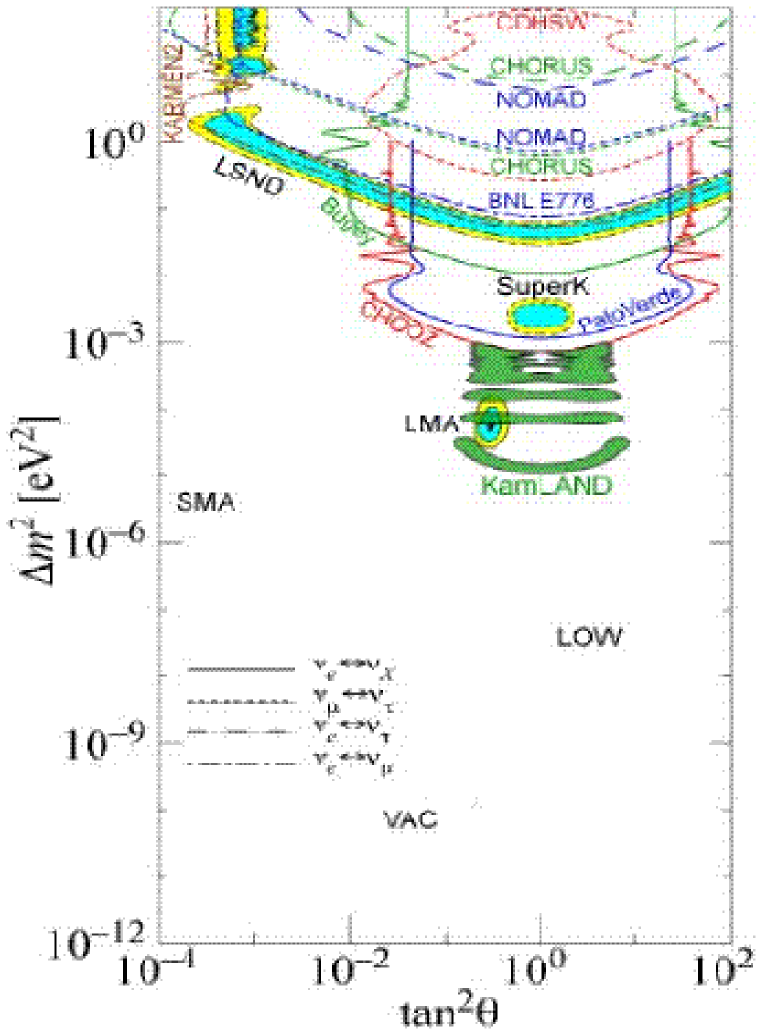
Near Future Accelerator-Based Experiments

(W.C. Louis, NUFACT03, June 5, 2003)

- Current State of ν Oscillation Evidence:
  Solar, Atmospheric, & LSND
  Physics Beyond the Standard Model!?!
- MiniBooNE at FNAL
- MINOS at FNAL/Soudan
- OPERA & ICARUS at CERN/Gran Sasso
- Conclusions

Current State of Neutrino Oscillation Evidence



Three Δm^2 Problem!

Physics Beyond the Standard Model!?!

Evidence for Neutrino Oscillations

Experiment	Type	Δm^2 (eV^2)	$\sin^2 2\theta$
Solar	$\nu_e \rightarrow \nu_{\mu,\tau}$	$\sim 6\times10^{-5}$	~ 0.8
Atmospheric	$\nu_\mu \rightarrow \nu_\tau$	$\sim 3\times10^{-3}$	~ 1
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~ 1	$\sim 3\times10^{-3}$

How Can We Explain Solar, Atmospheric, & LSND?

Problem:

3 separate Δm^2 observed, which cannot be explained by 3 $m_{\nu i}$!?!

Possible Solutions:

(1) Non-Standard Interactions (e.g. Lepton # Violating Muon Decay for LSND: $\mu^+ \to e^+ \bar{\nu}_e \bar{\nu}_i$, tested by TWIST)

(2) Sterile neutrinos (2+2 or 3+1 or 3+2)

(3) CPT Violation $(m_\nu = m_{\bar{\nu}}$?)

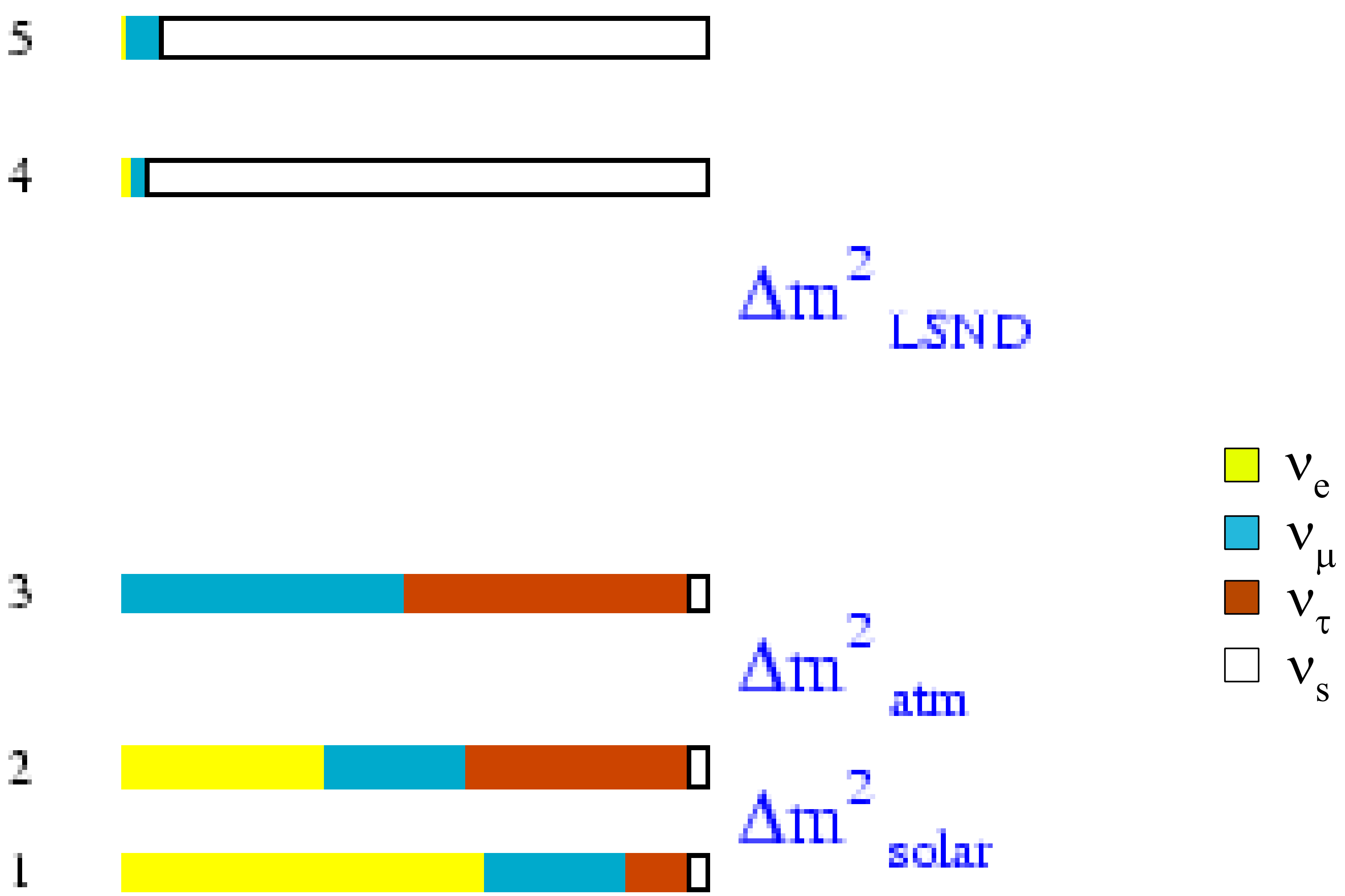
Light Sterile Neutrinos?

- In (2+2) models, solar and atmospheric can be explained by a combination of active & sterile oscillations.
- In (3+1) & (3+2) models, LSND can be explained by heavier sterile neutrinos.
- There is tension with sterile neutrino models explaining all of the data, but the (3+2) model is not too unreasonable.
- Light, sterile neutrinos could have a big impact on BBN, the R-process in Supernovae, and the mass of the universe (cold, warm, or hot).

3+2 Model

Sorel, Conrad, & Shaevitz

hep-ph/0305255



3+2 Model

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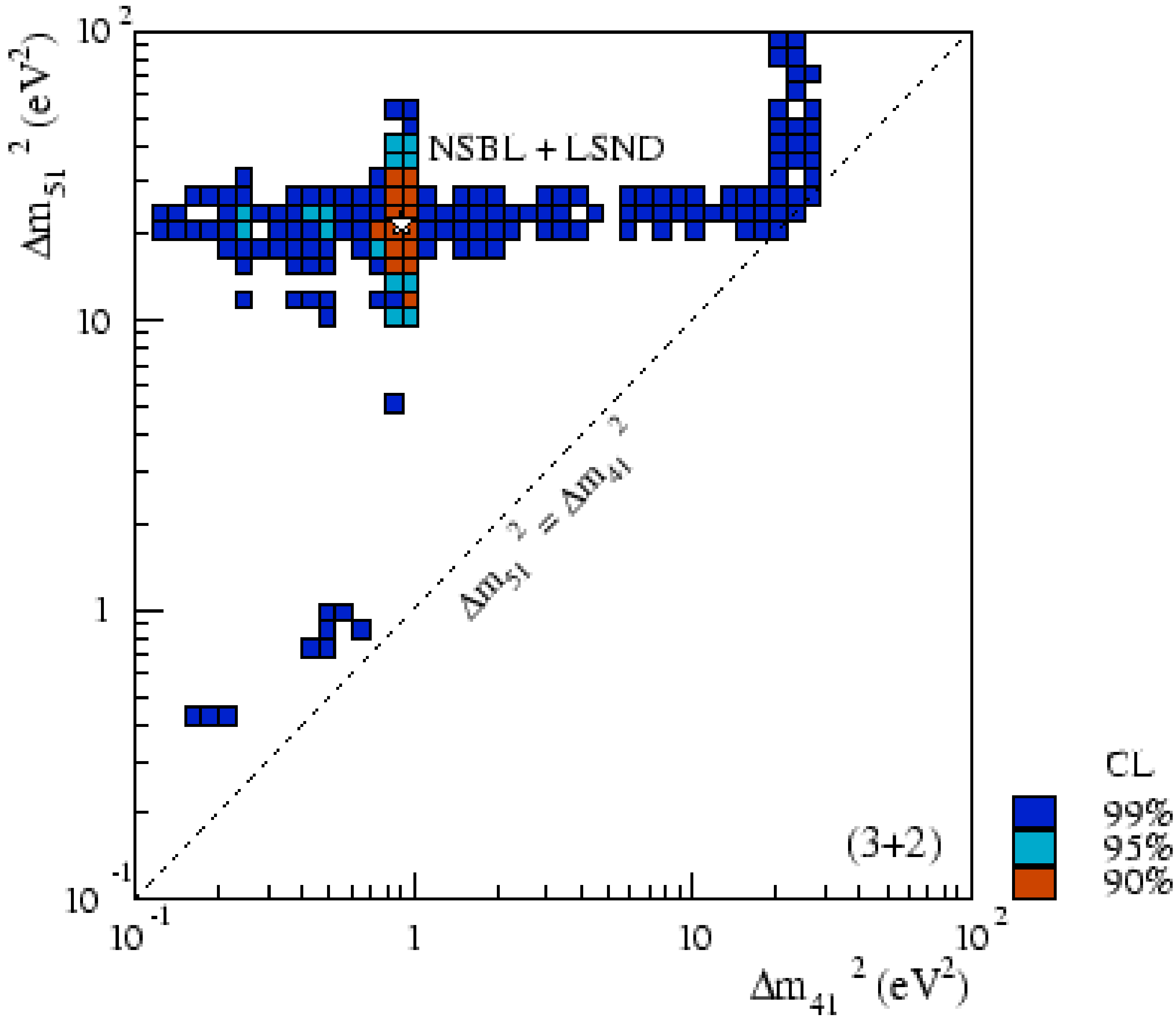


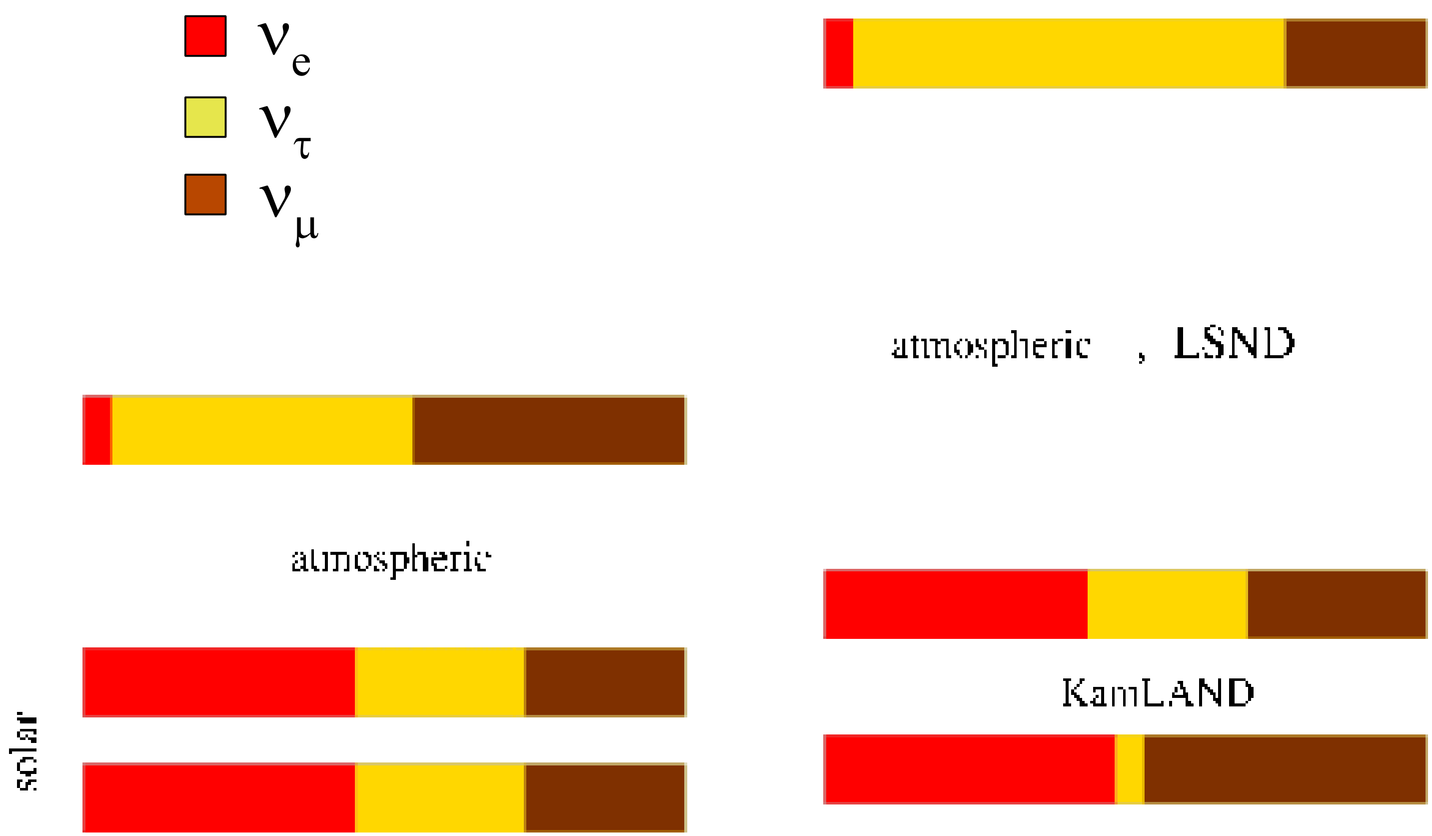
CPT Violation ?

- The possibility of CPT violation is motivated by theories of Extra Dimensions, where CPT is conserved in N dimensions but violated in 4 dimensions.
- If CPT is violated in the neutrino sector, then there are 4 independent Δm^2 and not just 2.
- CPT violation can provide a natural explanation for the baryon asymmetry of the universe.

