The Current Excitement in Neutrino Physics

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Lectures Presented to CTEQ 2007

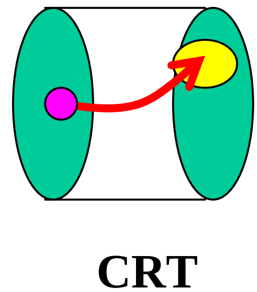
Part 1

Objectives of these Lectures

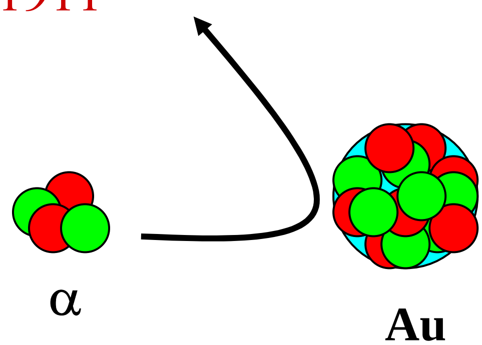
- Neutrinos in historical context
- Modern phenomenology of neutrinos
- The pioneers – solar and atmospheric
- Terrestrial long-baseline, especially MINOS and NoVA
- Other special types of Experiments
- Speculation and future initiatives

In the Infancy of Particle Physics

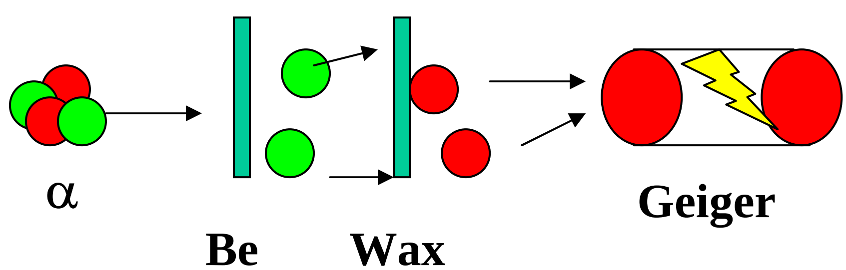
Electron - Direct Discovery 1897
J. J. Thomson



Nucleus - backscattering 1911
Rutherford

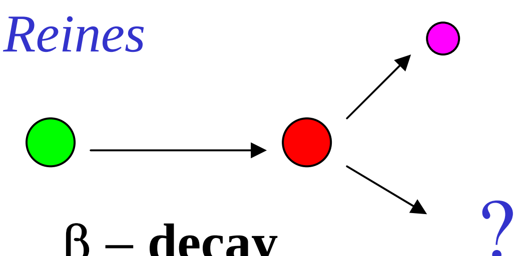


Neutron - programmatic experimentation 1932
Chadwick, Joliot-Curies



Neutrino - inferred solution to phenomenology crisis 1930
Pauli
Direct discovery only in 1956 - Reines

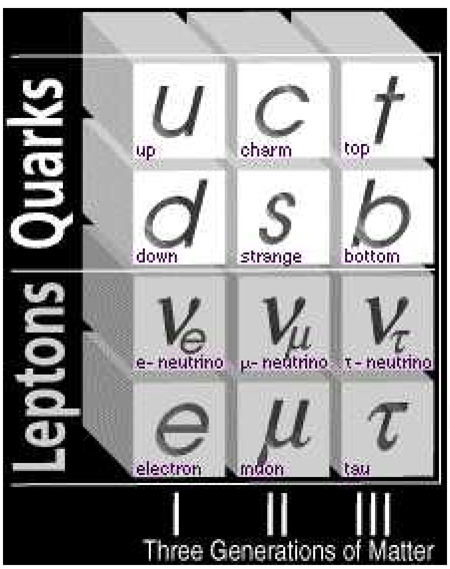
Indirect, lengthly



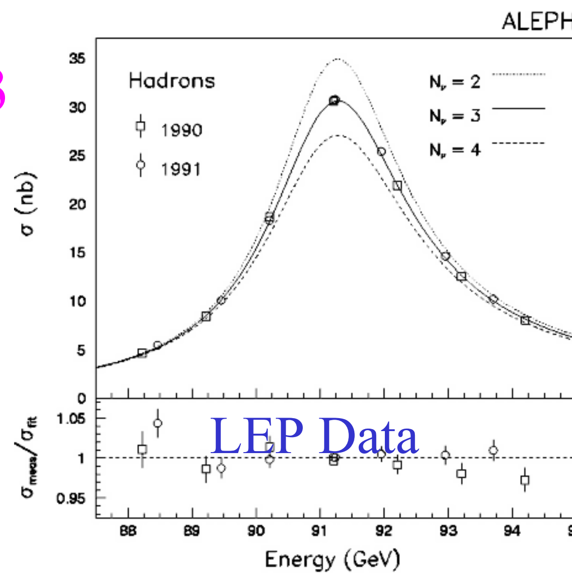
The Loneliness of the Neutrino

Other particles in the Standard Model of particle physics either have mass or have a symmetry that keeps them massless.

Photon is the main example



N.B Only 3 neutrinos allowed



There is no such known symmetry for the neutrinos.

In fact, since they are neutral, there are 2 frameworks to acquire mass ("Dirac" and "Majorana")

- Majorana particles are their own antiparticles.

Massless neutrinos were always odd, and are now excluded by experiments.

Neutrino participates only in weak interactions

Typical cross-sections:

Impressive mean free path ~ 10 A.U. of concrete!

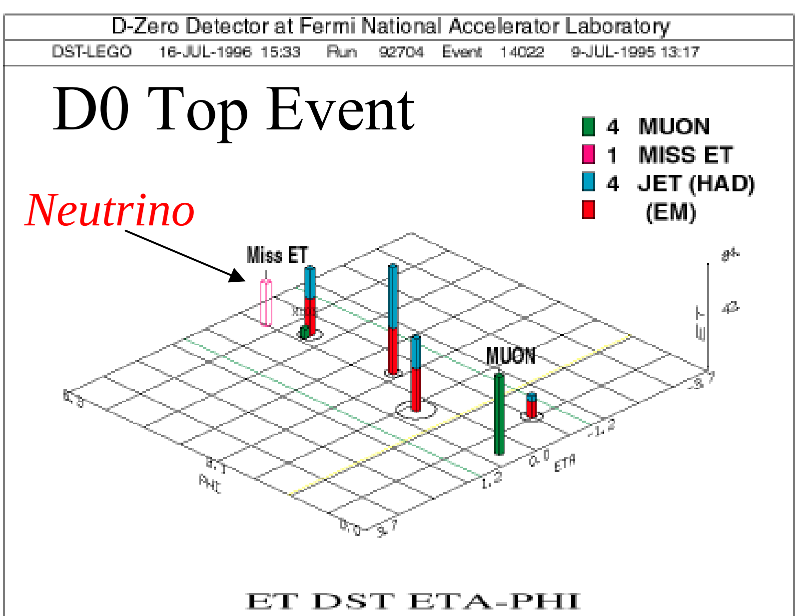
$\sigma_{pp} \sim 50\text{ mb} \sim 10^{-25}\text{ cm}^2$
$\sigma_{top} \sim 50\text{ pb} \sim 10^{-35}\text{ cm}^2$

$\sigma(\nu N;\ 1\text{ GeV}) \sim 10^{-38}\text{ cm}^2$

Certainly not unmeasurably small for accelerator, decay neutrinos.

Neutrino cross-sections usually decrease at least as fast ~ E_{ν}.

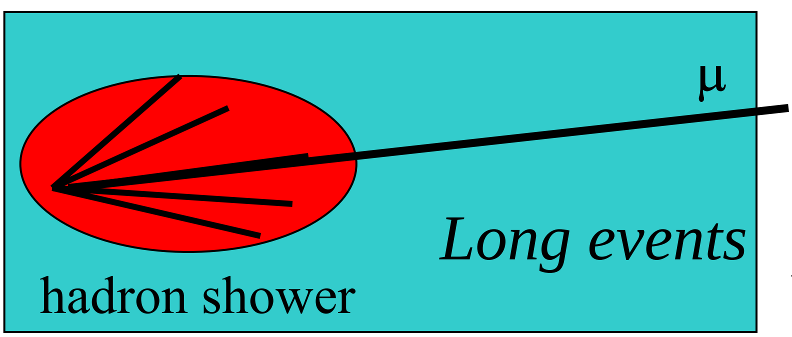
Many solar, cosmological relic neutrinos much more difficult.

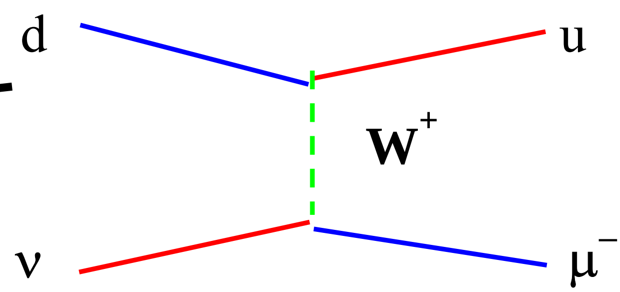


Still often detected simply by its absence!

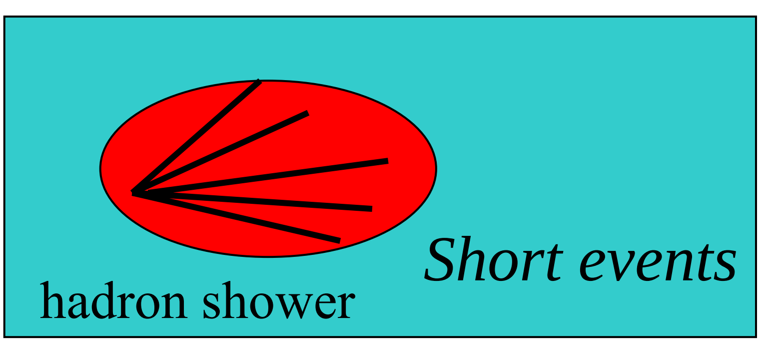
<u>*Basics of Neutrino Interactions*</u>

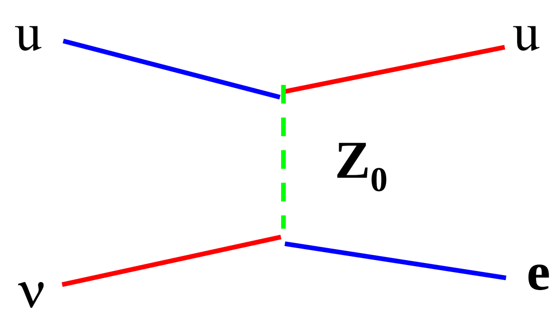
Charged current (CC)





Neutral current (NC)





Detector's-eye View

NC/CC constant for E_ν > 1GeV

Neutrino Oscillations I - Two Bases

Suppose neutrino mass is diagonal in a basis rotated w.r.t the "lepton number" states:

$$\nu_1 = \nu_e \cos\theta + \nu_\mu \sin\theta$$

(Ignore τ for now)

$$\nu_2 = -\nu_\mu \sin\theta + \nu_e \cos\theta$$

Similar rotation is well known in particle physics -- for example, neutral K's ...

$$K_S = \frac{1}{\sqrt{2}}(K_0 - \overline{K}_0)$$

$$K_L = \frac{1}{\sqrt{2}}(K_0 + \overline{K}_0)$$

Oscillations require at least one massive partner!

Complications of 3 families

$$|\nu_\ell\rangle = U|\nu_n\rangle, \quad \text{where}$$

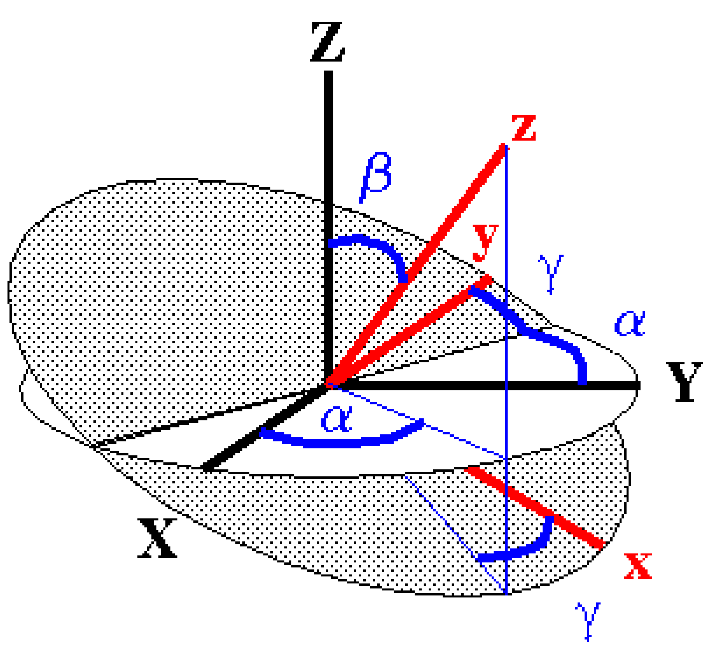
$$(c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

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

Atmospheric
$\nu_\mu \leftrightarrow \nu_\tau$

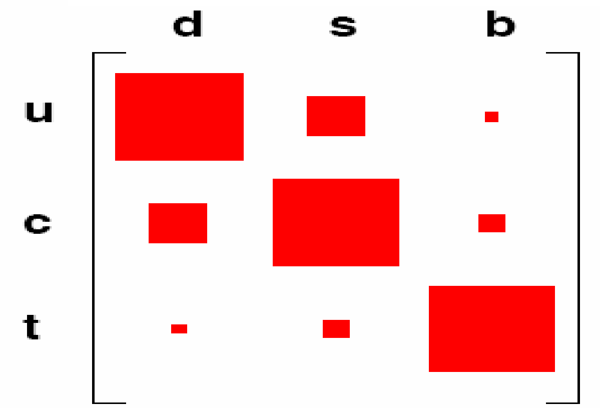
Atmospheric
$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

Solar



Mixing Matrix very different from standard model quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



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

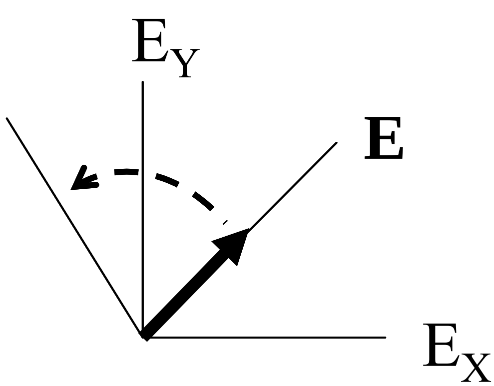
$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & >0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

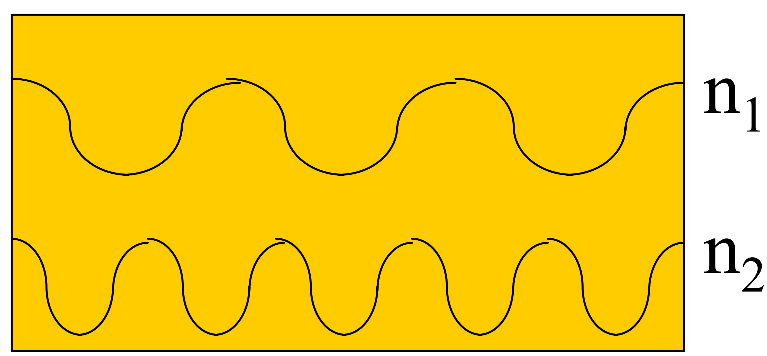
Neutrino Oscillations II - Optical Analogy

Birefringent crystal - different index of refraction (light speed) for different polarizations

