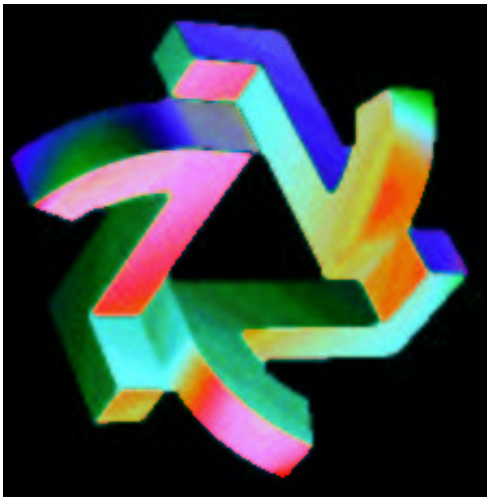
MINOS and the future



Milind V. Diwan

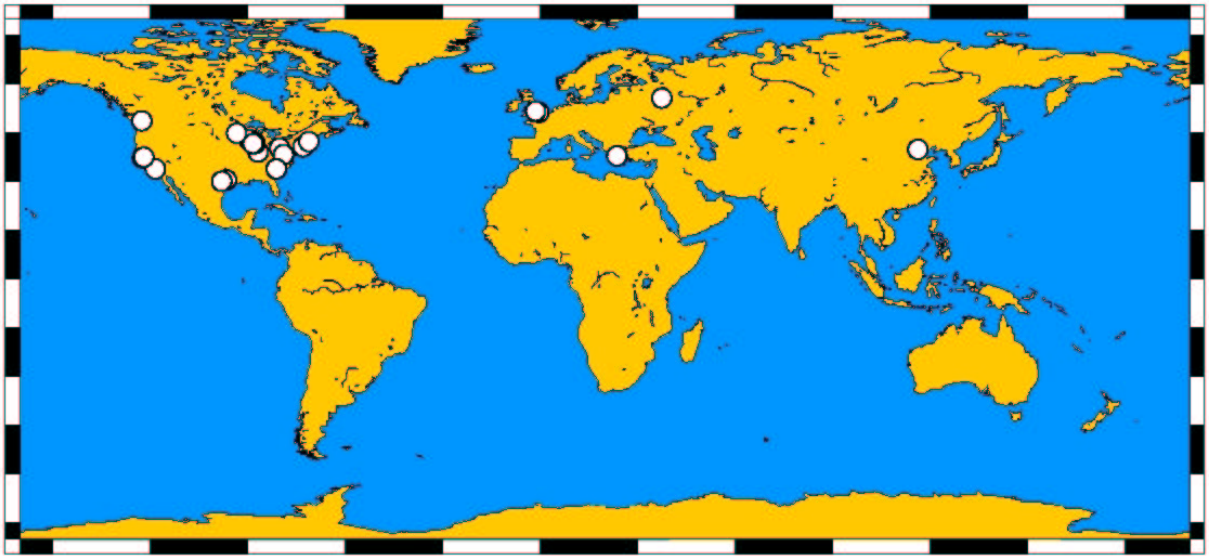
Brookhaven National Laboratory

7th workshop on tau-lepton physics

Santa Cruz, 10-13 Sep. 2002

- Neutrino Physics
- What needs to be measured ?
- MINOS Beam and Detectors
- MINOS physics potential and comparison
- Current status and schedule
- Possible/considered improvements

MINOS Collaboration



- ∼200 collaborators
- 30 institutions
- US, UK, Russia, Greece

Neutrino Physics: the simple stuff

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (1)$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned} \quad (2)$$

Sufficient to understand most of the physics:

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, ...$ $(\pi/2)$:
$\Delta m^2 = 0.003 eV^2$, $E = 1 GeV$, $L = 412 km$.

Neutrino Physics: the difficult stuff

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_1 c_3 & s_1 c_3 & s_3 e^{-i\delta} \\ -s_1 c_2 - c_1 s_2 s_3 e^{i\delta} & c_1 c_2 - s_1 s_2 s_3 e^{i\delta} & s_2 c_3 \\ s_1 s_2 - c_1 c_2 s_3 e^{i\delta} & -c_1 s_2 - s_1 c_2 s_3 e^{i\delta} & c_2 c_3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{3}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) \quad = \quad & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\ & +2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\ & +4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2 s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos\delta \\ & \quad - J_{CP} \sin\Delta_{31}) \sin^2 \frac{\Delta_{21}}{2} \\ & +8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2} \end{aligned} \tag{4}$$

$$\begin{aligned}\Delta_{31} &\equiv \Delta m^2_{31} L/2E_\nu \\ \Delta_{21} &\equiv \Delta m^2_{21} L/2E_\nu\end{aligned}$$

$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{5}$$

$$A \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \tag{6}$$

To leading order in Δ_{21} (assumed to be small), one finds

$$P(\nu_\mu \to \nu_e) \simeq 4 s_2^2 s_3^2 c_3^2 \sin^2 \frac{\Delta_{31}}{2} + \mathcal{O}(\Delta_{21}) \tag{12a}$$

$$A \simeq \frac{J_{CP} \sin\Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2 s_1 c_1 c_2 \sin\delta}{s_2 s_3} \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right) \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}(\Delta_{21}^2) \tag{12b}$$

Neutrino Physics: Super K result

Very large signal from asymmetry between upward and downward going muon neutrino rates.

Fit to all global data

C. K. Jung, T. Kajita, T. Mann, and C. McGrew Annu. Rev. Nucl. Part. Sci. 2001 , Vol. 51: 451-488.

Atmospheric Neutrinos $\nu_\mu \rightarrow \nu_\tau$ at 1 σ

$$\sin^2 2\theta_{23} > 0.9$$

$$\Delta m^2_{32} = (2.0 - 4.2) \times 10^{-3} eV^2$$

Best fit:$2.6 \times 10^{-3} eV^2$, $\sin^2 2\theta_{23} = 0.92$.

The most important contributor to the data is

Super-Kamioka collaboration.
Phys.Rev.Lett.81:1562-1567,1998

Next slide has the piture of the data from this PRL.

Neutrino Physics: K2K result

Make neutrino beam with 12 GeV protons from KEK. Approximately 5×10^{19} Protons delivered. KEK-SK distance: 250 km.

44 events (all types) observed out of 64 expected.

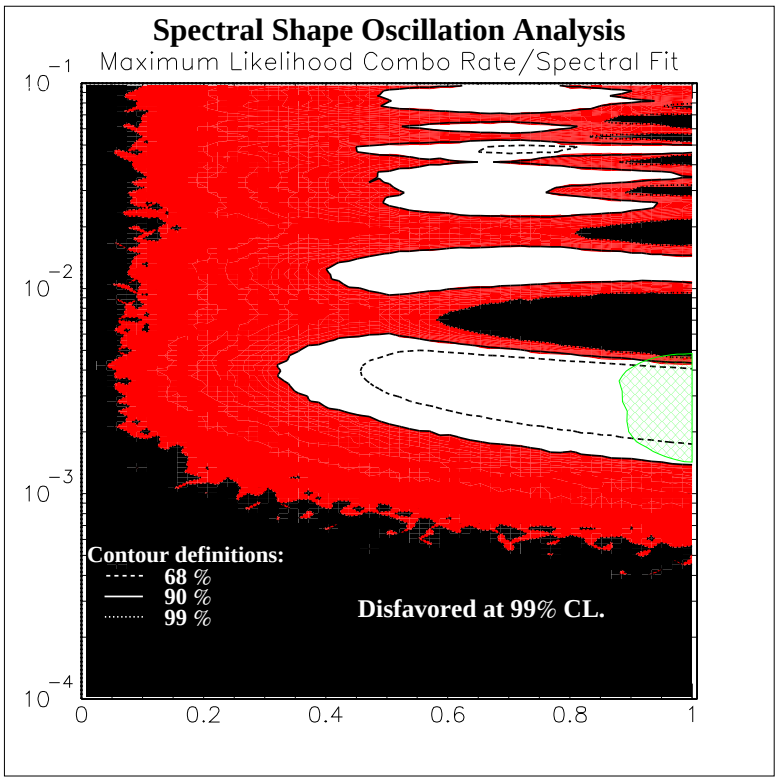


Figure 6.10: Oscillation Allowed Region, Combined Method

The allowed region from the K2K experiment.

From thesis by Eric Sharkey, SUNY at Stony Brook, 2002

Analysis includes fitting spectra.

Neutrino Physics: SNO result

Measure the flux of neutrinos from the SUN.

$\nu_e + d \rightarrow p + p + e^-(CC)$

$\nu + e^- \rightarrow \nu + e^-(ES)$

$\nu + d \rightarrow \nu + p + n(NC)$

Result: Phys.Rev.Lett.89:011301,2002

$$\phi_e = 1.76^{+0.05}_{-0.05} \pm 0.09 \times 10^6 cm^{-2} s^{-1}$$

$$\phi_{\mu\tau} = 3.41 \pm 0.45\ ^{+0.48}_{-0.45} \times 10^6 cm^{-2} s^{-1}$$

LMA solution greatly favored.

$$\sin^2 2\theta_{12} = (0.64 - 0.85)$$

$$\Delta m^2_{21} = (3.2 - 12.6) \times 10^{-5} eV^2$$

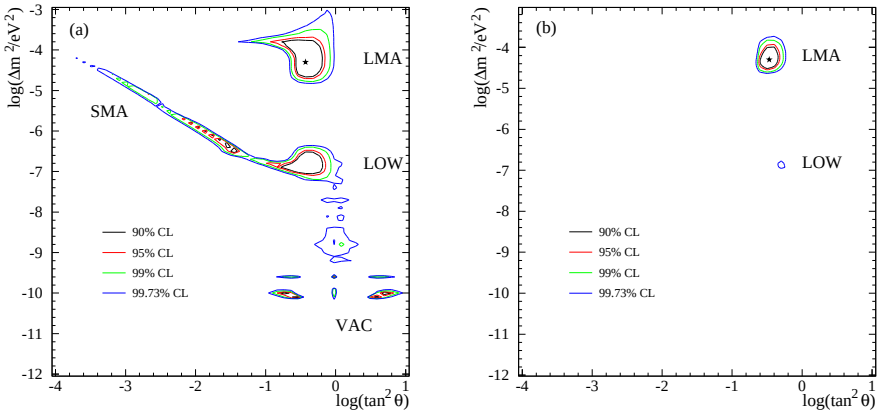


FIG. 4: Allowed regions of the MSW plane determined by a χ^2 fit to (a) SNO day and night energy spectra and (b) with additional experimental and solar model data. The star indicates the best fit. See text for details.

SNO web site: http://sno.phy.queensu.ca
[9] M. Dragowsky *et al.*, Nucl. Instr. and Meth. **A481**, 284 (2002).
[10] S. Fukuda *et al.*, Phys. Rev. Lett. **86**, 5651 (2001).
[11] J. N. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay (2002), hep-ph/0111150 v2.
[12] C. E. Ortiz *et al.*, Phys. Rev. Lett. **85**, 2909 (2000).
[13] S. Nakamura *et al.* (2002), nucl-th/0201062.
[14] J. N. Bahcall, H. M. Pinsonneault and S. Basu, Astrophys. J **555**, 990 (2001).
[15] B. T. Cleveland *et al.*, Astrophys. J **496**, 505 (1998).
[16] J. N. Abdurashitov *et al.*, Phys. Rev. C **60**, 055801 (1999).
[17] J. N. Abdurashitov *et al.* (2002), astro-ph/0204245
[18] M. Altmann *et al.*, Phys. Lett. B **490**, 16 (2000).
[19] W. Hampel *et al.*, Phys. Lett. B **447**, 127 (1999).
[20] C. M. Cattadori *et al.*, in *Proceedings of the TAUP 2001 Workshop*, (September 2001), Assergi, Italy.

What does it all mean ?

