Exploring the New World of Neutrino Physics

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Fermilab Academic Lecture Series

Section III - Spring 2006

Lecture 2 - MINOS coming on, off-axis beams, hierarchy and CP

MINOS Beam Event Characteristics

Simple event selections for both detectors.

Far Detector

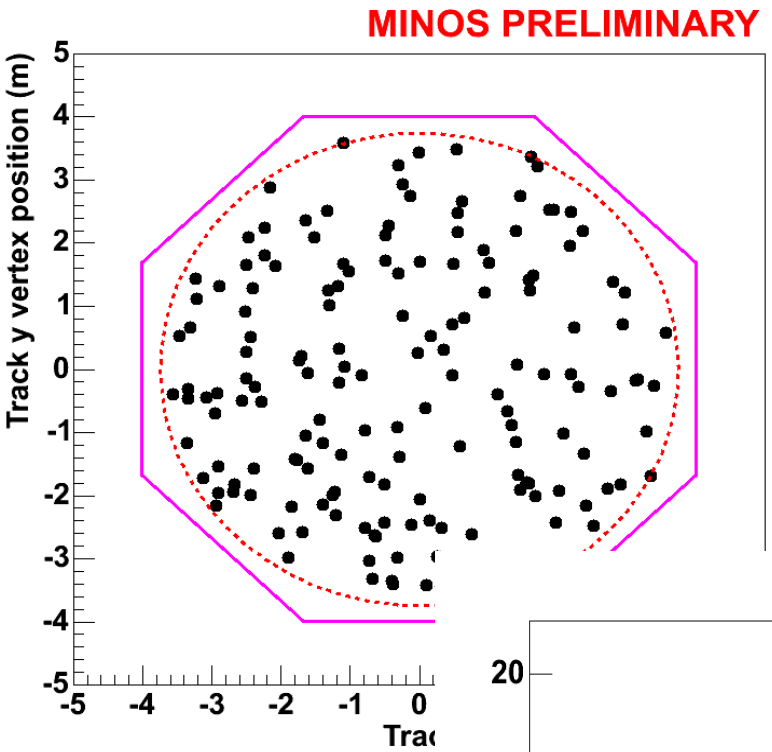
- 50 μs window around beam spill
- Reconstructed track within fiducial volume (70% for CC)
- Track angle along beam direction.
- Data and beam quality cuts (96%)

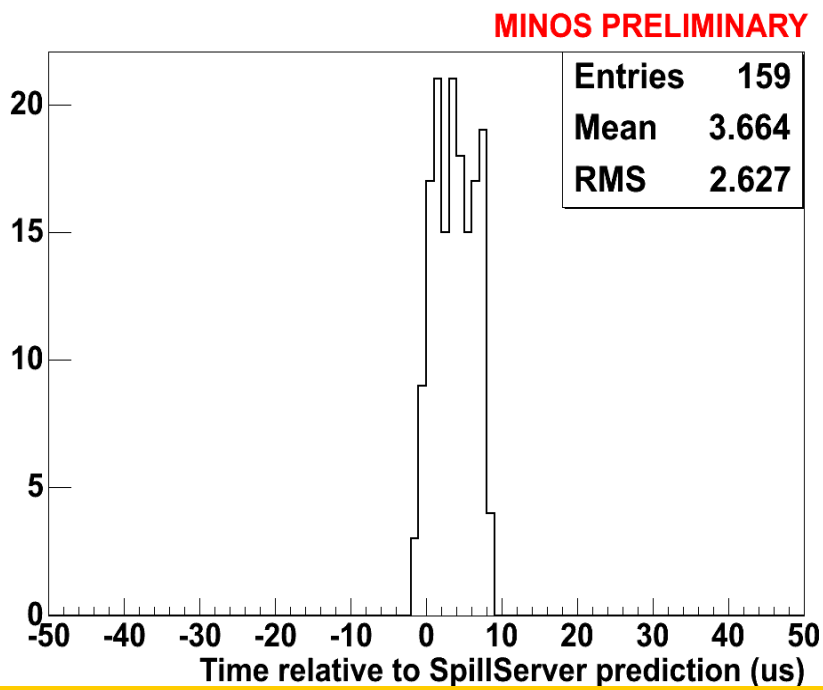
Only an unknown fraction of the far detector data is used for checks and testing.

Near Detector

- Fiducial cuts using track or event vertex for candidate neutral currents
- Track quality cuts for events with tracks
- Beam quality cuts

Vertex and Timing Distribution of Far Detector Events





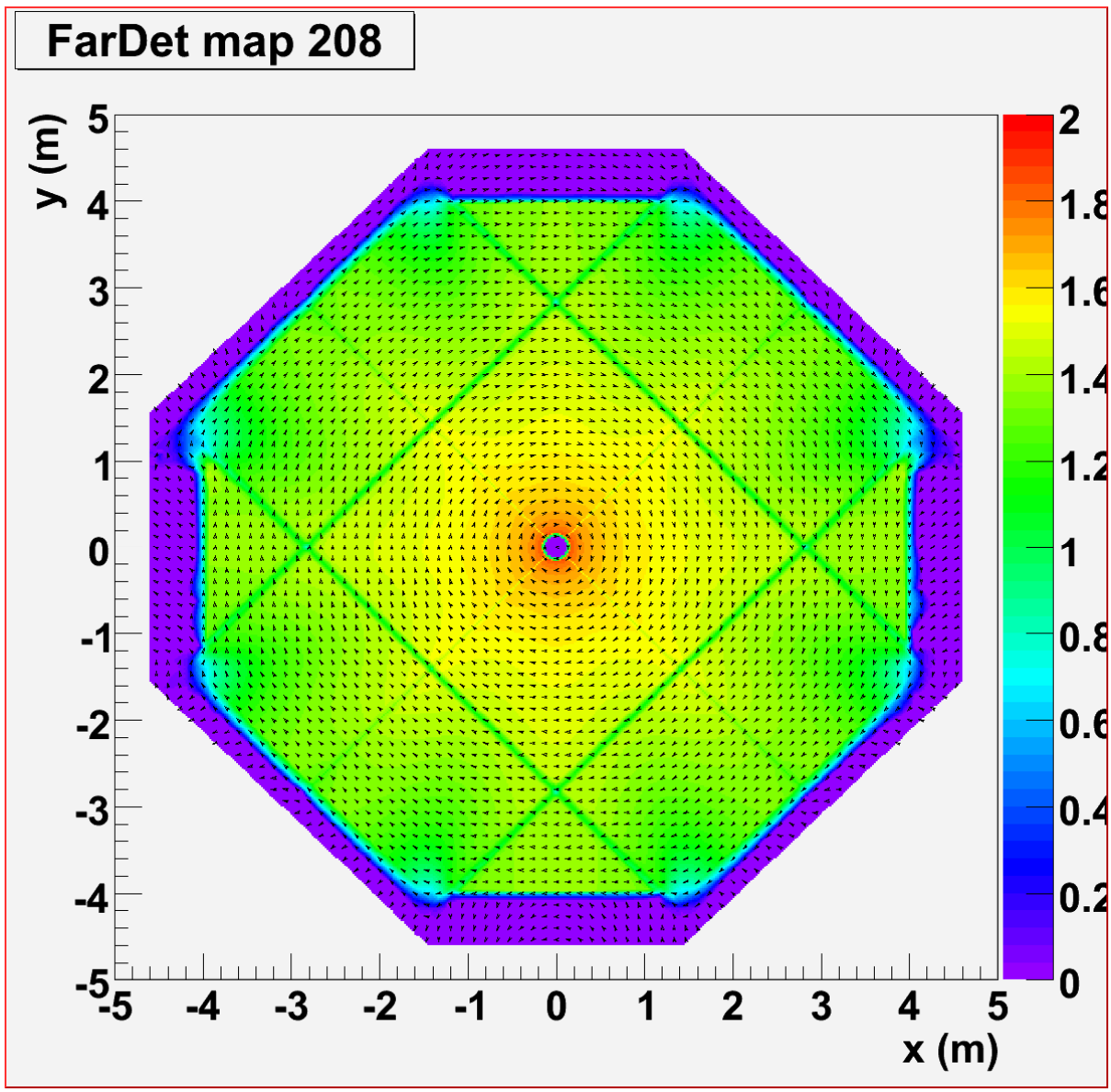
The cuts described result in 159 neutrino events.

Protons used for this work 9.3×10^{19}

Caution: This is MINOS open sample only

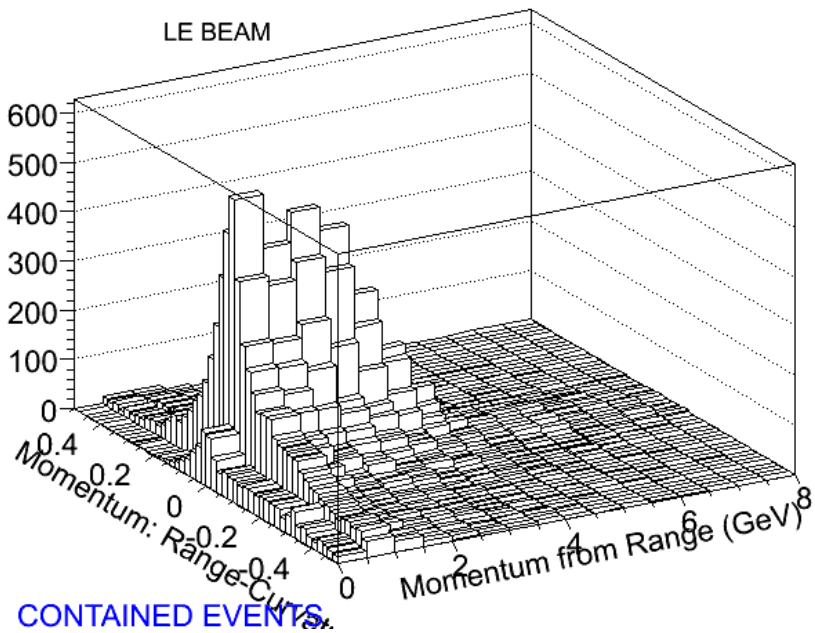
Tracking must go on in magnetized iron

Determine field map by finite element analysis, steel properties.



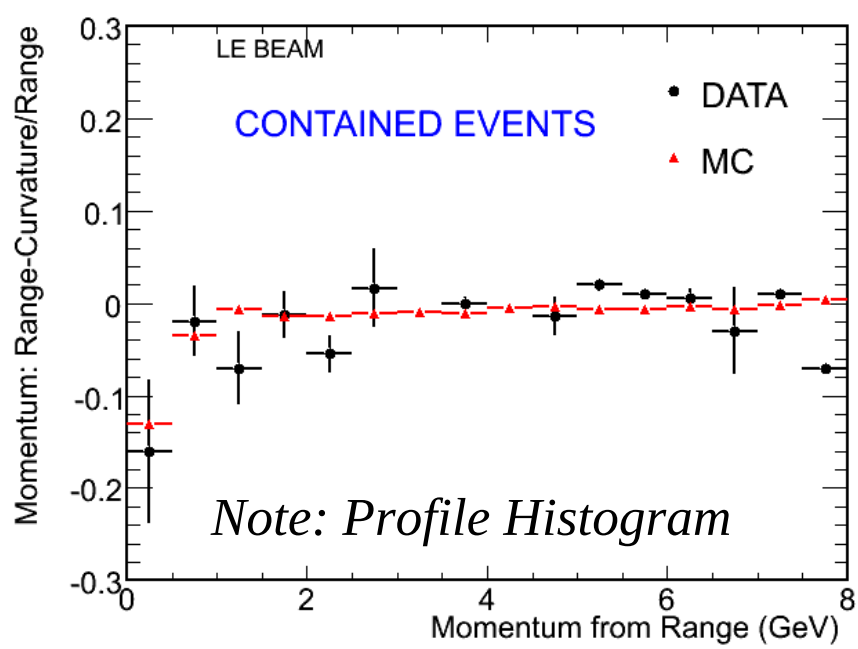
MINOS Far Detector B-field (Tesla)

Range and Curvature Momentum Comparison



Near Detector

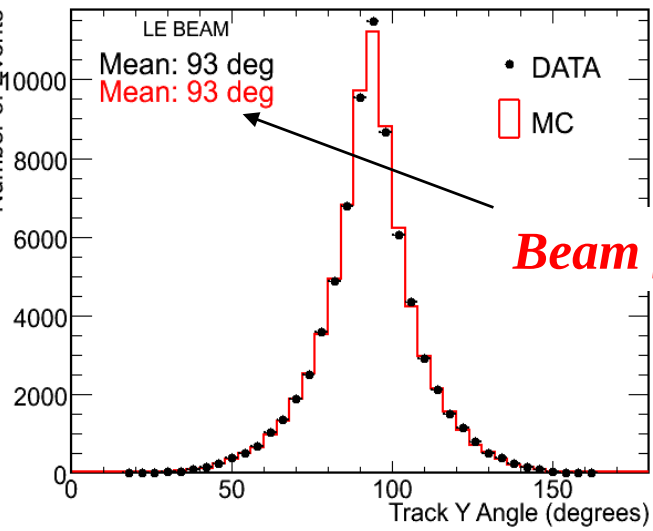
Far Detector

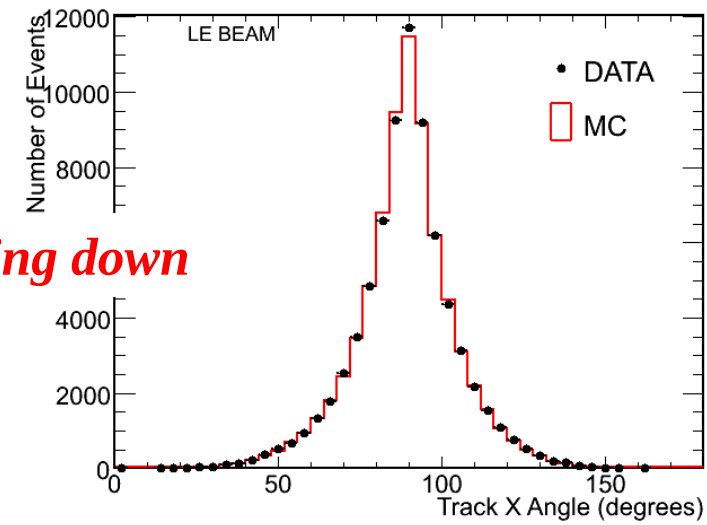


Comparison in momentum regime where events are contained.

