First MINOS Results from the NuMI Beam

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for the MINOS Collaboration

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Outline

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  - [illegible]
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Oscillation Physics

- There is experimental evidence that neutrino flavor is not conserved and thus **neutrinos have non-zero masses.**
- A neutrino of flavor $\alpha = e, \mu, \tau$ is a superposition of mass eigenstates described by the lepton mixing matrix ***U:***

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \qquad s_{ij} = sin\theta_{ij},\ c_{ij} = cos\theta_{ij}$$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle; \alpha = e, \mu, \tau, \ldots; i = 1,2,3,\ldots$$

$|U_{\alpha i}|^2$: probability that ν_i interaction will produce ν of flavor α

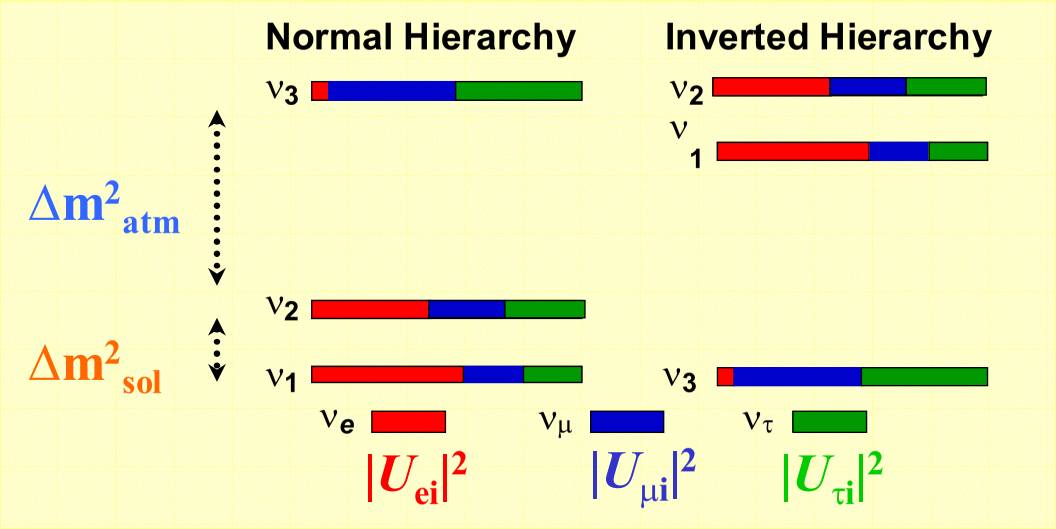
- In the two-flavor approximation:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E_\nu(GeV)}\right), \alpha \neq \beta$$

$\rightarrow$ L/E determines what Δm^2 is probed

Neutrino Mass Spectrum

(3 mass eigenstates - assume no $\nu_{sterile}$)



Two mass splittings:

Large (Δm^2_{atm}):
Atmospheric (up-down asymmetry)
Long baseline

Small (Δm^2_{sol}):
Solar + reactor

- $|U_{e3}|^2$ is not known (bounded by reactor expts) and neither is the mass hierarchy.
- Solar data suggests $|U_{e2}|^2 \sim 1/3$, and thus $|U_{e1}|^2 \sim 2/3$ (unitarity and small $|U_{e3}|^2$).
- **Also, data suggests $\nu_\mu \rightarrow \nu_\tau$ dominant at Δm^2_{atm} and maximal mixing angle,**

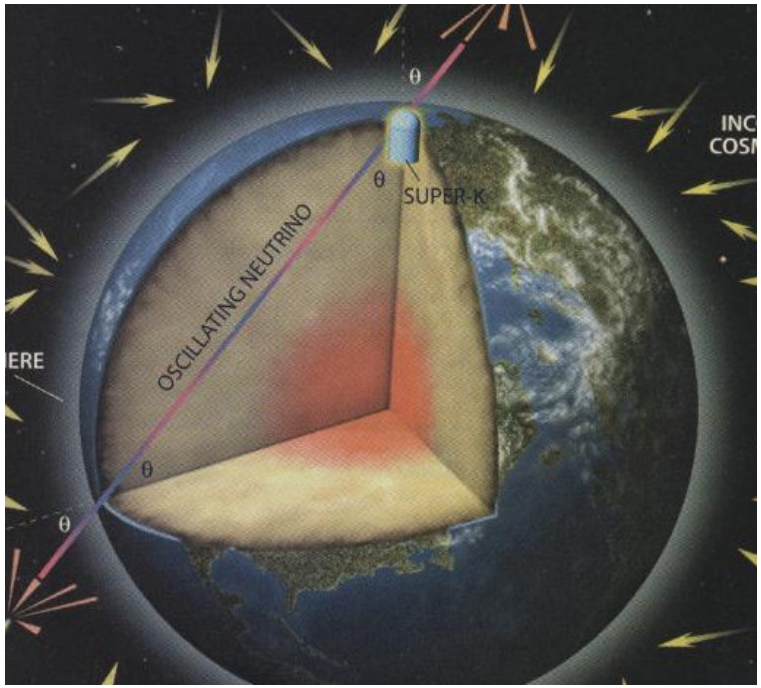
$|U_{\mu i}|^2 \sim |U_{\tau i}|^2$

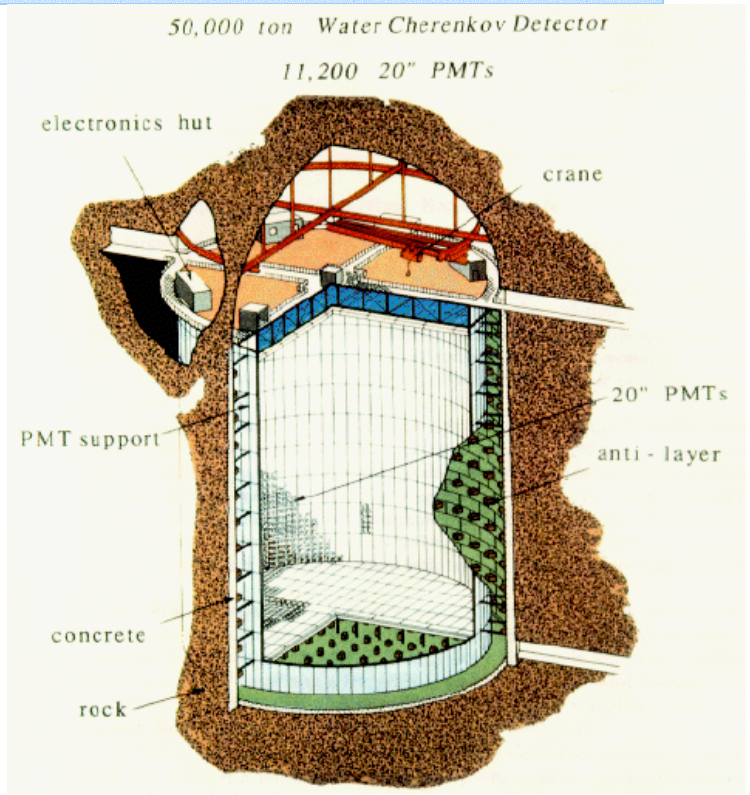
With L/E~10^3 MINOS is sensitive to Δm^2_{atm}
This scale will be the focus of this talk

Super-Kamiokande

Ref. hep-ex/0501064, T. Kajita WHEPP9

- Neutrinos produced by the interaction of primary cosmic rays in the Earth's atmosphere. Wide range of energies and travel distances.
- Measurement relies on knowledge of flux w/o oscillations

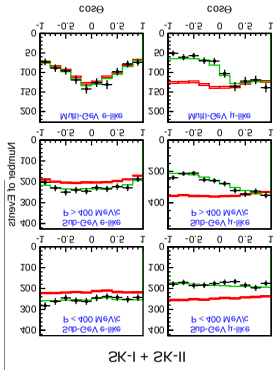


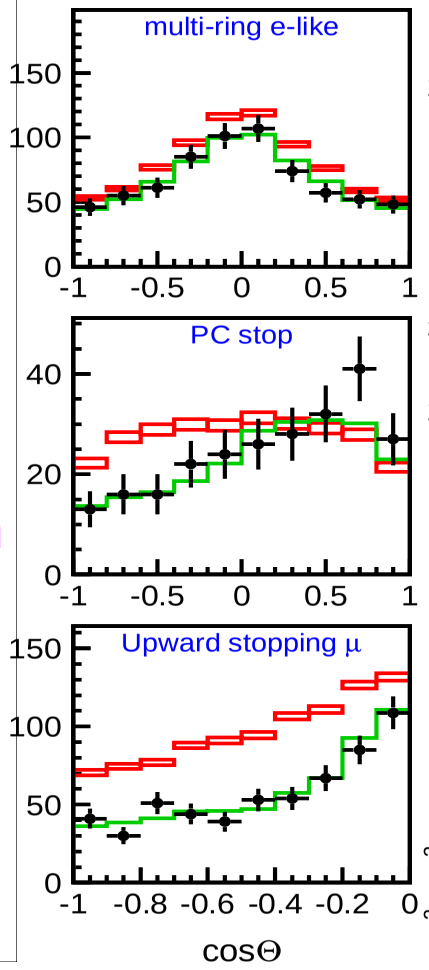


2,700 m.w.e. overburden
50 kT water Cherenkov detector

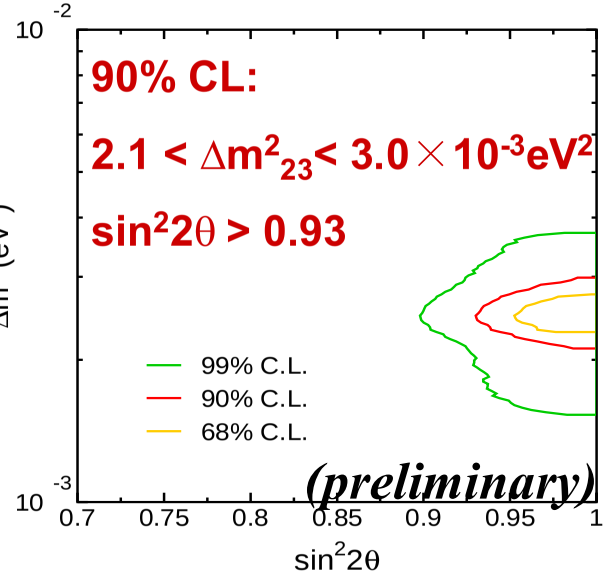
Super-K (I+II) – Zenith

SK-I + SK-II





Up Down



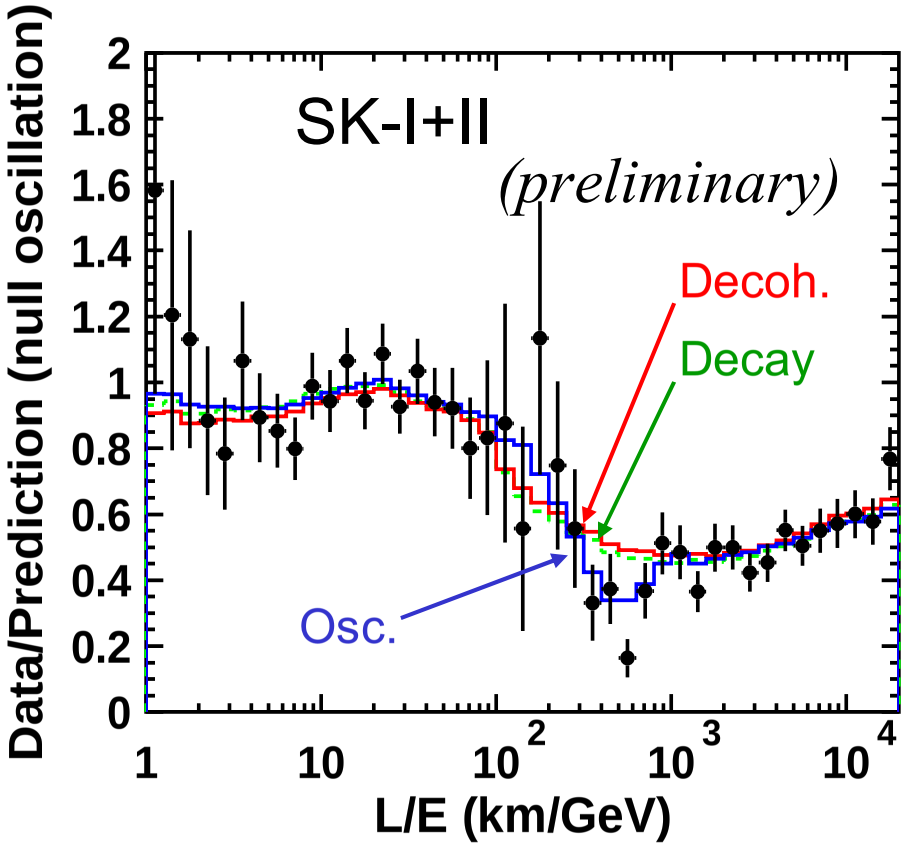
Unoscillated MC

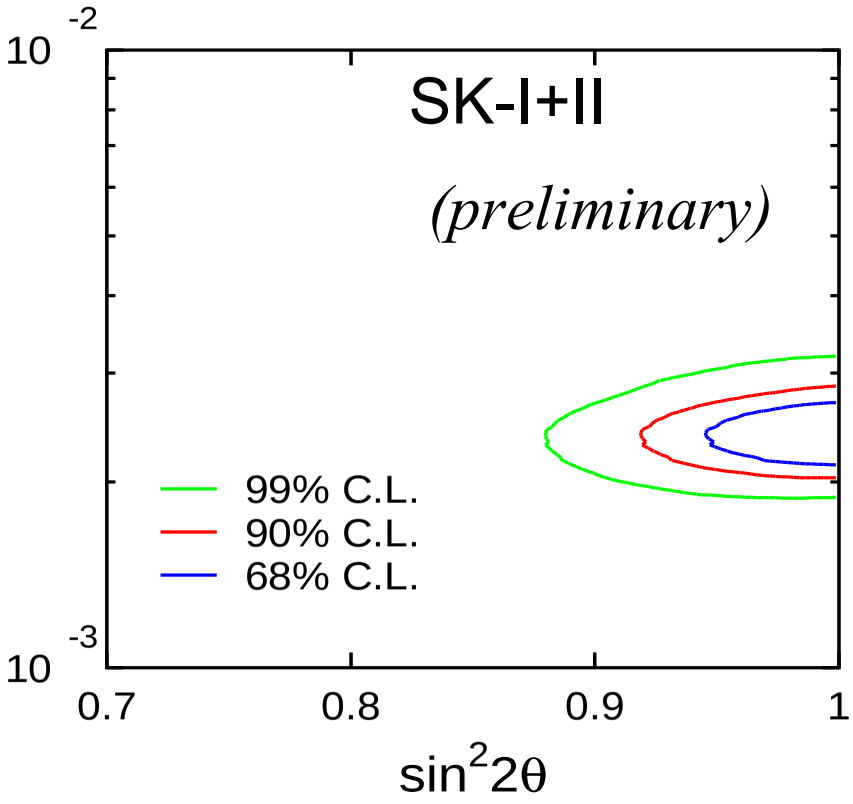
Best fit: $\Delta m^2_{23} = 2.5\times10^{-3}$ eV², $\sin^2 2\theta_{23}=1$