- Atmospheric Neutrinos $\nu_\mu \rightarrow \nu_\tau$ at 1 σ

$$\sin^2 2\theta_{23} > 0.9$$

$$\Delta m^2_{32} = (2.0 - 4.2) \times 10^{-3} eV^2$$

Best fit:$2.6 \times 10^{-3} eV^2$, $\sin^2 2\theta_{23} = 0.92$.

C. K. Jung, T. Kajita, T. Mann, and C. McGrew Annu. Rev. Nucl. Part. Sci. 2001 , Vol. 51: 451-488.

- Solar Neutrinos $\nu_e \rightarrow (\nu_\mu, \nu_\tau)$ at 1 σ New results from SNO. A complete fit to all data by the SNO collaboration (nucl-ex/0204008, nucl-ex/0204009)

LMA solution greatly favored.

$$\sin^2 2\theta_{12} = (0.64 - 0.85)$$

$$\Delta m^2_{21} = (3.2 - 12.6) \times 10^{-5} eV^2$$

- Null reactor Exps $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$\sin^2 2\theta_{13} < 0.12$$

- CP violation

  Nothing is known.

  Some additional information

  LSND Sterile neutrinos ?

$$\sin^2 2\theta_{12} \approx \ few \times 10^{-3}$$

$$3 \times 10^{-2} < \Delta m^2_{21} < 3eV^2$$

  Upward going muons
  No evidence for sterile neutrinos in atmospheric Osc.
  K2K (56 observed with 80 expected) disappearance agrees with ν_μ disappearance hypothesis.

- Most important: There is still no conclusive accelerator experiment.

4 GOALS OF NEUTRINO PHYSICS

- Precise determination of Δm^2_{32} and $\sin^2 2\theta_{23}$and definitive observation of oscillatory behavior.

  MINOS can do this in the near future.

- Detection of $\nu_\mu \rightarrow \nu_e$ in the appearance mode. If $\Delta m^2_{\nu_\mu \rightarrow \nu_e} = \Delta m^2_{32}$ then $|U_{e3}|^2 (= \sin^2 \theta_{13})$ is non-zero.

  MINOS can do this. And could get lucky if the rate is large. We have an opportunity to make this better.

- Detection of the matter enhancement effect in $\nu_\mu \rightarrow \nu_e$. Sign of Δm^2_{32}; i.e. which neutrino is heavier.

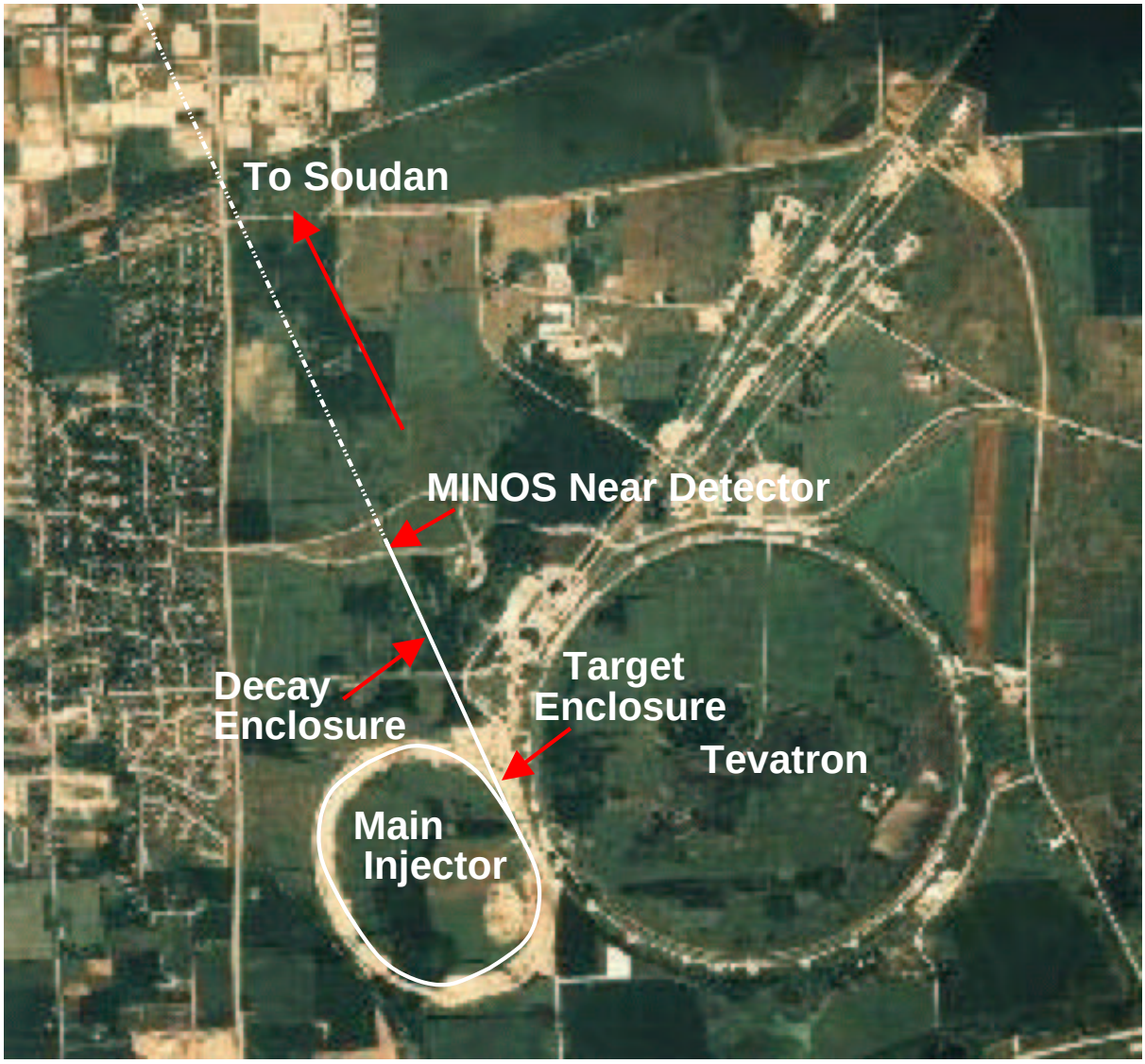
- Detection of CP violation in neutrino physics. Phase of $|U_{e3}|$ is CP violating and causes asymmetry in the rates $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

MINOS Overview

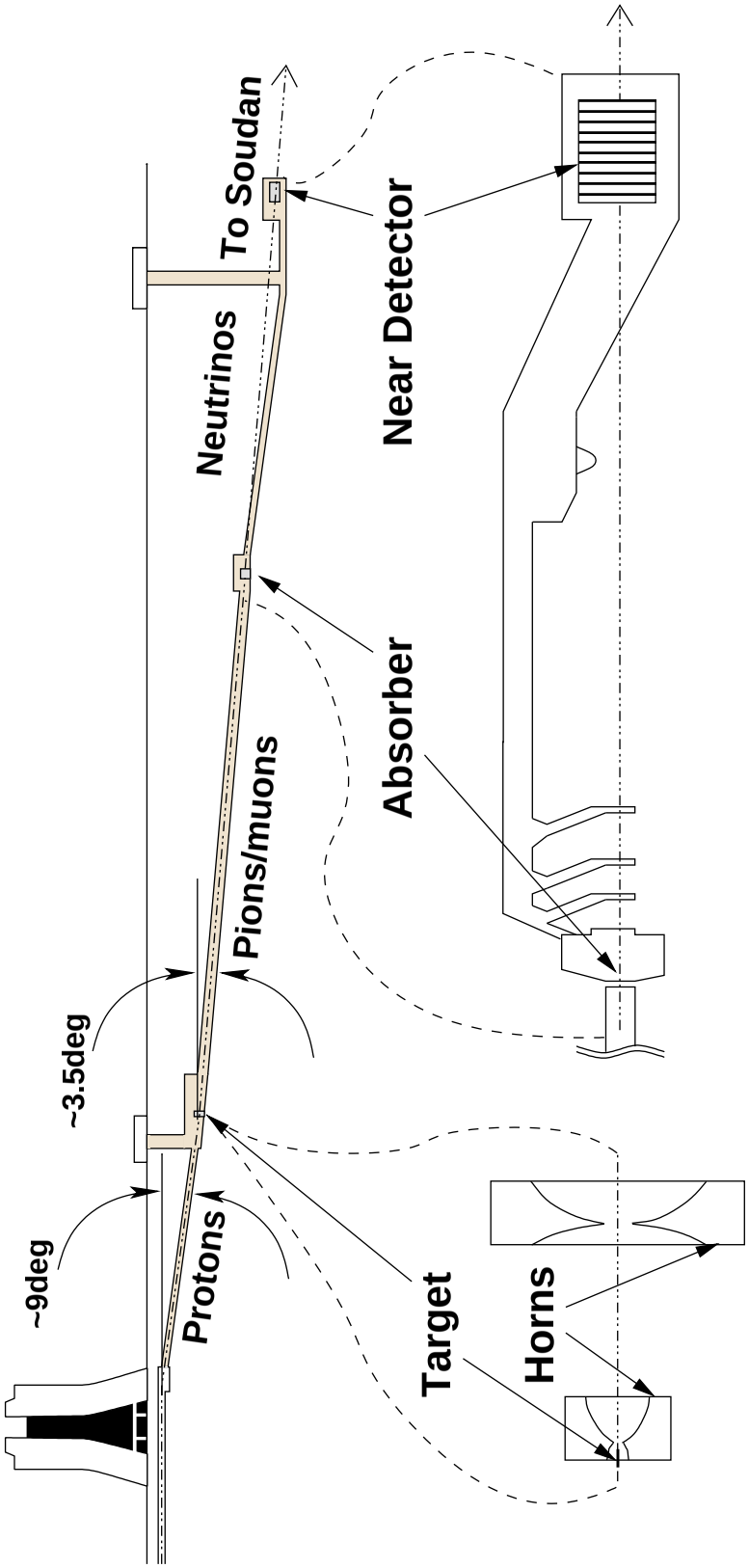
MINOS = **M**ain **I**njector **N**eutrino **O**scillation **S**earch

- 120 GeV MI protons on graphite target
  - 5/6 batches ($\bar{p}$/no $\bar{p}$)
  - 84 3-8 ns bunches/batch
  - 8.1 or 9.8 μsec spill every 1.9 sec
  - 4×10^{13} protons/spill (max)
  - 3.8×10^{20} protons/year
- 2 horn pion focusing
- "LE" 1-6 GeV neutrinos w/ tail out to 50 GeV
- 735.340 km baseline.
- Near and Far iron/scintillator detectors
  - Near @ FNAL: 3 events/spill in "target region"
  - Far @ Soudan, MINN: 3000 ν_μ CC events/kt/yr (no osc.)