CPT Violation Model

Barenboim, Borissov, & Lykken

hep-ph/0212116

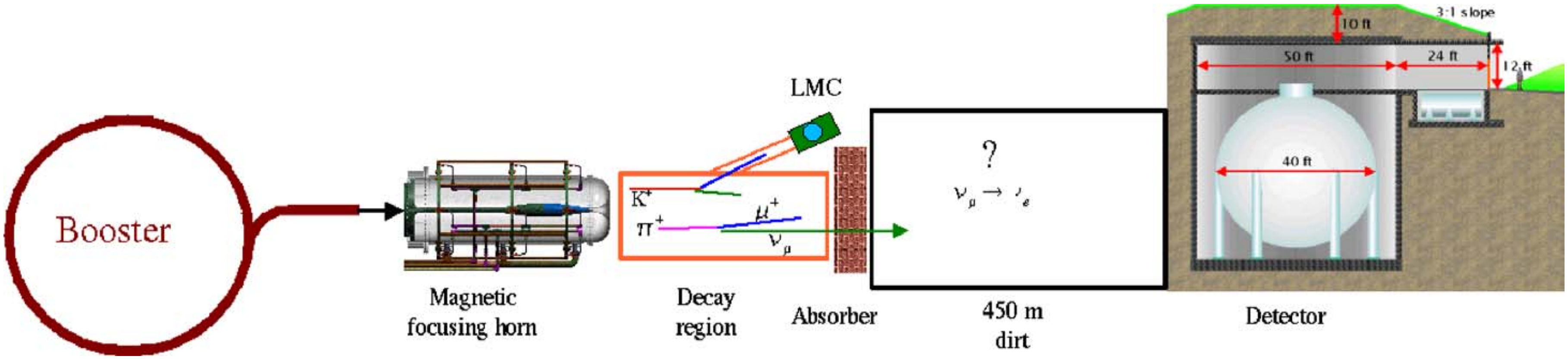


Fundamental Questions to be Answered

(Neutrinos are still largely unknown)

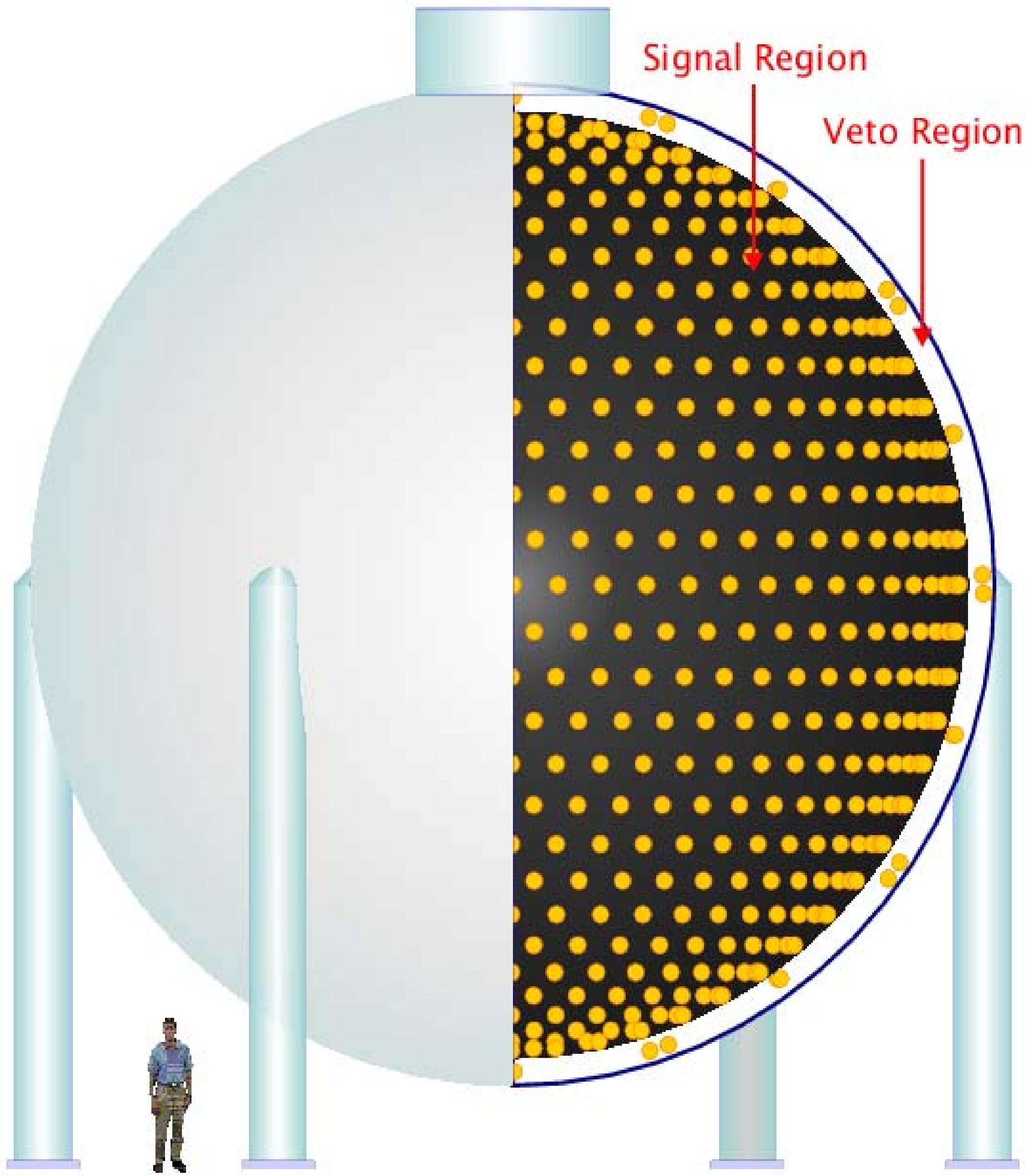
- What is the Resolution of the 3-Δm^2 Paradox?
- What are the Neutrino Masses & Hierarchy?
- What are the Neutrino Mixings?
- Do Light, Sterile Neutrinos Exist?
- Is CP Conserved in the Neutrino Sector?
- Is CPT Conserved in the Neutrino Sector?
- Are Neutrinos Dirac or Majorana?

MiniBooNE - A Definitive Test of the LSND Evidence for ν Oscillations

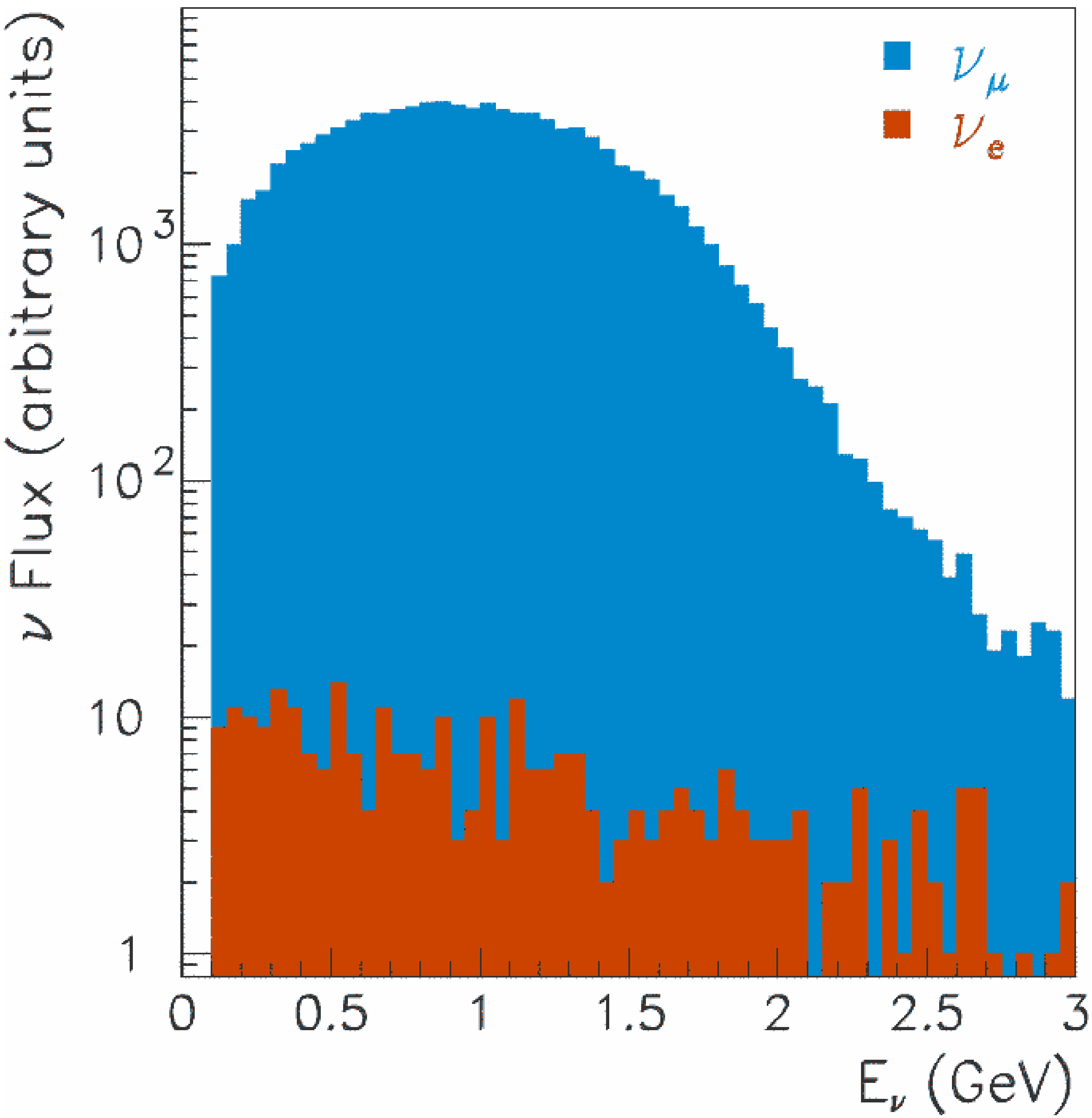


- Booster - 8 GeV proton beam (5 x 10^{20} POT/y)
- Target - 71 cm Be
- Horn - 5 Hz, 170 kA, 143 μs, 2.5 kV, 10^8 pulses/y
- Decay Pipe - 50 m (adjustable to 25 m)
- Neutrino Distance - ~ 0.5 km
- $\langle E_\nu \rangle \sim 1$ GeV
- $(\nu_e / \nu_\mu) \sim 3\times10^{-3}$
- Detector - 40' diameter spherical tank
- Mass - 800 (450) tons of mineral oil
- PMTs - 1280 detector + 240 veto, 8" diameter

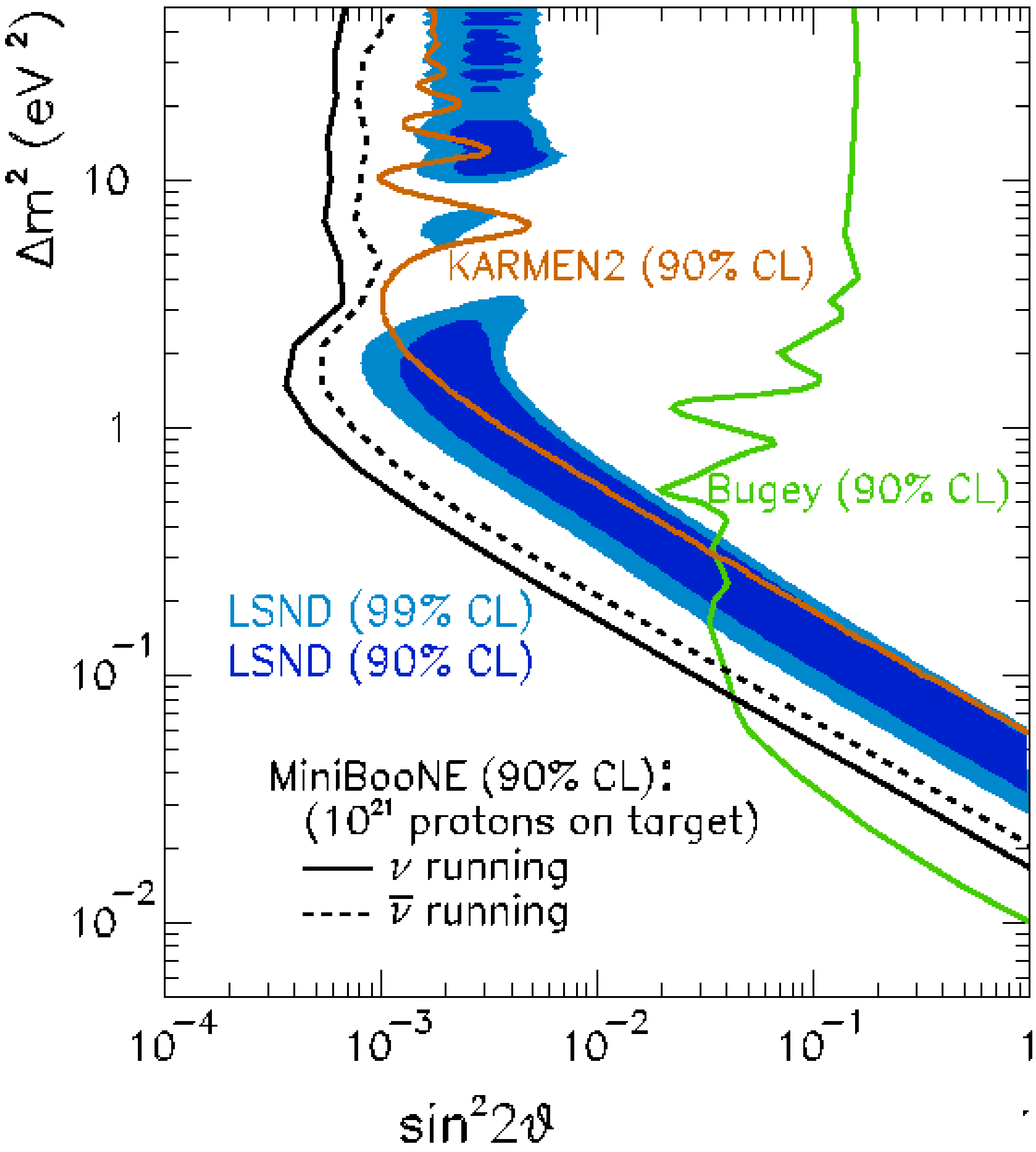
MiniBooNE Detector



MiniBooNE Estimated Neutrino Flux



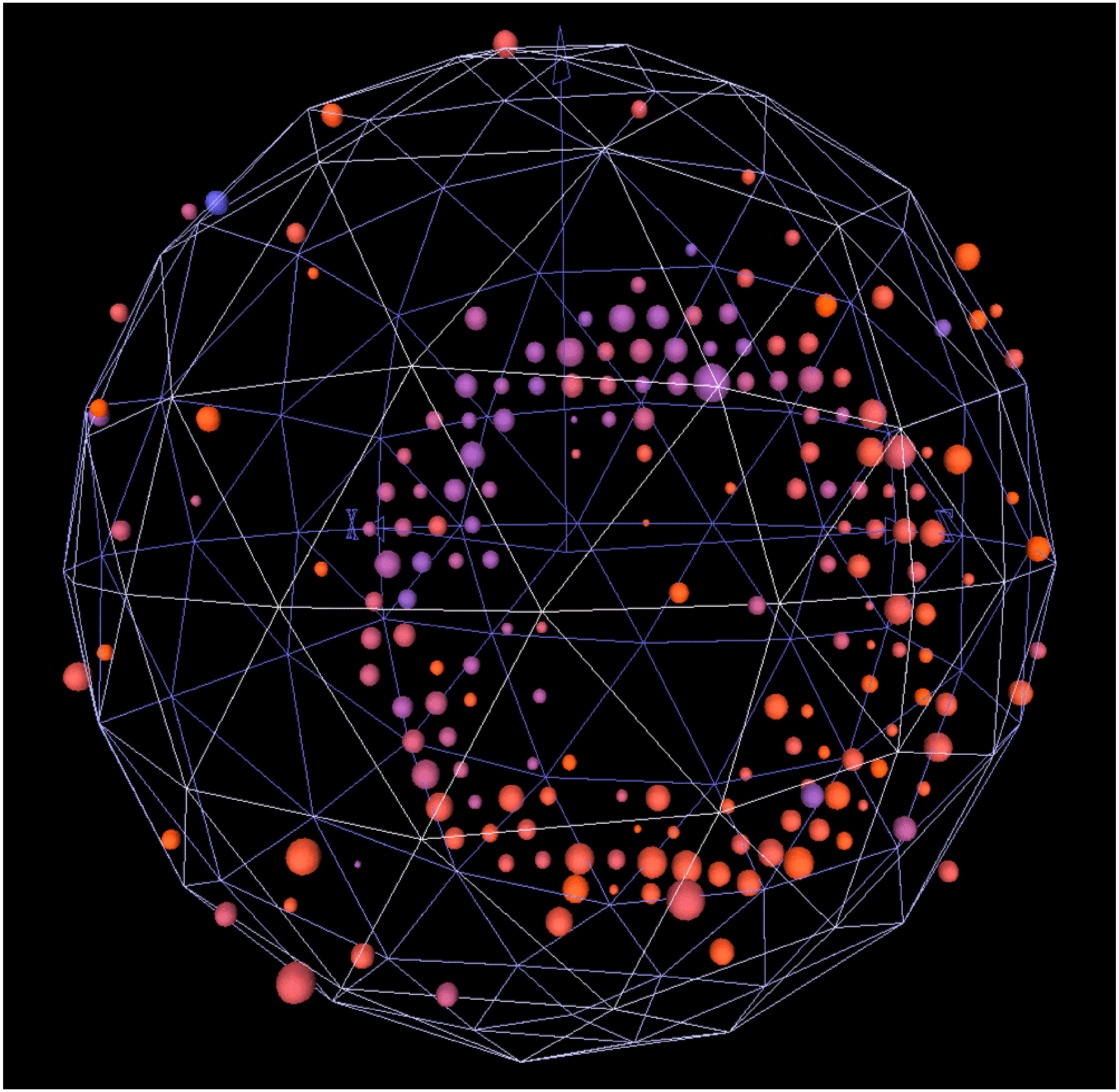
Expected MiniBooNE Sensitivity



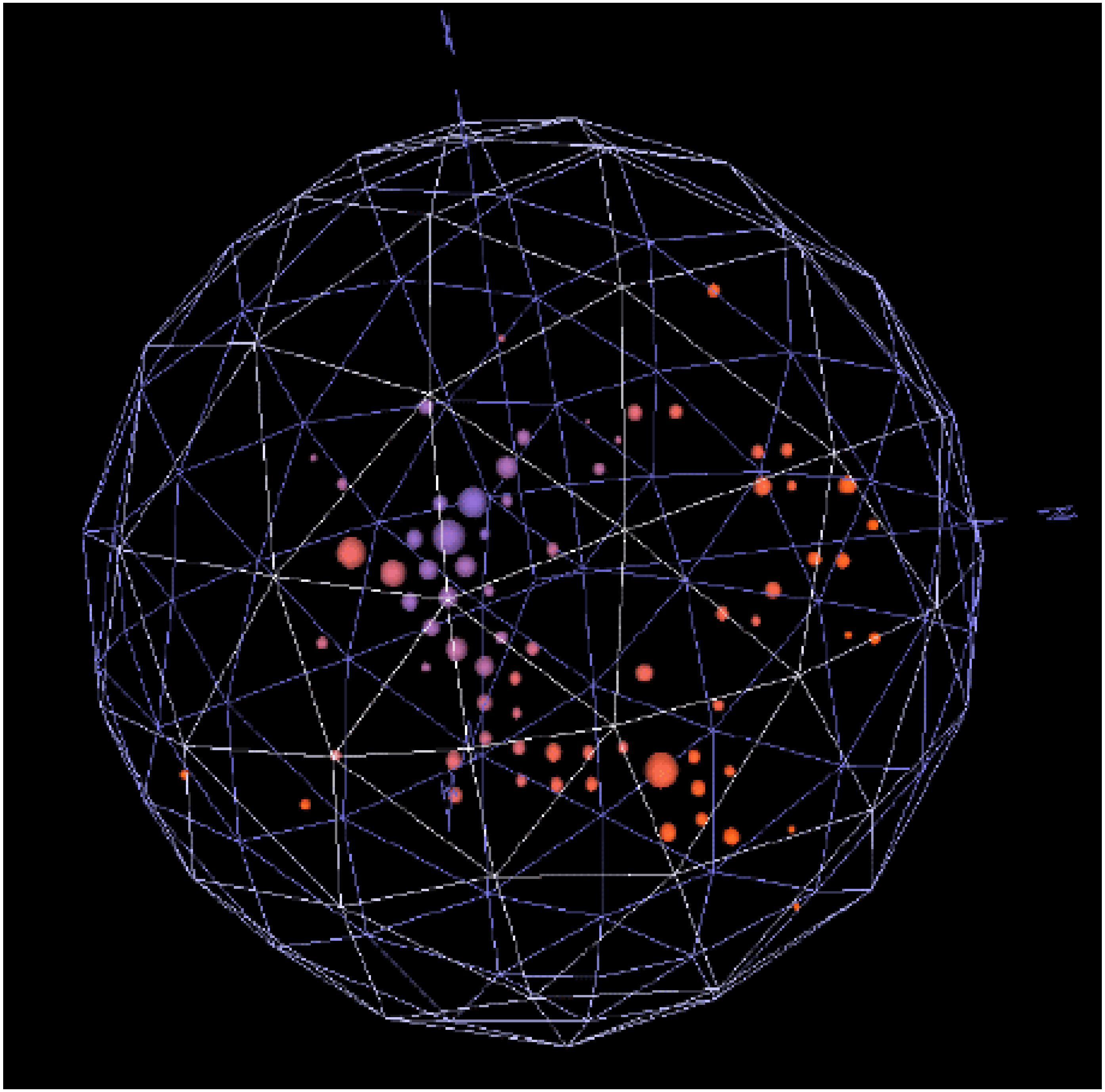
MiniBooNE Detector Status

- Beamline & Detector Working Beautifully!
- Booster Proton Intensity Within Factor 2 of Goal
- ~99% of all PMT channels working well
- DAQ Livetime is ~99%
- Time, Energy, Position, & Angular Resolutions Consistent with Expectations
- ν Event Rate Consistent with Expectations
- Clearly Reconstructing CC μ & NC π^0 Events

