Request for Run Plan and Protons for MINOS

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Dec. 12, 2003

Overview

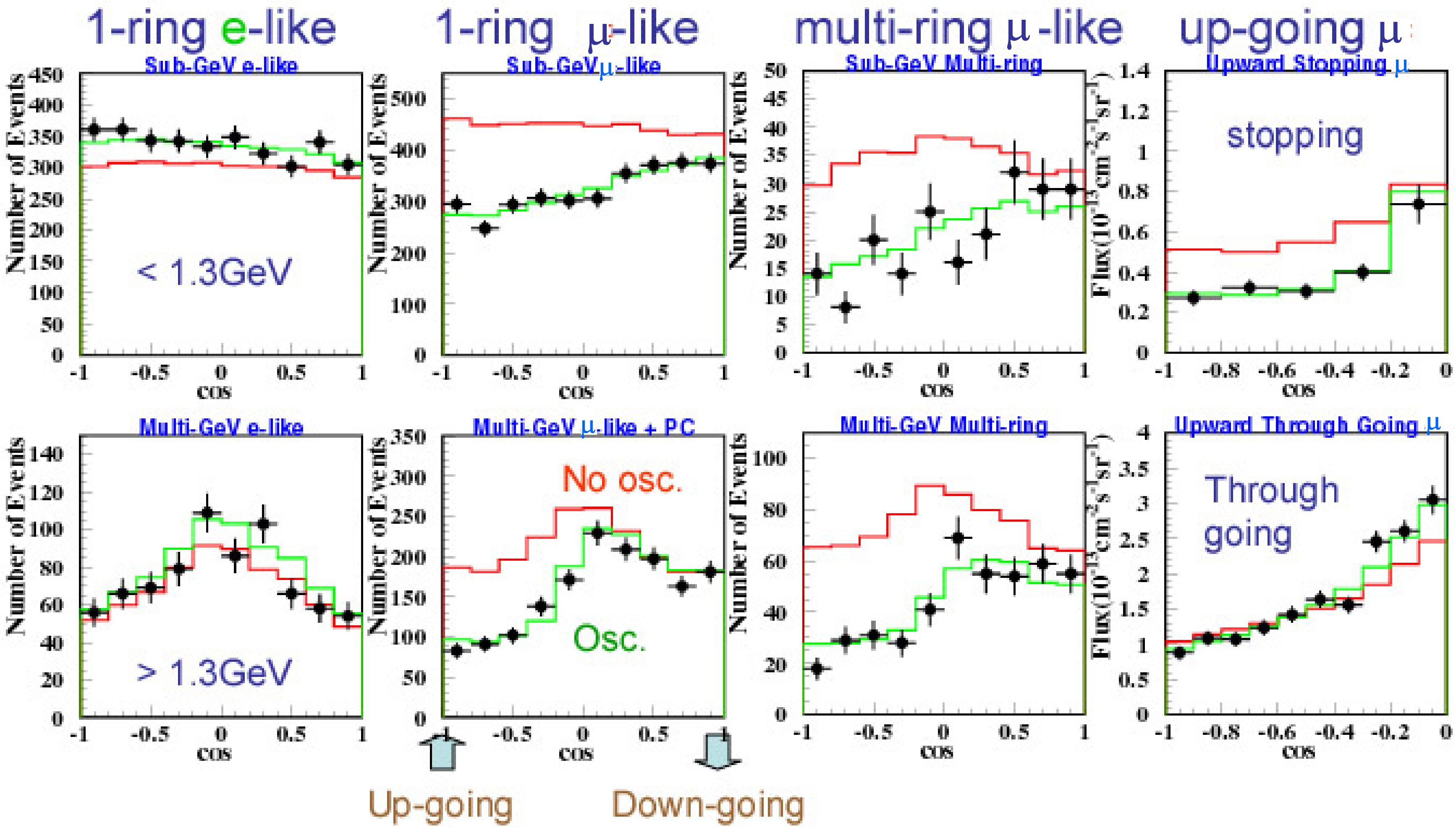
- The MINOS running request
- State of the art in atmospheric neutrinos and Long Baseline
- Quick look at MINOS atmospheric neutrinos
- Reminder of the NuMI beam spectra
- MINOS oscillation measurements with the NuMI beam vs proton intensity
- Answers to PAC questions from June
- Summary

MINOS Request for Running

- Current Fermilab Long-Range Plan:
  - NuMI beam commissioning starting in Dec. 2004.
  - 4 years of physics running for MINOS starting in April 2005.
  - Goal for protons on target in first year = 2.5×10^{20}
  - Plans are being developed for increased proton intensity.
  - Nominal total protons on target ~10×10^{20}?
- New MINOS Running Request
  - We request approval for 5 years of running with a total of 25×10^{20} protons on target in that time.
    - 5 years: With an aggressive investment in proton intensity we believe that MINOS will remain competitive in all neutrino oscillation measurements for that timescale.
    - 25×10^{20} protons: This requires increasing the proton intensity by roughly a factor of 3 during the 5 year running period. The request was based not just on what is necessary for physics measurements but also on what could be considered an aggressive but realistic investment in proton intensity during these years. We will re-visit what this means.

Latest Data Analysis from Super-K

1489day FC+PC data + 1646day upward going muon data

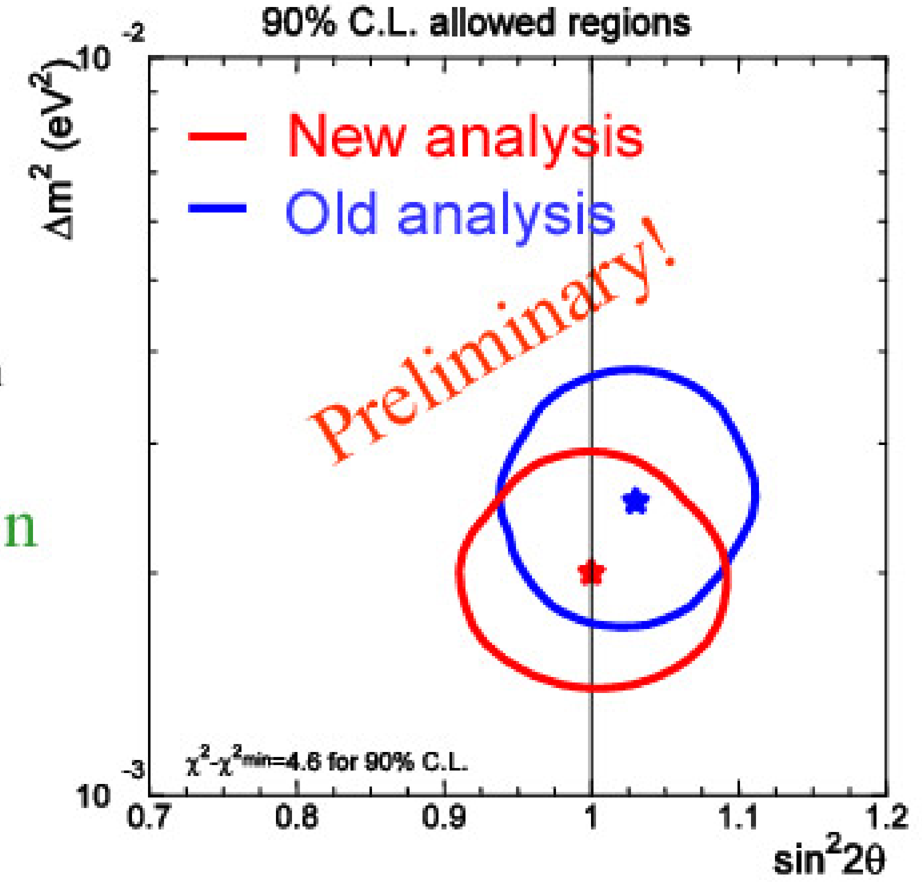


Note: No new data analysed yet but a new analysis of old data has been done.

From Kajita, WIN03

What Changed in the Super-K Analysis

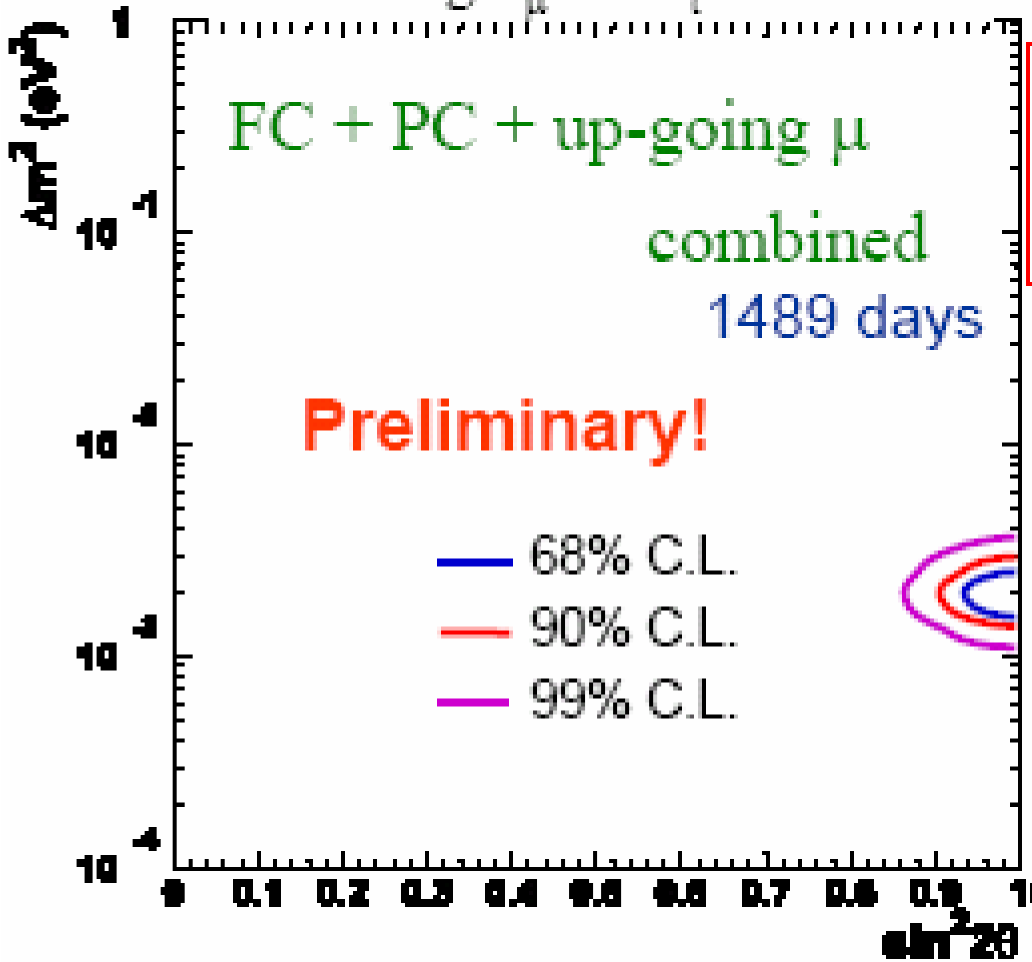
- Neutrino flux (hep-ph/0203272)
  (Honda 1995(1D) Honda 2001(3D))
- Neutrino interaction model
  (several improvements, agree better with K2K near-detector data)
- Improved detector simulation
- Improved event reconstruction



Allowed region in Super-Kamiokande atmospheric ν data

(complete SK-I data-set)

Assuming $\nu_\mu \rightarrow \nu_\tau$ oscillation

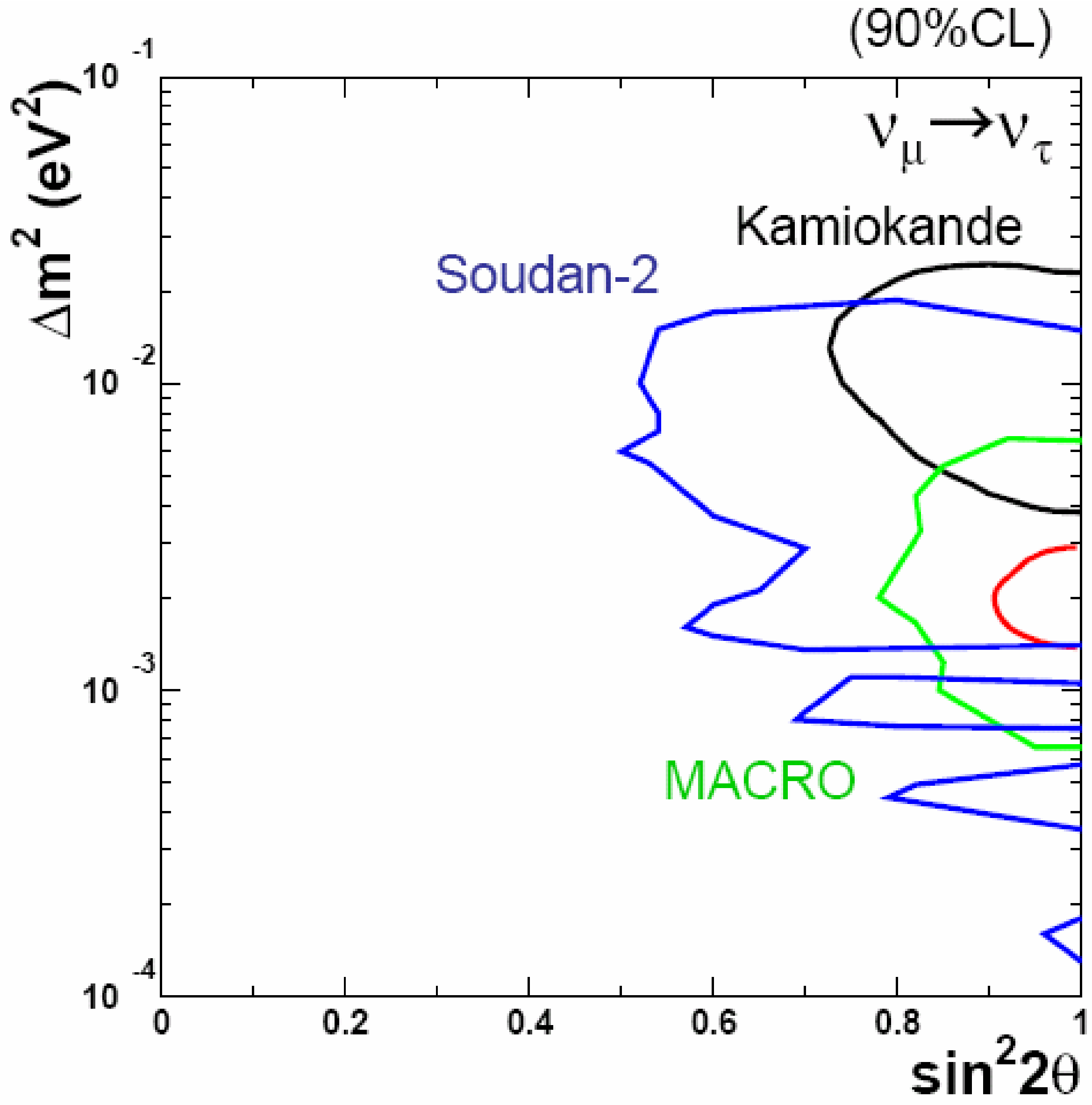


90% CL allowed region
$\sin^2 2\theta > 0.9$
$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$

Best fit
$(\sin^2 2\theta, \Delta m^2)$
$= (1.0, 2.0 \times 10^{-3} eV^2)$
$\chi^2_{min} = 170.8/170$ d.o.f.

