Neutrino Oscillations at the Atmospheric Scale

Jeff Hartnell

Rutherford Appleton Laboratory

One-day IoP/CfFP Meeting on Neutrinos

29th June 2005

Talk Outline

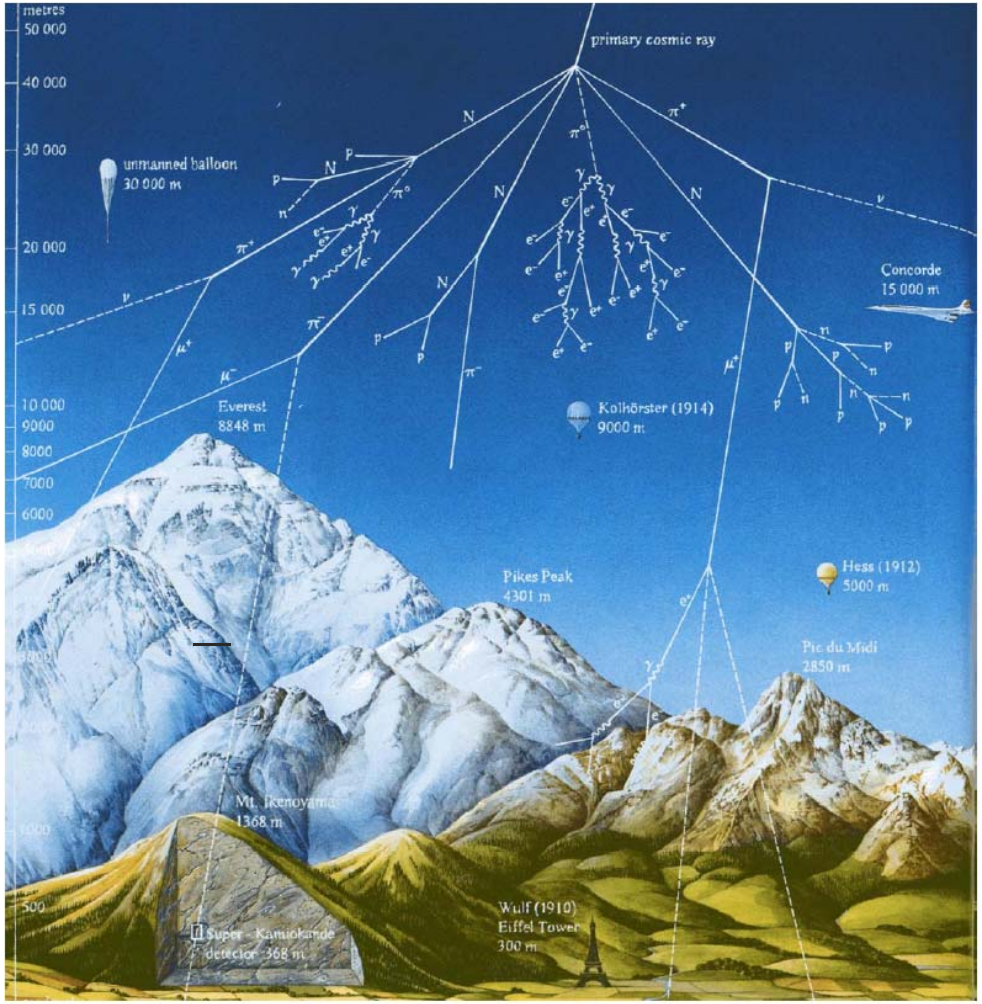
- Neutrino oscillation formulism
- Production of Atmospheric Neutrinos
- State-of-the-art:
  - Super-Kamiokande
  - K2K
- New Experiments:
  - MINOS
    - Beam Neutrinos
    - Atmospheric Neutrinos
  - Opera/Icarus

Neutrino Oscillation Formulism

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\vartheta \sin^2\left(\frac{1.27\Delta m^2(eV^2)L(km)}{E(GeV)}\right)$$

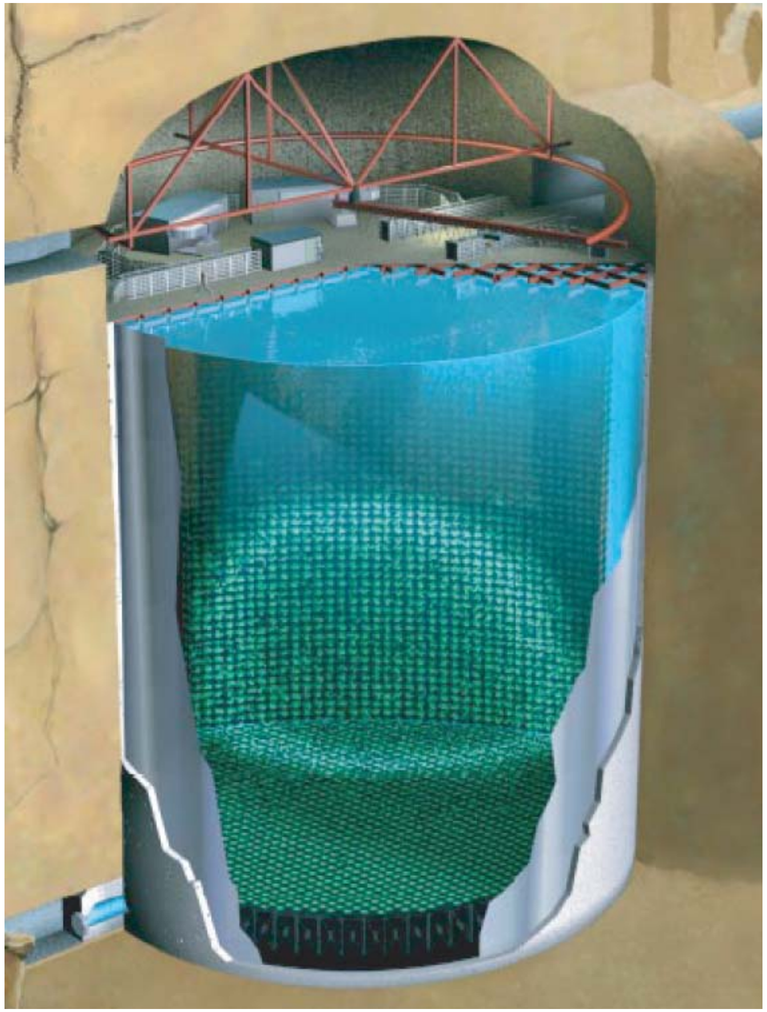
- Disappearance experiments
  - Look for neutrinos missing at particular energies (E) and distances (L)
- Appearance experiments
  - Look for neutrinos of a particular flavour not present at the source possibly as L/E

Production of Atmospheric Neutrinos

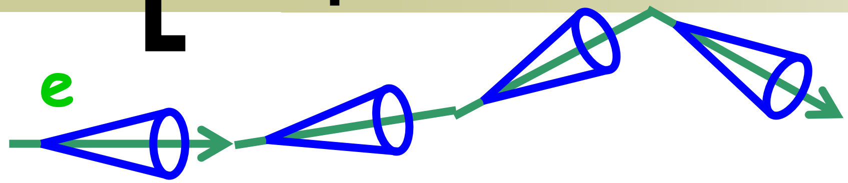


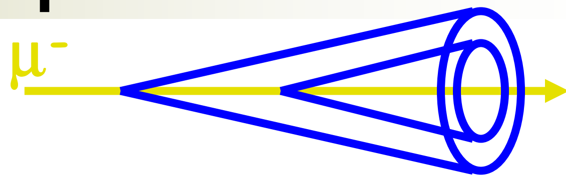
Super-Kamiokande

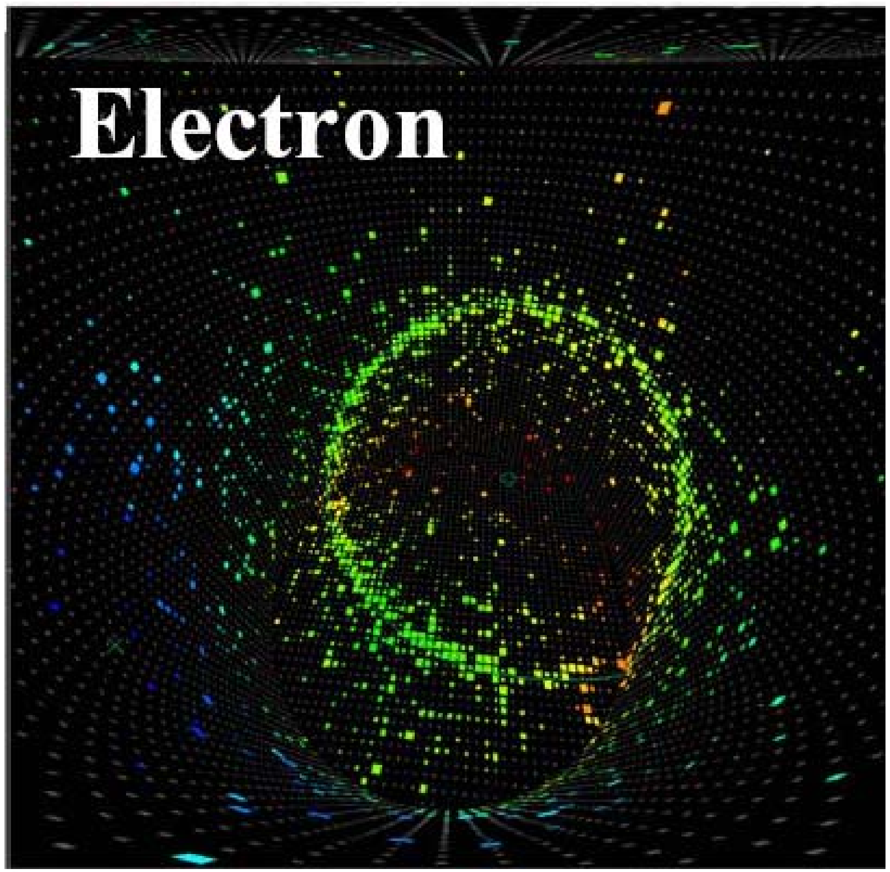
- Located in Kamioka, Japan
- 50 kT water Cerenkov detector (22.5 kT fiducial)
- ~12000 PMTs
- Overburden of 2700 mwe
- Separate muons and electrons by Cerenkov ring structure