Polarization rotates because of differential phase advance

$$R = \frac{e^{ik_1 x}}{e^{ik_2 x}}$$





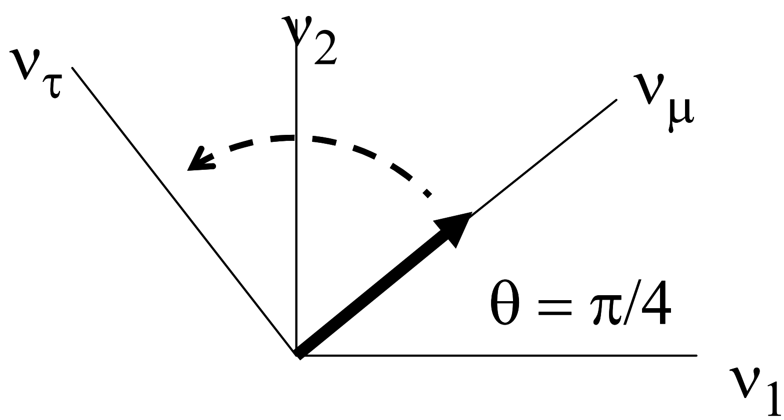
For neutrinos

$$k = \frac{\omega}{c} n = \frac{\omega}{c} \beta \qquad m\gamma = E_\nu$$

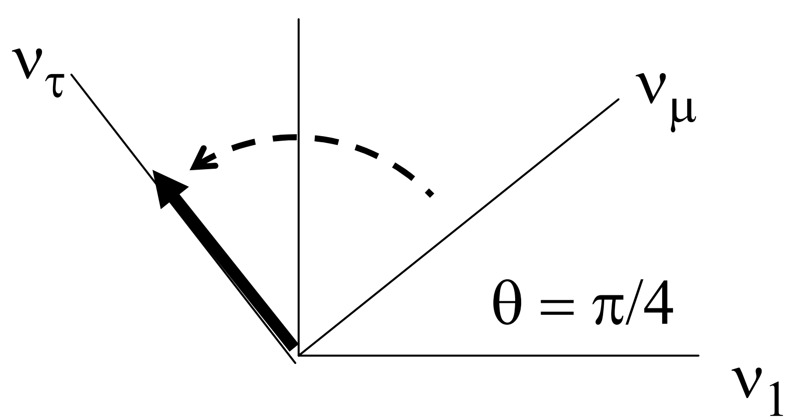
giving

$$R = e^{i\Delta k\, x} = e^{i \frac{m_1^2 - m_2^2}{2E} x}$$

Rotation of "Polarization" with Distance



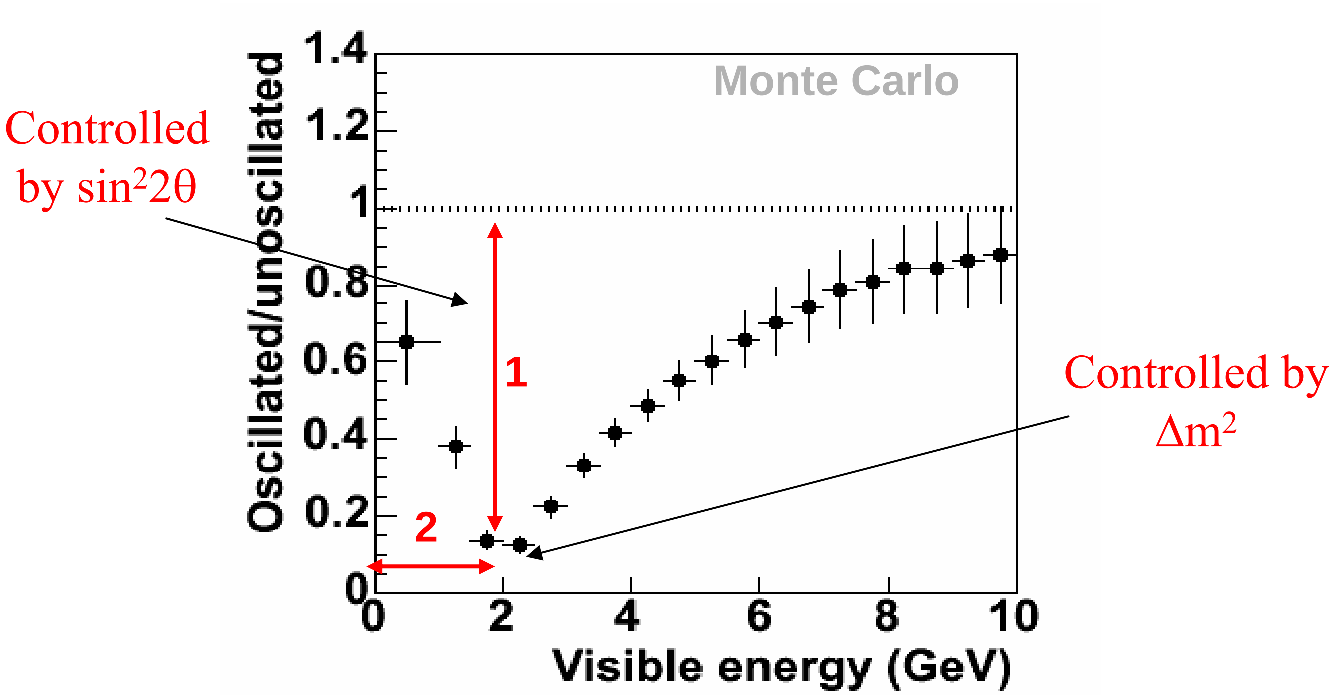
$$L = \frac{2\pi E}{\Delta m^2}$$

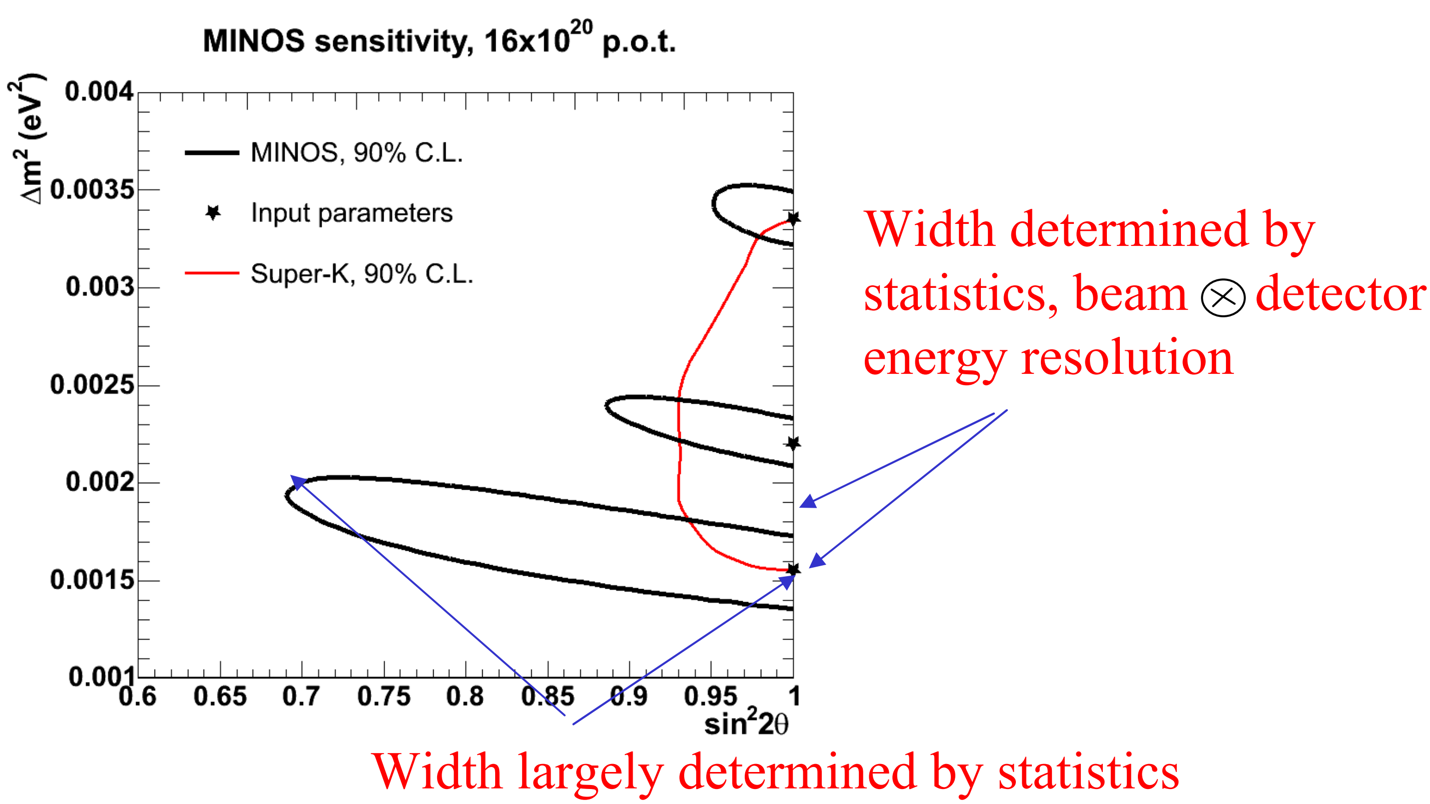


Amount of rotation determined by admixture in initial state, e.g mixing angle θ

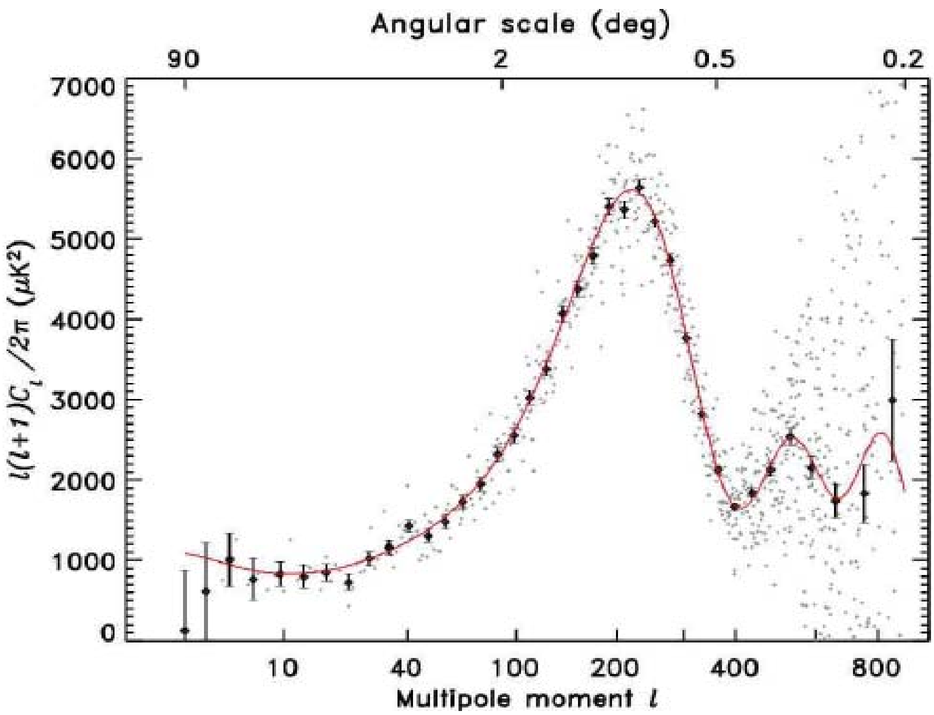
$$P(\nu_\mu^2) = 1 - \sin^2(2\theta)\sin^2(\frac{\Delta k\, x}{2})$$

How to Interpret Oscillation Results





Neutrino Masses and Cosmology



WMAP Data for angular correlations of CMB radiation as function of angle.

A large neutrino mass would cause modifications to the shape of galaxy correlation spectrum and its characteristic fluctuations

Analysis is done by combining WMAP with galaxy surveys, fit comparing to a simpler model

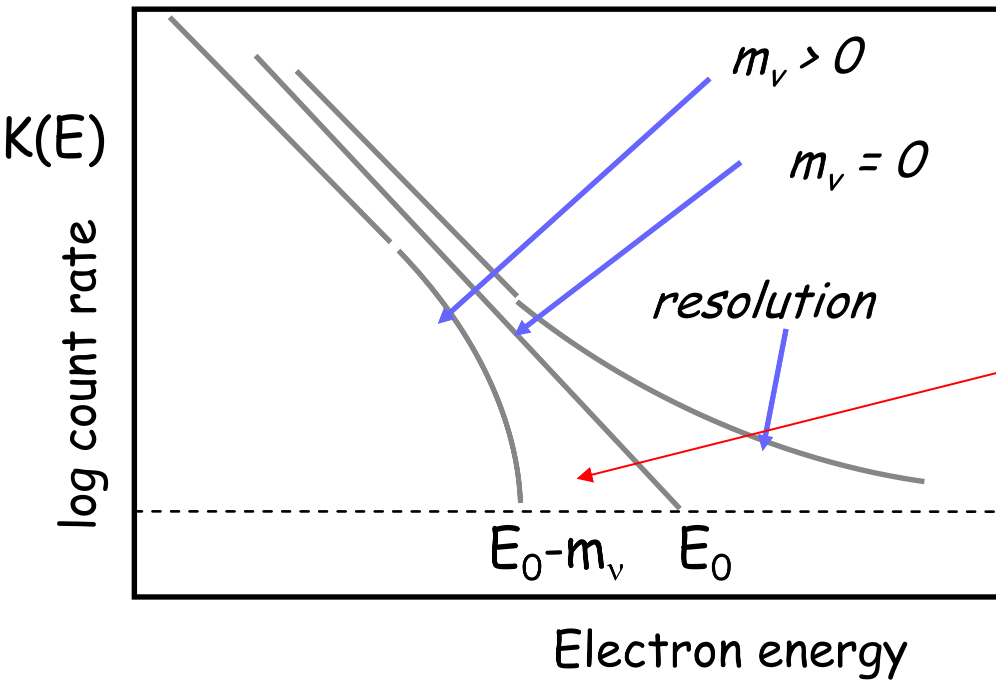
Result for 3 degenerate ν's:

$m_\nu < 0.23$ eV (95% C.L.)

Courtesy WMAP: astro-ph/0302209

Direct Mass Limits – Experimental Challenge

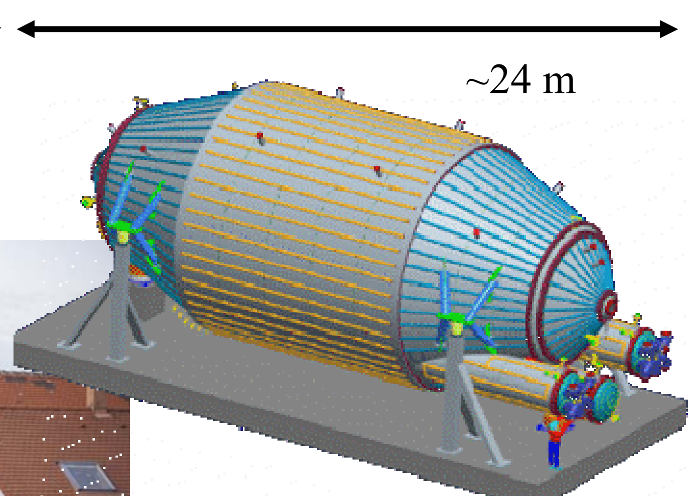
Tritium β-decay "Kurie" plot



2 x 10^{-13} decays in last eV

KATRIN experiment at Karlsruhe (2009)

Sensitivity (discovery) 0.35 eV



Main spectrometer tank

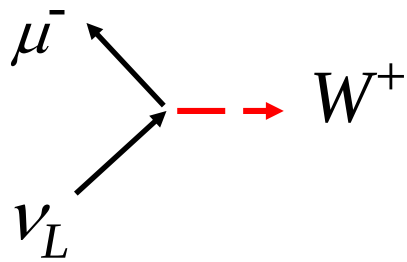
Uses 40 g of ^3H daily (recycled)

Chirality,helicity and pion decay

Fermions have chirality (handedness):

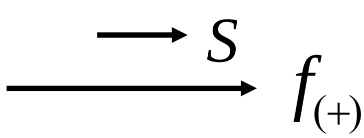
f_L (left) , f_R (right)

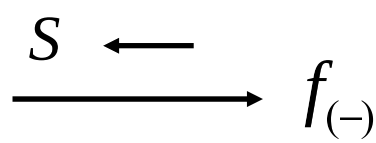
For neutrinos, only left-handed ν_L participate in standard model:



Helicity is spin projection along $\vec{P}$

For massless ν helicity = chirality





Mass – couples f_L and f_R

$$f_{(-)} = f_L + (m/E)\, f_R$$

Seen in π^+ decay at rest

$$\nu_{(-)} \cong \nu_L \longleftarrow \pi^+ \longrightarrow e^+_R \text{ has only } (m/E)\, e^+_{(-)}$$

"Helicity suppression" of $\dfrac{\pi^+ \to e^+\nu}{\pi^+ \to \mu^+\nu}$

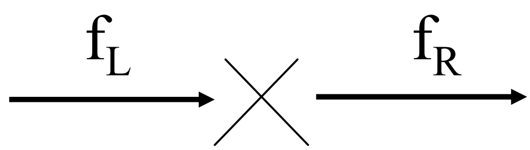
Neutral Particles can be their own antiparticles

Example $\pi^o = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ "Majorana"

Not its own antiparticle: $K^o = \bar{s}u$ $\bar{K}^o = s\bar{u}$

Associated: for fermions, two way to get mass

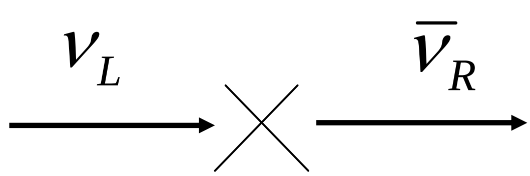
Dirac: $m_D \bar{f}_R f_L$



Linear superposition ~m/E for "wrong" sign

Majorana (only for neutral):

$m_M f_R f_L$

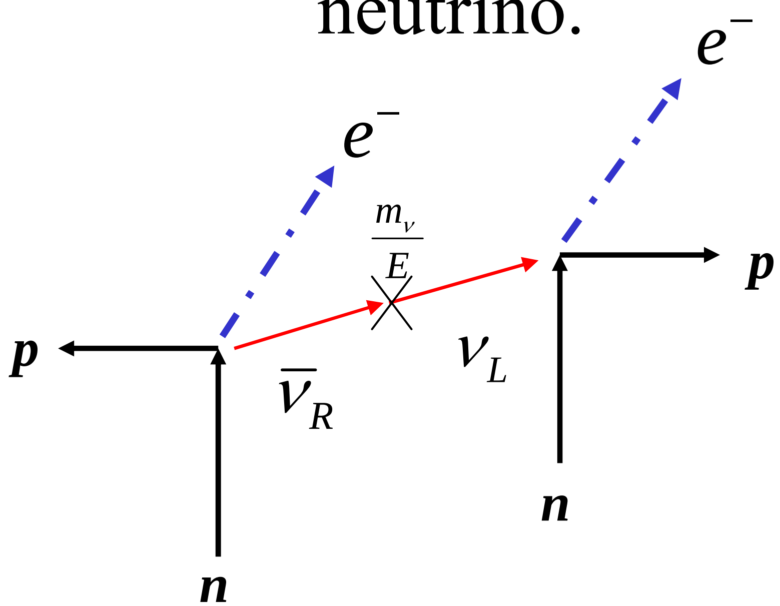


Note: Majorana mass conventionally and formally written as:

$$m_M \bar{f}_L^C f_L$$

This is rigorous from field theory point of view, but provides little physical insight.

Sidebar: Majorana Mass allows special Double beta-decay with no neutrino.



Reactions: $n \to p + e^- + \bar{\nu}_R$

$$\nu_L + n \to p + e^-$$

Positive-helicity has ***O(m/E)*** left-chirality component

Required for second interaction, suppresses rate

Add in U's ; get: $A \sim \left| \sum_i m_i U_{ei}^2 \right|$

Implcations for experiments from:

a) Mass Hierarchy

b) Absolute value of lowest mass

Majorana Mass and the See-Saw

Why is m_ν so small, e.g. compared to m_u or m_d?

Assume both L and R neutrinos and summarize their mass matrix as

$$\widetilde{M} = \begin{pmatrix} \mu & m_D \\ m_D & M \end{pmatrix} \quad \text{operating on} \quad \begin{pmatrix} L \\ R \end{pmatrix}$$

R-L Dirac (m_D) R-R Majorana (M)

Eigenvalues if m = 0 are simple

$$\lambda \cong \frac{M \pm \left(M^2 - 4m_D^2\right)^{1/2}}{2}$$

$$m_{heavy} \cong M \qquad m_{light} \cong \frac{m_D^2}{M}$$

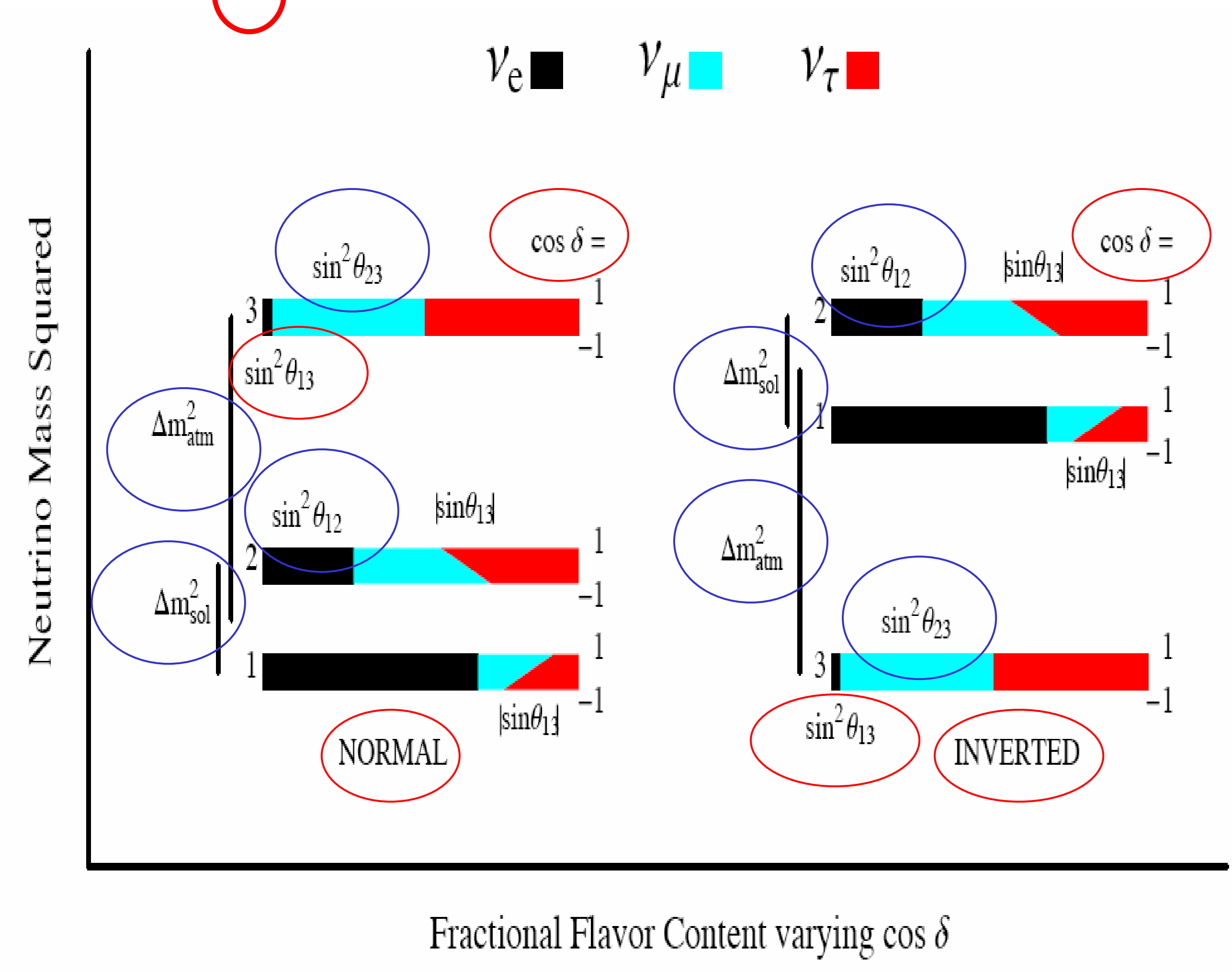
(GUT scale) (EW/GUT scale)

Heavy makes light (“See-Saw”)

Plausible in GUT context

Status of our Knowledge

- Know to some extent (green circle)
- Don't know (red circle)



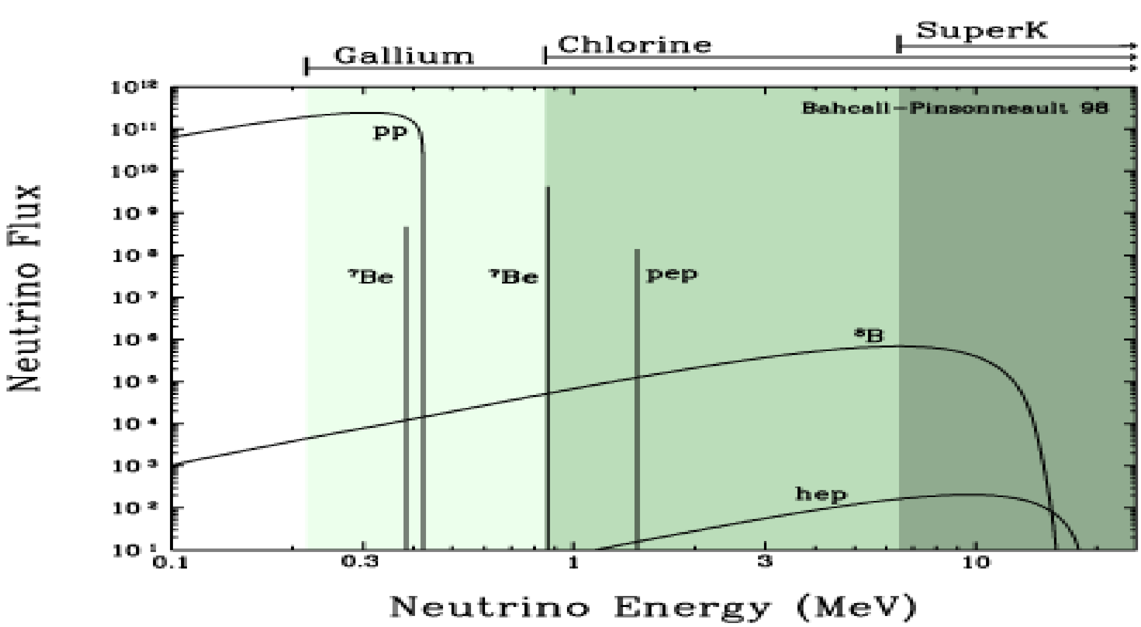
O. Mena and S. Parke, hep-ph/0312131

Hints of Oscillations #1 - Neutrinos from the Sun

Our sun is a plentiful source of
low energy electron neutrinos.

Principal reactions are

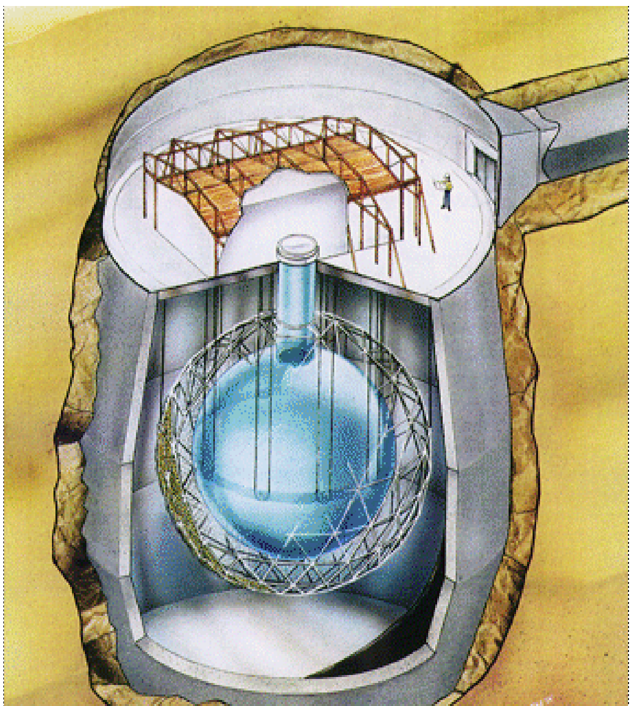
Reaction	E_{max}	*Rel. Flux (error)*	
$p + p \rightarrow d + e^{+} + \nu$	0.42 MeV	1.0	(1%)
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$	0.86 MeV	0.1	(10%)
$^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$	14.06 MeV	10^{-4}	(20%)



Fluxes are constrained with solar data
- Especially pp, using solar sound velocities

SNO and KamLand

SNO- Sudbury, Ont.