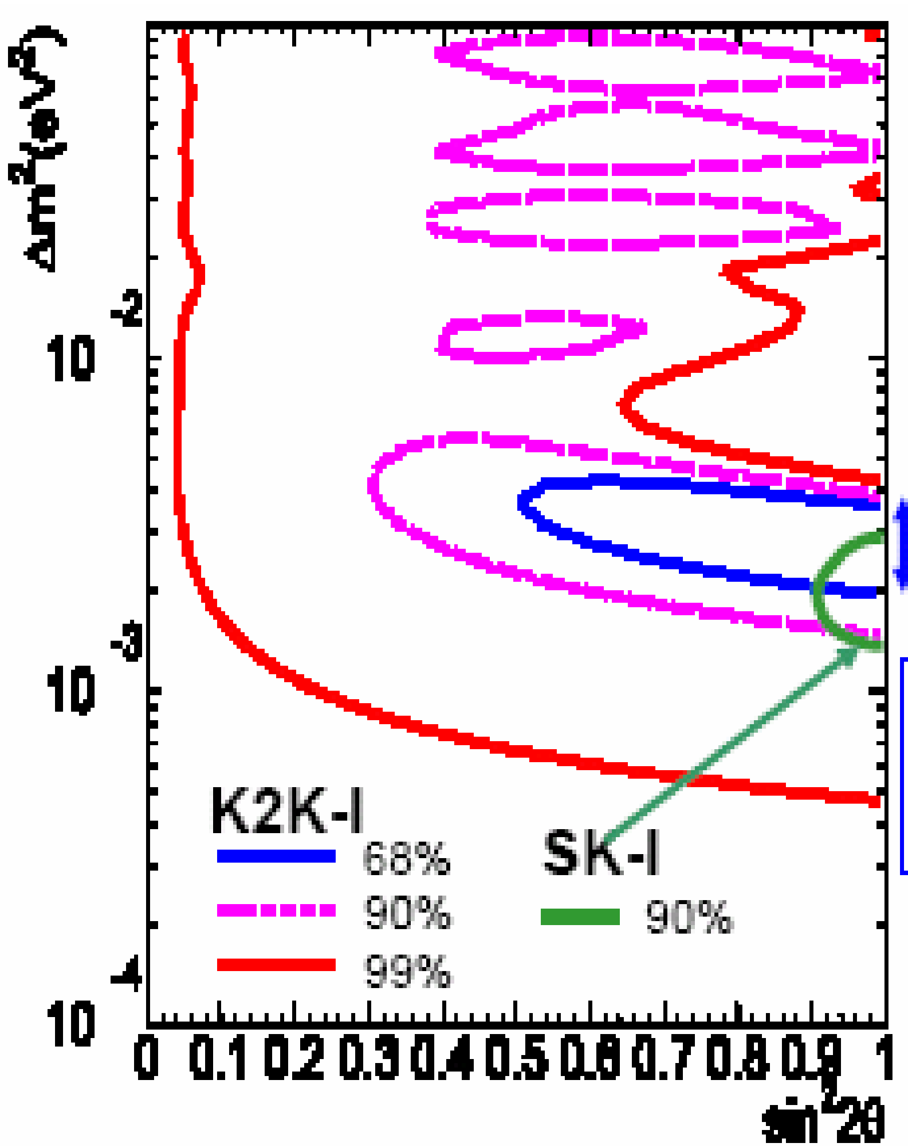
Assuming null oscillation
$\chi^2 = 445.2/172$ d.o.f.

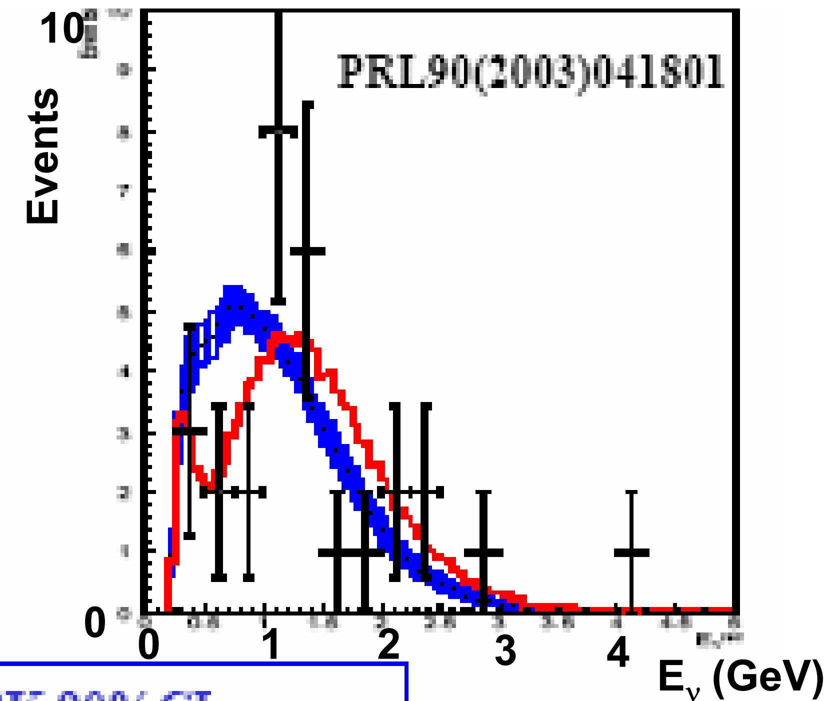
Comparison of Allowed Parameters for Atm. Expts.



Kajita, WIN03

Results from K2K





K2K 90%CL
$1.5\text{–}3.9 \times 10^{-3} eV^2$
@ $\sin^2 2\theta = 1$

K2K best fit $\Delta m^2 = 0.0030$
SuperK $= 0.0020$
MINOS will be able to clearly resolve.

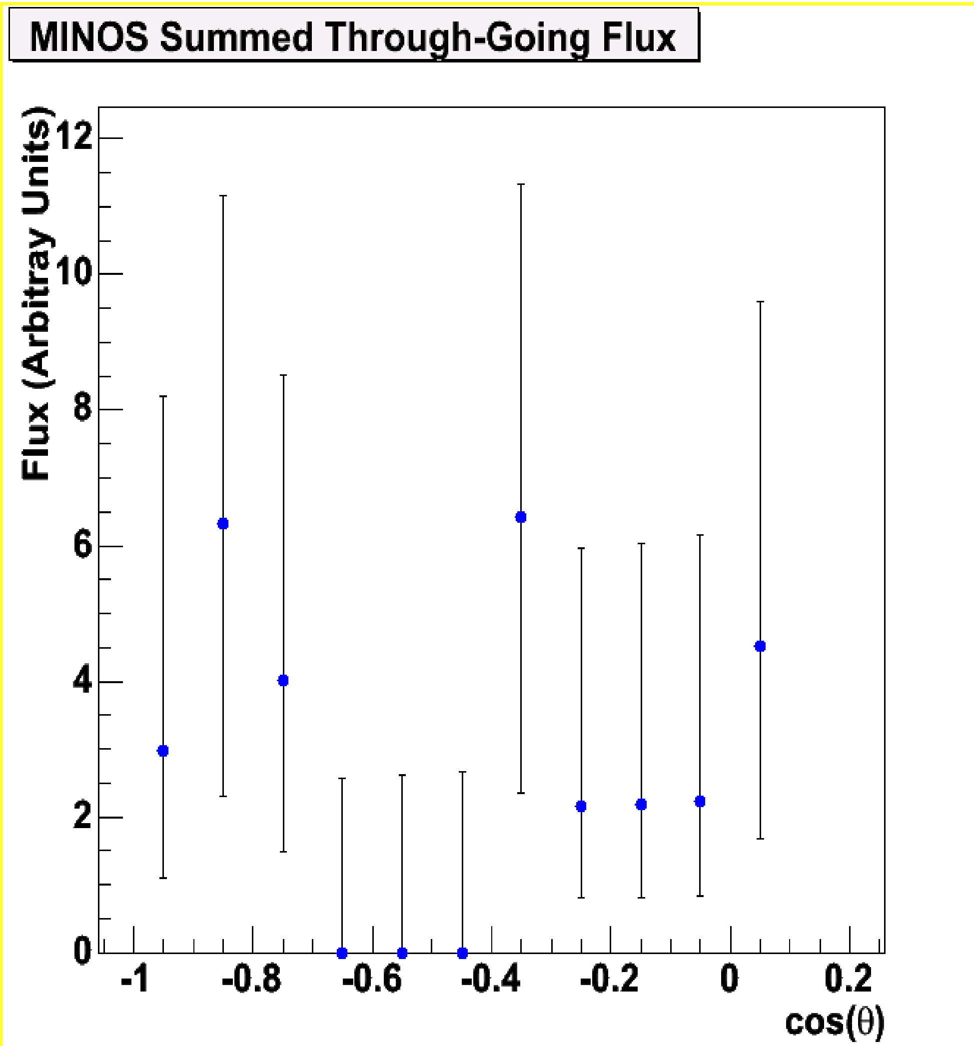
Atm. 90% CL
$\sin^2 2\theta > 0.9$
$1.3 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} eV^2$

Nishikawa, Lepton-Photon 03

A Glimpse of MINOS Status

- Far detector is now routinely collecting cosmic-ray and atmospheric neutrino data.
  - Typical uptime is currently around 80-85%.
  - We'd like to improve that over the next year to 95% and as close as possible to 100% for NuMI beam data.
- Near detector is mostly assembled and waiting in the Muon Lab.
- Calibration Detector running at CERN is now complete. This has been a large and successful effort:
  - Provided shake-down of both near and far electronics and readout systems.
  - Provides the fundamental energy calibration and relation for muons, hadrons and electrons.
  - Provides the measurement of hadronic and electromagnetic energy resolution.
  - Provides detailed data on low-energy calorimetry which is essential for precise understanding of MINOS topological event ID criteria.
  - We are very grateful to CERN for providing space, resources and beam for this 3-year running effort.
- The MINOS Collaboration now has physics analysis groups formed and actively pursuing development of optimal analysis techniques for the beam data to come.
- Proton intensity is an over-riding issue of importance and MINOS collaborators are increasing activity in this area.