Data

Super-K (I+II) – L/E

- Consistent with Zenith angle analysis results.
- At 90% CL: **$2.0 < \Delta m^2_{23} < 2.9 \times 10^{-3}$ eV^2 , $\sin^2 2\theta_{23} > 0.92$**



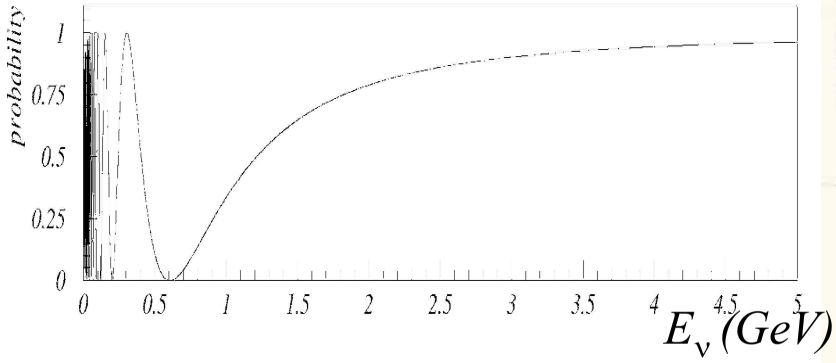


K2K

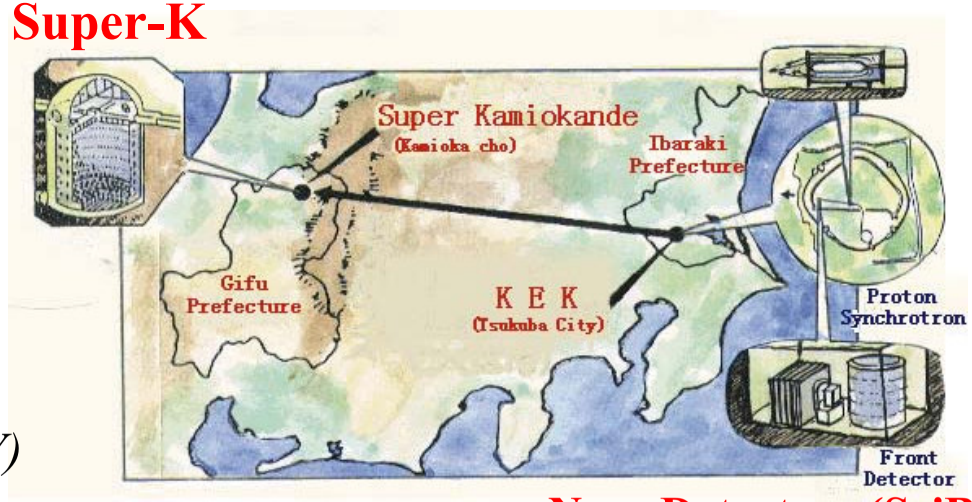
Ref. hep-ex/0411038, hep-ex/0512041

- First **long baseline** accelerator neutrino experiment.
- Accelerator produced ν_μ beam (**1.3 GeV mean energy**) travels **250 km** toward Super-K. The near detector is located 300 m from the production target.
- **Observe energy dependent ν_μ disappearance.**

Δm^2=0.003eV^2 , L=250km



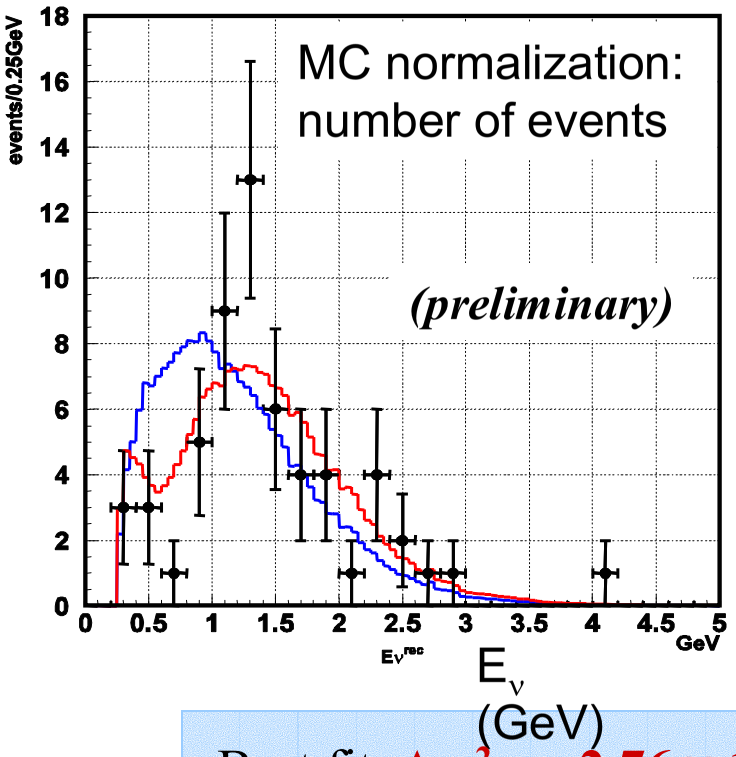
Super-K

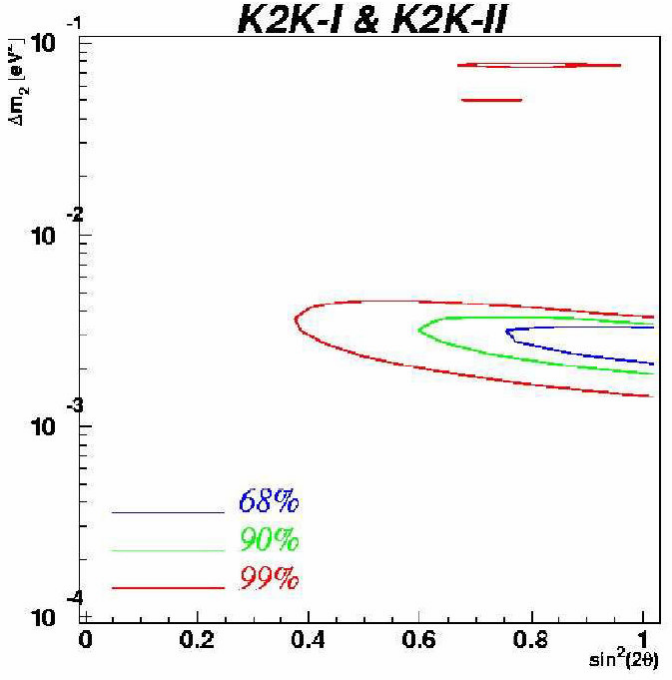


Near Detectors (SciBar, 1 kton water Cherenkov)

K2K - Results

- Observe deficit of ν_μ at SK and distortion in the energy spectrum:
  112 events at SK, expect $155.9^{+13.6}_{-15.6}$
- Well described by $\nu_\mu \rightarrow \nu_\tau$ oscillation



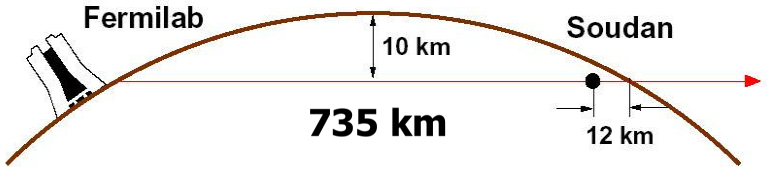


Best fit: $\Delta m^2_{23} = 2.76 \times 10^{-3}$ eV², $\sin^2 2\theta_{23} = 1$

For $\sin^2 2\theta_{23} = 1$: **90% CL** $1.9 < \Delta m^2_{23} < 3.5 \times 10^{-3}$ eV²

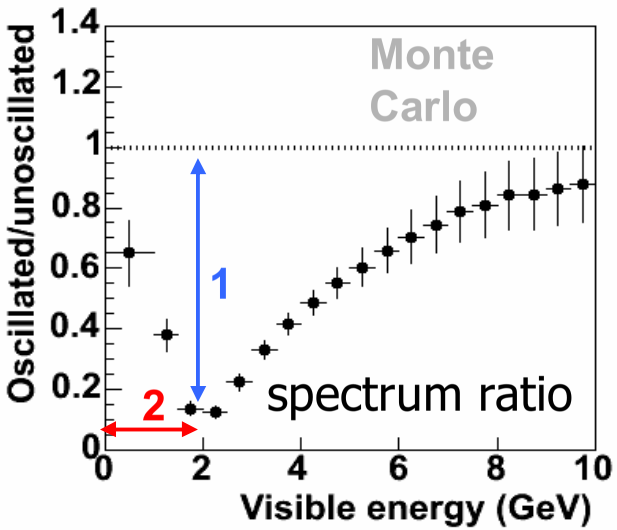
MINOS

Main Injector Neutrino Oscillation Search

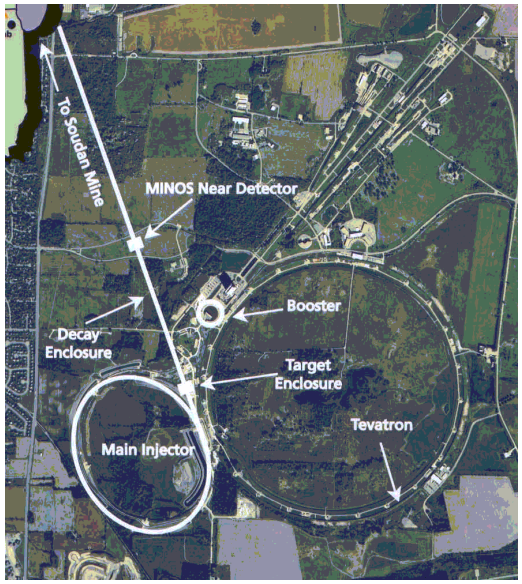


$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{23}(eV^2)L(km)}{E_\nu(GeV)}\right)$$

1 2



NuMI Beamline



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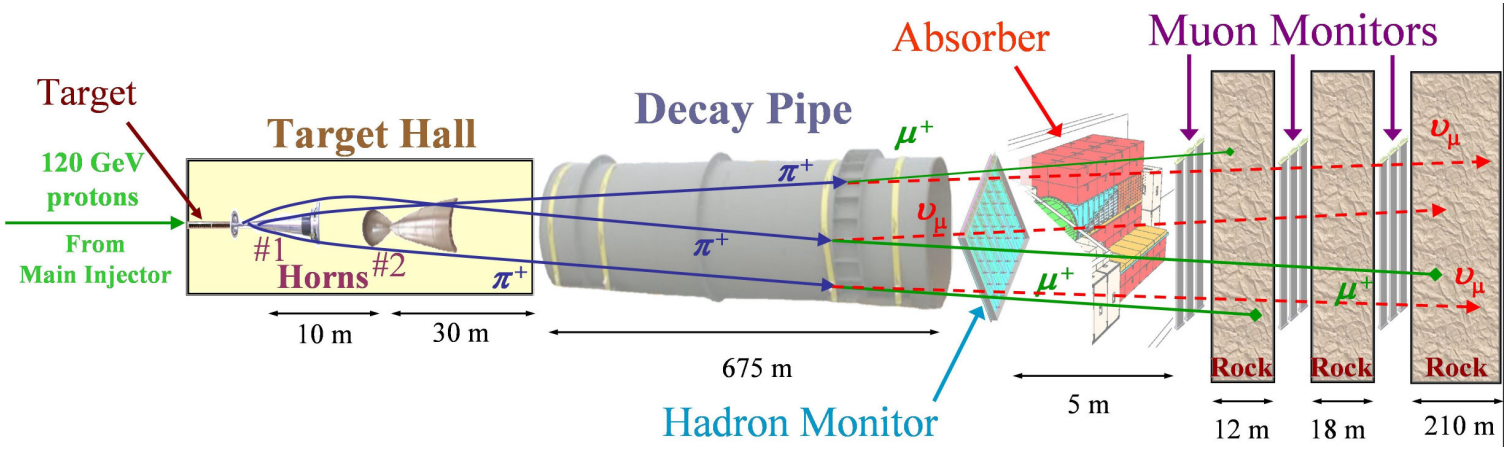