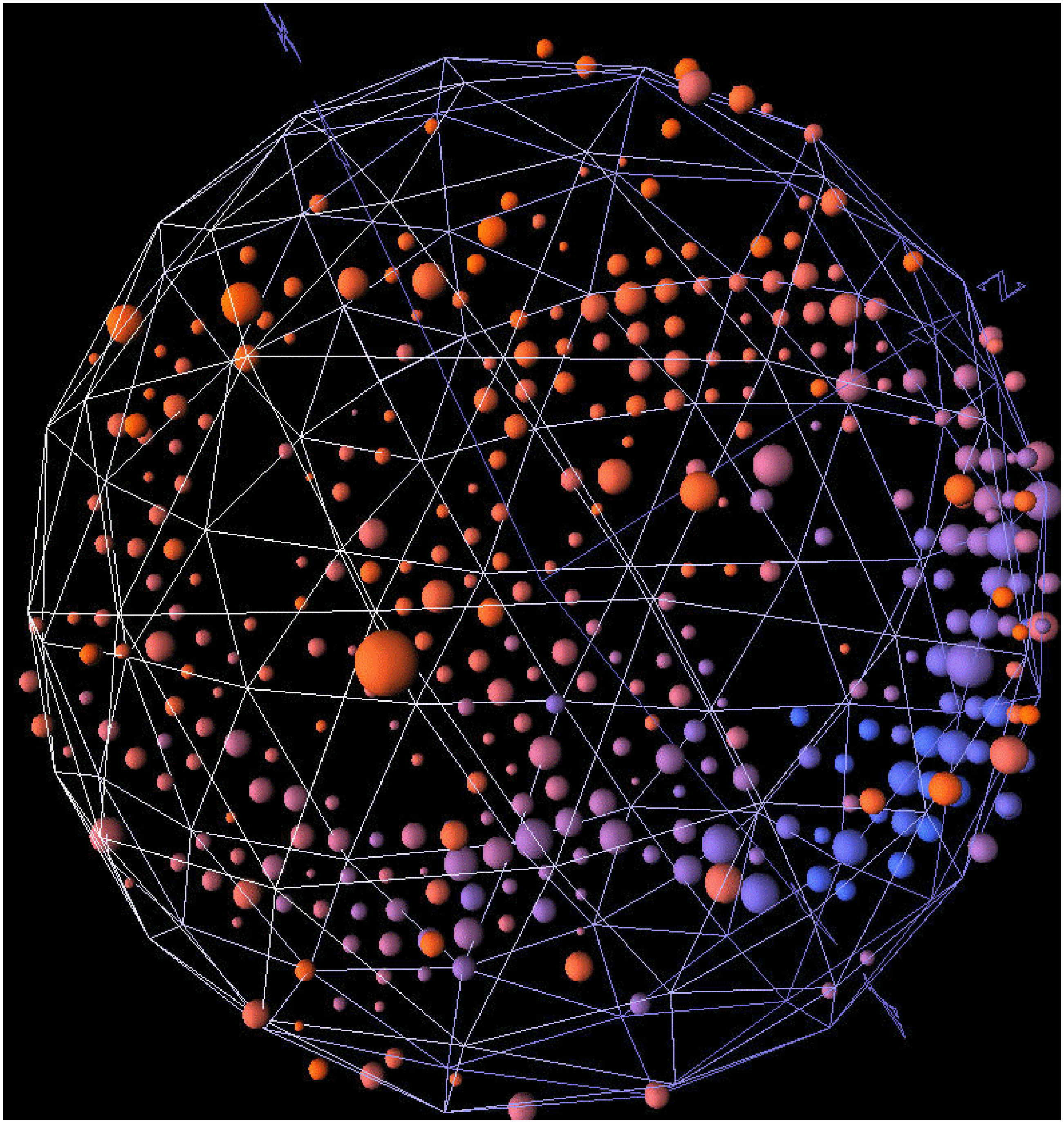
Typical ν_μ CC Event



Typical Michel Electron Event



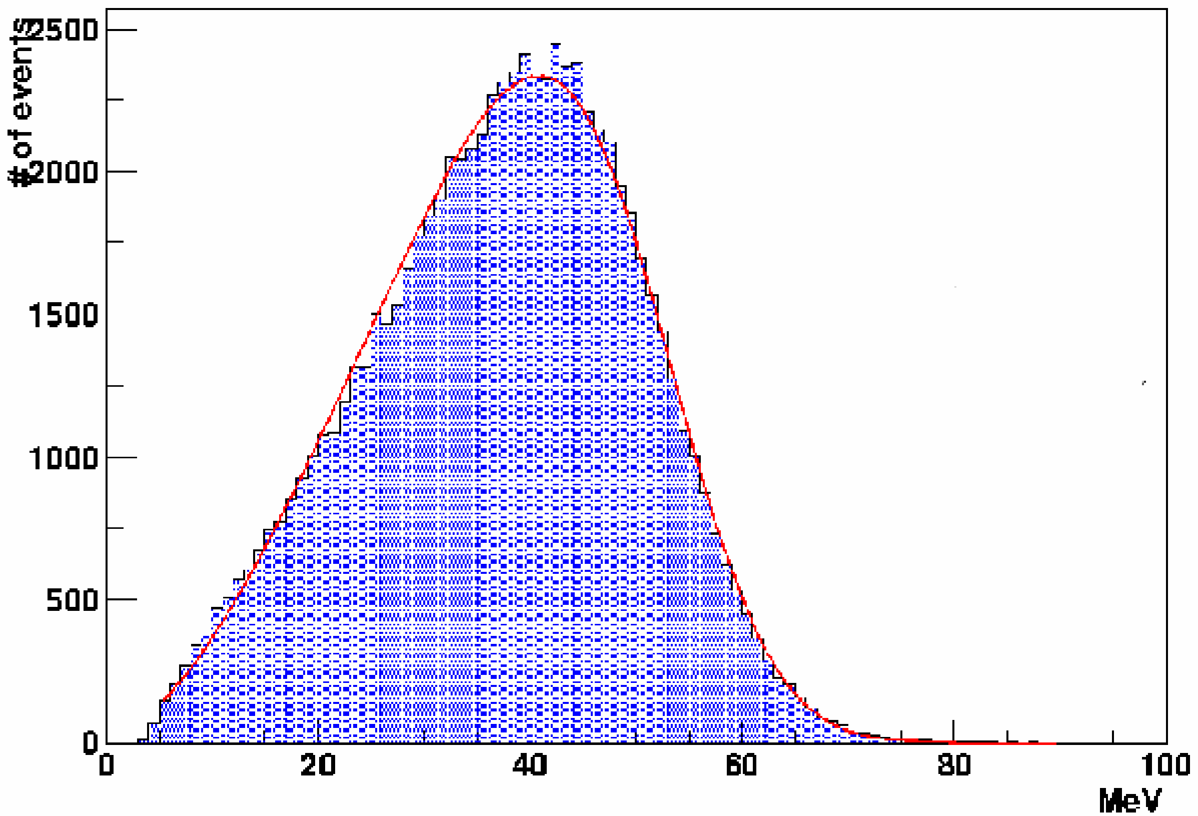
π^0 Candidate Event



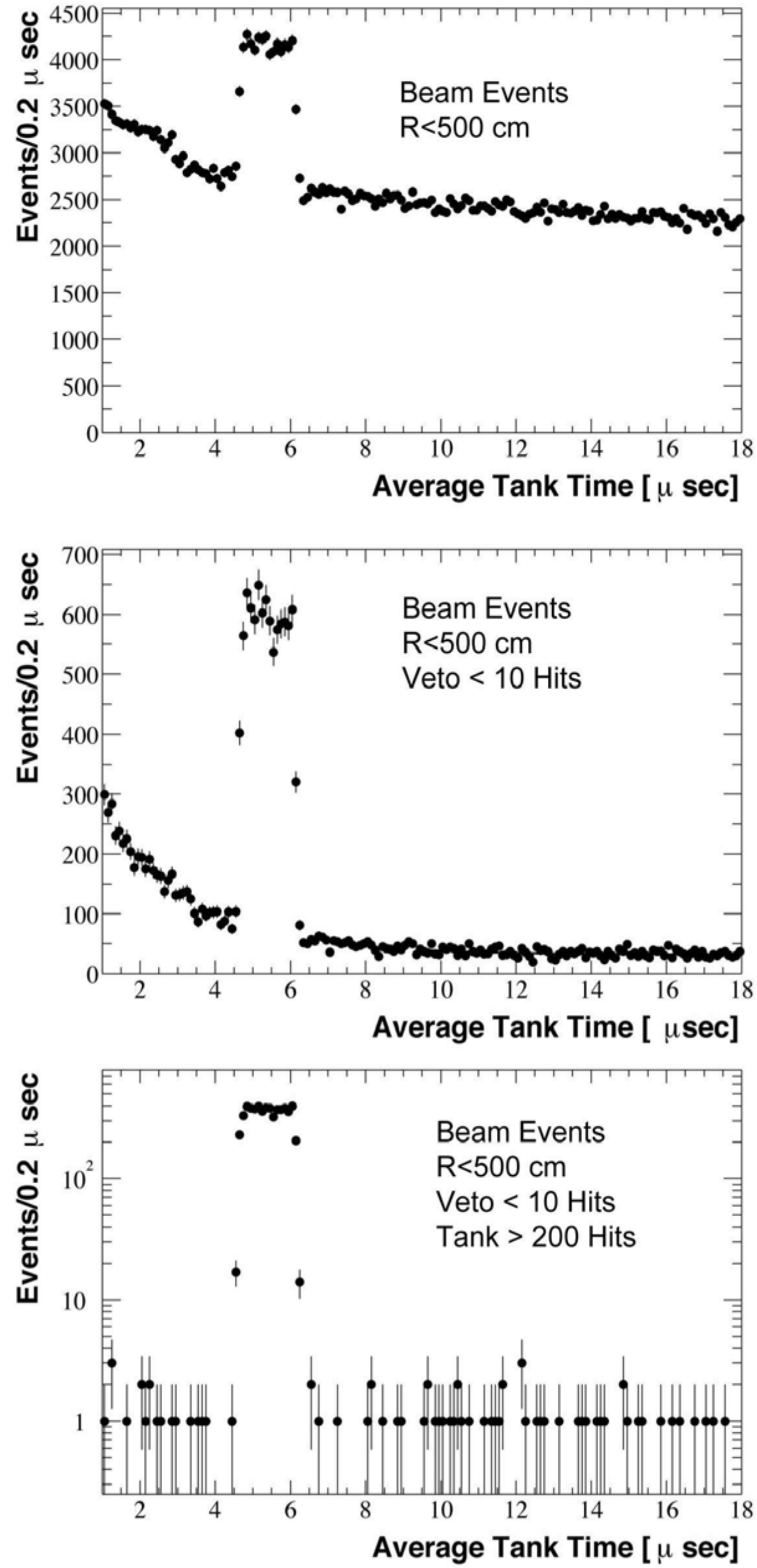
Energy Calibration

Use Michel electrons from μ decay to determine energy scale & resolution

Resolution ~ 14.8% at 52.8 MeV endpoint

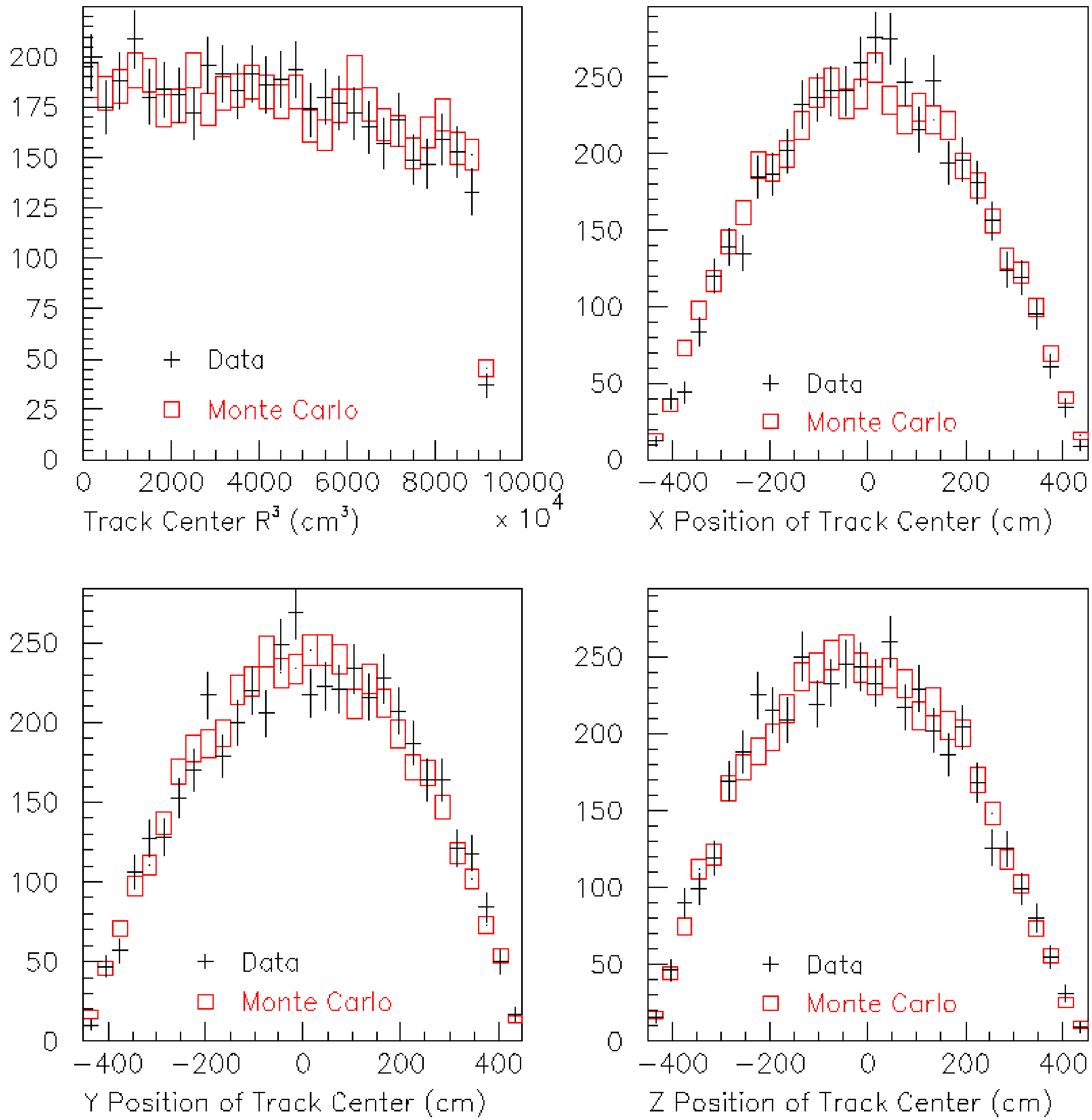


Neutrino Events
Are Very Clean!



