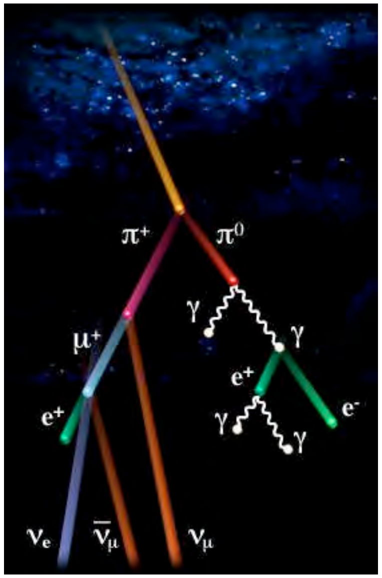
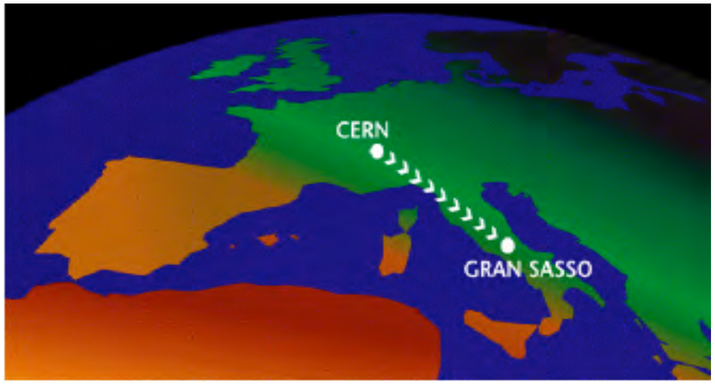
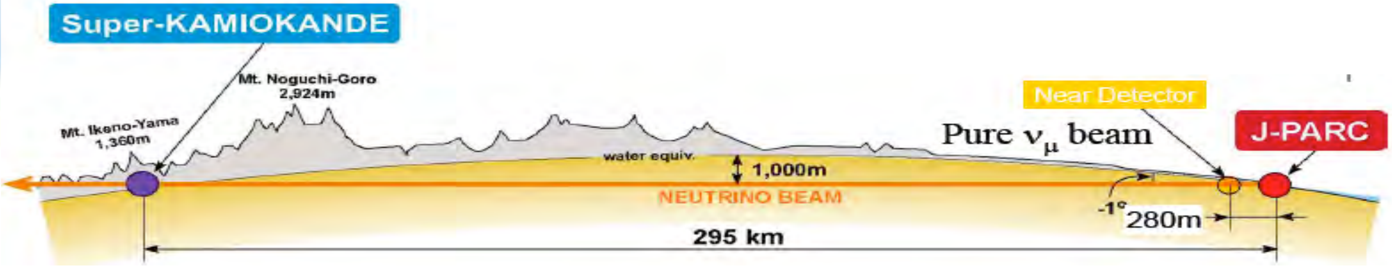




Neutrino Oscillations & interactions

Hugh Gallagher, Tufts University
NEPPSR – August 15, 2007



Masses and Mixing

H. Gallagher
Tufts University
NEPPSR
August 15, 2007

weak states

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

mass states

PMNS matrix - analogous to the quark CKM matrix

$$\begin{aligned} \mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) &= |\mathrm{Amp}(\nu_\alpha \rightarrow \nu_\beta)|^2 \\ &= \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2(\Delta m^2_{ij} \frac{L}{4E}) \\ &\quad + 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin(\Delta m^2_{ij} \frac{L}{2E}) \end{aligned}$$

In the limit where one mass scale dominates

$$\mathrm{P}(\nu_\alpha \rightarrow \nu_\beta) = \boxed{\sin^2(2\theta) \sin^2\left(\frac{1.27\, \Delta m^2\, L}{E}\right)}$$

Searching for Oscillations

For two generations, a good approximation is:

$$P(\nu_\alpha \longrightarrow \nu_\beta) = \left|\langle \nu_\alpha(t) | \nu_\beta(0) \rangle\right|^2 = \boxed{\sin^2(2\theta)\,\sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)}$$

With $\Delta m^2 = \left|m_1^2 - m_2^2\right|$ in eV^2, L in km, E in GeV

Δm^2 and $\sin^2(2\theta)$ are the physics we are after

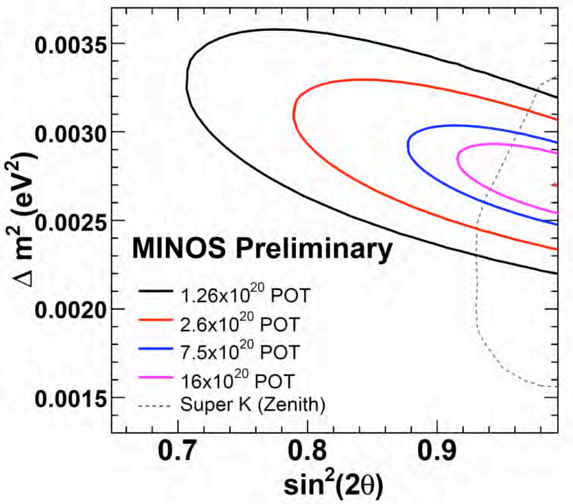
Disappearance experiments: Measure a deficit of ν_α at some later time.

$$P_{\alpha\alpha} = 1 - \sin^2(2\theta)\,\sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$

Appearance Experiment: Measure the presence of a new flavor of neutrino in the beam.

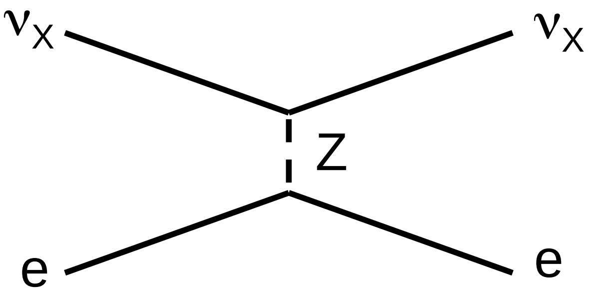
$$P_{\alpha\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{1.27\,\Delta m^2\,L}{E}\right)$$

Ideally measure the oscillation probability as function of L, E, or L/E.

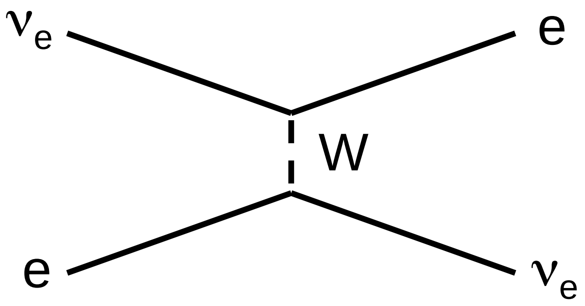


MSW Effect

When neutrinos travel through matter the presence of electrons introduces different “effective masses” which depend on the electron density.



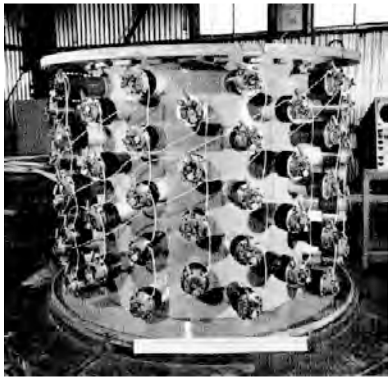
This can lead to an enhancement of neutrino mixing.



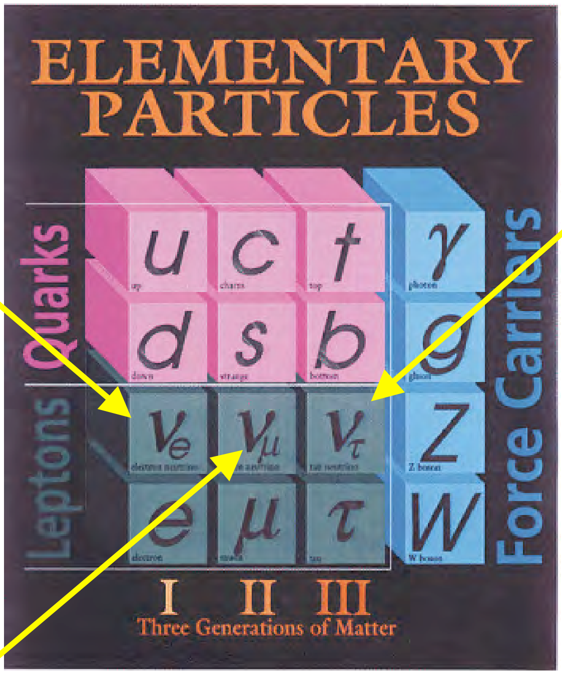
This is known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect.

50’s – 60’s: The Age of Discovery

Neutrinos have proved to be a valuable probe of the structure of matter and the nature of electroweak interactions.



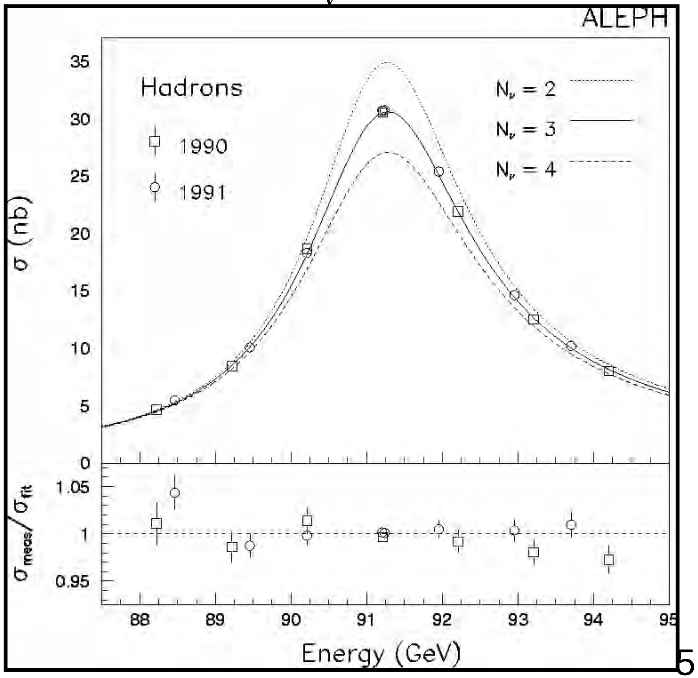
Reines and Cowan
First ν detection – 1952-3
(1995 Nobel Prize)



Observation confirmed (2000)
DONUT Experiment

Brookhaven 2 ν Experiment
(Lederman, Schwartz, Steinberger
1988 Nobel Prize)

From LEP we know that
$N_\nu = 3$

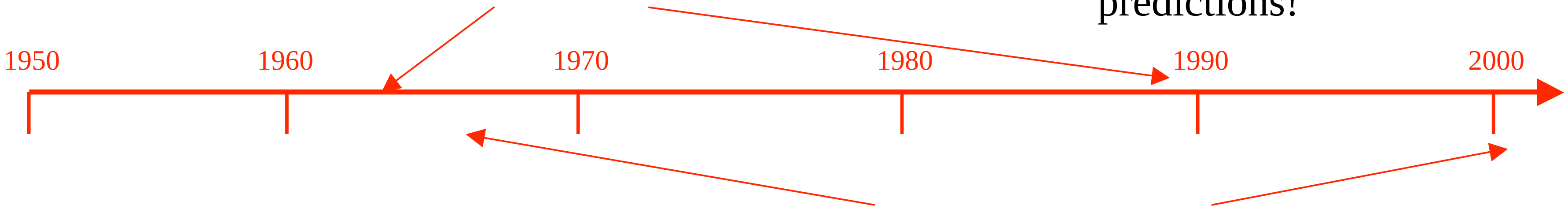


70’s – 80’s: Age of Exploration

Bubble chambers:
BNL, ANL, FNAL,
CERN, Serpukhov

- hadronic weak currents
- observation of neutral currents
- cross section measurements

SN9187A ν detection confirmed astrophysical predictions!



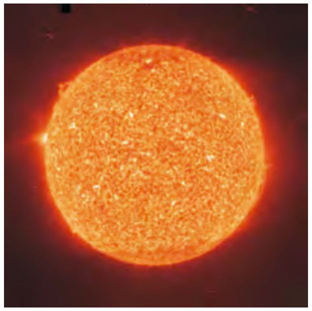
high statistics (~100k events)

- structure functions (F_2, F_3)
- parton universality: quarks are quarks!
- Electroweak studies: $\sin^2(\theta_w)$
- strange sea studies
- cross sections

counter experiments:
CDHS,
CHARM, CHARM II,
CCFR, NuTEV

80's-90's: The Age of Serendipity

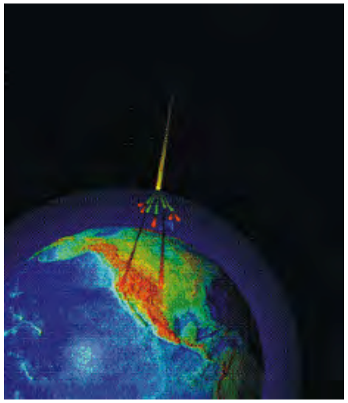
First evidence for neutrino oscillations (and neutrino mass) came from experiments designed to measure something else entirely!



"the solar neutrino problem"

set out to confirm the standard solar model

Homestake experiment:
Nobel prize 2002
Ray Davis



"the atmospheric neutrino anomaly"

Kamioka experiment:
Nobel prize 2002
Masatoshi Koshiba

Large underground experiments designed to detect proton decay originally worried about atmospheric neutrinos as a potential background

Today: The age of Excitement!

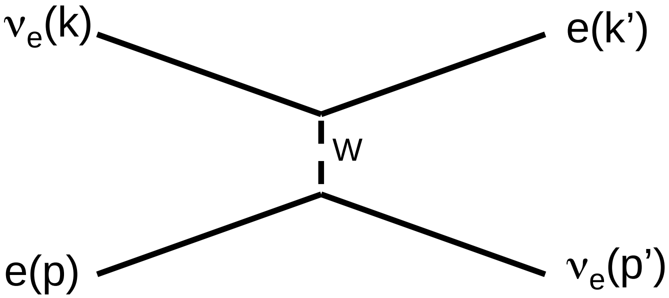
It has now been convincingly demonstrated that neutrinos have mass and undergo neutrino oscillations.

These discoveries open up many more questions which are the focus of vigorous experimental effort:

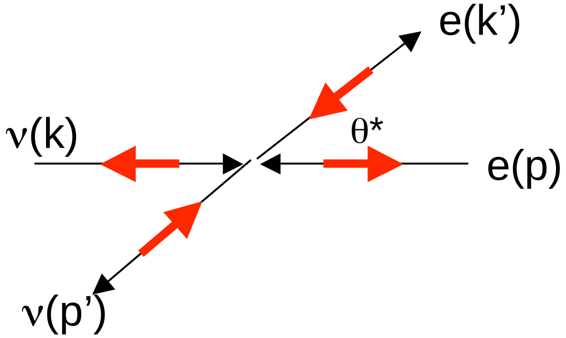
- –What are the precise values of the mixing parameters?
- –What are the neutrino masses?
- –What kinds of particles are neutrinos? Dirac or Majorana?
- –Is there CP violation in the neutrino sector?
- –What role does neutrino mass play in cosmology?

Neutrino-electron scattering

$\nu_e\, e \rightarrow \nu_e\, e$



In CM: $y = (1-\cos\theta^*)/2$

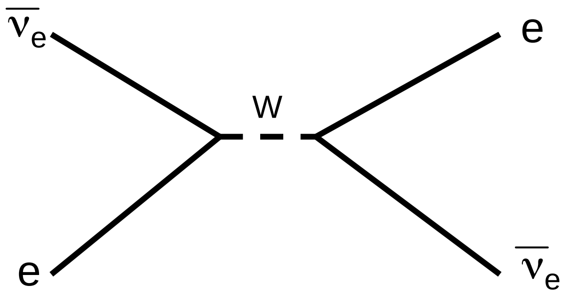


J=0 : M = constant

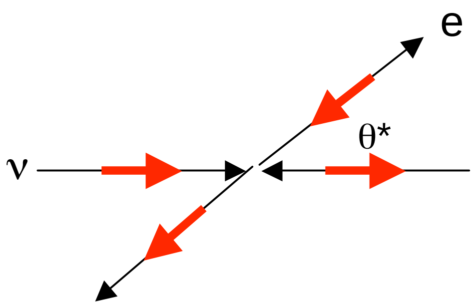
$\sigma = G^2 s/\pi \sim E_\nu(\mathrm{GeV})\times 10^{-41}\ \mathrm{cm}^2$

$\bar{\nu}_e\, e \rightarrow \bar{\nu}_e\, e$

$(p)/$



In CM:



J=1: $M \sim d^1_{-11}(\theta^*)_= (1-\cos\theta^*)/2$

$\sigma = (G^2 s/\pi)\ /\ 3$

Neutrino - Electron Scattering

1. Cross section is proportional to energy
2. LL, RR interactions are flat in y, LR,RL go as $(1-y)^2$
3. Ratio of total cross section for LR/LL is 1/3

For neutrino-electron scattering:

$d\sigma/dy$ = (constant) means that $d\sigma/dQ^2$ =(constant) also.

No matter what the length scale probed by the W/Z, the electron looks the same - *like a point particle*!

ν-quark scattering

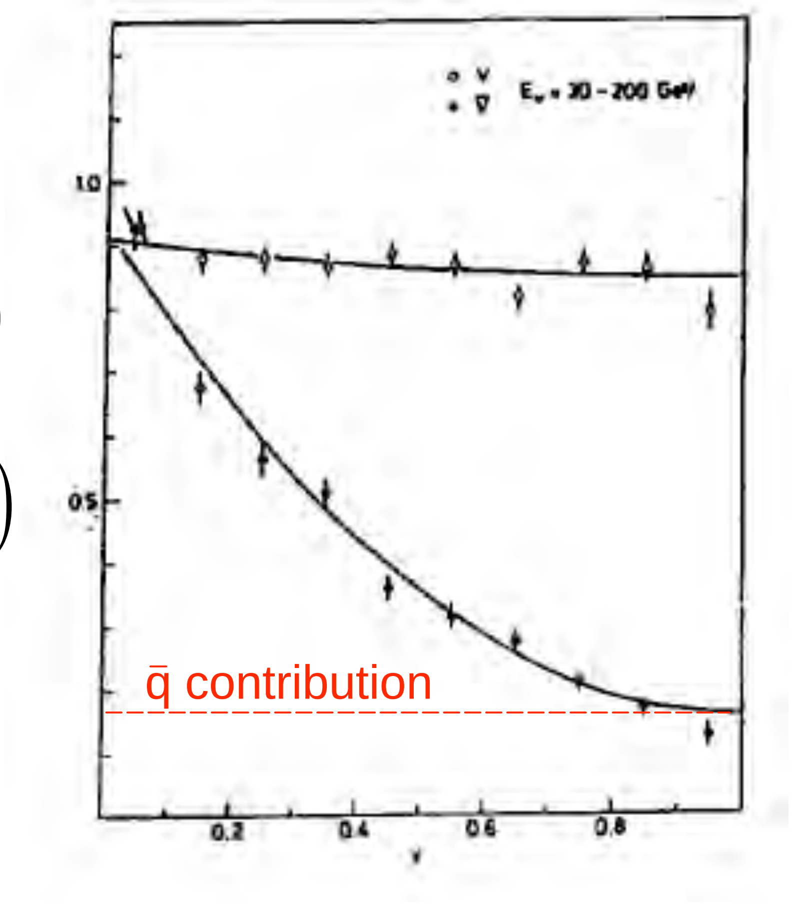
From our discussion of neutrino-electron scattering we found that the helicity combinations (LL,RR = νq, $\bar{\nu}\bar{q}$) are J=0 combinations with flat-y dependence, and LR,RL combinations ($\bar{\nu}q$, $\nu\bar{q}$) are J=1 combinations with $(1-y)^2$ dependence.

$$y = \frac{E_{had}}{E_\nu} \quad \text{(in the lab)}$$

$$\frac{d\sigma^{\nu p}}{dxdy} = \frac{G^2 s}{\pi}\left(xd(x) + xs(x) + x\bar{u}(x)(1-y)^2\right)$$

$$\frac{d\sigma^{\bar{\nu} p}}{dxdy} = \frac{G^2 s}{\pi}\left(x\bar{d}(x) + x\bar{s}(x) + xu(x)(1-y)^2\right)$$

(ignoring c, b,t quarks., c quark mass)



Overview

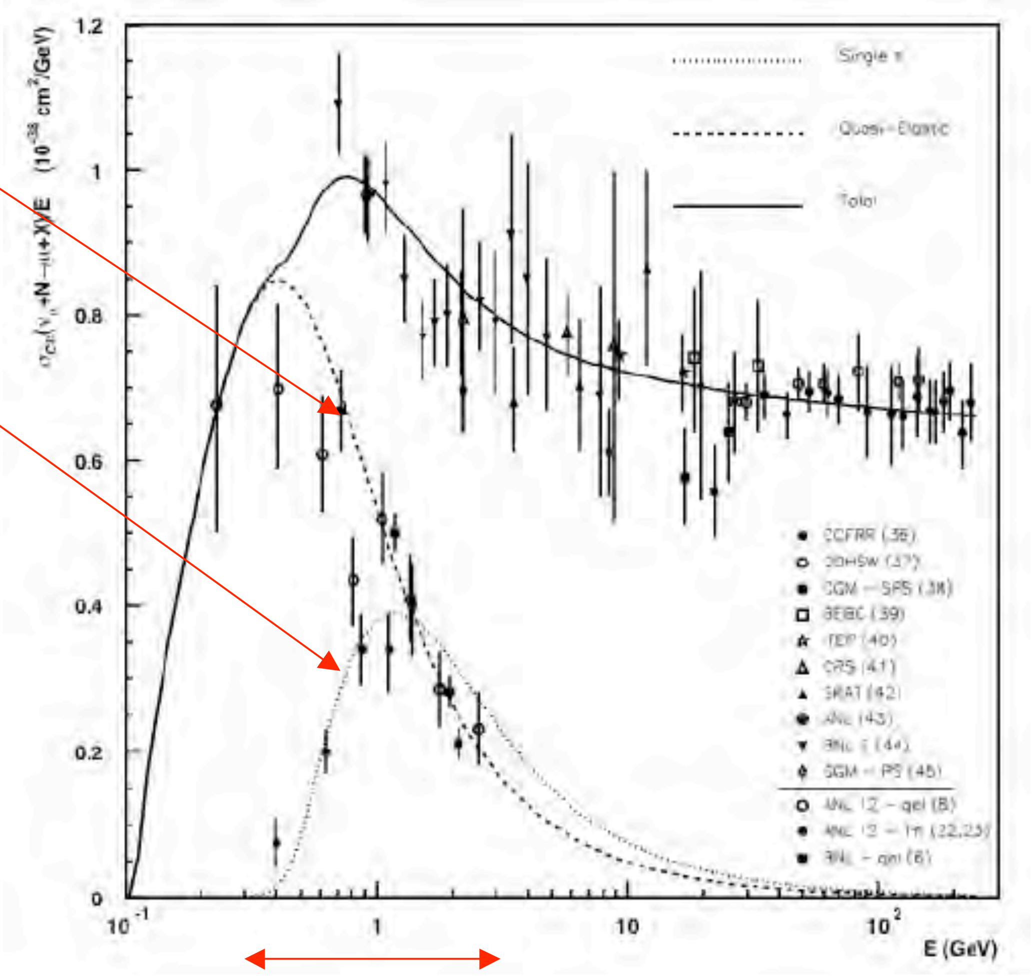
Elastic / Quasi-elastic:
ν_μ p --> ν_μ p
ν_μ n --> μ p

Single pion production
e.g. ν_μ n --> μ p π^0

Multi-pion production / DIS
ν_μ N --> μ + X

Neutrino - nucleus coherent scattering
ν_μ A -->μ π^+ A
ν_μ A -->ν_μ π^0 A

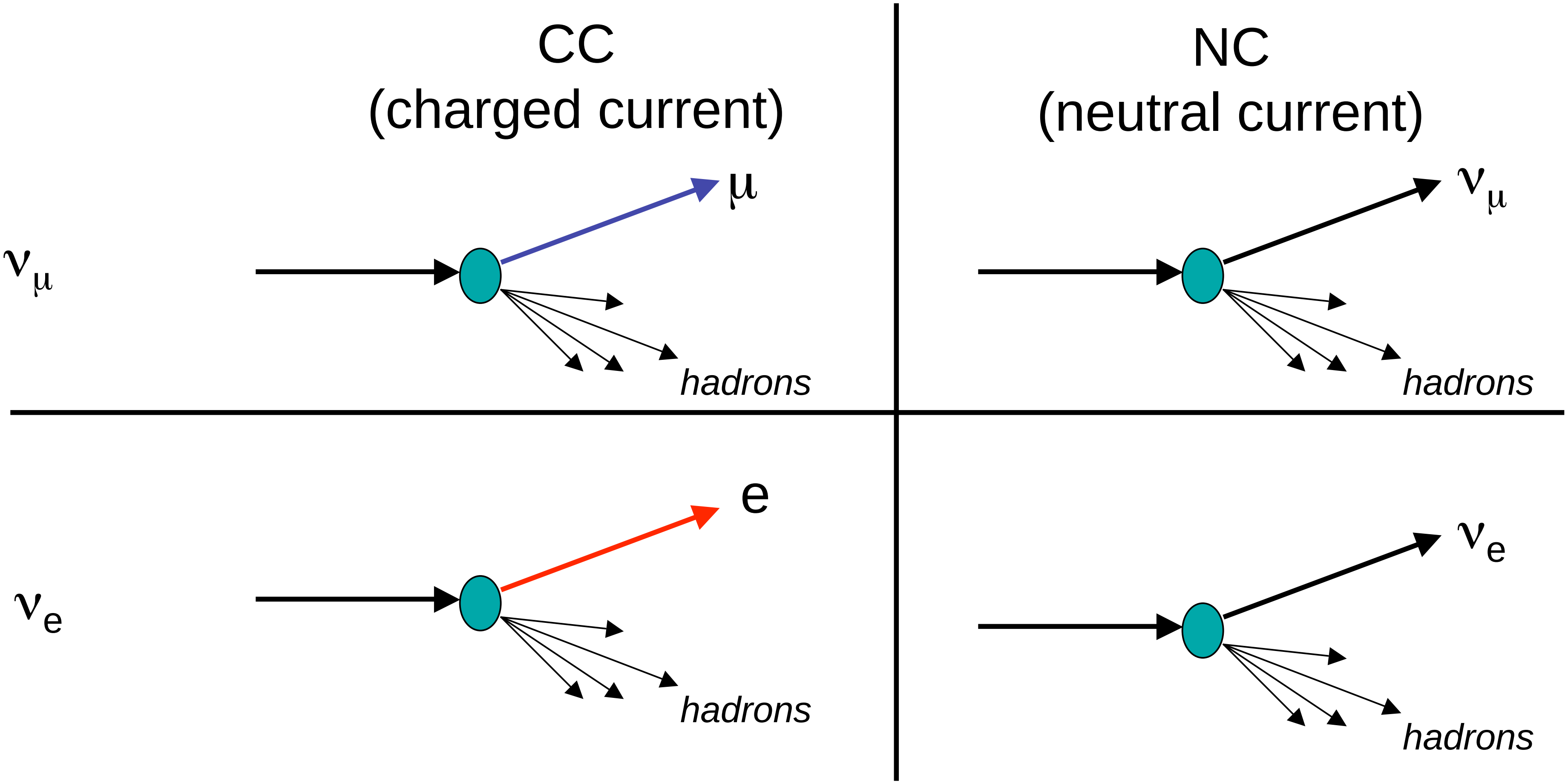
Neutrino - electron scattering
ν_μ e --> μ ν_e



In the energy range of interest to upcoming oscillation experiments, many processes contribute!