Builds confidence in magnetic field map and calibration

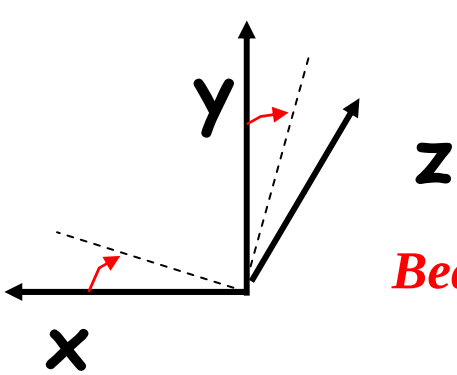
MINOS Reconstructed Track Angle

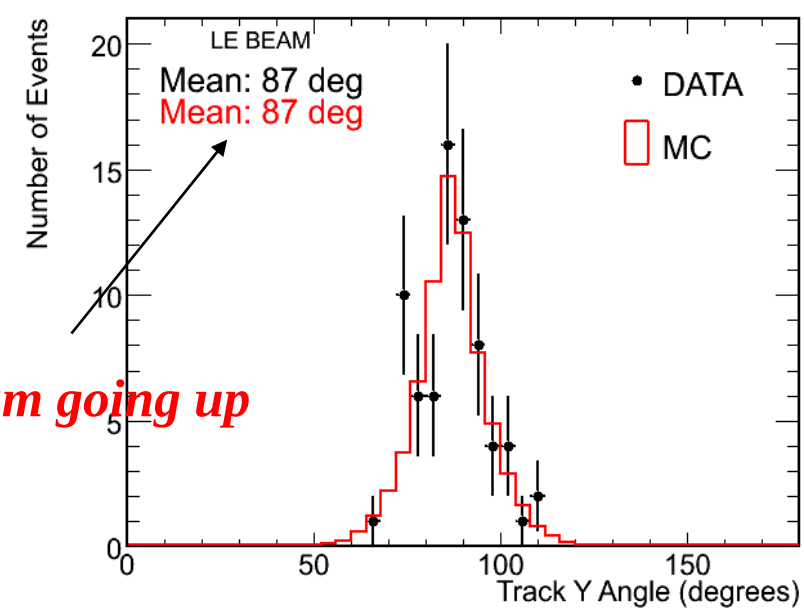




Beam going down

Near Detector





Beam going up

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

Example -MINOS CC Disappearance Analysis

Blind analysis - only <50% of data in open sample for comparisons.

Remainder modified by "blinding function".

Steps in analysis

Select neutrino events

Classify as CC events

Likelihood-based procedure using pulse height, event length.

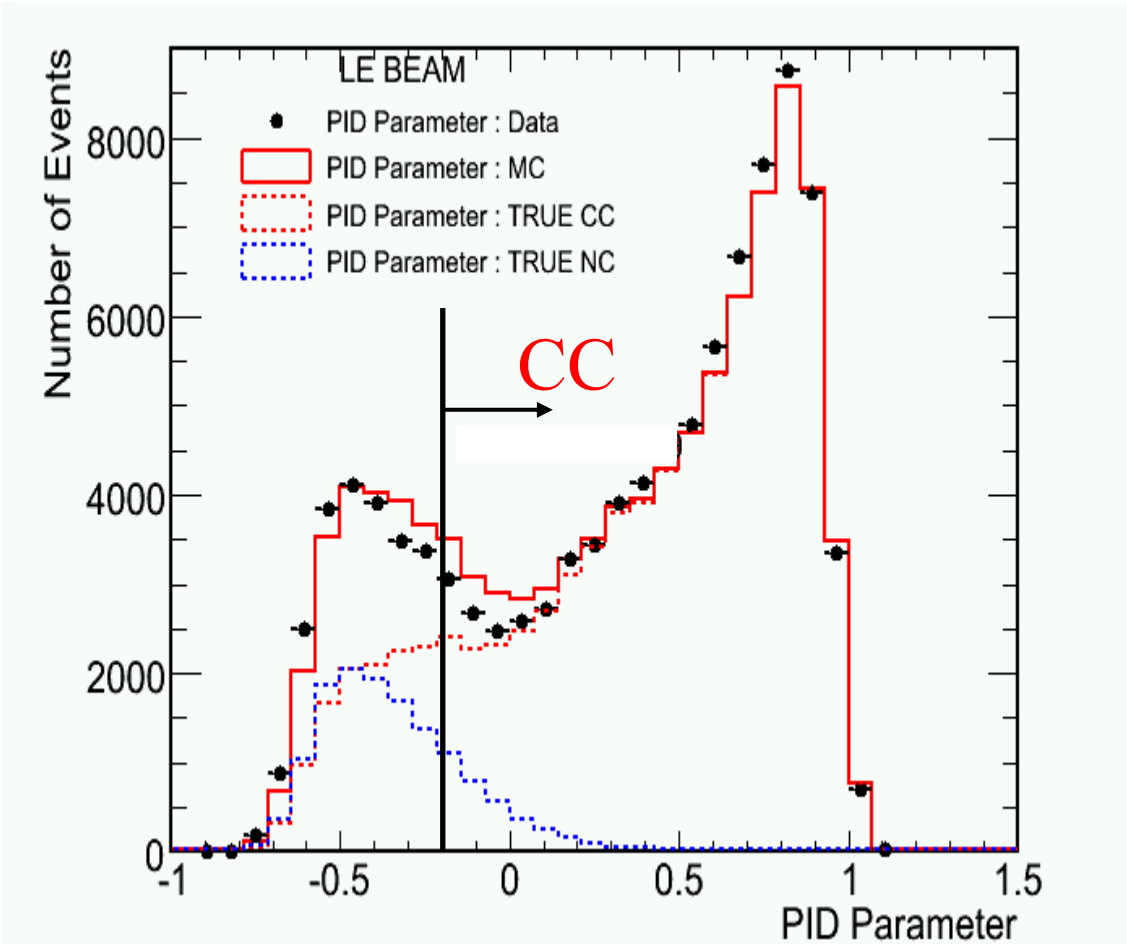
Check with neural net based procedure - good agreement. Also controlled scanning checks.

Extrapolate (using near) to far CC spectra to extract oscillation parameters.

Notes: NuMI/MINOS MC used to extrapolate far/near

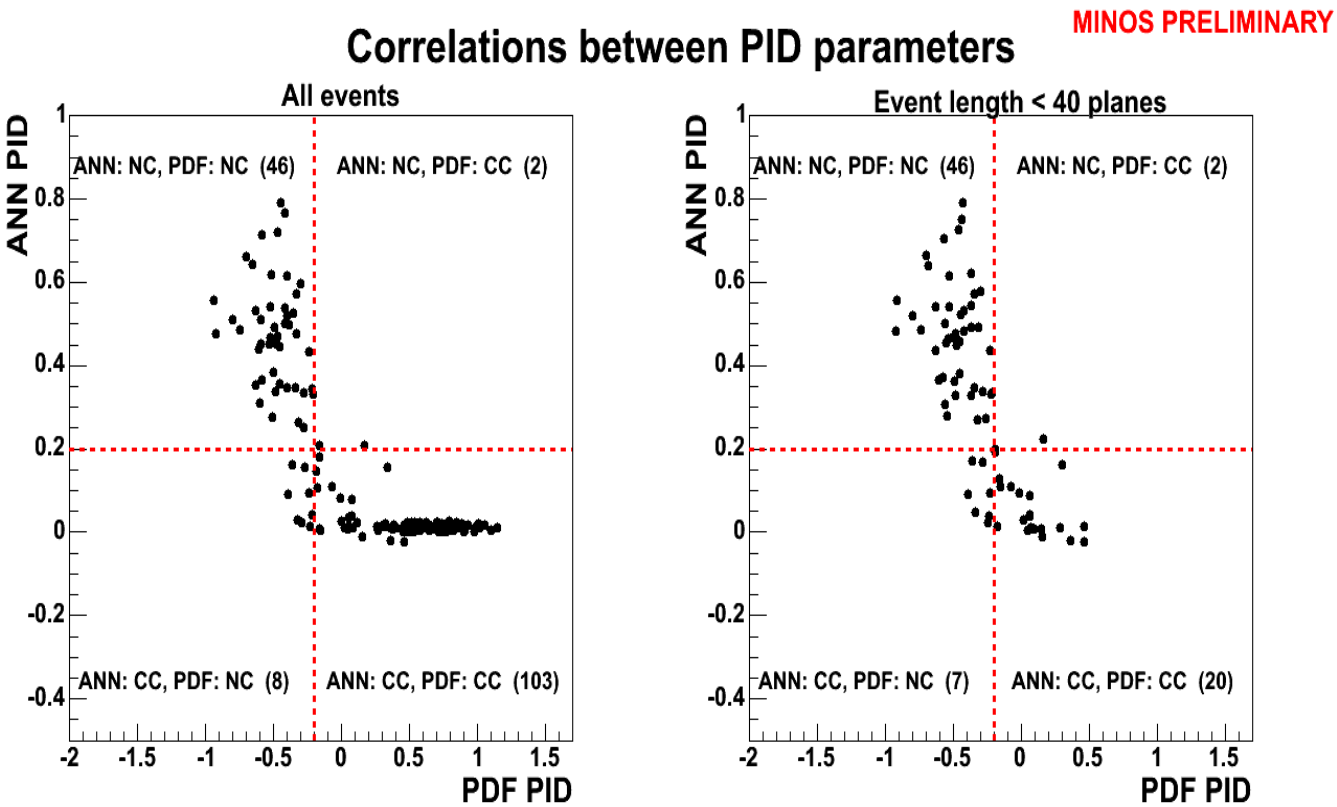
Fit χ^2 will include systematic errors.

Performance of Charged Current Selection Algorithm



With cut at -0.2, MC estimate of efficiency is 87%, with purity 98%

Stability of CC Selection Algorithms



Likelihood-Based

Likelihood-Based

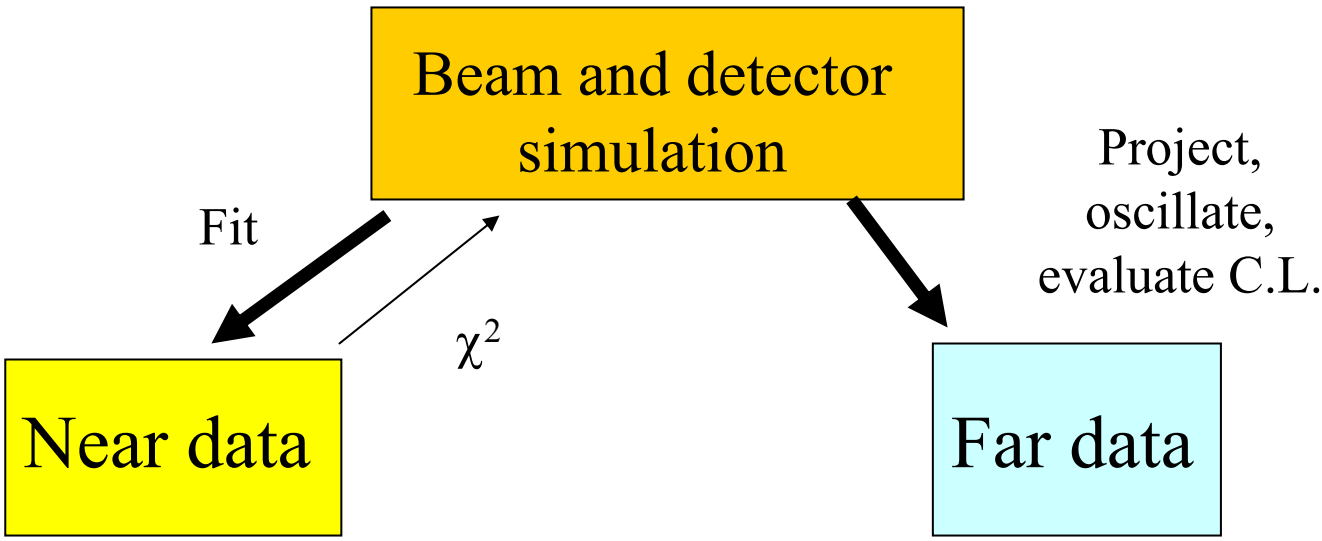
Excellent overlap between algorithms for charged-current selection.

