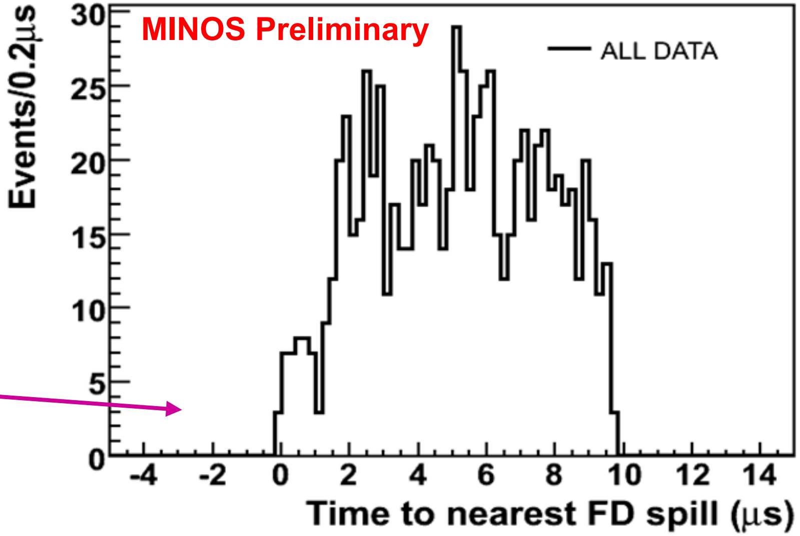
Cut	Number of Events
Track in fiducial volume	847
Data quality cuts	830
Timing cuts	828
Beam quality cuts	812
Track quality cuts	811
Track charge <= 0	672
CC PID parameter>0.85	564
Reco E_ν <200 GeV	563 (Final sample)

Reject non-beam background, cosmic ray muons, etc.

Reject CC $\overline{\nu}_\mu$ Events

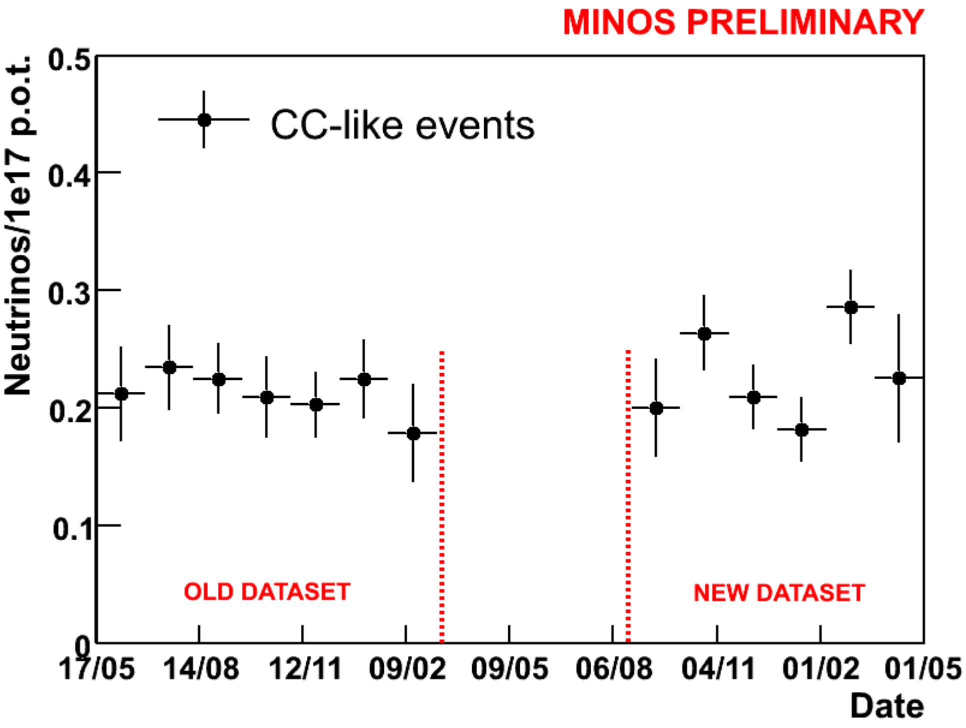
Reject NC Events

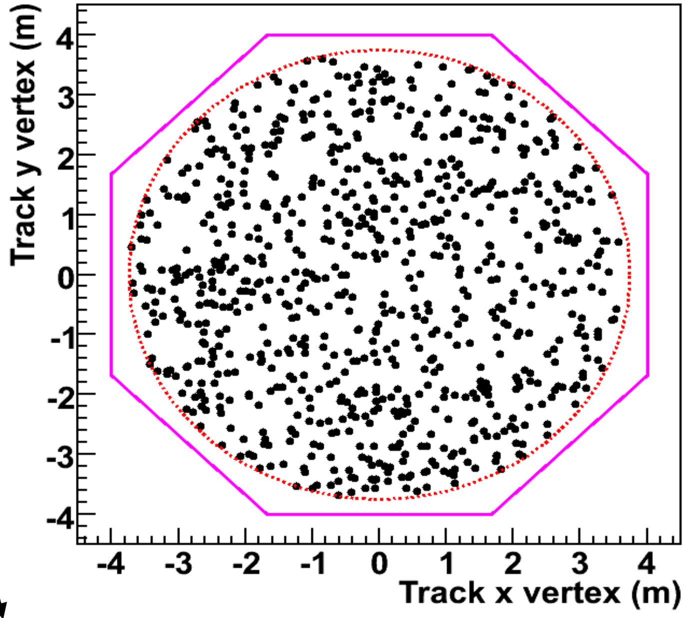
- ★ Very clean event sample
- ★ Non-beam background < 0.5 events
  (no candidates in 50μs window around spill time)

