Experimental challenges for future neutrino experiments

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William & Mary

11th International Workshop on
Neutrino Factories, Superbeams & Beta Beams

Illinois Institute of Technology *
July, 20th 2009

Outline

- Scope
- Solutions for recent & current experiments
  - > Introduce the technologies & their accomplishments
  - > Needs for further improvement and limitations
- The next generation's solutions
- Goals for the future
  - > The delivery of neutrinos [cartoon]
  - > The targeted physics
  - > The experimental challenges
  - > Moving forward

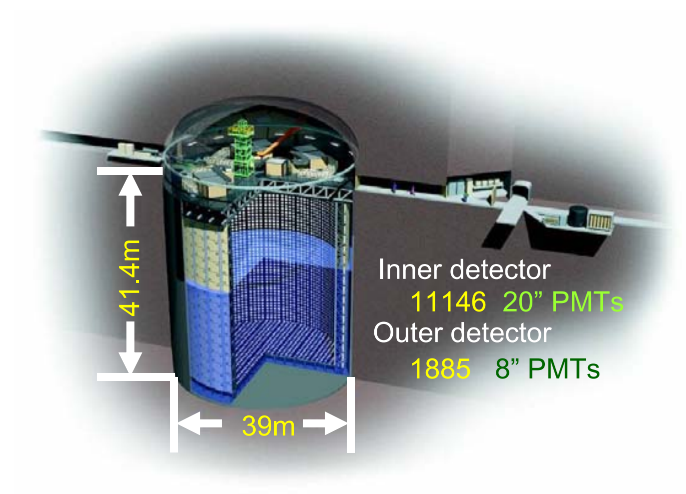
Things I want to talk about …

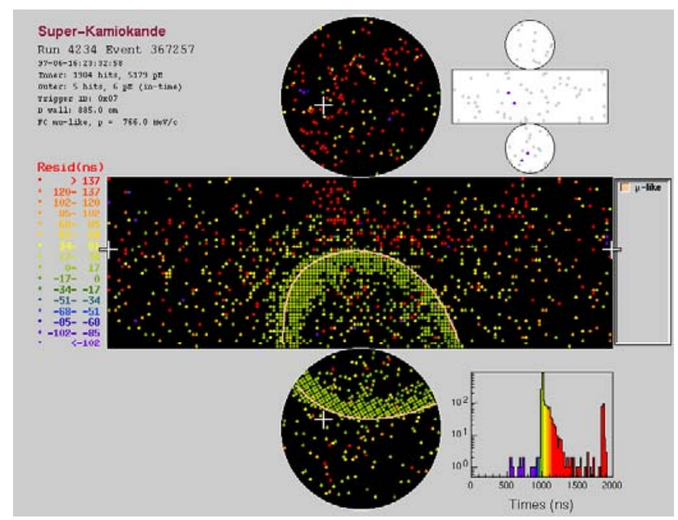
- The primary focus of the conference is neutrino oscillation measurements using accelerator-based neutrino beams
  - > Measure the parameters of neutrino oscillations
  - > Can we become sensitive enough to observe CP violation in neutrinos?
- This accelerator-based beams are not the whole game when it comes to neutrino measurements
  - > Throw other techniques and measurements in - as needed to reach our goals
  - > Will not be talking about neutrino astronomy, or particle astrophysics, double beta decay, cosmology, very low energy experiments and cross section, and many other really interesting things
  - > Will not focus on all of the possibilities for exotic oscillation models
  - > No coverage of muon physics, just a bit on neutrino interactions and beam production
    - Whole working groups on these at the conference

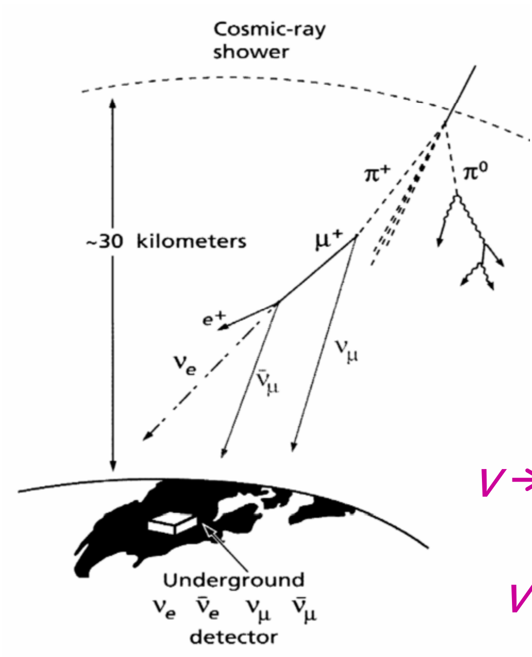
Let's start with a classic: Atmospheric neutrinos & SuperK

- Sees angle dependent deficit of muons from ν_{atm}
  - > Water Cherenkov detector
  - > Charged particles above threshold give light

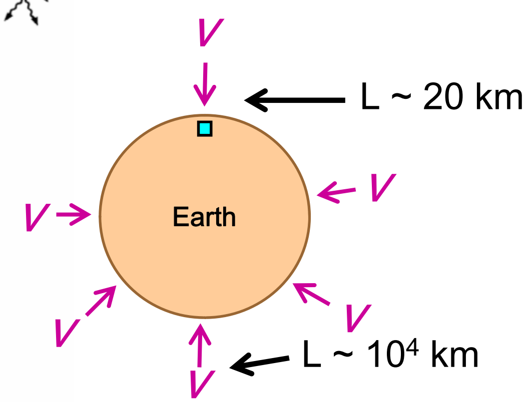
Super-Kamiokande





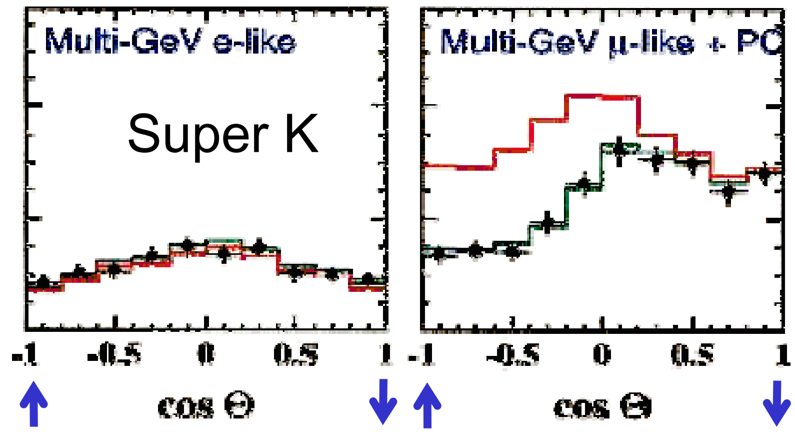


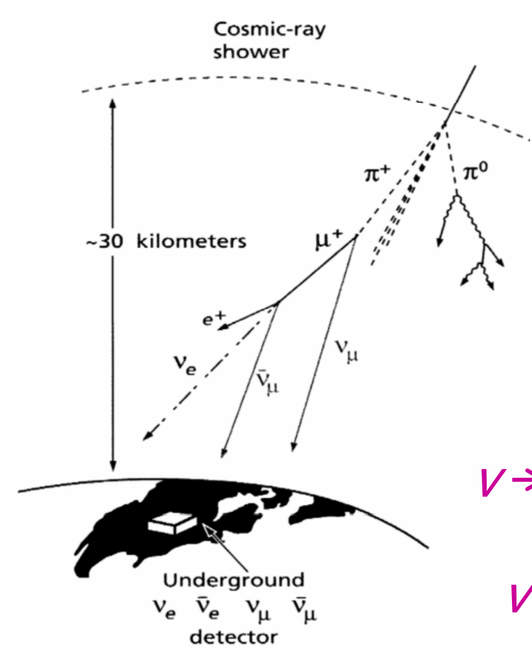
LANL graphic



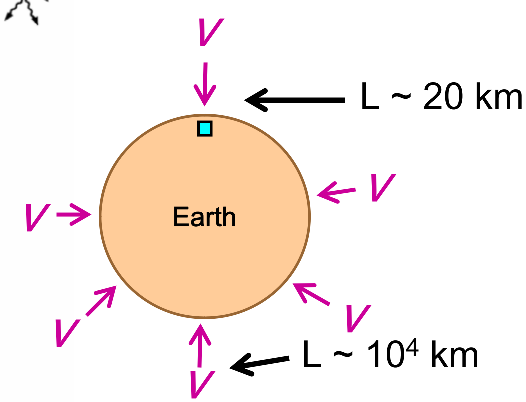
Let's start with a classic: Atmospheric neutrinos & SuperK

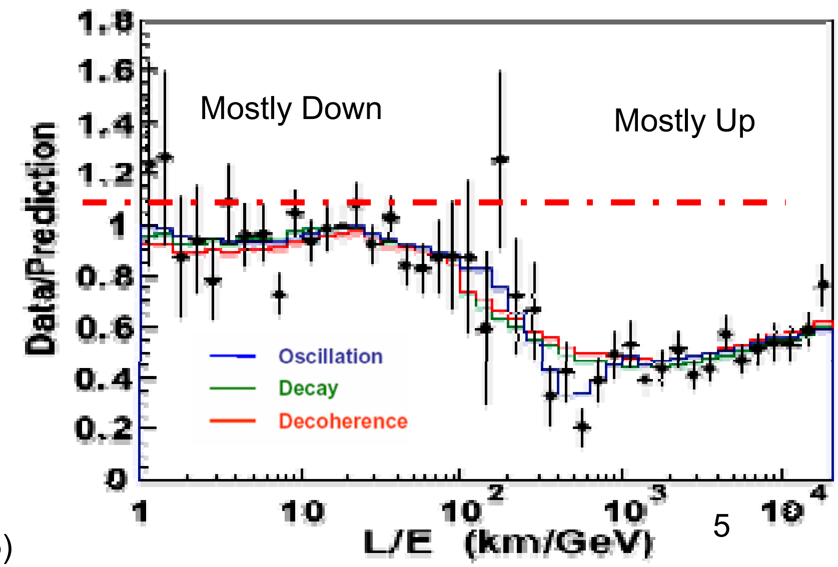
- Sees angle dependent deficit of muons from ν_{atm}
  - > Electrons show no effect
- Seen by 4 other experiments
  - > Some using sampling devices too





LANL graphic





PRL **93**, 101801 (2004) & PRD **71**, 112005 (2005)

Setting the stage: a slide from Mark Messier's NSS09 course on neutrino detectors

Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu, ...)\epsilon(E_\nu, ...)dE_\nu d... \right] \frac{M}{A\, m_N} T$$

N_{obs}	:	number of neutrino events recorded
$\mathcal{F}$	:	Flux of neutrinos ($\#/\mathrm{cm}^2/\mathrm{s}$)
σ	:	neutrino cross section per nucleon $\simeq 0.7 \frac{E_\nu}{[\mathrm{GeV}]} \times 10^{-38}\mathrm{cm}^2$
ϵ	:	detection efficiency
M	:	total detector mass
A	:	effective atomic number of detector
m_N	:	nucleon mass
T	:	exposure time

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{1}{\mathrm{cm}^2\mathrm{s}}\right] \left[0.7 \times 10^{-38} \frac{E_\nu}{\mathrm{GeV}} \mathrm{cm}^2\right] [\epsilon]\, [1\ \mathrm{GeV}] \left[\frac{M}{20 \cdot 1.67 \times 10^{-27}\ \mathrm{kg}}\right] [2 \times 10^7\ \mathrm{s}]$$

$$N_{\rm obs} = 4 \times 10^{-6} \frac{E_\nu}{[\mathrm{GeV}]} \epsilon \frac{M}{\mathrm{kg}}$$

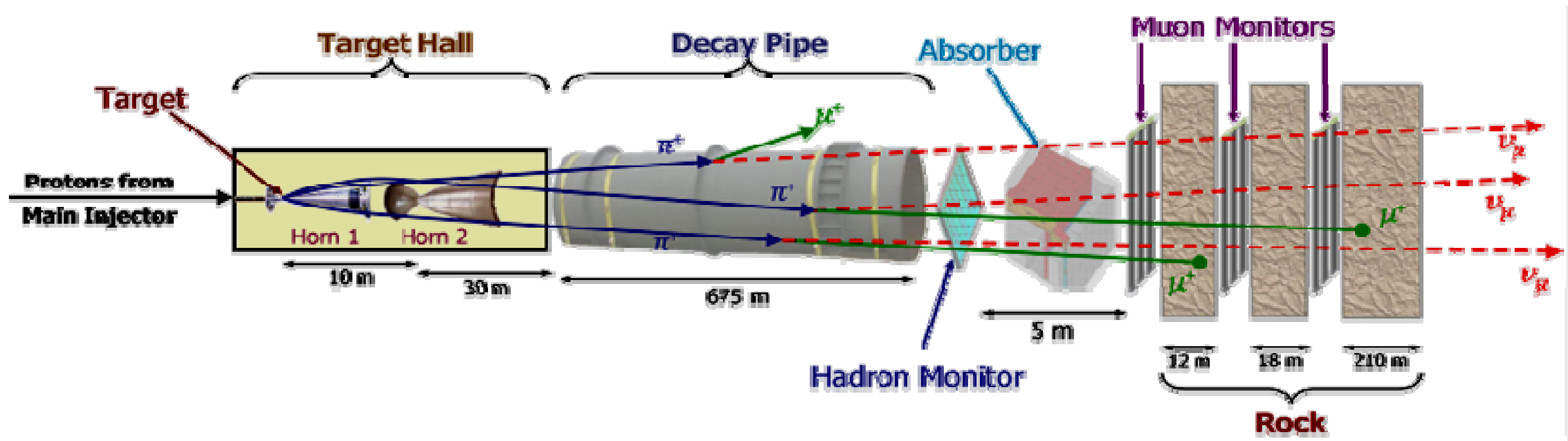
need detector masses of 10^6 kg = 1 kton to get in the game

work at high energies if you can

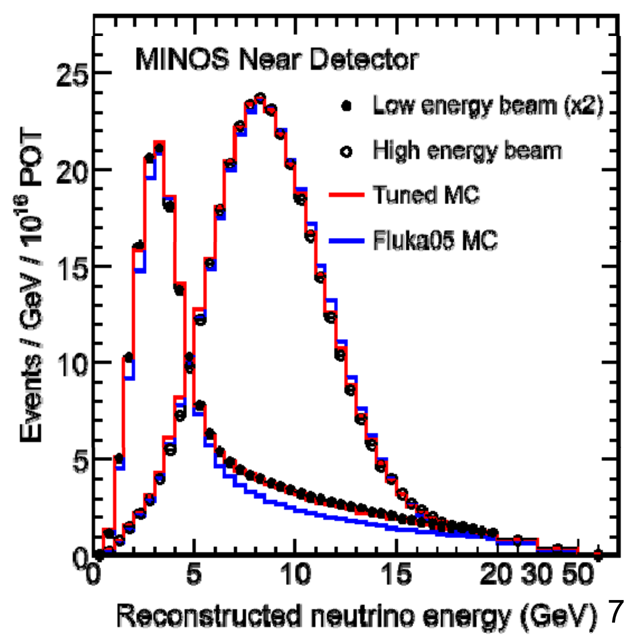
push this as high as you can

Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost

Producing the neutrino beam (NuMI)



- 120 GeV protons strike target
  - > 10 μs pulse every ~2.2s
  - > Typically running at 3e13 protons/pulse
- 2 magnetic horns focus secondary *π/K*
- *π/K* decays produce neutrinos
  - > Moveable target & horn provides variable beam energy
    - Used to constrain the hadron production & flux

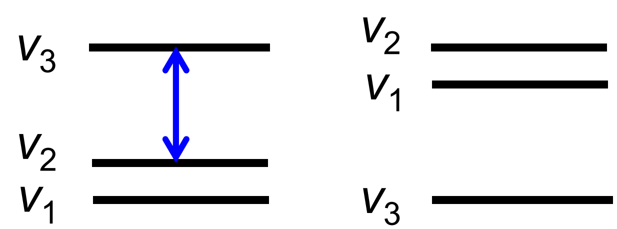


Basic LBL Physics Goals

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - > Measure precisely $|\Delta m^2_{32}|$ & $\sin^2 2\theta_{23}$
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for / constrain exotic phenomena
- Compare ν, $\bar{\nu}$ oscillations

- 2 detectors
  - ν_μ beam from meson decay
  - Near Detector
    - Measures flux × cross section
  - Far Detector
  - Measures distortions WRT the Near Detector predictions

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



$\Delta m^2_{32} = m_3^2 - m_2^2$

Useful Approximations

ν_μ disappearance (2 flavors):

$$P(\nu_\mu \rightarrow \nu_x) = 1 - \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32}\, \mathbf{L}/\mathbf{E})$$

ν_e appearance:

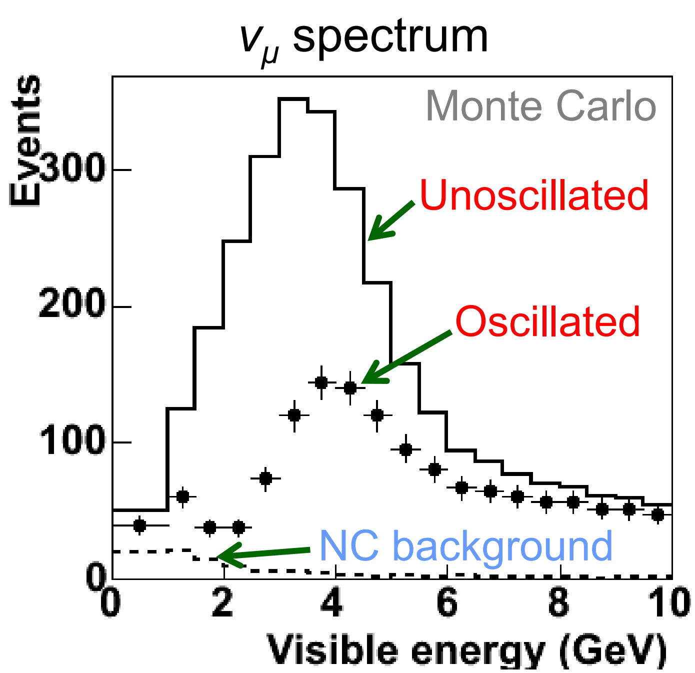
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31}\, \mathbf{L}/\mathbf{E})$$

