Neutrino Oscillations at Fermilab: Short-term and Possible Future Experiments

- Neutrino Oscillations
- The Fermilab Complex
- Mini-BooNE/BooNE
- MINOS
- NuMI Off-Axis and Beyond
- Conclusions

Douglas Michael
California Institute of Technology

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Mixing of Three Neutrinos

Flavor Eigenstates

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

Mass Eigenstates

$$\Delta m^2 = (m_3^2 - m_2^2), \quad \delta m^2 = (m_2^2 - m_1^2)$$

$$P(\alpha \to \beta) = \delta_{\alpha\beta} - 4 \Sigma\Sigma\, U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2[(m_i^2 - m_j^2)L/4E]$$

Doesn't cover the case of sterile neutrinos!

Is the anti-neutrino matrix the same as for neutrinos?

A Specific Form of the Mixing Matrix

The Maki-Nakagawa-Sakata (MNS) Matrix:

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

$c_{ij} = \cos\theta_{ij}$ $\quad$ $s_{ij} = \sin\theta_{ij}$

"Maximal Mixing" has $\theta_{12} = \theta_{13} = \theta_{23} = 45^o$

The CP violating phase, δ, is known to be sufficiently small from primordial nucleosynthesis that it will have small experimental consequences (for now). However, it could be very important!

Is the matter/anti-matter imbalance in the universe due to lepton ~~CP~~?

Neutrino Oscillations in Matter

- Matter can change the oscillation probability due to an effective mass difference which is generated between different types of neutrinos due to coherent interactions with matter:

  "$\sin^2 2\theta_{matter}$"$= \sin^2 2\theta/(\sin^2 2\theta + (\cos 2\theta - A/\Delta m^2)^2)$

  "L_{matter}"$= L\ \mathrm{sqrt}(\sin^2 2\theta + (\cos 2\theta - A/\Delta m^2)^2)$

  $A = +\text{-}2\ \mathrm{sqrt}(2)\ G_F\ Y\ n_B\ E_\nu$

  n_B = Baryon density

  $Y = -2Y_n + 4Y_e$ for ν_e (Y_n = neutrons/baryon)

  $Y = -2Y_n$ for ν_μ or ν_τ (Y_e = electrons/baryon)

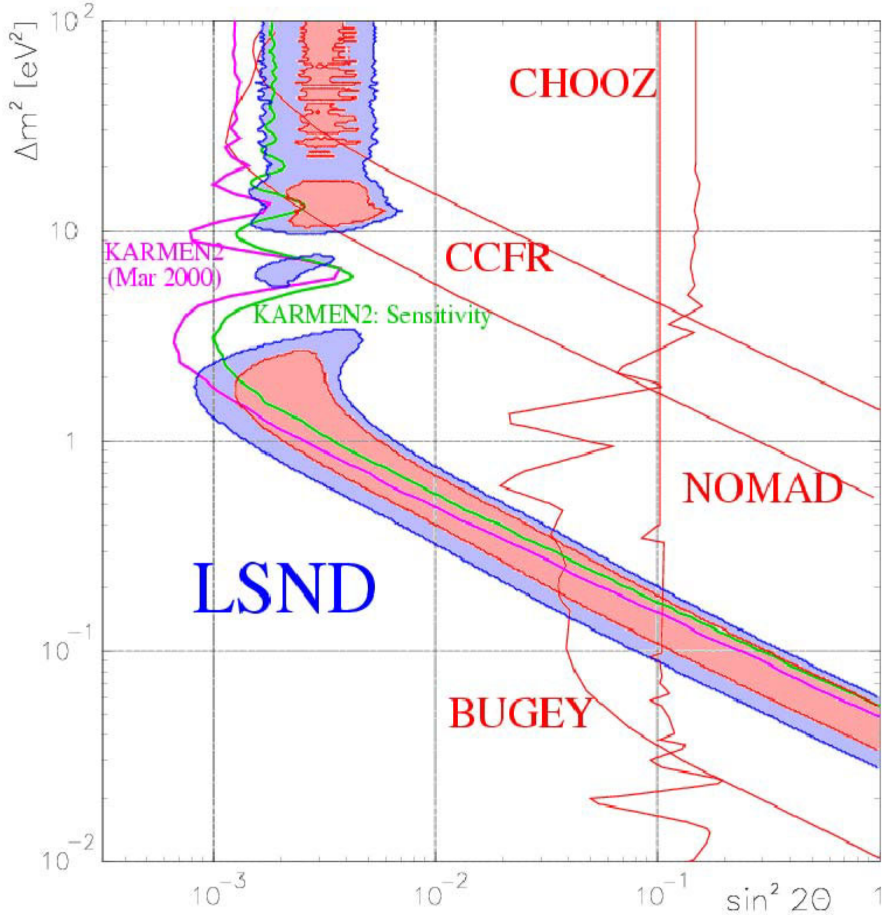
  $Y = 0$ for $\nu_{sterile}$

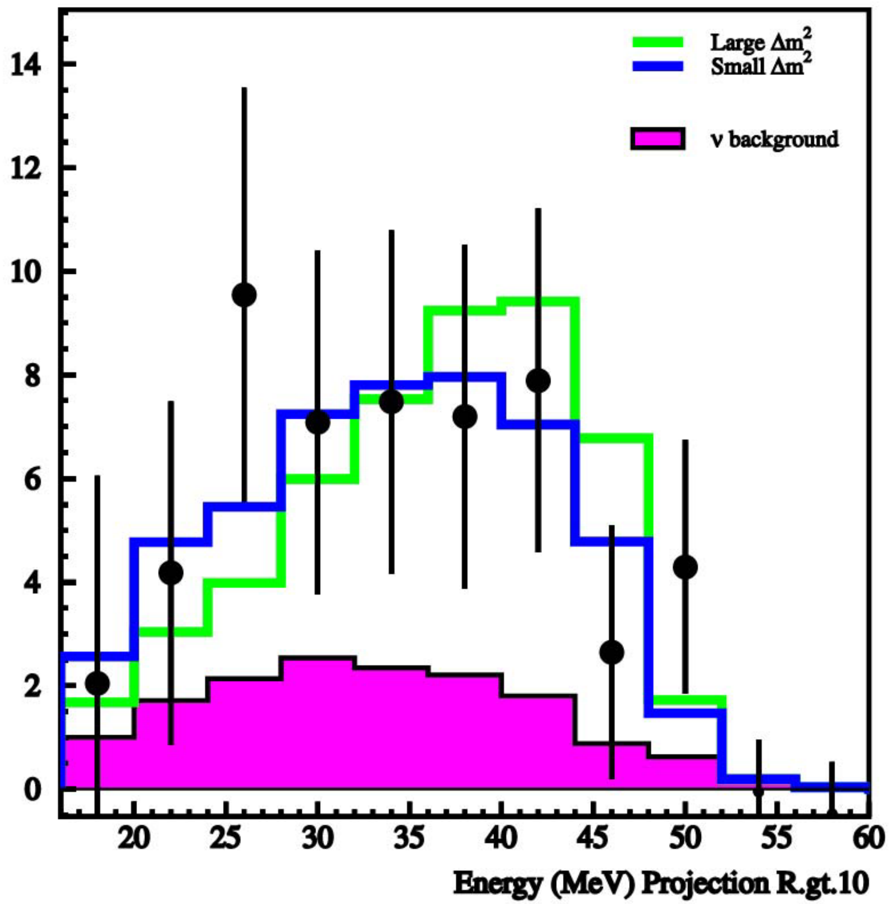
  – ν_e's have charged-current interactions with electrons in matter unlike any other neutrinos.
  – ν_e, ν_μ and ν_τ have neutral-current interactions with matter which $\nu_{sterile}$ do not.
- Resonant enhancement of oscillations is possible.
- Suppression or enhancement can depend on the sign of Δm^2 and will differ for neutrinos and antineutrinos. This is very important!

Oscillation Results from LSND

Los Alamos Scintillator Neutrino Detector

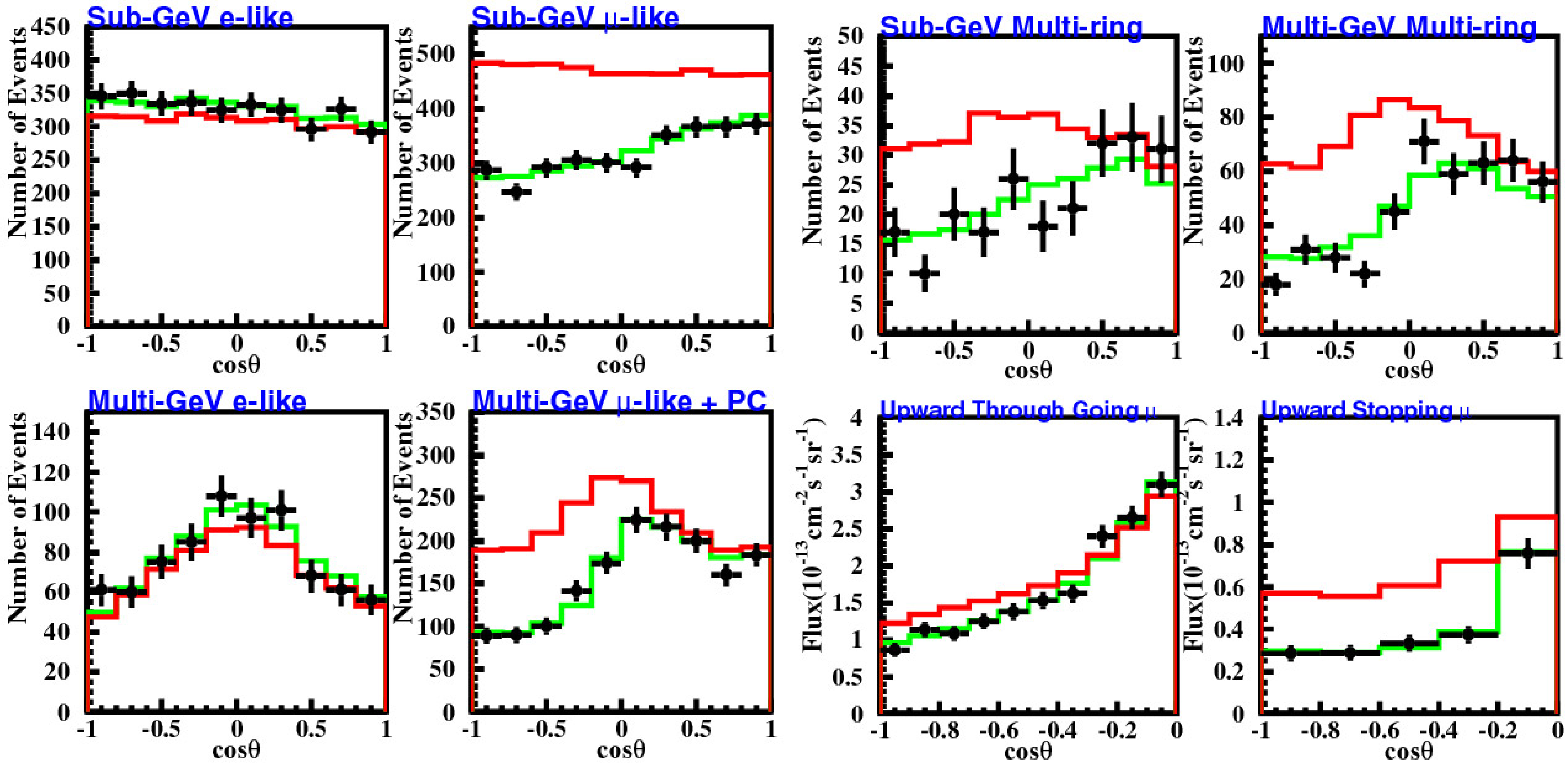
$$p + \overline{\nu}_e \longrightarrow n + e^+$$





