Long Baseline Neutrinos

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FERMILAB

SLAC SUMMER INSTITUTE
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Lecture 1 Outline

- Defining "Long" Baseline
- Experiment Ingredients
  - Neutrino Beams
  - Neutrino Interactions
  - Neutrino Cross sections
  - Calculating Neutrino Event Rates
  - Neutrino Detectors
  - Predicting and Measuring Backgrounds

Lecture 1 Outline cont.

- Long Baseline Basics
  - The mass-mixing matrix : mixing angles and phases
  - Oscillation Probability : Δm^2, L, E
    - Two-flavor approximation
    - Appearance and disappearance measurements
- Oscillation Searches
  - Setting limits
  - Measuring parameters

Lecture 1 Outline, cont.

- Experimental Examples :
  - Early Searches
  - LSND and MiniBooNE (E. Zimmerman Lecture)
  - K2K and MINOS
  - OPERA

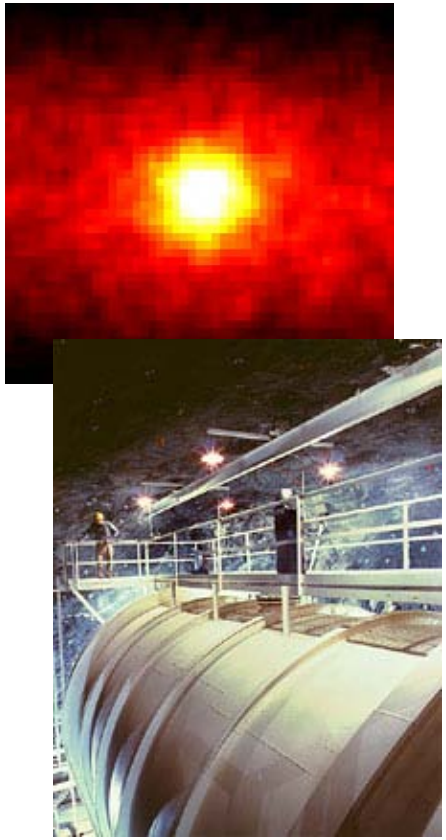
Lecture 2 Outline

- Three neutrinos, θ_{13} *and* δ_{CP}
  - Oscillation probability
  - Matter effects
  - Neutrino mass hierarchy
- Experimental Techniques :
  - Signals, backgrounds and ambiguities
  - Experiment baseline
  - Neutrino beam configurations
- Experimental Landscape
  - *Reactor Experiments :* $\bar{\nu}_e$ *disappearance* (Ed Blucher lecture)
  - ν_e appearance : T2K, NOvA, LBNE

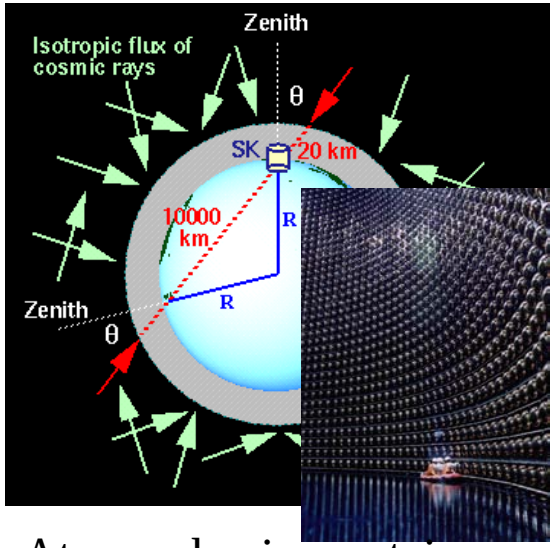
Lecture 2 Outline cont.

- Experiment Prospects
  - Understanding Sensitivity Calculations
  - Experiment Timelines
- New results to keep an eye on
- Beyond conventional beams?
- Conclusions

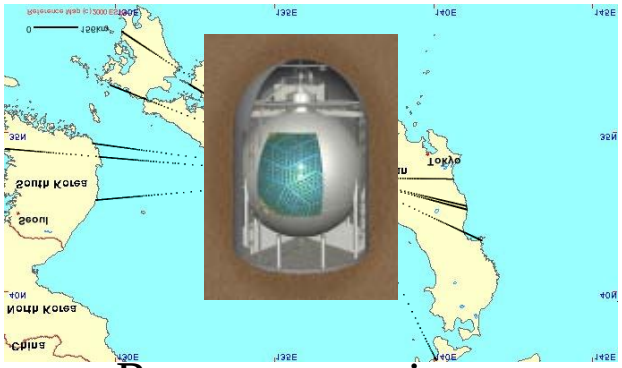
“Long” Baselines



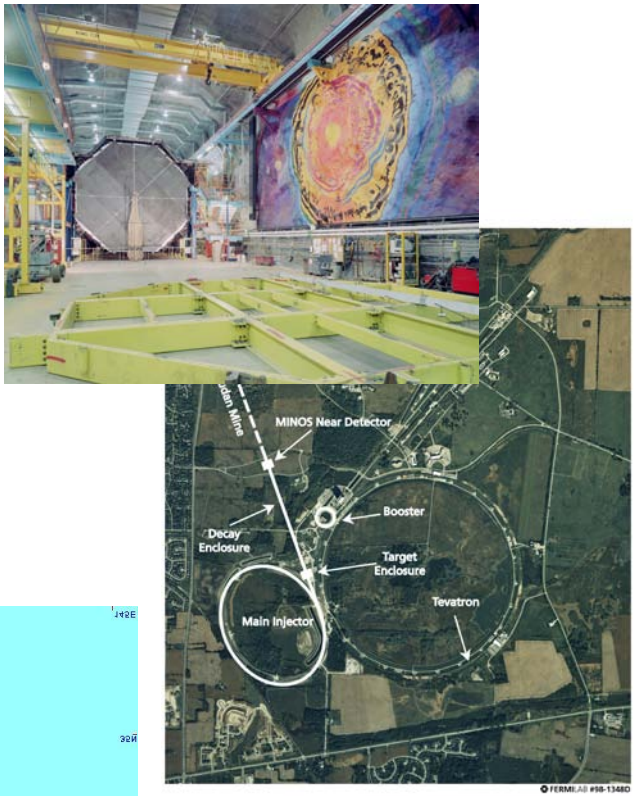
Solar neutrinos



Atmospheric neutrinos

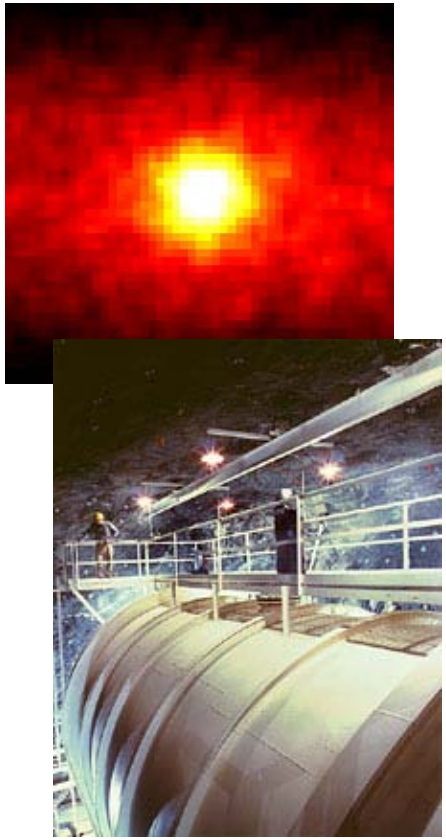


Reactor neutrinos

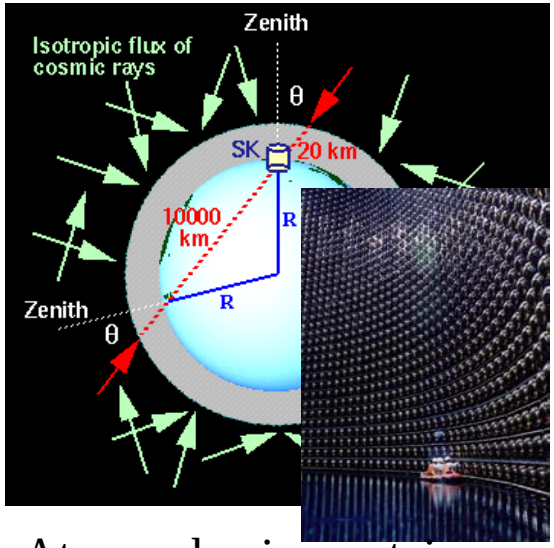


Accelerator neutrinos

“Long” Baselines

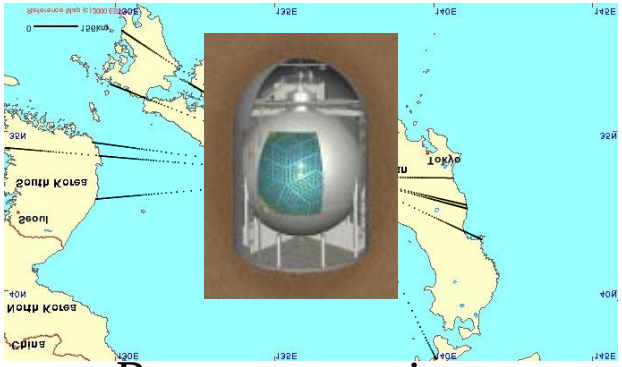


Solar neutrinos



Atmospheric neutrinos

Accelerator neutrinos



Reactor neutrinos

Experiment Ingredients

ACCELERATOR NEUTRINO BEAMS

NEUTRINO INTERACTIONS

NEUTRINO CROSS-SECTIONS

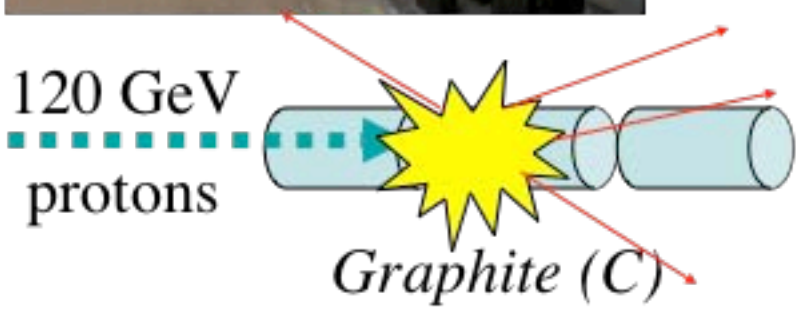
CALCULATING NEUTRINO EVENT RATES

NEUTRINO DETECTORS

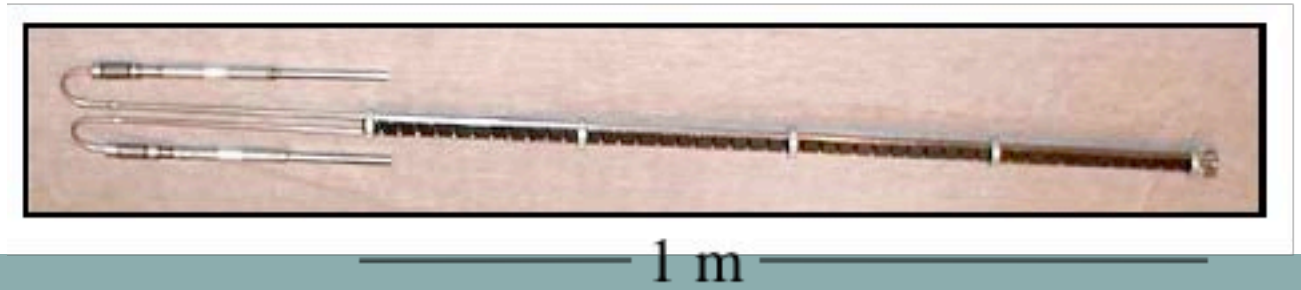
PREDICTING AND MEASURING BACKGROUNDS

Neutrino Beams

Accelerated protons produce
pions, kaons and other exotic particles



Main Ring and Main Injector



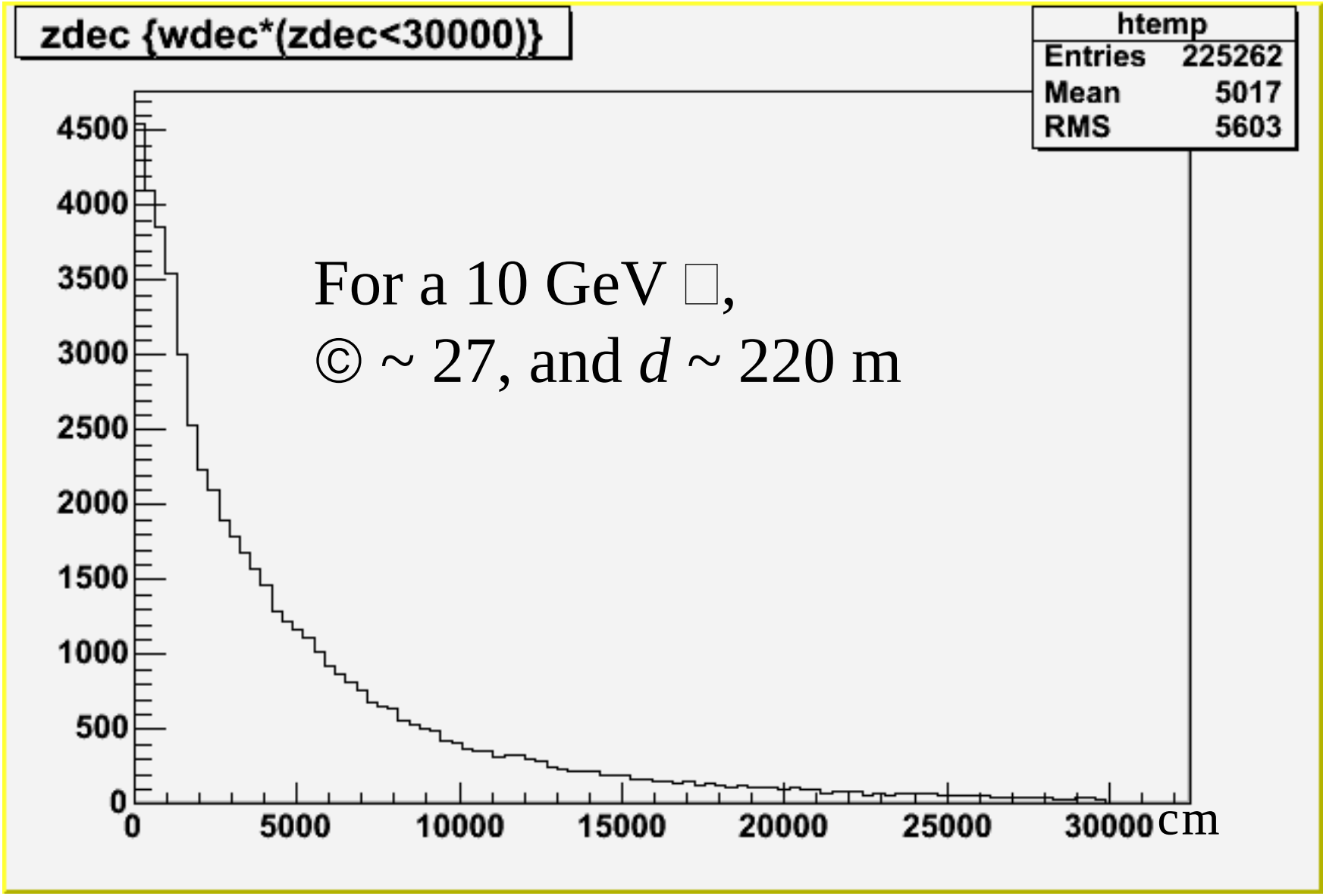
Neutrino Beams

- Neutrinos are produced from the decay of π and K mesons
  - - $\pi \rightarrow \mu + \nu_\mu$ (bf 99.9877%)
  - - $\pi \rightarrow e + \nu_e$ (bf 1.2x10^{-4})
  - - $K \rightarrow \mu + \nu_\mu$ (bf 63.55%)
  - - $K \rightarrow \pi^0 + e + \nu_e$ (bf 5.07%)

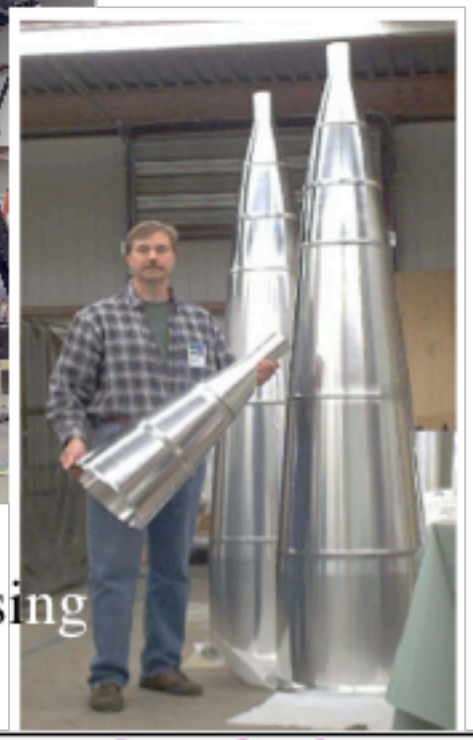
  Mostly ν_μ and a few % ν_e

- The average distance, *d*, traveled by an unstable particle before it decays is
  - - $d = \gamma c \tau, \ \gamma = 1/\sqrt{1-(v/c)^2}$
  - - $\tau_\pi = 2.6 \times 10^{-9}$ sec
  - - $\tau_K = 1.2 \times 10^{-8}$ sec

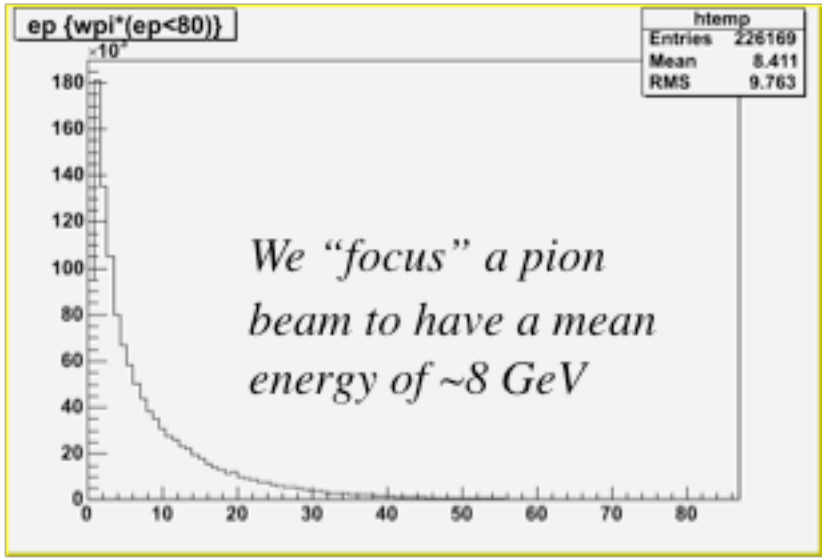
Decay length of pions produced by 120 GeV protons

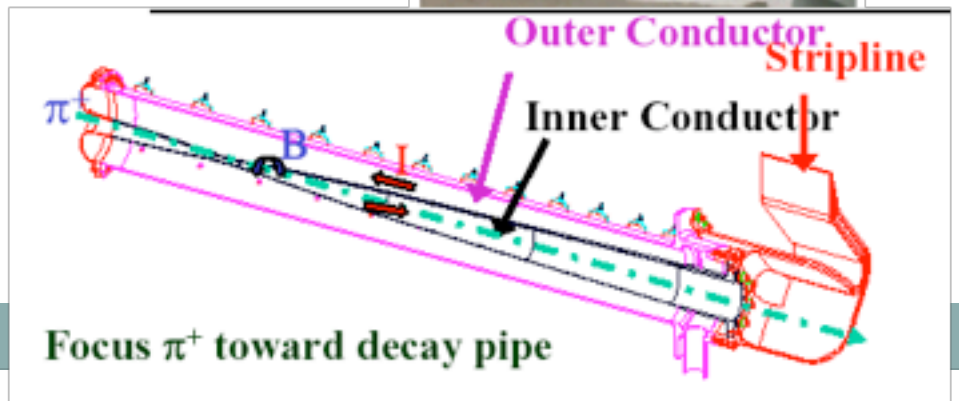


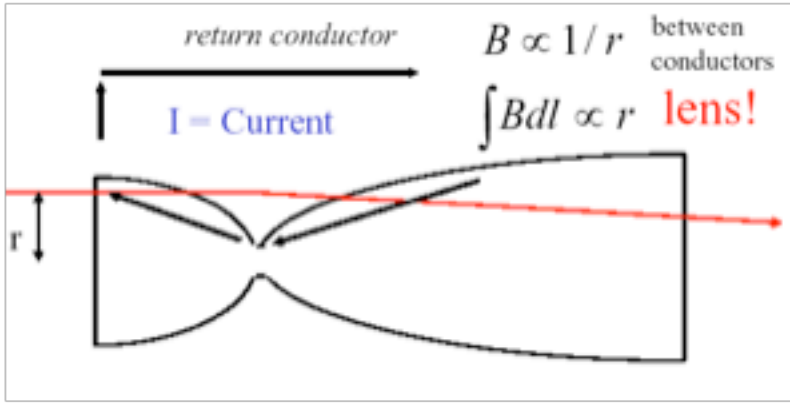
π's can be focused into a "beam"



