Long Baseline Neutrino Experiments

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❸ **Past Experiments: K2K**
❹ **Current Experiments: MINOS, OPERA**
❺ **The Next Generation: T2K, Nova**
❻ **Conclusions and Outlook**

Long Baseline Neutrino Experiments

★ Over the last decade studies of Atmospheric and Solar Neutrinos has **established the existence** of neutrino flavour oscillations

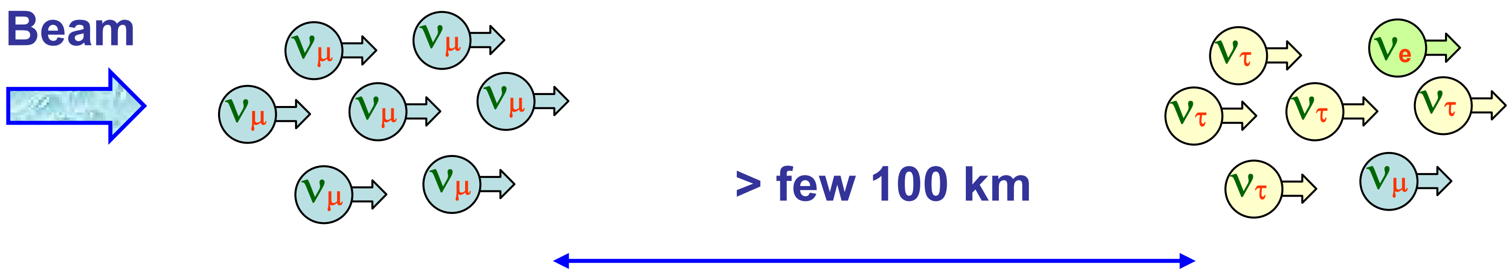
★ Main advantage of solar/atmospheric experiments
  • beam comes for free

★ But you get what Nature gives

★ Time for the physicists to take control…
  • Intense (>100 kW) neutrino beams and long baseline experiments

BASIC IDEA

★ Most experiments sample **unoscillated** neutrino beam close to production and at a few hundred km when **oscillations** are apparent



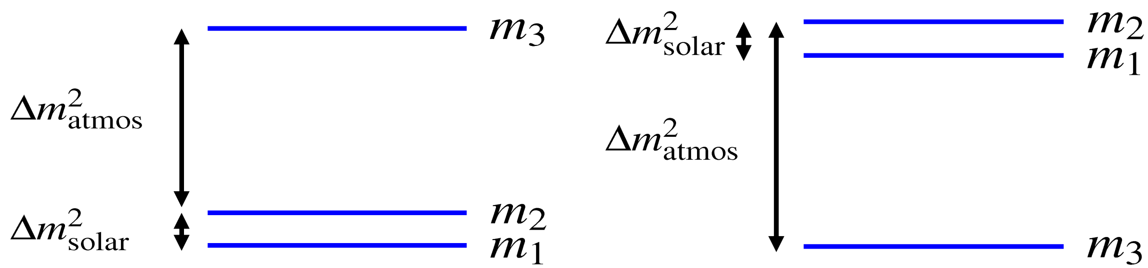
• "Clean" neutrino experiments – control of systematic uncertainties
• Baseline/beam energy chosen to match for physics goals

Neutrino Oscillations in the "SM"

★ **Two mass scales:**

$$|\Delta m_{21}|^2 = |m_2^2 - m_1^2|$$

$$|\Delta m_{32}|^2 = |m_3^2 - m_2^2|$$



★ **Unitary PMNS matrix, usually expressed in terms of 3 rotation angles** $\theta_{12}, \theta_{23}, \theta_{13}$ **and a complex phase** δ**, using the notation** $s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{"Atmospheric"}} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{"Solar"}}$$

Dominates: **"Atmospheric"** **"Solar"**

★ **There are six SM observables that can be measured in ν oscillation experiments**

$\|\Delta m_{21}\|^2 = \|m_2^2 - m_1^2\|$	θ_{12}	**Solar and reactor neutrino experiments**
$\|\Delta m_{32}\|^2 = \|m_3^2 - m_2^2\|$	θ_{23}	**Atmospheric and LBL beam neutrino experiments**
	θ_{13}	**Reactor and LBL beam neutrino experiments**
	δ	**Future beam experiments (CP violation)**

The Experiments: Past, Present and Future

★ Five main Long-baseline neutrino oscillation experiments

Experiment	Operational	Peak E_ν	Baseline	Detector
K2K	1999-2004	1 GeV	250 km	Water Č
NuMI/MINOS	2005-2010(?)	3 GeV	735 km	Iron/Scint
CNGS/Opera	2008-	17 GeV	735 km	Emulsion
T2K	2010-	0.7 GeV	295 km	Water Č
NOνA (?)	2012(?)-	1.8 GeV	810 km	Liq. Scint.

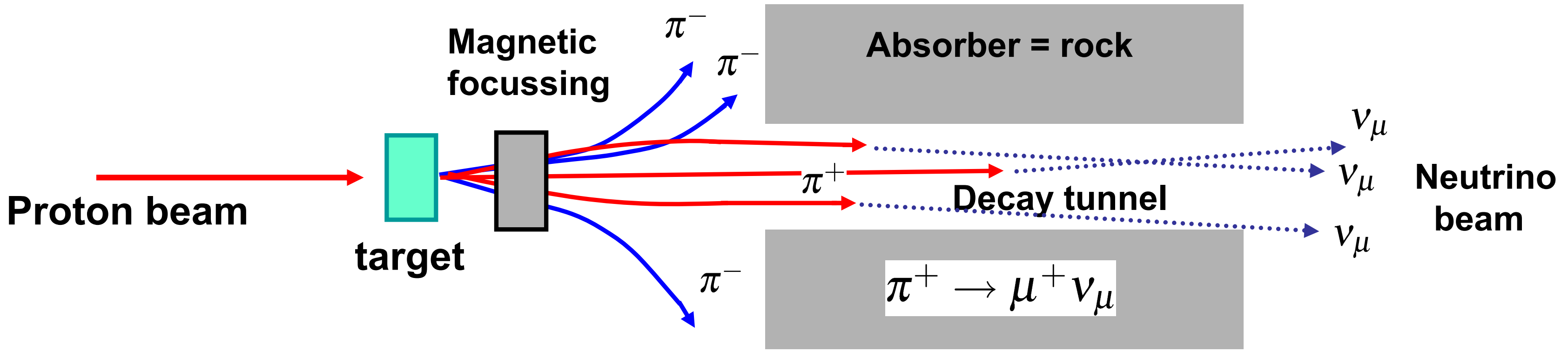
Main Experimental Goals:

- ★ K2K : confirm atmospheric neutrino oscillations
- ★ MINOS : precise measurement of $|\Delta m_{32}|^2$ (and θ_{23}) + shot at θ_{13}
- ★ Opera : observe tau appearance in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
- ★ T2K : observe $\nu_\mu \leftrightarrow \nu_e$ oscillations and measurement of θ_{13}
- ★ NOνA : $\nu_\mu \leftrightarrow \nu_e$ at a longer baseline (mass hierarchy)

❷ Neutrino Beams

★ **Neutrino Beams for beginners**

- Smash high energy protons into a fixed target ➡ hadrons
- Focus positive pions/kaons
- Allow them to decay $\pi^+ \rightarrow \mu^+\nu_\mu$ + $K^+ \rightarrow \mu^+\nu_\mu\ (BR \approx 64\,\%)$
- Gives a beam of "collimated" ν_μ



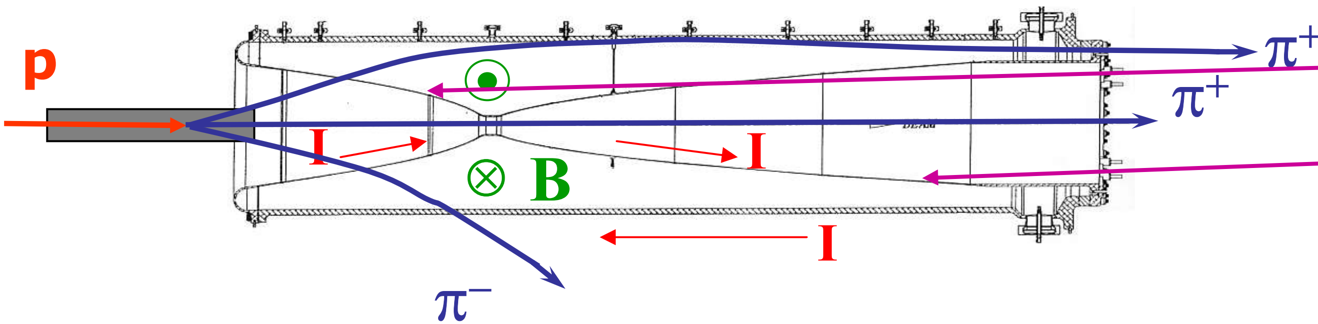
★ Neutrino energy spectrum determined by decay kinematics and magnetic focussing optics

Pion production from target not well modelled by MC
Significant uncertainties in neutrino energy spectrum !

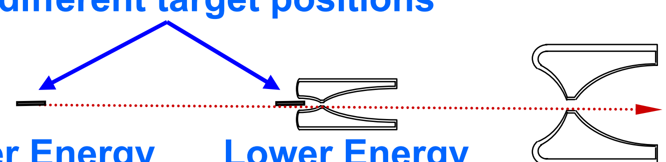
Neutrino Horns

e.g. MINOS

- Two focusing horns pulsed with 200 kA
- Magnetic field *B* ~ I/*r* between the inner and outer conductors
- Maximum field – 3 T



- Two horn system behaves like a pair of (achromatic) lenses
- Relative position of target determines energy spectrum



★ Choose "focussing optics" to give appropriate peak in neutrino energy spectrum for experimental baseline

❸ Past Experiments: K2K

★ **KEK to Kamiokande**: utilised large Super-Kamiokande water Čerenkov Detector

★ For θ_{13} small, to a good approximation

$$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

★ In LBL experiments, L is fixed, hence oscillations a function of neutrino energy

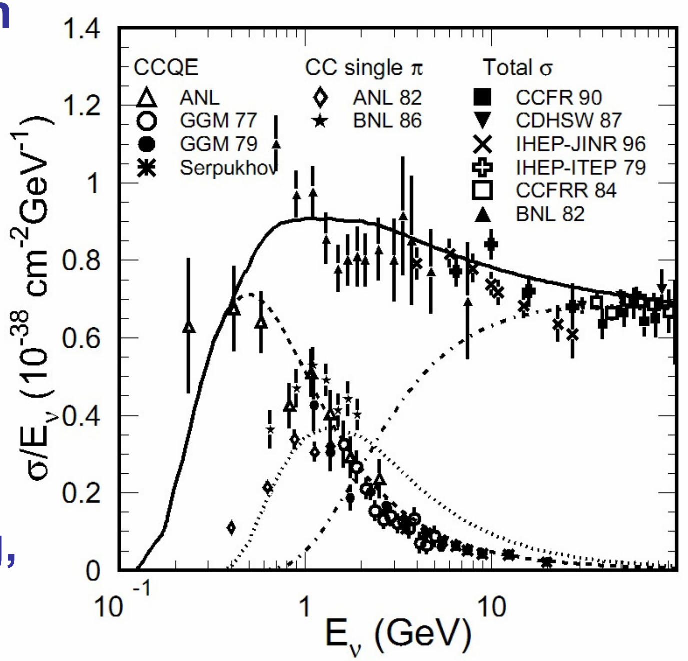
★ For K2K baseline, $L = 250\,\mathrm{km}$, and $|\Delta m^2|$ from Super-K atmospheric results, expected oscillation minimum at $E_\nu \approx 0.7\,\mathrm{GeV}$