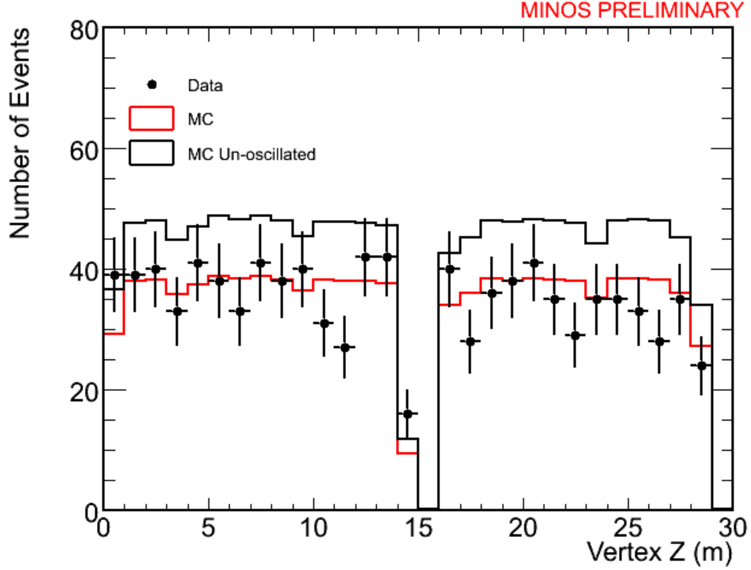


FD Events

- **Far detector data well modelled by MC**
- **No indication of any unexpected background**
- **Events distributed uniformly in time and space**