Magnetic focusing horn

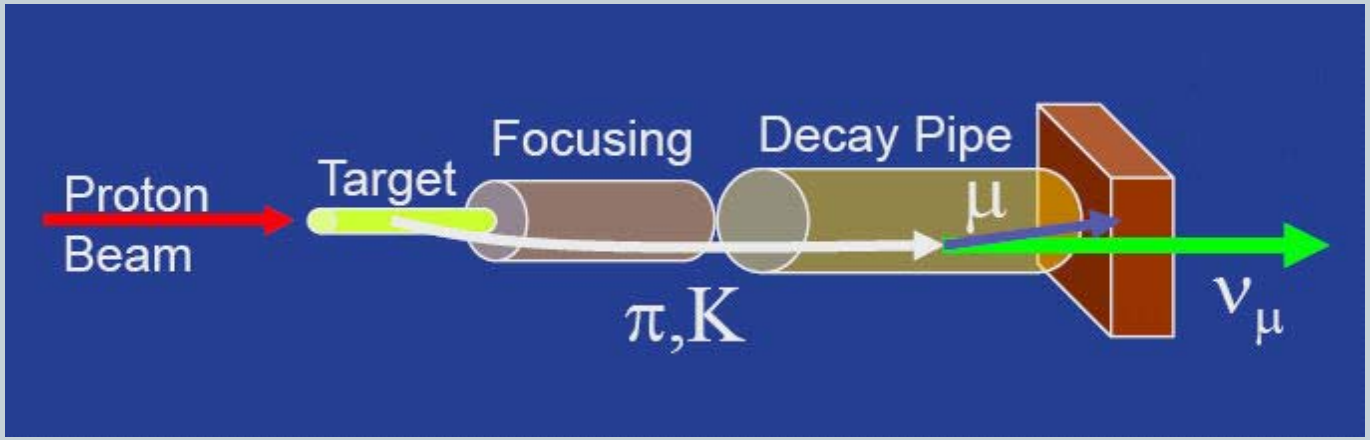






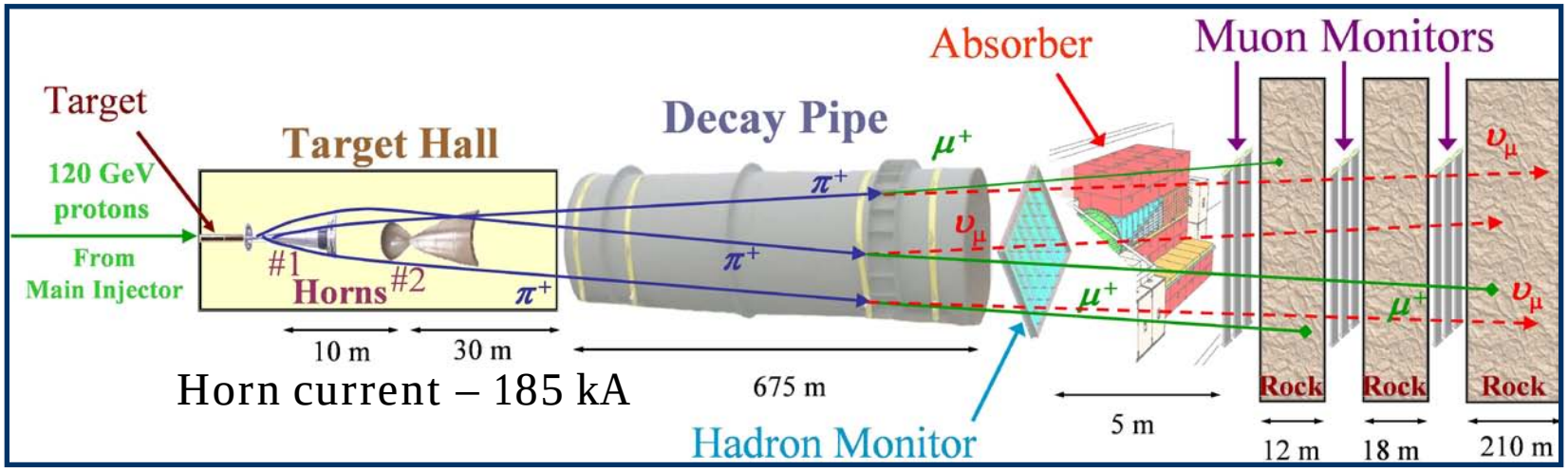
Neutrino Beams

- High energy protons hit a target
- Unstable pion and kaon charged particles are produced
- The pions and kaons are “focused” by a magnetic field to go in the desired direction
- The pions and kaons decay into muons and muon neutrinos
- The direction of the magnetic field determines whether neutrinos or anti-neutrinos are generated (focus π^+ or π^-)

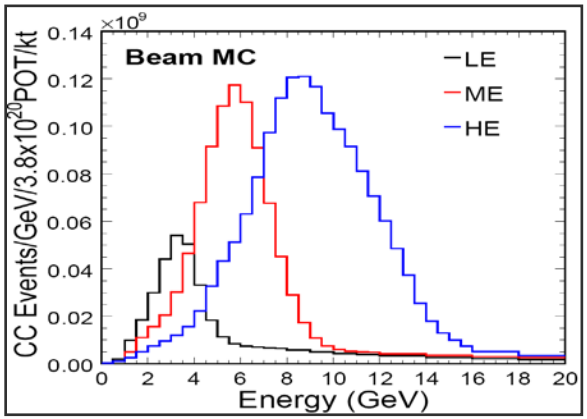


Neutrino Beams : Example – NuMI*

120 GeV protons, 10 microsec spill ~every 2 seconds ➔ 4 x 10^{13} protons/spill



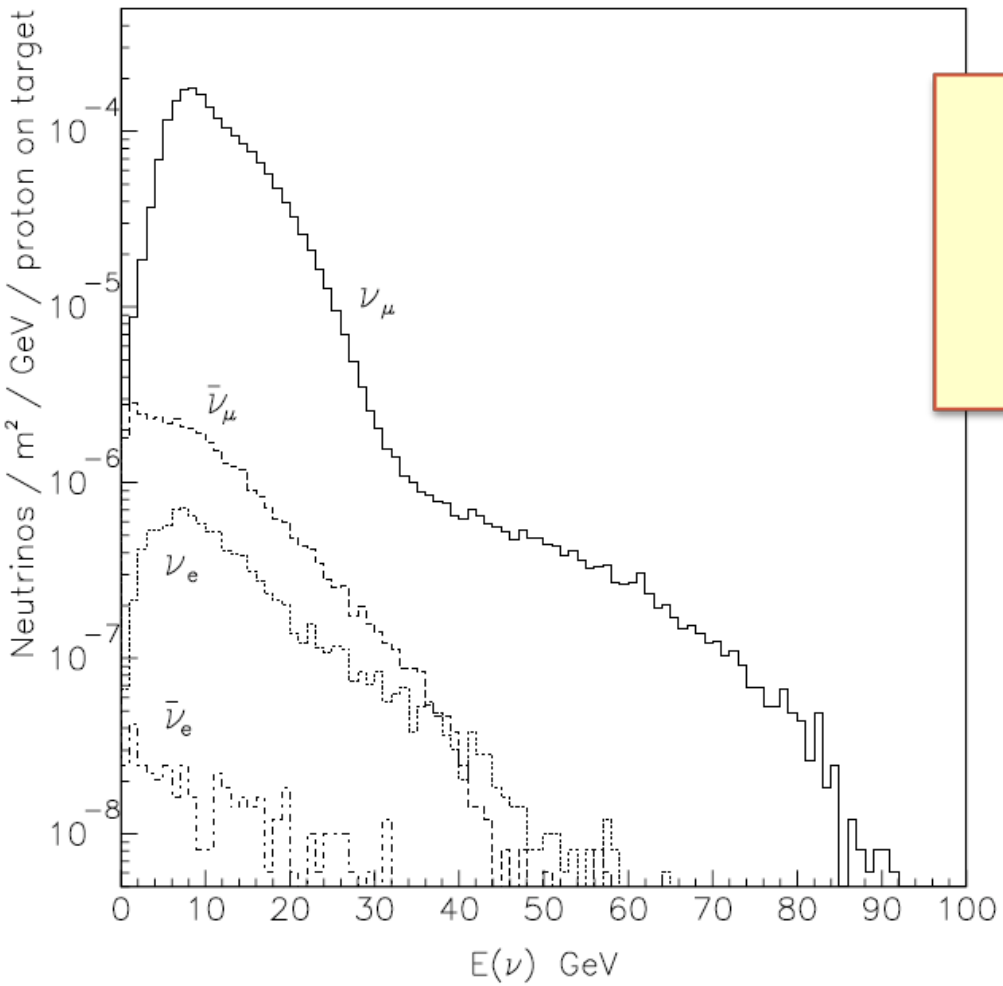
Horn current – 185 kA



By changing the relative position of the target and 1st horn, the neutrino energy spectrum can be changed

*Neutrinos at the Main Injector

Composition of a horn focused beam

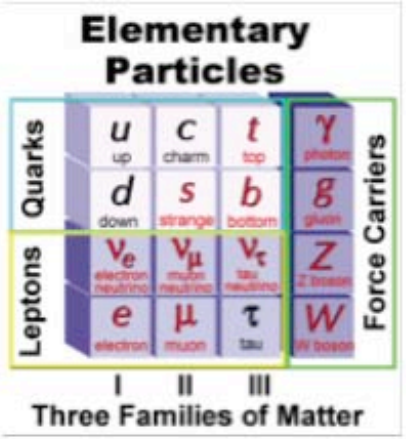


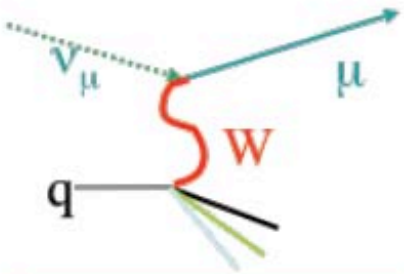
93% ν_μ

6% $\bar{\nu}_\mu$

1% $\nu_e + \bar{\nu}_e$

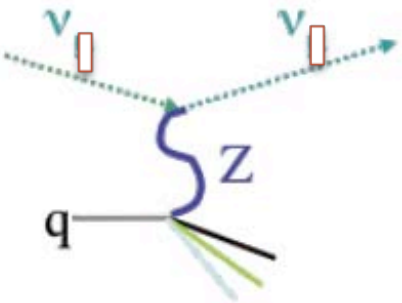
Neutrino Flavors & Interactions





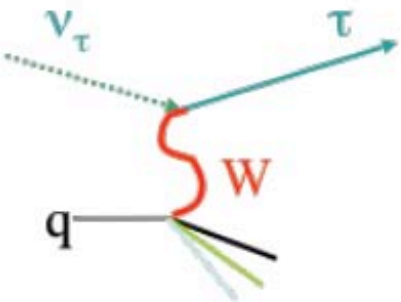
$$\nu_\mu + N \rightarrow \mu^- + X$$

Charged current



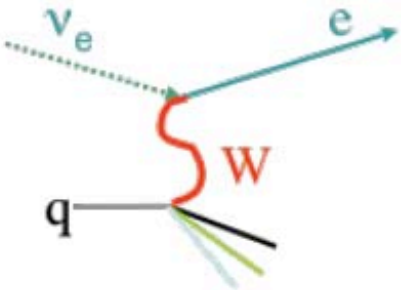
$$\nu_{[\,]} + N \rightarrow \nu_{[\,]} + X$$

Neutral current



$$\nu_\tau + N \rightarrow \tau^- + X$$

Tau Charged current



$$\nu_e + N \rightarrow e^- + X$$

Electron Charged current

Neutrino Cross sections

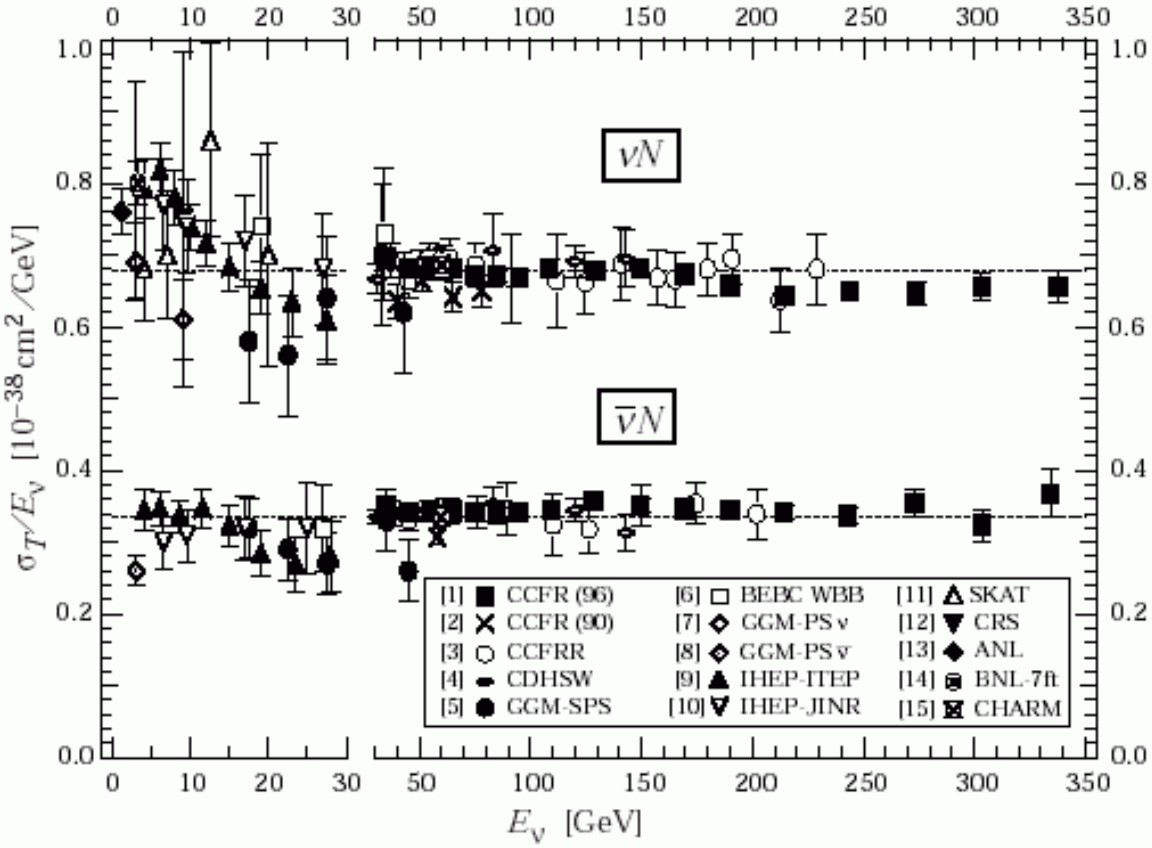
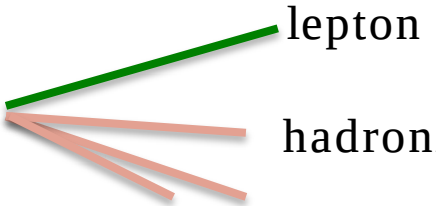


Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: $= 0.677 \pm 0.014$ $(0.334 \pm 0.008) \times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

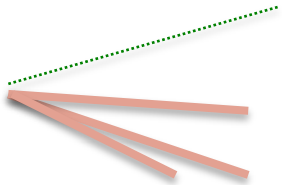
Types of interactions (example topologies)

Deep Inelastic (DIS)

CC



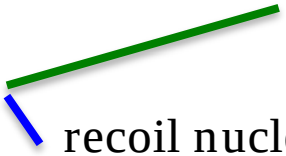
NC



Quasi-elastic (CCQE)

$\nu_\mu + n \rightarrow \mu^- p$

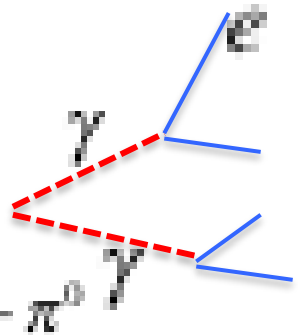
$\nu_e + n \rightarrow e^- p$



Neutral Current π^0 (NC π^0)

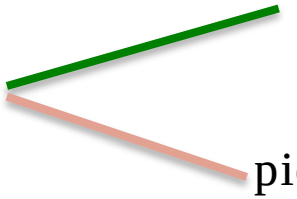
Resonant $\nu + N \rightarrow \nu + \Delta$

$N + \pi^0$

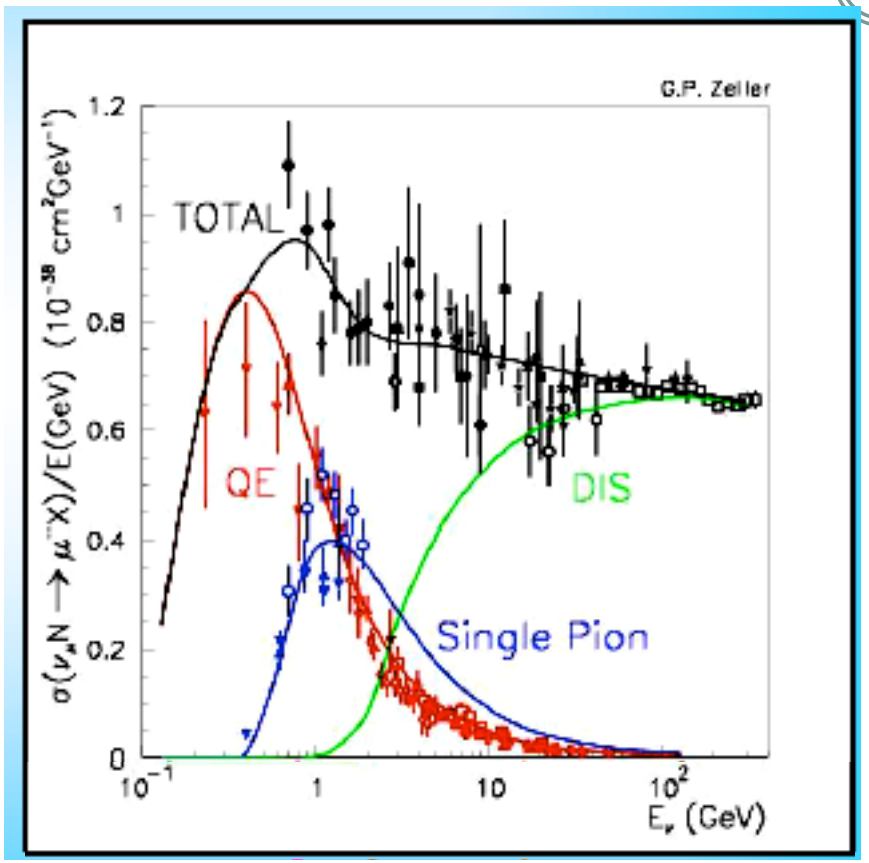


Coherent $\nu + A \rightarrow \nu' + A + \pi^0$

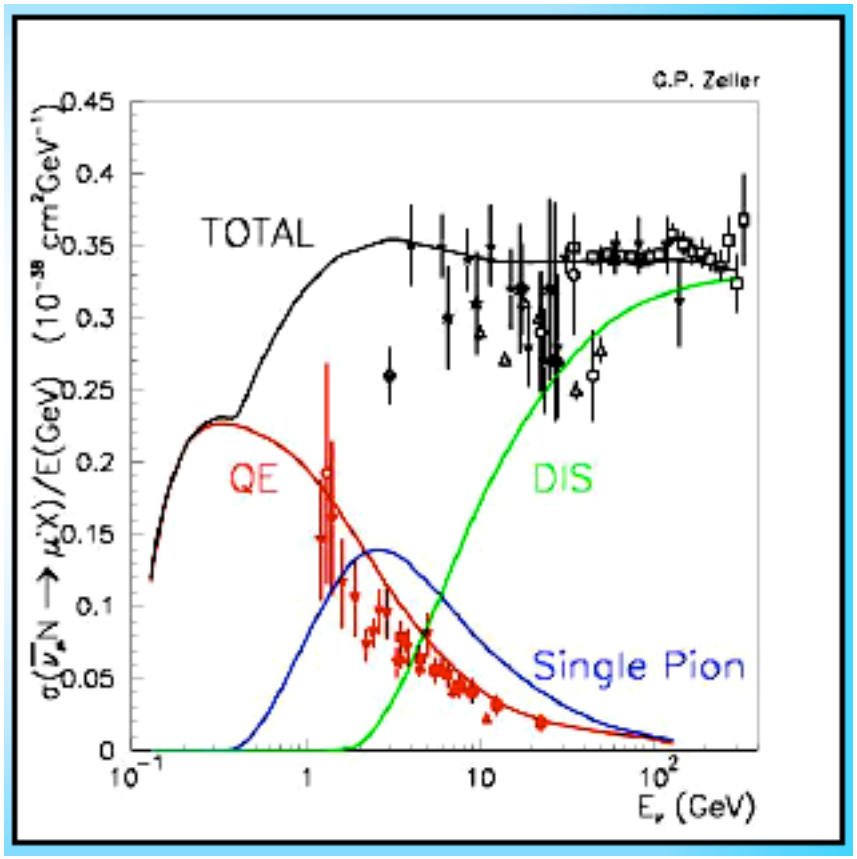
Single pion CC (CC π)



Low energy cross sections



neutrino



anti-neutrino

Neutrino CC Energy Spectrum

- Flux in *neutrinos/cm²/GeV/proton*
- Cross section=cross section/nucleon/GeV in *cm²-GeV⁻¹*
- $N_{tgt\ nucleons} = f\,(Mass, n_p, n_n)$
- N_{pot} =#protons/unit time × time