90% allowed regions from LSND, Karmen and others

Super-Kamiokande Atm. Data



No Oscillation

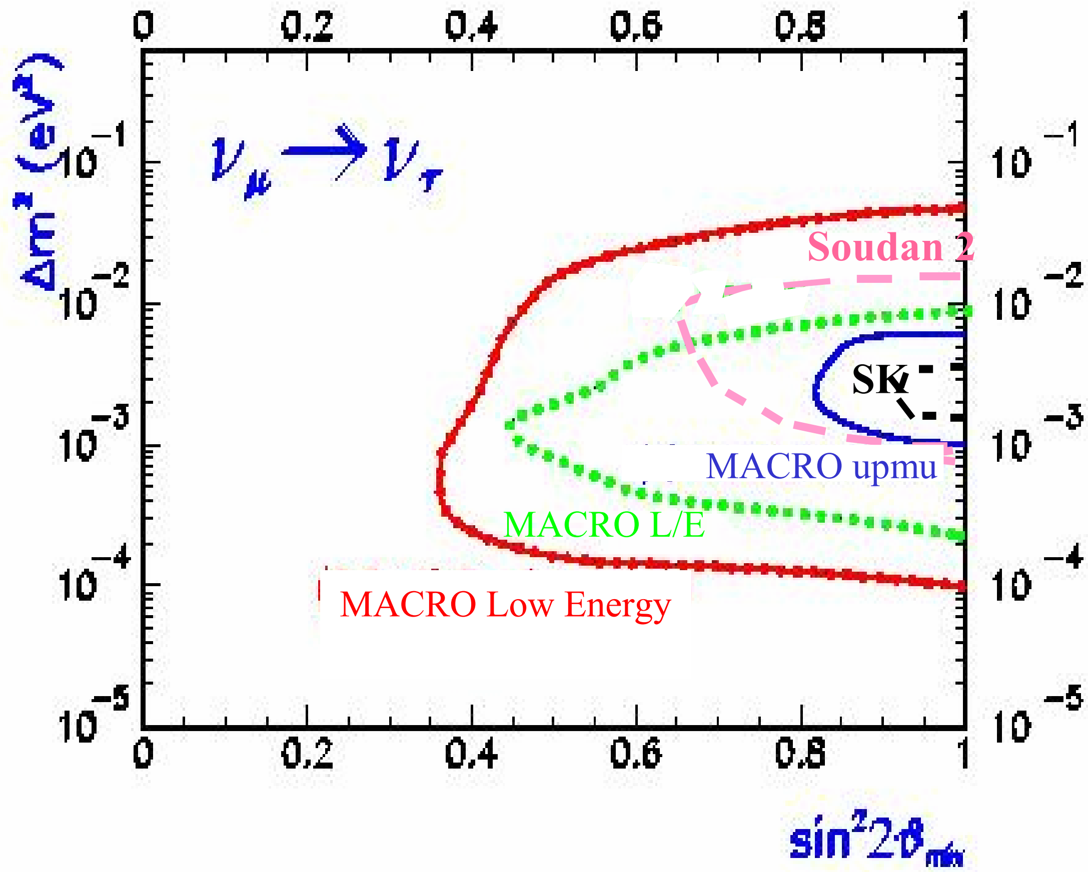
Best Fit $\nu_\mu - \nu_\tau$ oscillation: $\sin^2 2\theta = 1.0$, $\Delta m^2 = 0.0025\ \mathrm{eV}^2$

$$R = \frac{(N_\mu/N_e)_{data}}{(N_\mu/N_e)_{MC}} \quad \begin{array}{l} = 0.64 \text{ for } E<1.3 \text{ GeV} \\ = 0.66 \text{ for } E>1.3 \text{ GeV} \end{array}$$

Allowed Oscillation Parameters

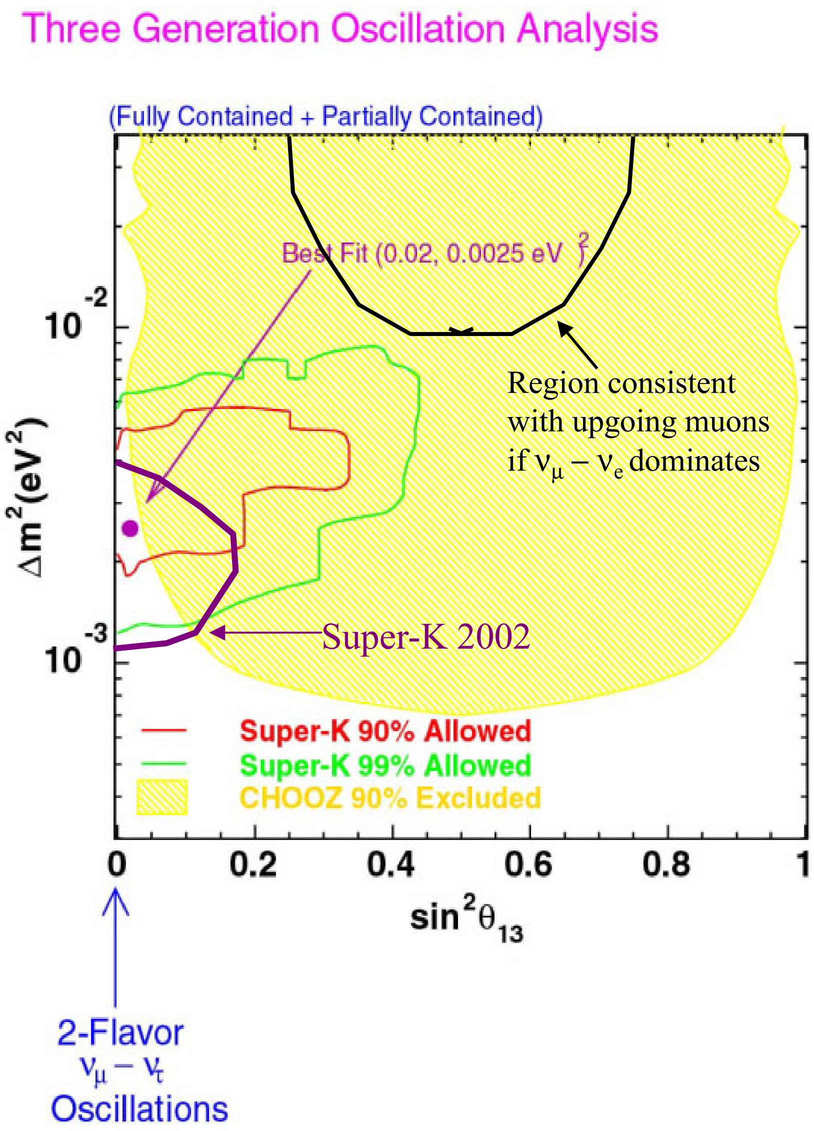
$\nu_\mu - \nu_\tau$

- Super-K Best Fit:
  $\Delta m^2 = 0.0025$ eV^2
  $\sin^2 2\theta = 1.0$
- MACRO Best Fit:
  $\Delta m^2 = 0.0025$ eV^2
  $\sin^2 2\theta = 1.0$
  since 1998!
- Soudan 2 Best Fit:
  $\Delta m^2 = 0.01$ eV^2
  $\sin^2 2\theta = 1.0$



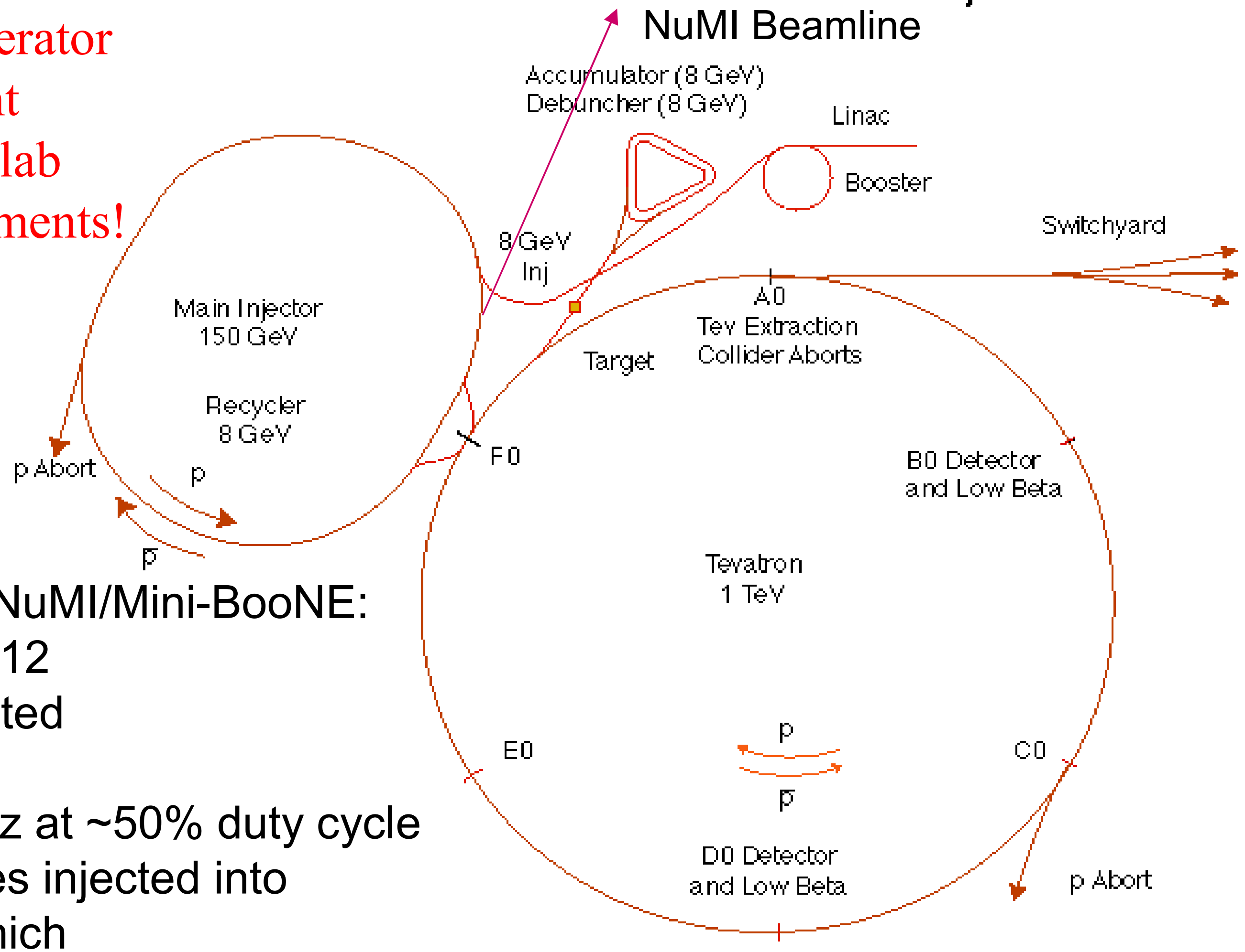
Atmospheric $\nu_\mu - \nu_e$?