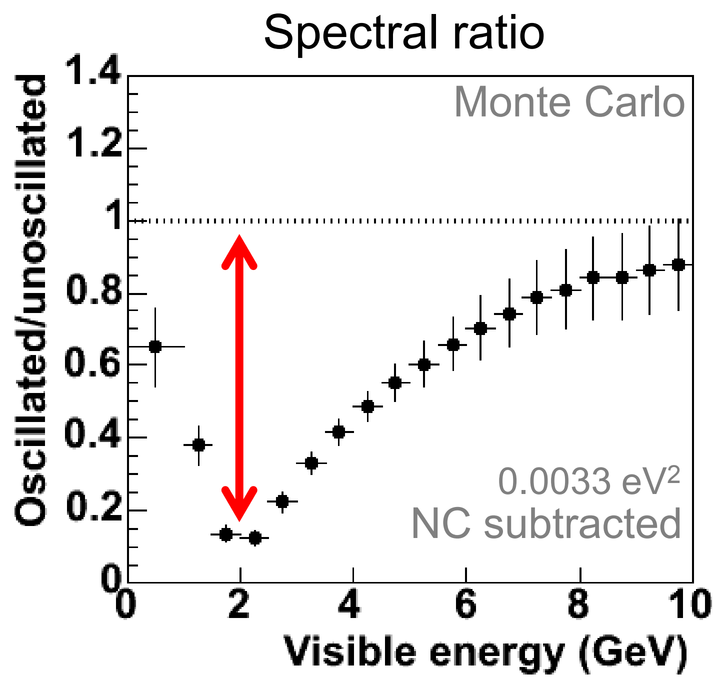
where **L**, **E** are experimental parameters & θ_{23}, θ_{13}, Δm^2_{32} are to be determined

Example of a disappearance measurement

Look for a deficit of ν_μ events at a distance…

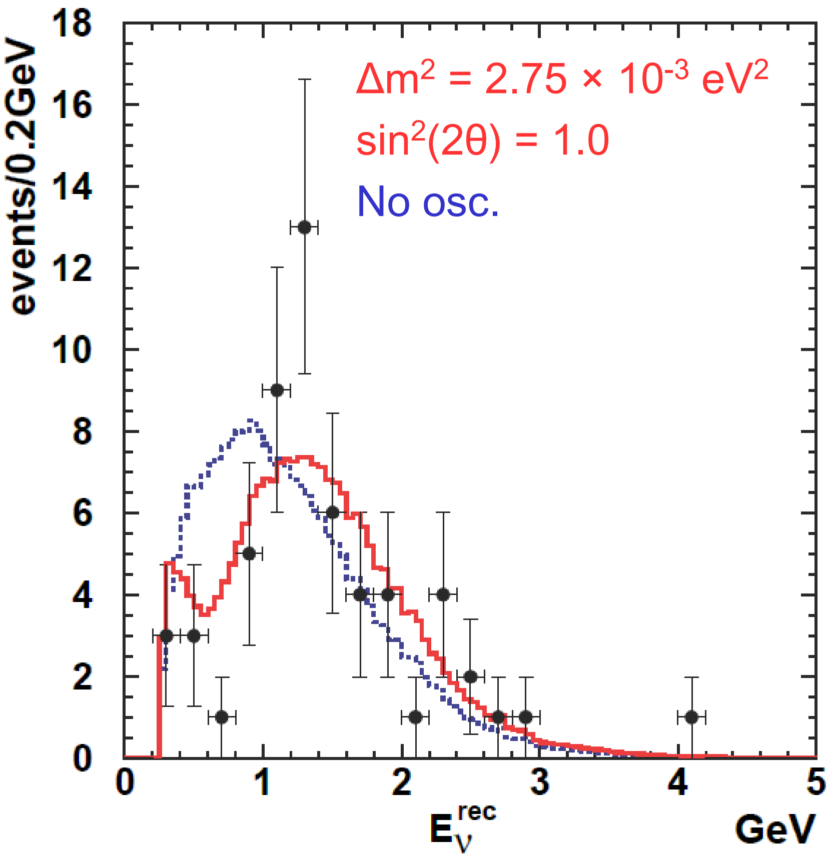
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.267 \Delta m^2 L / E)$$



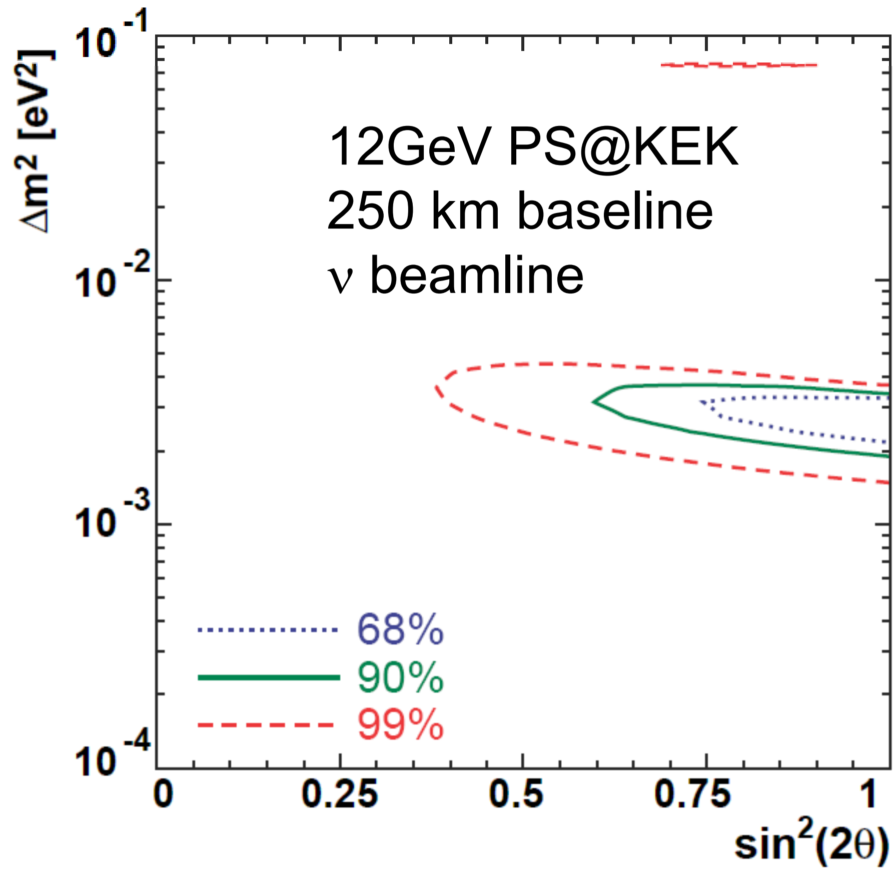


K2K
1st Long-Baseline Experiment

Based on 1.04 x 10^{20} POT 1999 - 2004



112 Observed & 158±9 Expected

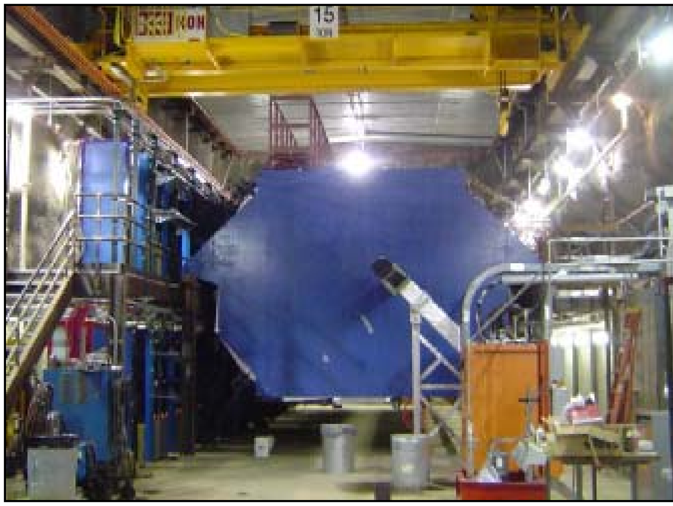


90% C.L. limits

$1.9 < \Delta m^2_{23} < 3.5 \times 10^{-3}$ eV^2

Phys. Rev. D **74**, 072003 (2006)

MINOS Detectors



Far Detector

5.4 kton

$8 \times 8 \times 30$ m^3

484 planes

Iron and Scintillator tracking calorimeters

2.54 cm thick steel target/absorber/magnet/structural plates

magnetized steel planes <B> = 1.2T

1×4.1 cm^2 scintillator strips, WLS fiber readout

Multi-anode PMT readout

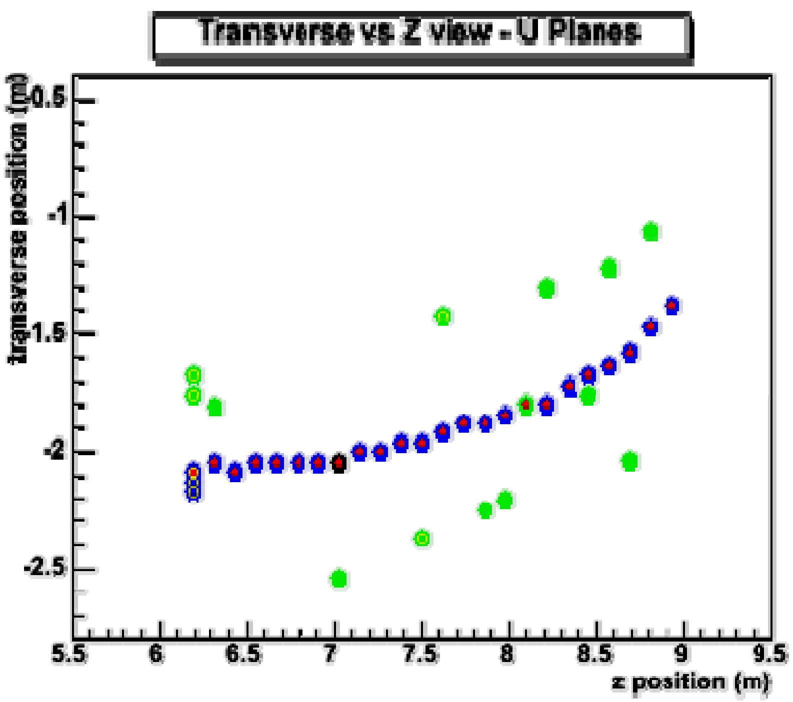
A 2 GeV ν_μ event in the far detector

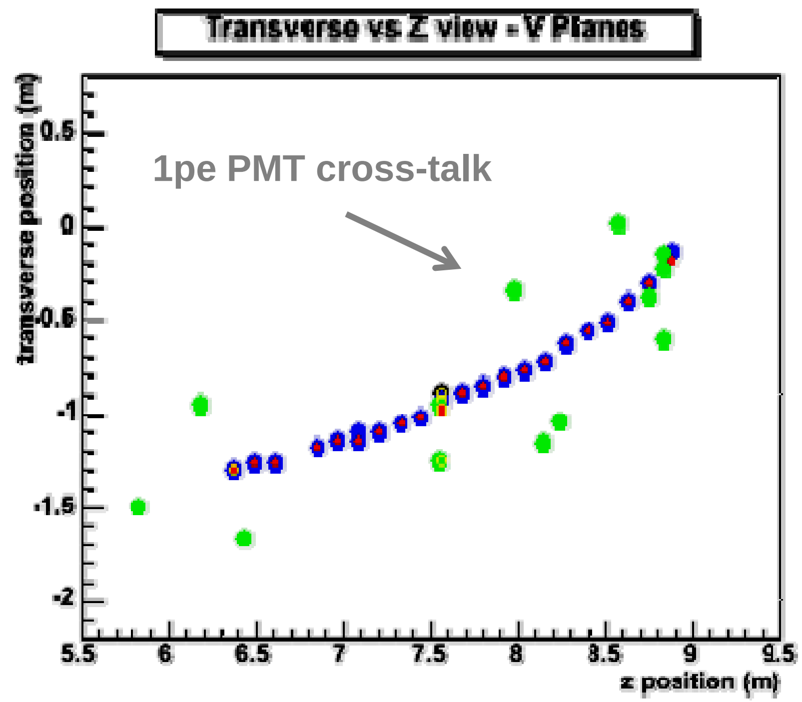
Track Energy 2.04 GeV

Shower energy 0.20 GeV

q/p = -0.52 ± 0.03

- < 2 PE
- 2 < PE < 20 PE
- > 20 PE
- Track hit



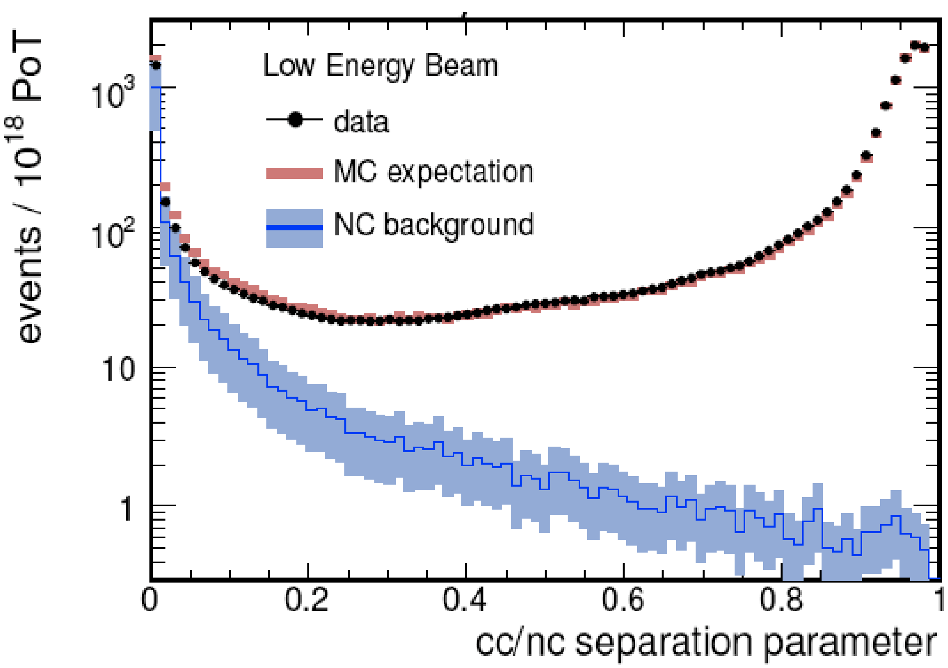


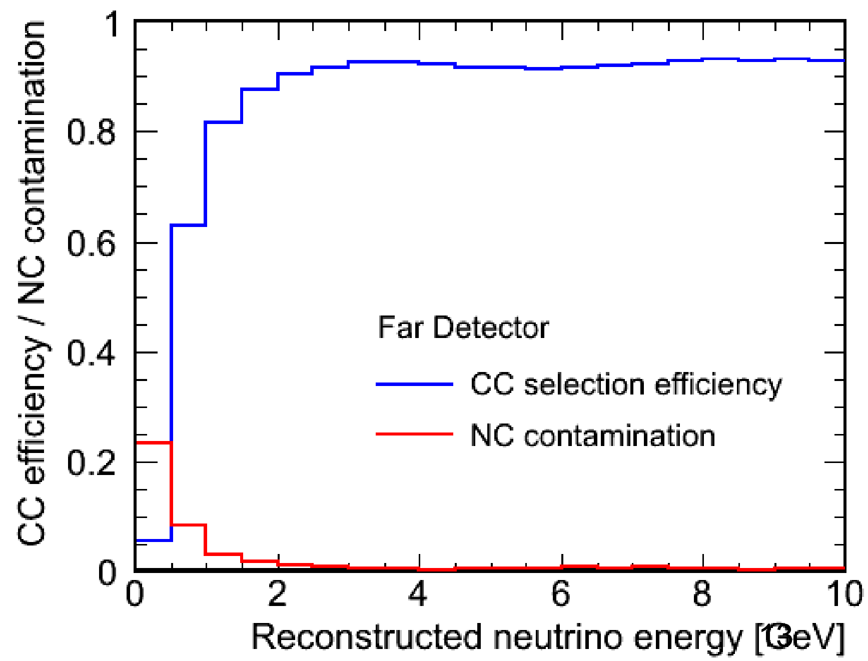
Charged current event selection

- A Particle ID (PID) parameter is defined

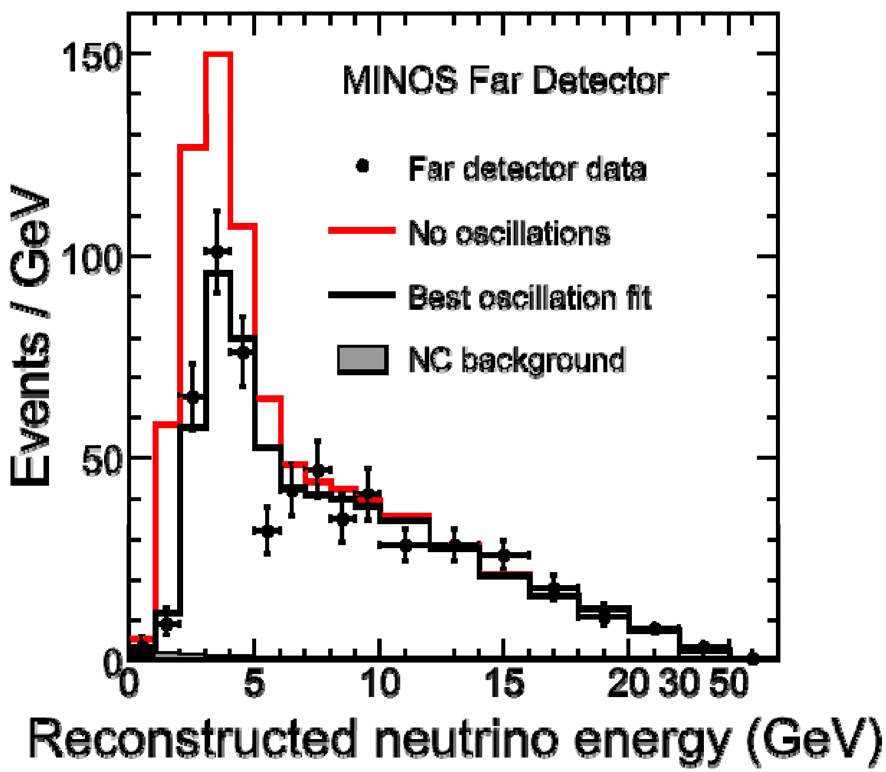
$$PID = -\left(\sqrt{-\log(P_{\mu})} - \sqrt{-\log(P_{NC})}\right)$$