★ For this energy, neutrino interaction cross-section dominated by quasi-elastic (QE) scattering

$$\nu_\mu + \mathrm{n} \to \boxed{\mu^-} + \mathrm{p}$$

★ Scattering via hadron resonances (e.g. Δ) next most important process, e.g.

$$\begin{aligned}\nu_\mu + \mathrm{n} &\to \mu^- + \Delta^+ \\ &\to \boxed{\mu^-} + \mathrm{n} + \boxed{\pi^+}\end{aligned}$$



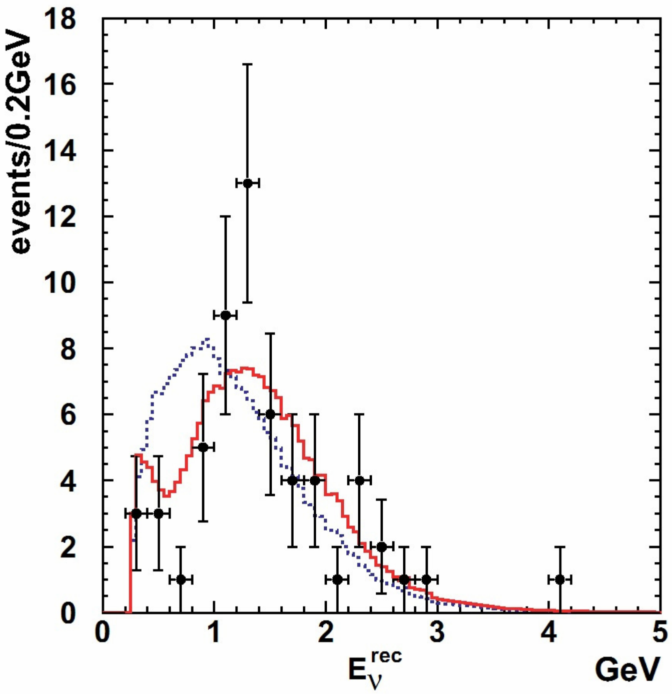
★ By selecting events with a single "muon-like" ring, preferentially select out QE events

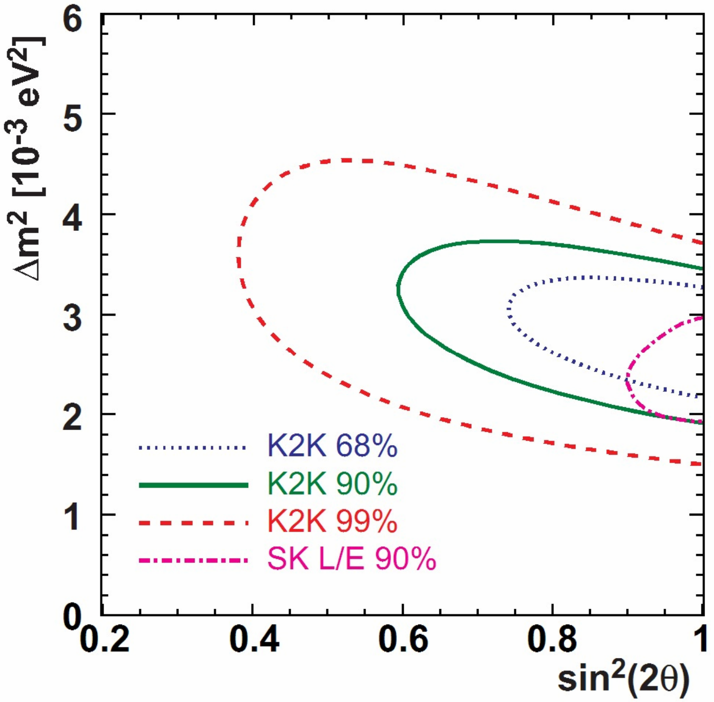
★ For **QE**, reconstructed neutrino energy can be obtained from **muon energy and scattering angle** measured from the muon Cerenkov ring

$$E_\nu^{\rm rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

(smeared by Fermi motion)

★ Fit to energy spectrum and normalisation excluded null oscillation hypothesis at **4.3 σ** level with best fit consistent with Super-K atmospheric results

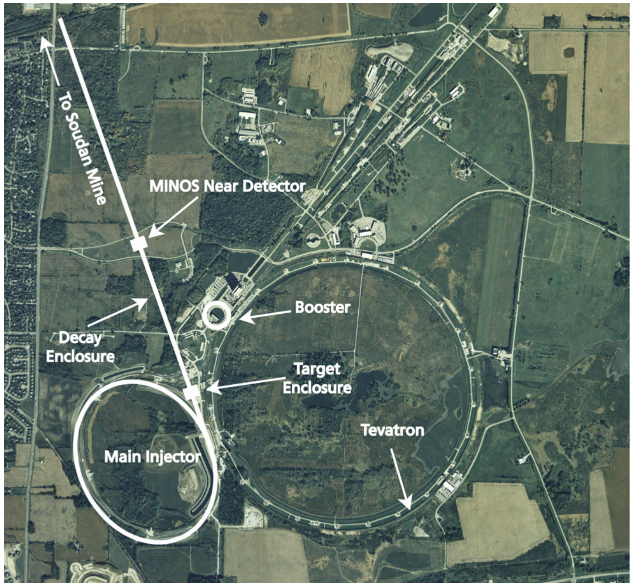


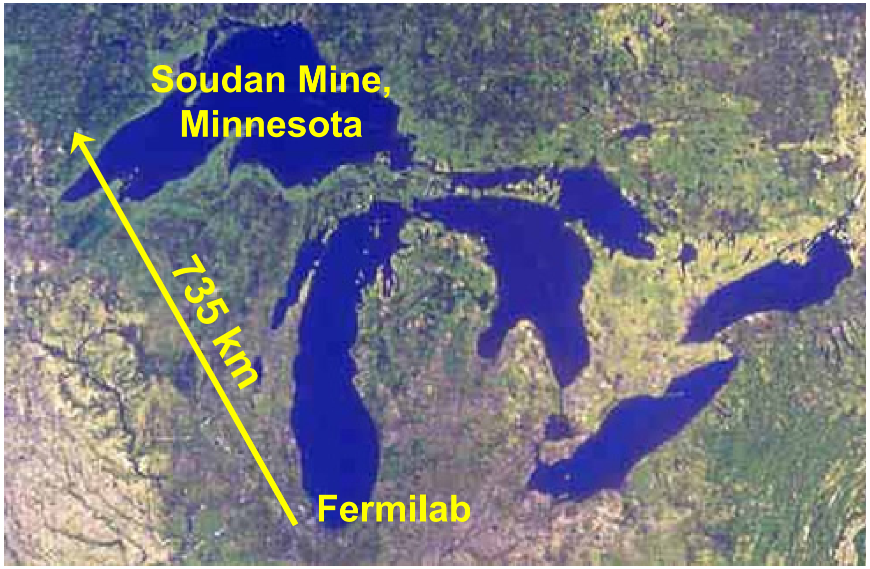


★ First observation of neutrino oscillations in a LBL experiment !

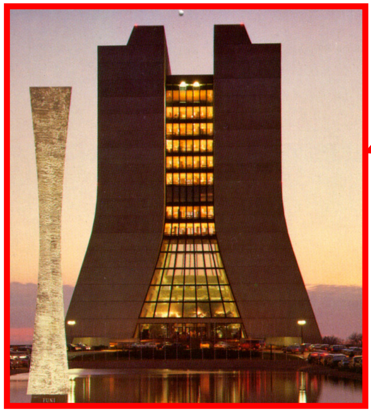
Current Experiments: MINOS

- **120 GeV** protons extracted from the MAIN INJECTOR at Fermilab
- **2.5×10^{13}** protons per pulse hit target → very intense beam - **0.2 MW** on target





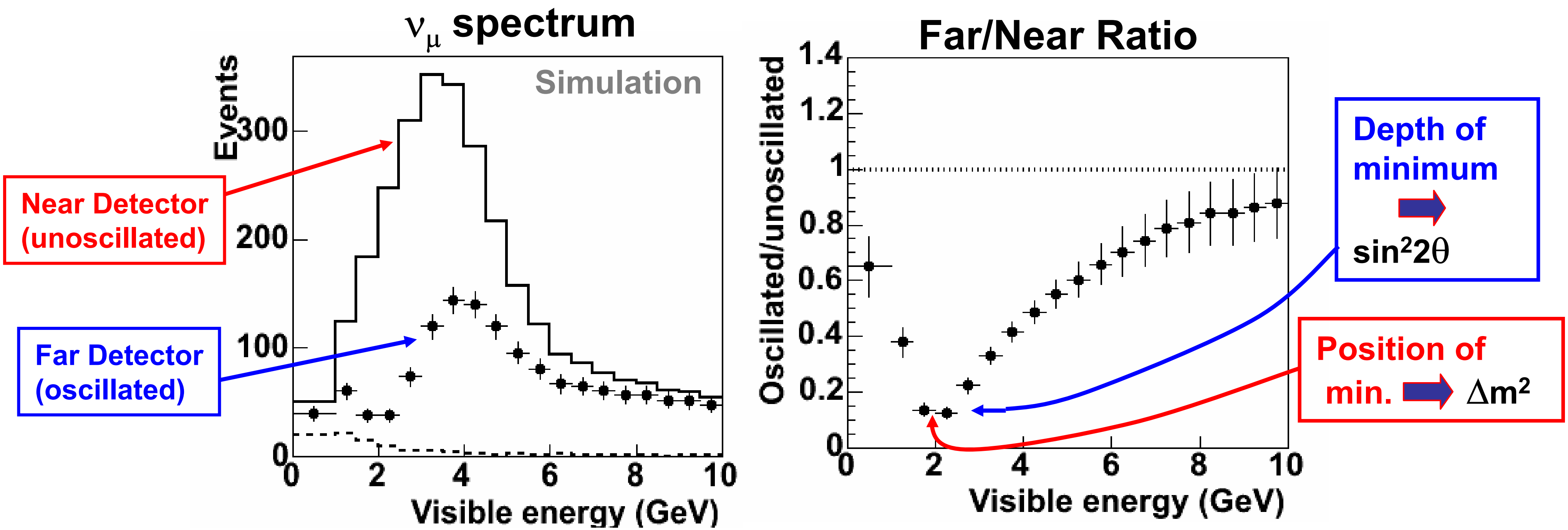
Two detectors:



- ★ 1000 ton, NEAR Detector at Fermilab: **1 km** from beam
- ★ 5400 ton FAR Detector, **720 m** underground in Soudan mine, N. Minnesota: **735 km** from beam