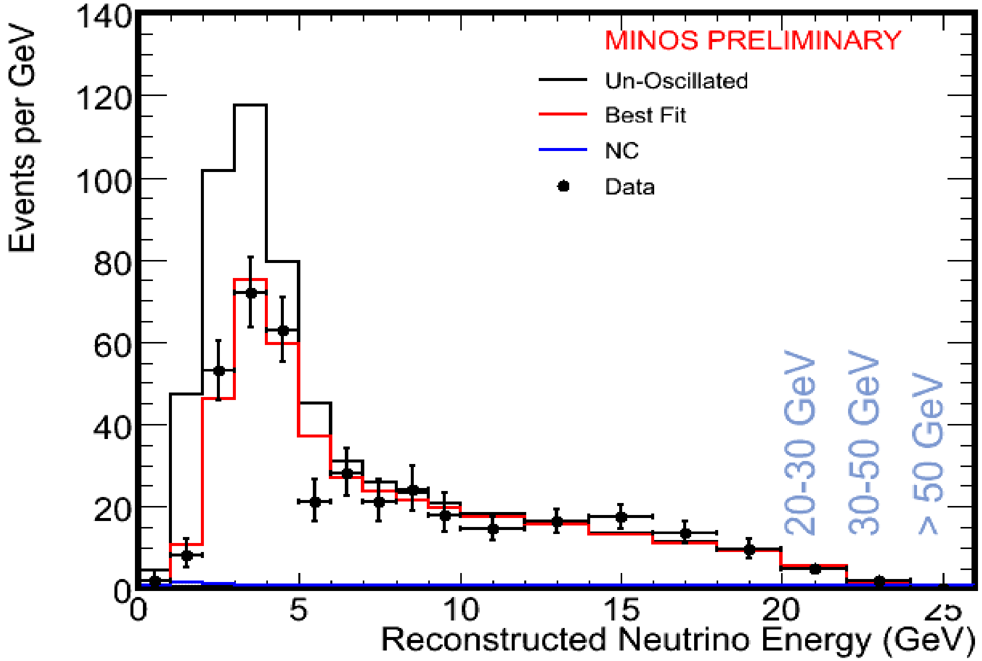


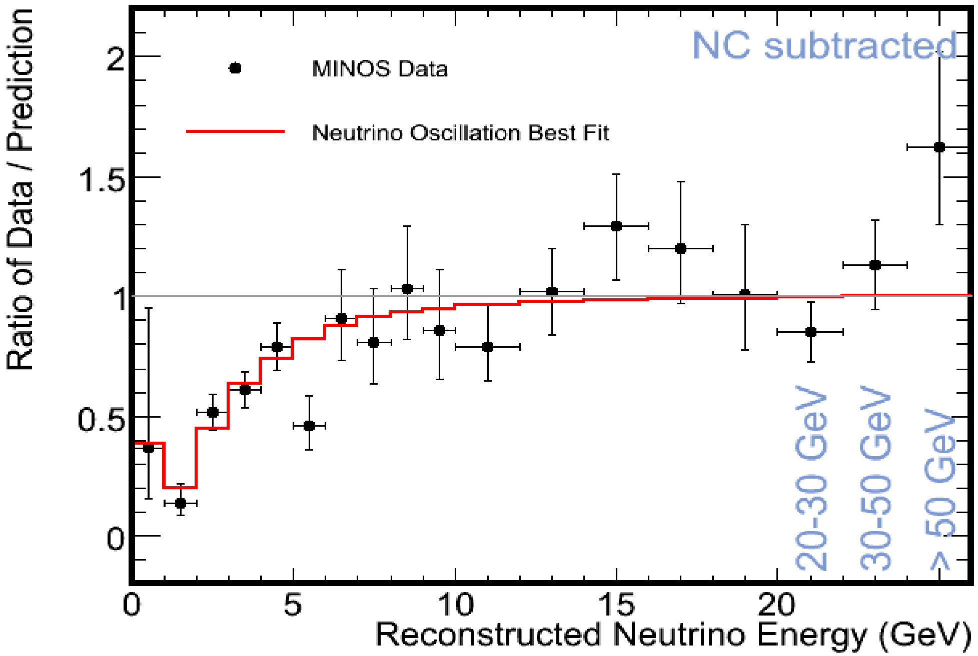




Oscillation Analysis

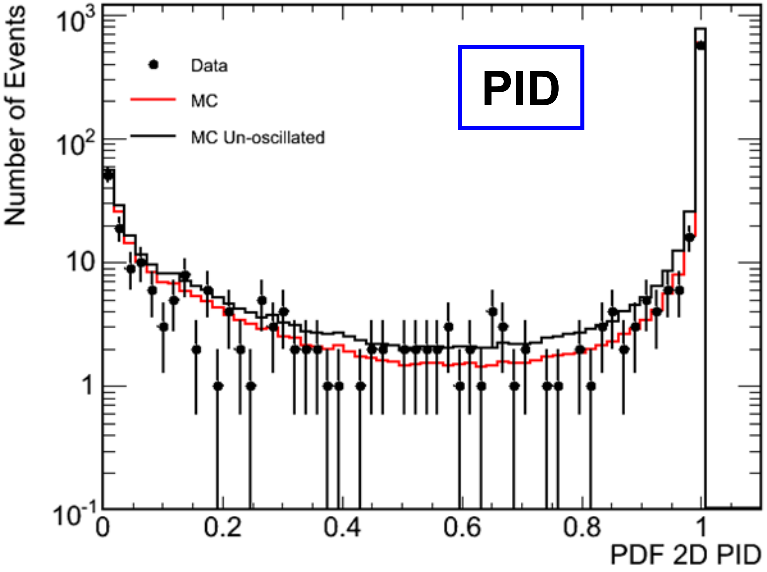
PRELIMINARY OSCILLATION RESULTS FOR 2.5x10^{20} POTs DATA.

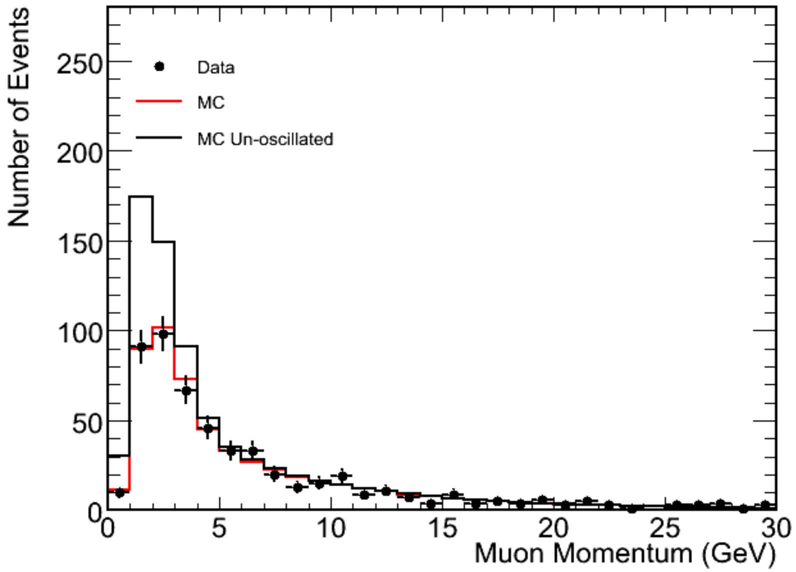


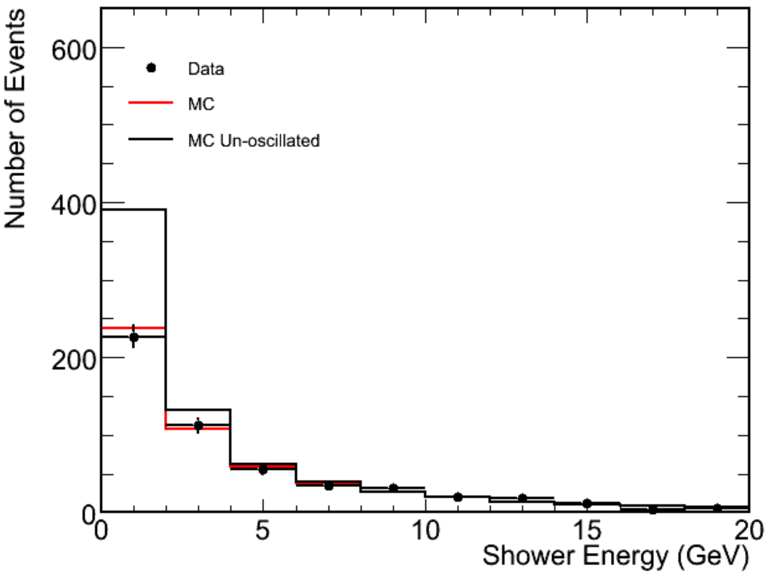


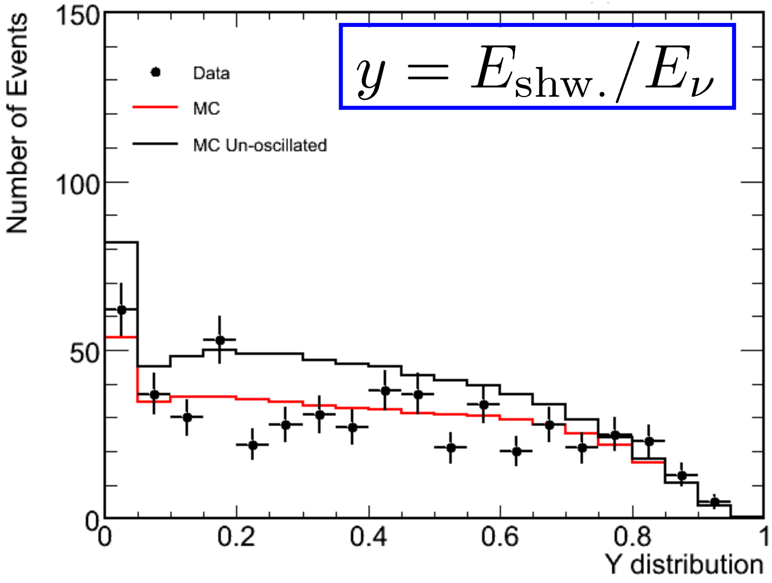
Data sample	Observed	Expected (no osc.)	Observed / Expected
ν_μ (all E)	563	738 ± 30	0.74 (4.4σ)
ν_μ (<10 GeV)	310	496 ± 20	0.62 (6.2σ)
ν_μ (<5 GeV)	198	350 ± 14	0.57 (6.5σ)

Far detector distributions









Oscillation Fit/Systematic Uncertainties

- Oscillation parameters extracted from likelihood fit to reconstructed energy distribution of 563 selected Far Detector events

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \sum_{i=1}^{nbins} \underbrace{2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{systematic errors}}$$

- The three largest uncertainties identified from this study are included as nuisance parameters in the oscillation analysis.