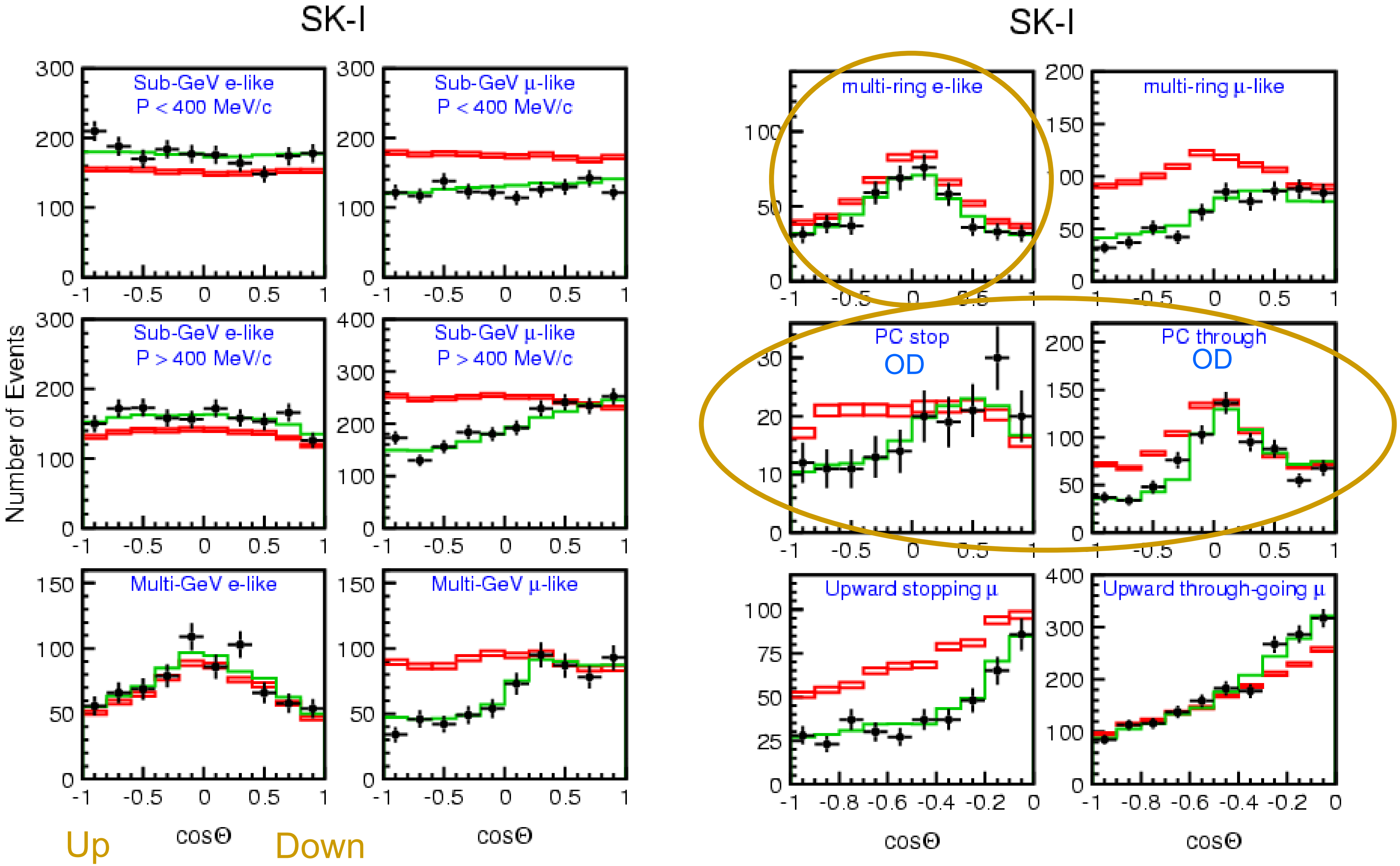
Super-K Flavour Separation







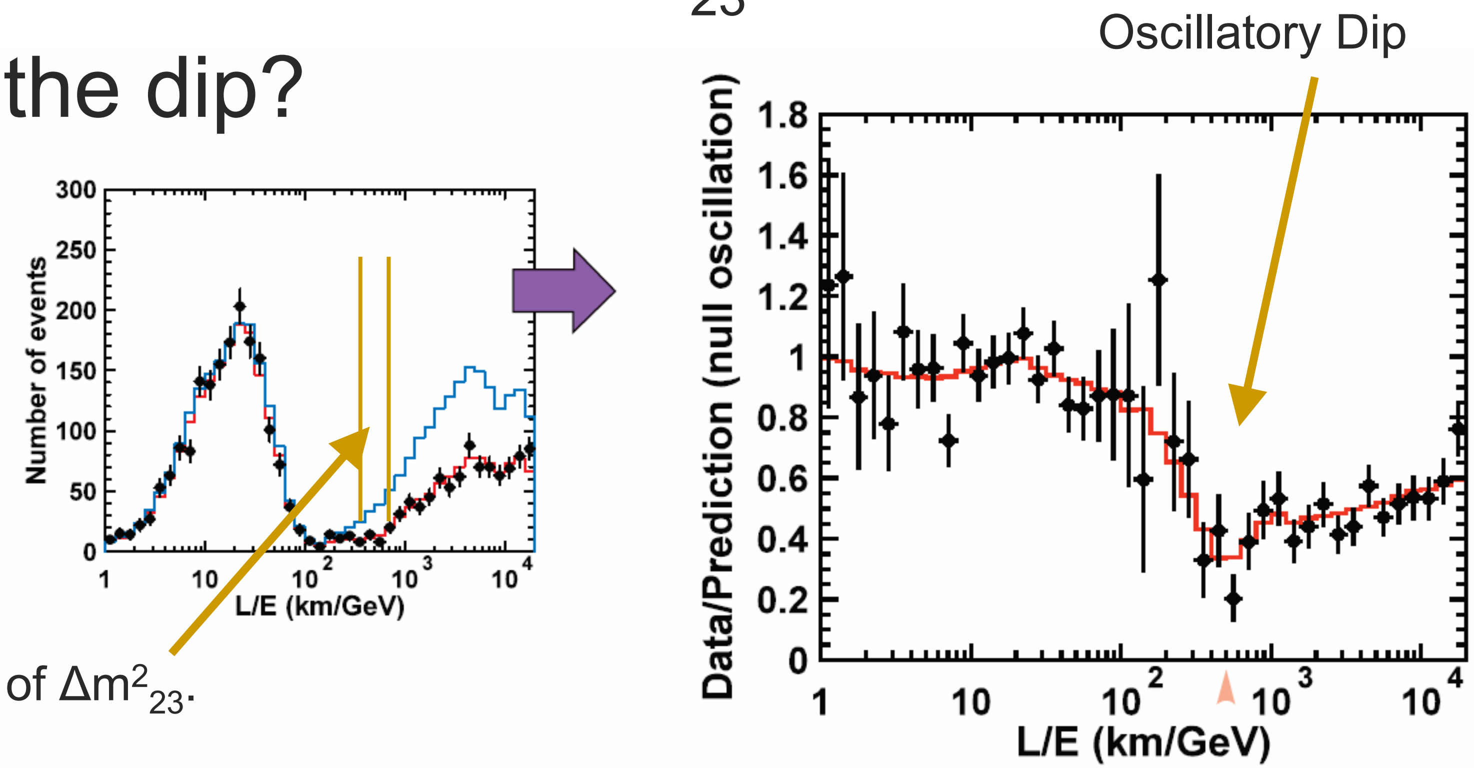
Latest Super-K Zenith Angle Results



New finer binned analysis and new distributions

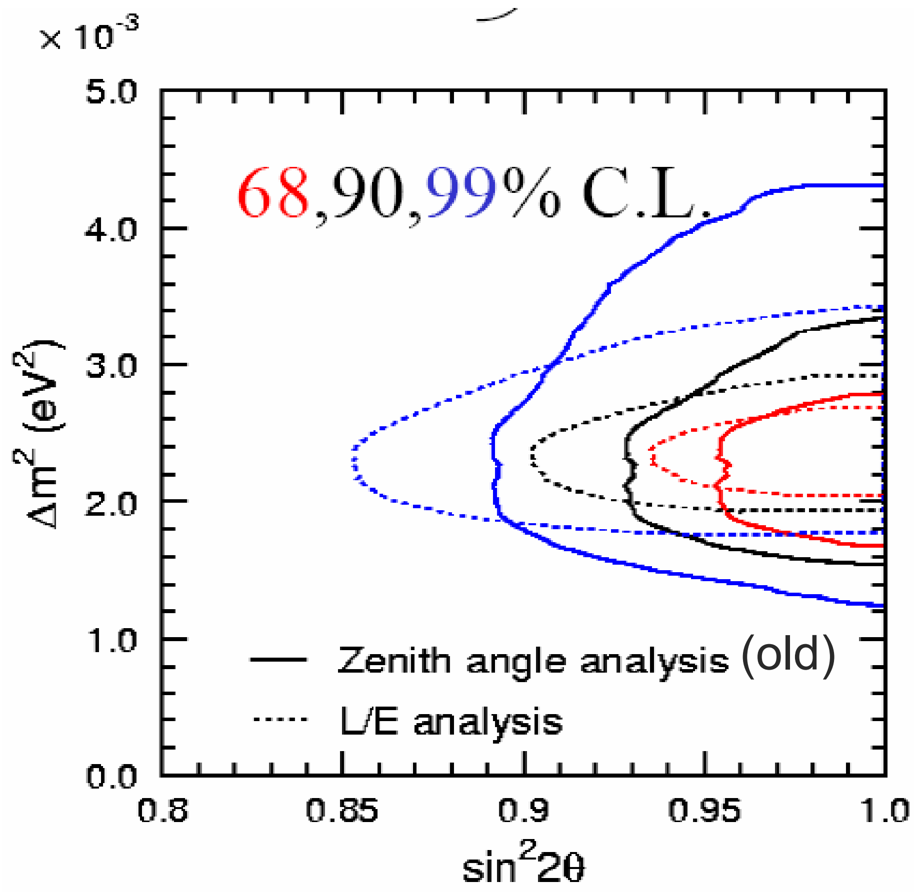
L/E Analysis (2004)

- Select high L/E resolution events
  - Can better constrain Δm^2_{23}
- "See" the dip?

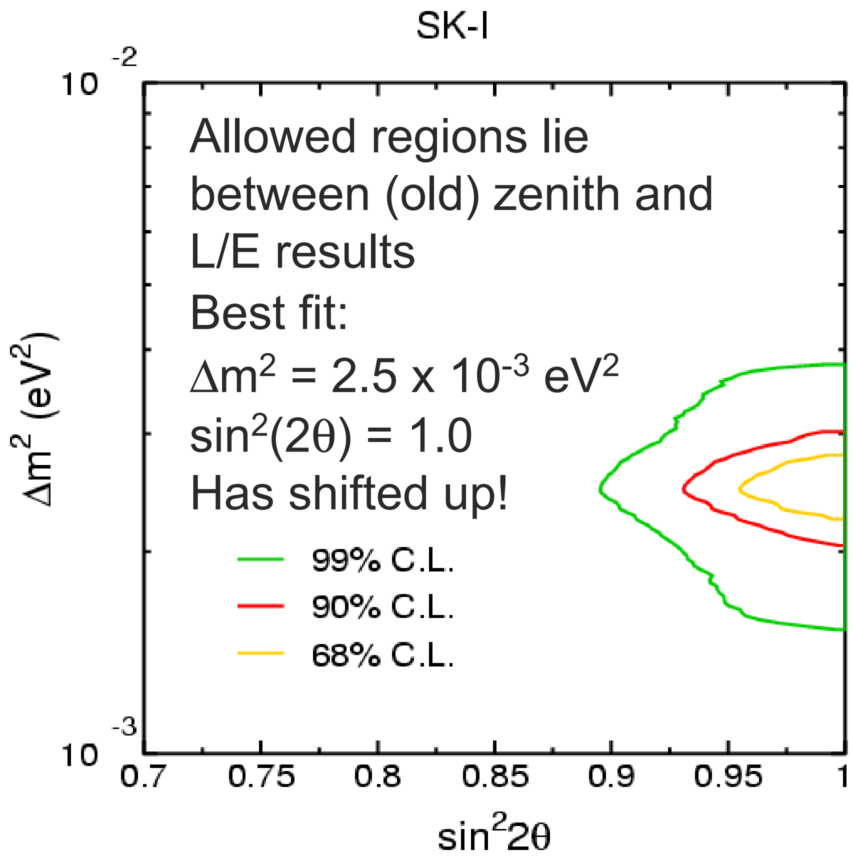


Best fit region of Δm^2_{23}.