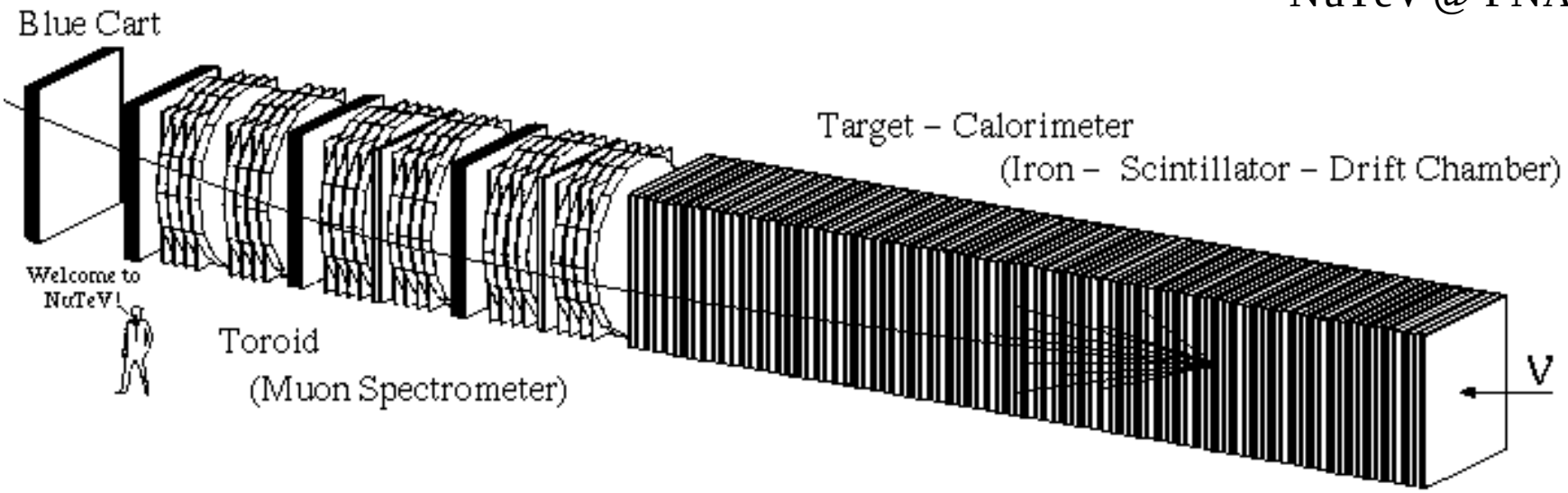
$$N_\nu(E) = \Phi_\nu(E) \times \frac{\sigma_\nu}{E} \times E \times N_{tgt\ nucleons} \times N_{protons}$$

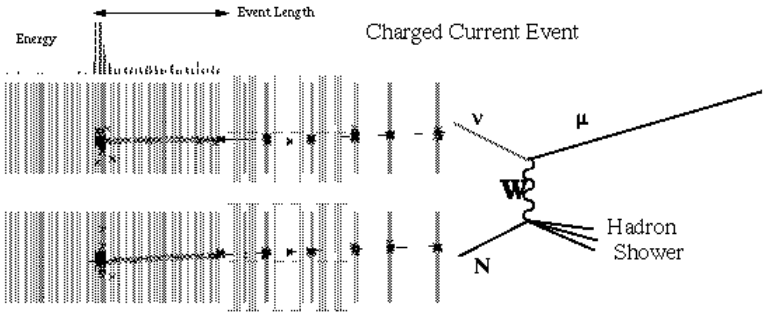
Neutrino Detectors

- Key Properties
  - Target Mass ➔ # of interactions *produced*
  - Particle ID, efficiency➔# of interactions *detected*
  - Energy, momentum measurement
  - Vertex resolution

Tracking Calorimeter

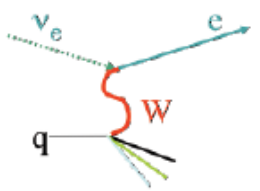
NuTeV @ FNAL



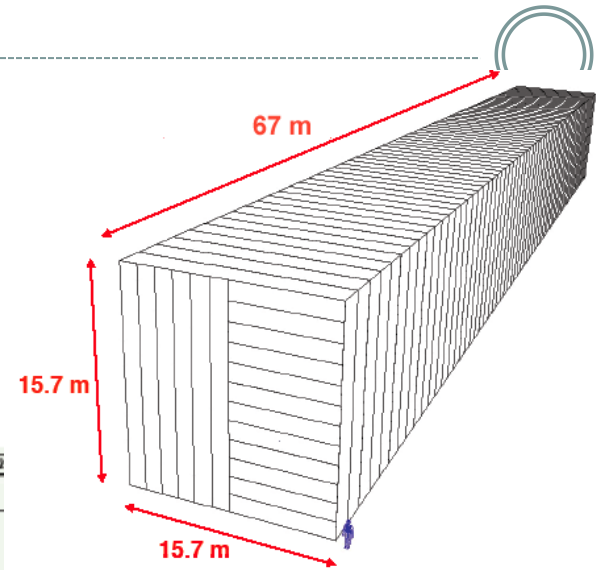


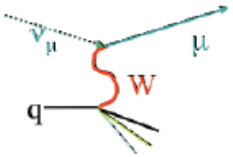
Liquid scintillator tracking calorimeter

NOvA



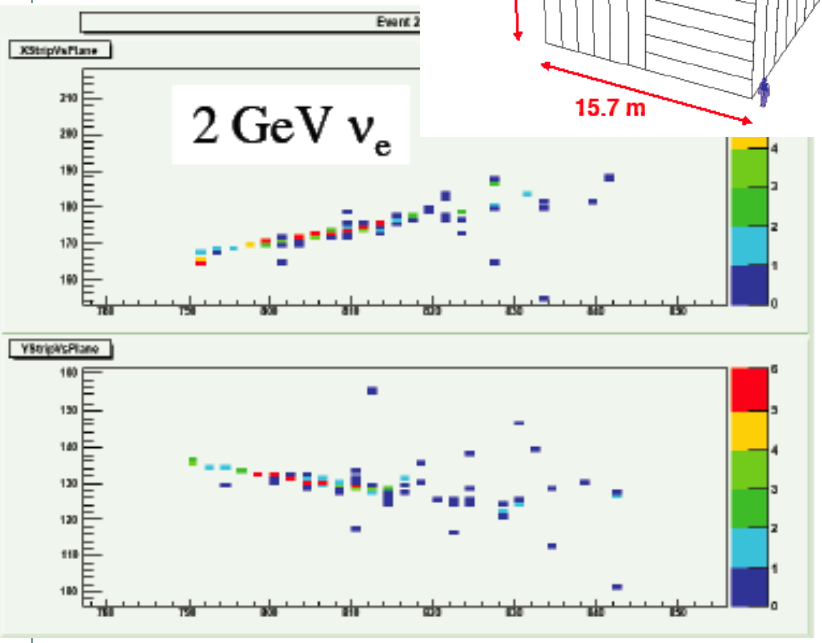
$\nu_e + N \rightarrow e^- + X$

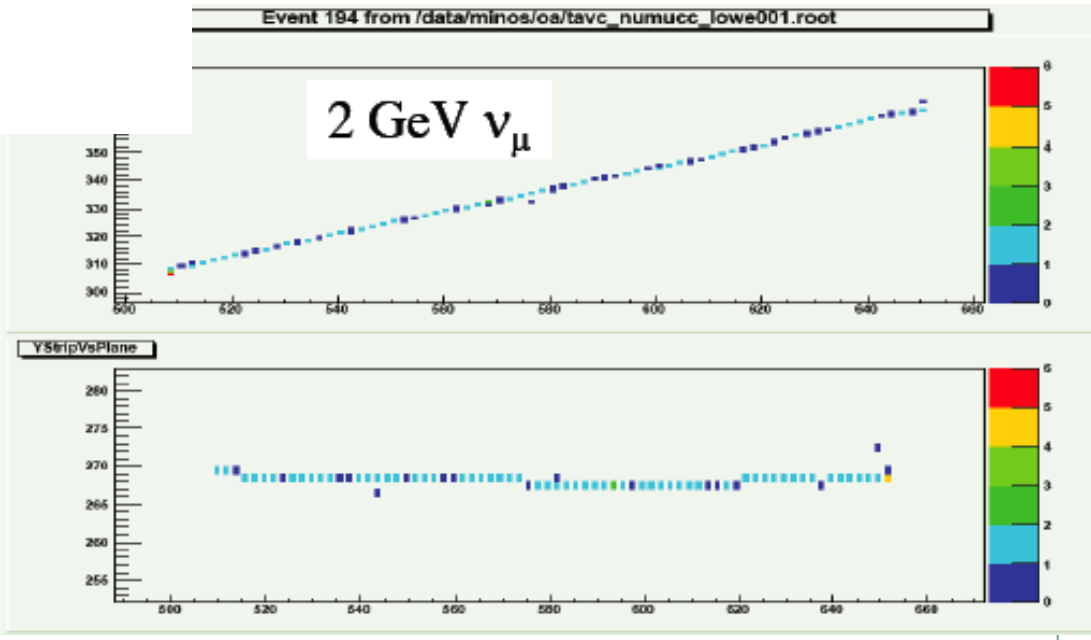




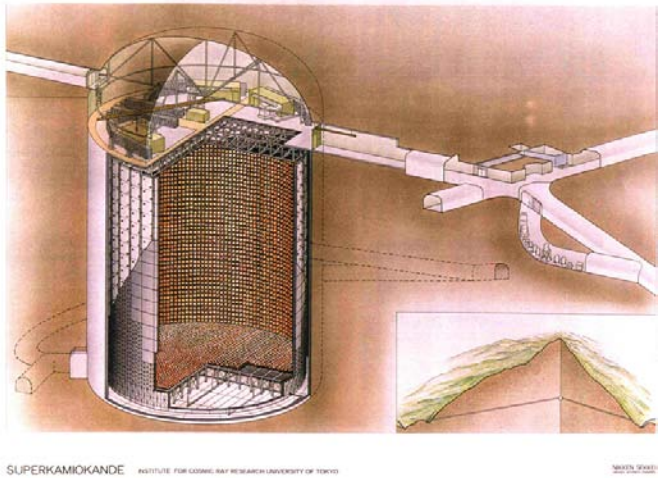
$\nu_\mu + N \rightarrow \mu^- + X$

A 2-GeV muon is 60 planes long.

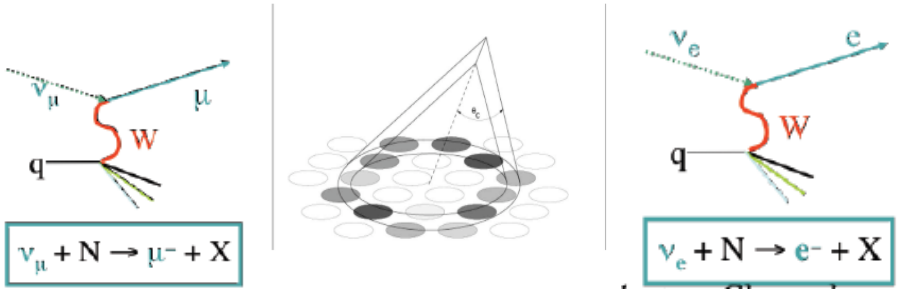


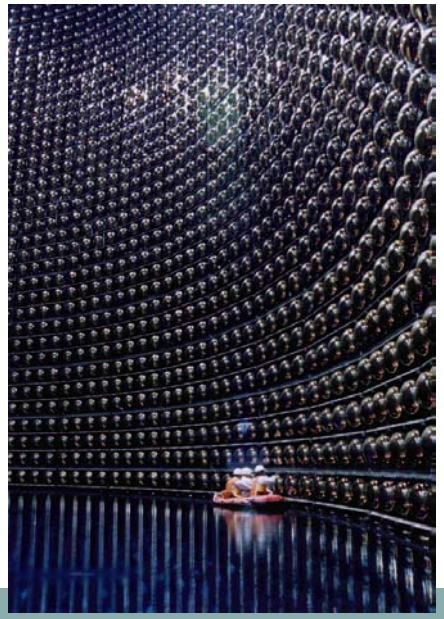


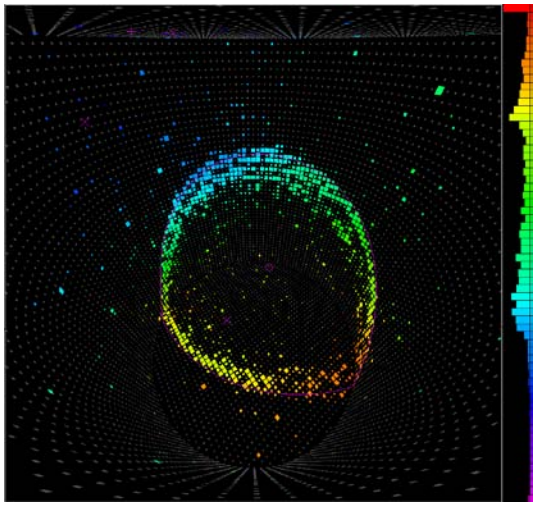
Ring imaging particle ID

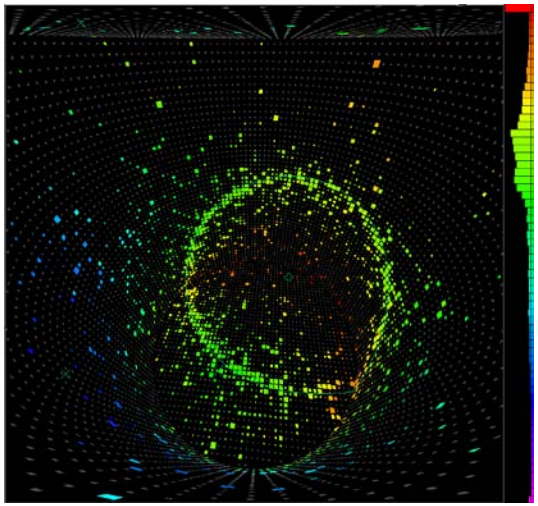


$$\cos\theta_c = \frac{1}{\beta n \lambda}$$





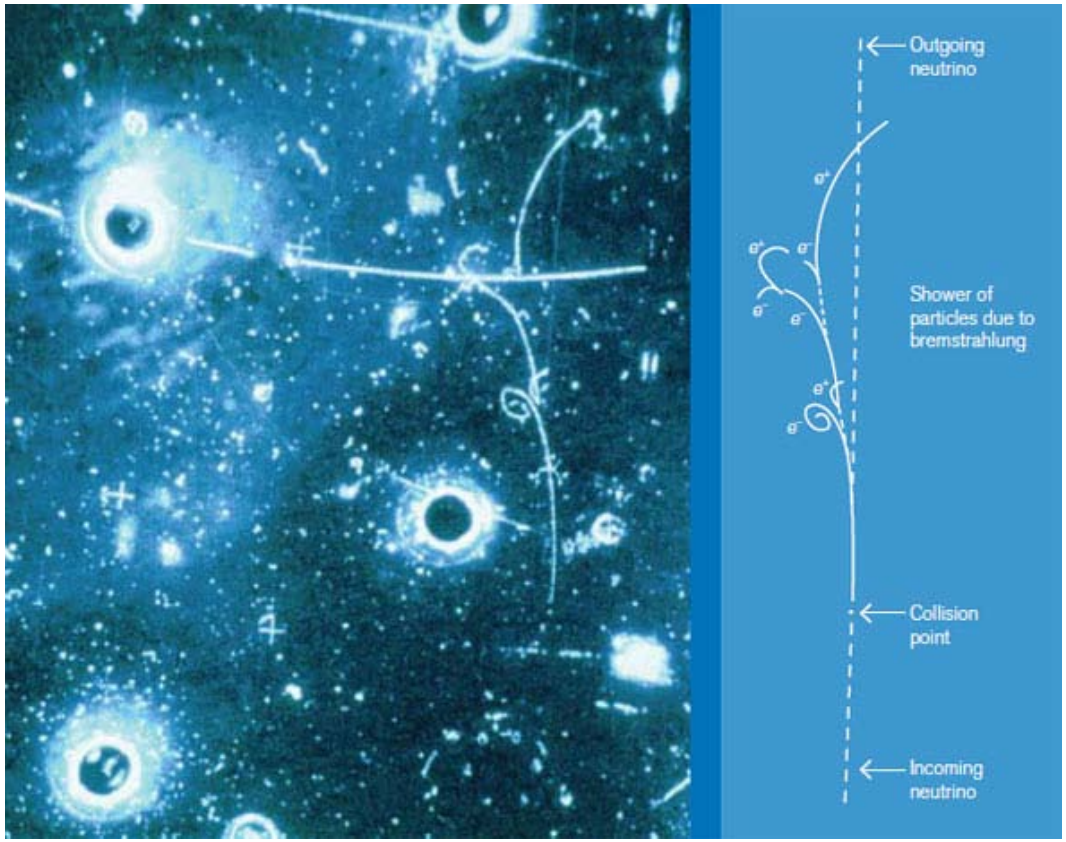




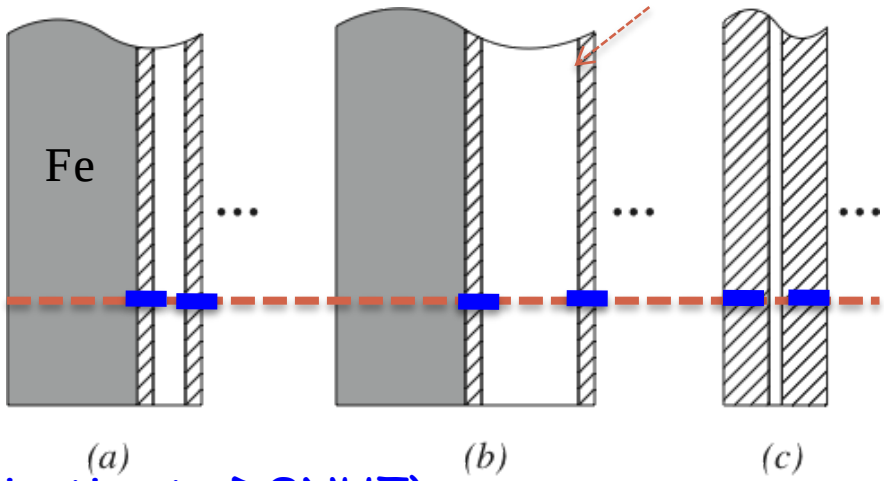
3-d imaging : Bubble chamber

Gargamelle Bubble Chamber

1st detection of a NC interaction

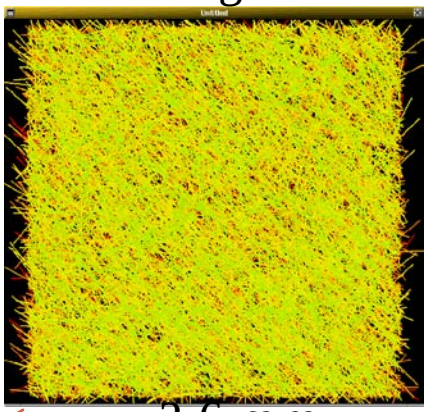


3-d imaging : Emulsion



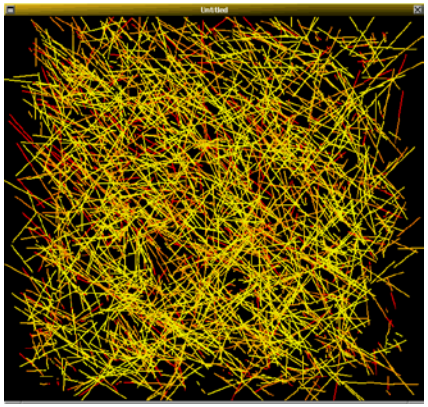
NET-scan (Application to DONUT)

50K segments

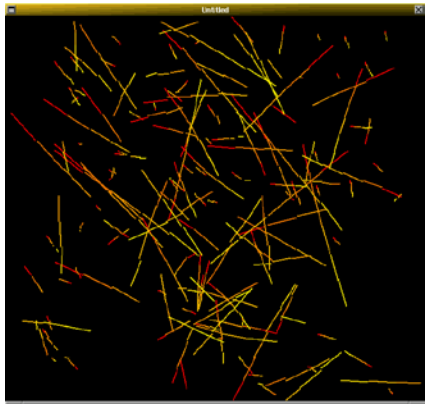


2.6 mm

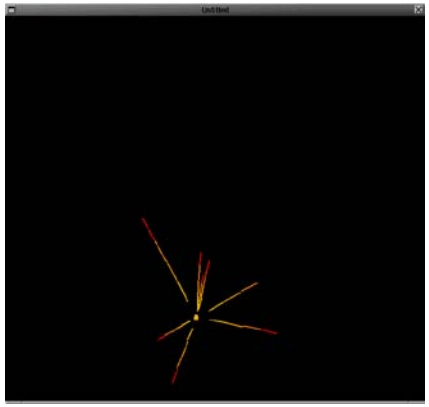
3K tracks



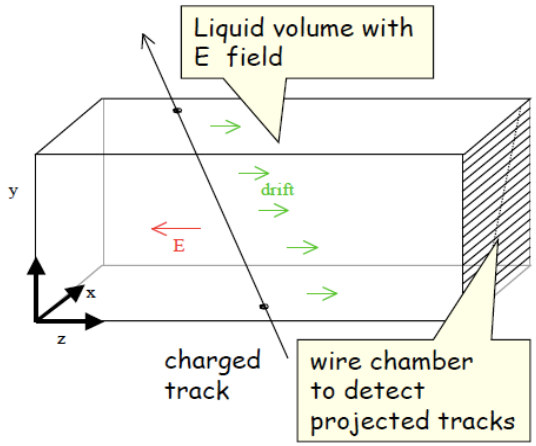
200 in vol

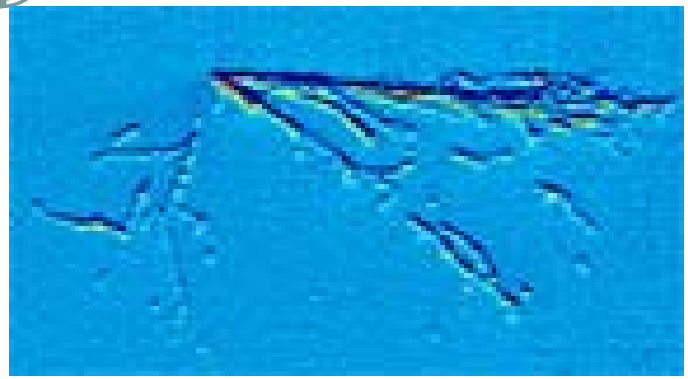


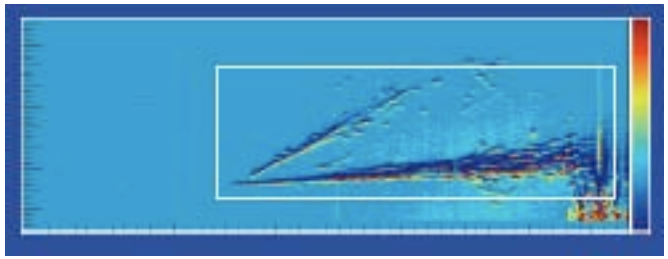
1 neutrino int.