MINOS in a Nutshell

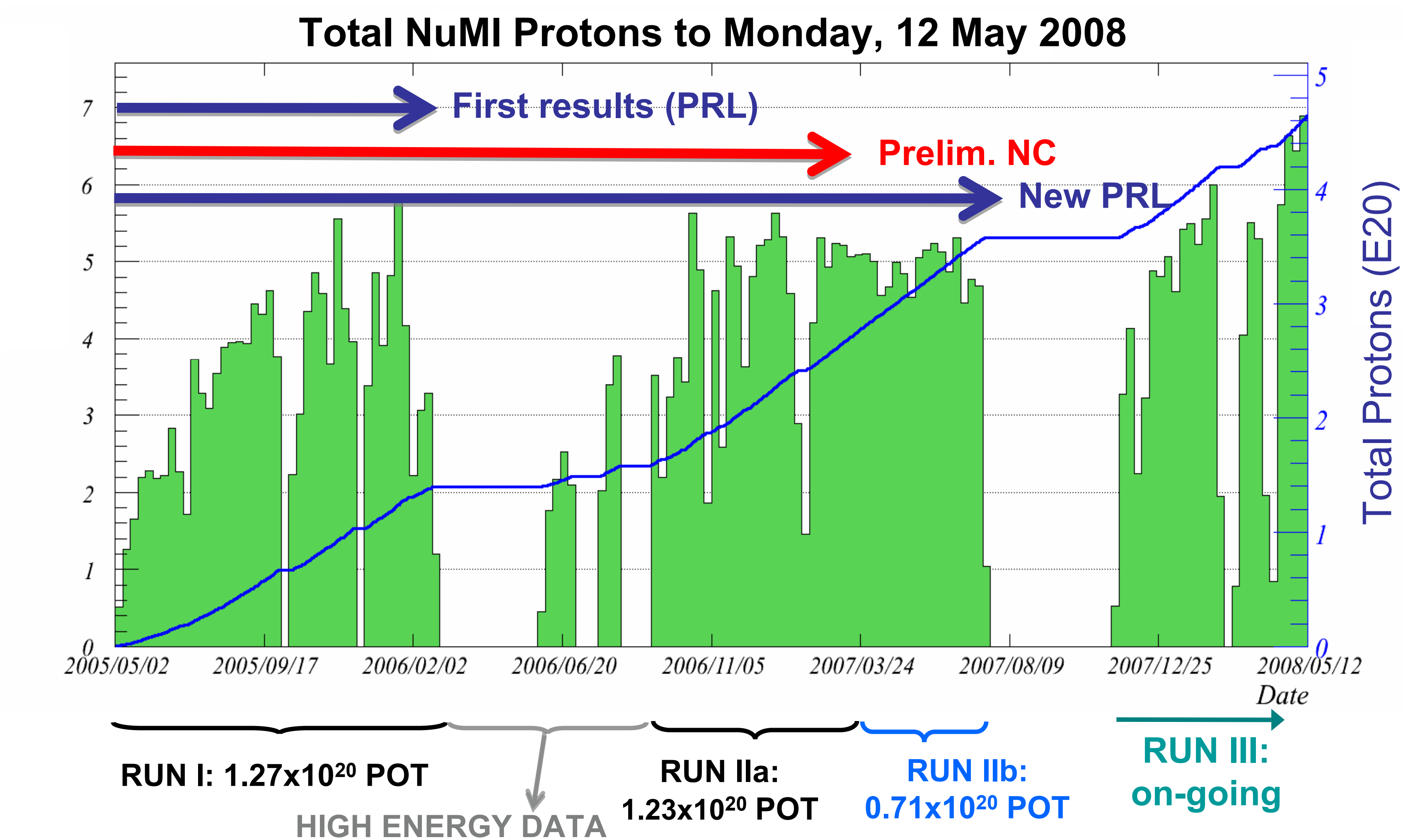
- ★ Measure ratio of the neutrino energy spectrum in far detector (oscillated) to that in the near detector (unoscillated)



- ★ Two detectors vital to understand beam ⇨ precise measurements
- ★ Leads to a significant cancellation of systematic biases

NOTE: longer baseline than K2K ⇨ higher energy beam
no longer dominated by QE interactions

MINOS Data Taking



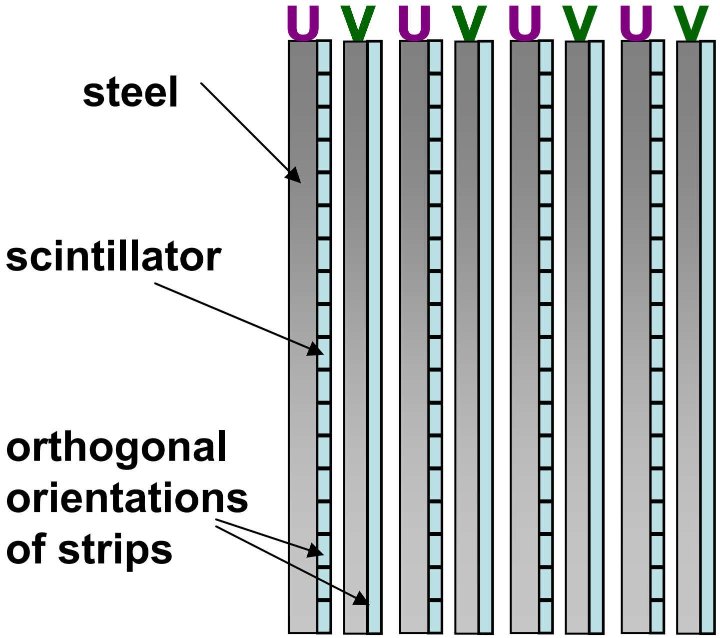
★ **Moveable target: some higher energy data to constrain systematics**

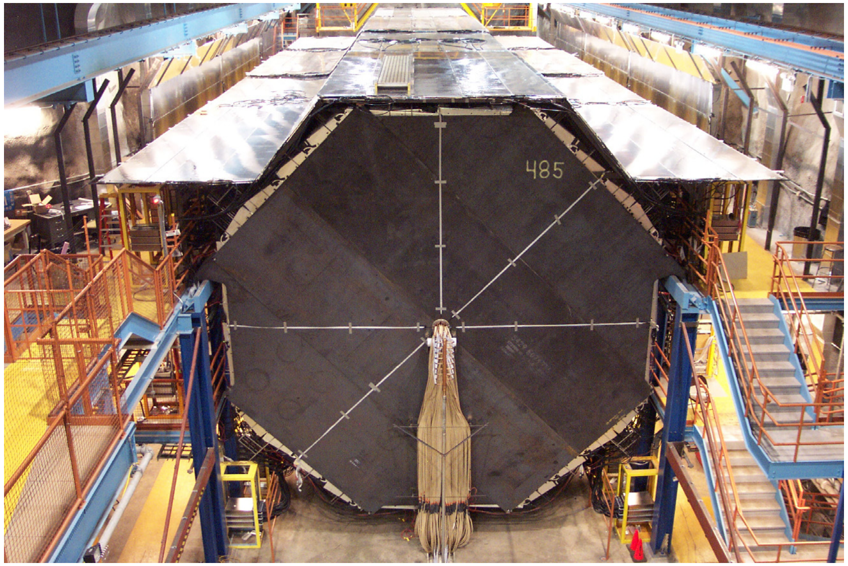
★ **Current results based on ~25-35 % of expected final data sample**

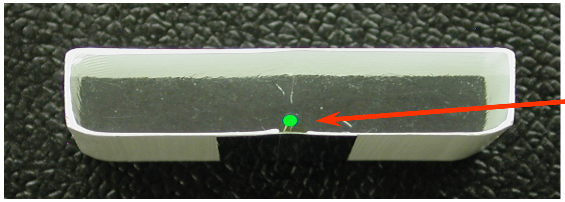
The MINOS Detectors

Basic Technology:

- ★ Steel-Scintillator sandwich : SAMPLING CALORIMETER
- ★ Each plane consists of a 2.54 cm steel +1 cm scintillator
- ★ Each scintillator plane divided into 192 x 4cm wide strips
- ★ Alternate planes have orthogonal strip orientations (U and V)







- ✦ Scintillation light collected by WLS fibre glued into groove
- ✦ Readout by multi-pixel PMTs

MINOS Near Detector

★ **1 km** from beam

★ **1 kton** total mass

★ Same basic design as Far Detector

steel, scintillator, etc

★ **But some differences:**

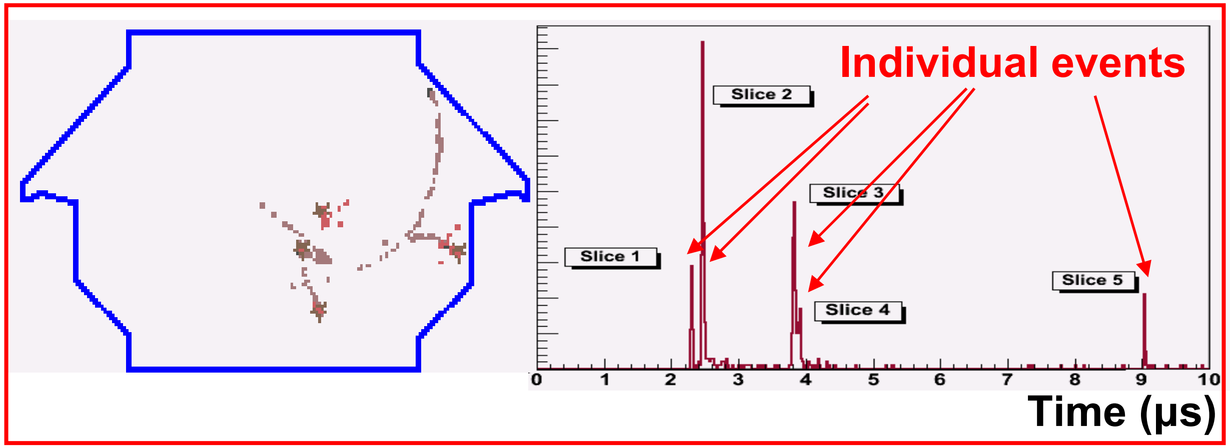
- Faster electronics
- Different PMTs (M64 vs M16)
- Different triggering
- Only partially instrumented
  - **282** planes of steel
  - **153** planes of scintillator
  - (Rear part only used to track muons)

★ But the main difference is

EVENT RATE

★ Multiple event interactions per beam spill

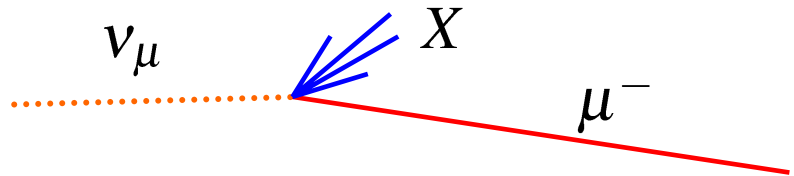
★ Separated using timing + spatial information