Neutrino Interactions

How does one distinguish between ν_μ and ν_e interactions?



CC
(charged current)

NC
(neutral current)

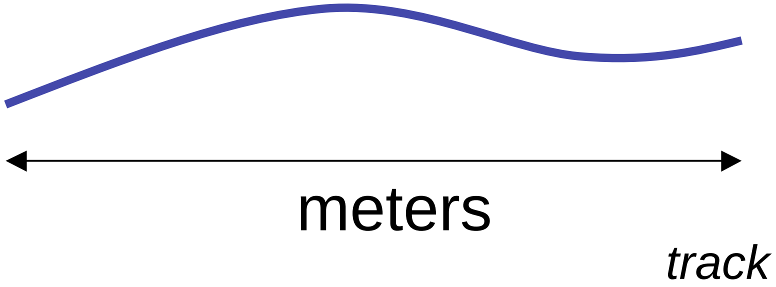
ν_μ

ν_e

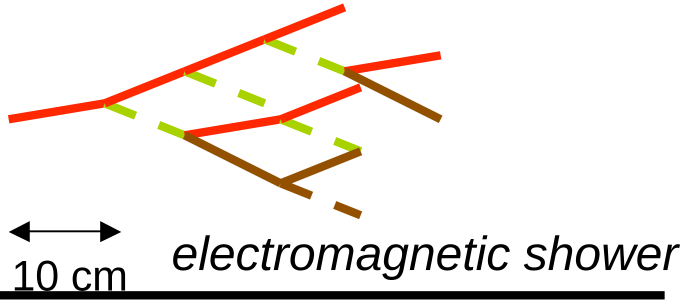
hadrons include: protons, neutrons, pions (π^+, π^-, π^0)

Particle interactions

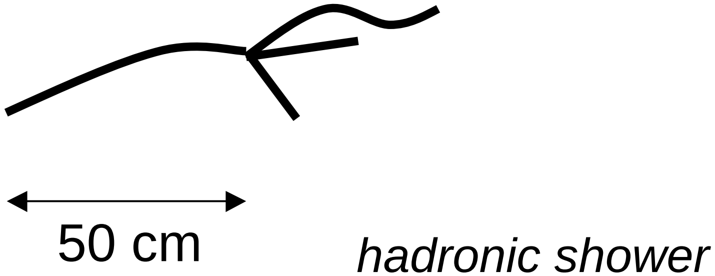
μ: lose energy slowly
(~ 1 GeV / 2 m)



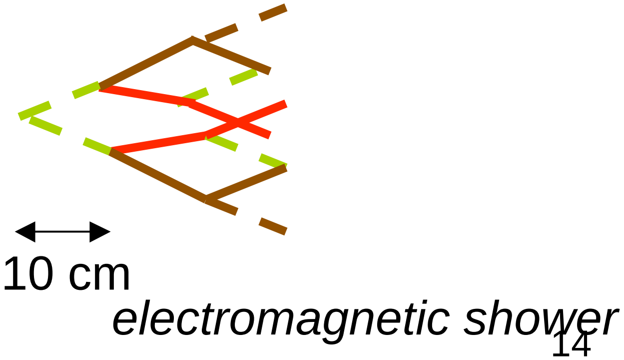
e: radiate energy rapidly, into photons, which produce electron - positron pairs



hadrons (except π^0): lose energy slowly, occasionally interact to produce more hadrons



The catch: π^0 hadrons decay immediately into two photons.

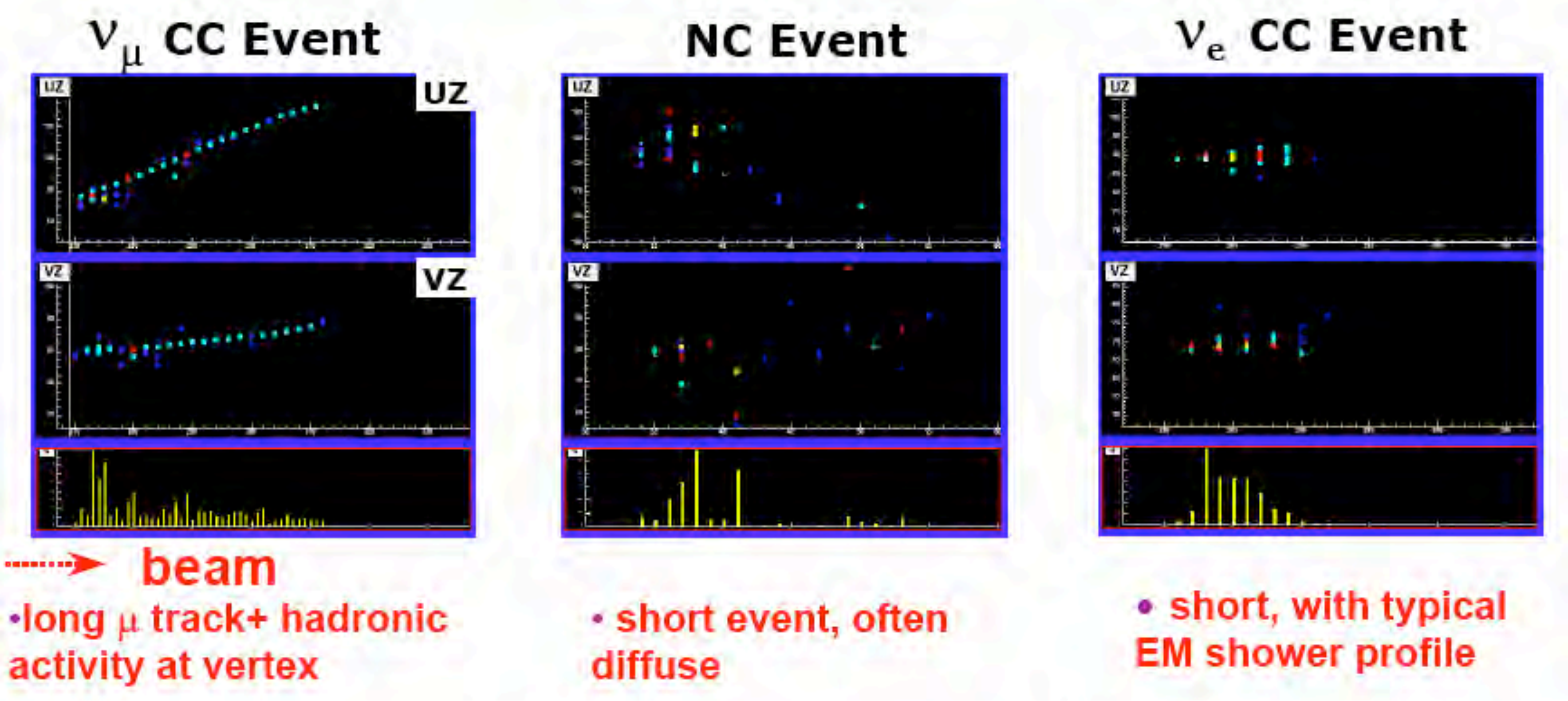


Identifying Interactions

Distinguishing CC from NC interactions, and identifying the neutrino flavor in CC events is a major issue for any experiment.

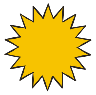
Interplay between the neutrino flavor / energies, and the detector technology.

(MINOS example)



- long μ track+ hadronic activity at vertex
- short event, often diffuse
- short, with typical EM shower profile

The Evidence

ν Source	E_ν	L	L/E (eV^{-2})
Accelerator 	1000 MeV	100 m	10^{-1}
Reactor 	1 MeV	10 m -10 km	10^{1} -10^{4}
Atmosphere 	1000 MeV	10^{6} m	10^{3}
Solar 	1 MeV	10^{10} m	10^{10}

Flavor Change?

yes! K2K, MINOS

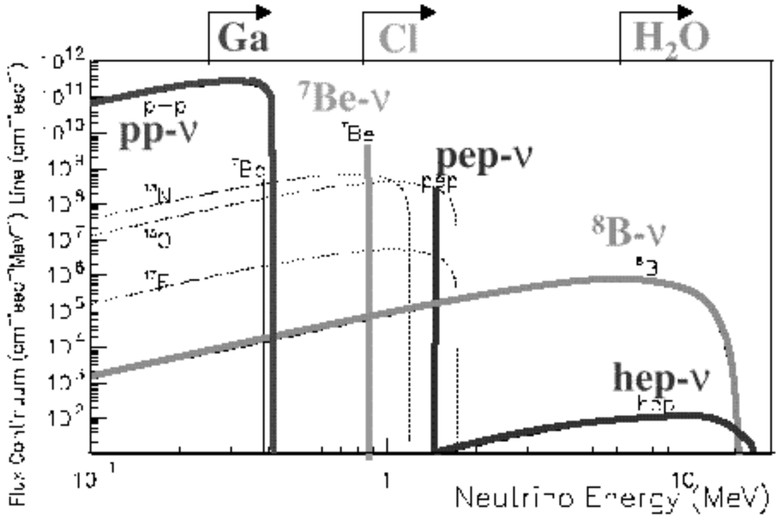
yes! LSND ?!?!?

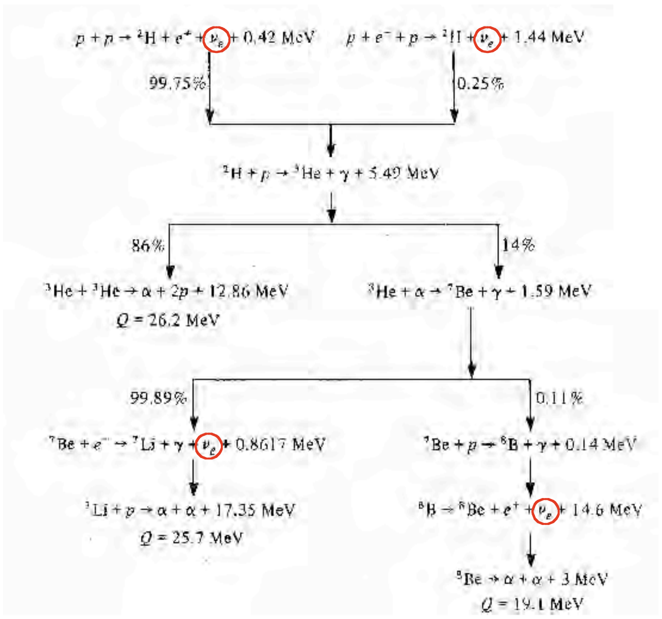
yes! Kamland

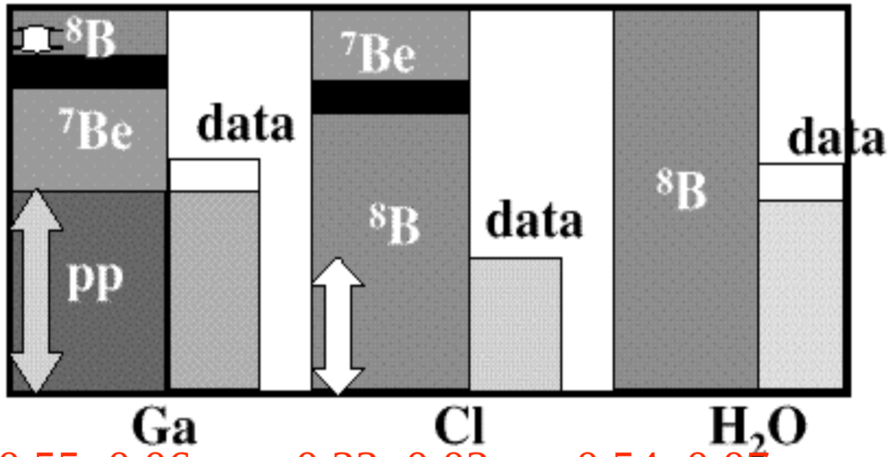
yes! SuperK, Soudan2, MACRO

yes! SuperK, SNO, Homestake, SAGE...

Solar Neutrinos



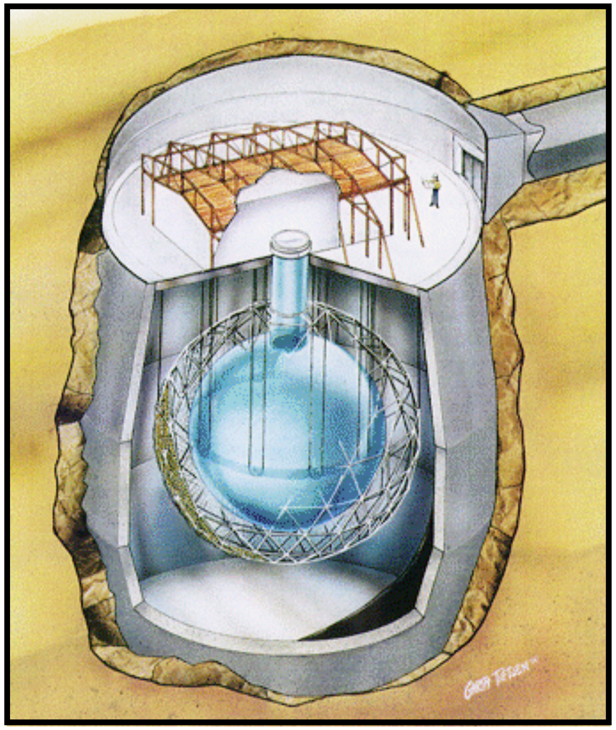




0.55±0.06 0.33±0.03 0.54±0.07

Process	Experiment	E Threshold
$\nu_e + e^- \longrightarrow \nu_e + e^-$	Kamiokande (Japan) SupeKamiokande	7.3 MeV 6.5 MeV
$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar$	Homestake (USA)	0.8 MeV
$\nu_e + {}^{71}Ga \rightarrow e^- + Ge$	SAGE	.233 MeV
$\nu_e + {}^{71}Ga \rightarrow e^- + Ge$	GALLEX	.233 MeV

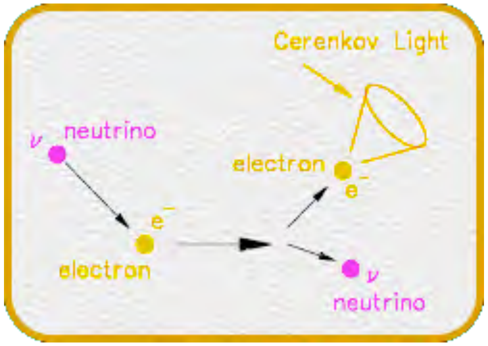
Sudbury Neutrino Observatory



- 1 kton ultra-pure D_2O
- 12 m diameter acrylic vessel
- 9456 PMTs surrounded by light water
- PMT times and hit patterns are used to determine location, direction, and energy

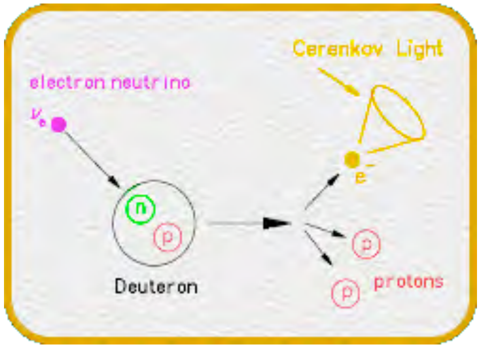
Elastic Events: $\nu_e \sim 6 \times (\nu_\mu, \nu_\tau)$

3 events / day
good directionality



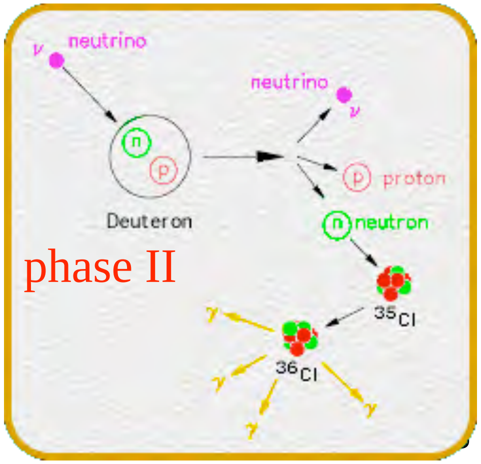
CC Events: ν_e only

30 events / day
spectral information



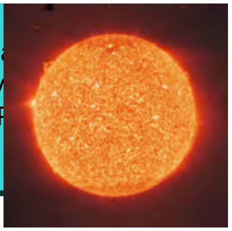
NC Events: ν_e, ν_μ, ν_τ

30 events / day
flavor independent!



phase II

SNO

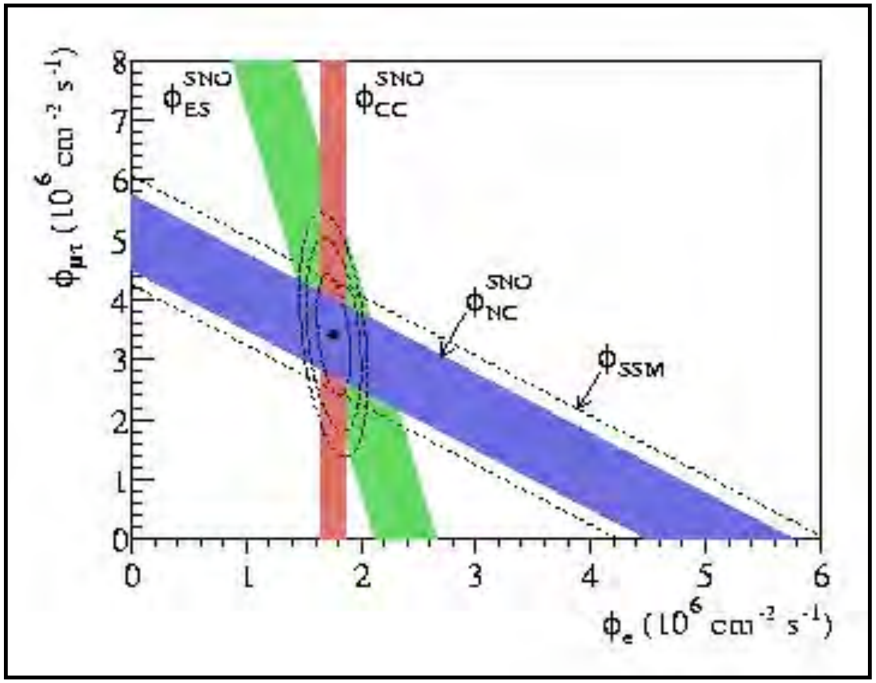


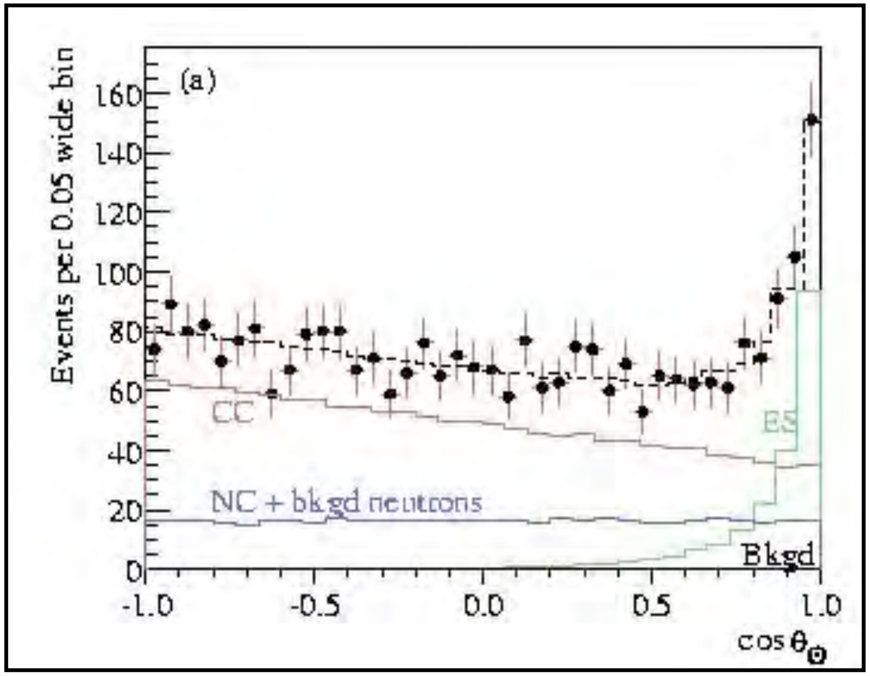
The total flux is measured with the NC reaction:

$$\phi_{NC} = 6.42\ ^{+1.57}_{-1.52}\ \text{(stat)}\ ^{+0.55}_{-0.58}\ \text{(syst)} \quad (10^6\ \text{cm}^{-2}\ \text{s}^{-1})$$

in good agreement with the prediction

$$\phi_{SSM} = 5.05\ ^{+1.01}_{-0.81} \quad (10^6\ \text{cm}^{-2}\ \text{s}^{-1})$$

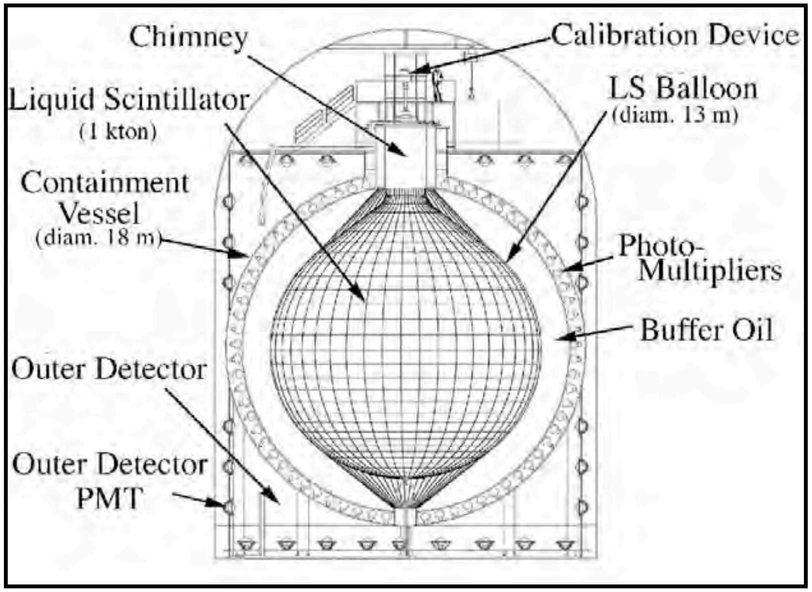




KamLand

KamLand is a long-baseline reactor neutrino experiment sensitive to the same Δm^2 as the solar neutrino experiments.