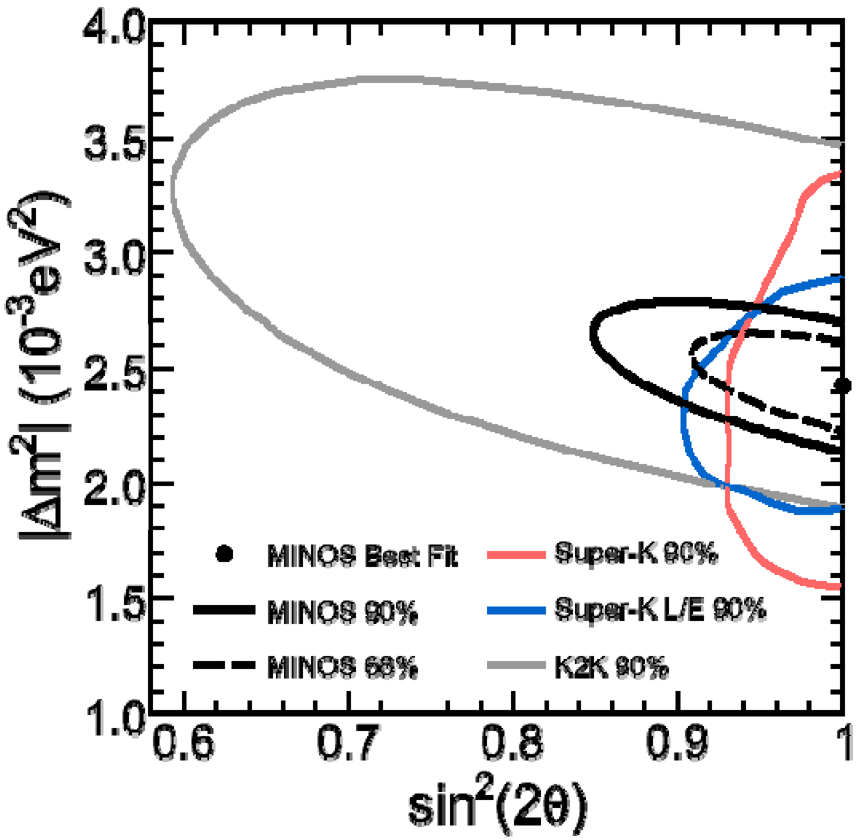
- CC-like events are defined by PID>0.5
  - NC contamination is limited to the lowest bins
  - Selection efficiency is quite flat as a function of visible energy above 1 GeV





MINOS best-fit spectrum
3.36×10^{20} POT



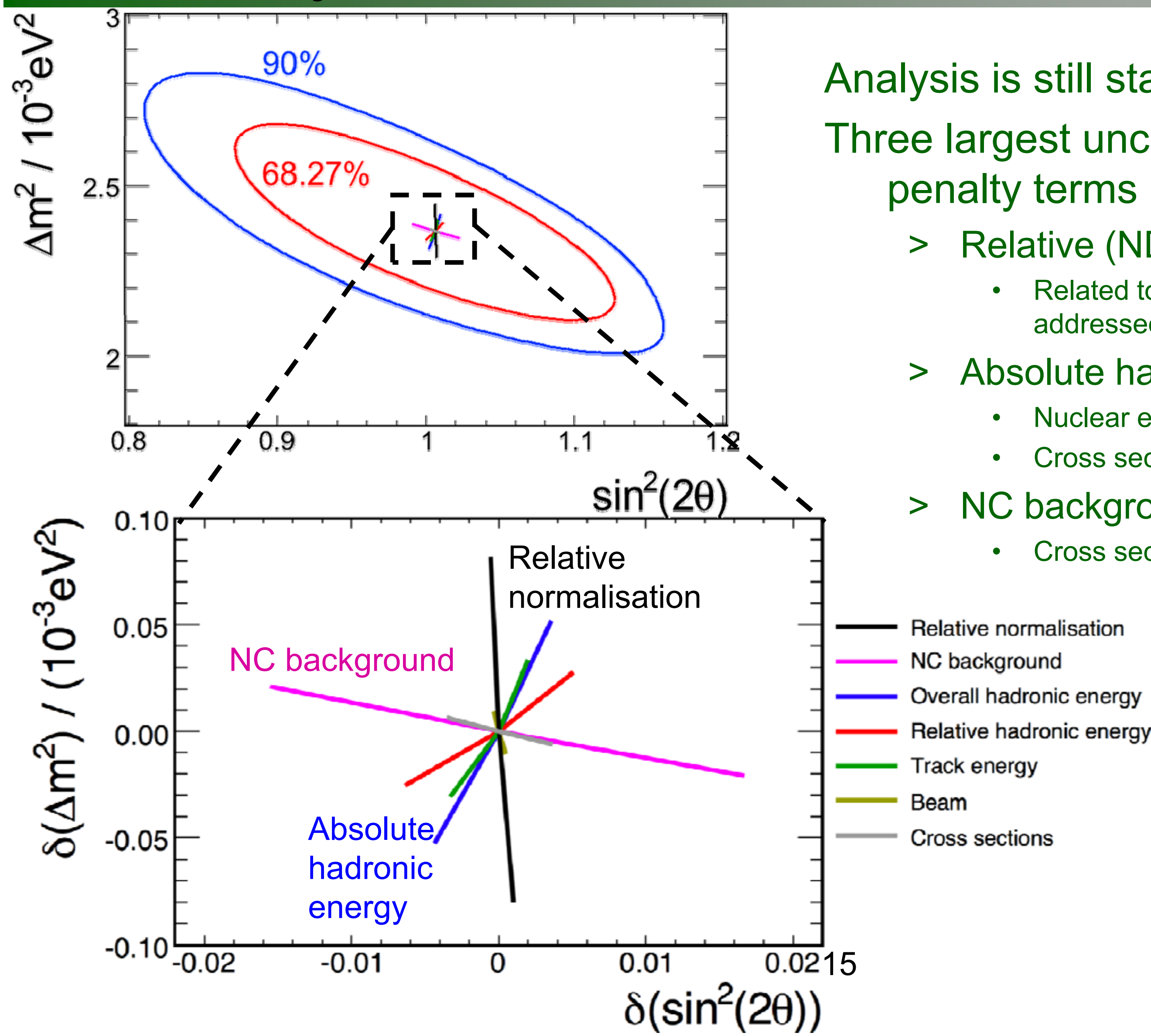


$$\left|\Delta m^2_{32}\right| = 2.43 \pm 0.13 \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} > 0.90\ (90\%\ \mathrm{C.L.})$$

PRL 101, 131802 (2008)

Systematic Uncertainties in MINOS



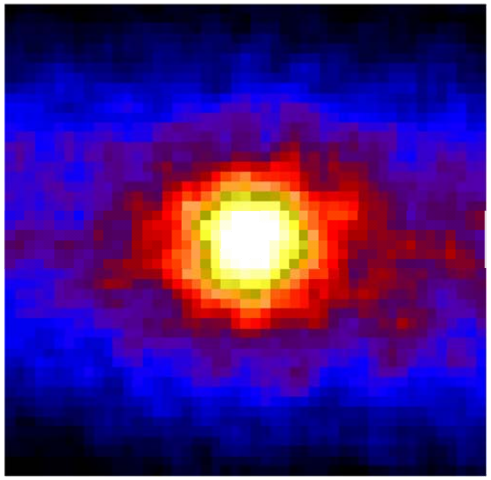
Analysis is still statistically limited

Three largest uncertainties included as penalty terms in fit to data

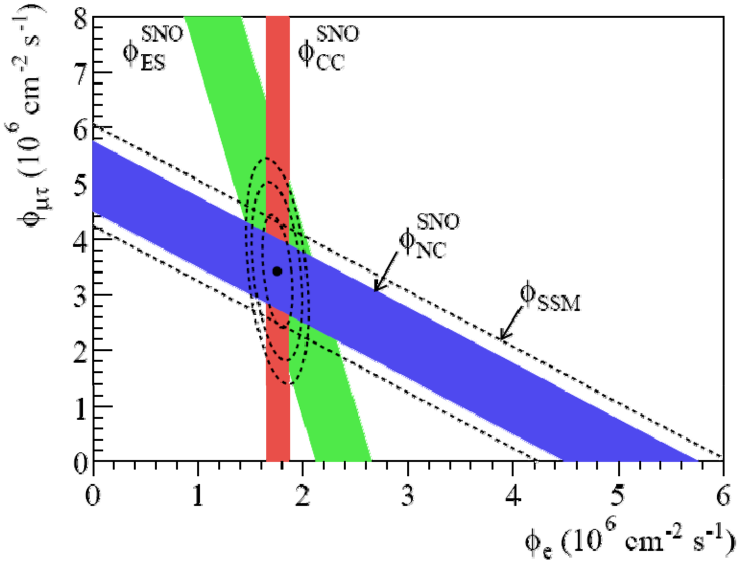
- > Relative (ND to FD) normalisation (4%)
  - Related to reconstruction knowledge and being addressed
- > Absolute hadronic energy scale (10%)
  - Nuclear effects, blocking, FSI,
  - Cross sections
- > NC background (50%)
  - Cross sections

Solar Neutrino Experiments

- Solar electron neutrinos seen by various techniques
  > Radiochemical
  > Electron neutrino scattering
  > Charged current scattering
  > Rates and spectrum different than standard solar model
- Solved by the SNO experiments
  > It's the neutrinos changing flavor
  > NC interactions
  > The total flux is right

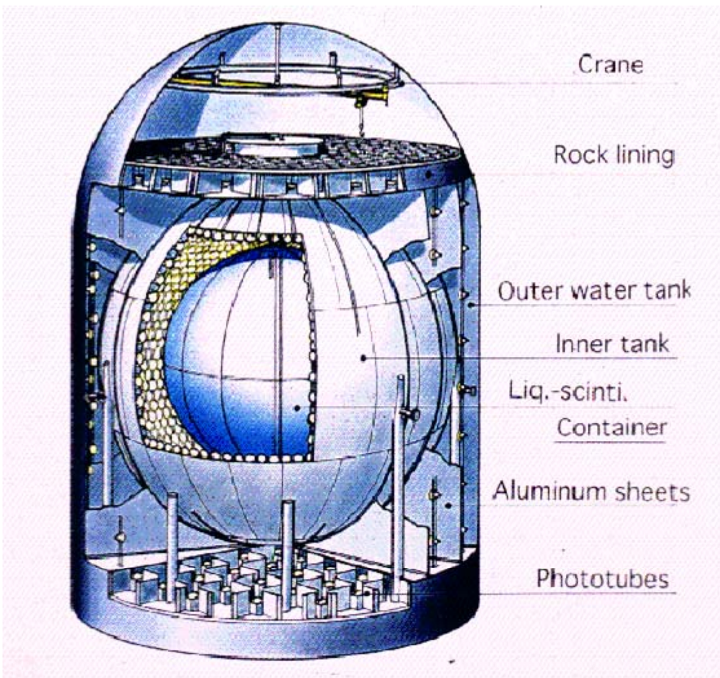


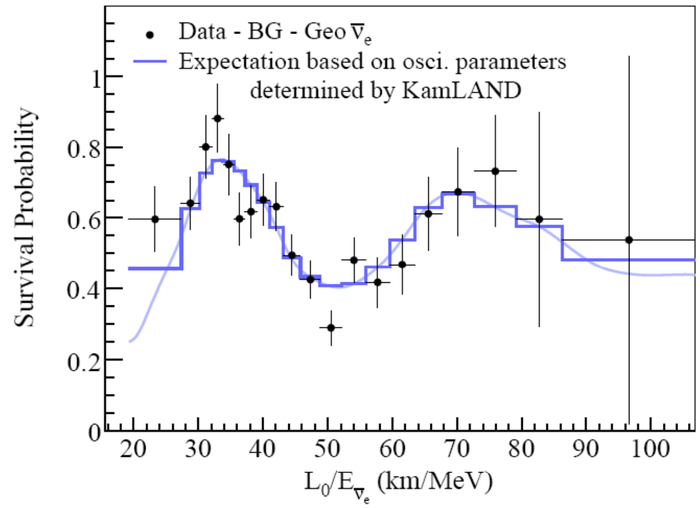
The sun imaged with neutrinos
(courtesy R.Svoboda and the SK collab.)

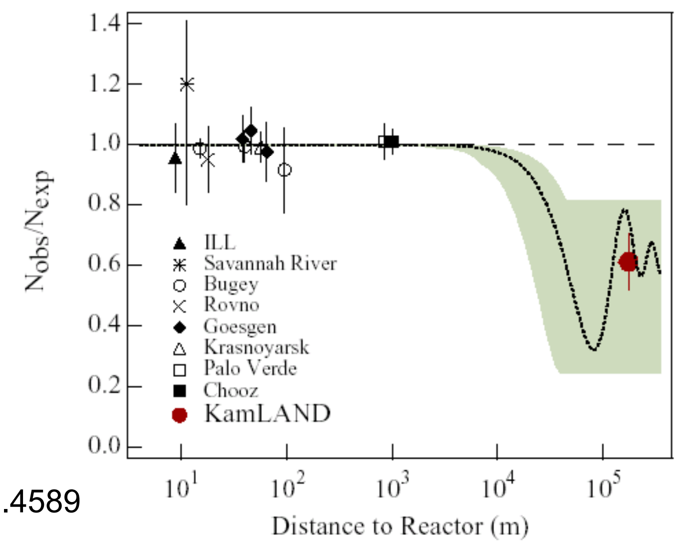


KamLAND's results

- Inverse beta decay 1609 events observed
- Expectations w/o oscillations was 2450±90
- Spectrum consistent with Solar results
- See the oscillation signal's dip and raise …



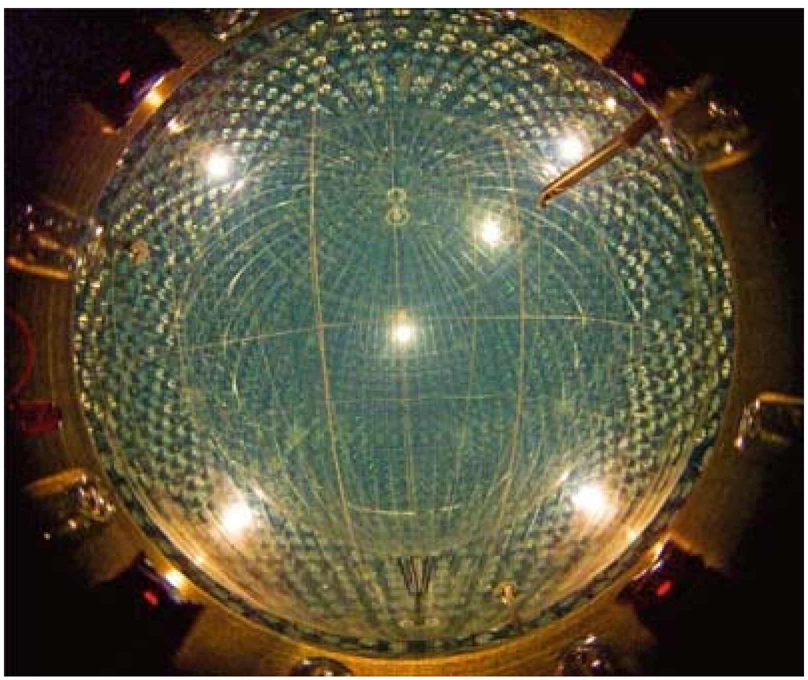


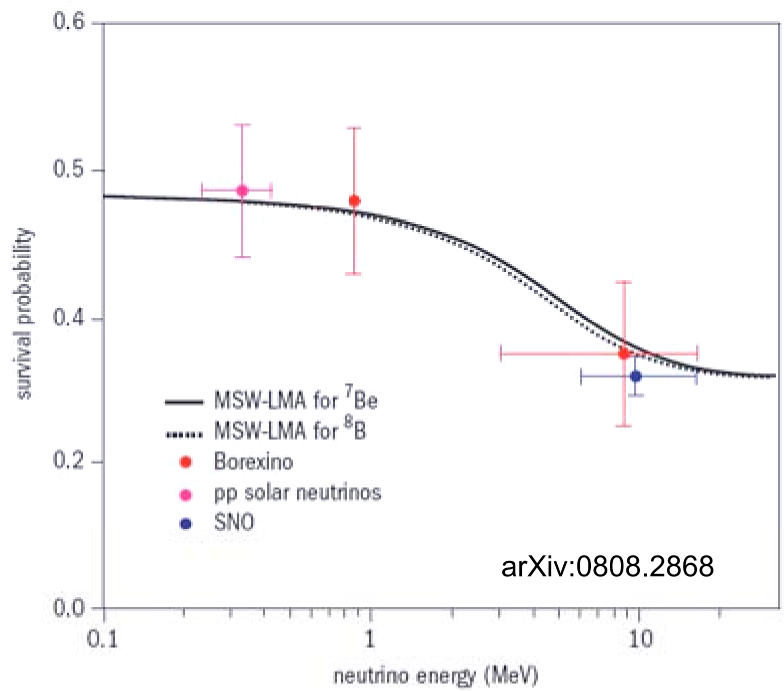


arXiv:0801.4589

Solar physics with neutrinos

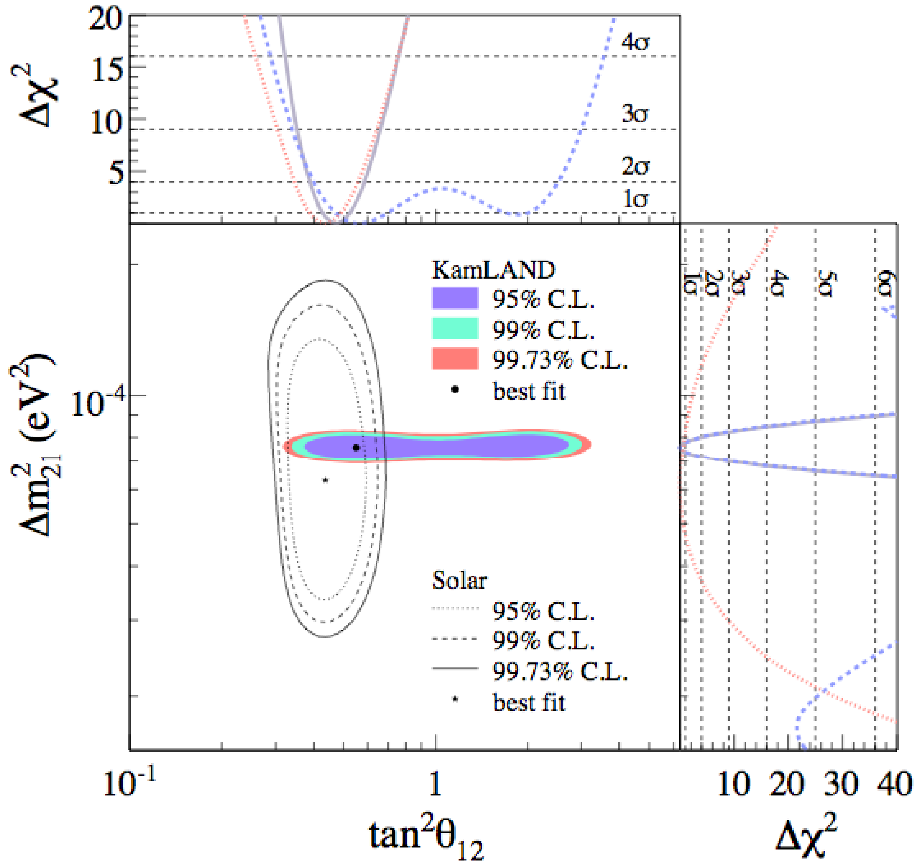
- The solar physics world is finally reaching its goal of probing the Sun with neutrinos
- Borexino's results include
  - > Using other solar-neutrino observations it is possible to determine P_{ee} for pp neutrinos
  - > Observation of the transition between the low energy vacuum-driven and the high-energy matter-enhanced solar neutrino oscillations
  - > Agreement with the prediction of the MSW-LMA solution for solar neutrinos