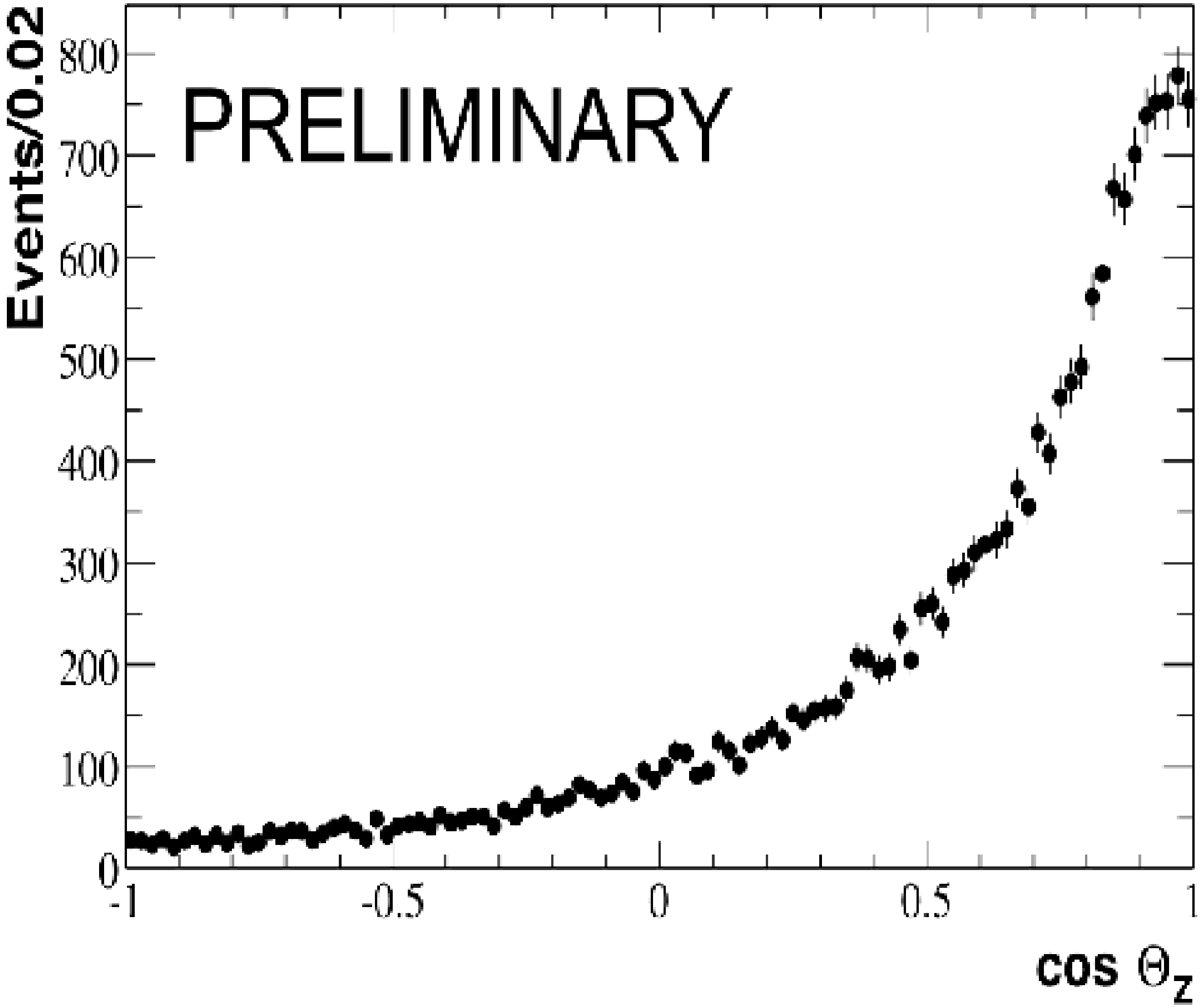
Spatial Distribution for ν Events

Good Agreement
Between
Data & MC



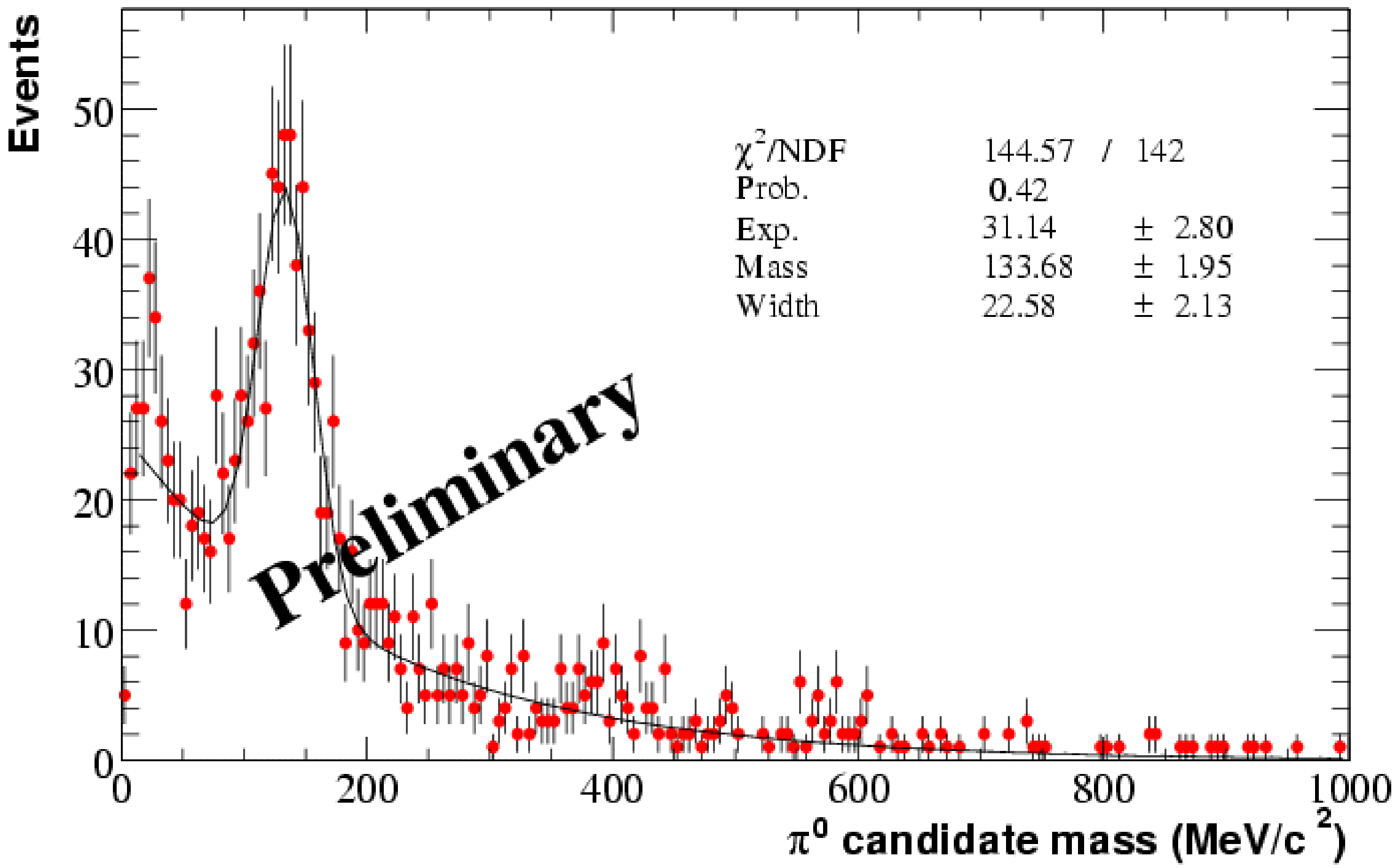
Angular Distribution for ν Events

Events are along νbeam direction!



π^0 Reconstruction

1 subevent with R<450 cm
time within beam spill
tank hits >200 & veto hits <6
>10 photoelectrons per ring



MiniBooNE Conclusions

- MiniBooNE Beamline & Detector Are Working Beautifully!
- Have Collected ~100K ν Events (~20% of $5x10^{20}$ POT Yearly Goal)
- Booster Intensity Is Steadily Increasing (Proton Intensity Now Within 2 of Goal)
- First σ & $\nu_\mu \rightarrow \nu_x$ Results in ~2003
- First $\nu_\mu \rightarrow \nu_e$ Results in ~2005
- If MiniBooNE Confirms LSND, Then Build a 2nd Detector at a Different Distance (BooNE!)

NuMI/MINOS - Definitive Test of Atmospheric Oscillation Results & Search for θ_{13}

- Main Injector - 120 GeV proton beam (ultimately 4 x 10^{20} POT/y)
- Target - 1 m-long segmented graphite
- Horn - Two horn focusing system
- Decay Tunnel - 675 m long
- Neutrino Distance - ~ 1 km & 735 km
- $<E_\nu>$ ~ 3-18 GeV
- $(\nu_e / \nu_\mu) < 1\%$
- Near Detector - 1 kton magnetized toroid & scintillator
- Far Detector - 5.4 ktons magnetized toroid & scintillator
- Magnetic Field ~ 1.5 T
- PMTs - 1452 R5900-M16 Hamamatsu PMTs
- Energy resolution ~ $60\%/E^{1/2}$ hadronic & $25\%/E^{1/2}$ e.m.

MINOS Physics Goals

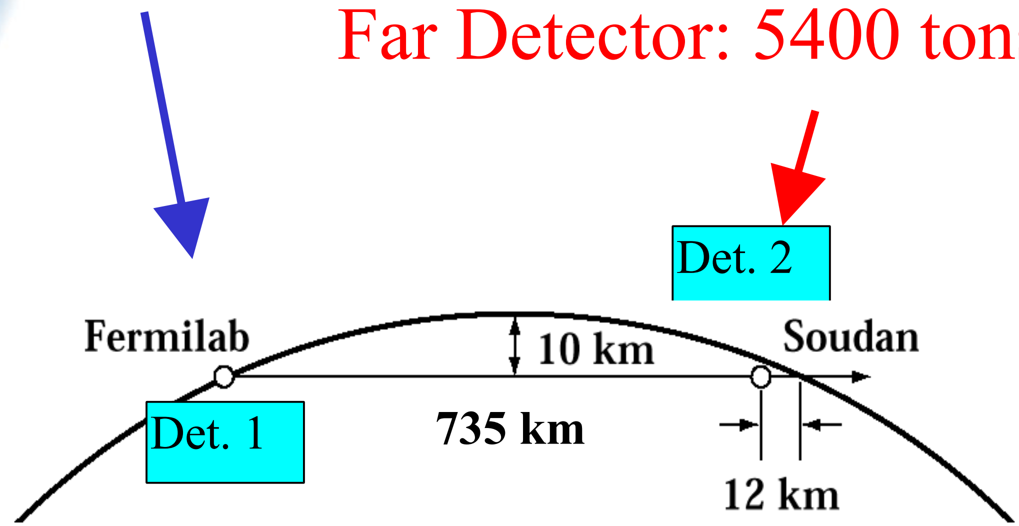
- Demonstrate Oscillation Behavior
  - Precise measurement of CC energy distribution between near and far detector (2-4% sys. uncertainty in E_ν per 2 GeV bin).
  - "Standard" or non-standard oscillations?
    - Can we see clear "oscillatory" behavior from the first osc. max? Rise at low energy?
    - Are there features in the energy spectrum not well described by a standard oscillation?
- Precise Measurement of Oscillation Parameters
  - How close to 1.0 is $\sin^2 2\theta_{23}$? Are we looking at a new fundamental symmetry?
- 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%. Discovery/first measurement of U_{e3}? For the future… CP violation?
  - Number of NC events far/near: probability for $\nu_\mu - \nu_{sterile}$ oscillation down to about 10%.
  - ν_μs which disappear but don't appear as ν_e or disappear to $\nu_{sterile}$ must be ν_τ!
- Direct Measurement of Atmospheric ν vs $\bar{\nu}$. CPT Violation?

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. νs.
  - Likely eventual measurement with beam

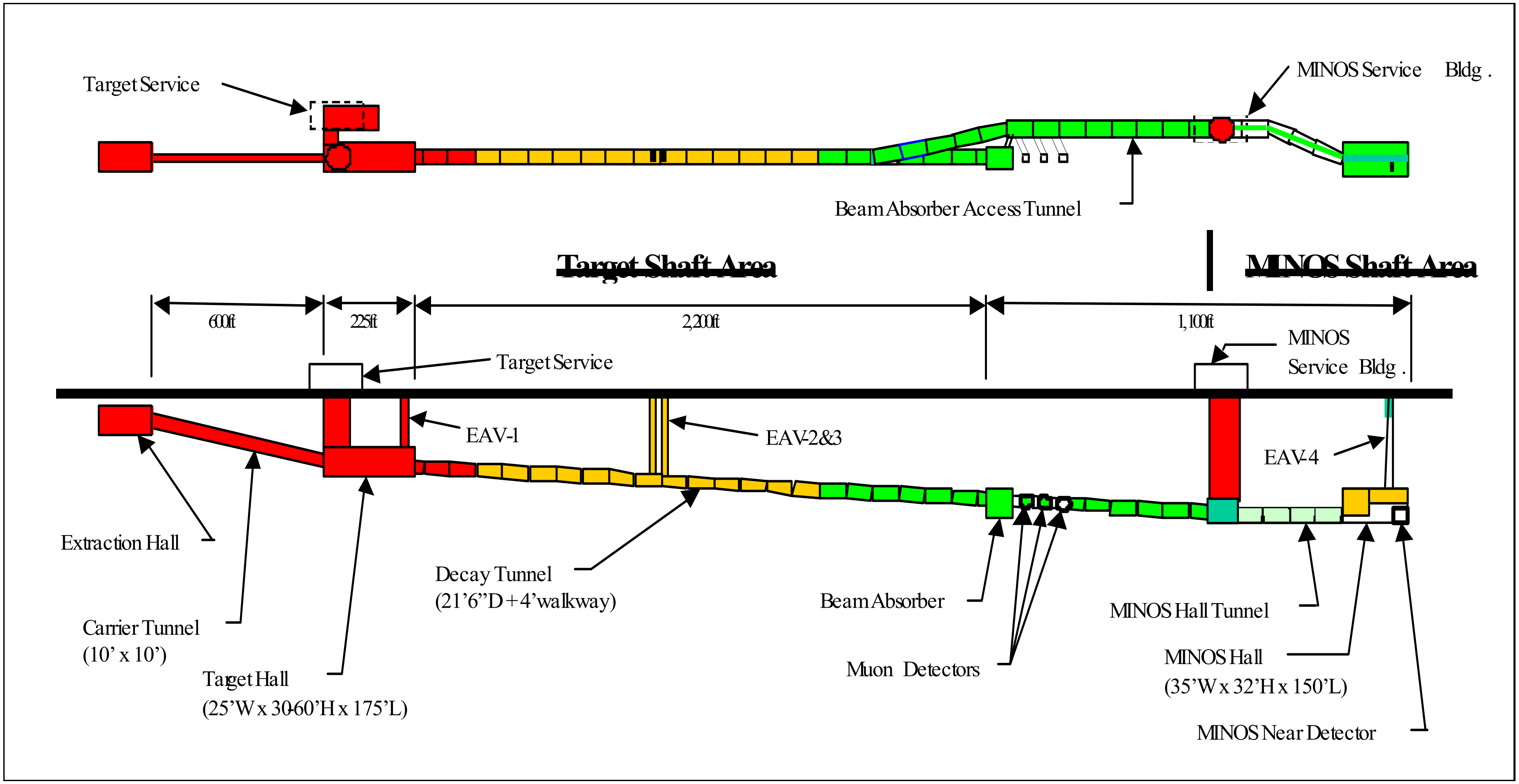
Near Detector: 980 tons

Far Detector: 5400 tons

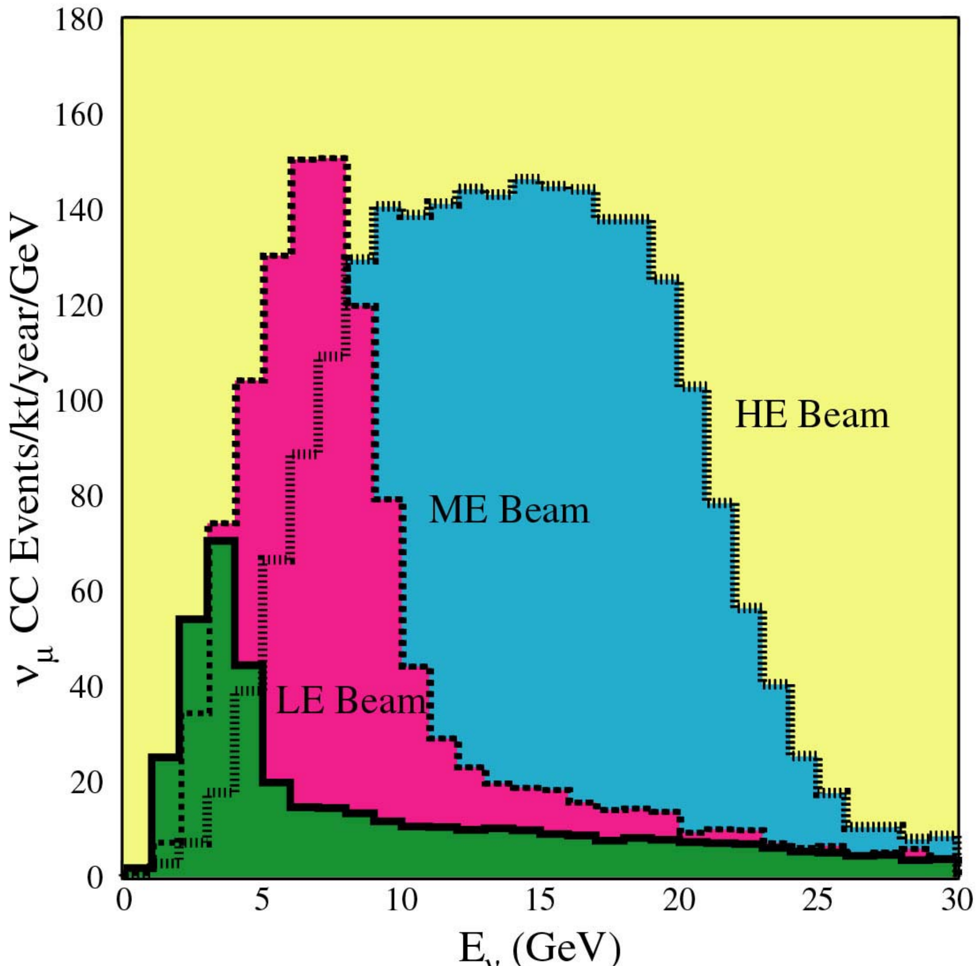


Status of NuMI Beamline Construction

- The excavation of the NuMI beamline halls and tunnels is complete.
- The decay pipe is installed along with the concrete shielding.
- The outfitting of the tunnels and halls is well advanced. Done by November.
- The surface buildings are being built.
- First protons on target expected in December 2004.