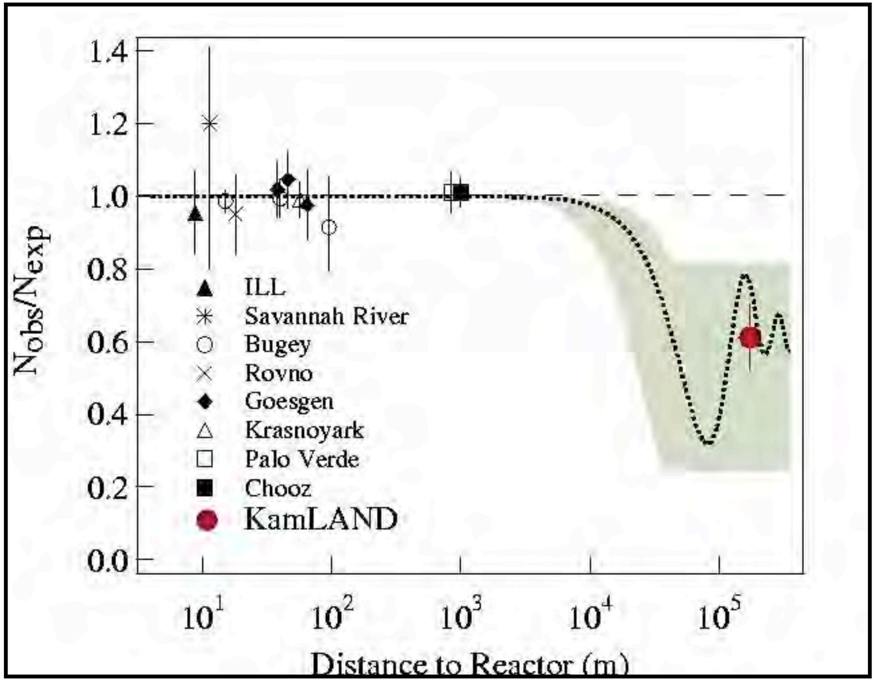
1kton ultra-pure liquid scintillator, measures a $\bar{\nu}_e$ flux from many reactors 79% from 26 reactors within 138-214 km. Location of the Kamioka experiment



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

detect prompt e^+

detect γ emitted after neutron capture



"First Results from KamLand: Evidence for Reactor Anti-Neutrino Disappearance"
PRL 90: 021802 (2003)
shows the first evidence for neutrino disappearance from a reactor!

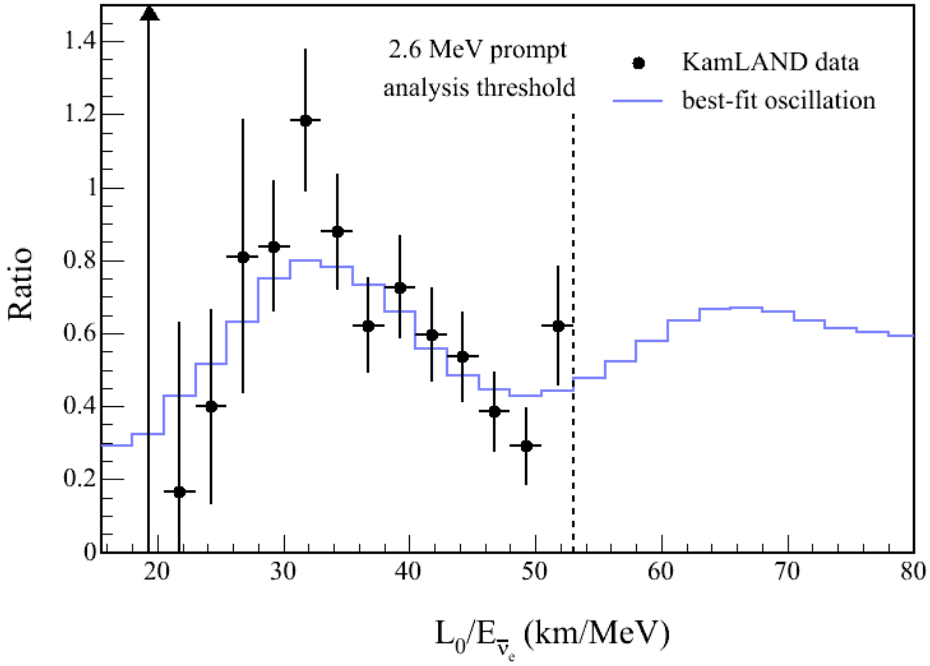
Solar Neutrinos

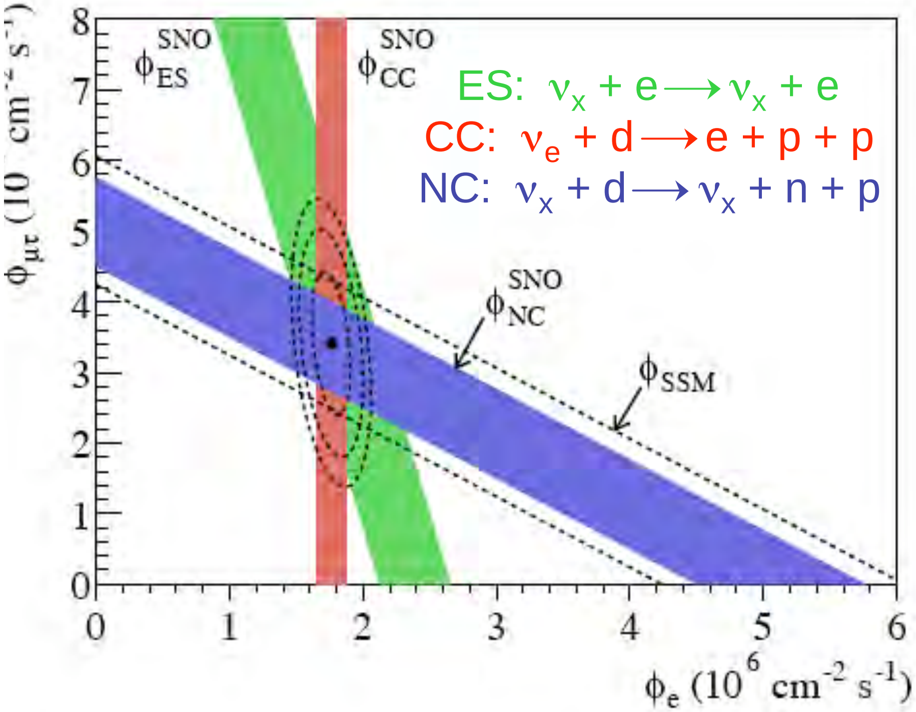
H. Gallagher
Tufts University
NEPPSR
August 15, 2007

1960’s - 1990’s : solar ν_e data/theory ~ 30-60%!

Kamland and SNO data have converged on MSW-enhanced mixing in the sun as the solution of the “solar neutrino problem”.

Δm^2_{sol}=7-9 x 10^{-5} eV^2 $\theta_{sol} = 34 \pm 2^o$



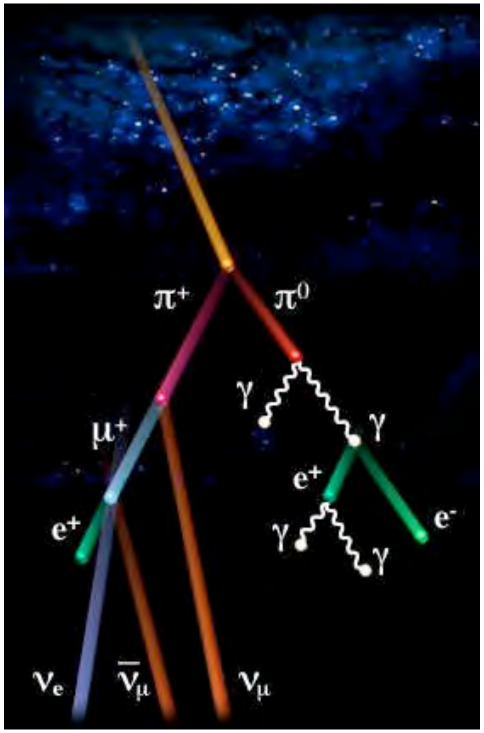


ES: $\nu_x + e \longrightarrow \nu_x + e$

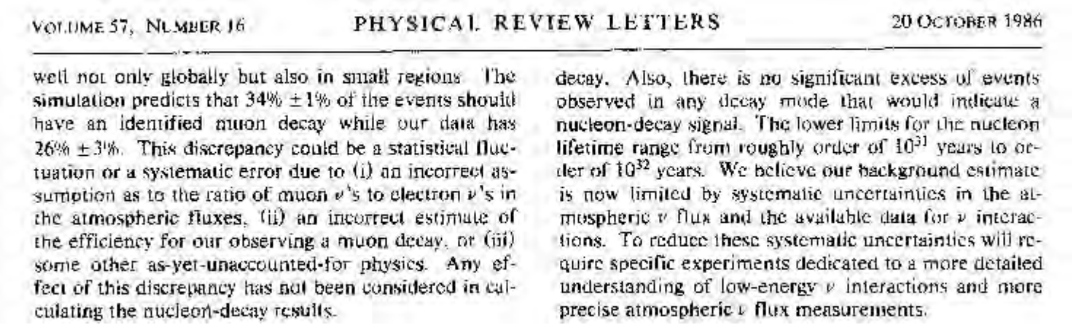
CC: $\nu_e + d \longrightarrow e + p + p$

NC: $\nu_x + d \longrightarrow \nu_x + n + p$

Atmospheric Neutrinos



Originally studied as a potential background for underground proton decay experiments. First hint of oscillations... 1986!

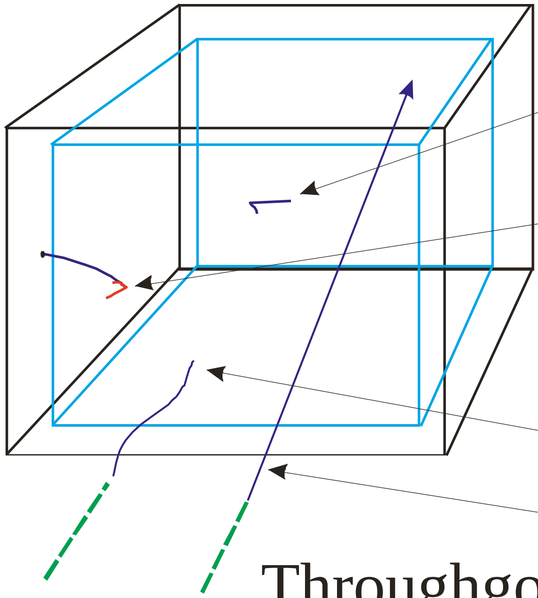


VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν's in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

decay. Also, there is no significant excess of events observed in any decay mode that would indicate a nucleon-decay signal. The lower limits for the nucleon lifetime range from roughly order of 10^{31} years to order of 10^{32} years. We believe our background estimate is now limited by systematic uncertainties in the atmospheric ν flux and the available data for ν interactions. To reduce these systematic uncertainties will require specific experiments dedicated to a more detailed understanding of low-energy ν interactions and more precise atmospheric ν flux measurements.

IMB collab.



Contained Events
E_ν~ 1 GeV

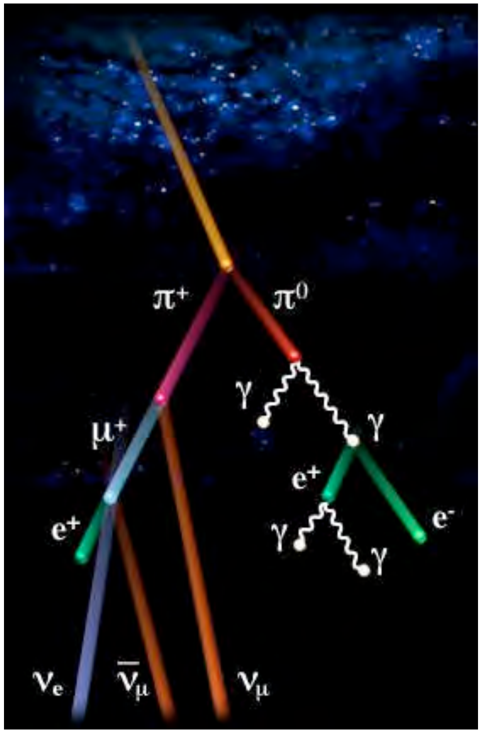
Semi-Contained Events
E_ν~ 10 GeV

Upgoing μ
Stopping E_ν~ 10 GeV

ν

Throughgoing E ~ 100 GeV

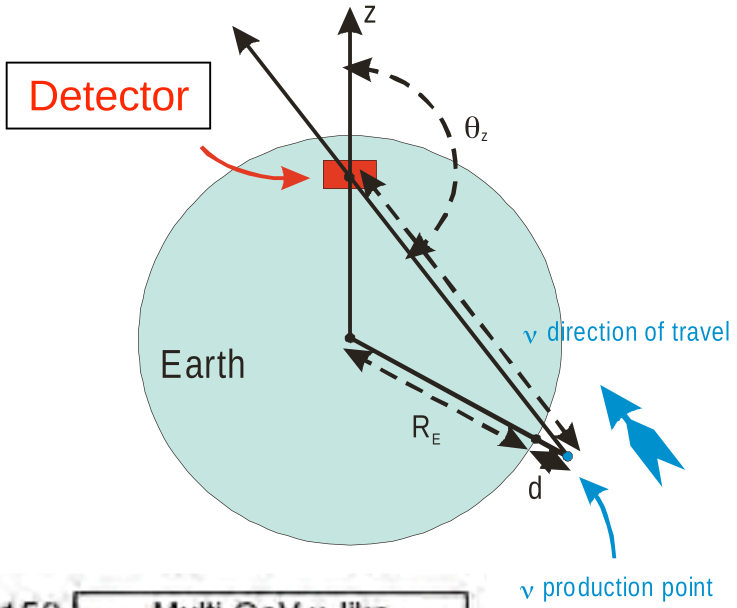
Atmospheric Neutrinos



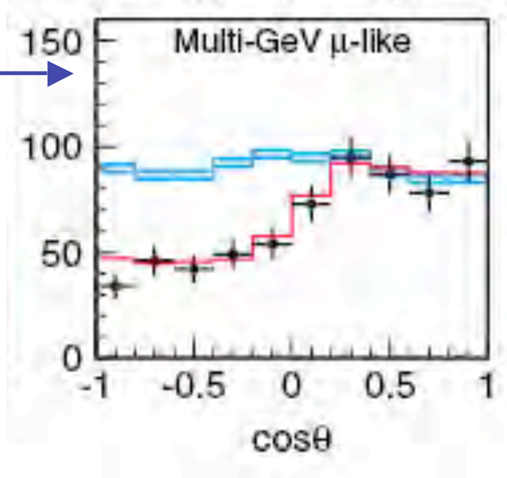
"Atmospheric Neutrino Anomaly" - flavor ratio ν_μ/ν_e (data/MC) was around 0.6. *Kamiokande, IMB, Soudan-2*

E: Independent samples containing neutrinos from 100 MeV - 100 GeV

L: spans 10-10^3 km flux up-down symmetric for E >1 GeV, look for zenith angle effects!



Large zenith angle effects seen by the Super-Kamiokande, Soudan-2, and MACRO experiments:



Δm^2_{atm}=1-3 x 10^{-3} eV^2 θ_{atm} = 45 ± 8°

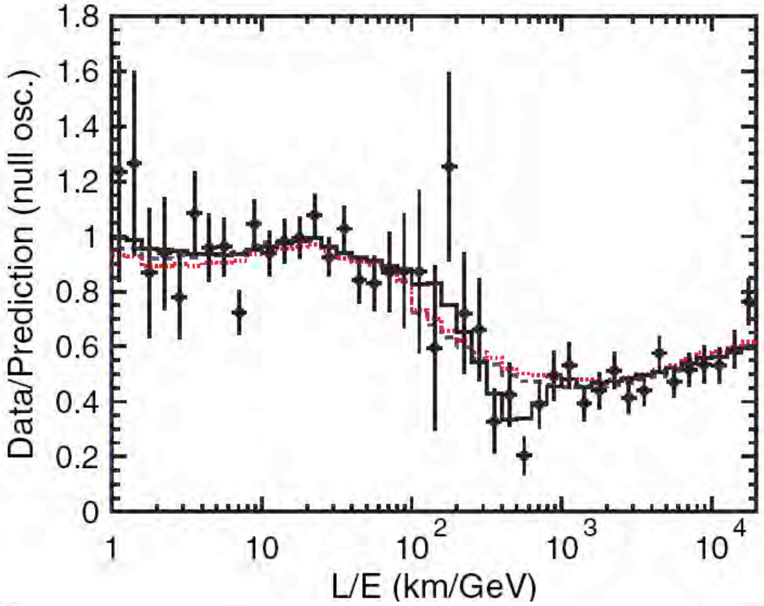
SuperKamiokande Atmos ν

Is it really oscillations??

Select events with good L/E resolution

Data agrees with two-flavor oscillations, disfavors exotic models like neutrino decay (dashed) and neutrino decoherence (dotted).

Phys. Rev. Lett. **93**, 101801 (2004)



Is it really $\nu_\mu \to \nu_\tau$ *??*

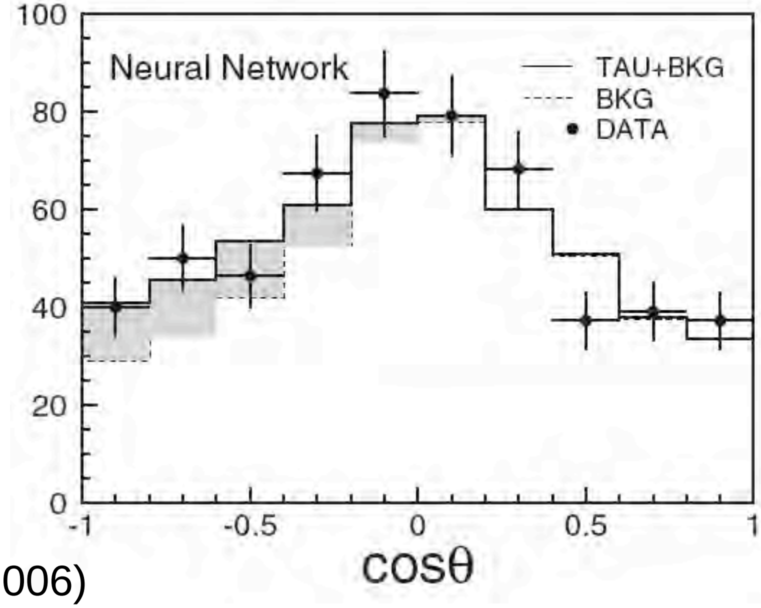
taus: energetic, 65% hadronic decays

Signal: $138 \pm 48(stat)^{+15}_{-32}(syst)$

Expectation: $78 \pm 26(syst)$

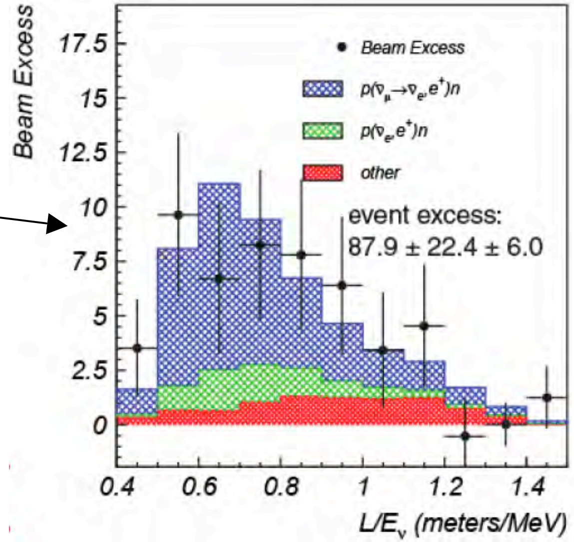
No τ appearance disfavored at 2.4 σ

Phys. Rev. Lett **97**, 171801 (2006)



LSND / miniBoone

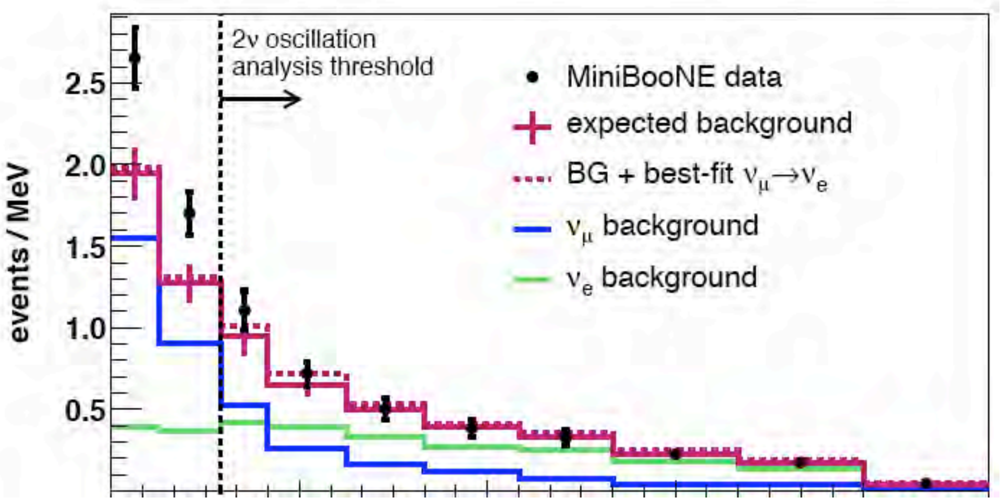
The LSND experiment had previously reported evidence for $\bar{\nu}_e$ appearance in a stopped pion beam.

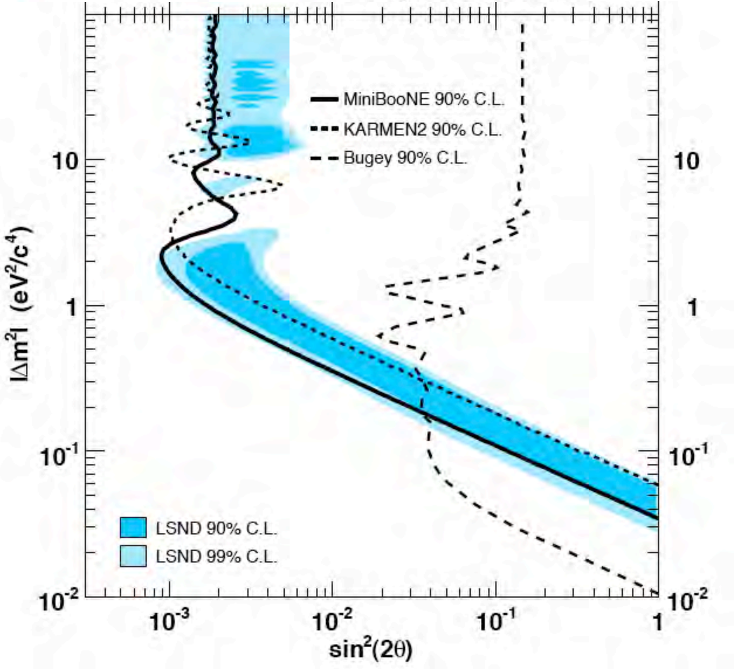


One problem: too many Δm^2 !

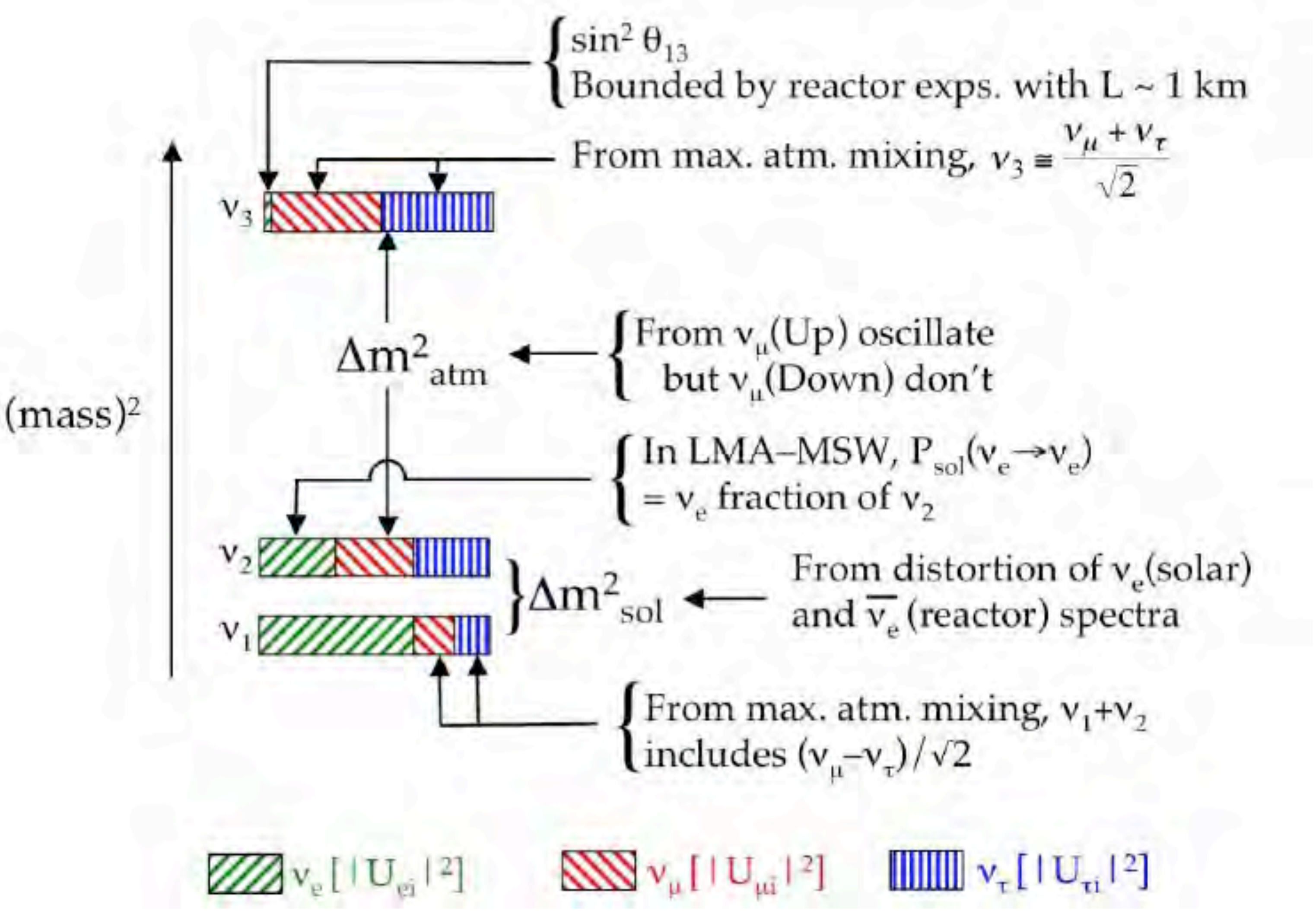
miniBoone (Fermilab) - April 2007

"The data are consistent with no oscillations within a two-neutrino appearance-only oscillation model."