Global fit

Both reactor neutrinos solar neutrinos need to get the best measurement of the oscillation parameter measurement



$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

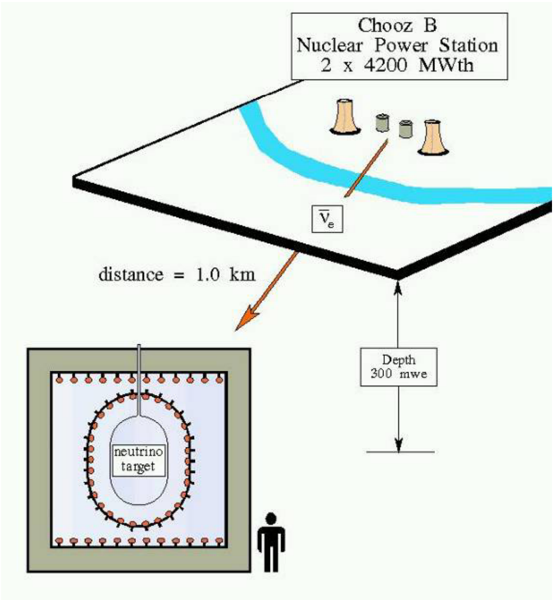
$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2$$

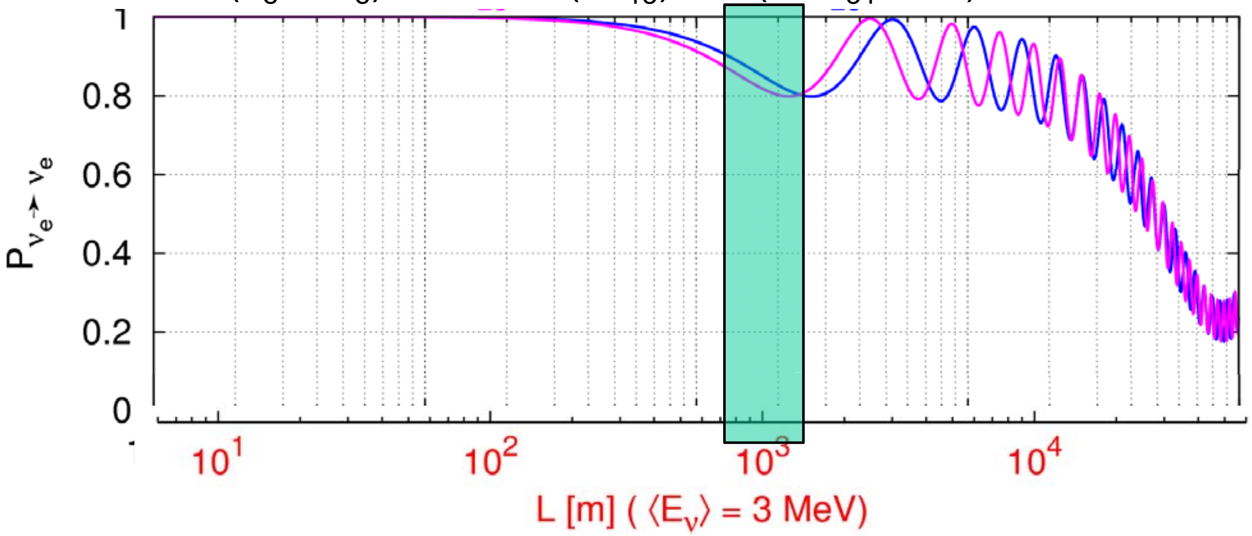
S. Abe et al., Phys. Rev. Lett. 100, 221803 (2008)

Experimental challenges

- Both reactors and solar neutrinos are <1 to ~10 MeV energy
  - > The need fully sensitive detector volumes
- They have continuous sources: addressing backgrounds is critical
  - > Move deep underground to shielding from cosmics
  - > Active and passive shielding
  - > For example Borexino intrinsic ^{238}U and ^{232}Th contamination levels to less than 10^{17}

Which Flavors for Atmospheric ν's?





Chooz & Palo Verde experiments limits the amount of $\nu_\mu \rightarrow \nu_e$ in the atmospheric region to less than ~13%

Issues: knowledge of flux, fiducial mass & statistics/lifetime – needs a far/near detector, overburden

Eur. Phys. J. C **27**, 331 (2003); PRD **64**, 112001 (2001).

MINOS Far Detector ν_e Data

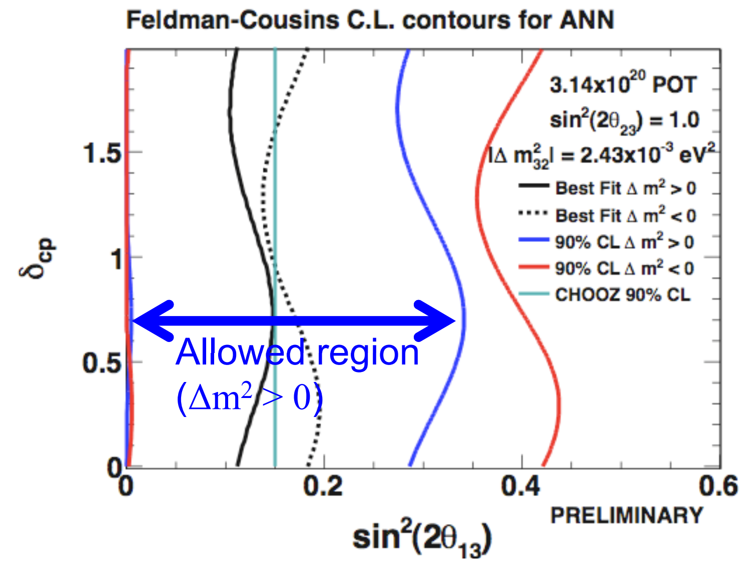
37 ν_e selected events seen (1.5σ excess)

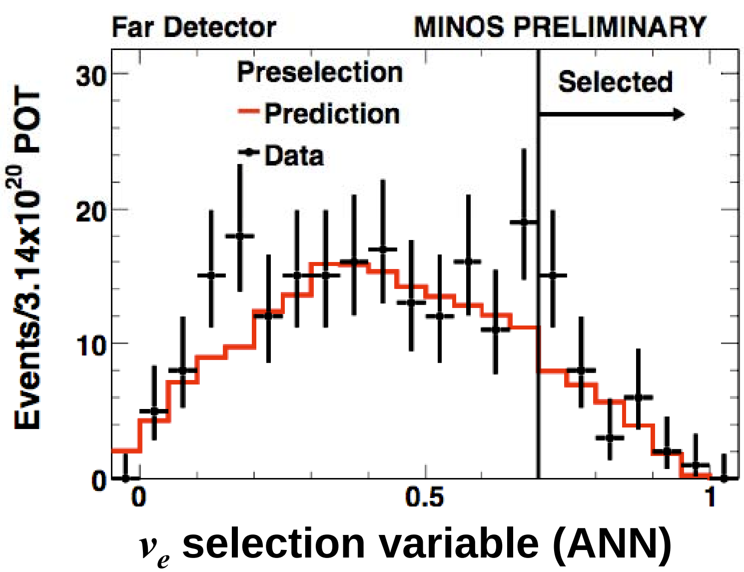
- Expected background: $27 \pm 5_{stat} \pm 2_{syst}$

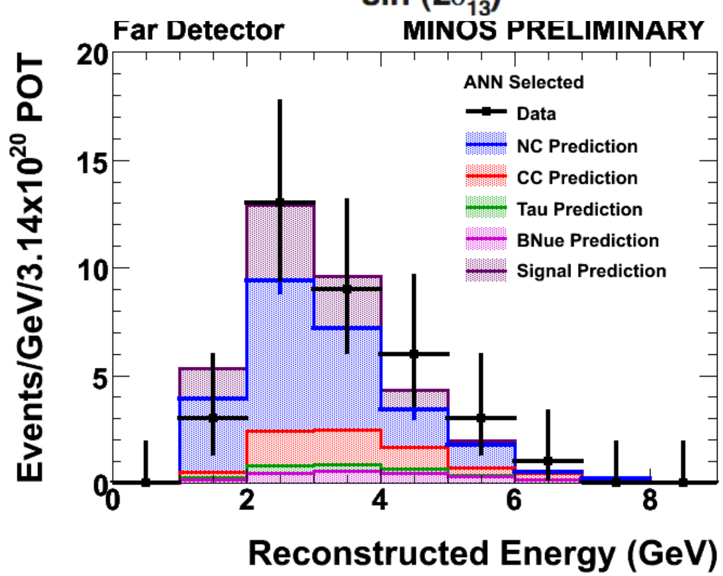
Fit to the oscillation hypothesis using Feldman-Cousins method

- Best fit is at the Chooz limit
- $\sin^2(2\theta_{13}) < 0.29$ (90% c.l.); $\Delta m^2 > 0$ $\delta_{CP} = 0$

Issues: more data, limited by segmentation: background rejection and cross-section/shower modelling

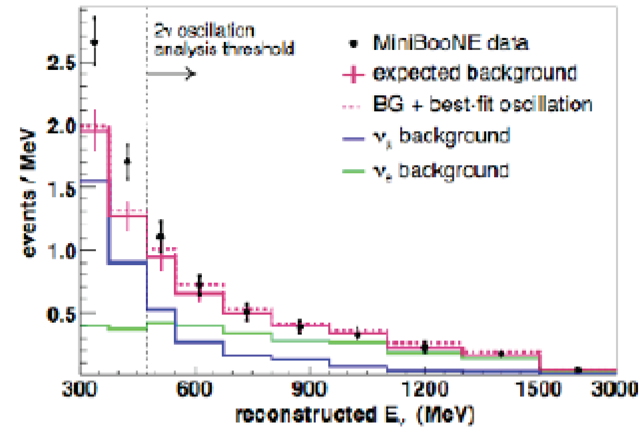


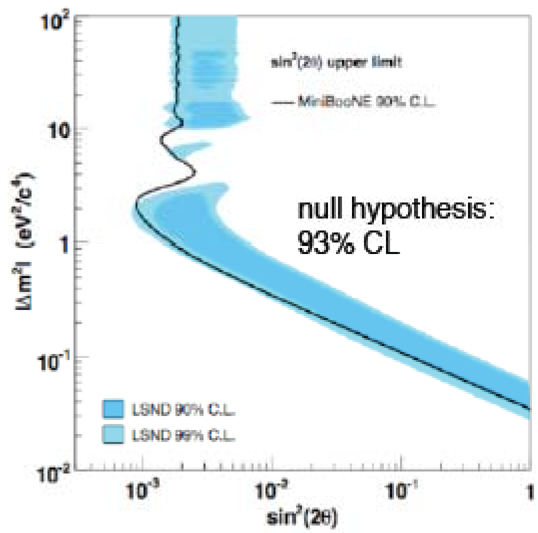




MiniBooNE

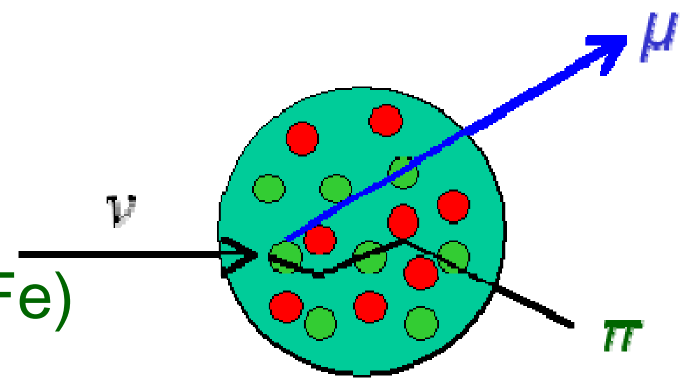
- 1 GeV neutrinos
- 800 ton oil Cerenkov & scintillation
  - > Operating since 2003
  - > ν_μ –> ν_e appearance
  - > Does not confirm the LSND signal as a single sterile neutrino, constraints on more complicated models
  - > Antineutrino and neutrino running
- Issues
  - > Near detector
  - > Complicated optical model
    - SciBooNE, MicroBooNE



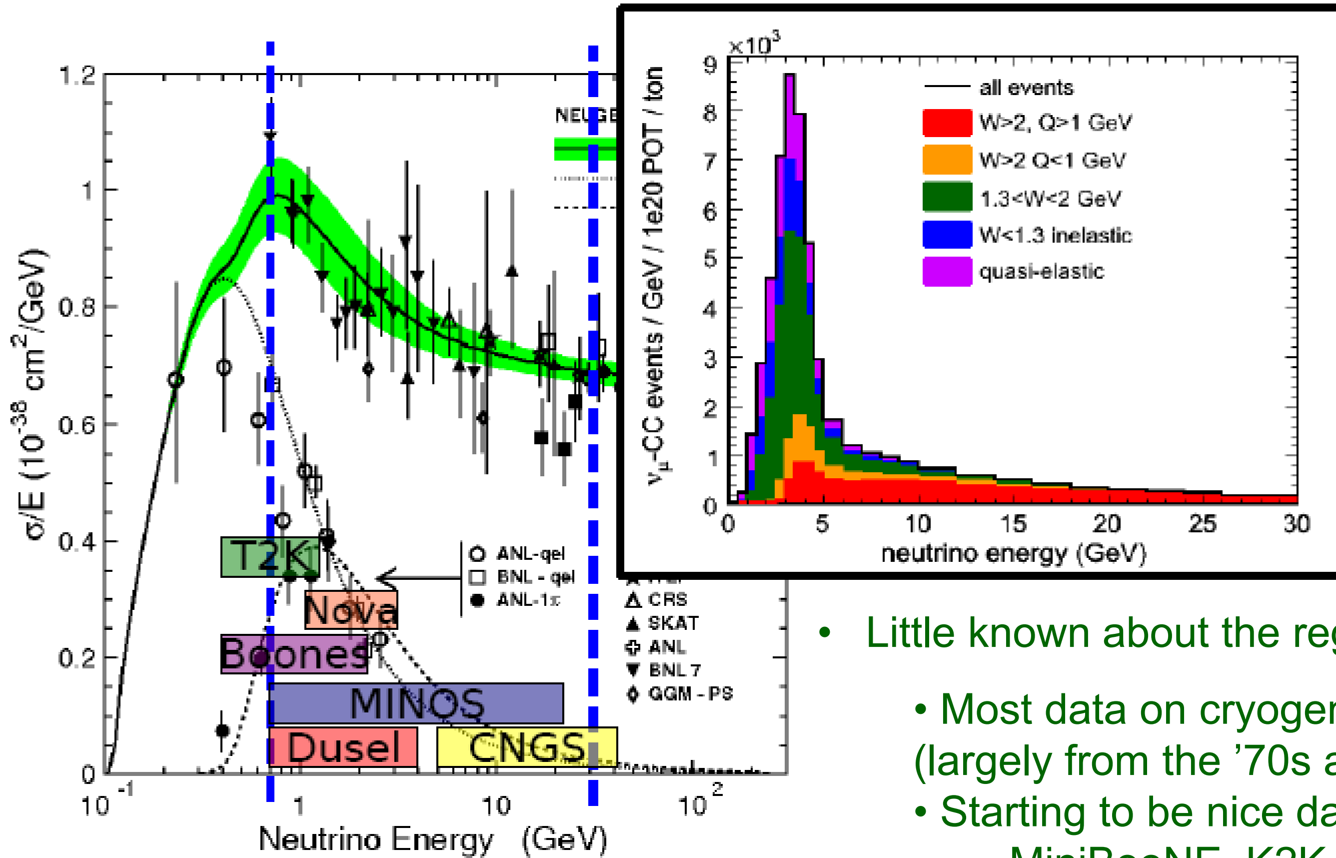


Neutrinos

- We need to estimate the energy of the incoming neutrino
  - > Different from the “visible” energy seen in the detector
- Neutrino oscillation experiments use high Z nuclei as targets (e.g. Fe)
  - > This affects the visible energy … compared to a free nucleon
  - > Intra-nuclear absorption, charge exchange and scattering
  - > Pauli blocking, Fermi motion
- All can cause one to misinterpret the visible energy, rate, and/or topology
  - > Affects any experiment at some level worst for detectors that cannot see all the particles due to threshold or segmentation



