Neutrinos: A History

Neutrino Mixing

The MINOS Experiment

The NuMI Beam

Finding νs in MINOS

Disapperance Results

Future prospects

Summary

Hunting Anti-neutrinos with MINOS

Stony Brook University, 10/11/2010

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October 11, 2010

Outline

1 Neutrinos: A History

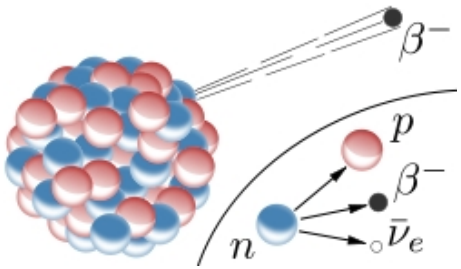
2 Neutrino Mixing

3 The MINOS Experiment
- The NuMI Beam
- Finding νs in MINOS
- Disapperance Results
- Future prospects

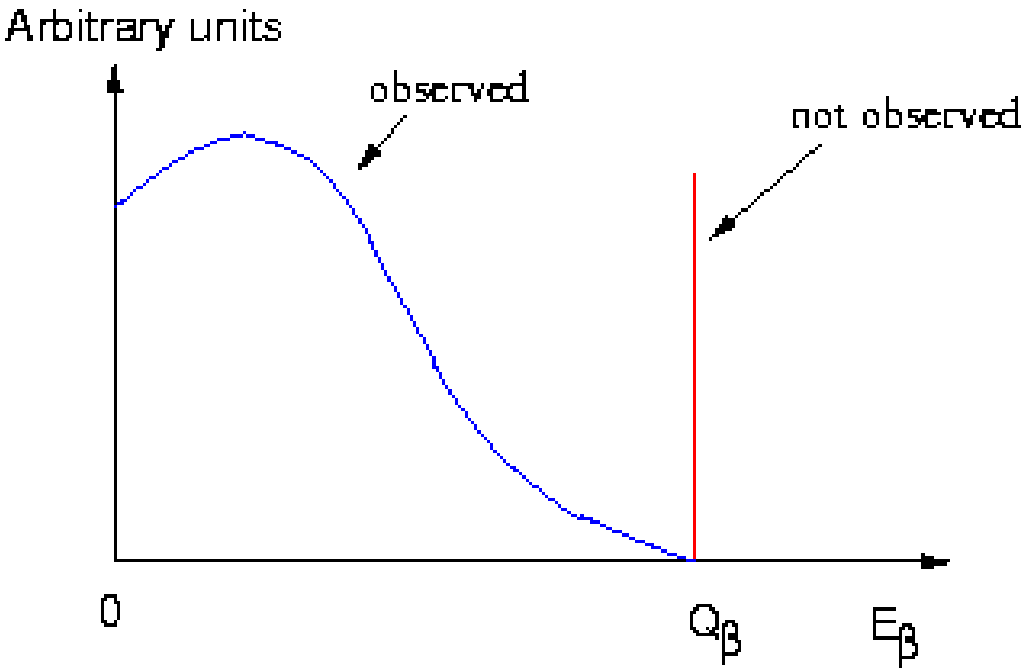
4 Summary

A BRIEF HISTORY OF THE NEUTRINO

Neutrino Conception



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

....., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.....
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

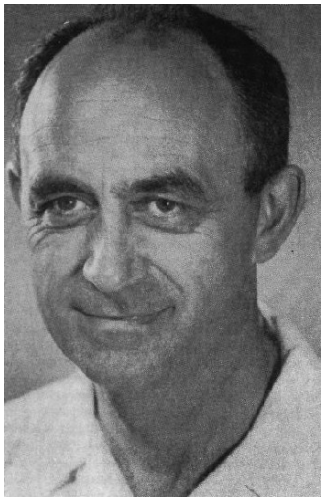
Neutrino Conception

1932: James Chadwick discovers the neutron, $\text{mass}_{\text{neutron}} = 1.0014 \times \text{mass}_{\text{proton}}$ - its too heavy - cant be Pauli's particle

James Chadwick

Neutrino Conception

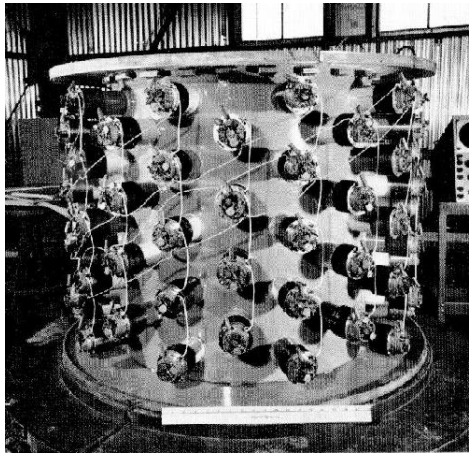
Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".



Enrico Fermi

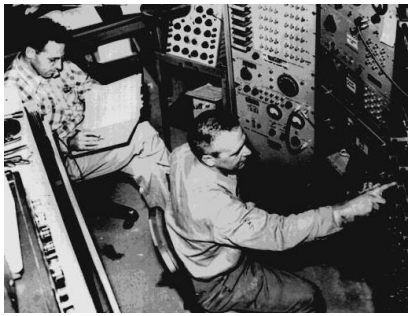
Finding Neutrinos...

1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n + {}^{108}Cd \rightarrow {}^{109}Cd* \rightarrow {}^{109}Cd + \gamma$ $(\tau = 5\mu s)$.



Neutrinos first detected using a nuclear reactor!

ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos.

The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (p,n).

$$\nu \text{ mean free path} = \frac{\text{Mass of the proton}}{\sigma \times \text{density}}$$

$$= \frac{1.67 \times 10^{-24}\mathrm{g}}{10^{-43}\mathrm{cm}^2 \times 11.4\mathrm{g/cm}^3} \approx 1.5 \times 10^{16}\mathrm{m} = \text{1.6 LIGHT YEARS}$$

A proton has a mean free path of 10cm in lead

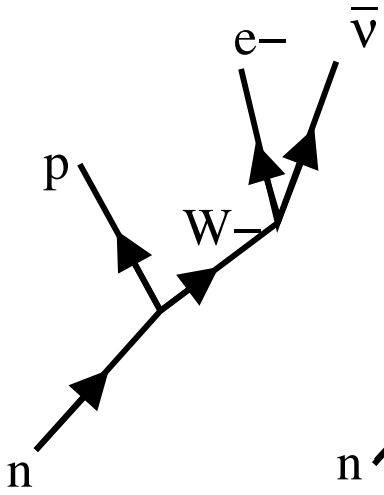
Neutrino detectors have to be MASSIVE

The Theory of Weak Interactions

$\geq$ 1933: **Fermi Glashow/Salam/Weinberg (1968) build the theory of weak interactions and beta decay**

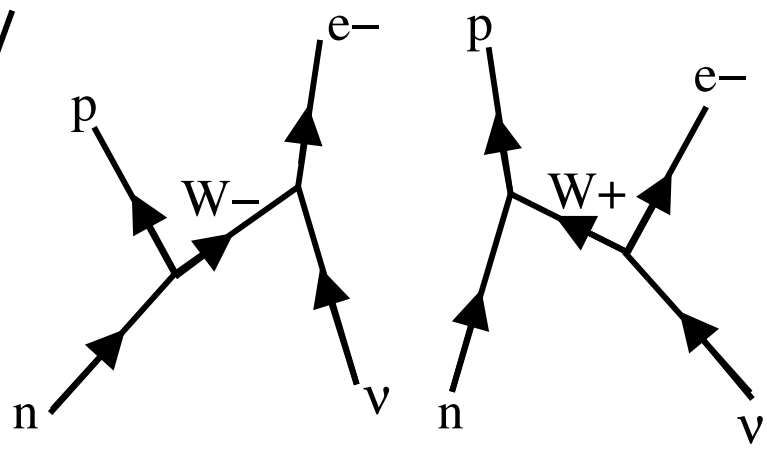
Charged current interactions

Decay of neutron



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

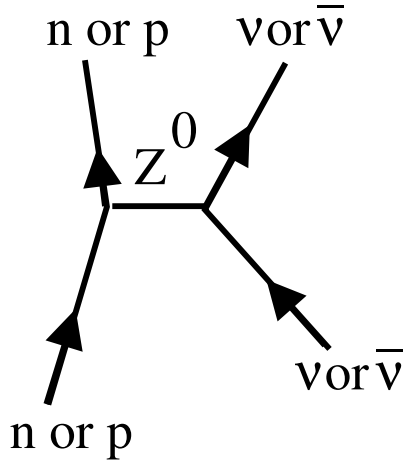
Neutrino interacts with neutron



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

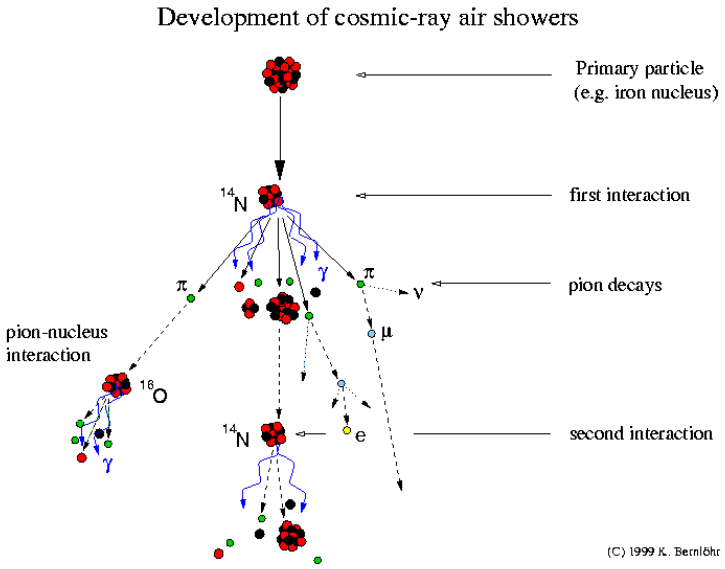
Neutral current interactions

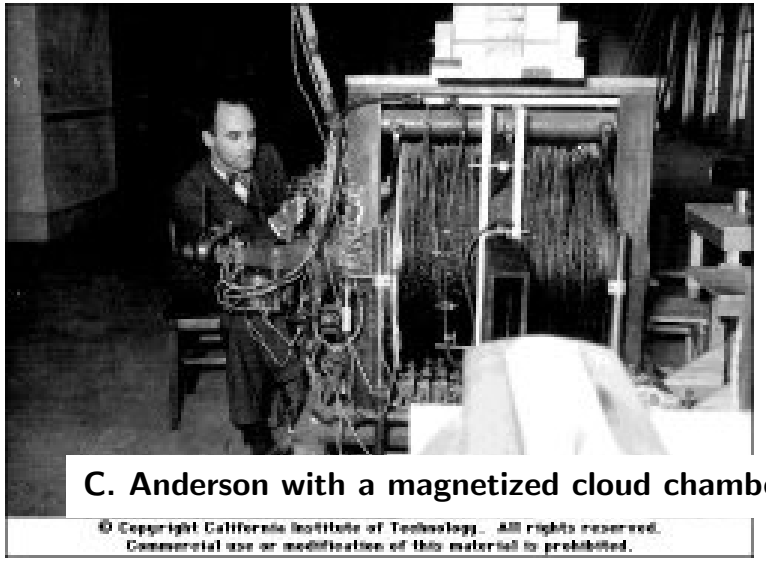
n or p interacts with neutrino or antineutrino



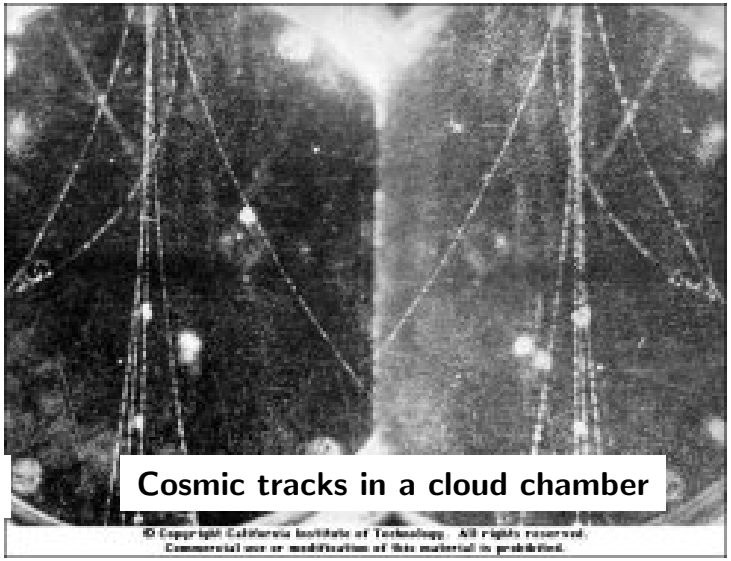
Discovery of the Muon (μ)

1936: Carl Andersen, Seth Neddermeyer observed an unknown charged particle in cosmic rays with mass between that of the electron and the proton - called it the μ meson (now muons).





C. Anderson with a magnetized cloud chamber



Cosmic tracks in a cloud chamber

The Lepton Family and Flavors

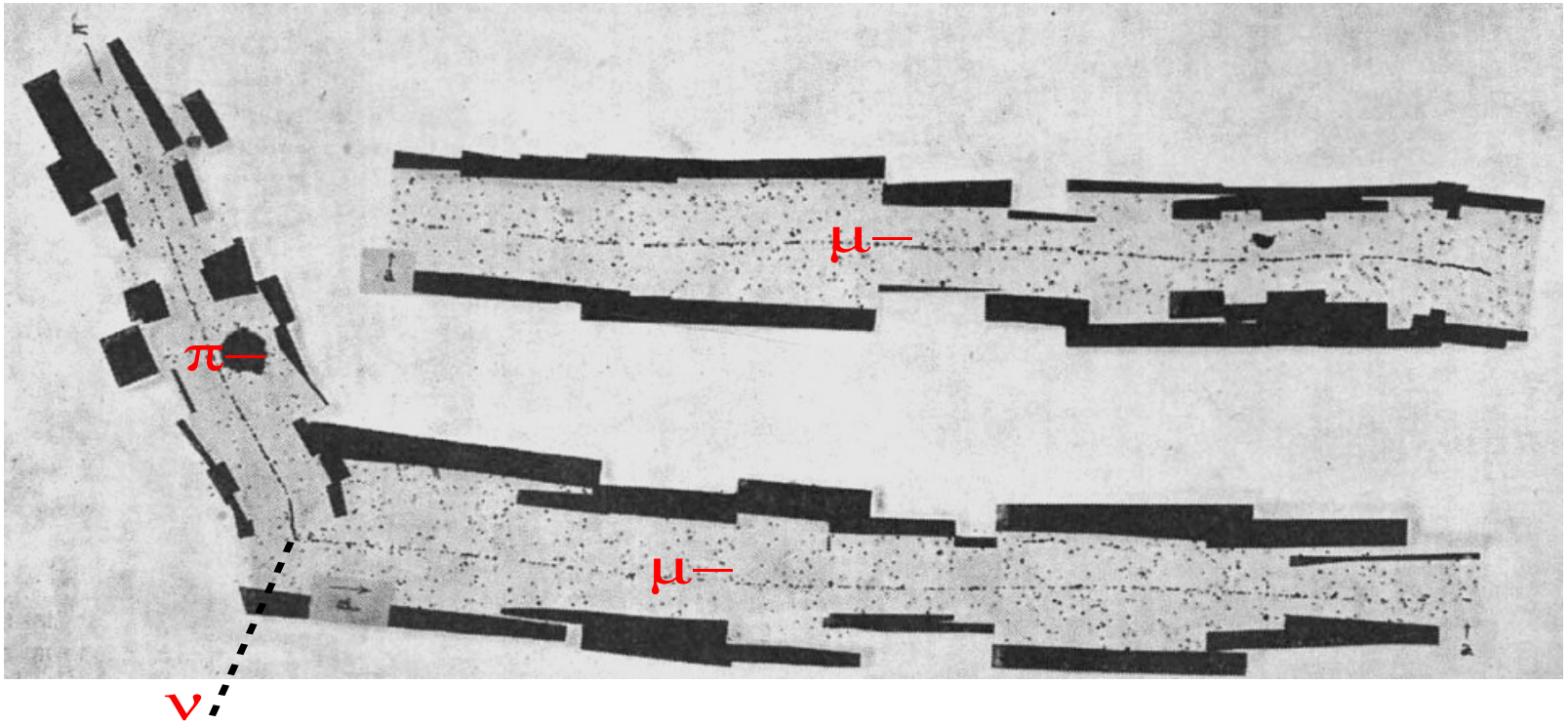
The muon and the electron are *different "flavors" of the same family of elementary particles called leptons*.

Generation	**I**	**II**	**III**
Lepton	e^-	μ	τ
Mass (GeV)	**0.000511**	**0.1057**	**1.78**
Lifetime (sec)	**stable**	2.2×10^{-6}	2.9×10^{-13}

Neutrinos are neutral leptons. **Do ν's have flavor too?**

Discovery of the Pion: 1947

Cecil Powell takes emulsion photos aboard high altitude RAF flights. A charged particle is found decaying to a muon:

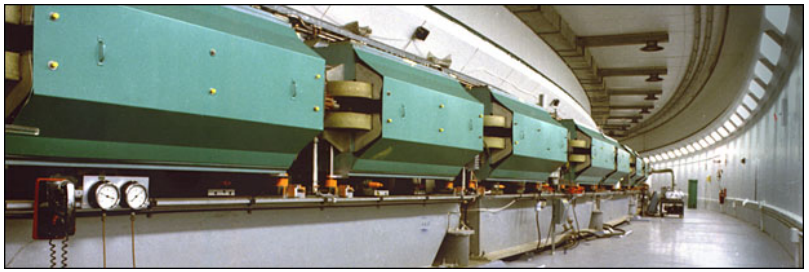


mass$_{\pi^-}$ = 0.1396 GeV/c^2 , τ = 26 ns.