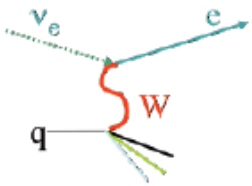


3-d imaging : Liquid Argon

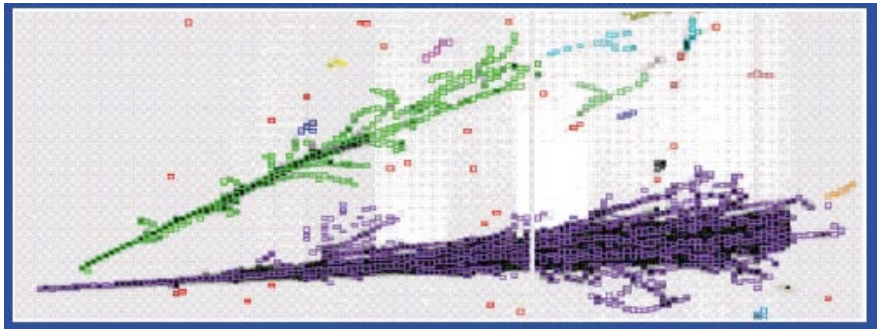








$$\nu_e + N \rightarrow e^- + X$$



Detector Summary

- Tracking Calorimeters
  - Target material
    - Steel
    - Carbon,lead, scint,water,He…
  - Tracking detectors
    - Gas tubes
    - Liquid scintillator
    - Solid scintillator
- Cherenkov radiation detectors
  - Target materials
    - Water
    - Scintillator
    - Mineral Oil
  - Active detectors : PMT's
- 3-d Imaging
  - Bubble Chambers
  - Emulsion
  - Liquid Argon

Calculating Neutrino Event Rates

- Ingredients
  - Flux
  - Cross section
  - Target Mass
  - Protons on target
  - Detection efficiency, $\varepsilon(E)$

$$N_\nu(E) = \Phi_\nu(E) \times \frac{\sigma_\nu}{E} \times E \times N_{tgt\ nucleons} \times N_{protons} \times \varepsilon(E)$$

NuMI – MINOS example

- Proton beam delivers 4×10^{13} protons every 2sec
  - ~10^{18} protons/day
  - Produce a few pions/proton
  - About half of the pions produce neutrinos aimed in the right direction
- Neutrino *flux* @500m is ~ 10^{-8} /cm^2/GeV/proton
- Neutrino cross section is ~10^{-38} cm^2/GeV
- Neutrino energy is ~1-10 GeV
- Near Detector – 1000 tons (~6×10^{32} target nucleons)
- Muon detection efficiency ~95%
  - ➔ Few neutrinos each spill
  - ➔ Thousands of neutrinos per day

Predicting and Measuring Backgrounds

- Intrinsic Backgrounds
  - Looking for an event signature : signal

$$\nu_\mu \rightarrow \underbrace{\nu_e + N \rightarrow e^+ + X}$$

  - Another process produces the same result

$$K \rightarrow \pi^0 + e + \nu_e$$
$$\downarrow$$
$$\nu_e + N \rightarrow e^+ + X$$

- Detector Performance
  - A process occurs and the detector reconstruction identifies it as a signal event

$$\nu + N \rightarrow \nu + \pi^0 \quad (NC\pi^0)$$
$$\downarrow$$
$$\cancel{\gamma}\gamma$$

Detector reconstruction says *e*

Predicting and Measuring Backgrounds

- Predicting : Monte Carlo simulation of processes
- Measuring : Make measurements where signal can’t occur

Long Baseline Basics

THE MASS-MIXING MATRIX : MIXING ANGLES AND PHASES

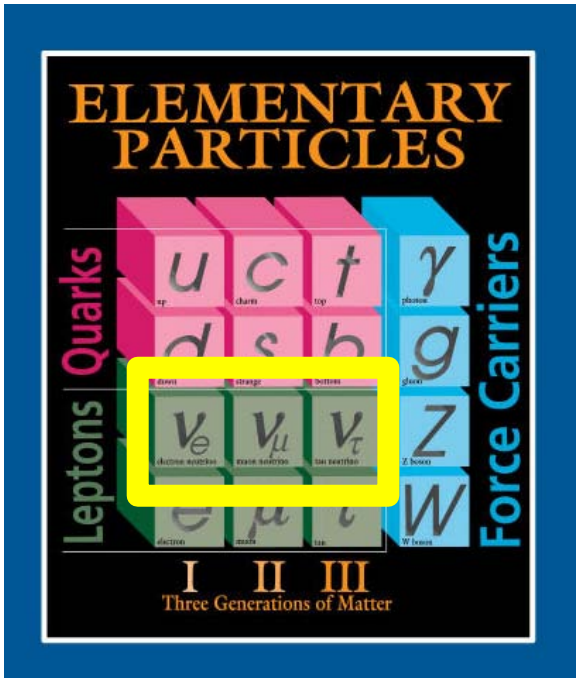
OSCILLATION PROBABILITY :

THREE NEUTRINOS

NEUTRINO MASS HIERARCHY

TWO-NEUTRINO APPROXIMATION

The Neutrino Mass-mixing matrix



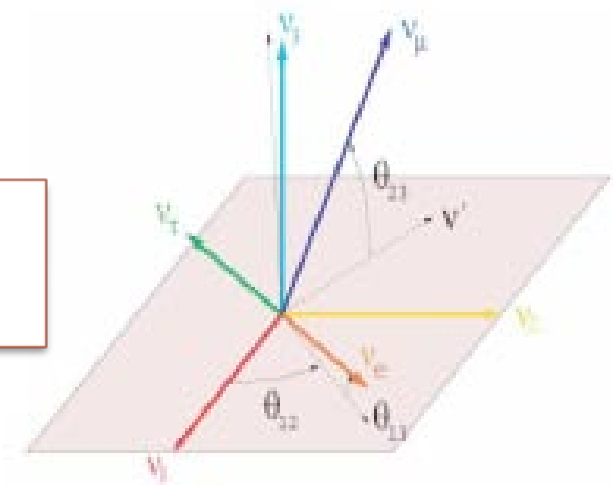
Three neutrinos having unique masses are related to the three flavor states via a Unitary mixing matrix.

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

The Neutrino Mass-mixing matrix

$$U = \begin{pmatrix} \cos\theta_{12}\cos\theta_{13} & \sin\theta_{12}\cos\theta_{13} & \sin\theta_{13}e^{-i\delta} \\ -\cos\theta_{23}\sin\theta_{12} - \sin\theta_{13}\sin\theta_{23}\cos\theta_{12}e^{i\delta} & \cos\theta_{23}\cos\theta_{12} - \sin\theta_{13}\sin\theta_{23}\sin\theta_{12}e^{i\delta} & \sin\theta_{23}\cos\theta_{13} \\ \sin\theta_{23}\sin\theta_{12} - \sin\theta_{13}\cos\theta_{23}\cos\theta_{12}e^{i\delta} & -\sin\theta_{23}\cos\theta_{12} - \sin\theta_{13}\cos\theta_{23}\sin\theta_{12}e^{i\delta} & \cos\theta_{23}\cos\theta_{13} \end{pmatrix}$$

$$\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3$$



Features of the matrix

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

- Two component mixing,1➔2;2➔3
- 1➔3 mixing and Complex phase

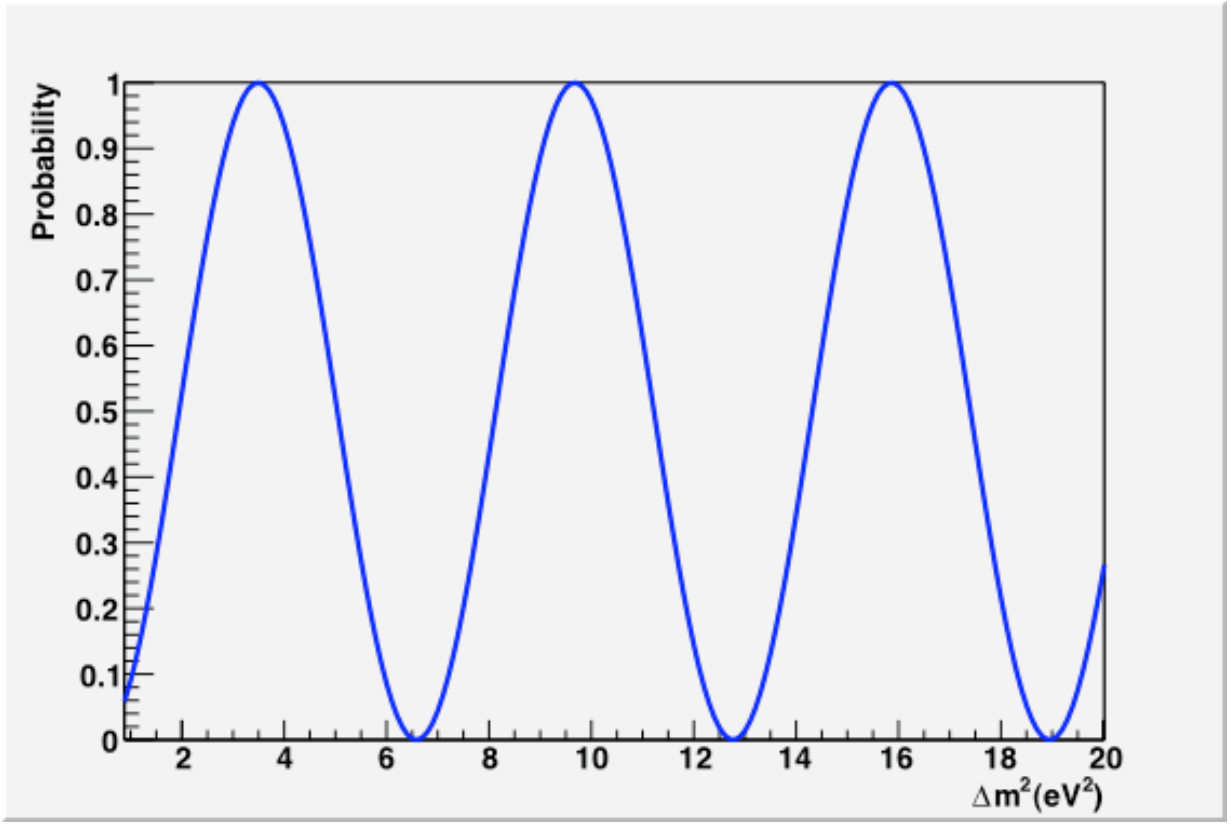
Let's first consider the case of two neutrinos :

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Neutrino Oscillation Probability

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

=1 =4



Oscillation Signatures

APPEARANCE AND DISAPPEARANCE

SETTING LIMITS

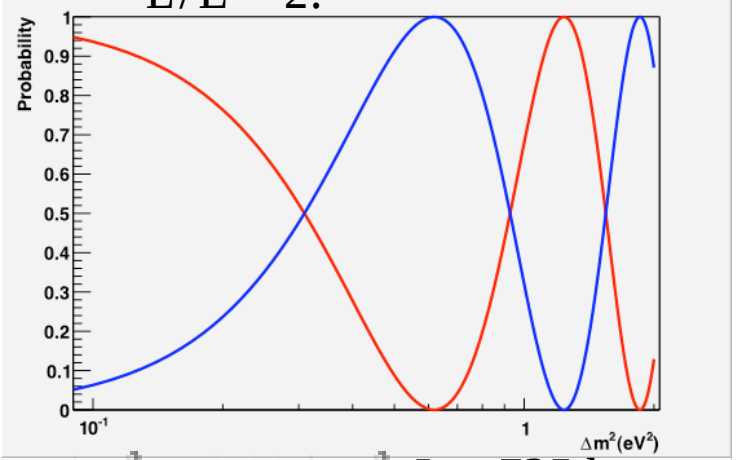
MEASURING PARAMETERS

Appearance and Disappearance Probability

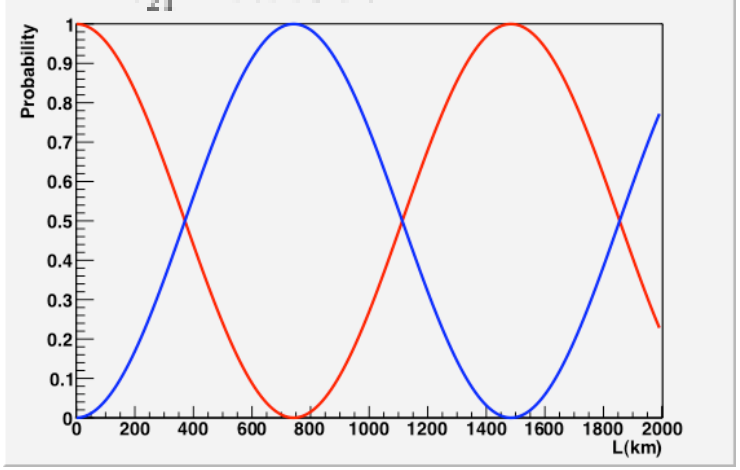
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12} \frac{L}{E})$$

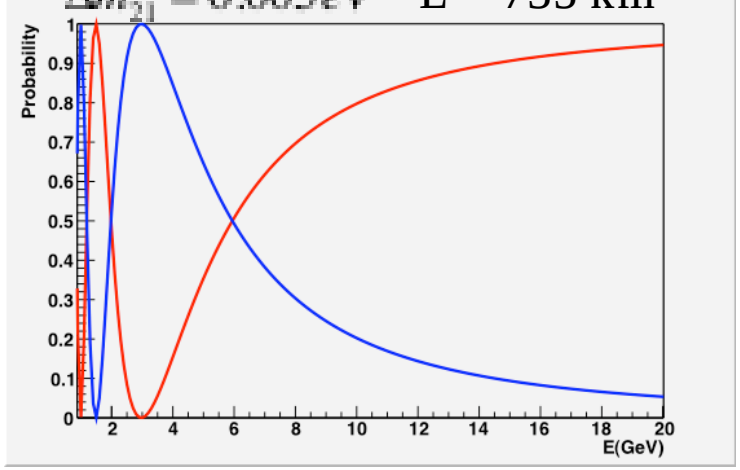
L/E = 2.



$\Delta m^2_{21} = 0.005 eV^2$ E = 3 GeV



$\Delta m^2_{21} = 0.005 eV^2$ L = 735 km

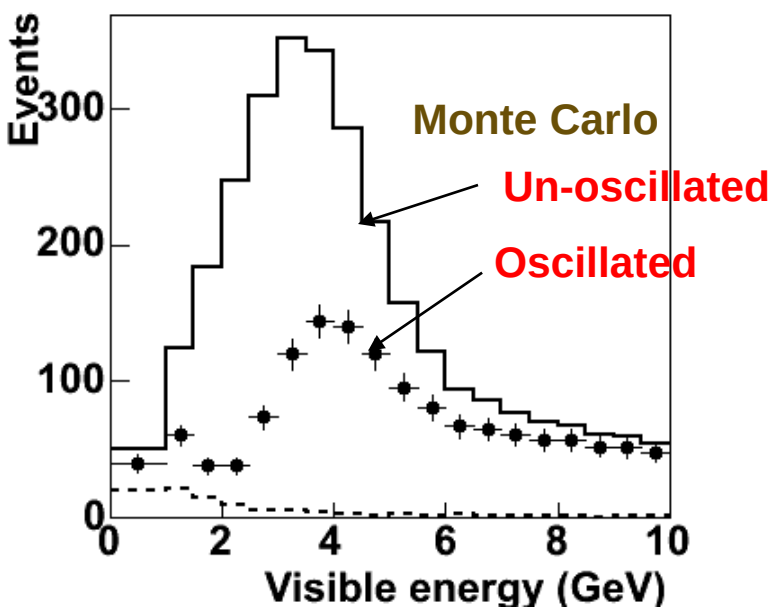


Disappearance "signals"

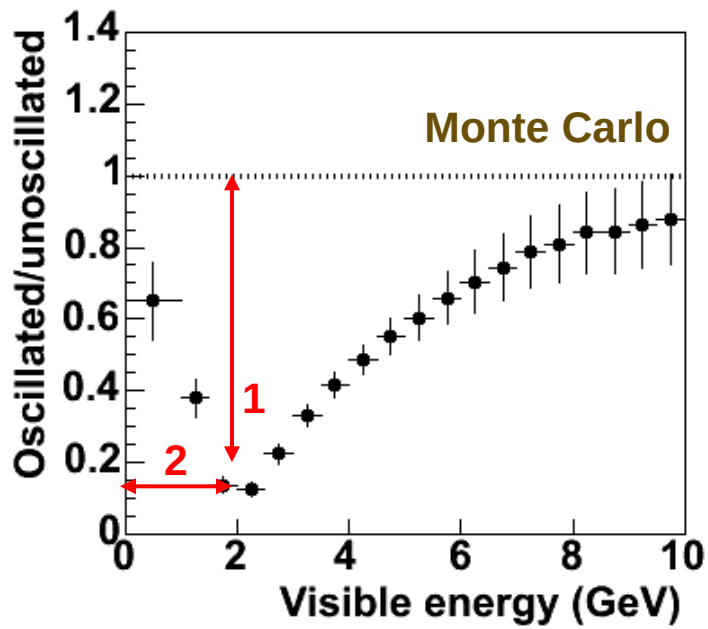
$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \overset{1}{\sin^2 2\theta_{12}} \sin^2(1.27 \overset{2}{\Delta m^2_{12}} \frac{L}{E})$$

$$N_{\nu_\alpha}(\text{"disappearance signal"}) = P(\nu_\alpha \rightarrow \nu_\alpha) \times N_{\nu_\alpha}(\text{predicted with no oscillations})$$

spectrum



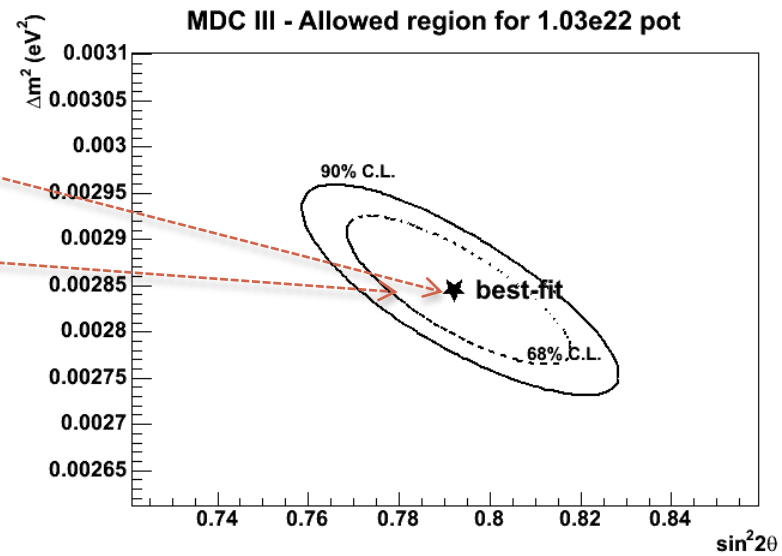
spectrum ratio

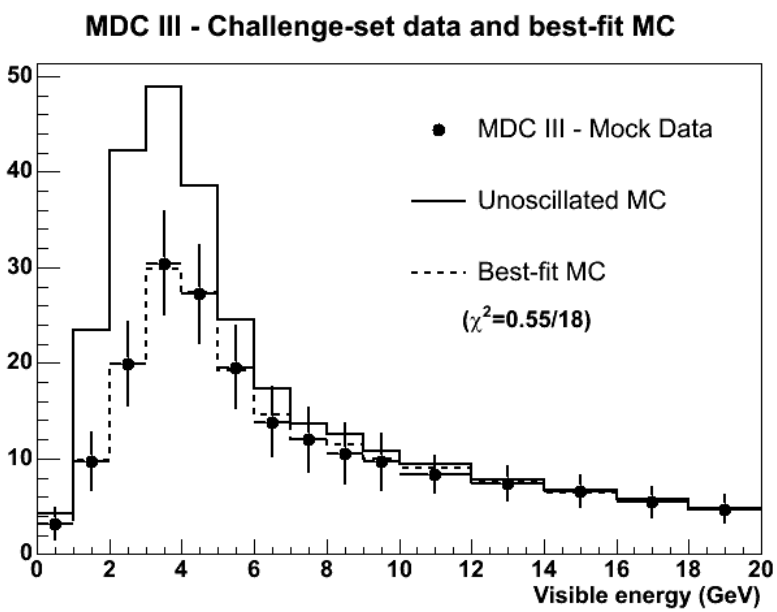


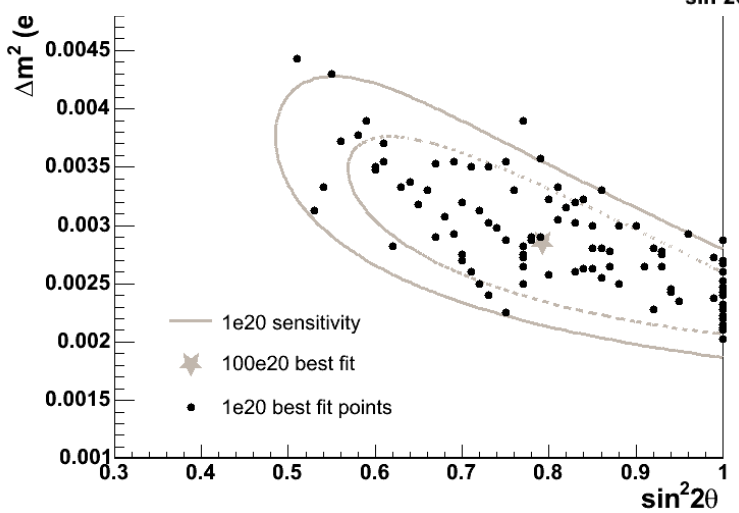
Measuring Parameters

What value of $\sin^2 2\theta$ and Δm^2 "best fit" the data?