Super-K Parameter Space

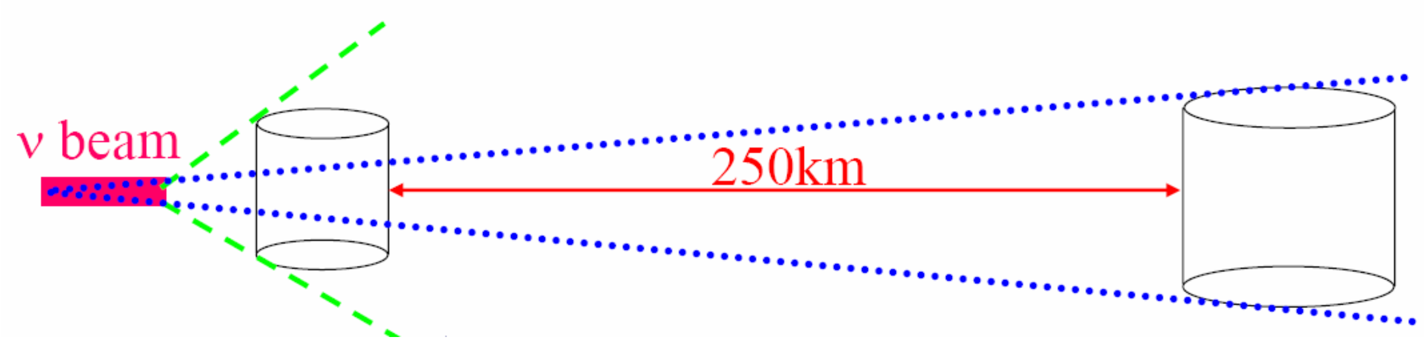


Latest zenith angle results



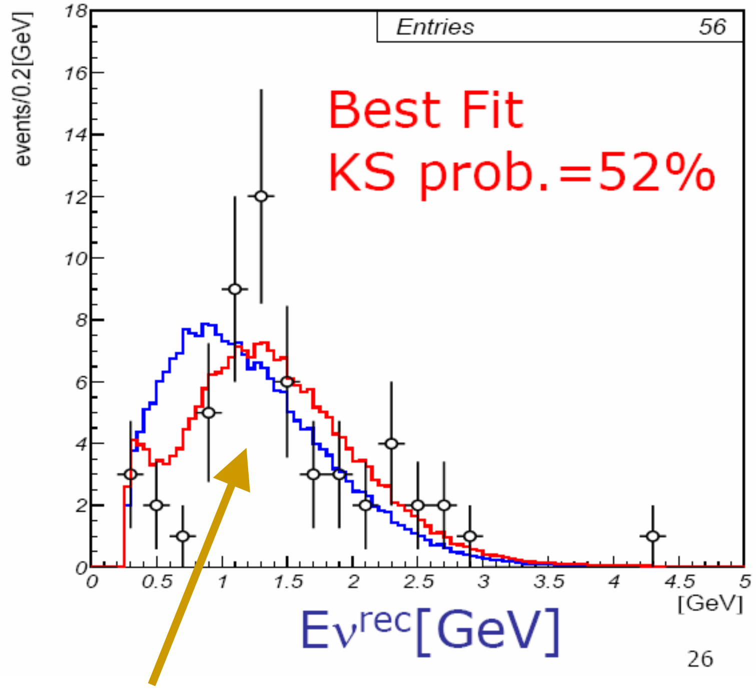
K2K (KEK to Kamioka)

- Neutrinos from KEK accelerator
- Uses Super-K as Far detector, 250 km baseline
- 2 Near detectors:
  - Water Cerenkov
  - “SciBar” scintillator detector

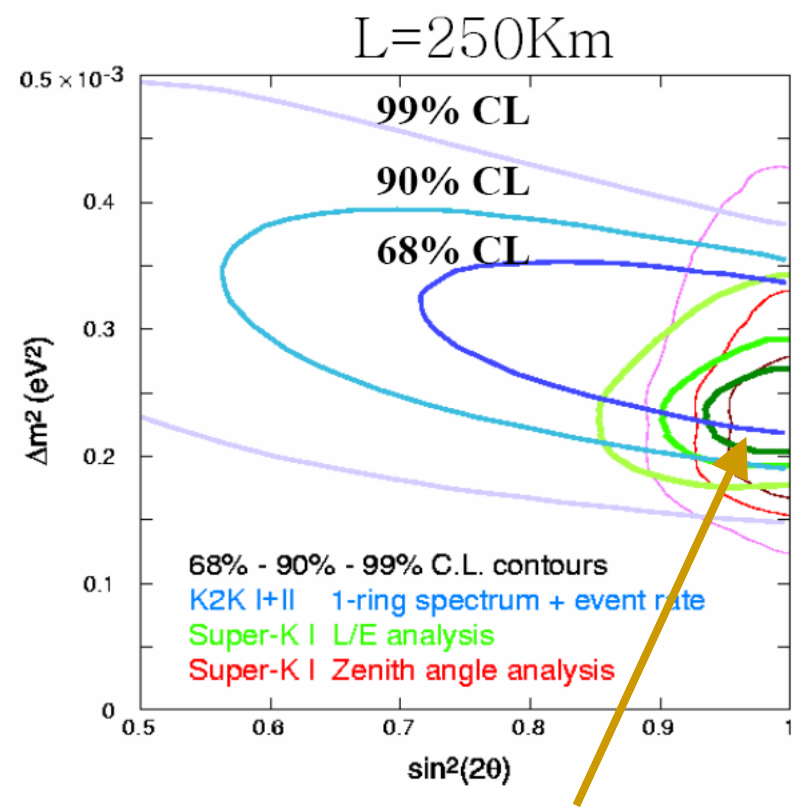


K2K Results

- $N_{SK}^{obs}=108$ (149.7 expected)
- N_{SK}^{exp} (best fit)=104.8



Shape comparison



Confirmation of Super-K Δm^2_{23} results

CCLRC Rutherford Appleton Laboratory

Challenges ahead

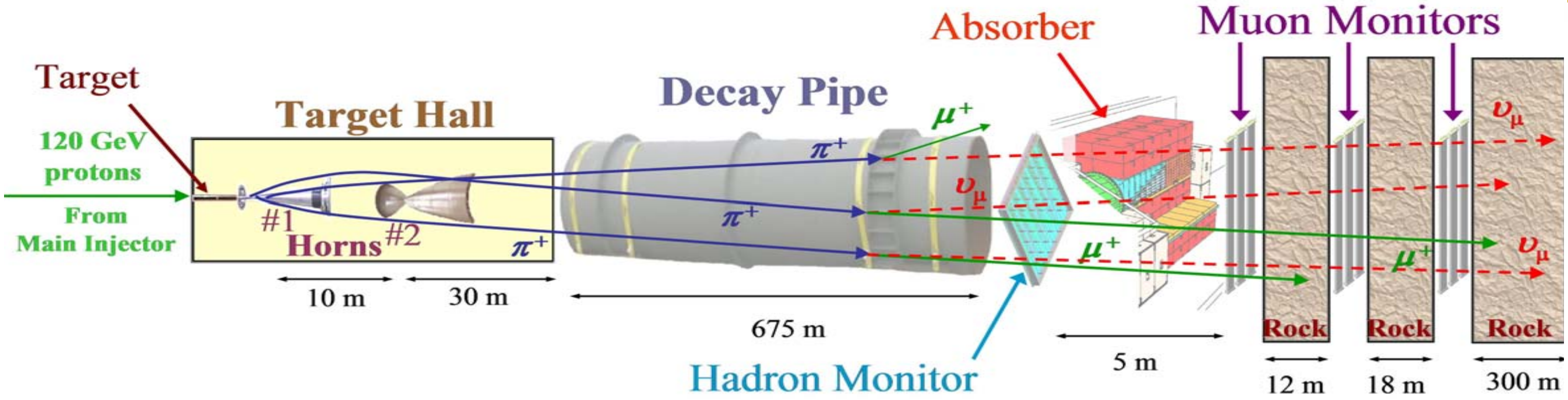
- Clearly "see" the oscillatory signature
- Show $\nu_\mu \rightarrow \nu_\tau$ rather than $\nu_\mu \rightarrow \nu_x$
- Precisely measure Δm^2_{23}
- Determine if $\sin^2(2\theta_{23})$ is maximal
- Measure sub-dominant oscillation mode: $\nu_\mu \rightarrow \nu_e$ (determine θ_{13})
- CP Violation… see later talks

New/Current Accelerator Experiments

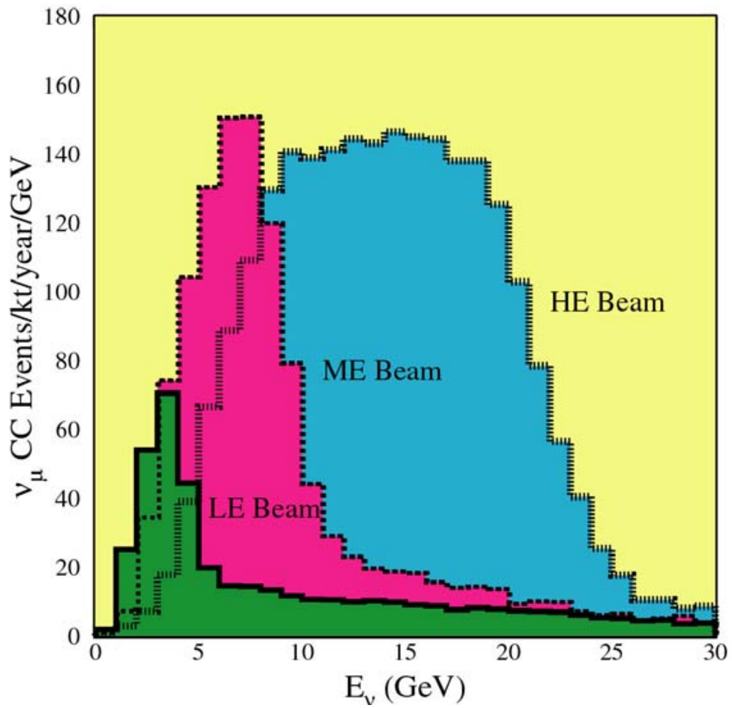
- NuMI (Neutrinos at the Main Injector)
  - Currently operating
    - First neutrinos seen in January
    - Operations started in March
    - Currently delivered ~1.2×10^{19} pot total
  - Experiment: MINOS
  - Future Experiments: Minerva, NOvA
  - Neutrino test-beam (!) for Opera