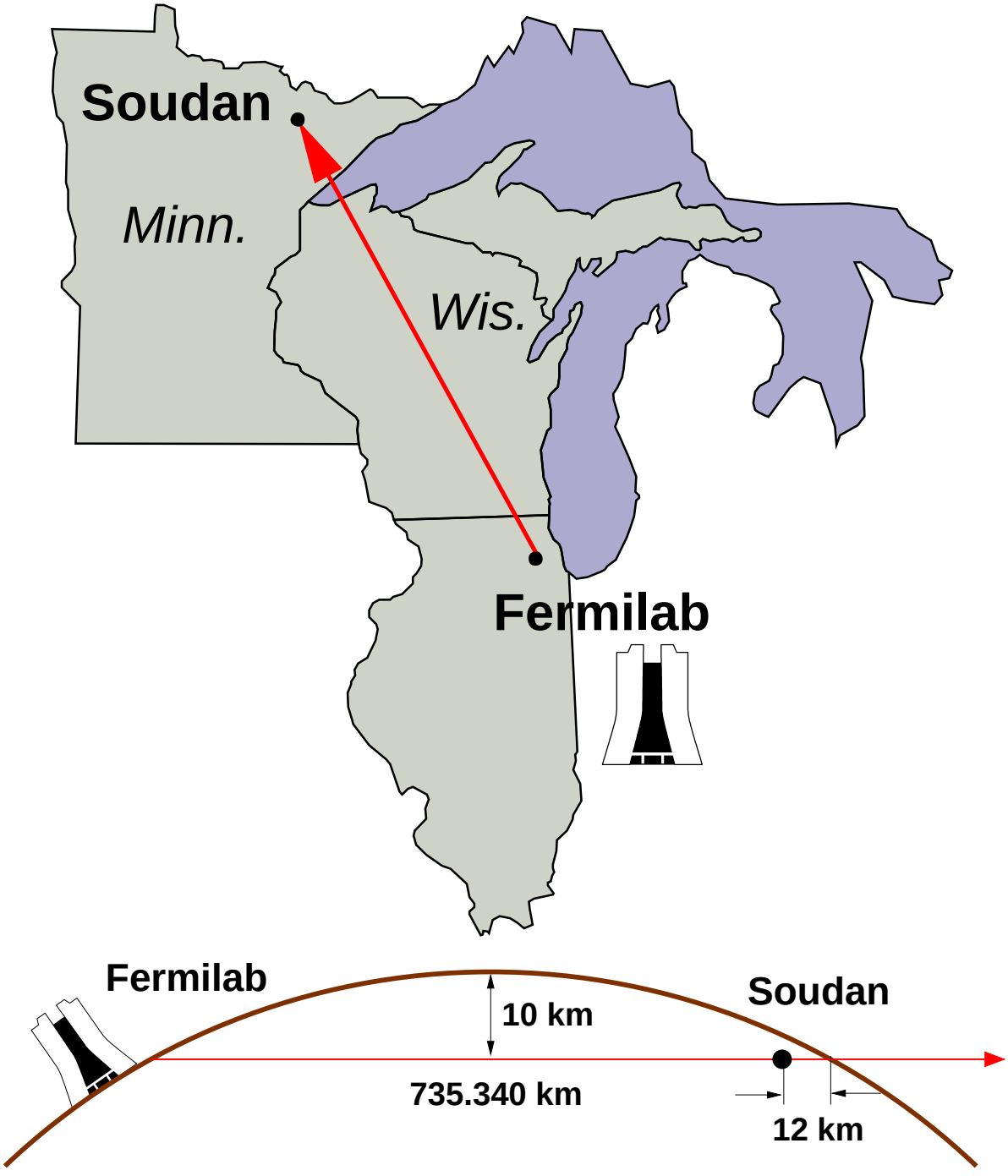
Aerial View


To Soudan
MINOS Near Detector
Decay
Enclosure
Target
Enclosure
Tevatron
Main
Injector

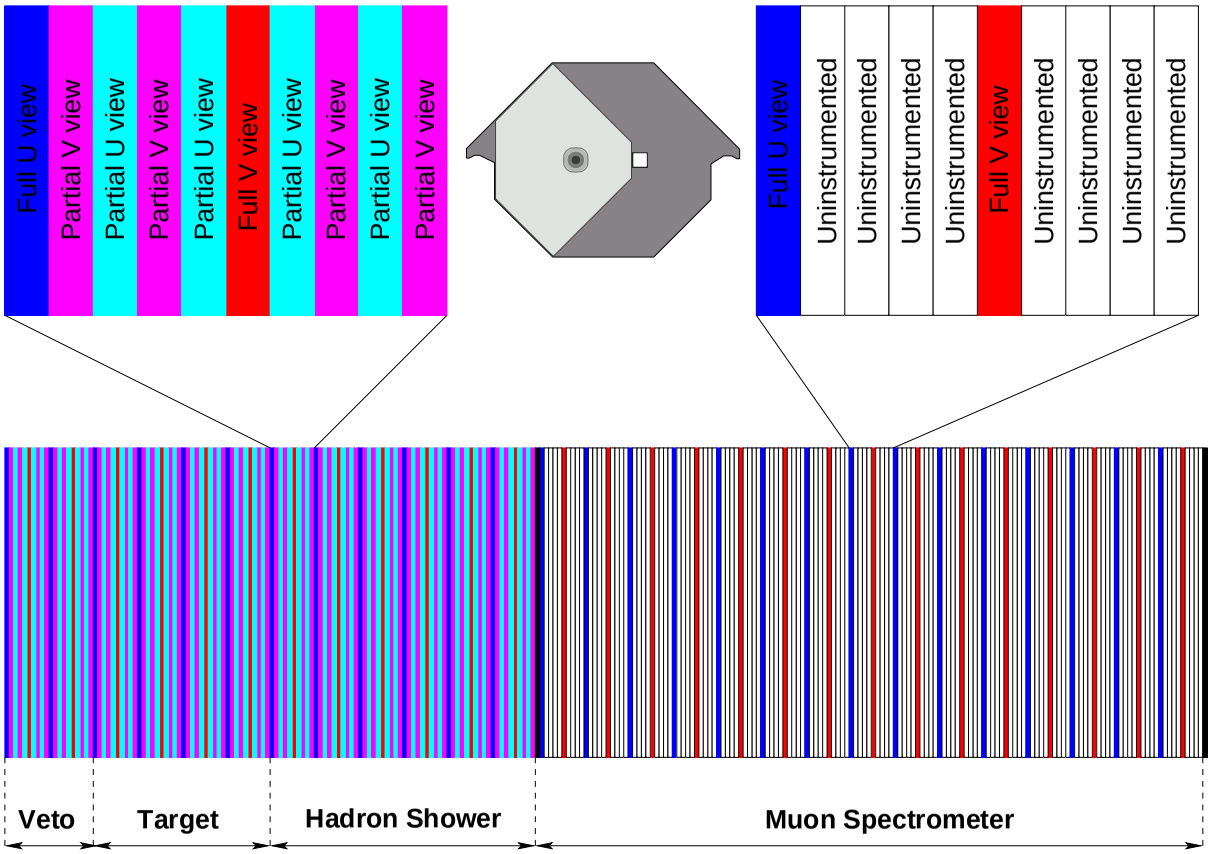
Neutrino Production



Base Line

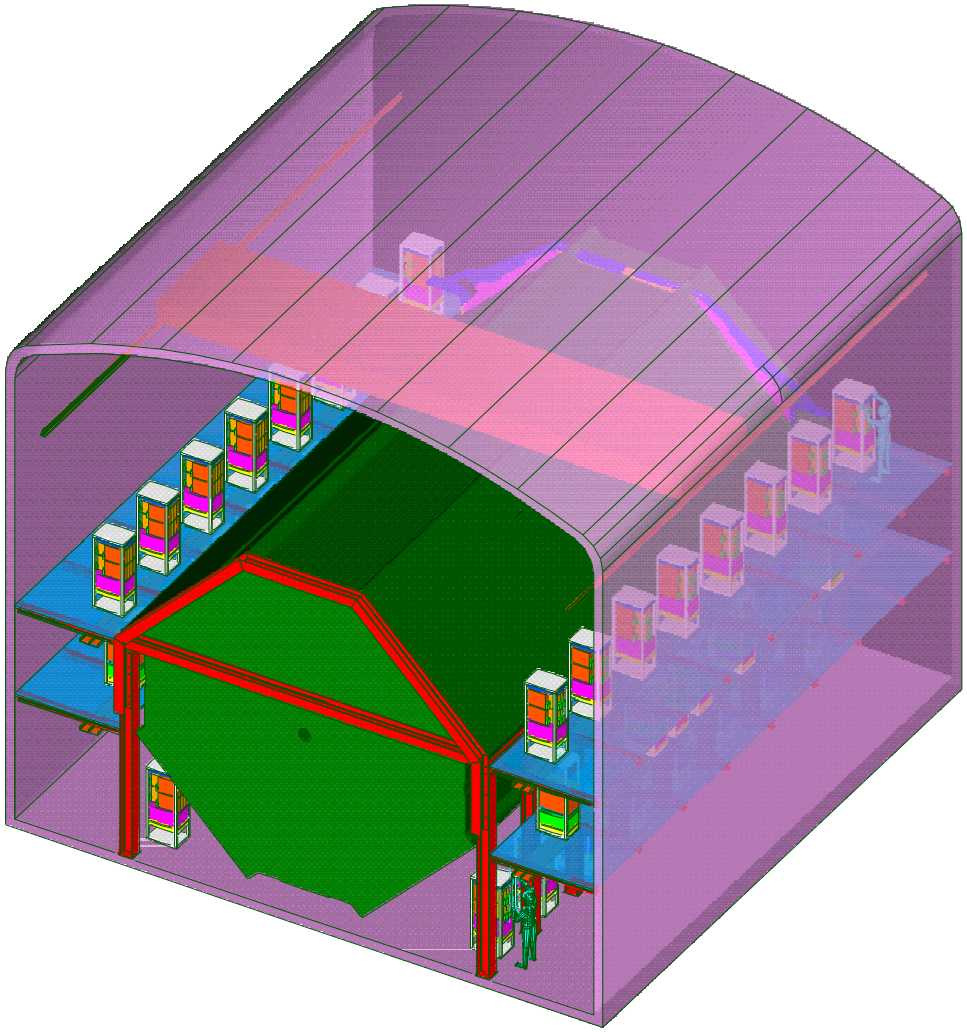

Soudan
Minn.
Wis.
Fermilab
Fermilab
10 km
Soudan
735.340 km
12 km

Near Detector



- 1kt (0.1kt fiducial).
- 282 steel planes
- 153 scintillator planes
- 68 or 96 scintillator strips/plane.
- 1 ended readout, no multiplexing

Far Detector



- 5.4kt (3.3kt fiducial)
- 486 steel planes (243/243)
- 484 scintillator planes (242/242)
- 192 scintillator strips/plane.
- 2 ended readout, 8x multiplexing

Current Status and Schedule

- Calibration Detector taking data at CERN.
- NuMI turn on: First protons Dec 2004, Fully commissioned Feb 9, 2005.
- Near Detector tunnel finished. Beampipe being installed.
- Far Detector hall finished
- 53 weeks of installation finished
- 2.9 kT finished.
- Magnet coil installed and turned on in Super Module 1.

  Finish both Super-Modules: Oct 2003.
- First upward going muon detected.

Some pictures

- Numi Tunnel finished
- Installation of decay pipe started
- Far detector hall in June 2001.
- Far Detector hall finished with first plane
- 53 weeks of installation finished
- Magnet coil installed and turned on in Super Module 1.
- First Bending muon.