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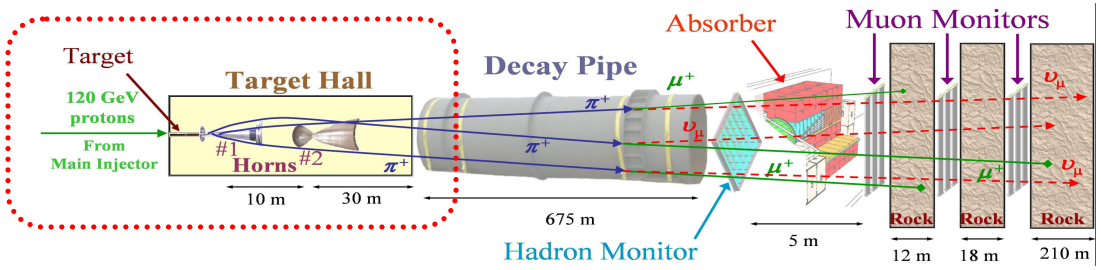
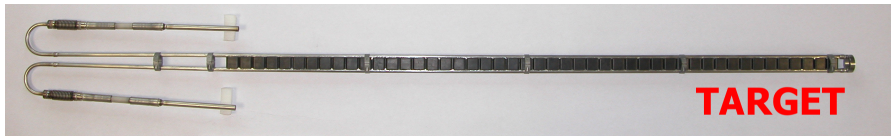
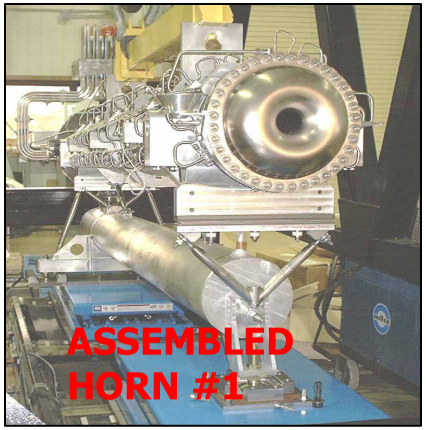
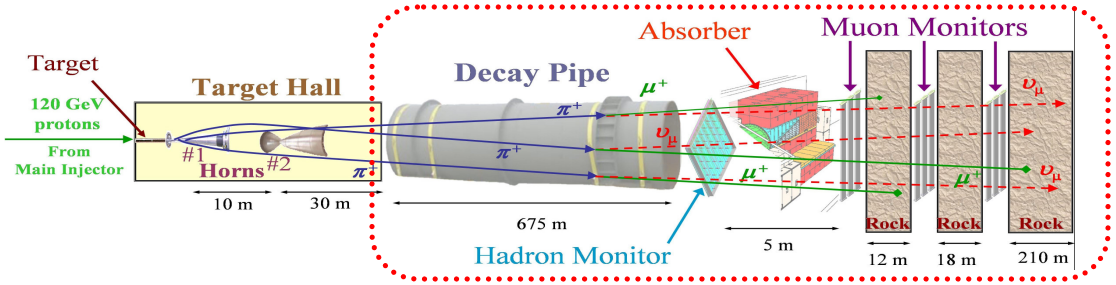
NuMI Target and Horns

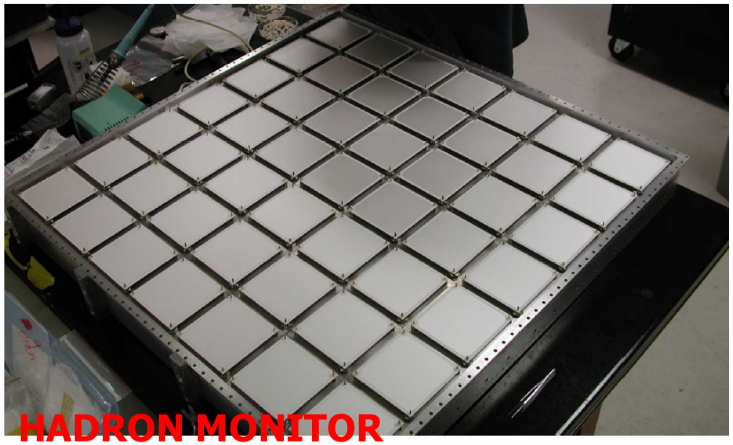




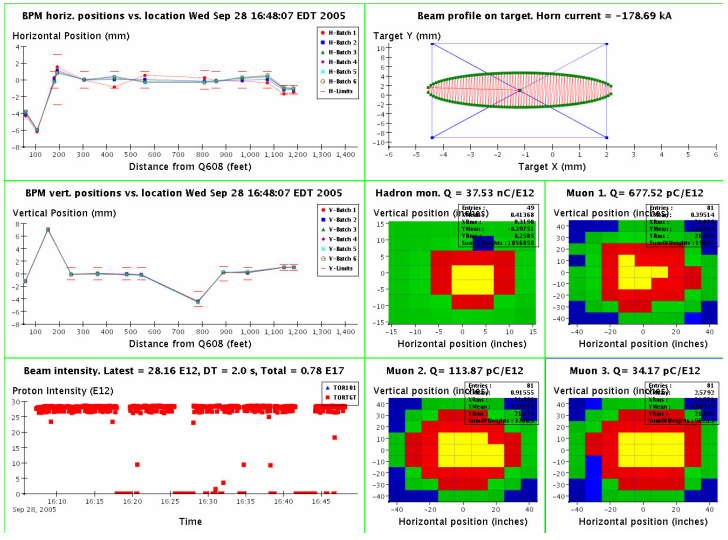


Hadron and Muon Monitors





BEAM MONITORING



The MINOS Detectors

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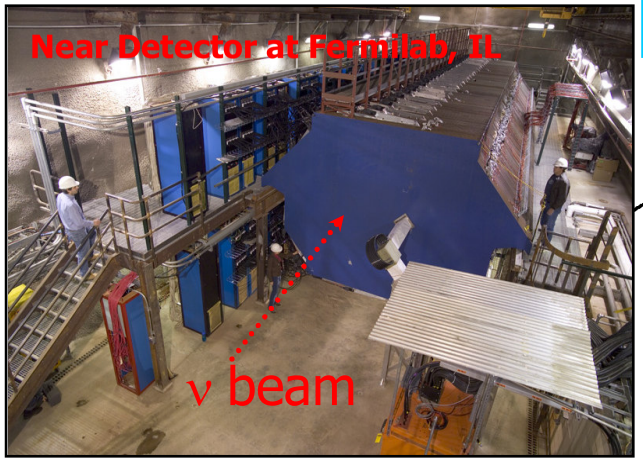

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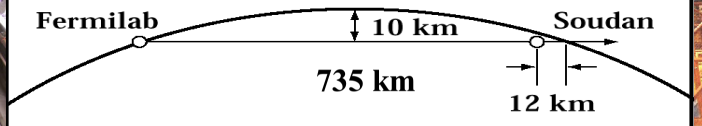

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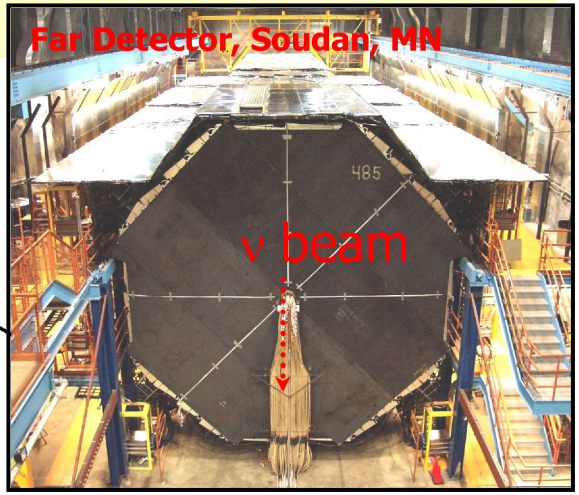

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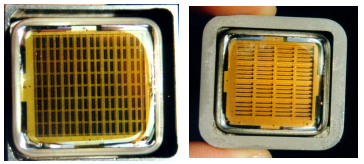

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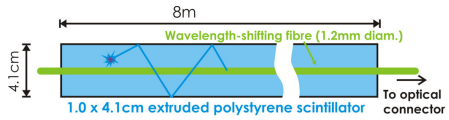
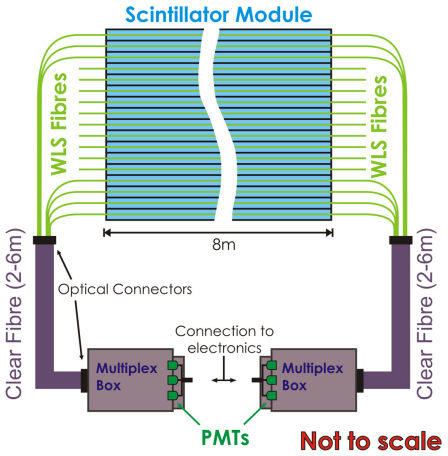
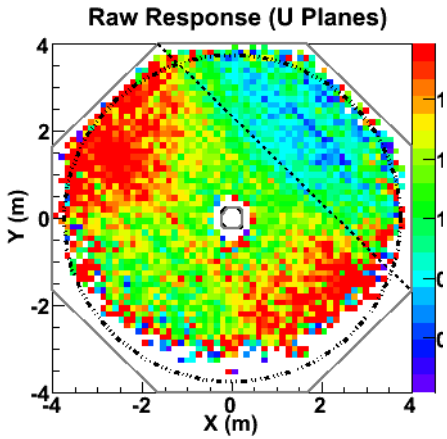
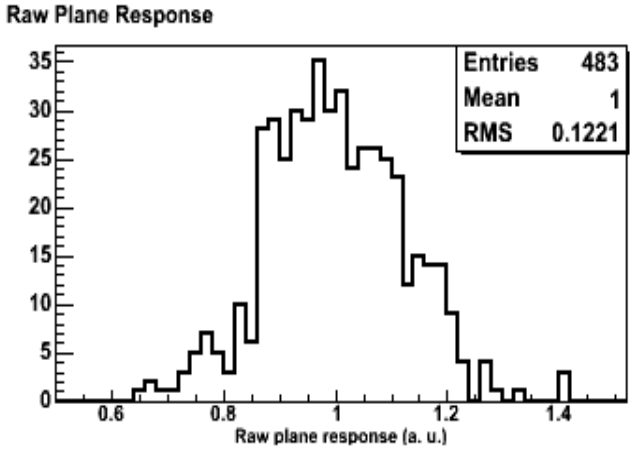
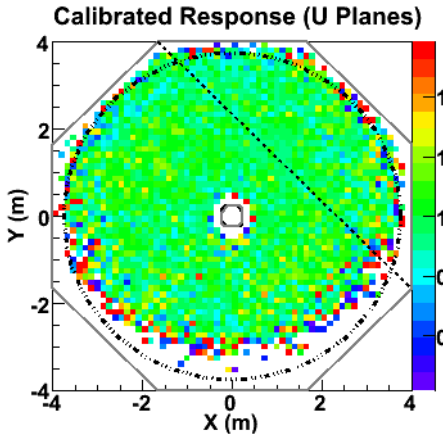


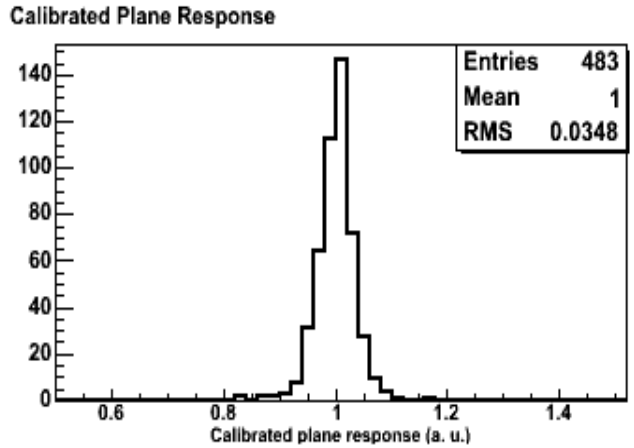


Calibration

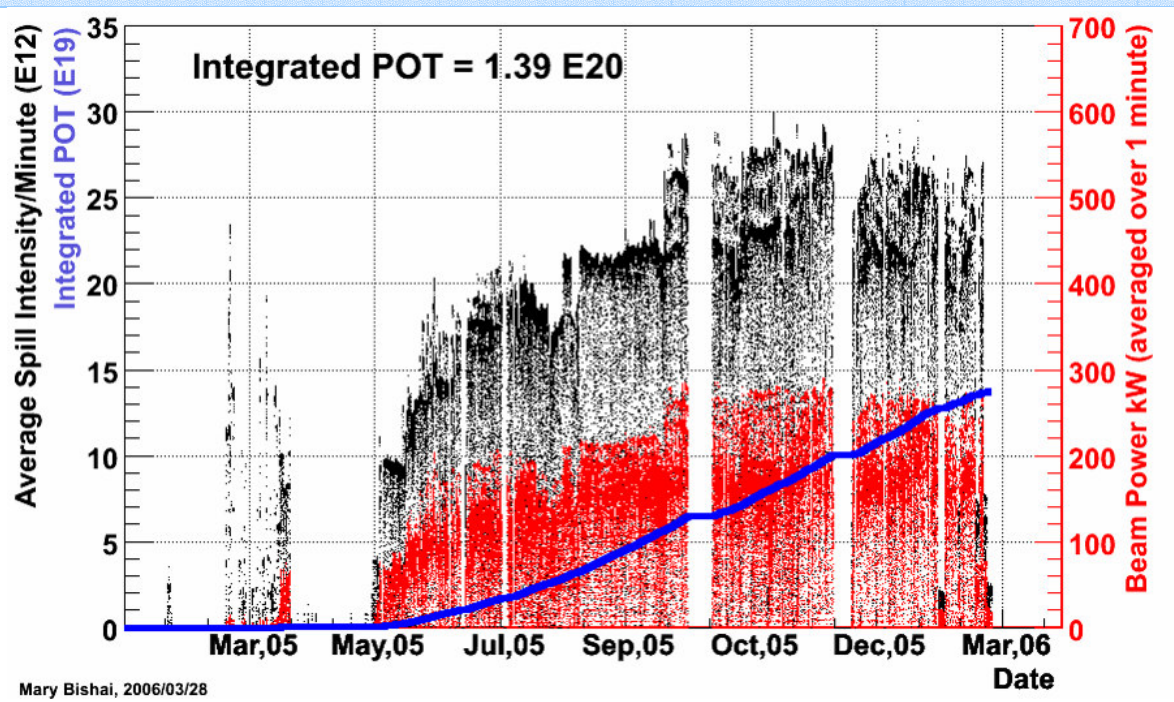








Start-Up and Running

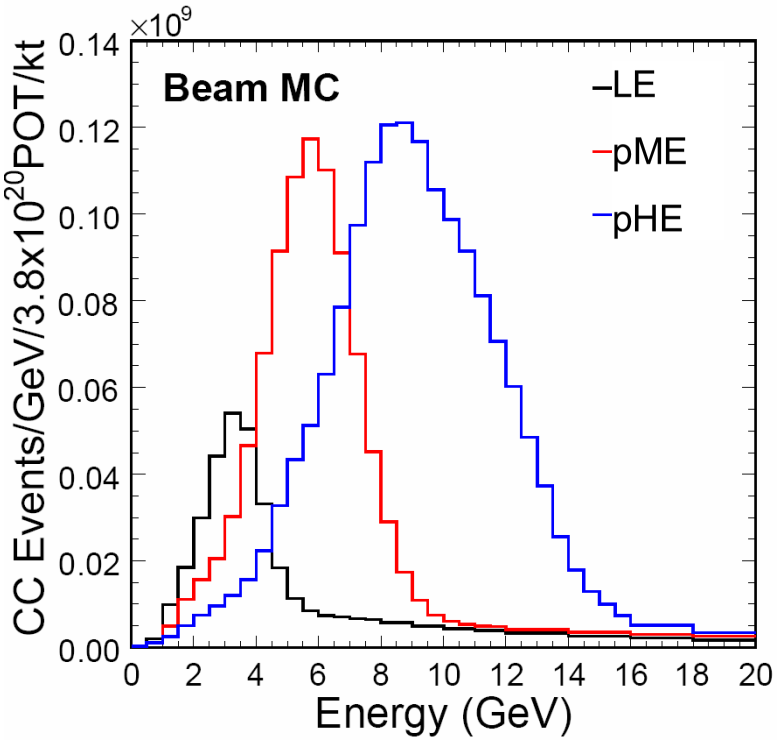


Neutrino Energy Spectrum

- [redacted]
- [redacted]