Extrapolations and use of near detector data

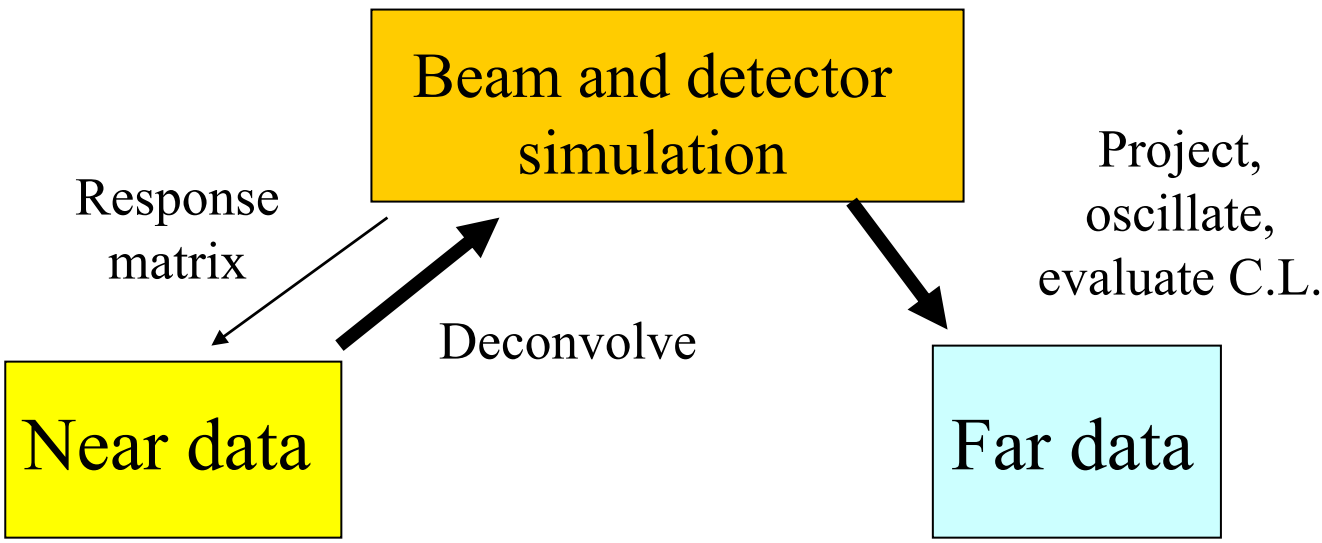
Two representative techniques

many common inputs

I) Fitting the near data



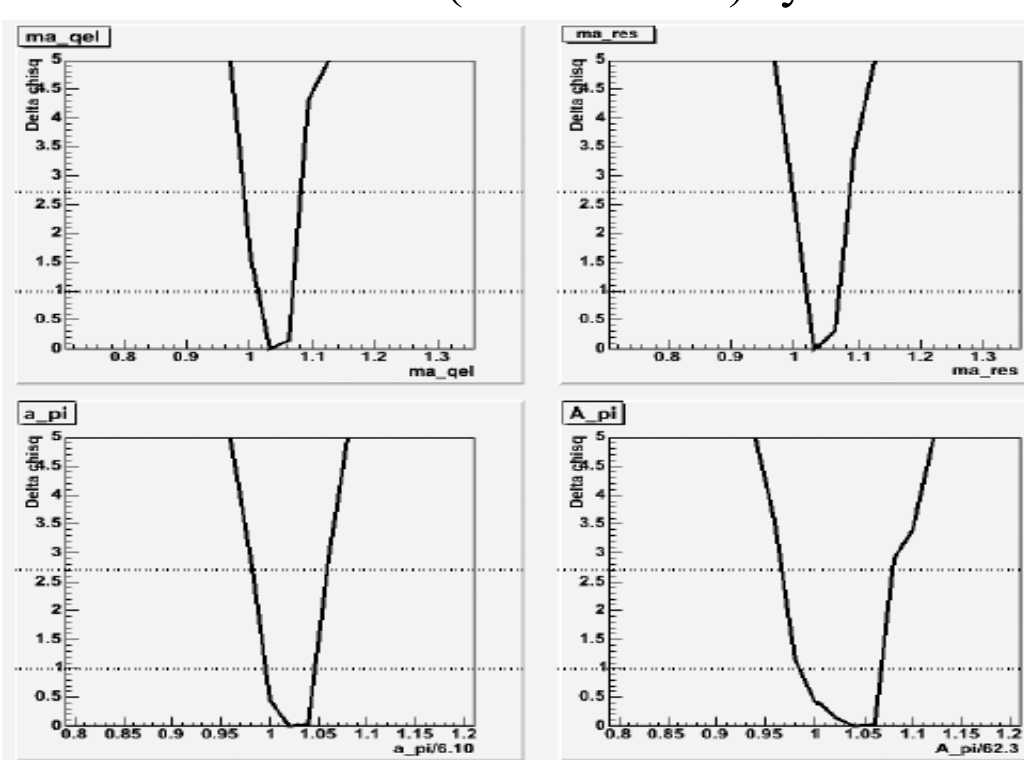
II) Deconvoluting the near data



Example of typical fitting procedure - MINOS Mock Data Challenge

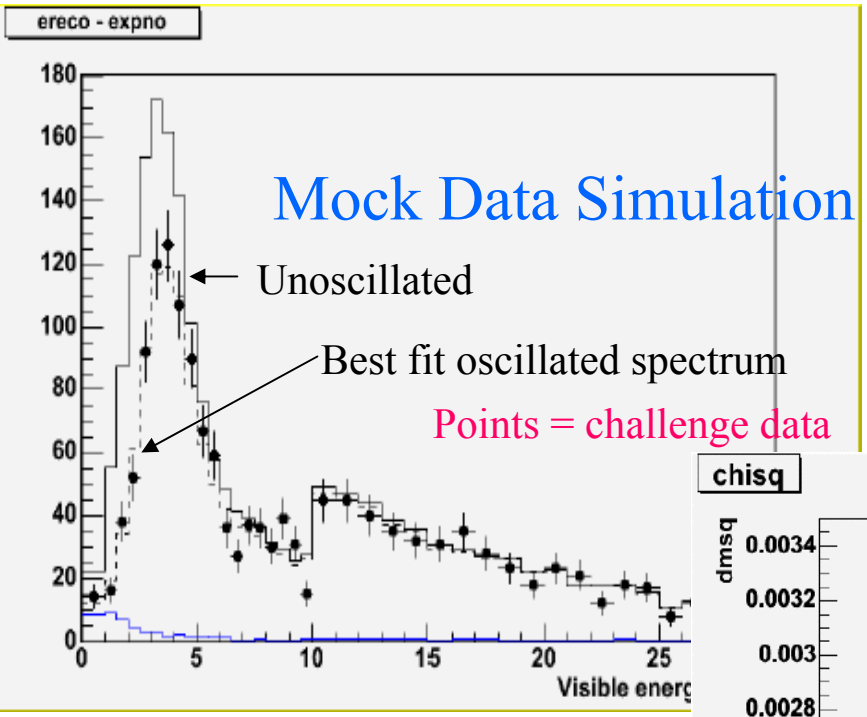
$$\chi^2(\vec{\alpha}) = \sum_{i=1}^{nbins} \frac{[n_i - m_i(\vec{\alpha})]^2}{\sigma_i^2} + \sum_{j=1}^{nsyst} \frac{\varepsilon_j^2}{\sigma_j^2}$$

where $\vec{\alpha}$ is a vector of parameters and ε is a fractional (uncorrelated) systematic error.

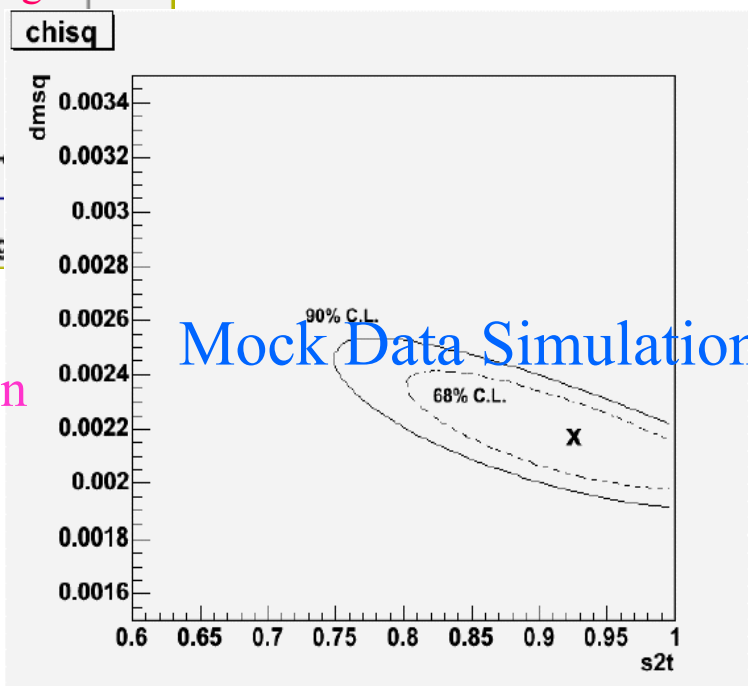


Typical Δχ2 plots for BMPT and cross-section parameters

Results of Mock Data Challenge (simulated 7.4 x 10^{20} protons



Fit to reconstructed far energy spectrum



Best fit results for oscillation parameters

	Challenge Value	Fitted Value
Δm^2	2.1×10^{-3}	2.2×10^{-3}
$\sin^2(2\theta_{23})$	0.88	0.93

ν_e Appearance and the Importance of θ_{13}

In our formalism, with $\Delta_{12} \cong 0$ (solar),

$$P_{\nu_\mu \to \nu_e} \propto 4(U_{e1}U_{\mu 1}U_{e3}U_{\mu 3} + U_{e2}U_{\mu 2}U_{e3}U_{\mu 3})$$

$$= 4\cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{23}$$

or finally to leading order and using $\cos\theta\sin\theta = \dfrac{\sin 2\theta}{2}$

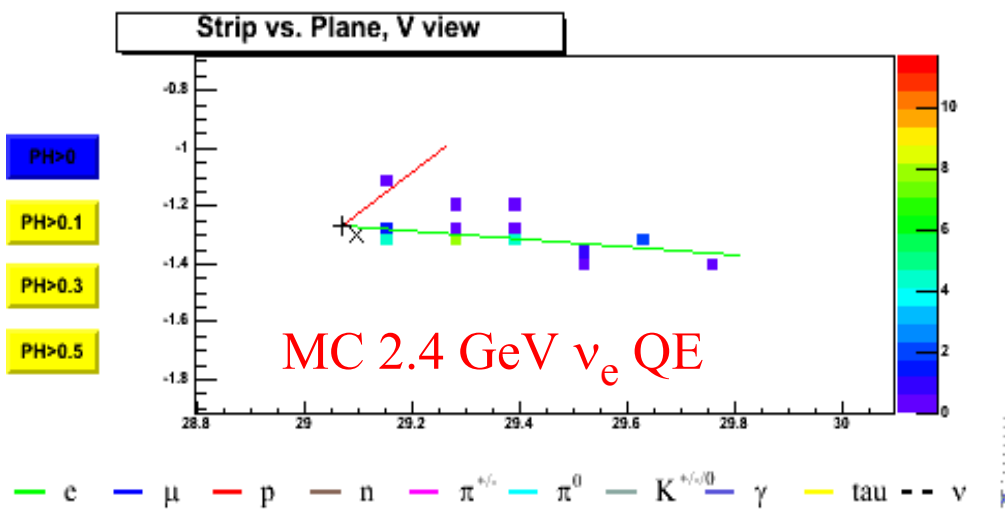
$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta_{13})$$

This small number will be seen again and again.