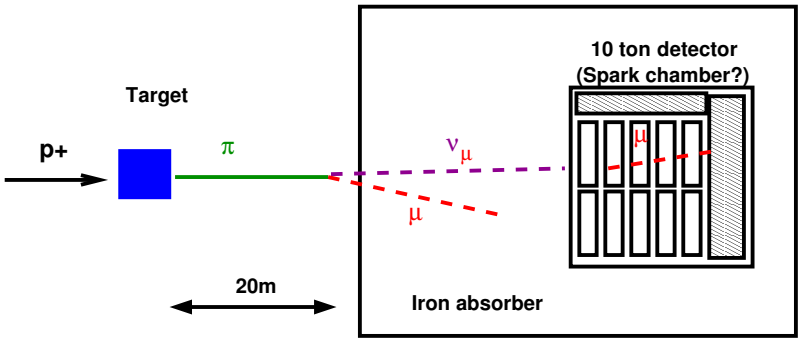
Pions are composite particles from the "hadron" family which includes protons and neutrons.

Neutrinos have Flavors

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \rightarrow \mu\nu_x$



The AGS



Making ν's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

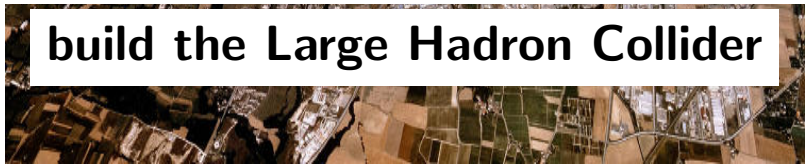
The first accelerator neutrino experiment was at the AGS.

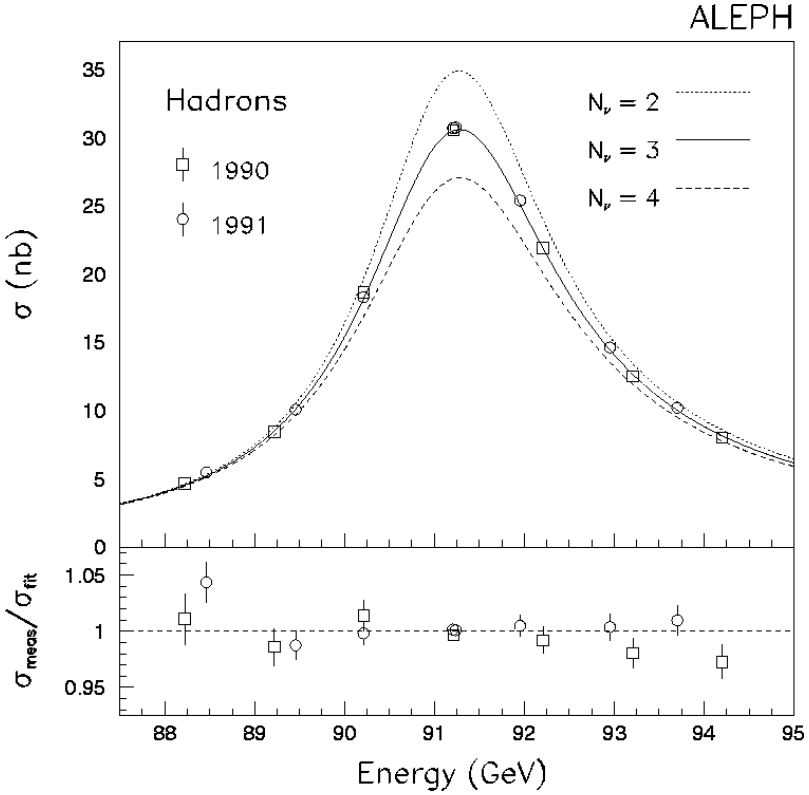
Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

The LEP e^+e^- collider at CERN, Switzerland

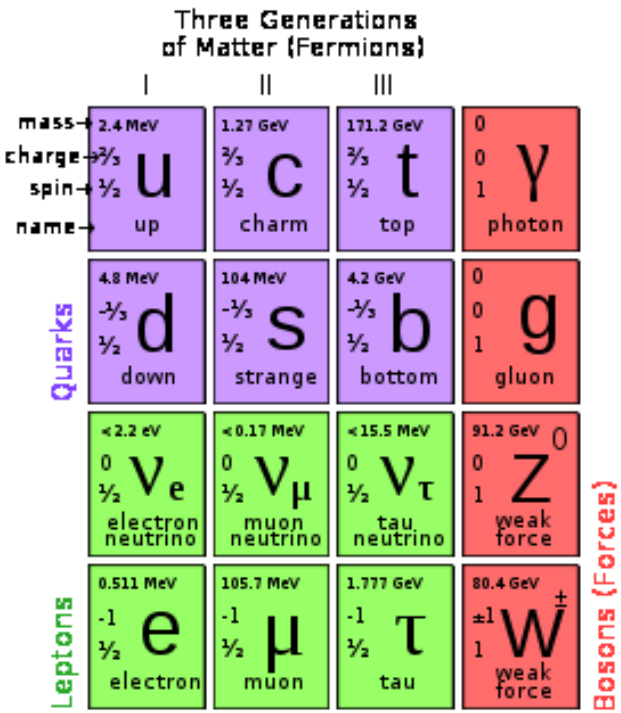
The 27km LEP ring was reused to build the Large Hadron Collider

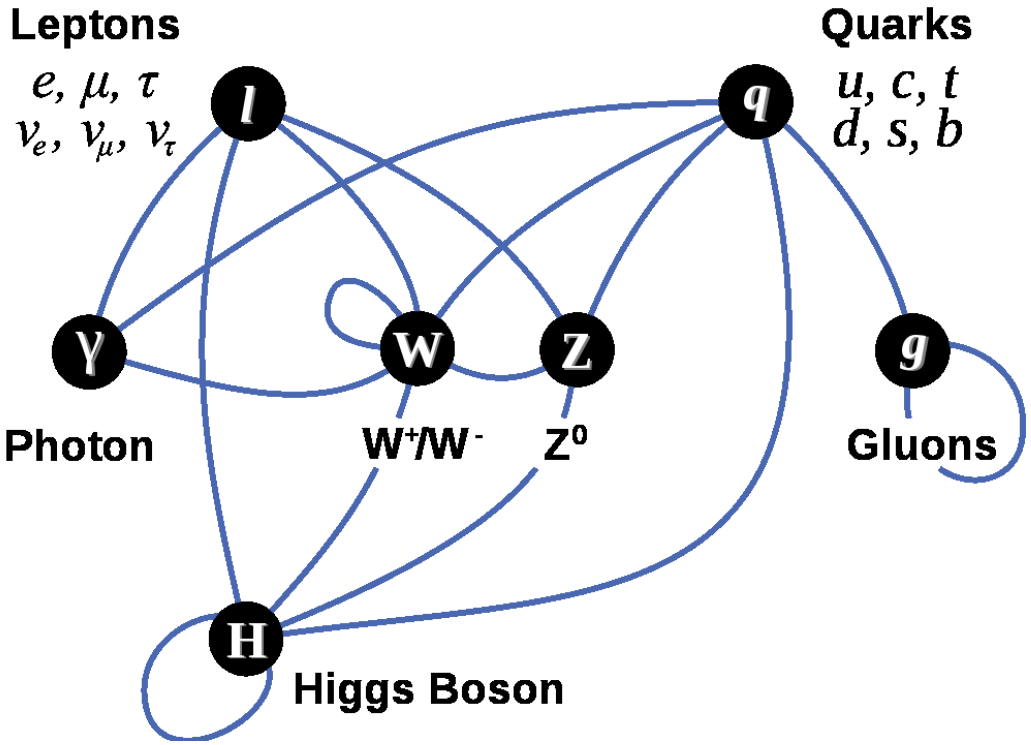




$N_\nu = 2.984 \pm 0.008$

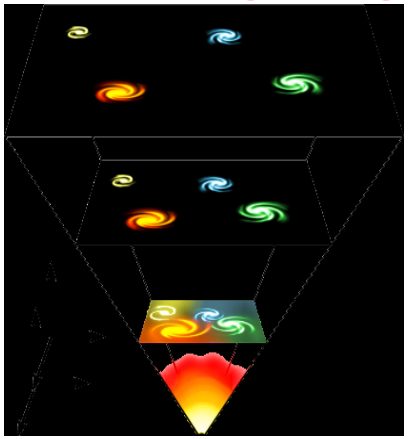
The Particle Zoo





Sources of Neutrinos

Big Bang



10^{-4} eV

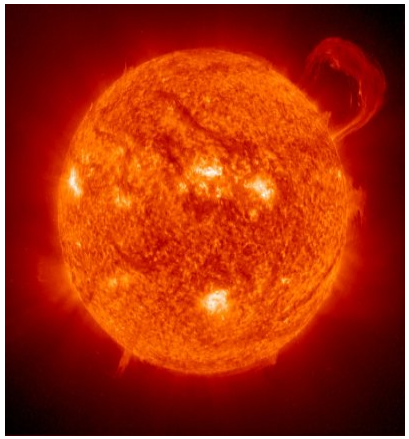
$300/\mathrm{cm}^3$

Reactors

few MeV

$10^{21}/\mathrm{GW_{th}}/\mathrm{s}$

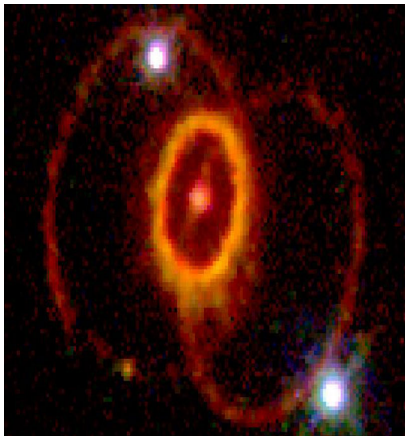
Sun



0.1-14 MeV

$10^{10}/\mathrm{cm}^2/\mathrm{s}$

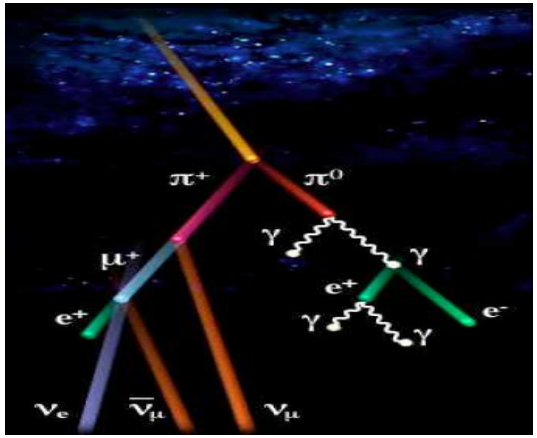
SuperNova



$\sim$ 10 MeV

$10^{9}/\mathrm{cm}^2/\mathrm{s}$

Atmosphere



$\sim$ 1 GeV

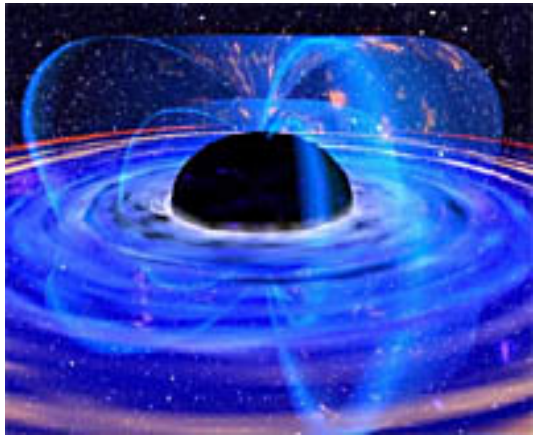
few/cm^2/s

Accelerators

1-20 GeV

$10^5/\mathrm{cm}^2/\mathrm{s}$ (at 1km)

Extragalactic



TeV-PeV

varies

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NEUTRINO MIXING AND OSCILLATIONS

Neutrino oscillations

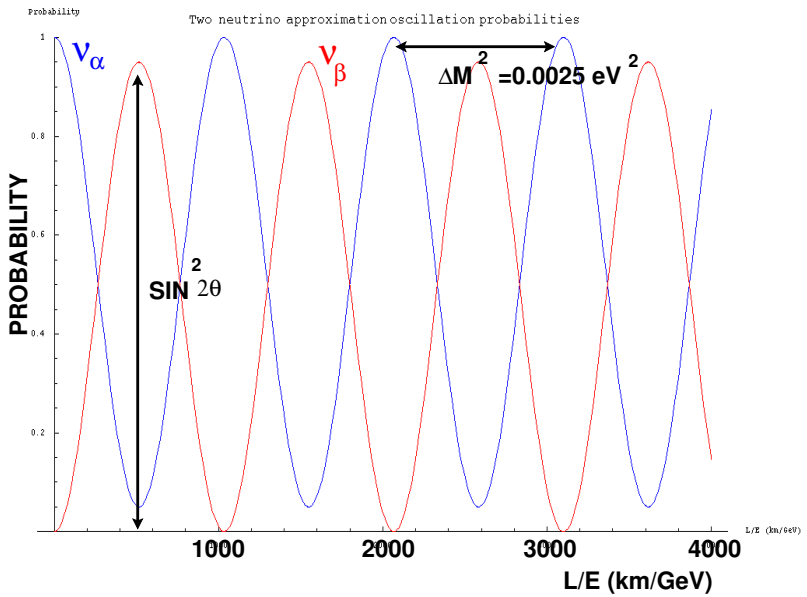
1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m_2^2 - m_1^2)$ in eV^2, L (km) and E (GeV).



Observation of oscillations implies non-zero mass eigenstates

The Homestake Experiment

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

Ray Davis

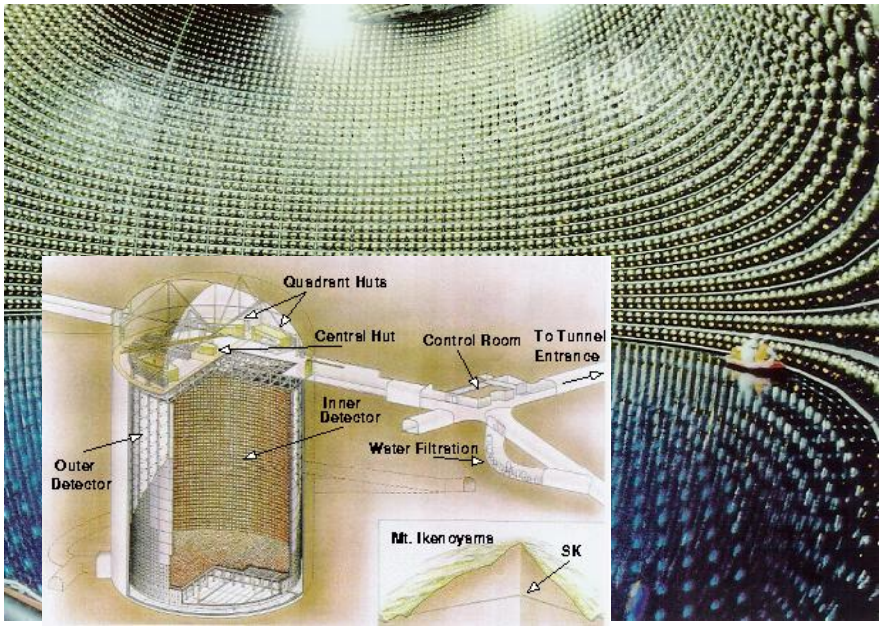
1. $\nu_e^{sun} + ^{37}\text{CL} \rightarrow e^- + ^{37}\text{Ar}$, $\tau(^{37}\text{Ar}) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

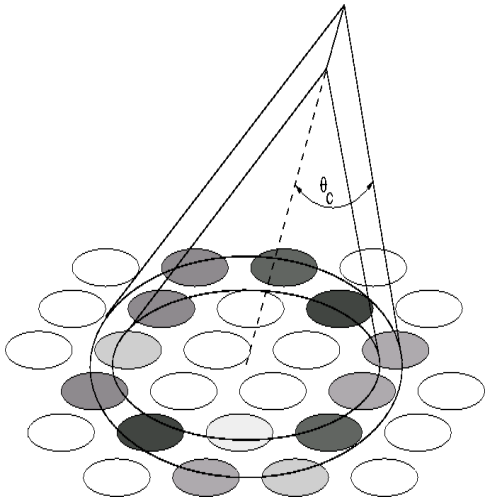
Results: 1969 - 1993 Measured 2.5 ± 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Solar ν_e disappearance $\Rightarrow$ first experimental hint of oscillations

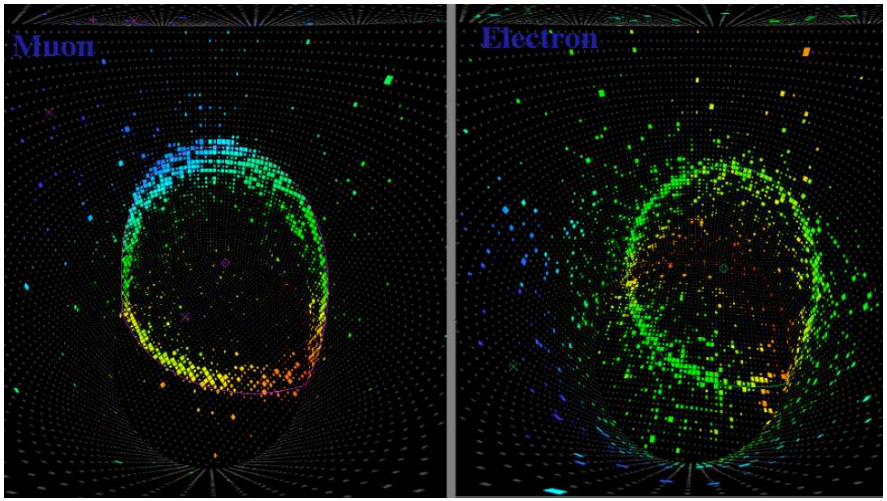
The Super-Kamiokande Experiment

A huge 50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes. Located in an old zinc mine 0.6km under Mount Ikena in the Japanese Alps, near the town of Kamioka. The project has been collecting data since 1 April 1996.