The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

ν_μ CC Events/MINOS/2 year

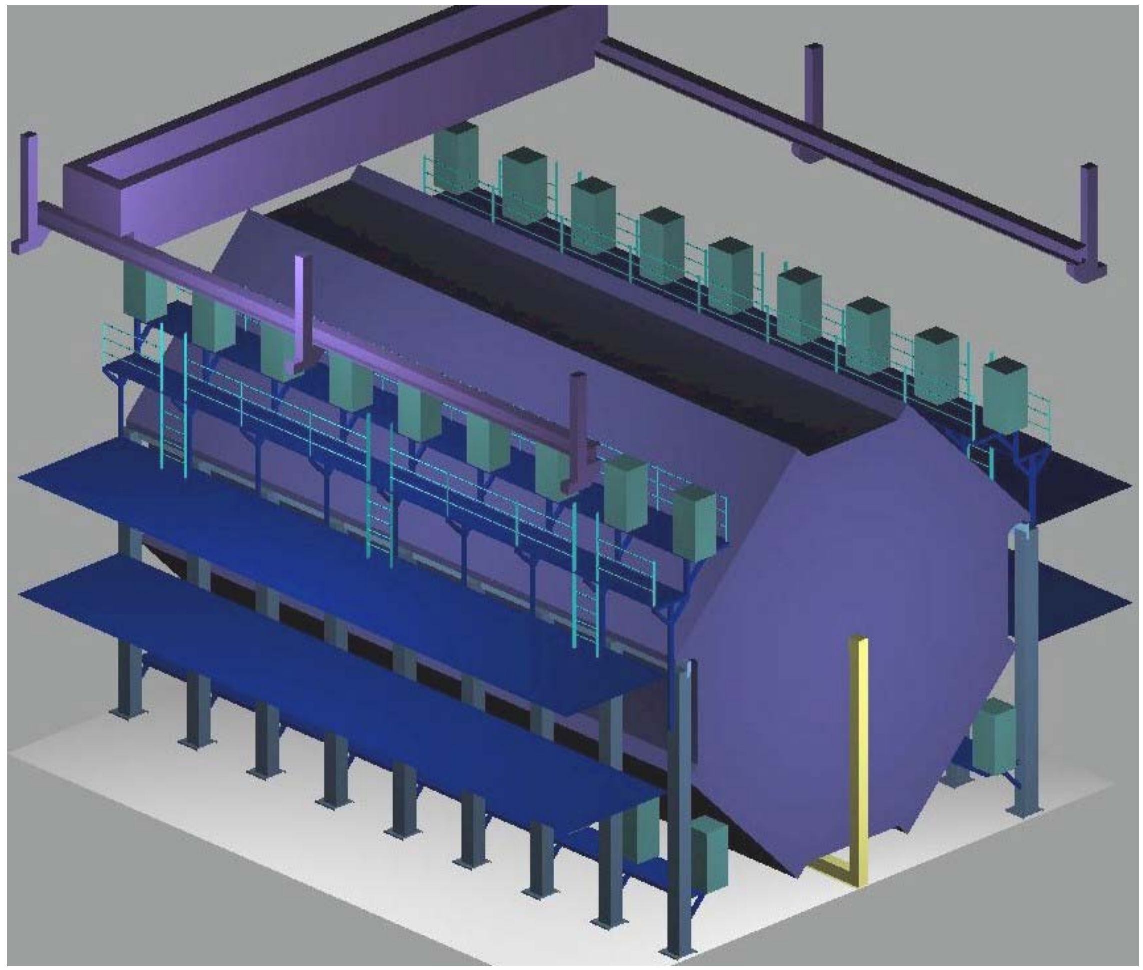
Low	Medium	High
5080	13800	29600

4×10^{20} protons on target/year
4×10^{13} protons/2.0 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.

The MINOS Far Detector

- 8m octagonal steel & scintillator tracking calorimeter
  - Sampling every 2.54 cm
  - 4cm wide strips of scintillator
  - 2 sections, 15m each
  - 5.4 kton total mass
  - 55%/√E for hadrons
  - 23%/√E for electrons
- Magnetized Iron (B~1.5T)
- 484 planes of scintillator
  - 26,000 m^2



One Supermodule of the Far Detector…
Two Supermodules total.

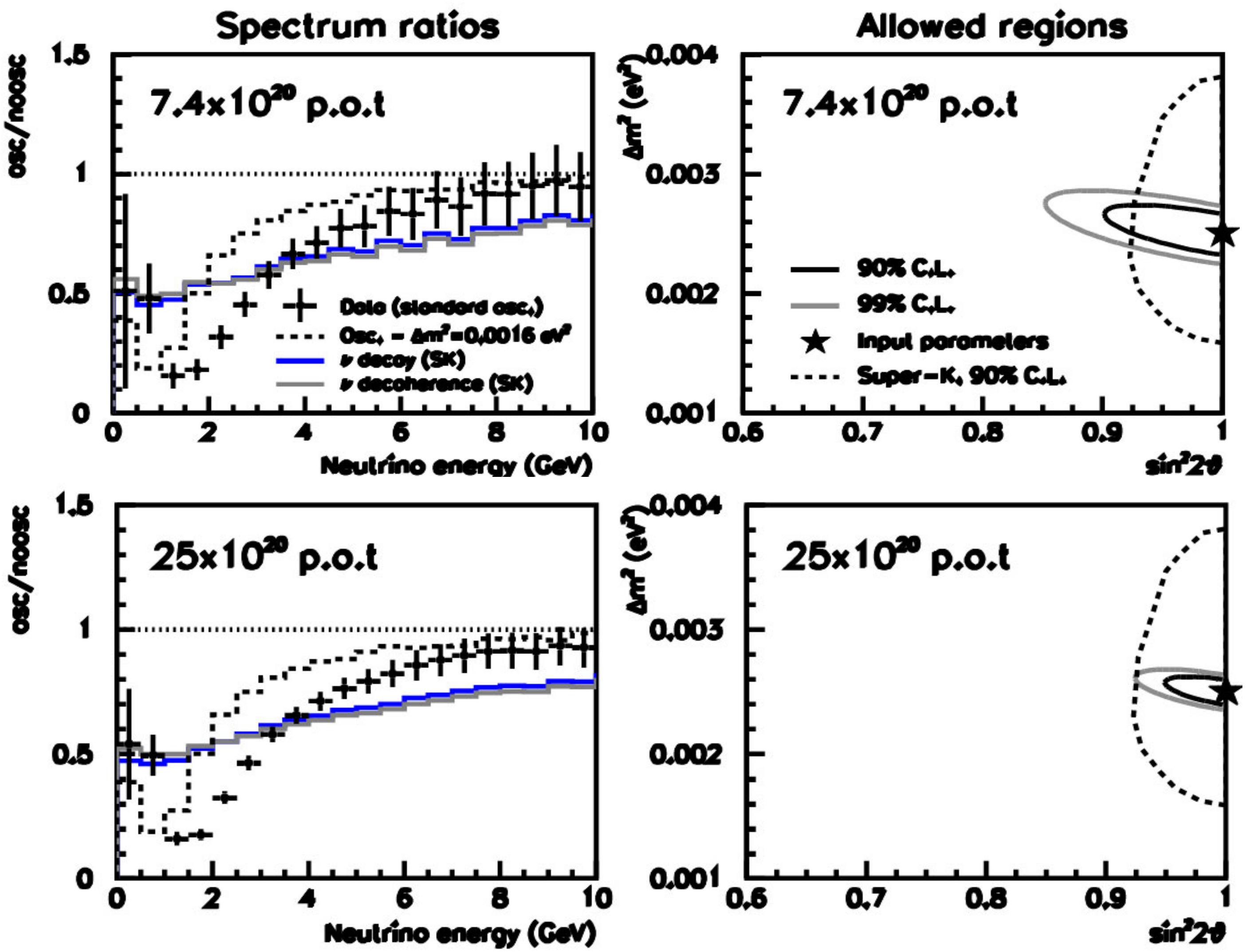
Status of MINOS Construction

Detector on June 2, 483/484 planes installed.

- Essentially all being read out.
- Working according to specs
- 9 photoelectrons/plane/muon
- 2.6 ns/plane time resolution

- The far detector is >99% built and operating.
- The magnetic field is on in the first half.
- The full detector will be complete in June 2003.
- A cosmic-ray veto shield is installed on 3/4 of the detector.
- Cosmic Ray data are being collected for calibration and commissioning.
- Atmospheric Neutrino data are being collected

Measurement of Oscillations in MINOS

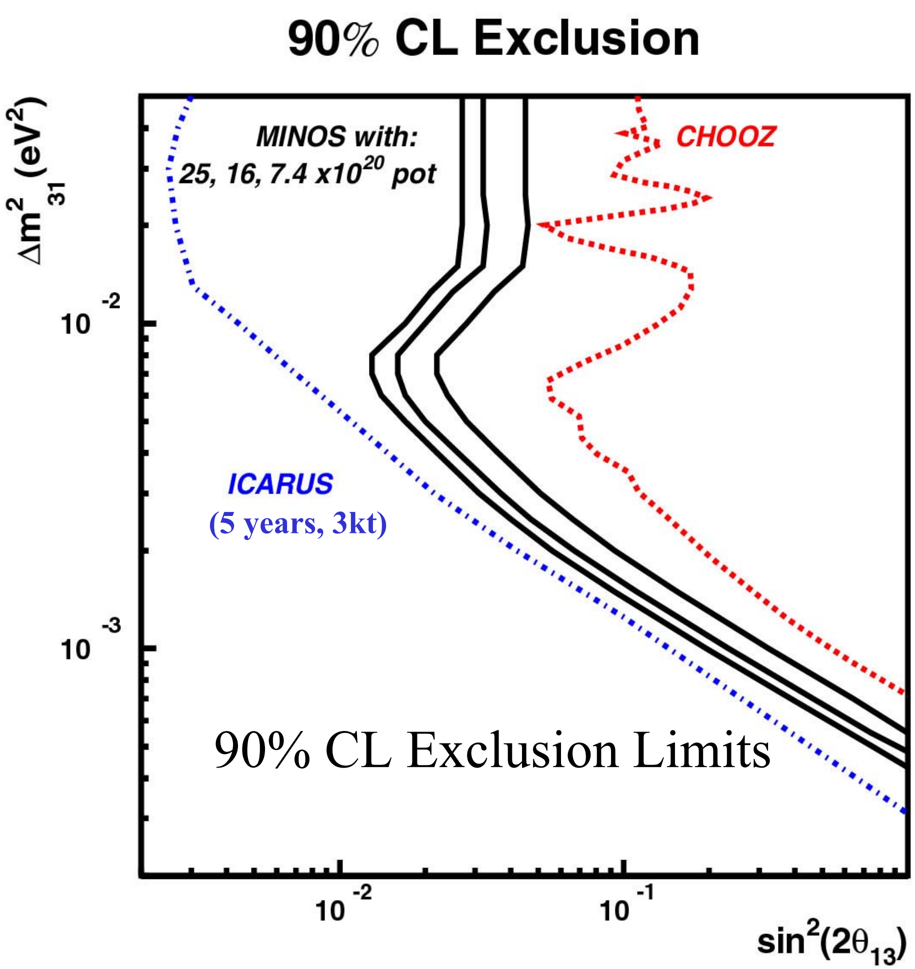


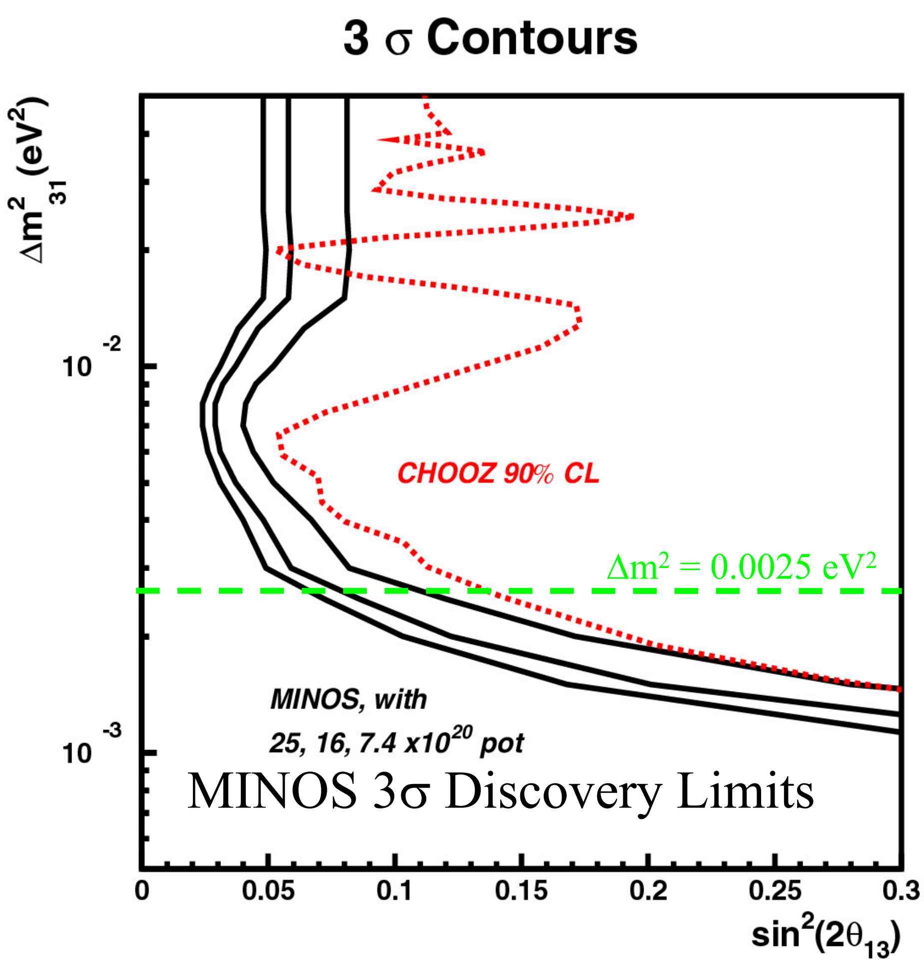
For $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\theta = 1.0$

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

MINOS 90% and 99% CL allowed oscillation parameter space.

Appearance of Electrons

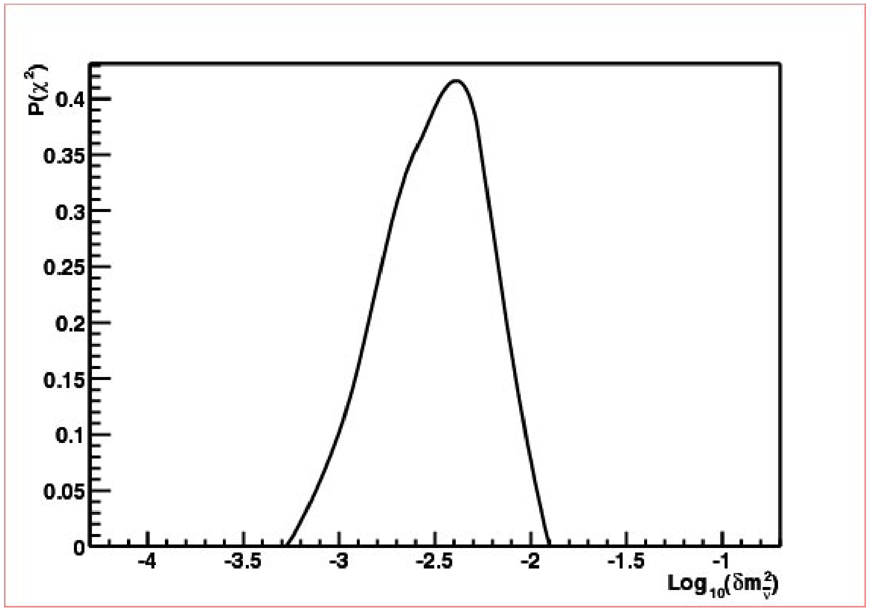




- MINOS sensitivities based on varying numbers of protons on target

Atmospheric Neutrino Measurements

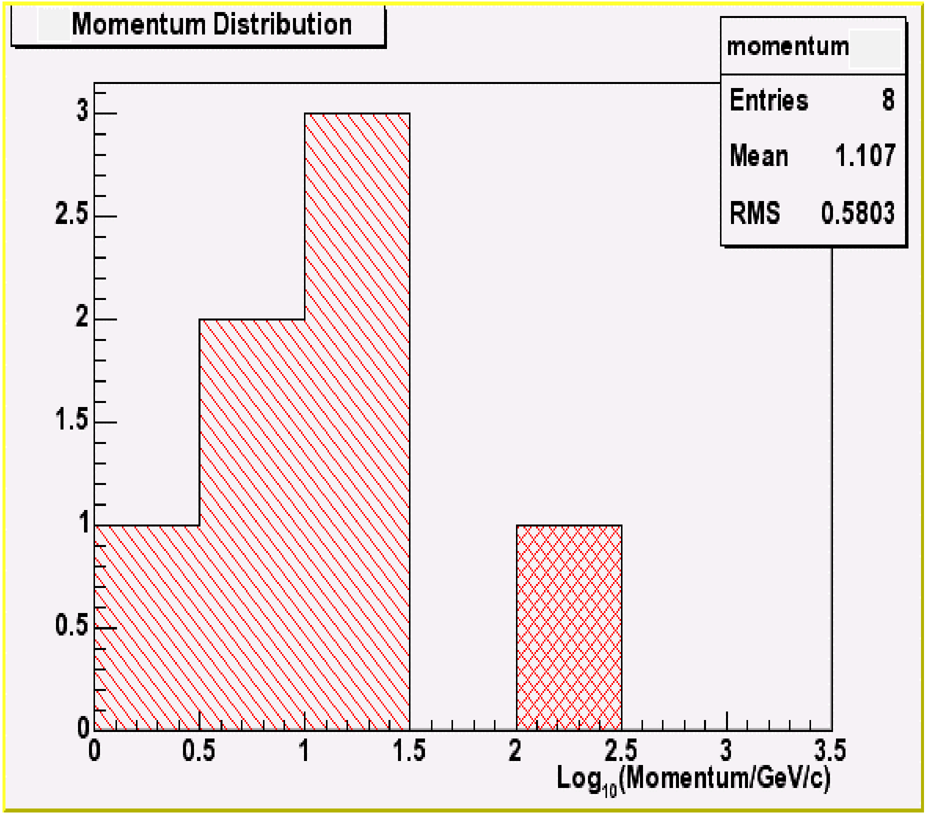
- MINOS is the first large underground detector which has a magnetic field.
  - Measure charge/momentum of muons from ~0.5-100 GeV/c momentum.
  - Events with the neutrino interaction in the detector but where the muon exits still have complete E_ν measurement: L/E measurements.
- Event direction reconstructed using timing and topology.
- Able to identify CC ν_μ and $\overline{\nu}_\mu$ events from NC and CC ν_e events over a very broad energy range as long as p_μ > ~1 GeV/c.
- We can directly compare whether atmospheric ν_μ and $\overline{\nu}_\mu$ oscillate in the same way.