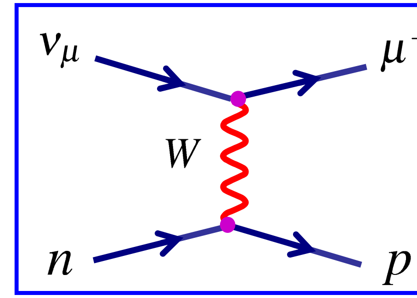


Event reconstruction

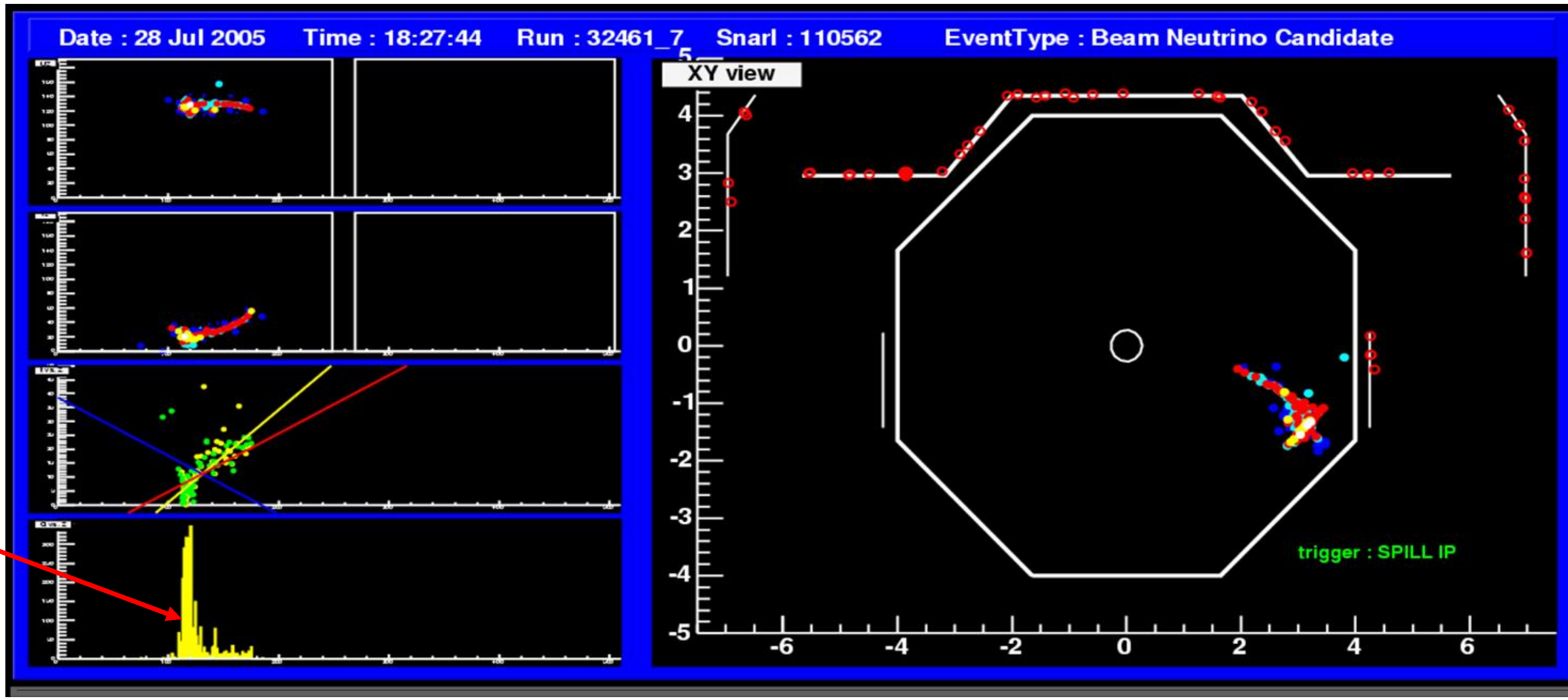
- Neutrino detection via CC interactions on nucleon (~5/day in FD)

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





Example event:



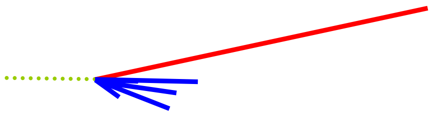
Signal from hadronic shower

- Reconstruct muon momentum + energy of hadronic system

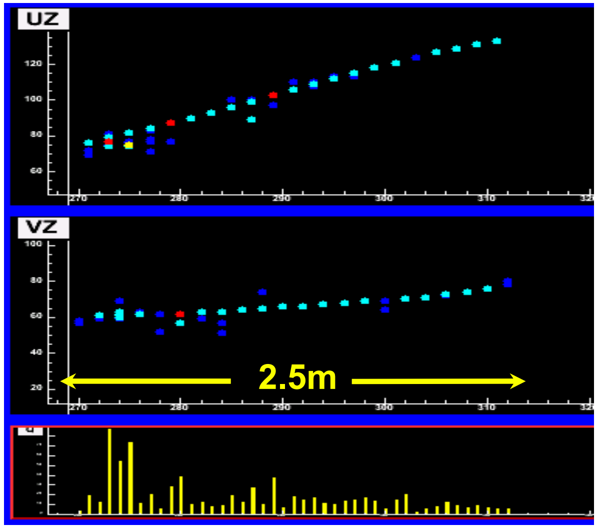
$$E_\nu = E_\mu + E_X \qquad y = E_X/(E_\mu + E_X)$$

Event Identification

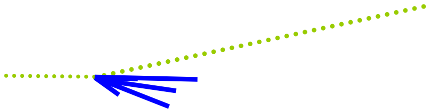
★ Different Neutrino interactions have very different event topologies



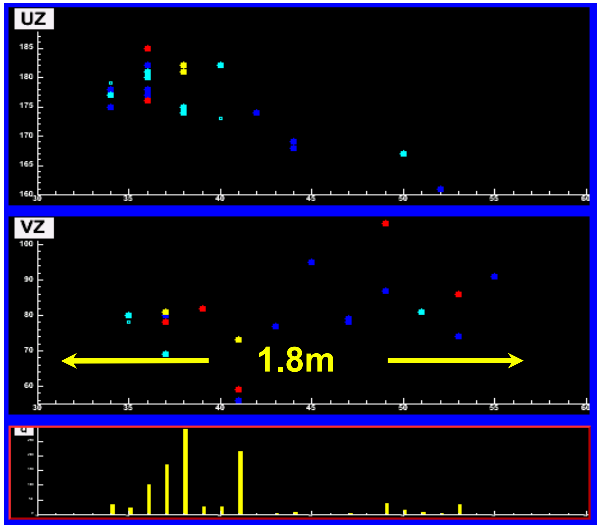
ν_μCC



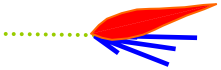
♦ Clear muon track
♦ Hadronic activity at interaction vertex



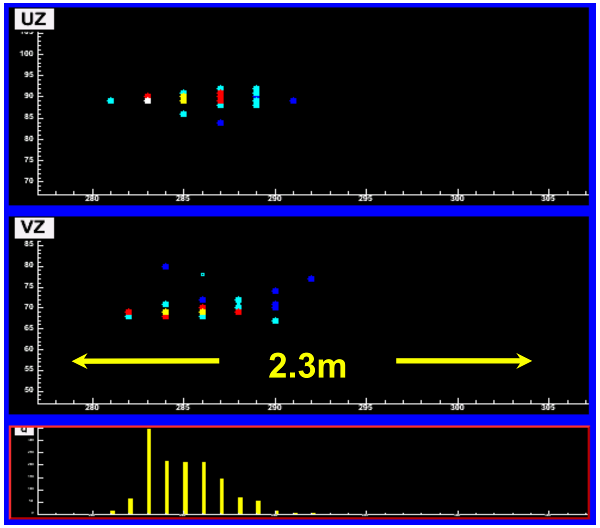
NC



♦ Short
♦ Diffuse



ν_eCC



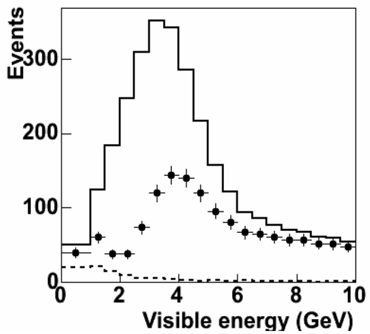
♦ Compact EM shower
♦ +Hadronic activity

Monte Carlo

★ Use multivariate kNN method to select ν_μCC events in **NEAR** and **FAR** detectors

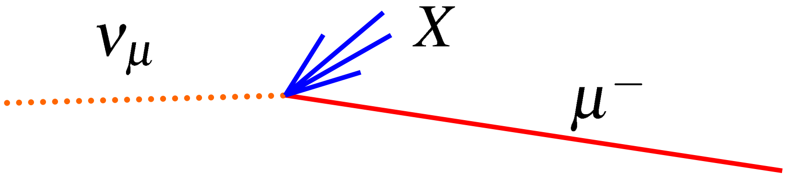
MINOS Physics: ν_μ disappearance

★ High statistics study of $\nu_\mu \leftarrow \nu_\tau$:
- Precise meas. of $|\Delta m_{32}|^2$ and ultimately(?) θ_{23}
- Test alternative models

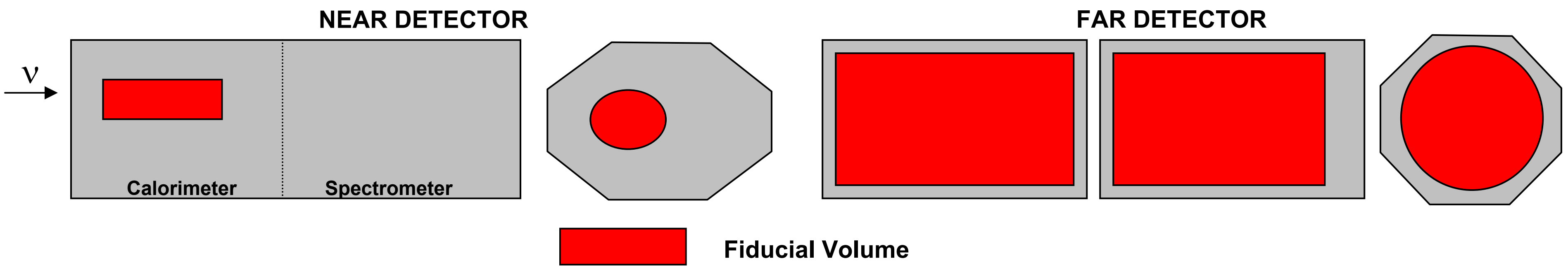


★ Threshold for ν_τ production ~3.5 GeV
- **DISAPPEARANCE** experiment

CC EVENT SELECTION:



- Reconstructed track
- Event vertex in ND/FD fiducial volume



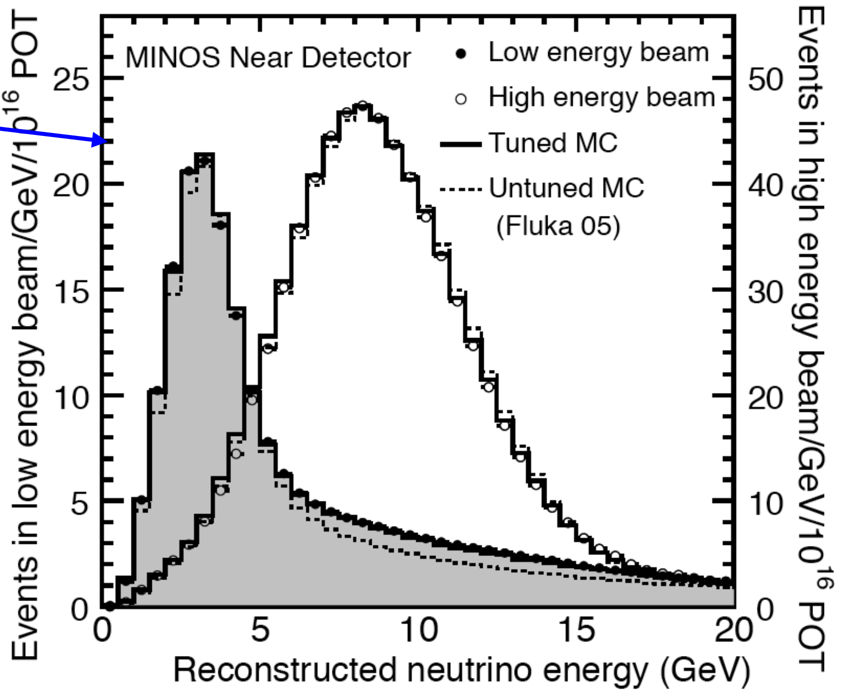
- Curvature of track in B-field consistent with being negatively charged
- Event vertex in ND/FD fiducial volume
- Passes kNN based CC/NC multivariate event identification

Precision Neutrino Physics

- ★ **For precision measurements – need to predict accurately FD energy spectrum**
- ★ **An a priori approach would require**
  - **accurate simulation of neutrino flux from 120 GeV protons hitting target**
  - **accurate simulation of (low energy) neutrino cross sections**
- ★ **NEITHER EXIST – large (>10%) uncertainties in hadron production and neutrino cross sections**

But MEASURE Spectrum in Near Detector

- ★ **"tune" Monte Carlo using ND data recorded in 7 different beam settings, e.g.**



- **Tune MC hadron production using a function that varies smoothly with hadronic x_F and p_T**
- **Tuned MC gives better agreement with data in all beam configurations**

Effectively use MEASURED ND Spectrum

Extrapolating to the Far Detector

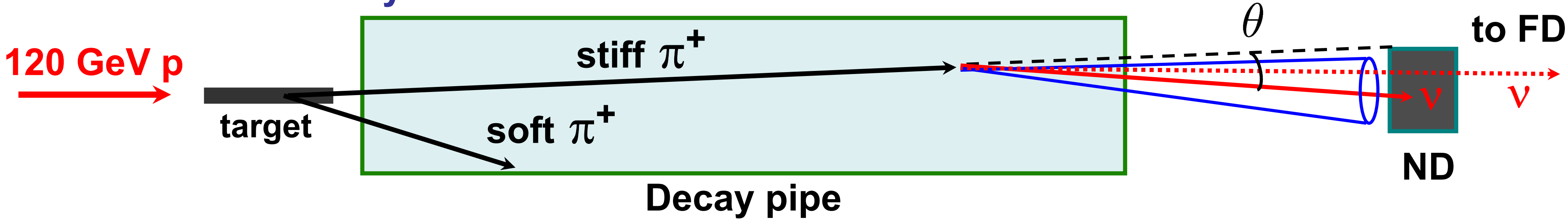
★ BUT: even in the absence of oscillations the NEAR and FAR detector neutrino spectra are different !

<u>**Easy to understand…**</u>

★ Consider a pion decaying in the decay pipe

★ Neutrino can intersect the ND for a relatively wide range of decay angles

★ For far detector only decays in a very small range of angles will cross the FD 735 km away

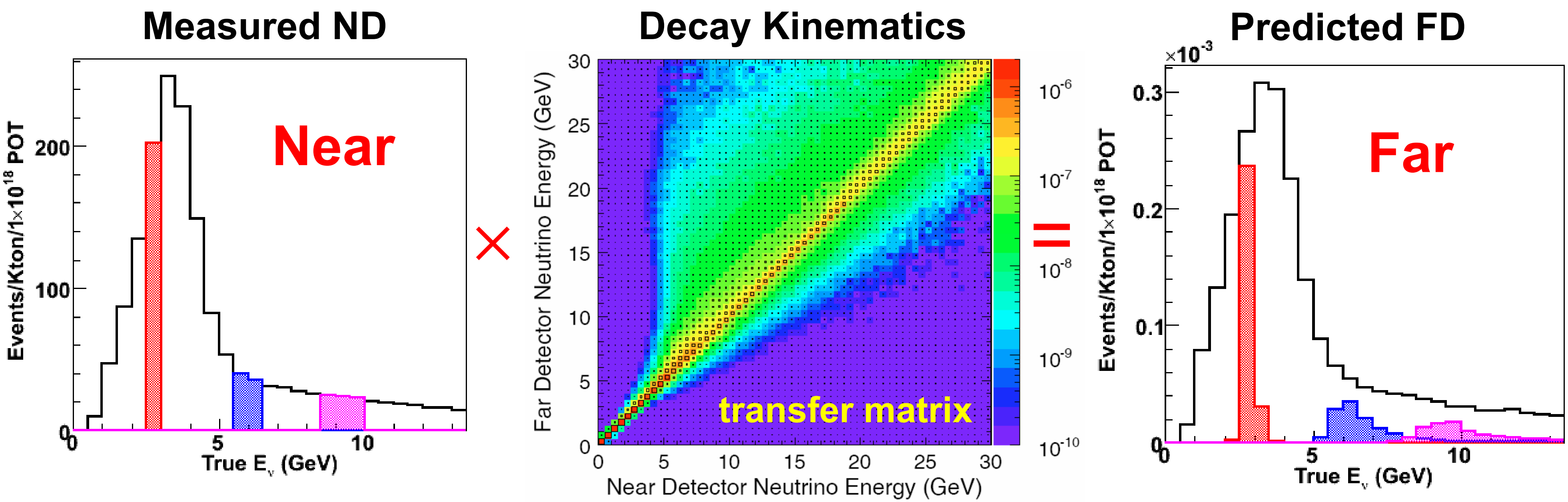


★ From simple relativistic kinematics for pion decay – neutrino energy depends on decay angle relative to pion line of flight

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

★ Decays with neutrinos pointing towards the FD tend to have smaller θ and hence have slightly higher energy

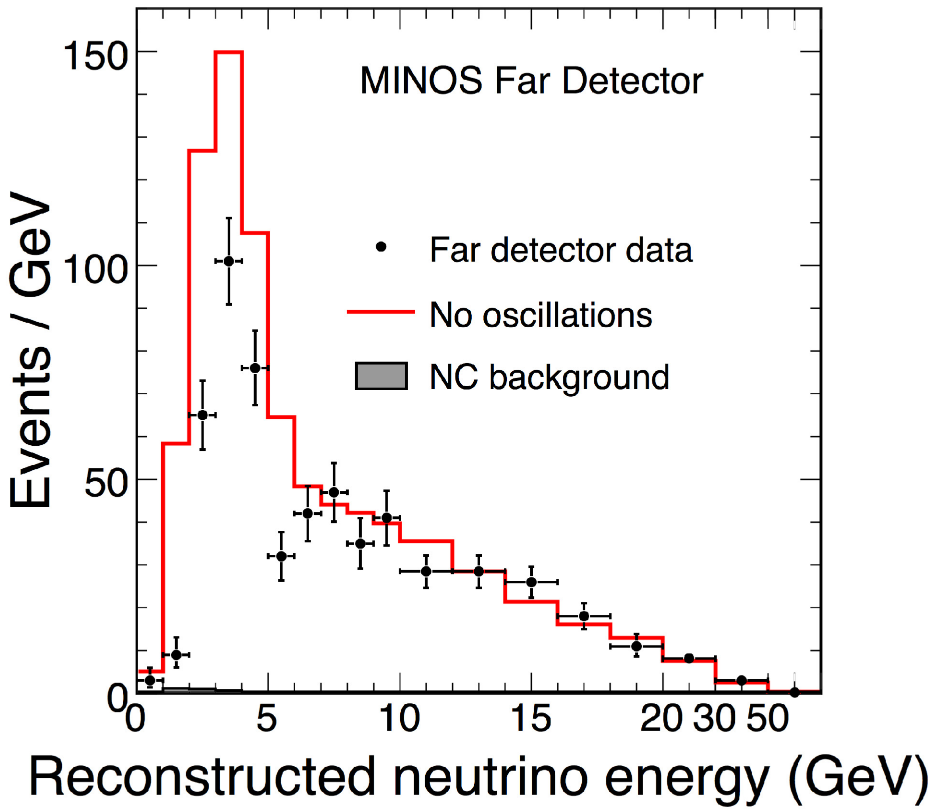
★ Difference is just kinematics, i.e. well understood !



<u>Beam Transfer Matrix:</u>

- Encapsulates knowledge of 2-body pion decay and geometry
- Provides a simple way of relating near and far detector energy spectra
- Beam matrix determined from MC but does not depend strongly on details; kinematics & geometry dominate
- Near detector data "directly" determines predicted Far Detector spectrum
- Monte Carlo tuning only enters as a second order effect in determining matrix