MINOS and the future of neutrino oscillations



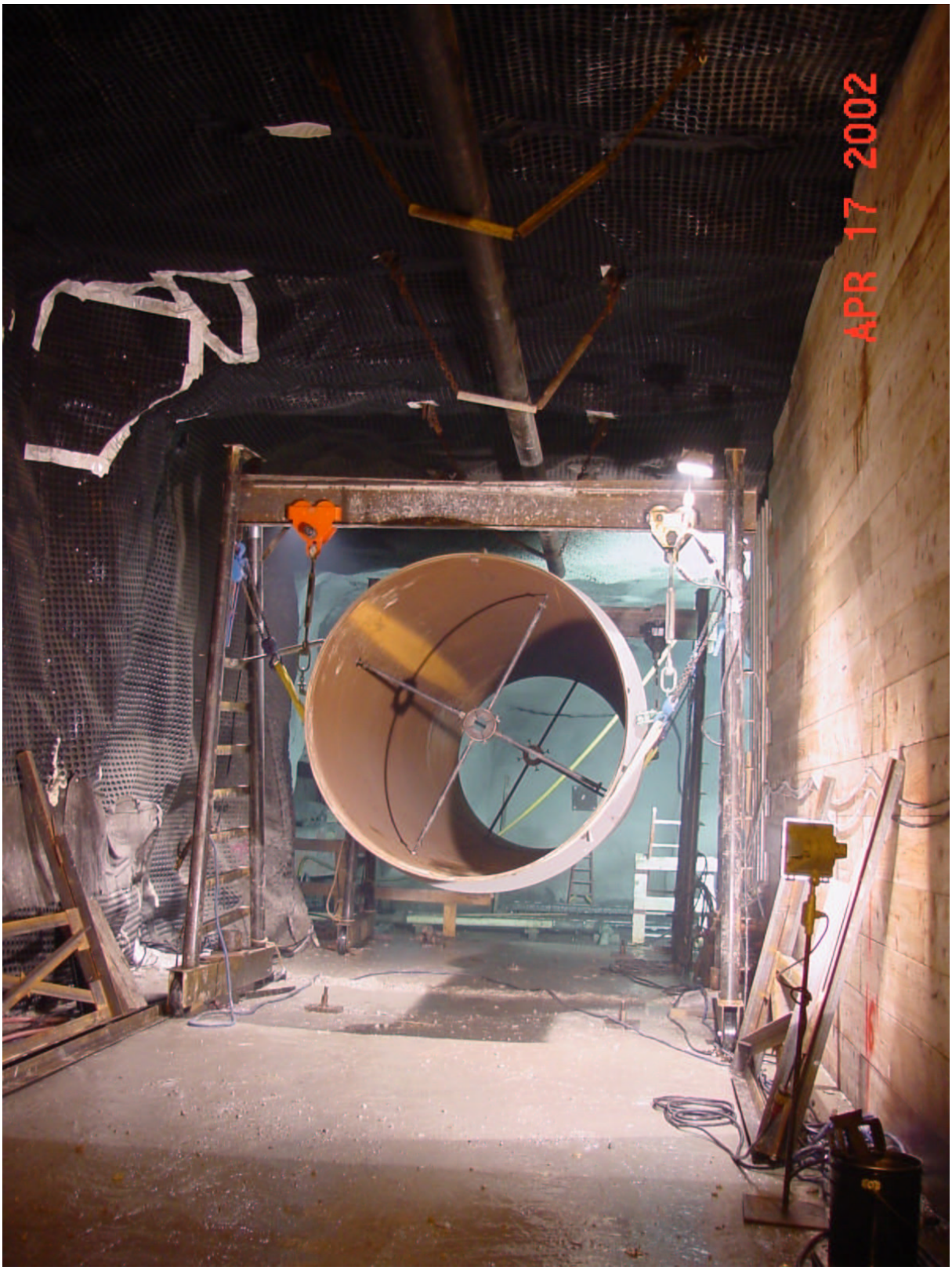
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MINOS and the future of neutrino oscillations



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MINOS and the future of neutrino oscillations



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MINOS and the future of neutrino oscillations



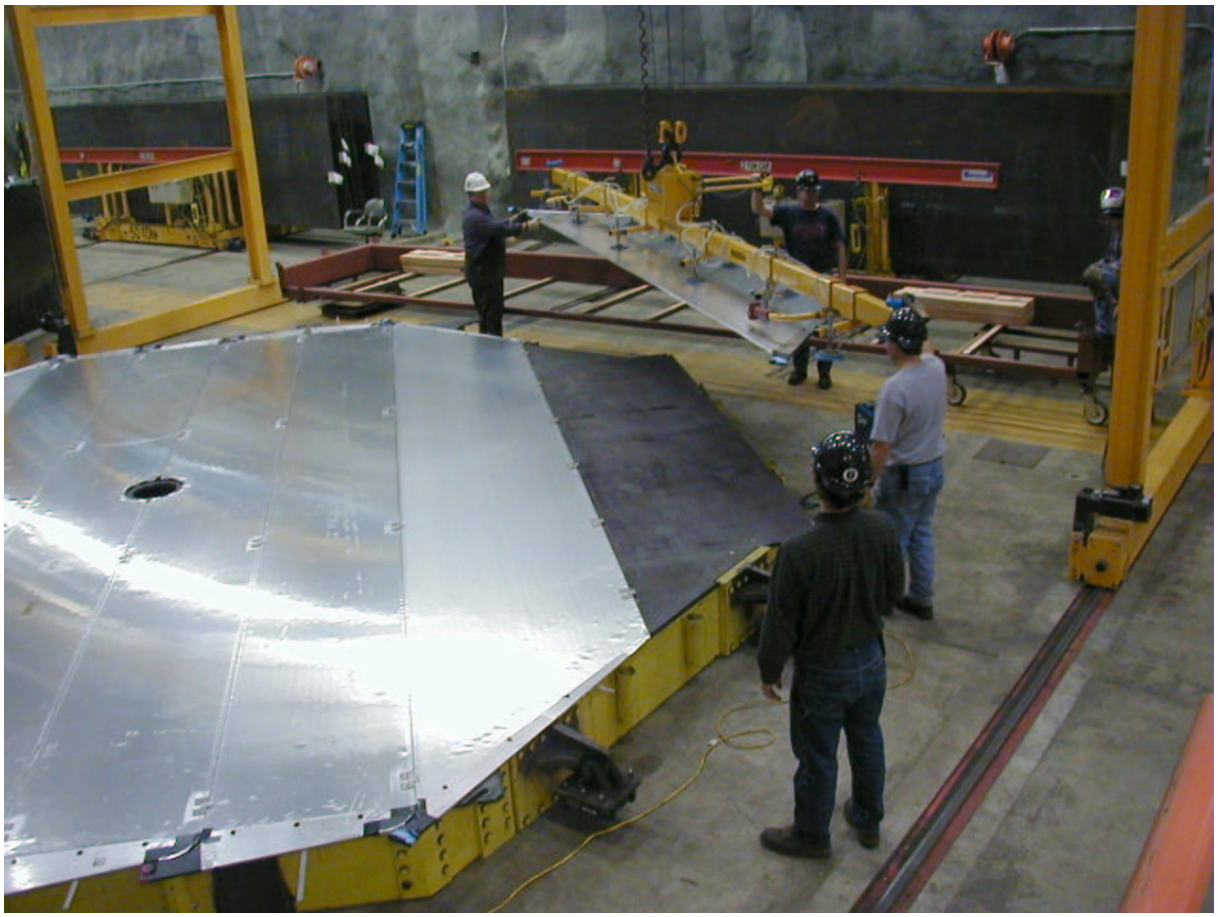
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MINOS and the future of neutrino oscillations



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MINOS and the future of neutrino oscillations

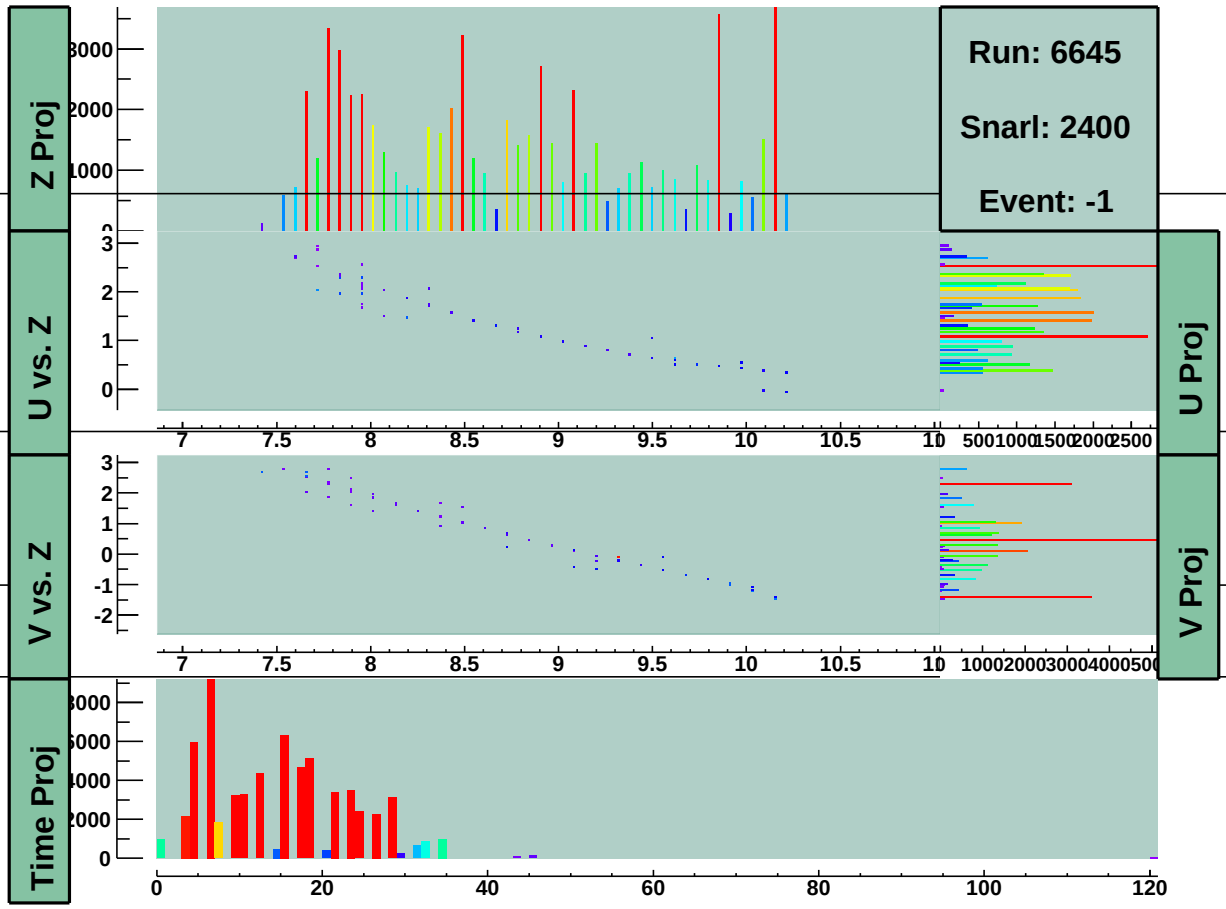


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MINOS and the future of neutrino oscillations

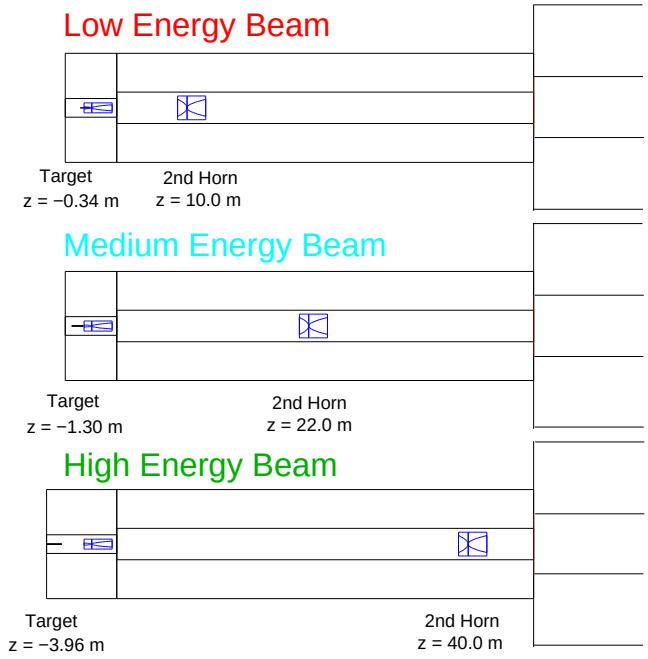


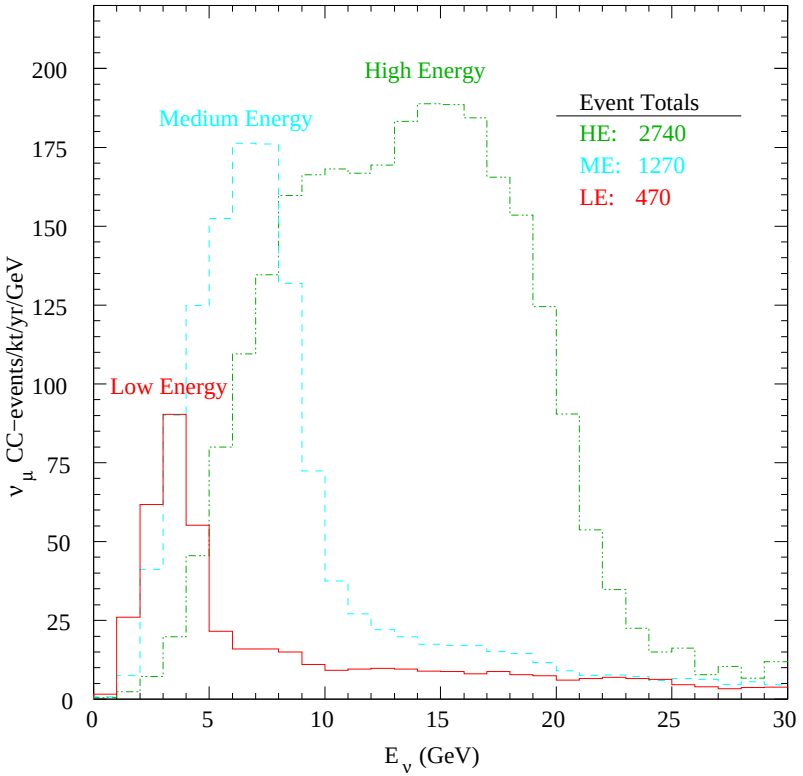
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Z Proj
U vs. Z
U Proj
V vs. Z
V Proj
Time Proj
Run: 6645
Snarl: 2400
Event: -1