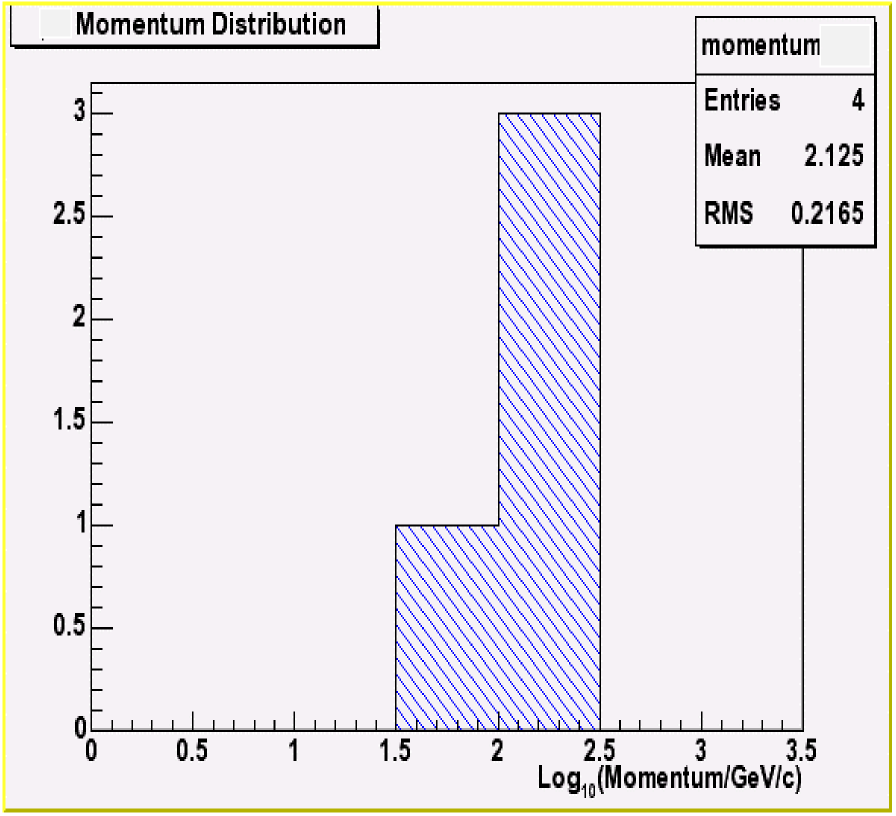


Probability of χ^2 for nominal neutrino oscillation Parameters compared to different values of dm**2 For antineutrinos.

Number of events in 24 kT years	Neutrino	Antineutrino
Reconstructed contained vertex with muon	620	400
Reconstructed upgoing muon	280	120

Charge and Momentum of Upgoing Muons





One Sign　　　　　The Other Sign

- All muons are assigned a charge based on the most likely hypothesis.
- Above 100 GeV, the charges and the momenta are not very reliably
- determined at this time.
- Below 70 GeV, charge and momenta are generally well determined.

Conclusions

- The MINOS Detectors together with the NuMI beam will permit a next step in precision measurements of “atmospheric” neutrino oscillations:
  - Precise energy distribution… Showing the oscillation signature (?)
  - Precise measurement of Δm^2
  - Precise determination of participation of different neutrino flavors
  - Extend sensitivity for small $\nu_\mu - \nu_e$ mixing
  - Measurement of anti-neutrino mixing for atmospheric neutrinos
- Construction of the MINOS far detector is ~99% complete and cosmic ray data is being accumulated with installed planes.
- Data acquisition for cosmic rays and atmospheric neutrinos underway!
- Construction of the NuMI beamline is nearing completion. The tunnel excavation is complete. The outfitting and final civil construction is on schedule. The installation of beam components and near detector is ready to go.
- First protons on target scheduled for December 2004.
- Running plans, including increased protons on target are being developed.
- New proposals for use of the NuMI Beamline are developing.

CNGS - Definitive Test of Atmos. $\nu_\mu \rightarrow \nu_\tau$ Osc. Results & Search for θ_{13}

- SPS - 400 GeV proton beam (4.5 x 10^{19} POT/y)
- Target - graphite rods
- Neutrino Distance - ~ 732 km
- $\langle E_\nu \rangle \sim 17$ GeV
- $(\nu_e / \nu_\mu) \sim 8 \times 10^{-3}$

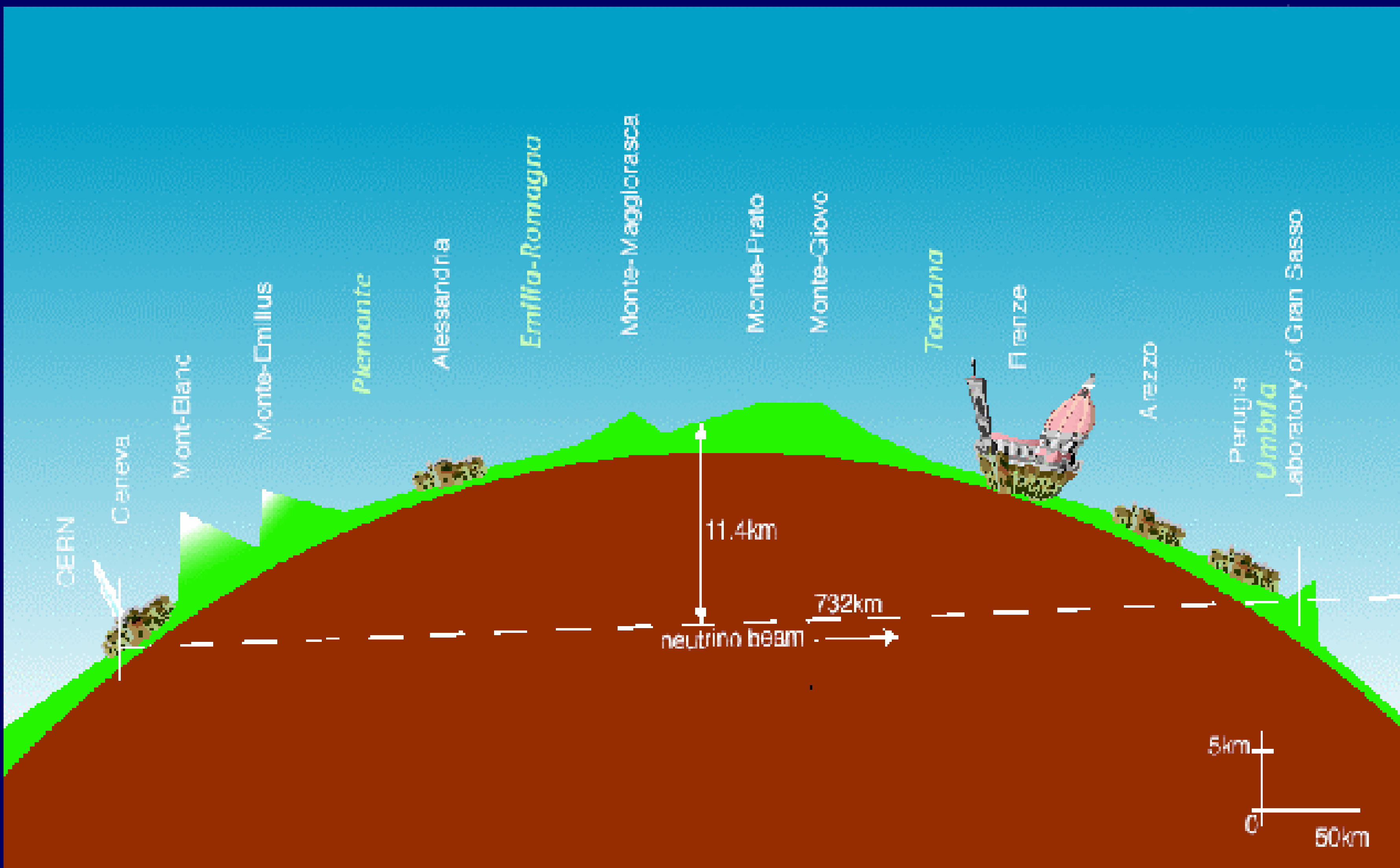
OPERA - Observe τ Decay Topology

- 1.8 ktons of emulsion interleaved with Pb plates
- 206,336 bricks, 56 emulsion & Pb layers per brick
- 1.6 T magnetic field transverse to neutrino beam
- Electronic Target Tracker determines event location
- Candidate bricks are removed for subsequent analysis
- Energy resolution ~ $40\%/E^{1/2}$; $\varepsilon \sim 9.1\%$
- Total background ~ 0.65 events after 5 years

ICARUS - Observe τ Decay Kinematically

- 3 kton Liquid Ar TPC (10 x 300 ton half modules)
- 4 x 4 x 20 m^3 Cryostat per half module
- Momentum resolution ~ 20% at 10 GeV; $\varepsilon \sim 5.9\%$
- Total background ~ 0.7 events after 5 years

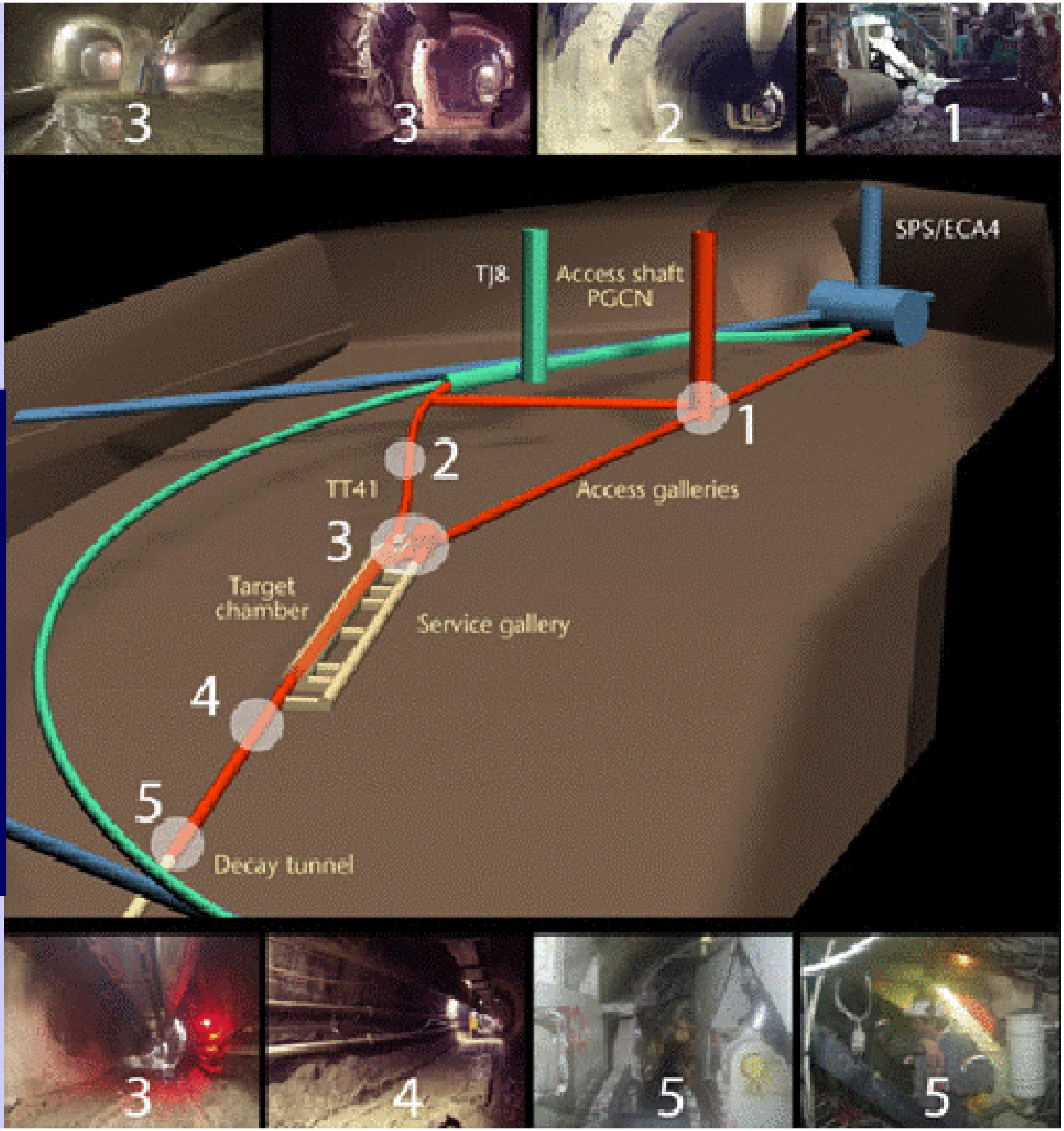
The CNGS neutrino beam



CNGS beam layout at CERN site.

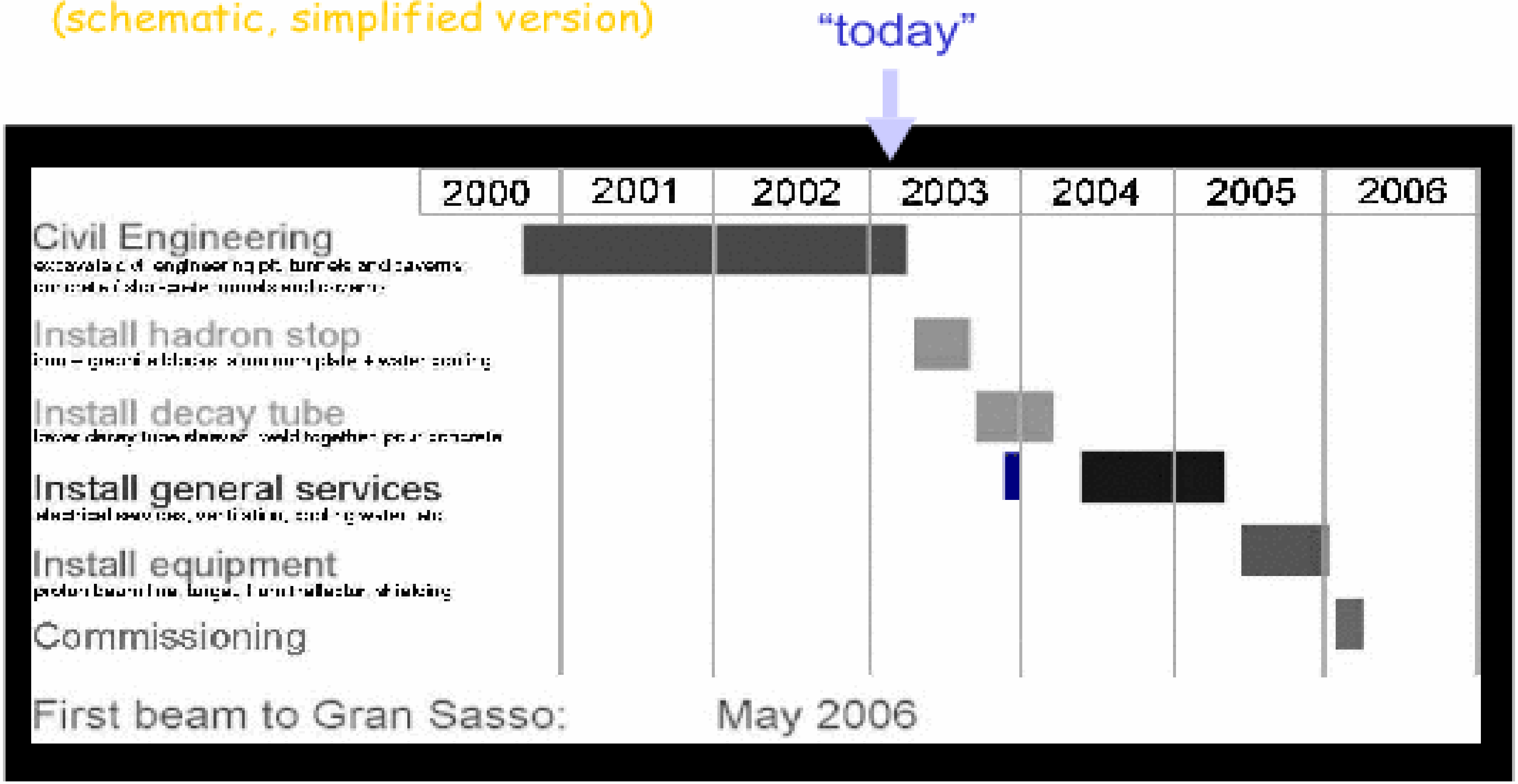
Progress in the civil engineering work:
excavation completed
concreting started

CNGS commissioning:
May 2006



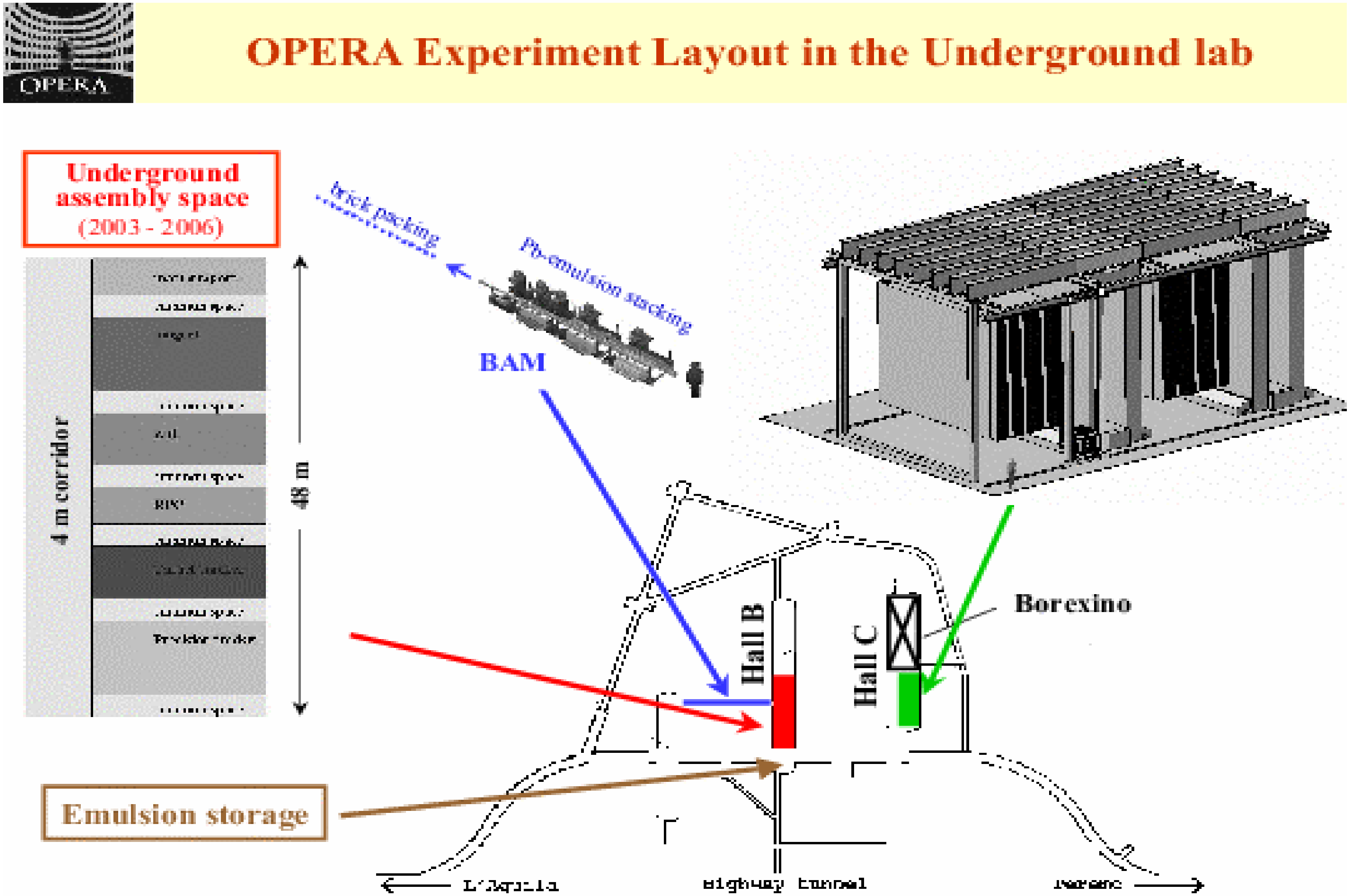
CNGS schedule

(schematic, simplified version)