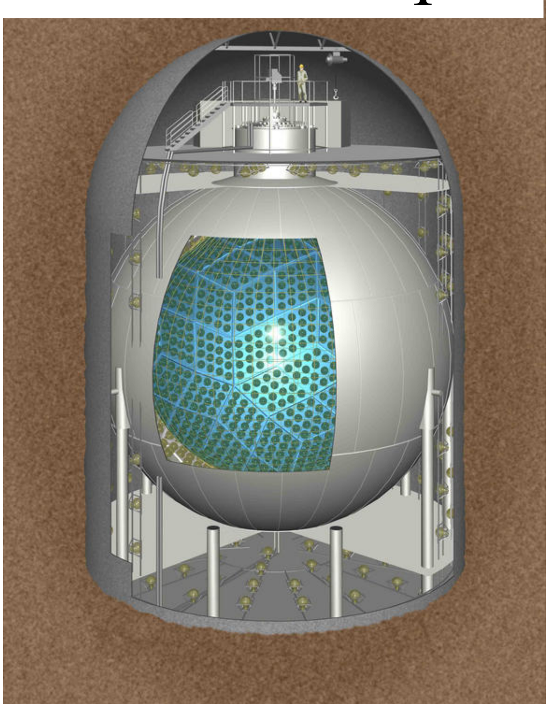


1 kton of D^{2}O
2100 m below surface
Charged (CC) and Neutral Current (NC

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

$$\nu_e + d \rightarrow n + p + \nu_e$$

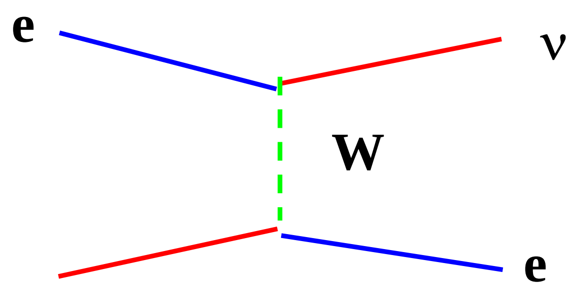
KamLand - Japan



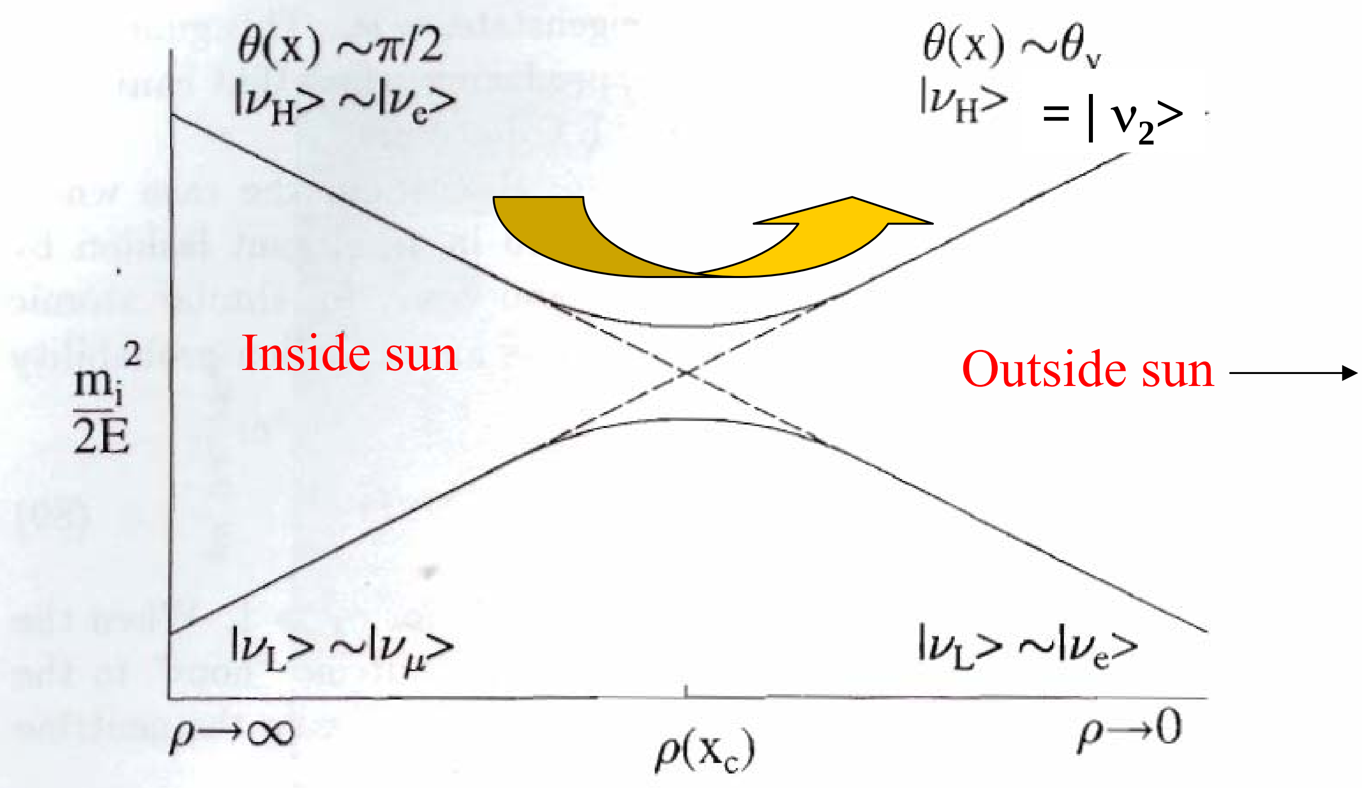
1 kton of liquid scintillator
looks at total Japanese reactor flux

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

Solar Oscillations are due to interactions within the sun



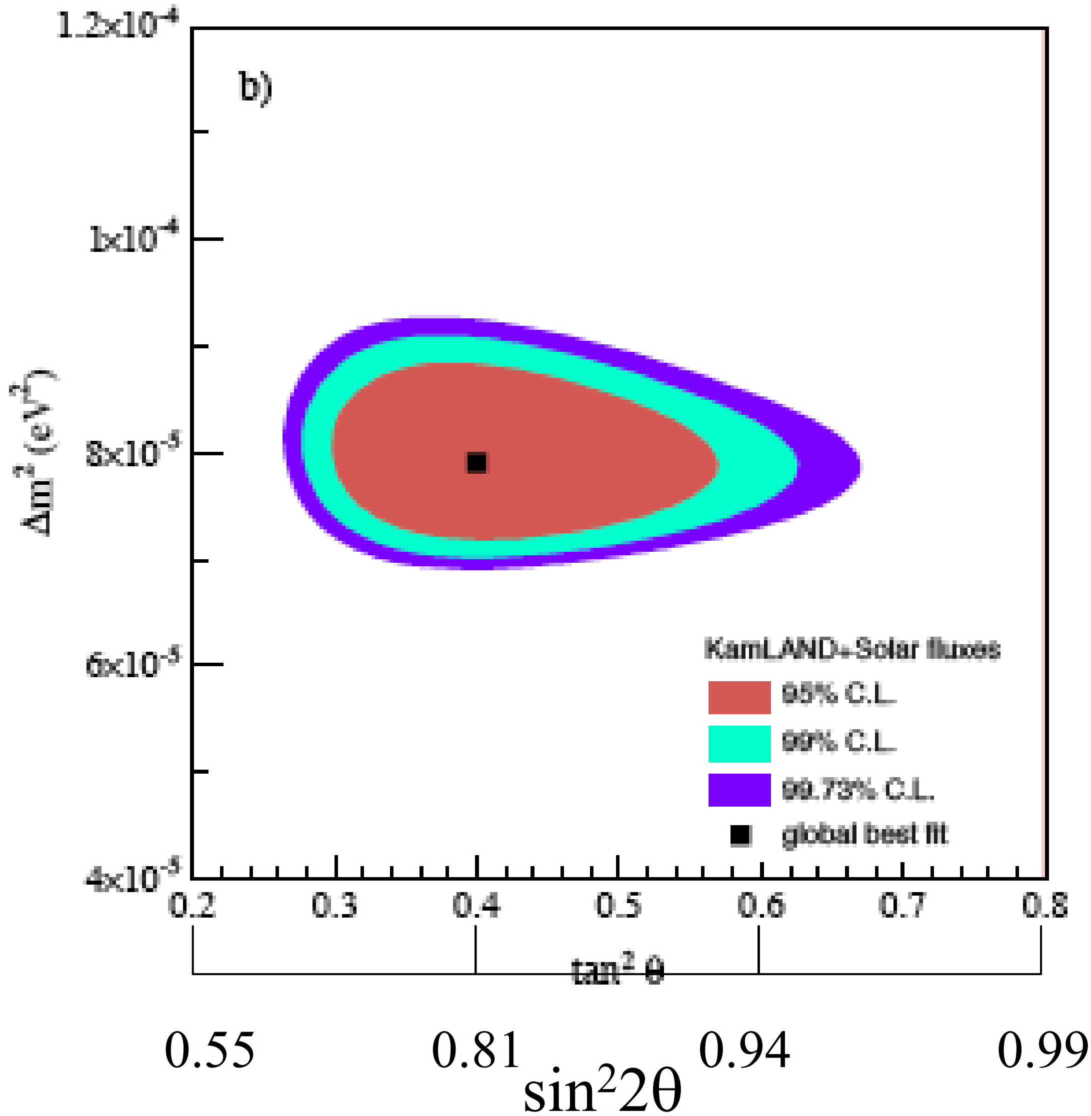
Matter effects from
ν_e W-exchange reaction



Neutrino follows adiabatic trajectory on level-crossing diagram.

Exits sun as mass eigenstate, no more oscillation.

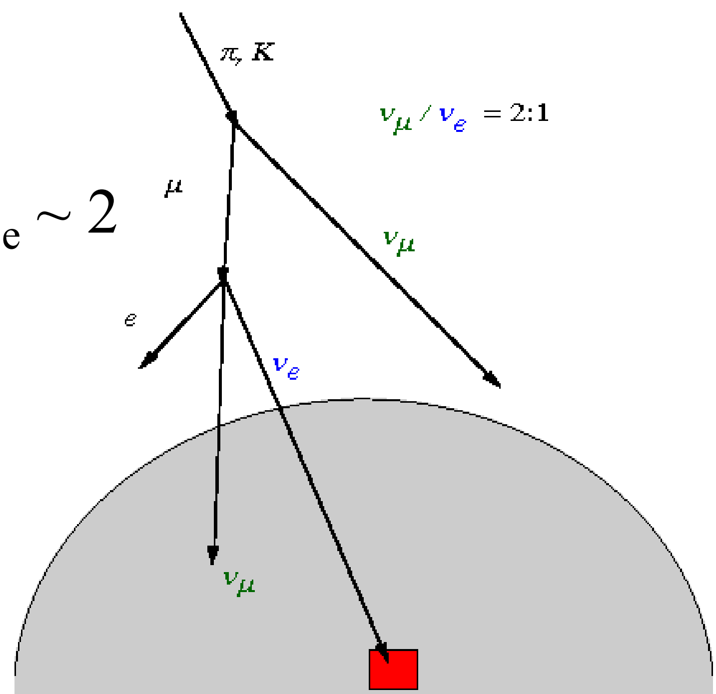
Solar Oscillations - Result from Fitting all Data



Oscillations #2 - Atmospheric Neutrinos

Source is primary cosmic radiation plus basic hadronic decay chain.

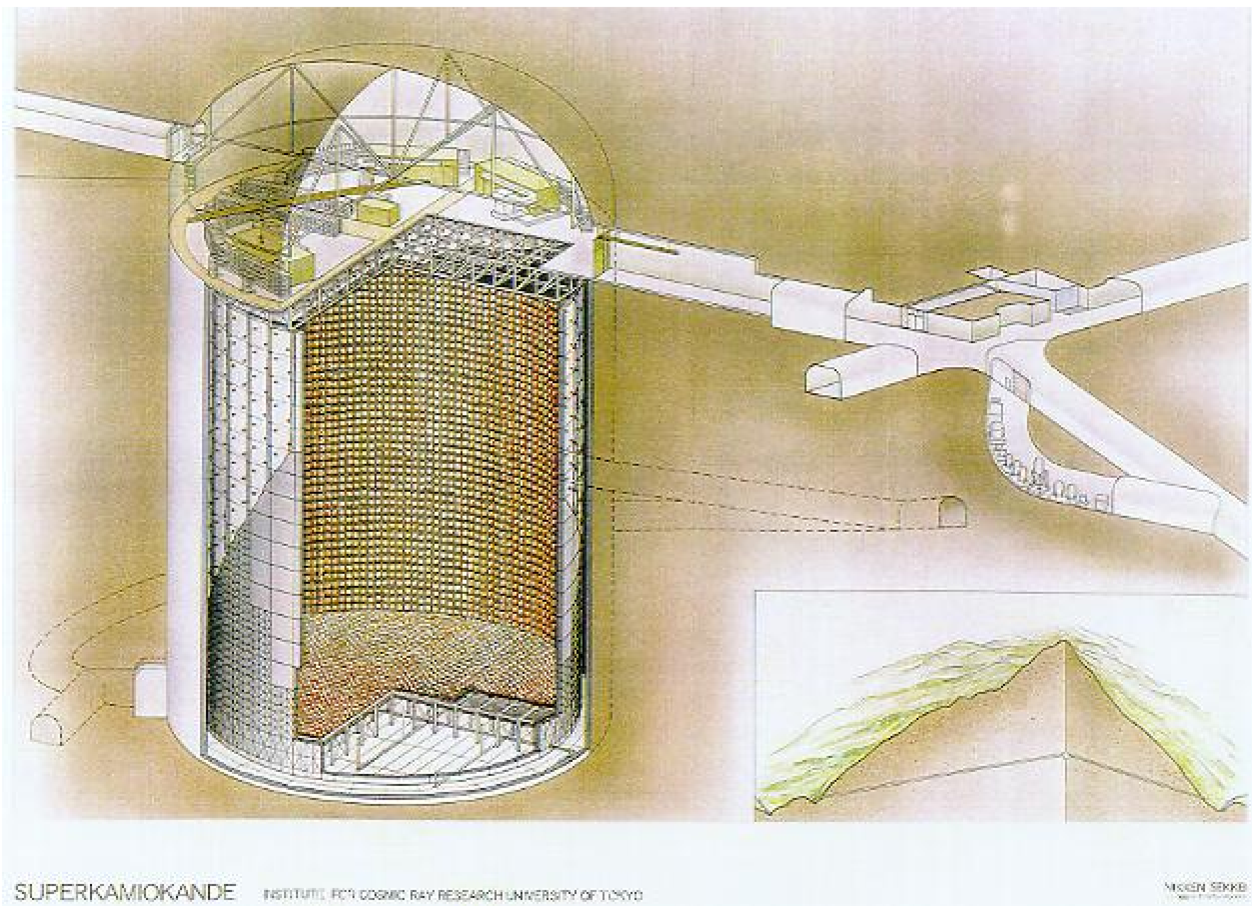
Expect $\nu_\mu/\nu_e \sim 2$



Prefer to look at ratio of ratios to control small model-dependencies

$$R_{double} = \frac{N_{\nu_\mu}^{data} \big/ N_{\nu_e}^{data}}{N_{\nu_\mu}^{sim} \big/ N_{\nu_e}^{sim}}$$

Super Kamiokande - a Second Generation Underground Experiment



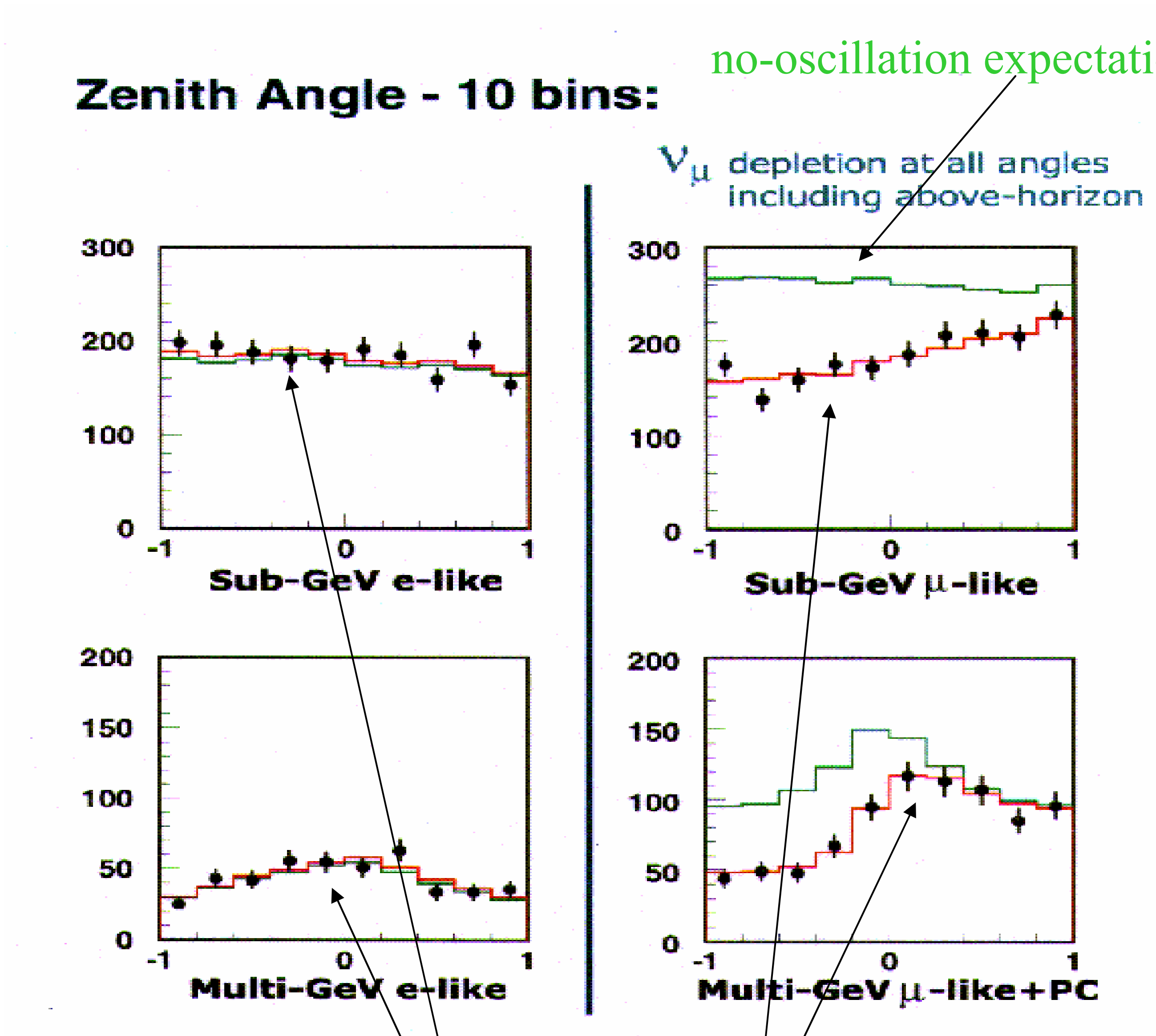
50 kiloton water interaction volume (22.5 fiducial)

More than 11,000 20" PMT's detect Cerenkov light from recoil electrons and muons.

Neutrino interaction rate - about 1/90 minutes.

Super K Results

no-oscillation expectation

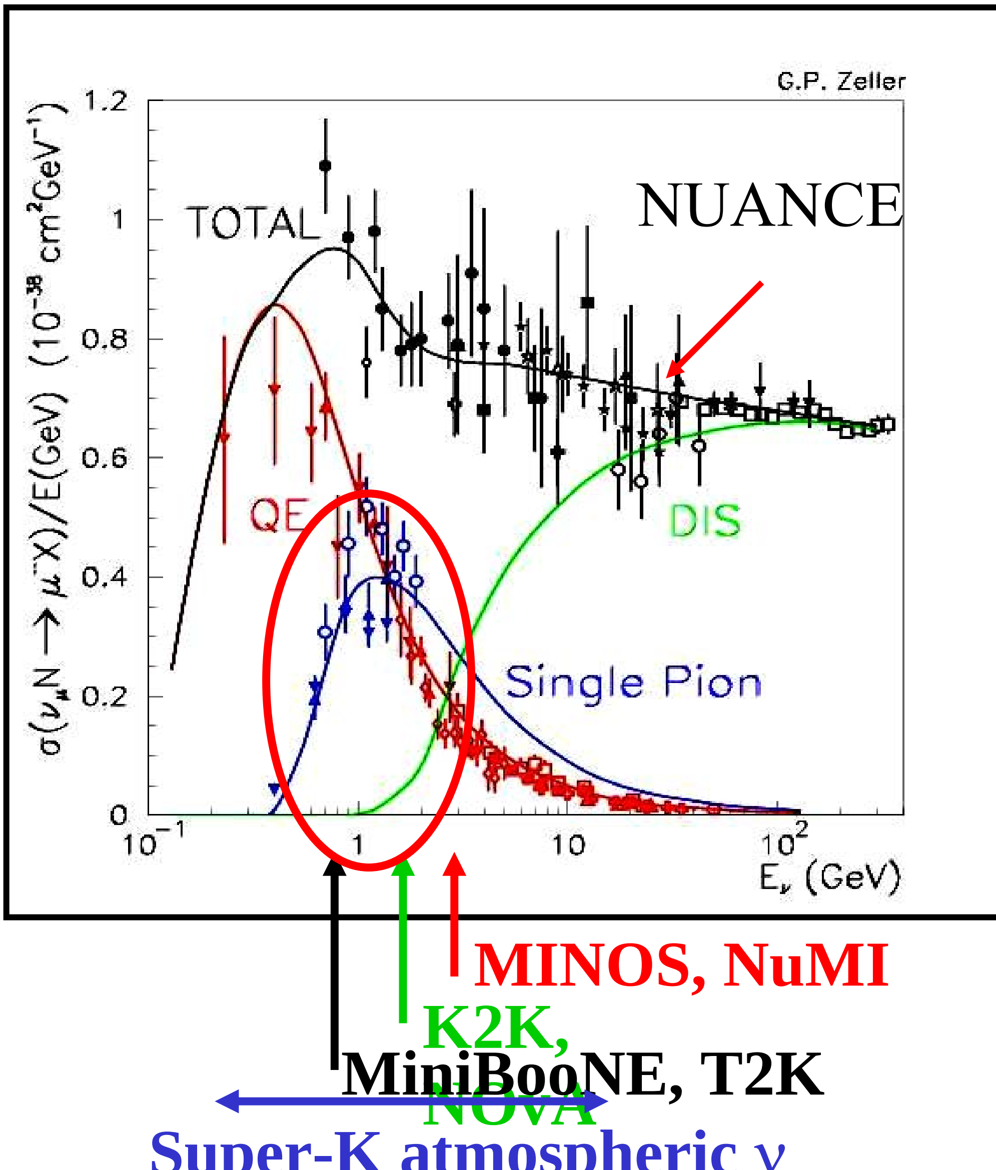


No big effect for electrons

Zenith angle effect SEEN

Interpretation: <u>Oscillations with ν_μ –> ν_τ dominant</u>.