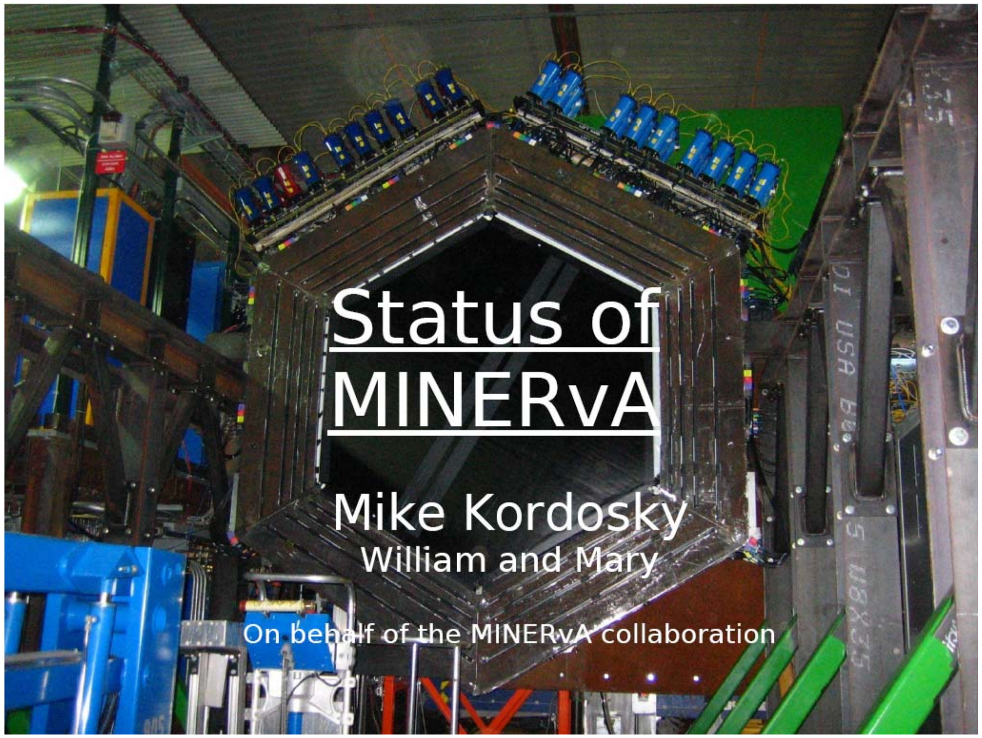
Neutrino-Nucleon Cross Sections



- Little known about the region of interest (1-10 GeV)
  - Most data on cryogenic gases (largely from the '70s and 80s)
  - Starting to be nice data at lower energies: MiniBooNE, K2K ND, SciBooNe
- The future (with solid scintillator)
  - MINERvA will give us 10-1000 times the statistics as other experiments
  - T2K ND 280

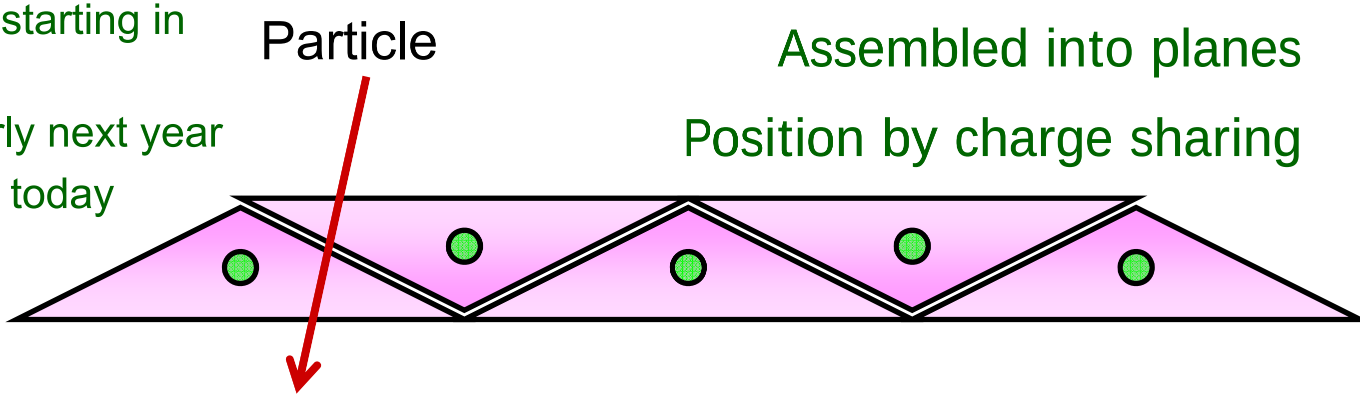
The MINERvA Detector

- Study neutrino nucleus interactions in detail
  - > Range of nuclear targets
  - > Fully active scintillator tracker
  - > Stereo readout
  - > Forward and side calorimeters
  - > MINOS for muon ranger
- First data shown at NuINT
  - > Ran in NuMI beam with 20% of the final detector starting in April
  - > Fully installed early next year
  - > See it on the tour today

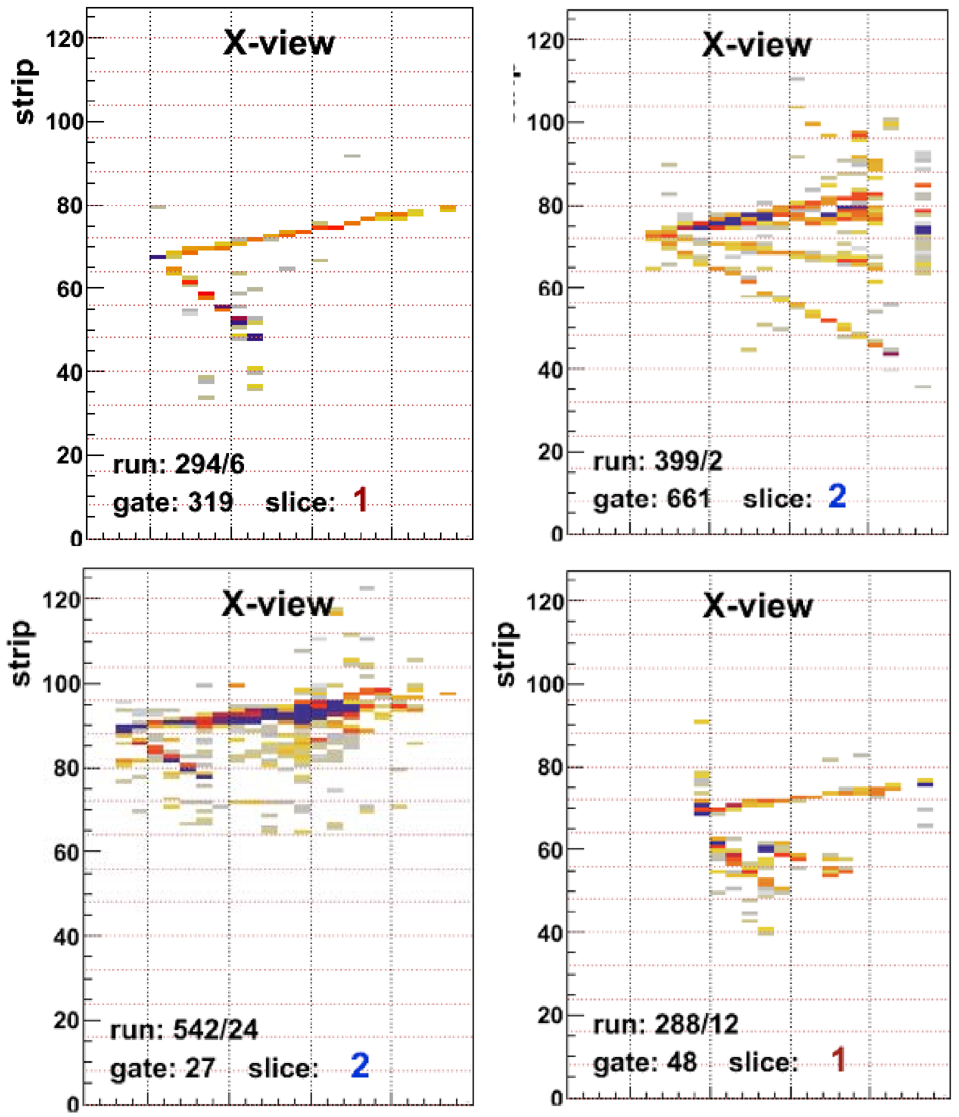


Assembled into planes

Position by charge sharing

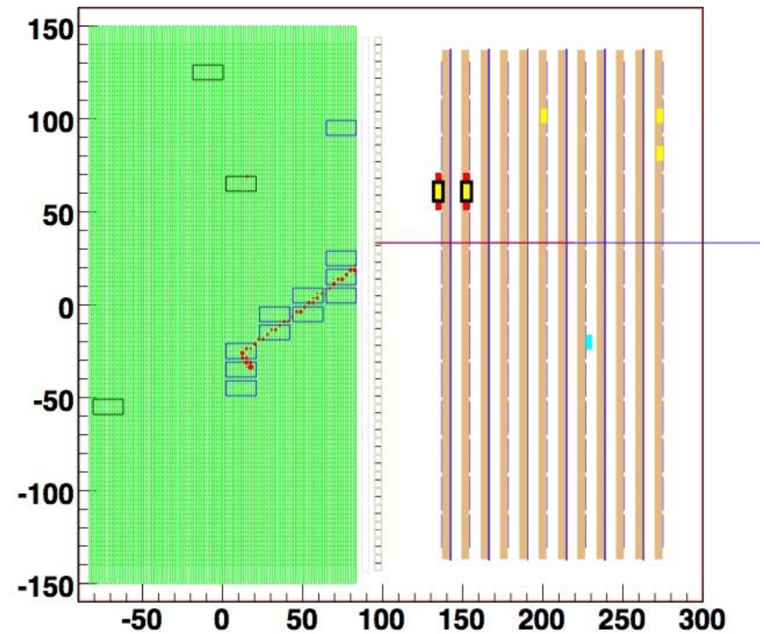


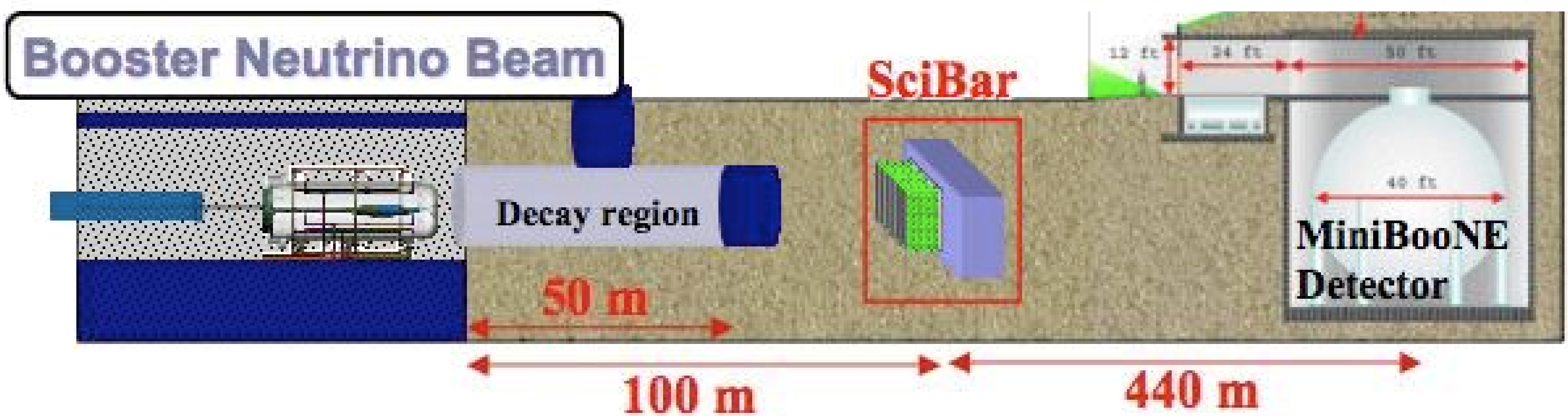
Minerva events



SciBooNE at Fermilab

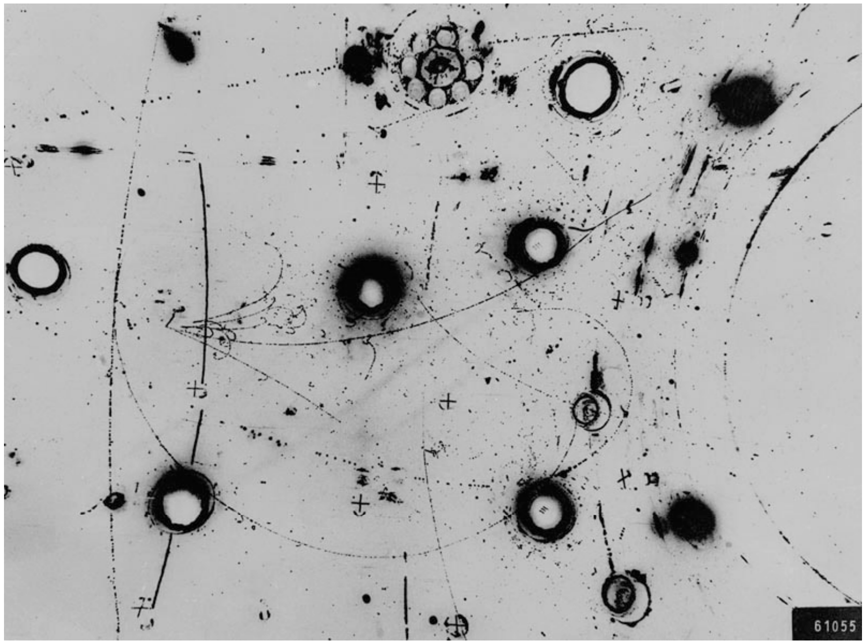
- Places the K2K scibar totally active segmented scintillator detector in the Fermilab booster neutrino beam
  - > Measure lower energy neutrino cross sections
  - > Finished run





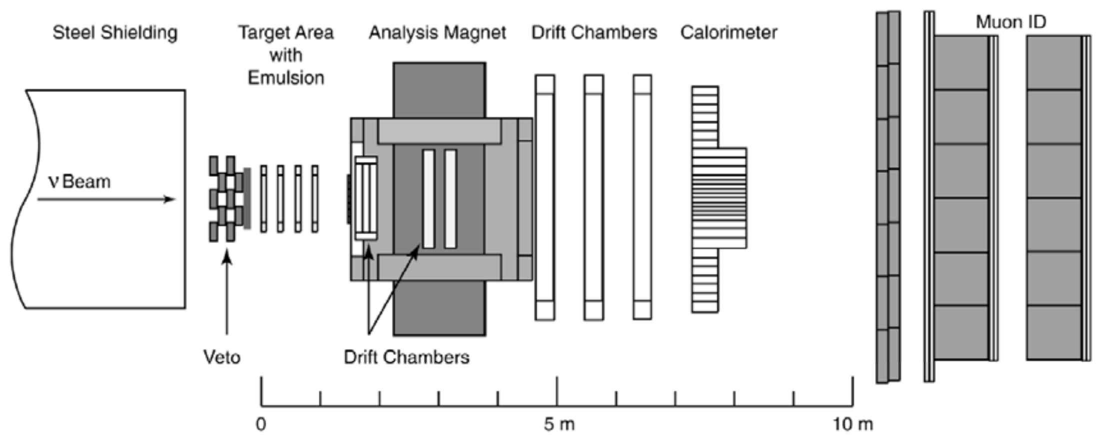
High resolution methods

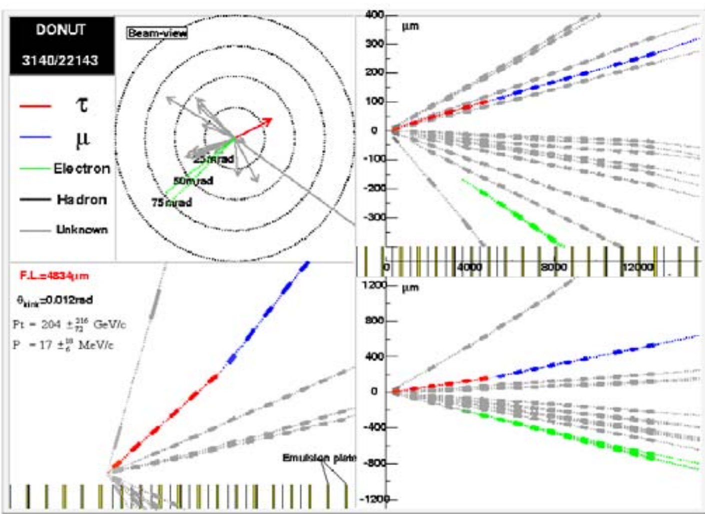
- Bubble chambers
  - > Beautiful
    - Still shown in many physics texts!
  - > Rates & reconstruction effort



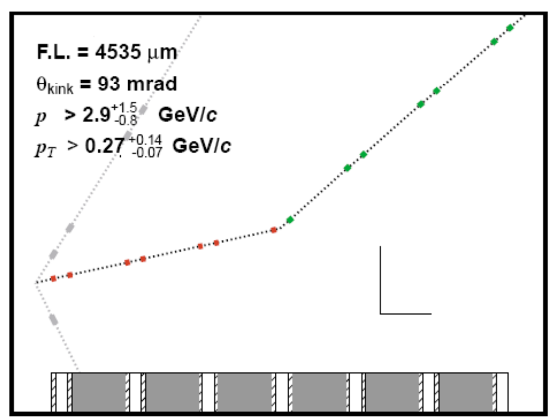
DONUT: Direct Observation of ν_τ

- Uses techniques tested at CERN in CHORUS SLB experiment and FNAL neutrino program
- 9 ν_τ found in 578 total ν
- Background ~1.5 events (charm + hadronic int)
- PRD 78, 052002 (2008)