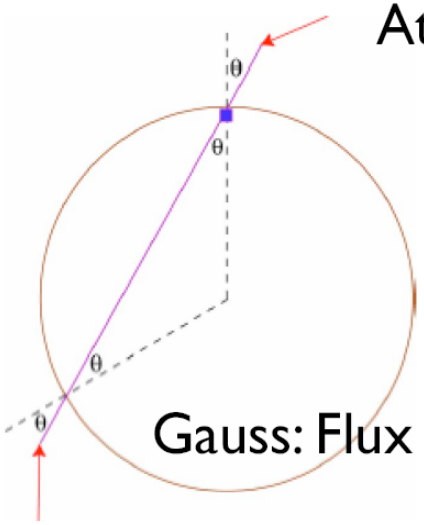
Particle id using rings of Čerenkov light

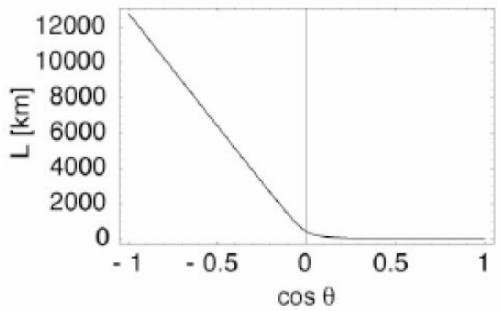


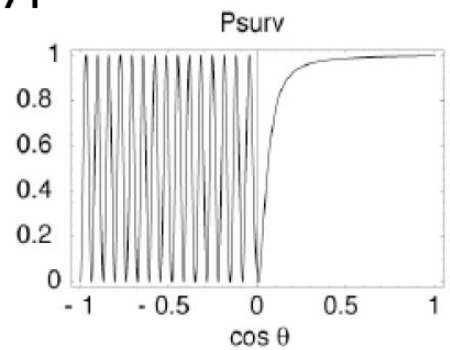
Super-Kamiokande: Atmospheric ν_μ Disappearance

Atmospheric neutrinos as a source for oscillation experiments

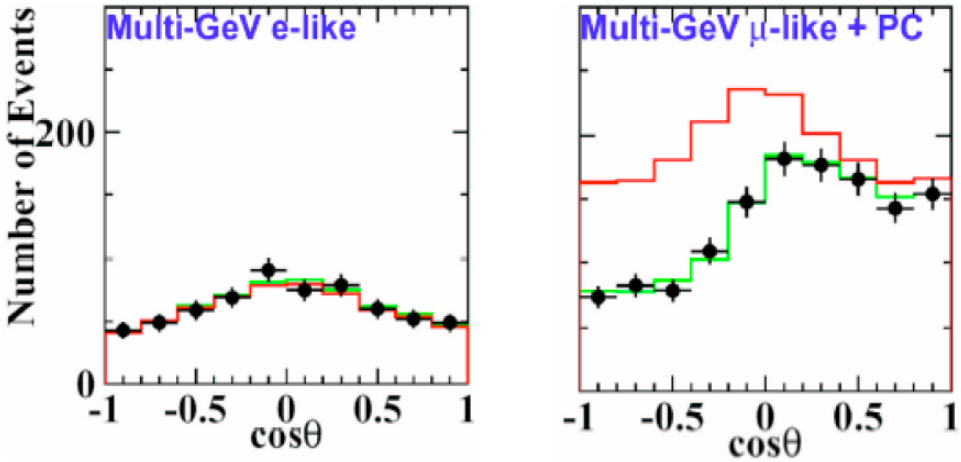
Atm. neutrinos 2:1 mu:e type







Gauss: Flux inside spherical shell isotropic

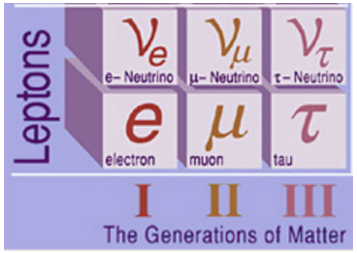


Evidence for neutrino oscillations from SuperK

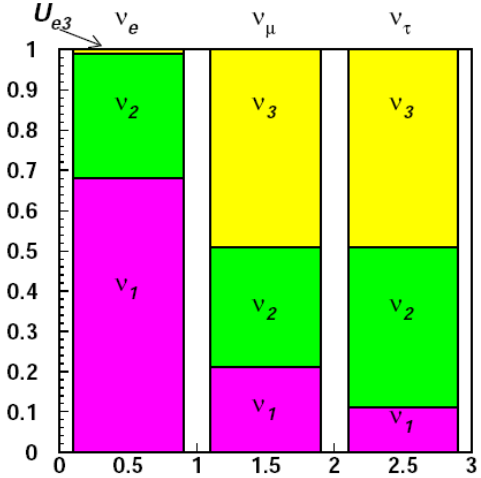
Best fit : $(\sin^2 2\theta_{23}, \Delta m^2_{32}) = (1.02, 2.4 \times 10^{-3} \mathrm{eV}^2) \Rightarrow$ maximal mixing of 2,3 states!

Neutrino Mixing: 3 flavours

We know now of 3 flavours of neutrinos: The 3 flavour PMNS mixing matrix was developed in 1962 by Maki-Nakagawa-Sakata based on Pontecorvo's earlier work:



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

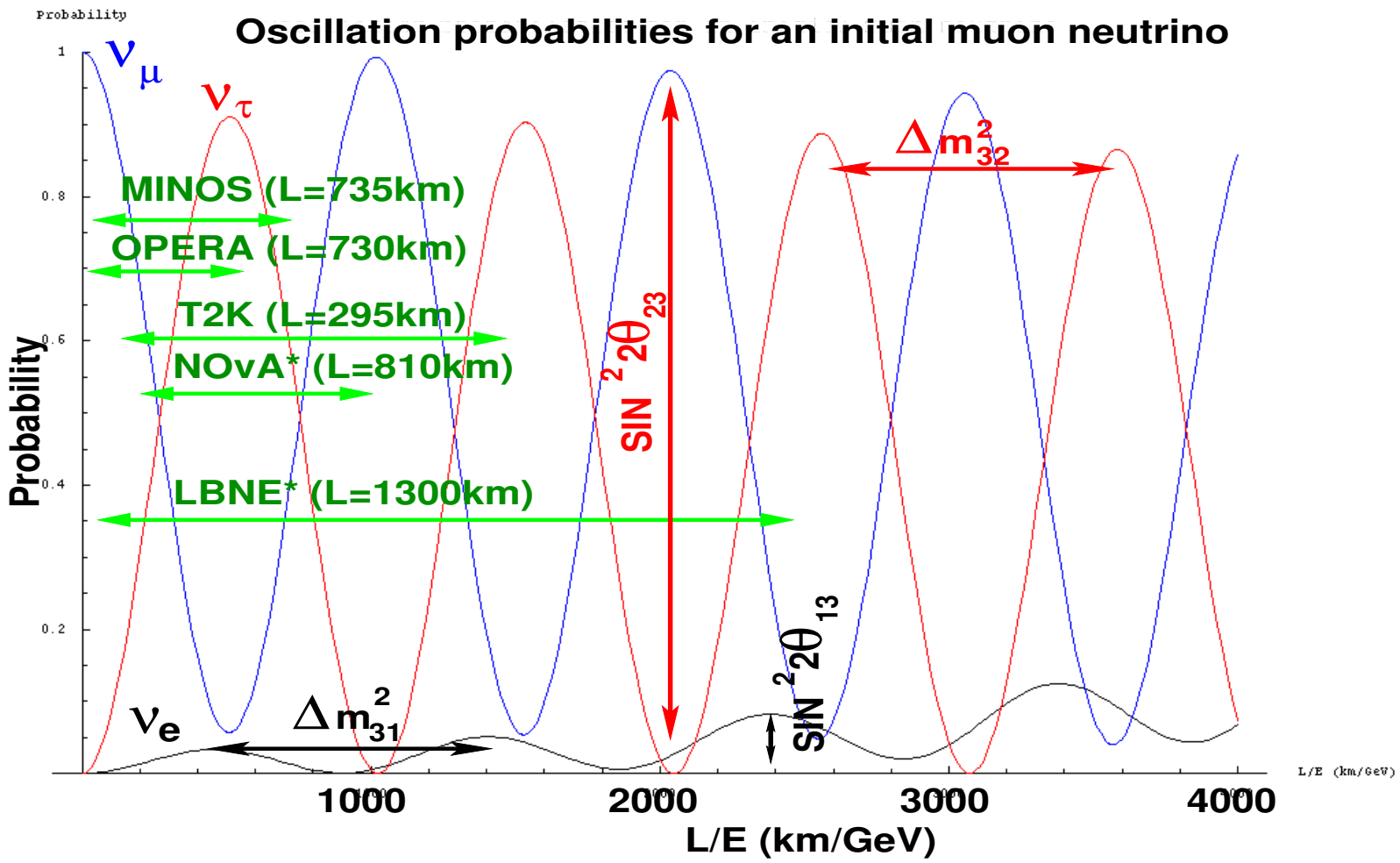


In the past 10 yrs we have measured most of the U_{PMNS} parameters

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & < 0.20\ ?? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

In contrast to CKM, large off diagonal terms:

Measuring ν_μ oscillations - Accelerator Expts

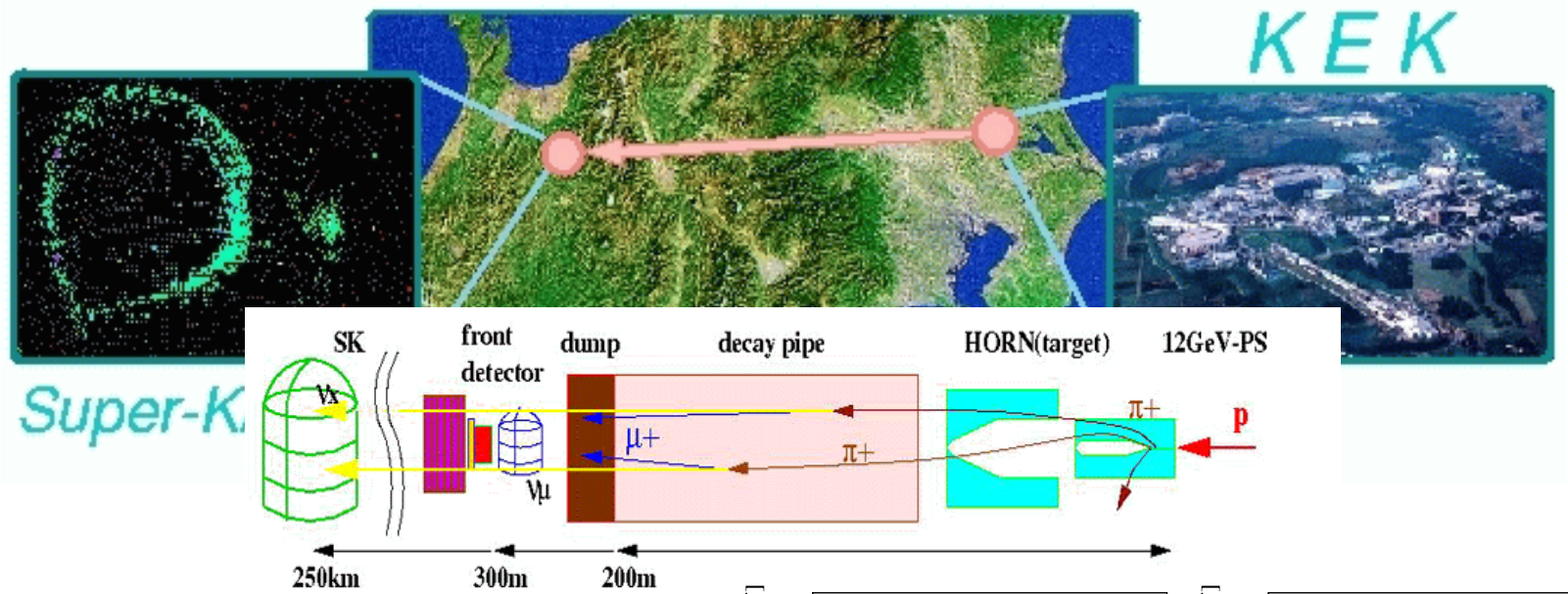


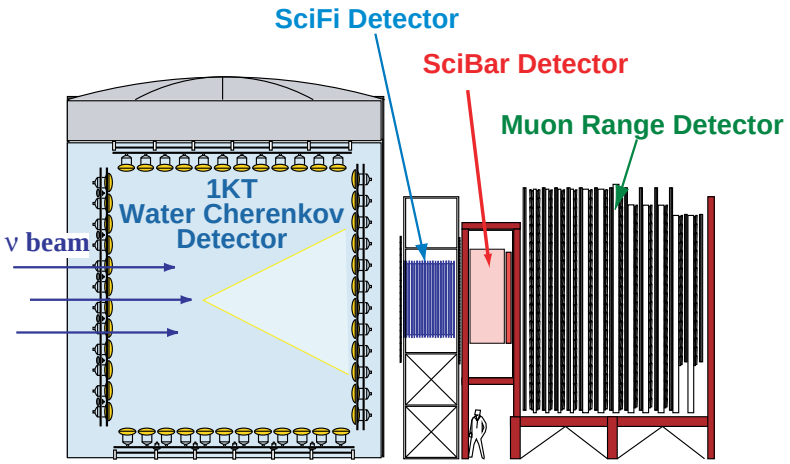
Accelerator expts access all 3-state oscillations using known $\nu/\bar{\nu}$ fluxes.

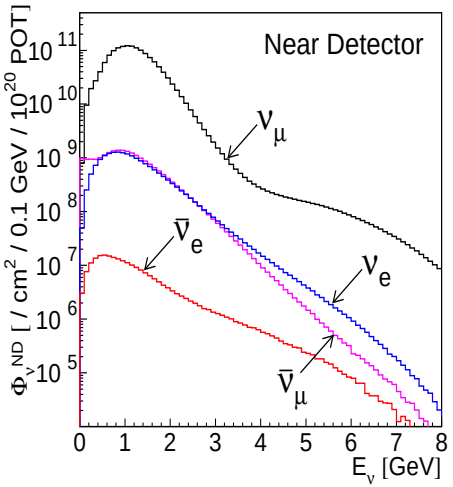
Can provide precision measurements of $\Delta m^2_{31,32}$, $\sin^2 2\theta_{13}$, δ_{cp}

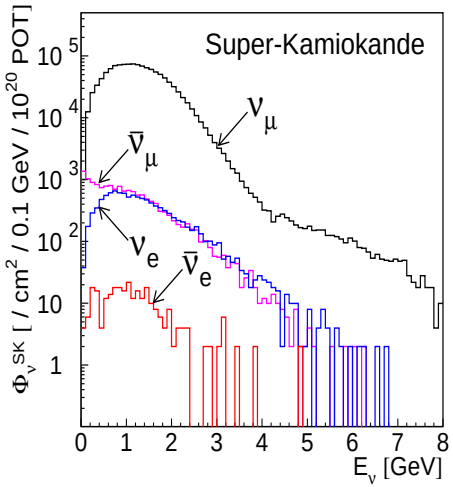
The K2K experiment

The first 2 detector long baseline accel. ν expt. Confirm the SK oscillation result using ν_μ beam from KEK. **L = 250 km.**









K2K results: Accelerator ν_μ Disappearance

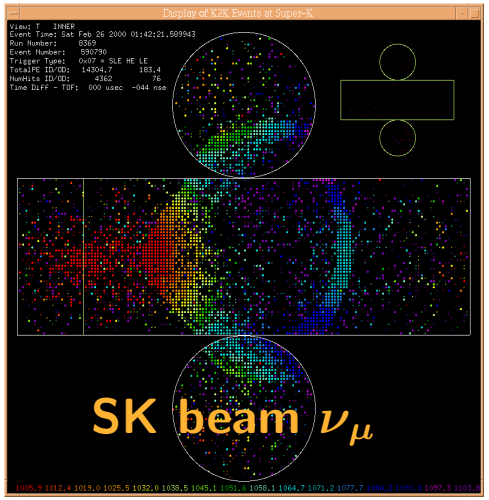
$2 \leftrightarrow 3$ mixing

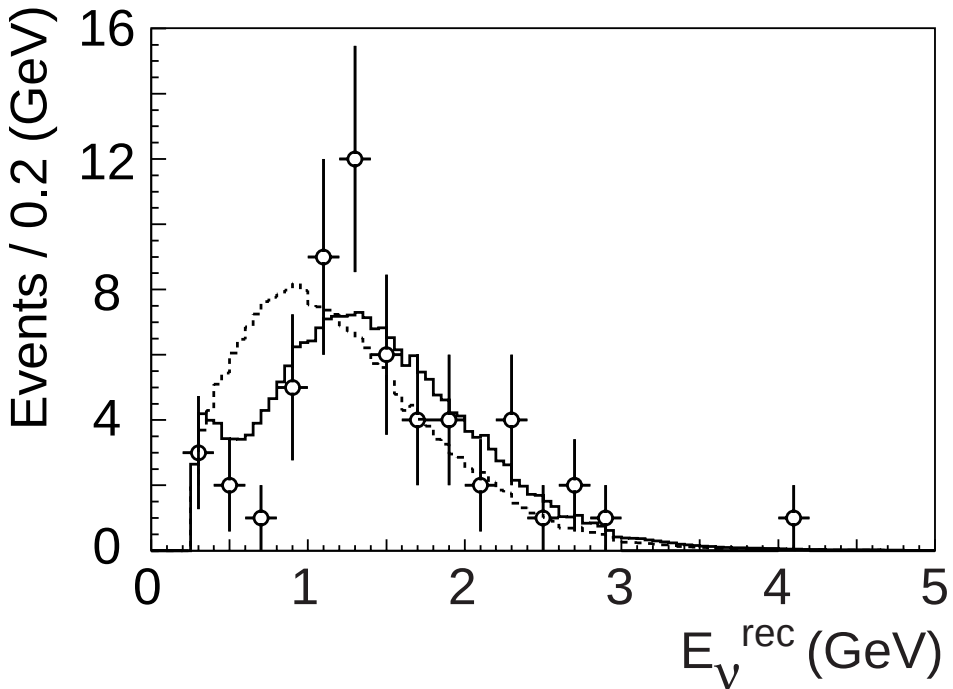
2005: *"Evidence for muon neutrino oscillation in an accelerator-based experiment" PRL 94 (2005) 081802*

Results: Using 8.9×10^{19} protons-on-target.