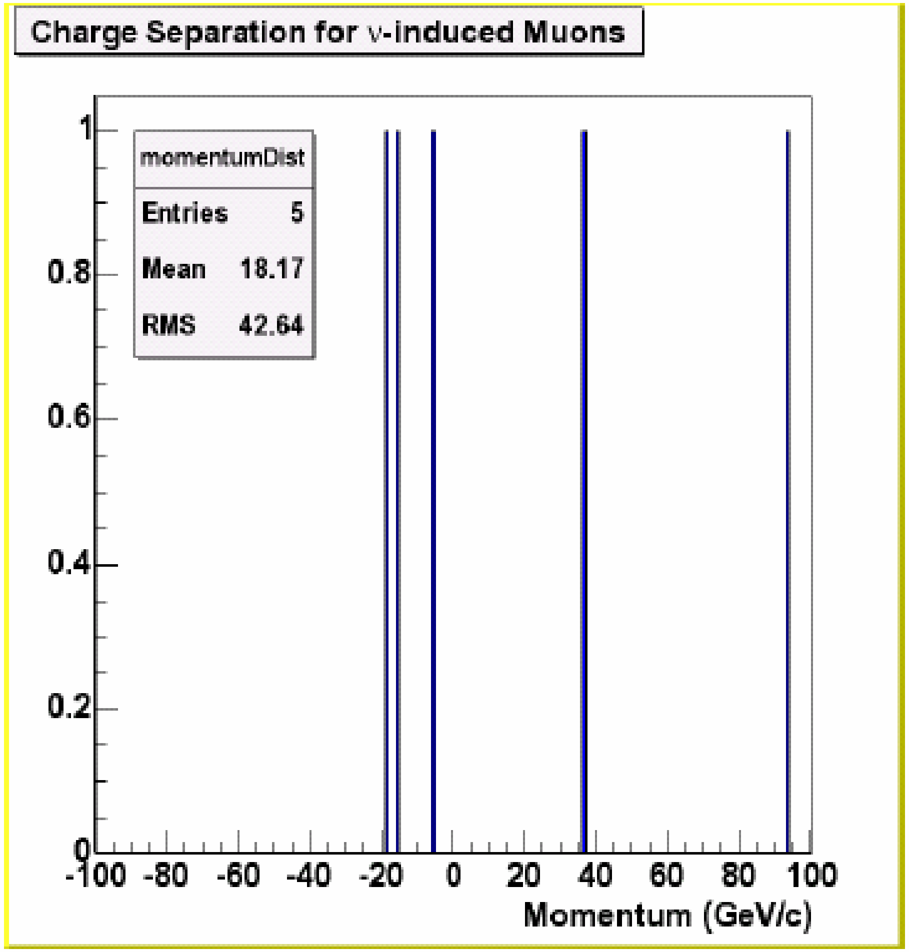
Upgoing Muon Analysis



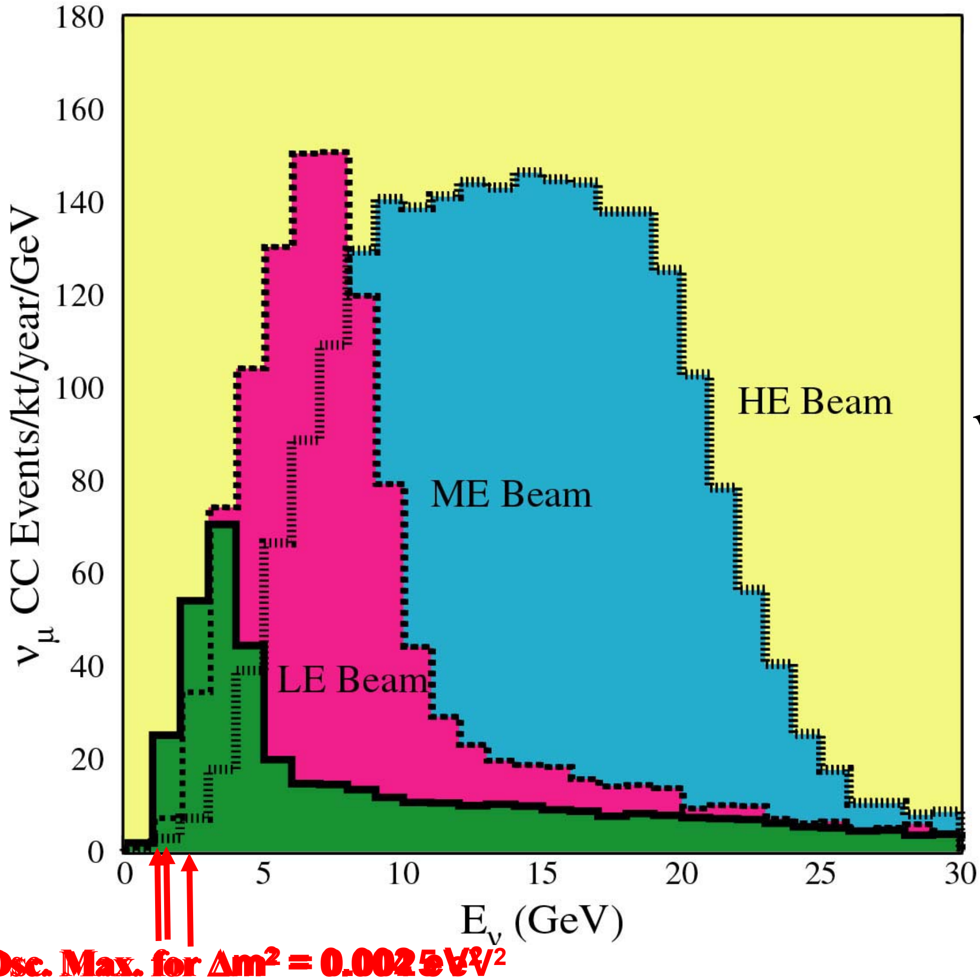
- Upgoing muon and atmospheric neutrino contained analyses are proceeding well.
- The upgoing muon flux is shown here in arbitrary units as a function of cosθ
- Both stopping and through-going events
- Only data from the full detector is shown here (data taken since August 03)

Upgoing Muon Analysis

- MINOS is the first atmospheric neutrino detector with a magnetic field and hence, charge ID.
- The upgoing muon analysis and statistics are approaching an ability to place constraints on some CPT violation models.
- Teaser plot at right. We now have ~40 upgoing muon events.



The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/3.7e20pot

Low	Medium	High
470	1270	2740

ν_μ CC Events/MINOS/7.4e20pot

Low	Medium	High
4760	11300	23400

3.7×10^{20} protons on target/year requires 4×10^{13} protons/2.0 seconds

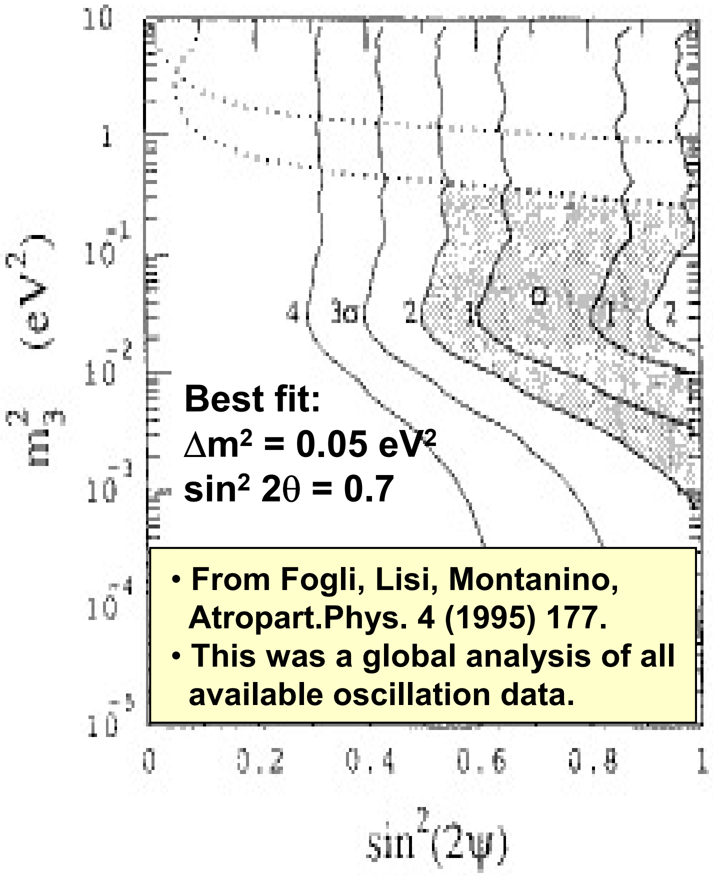
A somewhat lower energy focussing condition may be possible but requires a new target and first horn. We certainly will want to run first with this hardware, but perhaps be ready to act quickly.

MINOS Beam Oscillation Measurements

- In general, the sensitivity of MINOS physics measurements scale simply with the sqrt(N).
- Lower Δm^2 makes all measurements harder due primarily to the relative paucity of low energy neutrinos. (The detector resolution and efficiency are OK down to several hundred MeV)
- Proton intensity is the main handle for improvement in sensitivity.

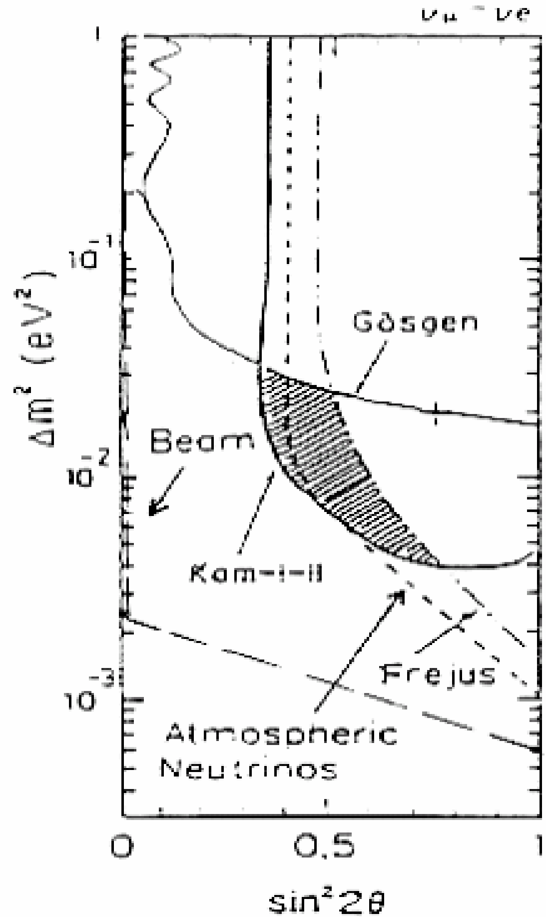
A Little History: At the time of the MINOS Proposal

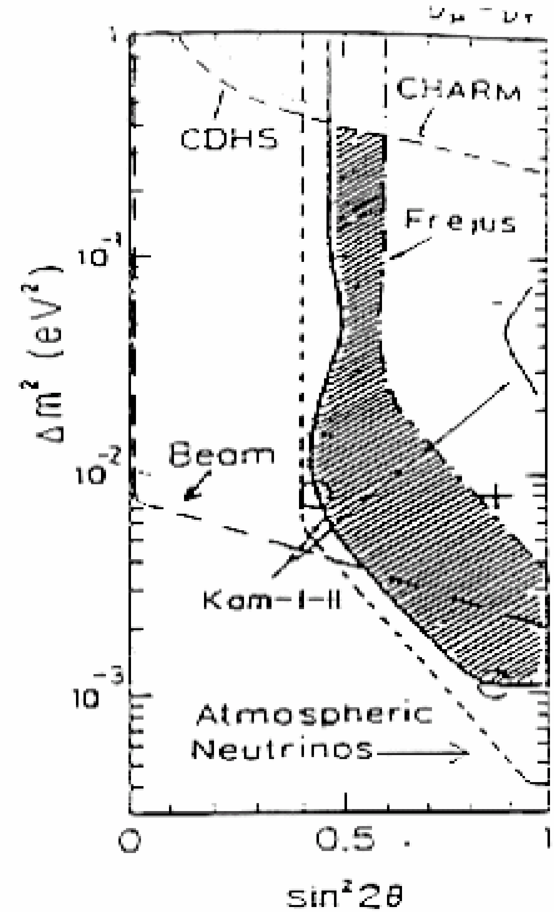
Some views of the allowed oscillation parameter space in 2004-2005.



Best fit:
$\Delta m^2 = 0.05\ eV^2$
$\sin^2 2\theta = 0.7$

- **From Fogli, Lisi, Montanino, Atropart.Phys. 4 (1995) 177.**
- **This was a global analysis of all available oscillation data.**





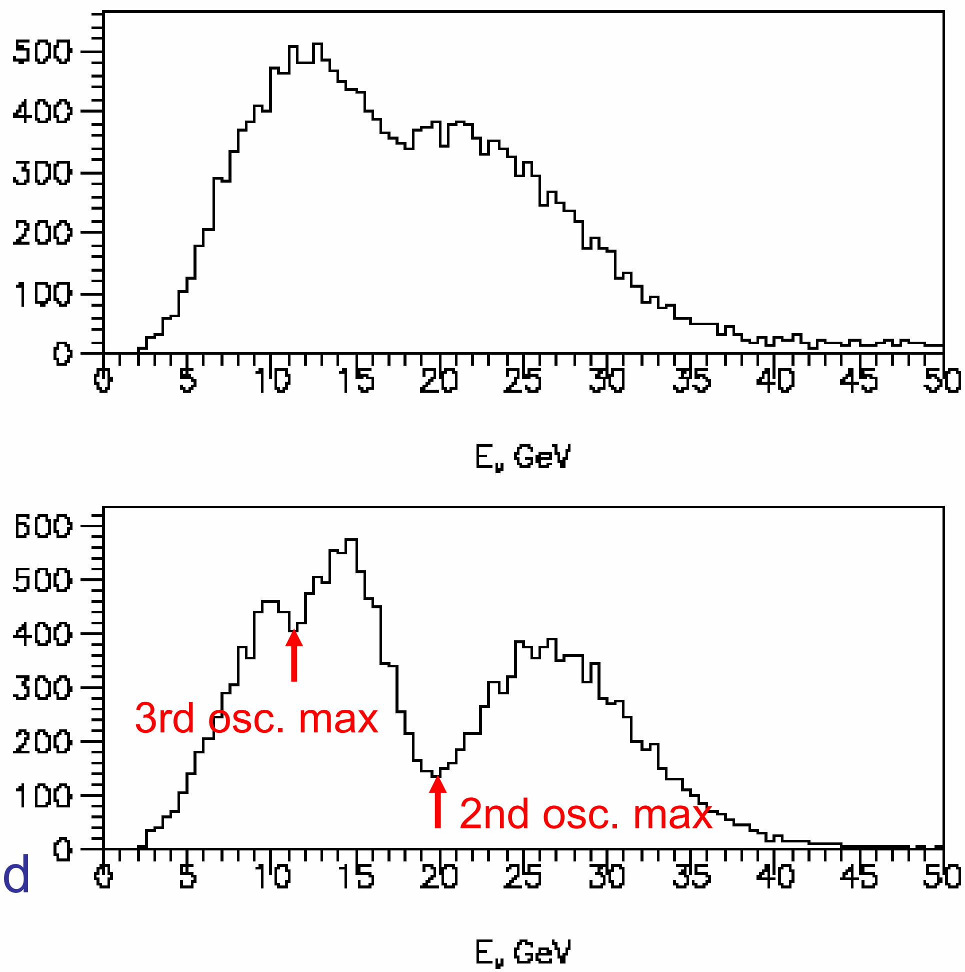
Questions of the time:

- **Was there really an anomaly?**
- **If so, was it oscillations?**
- **If so, was it ν_μ to ν_e or ν_τ ?**
- **Could mixing really be this large?**
- **What was Δm^2 within a factor of 10?**

- **From one of the "MINOS" EOIs.**
- **Large dashed line shows the expected NC/CC 90% CL limits for the NuMI high energy beam from one of the "MINOS" EOIs.**
- **The best fit for Δm^2 from Kamiokande *increased* the following year to above 0.01 eV^2.**

From the MINOS Proposal (1995)

The far detector CC energy spectrum using the NuMI high-energy beam with 7.4 x 10^{20} protons on target



No Oscillation

For $\Delta m^2 = 0.1$ eV^2
$\sin^2 2\theta = 1.0$

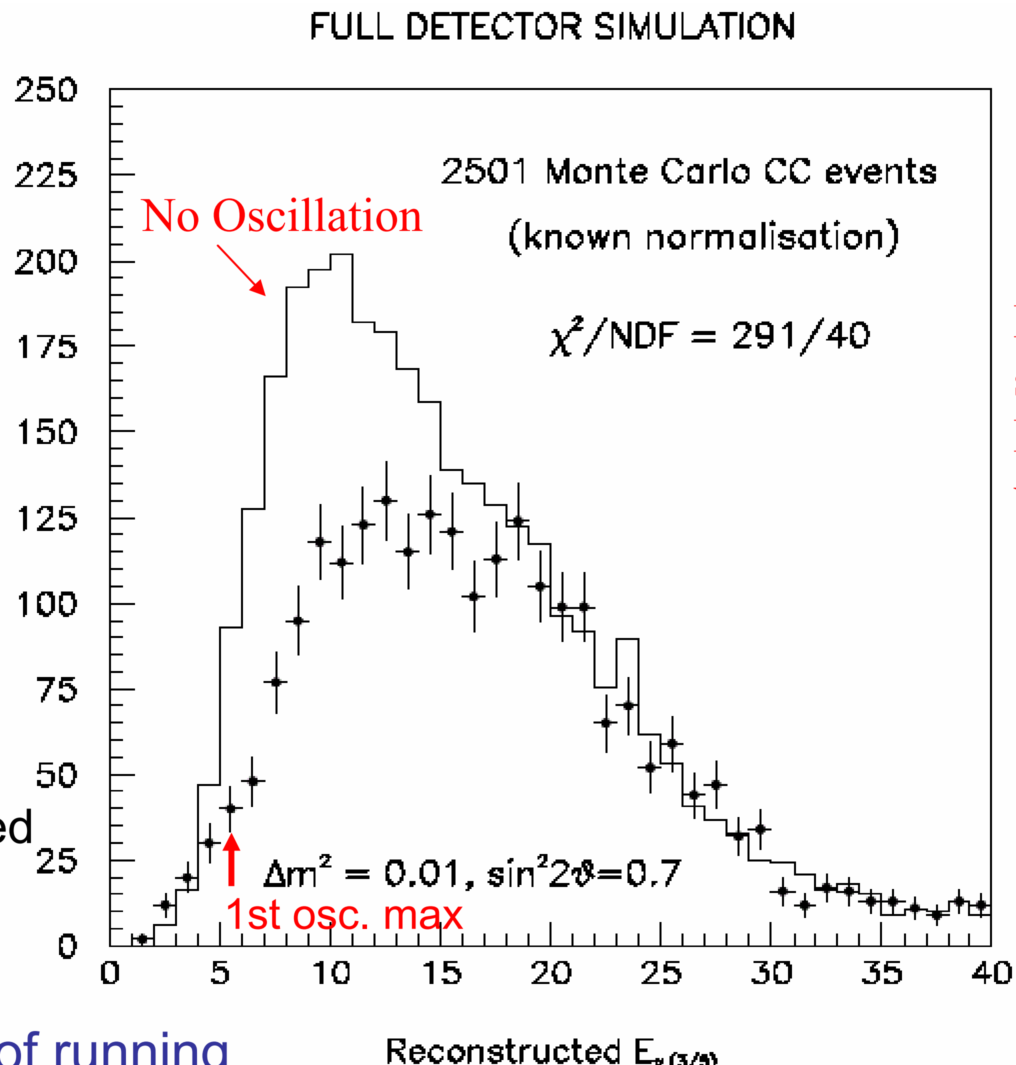
1st osc. max

Result was expected by 2002.