☞ [redacted] Δm^2_{23})

[redacted] 8.5% $\nu_\mu+\nu_\mu$ (6.5% ν_μ), 1.5% $\nu_e+\nu_e$ – – –



Beam	Target z position (cm)	FD Events (no osc) per 1 x 10^{20} POT
LE-10	**-10**	**390**
pME	-100	970
pHE	-250	1340

Events in fiducial volume

[redacted]

Oscillation Analysis

- [illegible]
- [illegible]

- [illegible]
- [illegible]
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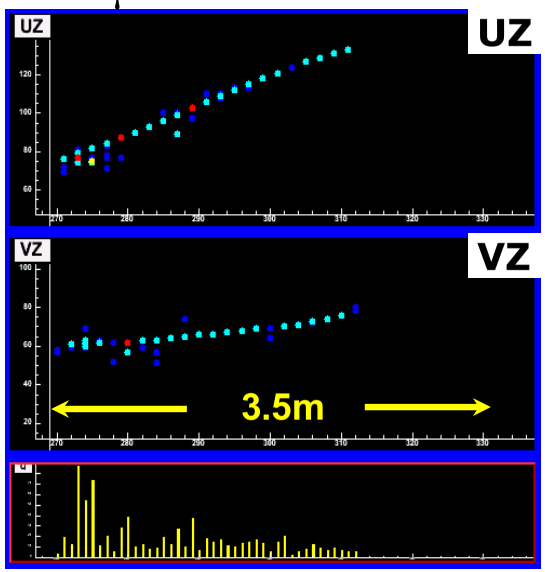
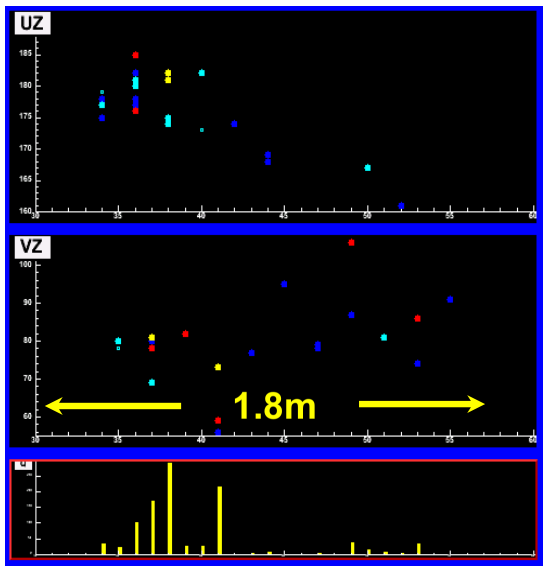
Event Topologies

Monte Carlo

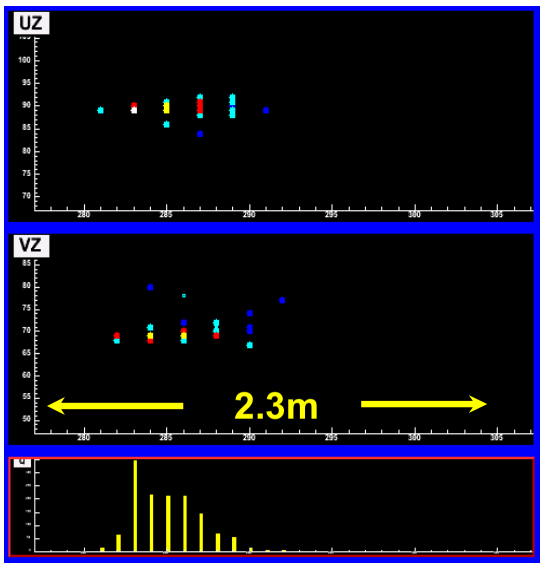
ν_μ CC Event



NC Event



ν_e CC Event



Data Selection

ν_μ

1

2

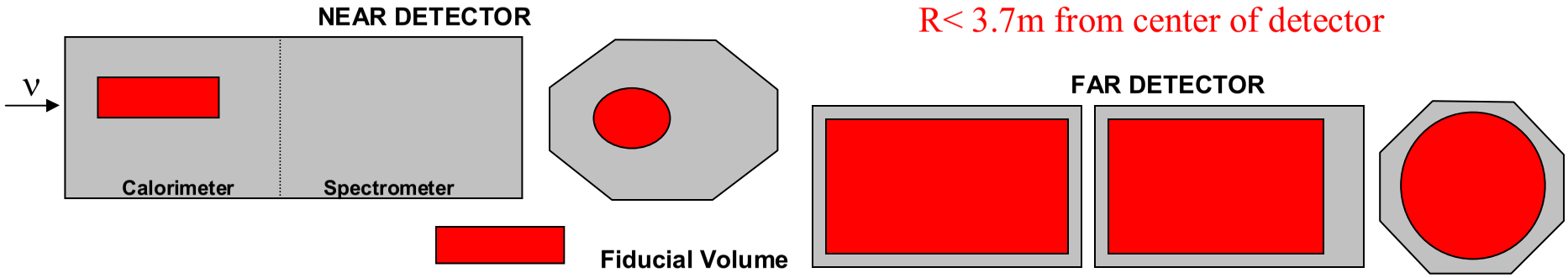
NEAR: 1m < z < 5m (z from front face)

R< 1m from beam center

FAR: z>50cm from front face

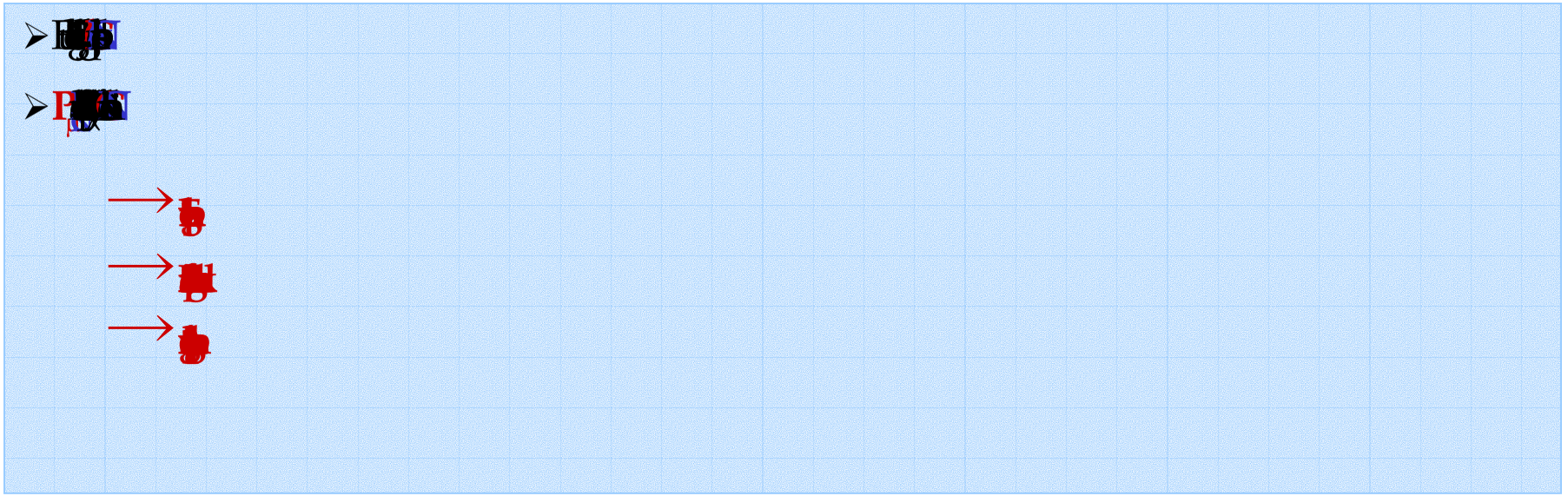
z>2m from rear face

R< 3.7m from center of detector

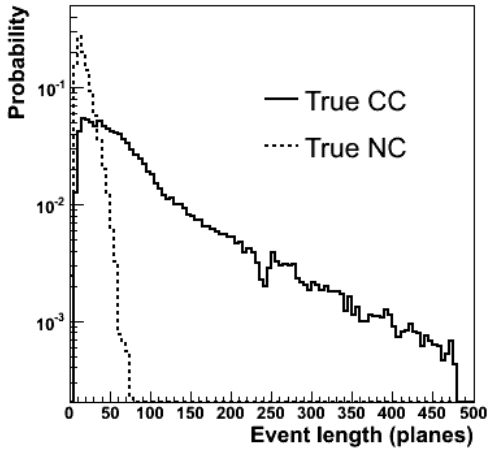


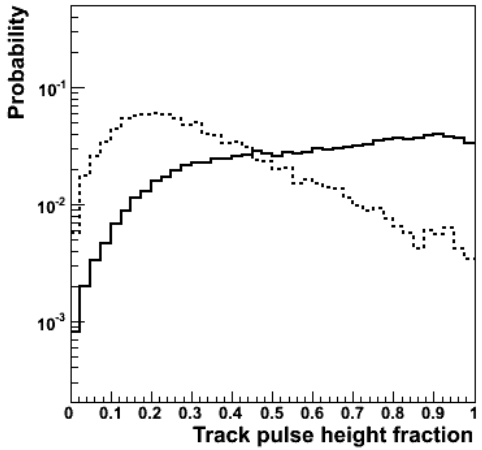
ν_μ)

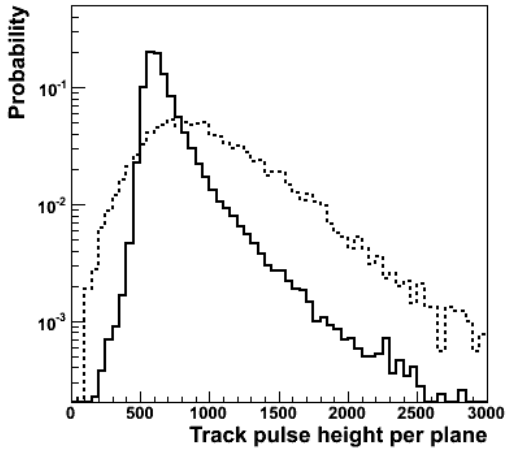
Selecting CC events



Input variables for PDF-based event selection







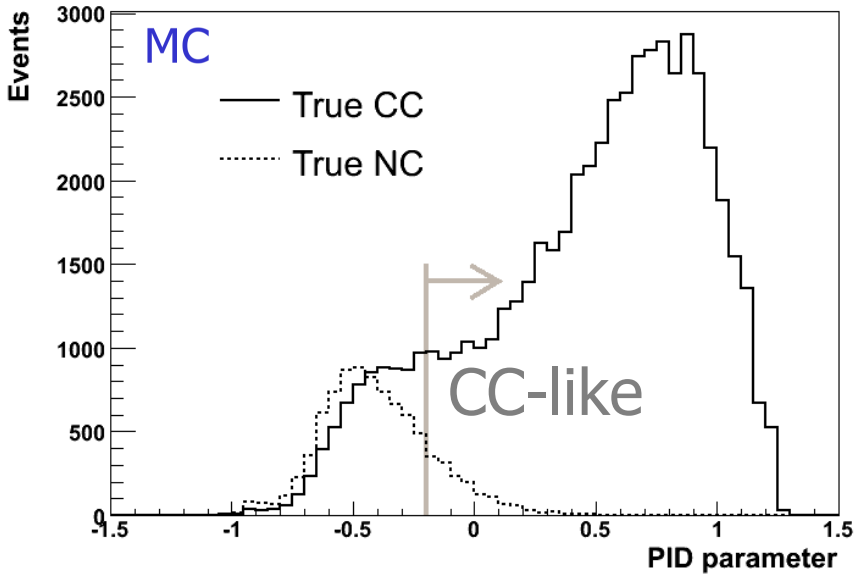
CC Selection Efficiencies

- [redacted]