For what set of points would the χ^2 differ by 1 (68% C.L.)?







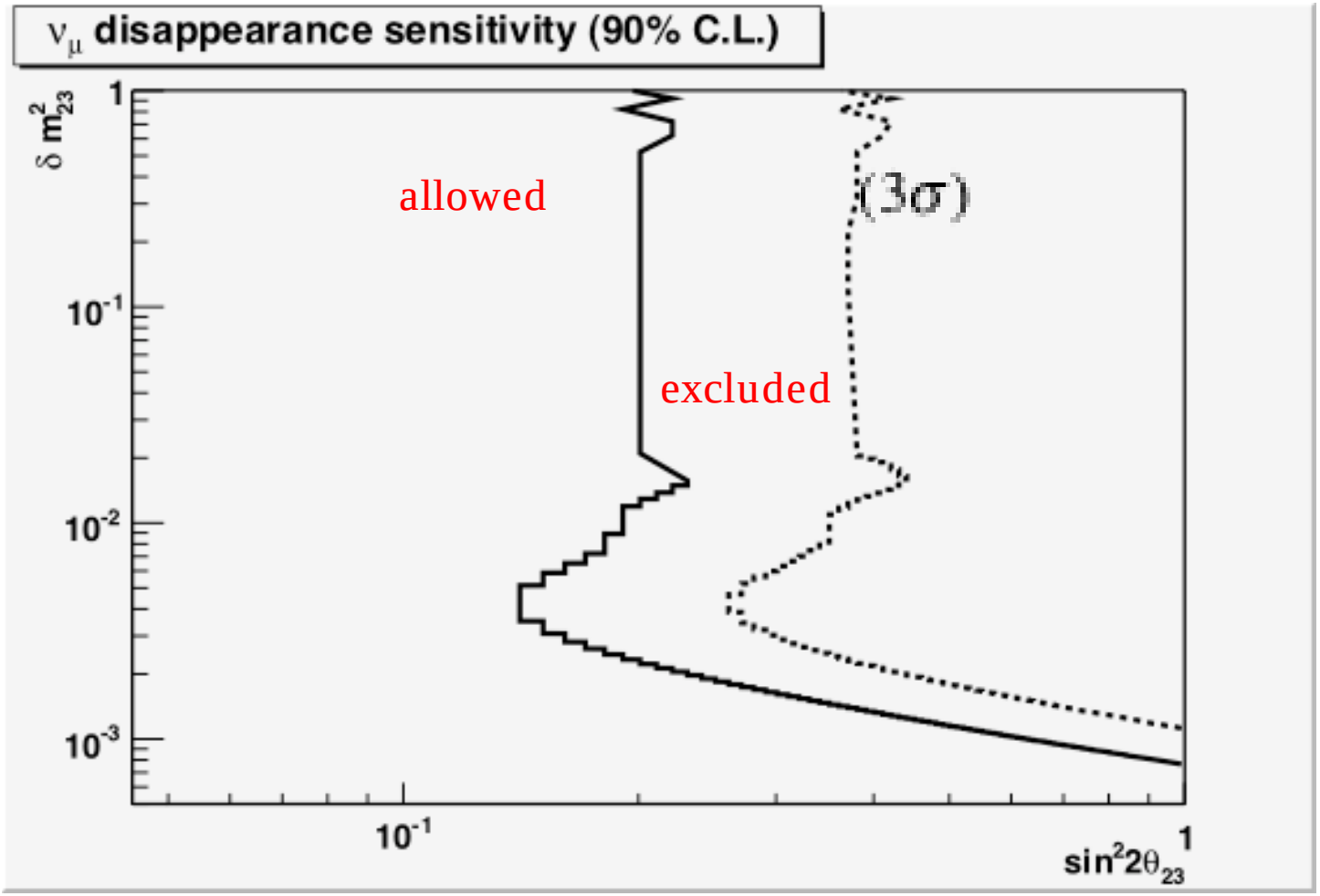
From a MINOS MC *mock data* challenge

Appearance signals

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$$

$$N_{\nu_b}(E) = \Phi_{\nu_a}(E) \times P(\nu_a \rightarrow \nu_b) \times \frac{\sigma_{\nu_b}}{E_{\nu_b}} \times E_{\nu_b} \times N_{tgt\ nucleons} \times N_{protons} \times \varepsilon(E)$$

Setting Limits for No Oscillations



Experimental Examples

EARLY SEARCHES FOR NEUTRINO OSCILLATIONS

LSND AND MiniBOONE

K2K AND MINOS

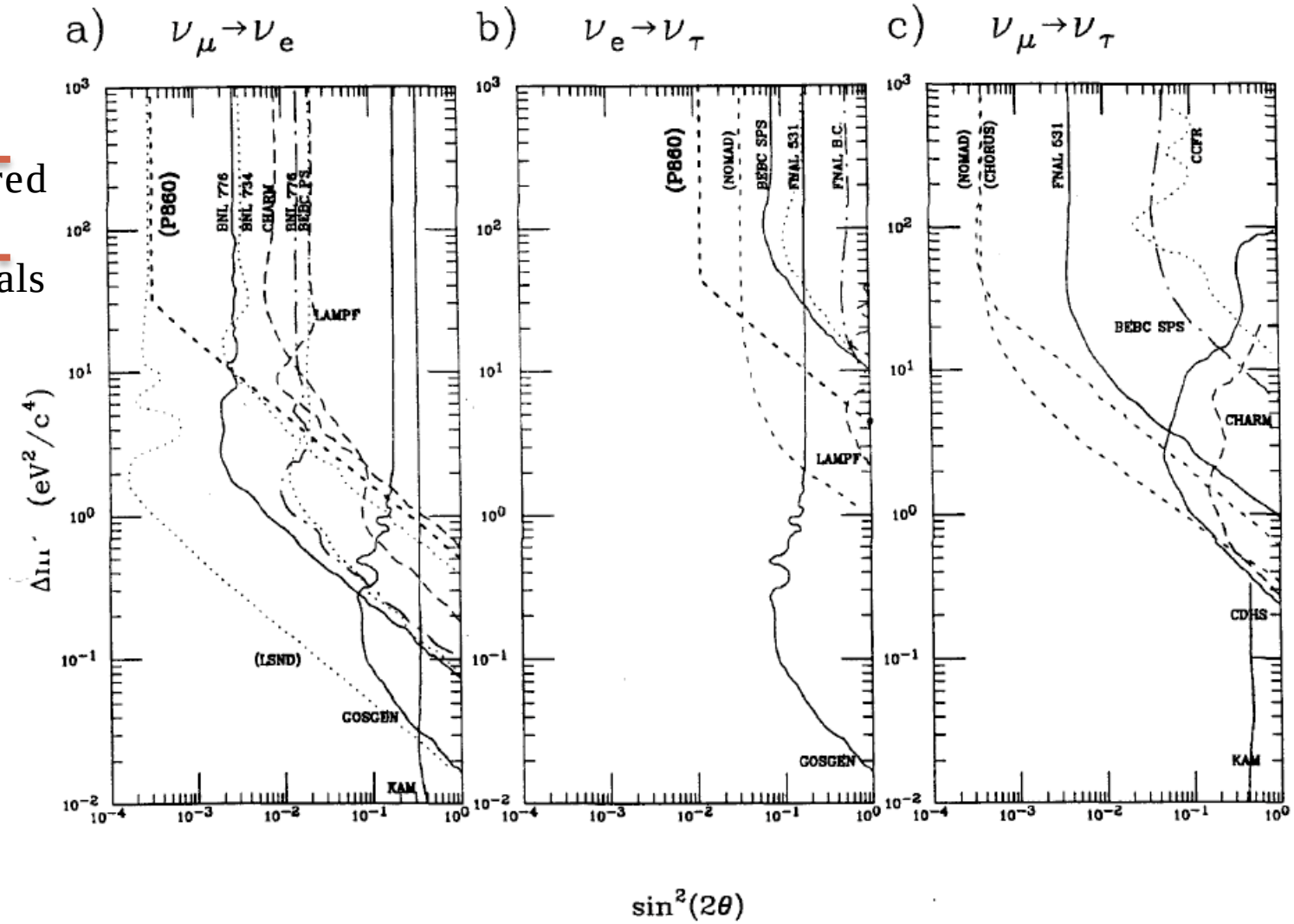
OPERA

Early searches : setting limits

1992

measured

proposals

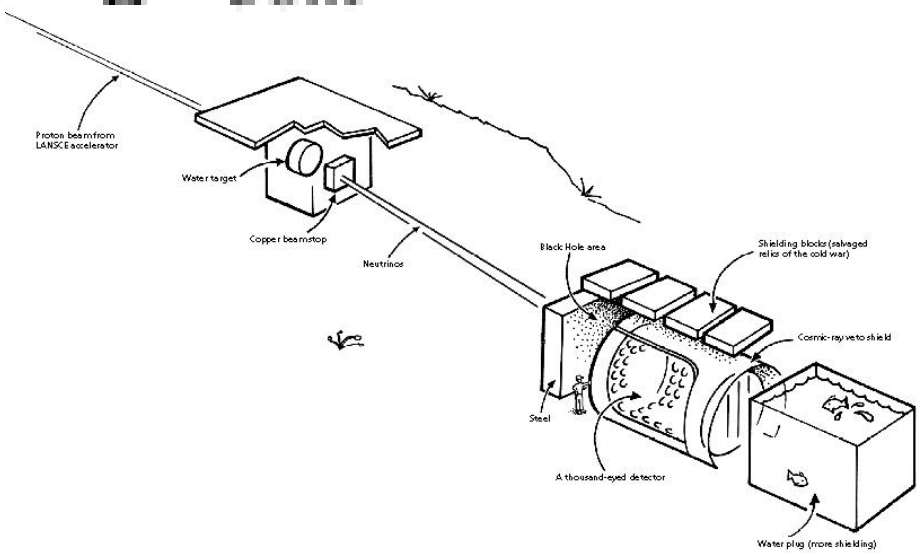


1995 : LSND

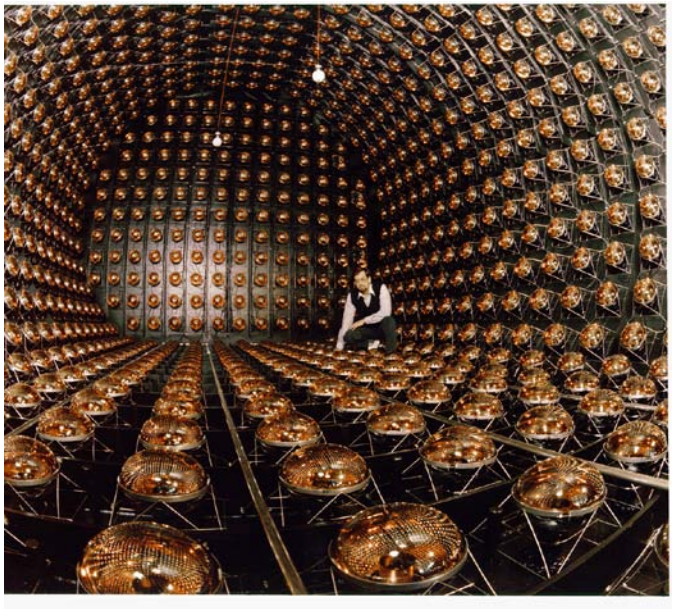
Los Alamos LANSCE 800 MeV accelerator

$$36MeV < E_\nu < 56MeV$$

$$L = 30m$$



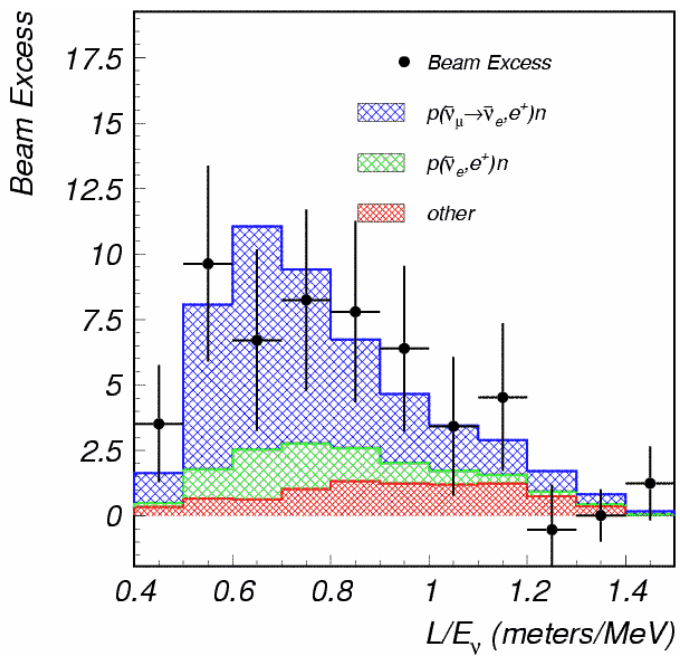
167 ton – liquid scintillator
1220 8” PMT
Scintillation & cherenkov light

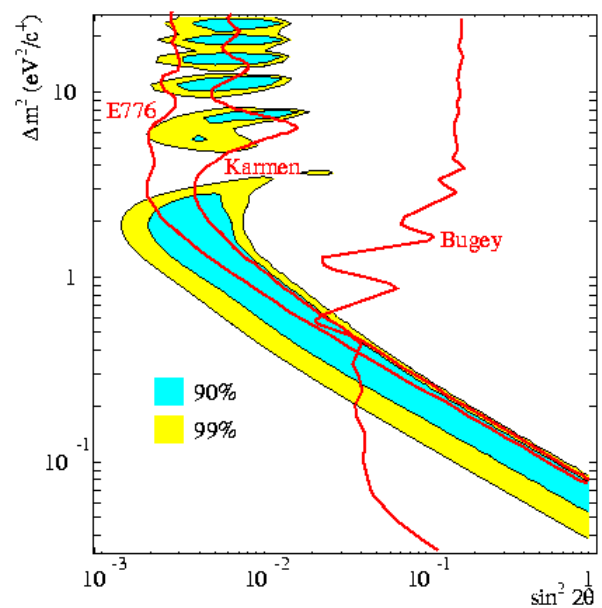


Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Table 2. LSND decay at rest oscillation search.

Selection	Beam on	Beam off	ν backgrounds	Excess signal
$36 < E_e < 60, R > 30$	29	5.2 ± 0.6	3.0 ± 0.6	20.8 ± 5.4
$20 < E_e < 60, R > 30$	61	15.6 ± 1.0	11.5 ± 0.6	33.9 ± 8.0
Fitted oscillation probability			$0.31 \pm 0.09 \pm 0.05\%$	



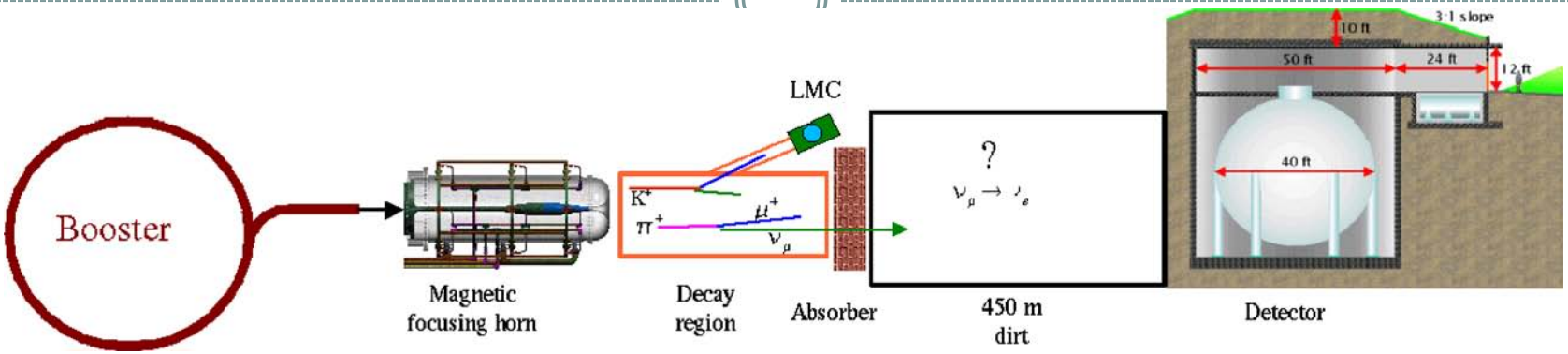


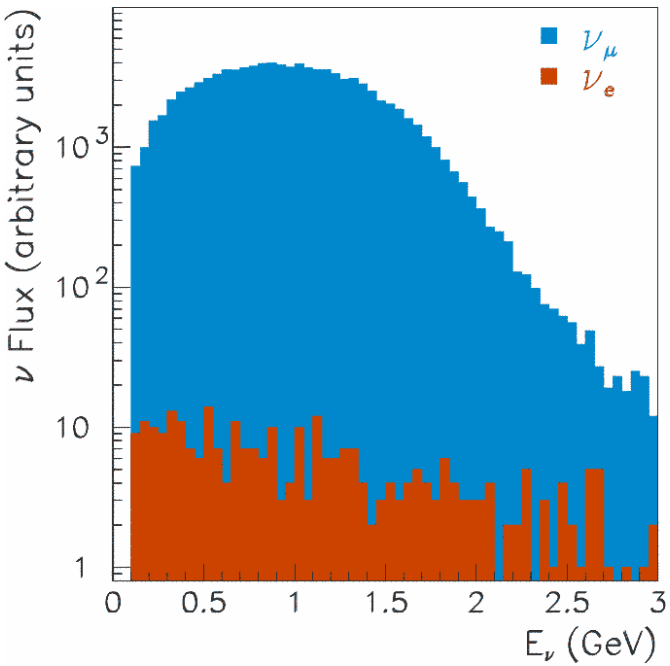
excluded

Also reported evidence for $\nu_\mu \rightarrow \nu_e$

This result ***was/is*** *controversial….*

1998 MiniBooNE Proposal



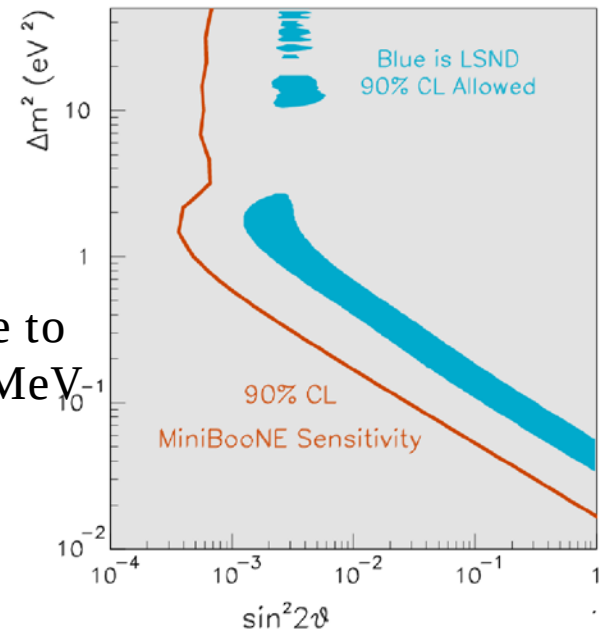


Search for

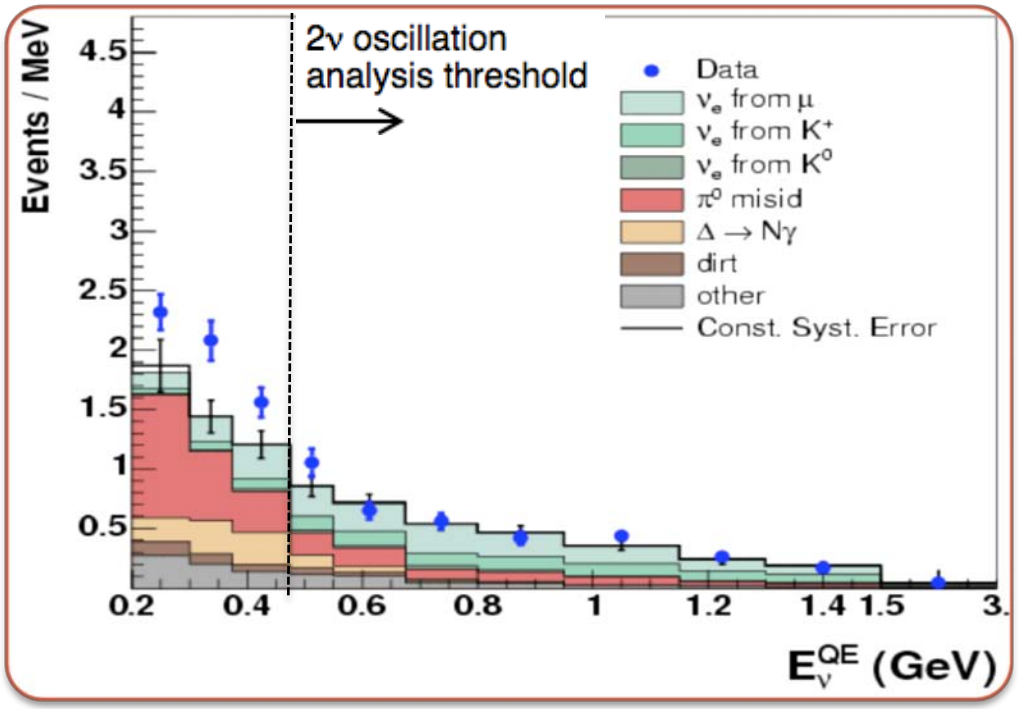
$$\nu_\mu \rightarrow \nu_e$$

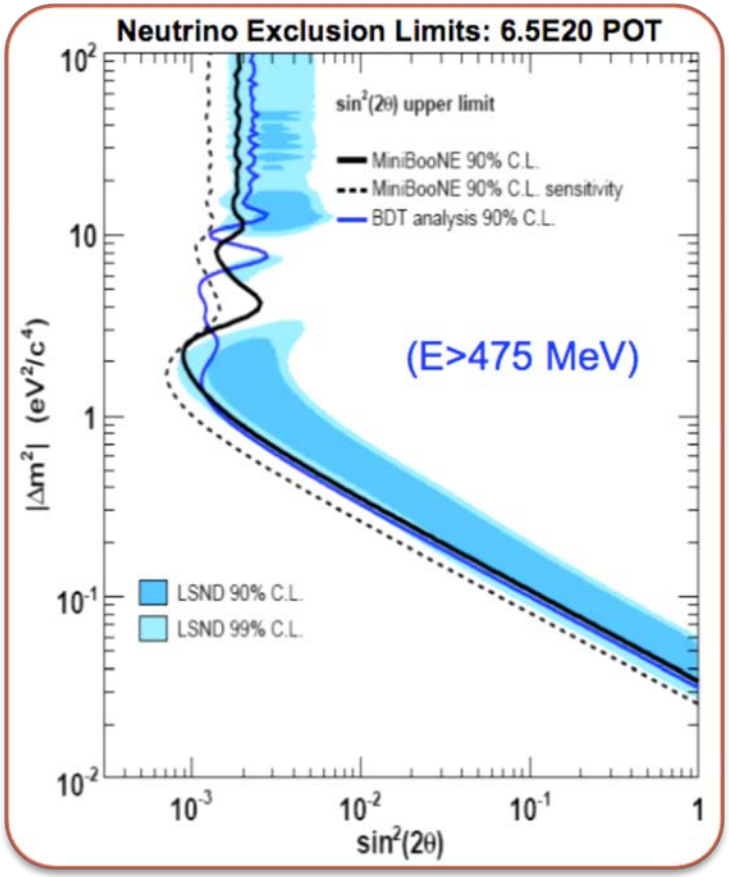
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