Uncertainty	Δm^2 (10^{-3} eV^2)	$\sin^2 2\theta$
Near/far normalization (4%)	0.065	<0.005
Abs. shower energy scale (10%)	0.075	<0.005
NC normalization (50%)	0.010	0.008
All other systematics	0.040	<0.005
Total uncertainty (quad. sum)	0.11	0.008
Statistical uncertainty	0.17	0.080

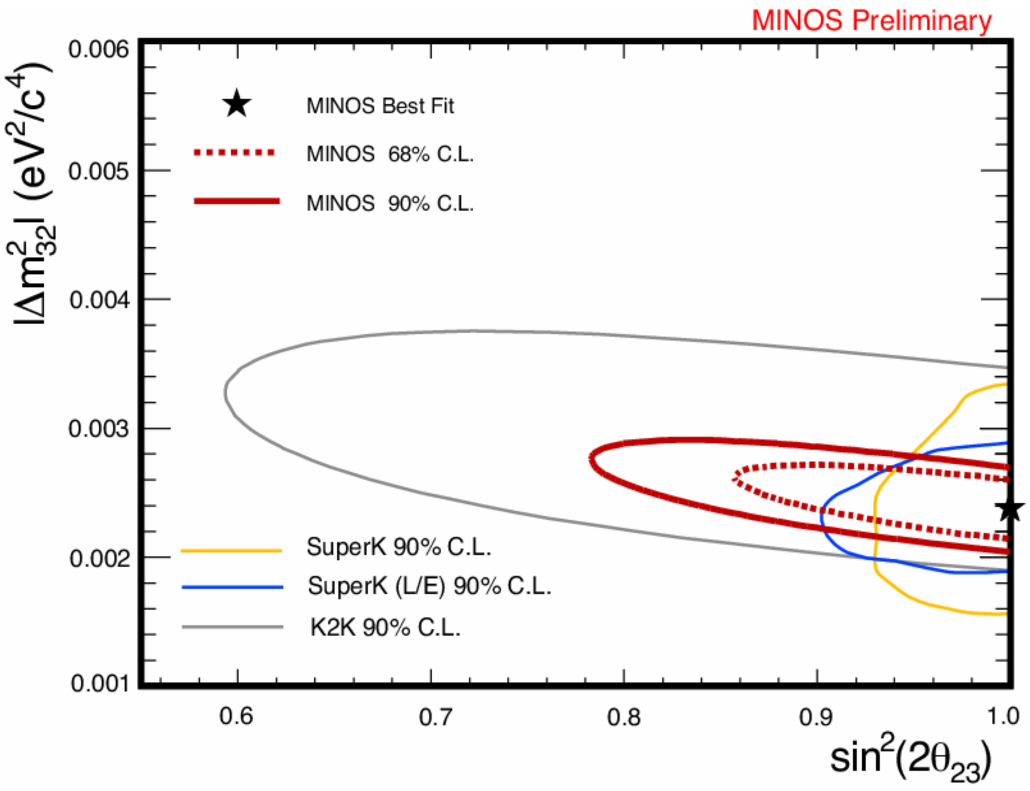
★ Currently statistical uncertainties dominate !

Results

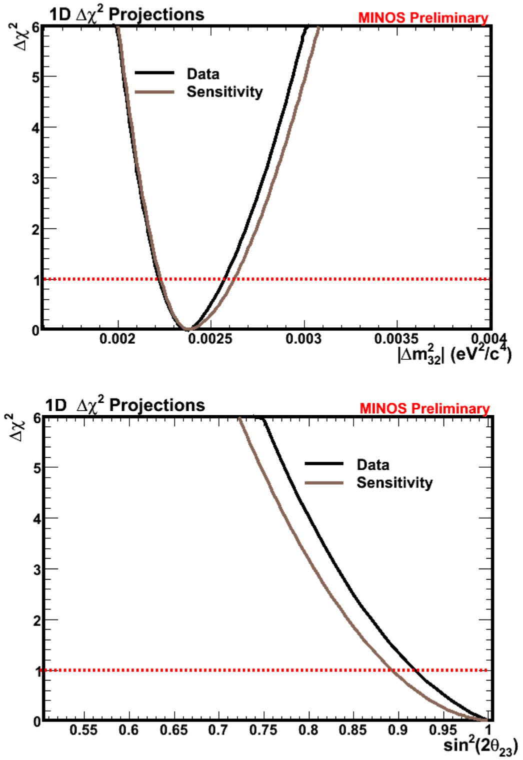
Best fit values:

$$|\Delta m^2_{32}| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2 2\theta_{23} = 1.0 \quad (> 0.92\,@68\,\%\mathrm{C.L.})$$