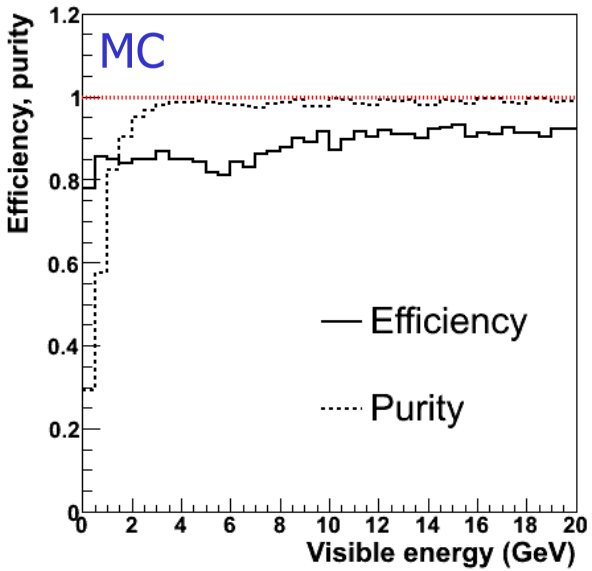
$$PID = -(\sqrt{-\log(P_{\mu})} - \sqrt{-\log(P_{NC})})$$

- [redacted]
  - [redacted]
  - [redacted]

PDF PID parameter distribution for true CC and NC events

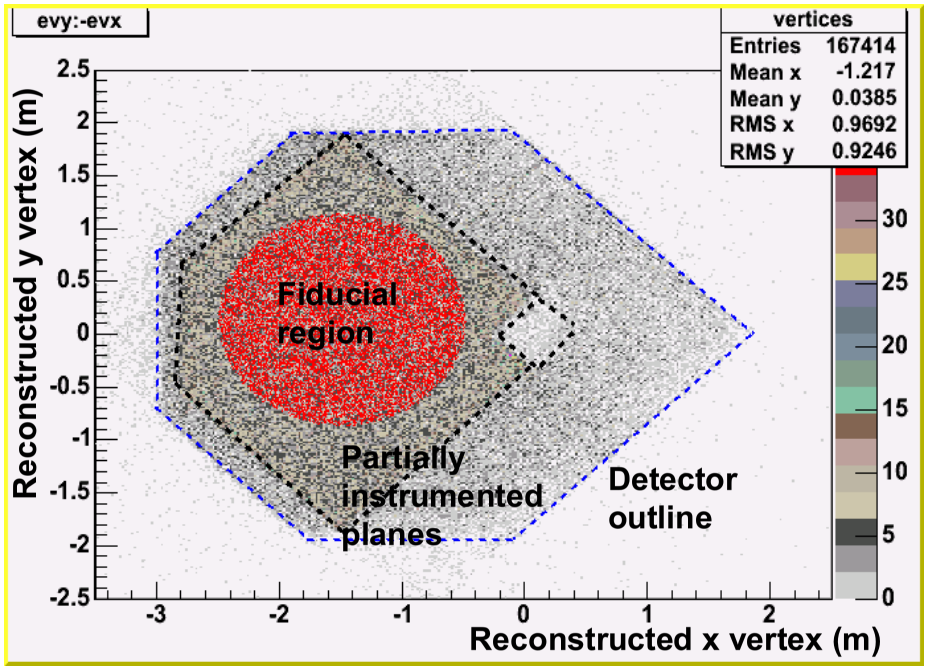


CC selection efficiencies and purities

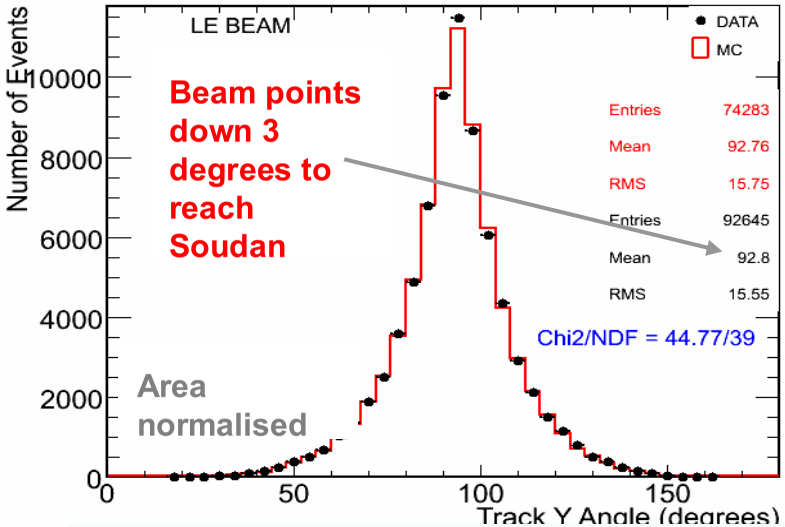


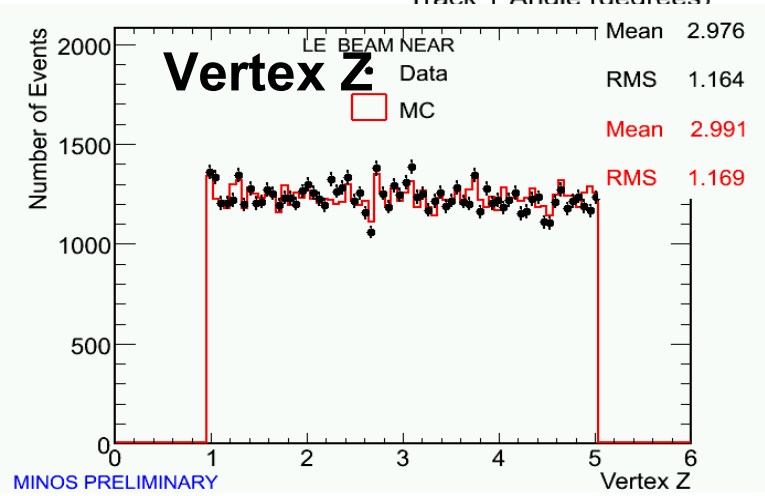
Near Detector Distributions

Distribution of reconstructed event vertices in the x-y plane



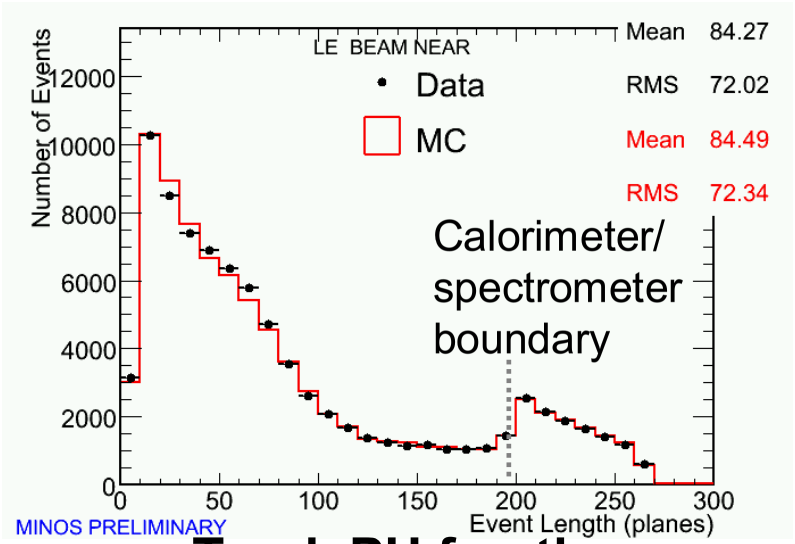
Reconstructed track angle with respect to vertical