With L/E comparable to LSND : E~400-800 MeV
L ~ 500 M



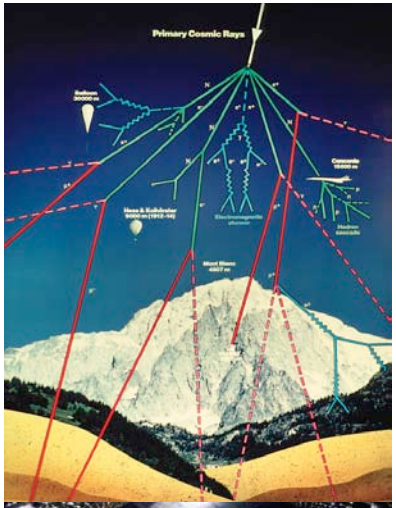
MiniBooNE Results

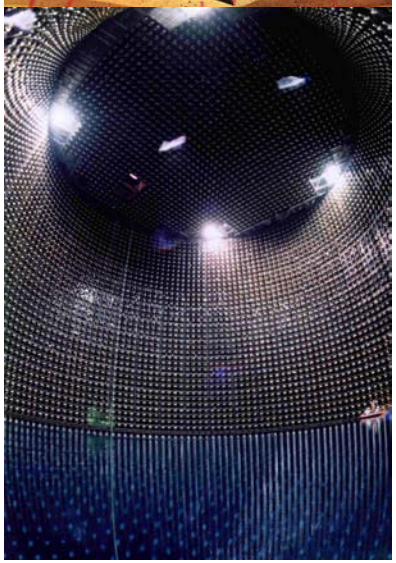




No signal is observed in the LSND L/E region

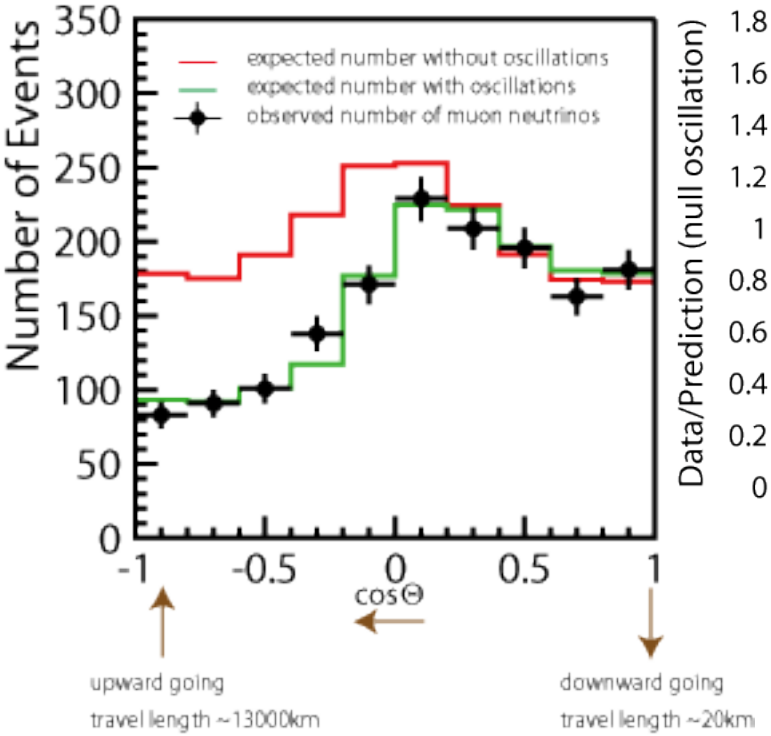
1998 : Super-K atmospheric neutrinos

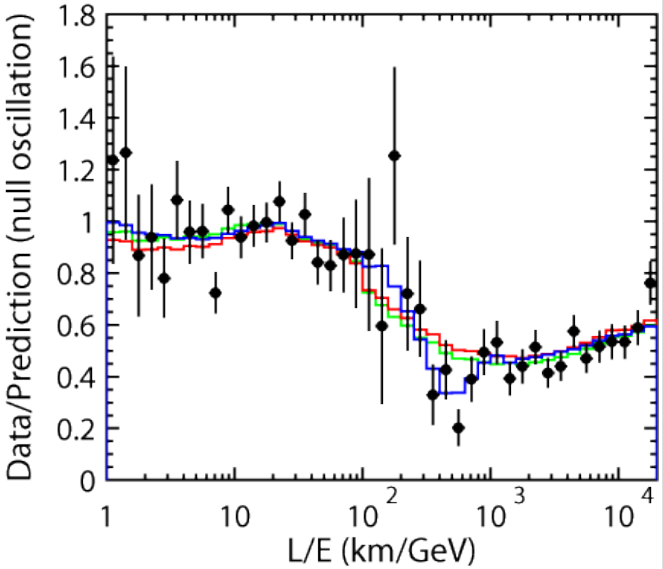




Disappearance of atmospheric ν_μ

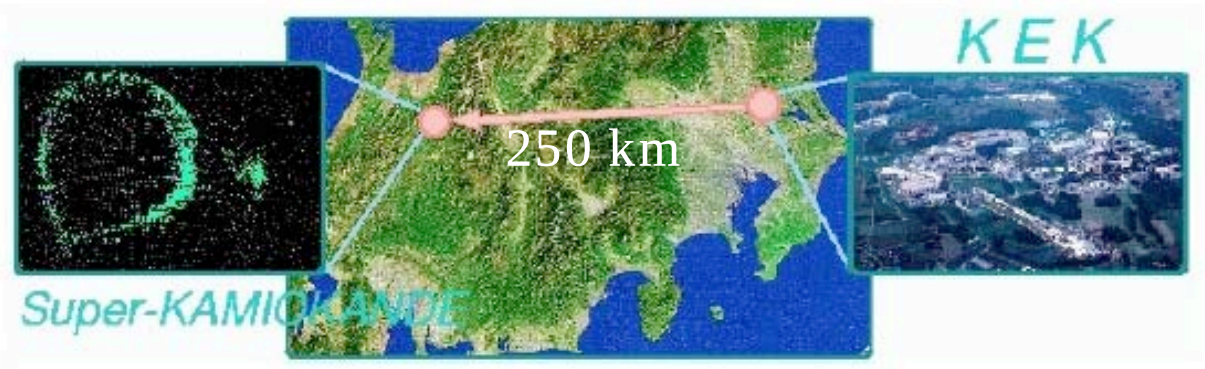
2004



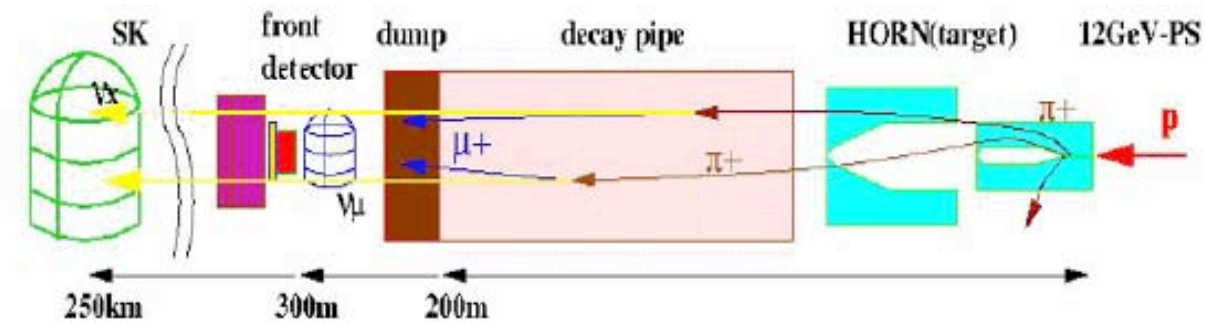


1st accelerator long-baseline experiment

The K2K Experiment



Goal: confirmation of atmospheric oscillations by measuring muon neutrino disappearance in a long-baseline accelerator-based experiment



K2K Disappearance Result

Sensitivity to oscillations: from rate suppression and spectrum distortion informations

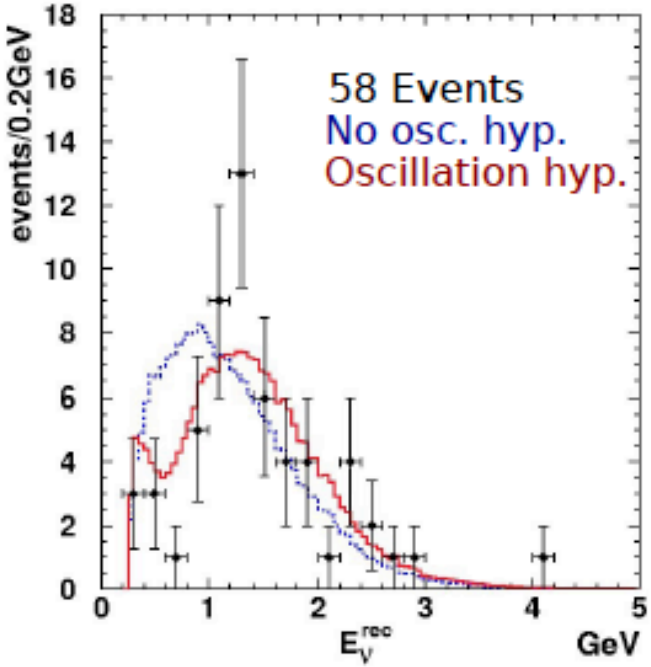
- Two different samples used:

Rate:

- Use all beam-induced events fully contained at SK
- Measure **112**, predict **158.1 + 9.2 – 8.6** for no osc.
- Dominant errors:
  - Statistical
  - 1KT+SK fiducial volume (5% norm. error)
  - Near-to-far flux extrapolation (reduced to 3% by HARP)

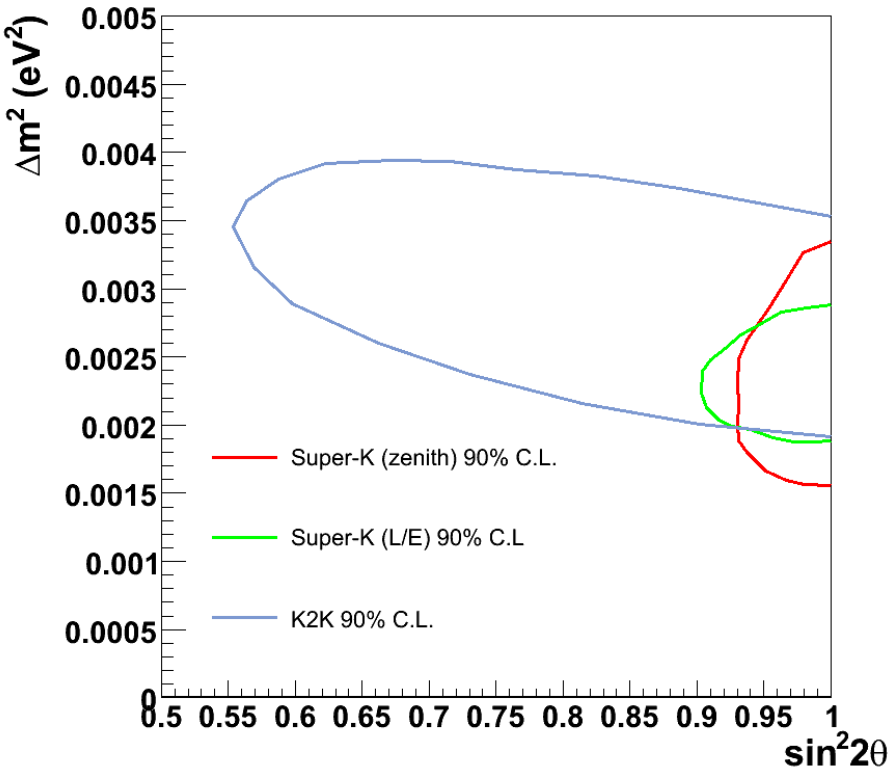
Spectrum:

- Use only CCQE candidate events ("1 ring events"), for better neutrino energy reconstruction
- Dominant errors:
  - Statistical
  - SK energy scale (2% uncertainty)

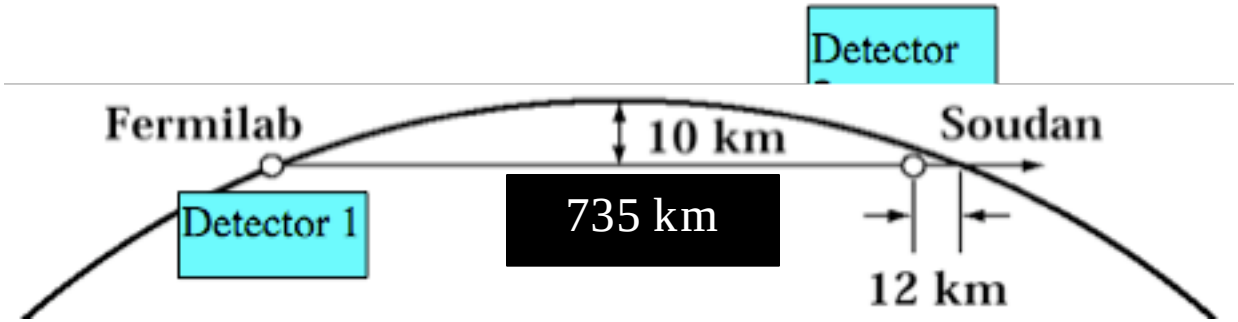


Super-K, K2K contours

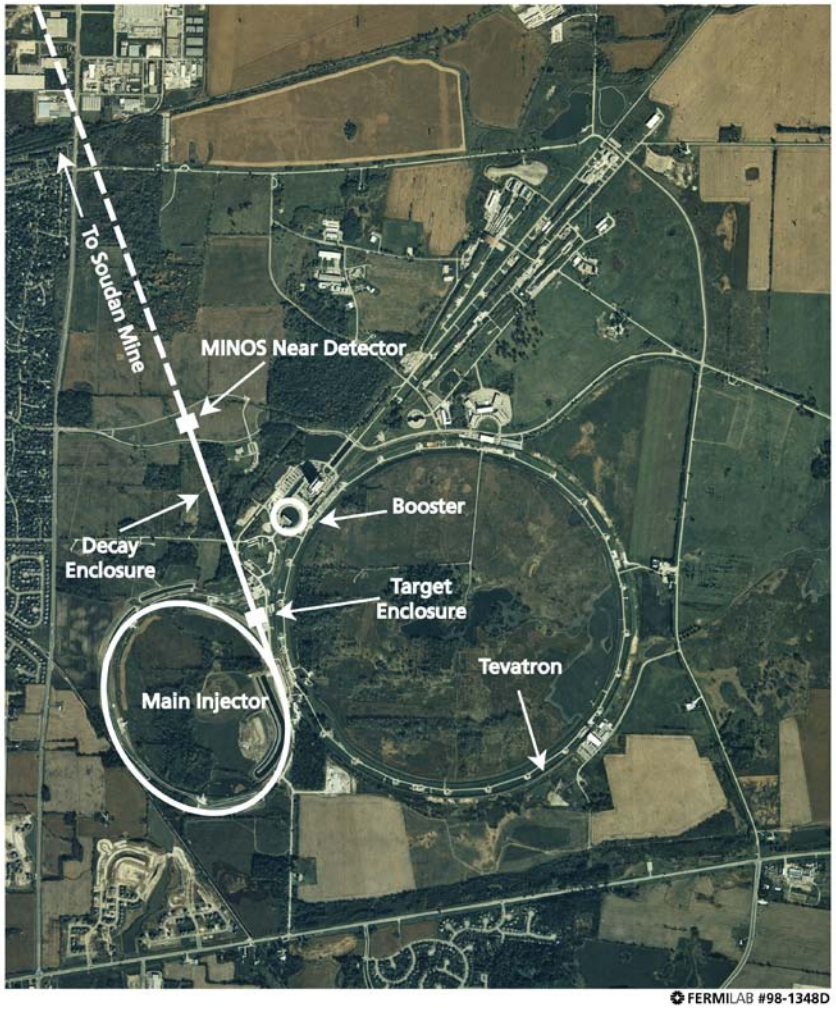
Allowed regions from Super-K and K2K

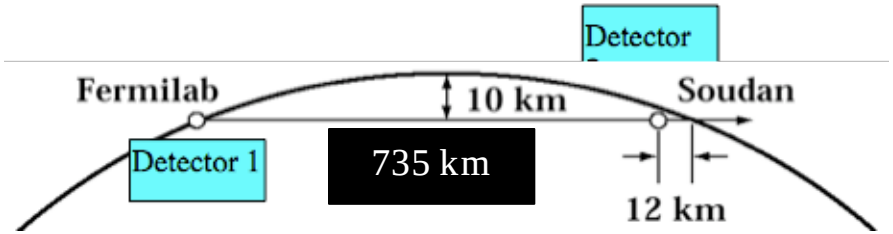


Main Injector Neutrino Oscillation Search : MINOS

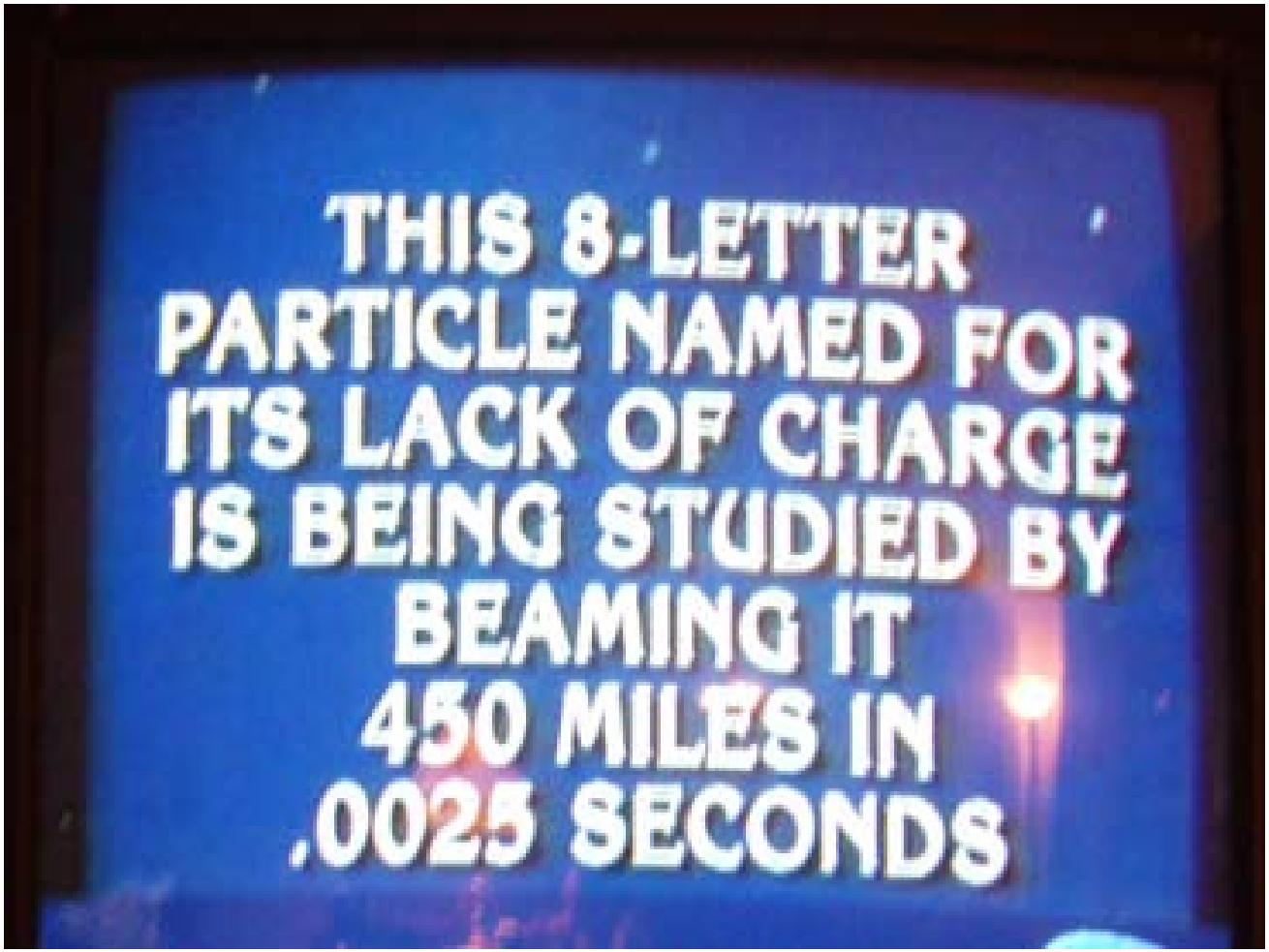


Neutrinos from the Main Injector





What is a *neutrino*?