- $\nu_\mu - \nu_e$ oscillations must comprise only a small fraction of the effect observed in atmospheric neutrinos:
  - Super-Kamiokande sees about the expected flux of ν_e at sub and multi-GeV energies.
  - The zenith distribution of upgoing muons is inconsistent with the low-energy parameters for $\nu_\mu - \nu_e$ oscillations.
  - The Chooz and Palo Verde reactor experiments see the expected flux of ν_e at the same oscillation parameters suggested from the higher energy atmospheric neutrinos.



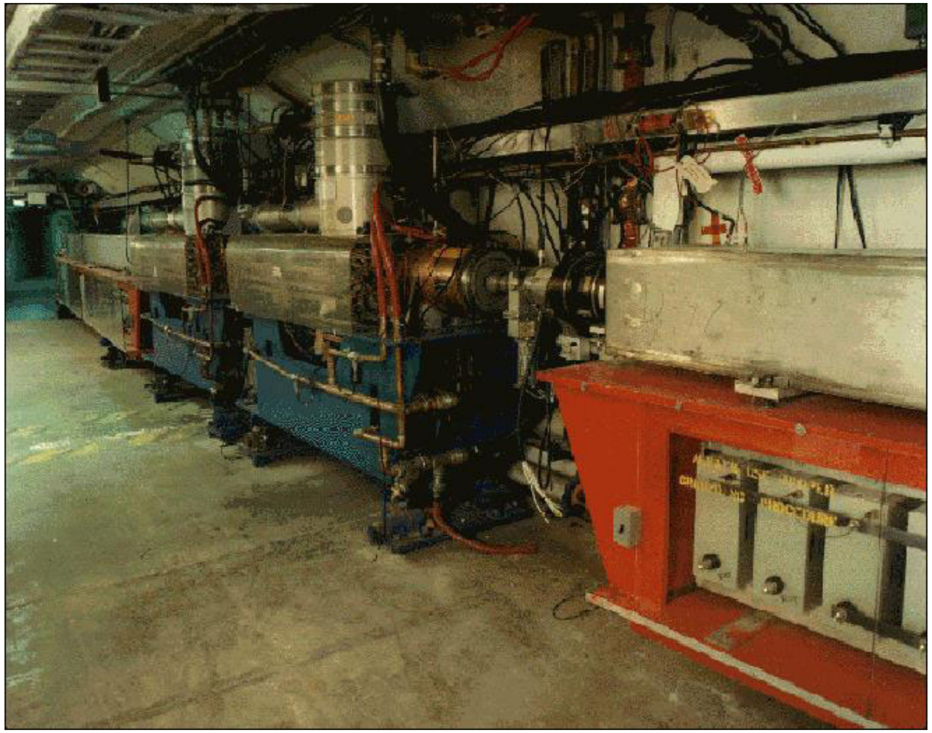
The Fermilab Accelerator Complex

Improvements in the accelerator complex are very important to the success of the Fermilab neutrino oscillation experiments!



- Current nominal plan for NuMI/Mini-BooNE:
  - Booster filled with 5e12 protons and accelerated to 8 GeV.
  - For Mini-BooNE: 6 Hz at ~50% duty cycle
  - For NuMI: Six batches injected into Main Injector, 5 of which go to the NuMI target.
    - 2.5e13 protons / 1.9 s cycle
    - 2.3e20 protons/ year compared to design 3.8e20/year.

The 8 GeV Booster



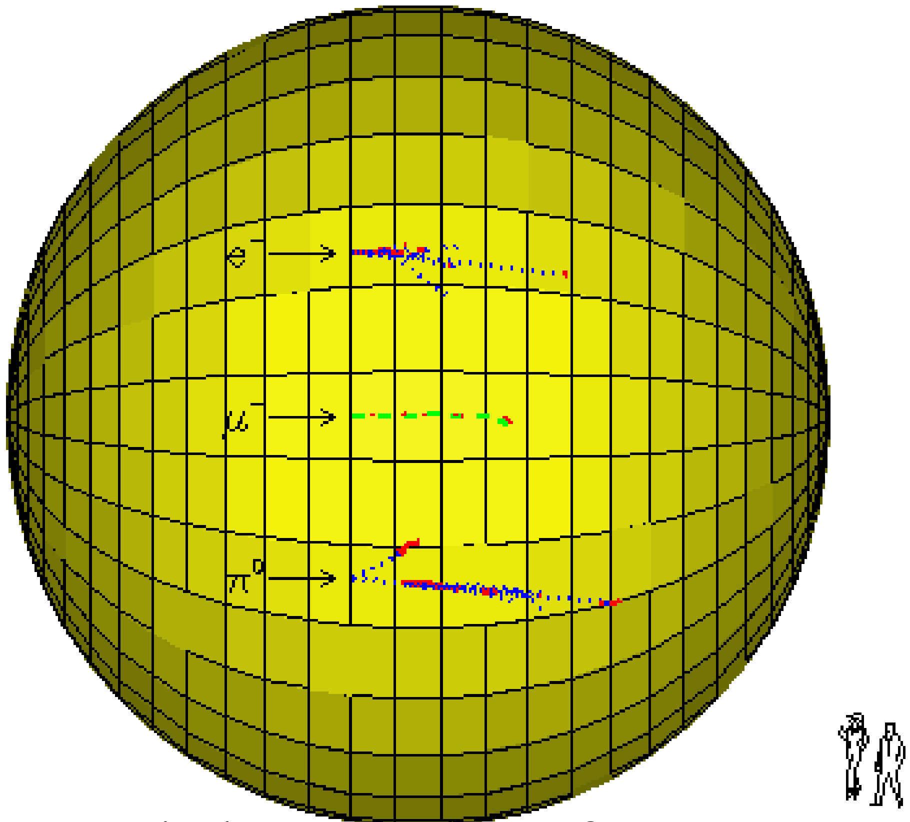
- 8 GeV Synchrotron with 15 Hz resonant magnet ramps.
- Currently accelerates ~4.5e12 protons per cycle. Limited by proton losses (7e12 injected)
- For NuMI/MiniBooNE, the Booster must:
  - Increase typical acceleration cycle rate from ~1 Hz capability to ~12 Hz (with many possible steps on the way)
  - Increase protons per cycle from typical 4.5e12 to 5-6e12.
  - Increase protons per year from ~3e19 to ~1.5e21… radiation and activation issues.
  - Decrease longitudinal emittance from ~0.15 eVs to ~ 0.07-0.1 eVs for MI stacking.

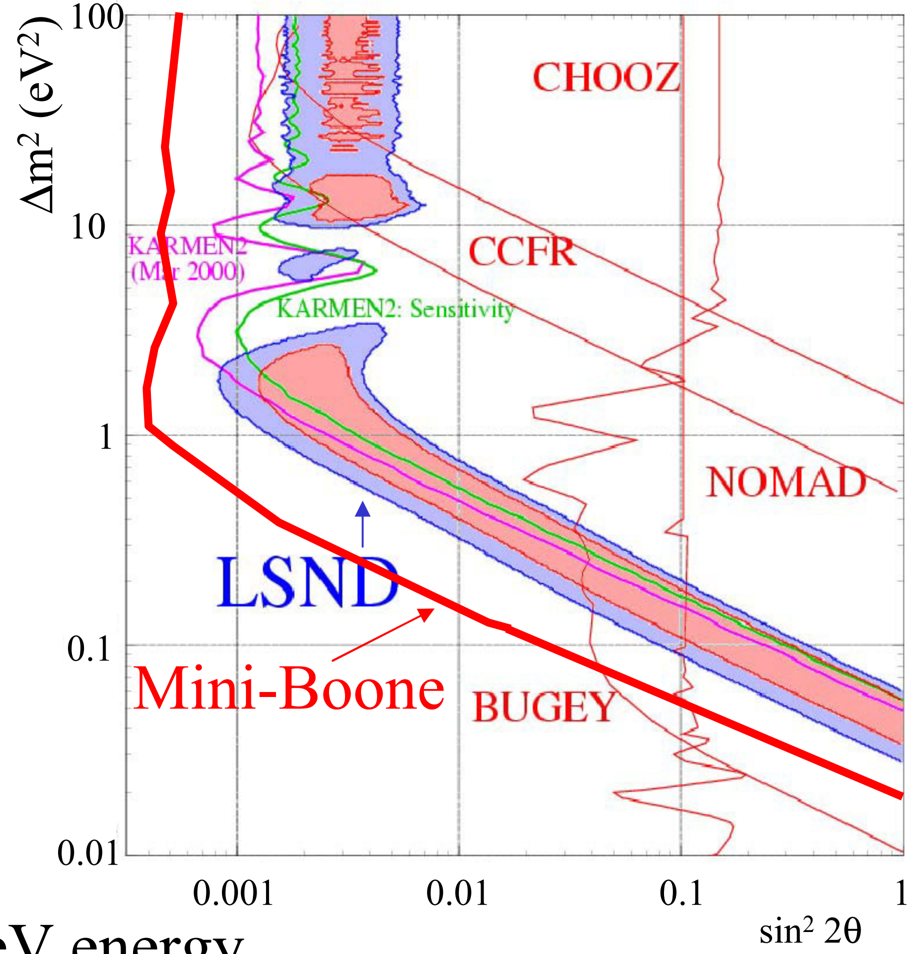
The Main Injector

- 150 GeV synchrotron run at 120 GeV (or lower) for NuMI.
- Circumference = 7x Booster: Room for 6 Booster batches. Antiproton production uses just one batch per cycle. The remainder are available for other experiments, NuMI being the primary user for the forseeable future.
- Minimum cycle time at 120 GeV = 1.5 s. Cycle time for multi-batch NuMI operation = 1.9 s due to multiple Booster cycles for filling.
- Nominal design for 2.5e13 protons per cycle. With only small modifications can probably handle up to 5-6e13. The main issue is how to get them there. There may be some stability issues too but this remains to be seen.
- To go higher than ~6e13 protons per cycle, additional RF power will be needed as well as additional systems to maintain stability.