Figure 8.4: Upper graph: Energy spectrum of CC events in the NuMI wide-band beam *without* oscillations. Lower graph: Energy spectrum of CC events in the NuMI wide-band beam *with* oscillations for $\Delta m_0^2 = 0.1$ eV^2 and $\sin^2(2\theta) = 1$. The resolution of the detector has been included in both graphs.

For the HEPAP Sub-panel (1995)

The far detector CC energy spectrum using the NuMI high-energy beam with 0.4 x 10^{20} protons on target! (Calculated due to lack of statistics for fully reconstructed MC events)



For $\Delta m^2 = 0.01$ eV^2
$\sin^2 2\theta = 0.7$
Best fit Kamiokande values at the time.

Clearly, we hadn't yet significantly developed the idea of lower energy beams. But that was coming.

Roughly 1 month of running

Figure 13: Expected WBB dN/dE distributions for CC events for oscillations (points with error bars) with $\Delta m^2 = 0.01\ eV^2$ and $\sin^2(2\theta) = 0.7$, and for the no oscillation hypothesis (solid histogram). The absolute normalization is assumed to be known. The χ^2/df between the two distributions is 291/40.

Questions for Today

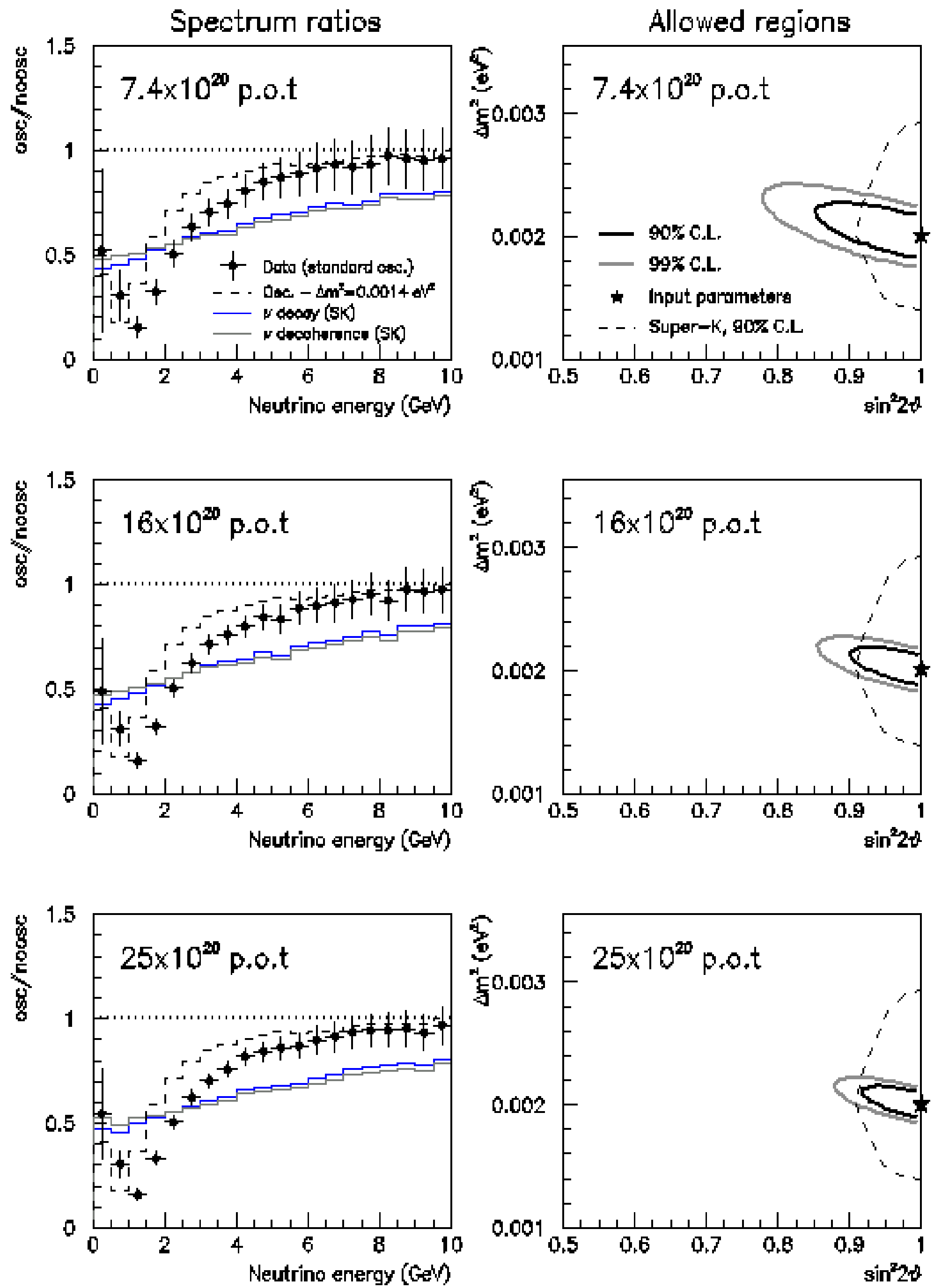
- Are we completely sure that the disappearance is consistent only with a “standard” oscillation?
- What is the value of Δm^2_{23} at the 10% level?
- Is $\sin^2 2\Theta_{23}$ sufficiently close to 1.0 that it suggests some new fundamental symmetry? What is its value at the 1% level?
- Are there sub-dominant oscillations?
  - What is the value of $\sin^2 2\Theta_{13}$? Is this angle anomalously small? Or “near” the other values?
  - Is there CP or CPT violation in neutrino mixing? Can we measure it?
  - What is the sign of Δm^2_{23} ? What does the normal or inverted heirarchy tell us about Grand Unified Theories?
  - Are there any light sterile neutrinos and do they participate in the oscillations?

Measurement of Oscillations in MINOS

For $\Delta m^2 = 0.0020\ eV^2$, $\sin^2 2\theta = 1.0$

Plots on the left: Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

Plots on the right: MINOS 90% and 99% CL allowed oscillation parameter space for the Super-K best fit point.

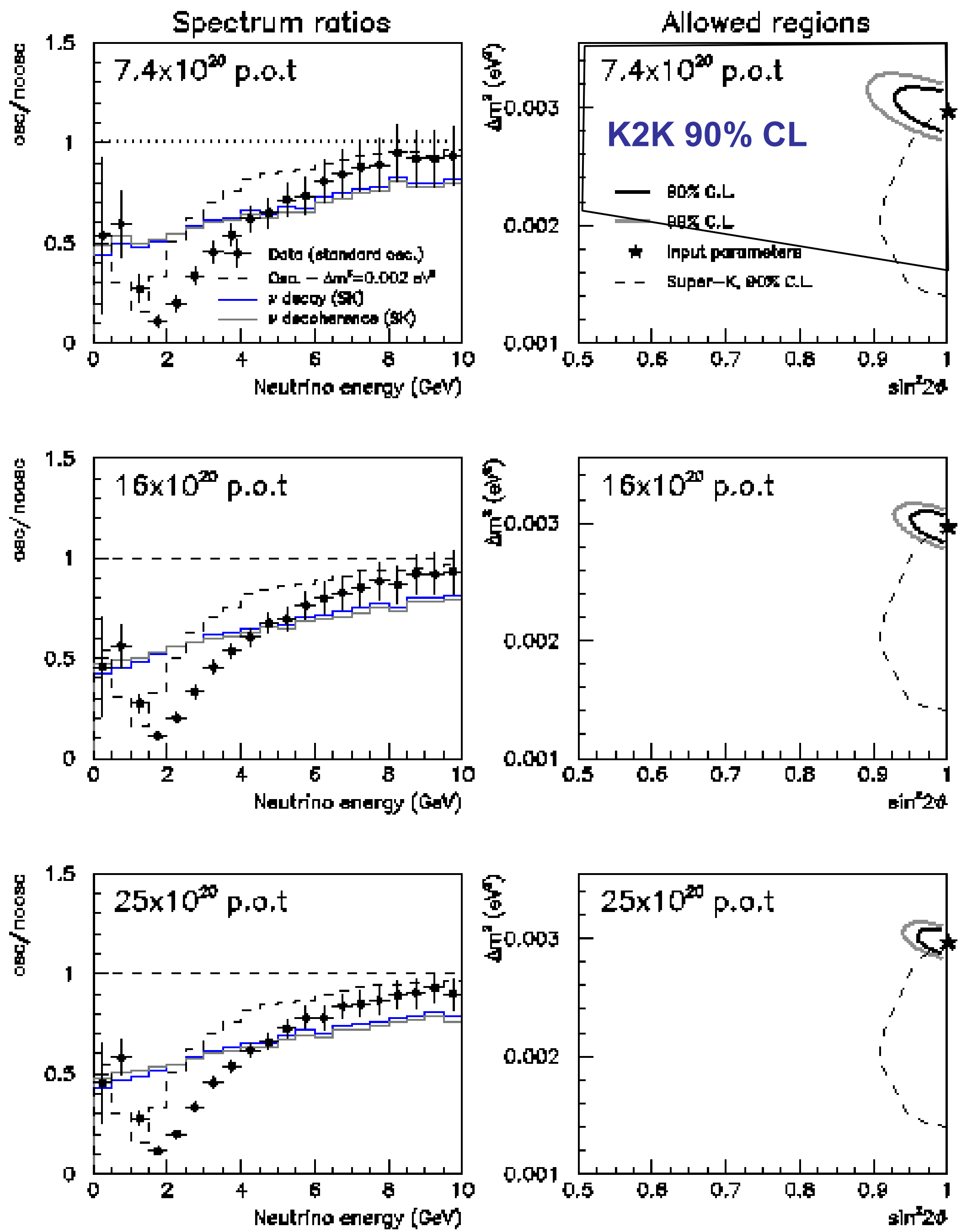


Measurement of Oscillations in MINOS

For $\Delta m^2 = 0.0030\ eV^2$, $\sin^2 2\theta = 1.0$

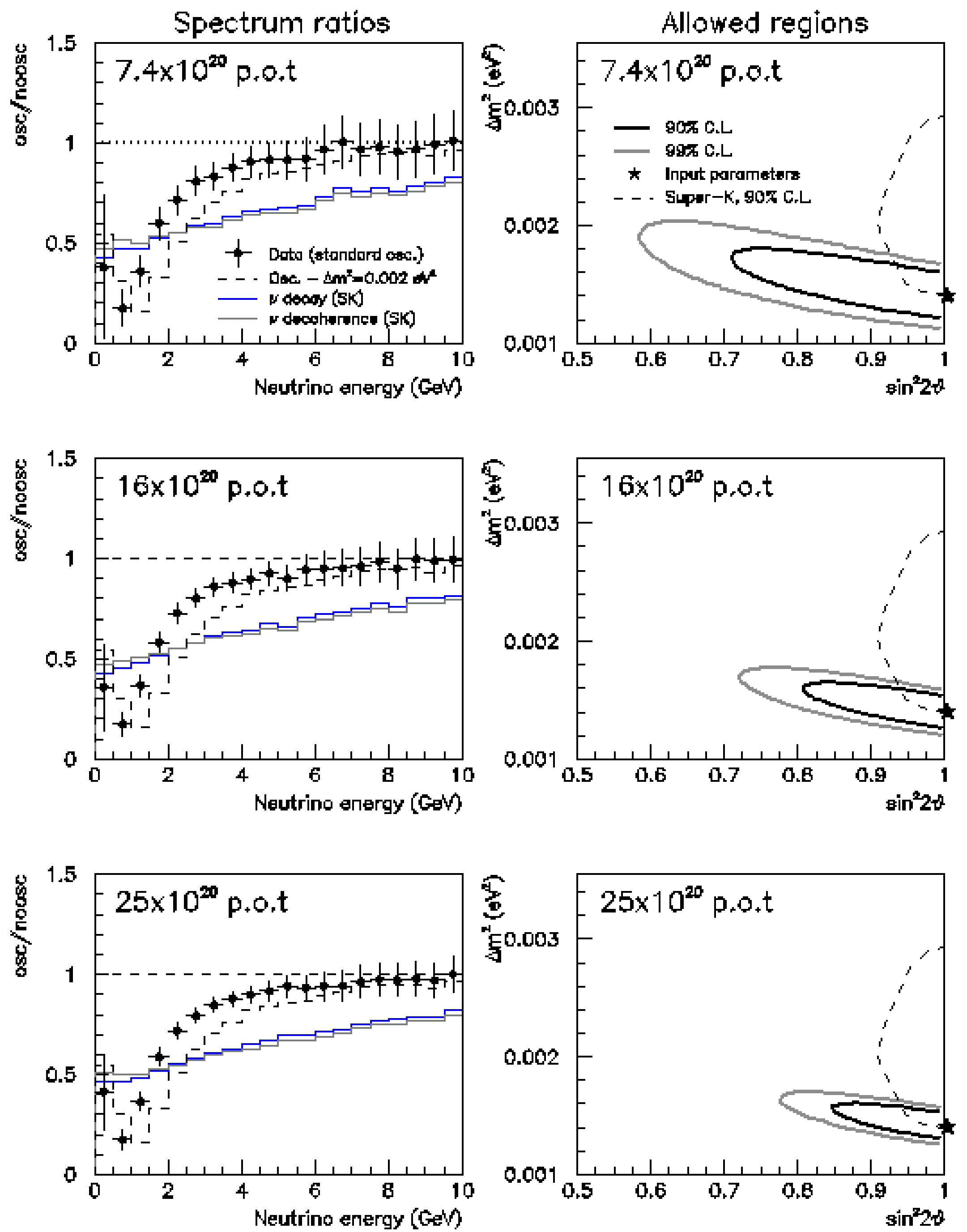
Plots on the left: Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

Plots on the right: MINOS 90% and 99% CL allowed oscillation parameter space for the Super-K best fit point.