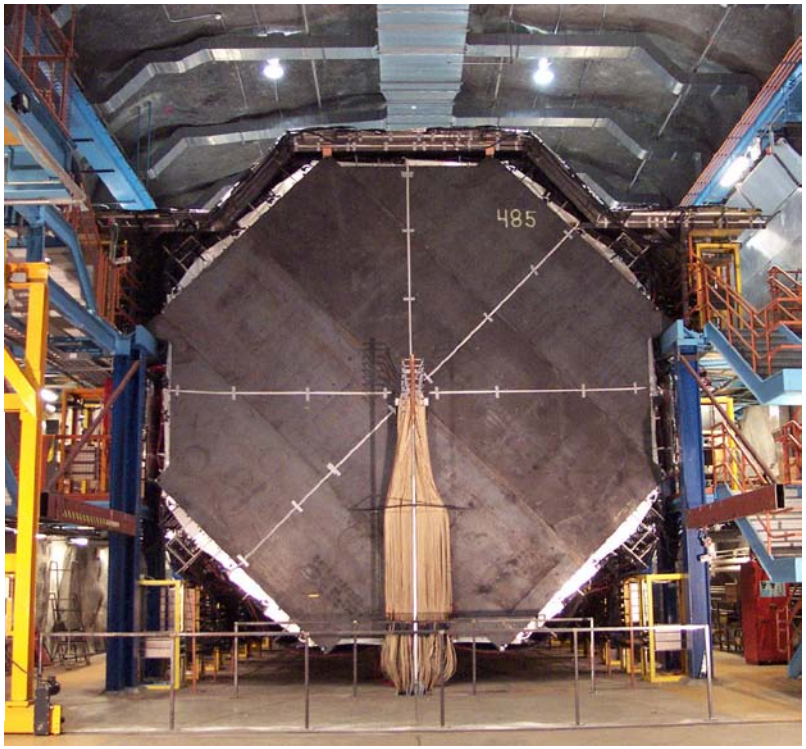


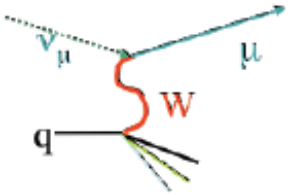
MINOS Detectors

1 kiloton Near Detector

Steel/solid scintillator, magnetized tracking calorimeters

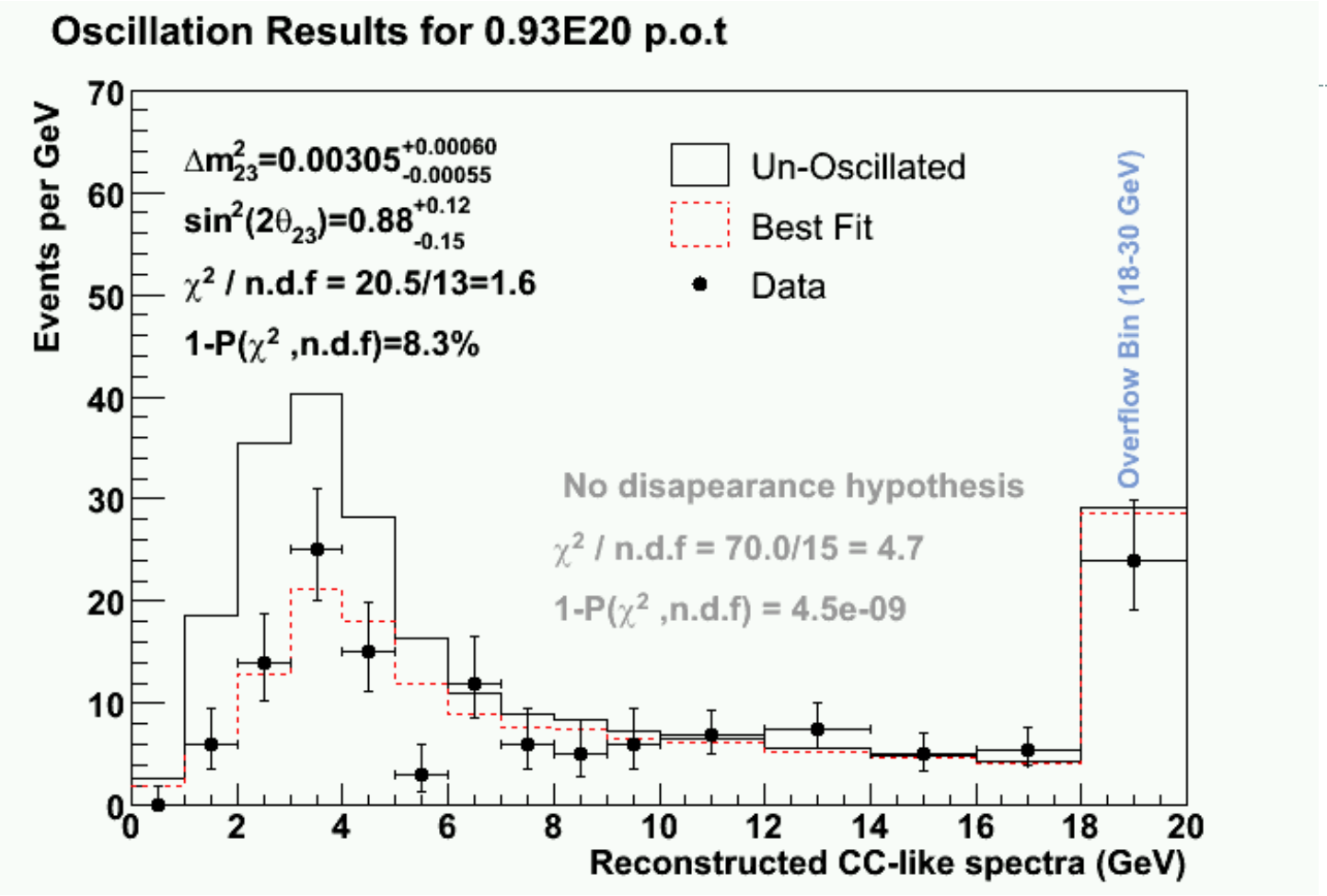
5.3 kiloton Far Detector





$\nu_\mu + N \rightarrow \mu^- + X$

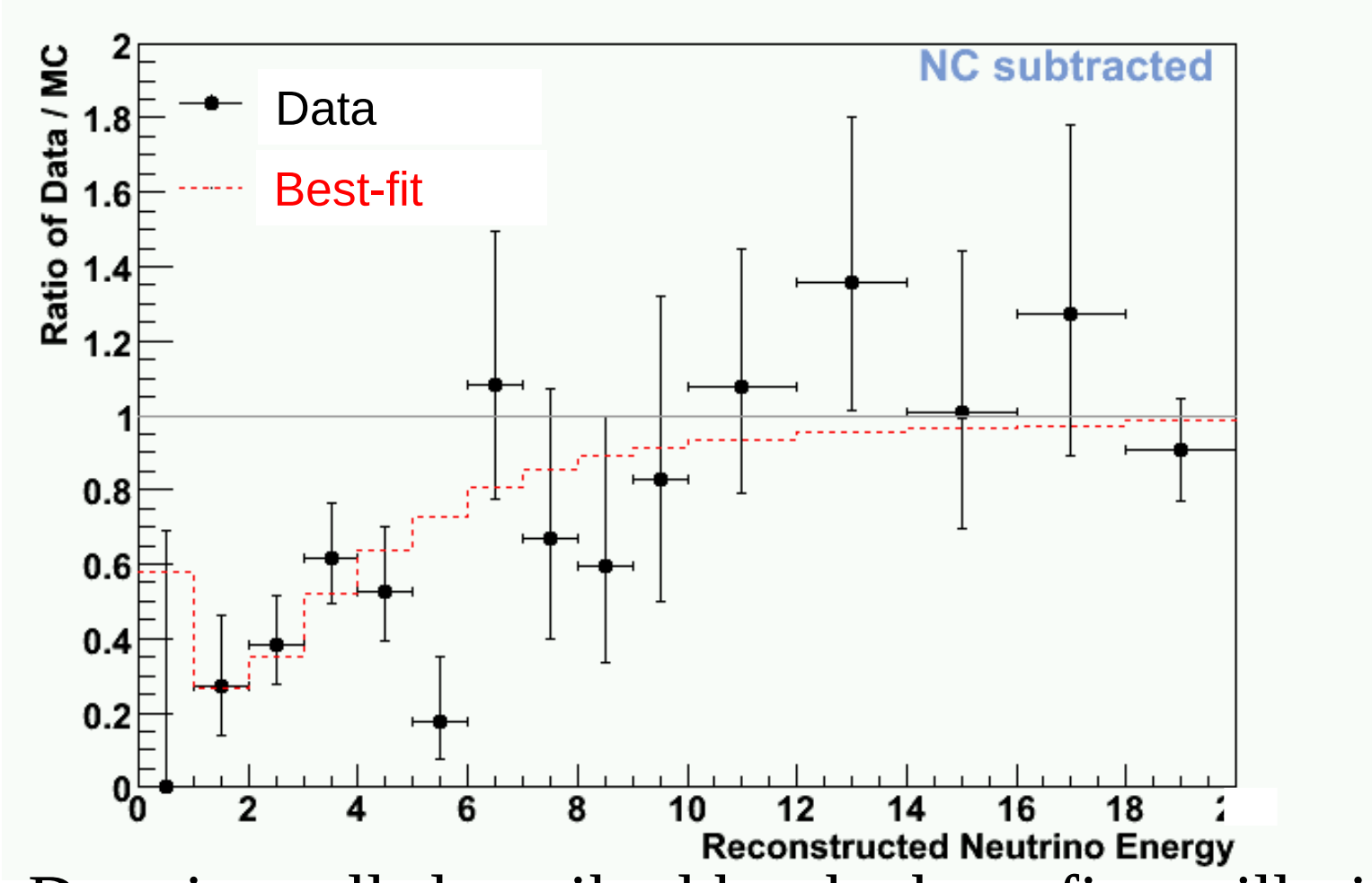
First Results - 2006



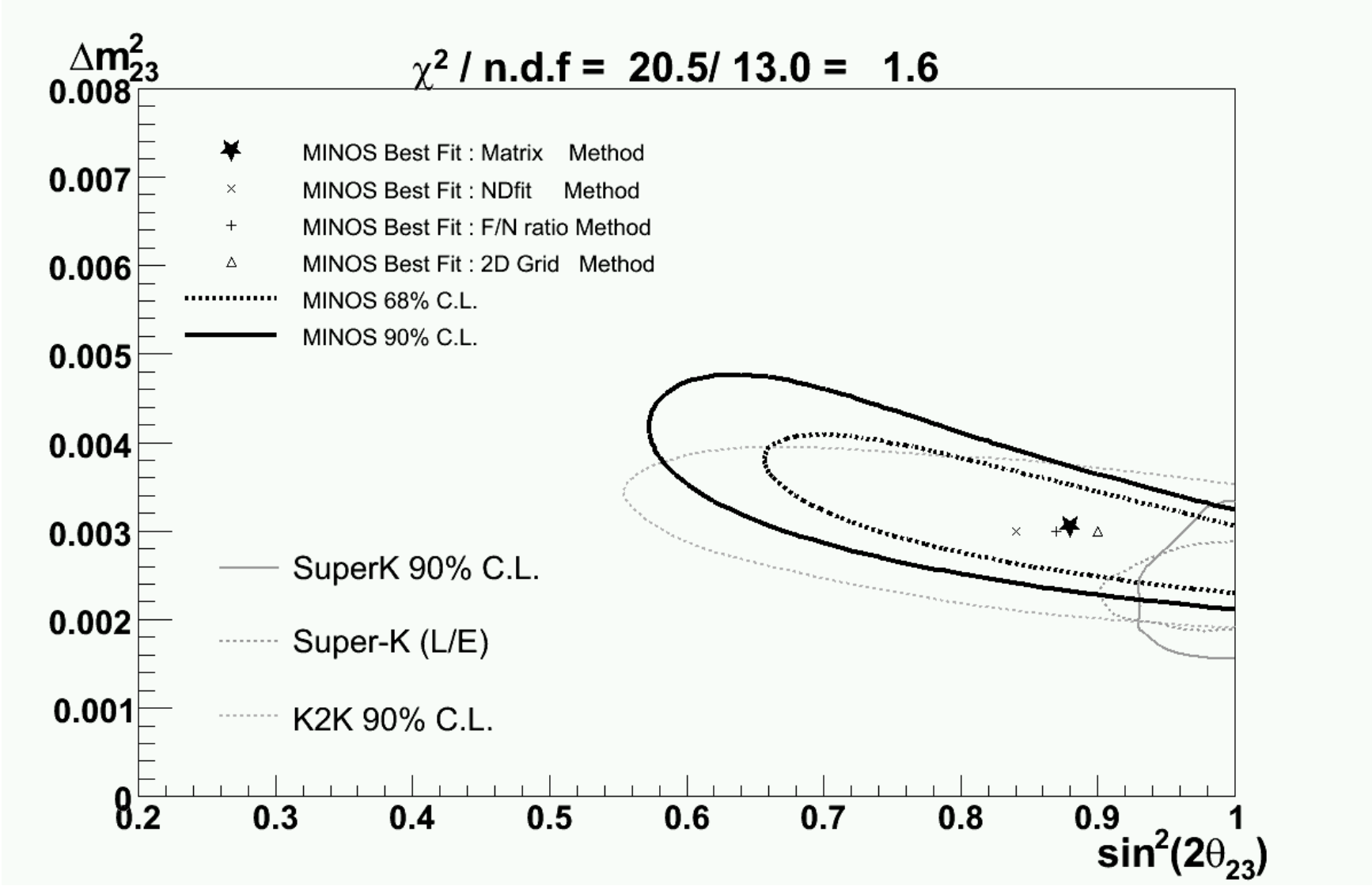
$$\chi^2(\Delta m^2, \sin^2 2\theta) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i / e_i)$$

- Measurement errors are 1 sigma, 1 d.o.f.

Ratio of Data/MC



- Data is well-described by the best-fit oscillation hypothesis


χ^2 / n.d.f = 20.5/ 13.0 = 1.6
Δm^2_{23}
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2(2\theta_{23})$
MINOS Best Fit : Matrix Method
MINOS Best Fit : NDfit Method
MINOS Best Fit : F/N ratio Method
MINOS Best Fit : 2D Grid Method
MINOS 68% C.L.
MINOS 90% C.L.
SuperK 90% C.L.
Super-K (L/E)
K2K 90% C.L.

Neutrino 2010

CC Neutrino Results

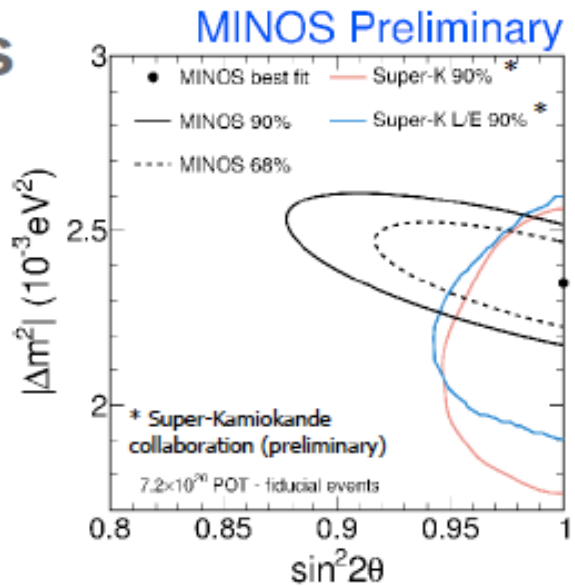
$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

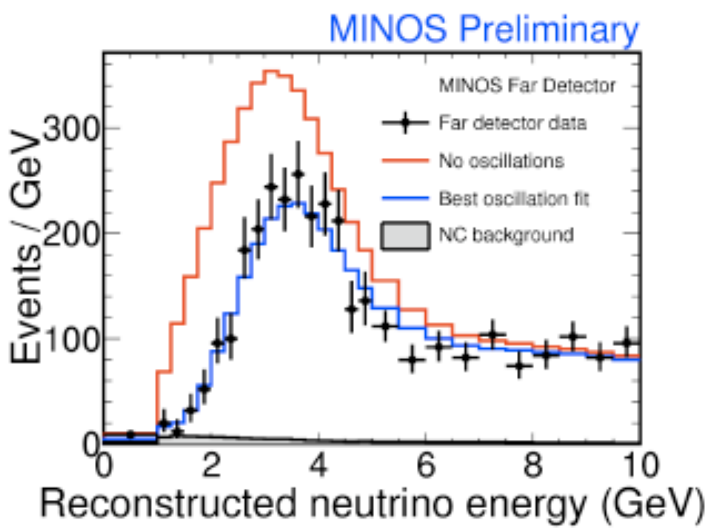
$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

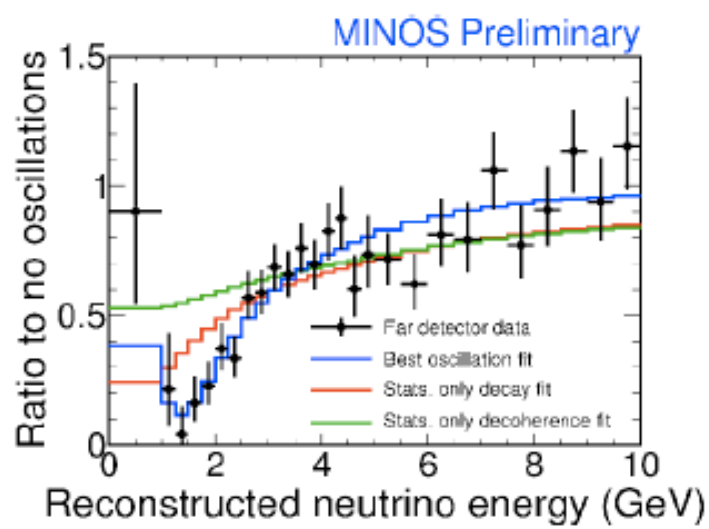
No oscillations: predict 2451 events
Observe 1986 events

Pure decoherence disfavoured at > 8σ
Pure decay disfavoured at >6σ

- **7.8σ if NC events included**







$\nu_\mu \rightarrow \nu_\tau$?

Tau Neutrinos Favored over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations

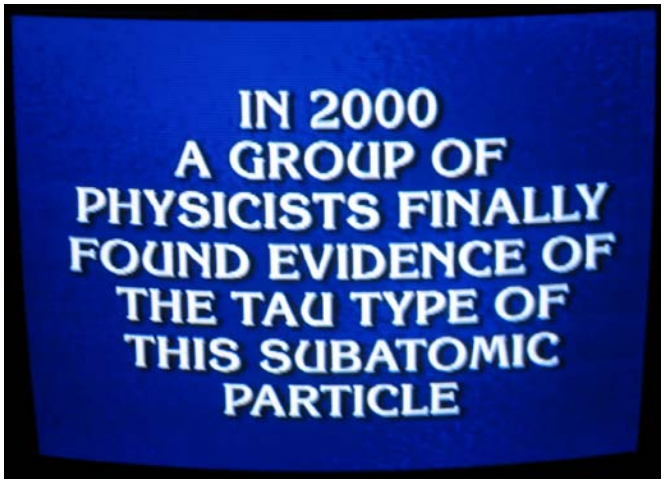
Revision of October 26, 2000

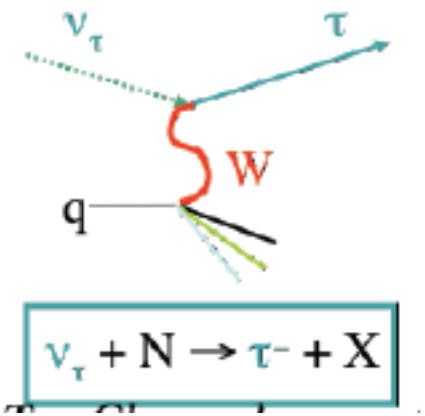
ABSTRACT

The previously published atmospheric neutrino data did not distinguish whether muon neutrinos were oscillating into tau neutrinos or sterile neutrinos, as both hypotheses fit the data. Using data recorded in 1100 live-days of the Super-Kamiokande detector, we use three complementary data samples to study the difference in zenith angle distribution due to neutral currents and matter effects. We find no evidence favoring sterile neutrinos, and reject the hypothesis at the 99% confidence level. On the other hand, we find that oscillation between muon and tau neutrinos suffices to explain all the results in hand.