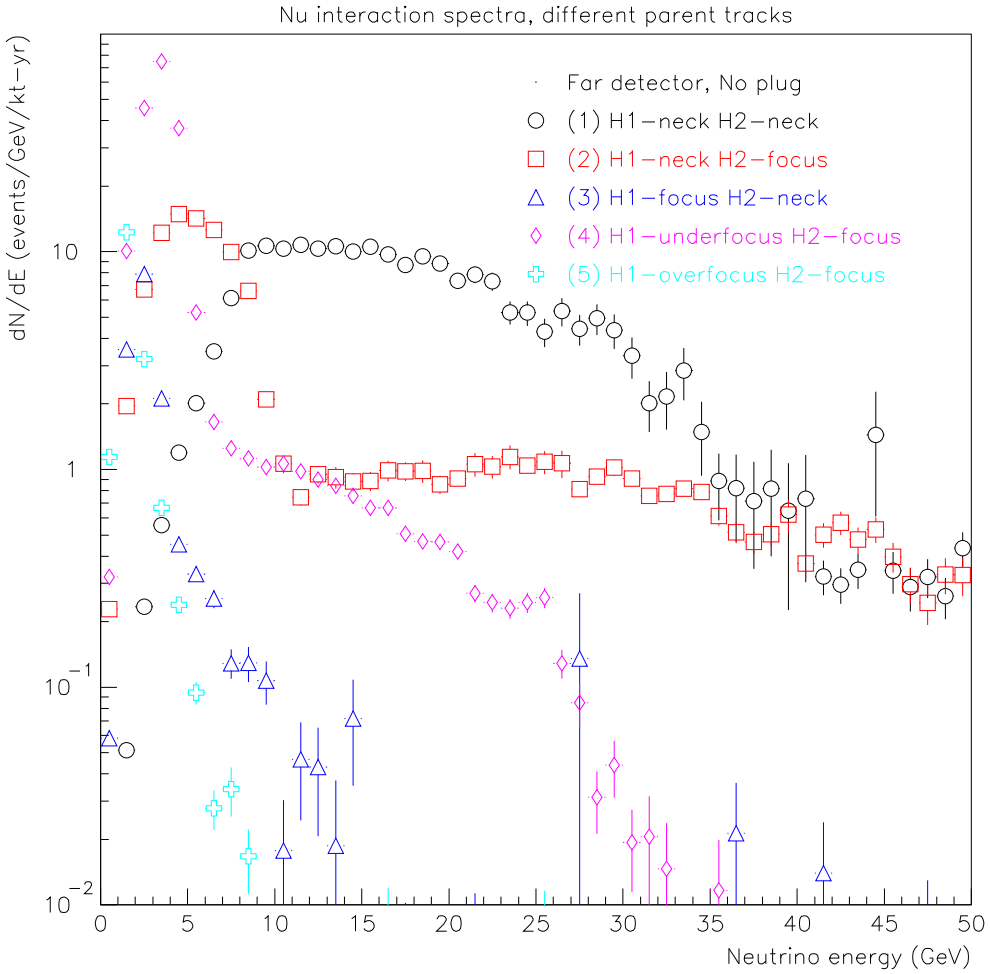
Expected Far Detector Interaction Spectra

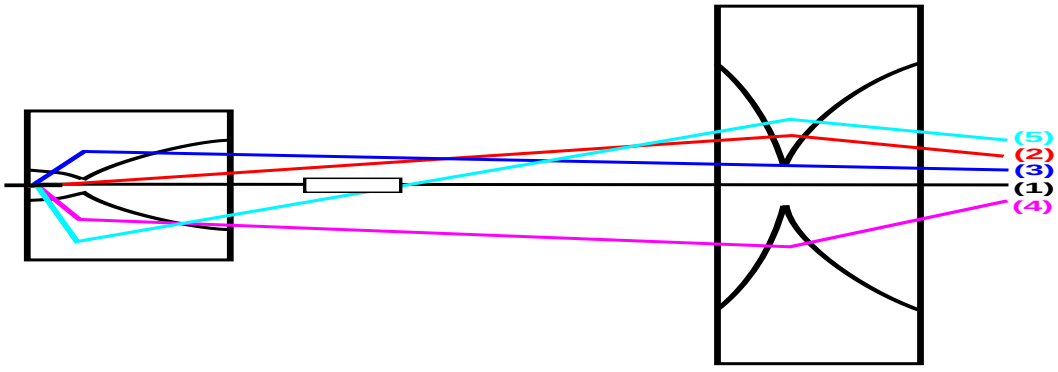
NuMI Beam Lines





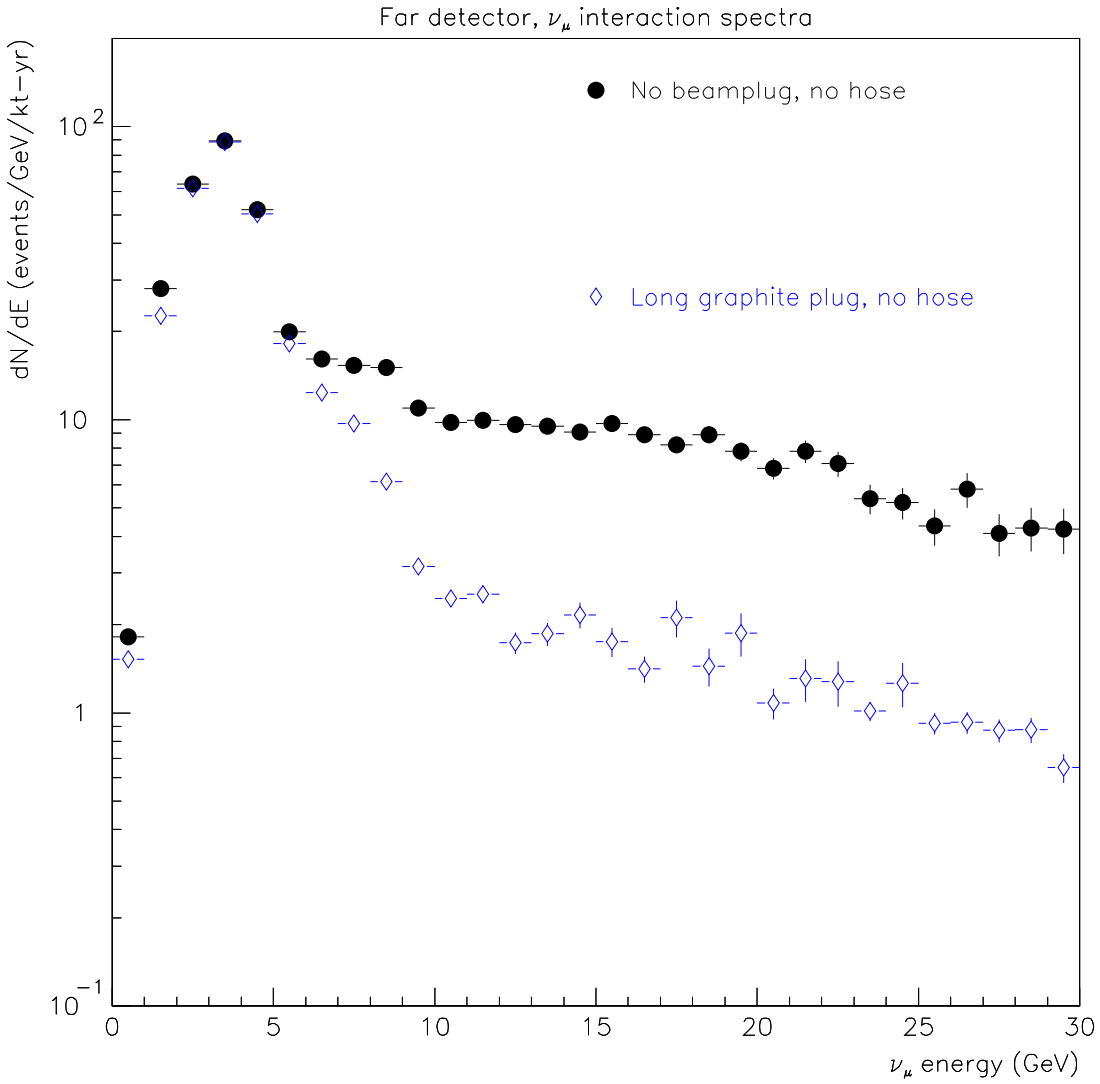
Neutrino Beam Components





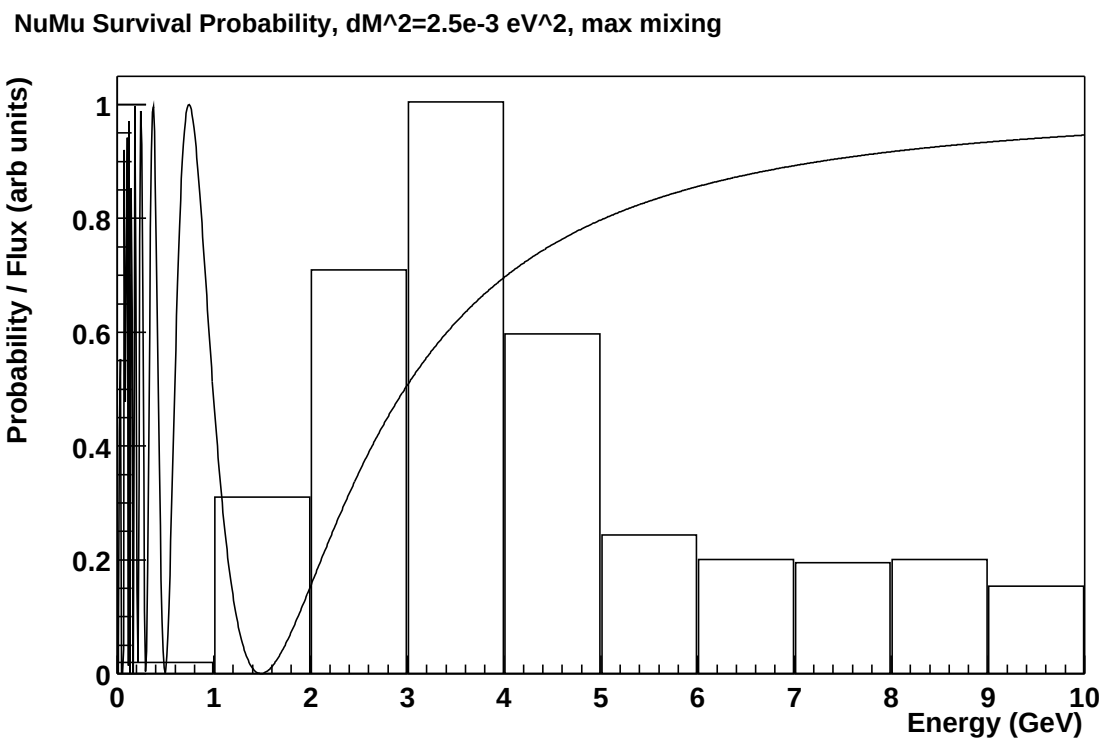
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Effects of 2.5m Graphite plug