Measurement of Oscillations in MINOS

For $\Delta m^2 = 0.0014\ eV^2$, $\sin^2 2\theta = 1.0$

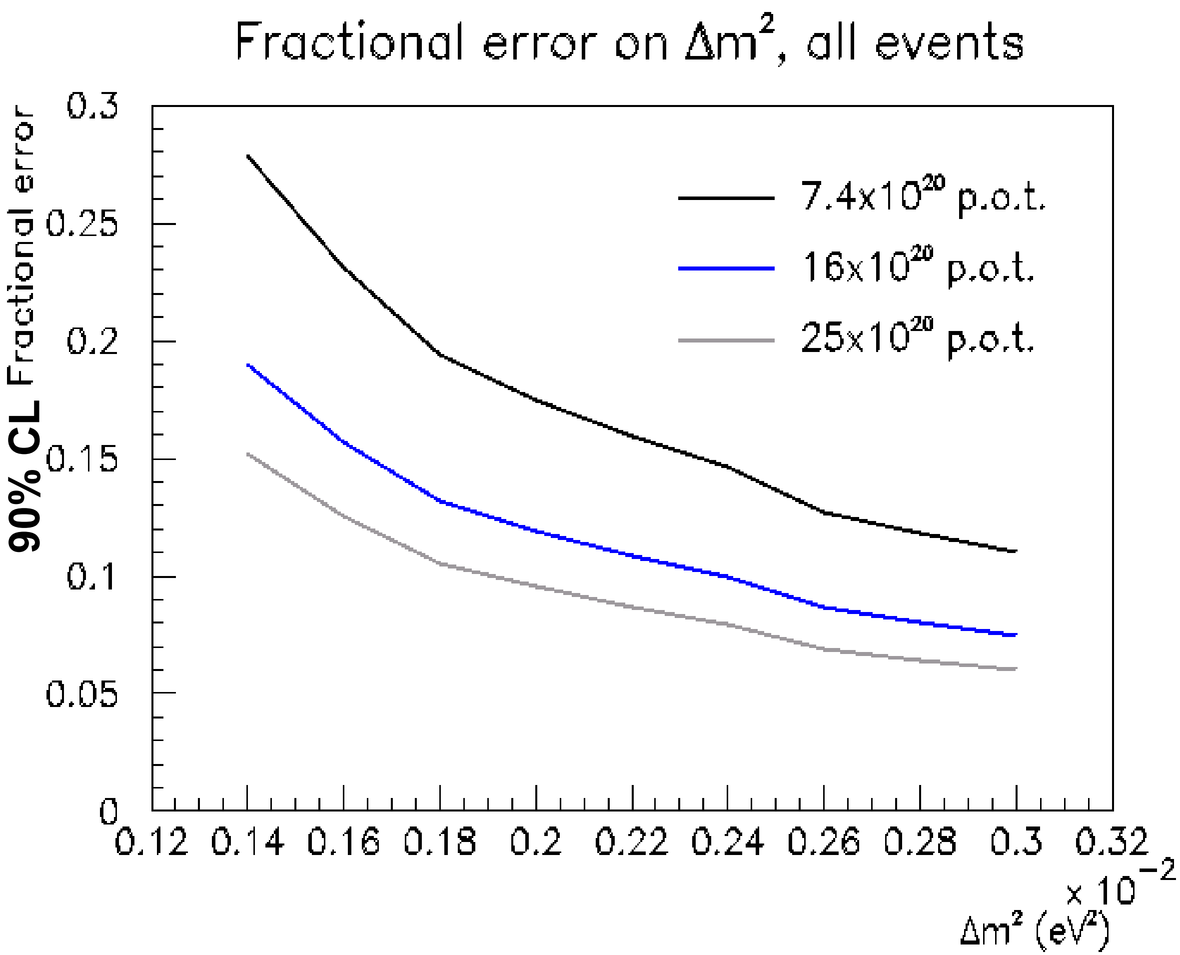


Plots on the left: Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

Plots on the right: MINOS 90% and 99% CL allowed oscillation parameter space for the Super-K best fit point.

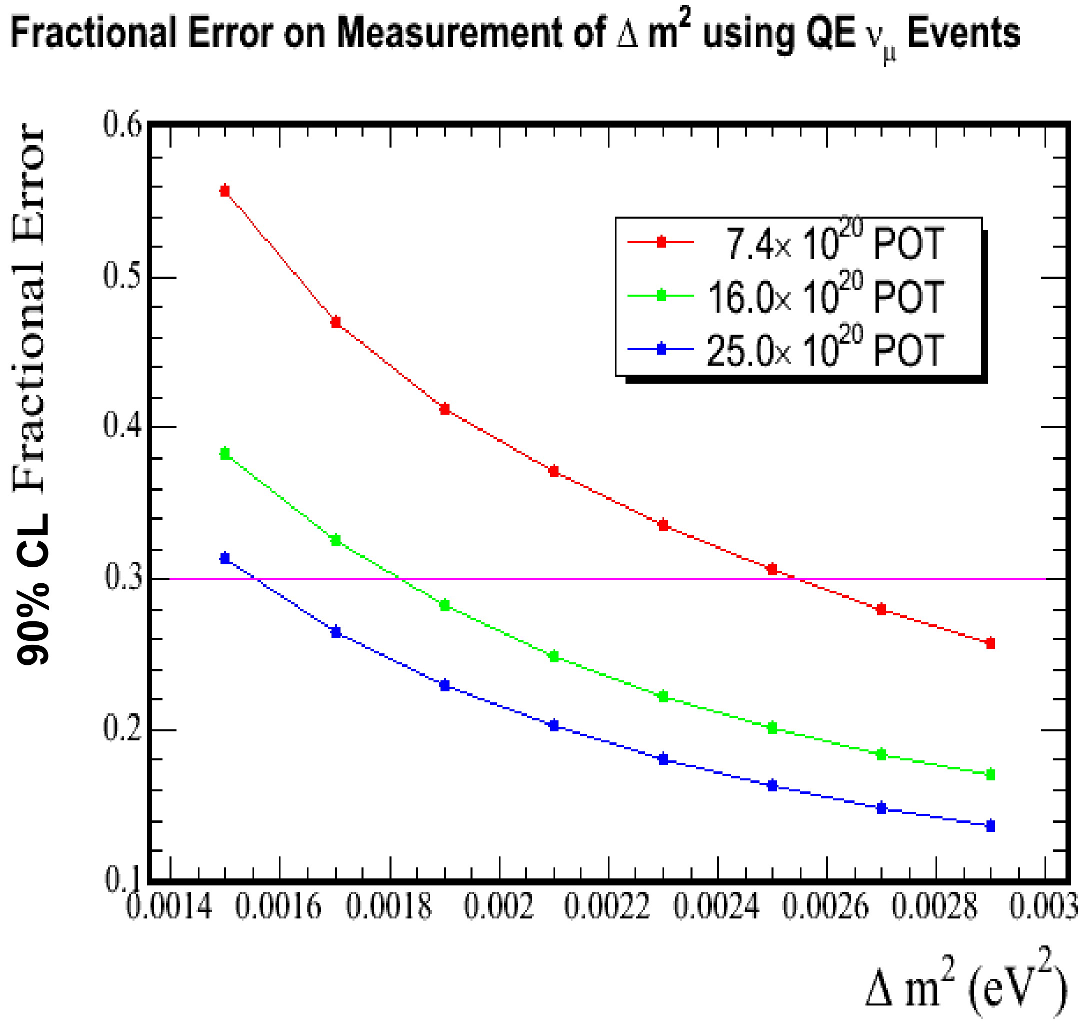
If this kind of measurement is made, the limit on $\sin^2 2\theta$ will be some convolution between MINOS and Super-K, not just the intersection of the 90% allowed regions.

Precision on Measurement of dm2



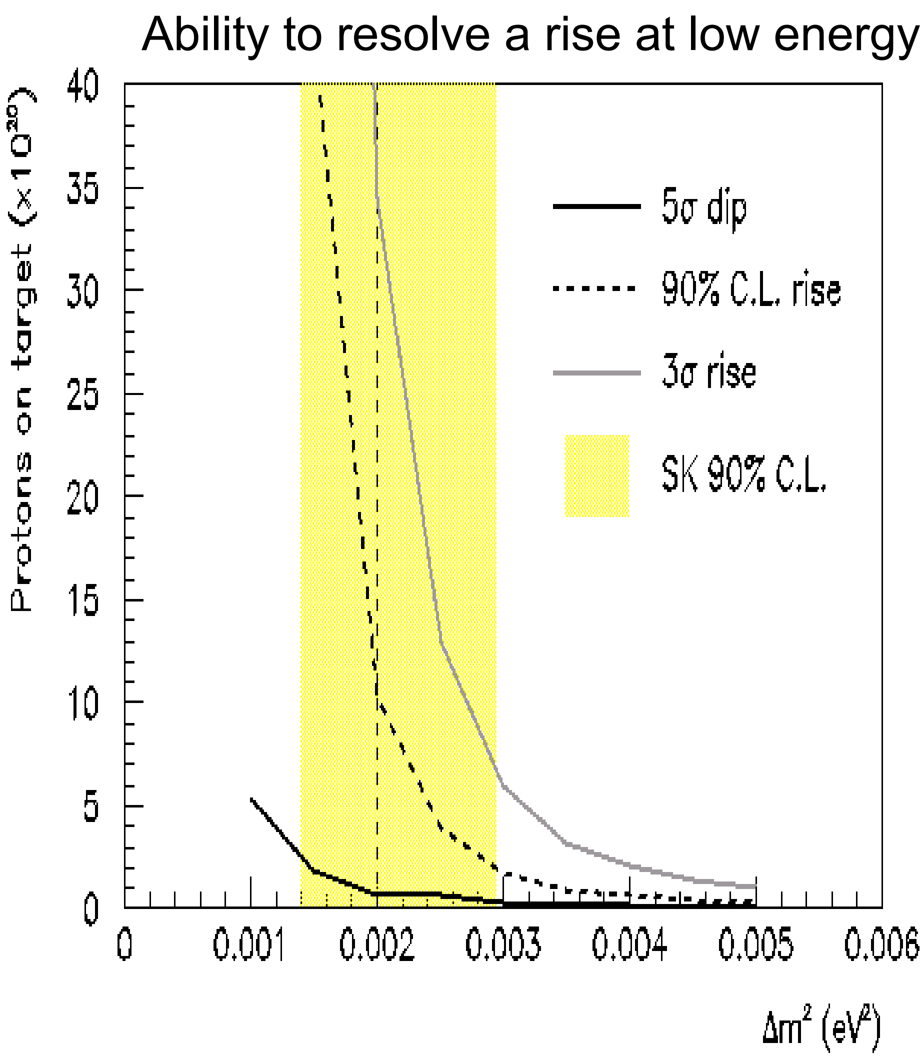
Current fractional error on Δm^2 from Super-Kamiokande is 0.85.

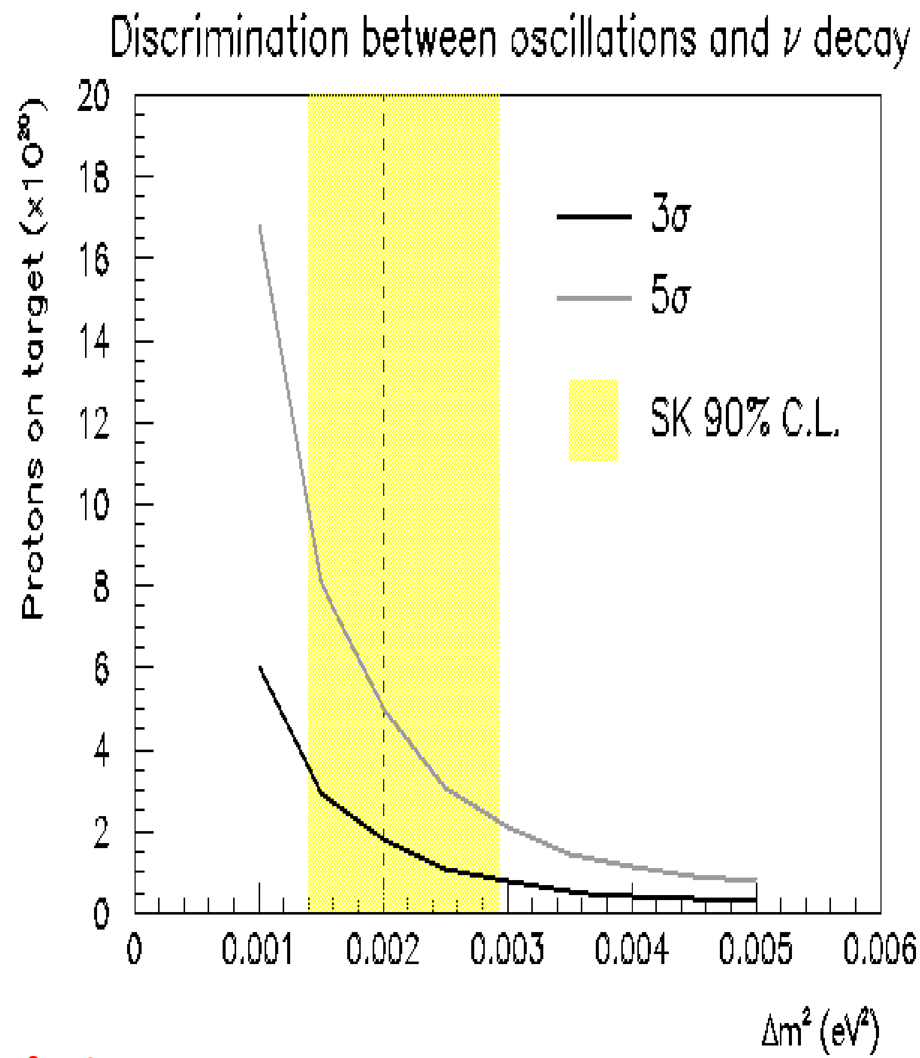
Precision on Measurement of dm2



- "Precision" measurements usually mean not just statistics, but ability to prove that the measurement is free of all thinkable large systematic uncertainty.
- Use effective quasi-elastic events ($E_{had} < 0.1\ E_{total}$ with a muon track) to identify a systematically different data sample.