Interlude - the physics of 0.5-5 GeV Neutrino Interactions



Complex physics modeled as a combination of low-multiplicity processes

Pions are produced via intermediate resonant states

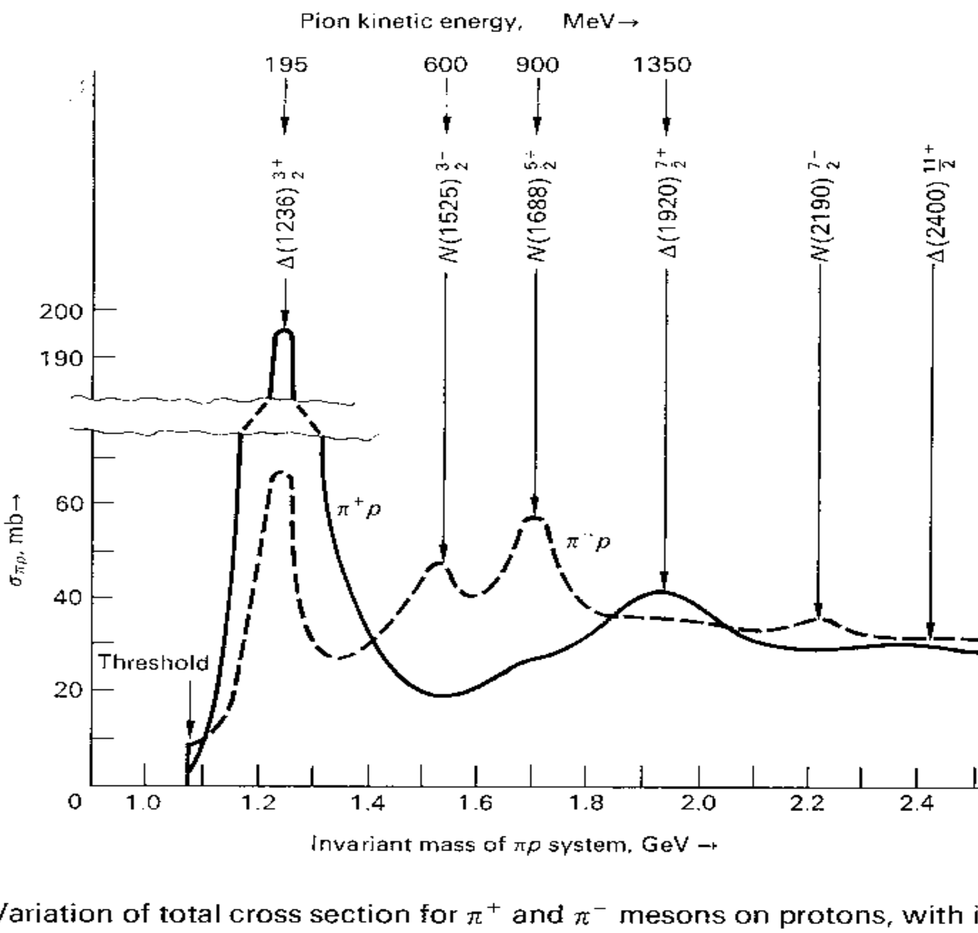
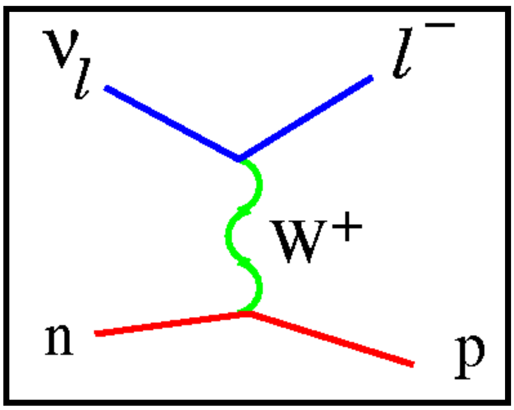


Fig. 4.6 Variation of total cross section for π^+ and π^- mesons on protons, with incident pion energy. The symbol Δ refers to resonances of $I = \frac{3}{2}$; N refers to $I = \frac{1}{2}$. The positions of only a few of the known states, together with their spin-parity assignments, are given.

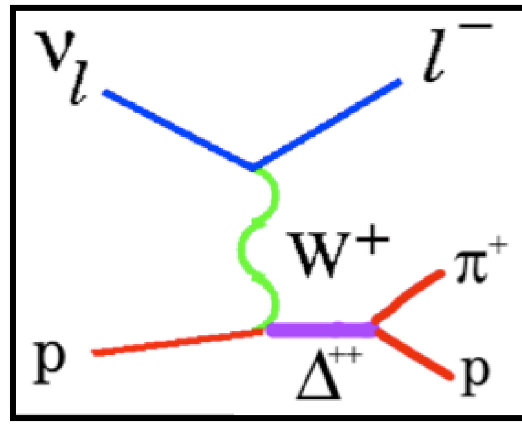
Resonances as observed in πn scattering experiments

(Figure from Perkins, <u>Introduction to High Energy Physics</u>

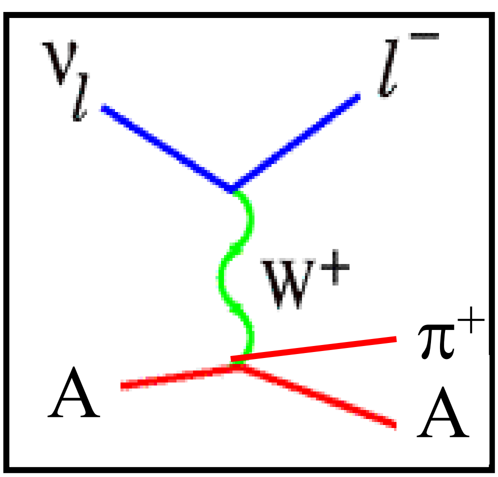
Different models have underlying physics in common



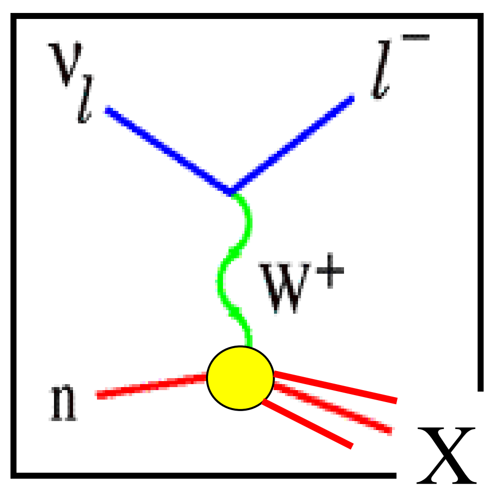
Quasi-elastic



Resonant π production



Coherent production



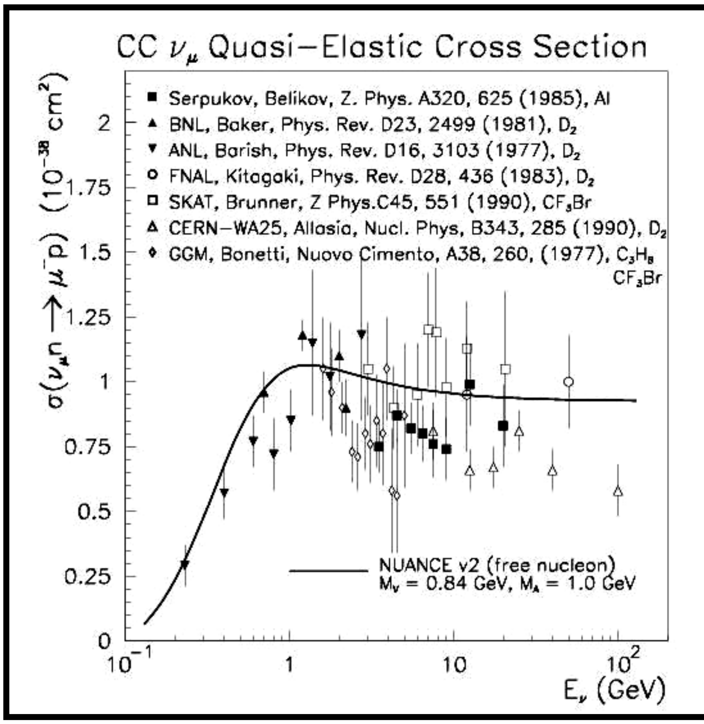
DIS

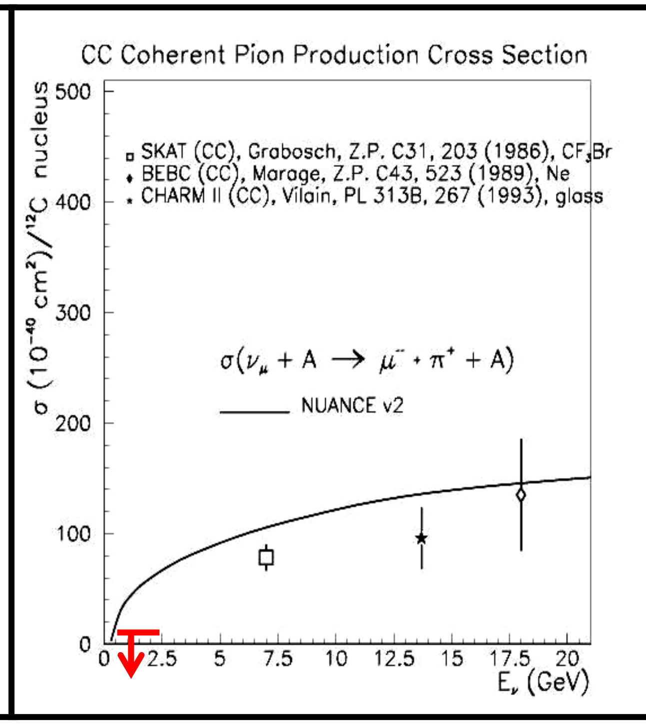
Different models combine channels differently.

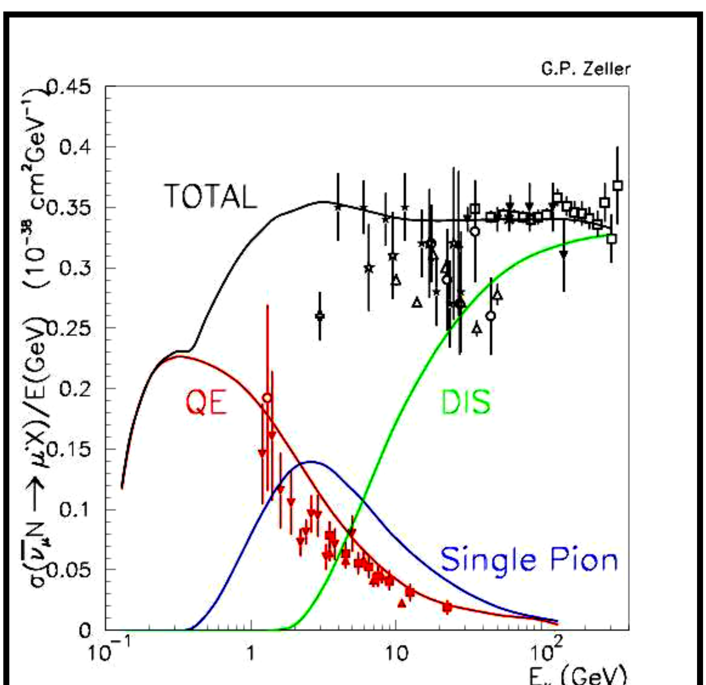
e.g. NUANCE - coherent addition of resonances

NEUGEN - incoherent addition

Existing data not strongly constraining



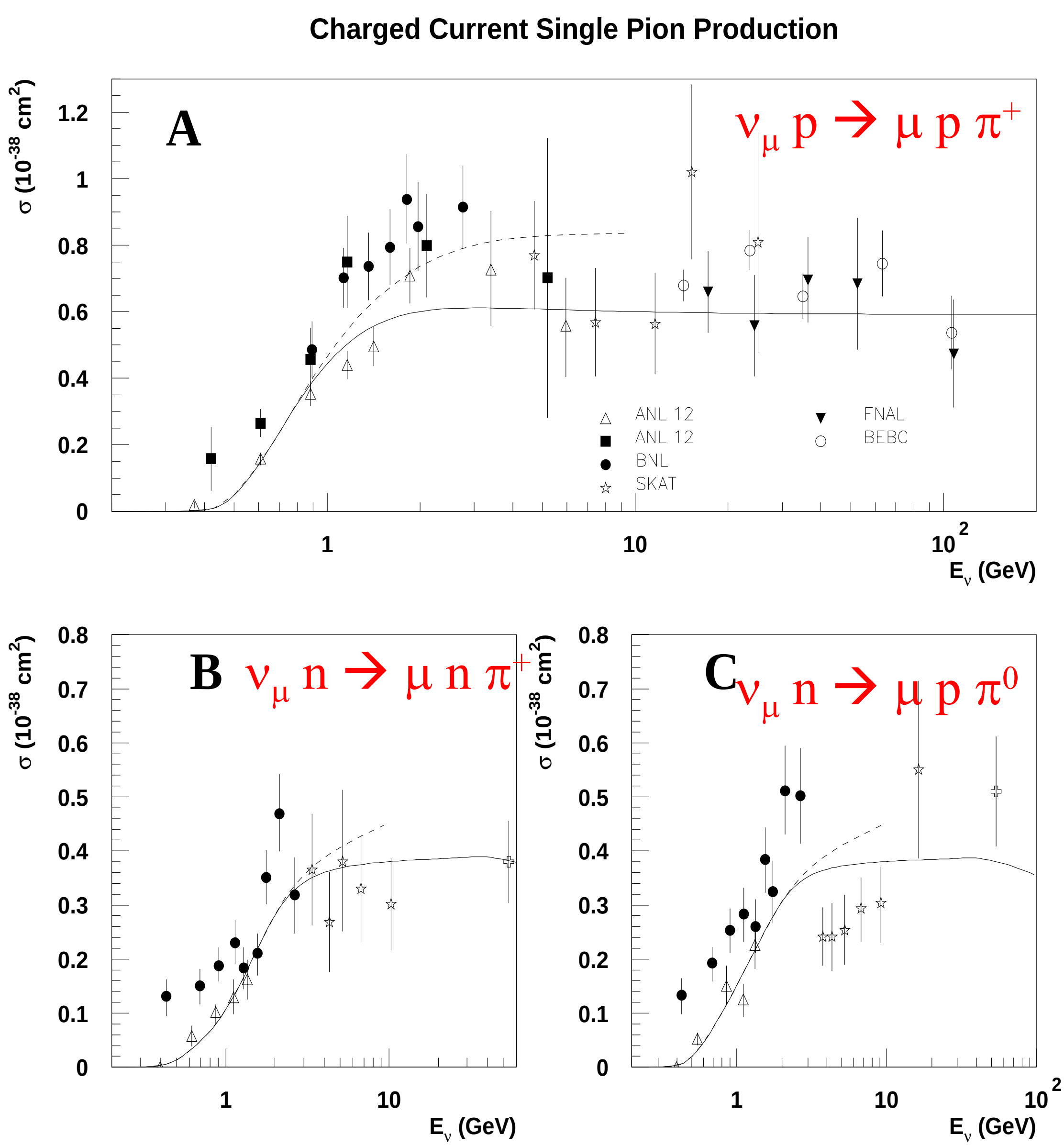




Coherent, ν–bar data basically nonexistent in region of interest.

Parameters in the models are tuned to exclusive channel cross sections.

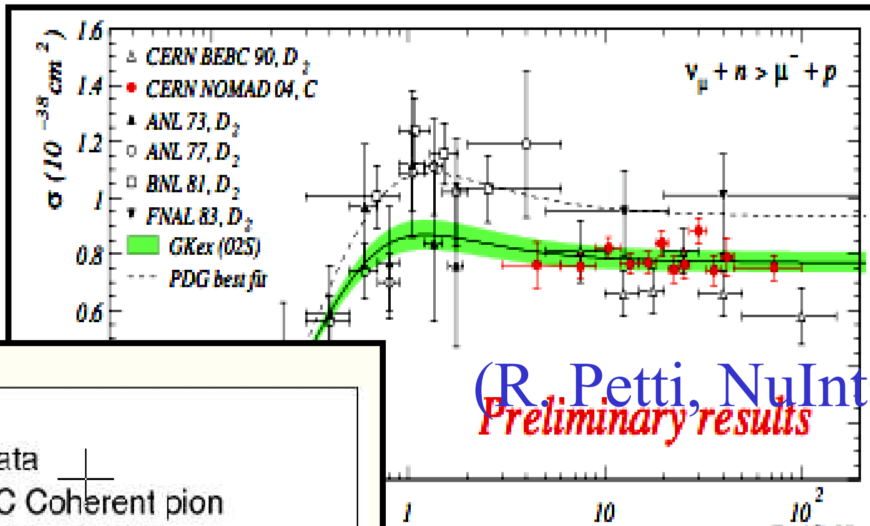
$$\sigma_{tot} = \sigma_{QE} + \sum_i (\sigma^i_{res} + f_i \sigma^i_{DIS})$$



Examples from NEUGEN courtesy H. Gallagher

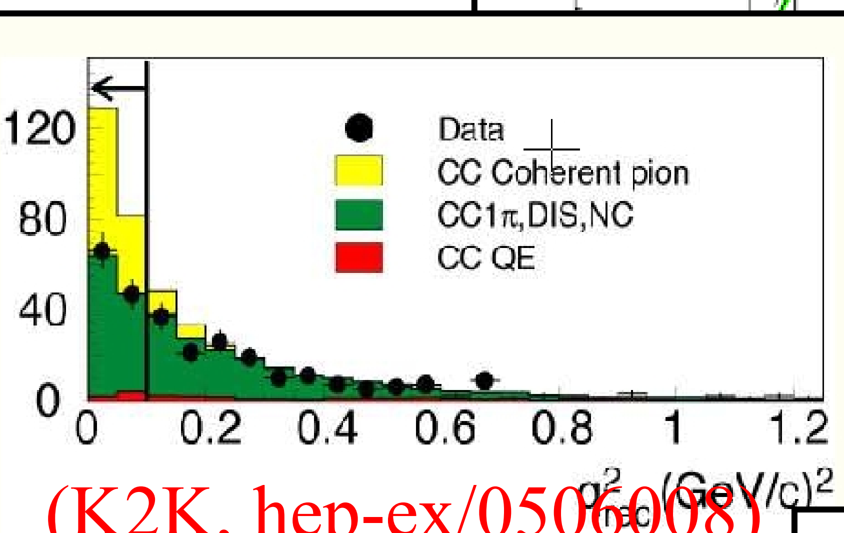
Worldwide effort to improve knowledge

•NOMAD, ^{12}C



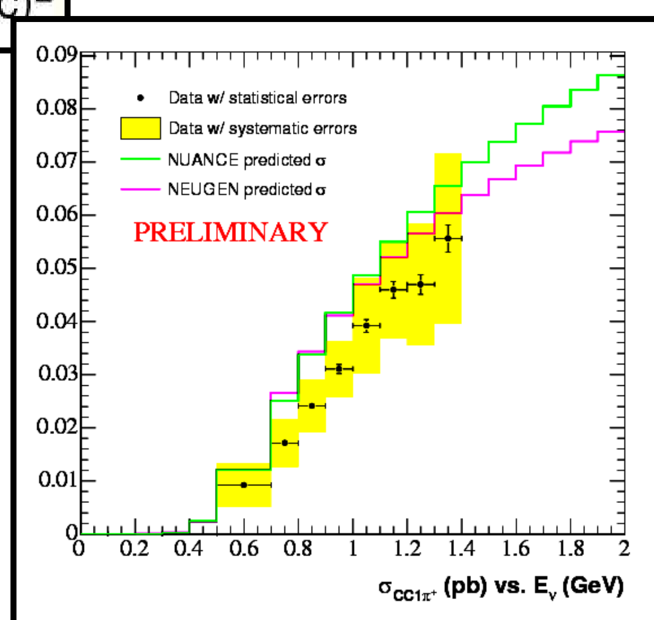
(R. Petti, NuInt05)

K2K, coherent $\pi+$



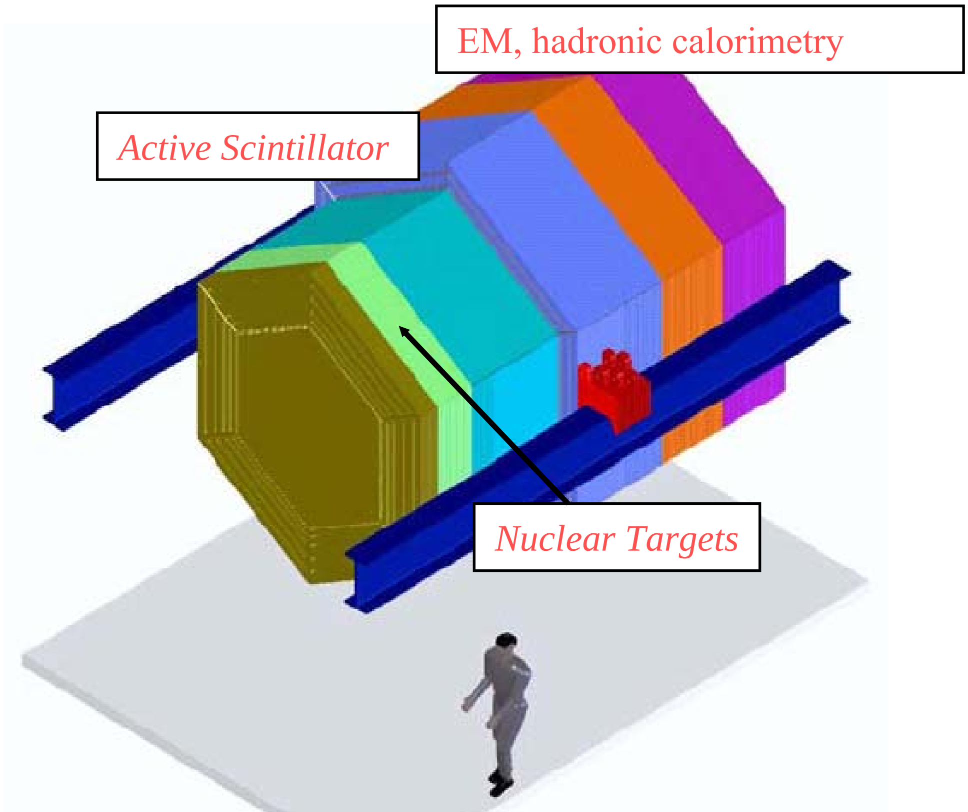
(K2K, hep-ex/0506008)

MiniBoone single π (Monroe,Wasco)



Plots courtesy G. Zeller, NOvE-06

MINERvA, a fine-grained neutrino scattering experiment



♦Precision study of ν - nucleus scattering.