Currently $\sin^2 2\theta_{13} \leq 0.14$

Electrons and $\sin^2 2\theta_{13}$ in MINOS

As an iron calorimeter, MINOS is not optimized for low-energy e^- detection (1-3 GeV)

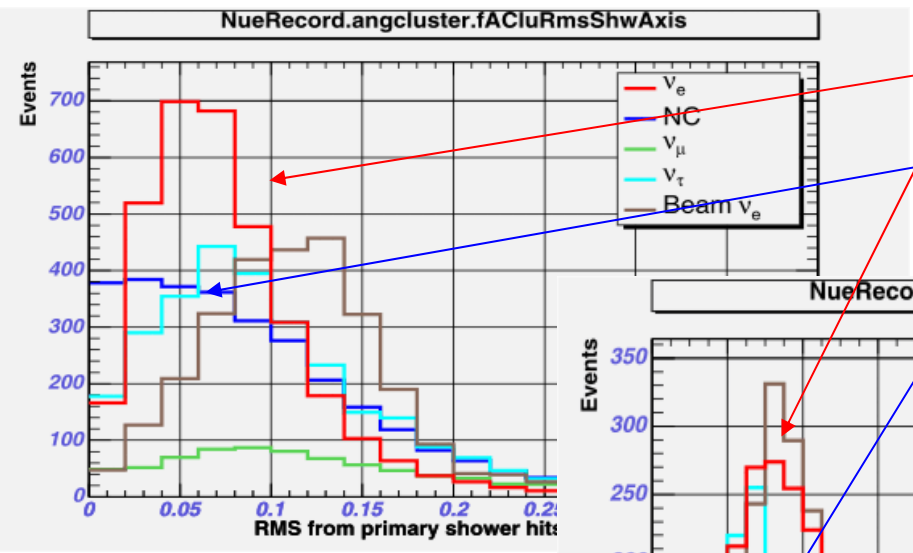


With appropriate attention, progress can be made on limits for $\sin^2 2\theta_{13}$

Principal background (~2/3) is from mis-identified π^0 NC events:

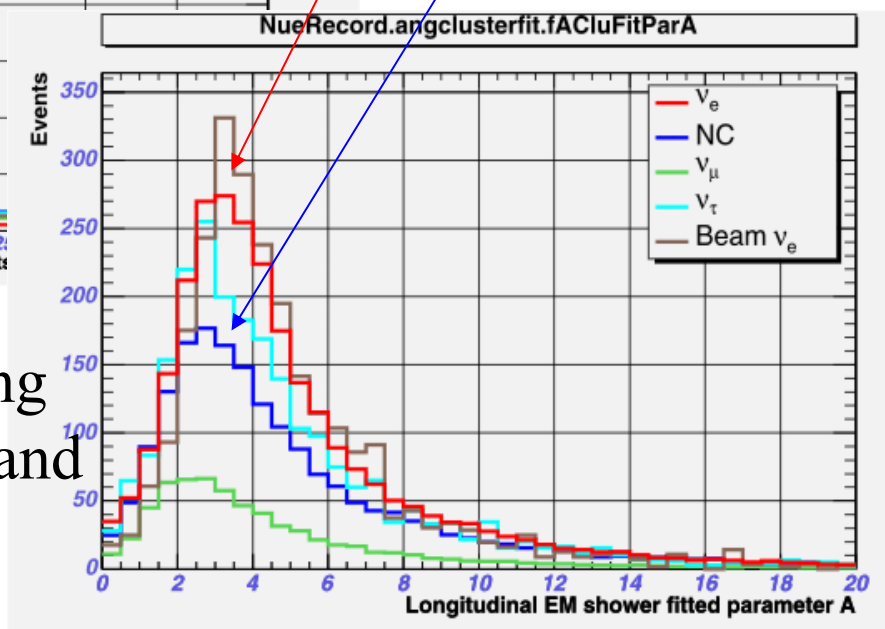
$$\nu_\mu + N \rightarrow \nu_\mu + N' + \pi^0, \quad \pi^0 \rightarrow \gamma\gamma$$

MINOS electrons and their sensitivity



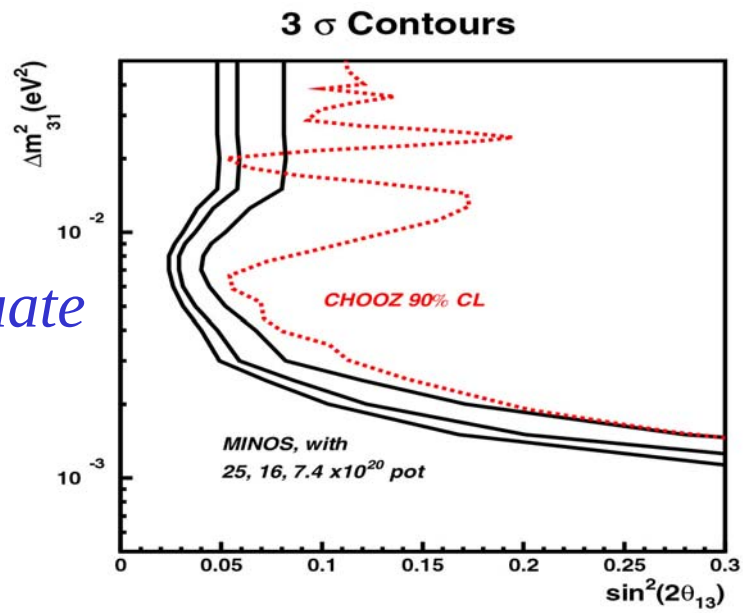
Electrons

NC



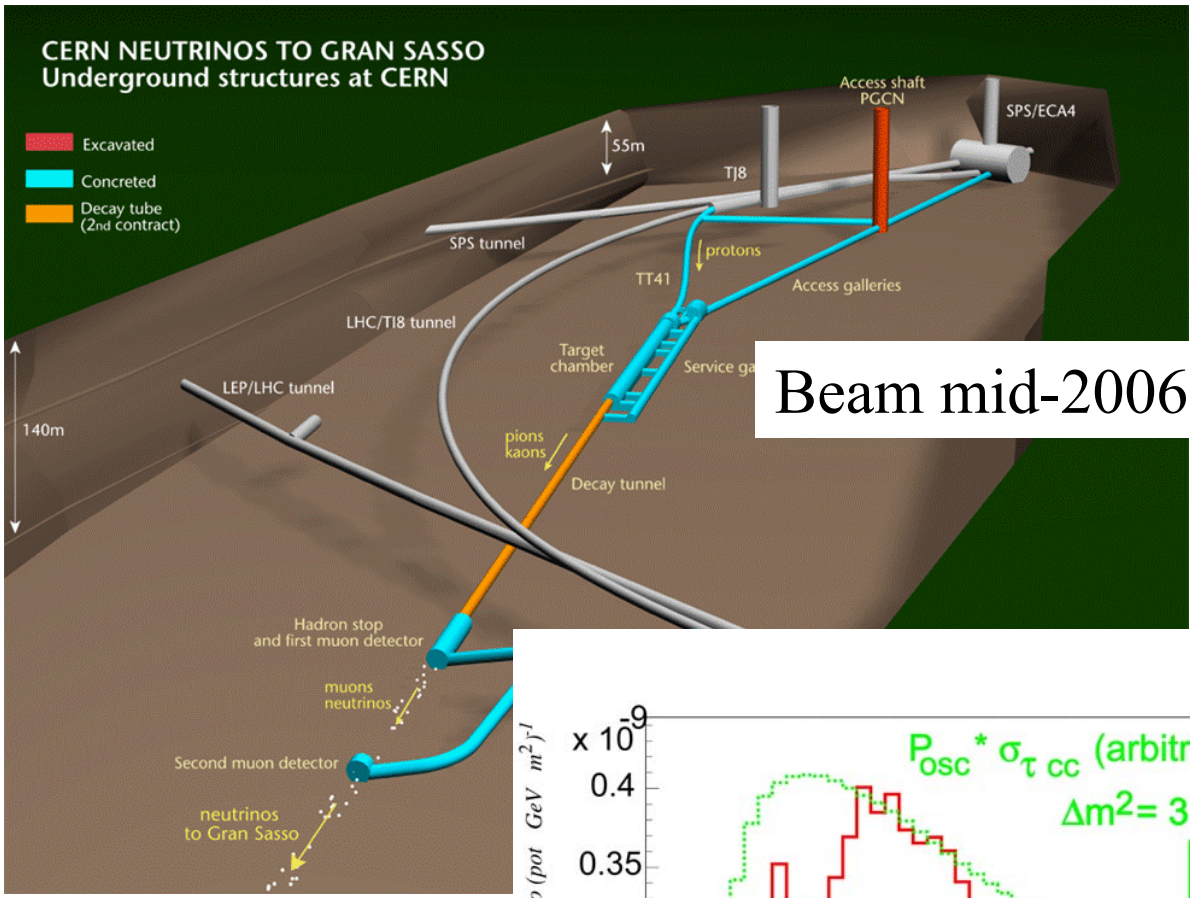
Typical discriminating variables:transverse and longitudinal shower shapes

Can improve CHOOZ limit by ~2 with adequate protons



CNGS Program at CERN

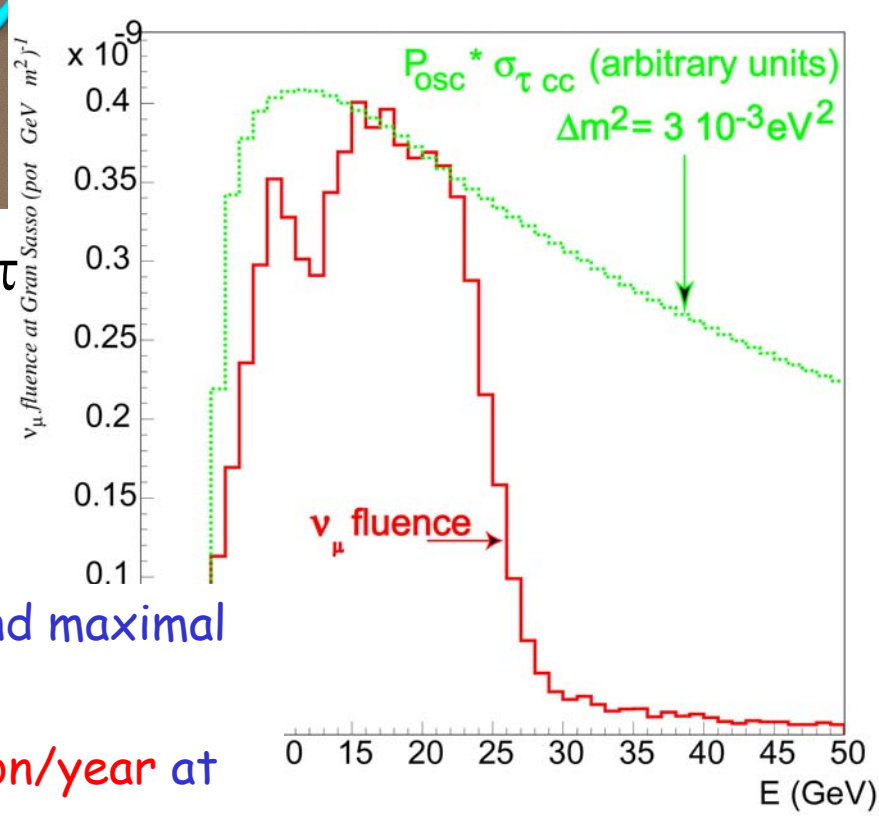
Migliozzi-NUFACT 05



Beam mid-2006

Higher Energy for τ appearance

4.5 x 10^{19} pot/year

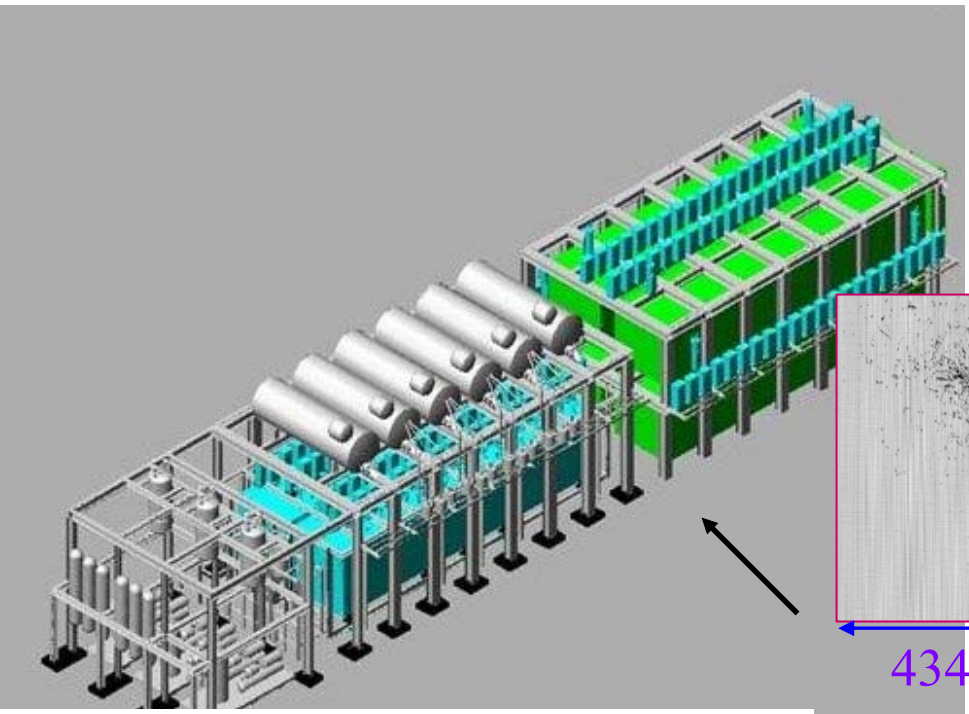


For $\Delta m^2 = 2.4 \times 10^{-3}$ and maximal mixing

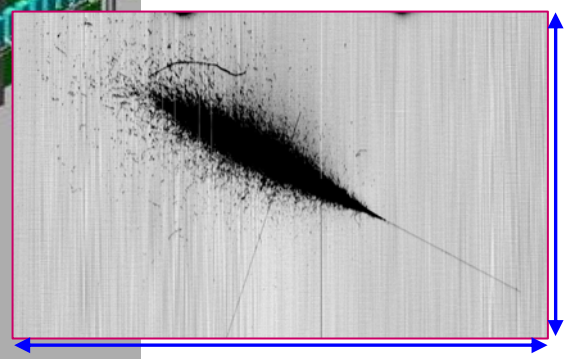
expect 16 ν_τ CC/kton/year at Gran Sasso

CNGS ν_τ appearance detectors

Migliozzi-NUFACT 05



em shower

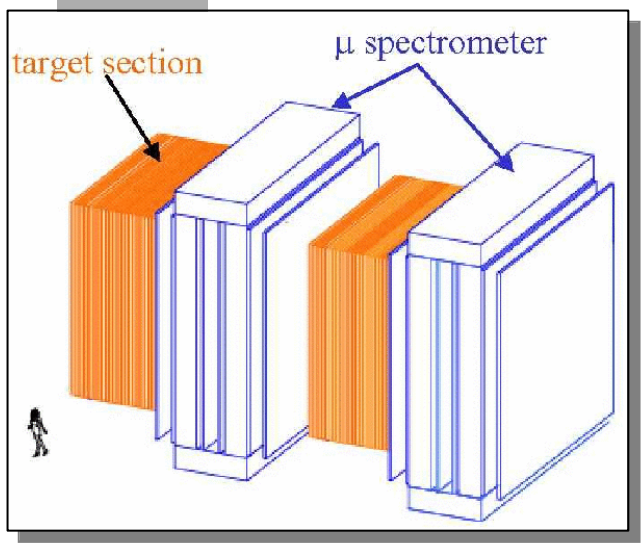


ICARUS liquid Ar T1800.