- CNGS (CERN Neutrinos to Gran Sasso)
  - Due to switch on in Summer 2006
  - Experiments: Opera and Icarus

The NuMI Beam

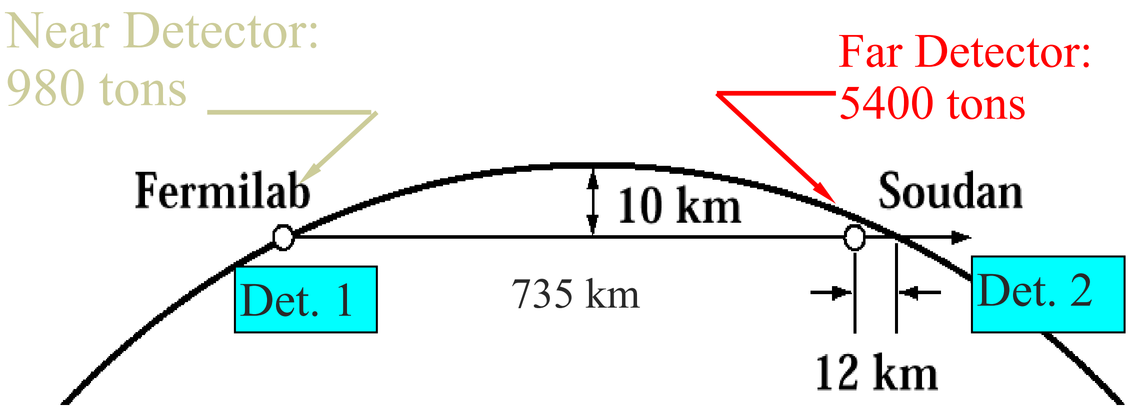


- Currently:
  - Running in the low-energy configuration
  - Delivering ~1.9×10^{13} protons per 10 usec pulse
  - Cycle time of 2-4 secs
- Goal:
  - 3.7×10^{13} ppp every 1.9 secs



MINOS

- 735 km baseline
- Two magnetised iron-scintillator tracking calorimeters
  - Near detector at Fermilab
  - Far detector at Soudan Underground Lab.

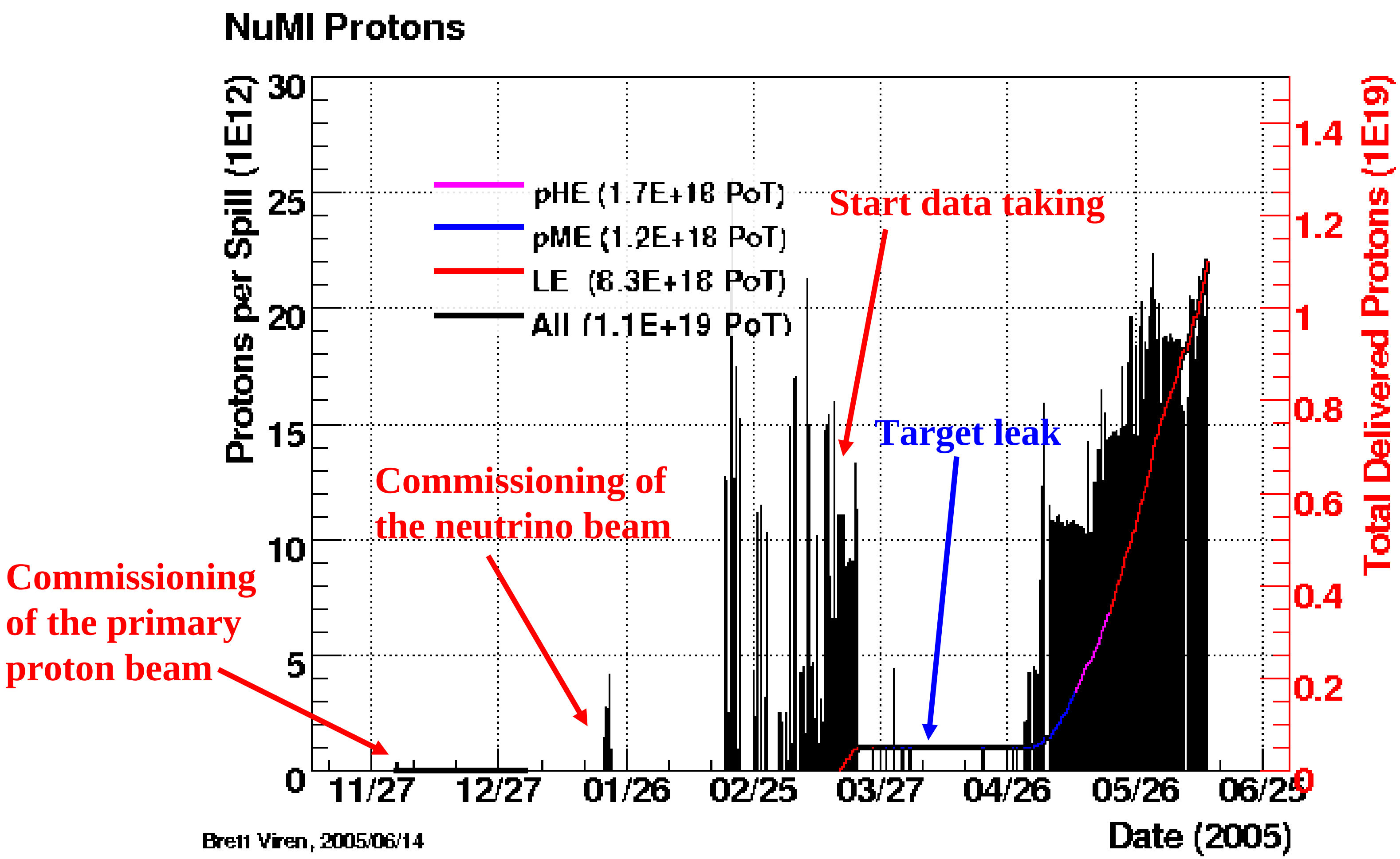


The MINOS Detectors

Near Detector, 980 tons

Far Detector, 5400 tons

- Identical in important features:
  - 2.54 cm thick steel planes
  - 1 cm thick scintillator planes
  - 1.5 T magnetic field



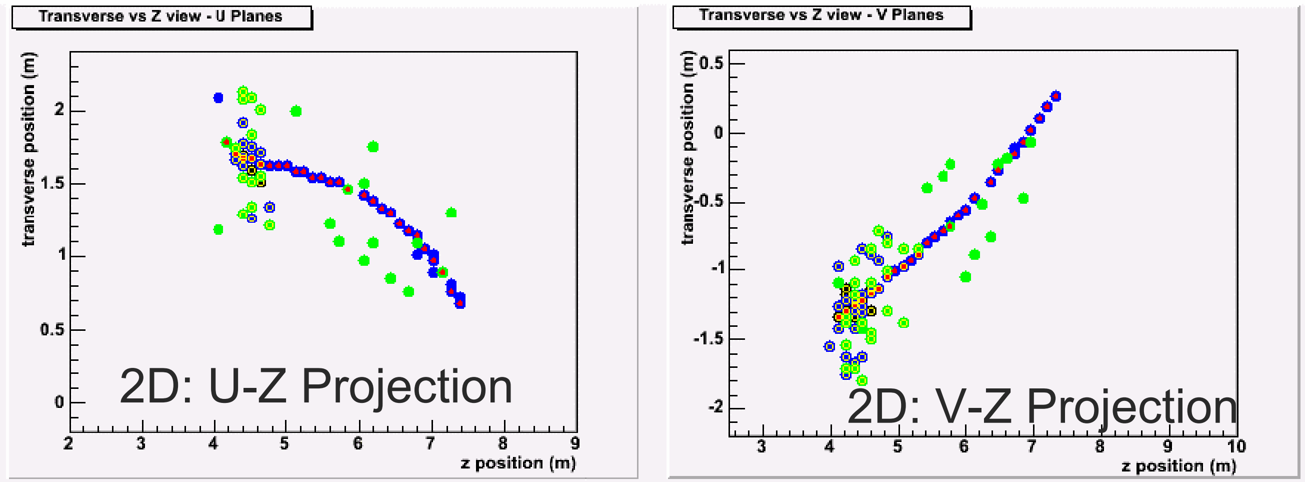
- In order to understand the systematic of neutrino production and detector response have run with different beam energies (LE, pME, pHE)

Consider High-energy Data Set

- 1.7×10^{18} pot
- ~150000 spills
- In the Far detector:
    - 21 charged-current-like events (contain a track)
    - 9 neutrino-induced rock muons
    - 6 cosmic muons (expected 7)

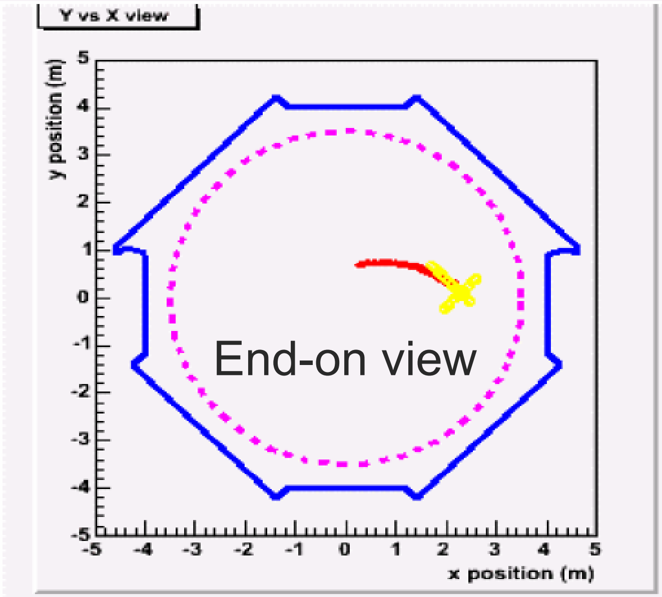
CCLRC Rutherford Appleton Laboratory

Far det. High-energy Event



~2.5 GeV muon

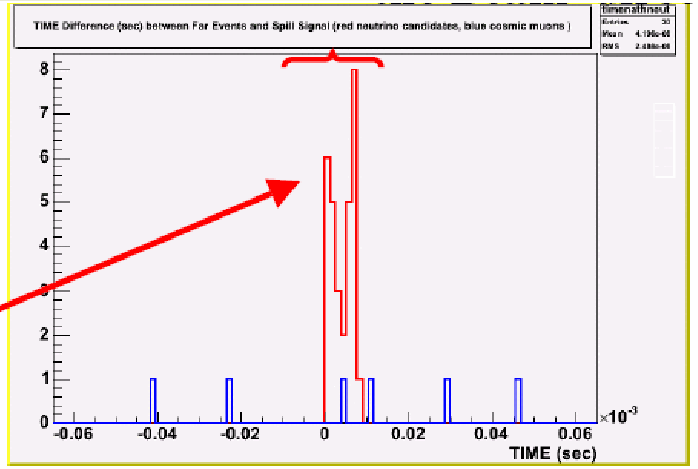
~5 GeV shower



U and V axes tilted at 45 deg to X and Y

Preliminary

Beam event separation (Far)