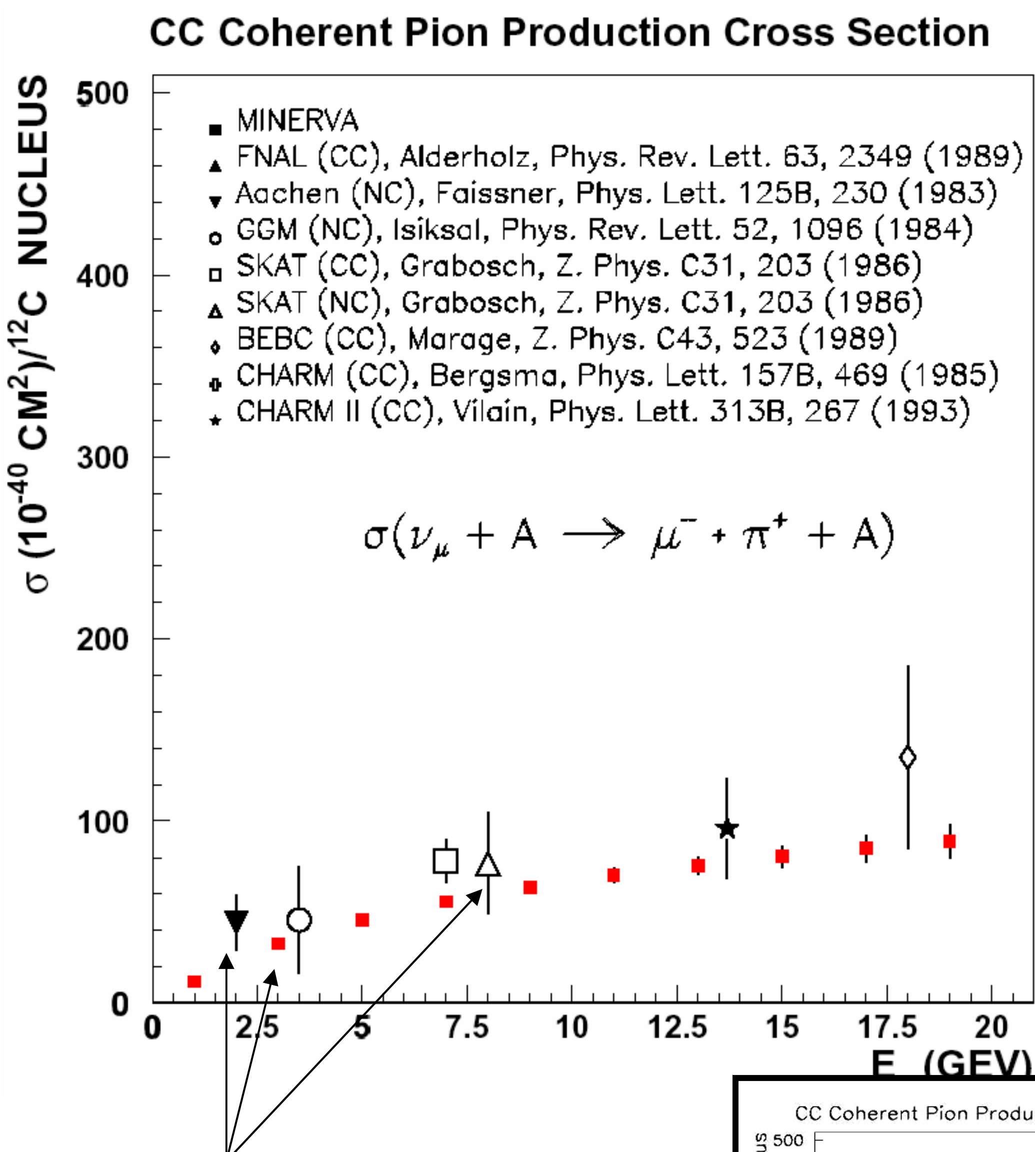
♦Important for minimizing systematic errors of neutrino oscillation experiments

♦To be located just upstream of MINOS Near Near Detector

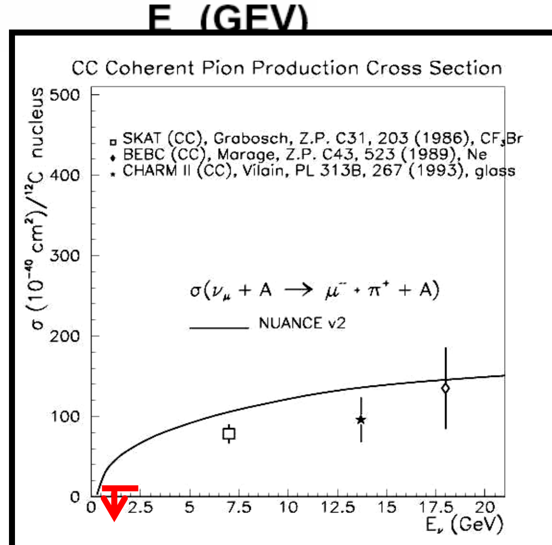
♦High-granularity, fully-active (~6T) scintillator strip based design.

♦~1 T of nuclear targets (C,Fe,Pb) form first detector section.

Example of MINERνA's Analysis Potential **Coherent Pion Production**



Some points are NC data rescaled to CC



MINOS Long-Baseline Experiment

Study the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis, by measuring precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$

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

Constrain contributions of exotic phenomena

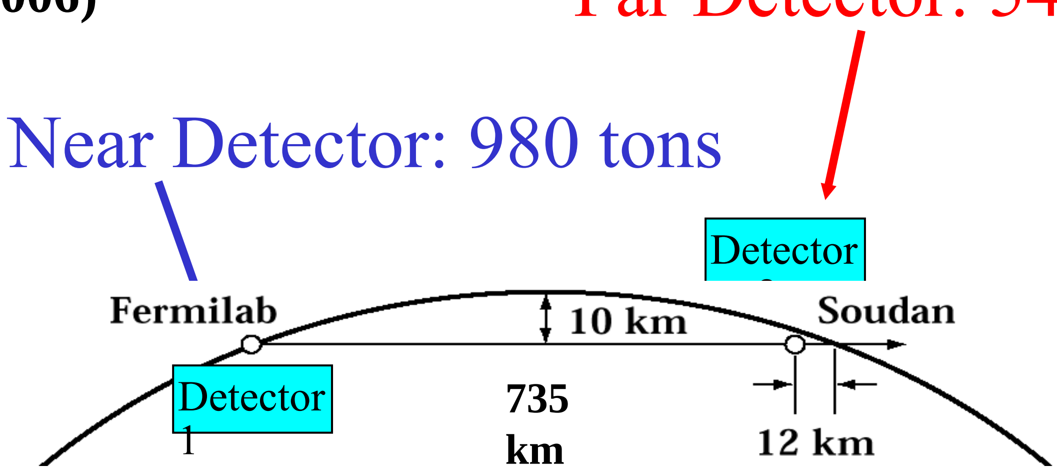
e.g Sterile ν or ν decay

Compare ν, $\bar{\nu}$ oscillations

Test of CPT violation

Atmospheric neutrino oscillations

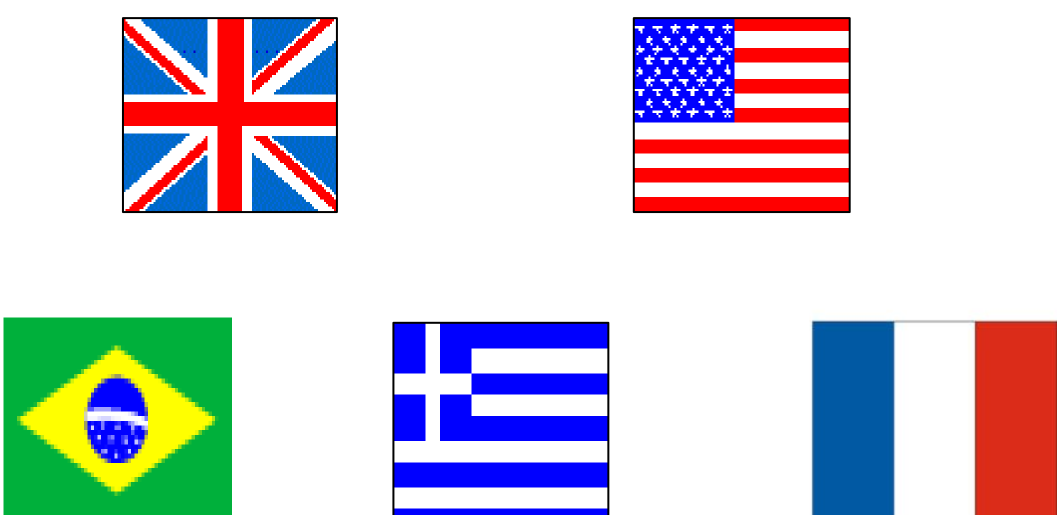
Phys. Rev. D73, 072002 (2006)



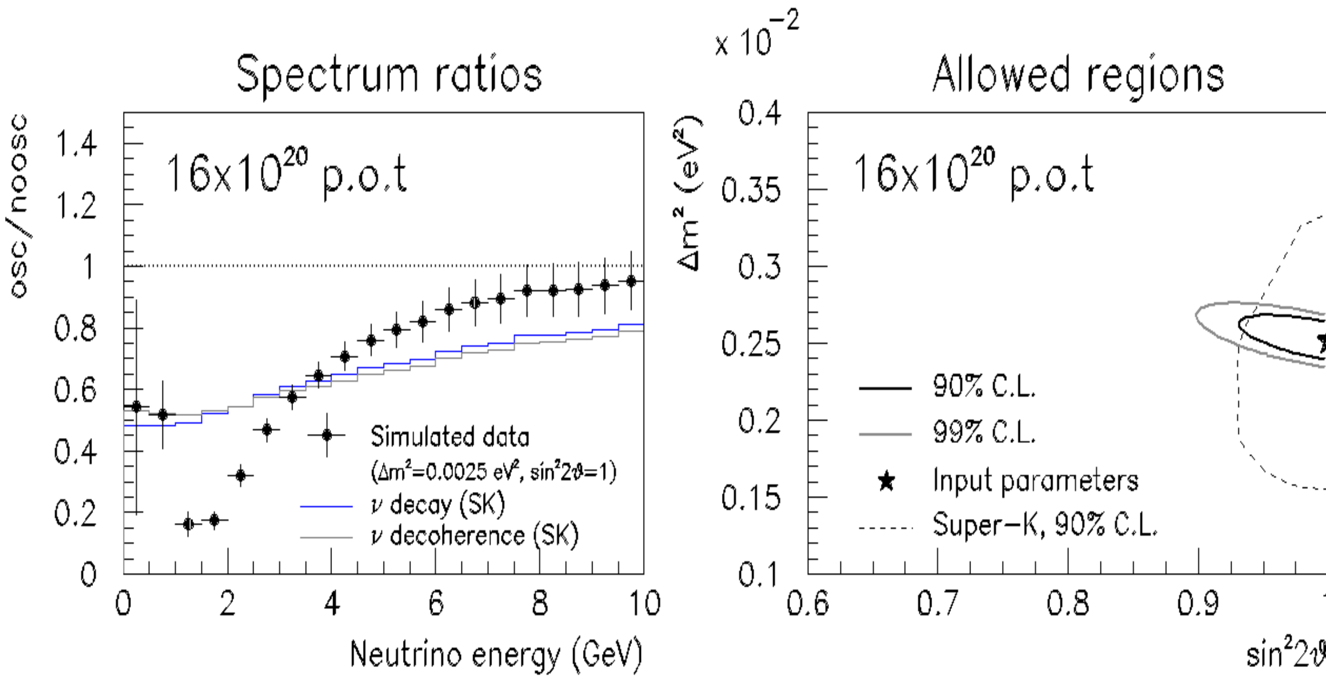
The MINOS Collaboration

Athens • Cambridge • College de France • Oxford • Rutherford • Sussex • UCL • Argonne • Benedictine • Brookhaven • Caltech • Fermilab • Harvard • IIT • Indiana • Minnesota • Minnesota-Duluth • Pittsburgh • South Carolina • Stanford • Texas-Austin •Texas A&M • Tufts • UNICAMP/Sao Paolo • William & Mary • Wisconsin

24 Universities, 3 National Laboratories, 5 Countries



Two-detector Disappearance Experiment



Study atmospheric scale

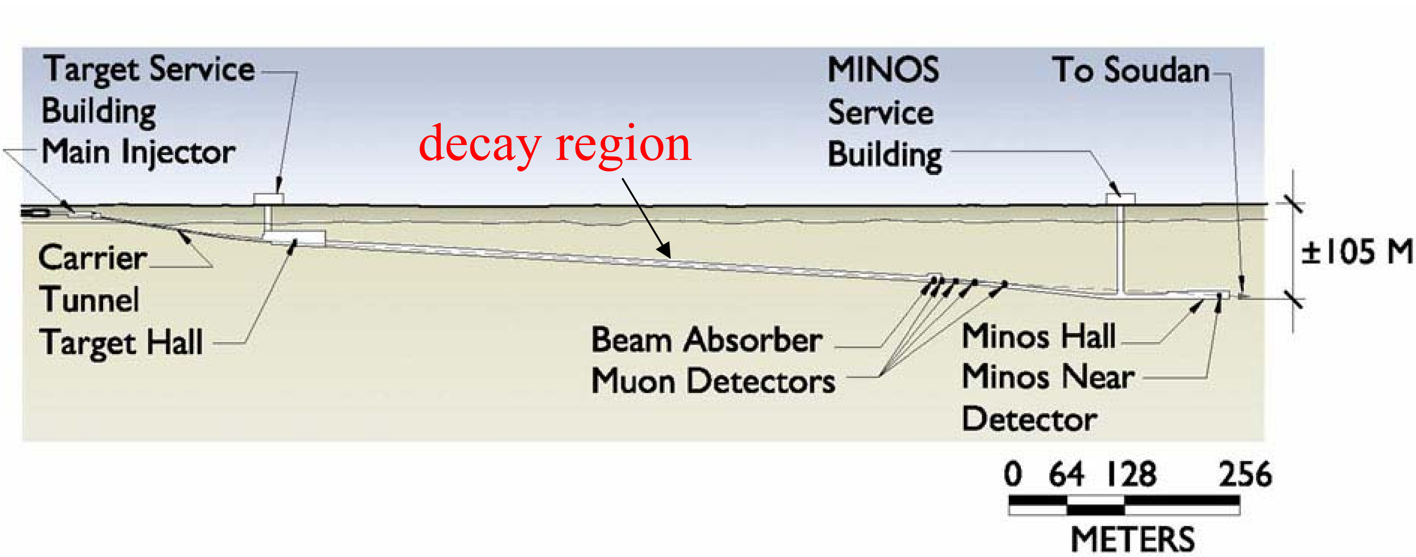
$\nu_\mu \rightarrow \nu_\tau$ Δm^2 *and* $\sin^2 2\theta_{23}$

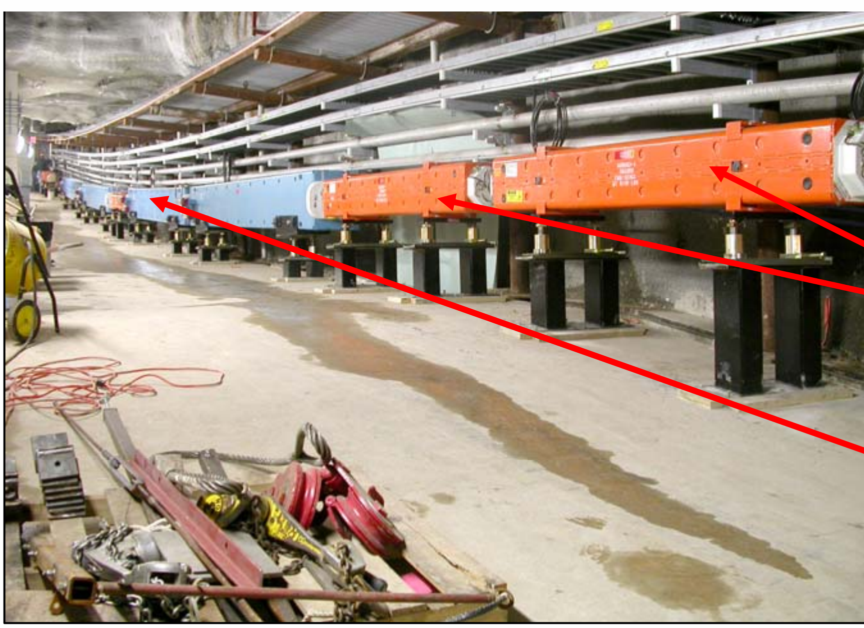
Greatly improve existing measurement;

excellent test against alternative hypotheses

Sensitivity to ν_e appearance discussed later

Real Elements of NuMI Beamline





NuMI Pretarget final transport

Completed NuMI Decay Tunnel

6m diameter excavated via Tunnel Boring Machine

Descends at 3.3 degrees – 6%

Now filled with decay pipe, shielding, and access passageway.

Secondary Particle Production

π and K production in the target are the ultimate source of neutrino flux

Knowledge and understanding of this is an important systematic for oscillation experiments.

Two types of modeling (using experimental data as input):

-Hadronic cascade Monte Carlos

FLUKA, MARS, GEANT

Tend to be "black boxes"