Knowns and Unknowns



$\sin^2\theta_{13}$
Bounded by reactor exps. with L ~ 1 km

From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$

ν_3

Δm^2_{atm}

From ν_μ(Up) oscillate
but ν_μ(Down) don't

$(\text{mass})^2$

In LMA–MSW, $P_{sol}(\nu_e \to \nu_e)$
$= \nu_e$ fraction of ν_2

ν_2

ν_1

Δm^2_{sol}

From distortion of ν_e(solar)
and $\bar{\nu}_e$ (reactor) spectra

From max. atm. mixing, $\nu_1+\nu_2$
includes $(\nu_\mu - \nu_\tau)/\sqrt{2}$

▨ $\nu_e\ [|U_{ei}|^2]$ ▨ $\nu_\mu\ [|U_{\mu i}|^2]$ ▥ $\nu_\tau\ [|U_{\tau i}|^2]$

Boris Kayser, hep-ph/0506165

Known and Unknowns

Questions for the current generation of experiments
(K2K, miniBoone, MINOS, OPERA)

- *Is there mixing to sterile neutrinos (needed to accommodate LSND)?*
- Better precision on parameters (how close is θ_{23} to 45^o?)
- Confirm neutrino appearance $\nu_\mu \rightarrow \nu_\tau$?

Questions for the next generation of reactor and accelerator experiments

- “Normal” or “Inverted” mass hierarchy (sign of Δm^2_{32})
- θ_{13} and δ_{CP} in the PMNS matrix

Questions for others (cosmology, $0\nu\beta\beta$, β decay)

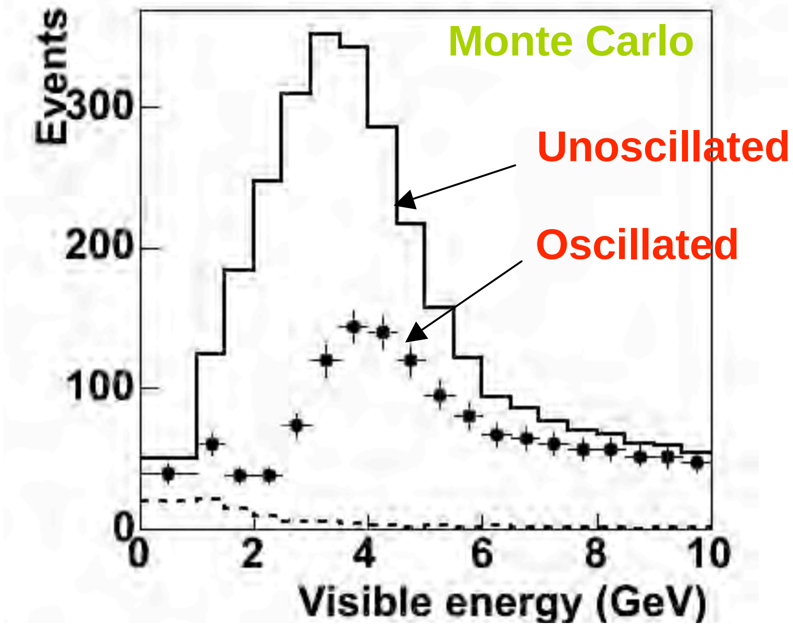
- Are neutrinos degenerate? – measuring m_ν not Δm^2.
- Majorana or Dirac particles?

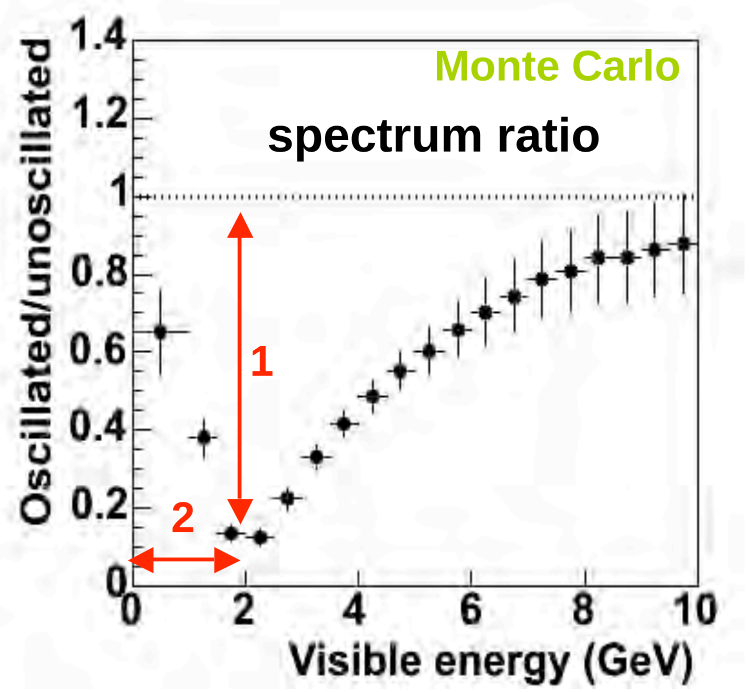
Long Baseline in a Nutshell

$$P(\nu_\mu \to \nu_\mu) = 1 - \underset{1}{\boxed{\sin^2 2\theta}}\sin^2(1.267\underset{2}{\boxed{\Delta m^2}}L/E)$$

1. Make a neutrino beam of pure flavor (usually ν_μ)
2. Construct a near detector to measure unoscillated distributions
3. Construct an identical far detector at optimal L
   - look for appearance of new flavor in the beam
   - look for disappearance of original flavor

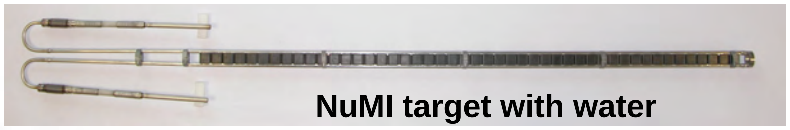
ν_μ spectrum





Making a Neutrino Beam (NuMI)

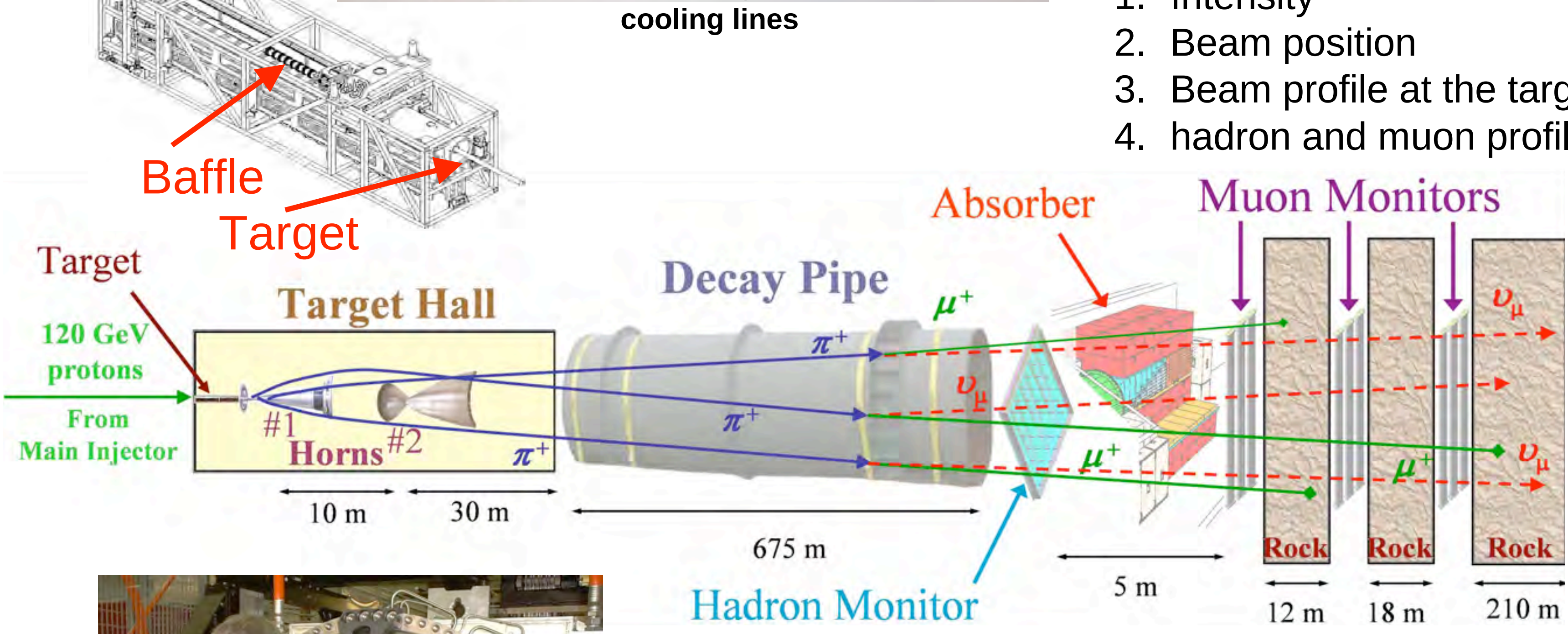
H. Gallagher
Tufts University
NEPPSR
August 15, 2007



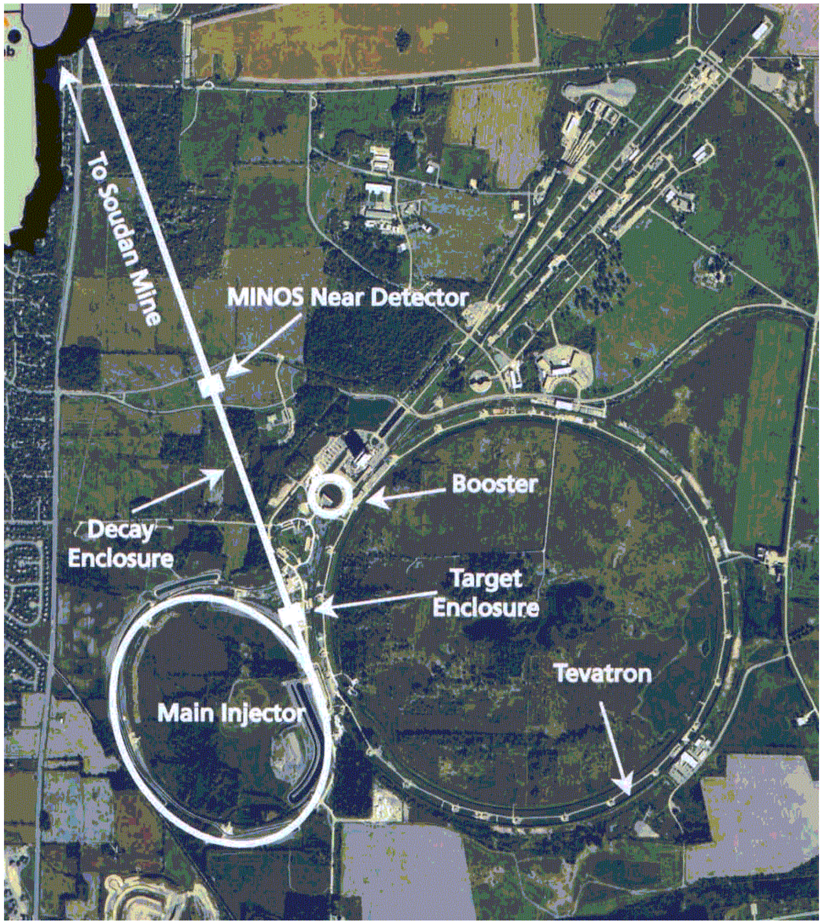
NuMI target with water cooling lines

Spill-by-spill monitoring:

1. Intensity
2. Beam position
3. Beam profile at the target
4. hadron and muon profiles



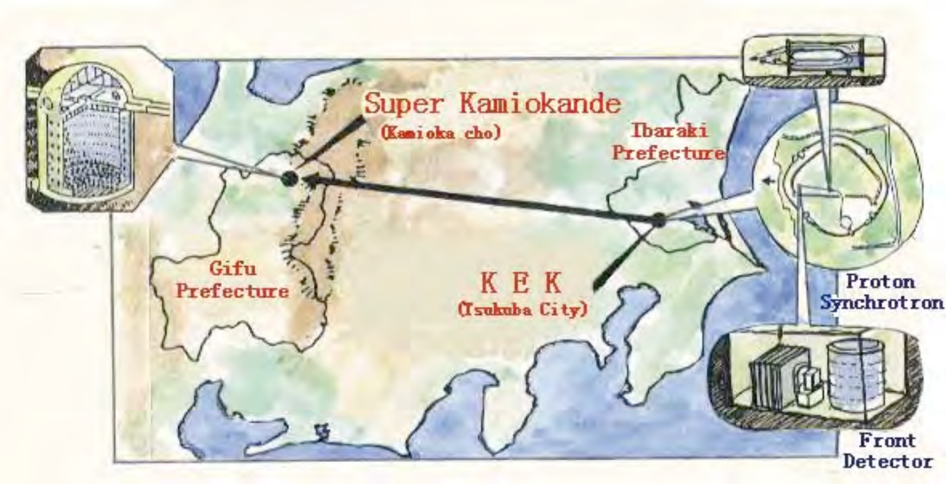
The NuMI Facility



Design parameters:

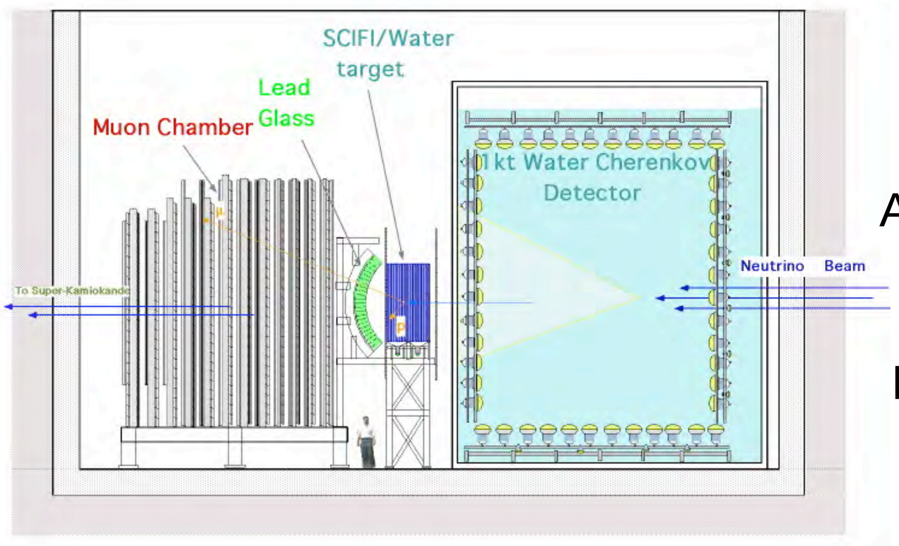
- 120 GeV protons from the Main Injector
- Main Injector can accept up to 6 Booster batches/cycle,
- Either 5 or 6 batches for NuMI
- 1.867 second cycle time
- 4×10^{13} protons/pulse
- 0.4 MW
- Single turn extraction (10μs)

The K2K Experiment



First long-baseline experiment!
1999-2004

KEK 12 GeV PS ν to SuperK
L= 250 km, E~1 GeV
9 x 10^{19} POT collected



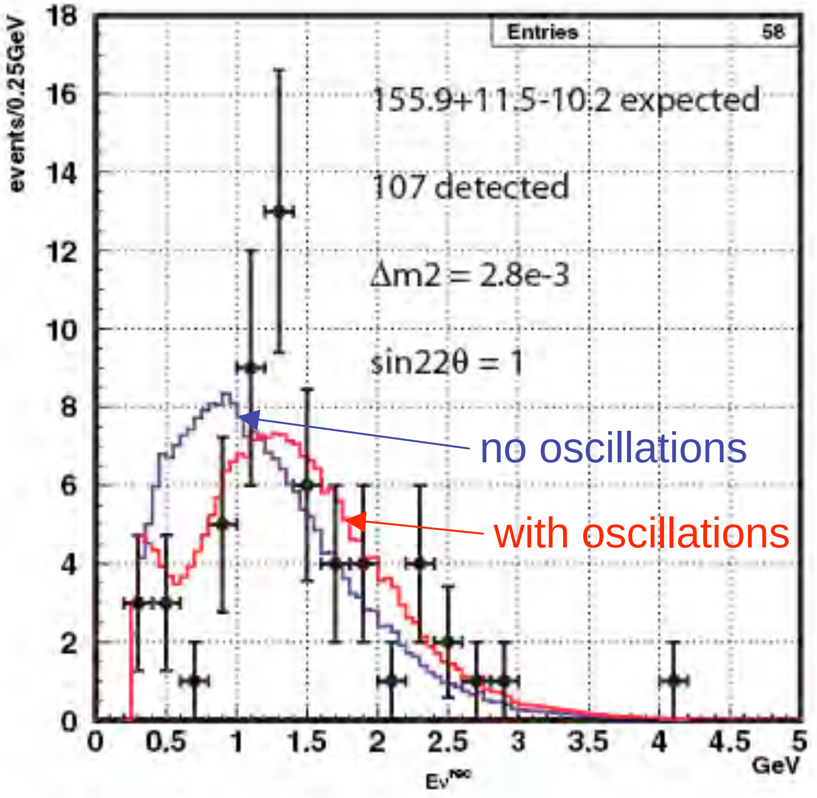
1 kt H_2O near detector similar to far

Additional near detectors for cross section measurements to improve systematics

Monitor pions and muons to predict beam

The K2K Experiment

Energy spectrum of 1-ring events

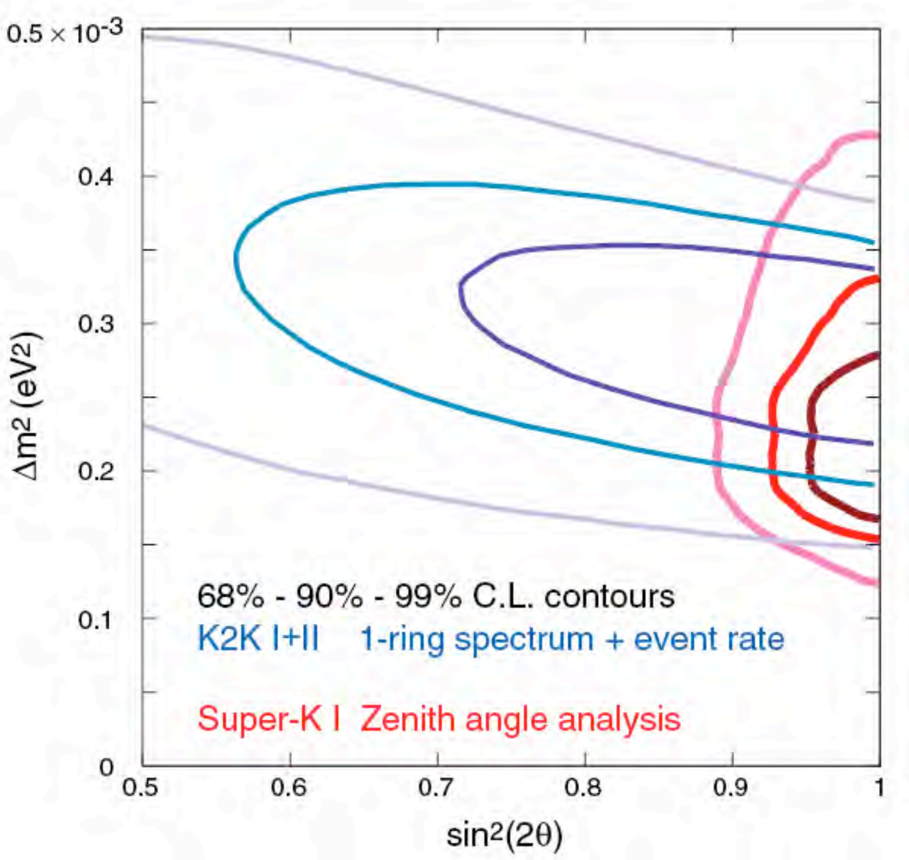


no oscillations

with oscillations

Phys. Rev. Lett. **94**, 081802 (2005).

Measurements from K2K agree well with those from atmospheric neutrino experiments.



The MINOS Experiment

MINOS (Main Injector Neutrino Oscillation Search) – a long baseline neutrino oscillation experiment:

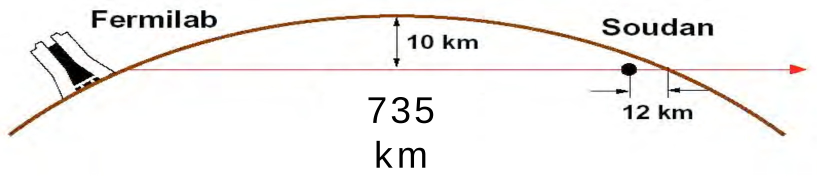
Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.

A Near detector at Fermilab to measure the beam composition and energy spectrum

A Far detector deep underground in the Soudan Mine, Minnesota, to search for evidence of oscillations

Analysis of 2 years of NuMI data:

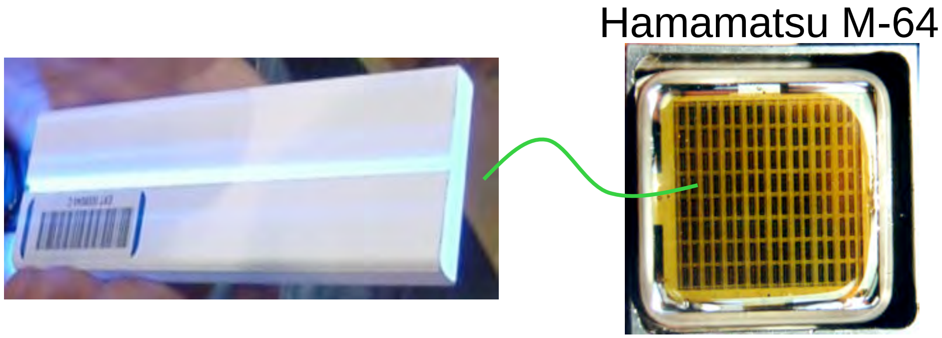
2.5×10^{20} POT → *EPS 2007 (A. Weber)*

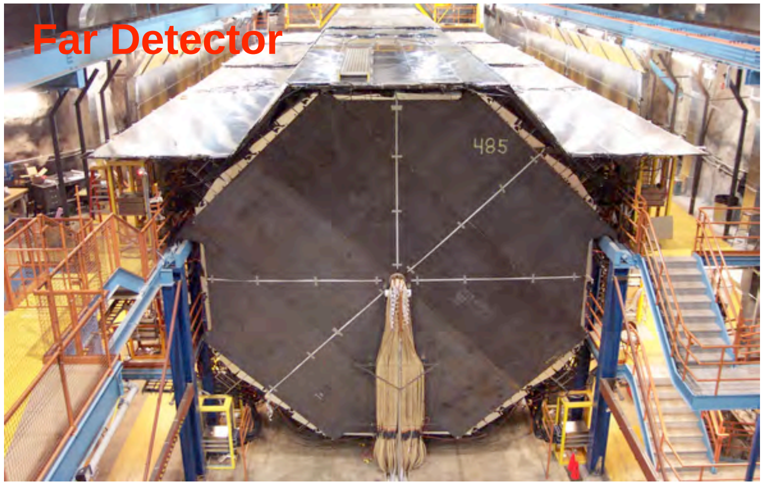


The MINOS Detectors

Functionally equivalent detectors:

- 2.54 cm thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips (MINOS developed technology)
- optical fiber readout to multi-anode PMTs

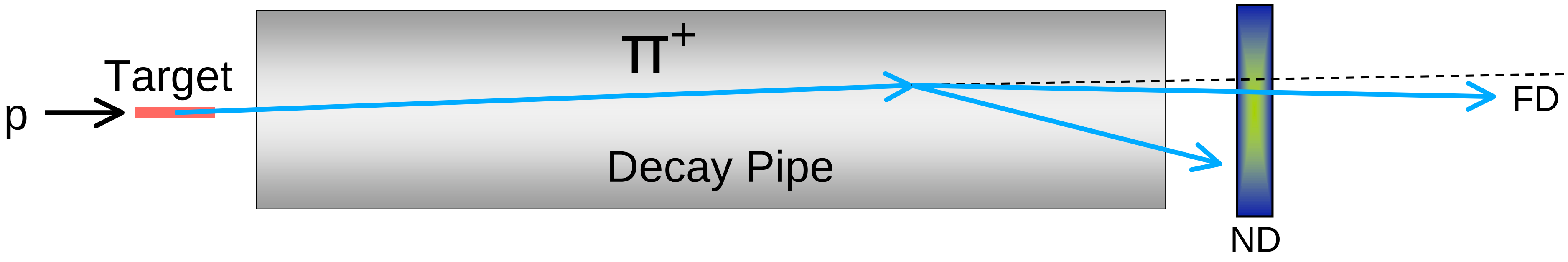




- 5.4 kton
- 8 x 8 x 30 m
- 484 steel/scintillator planes
- M16 PMT, x8 multiplexing
- VA electronics