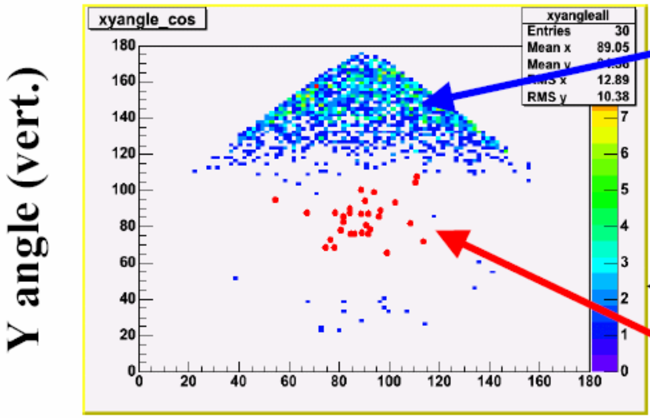


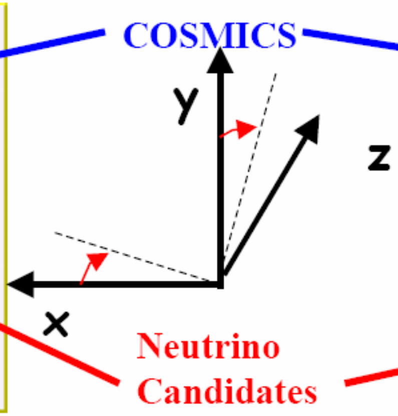
Time difference (in sec) between neutrino candidates and far spill signal in the +/-50 usec window.

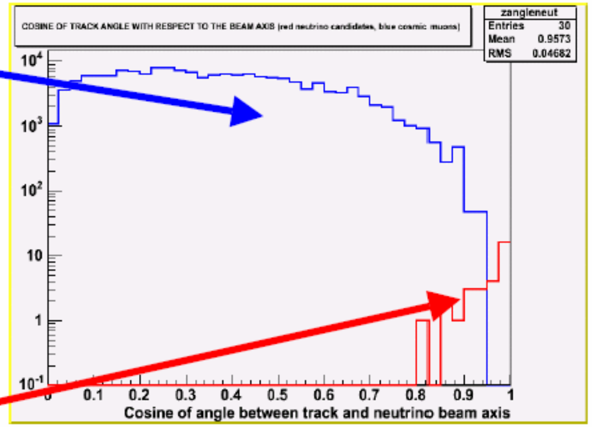
Beam neutrino candidates are within a 10 usec time interval, as expected for the 10usec width of NuMI beam.

(N. Saoulidou)

Beam neutrino candidates have quite a distinct topology





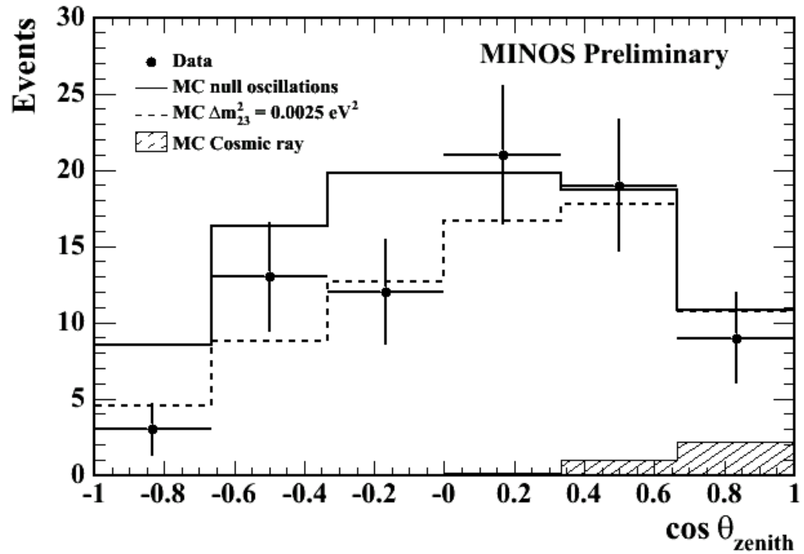


Track angle with respect to the Beam direction

Preliminary

MINOS Atmospheric Neutrinos (Preliminary results)

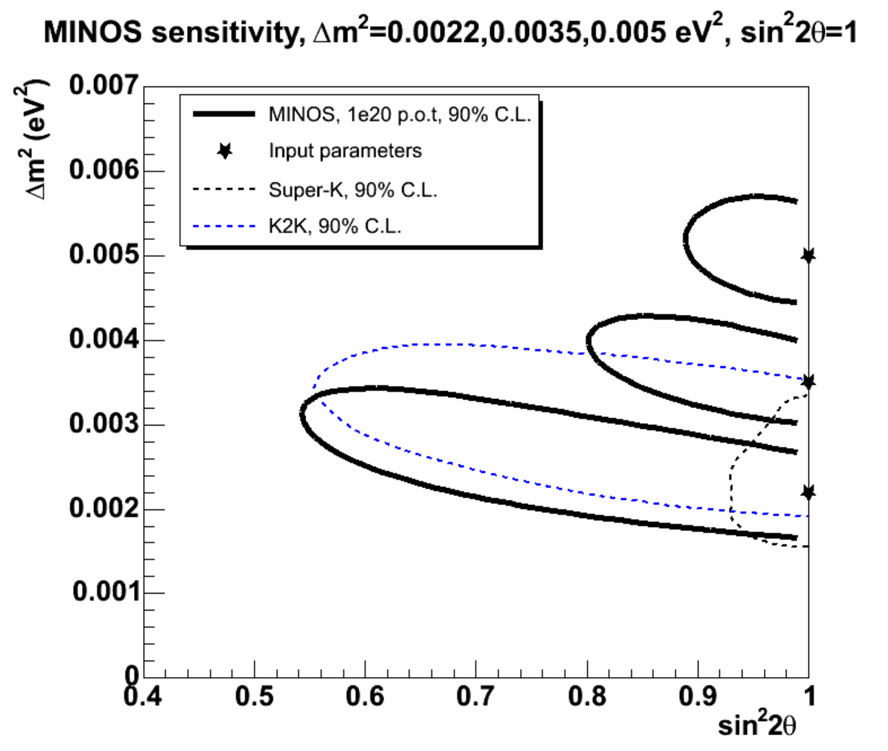
- ~7 kT-years of data
- Recorded 107 events
- See hints of zenith angle dependence



- Also: first deep underground detector that can resolve muon charge:
  - $N^+ / (N^+ + N^-) = 0.35 \pm 0.06$ (stat.) ± 0.02 (syst.)
  - Expect: $N^+ / (N^+ + N^-) = 0.35$ with CPT invariance

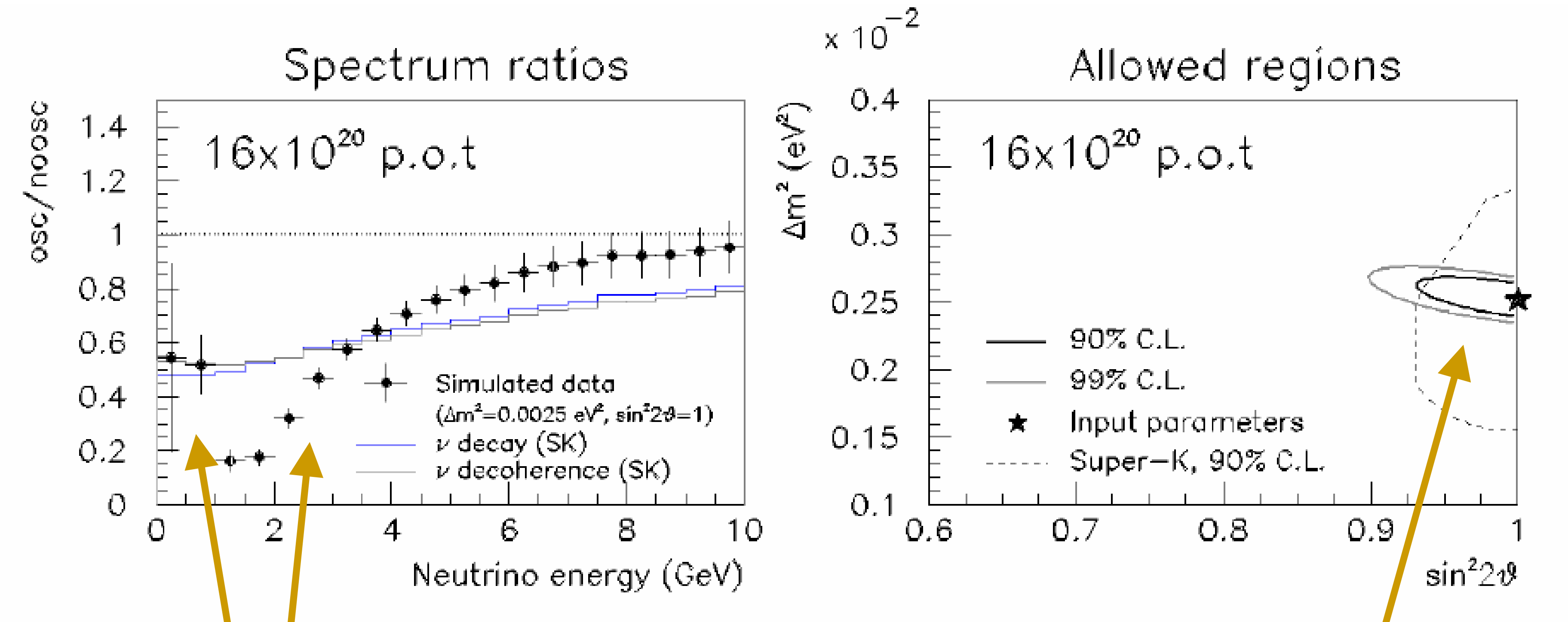
MINOS Time-line

- Collect $1x10^{20}$ protons on target (pot) by the end of the year
  - Sensitivity ~= SK / K2K results
- Ramp up beam intensity next year to $\sim 2.5x10^{20}$ pot/year
- Then up to $3.7x10^{20}$ pot/year
- Run for 5 years



MINOS sensitivity by the end of 2005 (~1e20 pot)

Sensitivity with 16e20 pot (~5 yr)