600 Tons built so far

About 15 events in 5 years.

OPERA hybrid emulsion detector

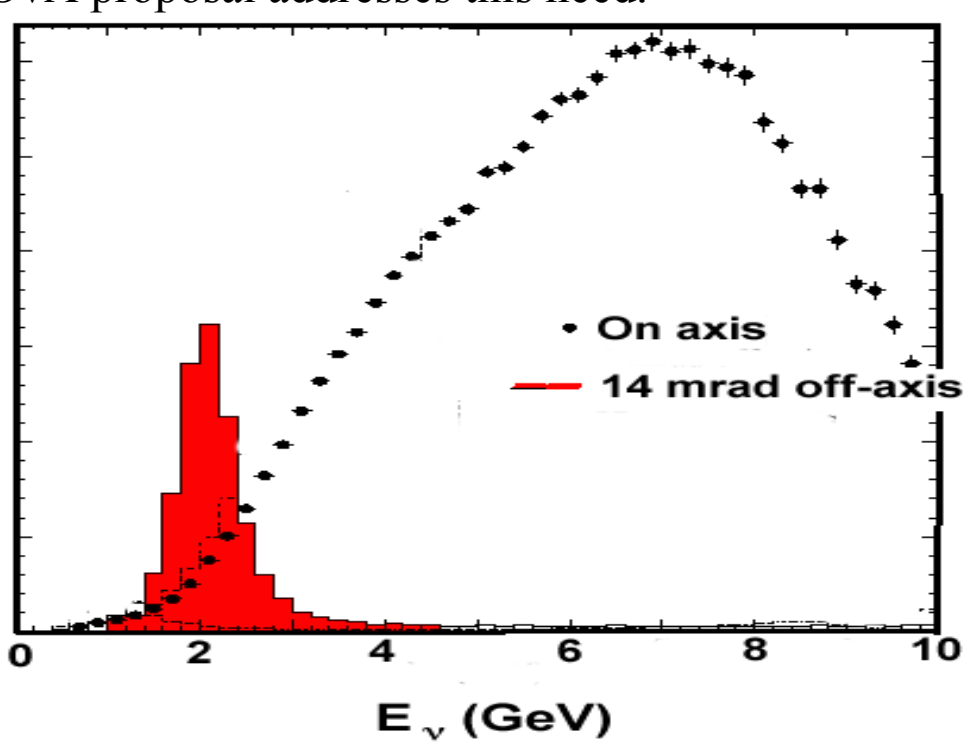


Petronzio-NO-VE 06

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

Off-axis beams and NOvA

- Off-axis neutrino beams provide narrow-band kinematics
  - Reduces backgrounds
    - mis-id NC
    - ν_e's from K decay (wrong kinematics)
- Increases flux at oscillation maximum.
- This provides a good setting for ν_e appearance exeriments
  - Will be focus of Japanese T2K effort.
- NuMI beam already exists, can be exploited by construction of new detector.
  - NOvA proposal addresses this need.



Understand Off-axis Mathematically

Model beam with $\theta^* = \pi/2$

$$P_T = P^* \sin\theta^*$$

$$P_L = \gamma P^* (1 + \cos\theta^*) \cong E_\nu$$

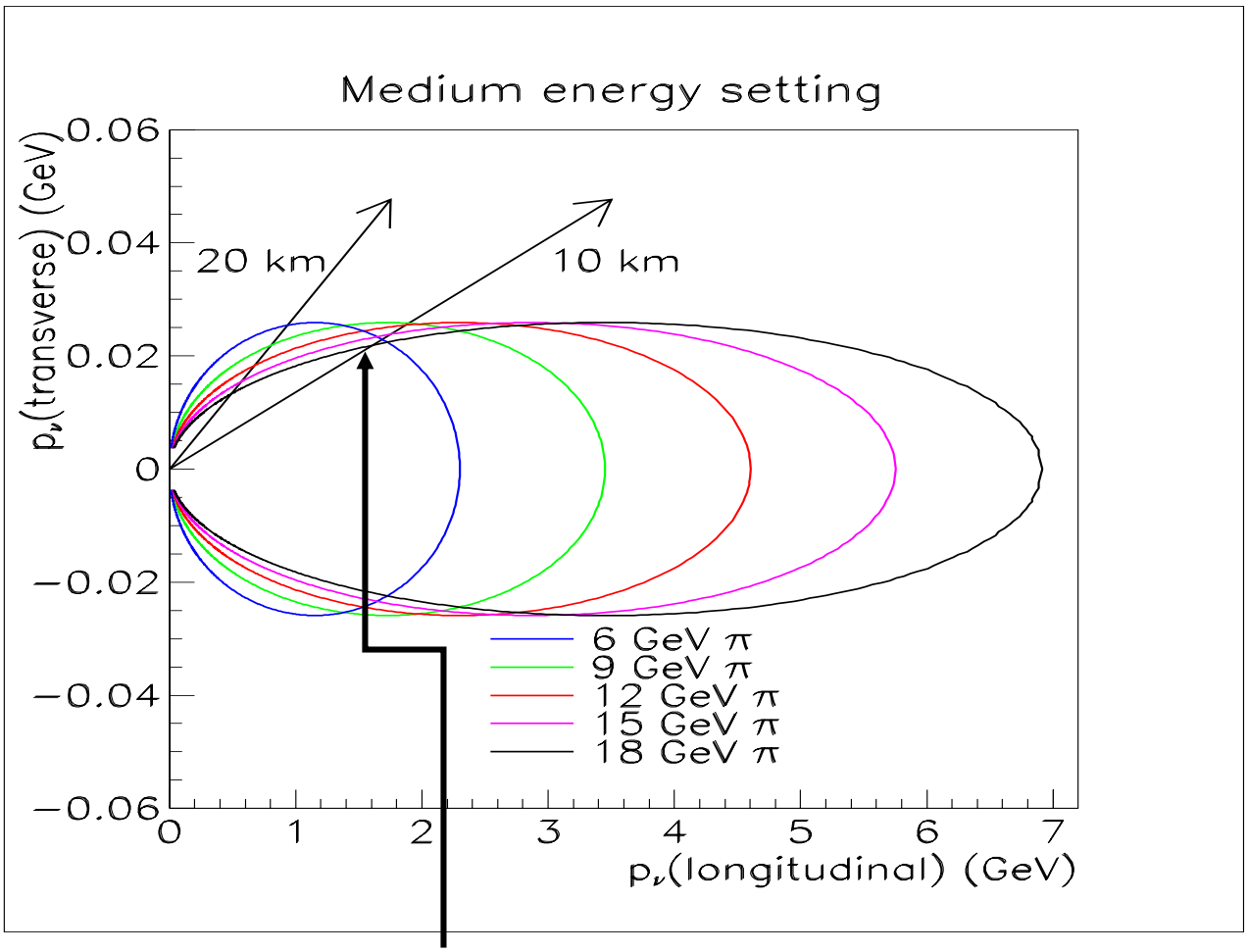
We fix $\theta_{lab} \equiv P_T / P_L$

At $\pi/2$ $\Delta P_T \cong 0$ as vary θ^*

$$\Delta P_L = \frac{\Delta P_T}{\theta_{lab}} \cong 0$$

Constraint on angle means γ compensates θ^* to fix P_L (at fixed θ_{lab})

Off Axis Beam Graphically



Length of this vector very insensitve to pion γ

$$E(\theta^* = \pi/2) \quad = \quad 1/2\ E(\theta^* = 0)$$

Flux Comparison between Off-Axis and Forward Beams

$$P_T(\pi/2) = P^* \sin(\pi/2) = P^*$$

$$P_L(\pi/2) = \gamma P^* = \frac{1}{2} P_L(0)$$

$$\frac{P_L}{P_T} = \gamma \quad \Rightarrow \quad \gamma_{\pi/2}\theta_{lab} = 1$$

Compare solid angle between fully forward beam (θ = 0) and model off-axis beam.

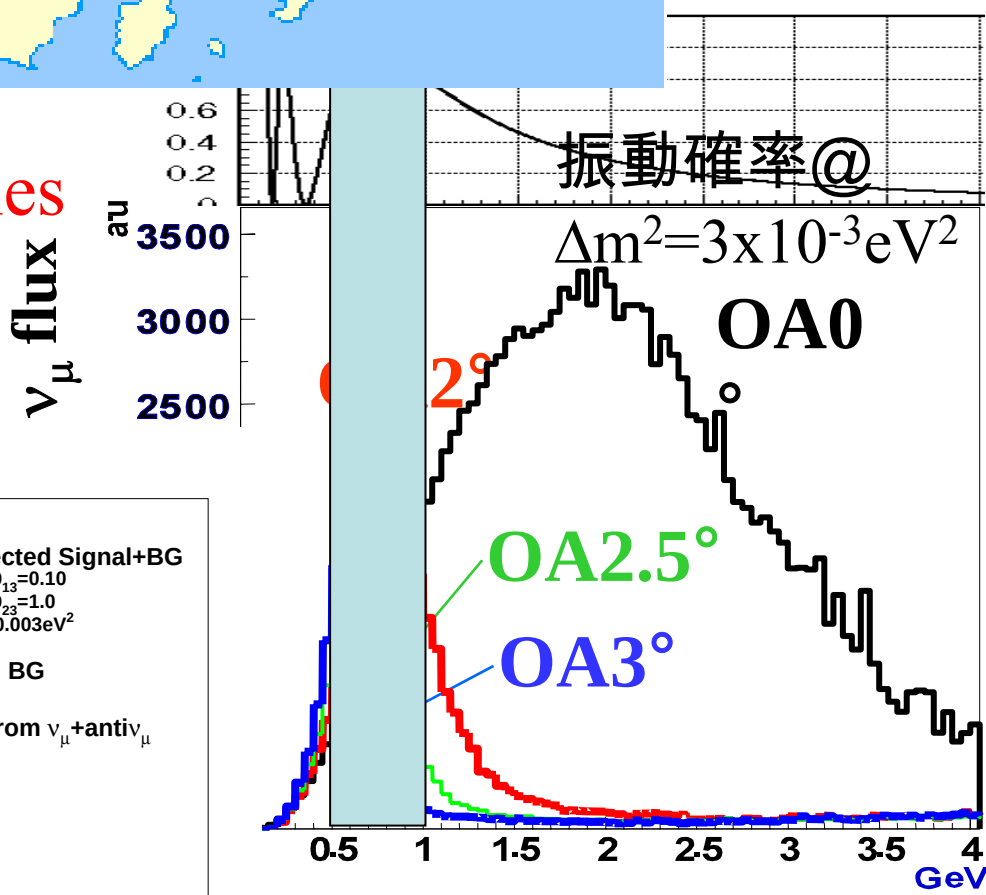
$$\Delta\Omega_{\pi/2} \propto \left(\frac{2\gamma_{\pi/2}}{1+\gamma_{\pi/2}{}^2 \theta_{lab}{}^2} \right)^2 = (2\gamma_0)^2 = \Delta\Omega_0$$

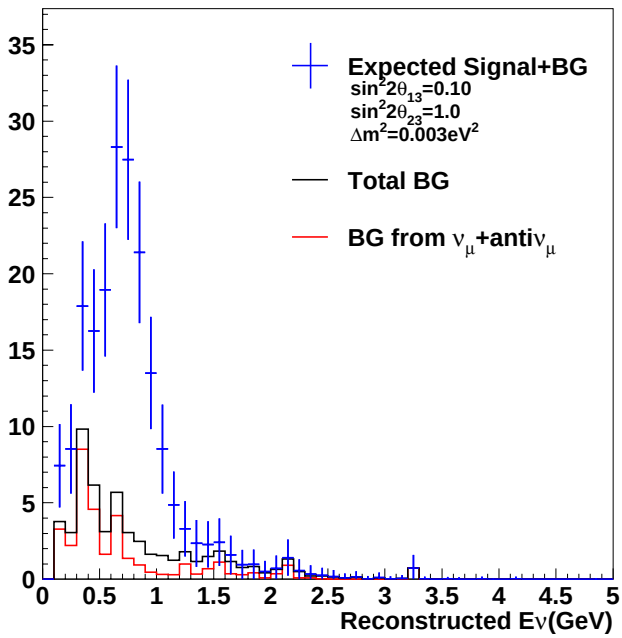
Hence flux can stay constant or even increase in region of interest.