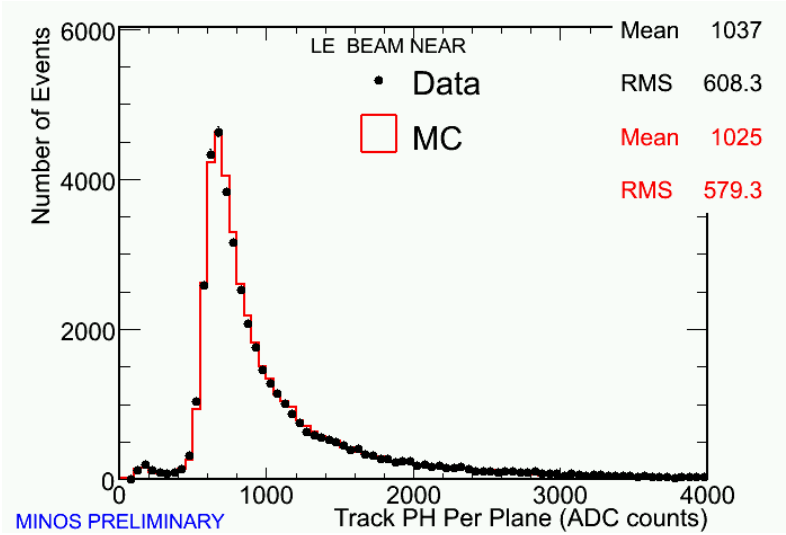


Near Detector - PID Distributions

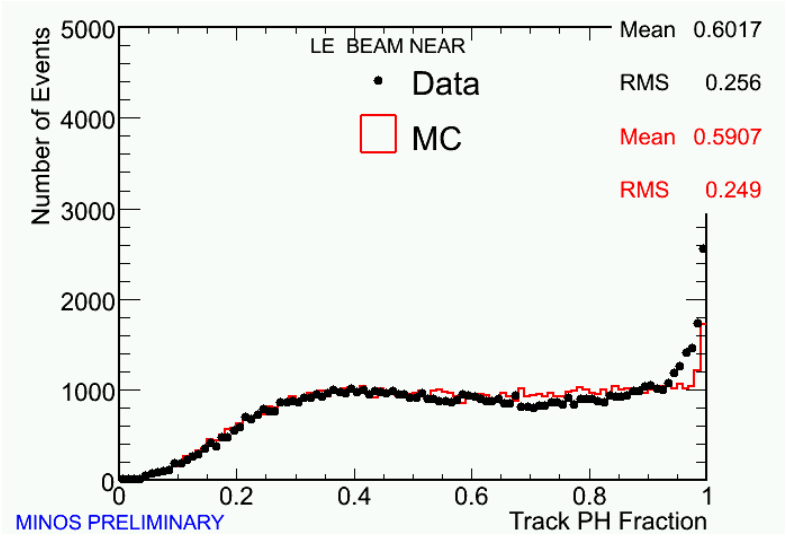
Event length

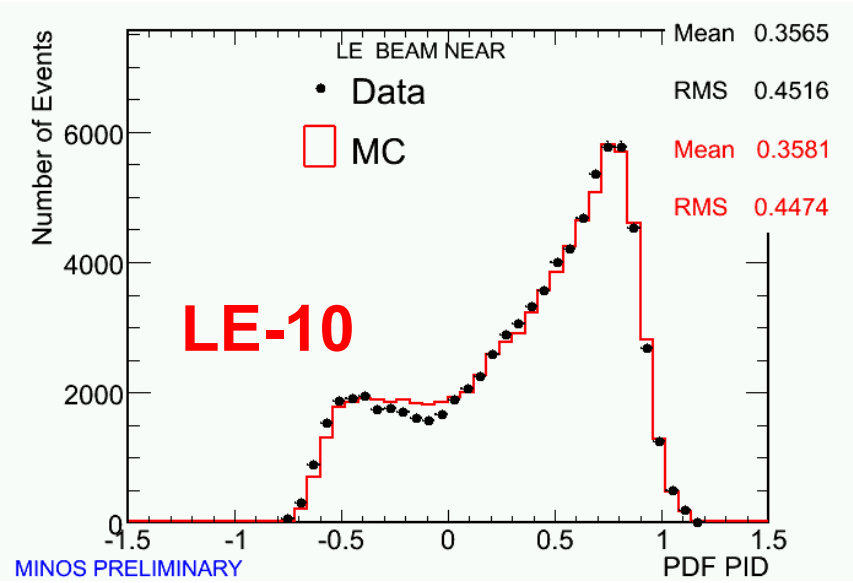


Track PH per plane

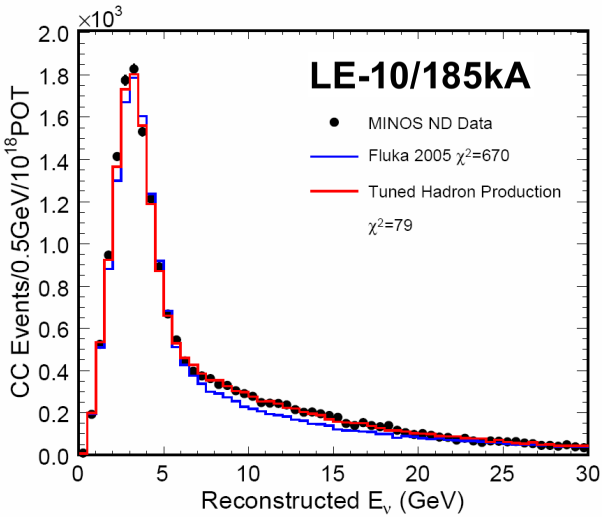


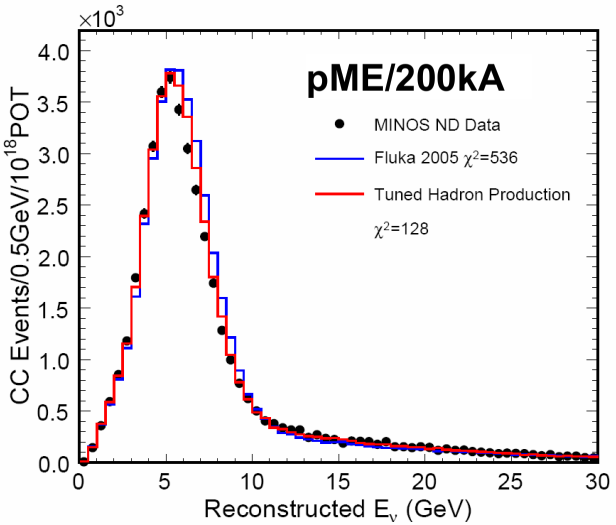
Track PH fraction

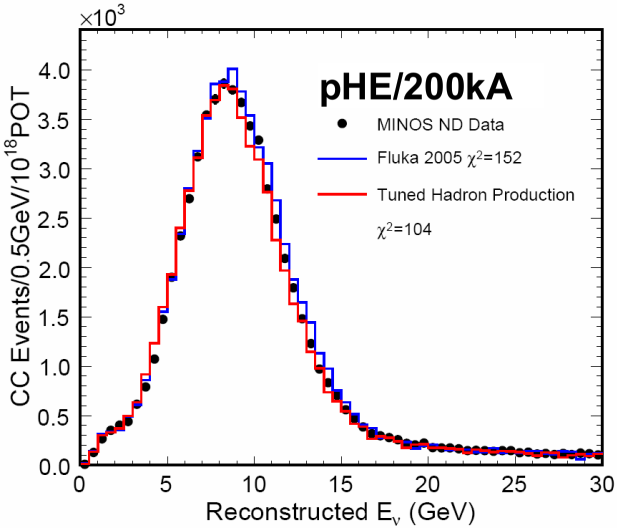


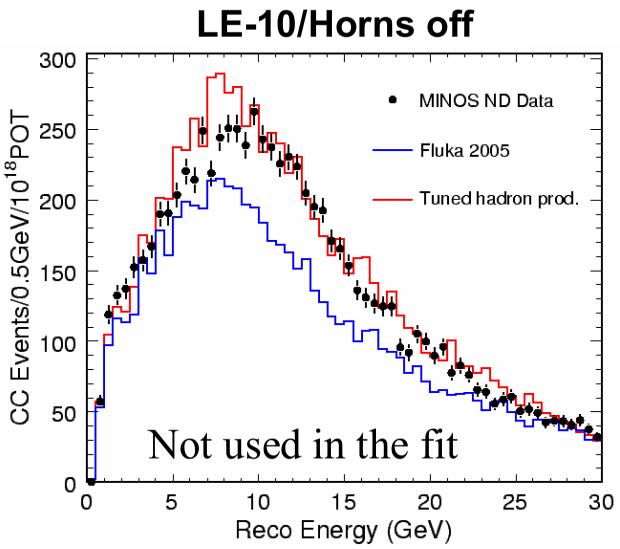


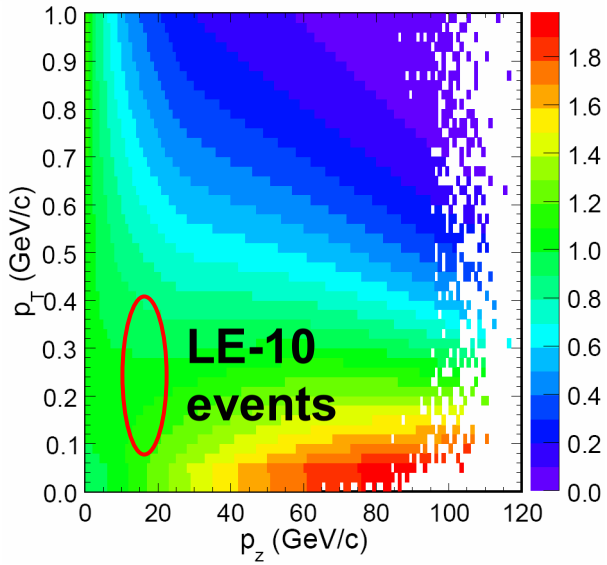
Hadron Production Tuning



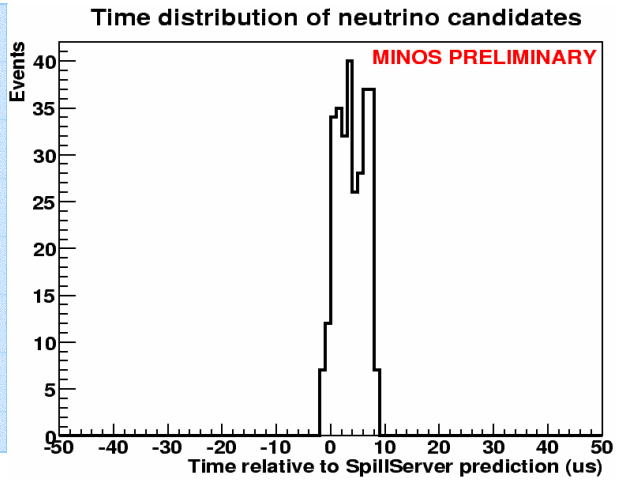


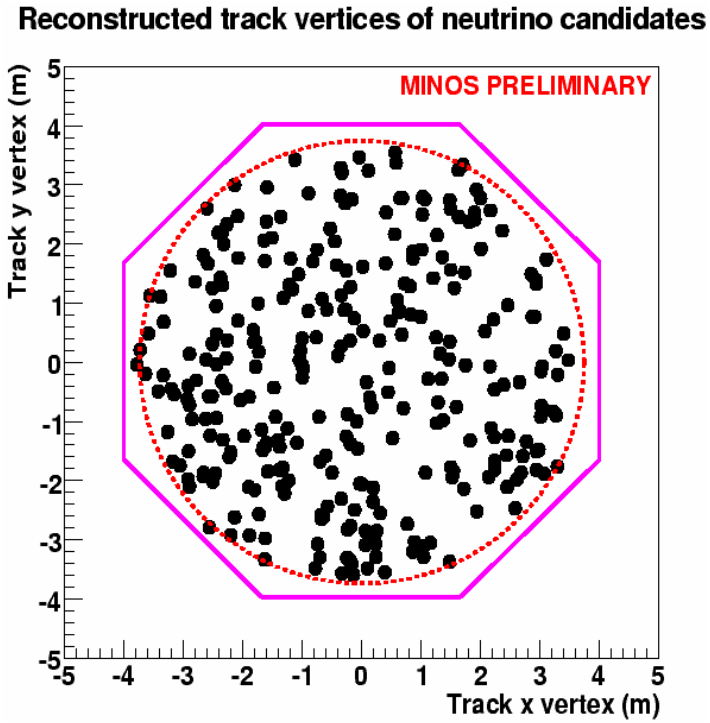


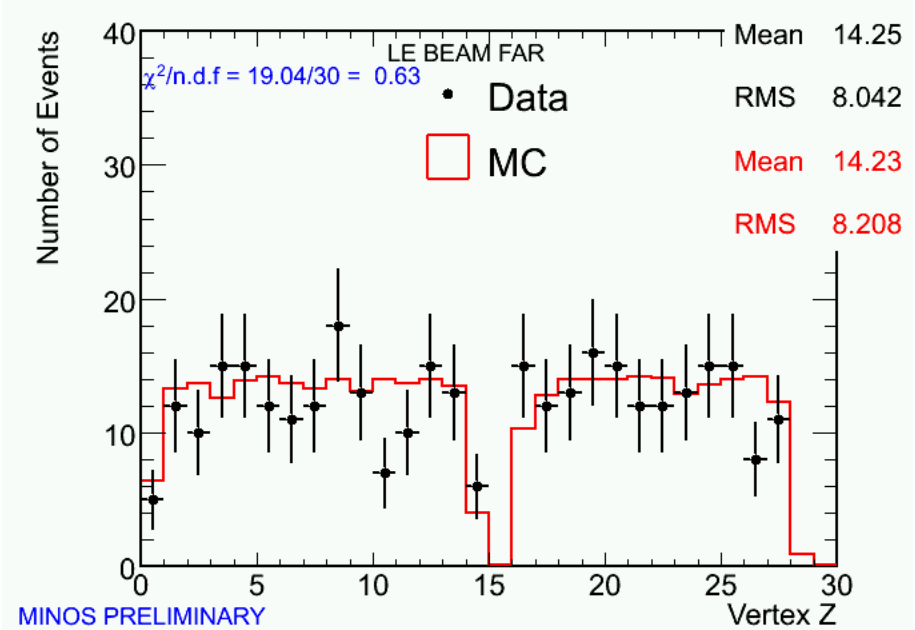




Far Detector Data







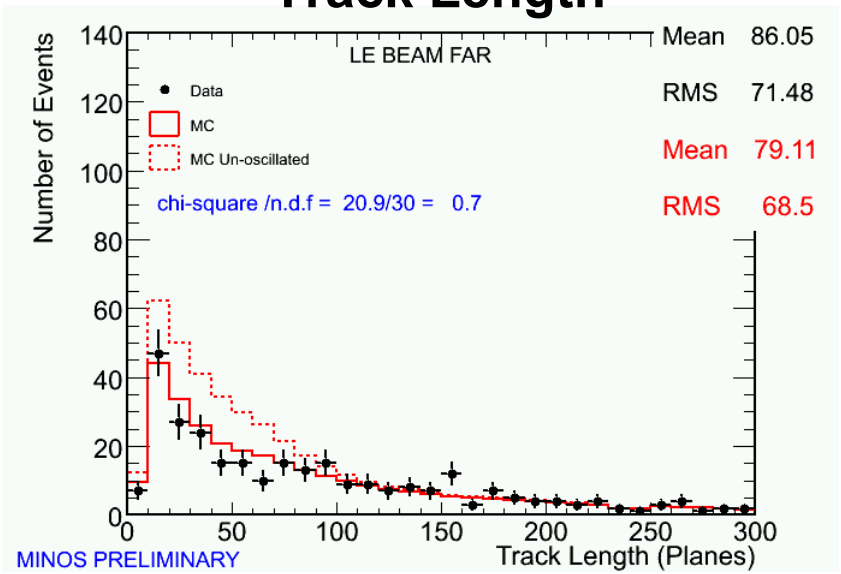
Observed/Expected Rates

- [illegible]
  - [illegible] $\nu_\mu+\nu_\mu$ [illegible]
- [illegible]

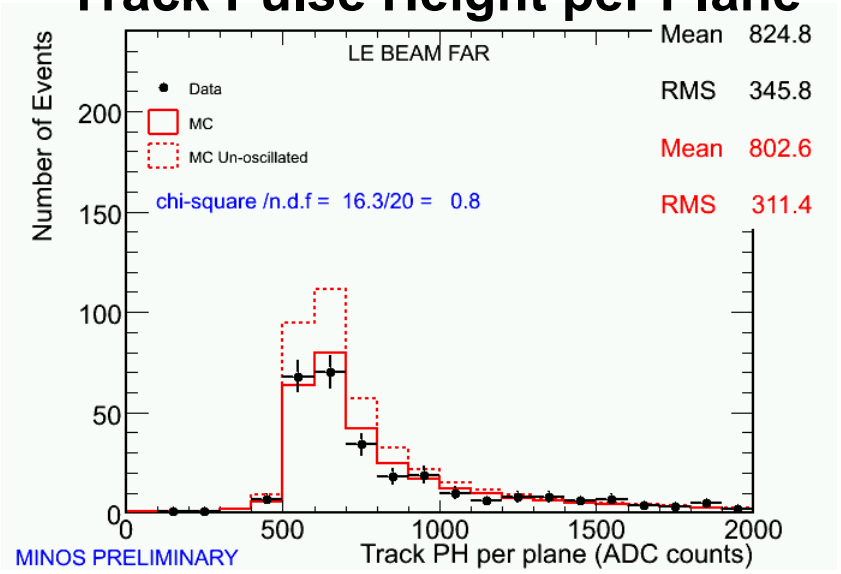
Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu+\bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