- 1 kton
- 3.8 x 4.8 x 15 m
- 282 steel, 153 scintillator planes
- M64 PMT
- Fast QIE electronics

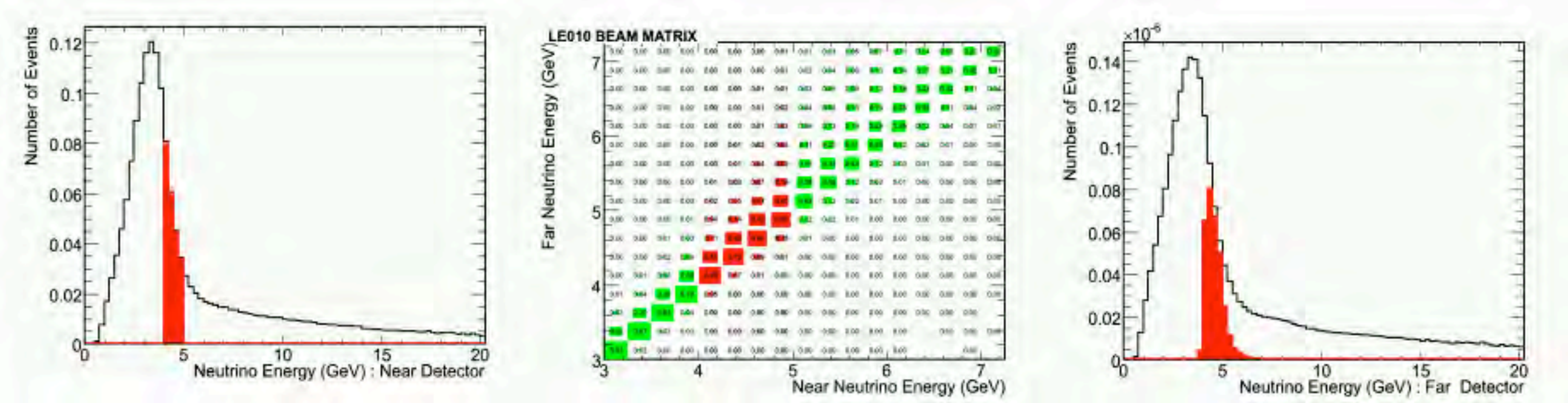
MINOS: Near to Far



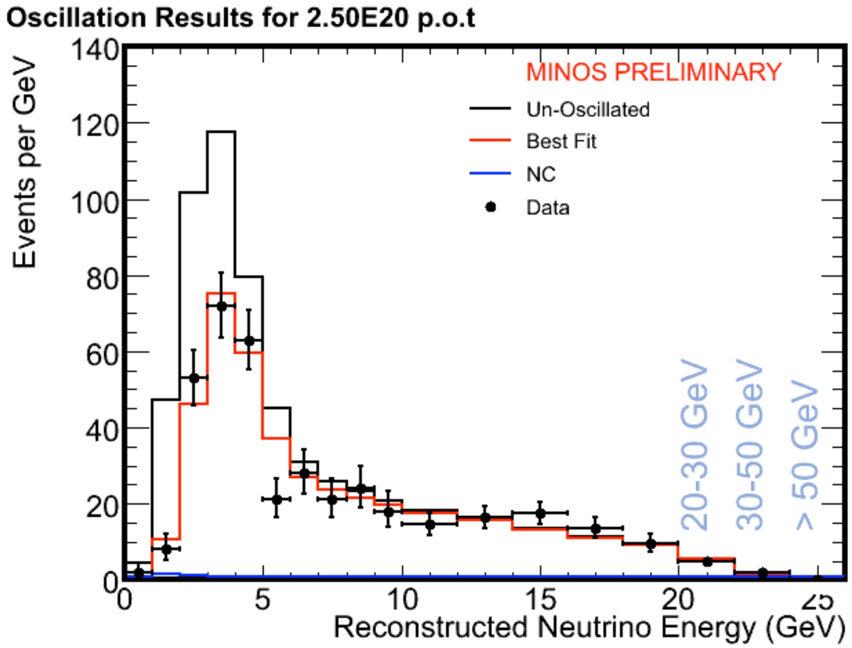
Start with near detector data & extrapolation to the far detector

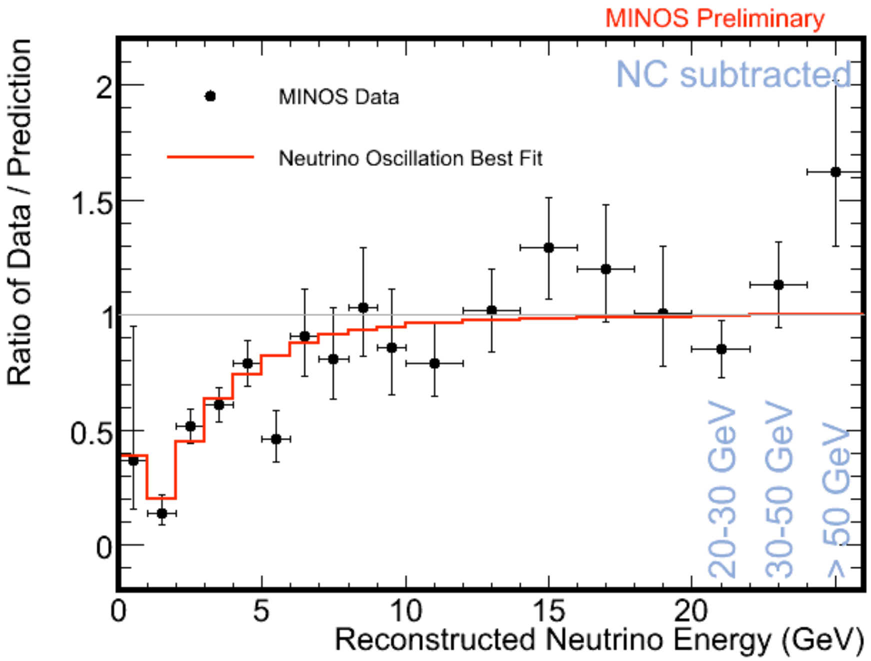
- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum

This is the primary method used in our analysis



MINOS: Energy Spectrum



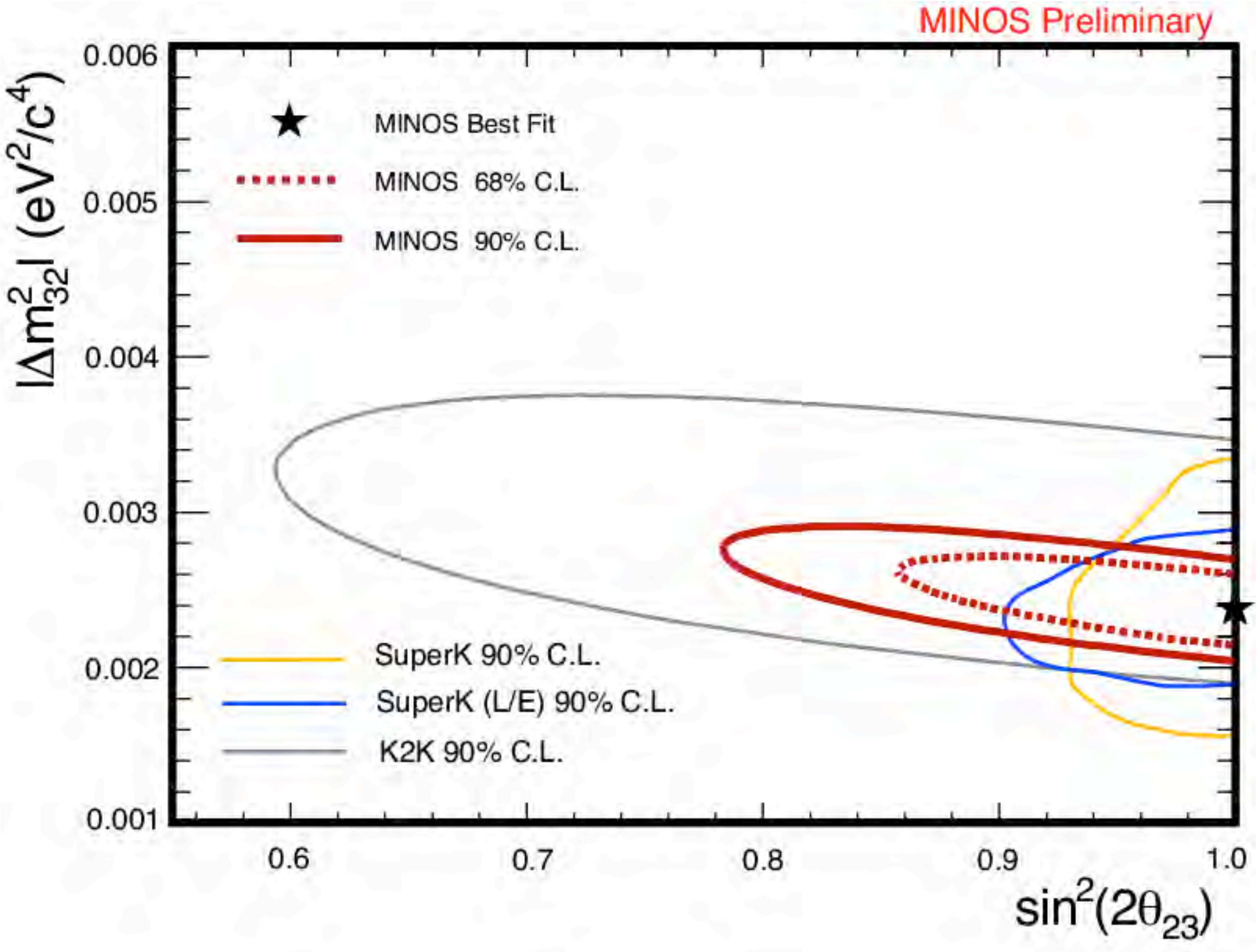


$$\left|\Delta m^2_{32}\right| = 2.38^{+0.20}_{-0.16} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2 2\Theta_{23} = 1.00_{-0.08}$$

$$\frac{\chi^2}{N_{DoF}} = \frac{41.2}{32}$$

MINOS: Allowed Region



OPERA

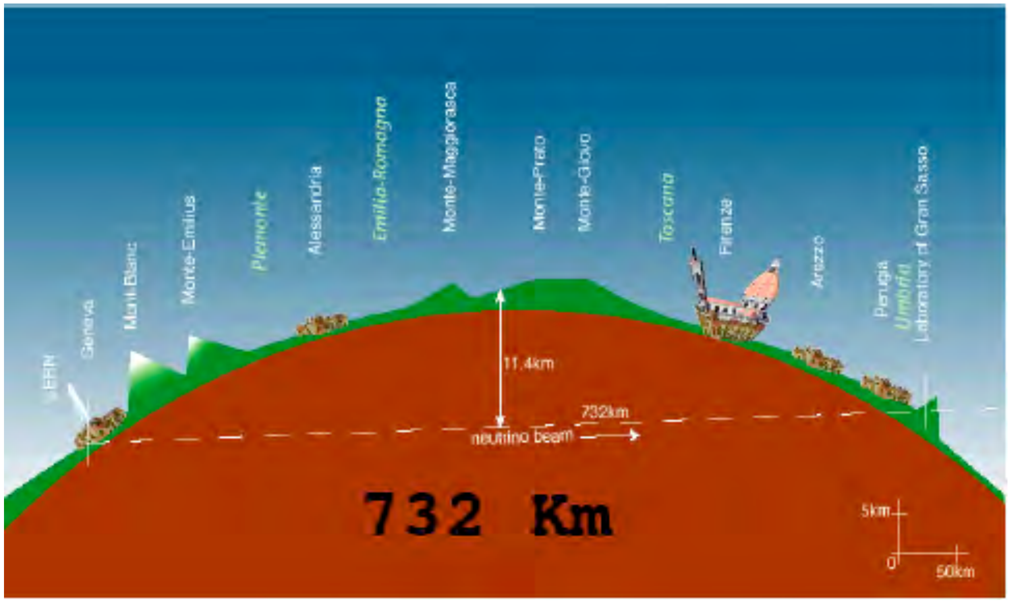
C. Sirignano (Neutrino 2006)

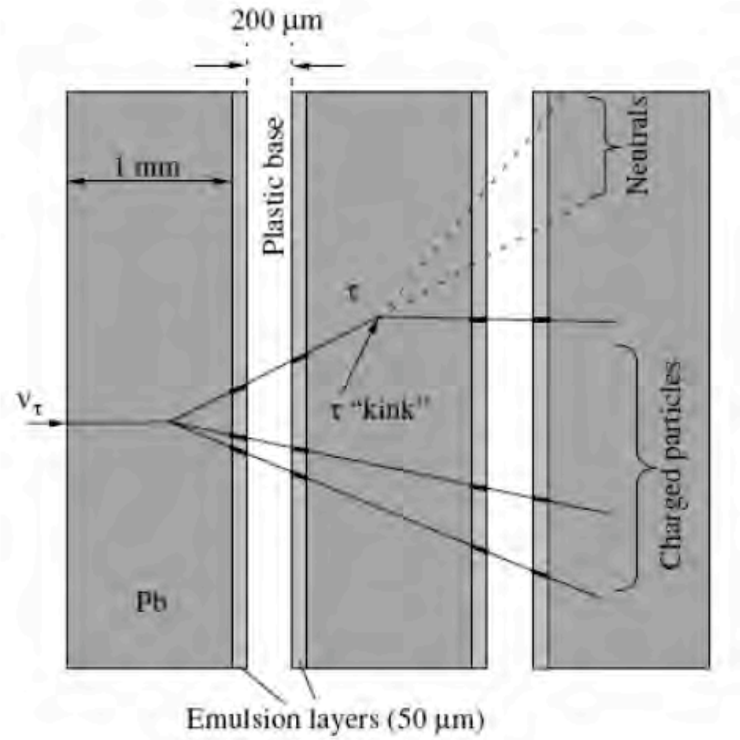
Goal is detection of ν_τ appearance at the atmospheric Δm^2.

Find O(1mm) track from tau with decay kink.

New CNGS neutrino beamline at CERN:

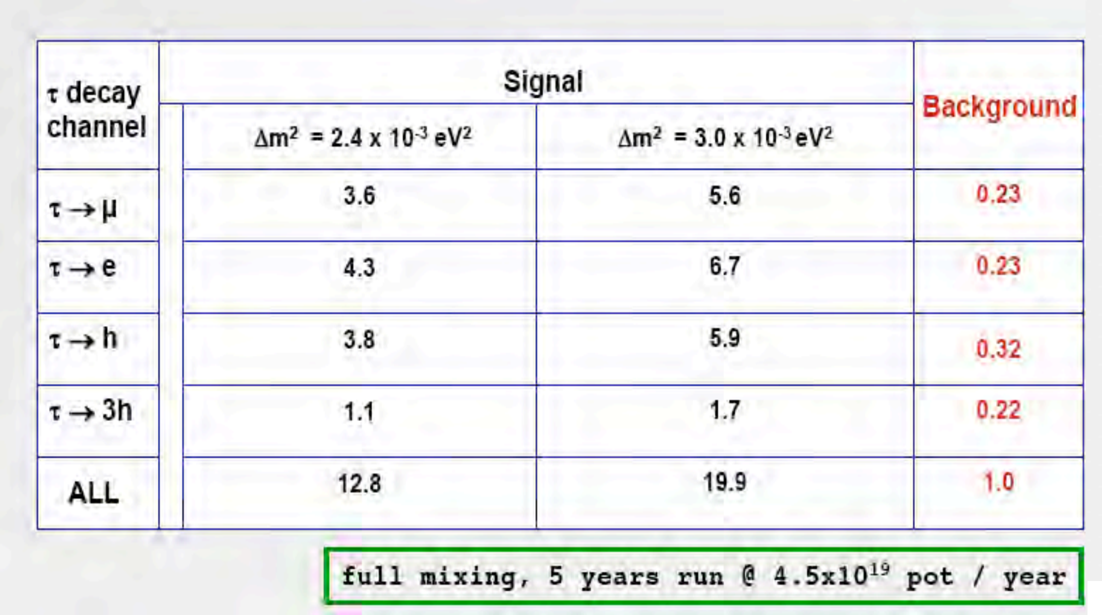
- 400 GeV proton beam
- $<E_\nu> = 17$ GeV, L=732 km
- CNGS+OPERA began in Sept 2006





Technique utilized by the DONUT experiment for the ν_τ discovery.

OPERA



τ decay channel	Signal		Background
	$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2	$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	
$\tau \to \mu$	3.6	5.6	0.23
$\tau \to e$	4.3	6.7	0.23
$\tau \to h$	3.8	5.9	0.32
$\tau \to 3h$	1.1	1.7	0.22
ALL	12.8	19.9	1.0

full mixing, 5 years run @ 4.5×10^{19} pot / year

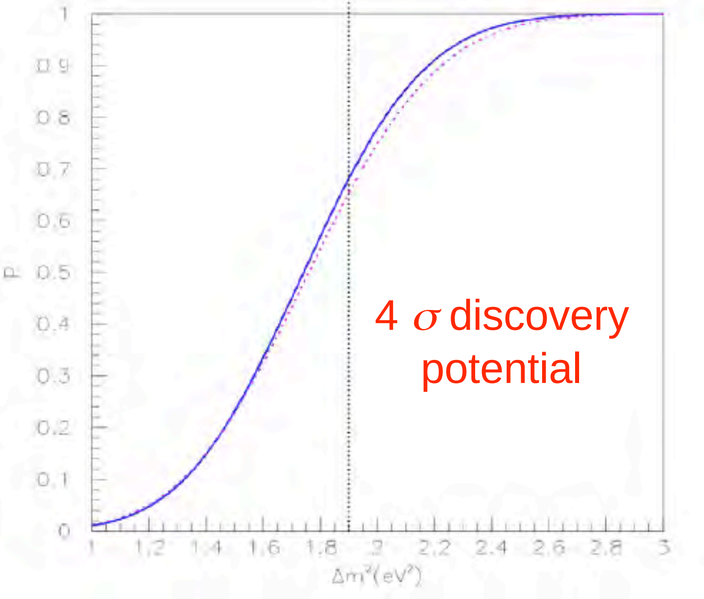
Goal is 4.5×10^{19} POT/yr

6200 ν_μ interactions / yr
~25 ν_τ CC / yr

Chances of discovery depend on Δm^2!

Can also do ν_e appearance:

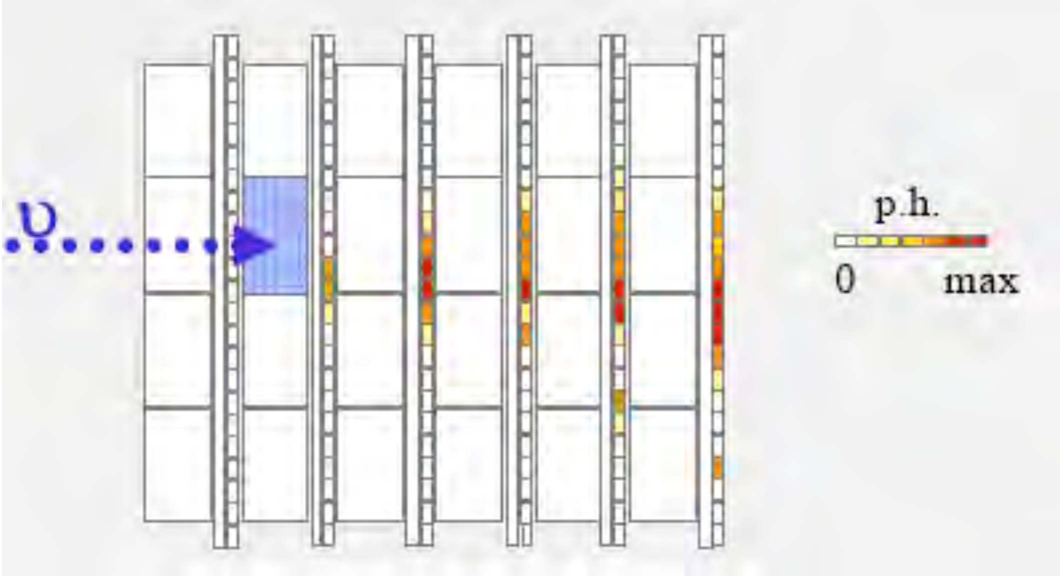
$\sin^2(2\theta_{13}) < 0.06$ in 5 years.



OPERA

206366 bricks stacked from 1 mm Pb plates and emulsion film.
1.8 kton target mass

Tracking in the target region identifies vertex brick which is robotically removed and sent for scanning (Europe / Japan).
30 / day!



2 supermodules ending with muon spectrometers:
magnetic fields, RPCs and drift tubes with σ ~300 μm

Next Goals

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{13} < 12^o$
δ unknown
hierarchy unknown

$c_{ij} = \cos \theta_{ij}$
$s_{ij} = \sin \theta_{ij}$
$\Delta_{ij} = 1.27\ \Delta m^2_{ij}$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) \sim\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31} && (1\pm 2x) \\ & + \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} + \underline{\delta}) && (1\pm x) \\ & + \sin^2 2\theta_{12} \cos^2\theta_{23} \cos^2\theta_{13} \sin^2\Delta_{21} \end{aligned}$$

matter effects
$x = E/12$ GeV

Sub-dominant mixing due to θ_{13} at atmospheric mass scale

Possible CP violation (though level related to θ_{13})

Reactor experiments sensitive to θ_{13} alone.

	ν	$\bar{\nu}$
normal	+	-
inverted	-	+

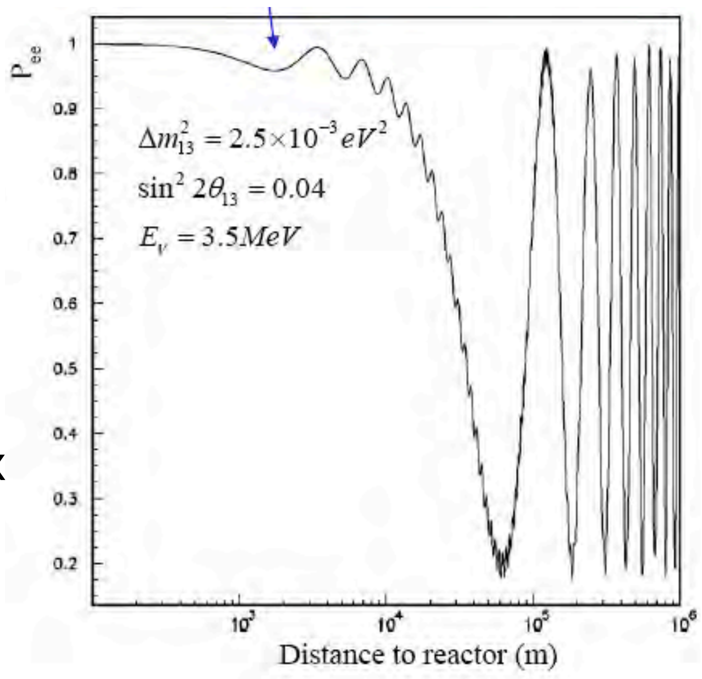
The Future: Measuring θ_{13}

Look for $\bar{\nu}_e$ disappearance at the atmospheric Δm^2
reactor experiments: Double Chooz, Daya Bay

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E} - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$

Use a near detector to measure the un-oscillated flux

Goal is to reach a sensitivity of 0.01 in $\sin^2 2\theta_{13}$.



Look for $\nu_\mu \rightarrow \nu_e$ appearance at the atmospheric neutrino Δm^2
Accelerator experiments: T2K, NoVa

Disentangling θ_{13}, δ, and mass hierarchy requires complementarity:

- reactors and long-baseline experiments
- neutrino and anti-neutrino running
- measurements at different baselines
- different energies (different matter effects)

Why Off-Axis?