Addressing the LSND Effect

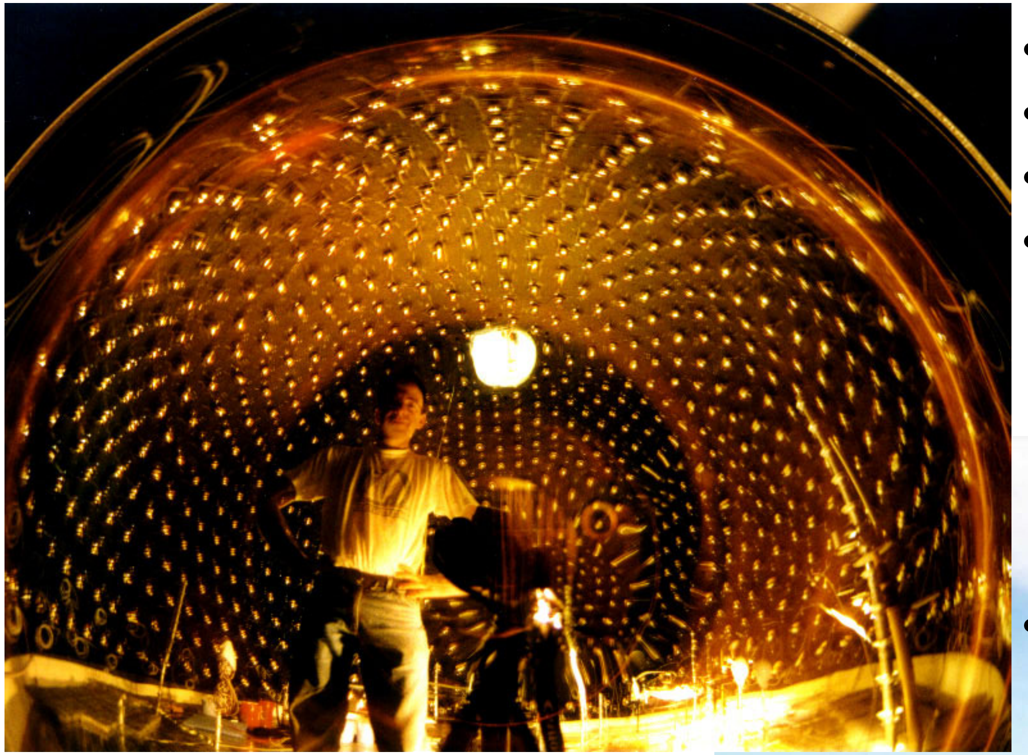
The "Mini"-BooNE Experiment
at Fermilab





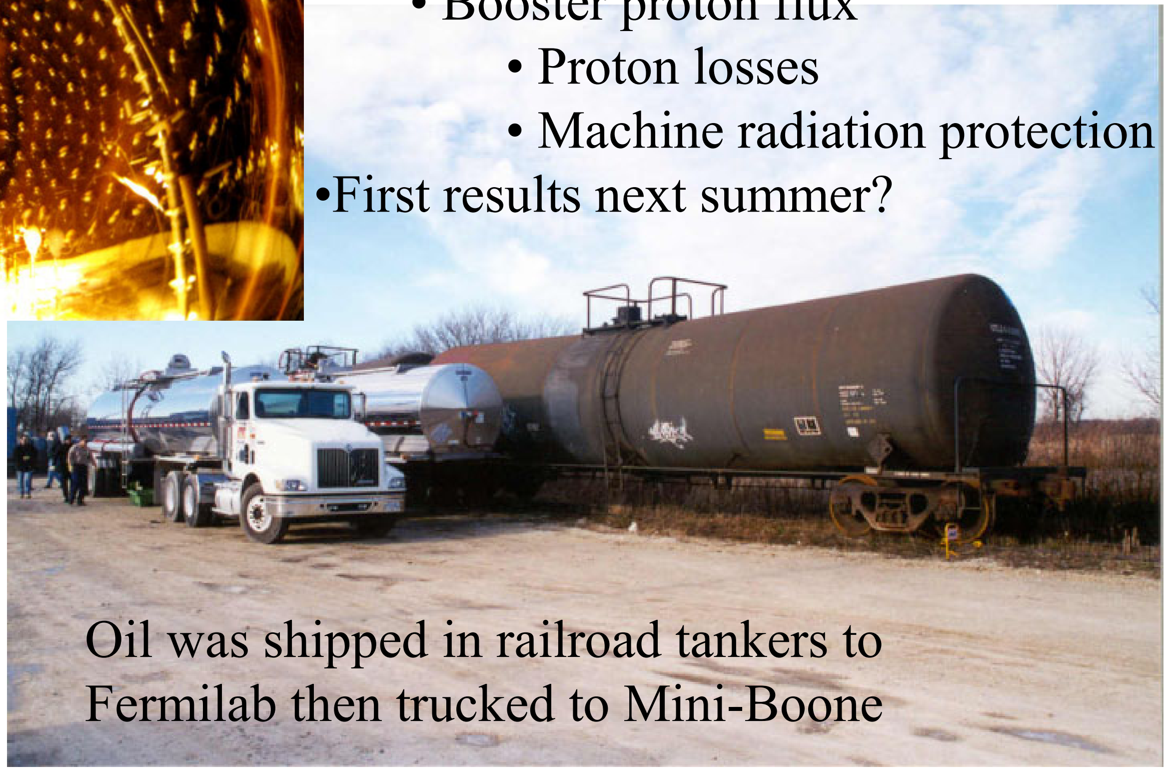
Scaled-up version of LSND
Uses neutrinos from 200-2000 MeV energy.
Uses 8 GeV protons from the Booster: ~3x10**20 protons per year.

Status of MiniBoone



Inside Mini-Boone before filling with oil.

- Construction complete.
- Beamline commissioned in August.
- Data acquisition now underway!
- Rate is still low, ~1% of design:
  - Booster rate (soon to go from 0.5 Hz to 3 Hz)
  - Booster proton flux
    - Proton losses
    - Machine radiation protection
- First results next summer?



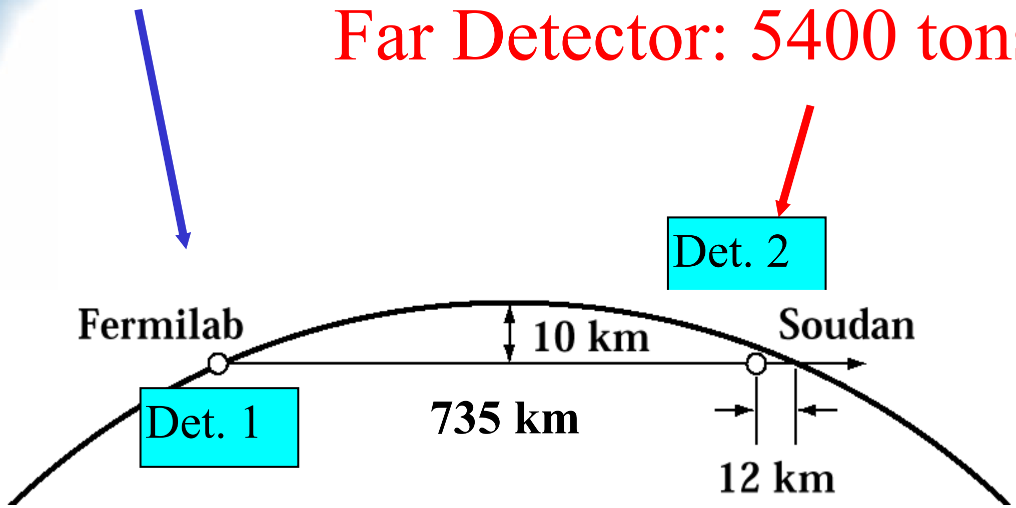
Oil was shipped in railroad tankers to Fermilab then trucked to Mini-Boone

The MINOS Experiment

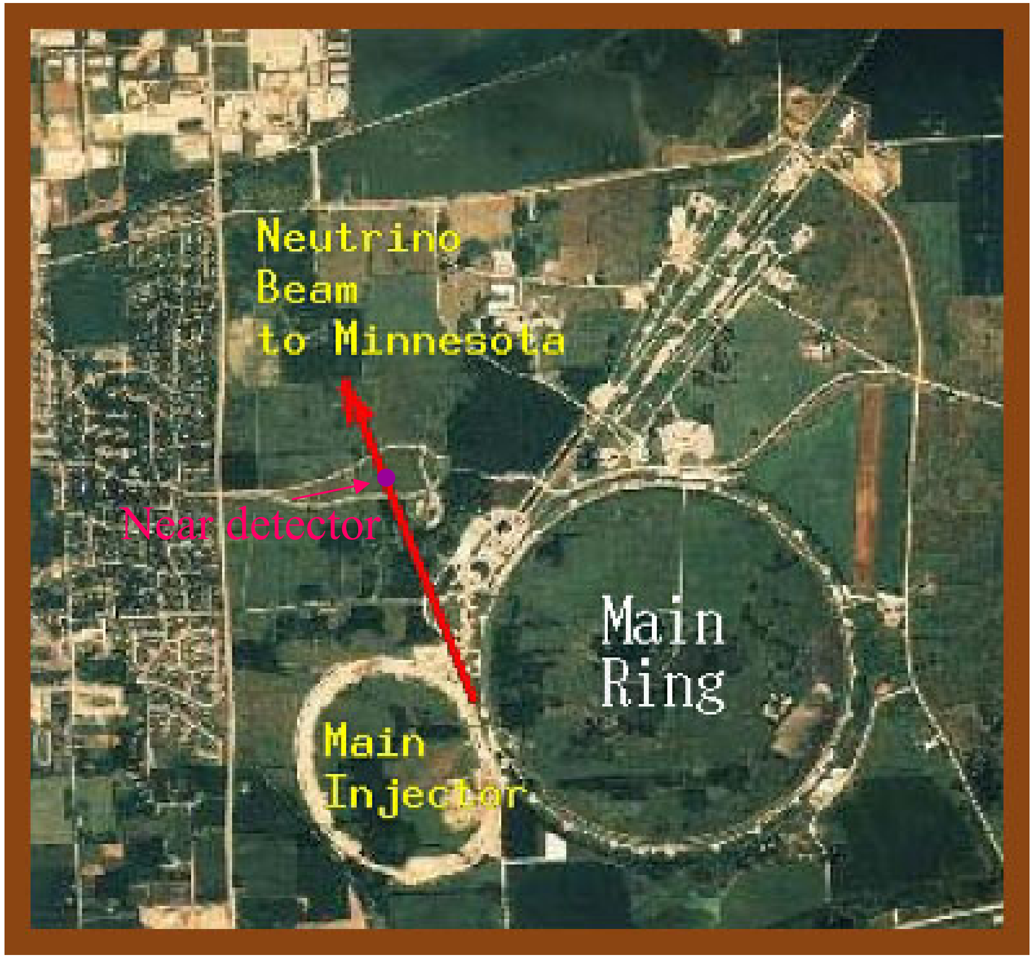
- Precision measurements of:
  - Energy distribution of oscillations
  - Measurement of oscillation parameters
  - Participation of neutrino flavors
- Direct measurement of ν vs $\overline{\nu}$ oscillation
  - Magnetized far detector: atm. ν's.
  - Likely eventual measurement with beam