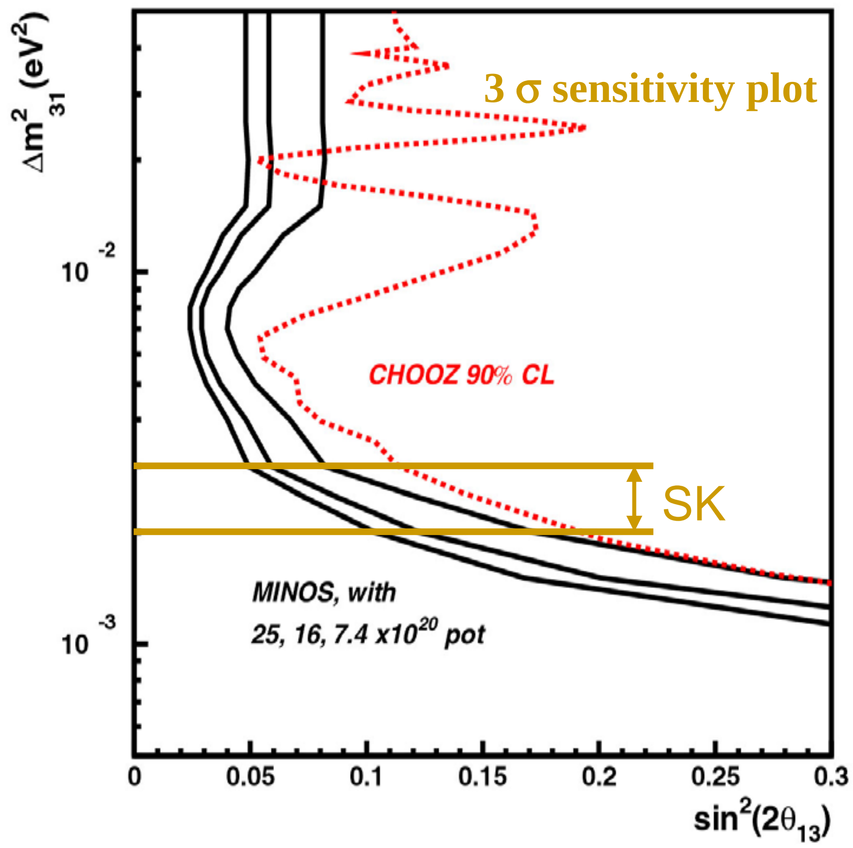


See the dip and the rise → "smoking gun" for neutrino oscillations

Significantly constrain Δm^2_{23} to 10% at 90% CL

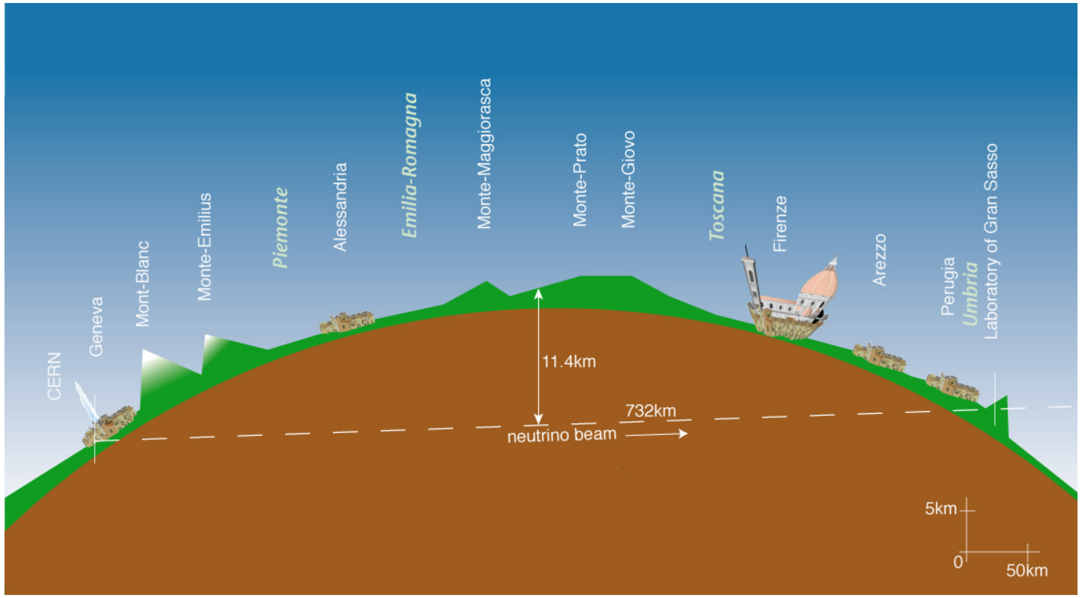
MINOS Sensitivity to ν_e Appearance

- Look for subdominant oscillation modes:
  - $\nu_\mu \rightarrow \nu_e$ (θ_{13})
- Achieve a factor of 2-3 over CHOOZ limit in 3-5 years at 3 sigma



CNGS: Opera and Icarus

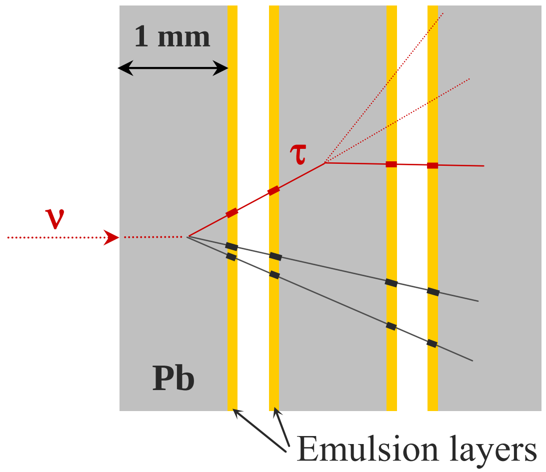
- Baseline: 730 km
- <E$_\nu$> = 17 GeV
- optimised for τ appearance

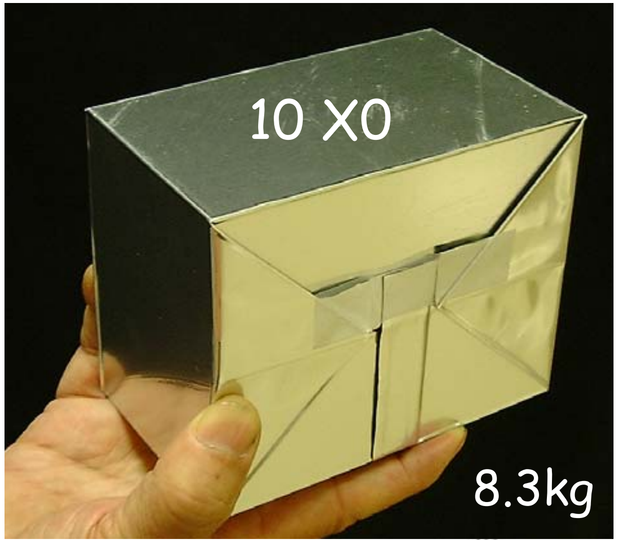


- Icarus is a liquid argon TPC with very high spatial resolution
- Can do lots of physics: beam tau appearance, electron appearance, solar & atmospheric neutrinos, supernova neutrinos, proton decay…
- Focus on Opera in this talk

Opera

- The "Brick" - Emulsion Cloud Chamber
  - Pb / emulsion layers
  - Look for kinks in tracks
- Electronic detectors (scint., RPCs, Drift tubes):
  - triggering and localisation of events
  - Muon ID and momentum



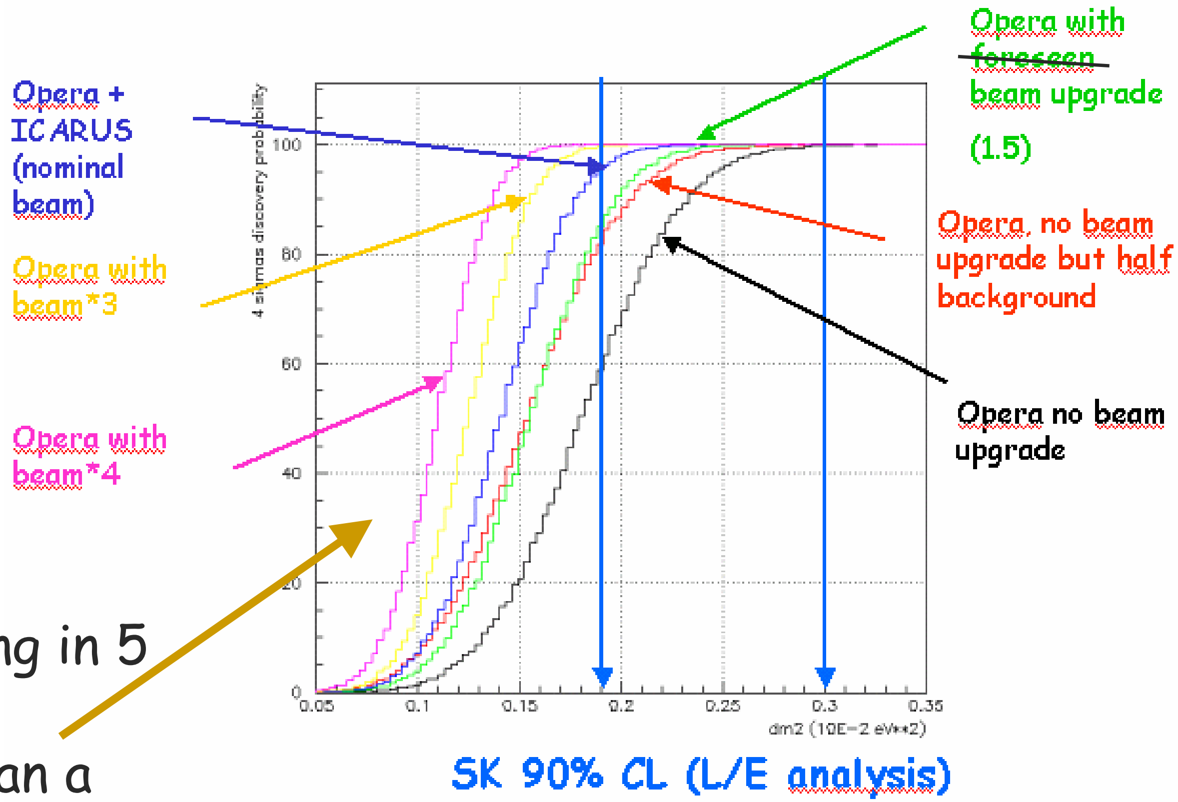


CCLRC Rutherford Appleton Laboratory

Opera Sensitivity (full mixing, 5 years run @ 4.5 x1019 pot / year)

	signal ($\Delta m^2 = 1.9 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 2.4 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 3.0 \times 10^{-3}$ eV^2)	BKGD
OPERA 1.8 kton fiducial	6.6	10.5	16.4	0.7

- Looking for a small number of events
- Very dependent on Δm^2_{23}



Probability of observing in 5 years a number of candidates greater than a **4σ** background fluctuation