Oscillation Analysis

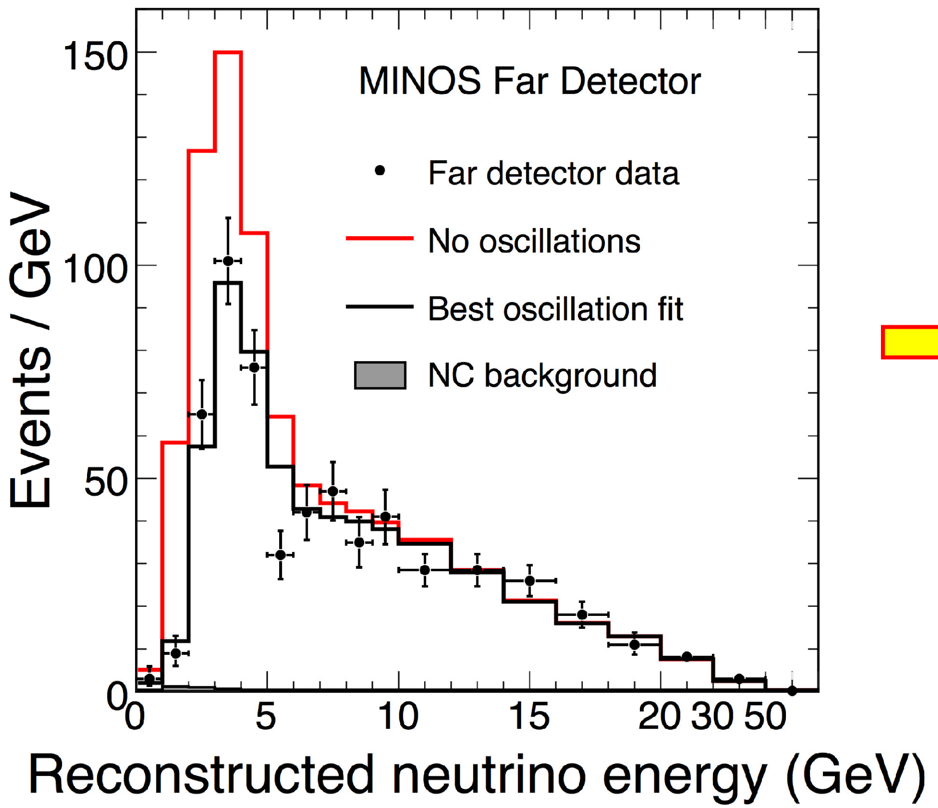


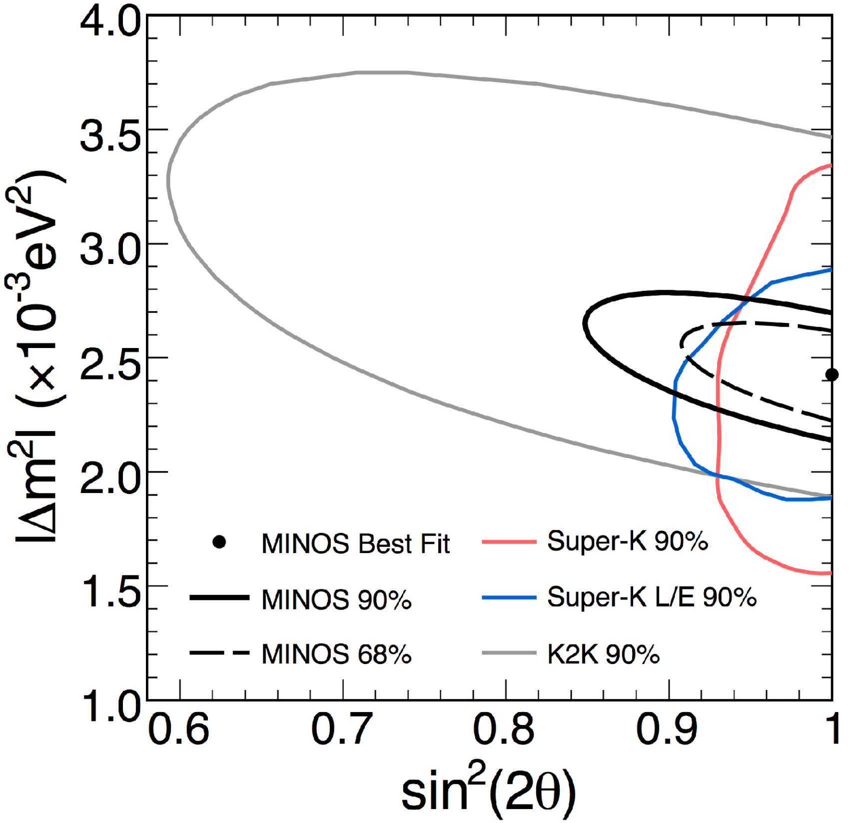
Data sample	Observed	Expected (no osc.)
ν_μ CC LE	730	936 ± 53

- Oscillation parameters extracted from likelihood fit to reconstructed energy distribution of selected Far Detector events

$$\chi^2(\Delta m^2, \sin^2 2\theta, \alpha_j, \ldots) = \underbrace{\sum_{i=1}^{nbins} 2(e_i - o_i) + 2o_i \ln(o_i/e_i)}_{\text{statistical error}} + \underbrace{\sum_{j=1}^{nsyst} \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j^2}}}_{\text{systematic errors}}$$

Oscillation Analysis





Results:

$$|\Delta m^2_{32}| = 2.43 \pm 0.13\,\mathrm{eV}^2$$

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

$$\chi^2/n_{d.o.f} = 90/97$$

- ★ **Good fit to oscillation hypothesis**
- ★ **Sufficient data to reject alternative hypotheses**

MINOS Physics : Alternative Scenarios

- ★ MINOS is the first **high statistics** long-baseline experiment
- ★ Can study shape of oscillation curve in detail
- ★ In particular, compare standard oscillation hypothesis to other scenarios, e.g.

Neutrino Decay

V. Barger *et al.*, PRL82:2640(1999)

$$P(\nu_\mu \to \nu_\mu) = (\sin^2\theta + \cos^2\theta e^{-\frac{\alpha L}{2E}})^2$$

$$\chi^2/ndof = 104/97 \qquad \Delta\chi^2 = 14$$

Disfavoured at 3.7 σ level

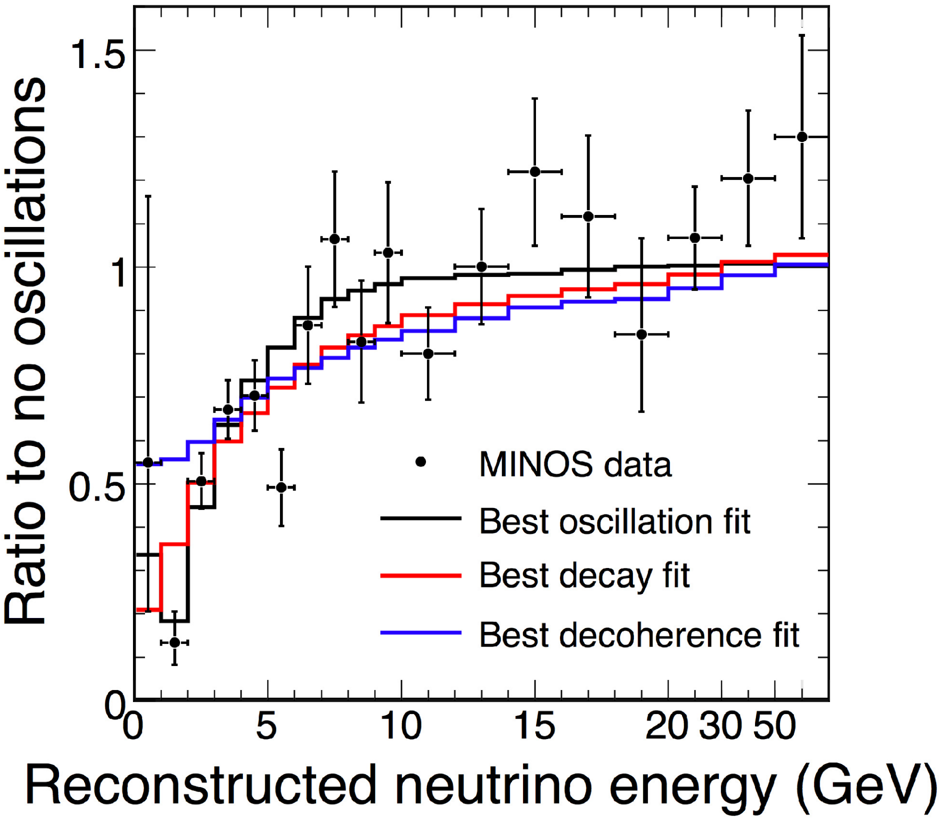
Neutrino Quantum Decoherence

G.L. Fogli *et al.*, PRD67:093006 (2003)

$$P(\nu_\mu \to \nu_\mu) = 1 - \frac{\sin^2 2\theta}{2}(1 - e^{\frac{\mu^2 L}{2E}})$$

$$\chi^2/ndof = 123/97 \qquad \Delta\chi^2 = 33$$

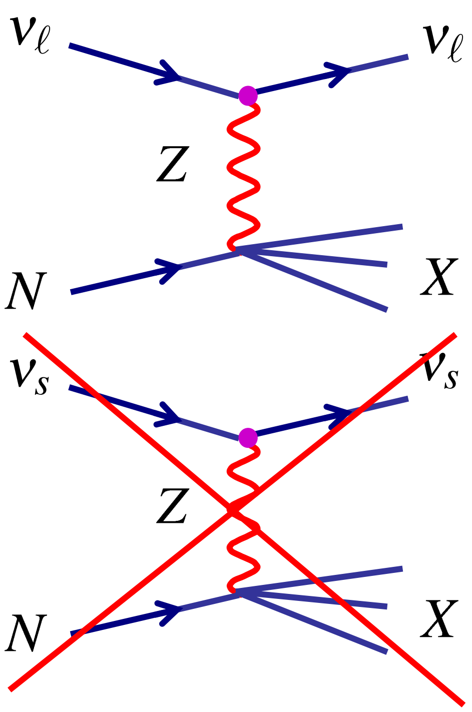
Disfavoured at 5.7 σ level

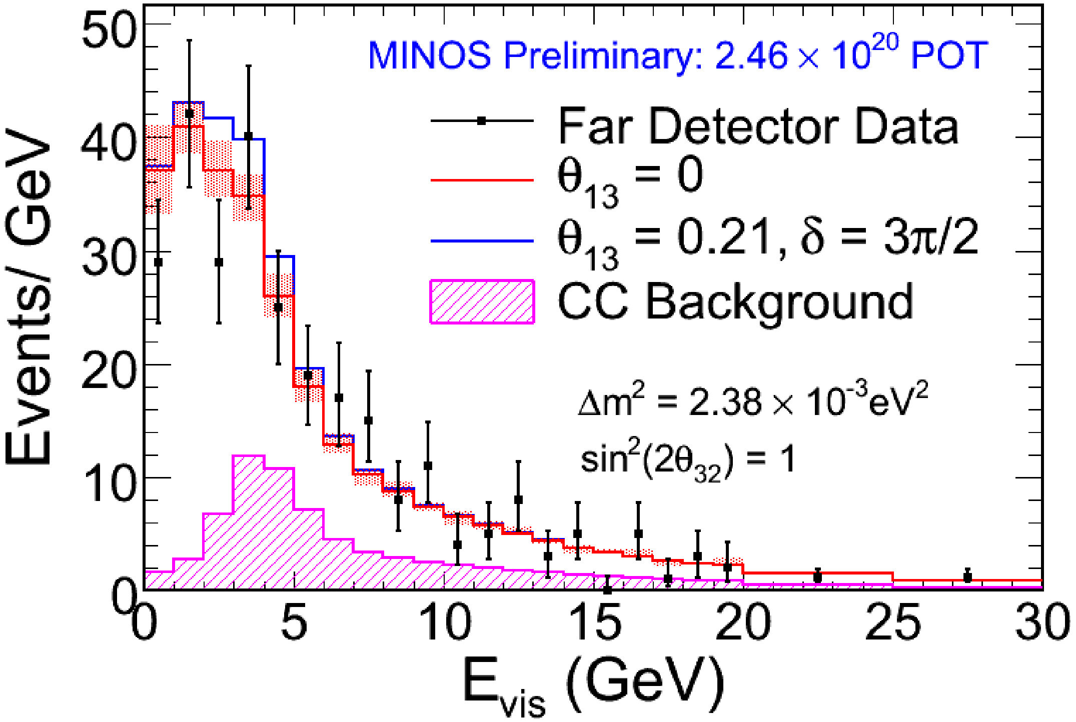


THERE BE OSCILLATIONS !