Near Detector: 980 tons

Far Detector: 5400 tons

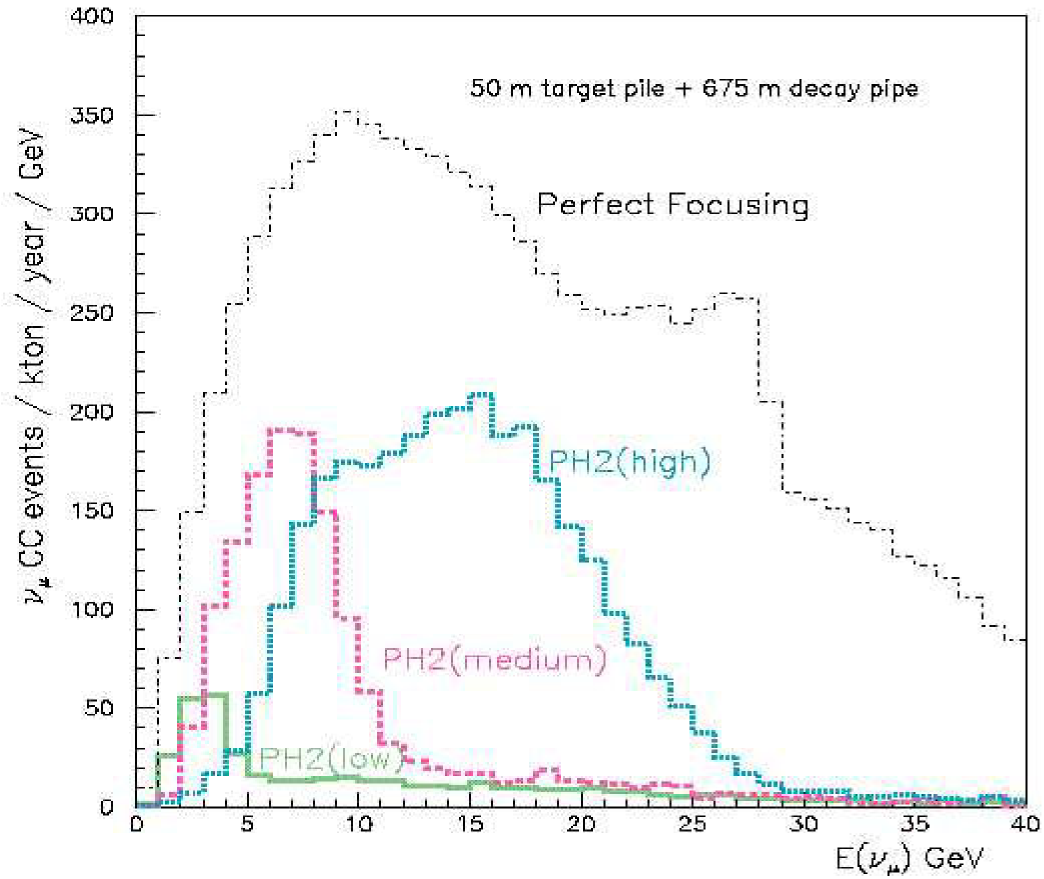


Neutrinos at the Main Injector (NuMI)



- 120 GeV protons
- 1.9 second cycle time
- $4x10^{13}$ protons/pulse
- 0.4 MW!
- Single turn extraction (10μs)
- $4x10^{20}$ protons/year
- 700 m x 2 m diameter decay pipe for neutrino beam.
- 200 m rock absorber.
- Near detector complex.

The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
400	1300	2900

ν_μ CC Events/MINOS/2 year

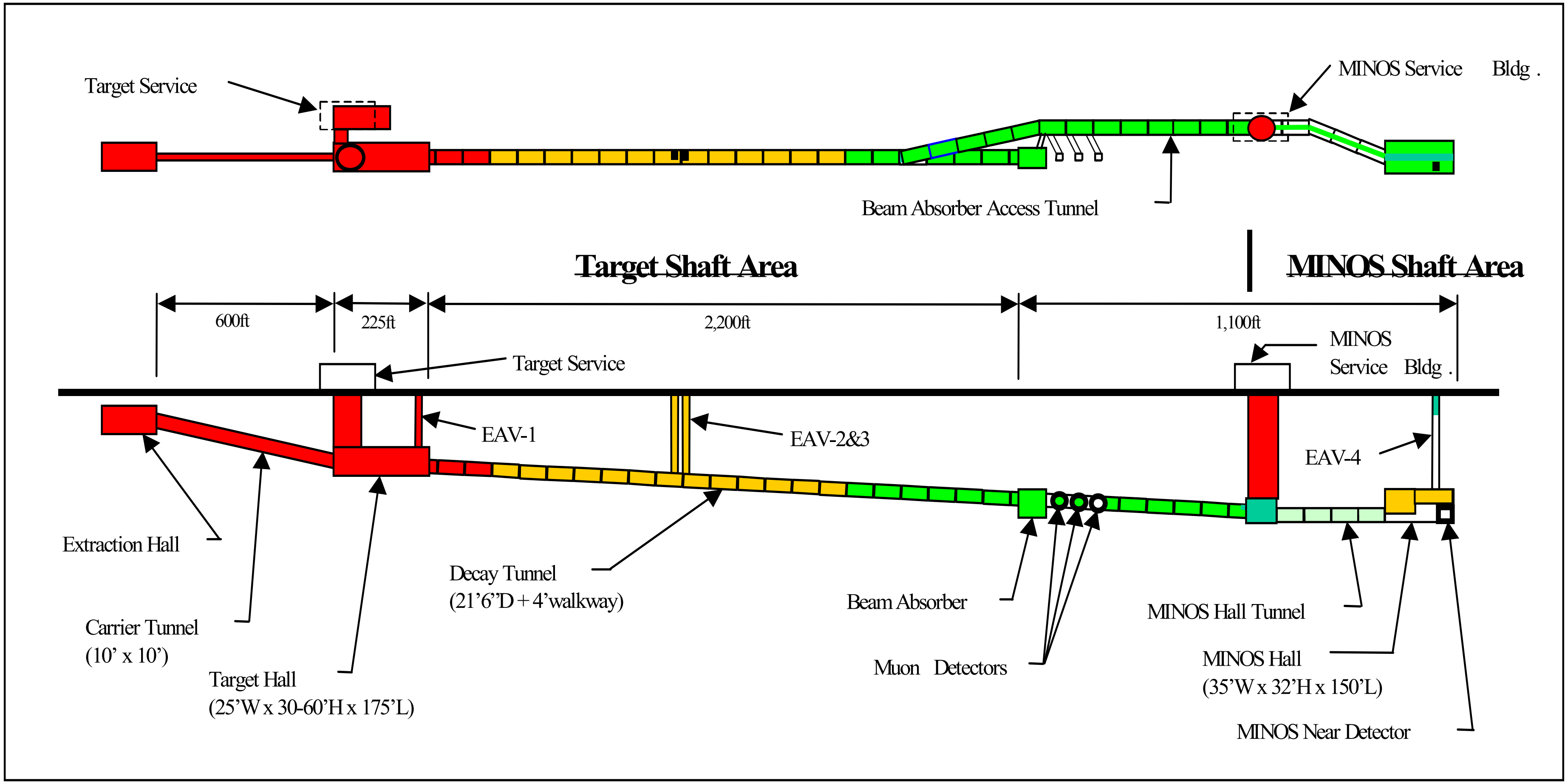
Low	Medium	High
4400	14300	31900

$4\text{x}10^{20}$ protons on target/year
$4\text{x}10^{13}$ protons/1.9 seconds

By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

Status of NuMI Beamline Construction

- The excavation of the NuMI beamline halls and tunnels is complete.
- The decay pipe is installed along with the concrete shielding.
- Final civil construction adjustments are in progress.
- Outfitting and installation of beamline components will take about two years.
- First protons on target expected in December 2004.



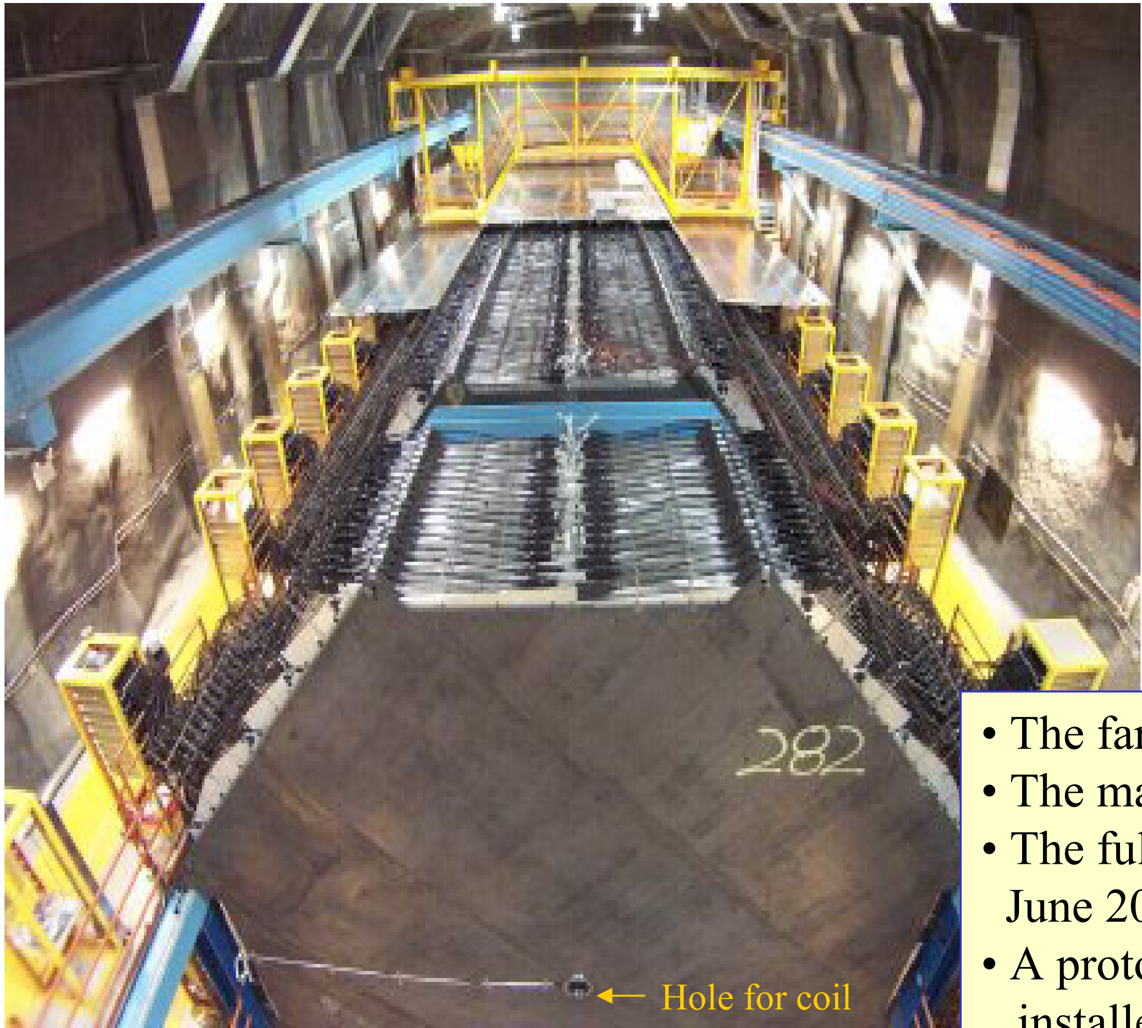
The NuMI Decay Tunnel

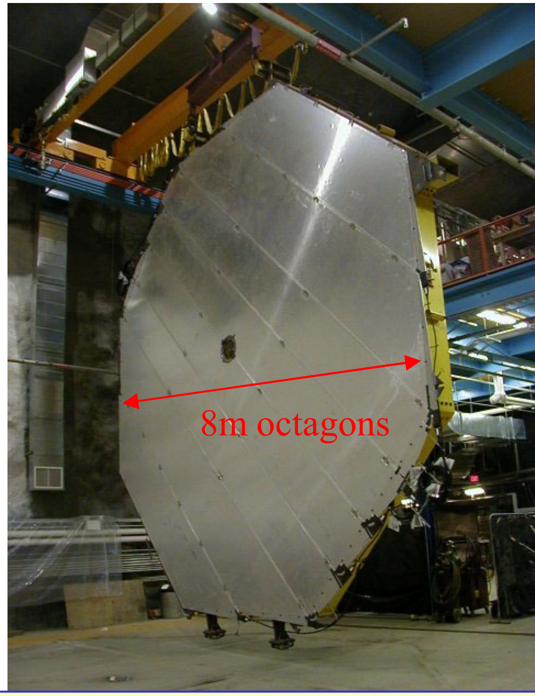
The Decay Pipe

- Installation of the decay pipe is complete.