Prepared by K. Elsener

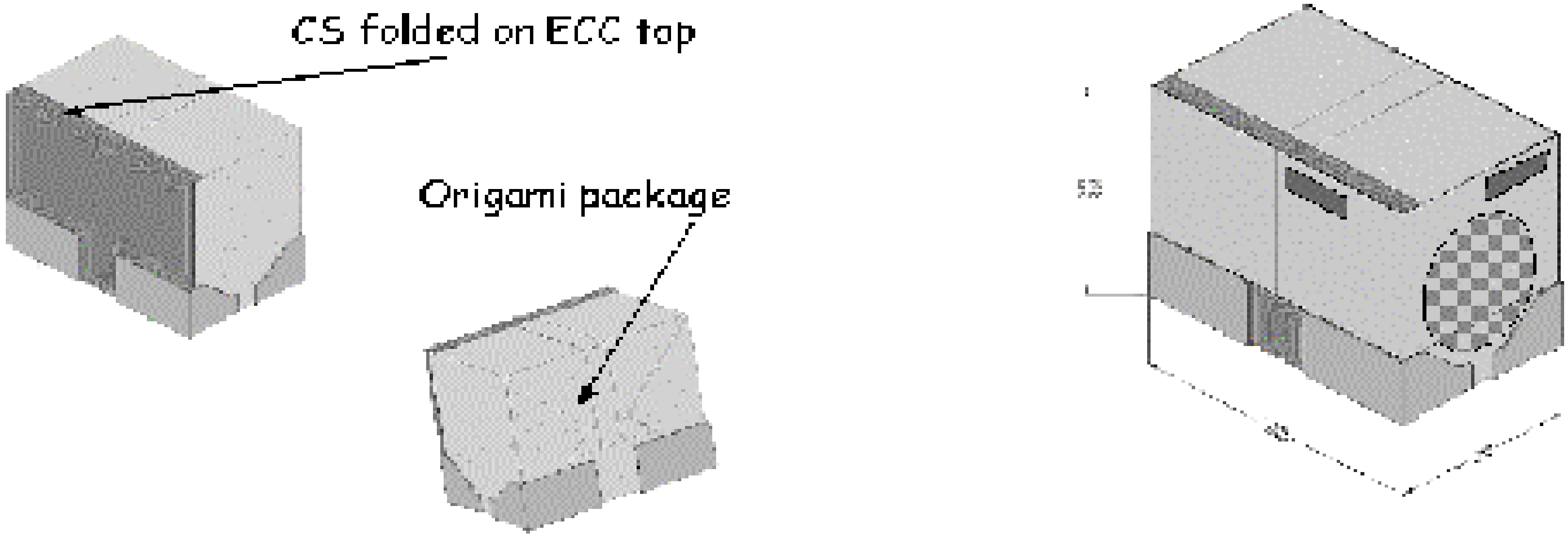
OPERA



OPERA Experiment Layout in the Underground lab
Underground assembly space (2003 - 2006)
4 m corridor
48 m
brick packing
Pb-emulsion stacking
BAM
Hall B
Hall C
Borexino
Emulsion storage
highway tunnel

The Brick Assembly Machine (BAM)

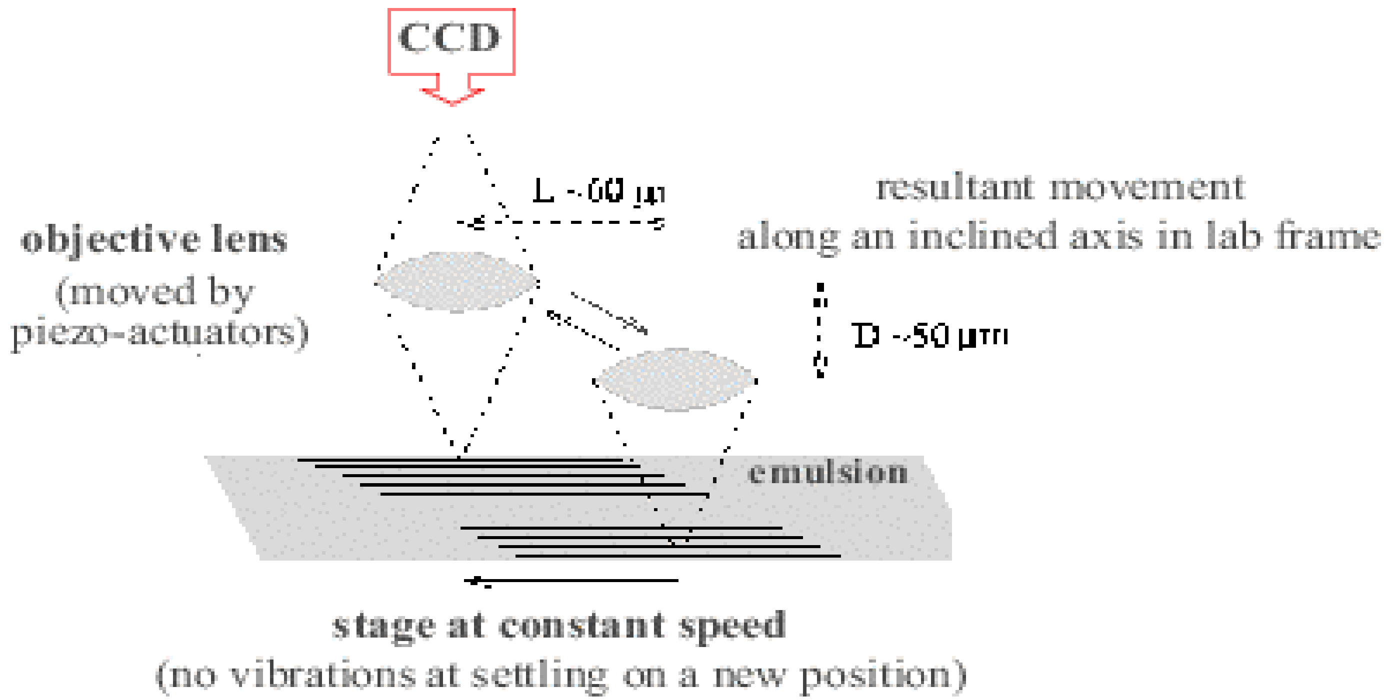
~ 23 million lead plates + emulsion sheets
~ 206,000 bricks at a rate of ~ 2 bricks/minute



- **SPECS document completed end 2002**
- **BAM suppliers are allowed to propose alternative for packaging material following European standard safety rules**
- **Studies with companies for laminated paper, welding tools, glues**
- **~10 companies are working for the preselection round**

Automatic scanning in Nagoya : the new mechanical concept

(take images without stopping the stage, to increase the speed)

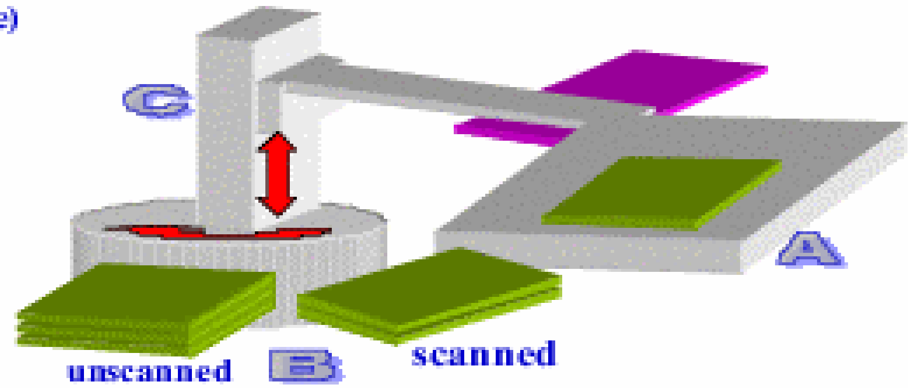


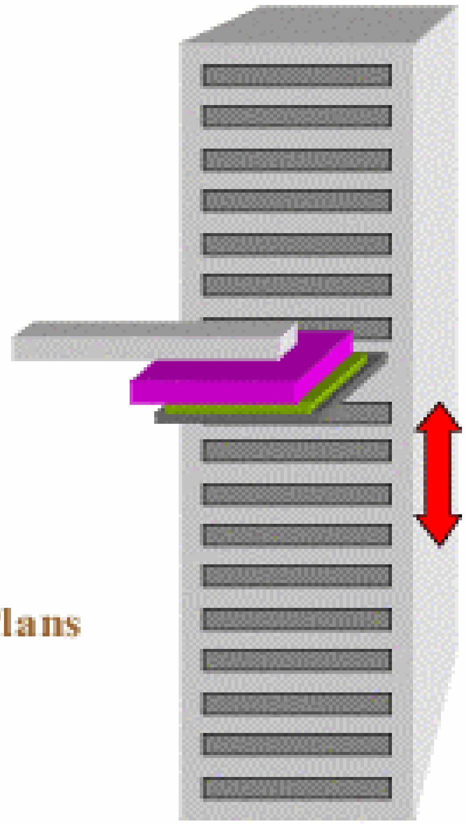
Objective and stage movements <u>have to be synchronised</u>

Emulsions are scanned vertically, in <u>their</u> reference frame

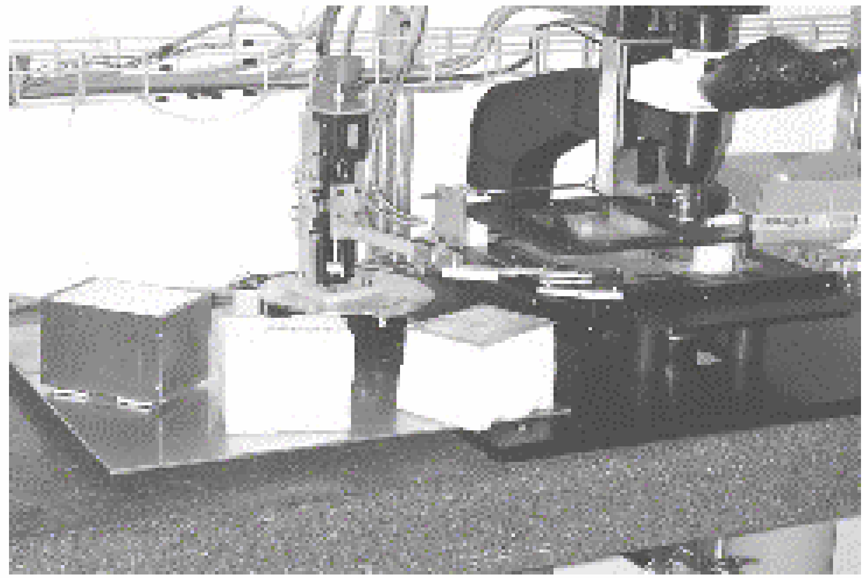
Automatic Emulsion Handling and Changing System

A: Vacuum holder (on the microscope)
B: Emulsion handling system
C: Emulsion changing system





Future Plans



Expected number of events

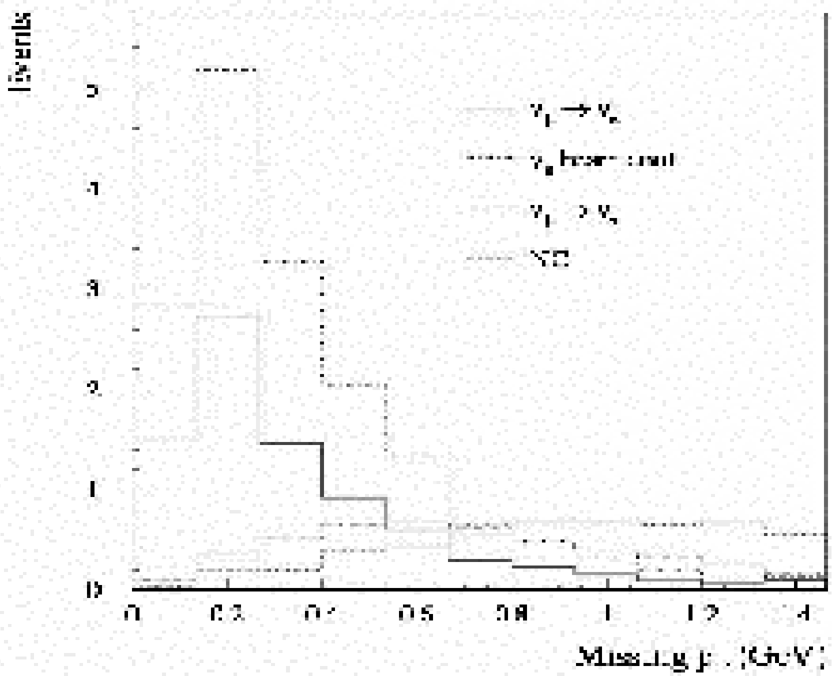
- full mixing
- 5 years run @ 6.76×10^{19} pot / year

	signal ($\Delta m^2 = 1.8 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 2.5 \times 10^{-3}$ eV^2)	signal ($\Delta m^2 = 4.0 \times 10^{-3}$ eV^2)	Back
Final Design	9.0	17.2	43.8	1.06
With possible improvements	10.3	19.8	50.4	0.67

Aim at the evidence of ν_τ appearance after a few years of data taking

OPERA sensitivity to θ_{13}

By fitting simultaneously the E_e, missing p_T and E_{vis} distributions we got the sensitivity at 90%



Limits at 90% C.L. on $\sin^2 2\theta_{13}$ and θ_{13}
($\Delta m^2_{23}=2.5\times10^{-3}$ eV^2; $\sin^2 2\theta_{23}=1$)

Experiment	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	< 0.14	< 11°
MINOS 2 yr	< 0.06	< 7.1°
ICARUS 5 yr	< 0.03	< 5.8°
OPERA 5 yr	< 0.05	< 7.1°
CNGS 5 yr	< 0.025	< 4.5°
JHF 5 yr	< 0.006	< 2.5°

Conclusions

➢ Achieved

- Studies and construction of full scale prototypes
- Detector design
- Progress in automatic scanning in Europe and Japan
- τ detection efficiency improved since CNGS approval

➢ Detector construction and installation

- Large and complex detector ready to be installed
- Detector (and CNGS beam !) will be ready in 2006
- Strong support still needed
- Scanning strategy to be optimised

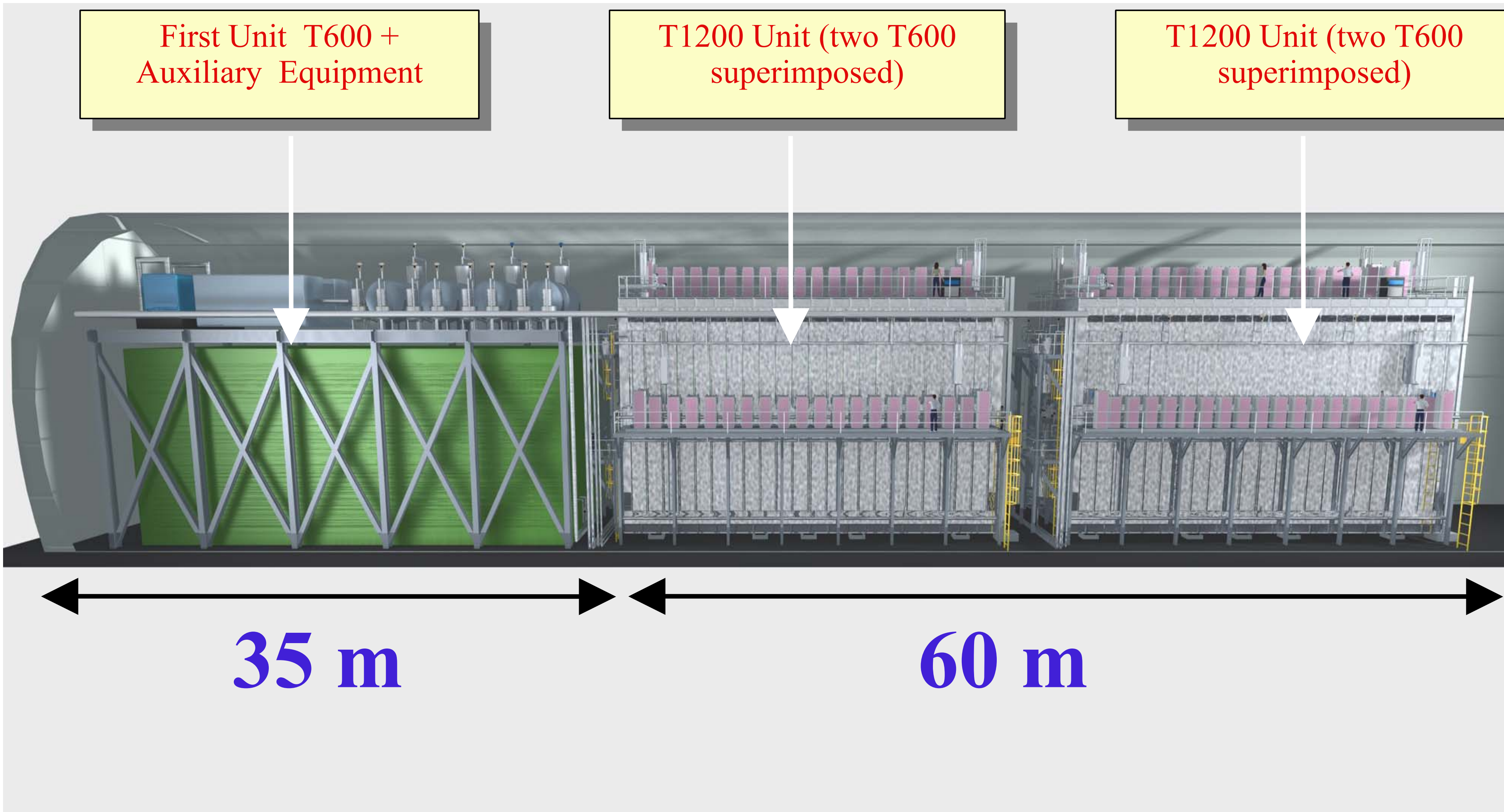
➢ Important Physics Program

- First evidence of ν_μ-ν_τ appearance in few years data taking
- In a five year run: 17.2 signal (SK best fit) and 1.06 background events
- Studies to improve efficiency ($\rightarrow$ 19.8 evts and background ($\rightarrow$ 0.67)
- Significant measurement of θ_{13}