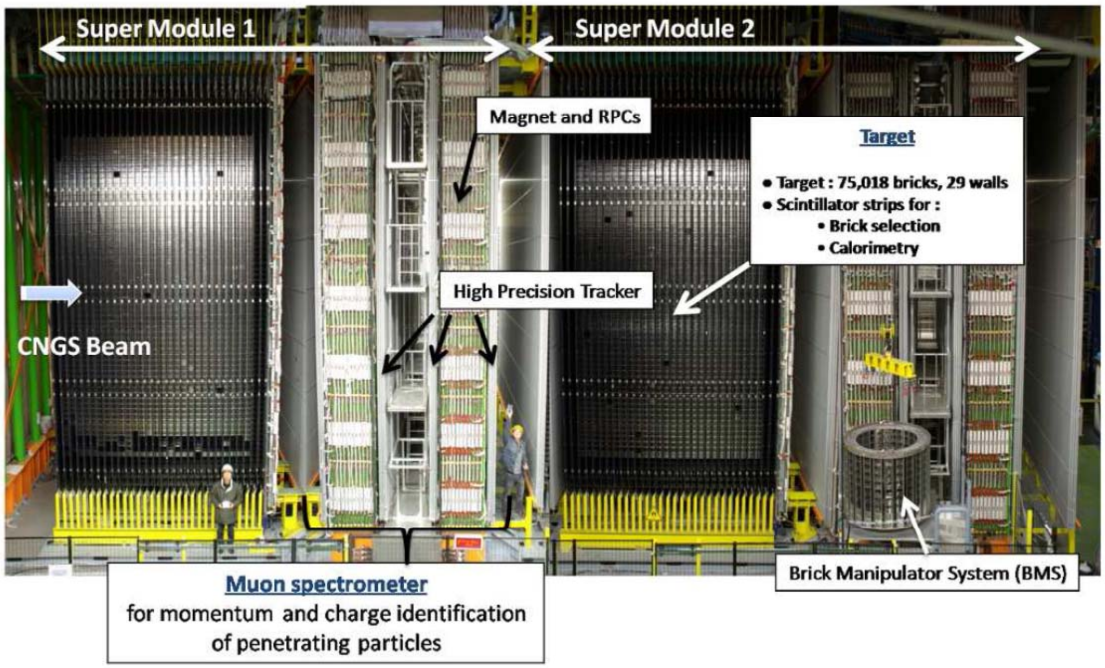


$$\nu_\tau N \to \tau \; X$$
$$\tau \to \mu \; \nu_\mu \; \nu_\tau$$



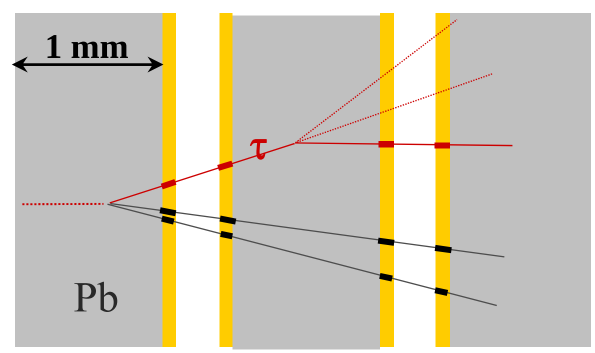
Proof of principle for Tau observation

Opera
appearance of tau and electron neutrinos

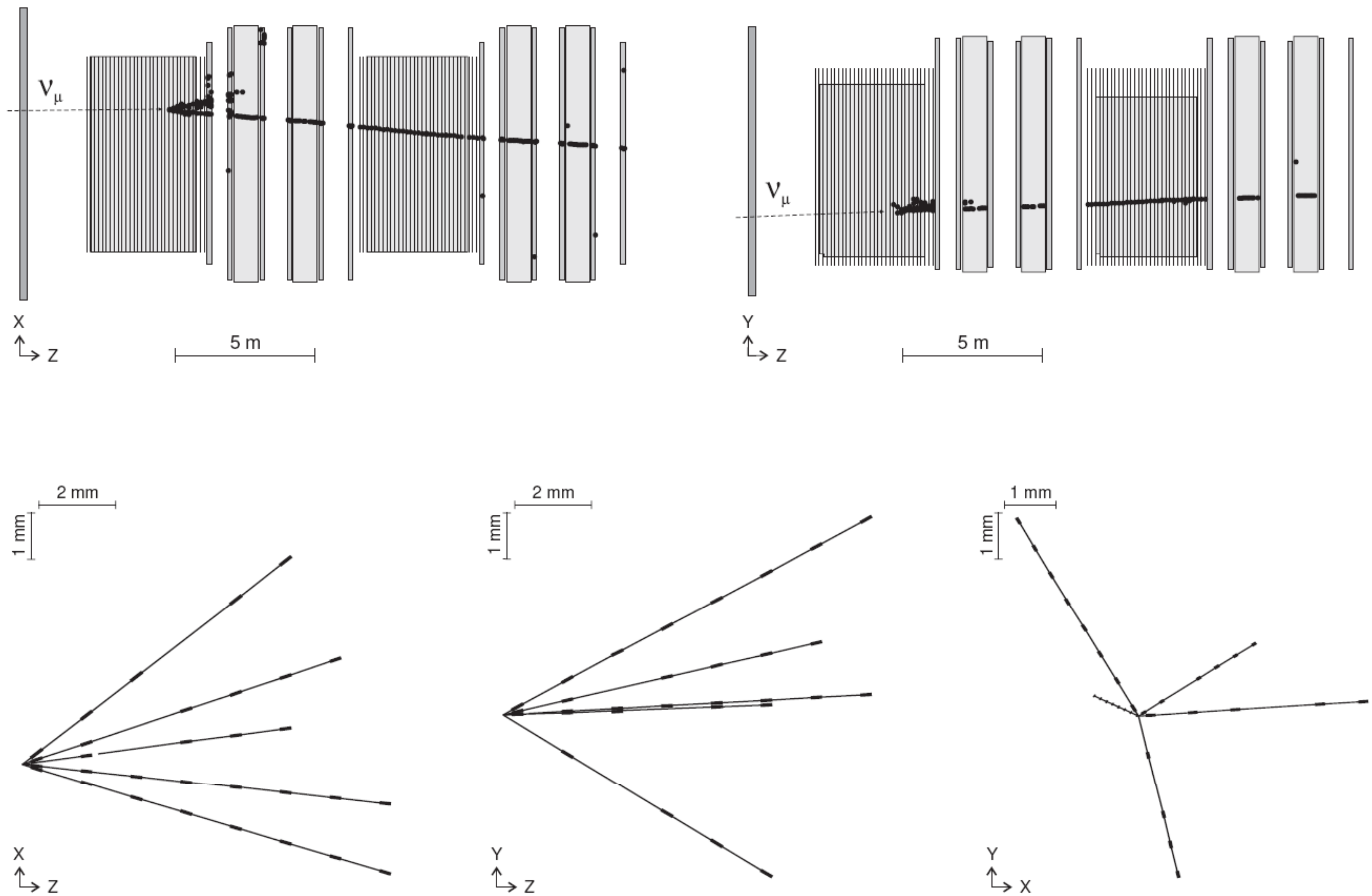


56 lead plates,
57 emulsion films,
2 changeable sheet.

- Physics goals:
  - > Verify oscillation is to ν_τ
  - > Search for ν_e appearance
- Started running in 2007
- ~1kt of emulsion stacks – intensive assembly effort, very event low rate

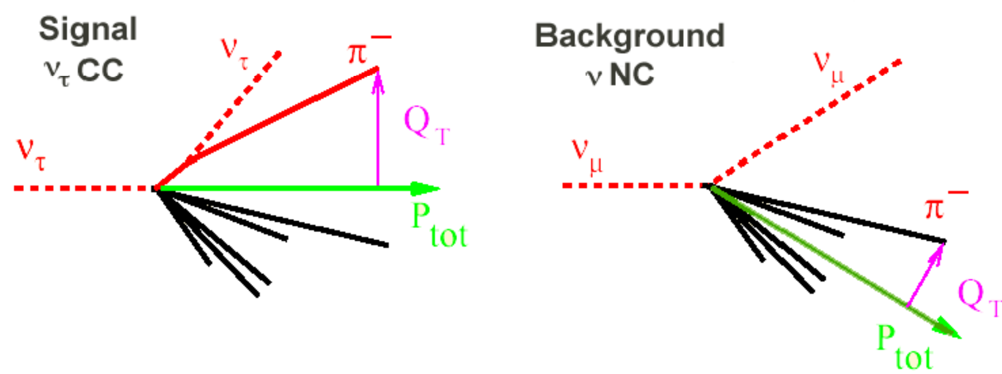


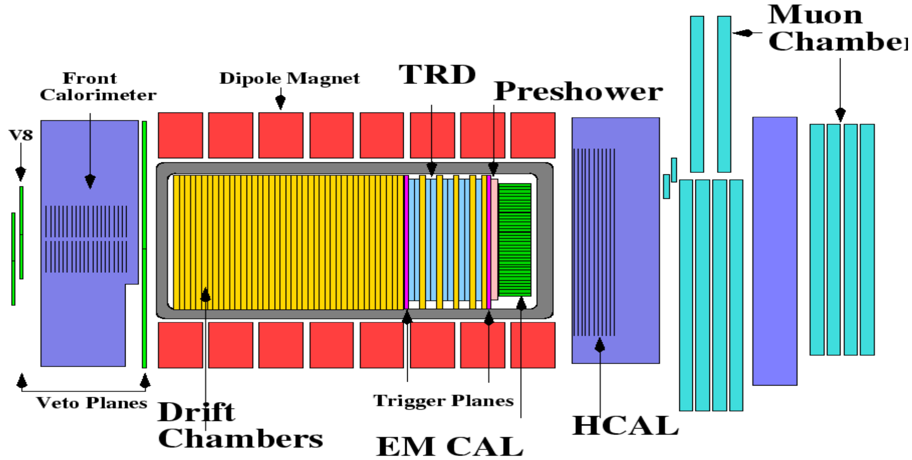
An Opera event

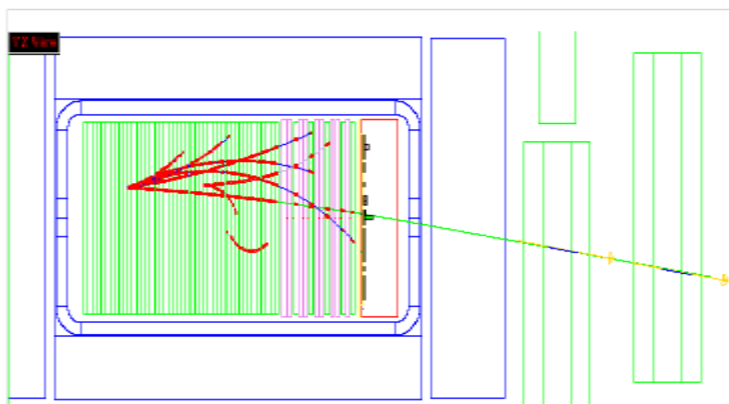


NOMAD

- High resolution
  - > Low density
  - > Gas based tracking
  - > Reconstruct the tau based on missing transverse momentum
  - > Search for neutrinos in the final state

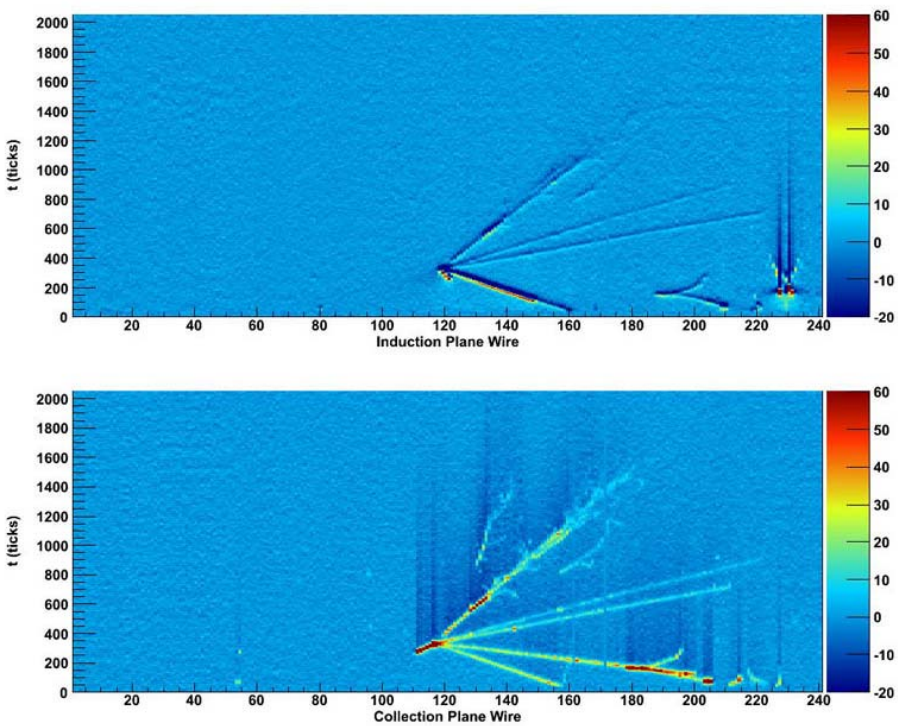


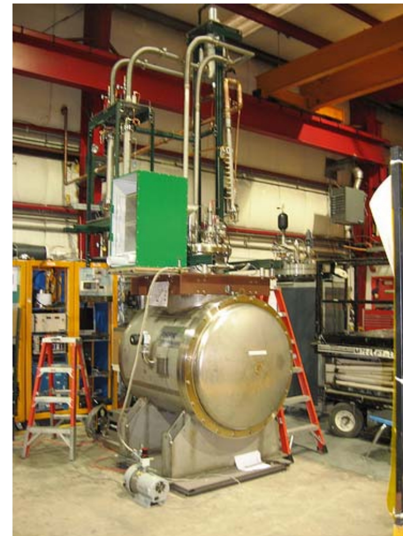




ArgoNeuT

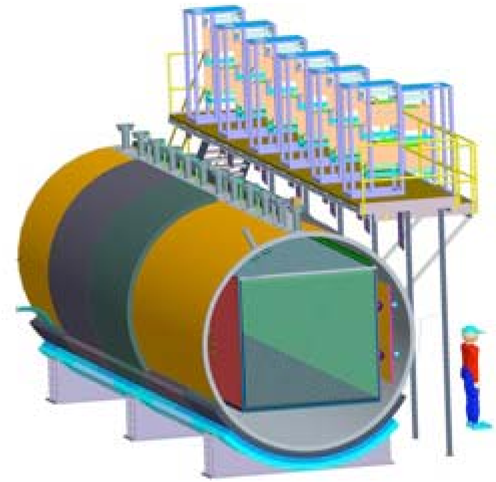
- LArTPC effort in U.S.
- ArgoNeuT 0.75 tons – exposure in NuMI beam
  - > Follow on all the work for ICARUS (including NOMAD exposure)
  - > Study hardware questions for future more massive detectors
- First beam data in Spring 2009 (between MINOS and MINERvA)





The next steps

- MicroBooNE is next LArTPC effort
  - > Perform physics measurements
    - e.g. MiniBooNE low-energy excess
  - > Investigate important hardware questions relevant for future more massive detectors
  - > 180 tons – Lab project office set up
- LAr5 5,000 tons Physics/Prototype (EOI)

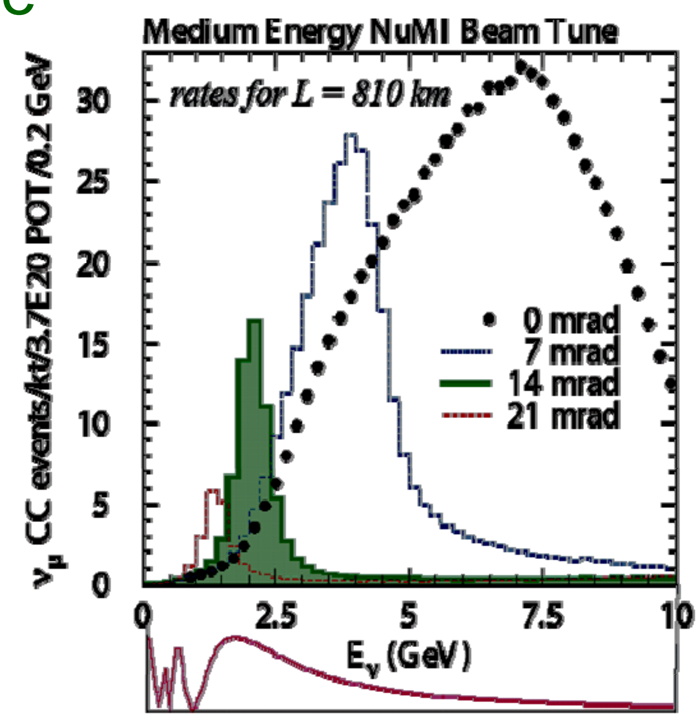


New generation LBL experiments (NOνA/T2K)

- Goals
  - <1% measurement of $\sin^2 2\theta_{23}$
  - ~10-5 eV^2 uncertainty on Δm^2_{23}
- Demands stringent control over E_ν reconstruction
  > e.g. ~few % on absolute energy sale
  > Calibration and interpretation of data
  > Understanding of flux & cross section to disentangle F/N extrapolation, beam backgrounds
- Probe ν_e to at least 10 times lower than CHOOZ limit
  > Knowledge of electron-like backgrounds, single photon production, detector response, beam composition

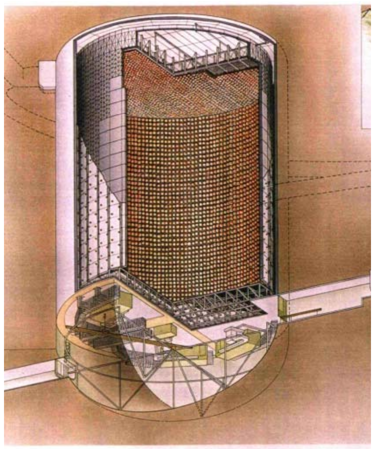
Future experiments
more intense and/or more mass