Find 107 ν_μ CC events in SK

Expected 151^{+12}_{-10}(syst) no-osc.

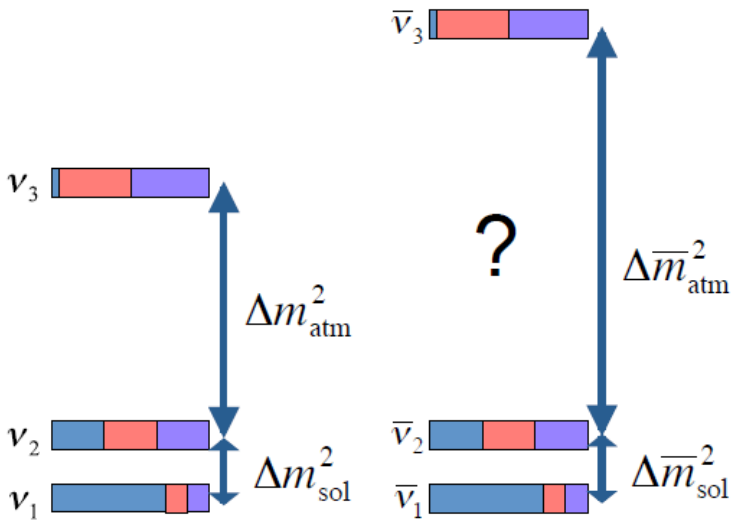


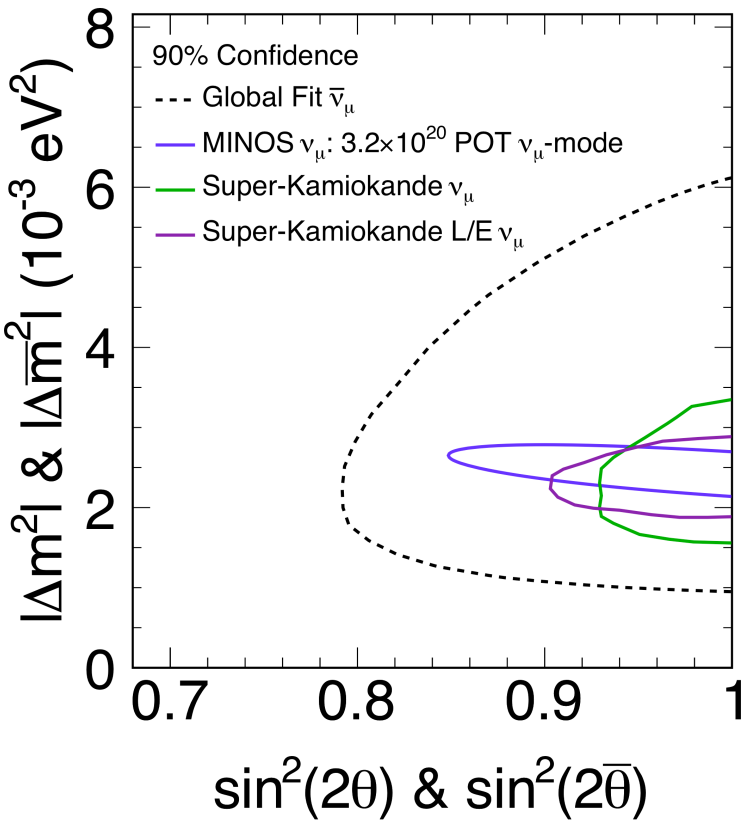


$\Leftarrow$ first evidence for accel. ν_μ disappearance

Anti-neutrino oscillations

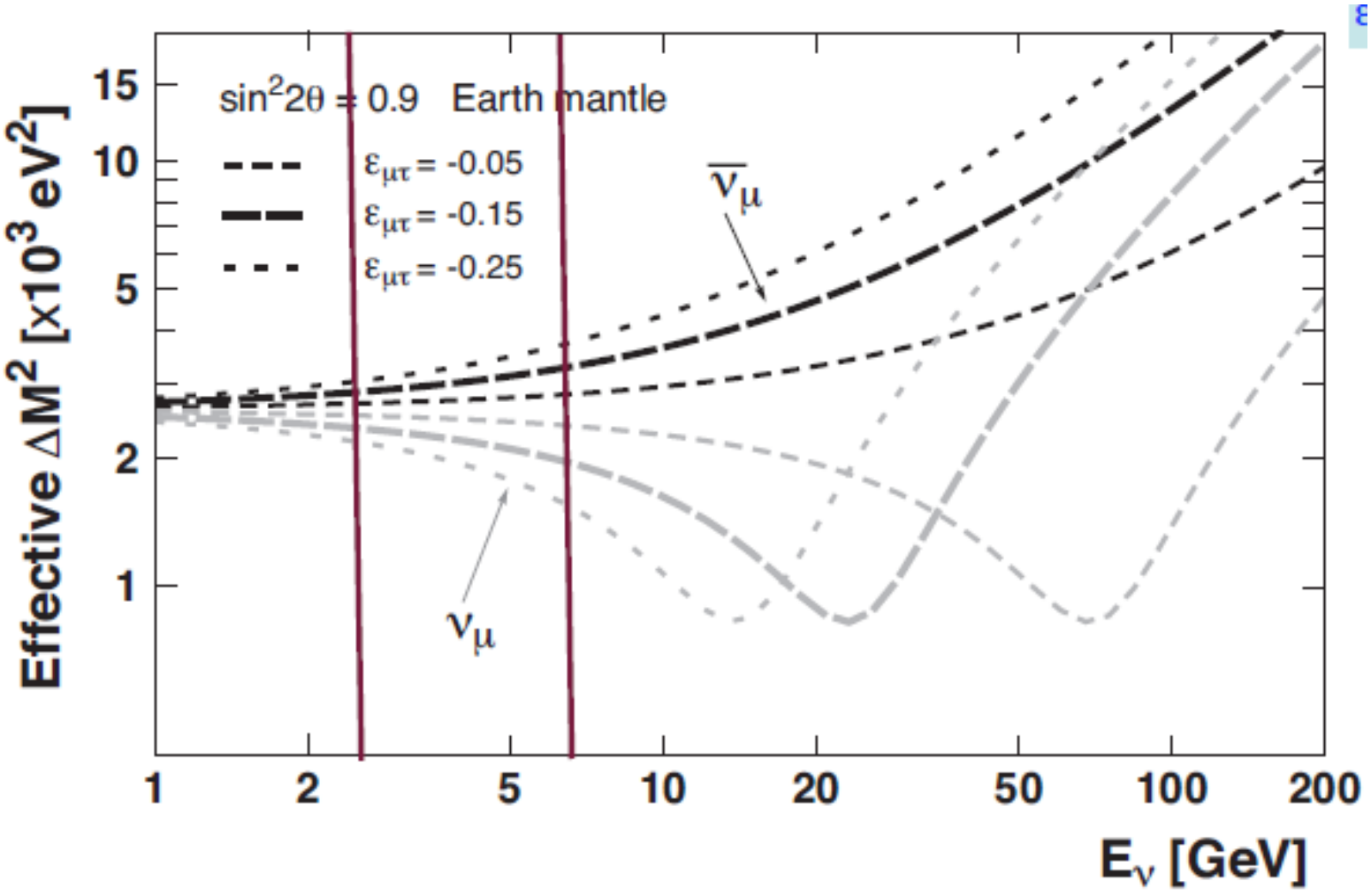
$$P(\nu_\mu \rightarrow \nu_\mu) \; =? \; P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$$





Anti-neutrino oscillations less precisely known

New Physics in Anti-neutrino Oscillations?

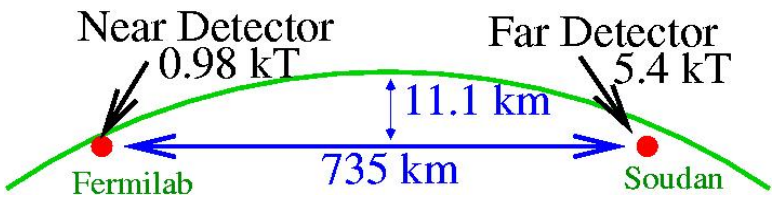


Mann A.W. et al., arxiv 1006.5720

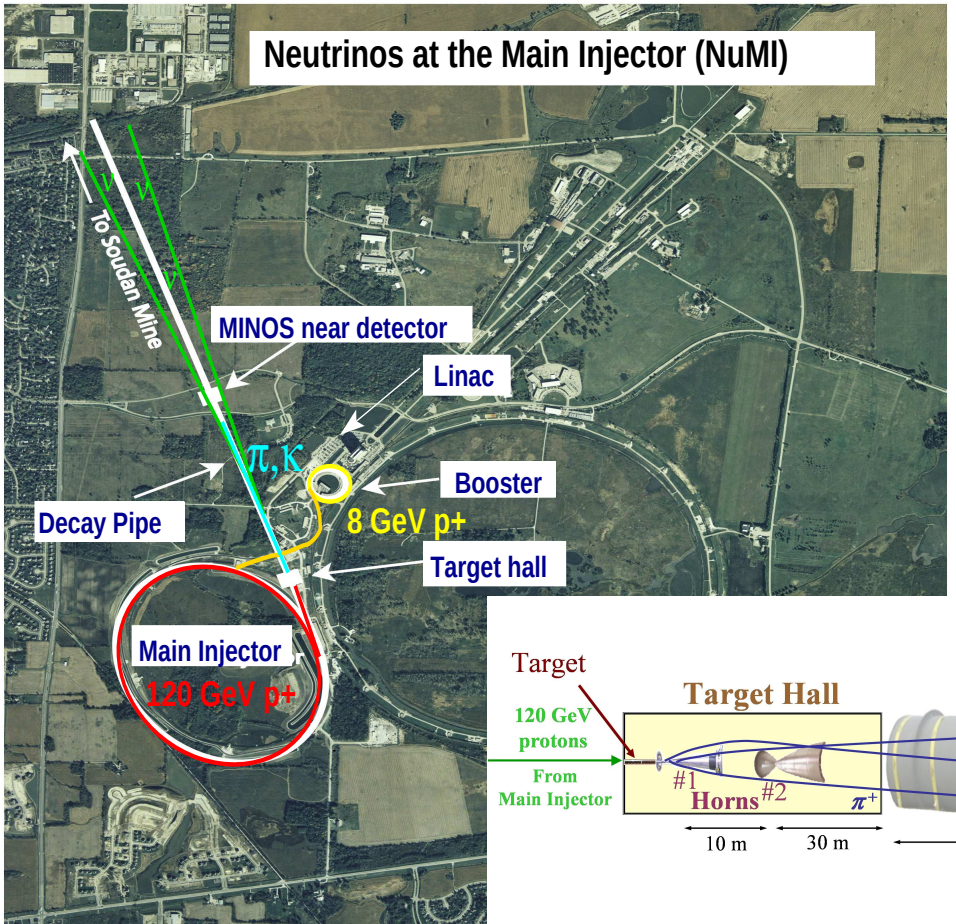
MAIN INJECTOR NEUTRINO OSCILLATION SEARCH (MINOS).

Neutrinos at the Main Injector

The longest baseline accel. ν expt in operation. Average power = 320 kW.