Pipe is embedded in concrete to protect groundwater.

Status of MINOS Construction





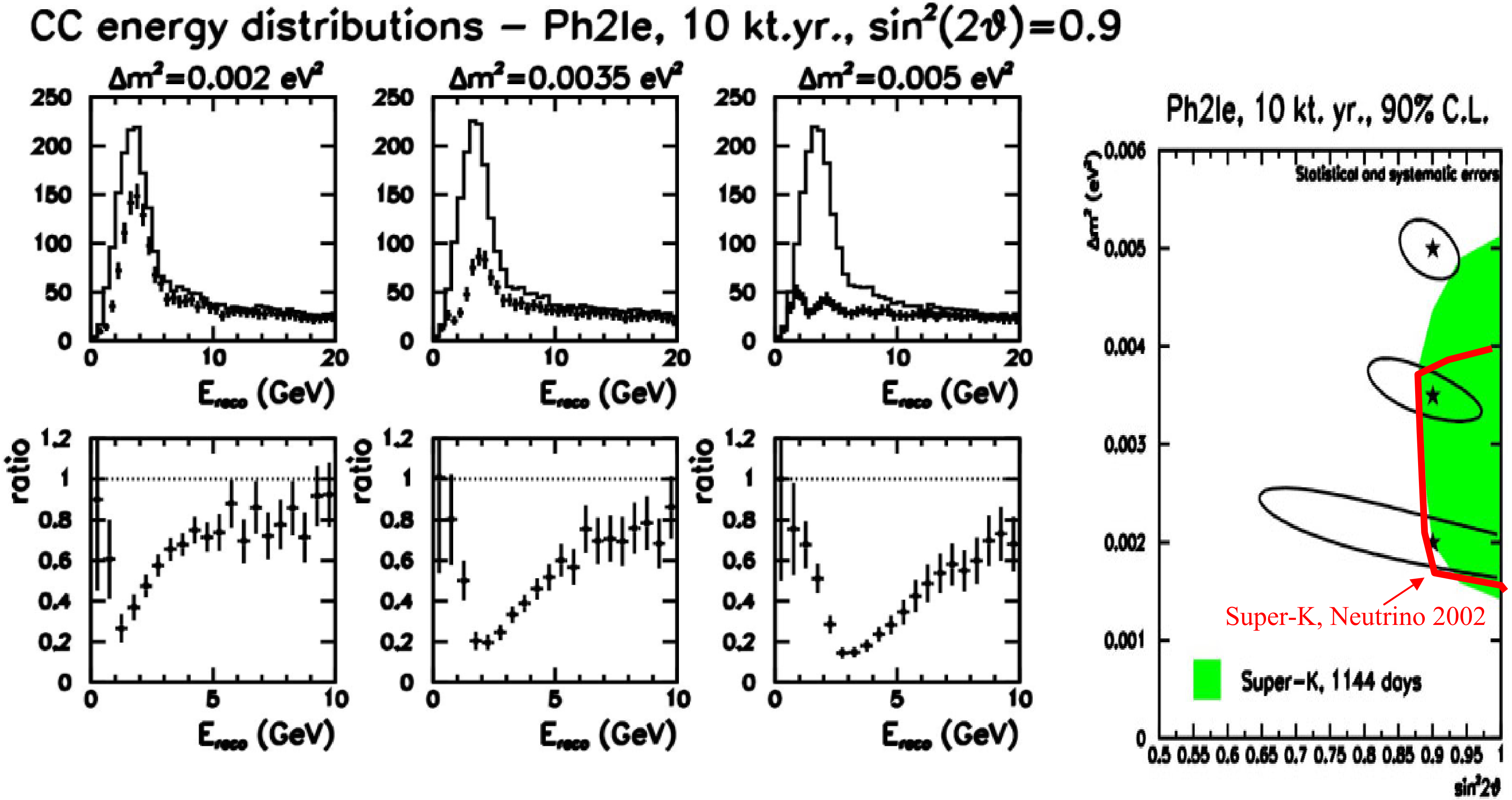
- The far detector is >70% built and operating.
- The magnetic field is on in the first half.
- The full detector will be complete by June 2003.
- A prototype cosmic-ray veto shield is installed on ¼ of the detector.
- Cosmic Ray data are being collected for calibration and commissioning.

- Fine-grained magnetized iron/scintillator tracking calorimeter
- 5.4 kT total mass

MINOS Physics Goals (by 2007)

- Demonstrate Oscillation Behavior
  - Precise measurement of CC energy distribution between near and far detector (2-4% sys. uncertainty in E_ν per 2 GeV bin).
  - "Standard" or non-standard oscillations?
    - Can we see clear "oscillatory" behavior from the first osc. max?
    - Are there features in the energy spectrum not well described by a standard oscillation?
- Precise Measurement of Oscillation Parameters
- Precise Determination of Flavor Participation
  - Number of CC ν_μ events far/near ~2%: Probability for $\nu_\mu - \nu_x$ oscillation.
  - Number of CC ν_e events far/near: Sensitive to $\nu_\mu - \nu_e$ oscillation down to about 2%.
  - Number of NC events far/near: probability for $\nu_\mu - \nu_{sterile}$ oscillation down to about 5%.
  - ν_μ's which disappear but don't appear as ν_e or disappear to $\nu_{sterile}$ must be ν_τ!
- Direct Measurement of Atmospheric ν vs $\bar{\nu}$.

Measurement of Oscillations in MINOS

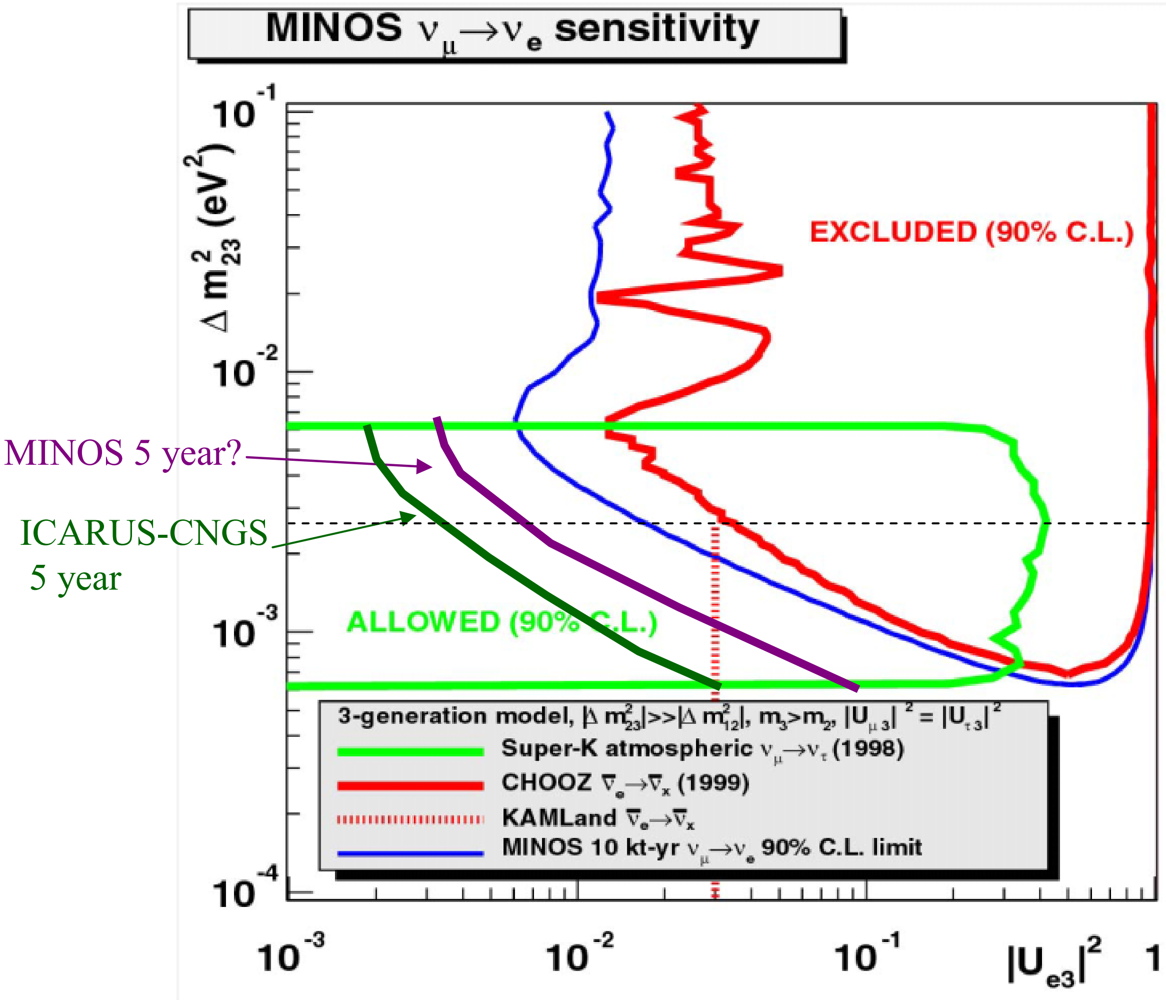


Note: MINOS beam results are presented for only 2 years of running! Longer-term running is certainly possible, even probable. Results are statistics limited.

Appearance of Electrons

10 kT Years of data

ν_e Appearance



- Sensitivity is determined by statistical fluctuation of the NC π^0 BG in the far detector.
- Limit on U_{e3}^2 will scale like 1/sqrt(N) and is not limited by systematics for any realistic exposure.
- Limit can be further improved by removing high-energy tail from the NuMI beam and increased proton flux in later years.
- Ultimate MINOS limits ~1/3 as shown here assuming extended running.