Far Detector - PID Distributions

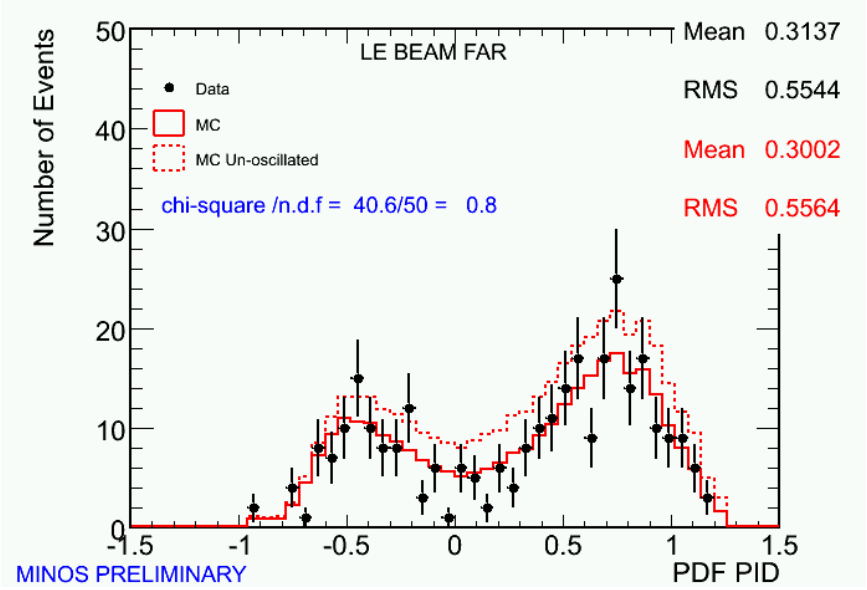
Track Length



Track Pulse Height per Plane

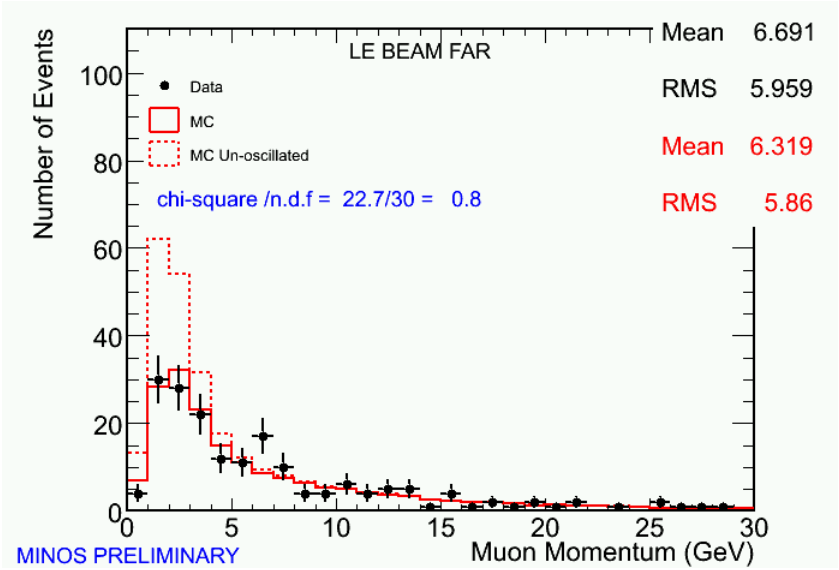


Particle Identification Parameter

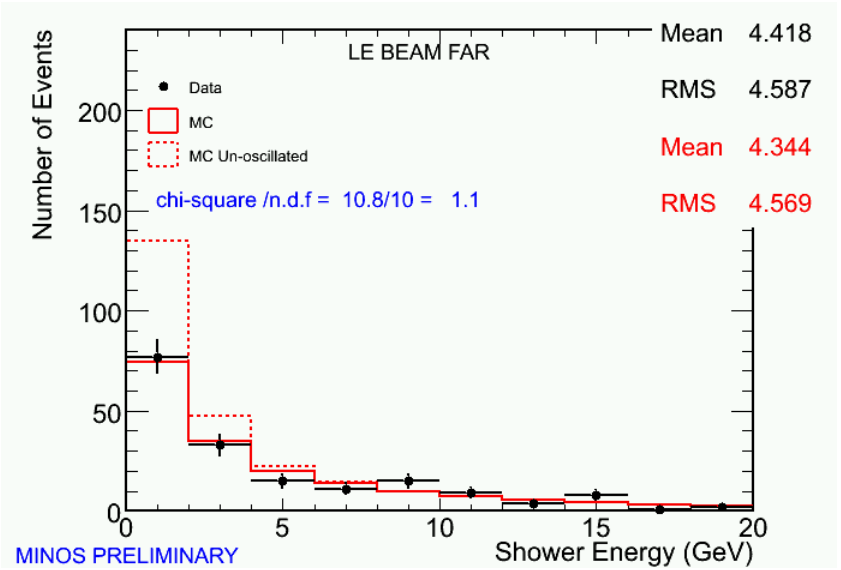


Far Detector -Physics Distributions

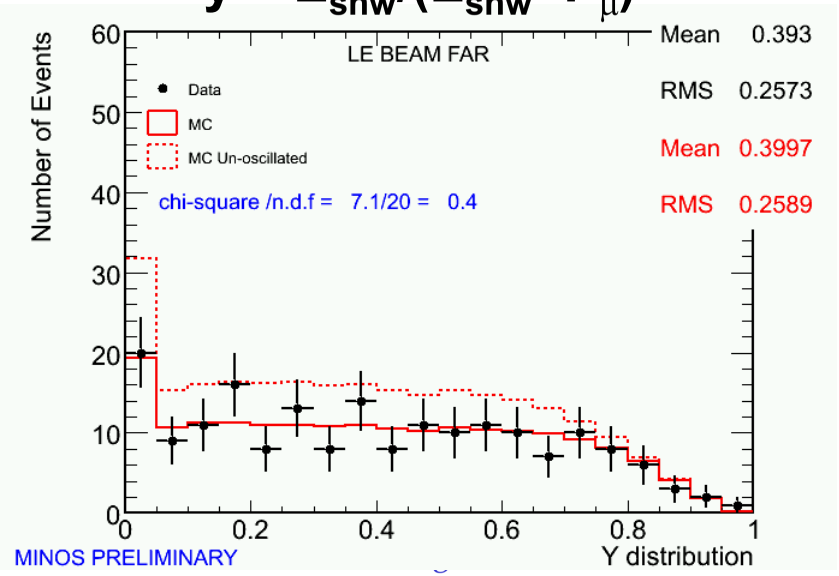
Muon Momentum (GeV/c)



Shower Energy (GeV)

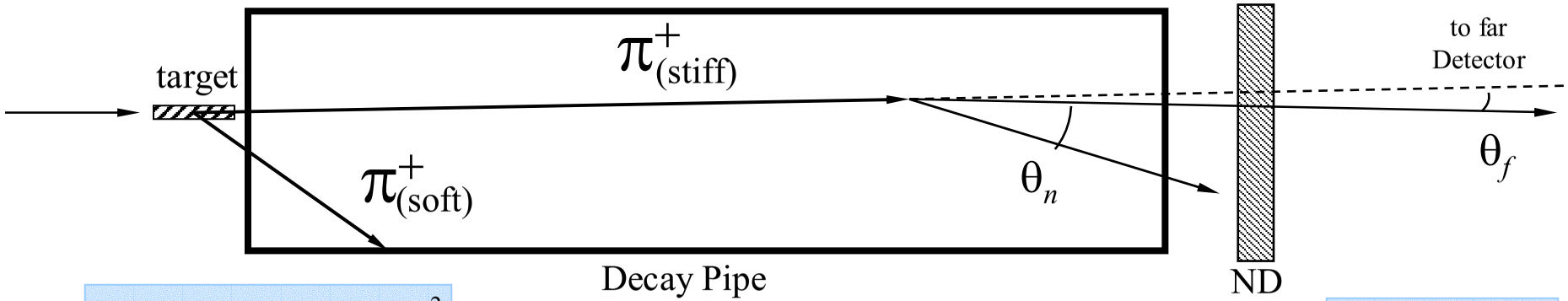


$y = E_{shw}/(E_{shw}+P_{\mu})$



Predicting the Far Detector Spectrum

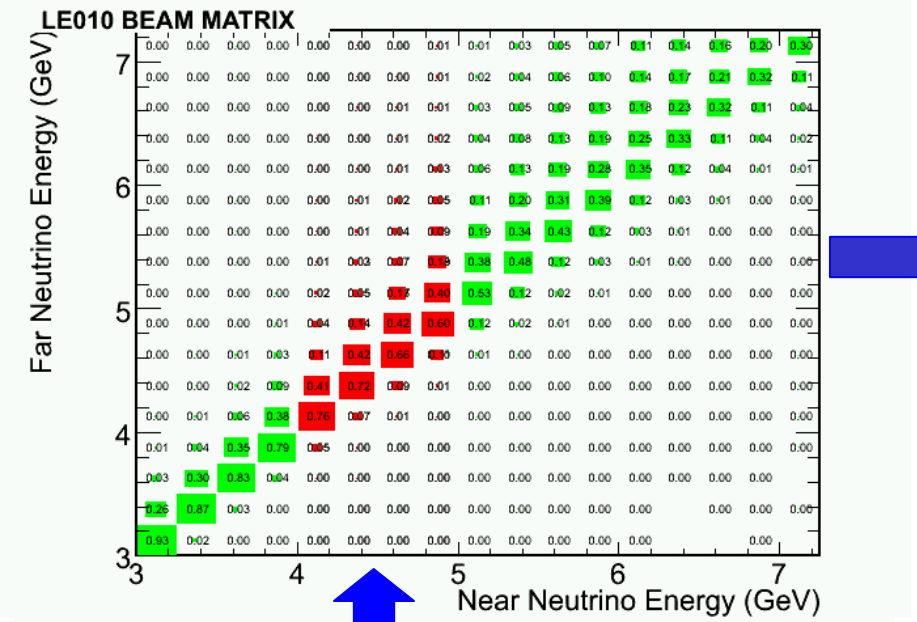
- [redacted]
- [redacted]
- [redacted]
- [redacted]

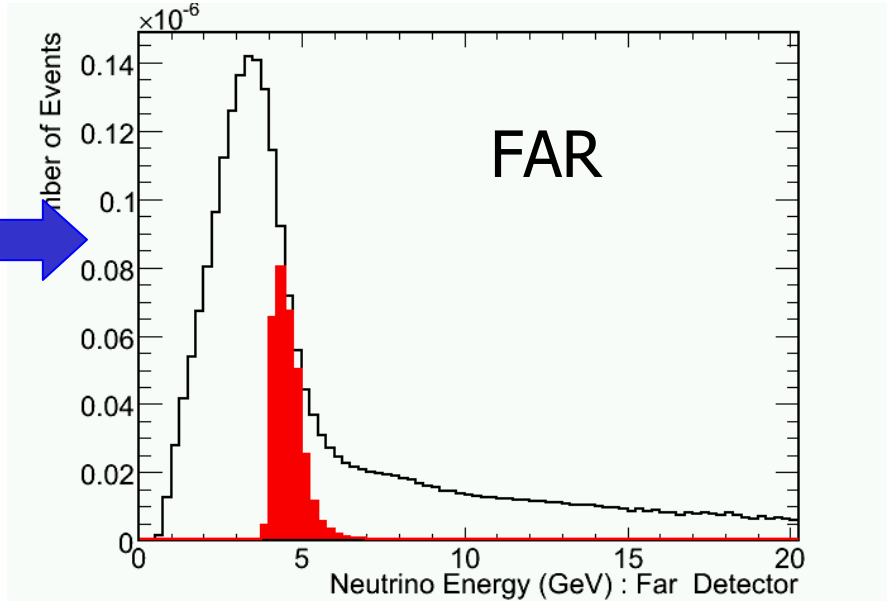


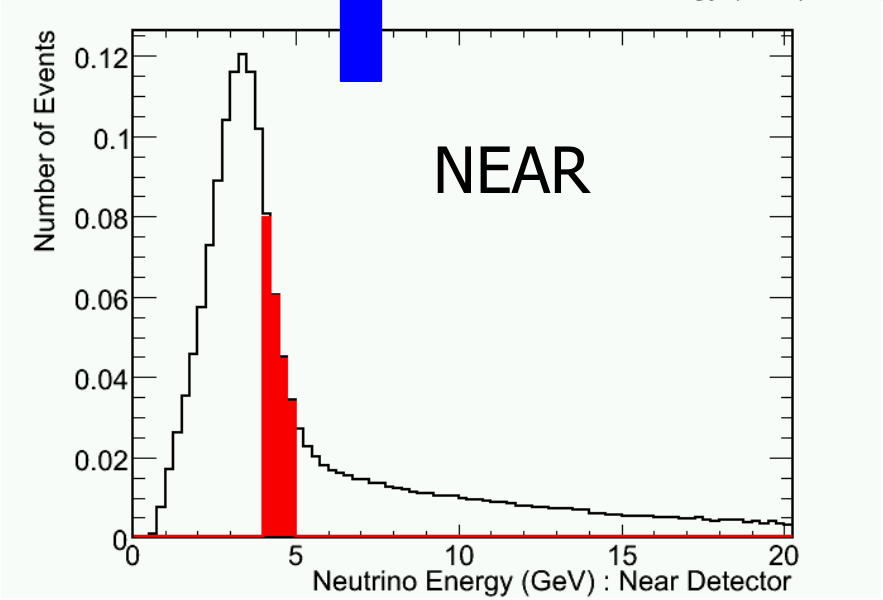
$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$