$$\chi^2/n_{d.o.f} = 41.2/32$$



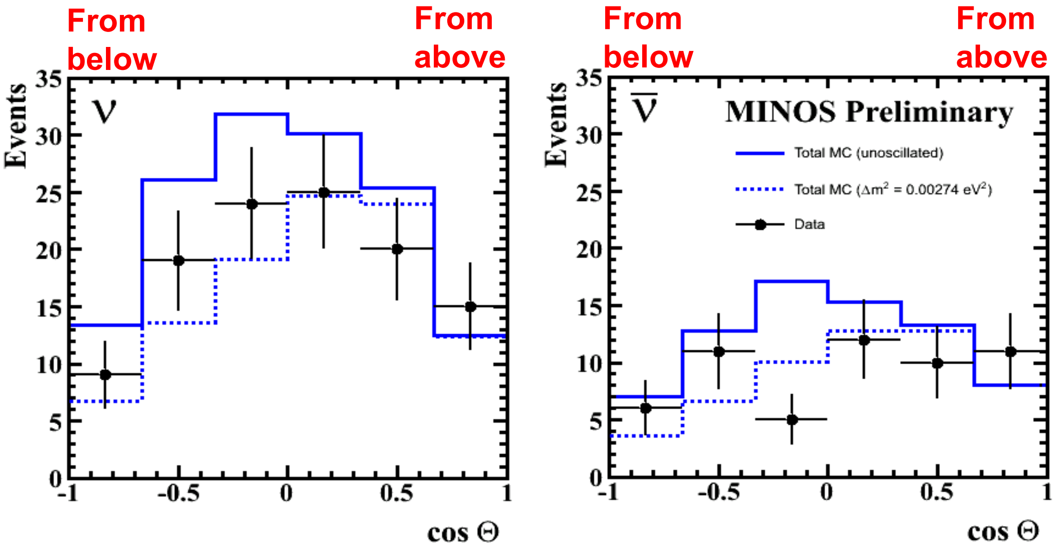
1D $\Delta\chi^2$ Projections



❻ Other Results: Atmospheric Neutrinos

- ★ Event rate for 5.4 kton FD: 200 per year
- ★ 700m depth provides shielding from cosmic-ray μ
  - ▪ Event rate ~0.5 Hz
- ★ Magnetic field enables separation of ν_μ and $\overline{\nu}_\mu$
  - ♦ MINOS is unique in this capability
- ★ Start to test oscillations separately for $\nu_\mu/\overline{\nu}_\mu$
  - ♦ Test of CPT in neutrino sector
- ★ Currently cleanly identify 112 ν_μ and 55 $\overline{\nu}_\mu$

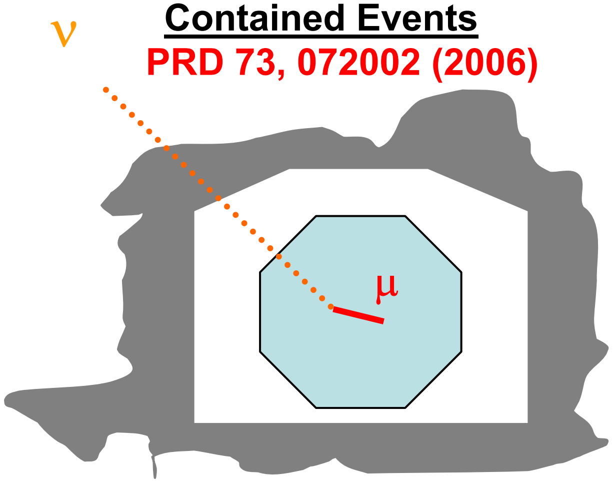
$$\boxed{R^{\text{data}}_{\overline{\nu}/\nu}/R^{\text{MC}}_{\overline{\nu}/\nu} = 0.93^{+0.19}_{-0.15} \pm 0.12(sys.)}$$



- ▪ Higher statistics results out later this year.

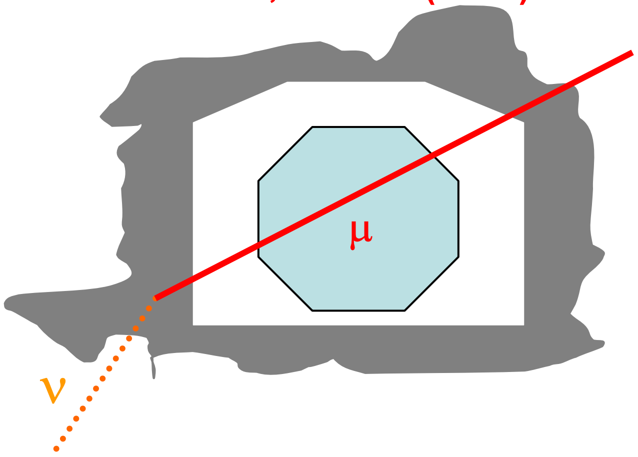
Contained Events

PRD 73, 072002 (2006)



Rock interactions

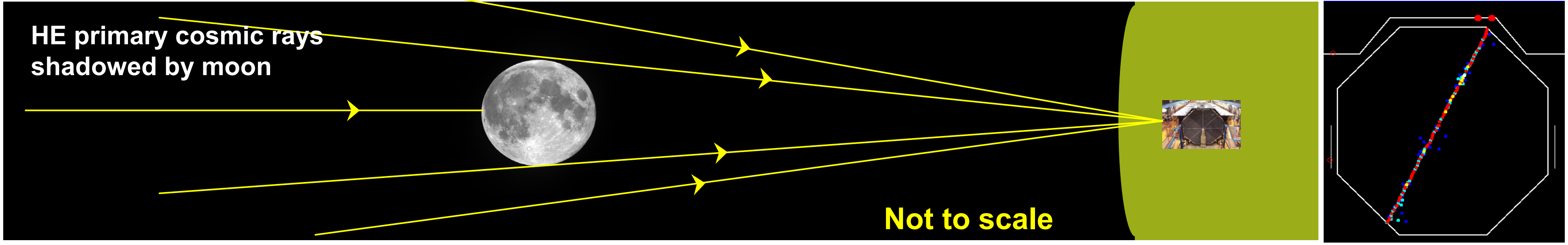
PRD 75, 092003 (2007)