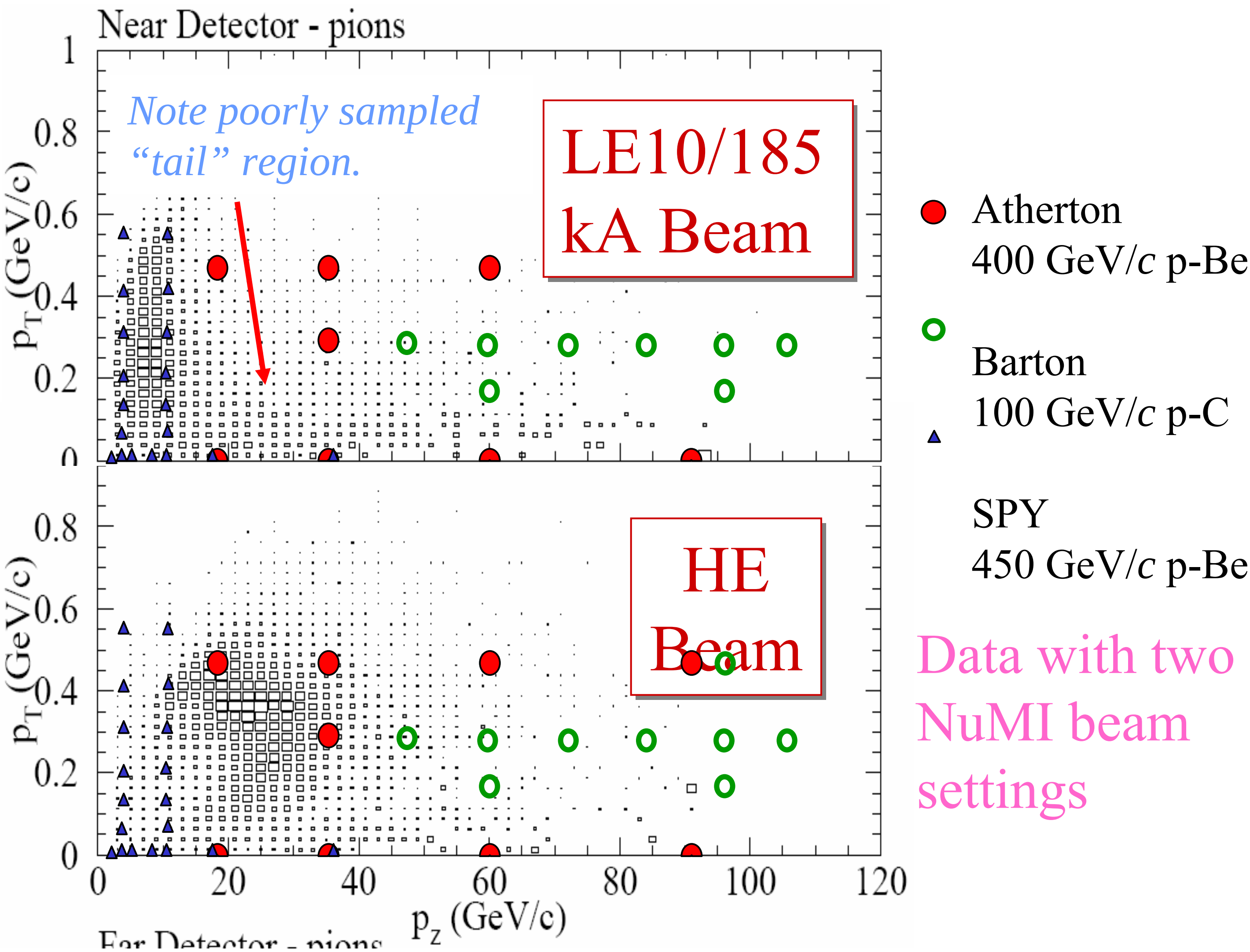
Hard to factorize errors

Parametrized Simulations

Example for these lectures: BMPT

Provide the experimenter with functions, errors

Experimental data compared to NuMI data range



Notes: in parametrizations, data may use scaling variables

$$x_F \equiv 2p_L^* / \sqrt{s}$$

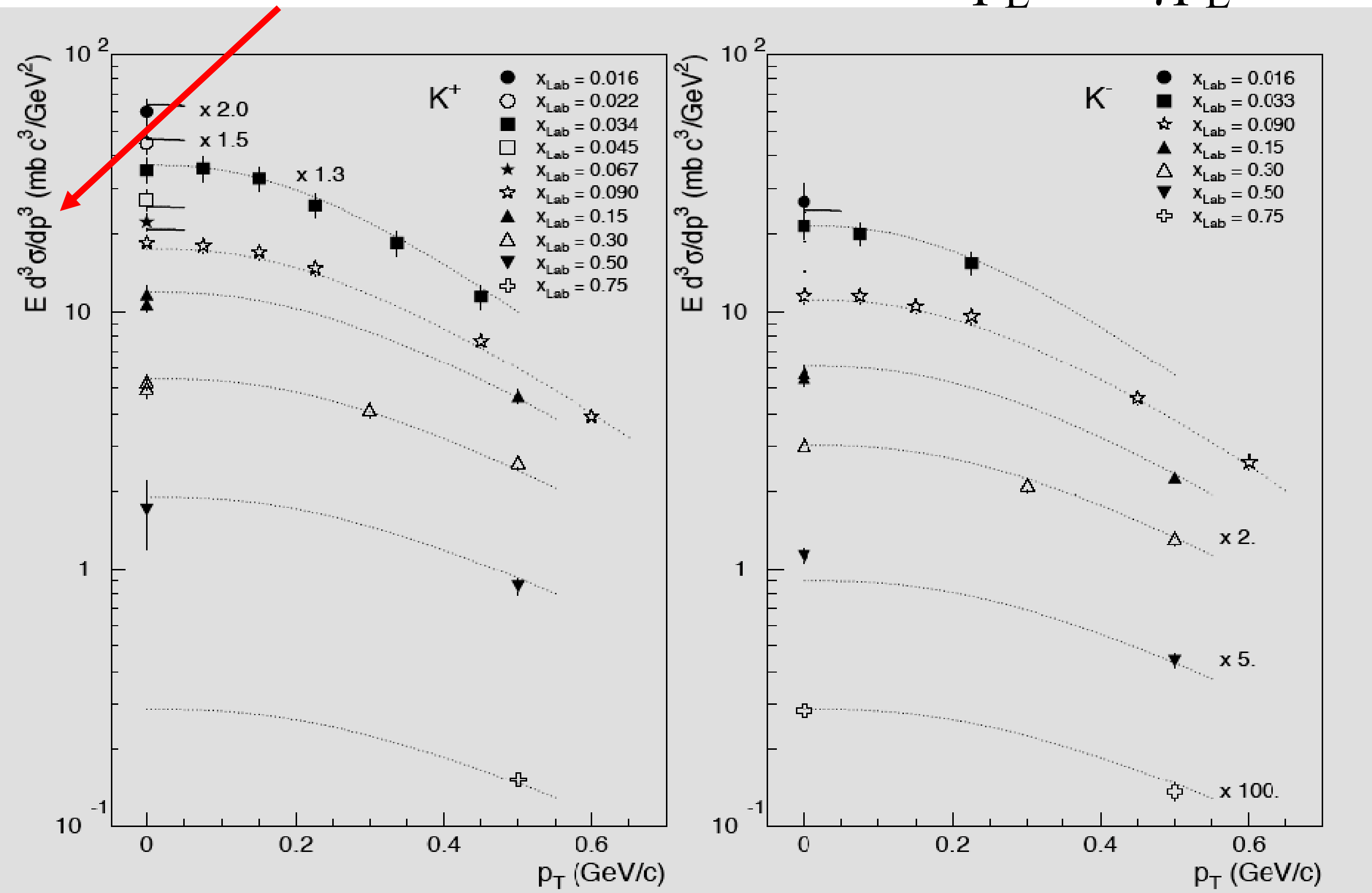
$$x_R \equiv E^* / E^*_{\max}$$

These two very similar, especially for π's

$$x_{lab} \equiv p_{lab} / p_{incident}$$

Example of BMPT parametrization - K's

Invariant cross-section under $p_L \longrightarrow \gamma p_L$



BMPT parametrization

$$E\frac{d^3\sigma}{d^3p} = A(1-x_R)^{\alpha} x_R^{-\beta} G(x_R, p_T) e^{-a(x_R)p_T}$$

Notes: Limited p_T !
Cutoff at high x
Enhancement at low x

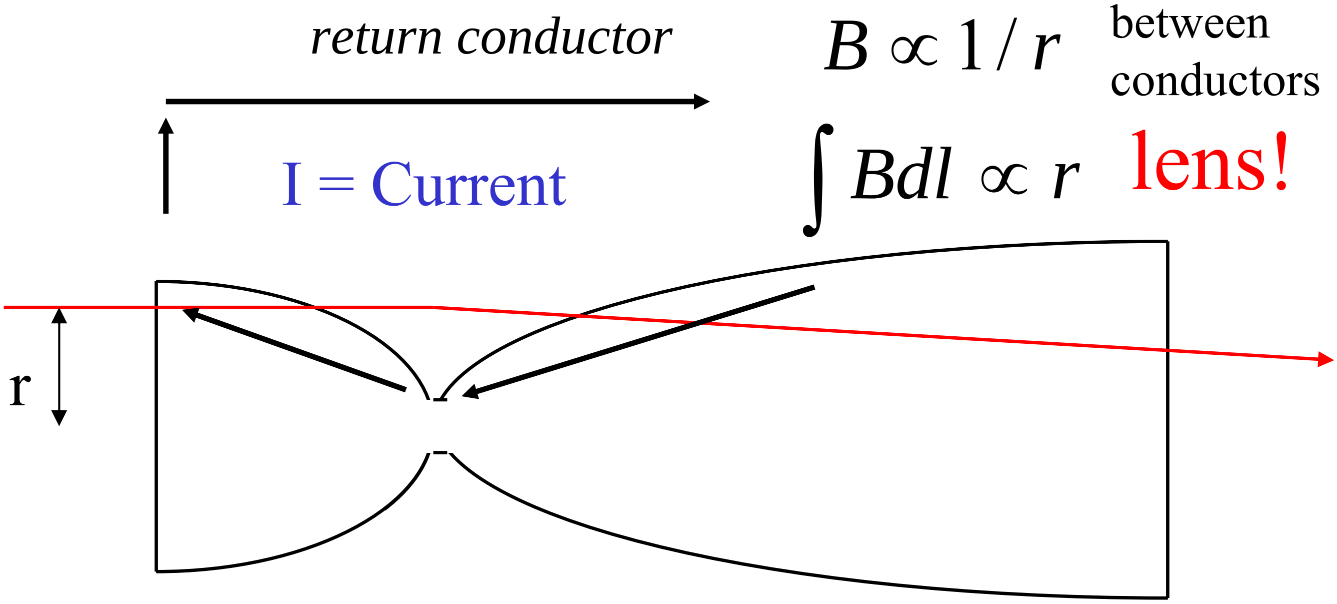
Example of Secondary Focusing: Hyperbolic Horn

Old technology - form pulsed sheets of current in a cylindrical geometry.

$$L \propto r^2$$

$$B \propto 1/r$$ between conductors

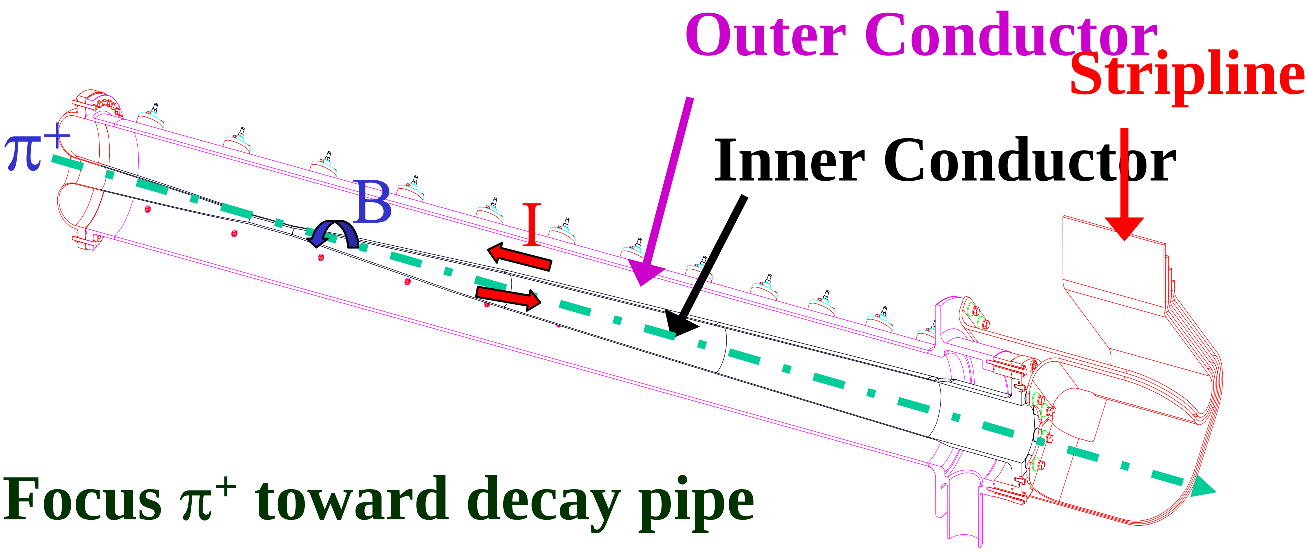
$$\int B dl \propto r$$ lens!



Many variations on this shape have been made, with different momentum acceptances

HIGH CURRENTS - e.g. NuMI horn uses 180 kA for ~2 mS.

NuMI Horns

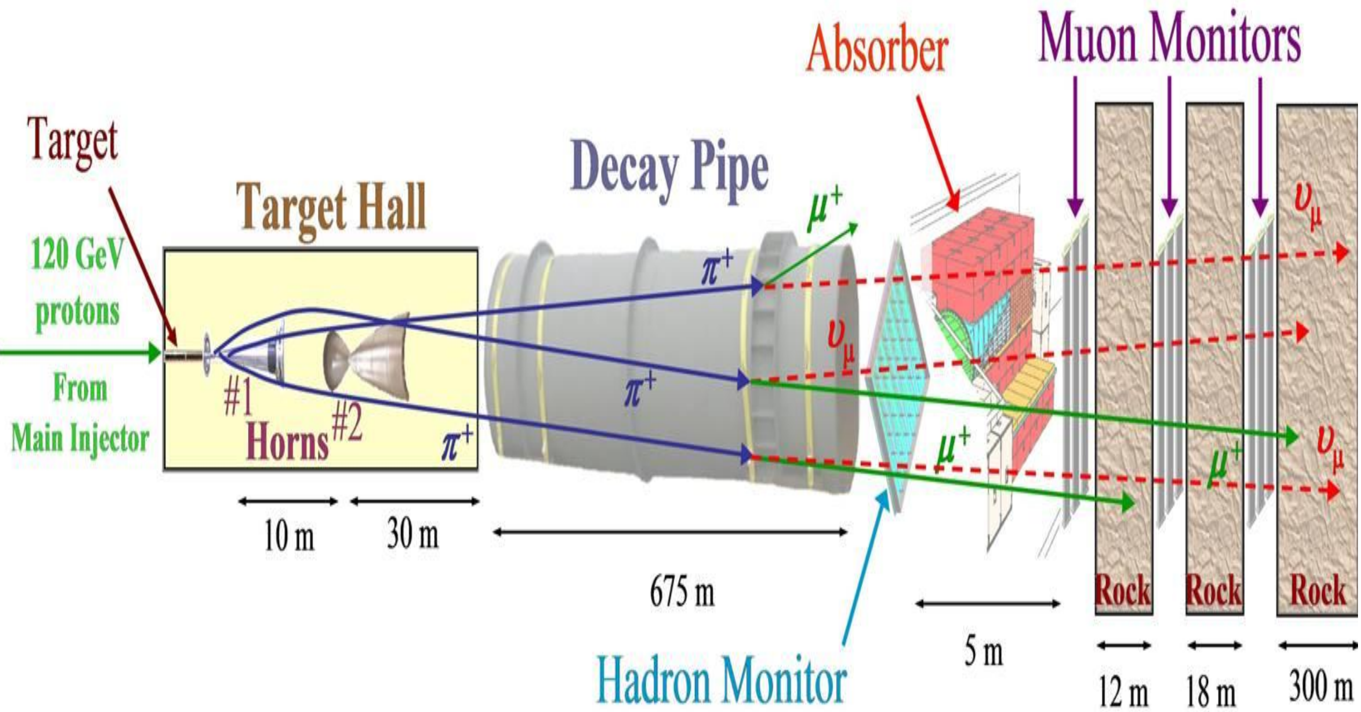


Focus π^+ toward decay pipe

Horn 2 inner conductors

Horn installation

NuMI Beamline Layout



120 GeV primary Main Injector beam

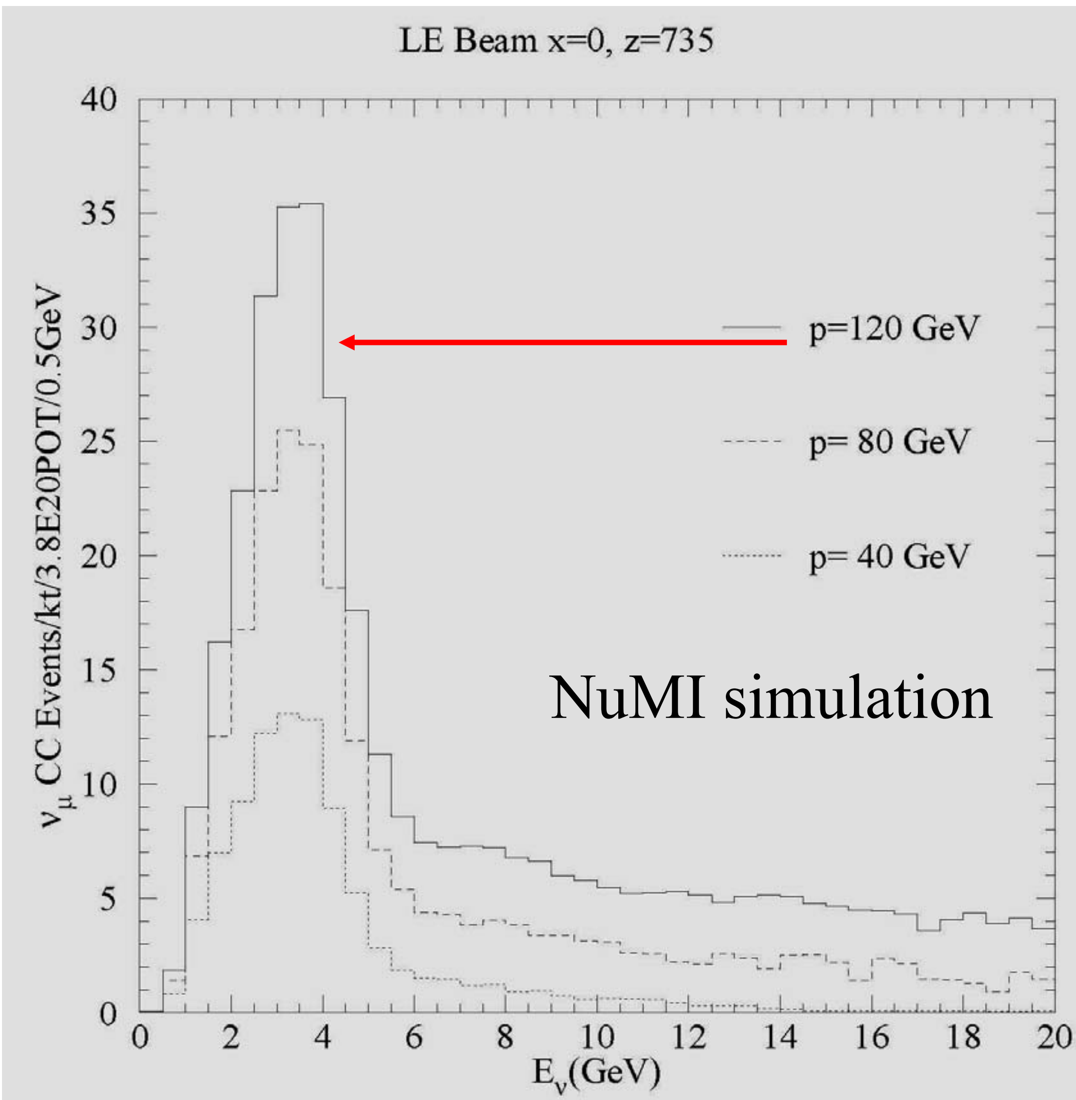
Target readily movable in beam direction

2-horn beam adjusts for variable energy ranges

675 meter decay pipe for π decay

Neutrino intensity depends on beam power

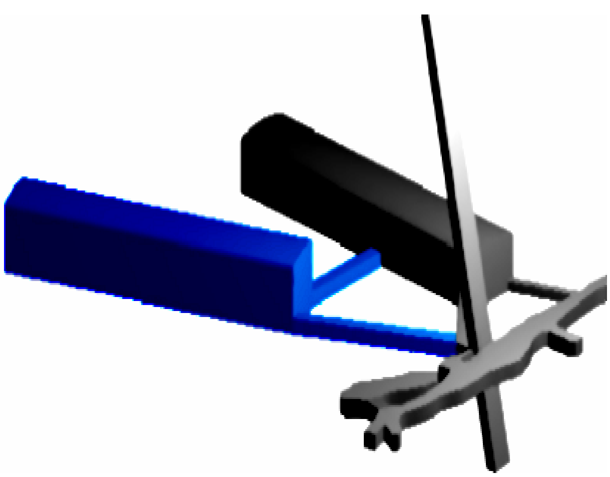
Counter-intuitive because fewer incident particles!



As primary beam energy increases, more low momentum particles are brought within the focussing zone

Soudan Underground Laboratory

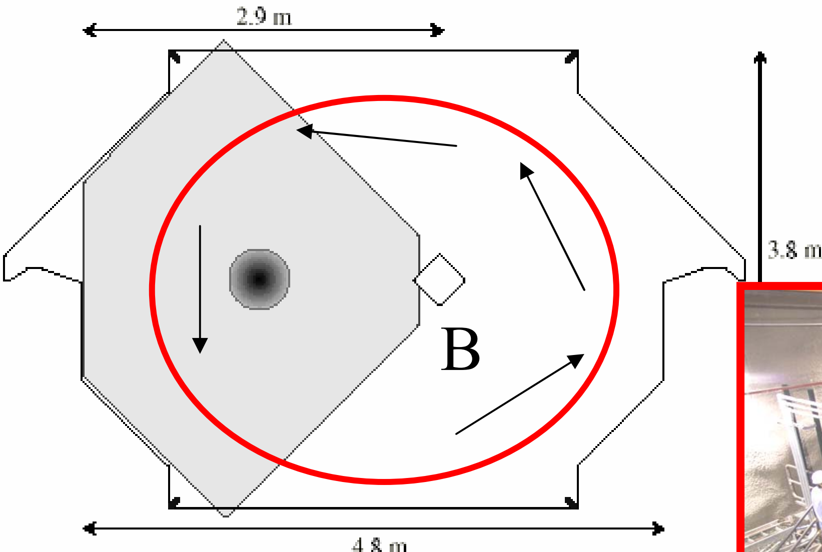
- Operated by U. of Minn. and Minnesota Dept. of Natural Resources
- Soudan Mine -tourist attraction during summer months
- 1 elevator shaft limits loads to 1m x 2m x 9m



The MINOS Far Detector

8m Octagonal Tracking Calorimeter
486 layers of 2.54cm magnetized Fe plates
2 sections, each 15m long
4.1cm wide solid scintillator strips with WLS fiber readout (both ends).
Hamamatsu M16 multi-anode PMT readout
Veto shield against entering cosmic ray muons

MINOS Near Detector - slightly different



280 single steel plates, shorter modules

Calorimeter (1st 3/7 - logically Veto, Target, Hadron Absorber is partially instrumented except for 1/5 of planes with full coverage

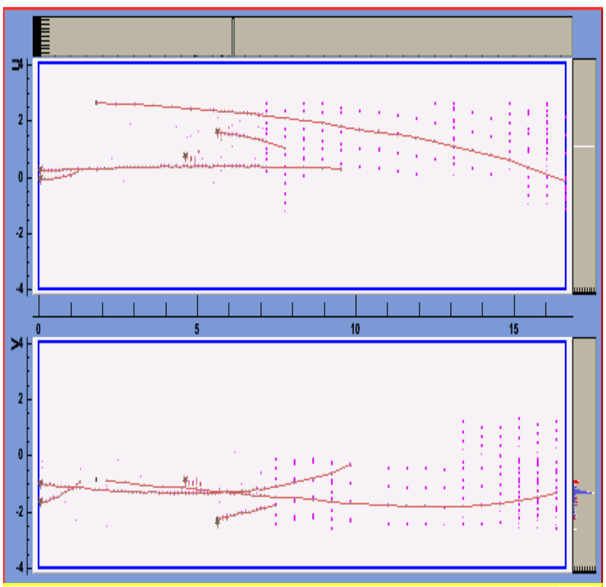
Muon Spectrometer section has only every 5^{th} plane instrumented