MINOS Physics : Neutral Current

- ★ MINOS CC analysis provides clear evidence of ν_μ disappearance
- ★ Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations
- ★ Alternative – oscillations to a sterile neutrino state $\nu_\mu \rightarrow \nu_s$
- ★ Distinguish from NC event rate in MINOS far detector





- ★ Preliminary study of NC events consistent with standard interpretation

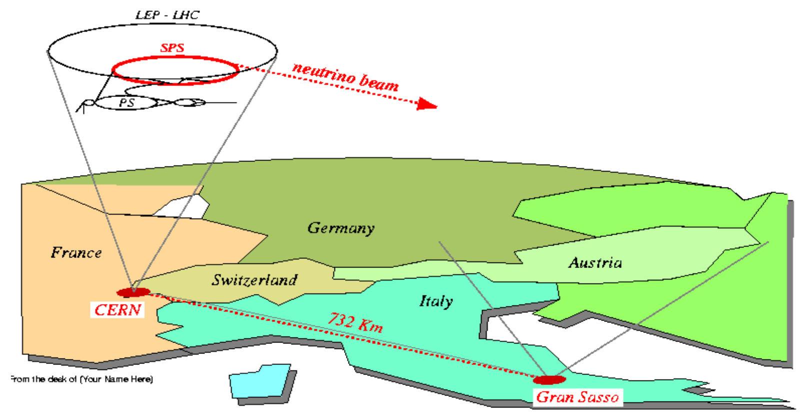
To confirm $\nu_\mu \rightarrow \nu_\tau$ oscillations – want to observer τ lepton from ν_μ beam !

CNGS - OPERA

see Andrea Longhin's talk

- ★ **CERN to Gran Sasso Neutrino Beam:** **baseline 732 km**
- ★ **"Unique selling point", ability to detect decays of tau leptons produced in $\nu_\mu \rightarrow \nu_\tau$ oscillations**
- ★ **For baseline of 732 km $\nu_\mu \rightarrow \nu_\tau$ oscillation probability maximum at ~1.5 GeV**

CERN to Gran Sasso Neutrino Beam



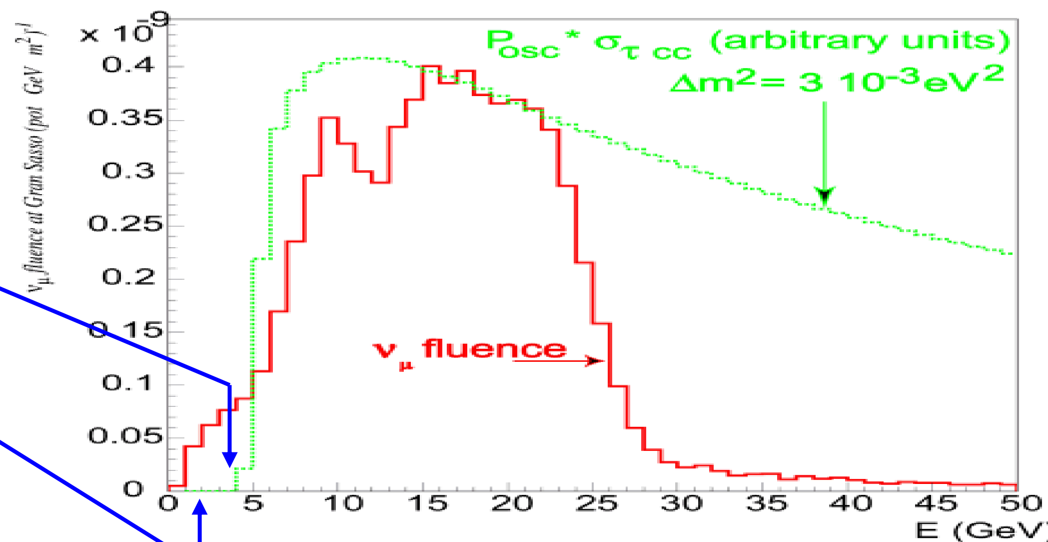
- ★ **BUT kinematic threshold for $\nu_\tau + \mathrm{n} \rightarrow \tau^- + \mathrm{p}$ is $E_{\nu_\tau} > 3.5\,\mathrm{GeV}$**

High energy beam

Tau threshold

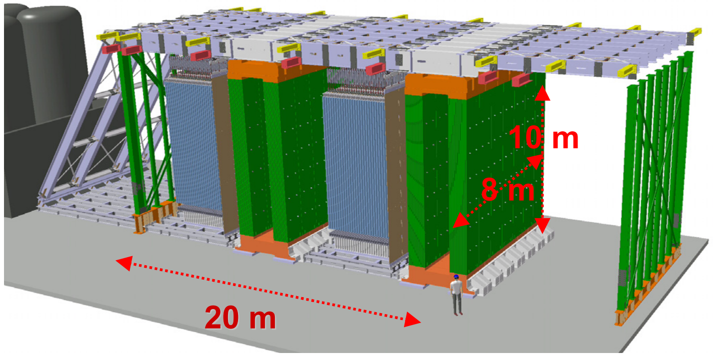
Oscillation max.

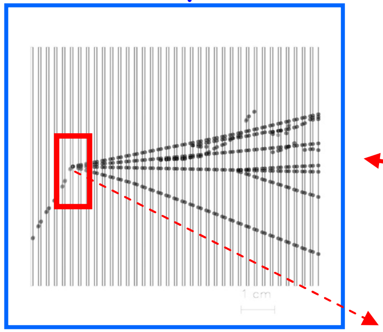
low event rate



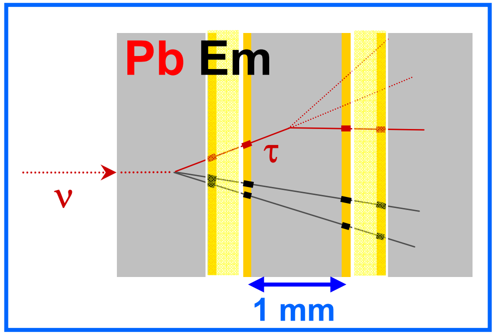
CNGS - OPERA

★ Detecting the small number of produced tau leptons is very challenging





- Approx. 150,000 Pb/Emulsion bricks
- Look for kinks/prongs
- First need to identify candidate interactions in Sci trackers
- Candidate brick removed robotically



★ First full physics run scheduled to start June 2008

★ In 5 year run (4.5×10^{19} PoT/year) : expect ~10 signal events, ~1 background

★ understanding background crucial

By end of year may have first tau candidate

MINOS Physics : $\nu_\mu \rightarrow \nu_e$

Electron Neutrino Appearance

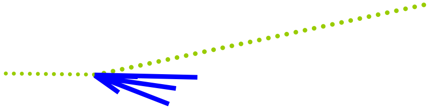
★ Search for $\nu_\mu \rightarrow \nu_e$ oscillations is a hot-topic in neutrino physics

★ Vital for longer term projects to probe **CP** violation in the neutrino sector as **CP** violating terms in **PMNS** matrix enter multiplied by $\sin\theta_{13}$

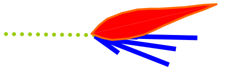
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-s_{13}e^{-i\delta}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

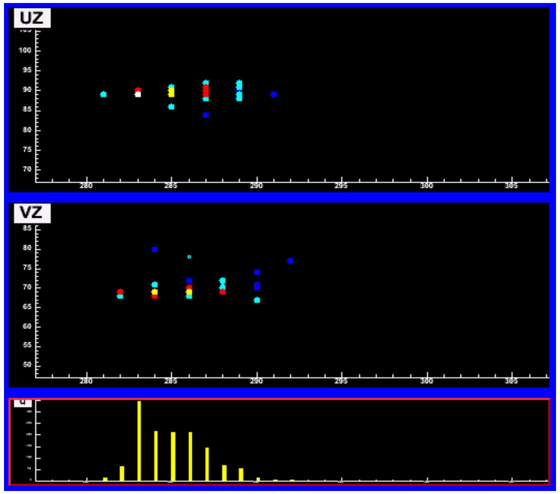
★ This is a **very** challenging analysis in **MINOS**
- course sampling
- events have relatively few "hits"
- event rate low <20 events in current data
- large background from NC interactions:
  π^0 in hadronic shower ⇨ EM shower

NC



ν_eCC



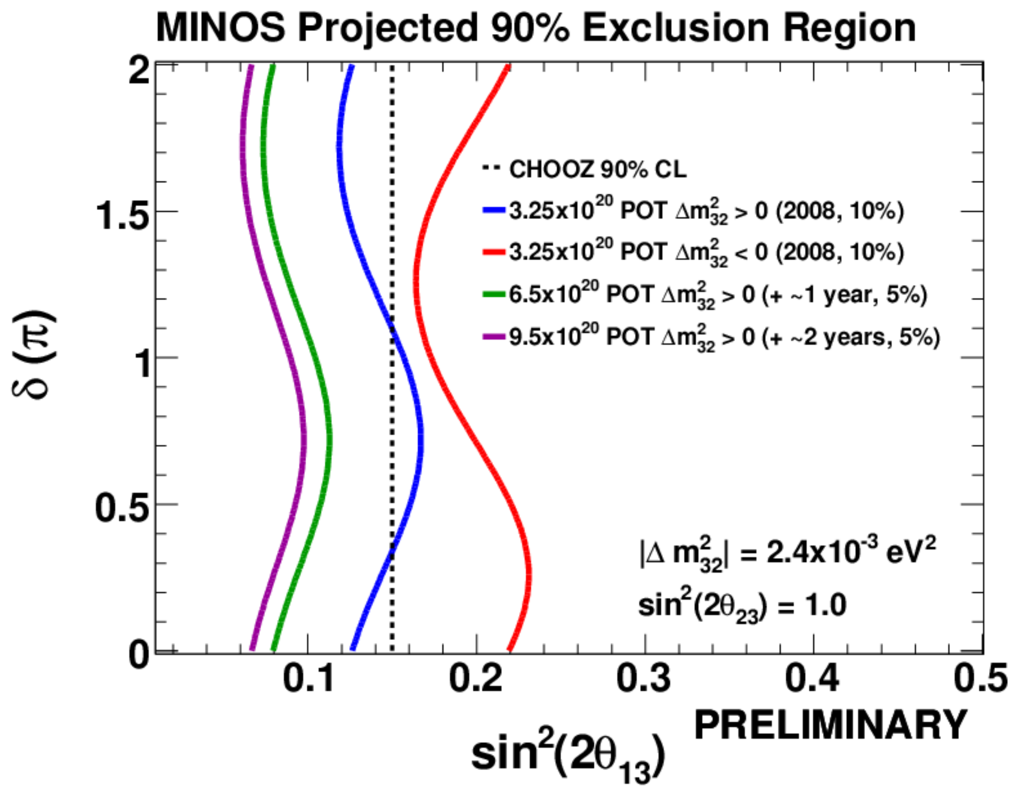


★ MINOS currently developing sophisticated event ID algorithms

★ MAIN problem : Large uncertainties in NC background from MC

★ Use Near Detector to provide **data-driven background estimate**

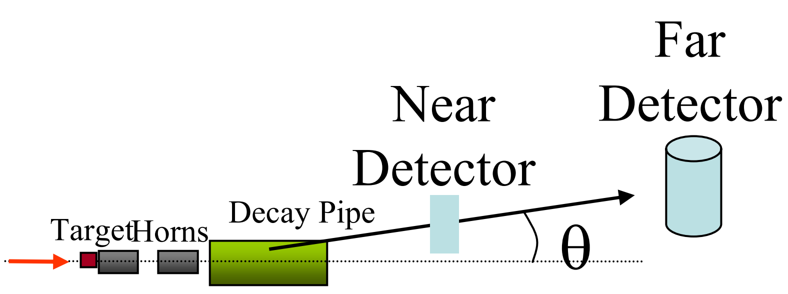
★ By 2010, MINOS will have sensitivity down to $\sin^2 2\theta_{13} \sim 0.06$