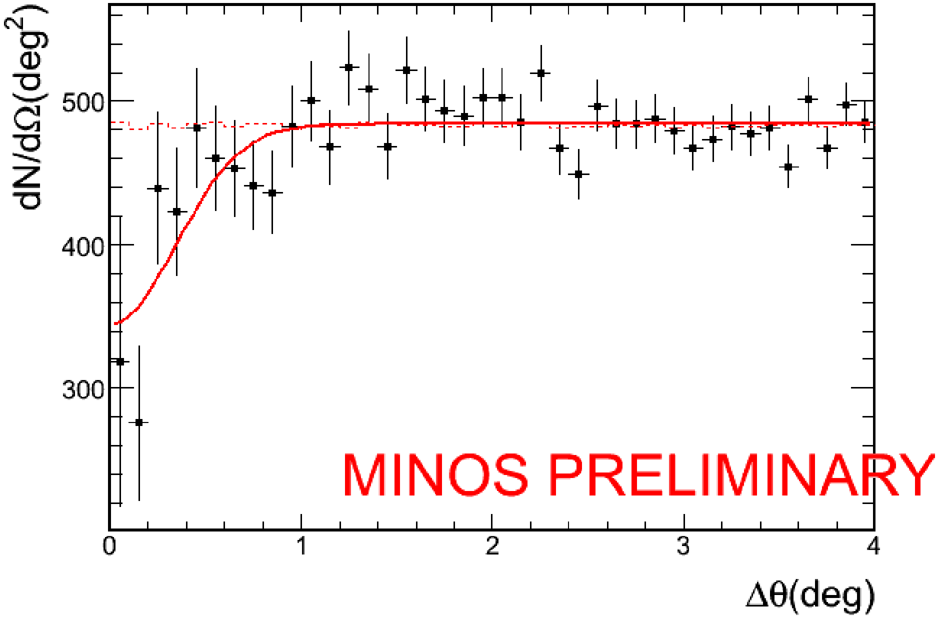


Other Results: Cosmic-Ray Physics

- ★MINOS is a large deep underground detector and can make a number of interesting cosmic-ray measurements, e.g.

Cosmic-ray Moon shadow





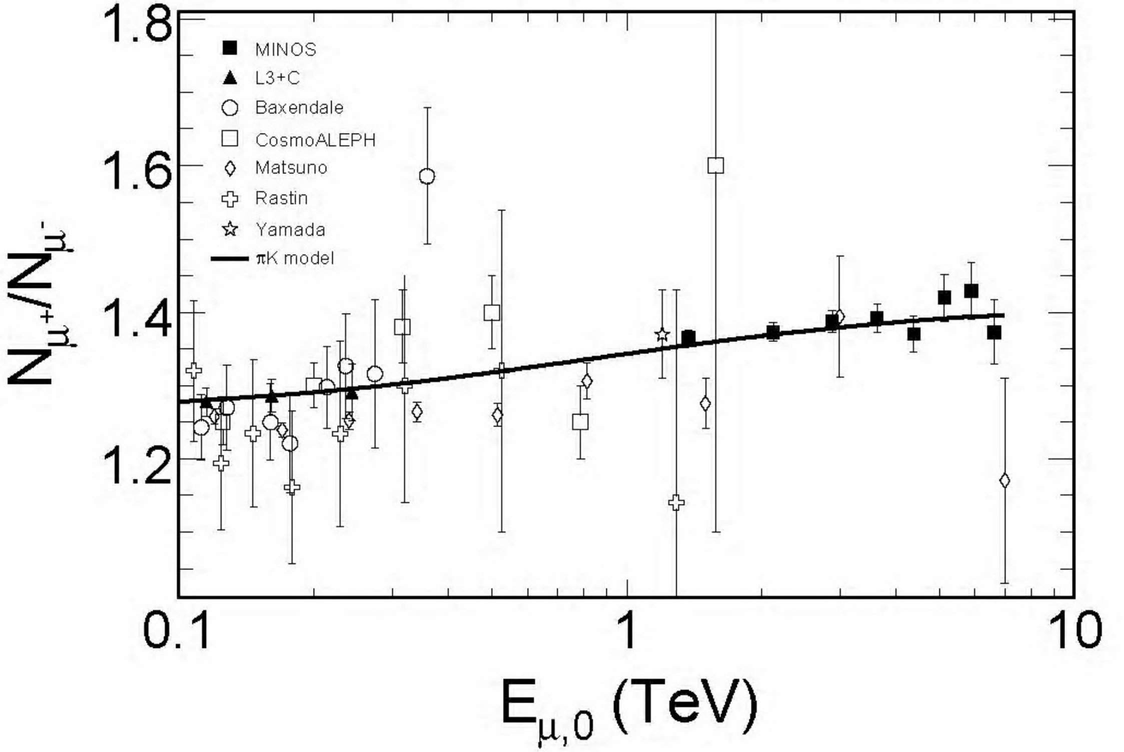
Demonstrates:

- that the moon exists
- we understand our reconstruction

Looking for sun-shadow is more interesting as it probes solar magnetic field (ongoing work)

Cosmic-Ray Physics cont.