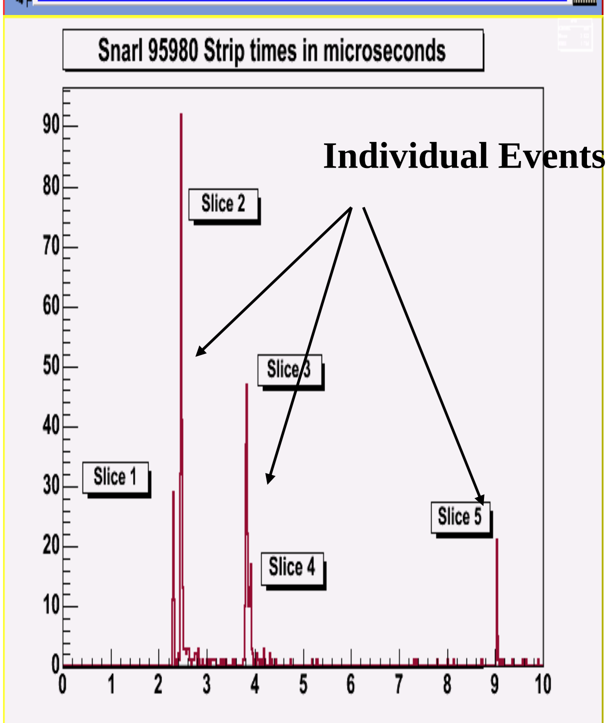
Magnet coil provides <B> ~ 1.3 T

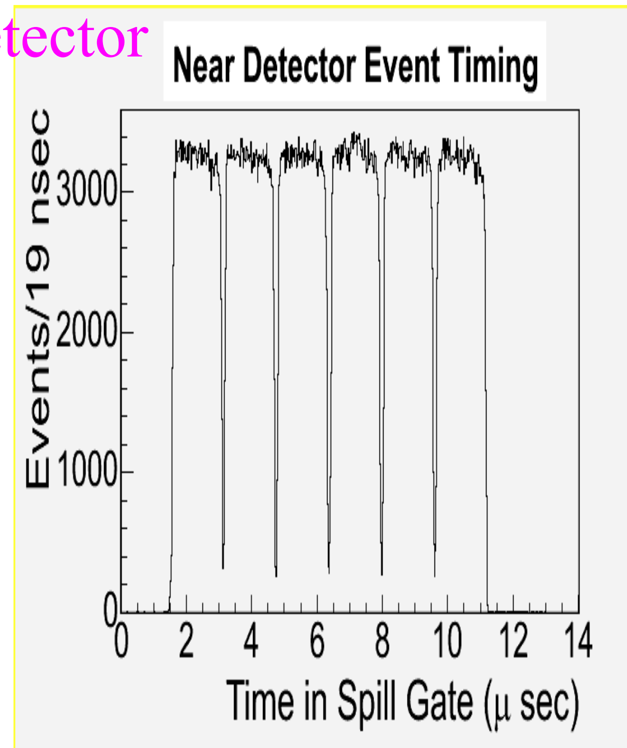
Near electronics optimized for high occupancy (~20) during 10 μs spill

Large event rate in near detector

A spill (10 μs) in near detector





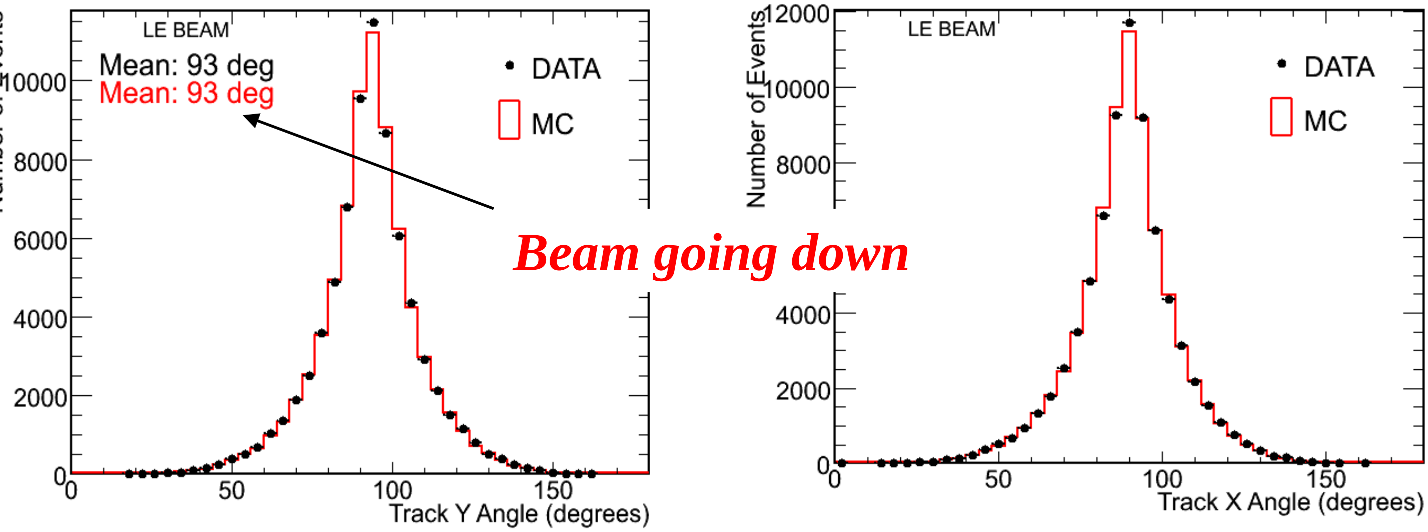


Beam arrives in 10 μs batches

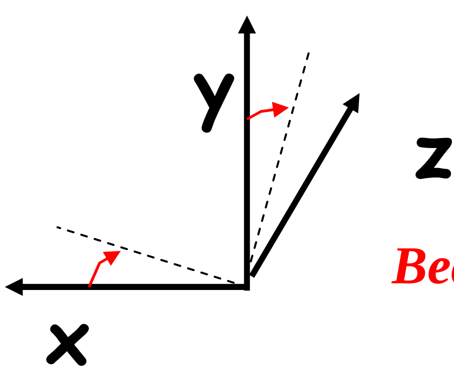
Multiple events separated by timing, topology.

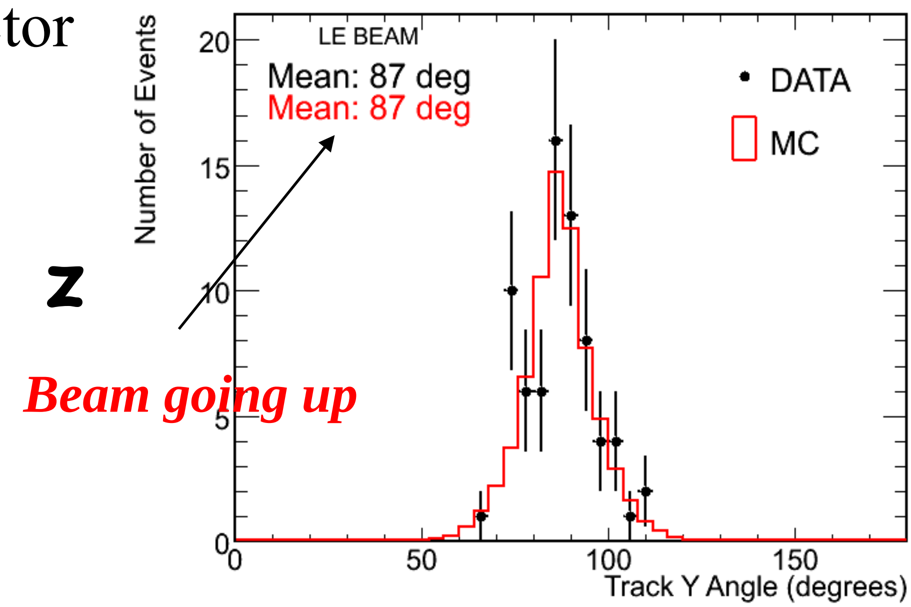
Relative timing greatly simplifies event identification at far detector

MINOS Reconstructed Track Angle



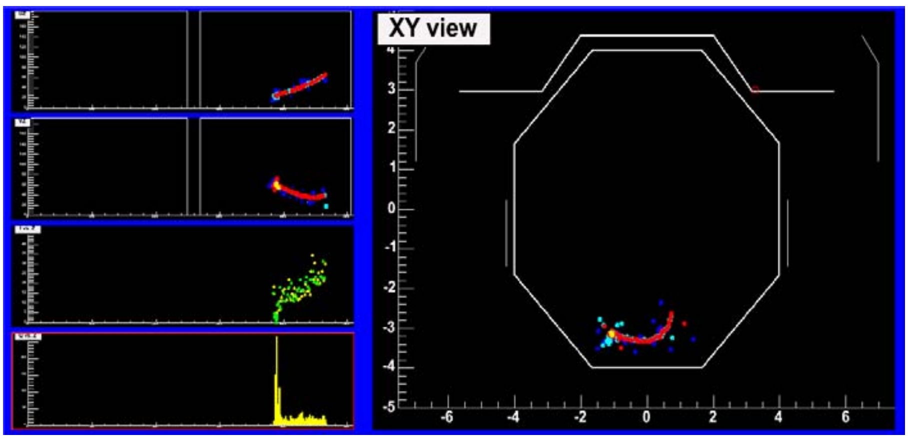
Near Detector



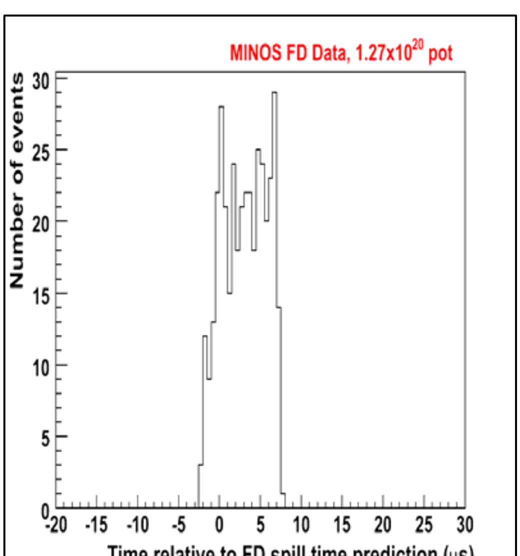


Far Detector, using longer events to get best angular resolution.

Minos Far Detector Events



Contained CC event
Expected rate ~3/day

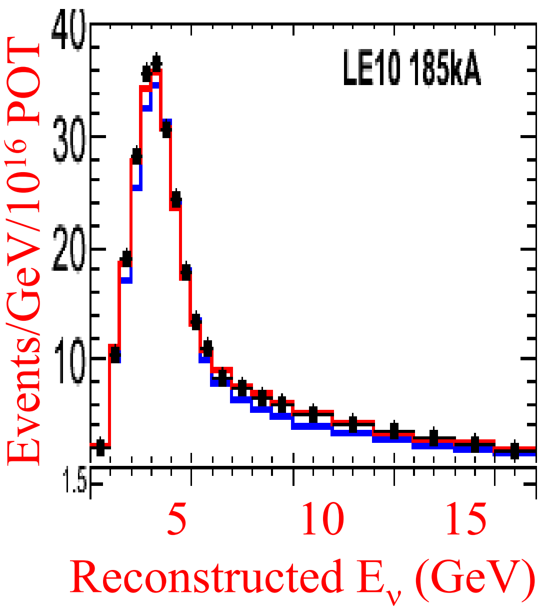


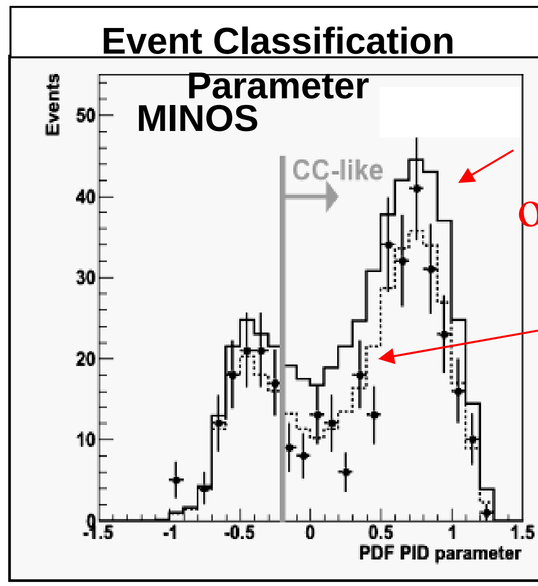
Far Detector triggers on spill time (50 μs window), also activity triggers

Further require fiducial, angle cuts

Estimate ~9% NC background, <1 cosmic event

Predicting the Spectrum





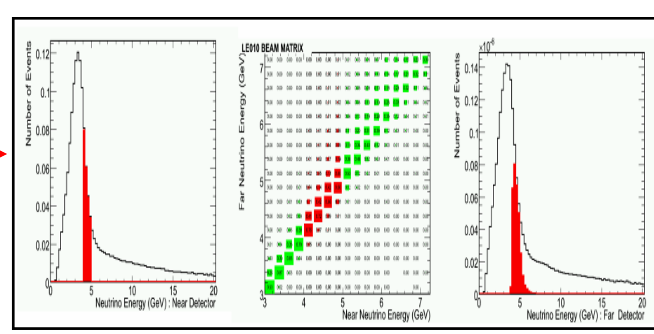
No oscillations

Best fit

Near Detector Spectrum vs. simulation

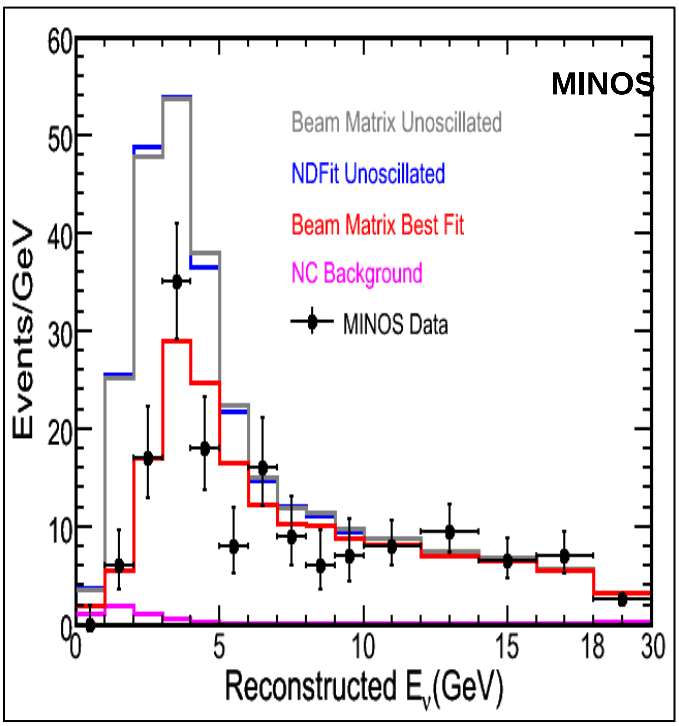
Likelihood based on event length, pulse height in track

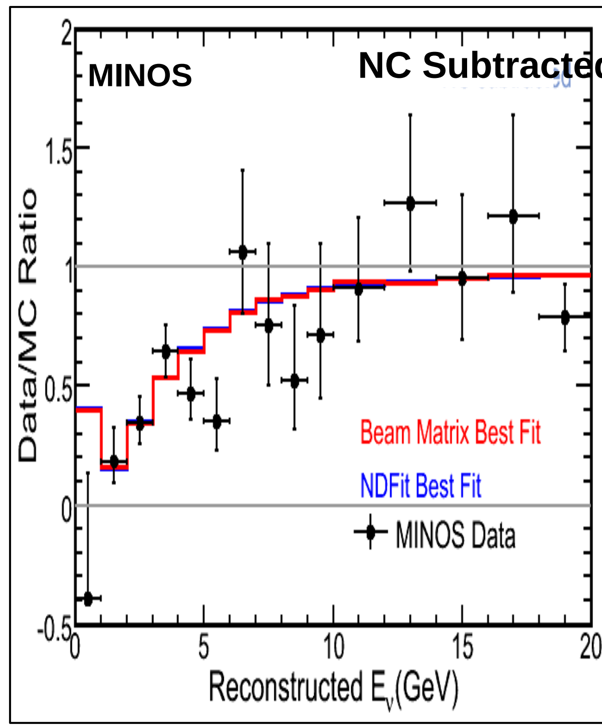
Use near detector data, beam kinematics to predict far spectrum



MINOS Results

FD neutrino spectrum and ratios

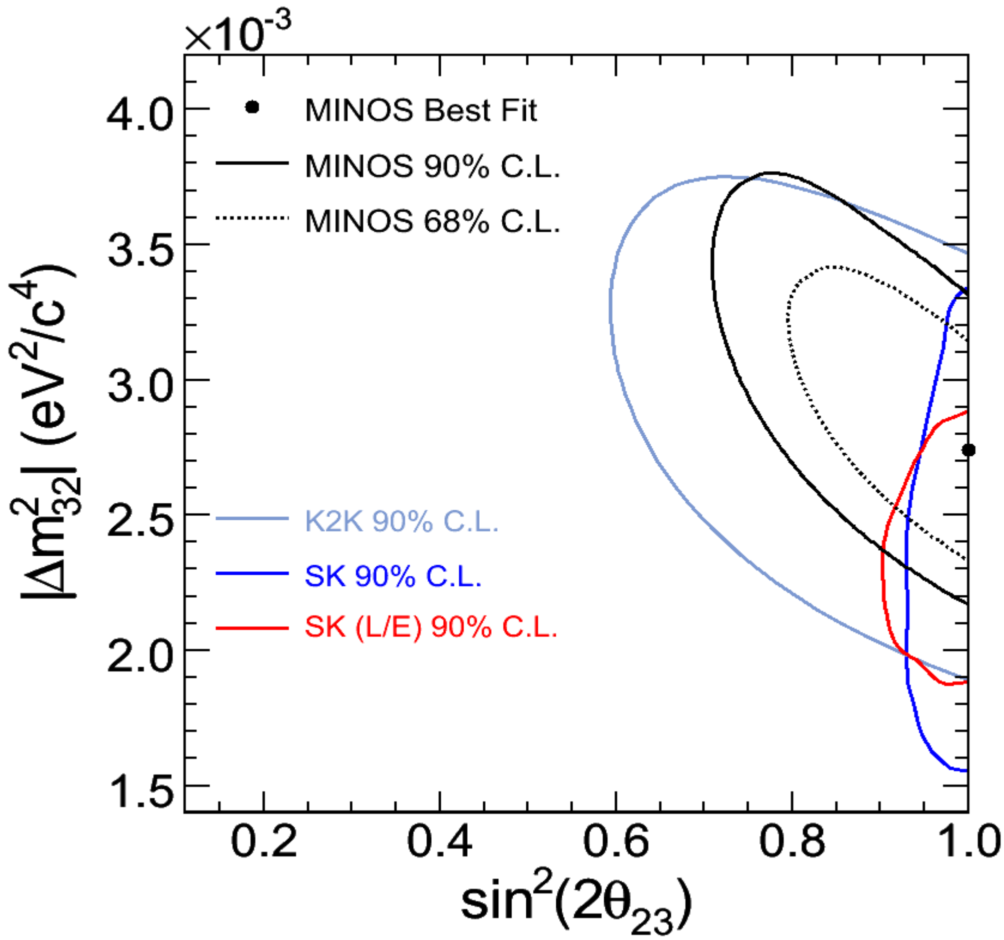




Sample	*Observed*	*Expected*	*Ratio*
ν_μ (<30 GeV)	**215**	**336.0±14.4**	**0.64±0.05**
ν_μ (<10 GeV)	**122**	**238.7±10.7**	**0.51±0.05**
ν_μ (<5 GeV)	**76**	**168.4±8.8**	**0.45±0.06**