Phys. Rev. Lett. 85(2000) 3999-4003

DONUT



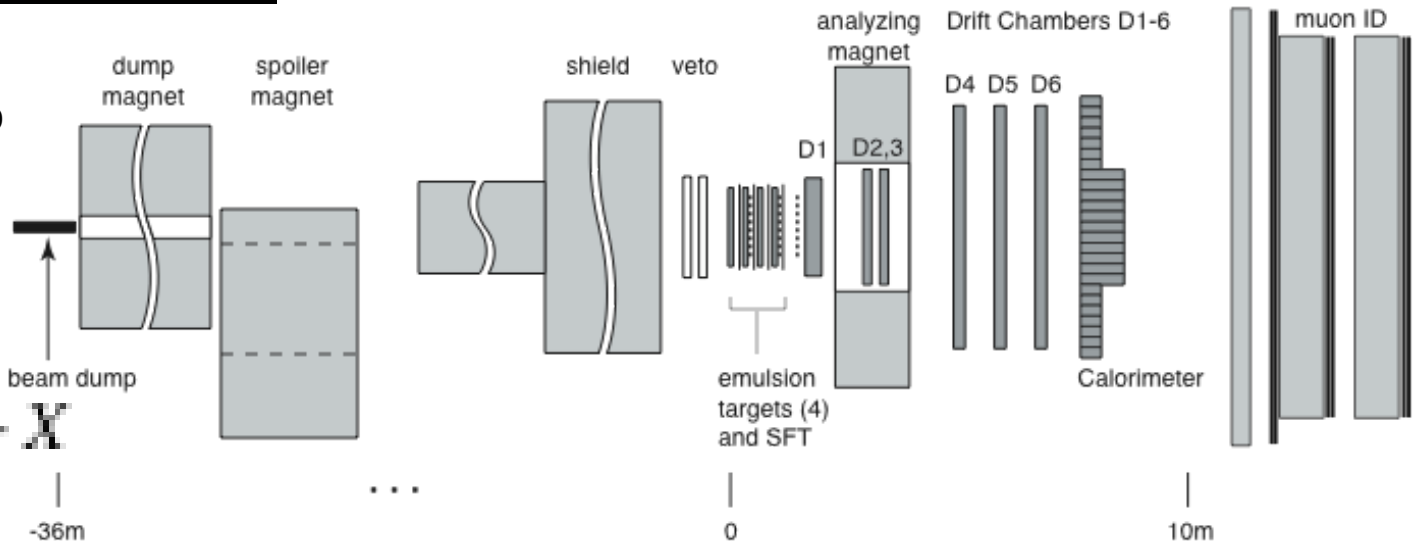


Prompt Neutrino Beam

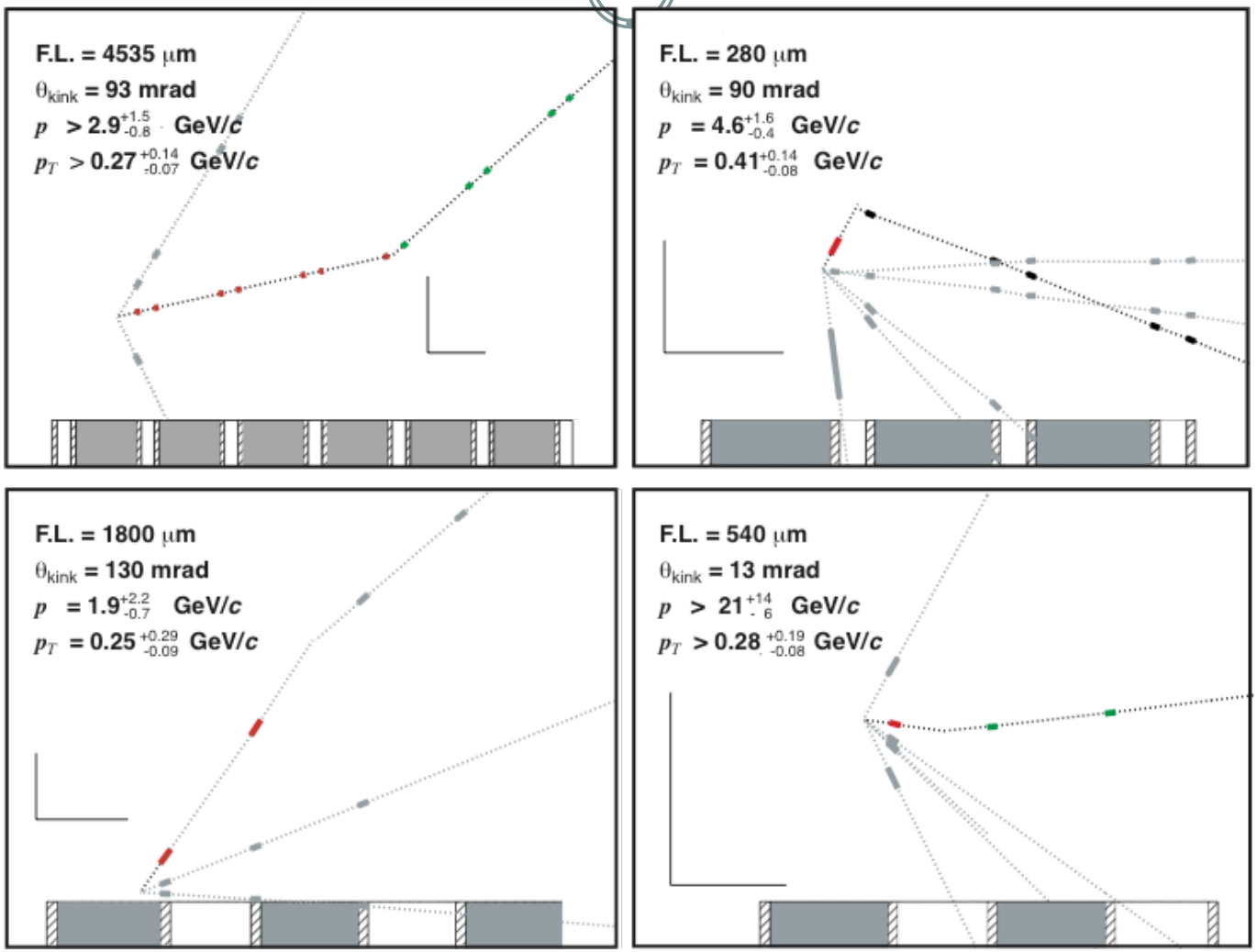
$$D_s \rightarrow \tau + \nu_\tau$$

$$\downarrow$$

$$\tau \rightarrow \nu_\tau + X$$

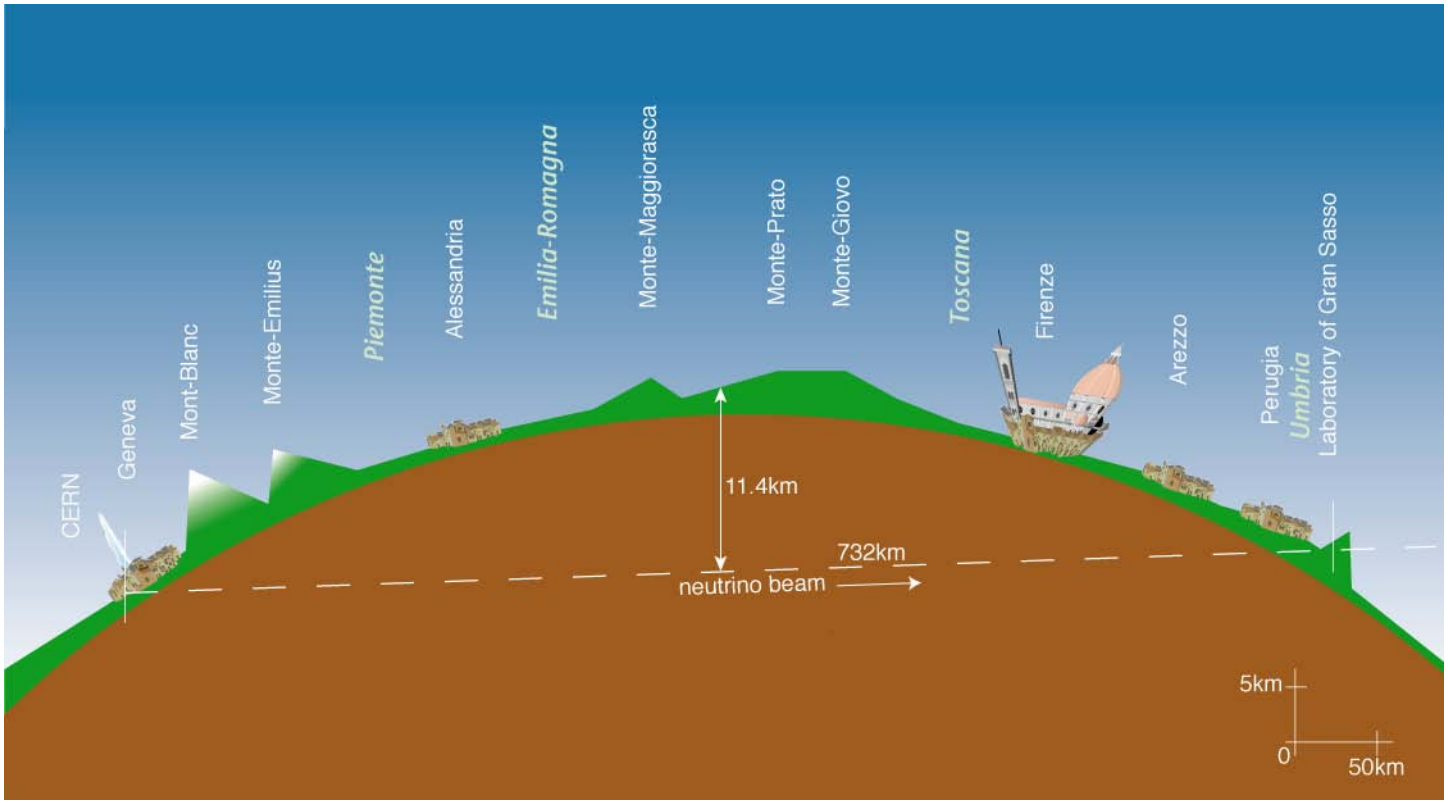


1st ν_τ events



CNGS

CERN to Gran Sasso Long Baseline Neutrinos



CNGS - OPERA

10th Int. Conf. on Topics in Astroparticle and Underground Physics (TAUP2007) IOP Publishing
Journal of Physics: Conference Series **120** (2008) 052042 doi:10.1088/1742-6596/120/5/052042

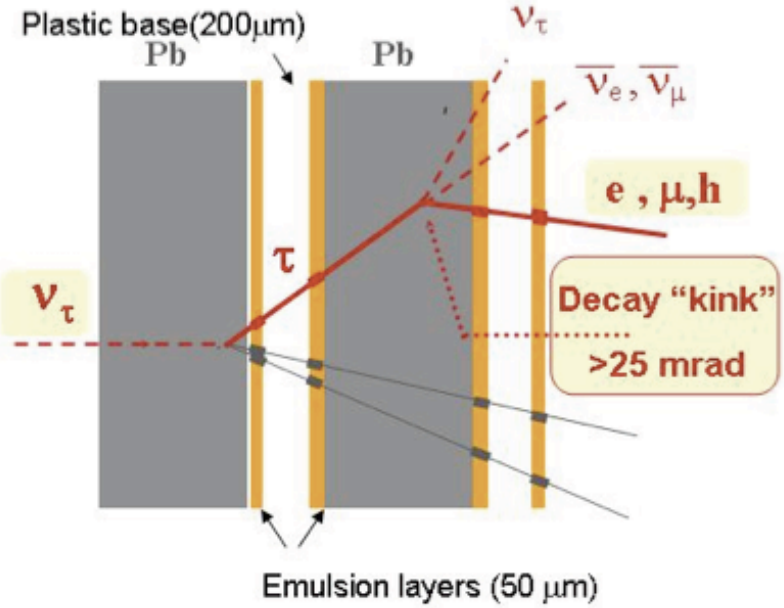


Figure 1: ν_τ and τ detection principle used by OPERA.

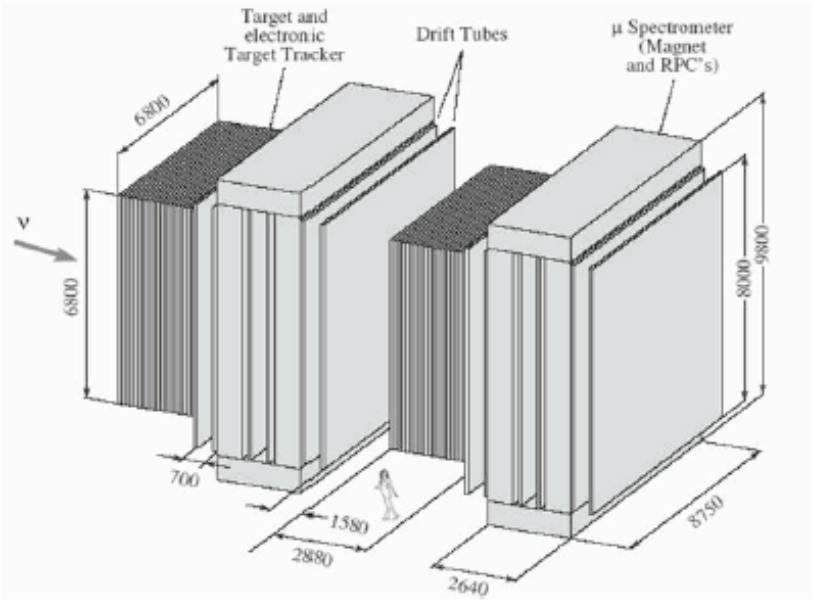
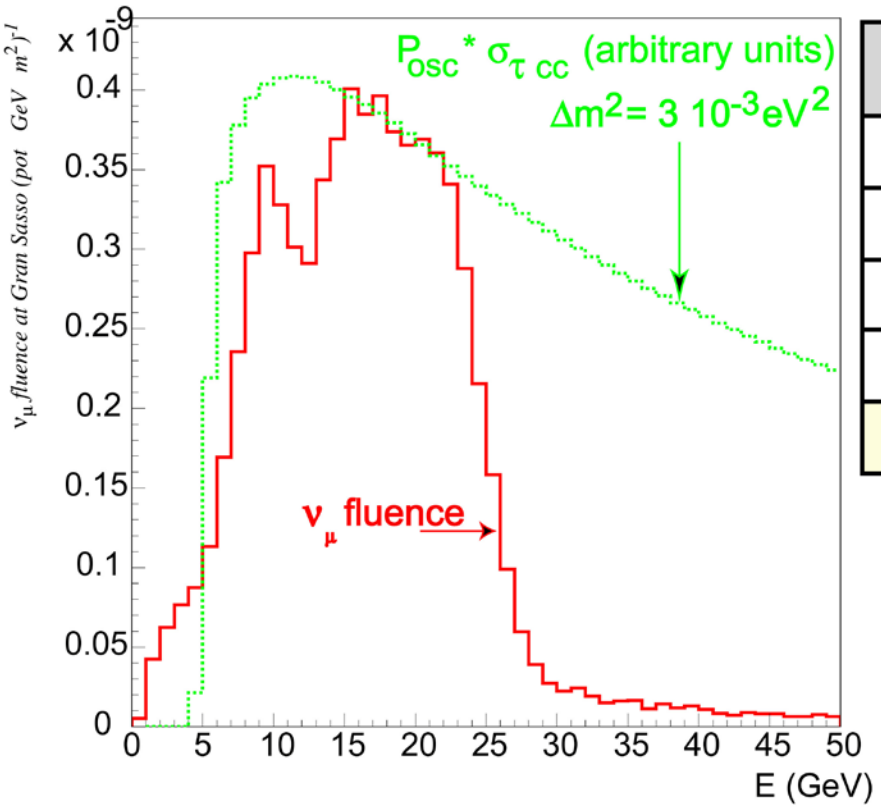


Figure 2: Schematic view of the OPERA detector.

$\nu_\mu \rightarrow \nu_\tau$ appearance



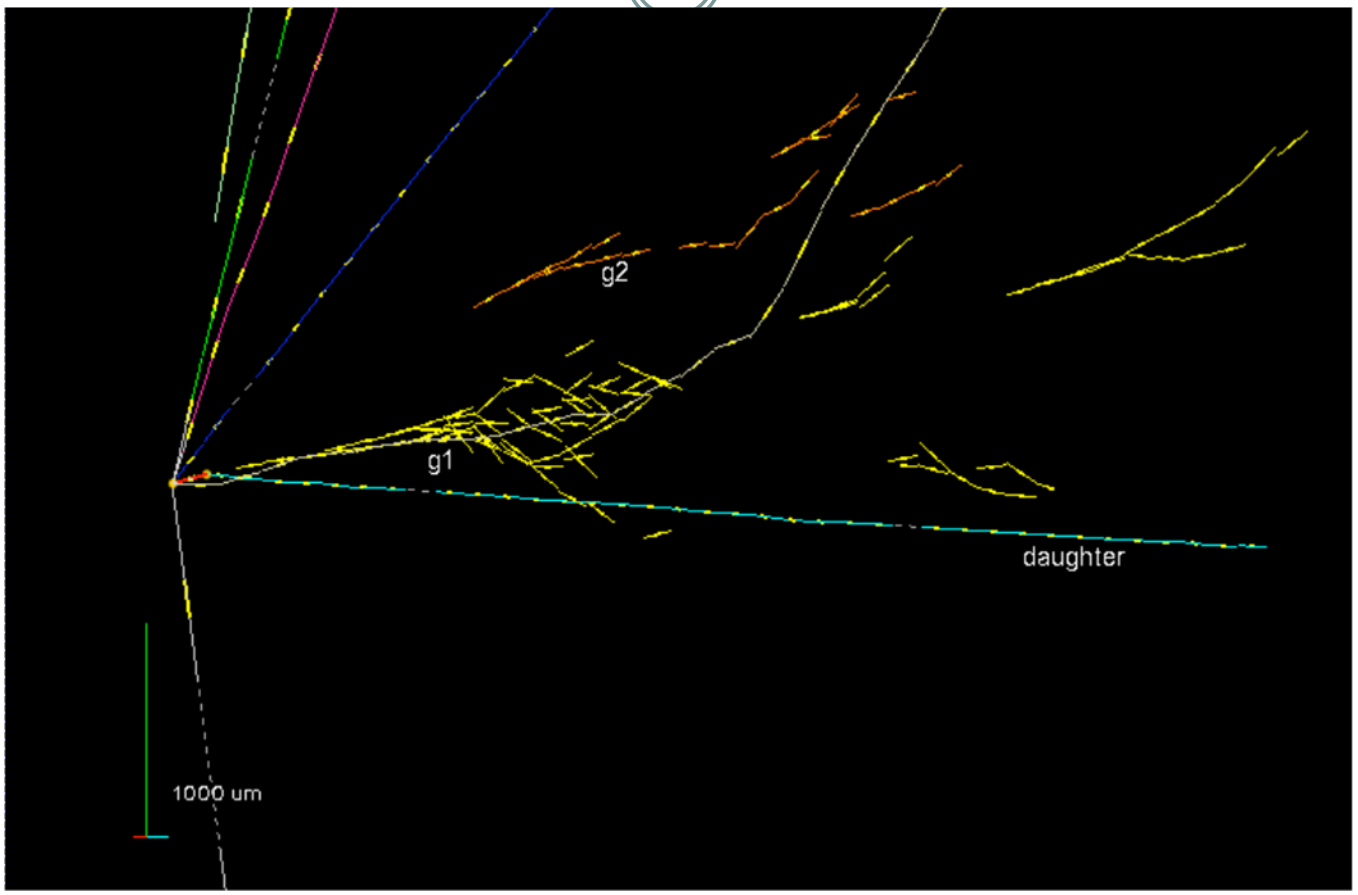
Decay channel	Detection efficiency(%)	Branching ratio(%)	Signal (Δm^2=2.5x10^{-3})	Background
$\tau \rightarrow \mu$	17.5	17.7	2.9	0.17
$\tau \rightarrow e$	20.8	17.8	3.5	0.17
$\tau \rightarrow h$	5.8	49.5	3.1	0.24
$\tau \rightarrow 3h$	6.3	15	0.9	0.17
ALL	effxBR=10.6%		**10.4**	**0.75**

5 year exposure @4.5x10^{19} POT/year

Difficult experiment, and can only expect a handful of events…

OPERA ν_τ candidate

May 2010



$$\nu_\tau + N \rightarrow h^-(n\pi^0)\nu_\tau$$

Summary

- It has long been hypothesized that neutrinos may oscillate and hence have mass, see :
  - Pontecorvo, 1961
  - Kayser, 1982
- Terrestrial based searches (accelerators and reactors) with L/E configurations sensitive to detecting Δm^2>0.01 all had null results
- Data from solar and atmospheric neutrinos fit to two neutrino oscillation hypothesis is consistent with two different values of , one small ( ) and the other very small( ) Δm^2_{23} Δm^2_{12}
- Long baseline accelerator experiments have confirmed and continue to explore the the mass-mixing parameters at the mass scale Δm^2_{23}

Lecture 2 Outline

- Three neutrinos, θ_{13} *and* δ_{CP}
  - Oscillation probability
  - Matter effects
  - Neutrino mass hierarchy
- Experimental Techniques :
  - Signals, backgrounds and ambiguities
  - Experiment baseline
  - Neutrino beam configurations
- Experimental Landscape
  - *Reactor Experiments :* $\bar{\nu}_e$ *disappearance* (Ed Blucher lecture)
  - ν_e appearance : T2K, NOvA, LBNE

Lecture 2 Outline cont.

- Experiment Prospects
  - Understanding Sensitivity Calculations
  - Experiment Timelines
- Nu results to keep an eye on
- Beyond Superbeams?
- Conclusions