- ★Can also take advantage of Magnetic field and measure the cosmic-ray muon charge ratio

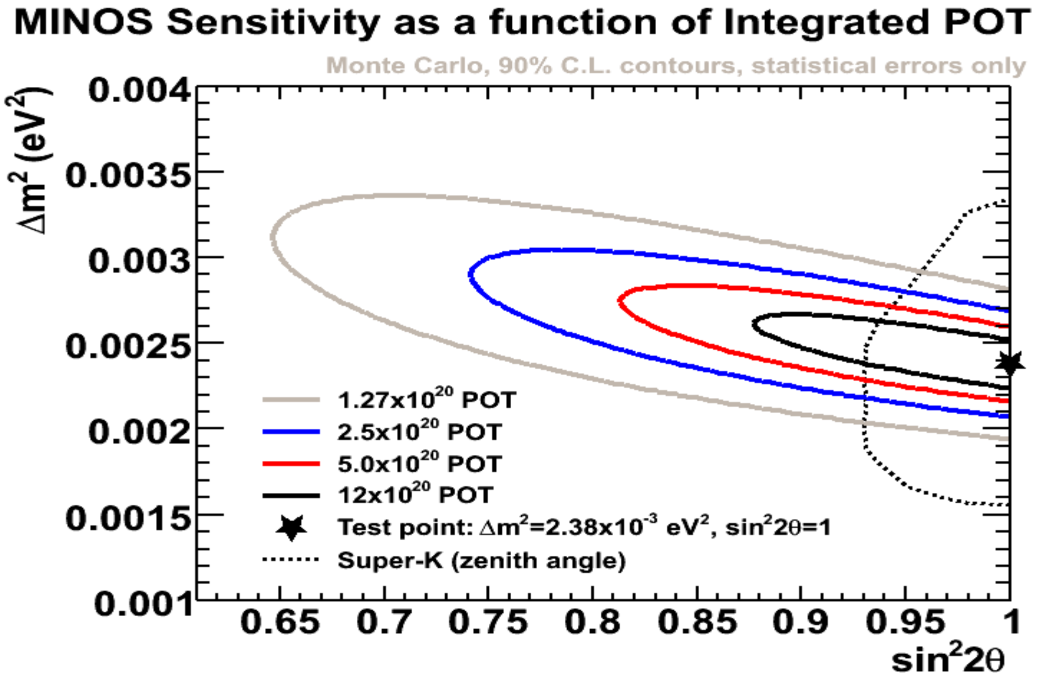


- ★MINOS data shows rise in ratio – sensitive to kaon fraction in cosmic-ray induced air showers

❼ Future Prospects

CC Disappearance:

- ★Currently expected to accumulate **12×10^{20} POT** of data by end of **2009**
- ★Significant improvements expected



+ significant improvements in analysis already in hand

★ hope to have sensitivity to $\sin^2 2\theta_{23}$ which is competitive with Super-K

will depend on success of analysis improvements

Alternative Scenarios

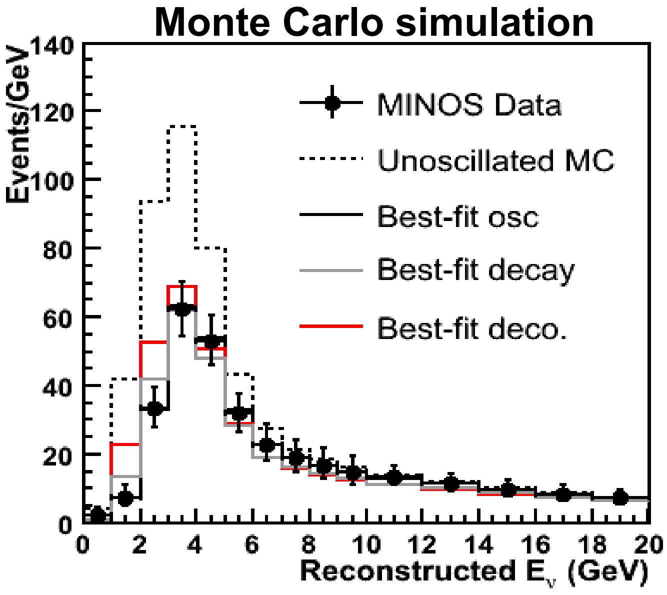
- ★MINOS is the first high statistics long-baseline experiment
- ★Can study shape of oscillation curve in detail
- ★Compare standard oscillation hypothesis to other scenarios, **e.g.**

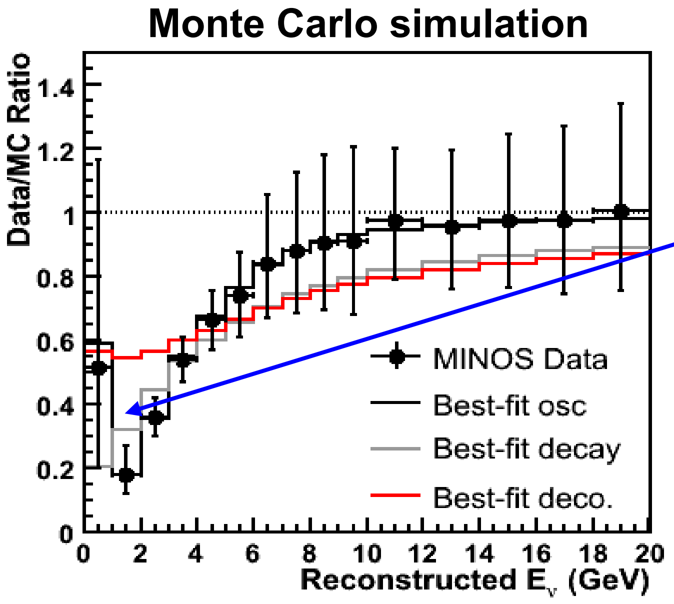
Neutrino Decay

$$P(\nu_\mu \to \nu_\mu) = (\sin^2\theta + \cos^2\theta e^{-\frac{\alpha L}{2E}})^2$$

Neutrino Decoherence

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{\sin^2 2\theta}{2}\left(1 - e^{-\frac{\mu^2 L}{2E}}\right)$$