Sidebar - T2K Project at KEK

Hope for 2009 startup

Off-axis fluxes

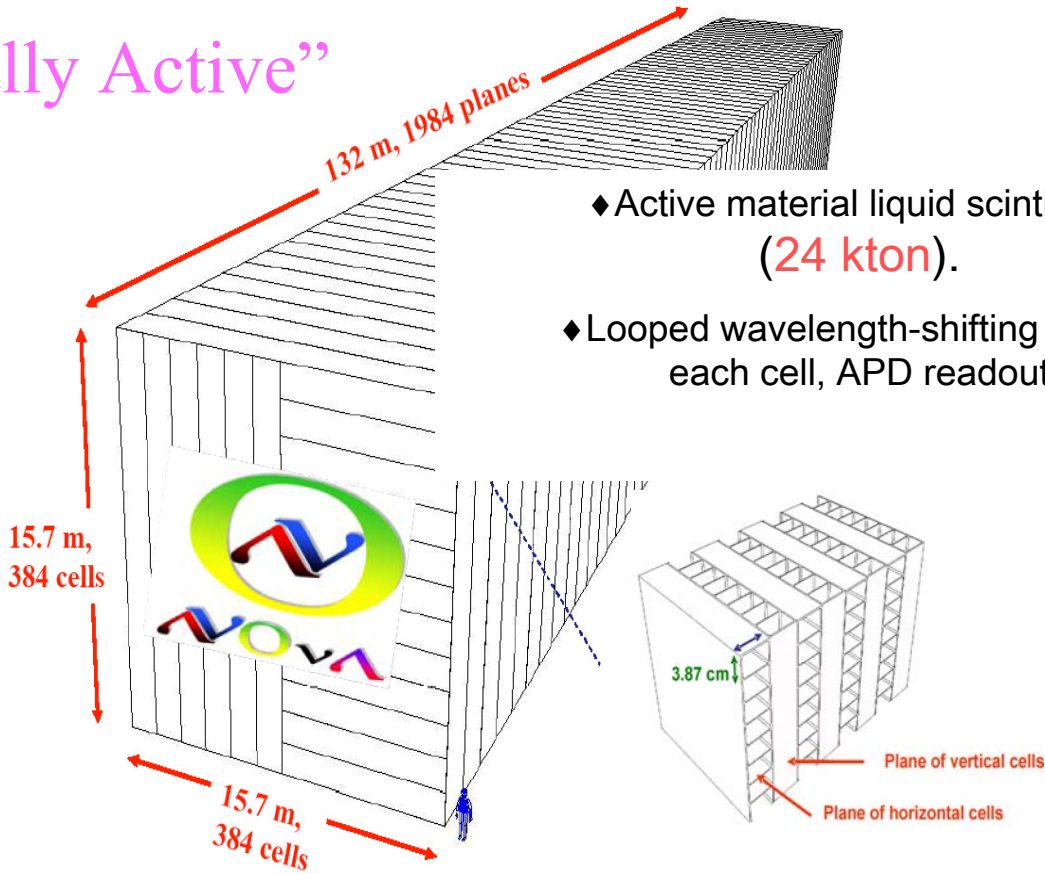




Results of 5 years running

NOvA, a large electron appearance experiment

"Totally Active"

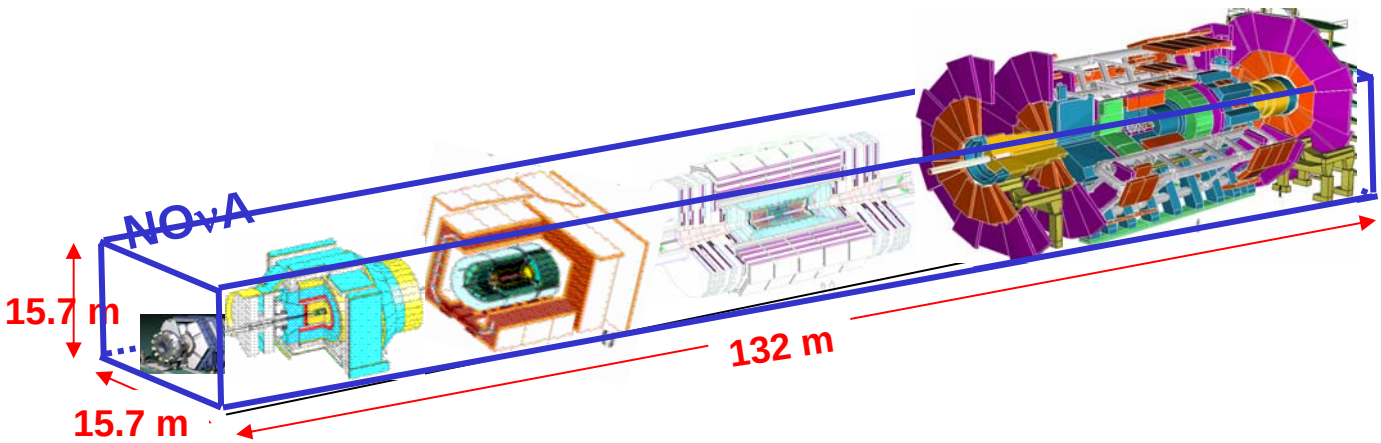


- ♦Active material liquid scintillator (24 kton).
- ♦Looped wavelength-shifting fiber in each cell, APD readout

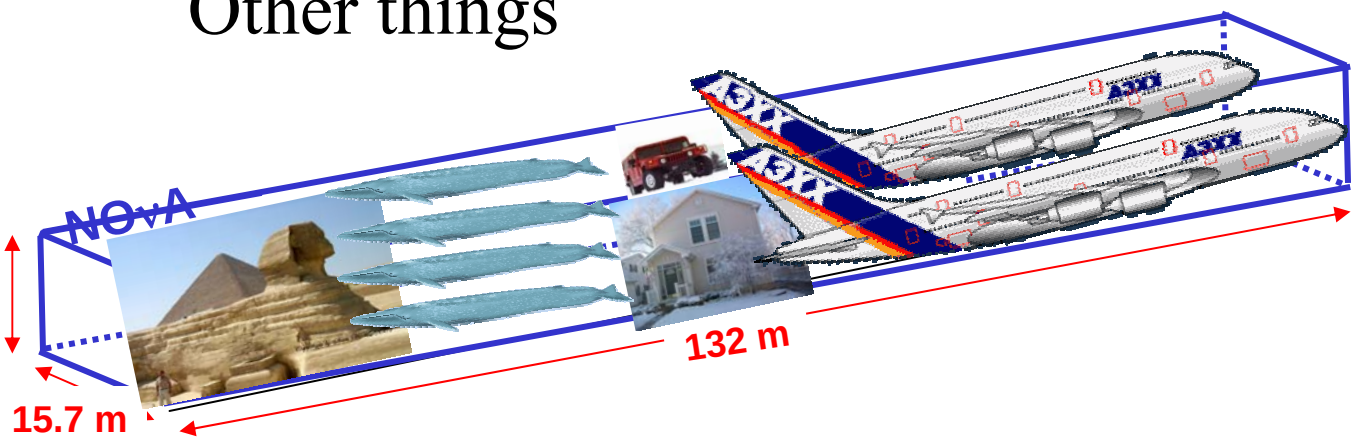
- 30 kton detector
- Baseline ~810 km
- ~2000 ν_μ CC events per 7e20 POT ($\Delta m^2 = 2.5 \times 10^{-3}$)
- Electron ID efficiency 24%
- For $\sin^2 2\theta_{13} \sim 0.1$ would see ~150 ν_e interactions in 5 years

Two Views of the very Large

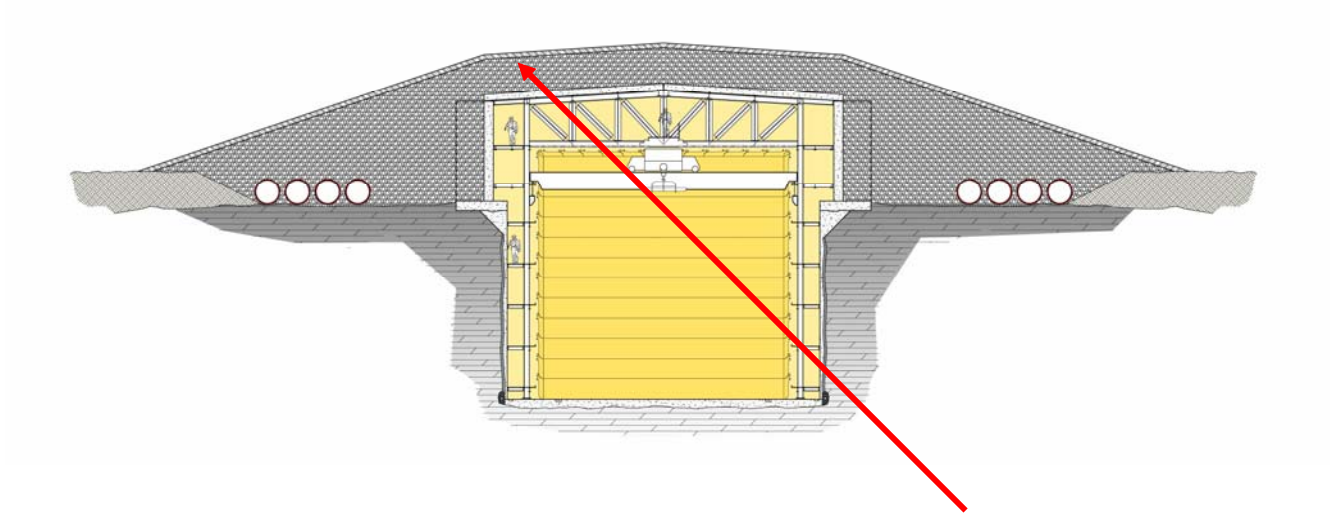
BaBar, CDF, D0, CMS, & ATLAS



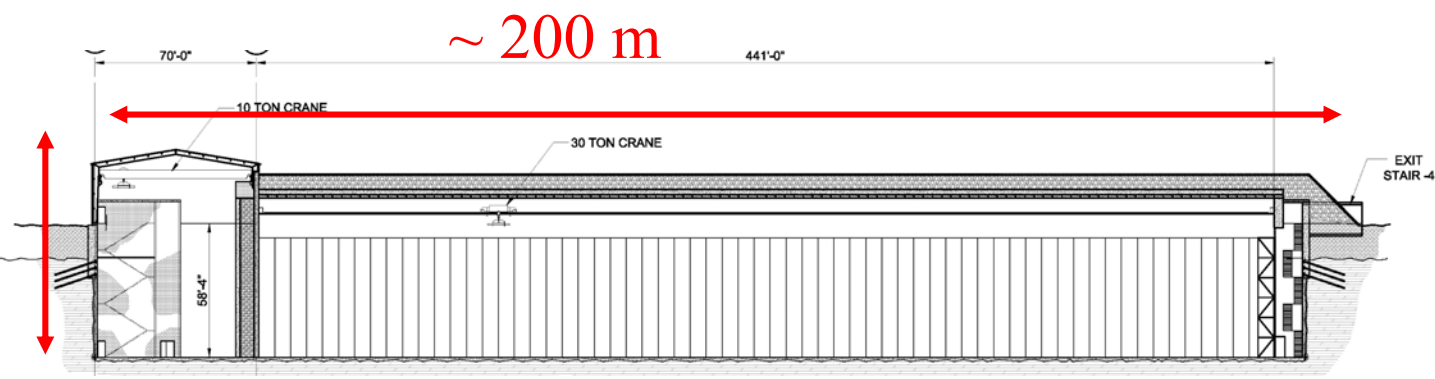
Other things



Large semi-underground building with overburden



2-3 m of overburden reduces background from cosmic γ (can fake electron)