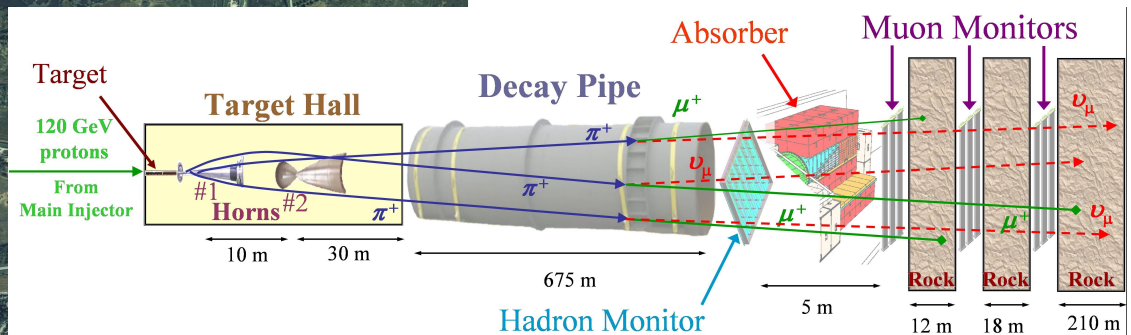


Fermi Natl. Lab., IL **Soudan Underground Lab, MN**

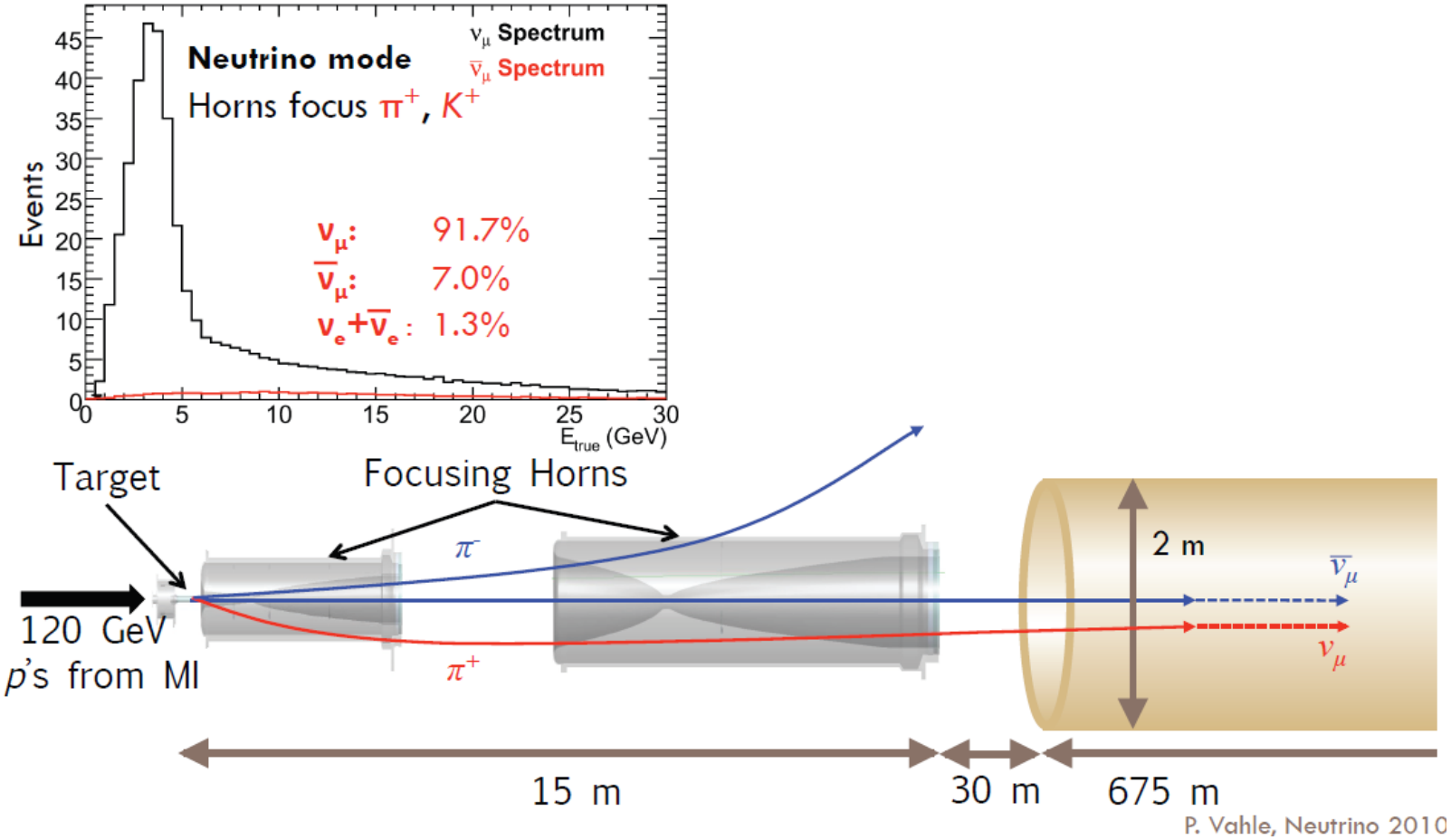


NuMI Horn 2 inner conductor
Radial field, B $\propto$ 1/r

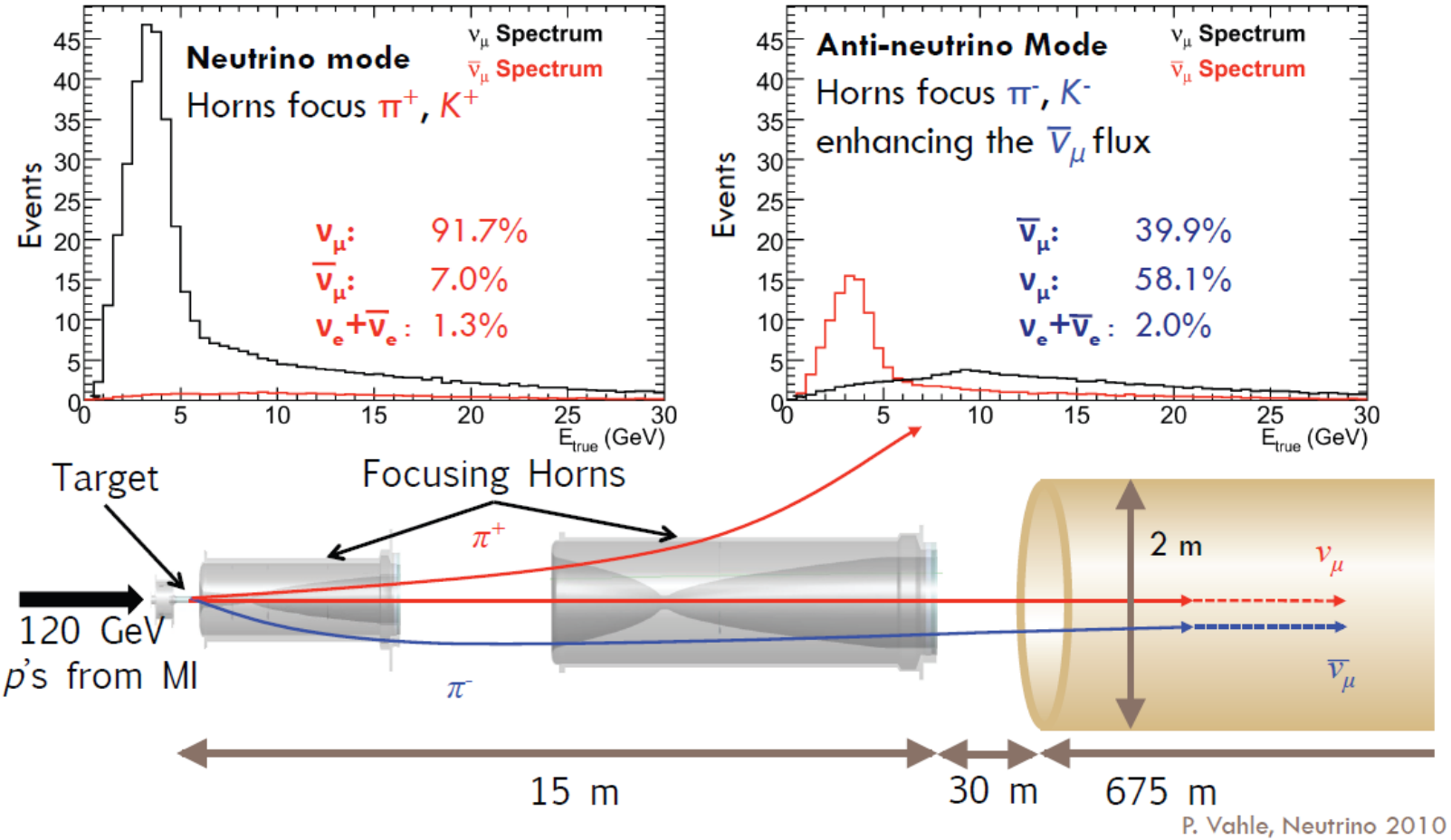
3T at 200 kA



Making Neutrinos and Anti-Neutrinos

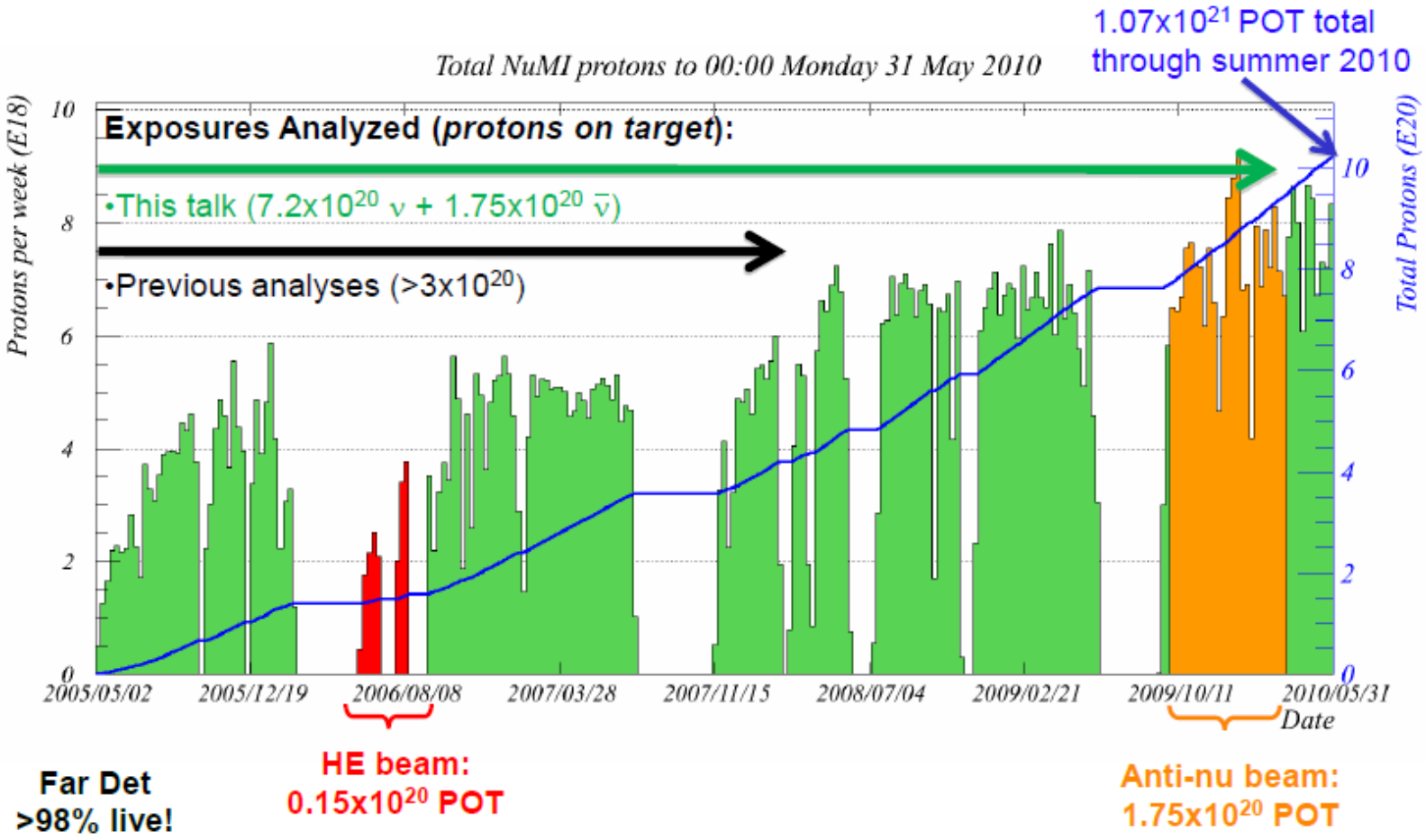


Making Neutrinos and Anti-Neutrinos

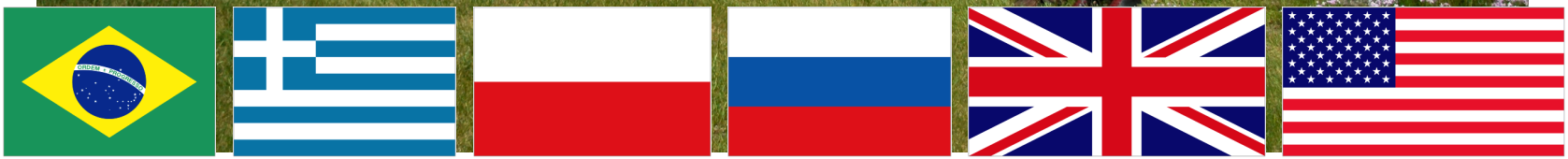


P. Vahle, Neutrino 2010

Accumulated Protons on Target at NuMI



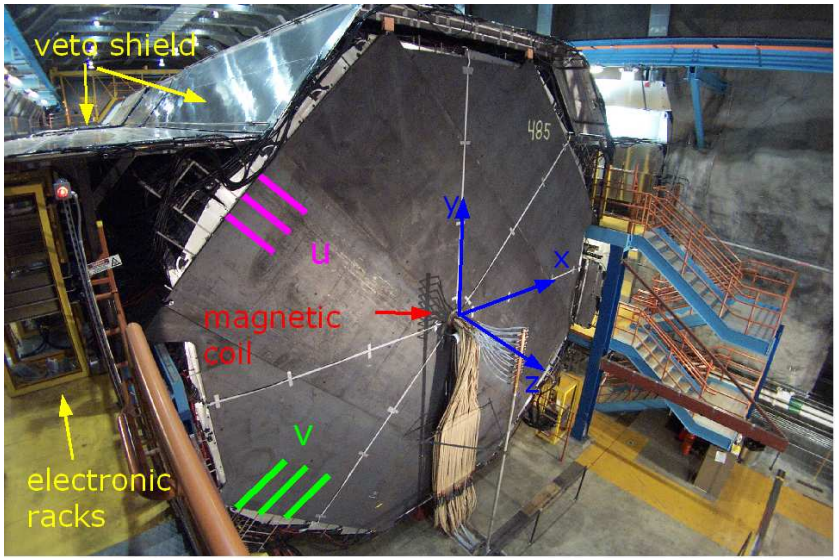
The MINOS Collaboration



140 scientists, 31 institutions, 6 countries

The MINOS Detectors

Far Detector



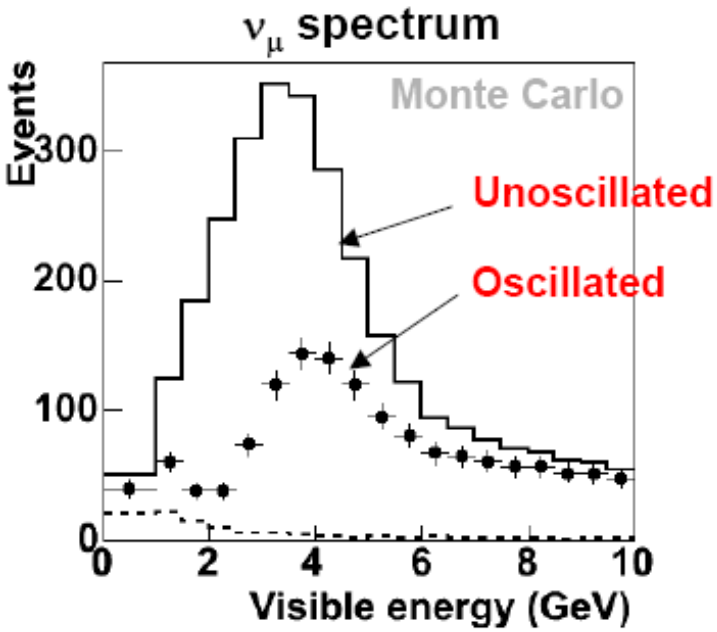
Near Detector

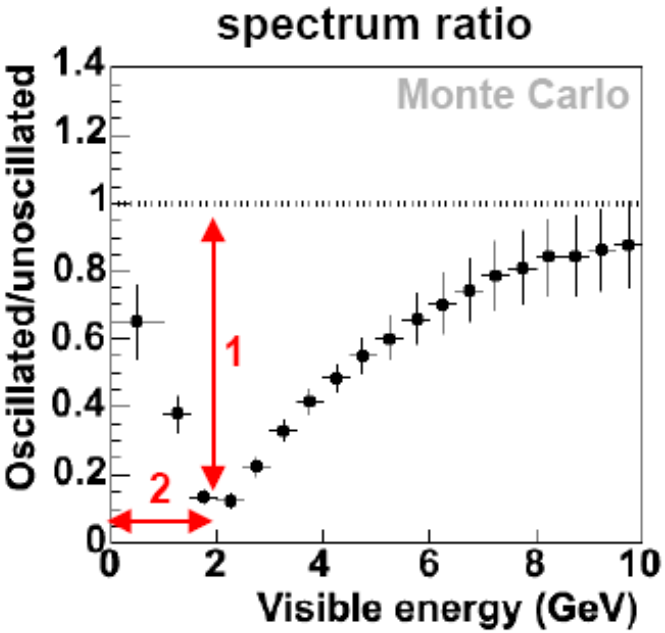
- **484 octogonal steel and scintillator plates 8m wide, $\Rightarrow$ 5.4kTon and 30 m in length.**
- **Magnetized**
- **Cosmic μ veto shield**

- **282 "squashed" octagonal steel plates, 153 scintillator planes. $\Rightarrow$ 1kTon and 16 m in length.**
- **Magentized**

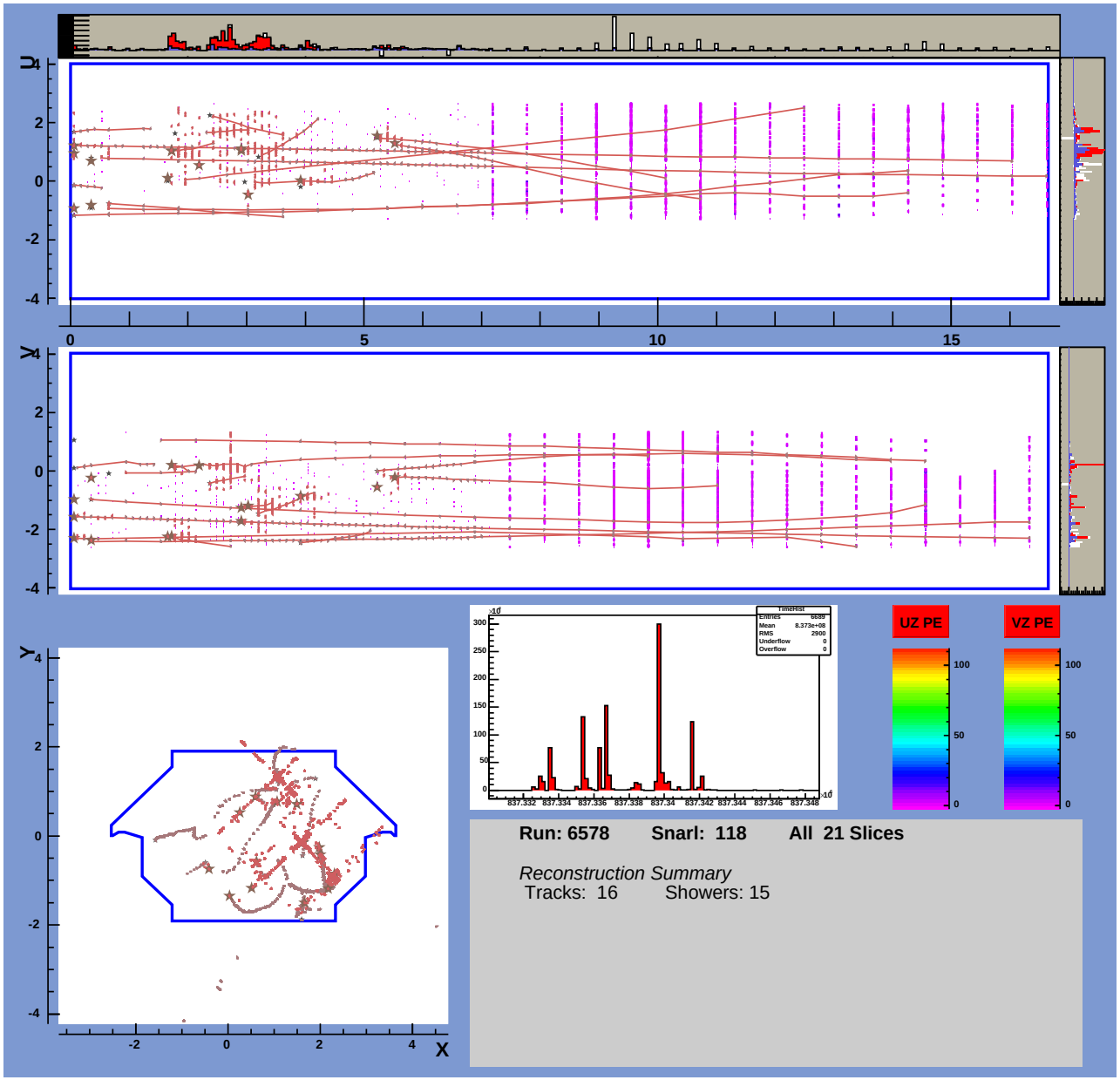
MINOS $\nu_\mu/\bar{\nu}_\mu$ Disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - \underbrace{\sin^2 2\theta_{23}}_{1} \sin^2(1.267\, \underbrace{\Delta m^2_{32}}_{2}\, L/E)$$