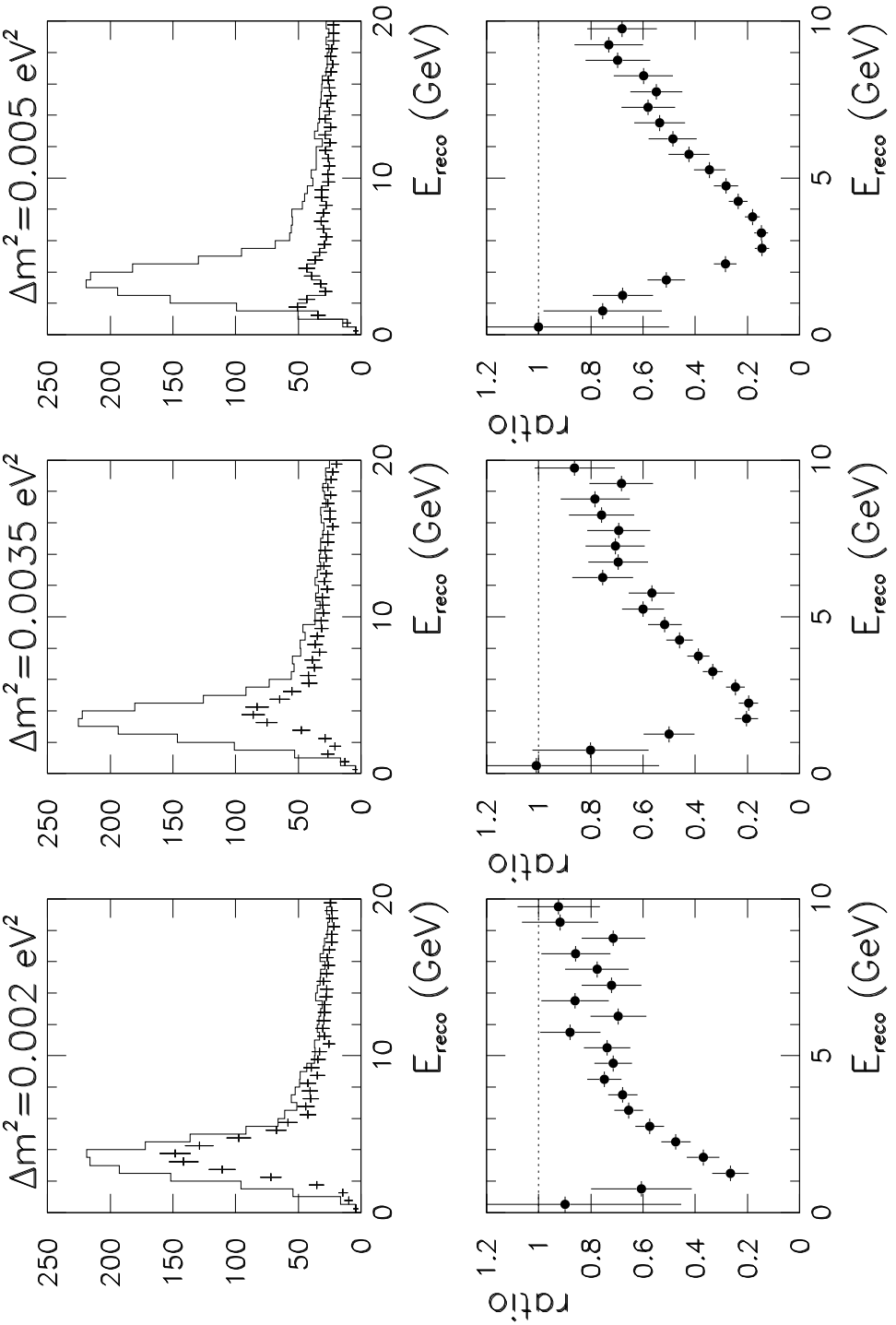


Energy (GeV) :	0 - 3	3 - 6	6 - 10	10 - 30
Reduction (%):	5	0.0	24	80

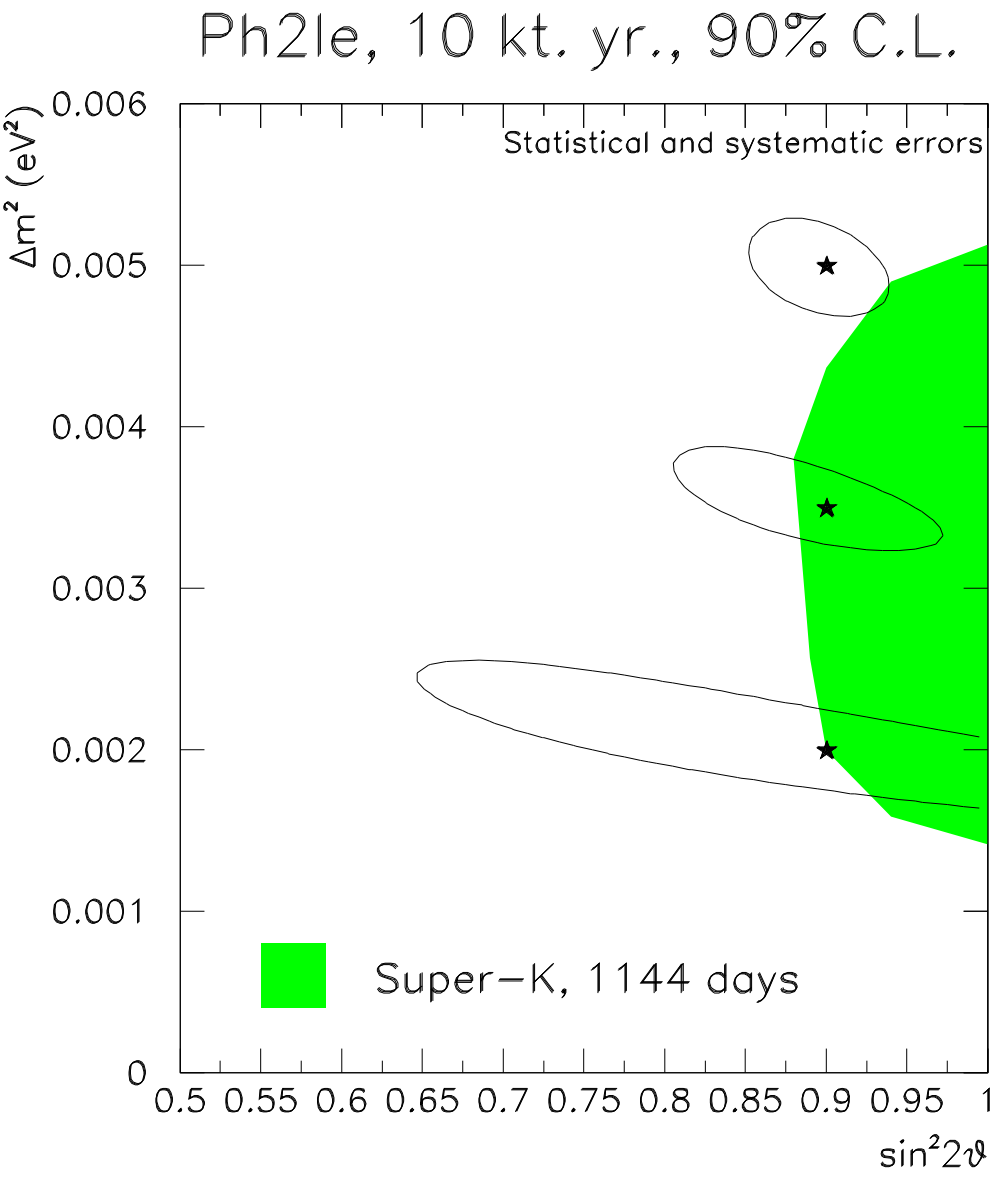
Oscillation Probabilities



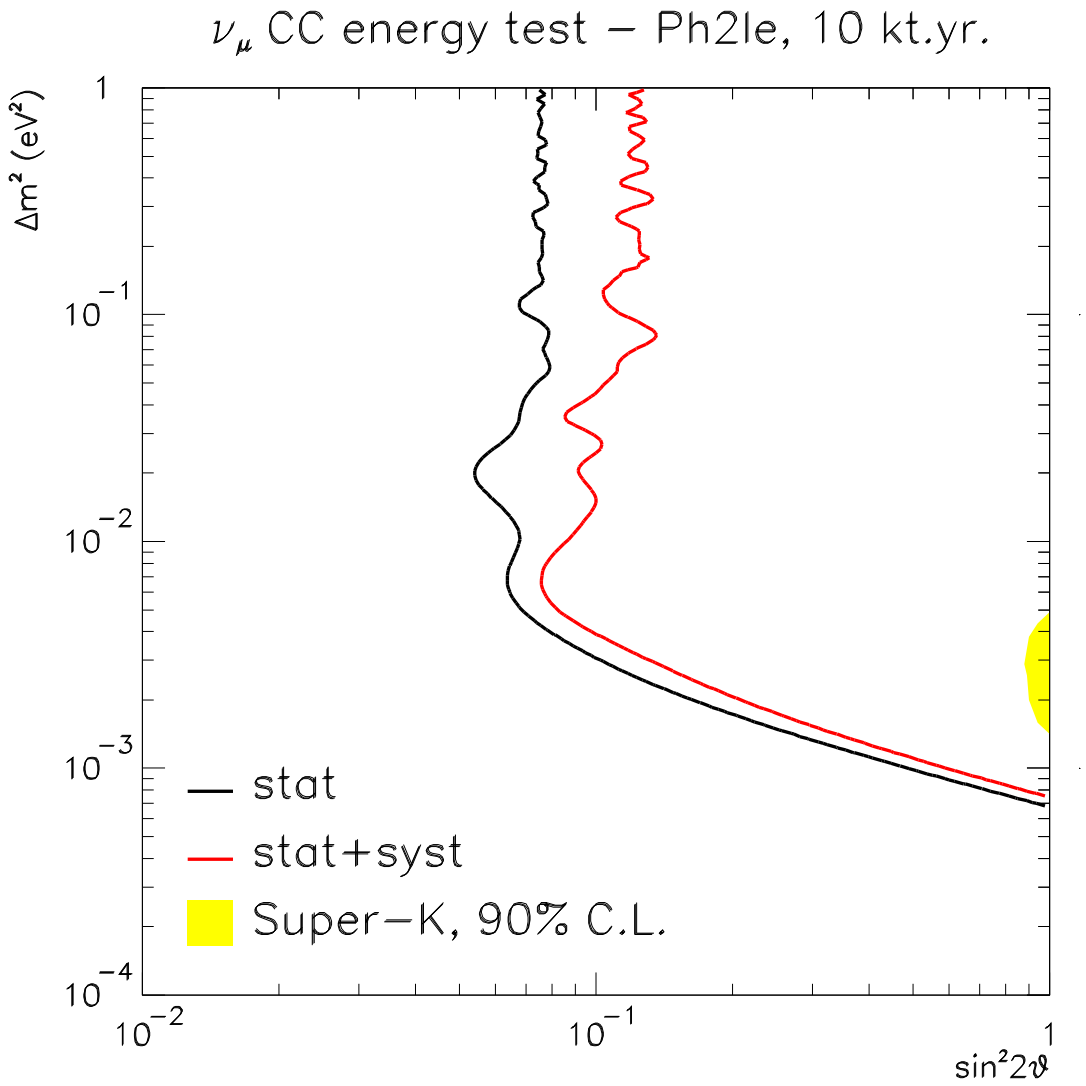
Expected Flux Distribution (ν_μ disappearance)