Backgrounds to ν_e appearance come from:

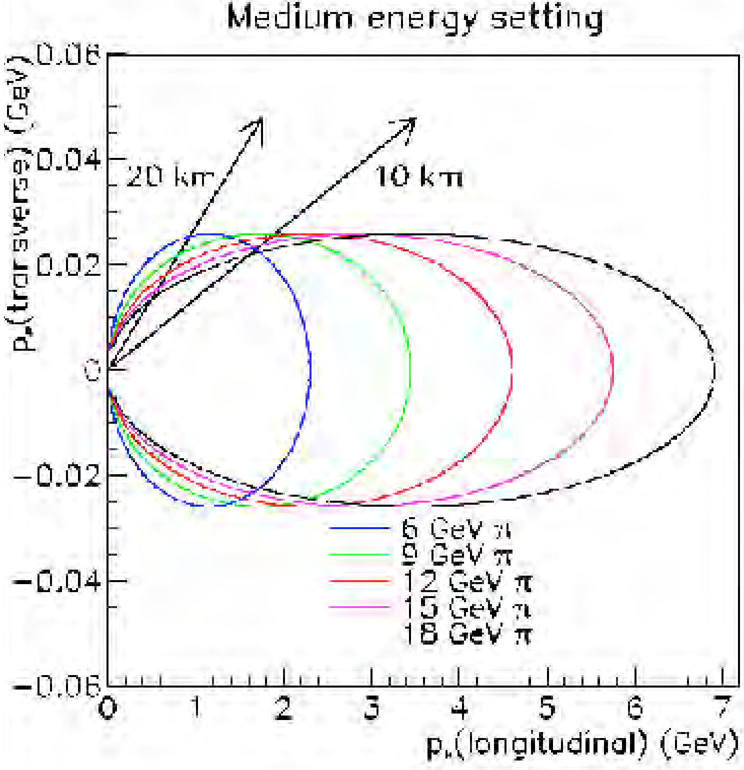
ν_e in the beam (0.7%)
NC events

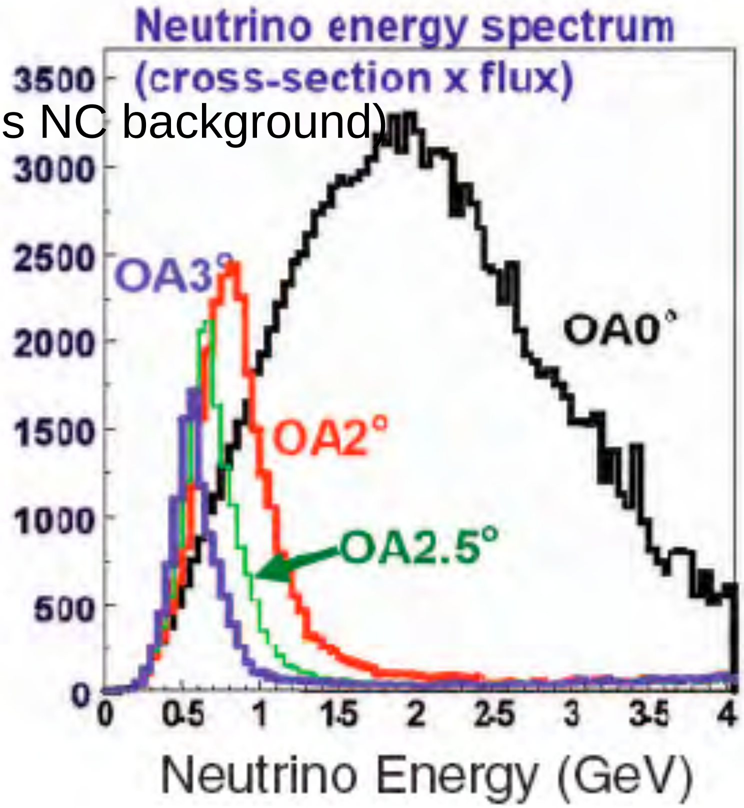
Requires:

- A big detector
- good pattern recognition (e/π^0)
- more neutrinos in the signal region!
- less neutrinos out of the signal region! (less NC background)

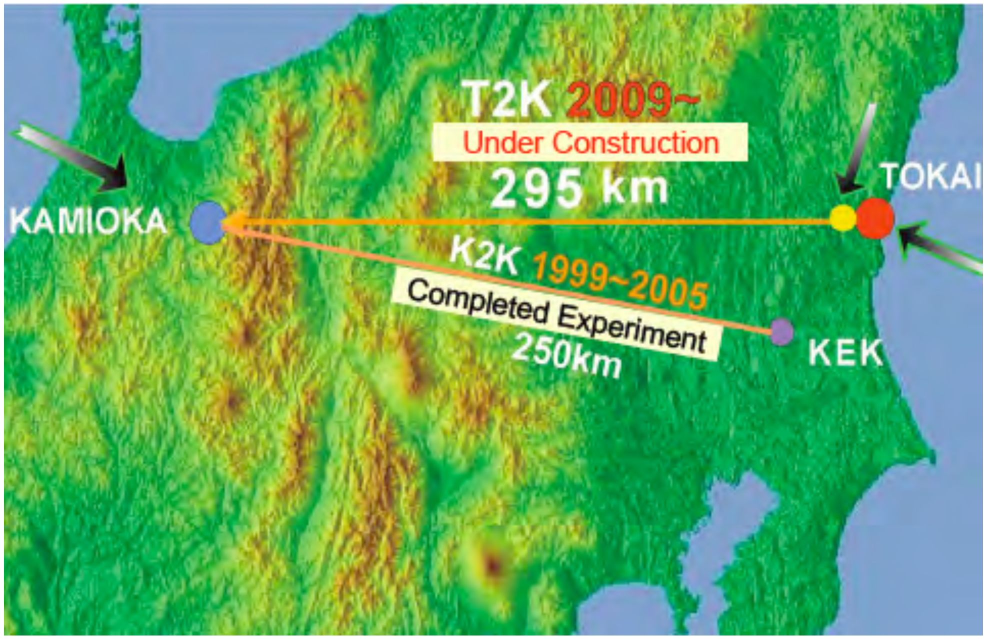
$$p_L = \gamma(p^* \cos\theta^* + \beta E^*)$$

$$p_T = p^* \sin\theta^*$$





Tokai to Kamioka (T2K)



Super K reconstruction completed April, 2006 returns the detector to 40% PMT coverage. Super-K III.

JPARC begins operation in 2008

ν beamline completed in 2009

T. Nakadaira (Neutrino 2006)

New neutrino beamline from the JPARC facility in Tokai.

750 kW conventional neutrino beam

50 GeV proton beam

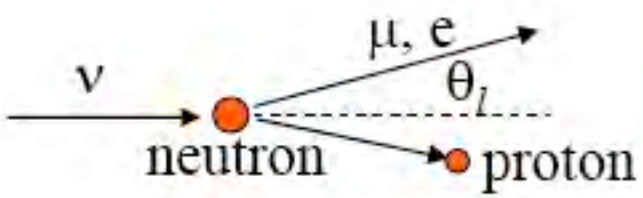
$\langle E_\nu \rangle = 0.6$ GeV

1×10^{21} POT/year

(K2K had 1×10^{20} in 6)

T2K

Peak of off-axis beam is at the oscillation maximum of 600 MeV.
Dominant scattering process is quasi-elastic ν_μ + n --> μ + p.



$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$

$$P(\nu_\mu \to \nu_e) \approx \underline{\sin^2 2\theta_{13}}\, \sin^2\theta_{23}\, \sin^2\left(\Delta m^2_{31} L/4E\right)$$

$$\mp 4J_r\, \underline{\sin\delta}\left(\Delta m^2_{21} L/2E\right)\sin^2\left(\Delta m^2_{31} L/4E\right) + \ldots$$

− for ν
+ for $\bar{\nu}$

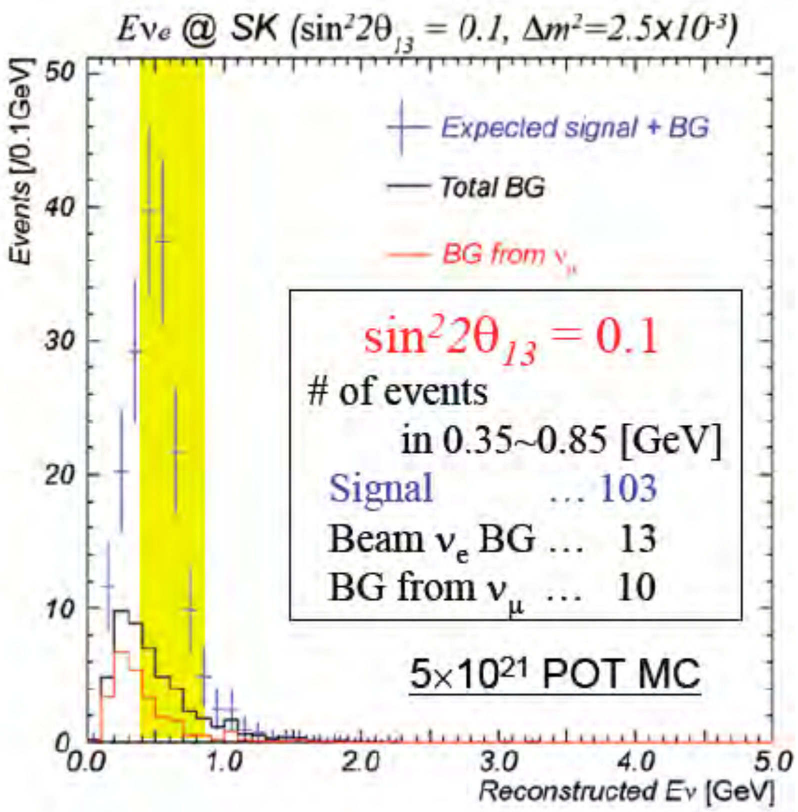
(Approximation @ $\Delta m^2_{31} L/4E \sim \pi/2$, $\Delta m^2_{32} \sim \Delta m^2_{31}$)

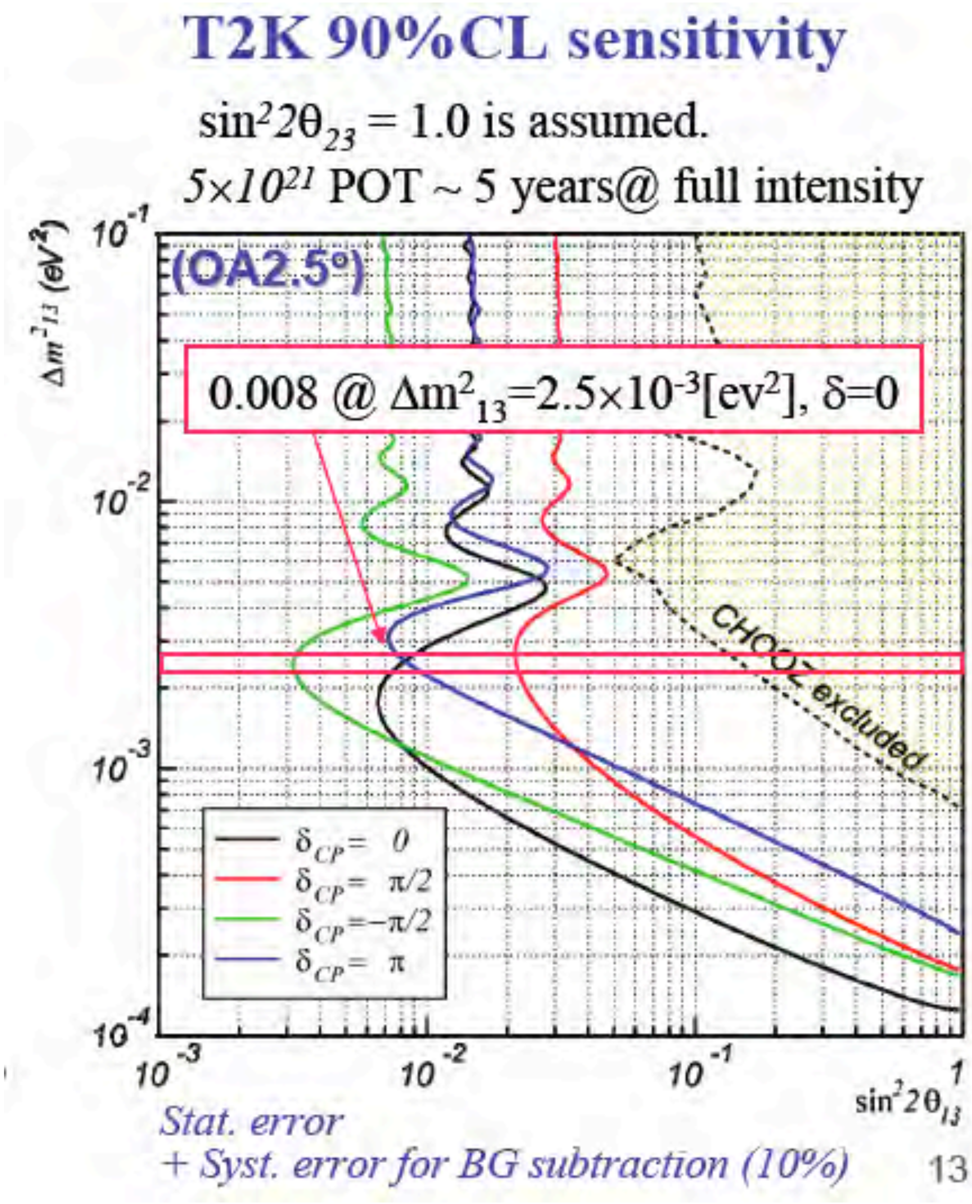
$$J_r \equiv \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\,\underline{\cos^2\theta_{13}\sin\theta_{13}}$$

3 near detectors:

1. on-axis at 280 m: measures beam profile
2. off-axis at 280 m: measures unoscillated flux to SuperK, cross sections
3. off-axis at 2 km: measures unoscillated flux to SuperK, cross sections

T2K Sensitivities





T2K 90%CL sensitivity

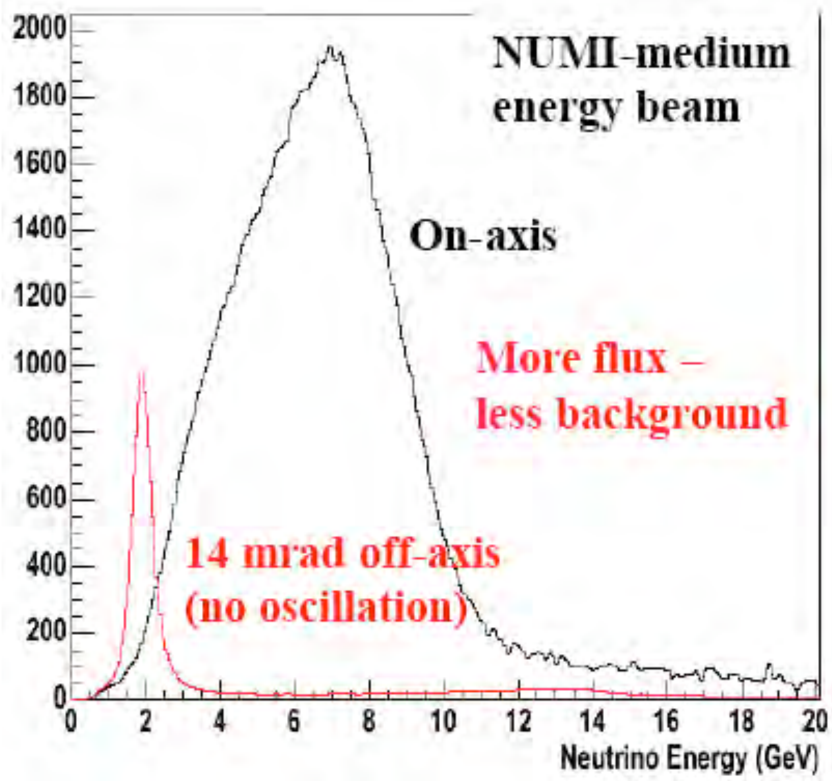
$\sin^2 2\theta_{23} = 1.0$ is assumed.

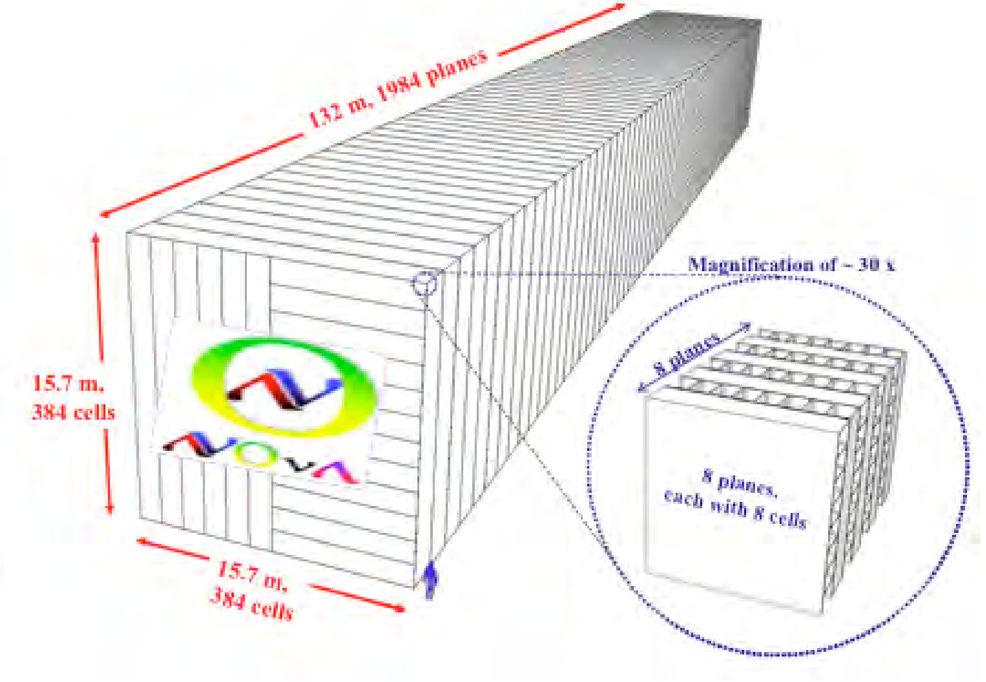
5×10^{21} POT ~ 5 years@ full intensity

Stat. error
+ Syst. error for BG subtraction (10%)

NoVA

1. Measure θ_{13}
   $\sin^2(2\theta_{13})\sim 0.01$ *in 5 yrs*
2. Determine hierarchy
3. Measure δ if θ_{13} large enough





New 25 kt detector in NuMI beam at 810 km (Ash River, MN).

Extruded PVC cells filled with liquid scintillator, WLS fiber readout to APDs.

Increase NuMI intensity by:
x2 (post-collider)
x8 (proton driver)

Future Ideas

Better beams:

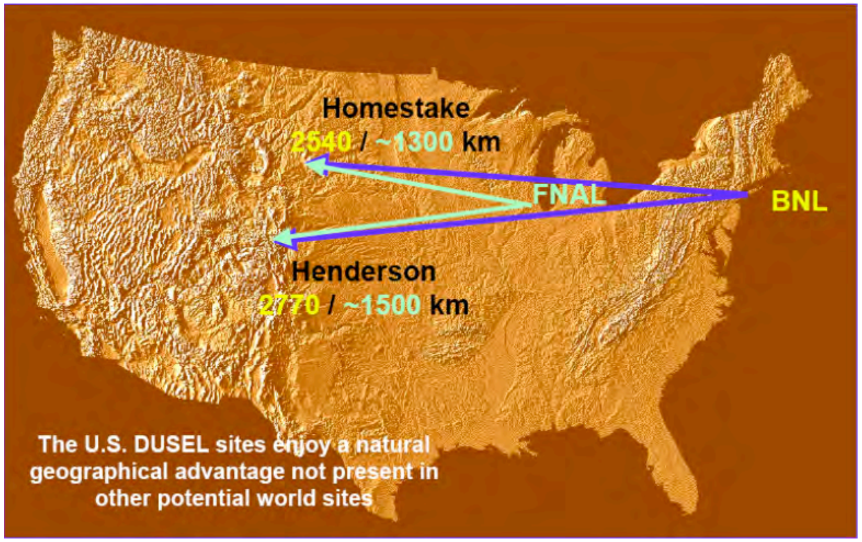
Conventional “superbeams” --> MW scale proton drivers
Neutrino factories from muon beams
Beta-beams from radioactive element accelerators

Bigger / Better Detectors:

multi kTon liquid Argon detectors
1 Mton water Cerenkov detectors (HyperK)

Very Long Baselines:

Tokai --> Korea
FNAL/BNL --> DUSEL

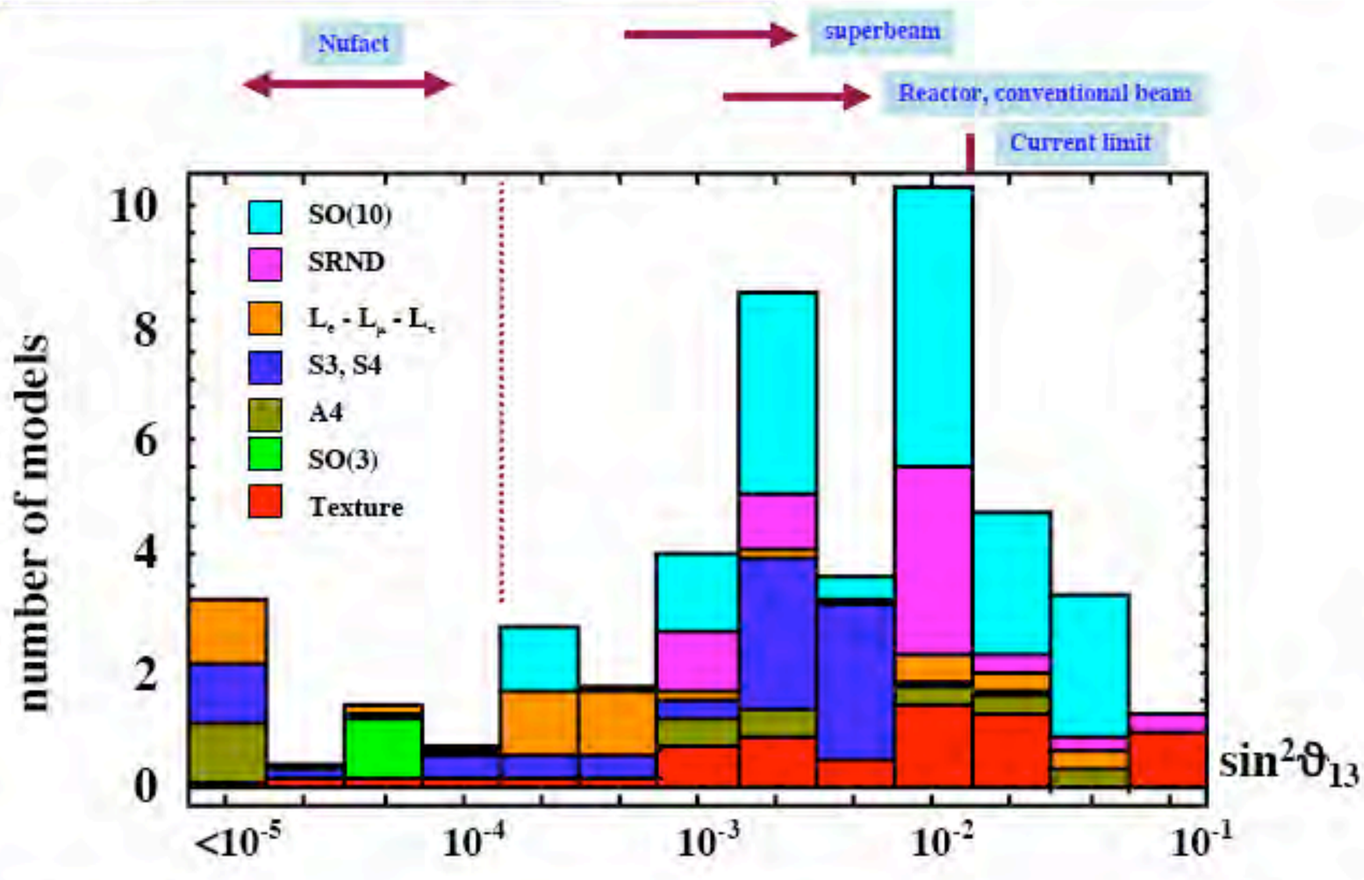


The U.S. DUSEL sites enjoy a natural geographical advantage not present in other potential world sites

Big Picture

What is the PMNS matrix telling us about GUTs?

Leptogenesis?



Mu-Chun Chen, 3rd ISS Meeting on a Future Neutrino Factory and SuperBeam FacilityRAL, April 25, 2006

Oscillations + Cross Sections

The focus of experimental neutrino physics will continue to be on mixing phenomena and fundamental questions like Majorana vs. Dirac masses and the mass hierarchy.

Future high-statistics experiments will be more sensitive to uncertainties in interaction physics

At the same time the new beam facilities being developed to perform these oscillation experiments (J-PARC, NuMI, CNGS) will make possible new generations of experiments dedicated to neutrino interaction physics measurements.

- –T2K Near Detectors
- –Minerva and SciBoone experiments at Fermilab

From the APS Multi-Divisional Study on the Physics of Neutrinos

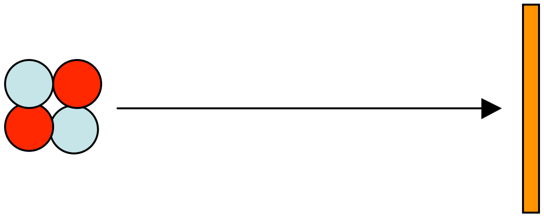
Among the APS study assumptions about the current and future program:

“determination of the neutrino reaction and production cross sections required for a precise understanding of neutrino-oscillation physics and the neutrino astronomy of astrophysical and cosmological sources. Our broad and exacting program of neutrino physics is built upon precise knowledge of how neutrinos interact with matter.”

Scattering Experiments

Prototypical Experiment of this type is Rutherford Scattering experiment:

Scatter a particles from a gold foil - backscattering at a large angle indicates the positive charge of an atom is located in a small region of space:



$$dN/d\Omega = ?$$

Scattering Experiments

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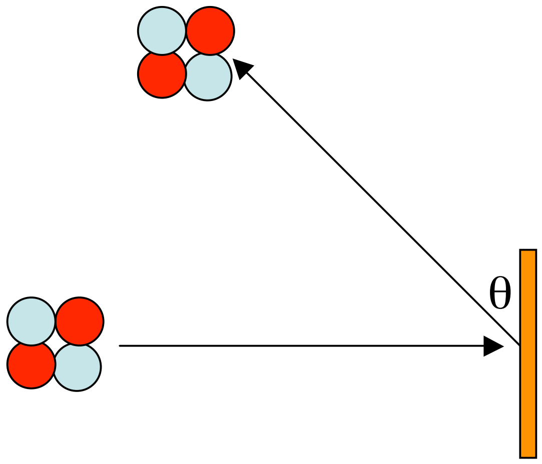

$$dN/d\Omega = \frac{\alpha^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}}$$

Scattering Experiments

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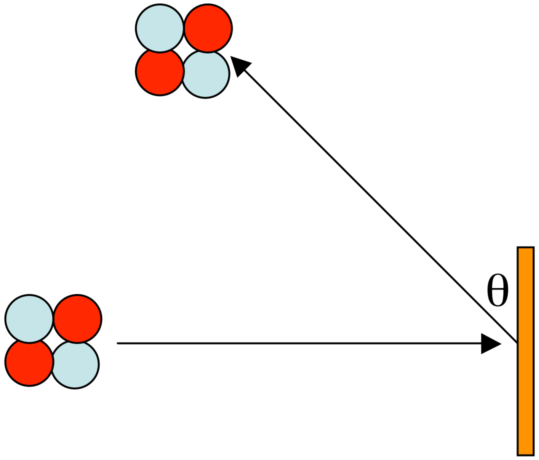

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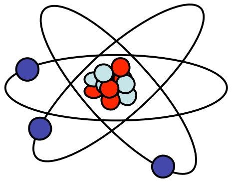
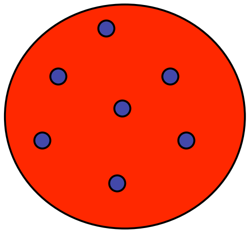
Models



atom looks like this - nucleus!