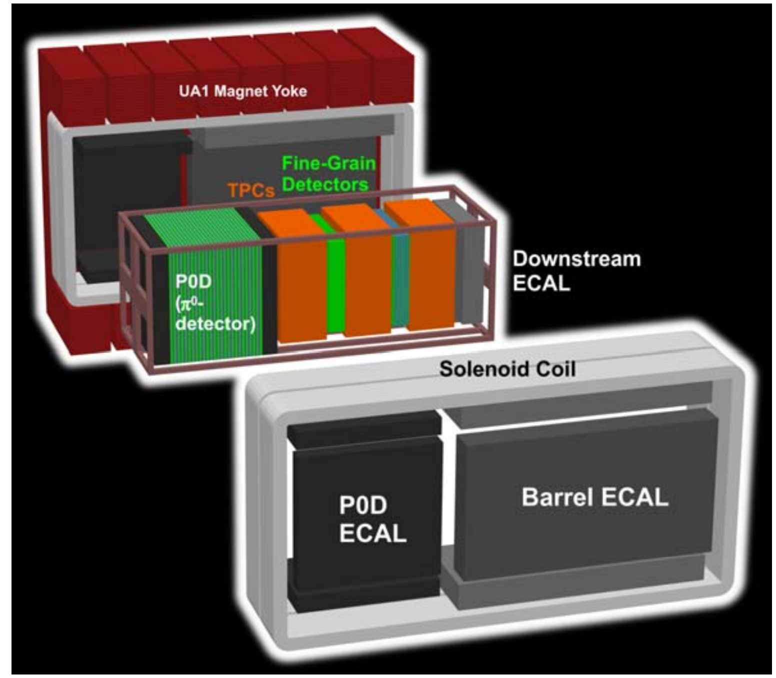
- Reactor experiments to probe 3rd angle
  - > Double Chooz, Daya Bay, RENO
- Beam experiments to probe 3rd angle
  - > NOvA experiment
    - SNuMI beam (S = more protons)
    - 18 kt detector 810 km away
  - > T2K
    - New beam from the JPARC accelerator
    - 560 kt Super-K detector 285 km away
  - > Both experiments
    - Will use off axis detector location to make a "more precise beam"
    - Have future staging plans beyond 1st phase



- Combinations of these experiments are sensitive to 3rd angle, mass hierarchy & CP

T2K
JPARC to Super-K





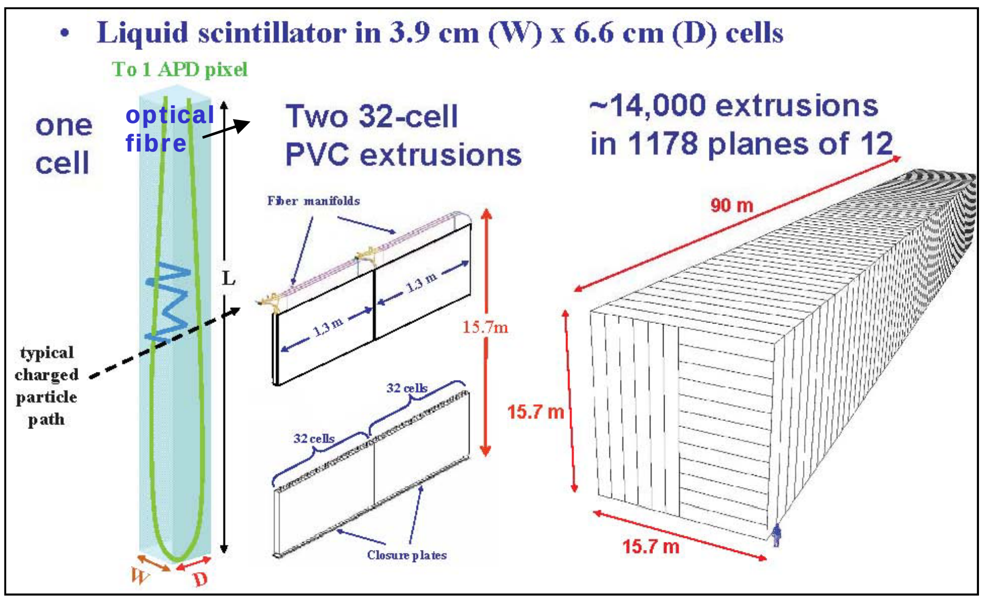
- Near Detector at 280m, 2.5mrad off-axis
- Inside UA1/Nomad magnet for momentum measurement
- Sandwich calorimeters/ fully active segmented trackers for precision beam measurement
  - E_ν~0.8GeV
- Will be a excellent detector for interaction physics too

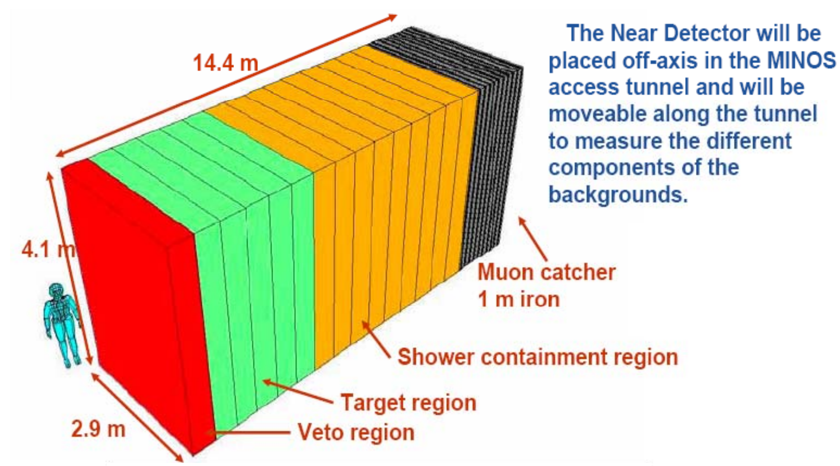
- Ingrid detector @ 280m (on-axis)
- Iron scintillator tracker
- Determines beam profile and direction

T2K – test beams and now onto installation running this Fall

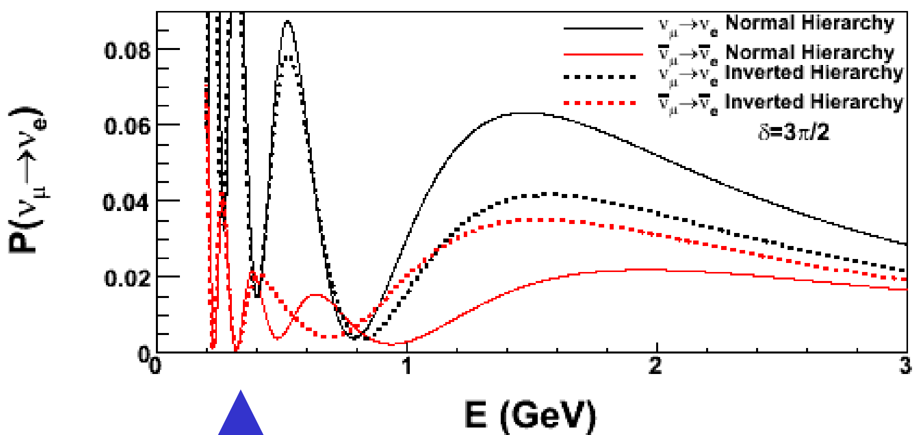
NOvA

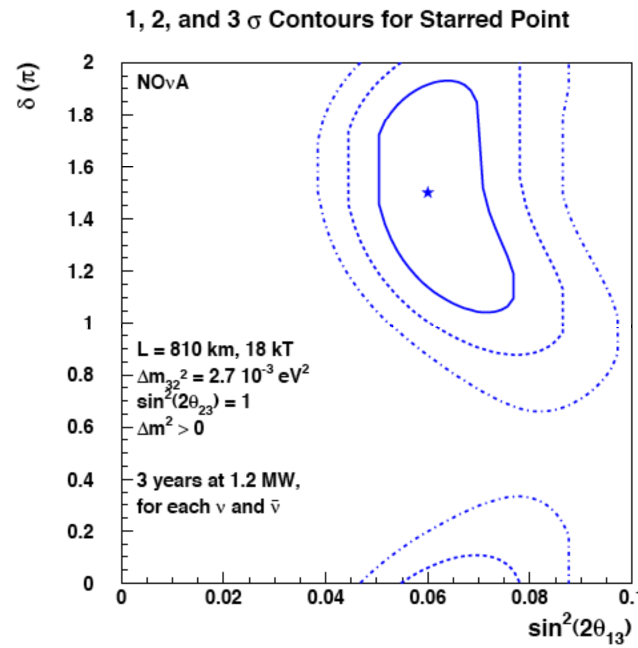
- Far detector
  - 15 kton, fully active segmented
  - 14.5 mrad off NuMI beamline axis
  - 810 km baseline, E_ν~2GeV
- Near Detector
- Same beam as MINOS with significant intensity improvements



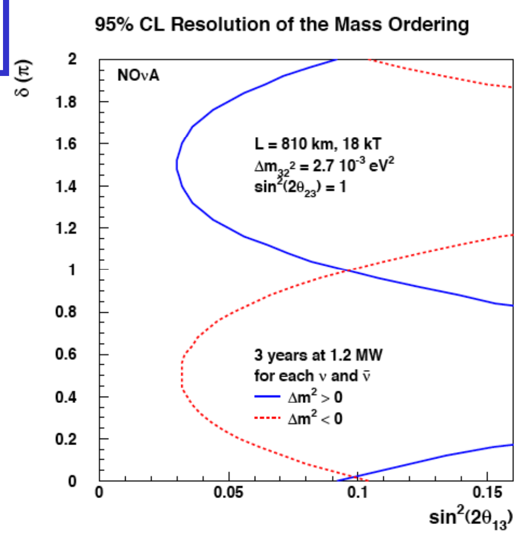


NOvA future reach





MATTER EFFECT IN

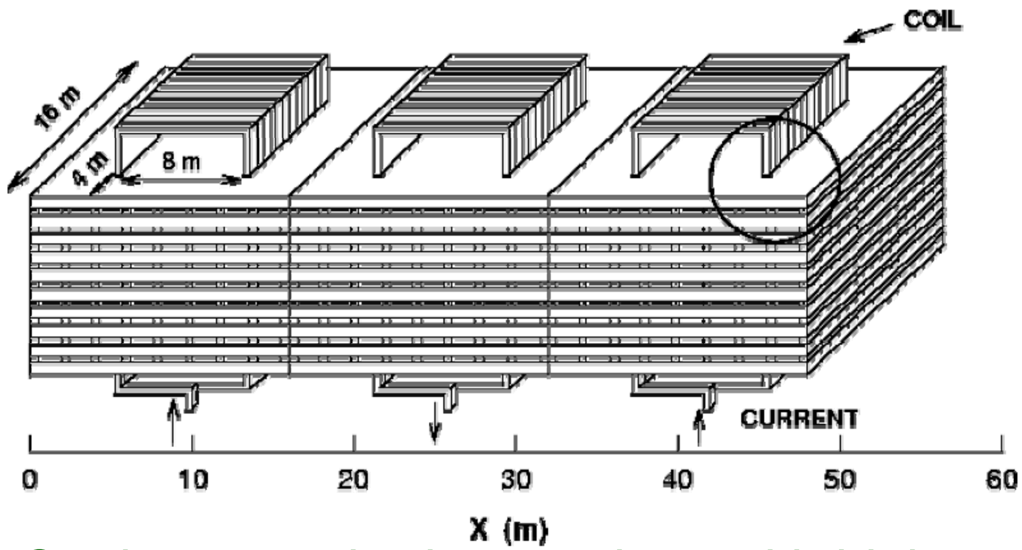


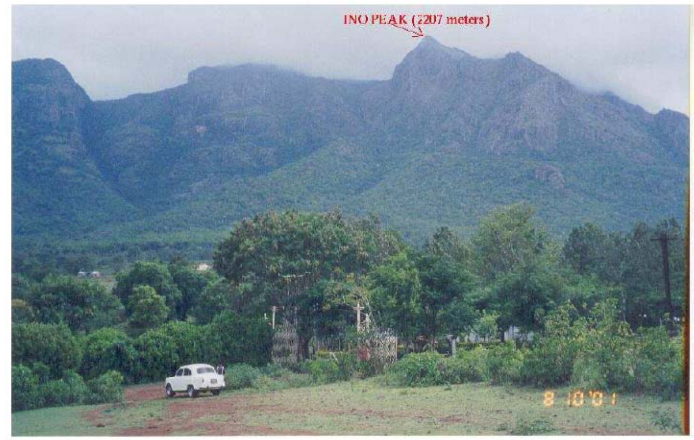
Nova has longest baseline: 810km

run with ν and $\bar{\nu}$

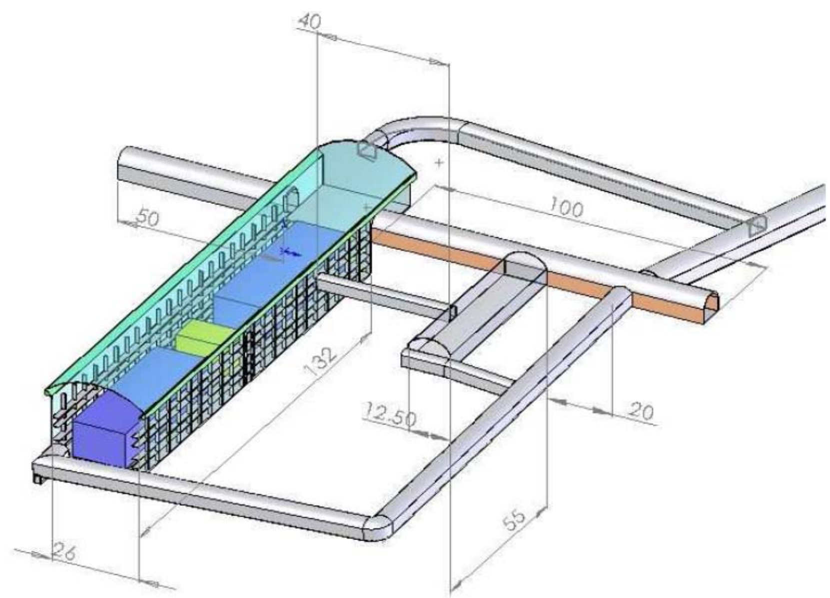
- Matter effects increase (decrease) oscillations for normal (inverted) hierarchy
- Hierarchy can be resolved if θ_{13} near to present limit
- T2K has effect at a lower level

Indian Neutrino Observatory (INO)



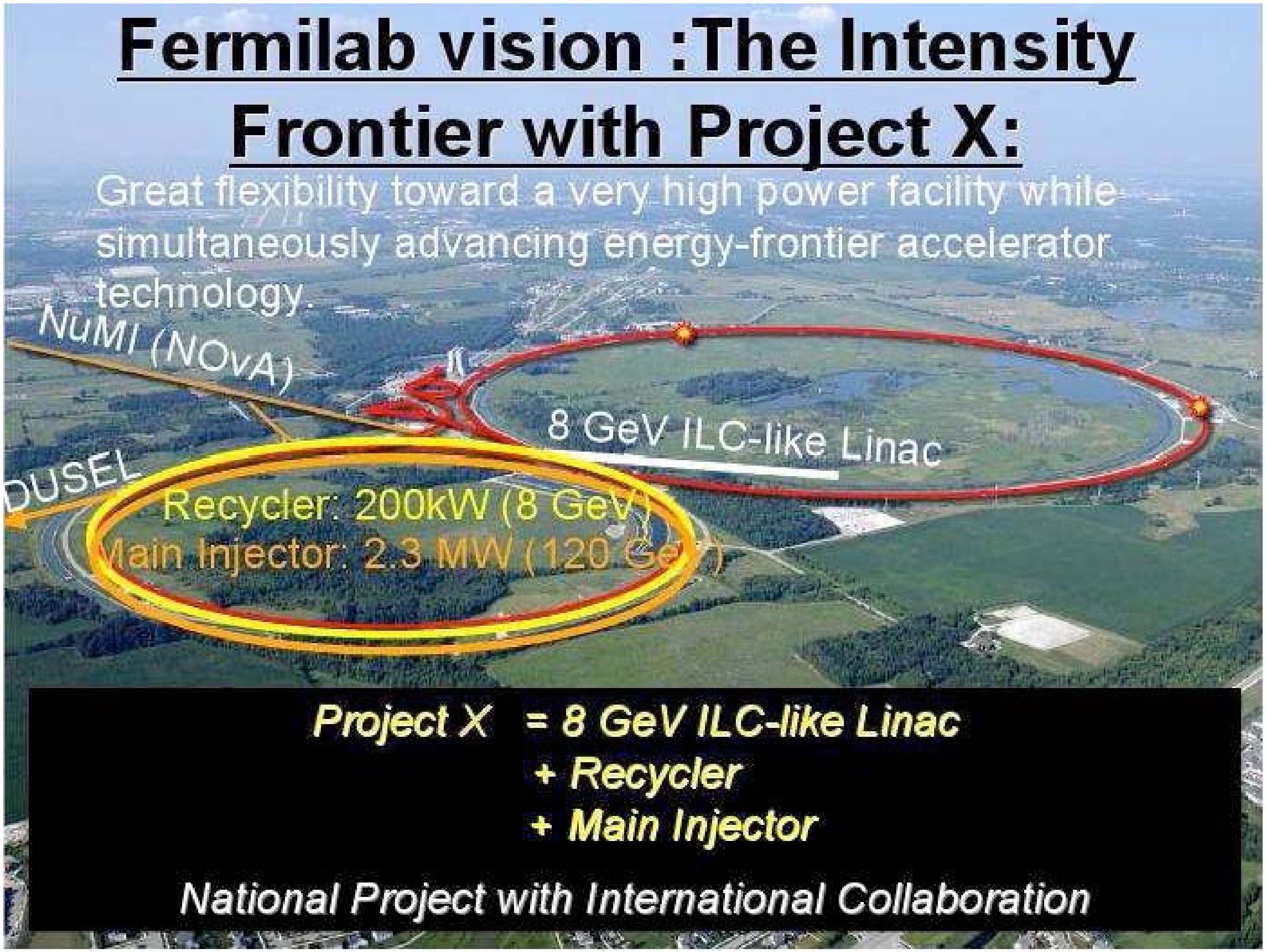


Study atmospheric neutrinos with high statistics and look for resonances in core crossing neutrinos; possible NF target too



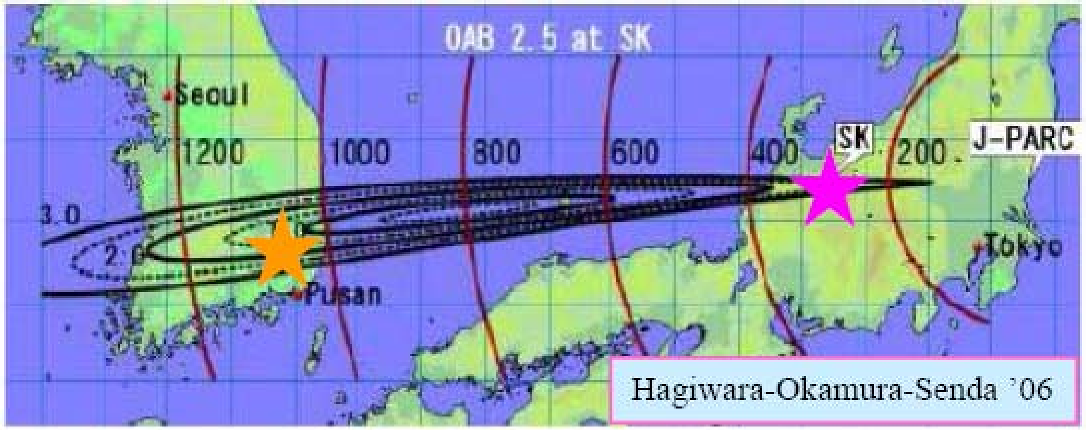
Mass: 50 kTon
Size : 48 m (x) ×16m (y) ×12 m (z)
140 layers of 6 cm thick iron
with 2.5 cm gap for RPCs
Making prototype