Possible NuMI Proton Intensity Math

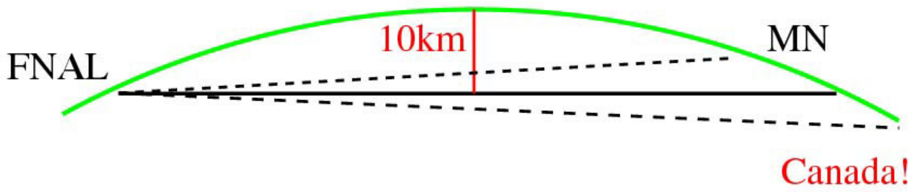
	1998 Letter from John Peoples	"Now"	2005 "current plan"	2005 possible	2008 possible	2010 Recycler Stacking	2010+ New Booster
Protons per Booster batch	7.00E+12	4.50E+12	5.00E+12	5.50E+12	6.00E+12	6.50E+12	
Batches available for MINOS	5	5	5	10	10	10	
Relative Efficiency per batch	1	1	1	0.7	0.9	0.95	
Protons per MI Cycle	3.50E+13	2.25E+13	2.50E+13	3.85E+13	5.40E+13	6.18E+13	1.00E+14
MI Cycle Period (seconds)	1.9	2.5	1.9	2.22	1.72	1	1
Beam Power (MW)	0.35	0.17	0.25	0.33	0.60	1.17	1.90
NuMI Running time per year (seconds)	2.00E+07	1.50E+07	1.80E+07	1.80E+07	2.00E+07	2.00E+07	2.00E+07
Protons per year	3.68E+20	1.35E+20	2.37E+20	3.12E+20	6.28E+20	1.24E+21	2.00E+21

- From 2003 to ~2008 improvements will come from investment in the existing accelerator complex.
- This table represents one possible upgrade path. Other approaches are possible.

Note: Other uses of Main Injector protons and cycles will decrease the proton intensity for NuMI. Test beam running will presumably be kept small enough to keep impact <10%. CKM or other experiments could have larger impacts, possibly around 30-40%.

Fermilab NuMI Beam Off/On Axis

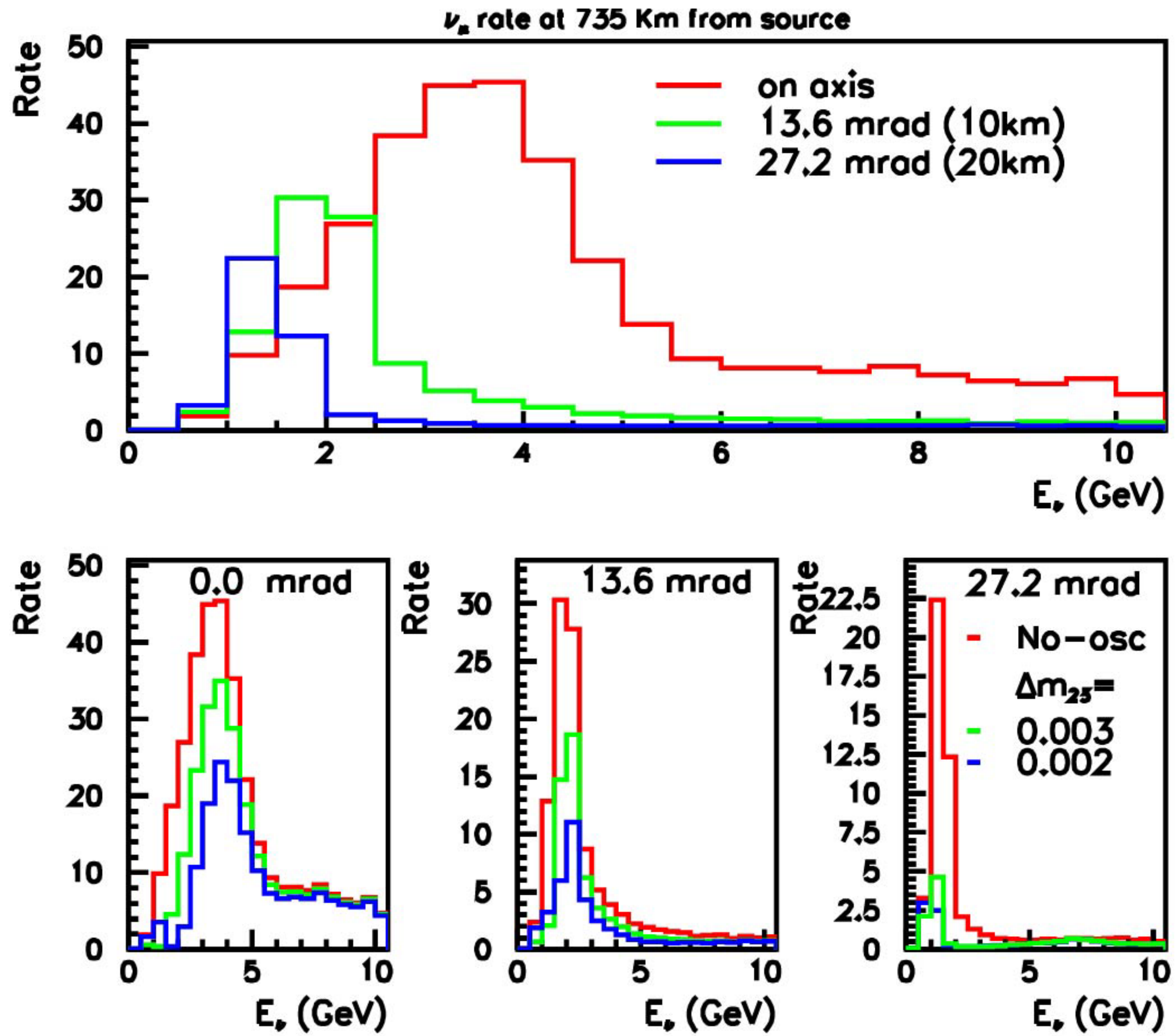
- Several possible locations for detector(s).
- The only existing deep sites (within ~30 km of the beam axis) are:
  - Soudan (735 km)
  - Lake Superior (~600 km)
- Several Surface sites:
  - Along Trans-Canada Highway
    - ~985 km, ~20 mR off-axis
    - Commercial air access to Kenora with good support infrastructure.
    - Biggest matter effects
  - Former LTV Mine site near Soudan (711 km, ~18 mR off-axis)
    - Well developed site.
    - Easy to share resources and manpower with Soudan



NuMI Off-axis Detector

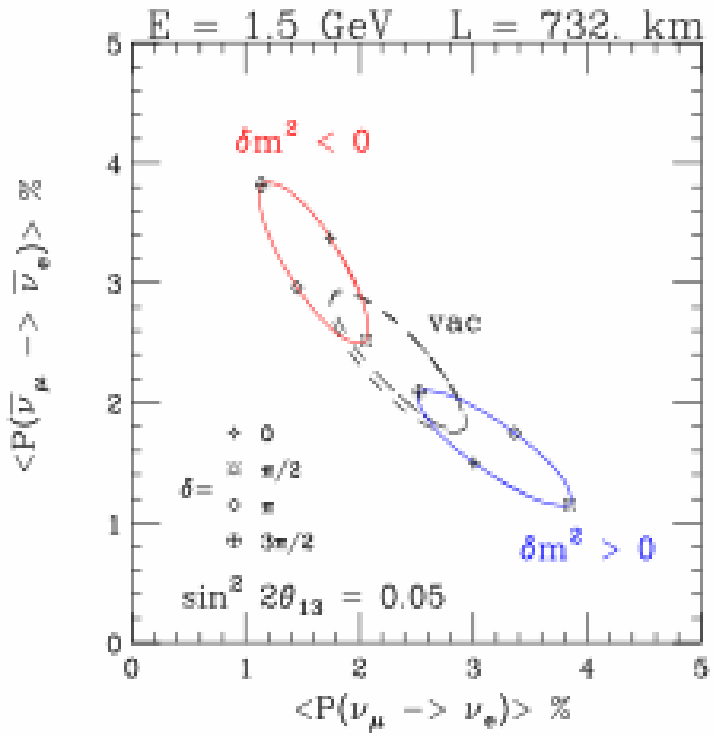
- Different detector possibilities are currently being studied
- The goal is an eventual 20 kt fiducial volume detector
- The possibilities are:
  - Low Z target with RPC's, drift tubes or scintillator
  - Liquid Argon (a large version of ICARUS)
  - Water Cherenkov counter
- Surface or near-surface operation must be possible
- Principal focus: electron neutrino identification
  - Good sampling (in terms of radiation/Moliere length)
  - maximize mass/radiation length
  - cheap

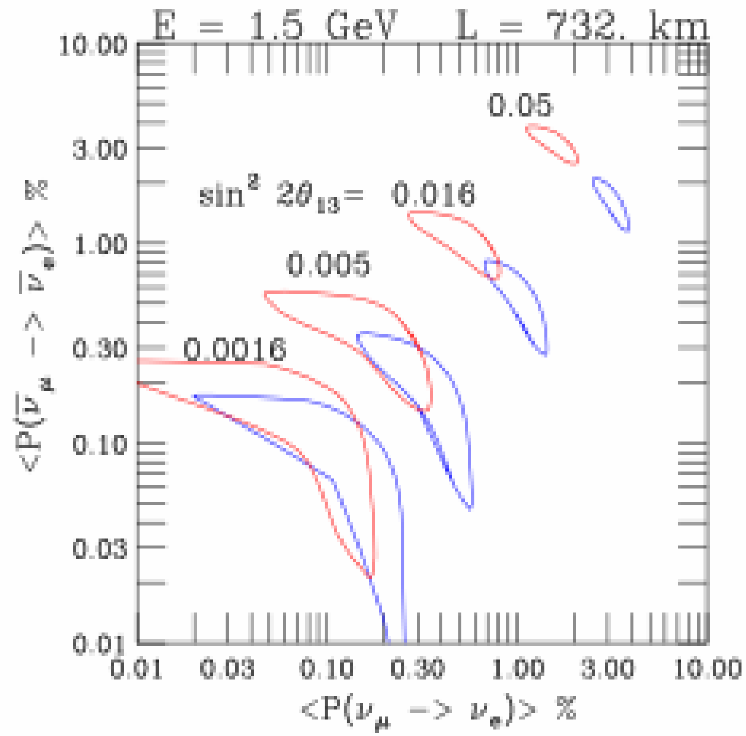
Fermilab NuMI Beam Off/On Axis



Velasco etal.