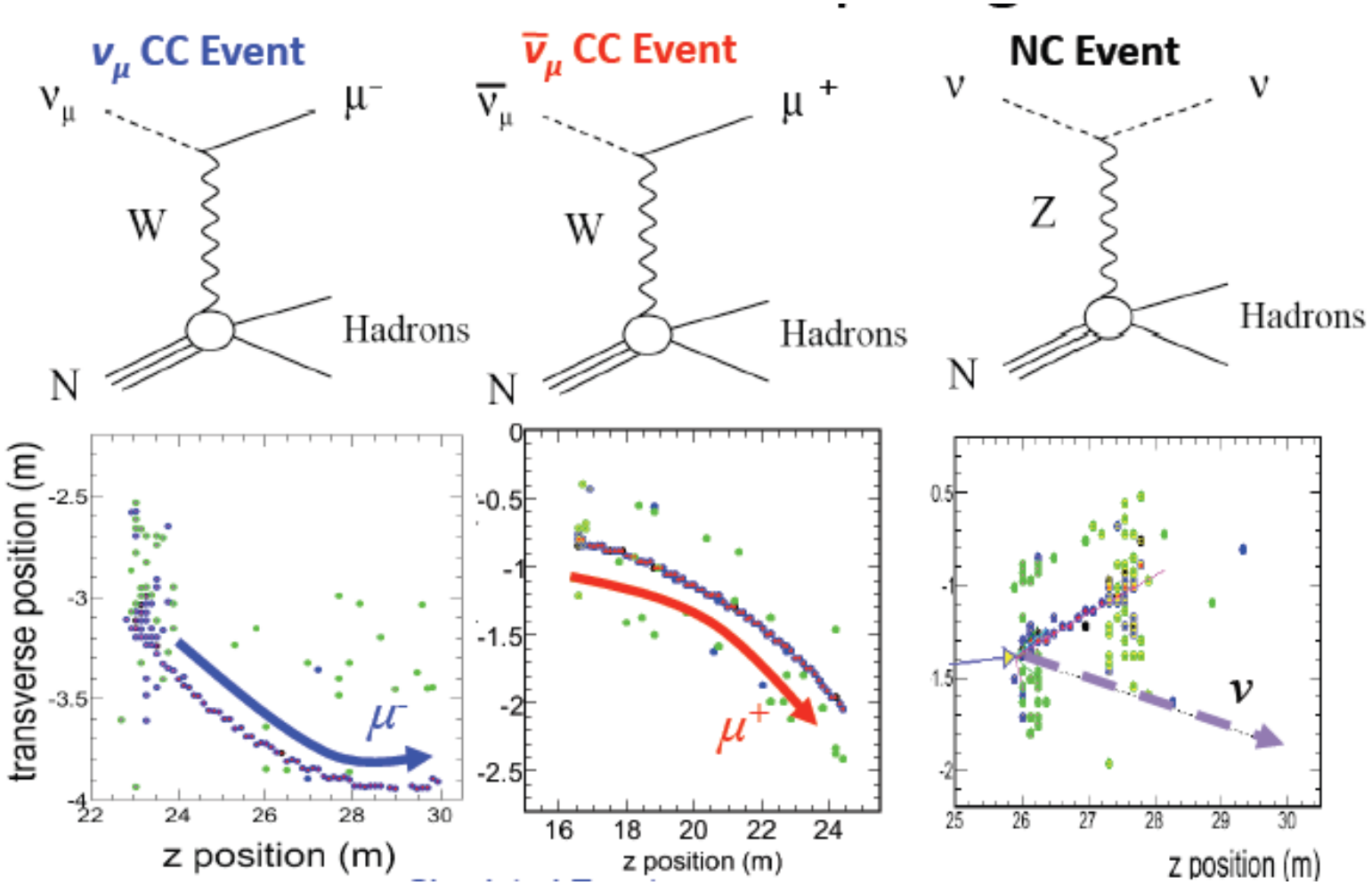




Neutrinos in the MINOS Near Detector



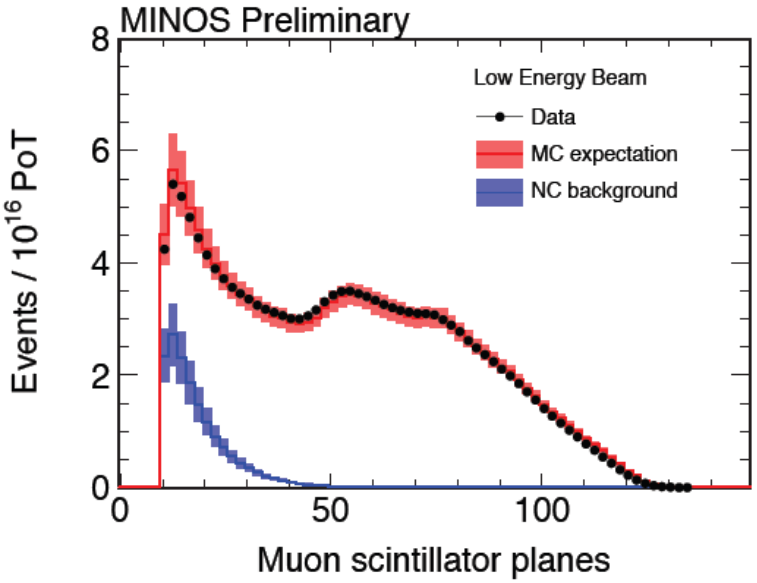
Event Topologies



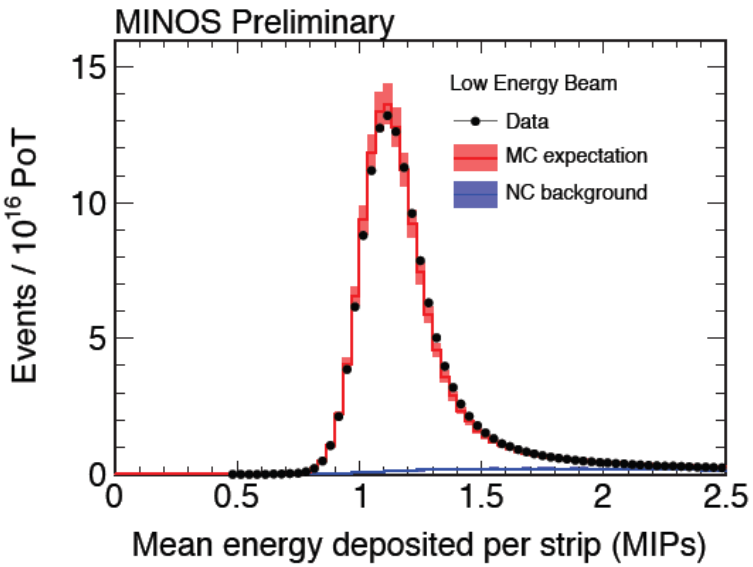
$$E_\nu^{CC} = \underbrace{E_\mu}_{\sigma_P \sim 10\%} + \underbrace{E_{shower}}_{\sigma_{had} = 55\%/\sqrt{E}}$$

ν_μ CC Event Selection

Basic selection is an event with a track in it, a kNN algorithim based on 4 parameters:



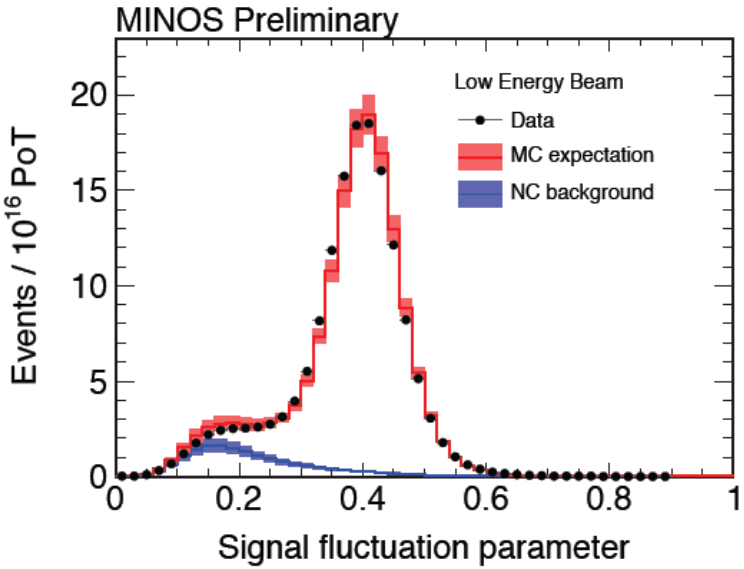
Track length



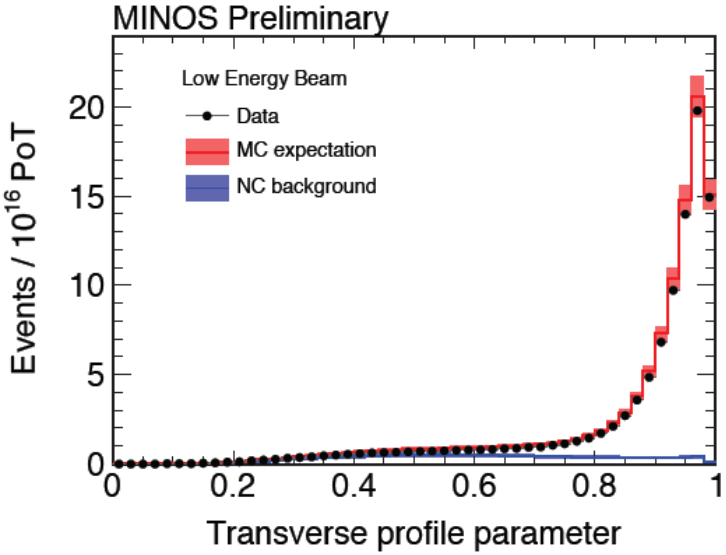
Mean energy trk hit

ν_μ CC Event Selection

Basic selection is an event with a track in it, a kNN algorithim based on 4 parameters:



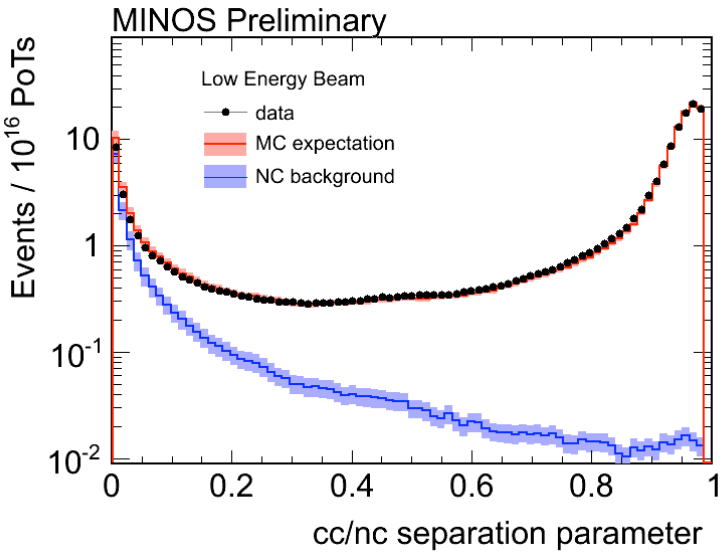
Track energy fluctuations



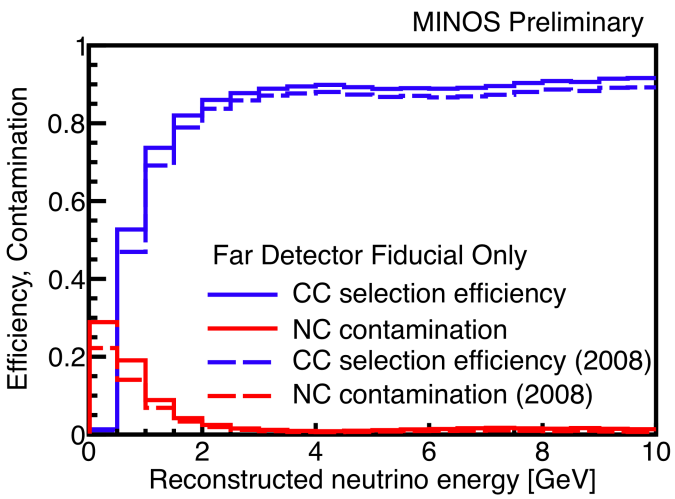
Transverse track profile

ν_μ CC Event Selection

Basic selection is an event with a track in it, a kNN algorithim based on 4 parameters:

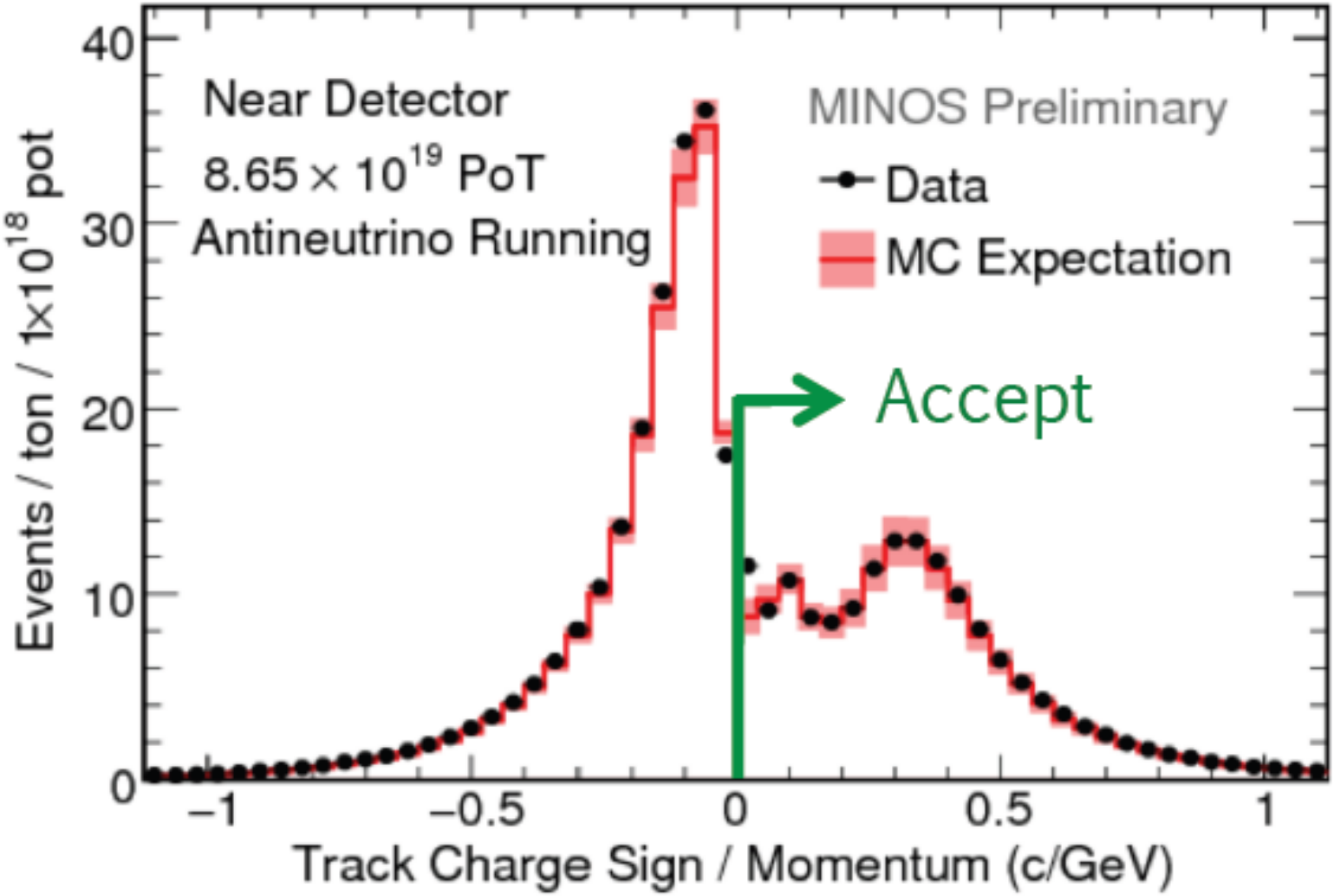


CC selector



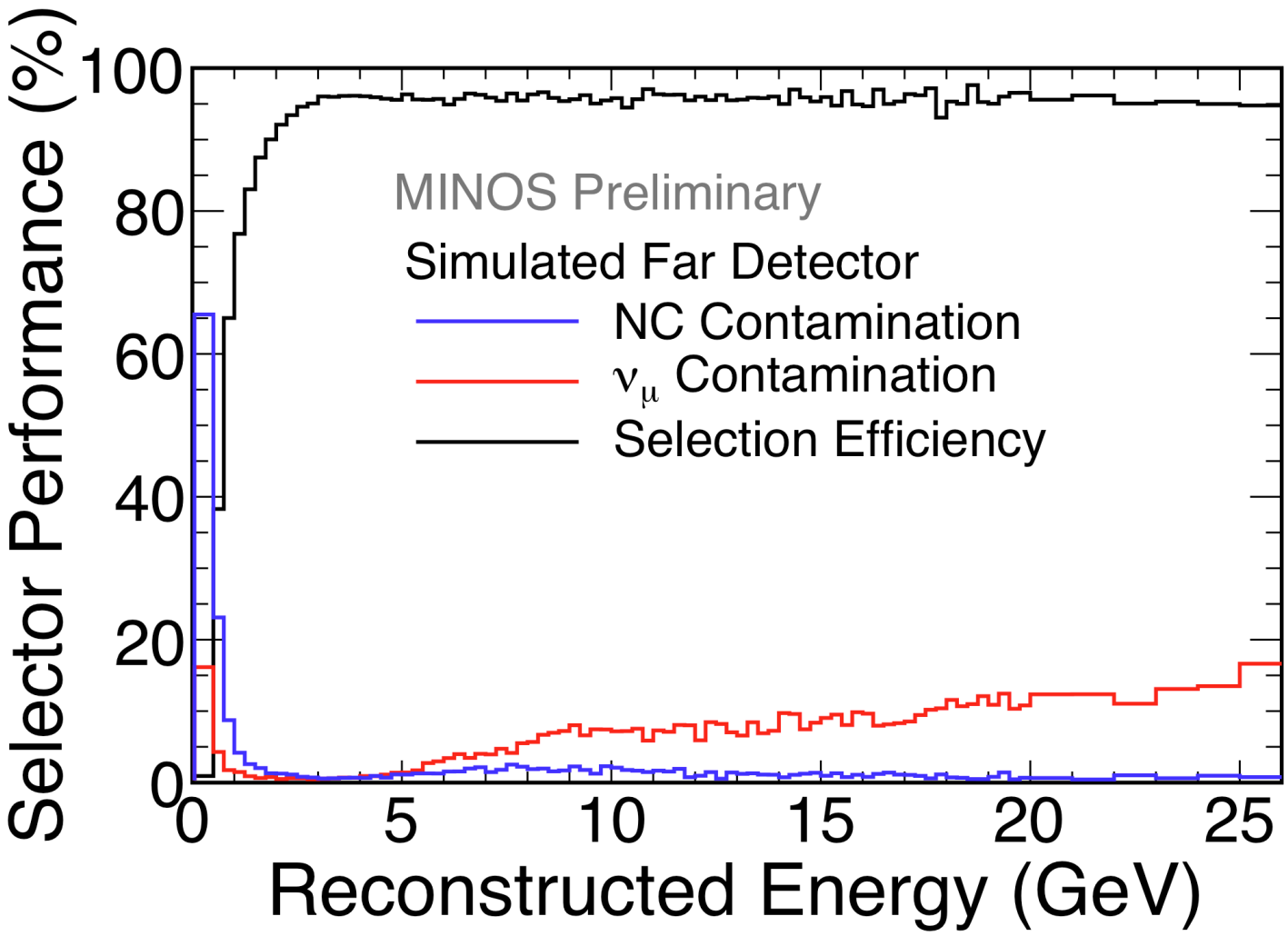
ν_μ selection purity

ν_μ CC Event Selection



Selecting $\bar{\nu}_\mu$

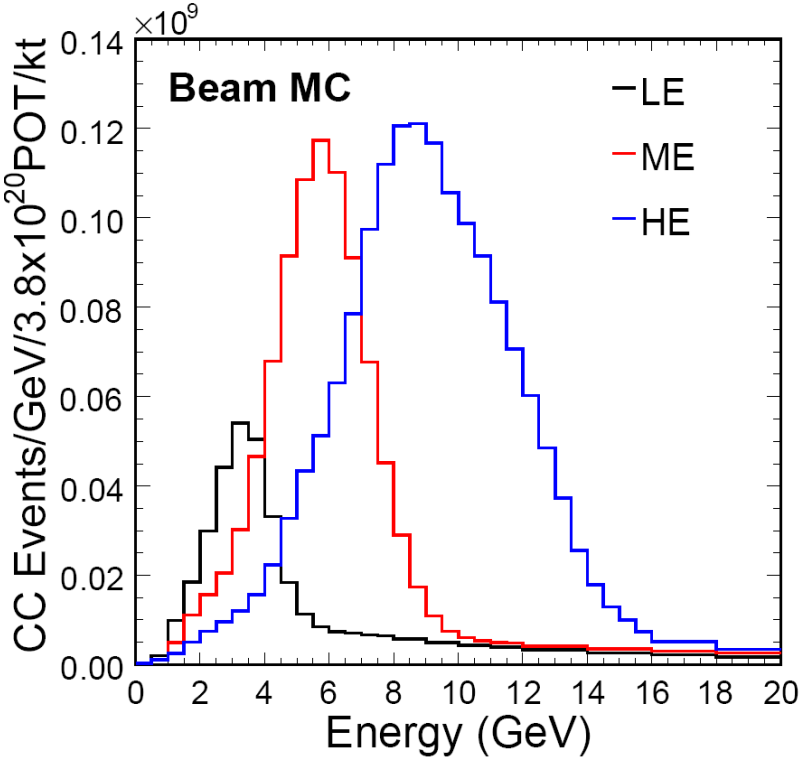
ν_μ CC Event Selection



$\bar{\nu}_\mu$ **selection purity**

Using the MINOS ND to constrain NuMI Simulation

The NuMI flux can be changed by moving the target w.r.t horns. LE: target 35cm into horn 1, ME: target -1m from LE position HE: target -2.5m from LE position

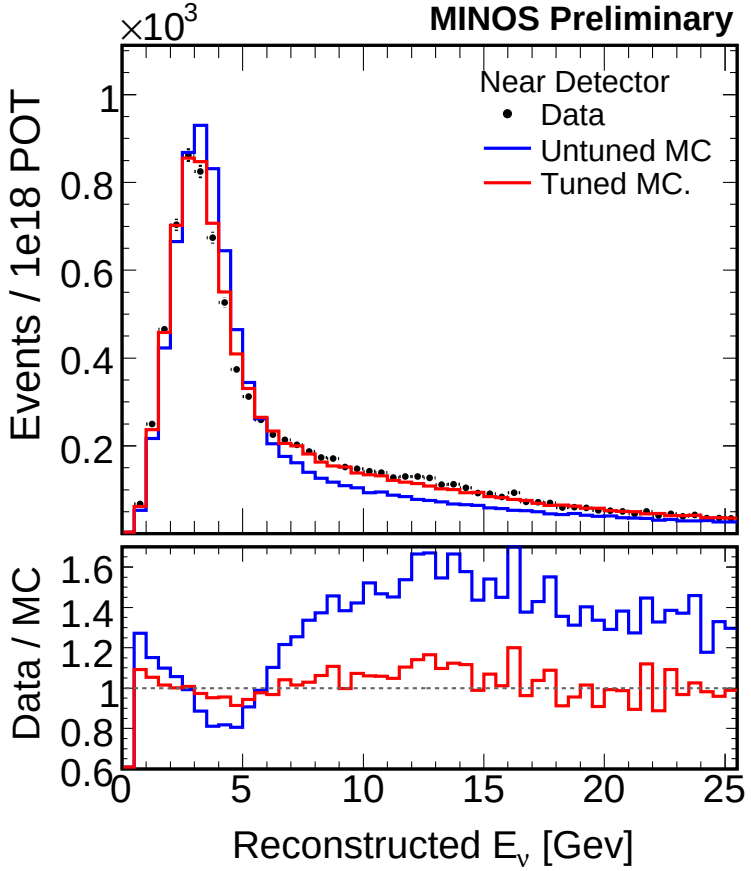


A simultaneous fit to the ν_μ and $\bar{\nu}_\mu$ ND event rates produced in different beam tunes and with different horn currents is performed.

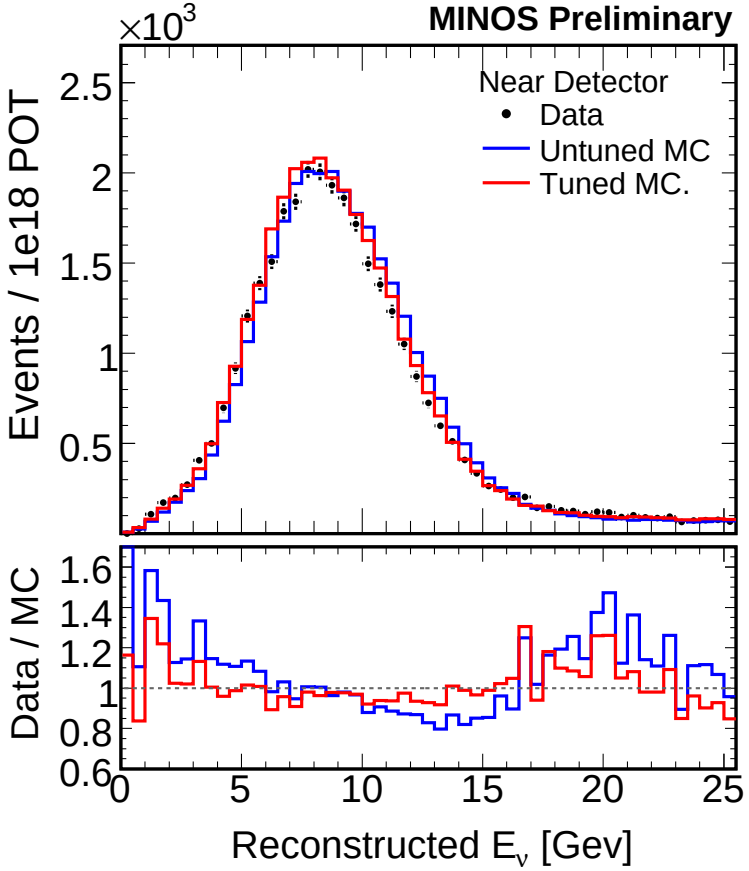
Beam fits to MINOS ND Data, 2010

Effects included in fit: target hadro-production, horn current, horn current distributions, target position, E_ν scale and offset:

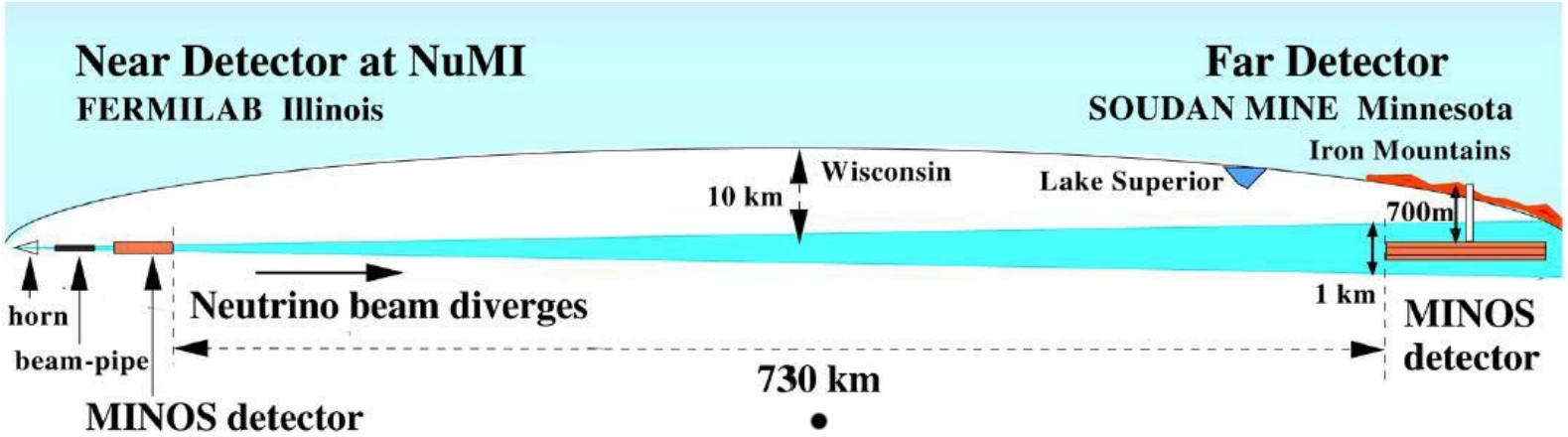
NuMI low-energy beam tune

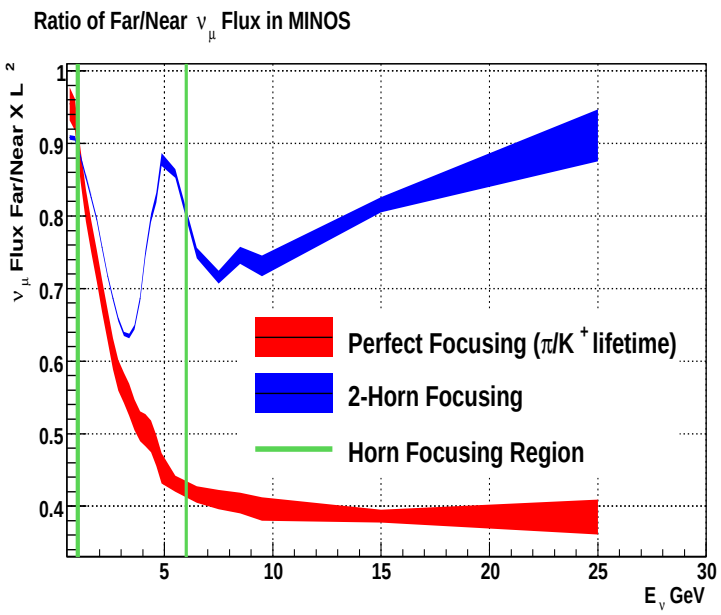


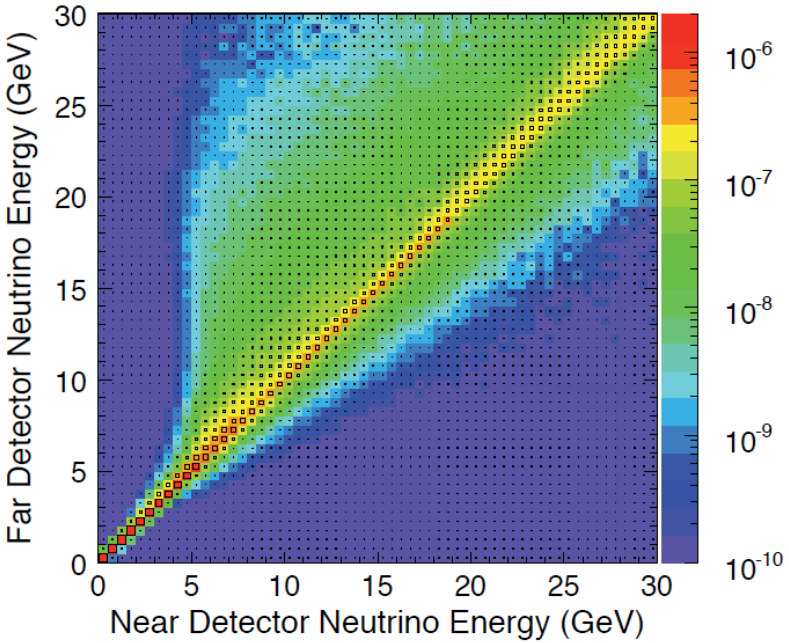
NuMI high-energy beam tune



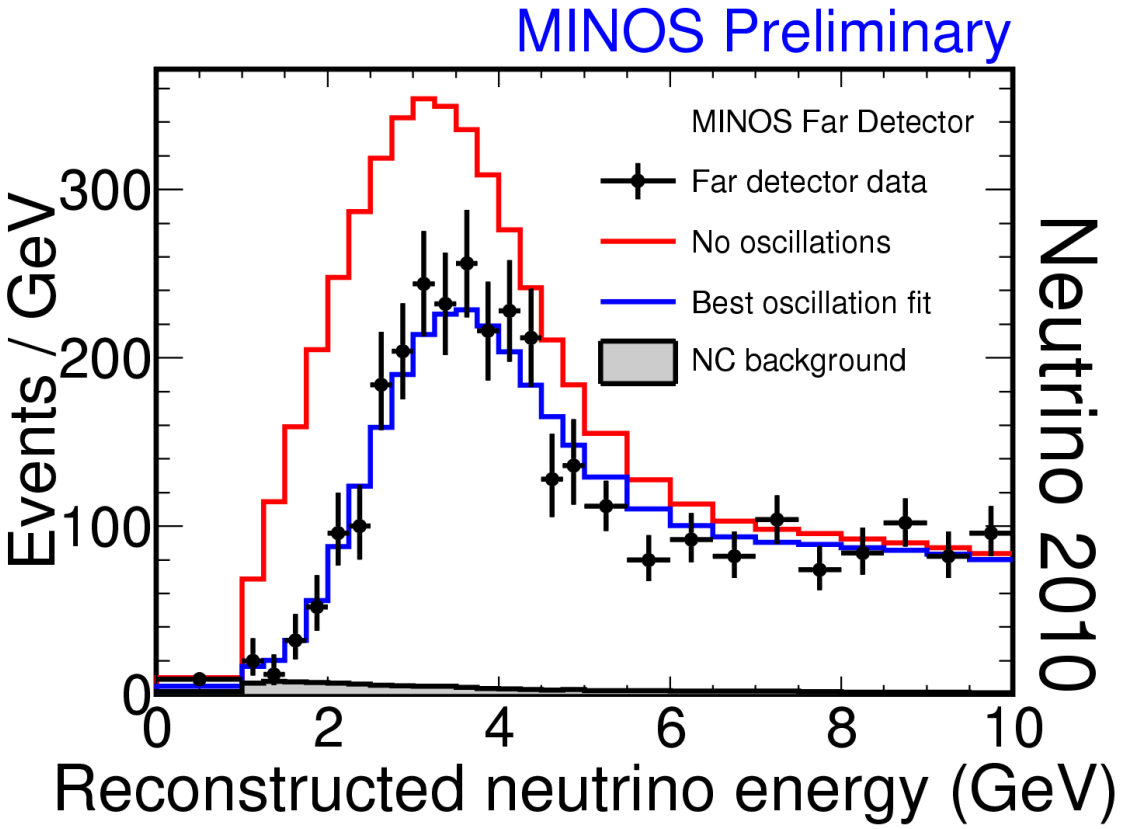
The NuMI Near to Far Extrapolation







Neutrino Disappearance Results - 2010

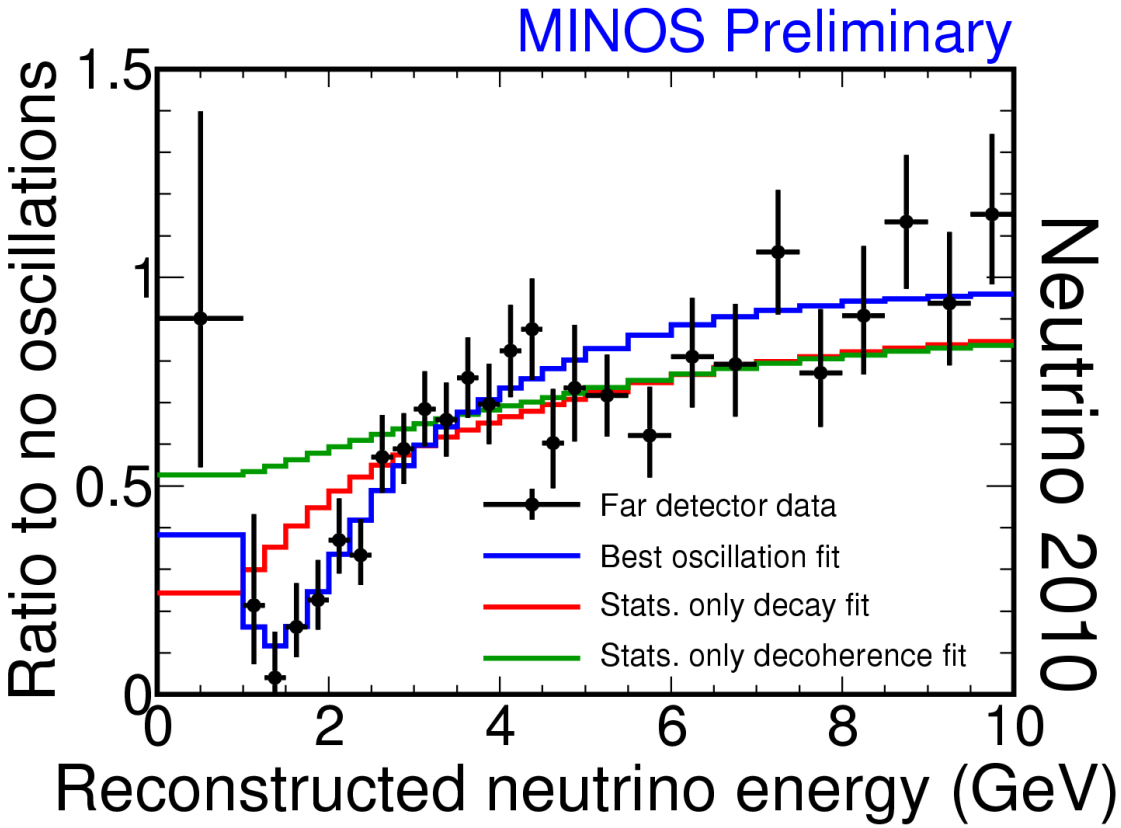


Expected no-osc 2451.