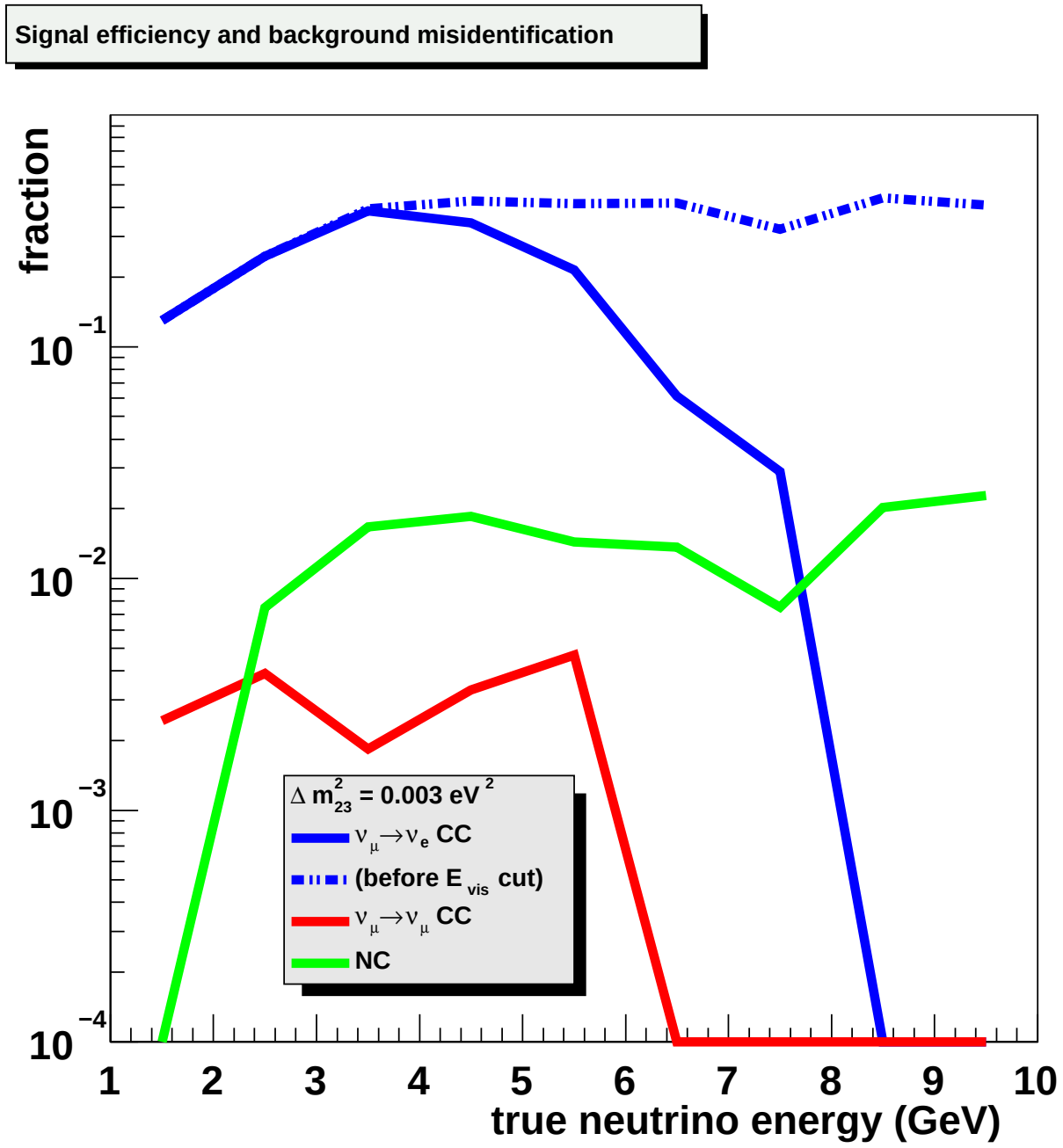
Expected Sensitivities (ν_μ disappearance)



Expected Limits (ν_μ disappearance)



Expected Efficiency (ν_e appearance)



$$\delta m^2 = 0.003\mathrm{eV}^2$$

Problem for ν_e: background

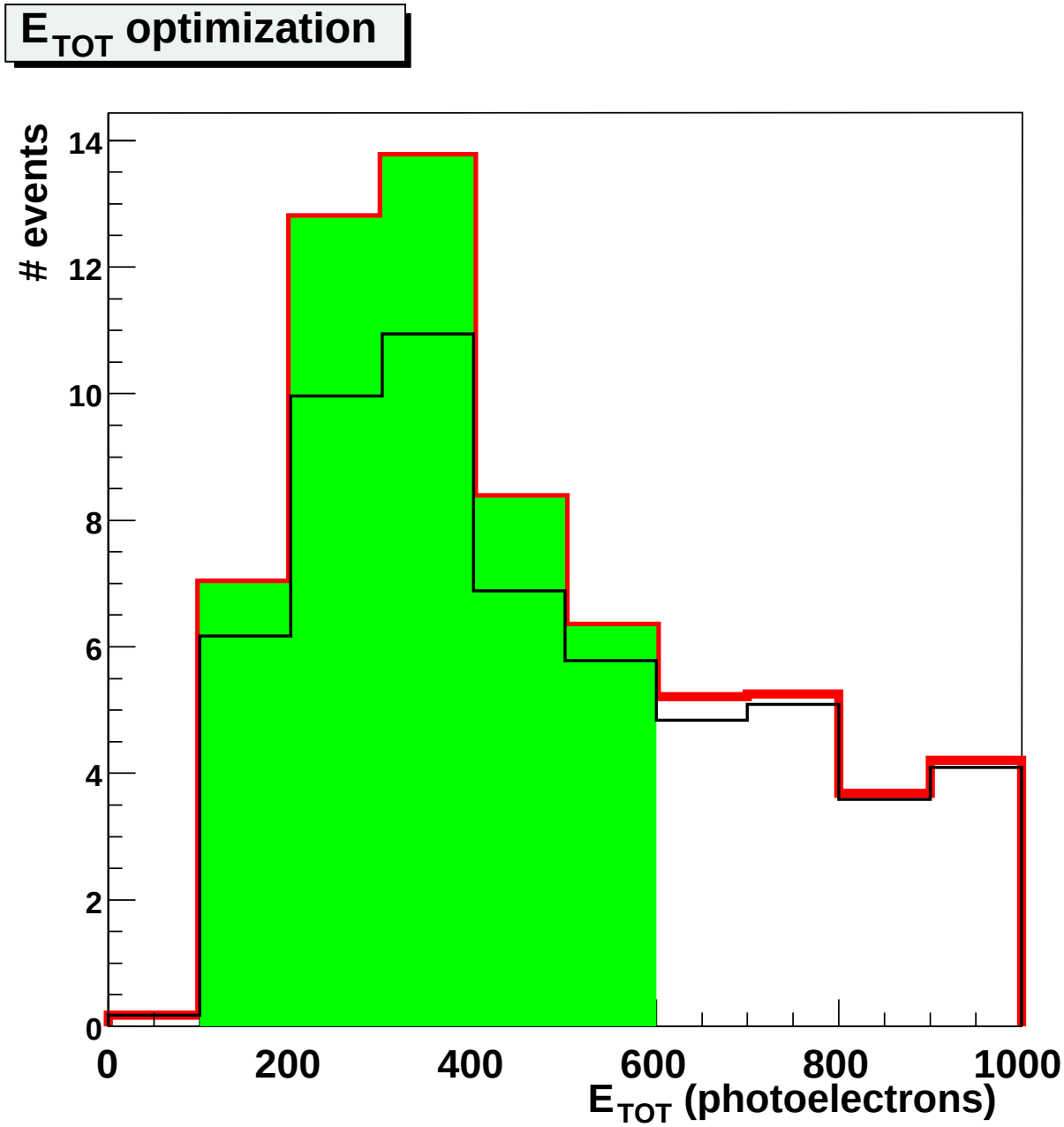
δm^2	signal	ν_e (intrinsic)	ν_μ CC	ν_τ CC	NC (E_ν <10 GeV)	NC (E_ν >10 GeV)
0.002	8	5.6	3.9	2	15.7	11.5
0.003	8.5	5.6	3.9	3	15.7	11.5
0.004	20	5.6	3.9	10	12.0	11.5

At $|U_{e3}|^2 = 0.01$

Baseline LE beam.

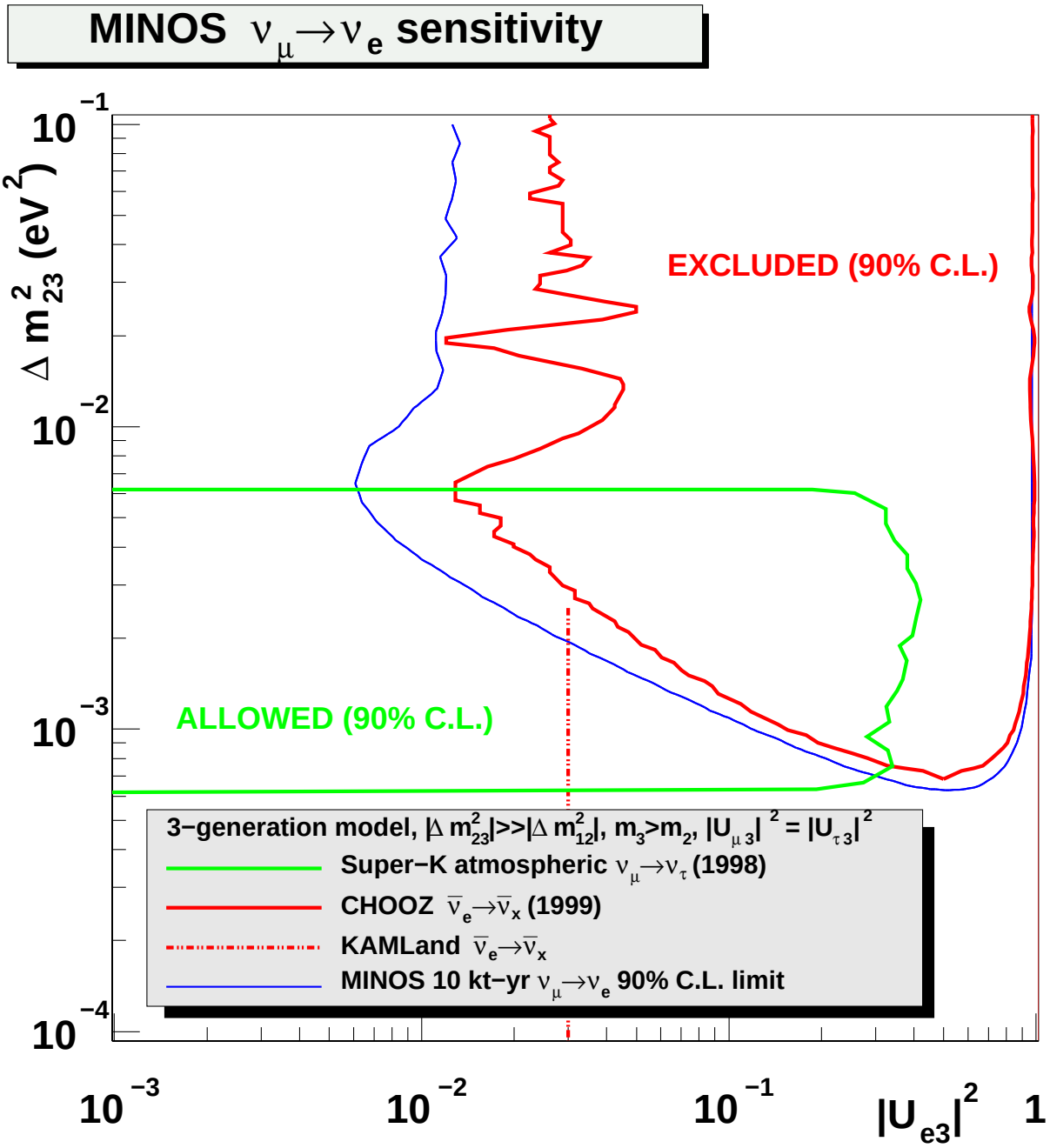
10 kton·years.