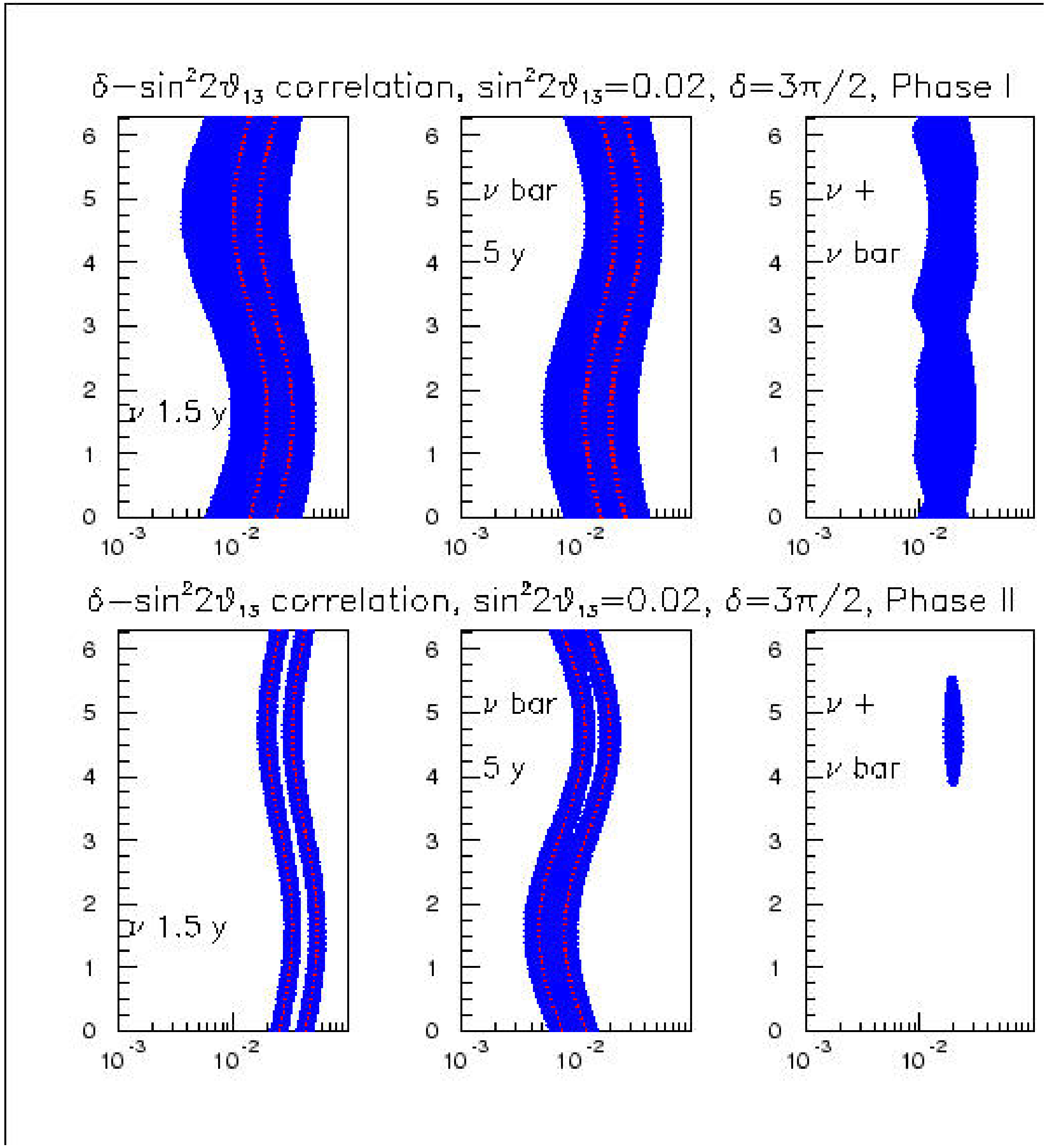
CP and Matter Effects





- Oscillation Probability (or $\sin^2 2\theta_{\mu e}$) is not unambigously related to fundamental parameters, θ_{13} or U_{e3}^2
- At low values of $\sin^2 2\theta_{13}$ (~0.01), the uncertainty could be as much as a factor of 4 due to matter and CP effects
- Measurement precision of fundamental parameters can be optimized by a judicious choice of running time between ν and ν

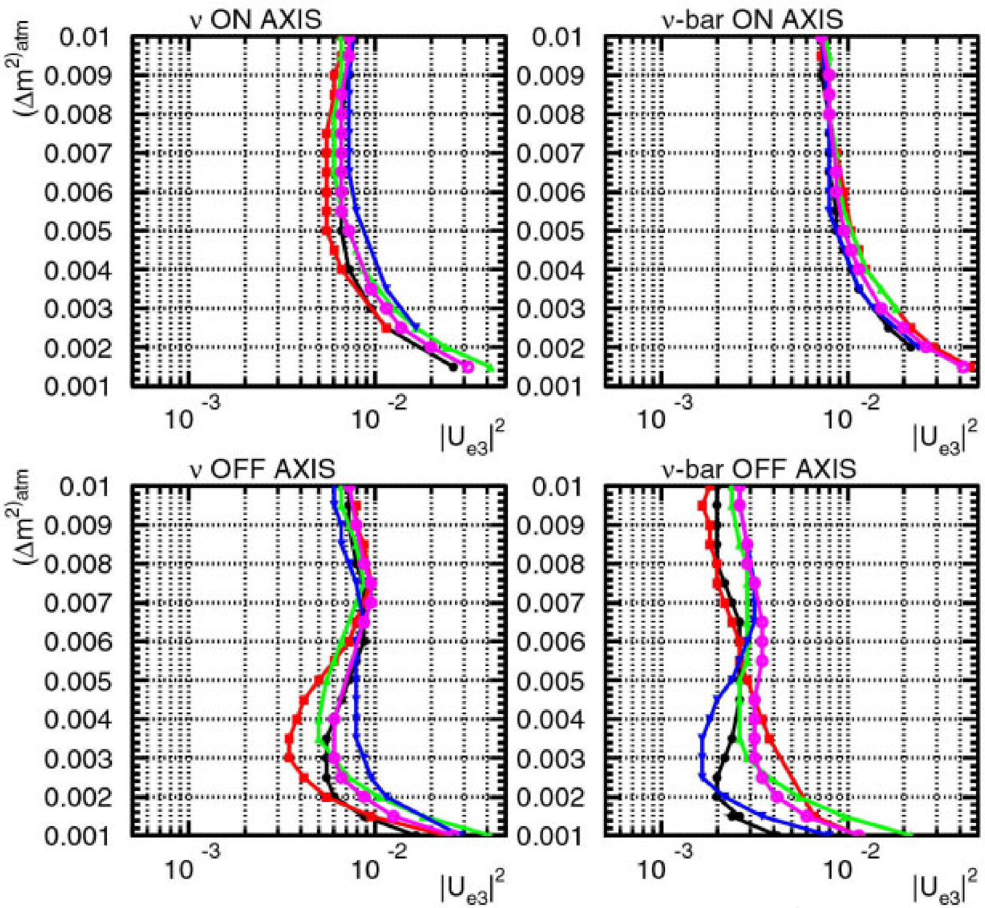
Sensitivity for "Phase I and II"



- "Phase I":
  - 20 kT "low-z"
  - "fine-grain"
  - 20×10^{20} protons
    - 5 yrs at 0.4 MW
    - 1 yr at 2 MW!
  - 711 km
  - 1.5 GeV beam
- "Phase II"
  - 25 times higher POT x Detector mass
  - Neutrino energy and detector distance remain the same.
  - 500 kT detector or 100 kT det+2MW beam

Fermilab NuMI Beam On/Off Axis

Compare measurements on neutrinos and anti-neutrinos on and off axis

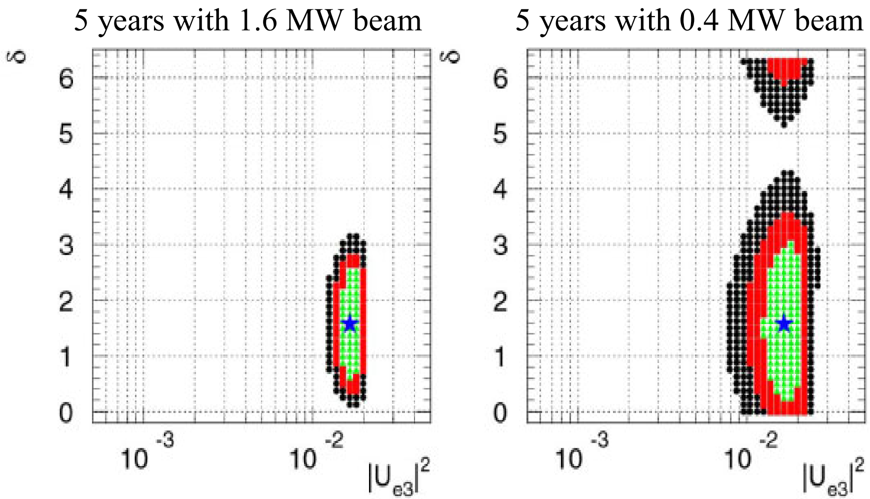


90% CL limits for a variety of CP phase δ

Nominal NuMI proton intensity.

Barenboim, DeGouvea, Velasco

Measurement sensitivity to possible CP violating phase



Combined Measurement of the CP-odd phase δ and $|U_{e3}|^2$ in a 20 kton Off Axis Detector, 900 km from Fermilab.

Recent Initiative

- A Letter of Intent has been submitted to Fermilab in June expressing interest in a new ν effort using off-axis detector in the NuMI beam.
- This would most likely be a ~15 year long, 2 phase effort, culminating in study of CP violation.
- The LOI was considered by the Fermilab PAC at its Aspen July, 2002, meeting.
- Long-term connection with a large detector for proton decay is a possibility, but not the obvious starting point. Investment in the proton complex rather than just detector mass gives the most long-term flexibility.

Fermilab Official Reaction

Given the exciting recent results, the eagerly anticipated results from the present and near future program, and the worldwide interest in future experiments, it is clear that the field of neutrino physics is rapidly evolving. Fermilab is already well positioned to contribute through its investment in MiniBooNE and NuMI/MINOS. Beyond this, the significant investment made by the Laboratory and NuMI could be further exxploited to play an important role in the elucidation of θ_{13} and the exciting possibility of observing CP violation in the neutrino sector.The Committee encourages the Laboratory to continue to engage with the neutrino community through workshops and colloquia in an ongoing exploration of the experimental possibilities utilizing Fermilab's unique resources. The Committee anticipates that the Laboratory may want to issue a Call for Proposals in a year or two if a compelling role for Fermilab is identified.

(June 2002, PAC Recommendation)

We will encourage a series of workshops and discussions, designed to help convergence on strong proposals within the next few years. These should involve as broad a community as possible so that we can accurately guage the interest and chart our course. Understanding the demands on the accelerator complex and the need for possible modest improvements is also a goal. Potentially, an extension of the neutrino program could be a strong addition to the Fermilab program in the medium term. We hope to get started on this early in 2003.

Michael Witherell

Conclusions

- The Fermilab accelerator and beamline complex provide excellent opportunities for neutrino oscillation experiments:
  - 8 GeV Booster for short-baseline experiments, Mini-BooNE/BooNE
  - 120 GeV Main Injector with nominal 0.4 MW beam, continuously upgradable to 2 MW (beyond?) over a period of ~10 years.
  - NuMI Beamline
    - Designed for 4e13 protons/pulse, nominally 0.4 MW
    - $110M investment, nearing completion.
    - Can likely handle higher fluxes. 0.8 MW with modest upgrades… not sure what 2 MW might mean yet. Higher repetition rate will be easier to handle than higher intensity.
- Mini-BooNE
  - Now running but at rather low intensity
  - Could provide some answer on LSND oscillations by next summer… But will need to run with anti-neutrinos?
  - Should any positive signal be observed, a second detector will be built at longer baseline.
- MINOS
  - Unambiguous demonstration of oscillations characteristics
  - Precise measurement of oscillation parameters
  - Extend search for sub-dominant flavor participation and/or sub-dominant oscillation features
- NuMI Off-Axis
  - Another factor of 10-20 sensitivity to ν_e appearance compared to MINOS.
  - Excellent opportunity to eventually make precision measurements on CP violation.
  - High energy, long-baseline, intense neutrino/anti-neutrino fluxes permit separation of matter effects from CP and measurement of sign of Δm^2.
  - Very long-term program, just getting underway.
- Investment in proton intensity must be considered an integral part of both the current and future neutrino program at Fermilab.