Observe 1986.

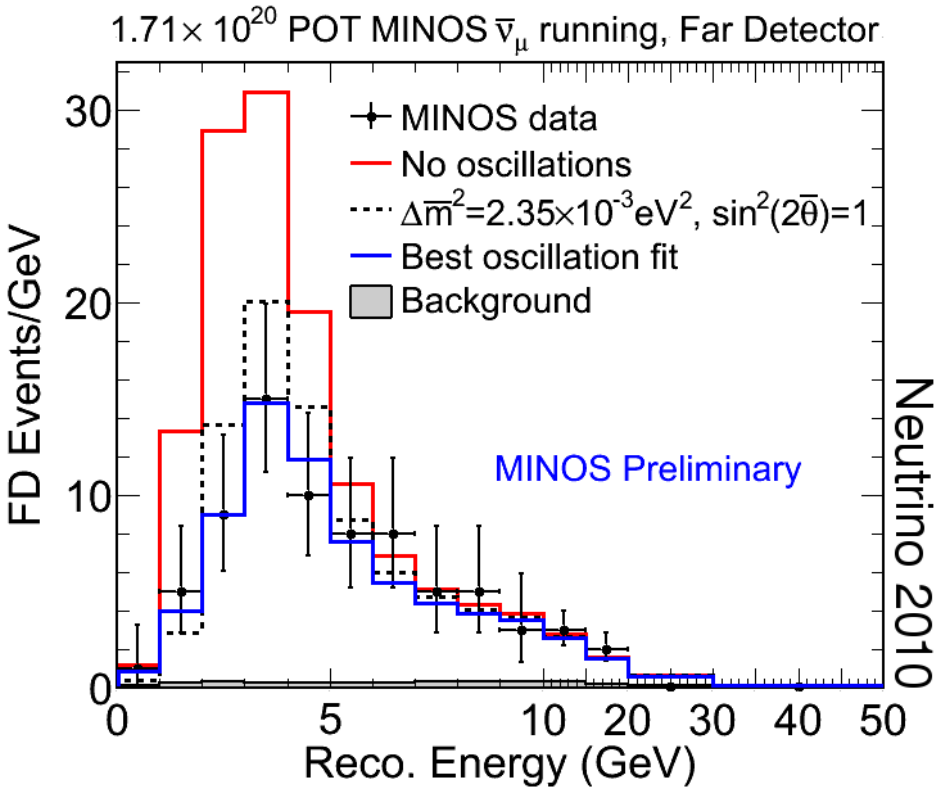
Fit results: $|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$ $\sin^2(2\theta) > 0.91$ **(90%C.L)**

Neutrino Disappearance Results - 2010



Fit results: $|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2(2\theta) > 0.91 (90\%\mathrm{C.L})$

Anti-Neutrino Disappearance Results - 2010

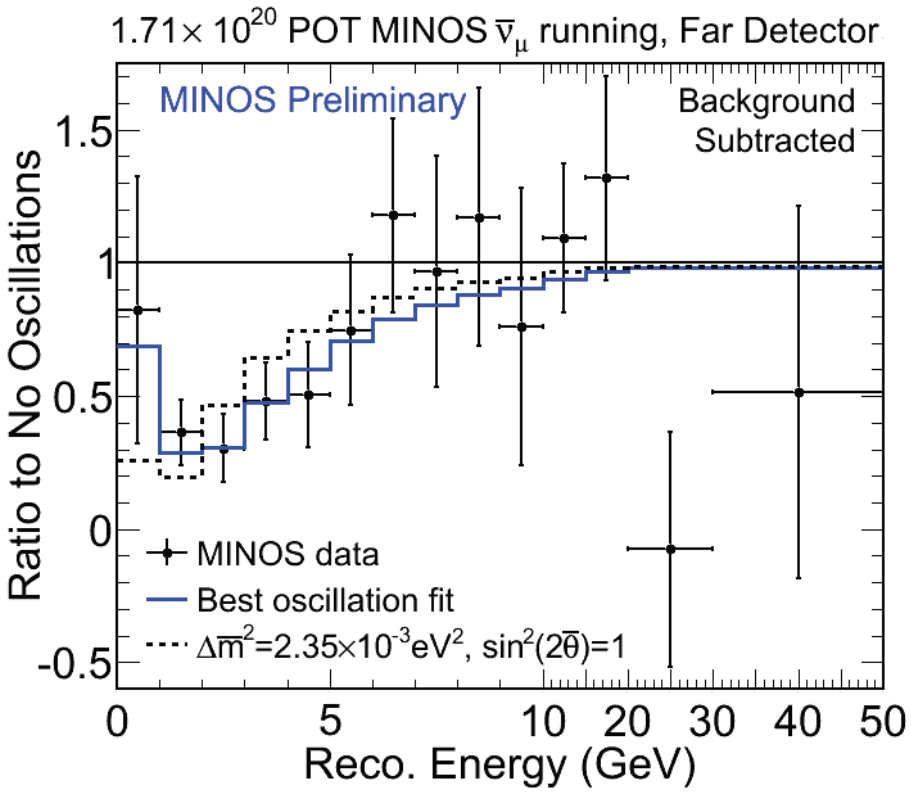


Expected no osc 155.

Observe 97.

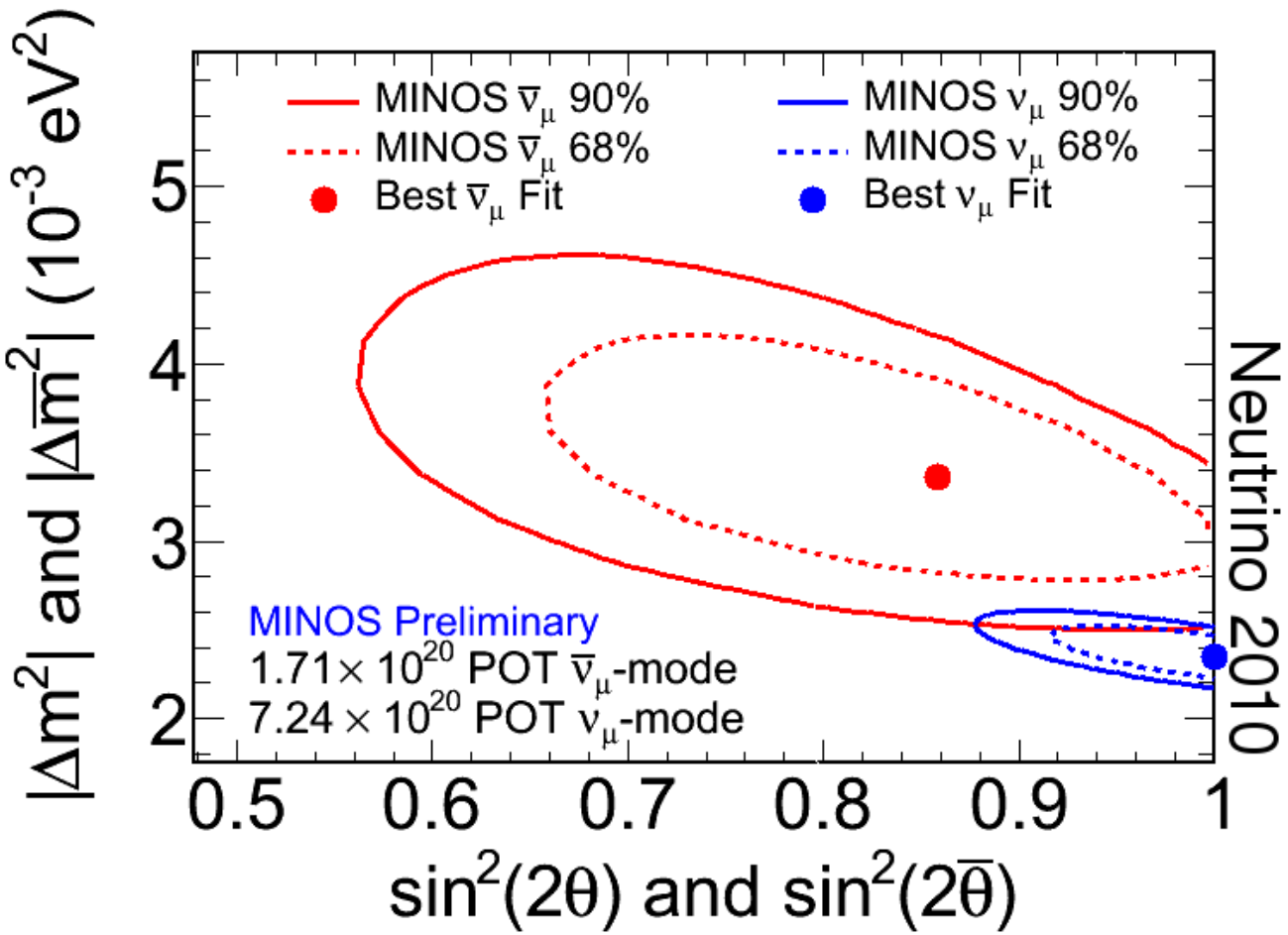
Fit results: $|\Delta\bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2(2\bar{\theta}) = 0.86 \pm 0.11$

Anti-Neutrino Disappearance Results - 2010



Fit results: $|\Delta\bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2(2\bar{\theta}) = 0.86 \pm 0.11$

Disappearance Summary

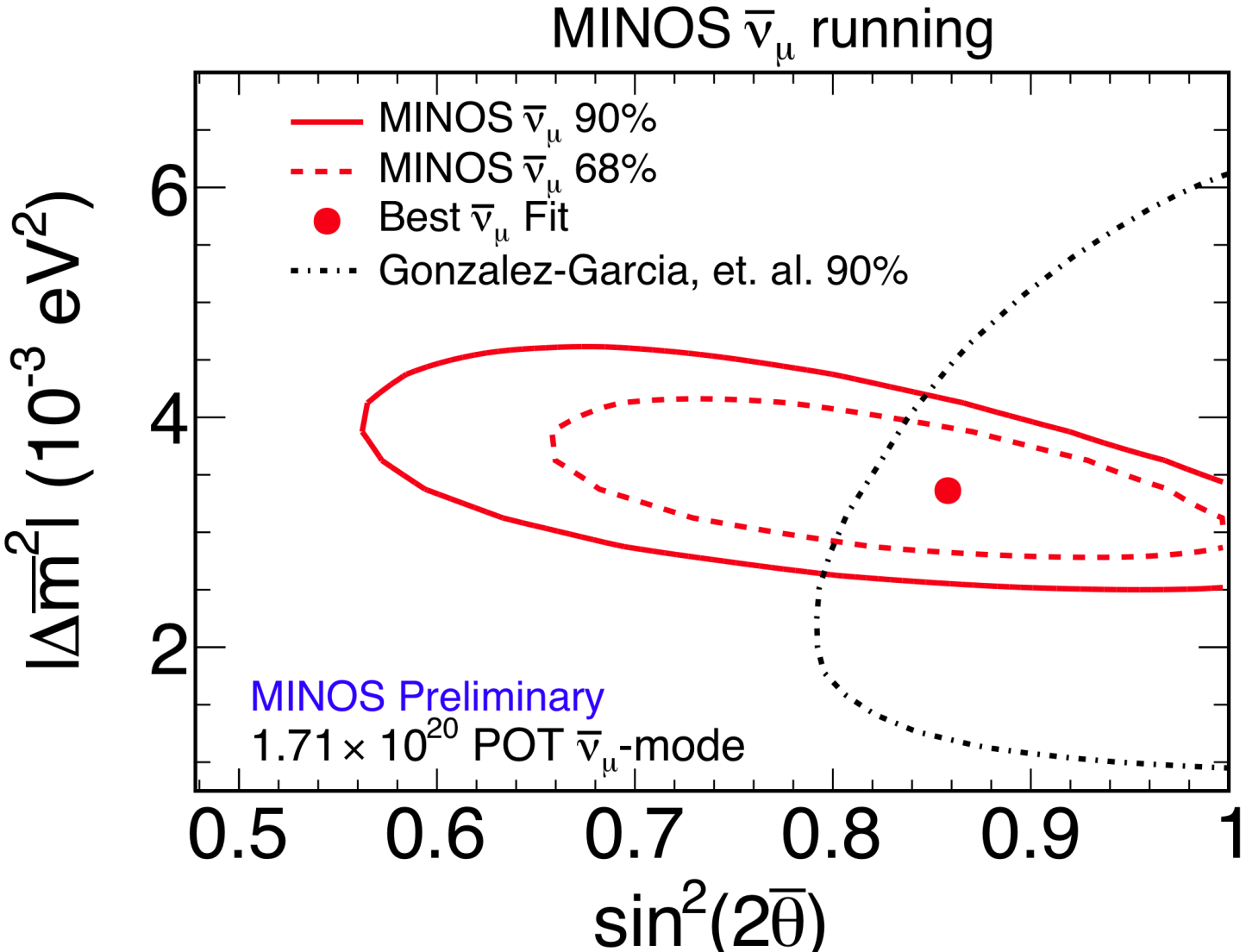


$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2(2\theta) > 0.91 (90\%\mathrm{C.L})$$

$$|\Delta \bar{m}^2| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\ \mathrm{eV}^2 \quad \sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

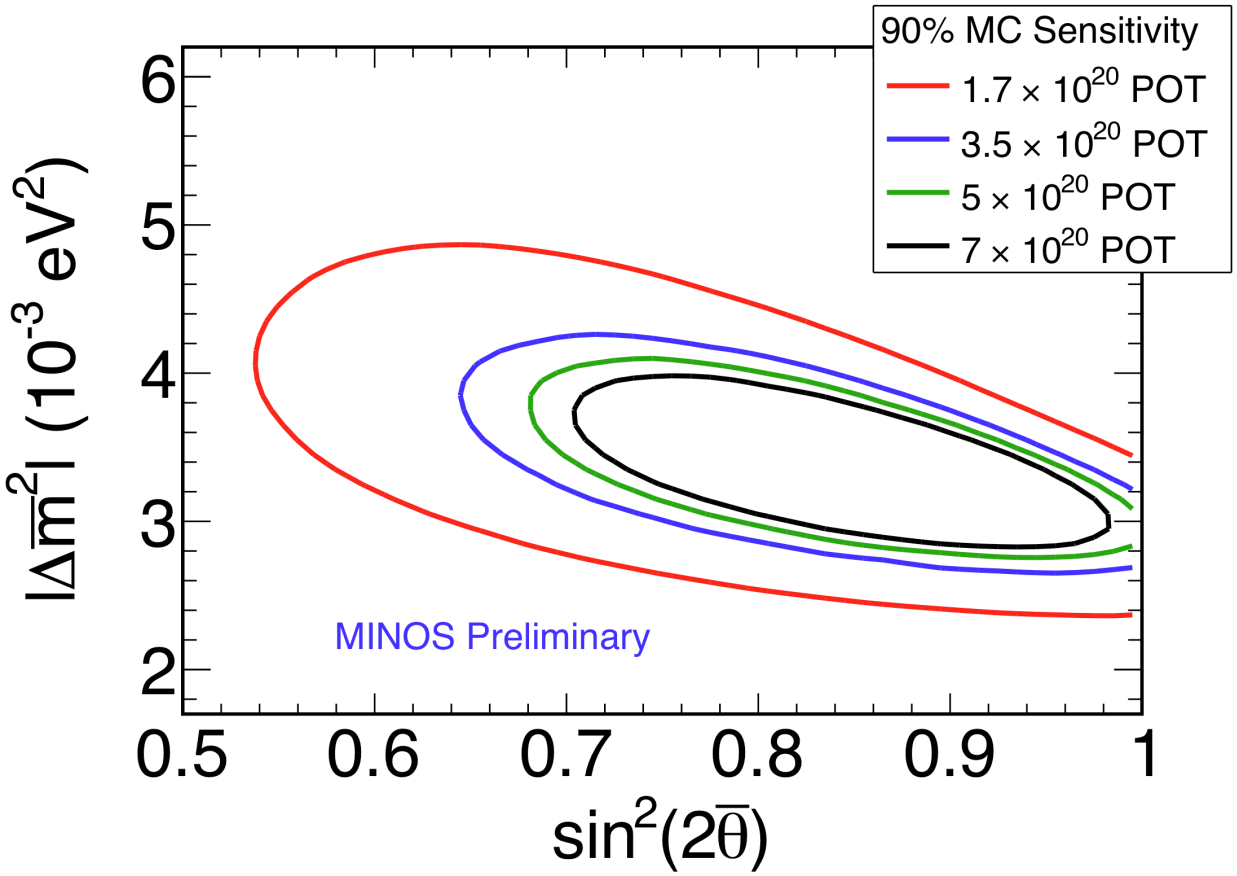
Global fit to $\bar{\nu}_\mu$ oscillation

-.-.-.- Global fit to non-MINOS data: M.C. Gonzalez Garcia and M. Maltoni Phys. Rept. 460, 2008.



Future $\bar{\nu}_\mu$ Running

Nov 1st: Start of second MINOS $\bar{\nu}_\mu$ run:



Summary and Conclusions

MINOS has completed the most accurate measurments of Δm^2_{32} ($\sim$ 5%) and $\Delta \bar{m}^2_{32}$ ($\sim$ 13%) to date. Results are still statistically limited.

No *statistically* significant difference between ν_μ and $\bar{\nu}_\mu$ disappearance has been observed