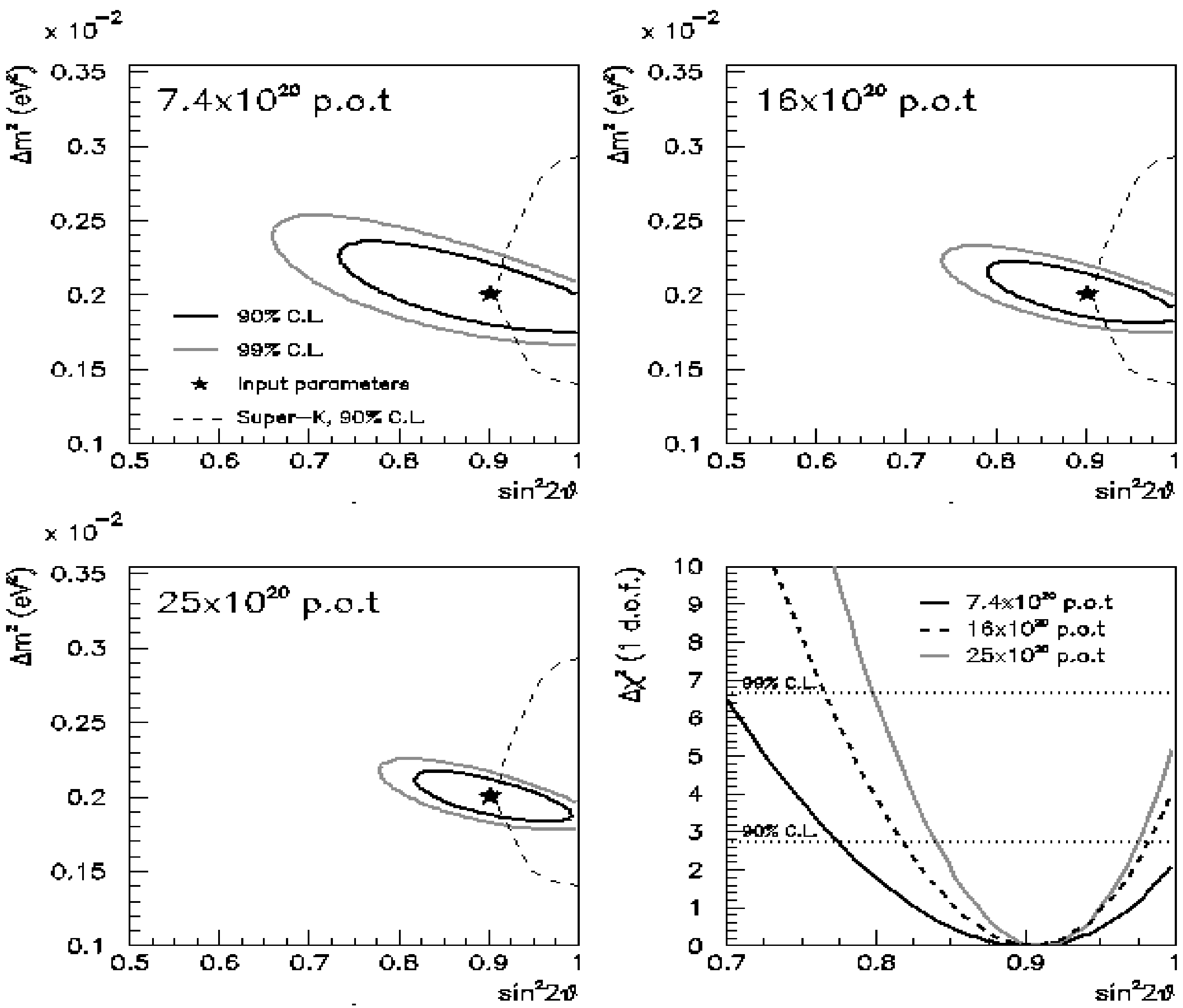
Discrimination against alternate spectra