FD Event totals

MINOS Allowed Region

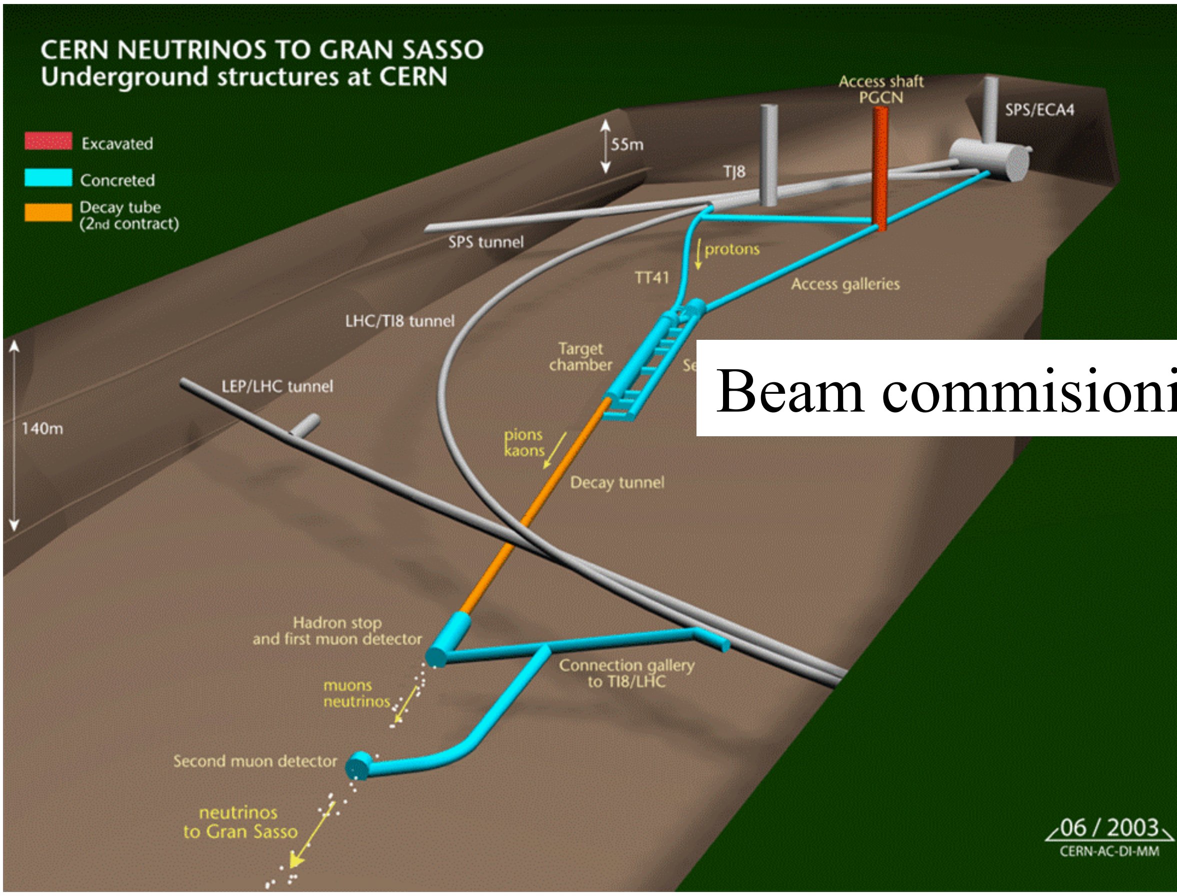


$$\left|\Delta m^2_{32}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

CNGS Program at CERN

Migliozzi-NUFACT 05



Beam commisioning

Higher Energy for τ appearance

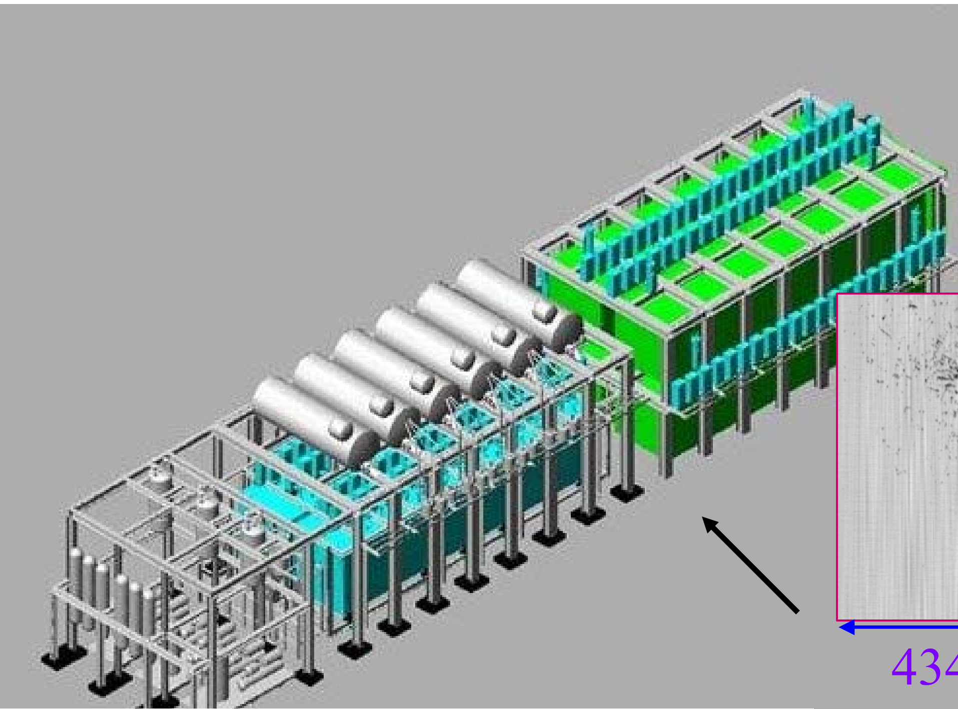
4.5 x 10^{19} pot/year

For $\Delta m^2 = 2.4 \times 10^{-3}$ and maximal mixing

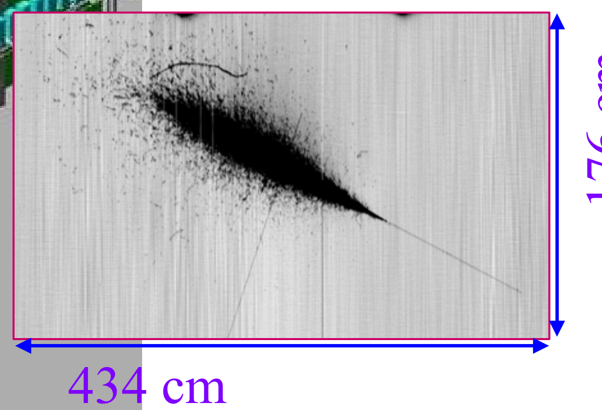
expect 16 ν_τ CC/kton/year at Gran Sasso

CNGS ν_τ appearance detectors

Migliozzi-NUFACT 05



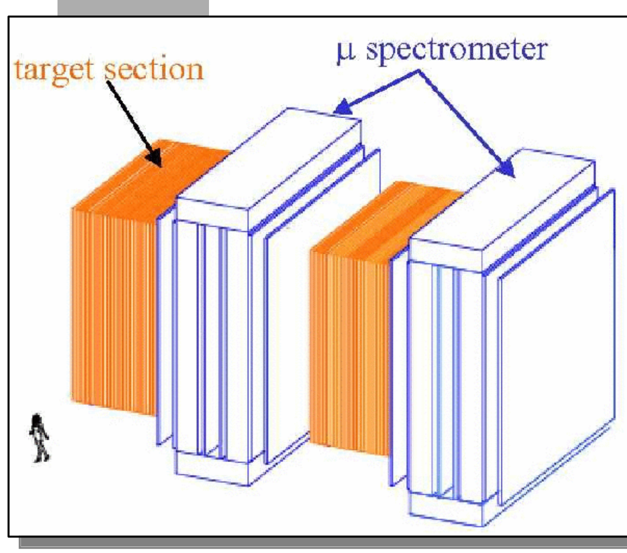
em shower



ICARUS liquid Ar T1800.

600 Tons built so far

About 15 events in 5 years.



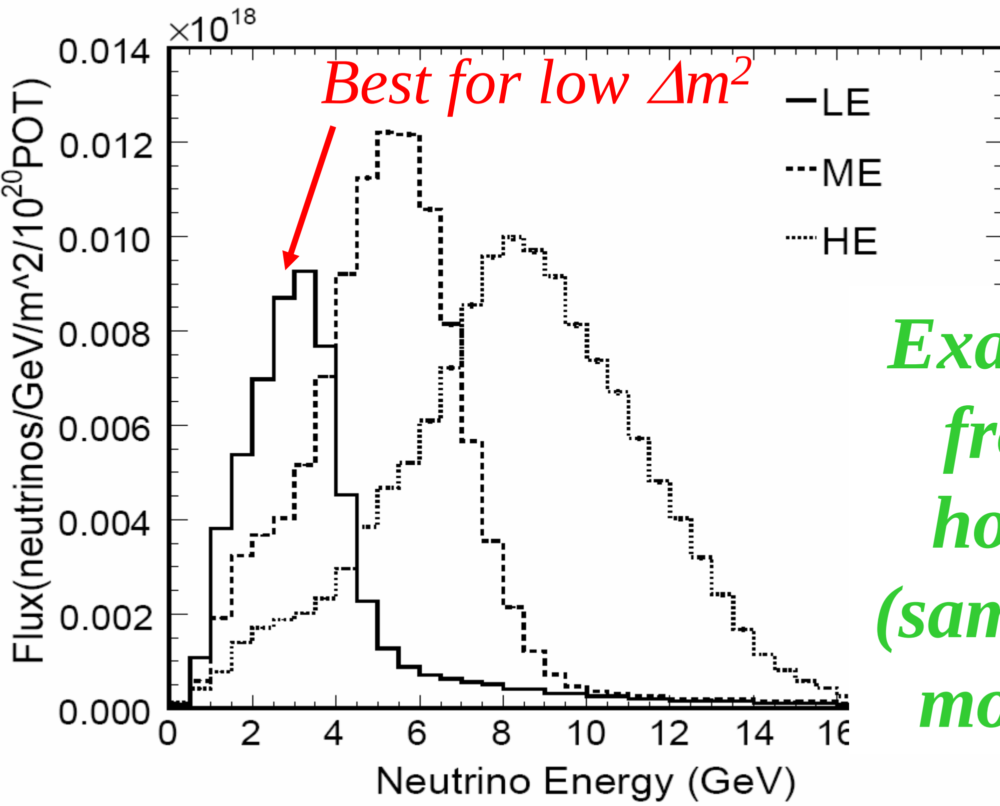
OPERA hybrid emulsion detector

Fiducial Target Mass	1.8 kton
ν_τ signal ($\Delta m^2 = 2.4 \times 10^{-3}$ eV^2)	12.8 events
Background	0.8 events

Petronzio-NO-VE 06

BACKUP SLIDES

Beam Energy Variability



Example spectra from varying horn positions (same effect from moving target)

ν_μ CC Events in MINOS 5kt detector (2.5 x 10^{20} POT/yr)

Low	~ 1600/yr
Medium	~ 4300/yr
High	~ 9250/yr

Detector Assembly at Soudan

Steel Welded and modules placed.

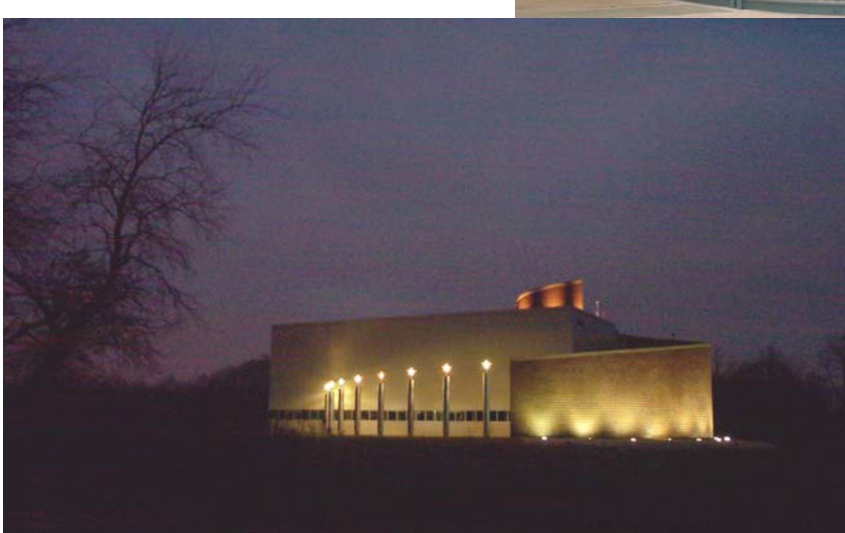
Plane lifted to vertical

6-8 Planes per week

Crane carries plane down the hall for installation!

Completed 2003

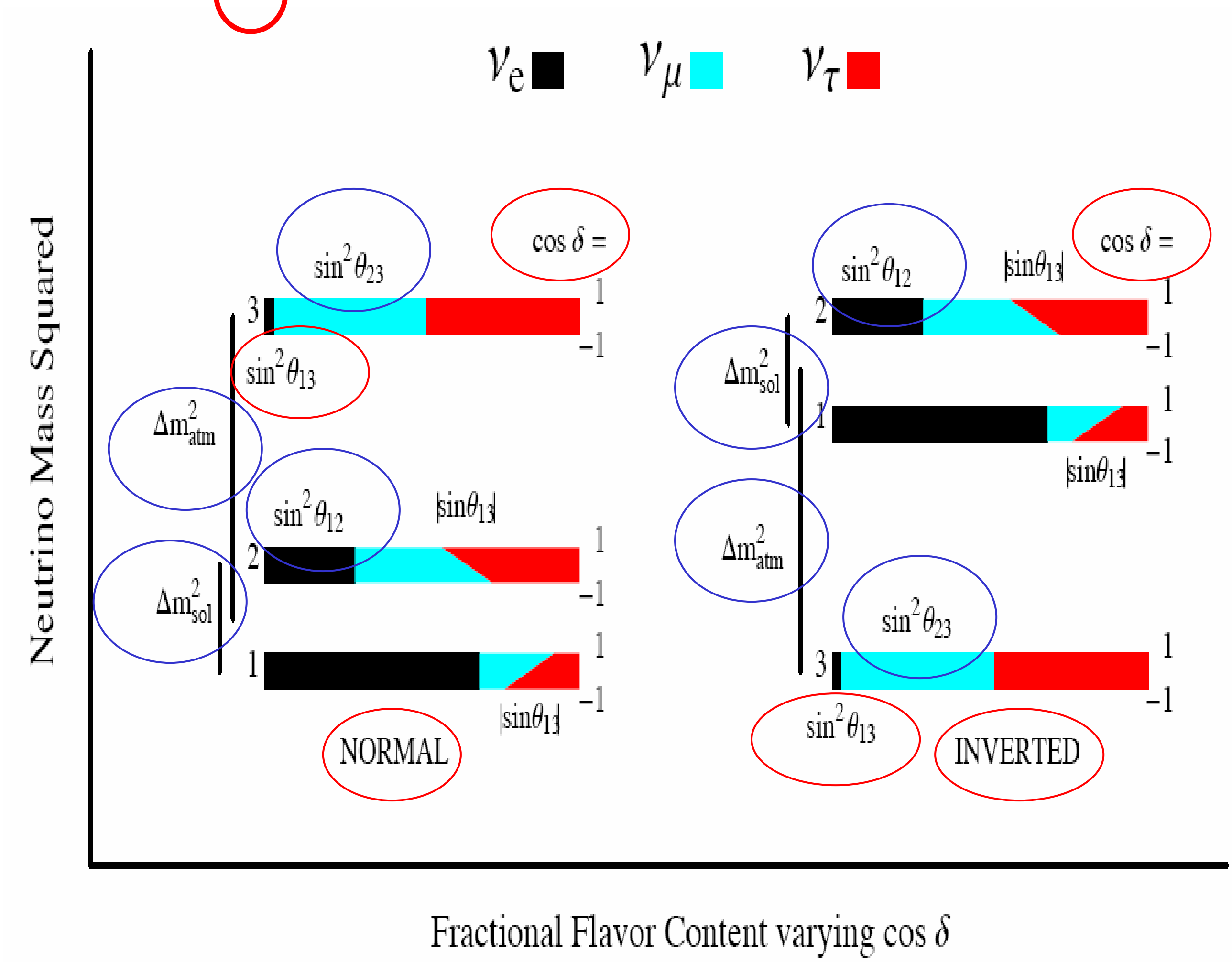
Completion of Buildings, Shafts



Status of our Knowledge

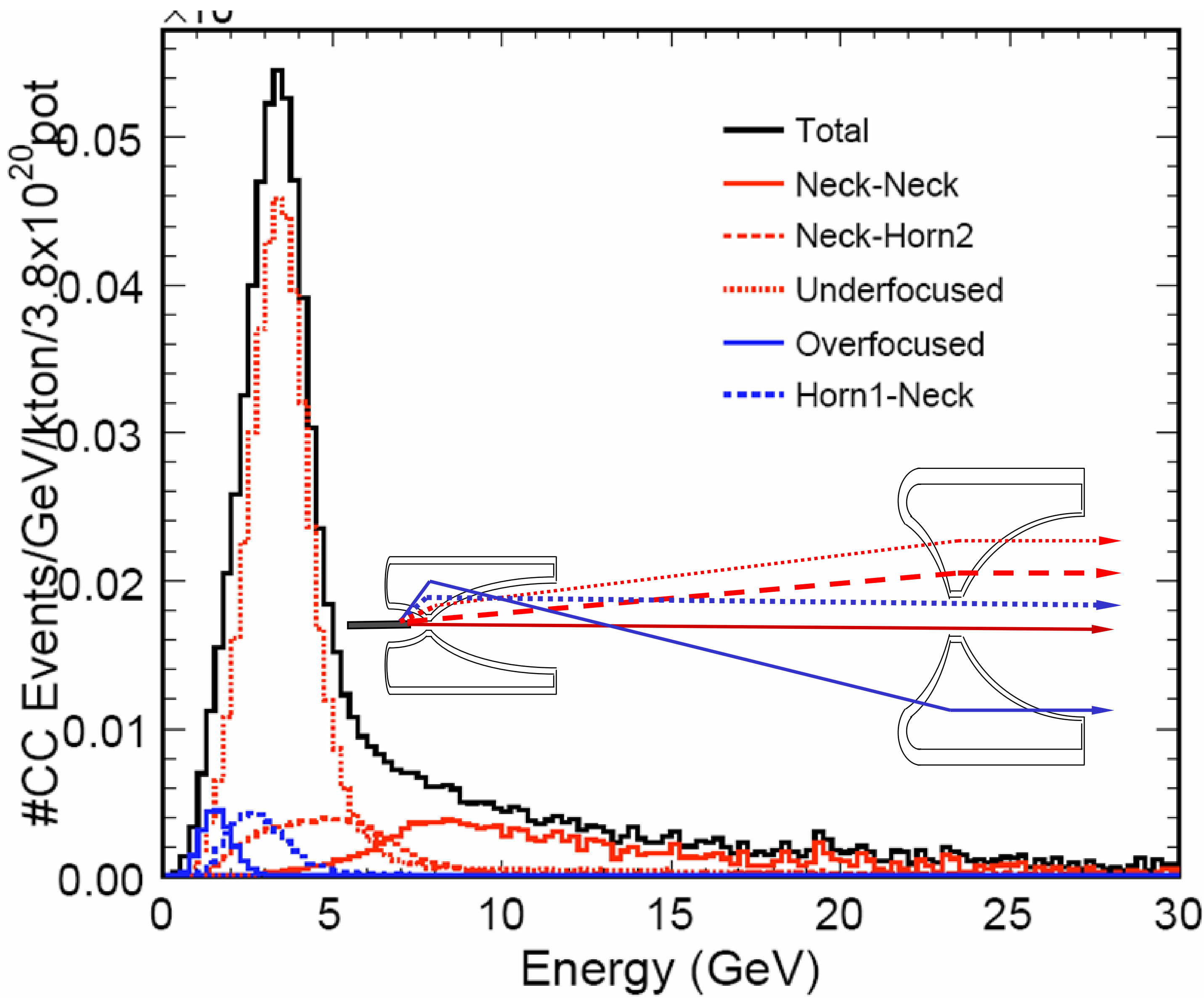
Know to some extent

Don't know

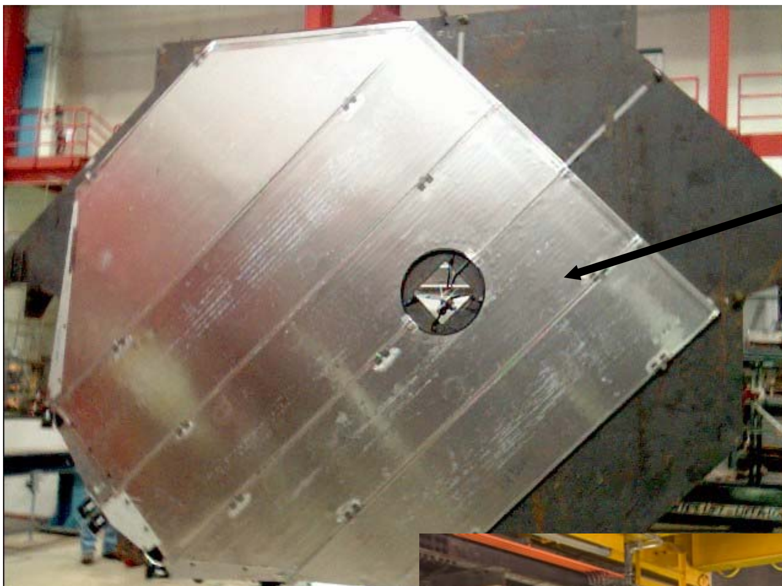


O. Mena and S. Parke, hep-ph/0312131

Neutrino Beam 101 (from Sacha Kopp)



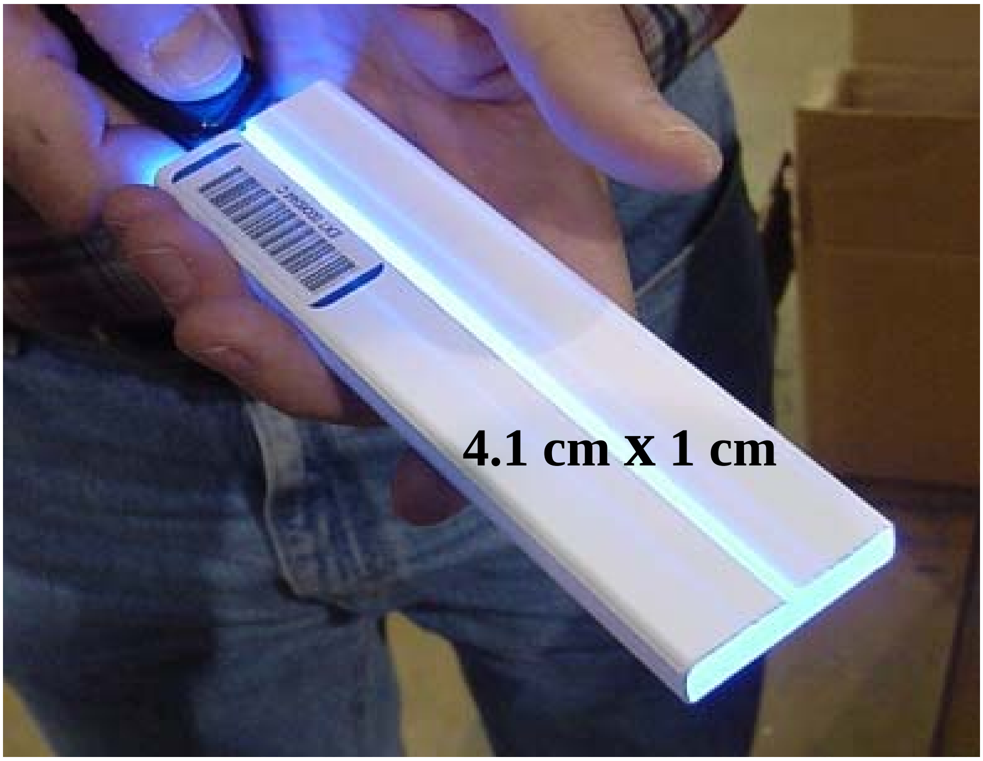
Near Detector Assembly at Fermilab



Scintillator modules

• Planes assembled above ground, then moved to final location.

Detector Technology



Scintillator strips are extruded polystyrene (Itasca Plastic)

1.2 mm Kuraray wavelength shifting fiber fits into groove

Groups of 20 or 28 strips are assembled into “modules”

Both ends read out to increase light yield.