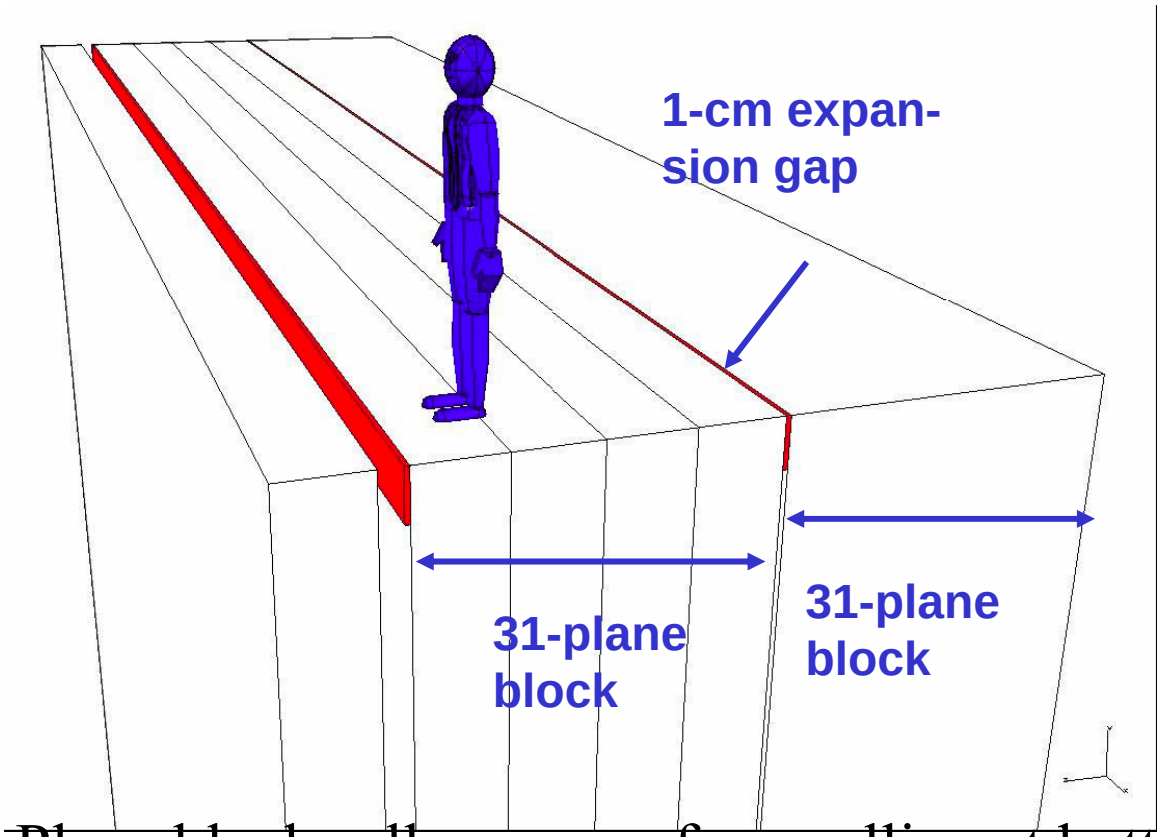


Probable location at Ash River, MN

14 mrad off axis

Trigger on timing –> surface location OK

For structural reasons, detector is built in 31 plane blocks



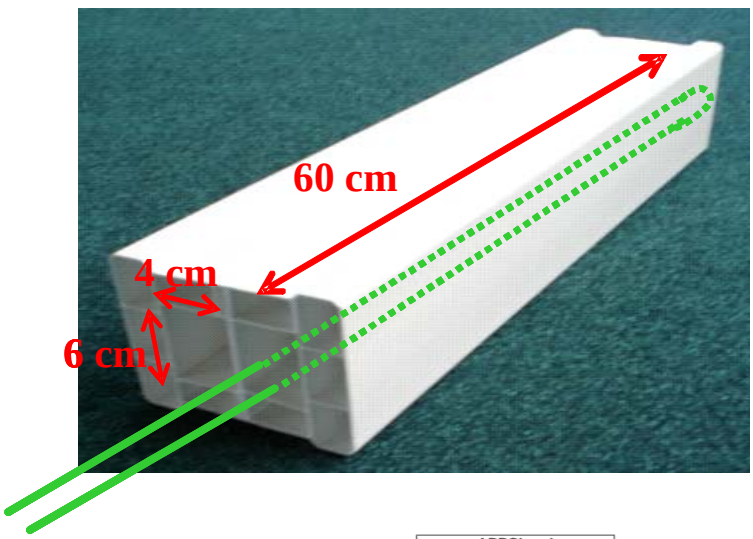
31 Plane blocks allow space for swelling at bottom of tubes.

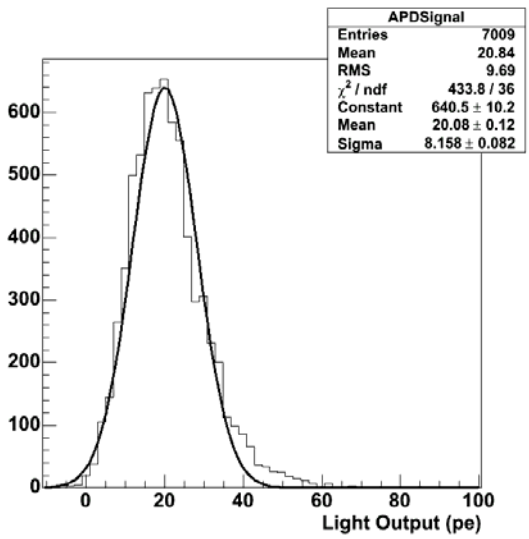
Structure erected block-by-block

Weight of each block (empty): ~125 tons

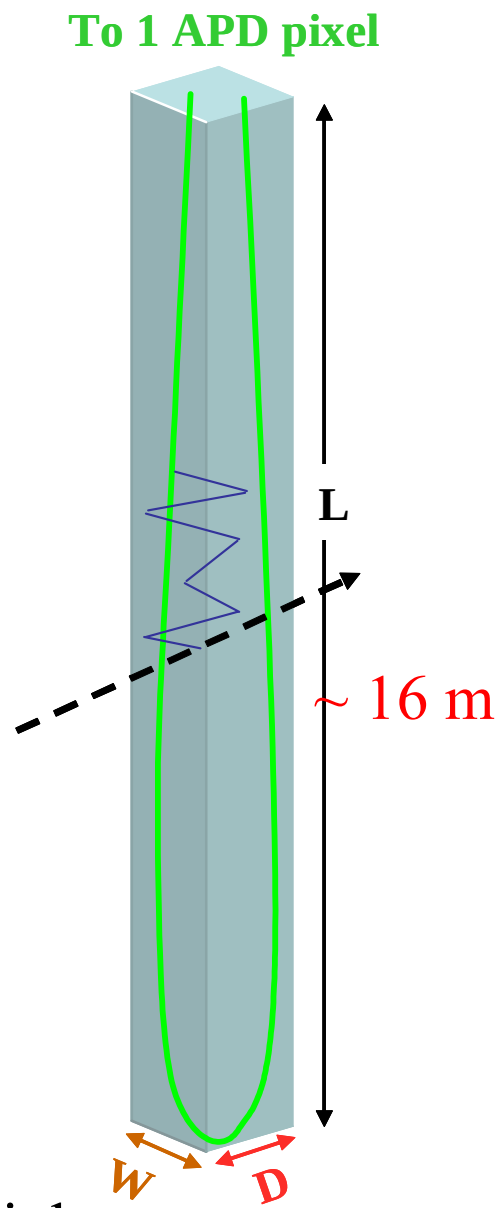
Extruded PVC tubes filled with liquid scintillator

Prototype with full-length fiber
Readout cosmic muons



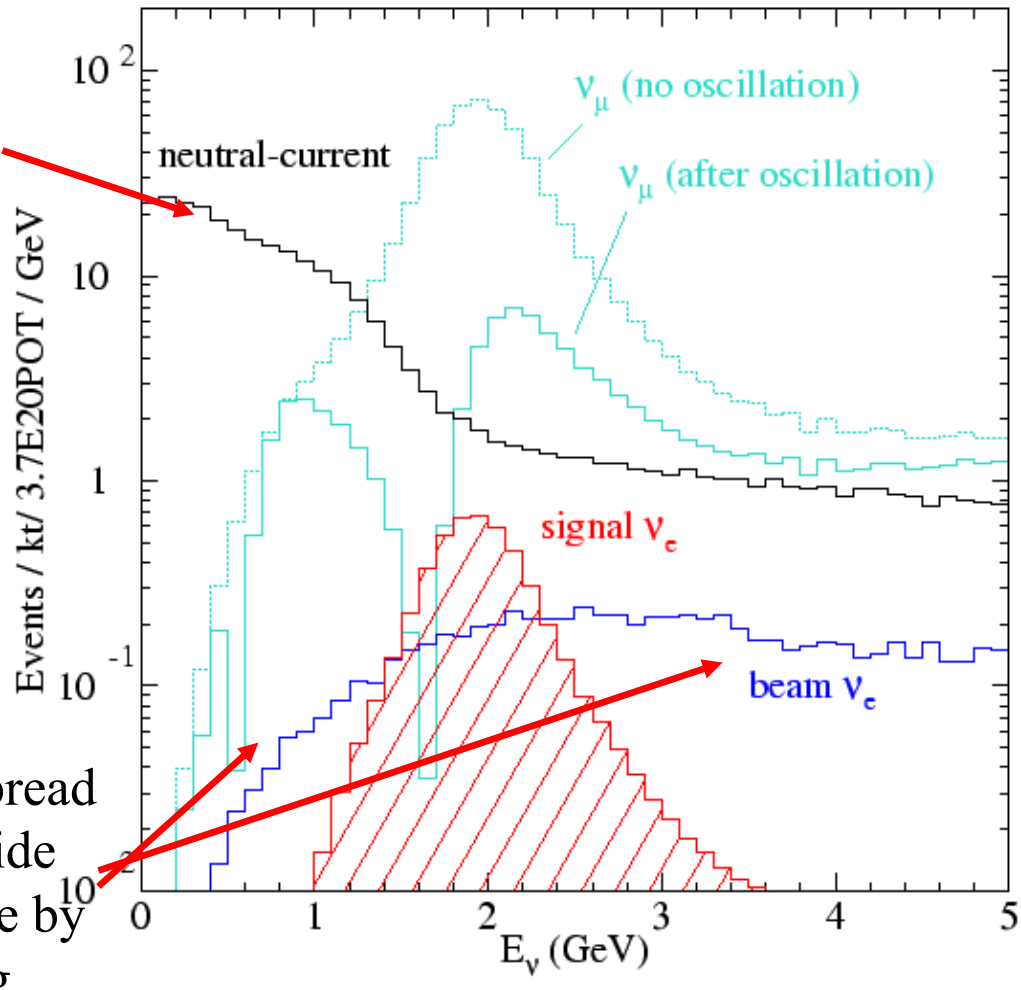


Prototype APD readout showing light output



Combination of off-axis "narrow-band" beam and good energy resolution.

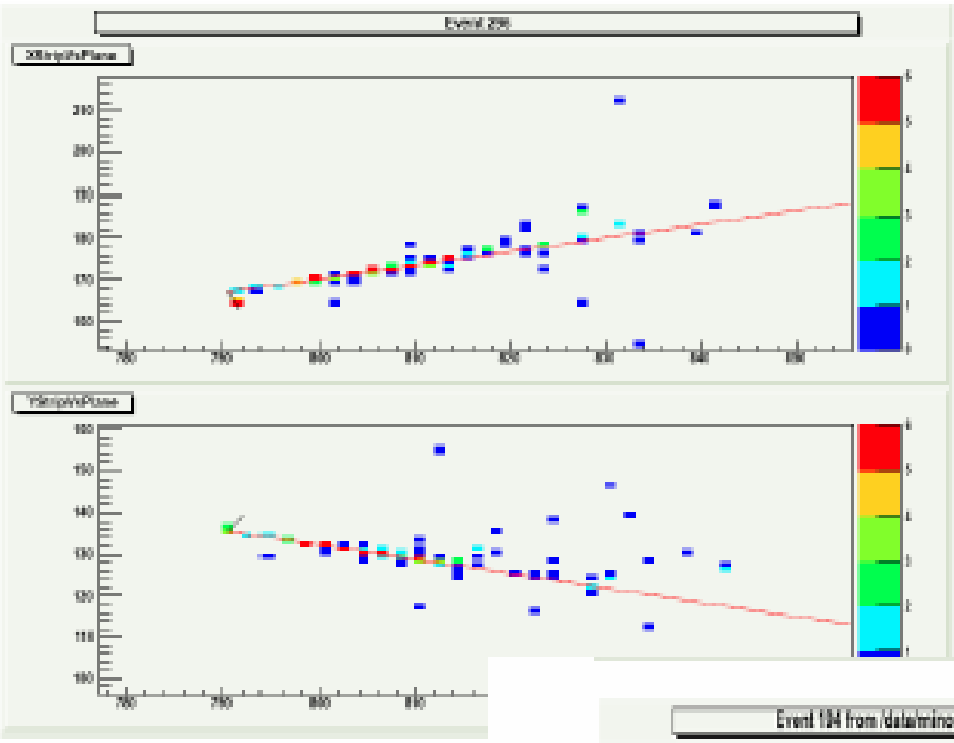
NC at low energy because no high energy tail



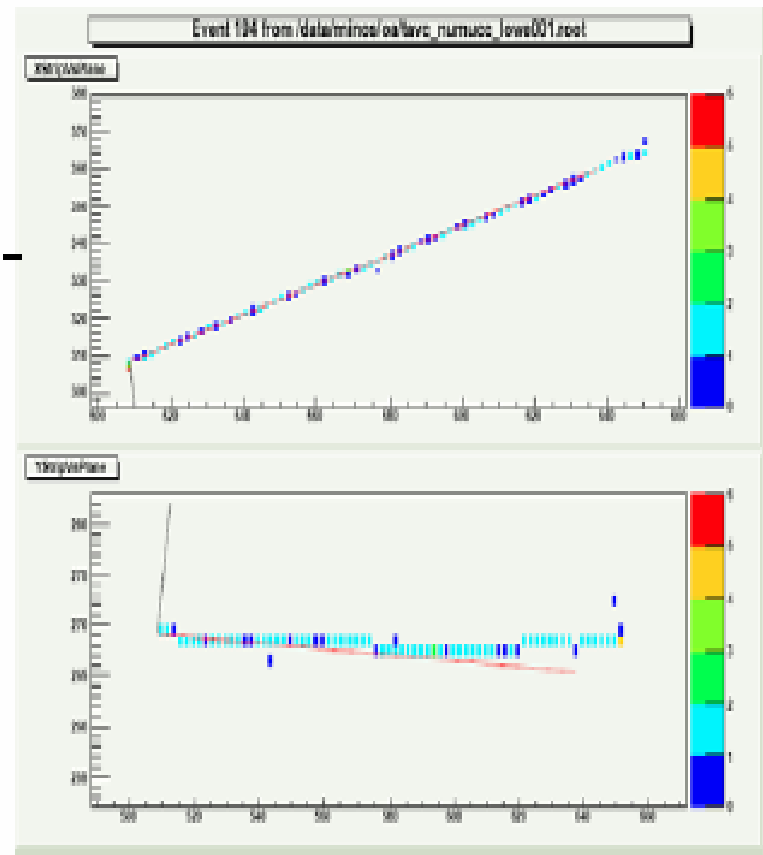
Beam ν_e are spread out over a wide range - remove by windowing

Backgrounds show a different energy spectrum and can be removed during analysis.