Very low background is the key issue

ICARUS

ICARUS detector configuration at LNGS Hall B (T3000)



Liquid Argon TPC properties

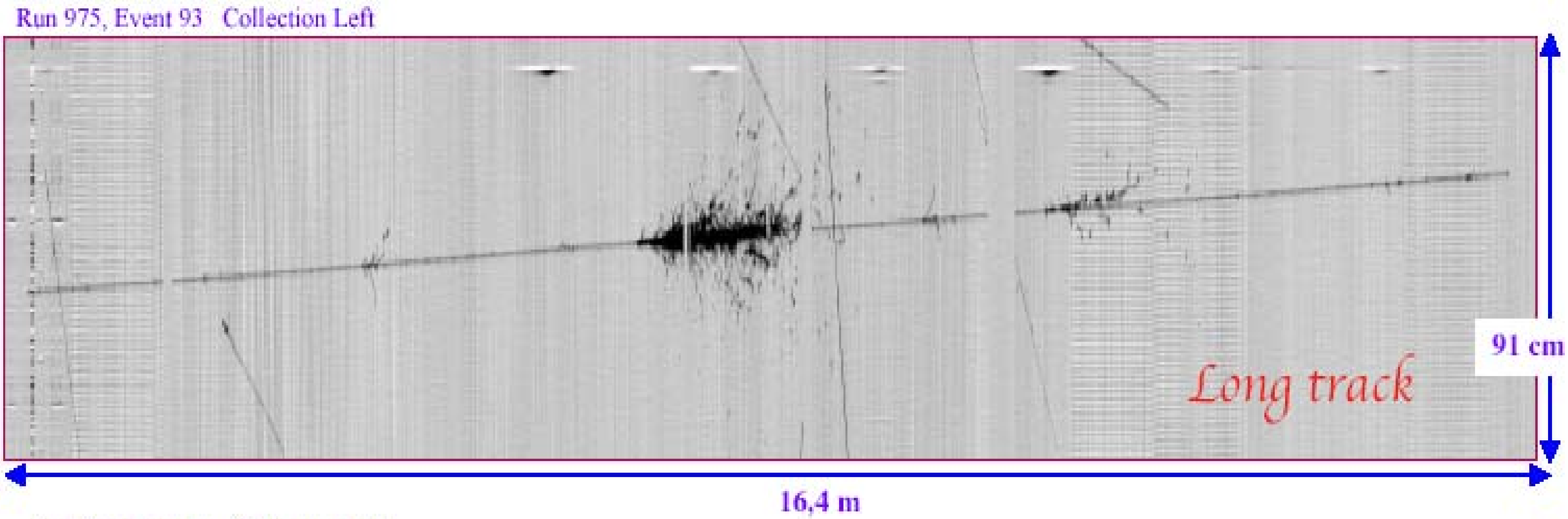
- High density, heavy ionization medium
  - ρ = 1.4 g/cm^3, X_0=14 cm, λ_{int} = 80 cm
- Very high resolution detector
  - 3D image 3 x 3 x 0.6 mm^3 (400 ns sampling)
- Continuously sensitive
- Self-triggering or through prompt scintillation light
- Stable and safe
  - Inert gas/liquid
  - High thermal inertia (230 MJ/m^3)
- Relatively cheap detector
  - Liquid argon is cheap, it is only "stored" in the experiment
  - TPC: # of channels proportional to surface
- Cryogenic temperature
  - T = 88 K at 1 bar
- High purity required for long-drift time
  - 0.1 ppb of O_2 equivalent for 3 ms drift
- No signal amplification in liquid
  - 1 m.i.p. over 3 mm yields 20000 electrons
  - equivalent noise charge 1200 electrons

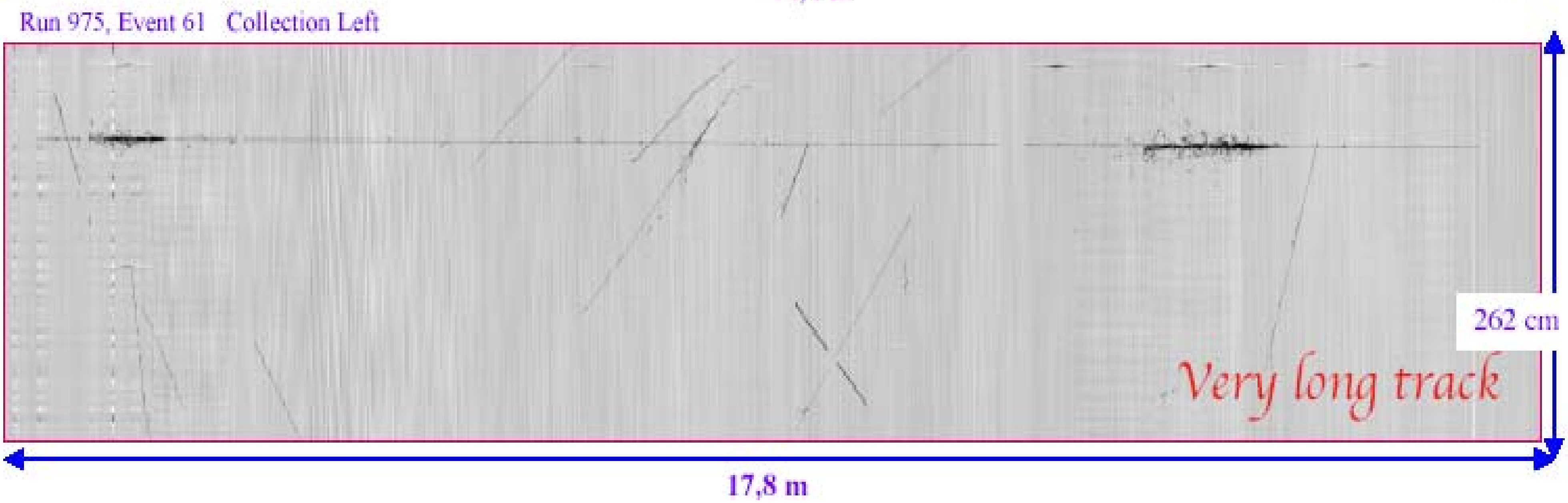
Cryogenic plant

Argon purification

Low noise electronics

“Electronic” bubble chamber





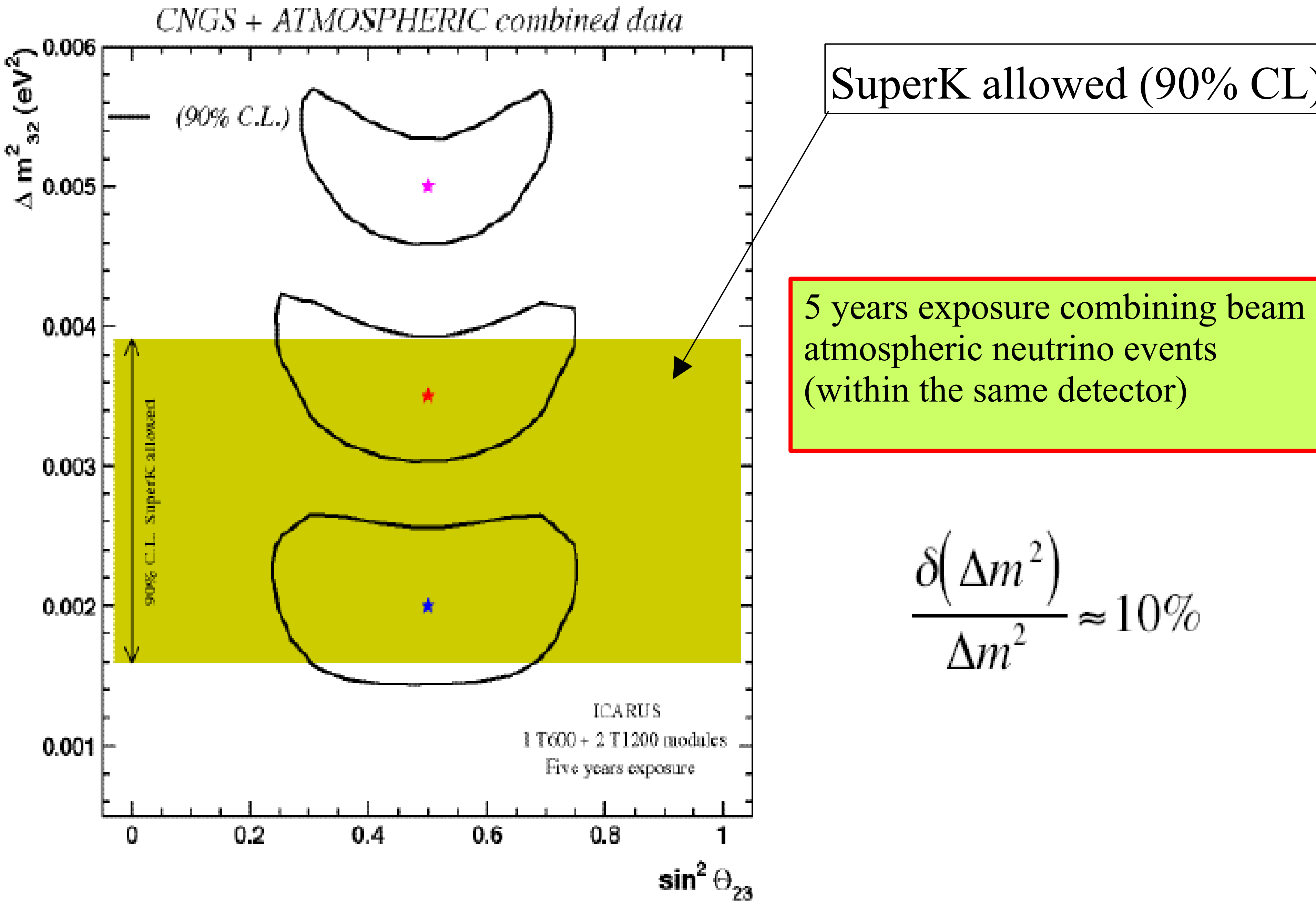
CNGS $\nu_\mu \rightarrow \nu_\tau$ appearance search

- T3000 detector (2.35 kton active, 1.5 kton fiducial) 5 years running
- Integrated pots = 2.25 x10^{20}, about 33000 CC neutrino interactions
- 280 CC τ interactions for Δm^2_{23}=3 x 10^{-3} eV^2 and max. mixing
- Several decay channels are exploited (electron = golden channel)
- (Low) backgrounds measured in situ (control samples)
- High sensitivity to signal, and oscillation parameters determination

Super-Kamiokande: 1.6 < Δm^2 < 4.0 at 90% C.L.

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	BG
$\tau \rightarrow e$	3.7	9	13	23	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

Oscillation parameters determination



5 years exposure combining beam and atmospheric neutrino events (within the same detector)

$$\frac{\delta(\Delta m^2)}{\Delta m^2} \approx 10\%$$

Search for subleading $\nu_\mu \rightarrow \nu_e$

- Search for excess of electrons, on top of τ electronic decays
- Takes advantage of unique e/π separation in ICARUS
- Assume 5 years @ 4.5×10^{19} pots/year, 2.35 kton fiducial
- Limited by statistics: needs more intensity (low E) to exploit ICARUS features

$\Delta m^2_{32} = 3 \times 10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1$

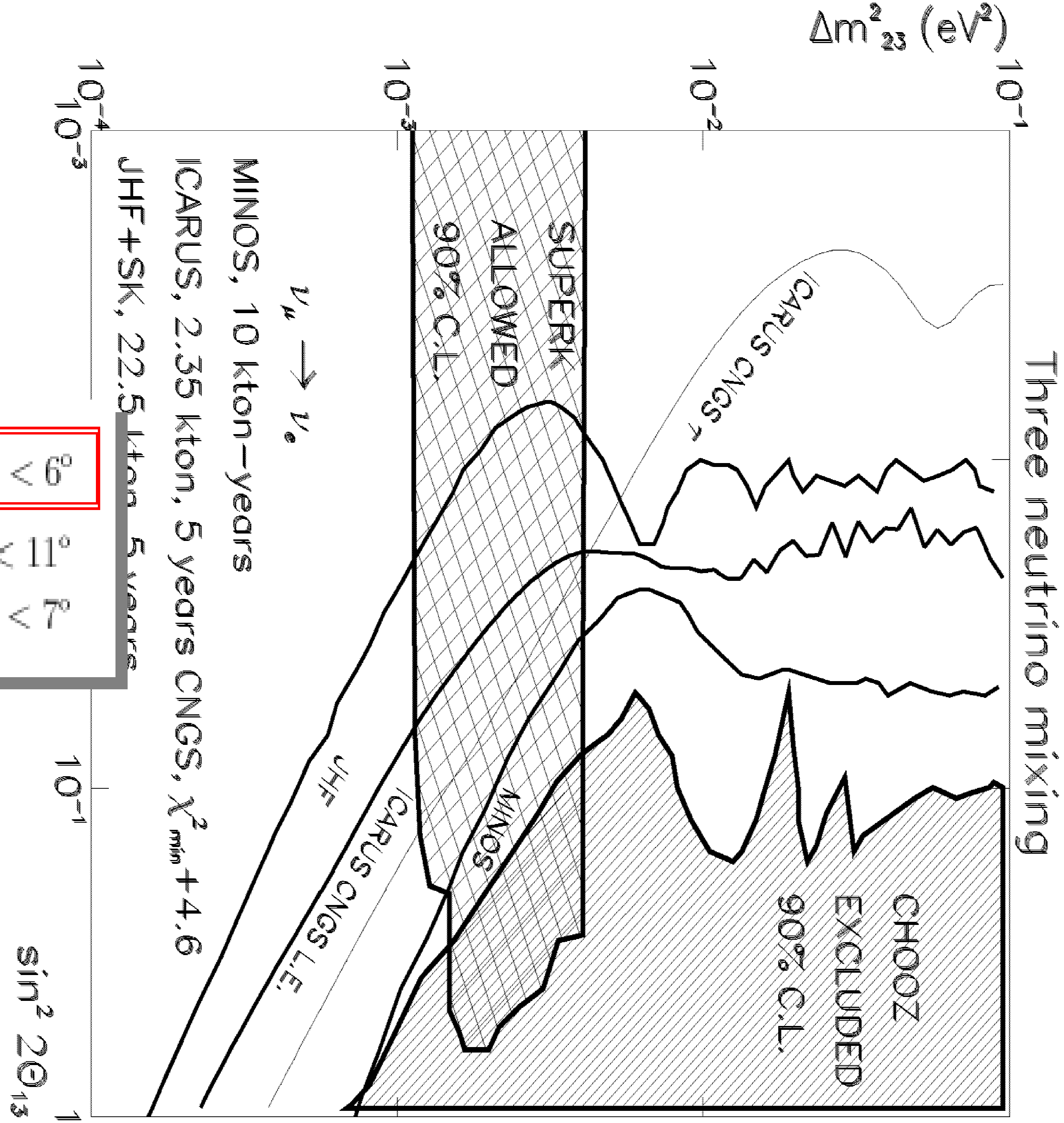
θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \rightarrow \nu_e$	
		$E_\nu < 4$ GeV	$E_\nu < 50$ GeV	$E_\nu < 4$ GeV	$E_\nu < 50$ GeV
9	0.095	1.5	150	4	42
8	0.076	1.5	150	3.1	34
7	0.059	1.5	150	2.4	26
5	0.030	1.5	150	1.2	14
3	0.011	1.5	150	0.4	5
2	0.005	1.5	150	0.2	2.2
1	0.001	1.5	150	0.1	0.5

For Δm^2_{23} = 2.5 x 10^{-3}

$$(\sin^2 2\theta_{13})_{CNGS,\tau} < 0.04 \quad \text{or} \quad \theta_{13} < 6^\circ$$

$$(\sin^2 2\theta_{13})_{CHOOZ} < 0.14 \quad \text{or} \quad \theta_{13} < 11^\circ$$

$$(\sin^2 2\theta_{13})_{MINOS} < 0.06 \quad \text{or} \quad \theta_{13} < 7^\circ$$



Conclusions

After many fruitful years of R&D the ICARUS Collaboration has operated at surface a large mass (300 ton) liquid Argon TPC proving that the scaling from prototypes to full scale detectors is successful. The ICARUS agenda now foresees:

- the completion of the 2^{nd} 300 ton half-module to form the T600 detector
- operation with the T600 at LNGS with data taking of astrophysical events by 2003
- the progressive realisation of two additional T1200 modules, with the T600 as basic cloning unit, to be operational by 2006

Thanks to the potential offered by the LAr technology, ICARUS will be able to perform a vast physics program in the domain of

- nucleon decay
- atmospheric neutrinos
- solar and supernovae neutrinos
- accelerator neutrinos

ICARUS will run with the CNGS beam from 2006 to

- provide real-time study of the beam properties
- search for $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ flavor appearance
- further future: exploit ICARUS with a LE beam for an improved measurement of the subleading $\nu_\mu \rightarrow \nu_e$ oscillation

FINAL Conclusions

- We have just begun to learn about neutrinos
- Many questions remain to be answered
- MiniBooNE will be a definitive test of LSND $\Rightarrow$
  New Physics Beyond the Standard Model?!?
- NuMI/MINOS will be a definitive test for atmospheric
  ν oscillations $\Rightarrow$ Precision oscillation parameters!
- CNGS/OPERA/ICARUS will be a definitive test for
  atmospheric $\nu_\mu \rightarrow \nu_\tau$ oscillations $\Rightarrow$ τ appearance!
- The results from these experiments will lead to a rich
  program at a future Neutrino Factory