Expected Signal/Background (ν_e appearance)

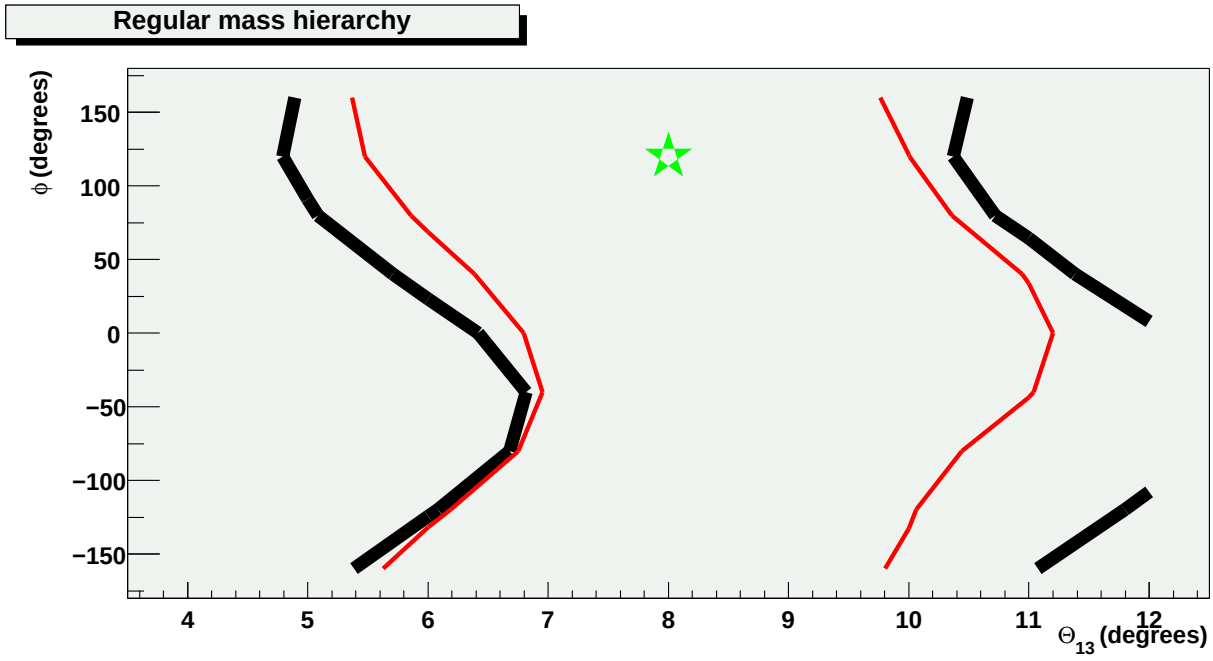


10 kt-yr, $U^2_{e3} = 0.01$, $\delta m^2 = 0.003\,\mathrm{eV}^2$, $U^2_{\mu 3} = U^2_{\tau 4}$

Expected Limits (ν_e appearance)



Expected Sensitivities (ν_e appearance)



Green test point at $\theta_{13} = .14$, $\theta_{12} = \pi/4$, $\theta_{23} = \pi/4$, $\delta m^2_{12} = 0.0001\text{eV}^2$, $\delta m^2_{23} = 0.003\text{eV}^2$, $\phi = 2\pi/3$.

Black line is 1-σ, 10 kt-yr $\nu_\mu \rightarrow \nu_e$

Red line is 1-σ, 20 kt-yr $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Future Experimental Approach

- More flux at lower energy

  Improve Δm^2 resolution. Observe a dip in the spectrum.

  - New target/horn design
  - Event rate
  - Muon detection threshold in detector ?

- Enhance sensitivity to ν_e
  - Reduce high energy flux (NC back.)
  - Make detector better ?
  - Build another detector ?

- Build a separate detector Off-axis.

- Build a new beam to send to very long distances. Focus of our working group.

Why go off-axis for neutrino beam ?

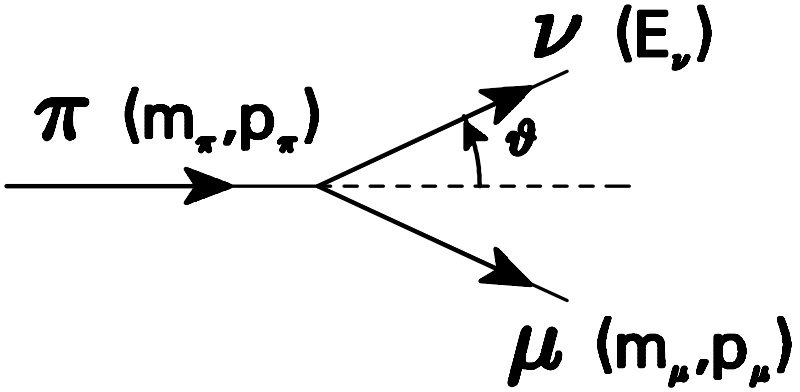
- Natural way to get a narrow band beam.
- Beam energy is almost independent of pion energy.
- Pions of a broad energy spectrum contribute to the same neutrino energy bin.
- No sacrifice of flux to get a narrow band beam.

Originally proposed by E889 Collaboration

Long Baseline Neutrino Oscillation Experiment, D. Beavis et al., Physics Design Report, BNL 52459. April 1995.

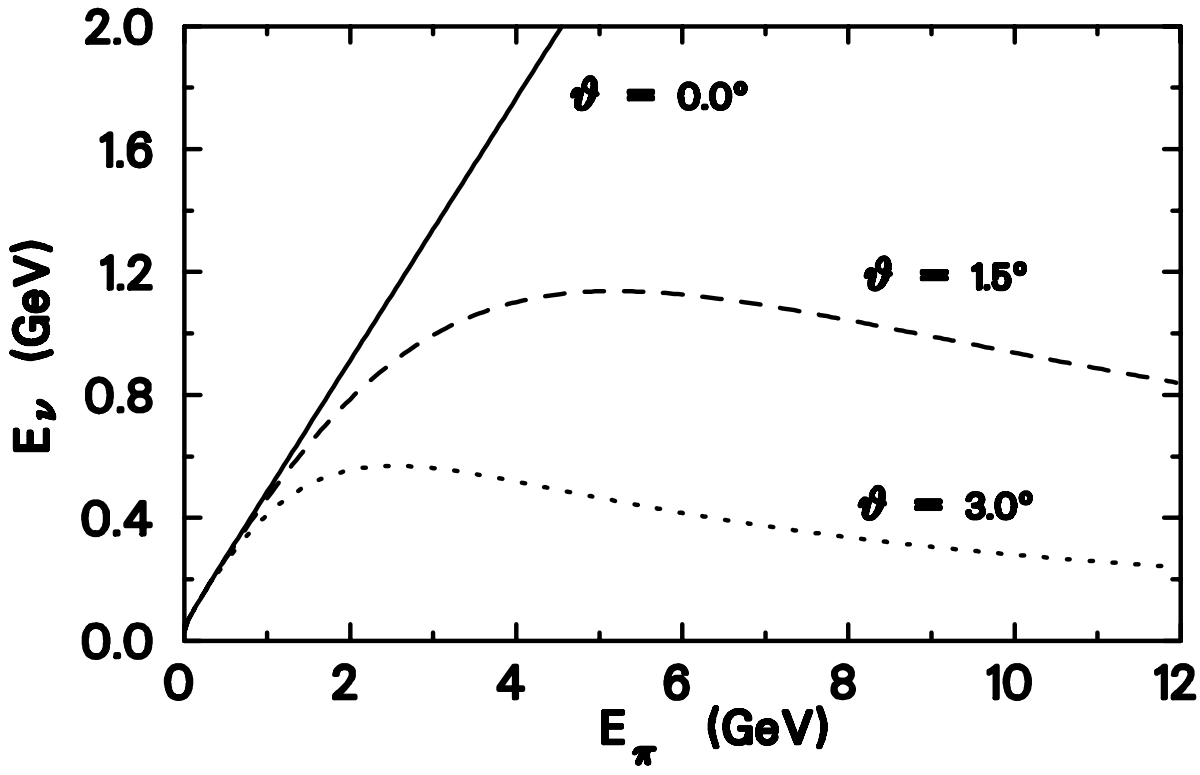
Now being considered for the JHF-SK proposal.

And new initiatives for the NUMI beam.

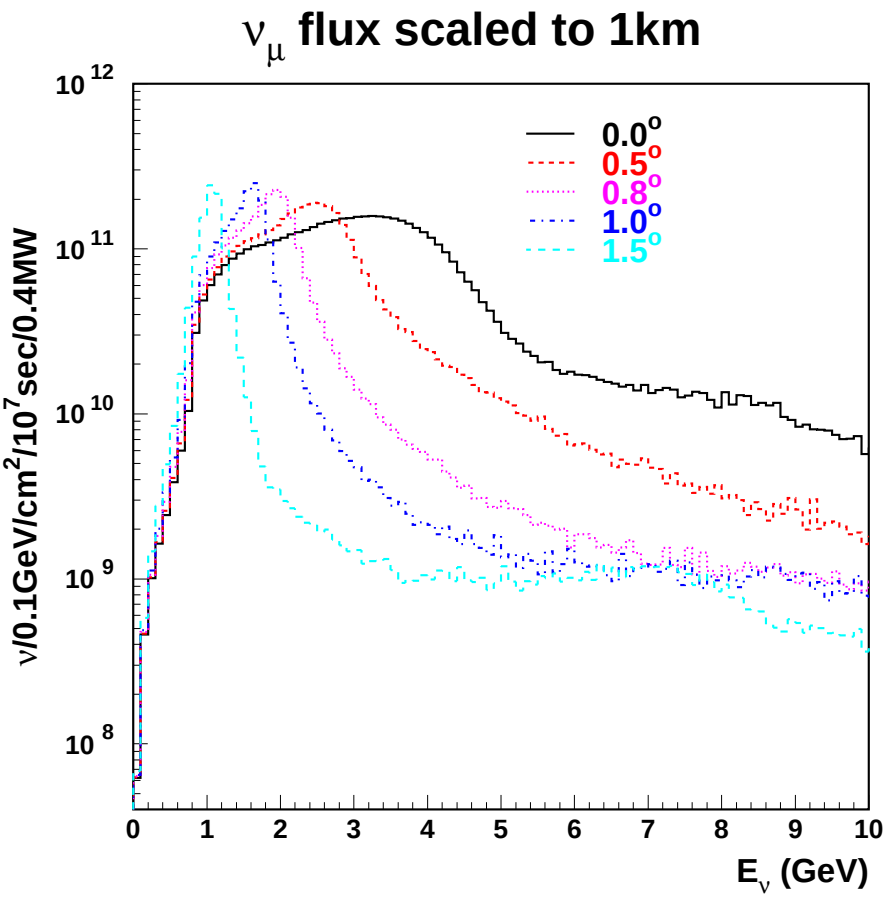


From energy, momentum conservation

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\vartheta)}$$



FNAL LE beam



@ $\Delta m^2_{atm} = 2.5 \times 10^{-3}$

Angle (deg)	E_{peak} (GeV)	L_{osc} (km)	
0.0	3.0	1500	
0.5	2.5	1250	
0.8	2.0	1000	(L. Lake)
1.0	1.5	750	(Soudan)
1.5	1.0	500	(Keenan)
2.0	0.7	350	

Conclusions

- MINOS will measure Δm^2_{32} with $\sim 10\%$ error.
- New initiatives for NUMI beam sought.

  Original idea from BNL-E889 of using an off-axis beam to make a narrow band beam being revived.

  Considerable interest in redesigning the beam to make it lower energy.
- Neutrino oscillations and mixing has the same "dignity" as quark mixing and must be understood with the same scale of effort.