D.Autiero (Neutrino '04)

Summary-to-date

- It's now 40 years since the first atmospheric neutrinos were detected and a lot has happened since:
  - Deficit of muon neutrinos discovered
  - Zenith angle dependence shown
  - SK L / E analysis shows possible oscillatory dependence
  - K2K observes ν_μ disappearance and a spectral distortion using accelerator neutrinos
- The latest (fine binned) SK analysis gives:
  - $2.0 \times 10^{-3} < \Delta m^2_{23} < 3.0 \times 10^{-3}$ eV^2 at 90% CL (~40% range)
  - $0.93 < \sin^2(2\theta_{23}) < 1.0$ at 90% CL (~7% range)

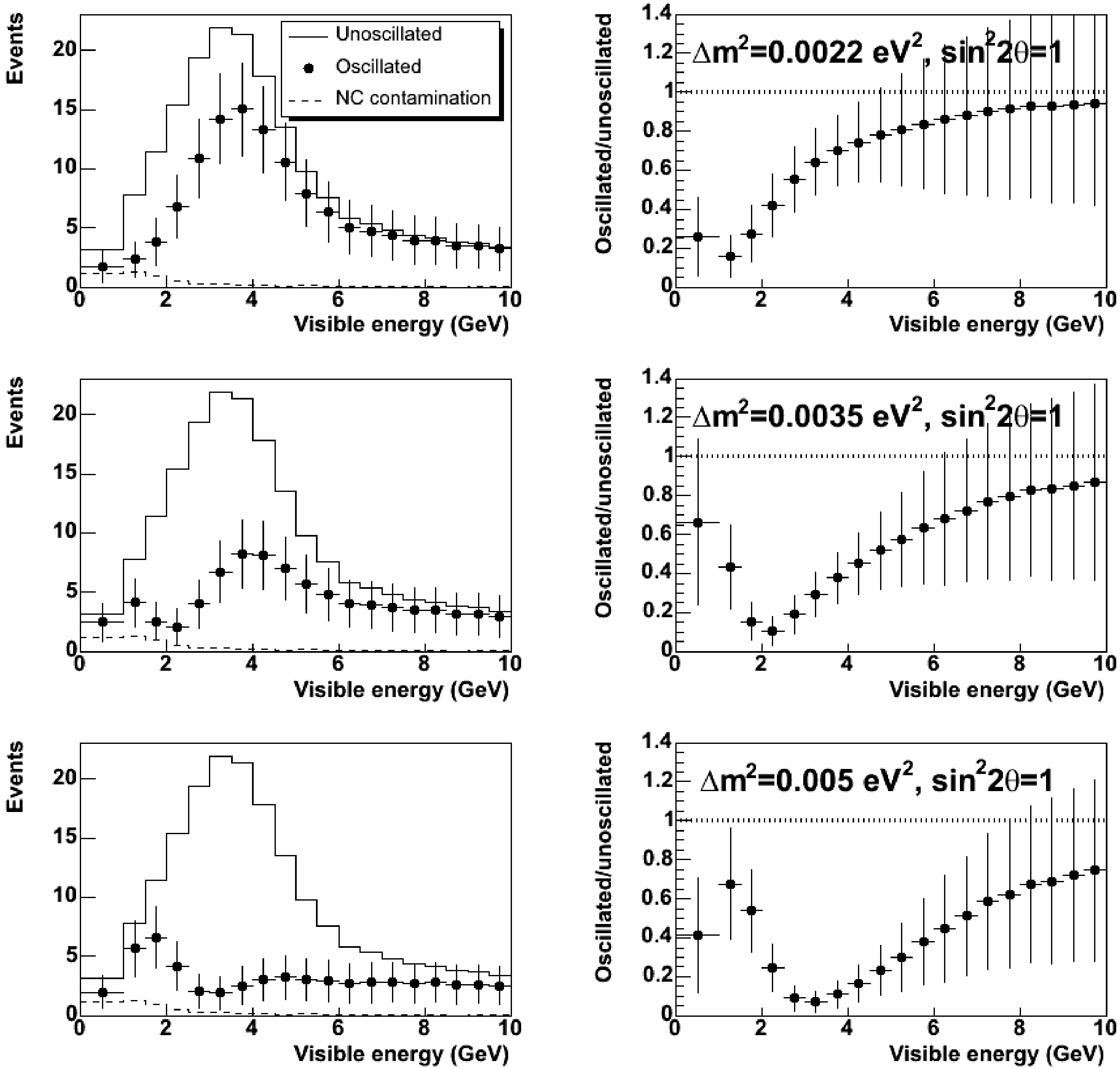
Challenges ahead (the roadmap)

- Confirm SK and K2K allowed region
  - MINOS (~2006)
- Clearly "see" the oscillatory signature
  - MINOS (~2010)
- Show $\nu_\mu \rightarrow \nu_\tau$ rather than $\nu_\mu \rightarrow \nu_x$
  - Opera/Icarus (~2011)
- Precisely measure Δm^2_{23}
  - MINOS: 10% (~2008)
  - NOvA / T2K: 3% (~2015) (see Gary Barker's talk)
- Determine if $\sin^2(2\theta_{23})$ is maximal
  - NOvA / T2K: 1% (~2015)
- Sub-dominant mode, ν_e appearance (θ_{13})
  - MINOS: Factor of 2 over CHOOZ (~2010)
  - NOvA / T2K: ~order of magnitude better (~2015)
- CP Violation… neutrino factory / super beams?

Note: all these results depend on #pot delivered and the value of Δm^2_{23} and $\sin^2(2\theta_{23})$

Backup slides

MINOS sensitivity, 1×10^{20} p.o.t.

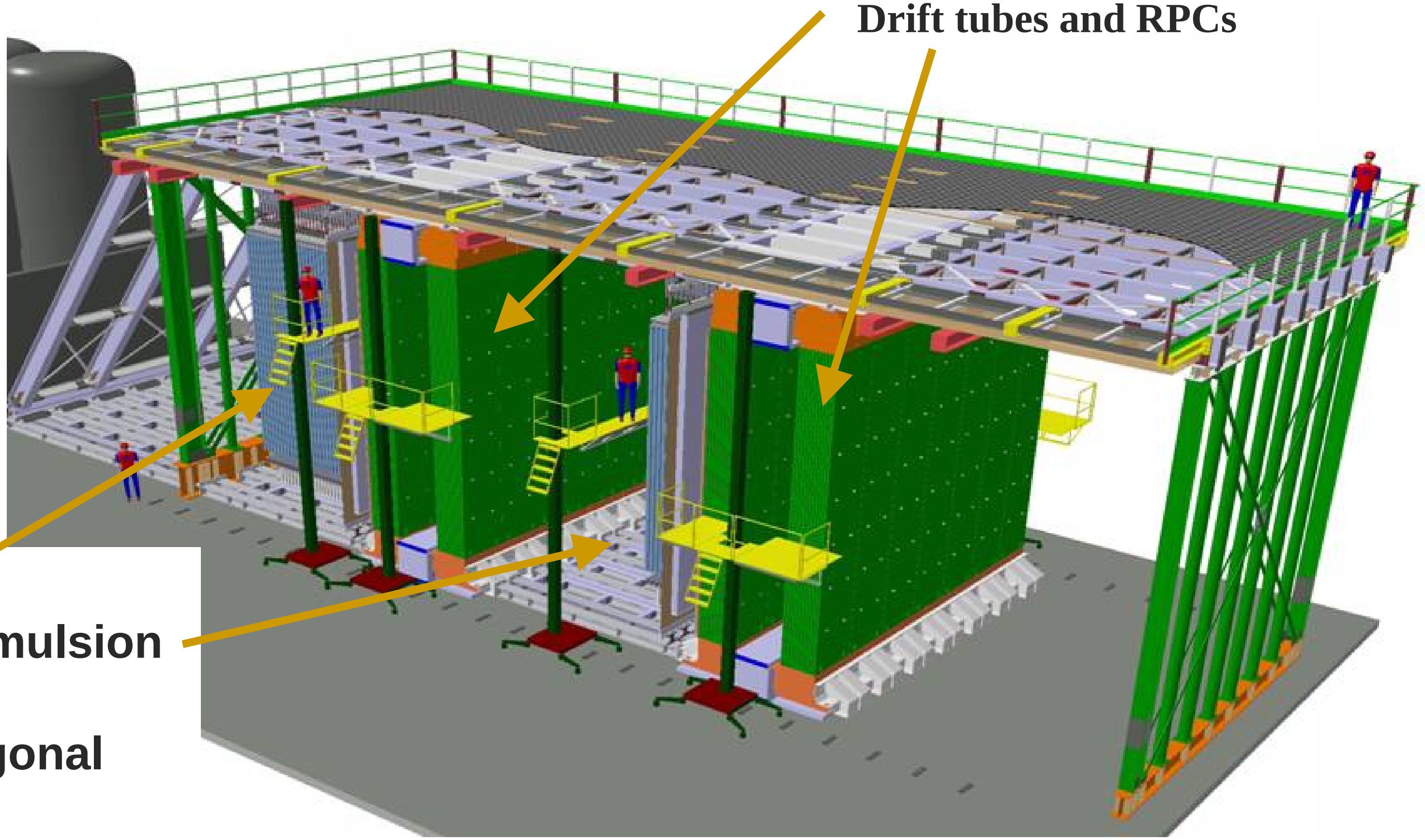


Opera

μ spectrometer

Magnetised Iron Dipoles
Drift tubes and RPCs

ν_τ

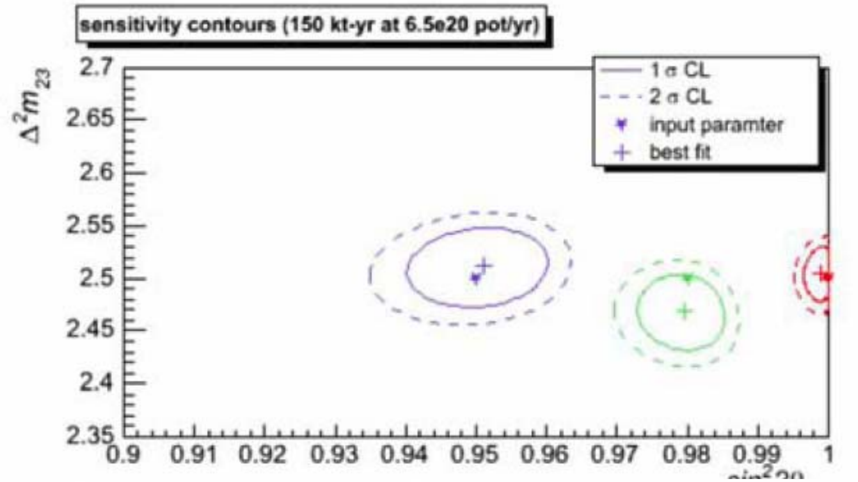


Target:
- a “wall” of Pb/emulsion “bricks”
- planes of orthogonal scintillator strips