Resolving dip crucial

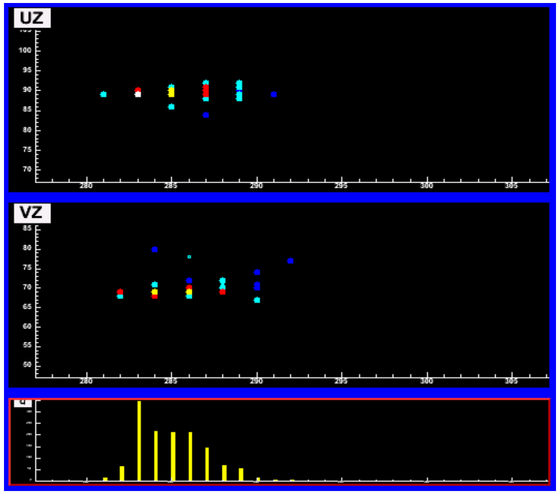
★**First results due this Summer…**

Electron Neutrino Appearance

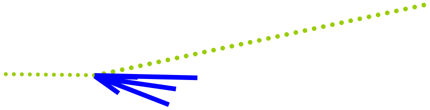
- ★ Search for $\nu_\mu \rightarrow \nu_e$ oscillations is a hot-topic in neutrino physics
- ★ The next generation of neutrino experiments (T2K, Double-Chooz, Nona) all designed to search for $\nu_\mu \rightarrow \nu_e$ oscillations and measure θ_{13}
- ★ Vital for longer term projects to probe CP violation in the neutrino sector as CP violating terms in PMNS matrix enter multiplied by $\sin\theta_{13}$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-s_{13}e^{-i\delta}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

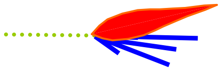
- ★ This is a **very** challenging analysis in MINOS
  - course sampling
  - events have relatively few “hits”
  - event rate low <20 events in current data
  - large background from NC interactions: π^0 in hadronic shower ⇨ EM shower



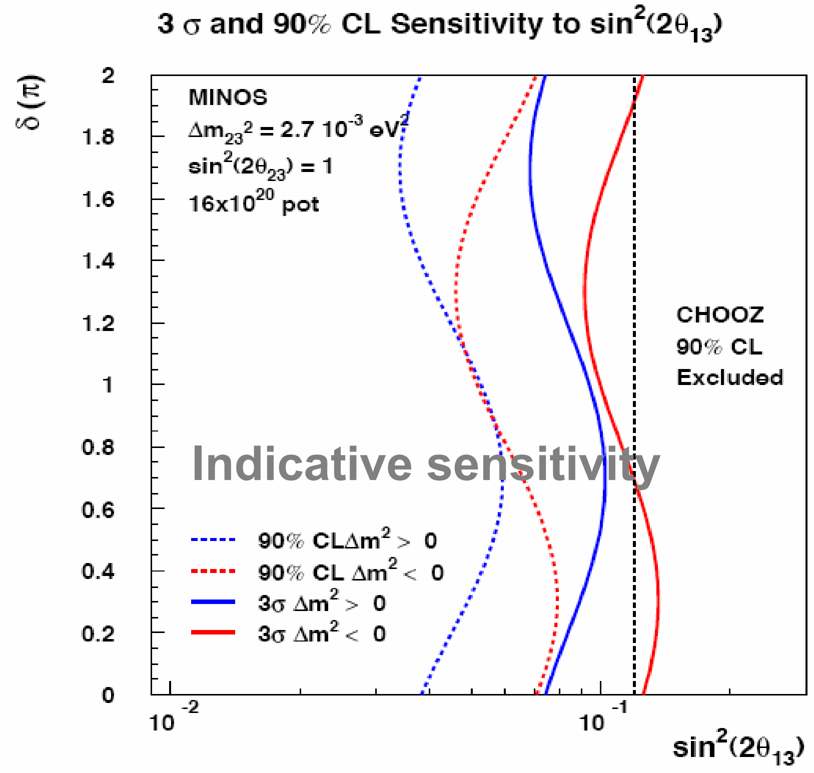
NC



ν_eCC



- ★ Sophisticated analyses being designed to efficiently separate signal from background
- ★ For example, Monte Carlo Nearest Neighbour (**MCNN**) method:
  - rather than perform multivariate analysis on reconstructed quantities
  - directly compare patterns of hits in event to large MC libraries of NC and ν_e events (~50 million)
  - identify best matches and for discriminant variable from fraction of N best MC matches that were ν_e



- Expect first results before Summer
- MINOS has the possibility to discover $\nu_\mu \rightarrow \nu_\mathrm{e}$ oscillations
- Will need entire MINOS data set
- However, MINOS is ahead of the game; will publish before Double-Chooz/T2K

Future Prospects, cont.

In addition,…

- ★Updated atmospheric neutrino results on anti-neutrinos
- ★Cosmic-ray measurements
- ★Structure function/cross section measurements - in progress.

★Possibility of anti-neutrino running to provide first precise measurement of $\overline{\nu}_{\mu} \longrightarrow \overline{\nu}_{\tau}$: 10 % precision achievable with ~6 months running

Is this sufficiently interesting ?

❽ Summary

Summary

- MINOS/Numi running since **mid-2005**
- Already accumulated a large data sample, **3.2×10^{20} POT**
- Data analysis in advanced stage
  - Good understanding of beam – 2 detectors vital !
  - First results on beam data published (PRL)
  - MINOS already has most precise measurement of $|\Delta m^2_{32}|$
- Many other analyses reaching maturity
  - Search for sub-dominant $\nu_\mu \rightarrow \nu_{\mathrm{e}}$ oscillations is perhaps the most exciting

Outlook

- MINOS remains a very high priority for Fermilab
- Expect to run through US FY2010, i.e. until October 2010
- Final data sample of > **1.2×10^{21} POT**
- With these data:
  - 5 % measurement of $|\Delta m^2_{32}|$
  - And maybe the first observation of $\nu_\mu \rightarrow \nu_{\mathrm{e}}$ oscillations
  - + much more

The End

Thank you