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

Beam Matrix Method

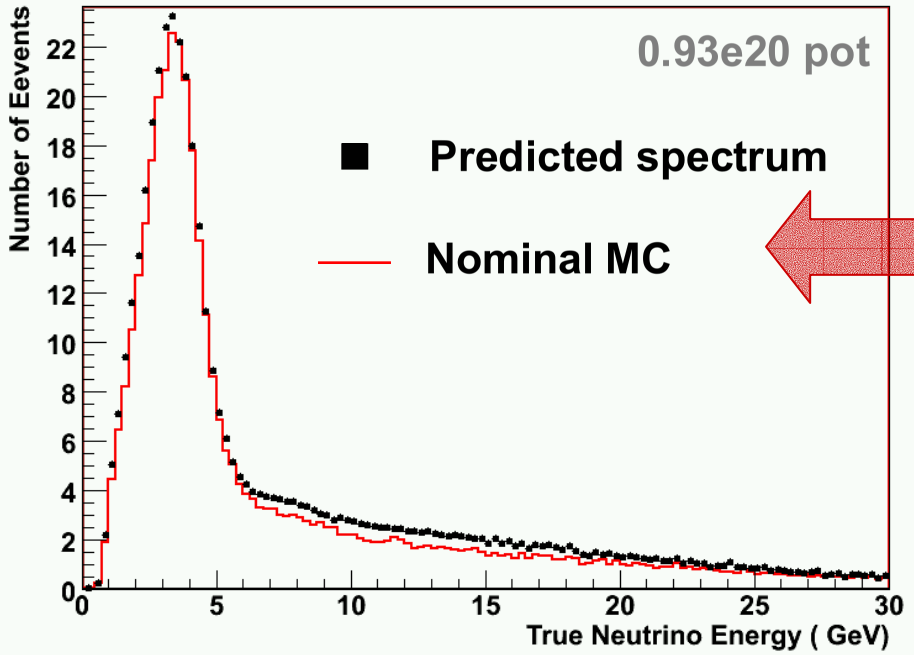




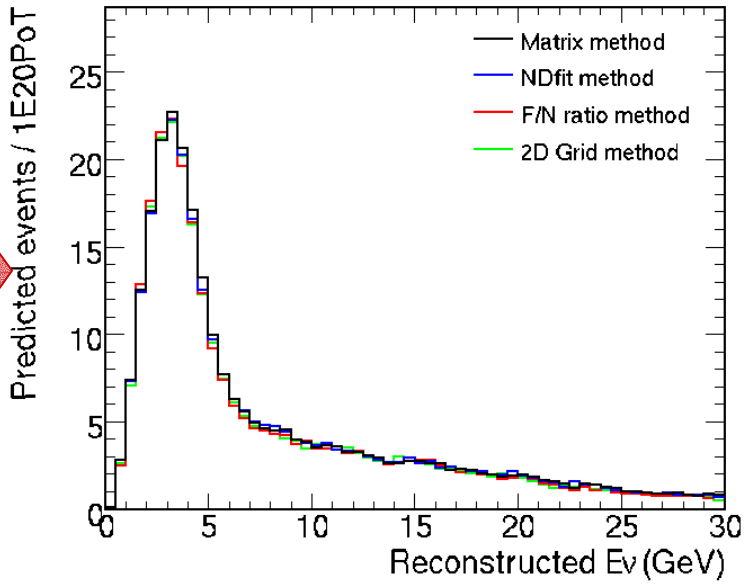


Predicted Spectrum

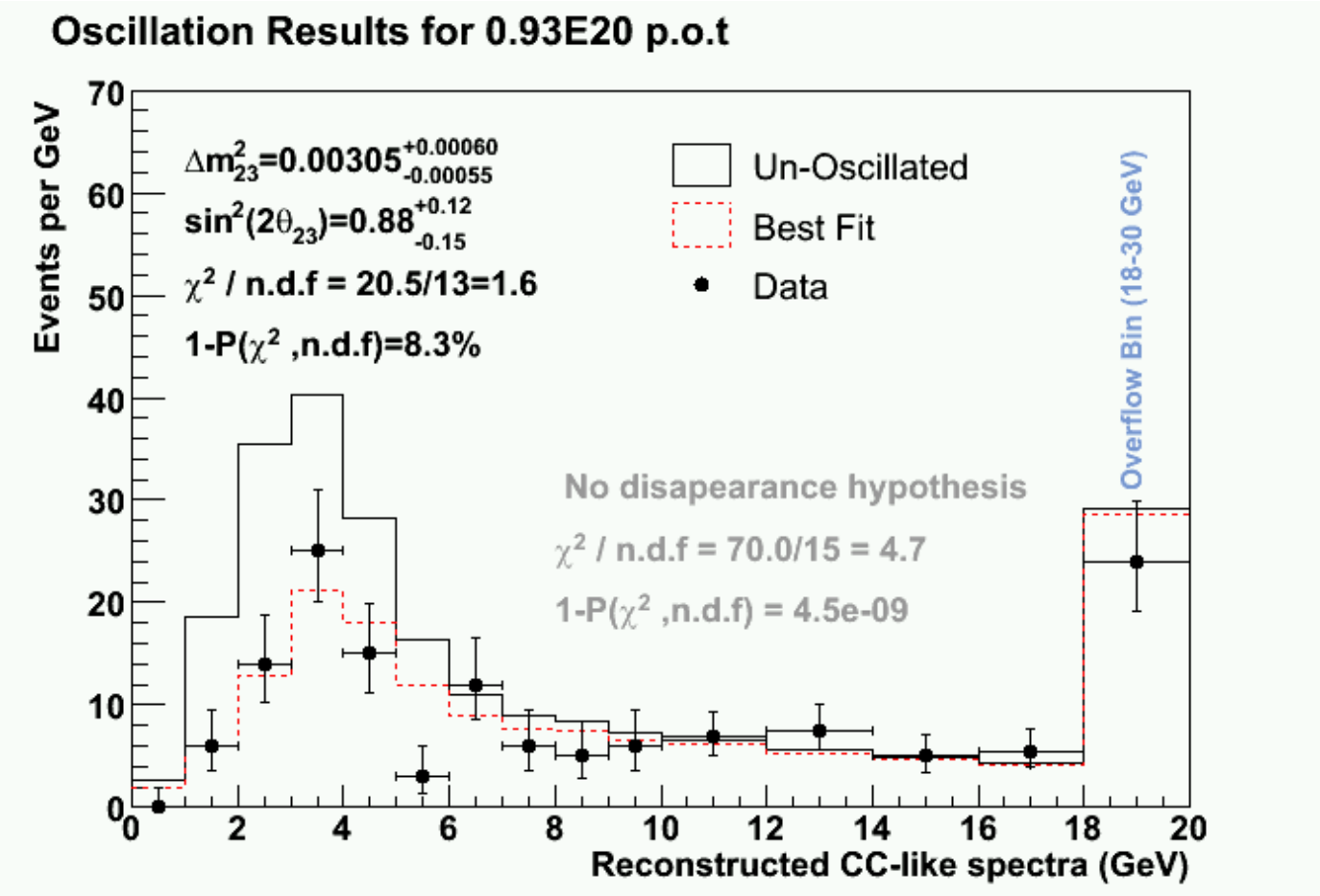
Predicted FD unoscillated spectra



Predicted FD unoscillated spectra



Oscillation Parameters

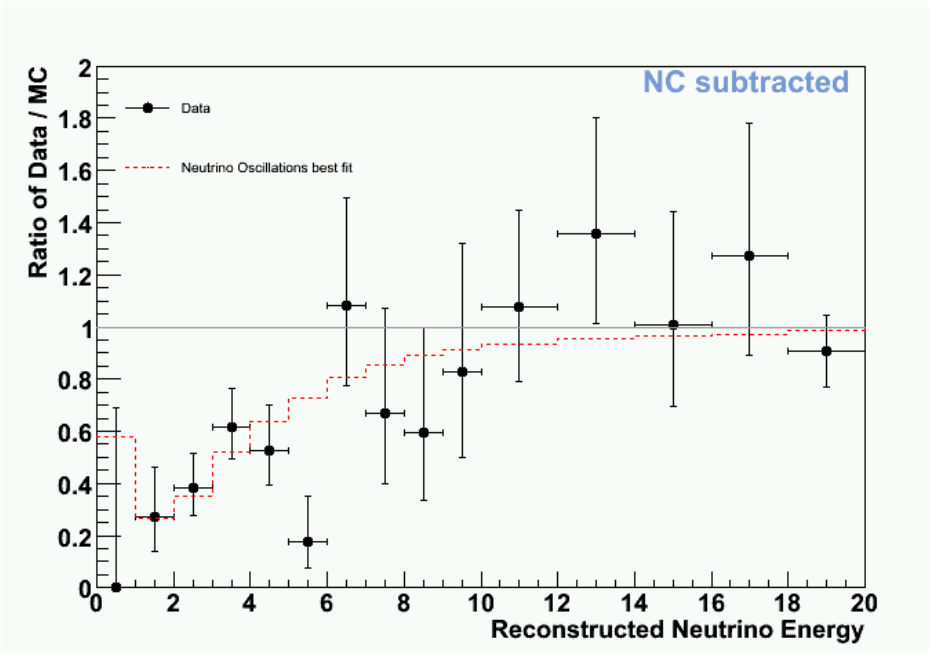


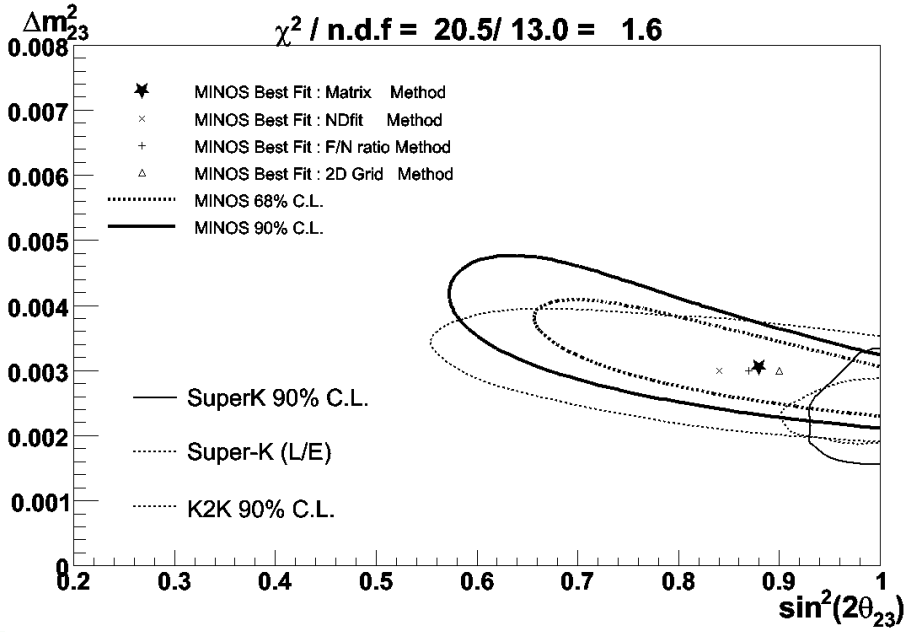
$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

o_i = observed

e_i = expected

Ratio Data/MC and Allowed Regions





Systematic Errors

- Systematic shifts in the fitted parameters have been computed with MC "fake data" samples for $\Delta m^2=0.003$ eV^2, $\sin^2 2\theta=0.9$ for the following uncertainties

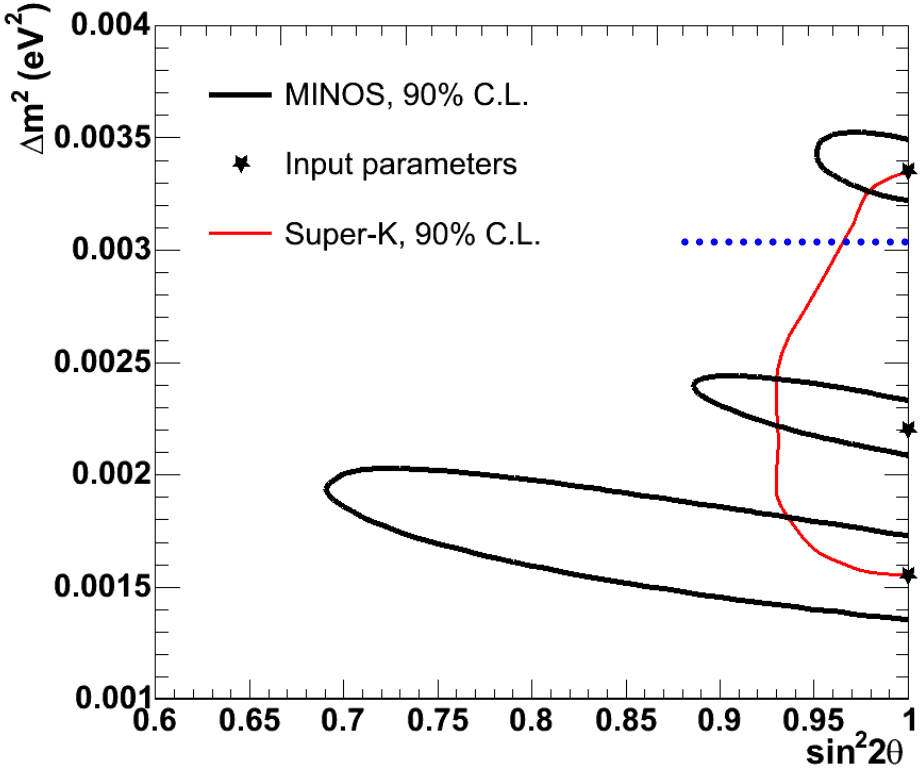
Uncertainty	Δm^2 shift (eV^2)	$\sin^2 2\theta$ shift
Normalisation +/- 4%	0.63e-4	0.025
Muon energy scale +/- 2%	0.14e-4	0.020
Relative Shower energy scale +/- 3%	0.27e-4	0.020
NC contamination +/- 30%	0.77e-4	0.035
CC cross-section uncertainties	0.50e-4	0.016
Beam uncertainty	0.13e-4	0.012
Intranuclear re-scattering	0.27e-4	0.030
Total (sum in quadrature)	**1.19e-4**	**0.063**
Statistical error (data)	**6.4e-4**	**0.15**

Outlook

- [redacted] Δm^2_{23} [redacted]
- [redacted] $\nu_\mu \rightarrow \nu_e$ [redacted]
- [redacted]

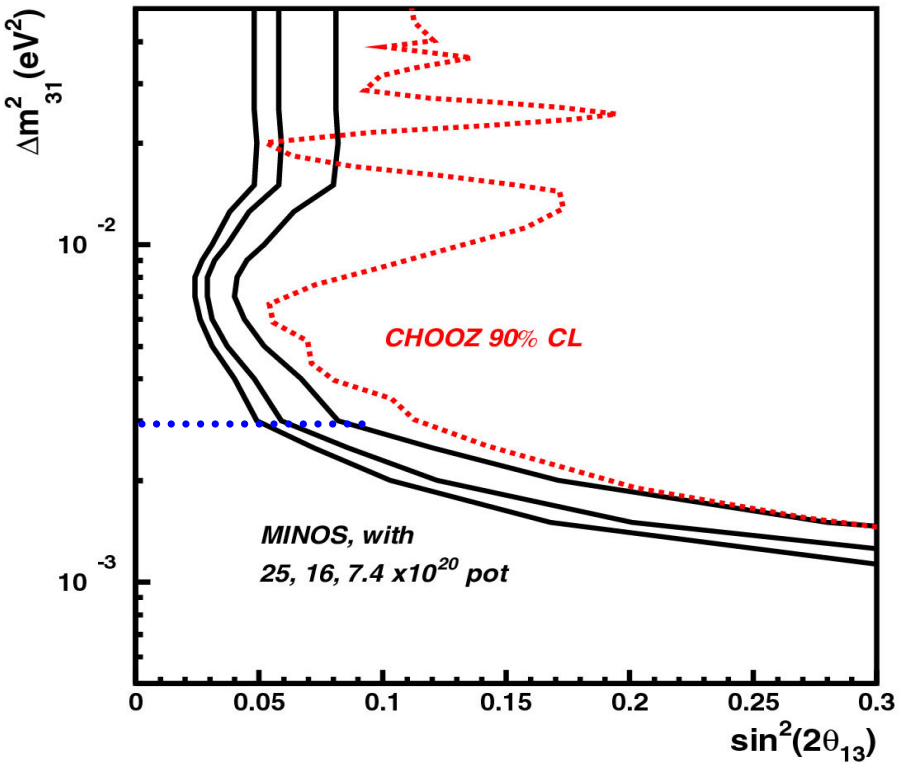
ν_μ disappearance

MINOS sensitivity, 16×10^{20} p.o.t.



$\nu_\mu \rightarrow \nu_e$

3 σ Contours



Summary

- [illegible]
- [illegible]
- [illegible]

$$\Delta m^2_{23} = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \times 10^{-3}\, eV^2$$

$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- [illegible]

$$\Delta m^2_{23} = 2.70^{+0.263}_{-0.305} \times 10^{-3}\, eV^2$$

- [illegible]
- [illegible]