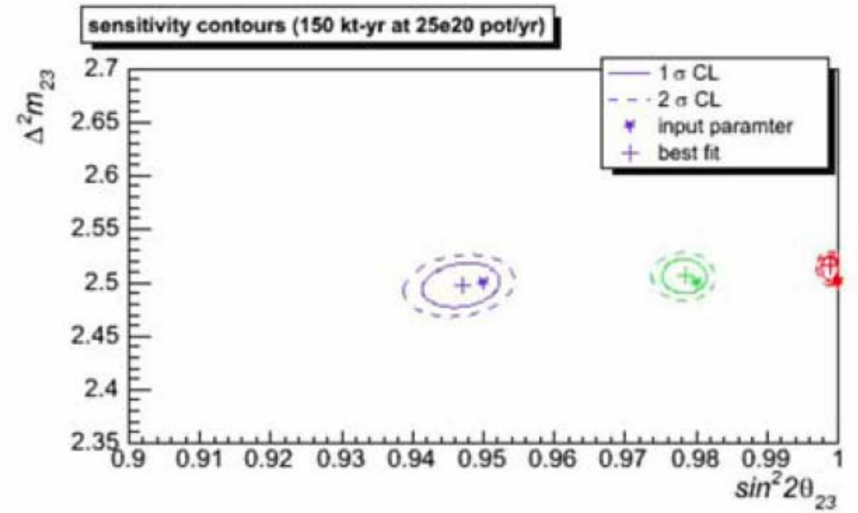
Future Experiment: NOvA

- 15 mrad off-axis in the NuMI beam
- 30 kTon Totally Active Scintillator Design
- 810 km baseline
- Stage 1 approval from Fermilab and R&D money
- Aim to have 5 kT by early 2010 and complete detector by mid-2011.
- Physics:
  - Measure Δm^2_{23} to 2-4% at 90% CL
  - Quasi-elastic events very clean:
    - Measure $\sin^2(2\theta_{23})$ to 0.5-3% at 90% CL
- For details on sensitivity to θ_{13}, CPV and mass hierarchy see Gary Barker's talk

NOvA Sensitivities



5-year ν run



5-year ν run
with Proton Driver

Future Exp.: T2K (Tokai to Kamioka)

- J-PARC accelerator facility in Tokai
- Use SK detector as with K2K
- ~45 mrad off-axis (2.5 deg)
- 295 km baseline
- Start physics running in 2009
- Similar sensitivity to NOvA on atmospheric scale parameters:
  - Measure $\sin^2(2\theta_{23})$ to 1-2%
  - Measure Δm^2_{23} to 2-4% at 90% CL
- As with NOvA, for details on θ_{13}, CPV and mass hierarchy see Gary Barker's talk

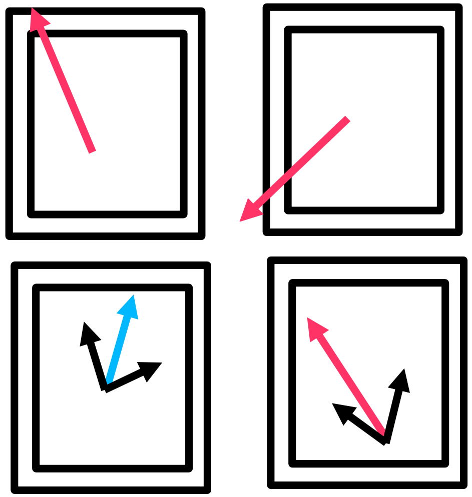
Brief History of Atmospheric Neutrino Measurements

- First detected, via neutrino-induced muons, in 1965 (very deep: ~3 km, ~8000 mwe)
  - Kolar gold fields in S. India
  - East Rand Proprietry mine in S. Africa
- First fully contained events in early 1980s
  - Proton decay experiments (a background!)
- First hint of atmospheric anomaly in 1986
  - IMB proton decay experiment noticed a deficit in events with an identifiable muon decay:
    - Measured $N(\nu_\mu) / N_{Total}$ = 26% ± 3%
    - Expected 34% ± 1%
- In 1988 the Kamiokande experiment went further and suggested that neutrino oscillations could be the cause of the deficit
  - Determined R’ = 0.59 ± 0.07 (stat.)
- Fine-grained iron calorimeters NUSEX and Frejus experiments reported no deficit within statistical errors but Soudan-2 did
- In 1998 the breakthrough came with Super-Kamiokande…

CCLRC Rutherford Appleton Laboratory

NEW **Finer-Binned 2-Flavor Analysis** **Preliminary**

Combine advantages of standard and L/E analyses



- PC events divided
into OD stop/OD through-going

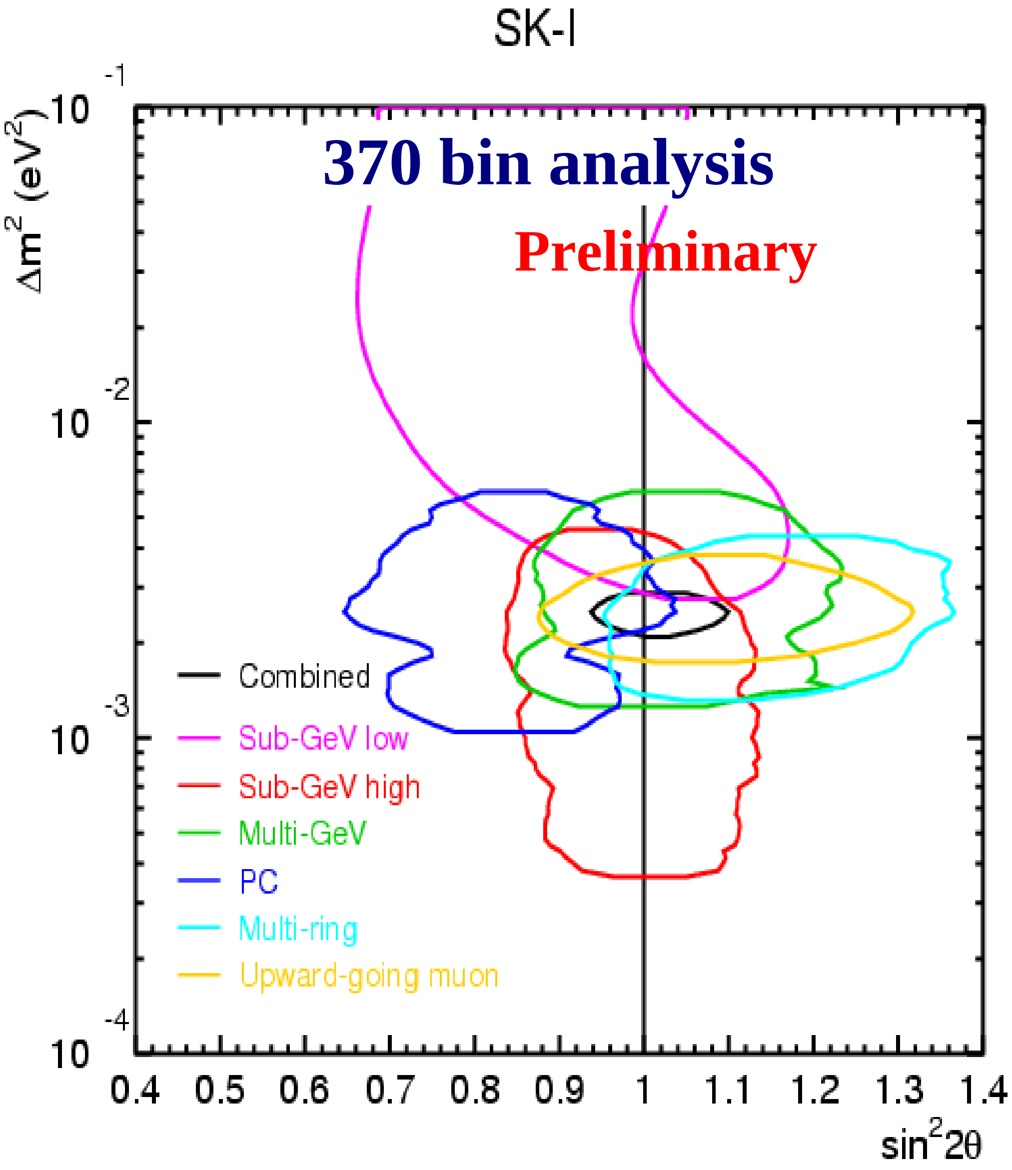
- New FC multi-ring e-like category

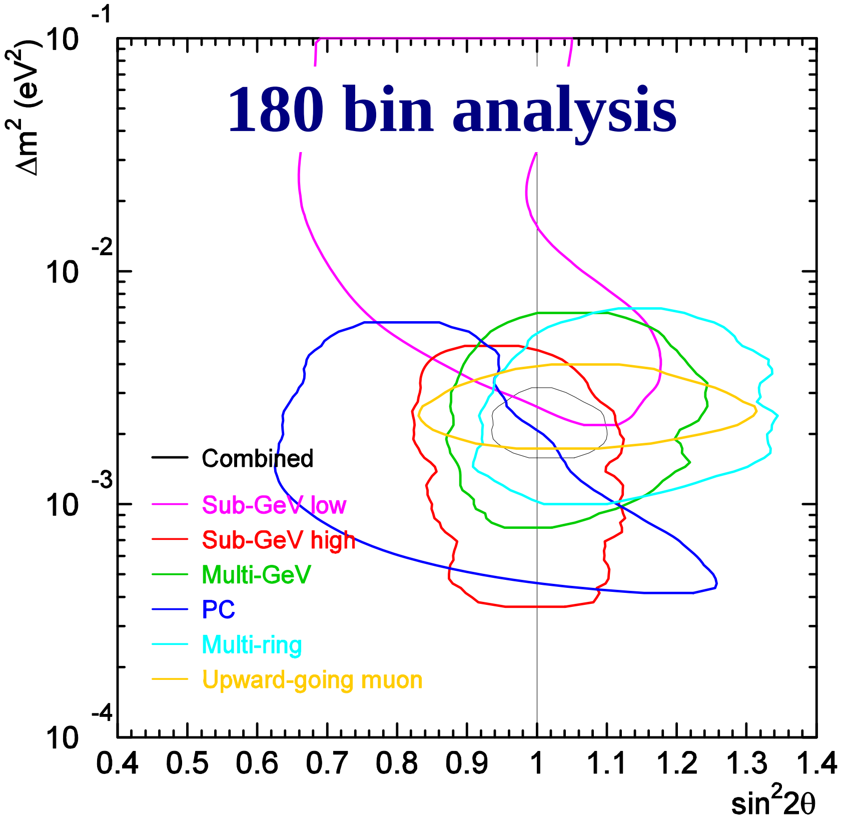
- Finer μ-like momentum binning;
coarser e-like momentum binning

Total of 370 bins in zenith angle, momentum

χ^2 incorporates Poissonian uncertainties

Allowed regions for the various subsamples





Finer binning for multi-GeV, PC, multi-ring improves the Δm^2 constraint