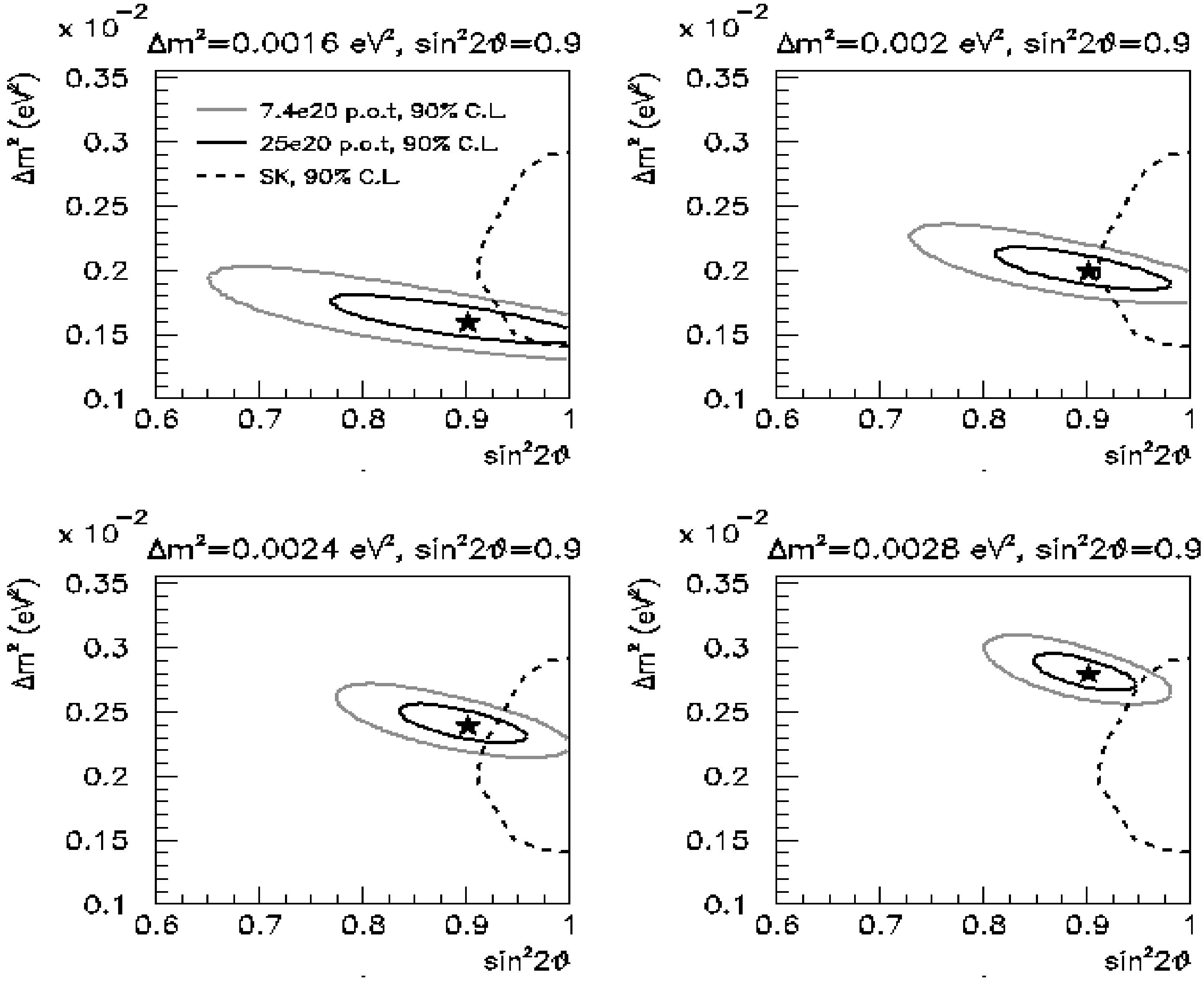
For $\sin^2 2\theta = 1.0$

Measurement of the Mixing Angle

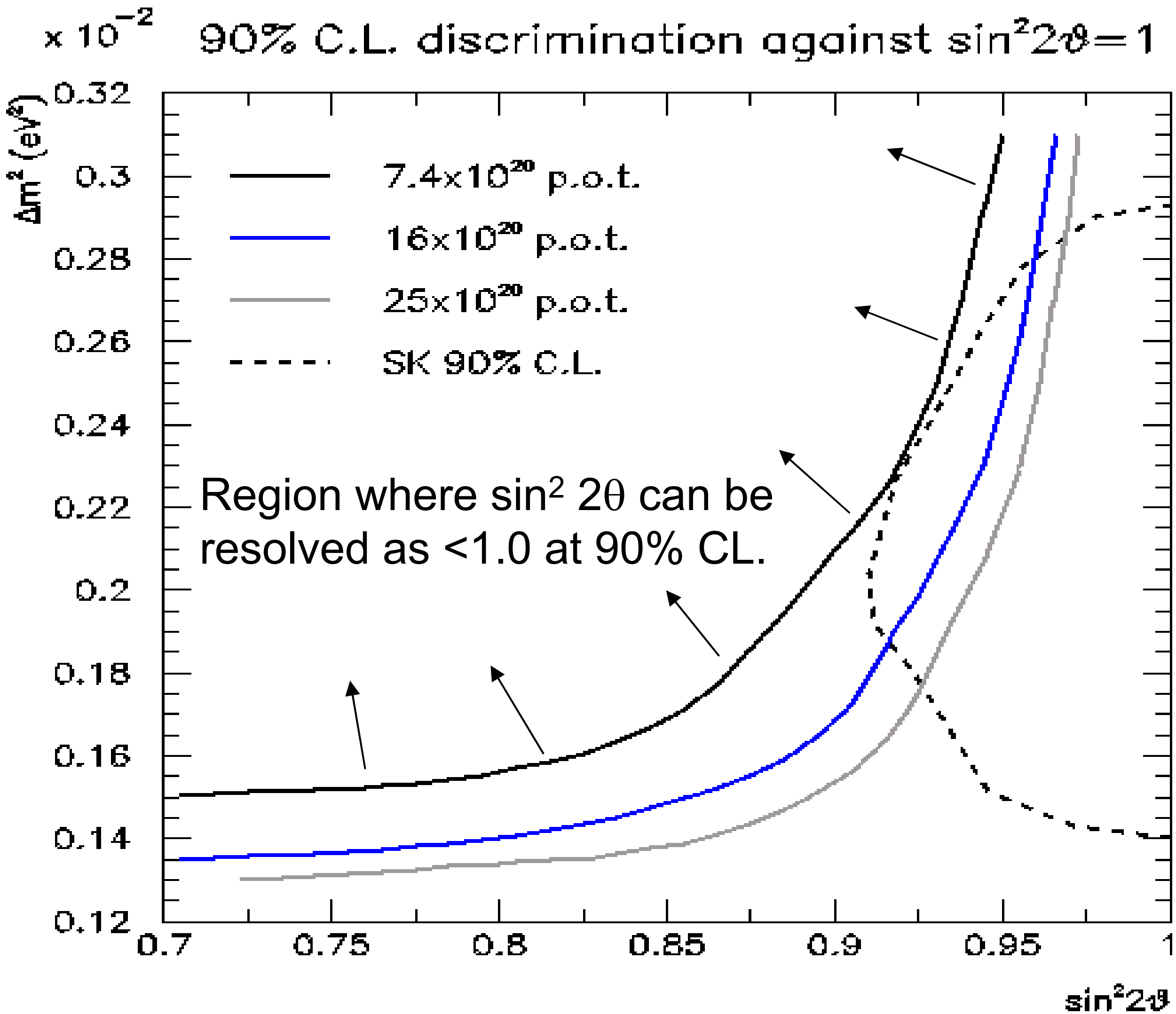


For $\Delta m^2 = 0.0020$ eV^2, $\sin^2 2\theta = 0.90$

Measurement of the Mixing Angle

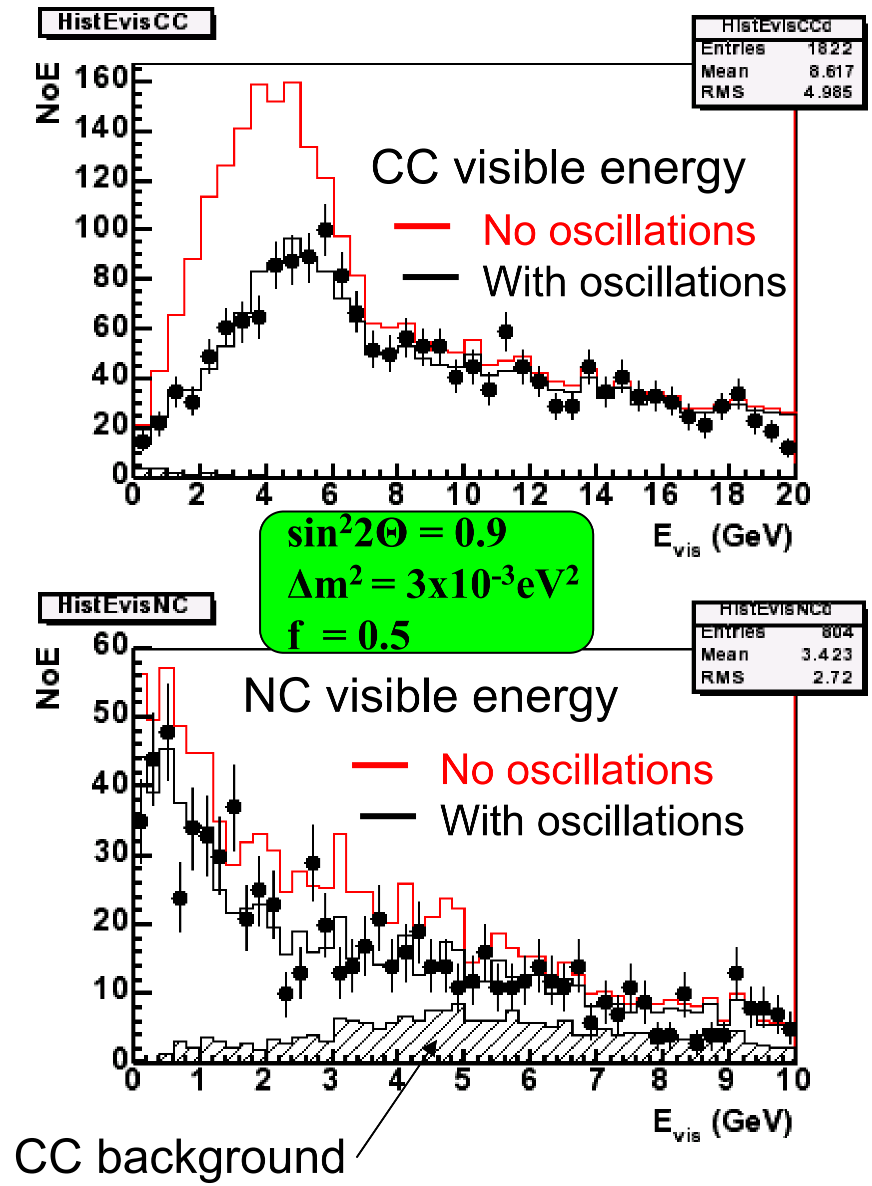


Ability to resolve non-maximal mixing



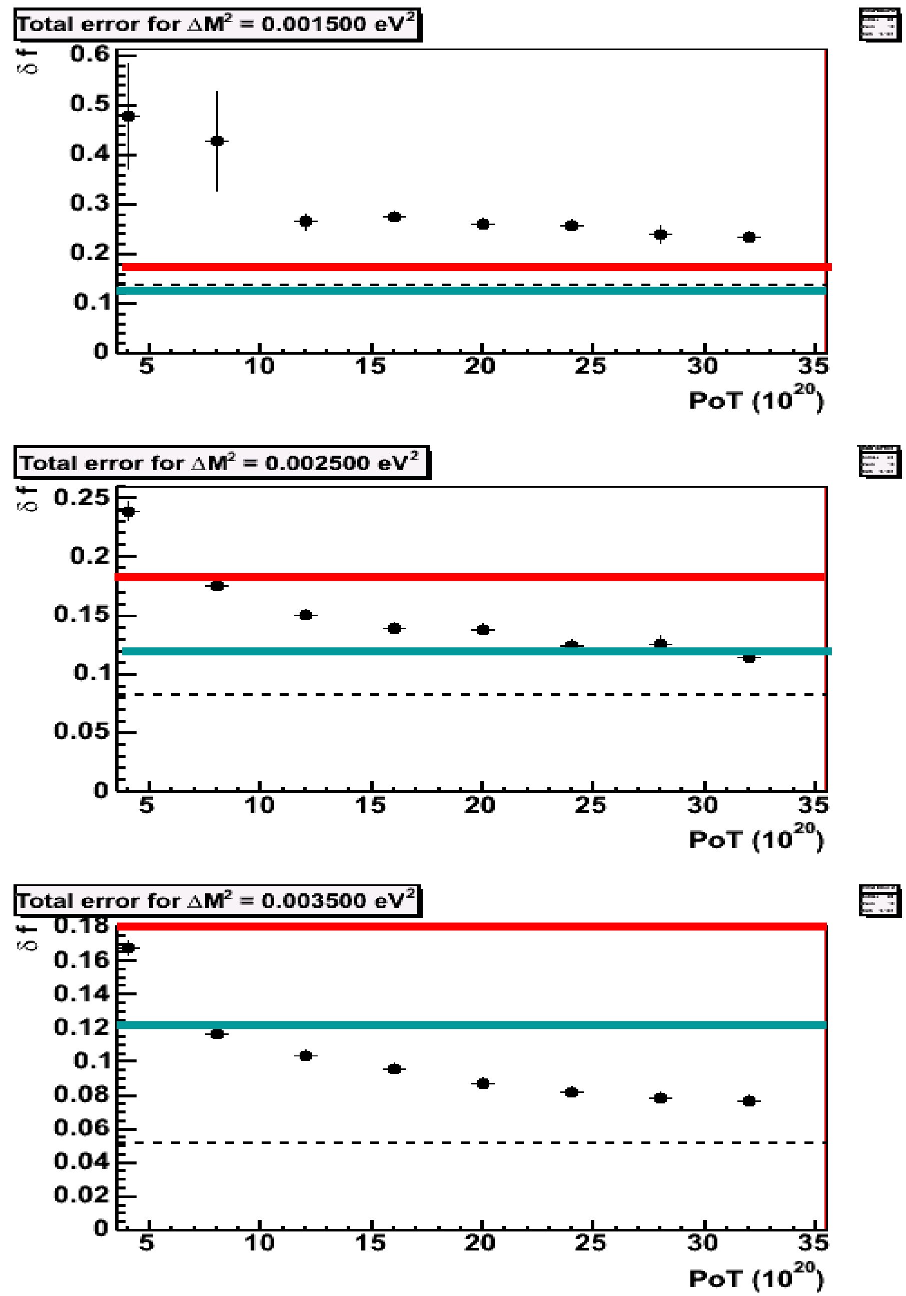
Neutral Current Events

- A possible admixture of $\nu_\mu - \nu_{sterile}$ oscillations can be measured by the disappearance of NC events in the far detector relative to the near detector.
- First, it is important to determine the CC spectrum at the far detector (given oscillations) since there is always some CC background in the NC sample.
- The NC distribution, accounting for different CC backgrounds in the near and far detectors determines the sterile oscillation fraction.

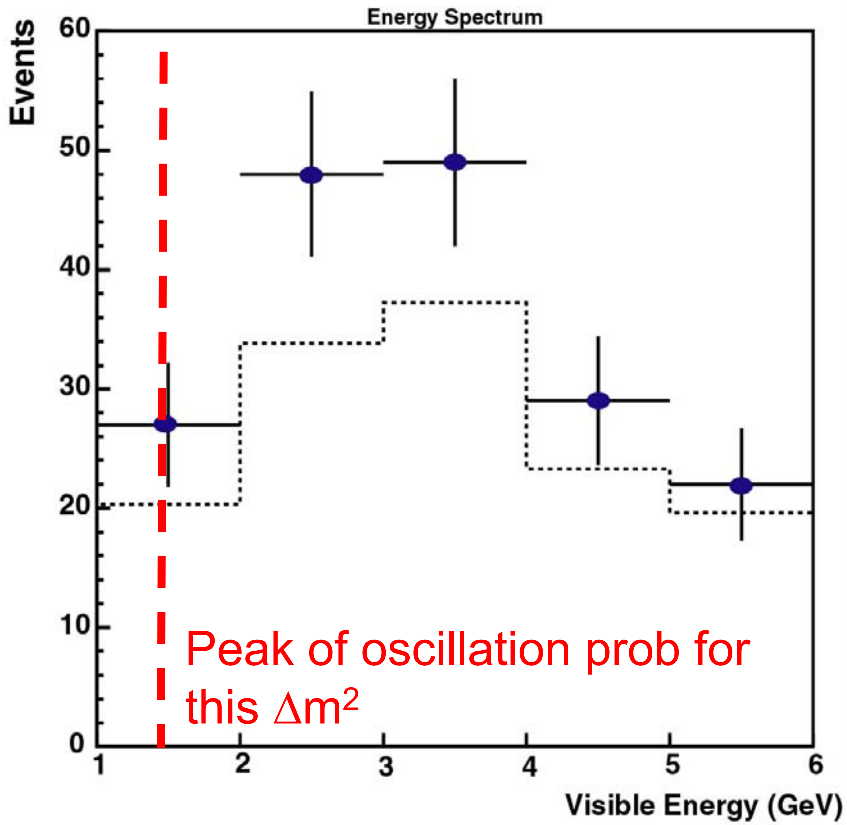


Sensitivity for sterile neutrinos

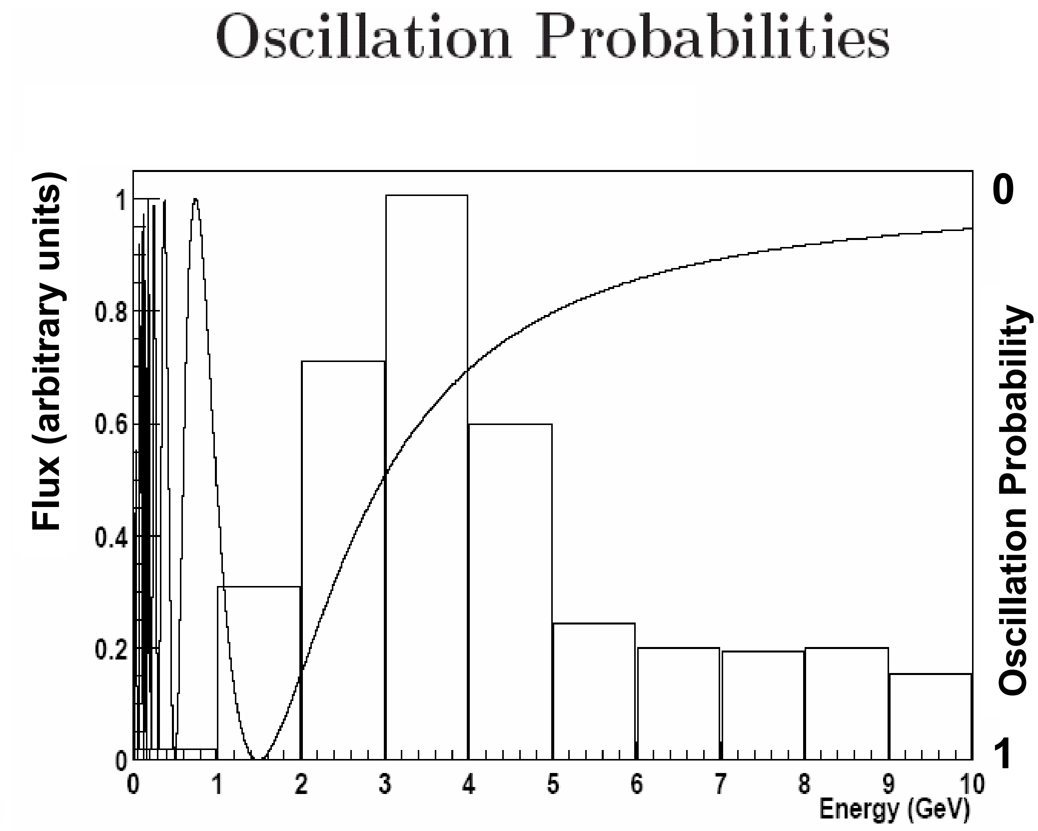
- Variation of Sensitivity with POT for different Δm^2
- The errors shown for MINOS are 1σ.
- Dashed horizontal line indicates total systematic error
- Horizontal red line is what is the currently allowed 90% limit by Super-K data. Blue line is SuperK 1σ constraint.
- Need both protons and Δm^2 on the high side to make improvements.
- The MINOS measurement will have very different systematics than SuperK in any case.



Appearance of Electrons



For $\Delta m^2 = 0.0025\ eV^2$, $\sin^2 2\theta_{13} = 0.067$

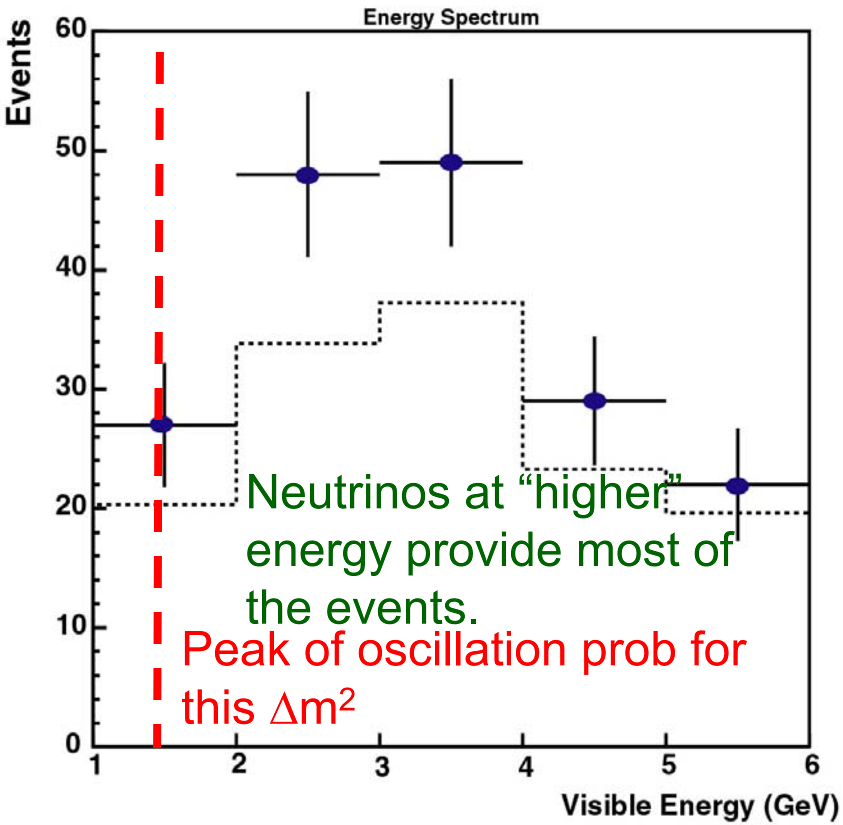


For $\Delta m^2 = 0.0025\ eV^2$

Observed number of events identified as coming from ν_e CC interactions with and without oscillations. 25×10^{20} protons on target.

Neutrinos at "higher" energy provide most of the events. Lower energy beams will likely not improve this measurement much.