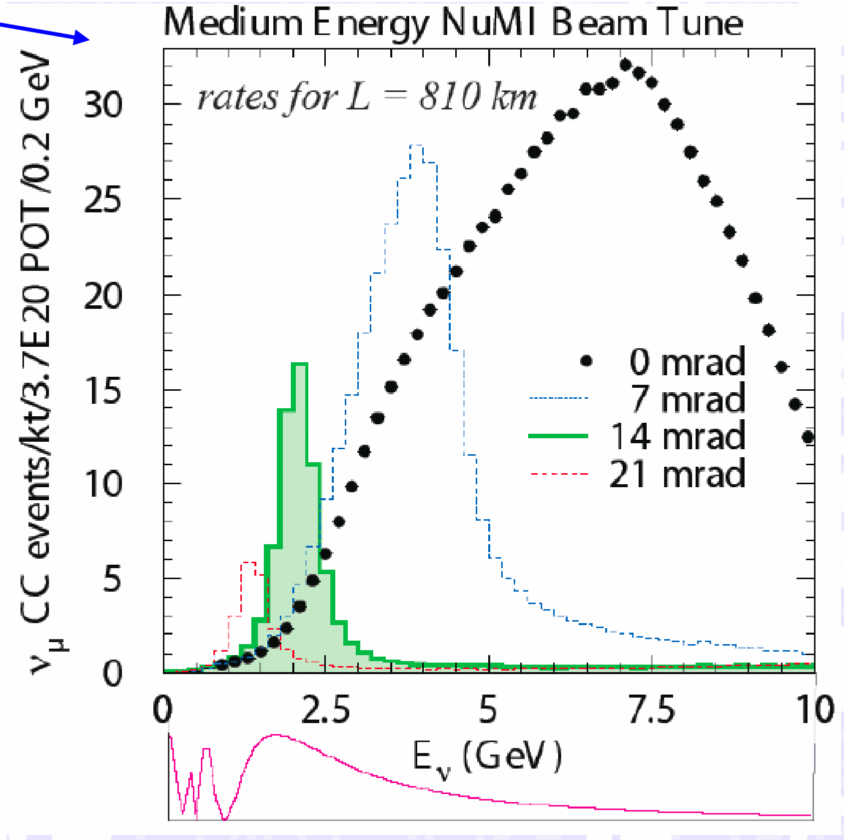


θ_{13} Focus of next generation experiments

Future Experiments: Off-axis

- ★ Main problem in searching for $\nu_\mu \to \nu_e$ is the NC background
- ★ Mainly comes from higher energy (i.e. above oscillation max) neutrinos
- ★ Solution : produce narrow-band beam
- ★ Achieved by placing far detector off-axis
  e.g. NuMI beam for NOνA

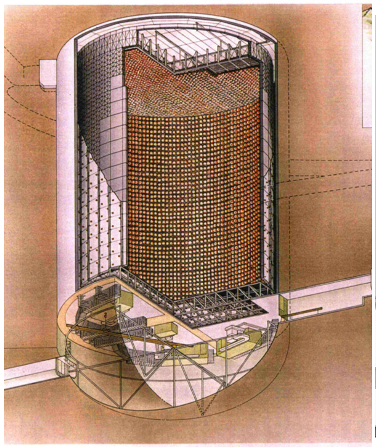


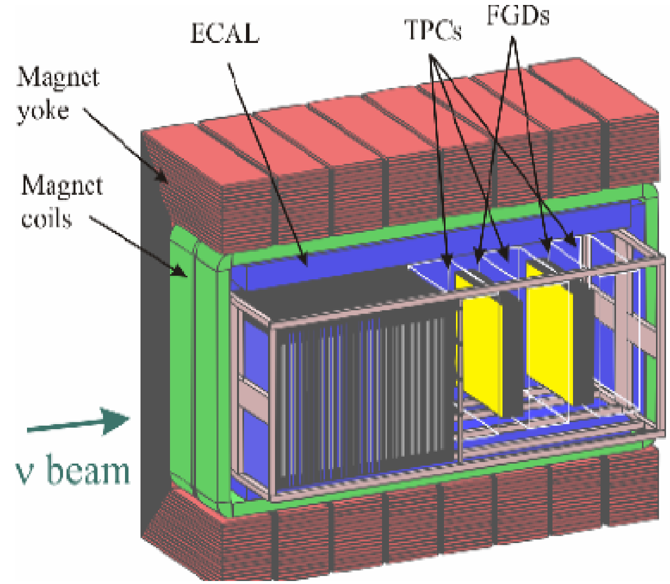


★ Two (?) projects in near future:
- T2K (2010-)
- NOνA (201?-)

Future Experiments: T2K

- Tokai to Kamioka





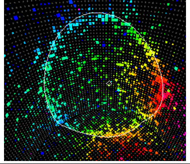
Far detector:
- Super-Kamiokande
- at 295 km
- 2.5 degress off-axis

"Beam Profiler"
- at 280 m
- on-axis
- Fe/Sci Tracker
- Measure beam profile

Near detector:
- at 280 m
- off-axis
- Calorimeters + Trackers + TPC
- Inside UA1 magnet
- P0D : Scintillator fibre to measure NC π^0 content

- First beam operations ~April 2009
- First physics beam run ~2010

T2K $\nu_\mu \rightarrow \nu_e$



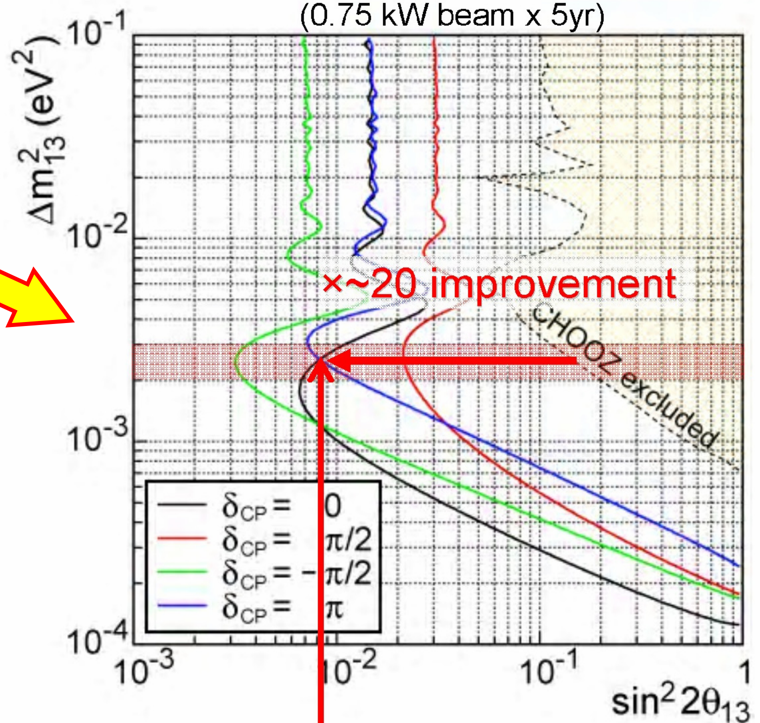
★ **Look for excess of 1-ring e-like events in Super-K**

Expected number of events at SK (0.75kW beam x 5yr)

$\sin^2 2\theta_{13}$	Backgrounds			Signal
	ν_μ induced	Beam ν_e	**Total**	
0.1	10	13	**23**	**103**
0.01				**10**

20x improvement wrt to current limit

90% C.L. sensitivity
(0.75 kW beam x 5yr)

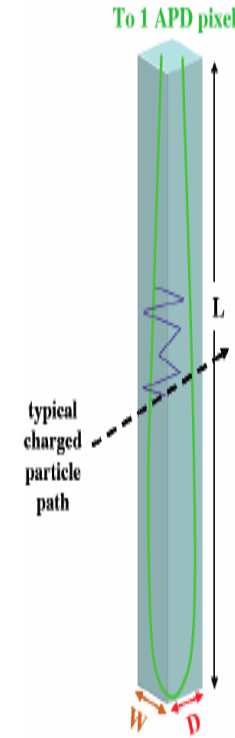


$\sin^2 2\theta_{13} \sim 0.008$ ($\delta_{CP} = 0,\pi$)

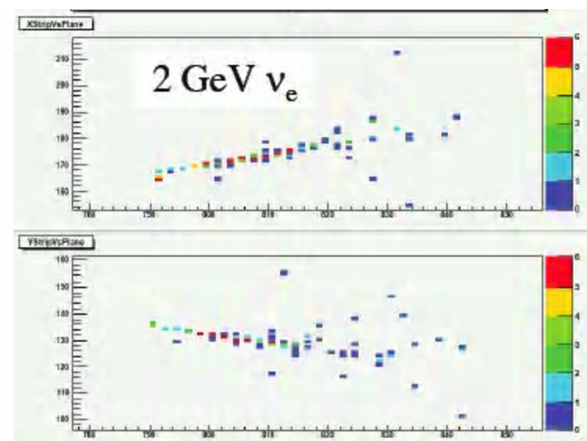
NOTE:

- ★ **Signal may not be large**
- ★ **Must understand background in detail**
  - **beam ν_e irreducible, but diff. spectrum**
  - **NC events with $\pi^0 \rightarrow \gamma\gamma$ which gives only 1 reconstructed ring**
- ★ **Near detector vital to understand this background**
- ★ **how well this can be achieved, may determine ultimate sensitivity**
- ★ **may not be trivial as ND and FD are very different…**

Future(?) Experiments: NOνA



- ★ **810 km baseline: Fermilab to Ash River**
- ★ **Upgraded NuMI beam (400-700 kW)**
- ★ **Liquid scintillator detector (off-axis)**
  - **high granularity**
  - **little dead material**
  - **low density → large detector**



- ★ **Main physics goal:** $\nu_\mu \to \nu_e$
- ★ **Because of longer baseline, sensitive to matter effects**
- ★ **By comparing results with T2K may be able to resolve mass hierarchy, and if** θ_{13} **large mixing, possibly some sensitivity to CP**

Conclusions

We have entered the age of LBL neutrino oscillations experiments:

- ★ First generation (K2K) confirmed Super-K atmospheric neutrino results
- ★ Second generation (MINOS, CNGS/OPERA) give precise measurements of atmospheric neutrino sector $|\Delta m^2_{32}|$ and θ_{23}
- ★ Second generation (OPERA) will(?) confirm $\nu_\mu \rightarrow \nu_\tau$ hypothesis
- ★ Second generation (MINOS) may make first measurement of θ_{13}
- ★ Third generation (T2K/NOνA) should determine θ_{13}
- ★ Third generation (T2K+NOνA) may resolve mass hierarchy and may have some sensitivity to δ

★ By middle of next decade could have a fairly "detailed" understanding of the neutrino mixing sector

!
- What if $\theta_{23} \approx \pi/4$ and/or $\theta_{13} \approx 0$
- Theoretically very interesting, but experimentally challenging

Nevertheless: strong and coherent experimental program
LBL experiments central to understanding of the neutrino