Not like this!

Measuring a kinematic distribution from a scattering process (dN/dΩ) gives information about the structure of the target!

Scattering Experiments

Our Model of the nucleon (proton):

A proton is made up of 3 valence quarks (uud), where a quark is a point-like, spin 1/2 fermion. In addition there are virtual quark-antiquark pairs (sea quarks and antiquarks) and gluons. The whole thing is held together by the strong force which is described by QCD.

$$F_2^{\nu,\bar{\nu}} = 2\sum_i x(Q_i(x) + \overline{Q}_i(x))$$

$$xF_3^{\nu,\bar{\nu}} = 2\sum_i x(Q_i(x) - \overline{Q}_i(x))$$

quarks and anti-quarks - determined by shapes of y-distributions:
(LL vs LR helicity combinations).

point-like: structure functions independent of Q^2, cross section linear with energy.

valence quarks: Measured by xF_3.

spin 1/2: $F_2 = 2xF_1$

gluons: (only indirectly probed by ν/e)

Conclusions

Current generation of long-baseline experiments are probing neutrino oscillations with improved precision:

- mixing parameters (MINOS)
- sterile neutrinos (miniBoone)
- ν_τ appearance (OPERA)

The next generation of accelerator and reactor experiments will push for a measurement of θ_{13}, resolution of the mass hierarchy and point the way towards possible measurements of CP violation in the lepton sector.

These high-intensity beams will provide an opportunity to use neutrinos to probe nucleon and nuclear structure at a new level of precision.

Backup Slides

The NuMI Neutrino Beam

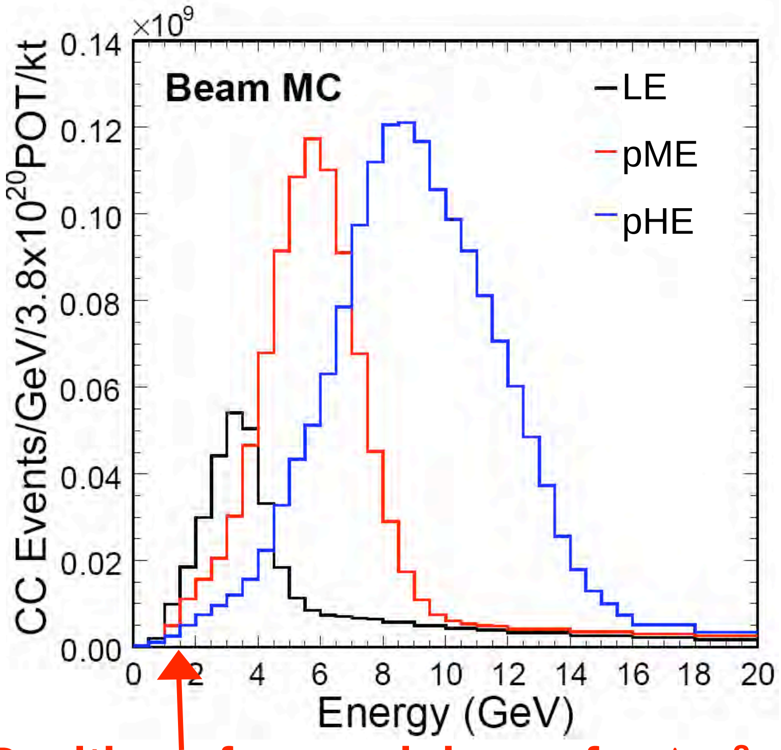
H. Gallagher
Tufts University
NEPPSR
August 15, 2007

Currently running in the LE-10 configuration

Beam composition (events in low energy configuration):

98.5% $\nu_\mu+\bar{\nu}_\mu$ (6.5% $\bar{\nu}_\mu$), 1.5% $\nu_e+\bar{\nu}_e$

Took ~1.5e18 protons on target (POT) in pME and pHE configurations early in the run for commissioning and systematics studies



Position of osc. minimum for Δm^2=0.0025 eV^2

Expected no of events (no osc.) in Far Detector

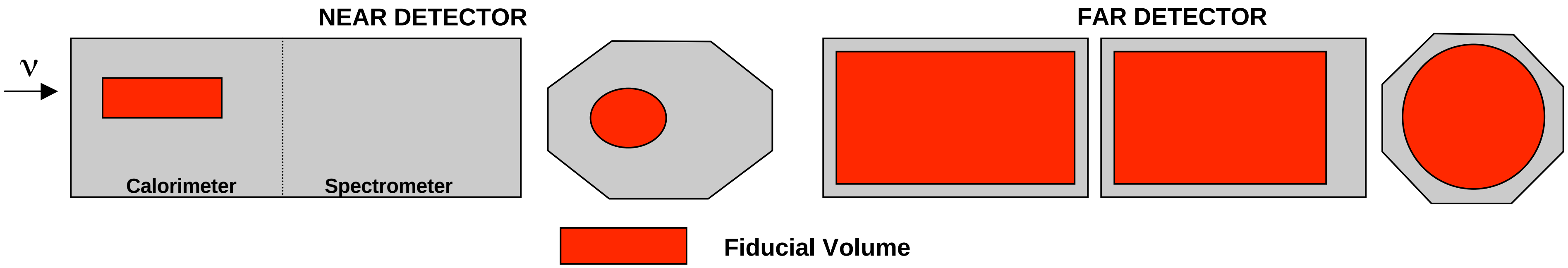
Beam	Target z position (cm)	FD Events per 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Events in fiducial volume

MINOS: Pre-Selection Cuts

ν_μ CC-like events are selected in the following way:

- Event must contain at least one good reconstructed track
- The reconstructed track vertex should be within the fiducial volume of the detector:
  - NEAR: 1m < z < 5m (z measured from the front face of the detector), R< 1m from beam centre.
  - FAR: z>50cm from front face, z>2m from rear face, R< 3.7m from centre of detector.

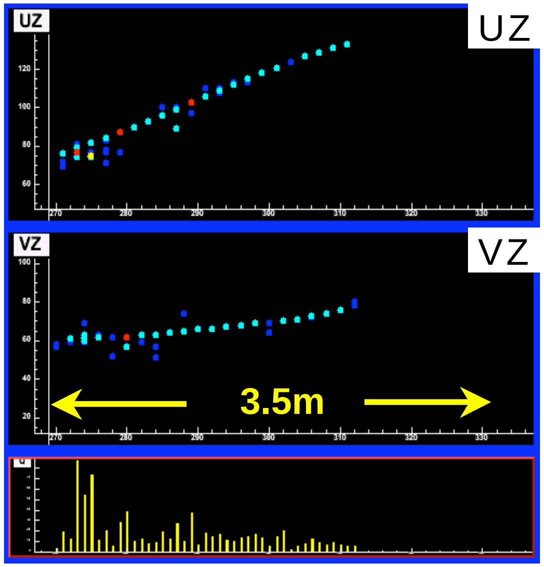


- The fitted track should have negative charge (selects ν_μ)
- Cut on likelihood-based Particle ID parameter which is used to separate CC and NC events.

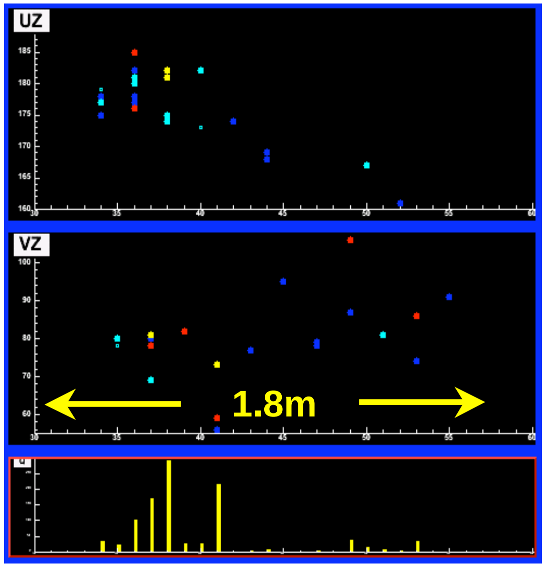
Event Topologies

Monte Carlo

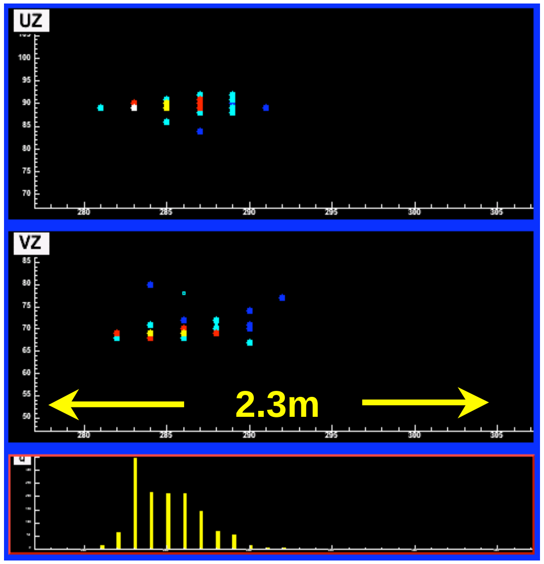
ν_μ CC Event



NC Event



ν_e CC Event



- **long μ track+ hadronic activity at vertex**
- **short event, often diffuse**
- **short, with typical EM shower profile**

$$E_\nu = E_{shower} + P_\mu$$

55%/√E

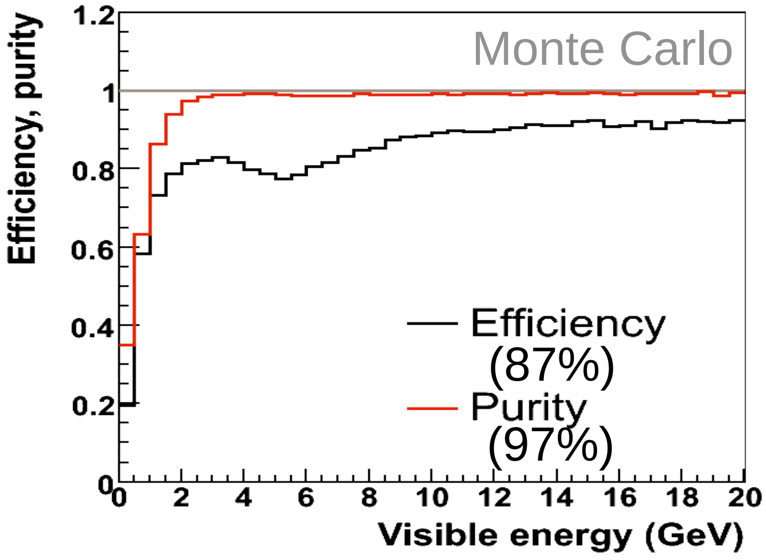
6% range, 10% curvature

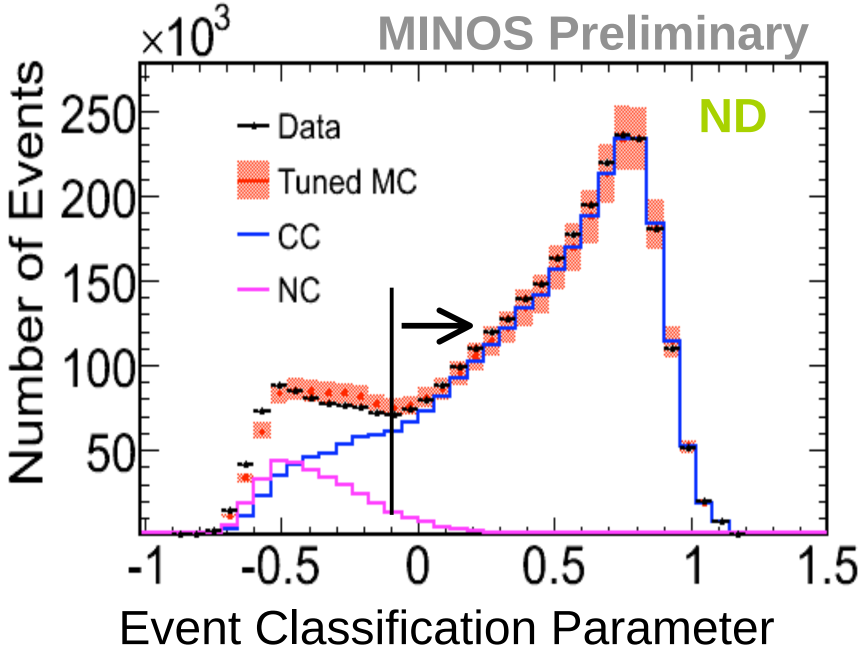
MINOS: Event Selection

H. Gallagher
Tufts University
NEPPSR
August 15, 2007

Charged current events are selected using a likelihood procedure

- Combine probability density functions for 3 low level variables to differentiate CC & NC interactions
- Efficiency is reasonably flat vs visible energy over most of the energy range
- NC contamination is limited to the lowest bins (below 1.5 GeV)





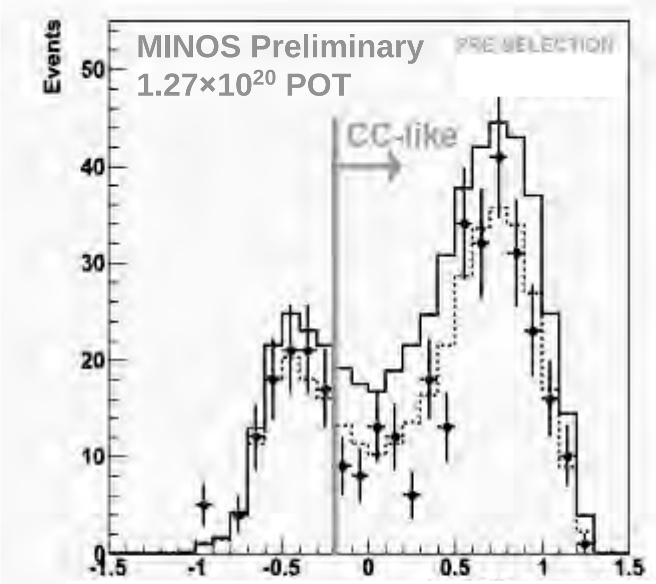
MINOS: Numbers of Events

Data sample	Data	Expected (Matrix Method; Unoscillated)	Data/MC (Matrix Method)	Expected (Fit Method; Unoscillated)
ν_μ (<30 GeV)	215	336±21	0.64±0.08	332.8
ν_μ (<10 GeV)	122	239±17	0.51±0.08	237.7
ν_μ (< 5 GeV)	67	168±12	0.45±0.09	168.6

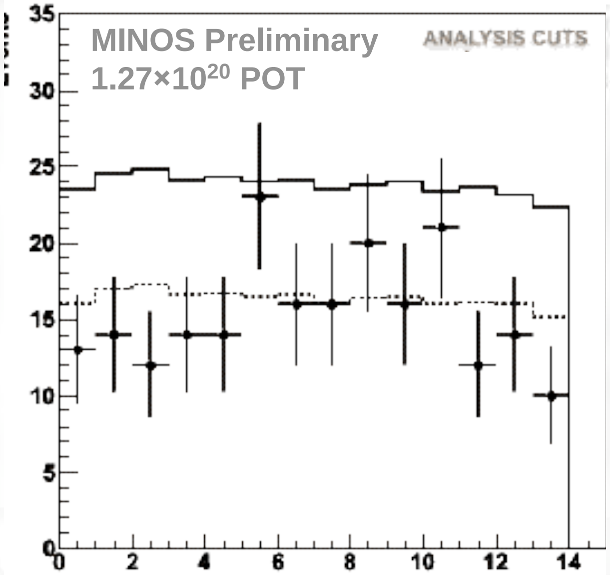
A large energy dependent deficit

- Below 10 GeV the significance of the deficit is 5.9σ (stat+syst)
- Preliminary result from the 1.27×10^{20} POT sample

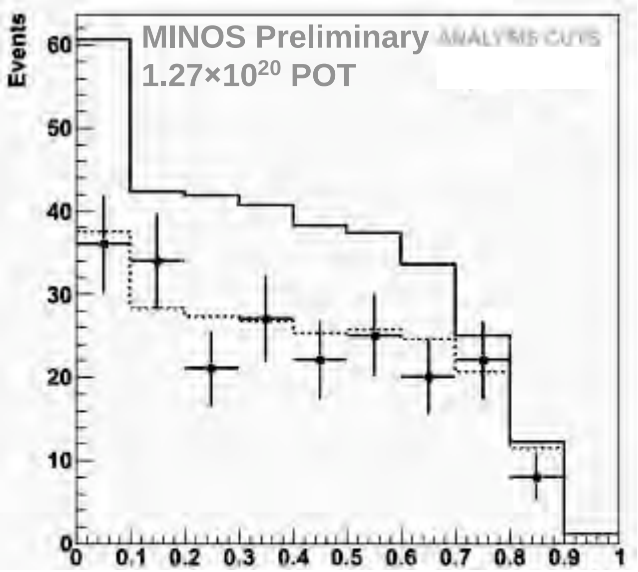
MINOS: FD Distributions



Event Classification Parameter



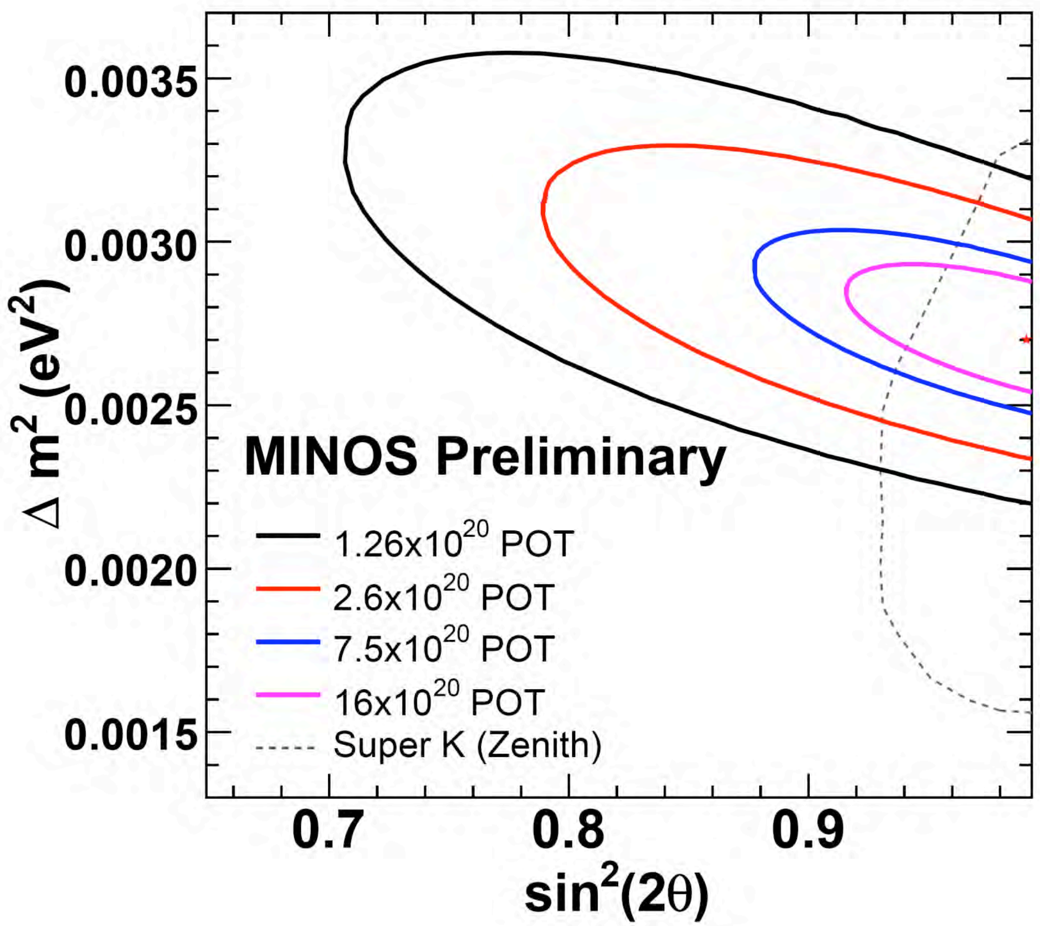
Track Vertex r^2 (m^2)



$y = E_{shw}/(E_{shw}+P_{\mu})$

Predicted no oscillations (solid)
Best fit (dashed)

MINOS: Sensitivity



Input parameters

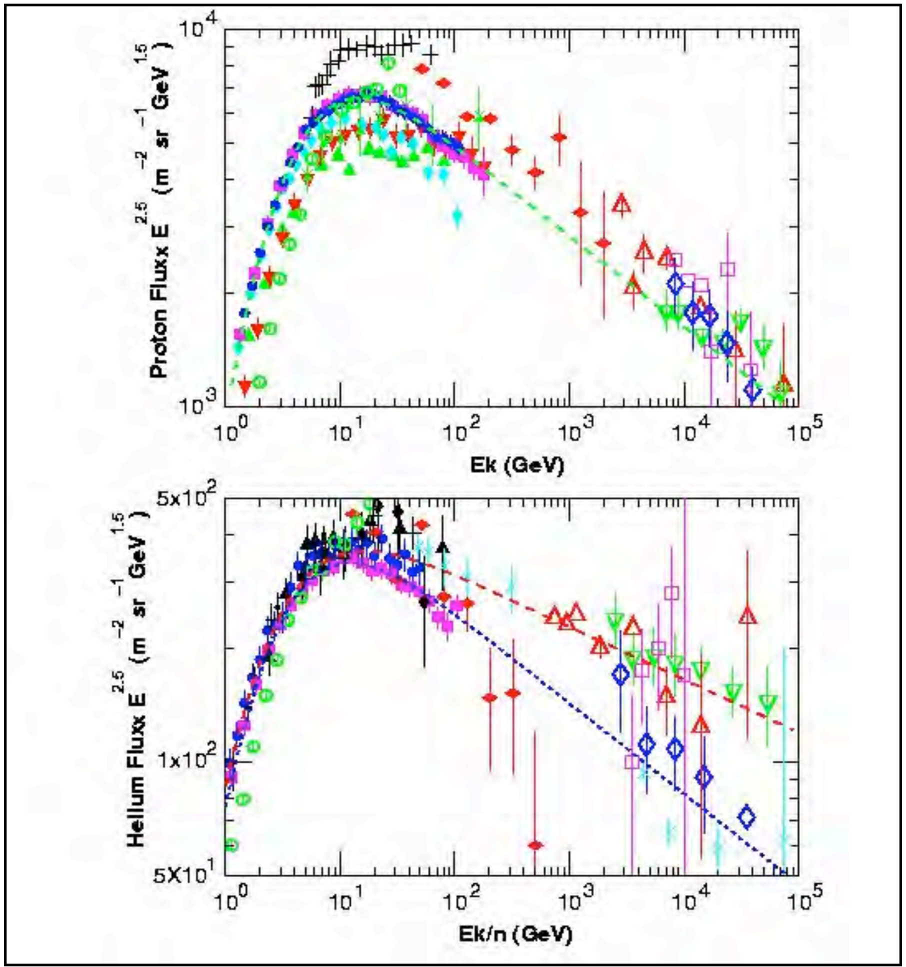
$|\Delta m^2_{32}| = 2.72 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.00$

Statistical errors only

90% C.L.