Appearance of Electrons



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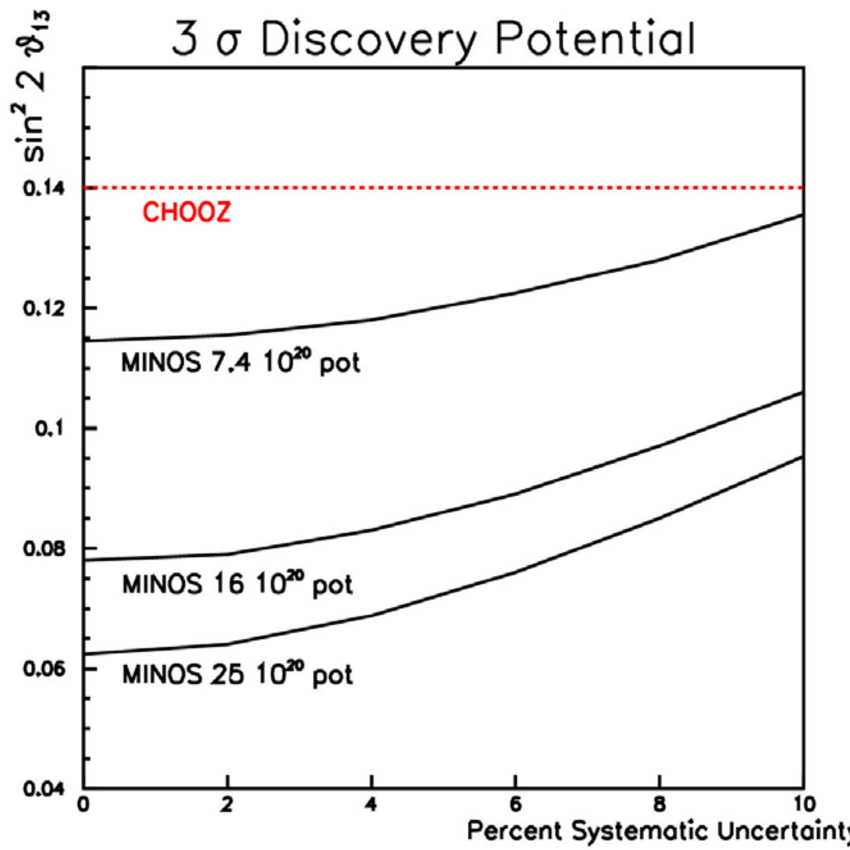
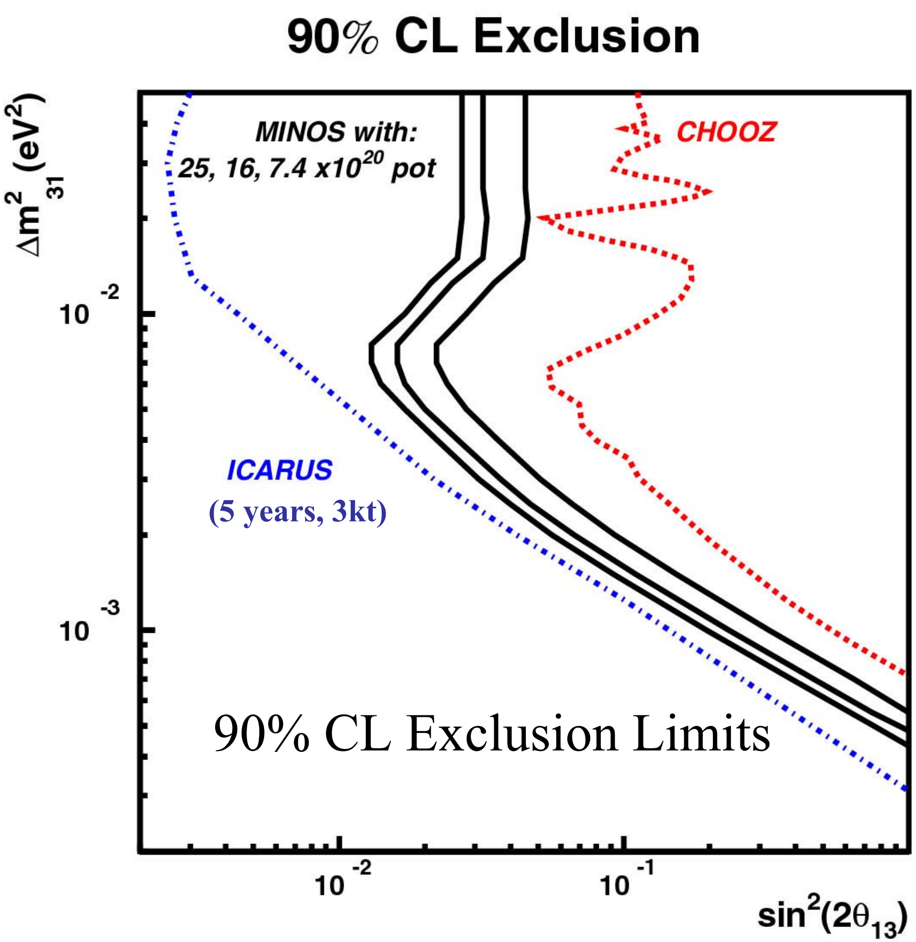
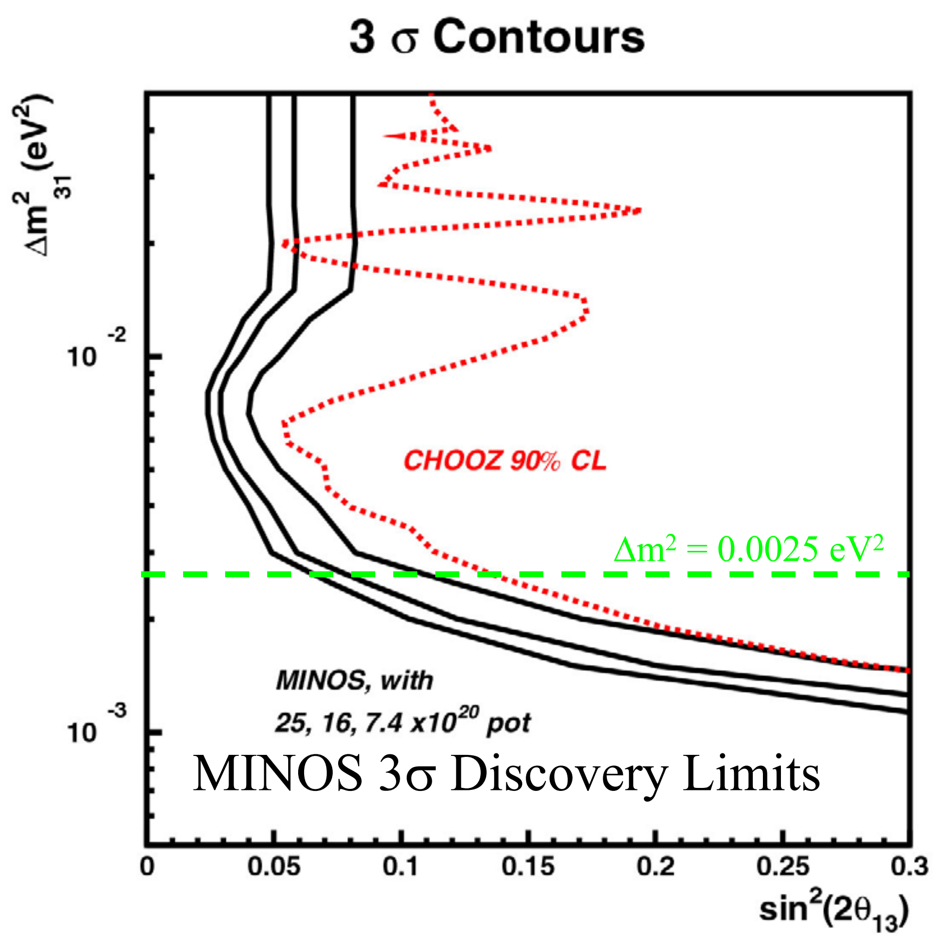


For $\Delta m^2 = 0.0025\ eV^2$

3 σ discovery potential for three different levels of protons on target and versus systematic uncertainty on the background.

Appearance of Electrons

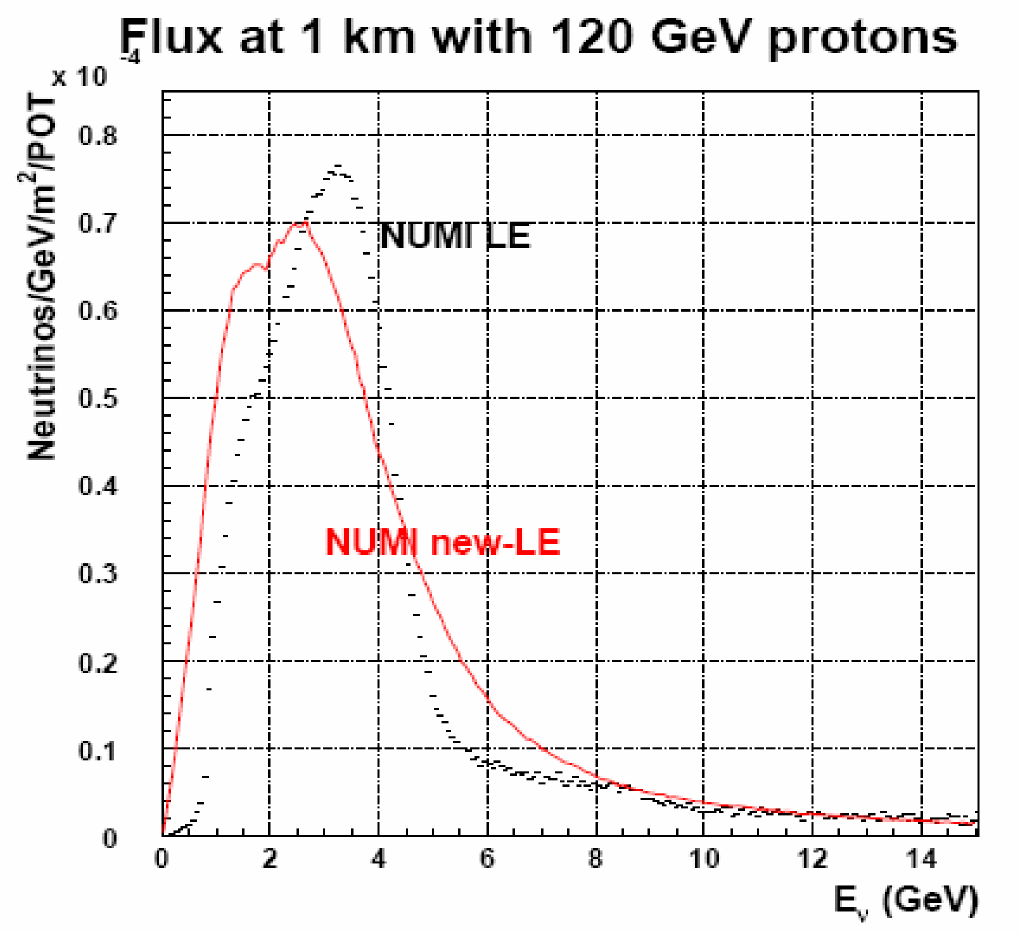




- MINOS sensitivities based on varying numbers of protons on target

A Very Low Energy Beam?

- Some work has been done on this at Brookhaven and Protvino.
- Use target completely imbedded in horn. Perhaps of higher density.
- There are several practical issues with design and construction.
- It does appear possible to boost the number of events around 1 GeV.
- May offer improved measurement of $\sin^2 2\theta_{23}$ and dip in spectrum.
- Probably does not offer improvement for $\sin^2 2\theta_{13}$



Caution: These are fluxes, not events.

What does it take to get 25e20 protons?

- 10 years at the nominal first year plan
- 5 years if all that is done is just a factor of 2 in the proton intensity… Possible by reducing the MI cycle time.
  - This requires doubling magnet and RF power at cost ~$40M.
  - Note that all of this investment will remain completely useful for future experiments and with the new proton driver.
  - Also note that smaller improvements can be proportionally useful.
- Stacking of Booster batches into the MI could add an additional 30-50% depending on other operating conditions of the complex. This is something to start testing now (a new barrier RF cavity has just been installed!).
- Improvements in the Booster proton intensity could add up to 30%. It is important to be pushing the performance of this machine now, both in the cycle rate and protons per cycle.
- A combination of the above techniques should make it possible to meet the MINOS request if pursued rapidly and aggressively.
- The Booster cycle time presents an important limitation on the number of protons for NuMI. The preferred long-term solution is a new proton driver. If necessary, an alternative using the Recycler to hide the cycle time of the Booster could be a cost effective means of another 30-50% increase in intensity. This would require moving secondary pbar stacking to another location. The combination of this with barrier stacking and reduced MI cycle time would produce a 1 MW 120 GeV source.
- The hitch. Can the current Booster survive this?

PAC Questions from June

- In the recent run plan submitted to the Committee, the errors on Δm^2_{23}, $\sin^2 2\theta_{23}$ and the upper limit on $\sin^2 2\theta_{13}$ decrease only slowly beyond the level of 10×10^{20} pot. What physics justifies additional running, up to the level of 25×10^{20} pot?
  - There is no magic goal. We are still exploring and trying to push as far as practical.
  - Precision of measurements of Δm^2
  - Δm^2 measurement with quasi-elastic events with significant precision.
  - All sensitivity to improved measurements in $\sin^2 2\theta_{23}$ depends on a higher level of protons. Showing this to be non-maximal would be very important! It is probably beyond MINOS capabilities to constrain this angle to require a new fundamental symmetry.
  - Discovery potential for ν_μ to ν_e beyond the current constraints depends on higher level of protons. 3σ discovery at ~1/3 the Chooz 90% bound is possible with the higher level of protons.
  - Investment in protons will be useful for all future experiments, including Off Axis… Why not do the things first that will establish Fermilab as the leader now and later?
- In the scenarios considered in the run plan, the error on Δm^2_{23} comes close to the asymptotic value with a relatively small number of protons. What, then, is the optimal run plan, including the possibility of using NuMI beams at different energies, to minimize the error on $\sin^2 2\theta_{23}$?
  - The errors continue to scale with sqrt(N) at all proton intensity levels envisaged.
  - Switching to a lower energy beam could help boost statistics if Δm^2_{23} is on the low side of the allowed region. Depending on the specific new beam design, this may reduce sensitivity to $\sin^2 2\theta_{13}$. We need to begin an effort to find an optimized design for both.
  - Some very limited running with medium and high energy beams to shore-up our full understanding of the energy region may be useful. Possible surprises? Given the expected range of Δm^2 we expect the best precision on measurement of $\sin^2 2\theta_{23}$ with the LE beam only.
  - Anti-neutrino running? Seems interesting, but difficult. Could change depending on our data!
- Similarly, what is the optimal run plan to minimize the upper limit on $\sin^2 2\theta_{13}$?
  - Probably it will be hard to beat just running with the current low energy beam.

Summary

- Much has happened in the measurement and understanding of neutrino oscillation effects since the MINOS proposal in 1995 (the last time the PAC considered the issue of a MINOS running plan!?).
- The measurements of interest have evolved in that time. More precision in measurement of all parameters is of interest, including sub-dominant modes.
- At the same time, the expected value of Δm^2 has dropped by more than a factor of 10. This pushes the limits of flexibility in the NuMI beam to deliver adequate numbers of neutrinos. Delivering significantly more protons than ever anticipated is the only real solution for MINOS.
- MINOS will clearly offer high quality measurements of the energy dependence of ν_μ disappearance and good precision (eventually) on measurement of Δm^2 even with the nominal protons on target in the current Fermilab plan. The ability to "see the low energy rise" will depend both on protons and a bit of luck. A lower energy beam may help somewhat, depending on the actual value of Δm^2.
- The ability of MINOS to offer significant new discovery potential in precision measurement of dominant and sub-dominant mixing angles depends critically on increasing the total protons on target.
- An aggressive program of investment in proton intensity could keep MINOS in the lead of such measurements until at least 2009. Such an investment will be of great importance for an Off Axis experiment as well, but offer relatively early payoff through MINOS.