The future beam for Fermilab



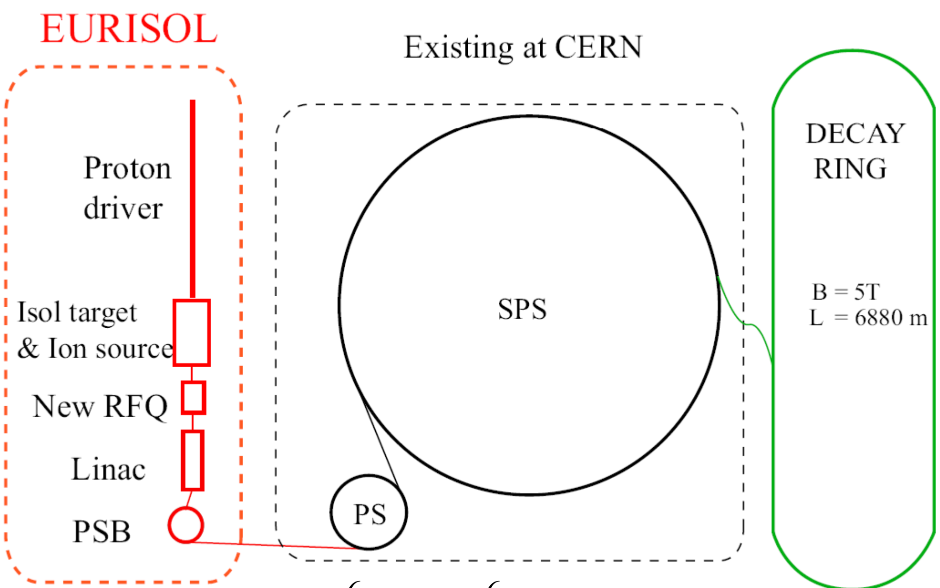
T2KK or T2HK

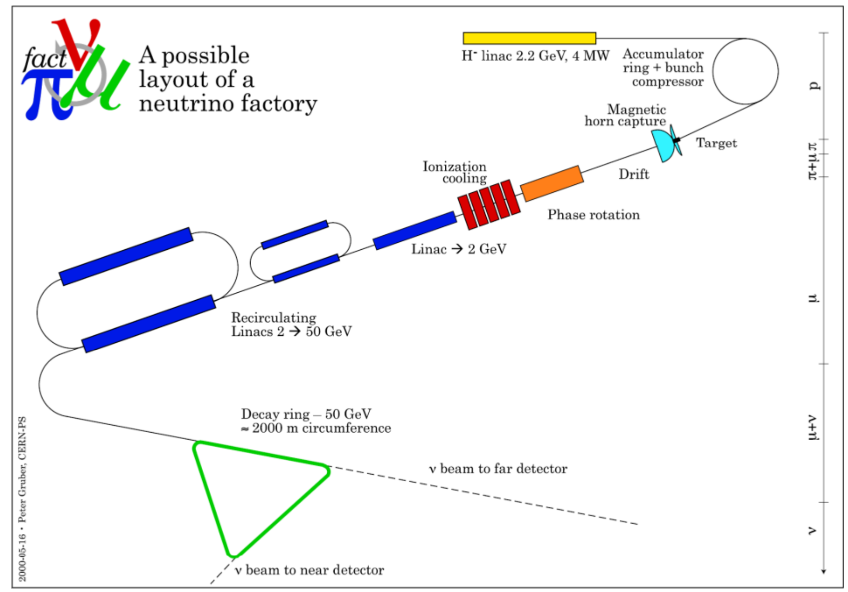
- **Upgraded J-PARC 4 MW proton beam, 4+4 years of nu, anti-nu,**
- **0.27 Mton detectors at 295km(Kamioka) and 1050km(Korea)**
- **Both 2.5 degree off-axis**



Future neutrino facility concepts

beta beam | neutrino factory



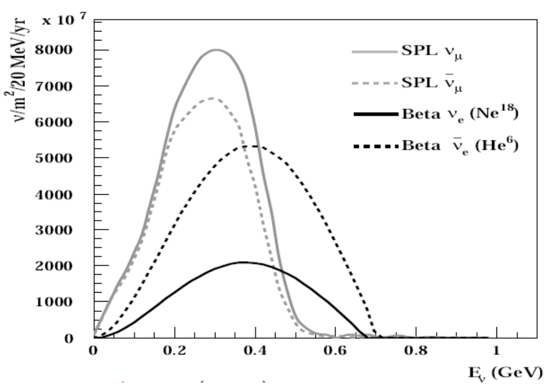


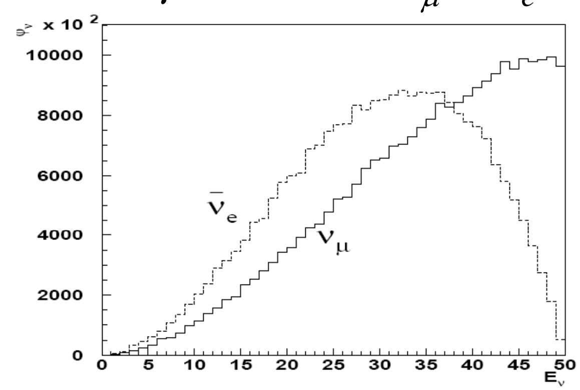
$${}^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^{-} + \overline{\nu}_{e}$$

$${}^{18}_{10}Ne \rightarrow {}^{18}_{9}F + e^{+} + \nu_{e}$$

$$\mu^{+} \rightarrow e^{+} + \overline{\nu}_{\mu} + \nu_{e}$$

$$\mu^{-} \rightarrow e^{-} + \nu_{\mu} + \overline{\nu}_{e}$$





Way to use the neutrino factory beam

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \longrightarrow \mu^-$$

Distinguished by the charge sign

$$\overline{\nu}_\mu \rightarrow \mu^+$$

Excess (Golden ch.)

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e \longrightarrow e^+$$

Possibly distinguished by the charge sign?

$$\nu_e \rightarrow e^-$$

Excess (Platinum ch.)

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

NuFact
International Scoping Study (ISS)

Science & Technology Facilities Council

Technical Report RAL-TR-2007-019

arXiv: 0712.4129

Physics at a future Neutrino Factory and super-beam facility

The ISS Physics Working Group

Science & Technology Facilities Council

arXiv: 0802.4023v1

International scoping study of a future Neutrino Factory and super-beam facility: Summary of the Accelerator Working Group

The ISS Accelerator Working Group

December 2007

RAL-TR-2007-023

Science & Technology Facilities Council

arXiv: 0712.4129

International scoping study of a future Neutrino Factory and super-beam facility: Summary of the Detector Working Group

The ISS Detector Working Group

December 2007

RAL-TR-2007-024

Neutrino Factory International Scoping Study (ISS)

- Baseline detector requirements
  - > 2 detectors at 4000 km & 7500 km to solve degeneracies
    - Matter effects, U_{e3}, CP phase
- For a high energy Neutrino Factory facility
  - > Magnetized Iron Neutrino Detector (MIND) of 50 kton fiducial (Super MINOS)
    - Gold channel – ν_μ neutrino appearance by charge sign
  - > Magnetized Emulsion Detector of 10 kton (Super OPERA)
    - Silver channel - ν_τ appearance
  - > Beyond the baseline improvements for Neutrino Factory include (R&D needed)
    - Platinum channel - ν_e appearance by charge sign
    - Magnetized Liquid Argon TPC (LAr) 10-100 kton
    - Magnetized Totally Active Scintillating Detector (TASD) 20-30 kton (Like NOvA in an air-core magnet)
- For low energy super beam or beta beam
  - > Do not need magnetization
  - > Baseline is water Cherenkov detector (~500 kton)
- Other options beyond the baseline
  - > LAr TPC and TASD without magnet

A detector aiming to study the golden channel should…

- Be able to identify muons and measure their momenta and charge with high efficiency and purity
- Magnetized iron calorimeters have been considered
  - > The wrong sign muon detection efficiency can be kept above 50% for a background level of the order of 10^{-5}
  - > This kind of detector is extremely powerful for the measurement of very small θ_{13}, reaching values of $\sin^2(2\theta_{13})$ below 10^{-4}
- They may have trouble in studying CP violation because the high density of the detector prevents the detection of lowest energy neutrinos (below few GeV), which could provide very valuable information for the simultaneous measurement of δ_{CP} and θ_{13}.

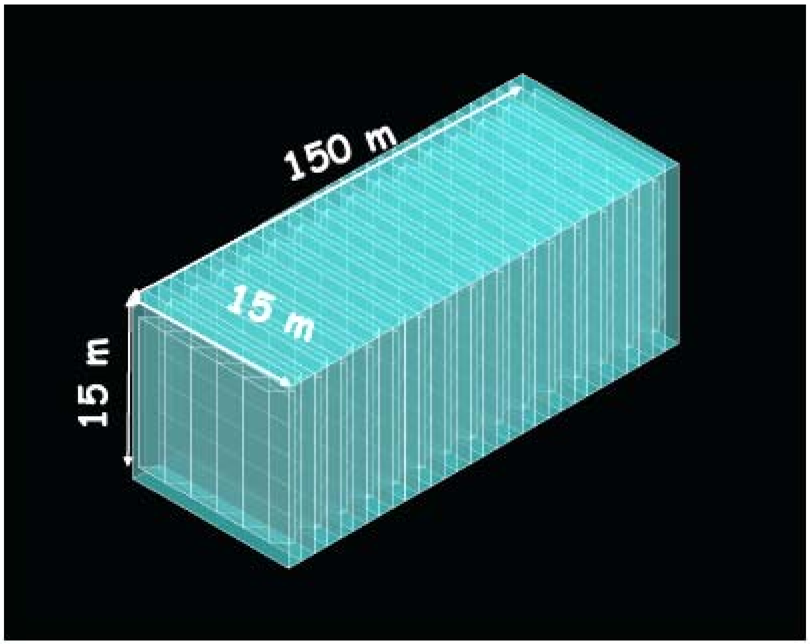
MIND

- The concept of a super-MINOS detector
  - > Sandwich of 4 cm thick iron plates (could be thinner)
  - > ~2-4 cm thick detection layers, with transverse dimensions the size of NOvA
  - > Transverse resolution, ε, of 1 cm
  - > A detector with total mass of 60 kton
  - > Fiducial mass of the order of 50 kton
    - ~10x MINOS
    - Comparable instrumentation to NOvA
    - Could do MINERvA type triangles

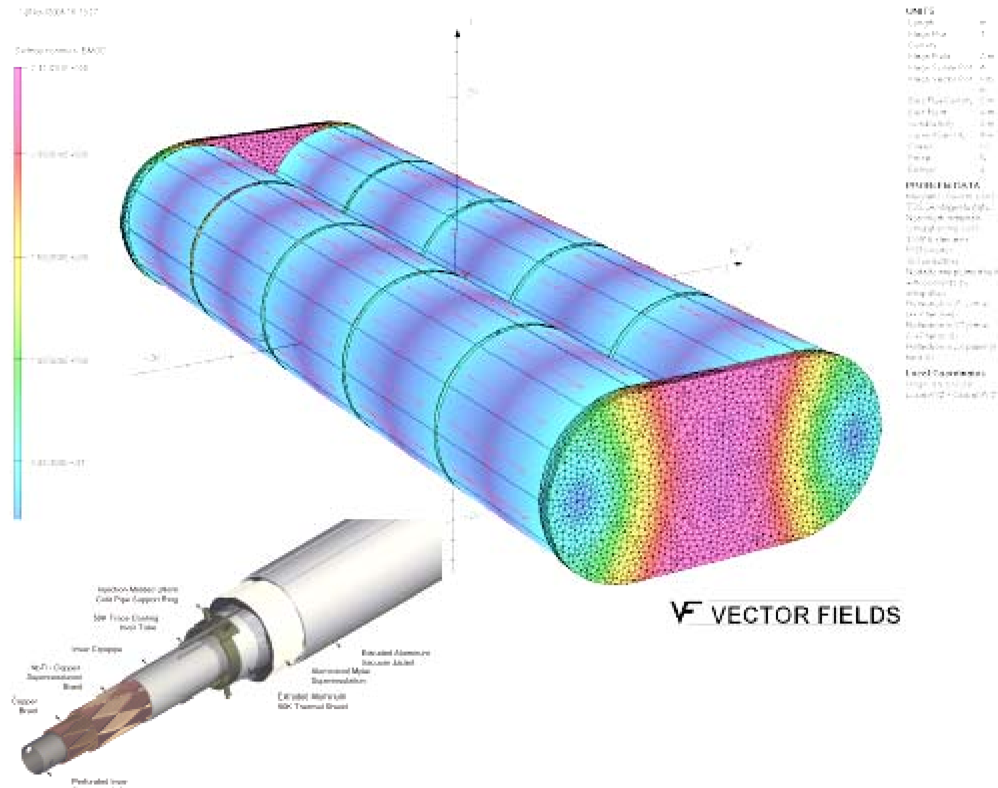
Source of background for Golden Channel

- Assuming stored positive muons, the main backgrounds for wrong-sign search are
  - > Right-charge muons whose charge has been misidentified, in ν_μ CC events
  - > Wrong-sign muons from hadron decays
  - > Wrong-sign hadrons misidentified as muons events
- How to address: higher field, better resolution, finer sampling can push these down, higher energy helps most
- Note: current simulations are behind the capabilities presented by MINOS
  - > Systematic exploration of phase space of designs and algorithms not in place yet

Totally active scintillator detector (TASD)



B = 0.5T



R&D for segmented detectors

- Magnetized Iron Neutrino Detector (MIND) and Totally Active Scintillator Detector (TASD)
  - Design, cost and engineering solutions for the magnet system for an iron calorimeter (straightforward)
  - Design, cost and engineering solutions for the magnet system for a large volume totally active scintillation detector
  - R&D on magnetic field resistant photon detector technology, which could include testing of Multi-Pixel Photon Counters (MPPC), Silicon Photo-multiplier tubes (SiPM), Avalanche Photo Diodes (APD) or other similar technologies
  - Feasibility and cost of long strips of extruded scintillator with optic fiber readout
  - Building prototype scintillator-fiber systems of varying lengths (5-20 m) and measurements of the attenuation of the signal as a function of the length of scintillator, measurement of the number of photoelectrons collected and studying the optimal geometry for the scintillator strips (for example, a comparison of the performance of square versus triangular cross-section of the scintillator strips).
  - Study whether a different detector technology (such as Resistive Plate Chambers, RPC) would deliver the same performance at a reduced cost.
  - Build a prototype to put in a suitable test beam and test its performance inside a magnetic field

Emulsion R&D

- The main issues that need to be addressed in further R&D are
  - Improvement to the automated scanning stations to reduce the overall scanning time and to improve the scanning accuracy
  - Further R&D on operating emulsion-iron sandwich systems in a magnetic field and adapting the scanning algorithms to recognize tracks inside a magnetic field

Large Water Cherenkov

- Based on the experience of running the Super-Kamiokande detector

- Further R&D is identified as possible a variety of topics
- Engineering and cost of cavern excavation for Megaton water Cherenkov detectors at different sites
- The optimal modularity of such a system
- R&D on photon detectors, such as large area Hybrid Photon Detectors (HPD), or standard Photo Multiplier tubes, including
  - Reduction of the photon detection cost
  - Reducing the risk of implosion
  - Electronics readout costs
  - Timing
  - Reduction of energy threshold through the selection of low activity materials for the detectors and associated mechanics
- Engineering studies of the mechanics to support the photon detectors
- Studies of energy resolution of water Cherenkov detectors, especially at low energy (i.e. 250 MeV)

LAr TPC R&D

- Feasibility and cost of using industrial tankers developed by the petrochemical industry and their deployment for underground liquid argon storage
- Demonstration of detector performance for very long drift paths, including liquid argon purification
- R&D on detectors for charge readout (for example, with a Large Electron Multiplier, LEM)
- Photon detector readout options (for example, wavelength shifting coated photomultiplier tubes)
- R&D on ASICs for electronics readout and data acquisition system
- Development of new solutions for drift in a very high voltage (such as the Cockcroft-Walton style Greinacher circuit)
- The possibility to embed the liquid argon in a B-field has been conceptually proven
  - However, the magnetic field strength needs to be determined by physics requirements and the feasibility and cost of the magnetic field design for large liquid argon volumes needs to be established
  - Study of high temperature superconducting coils to operate at liquid argon temperatures is an essential R&D task to demonstrate this feasibility
- Dedicated test beams to study prototype detectors and to perform tracking and reconstruction of clean electron and π^0 samples

- Large program for this work has gained momentum since the ISS…

Summary of ISS's to-do lists …

Alternative technologies

Beam energy	Beam type	Far detector	R&D
Sub-GeV	BB and SB	100 kton LAr TPC	Clarify advantage of LAr with respect to WC
1-5 GeV	BB and SB	TASD or LAr TPC or Megaton WC	Photosensors and detectors. Long drifts and wires, LEMs, etc
20-50 GeV	Nufact	Platinum detectors Magnetised TASD Magnetised LAr Magnetised ECC	Engineering study. Large volume magnet. Simulations, physics. studies

Baseline detector

Beam energy	Beam type	Far detector	R&D
Sub-GeV	BB and SB	Megaton WC	Photosensors, cavern and infrastructure
1-5 GeV	BB and SB	TASD or LAr TPC or Megaton WC	Photosensors and detectors. Long drifts and wires, LEMs, etc
20-50 GeV	Nufact	100 kton MIND (golden) + 10 kton NM-ECC (silver)	Simulation + physics studies Charge at low momenta