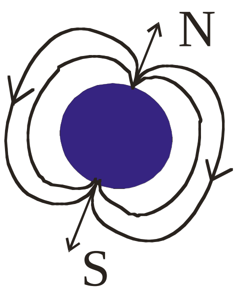
Flux Calculations

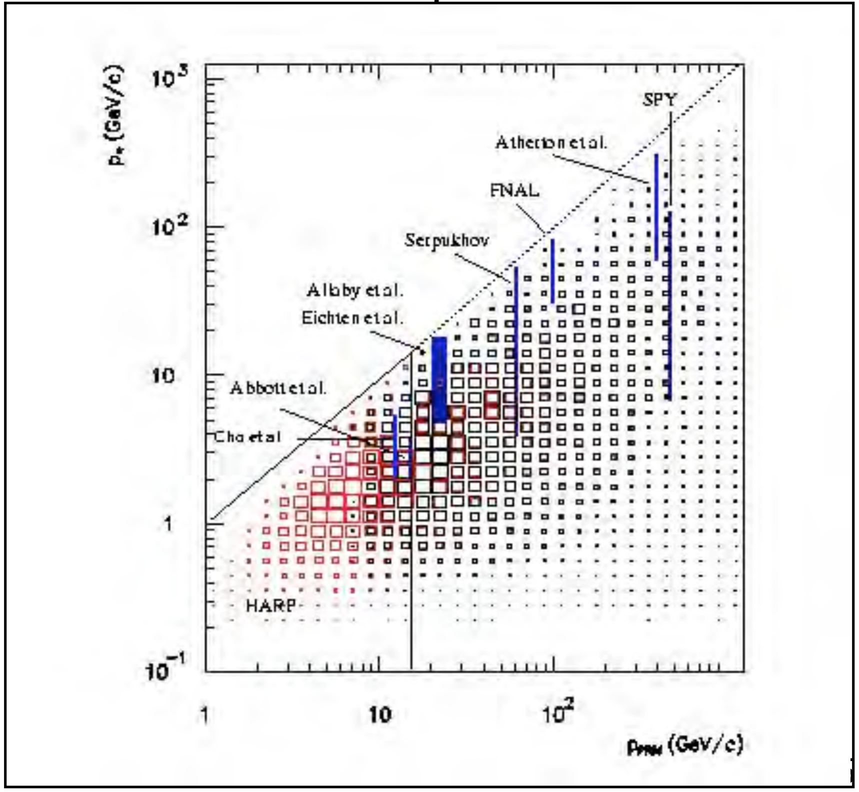


Flux of primary cosmic rays
(from Gaisser and Honda,
Ann. Rev. Nuc. Part. Sci (2002))

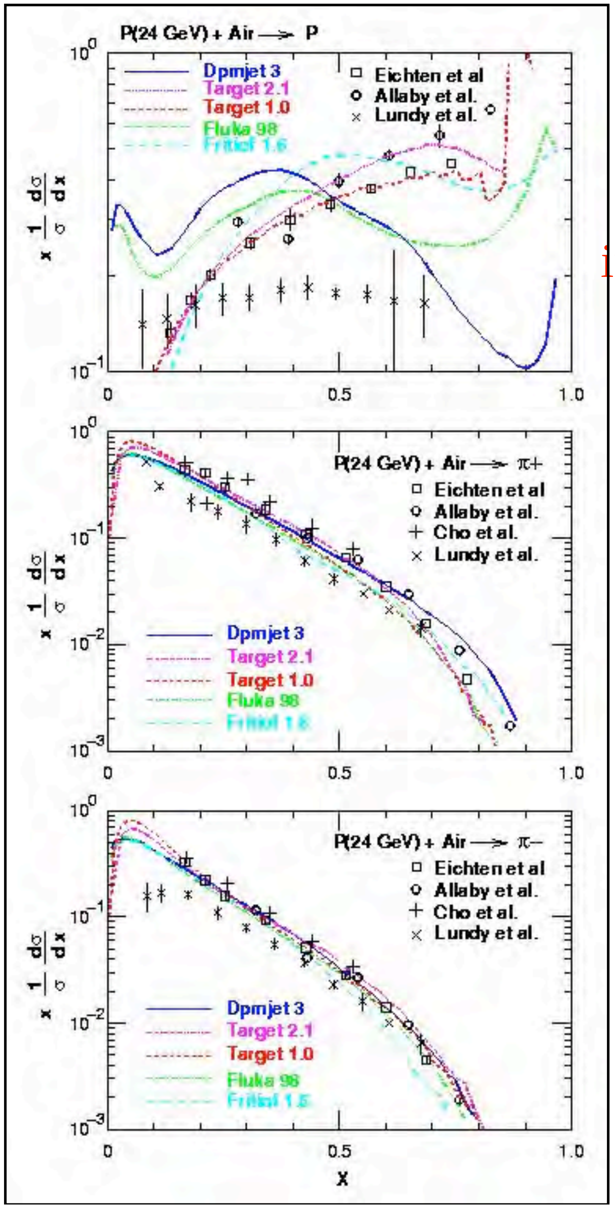
Ingredients:

1. Primary cosmic ray flux (time-dependent)
2. Geomagnetic model
3. Hadronic interactions in the atmosphere

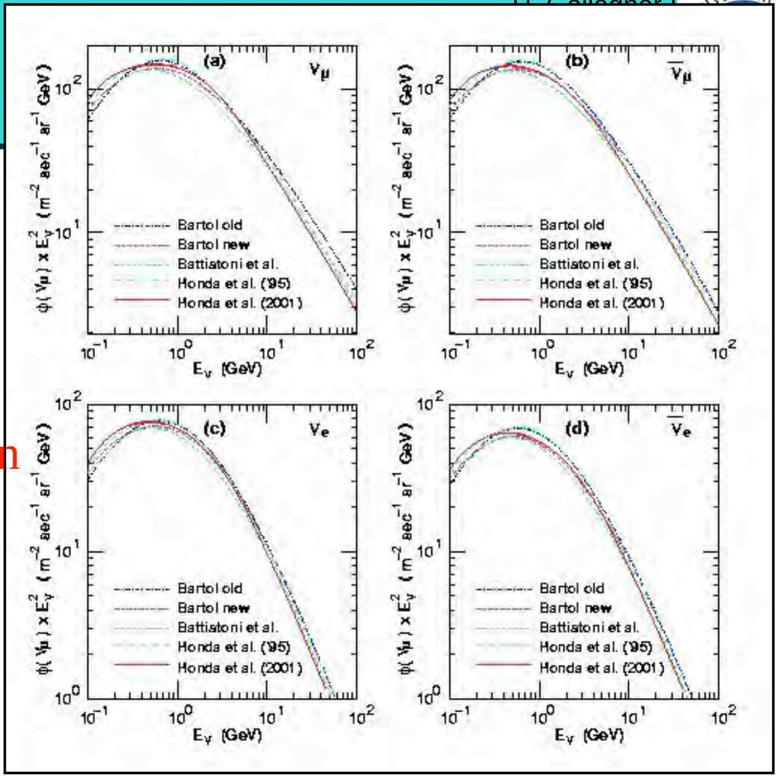




Flux Calculations (2)



overall uncertainty
in the flux normalization
is 20-25%



The most robust prediction is that of the flavor ratio ν_μ / ν_e.

	⟵ $\nu_\mu + \bar{\nu}_\mu$ ⟶			⟵ $\nu_e + \bar{\nu}_e$ ⟶			$R_{e/\mu}$
E(GeV)	.4-1.0	1 - 2	2 - 3	0.4 - 1.0	1 - 2	2 - 3	
BGS Barr, Gaisser, Stanev	1.0	1.0	1.0	1.0	1.0	1.0	.49
HKHM Honda, Kasahara, Hidaka, Midorikawa	.90	.95	1.04	.87	.91	.97	.48
BN Bugaev, Naumov	.63	.79	.95	.62	.74	.87	.50

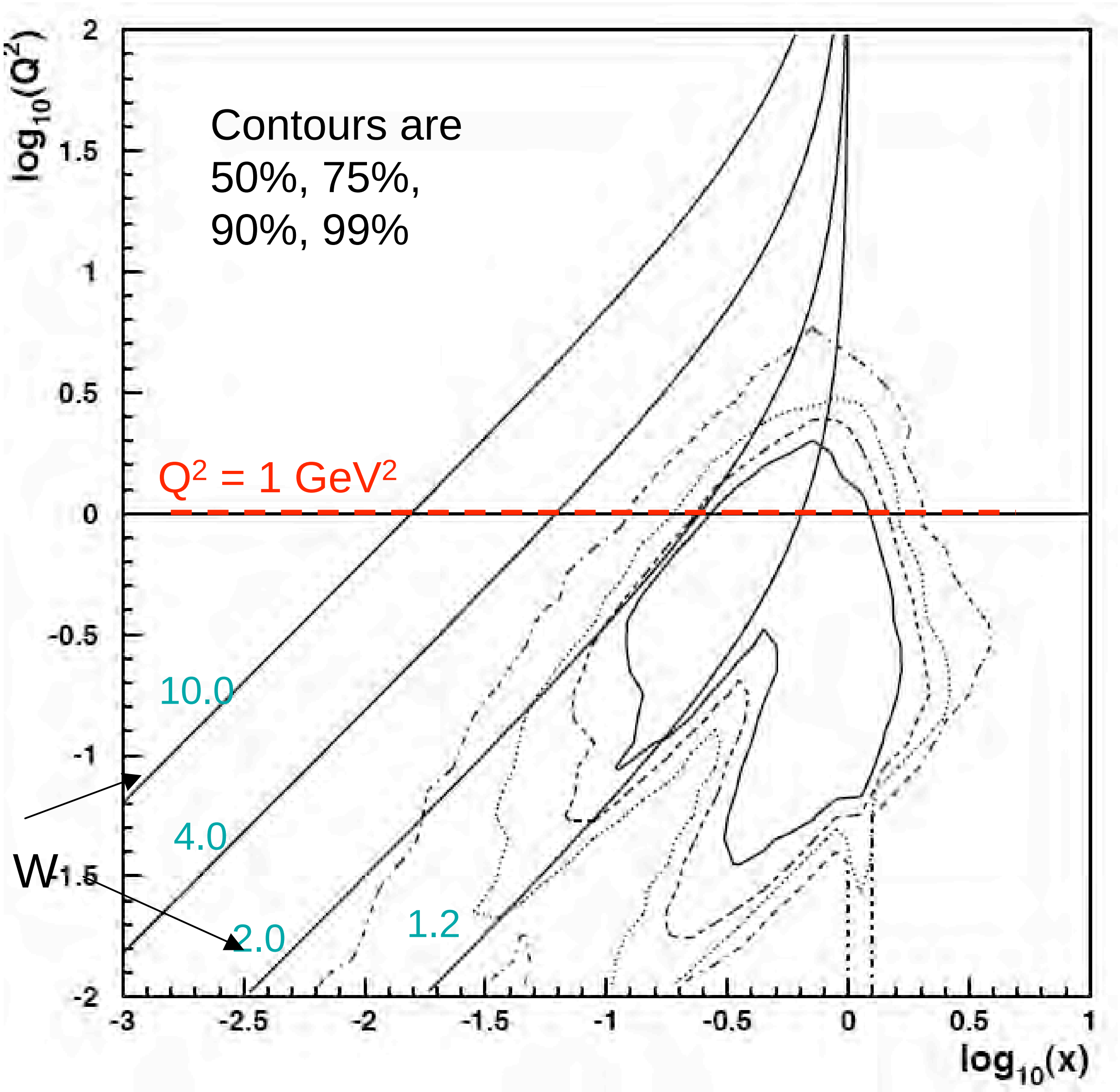
Low E Beam Kinematics

Low energy beams

Kinematic exposure from a 4-vector calculation using a cartoon miniBoone flux.

(a guess, for illustrative purposes only)

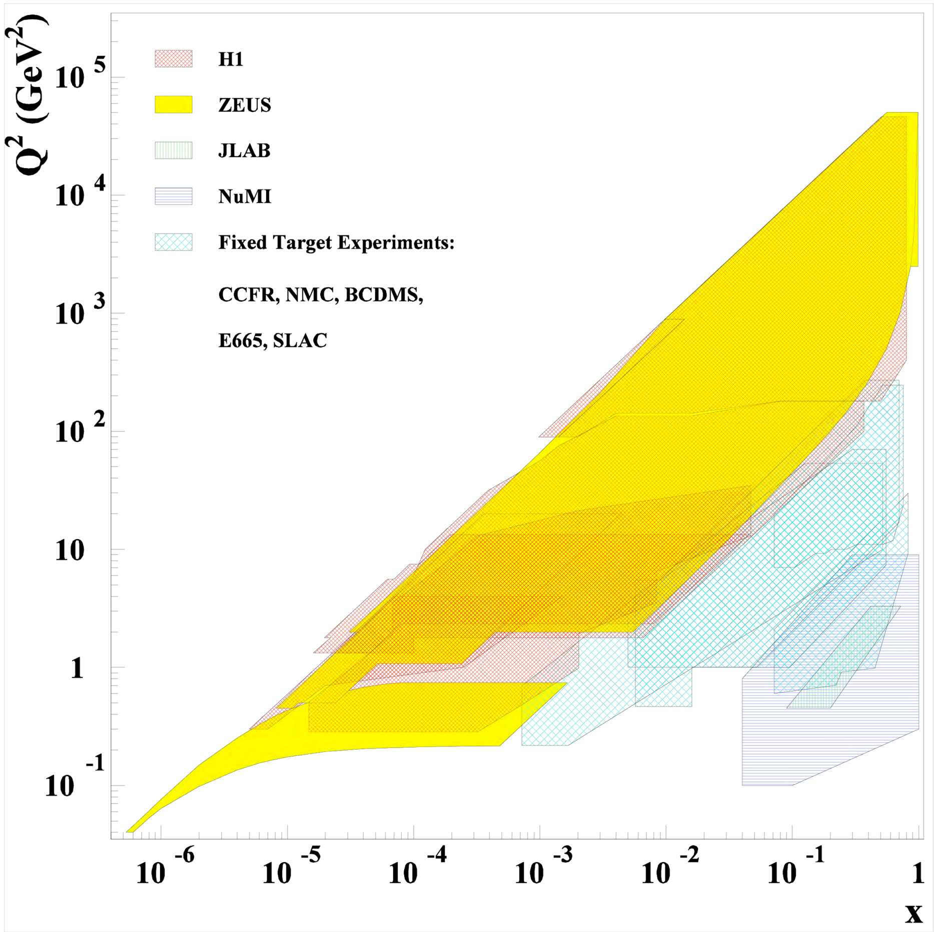
Quasi-elastic, Δ, gap between them of primary importance, everything is low Q^2!



Contours are 50%, 75%, 90%, 99%

$Q^2 = 1\ \text{GeV}^2$

Lines of constant W


Q^2 (GeV^2)
10^5
10^4
10^3
10^2
10
1
10^{-1}
H1
ZEUS
JLAB
NuMI
Fixed Target Experiments:
CCFR, NMC, BCDMS,
E665, SLAC
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

Structure Functions

Recall Neutrinos have the ability to directly resolve flavor of the nucleon’s constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$.

Using Leading order expressions:

$$F_2^{\bar{\nu}N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2\bar{s}+2c\right]$$

$$F_2^{\nu N}(x,Q^2) = x\left[u+\bar{u}+d+\bar{d}+2s+2\bar{c}\right]$$

$$xF_3^{\bar{\nu}N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}-2\bar{s}+2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u+d-\bar{u}-\bar{d}+2s-2\bar{c}\right]$$

Taking combinations of the Structure functions

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u}+\bar{d}+2\bar{c}\right)$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u}+\bar{d}+2\bar{s}\right)$$

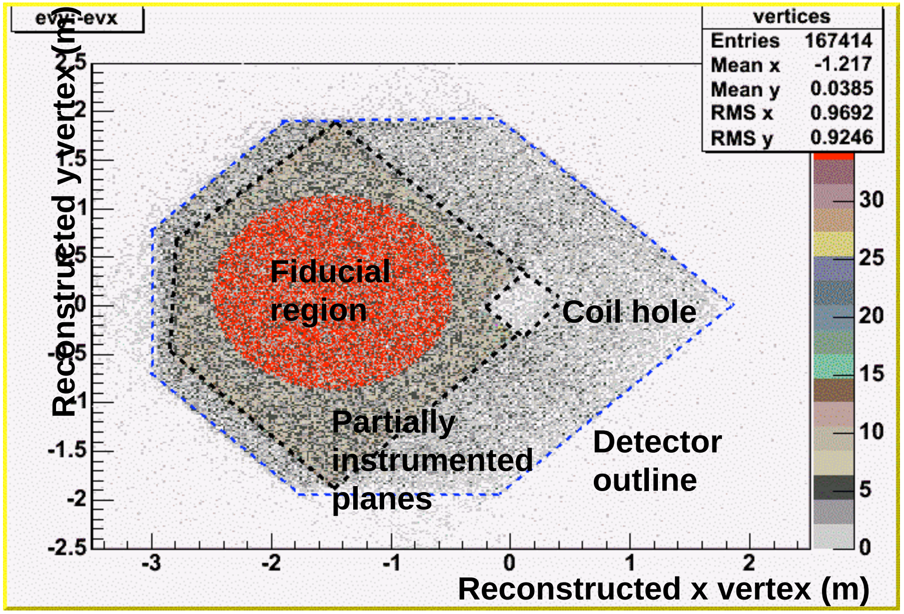
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[\left(s+\bar{s}\right)-\left(\bar{c}+c\right)\right]$$

MINOS: Near Detector Distributions

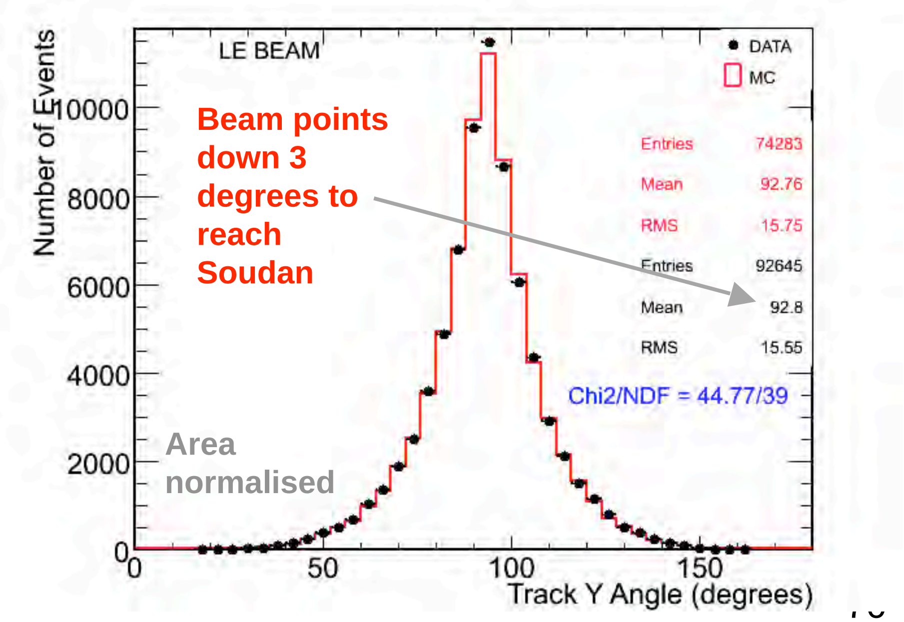
We observe very large event rates in the Near detector (~1e7 events for 1e20 pot)

This provides a high statistics dataset with which we can study how well we understand the performance of the Near detector and the check the level to which our data agrees with our Monte Carlo predictions

Distribution of reconstructed event vertices in the x-y plane



Reconstructed track angle with respect to vertical

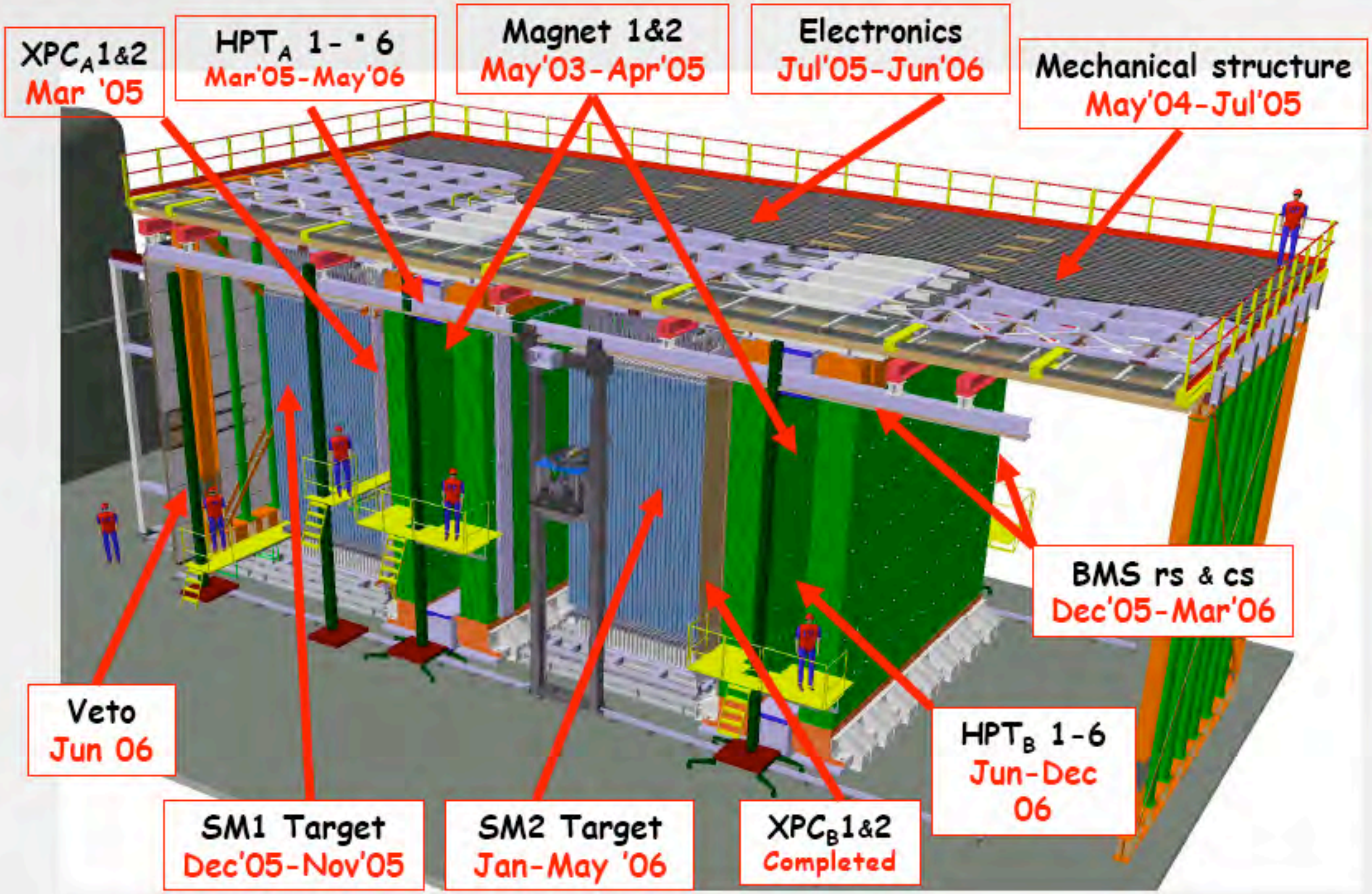


Beam points down 3 degrees to reach Soudan

Area normalised

OPERA

Detector construction status



XPC$_A$1&2
Mar '05

HPT$_A$ 1-6
Mar'05-May'06

Magnet 1&2
May'03-Apr'05

Electronics
Jul'05-Jun'06

Mechanical structure
May'04-Jul'05

BMS rs & cs
Dec'05-Mar'06

Veto
Jun 06

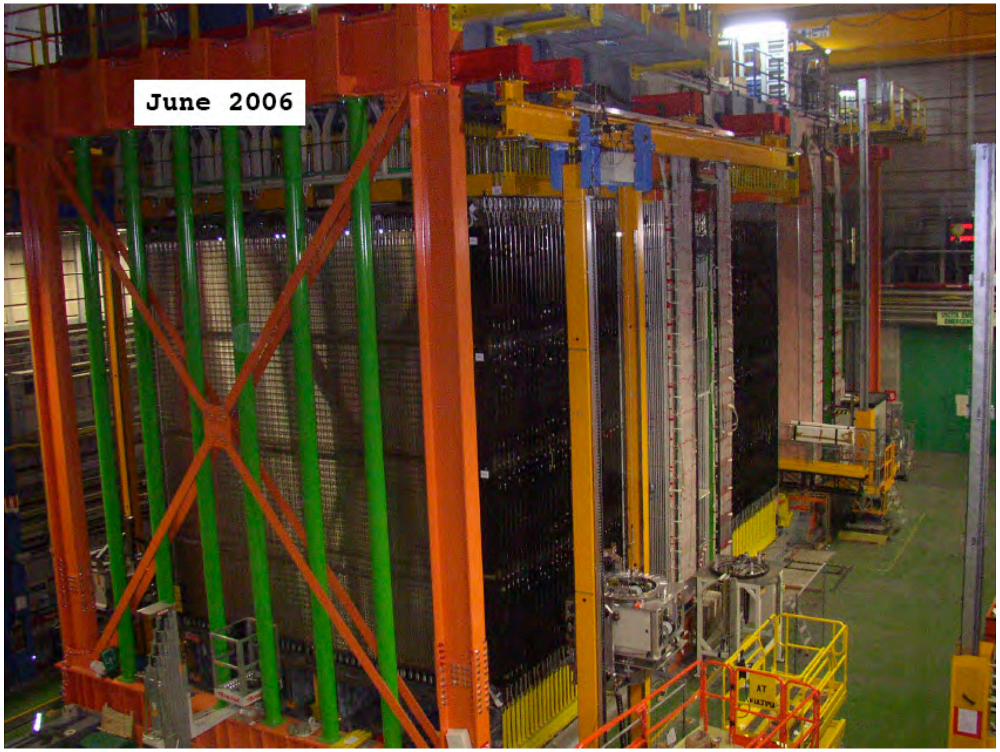
SM1 Target
Dec'05-Nov'05

SM2 Target
Jan-May '06

XPC$_B$1&2
Completed

HPT$_B$ 1-6
Jun-Dec
06

OPERA: Status



Construction and installation at Gran Sasso is nearly completed.

Electronics is being commissioned.

DAQ is ready.

Low intensity CNGS beam will be delivered in August!

Test of emulsion scanning with PEANUT detector in NuMI near hall.
~ 5 interactions / day

Emulsion scanning successful in Europe and Japan.

Kamland

Neutrino Oscillations enhanced by the MSW effect in the sun.

day/night differences: SK and SNO
spectral distortions (KamLand)