Representative NOvA MC Events



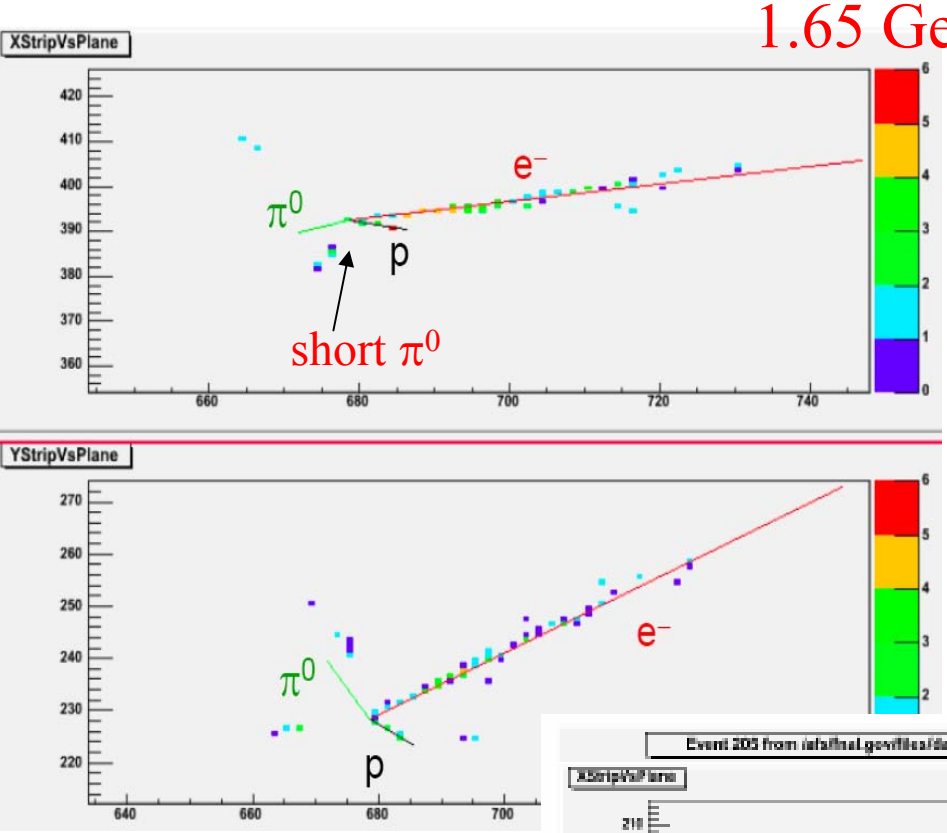
2 GeV ν_e QE - 60 planes



2.2 GeV ν_μ QE - 140 planes

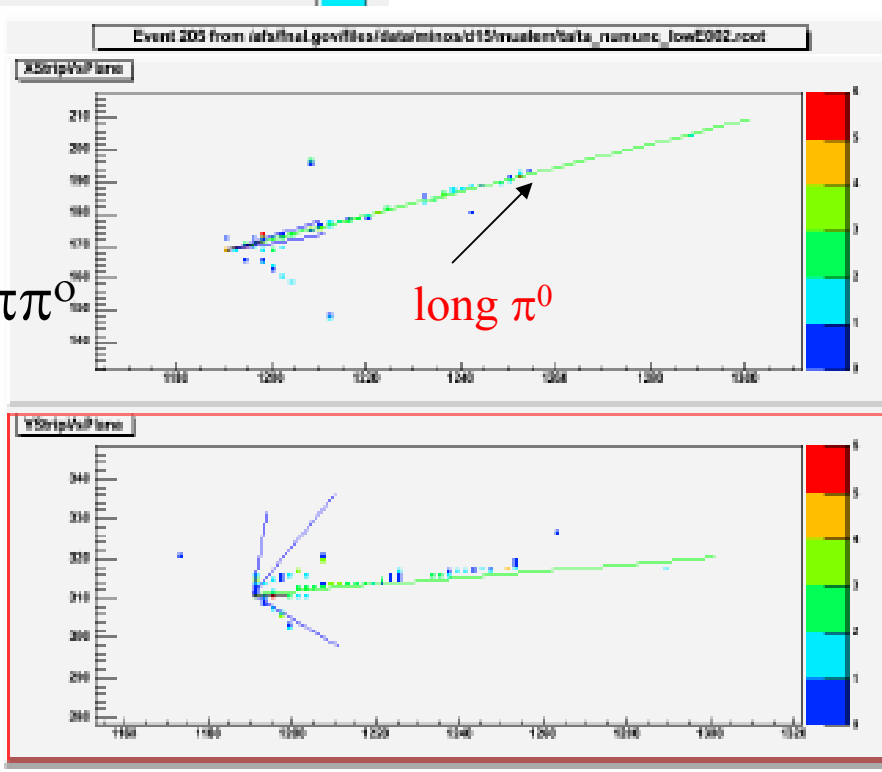
NOvA MC events showing successful and unsuccesful π^0 rejection.

1.65 GeV $\nu_e N \rightarrow ep\square^0$



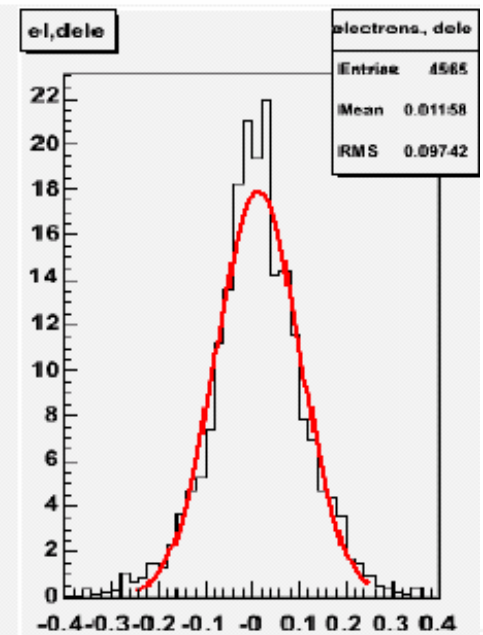
55 planes
Success!!

4.95 GeV $\nu N \rightarrow \nu\pi\pi\pi^0$



70 planes
Failure!!

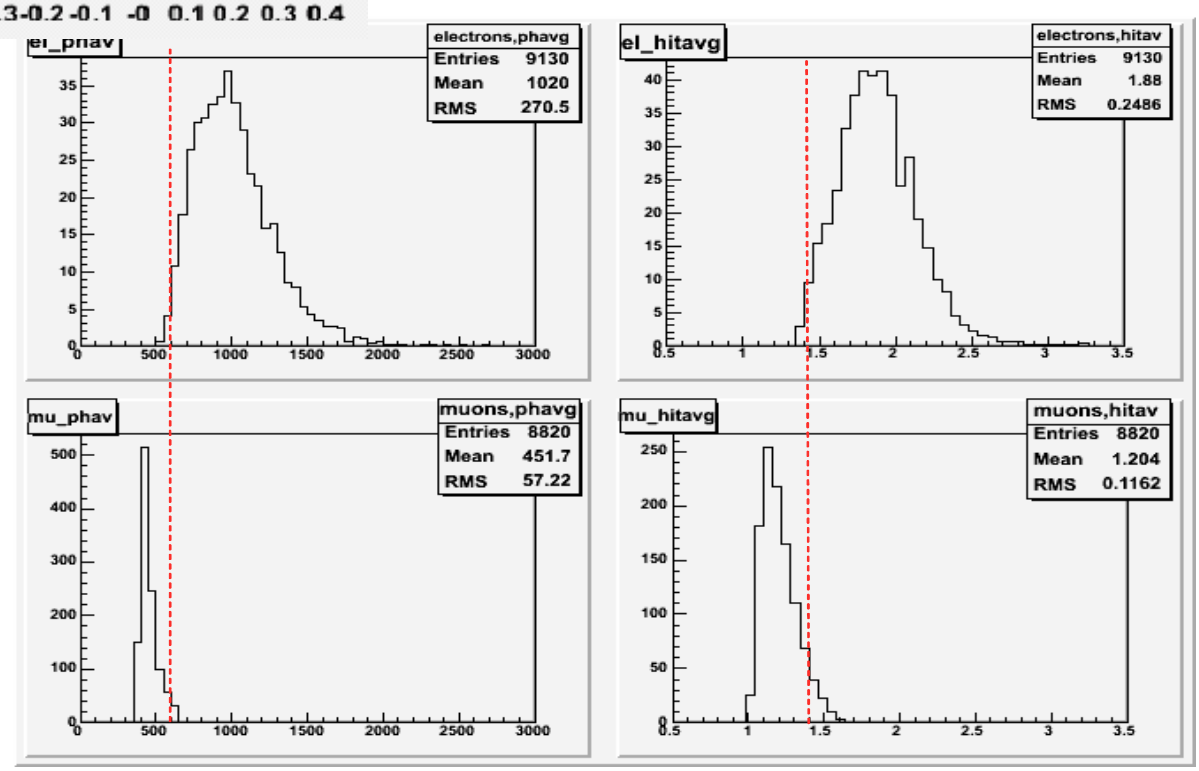
NOvA performance and event classification variables



Active detector gives good resolution

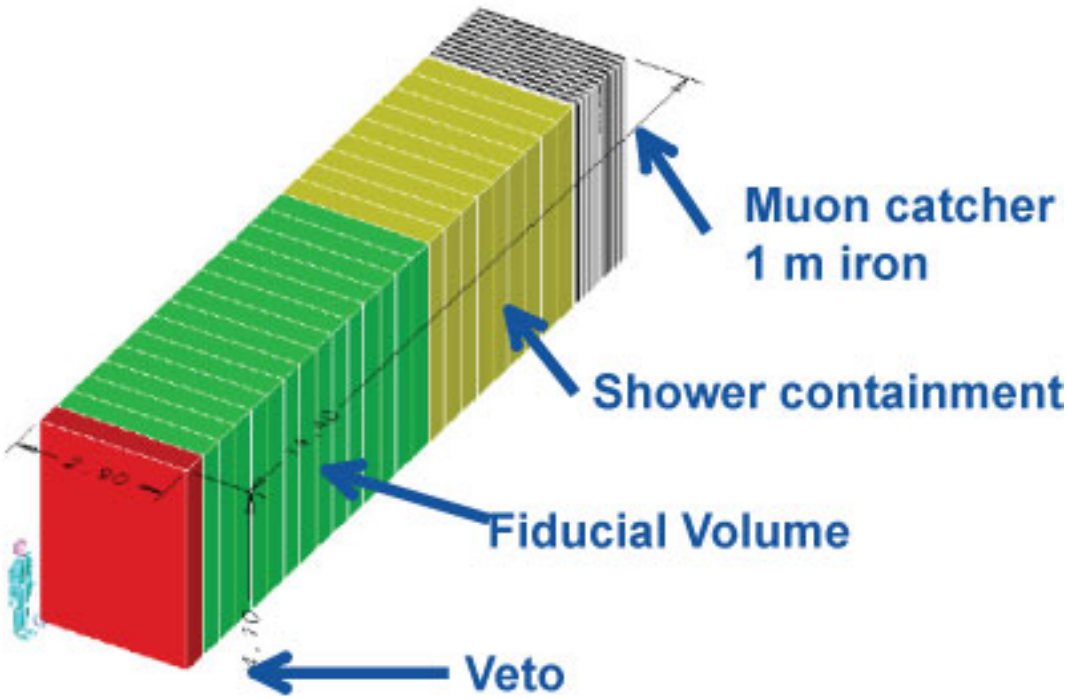
$$\frac{\Delta E}{E} = \frac{9\%}{\sqrt{E}}$$

Overall $\nu_\mu \rightarrow \nu_e$ efficiency ~24%

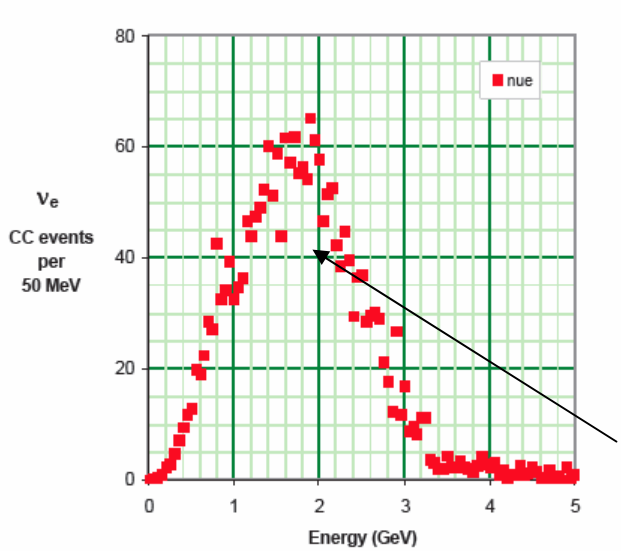


e-μ discrimination using average pulse height/plane and <hits>/plane

NOvA also has a near detector as a crucial component



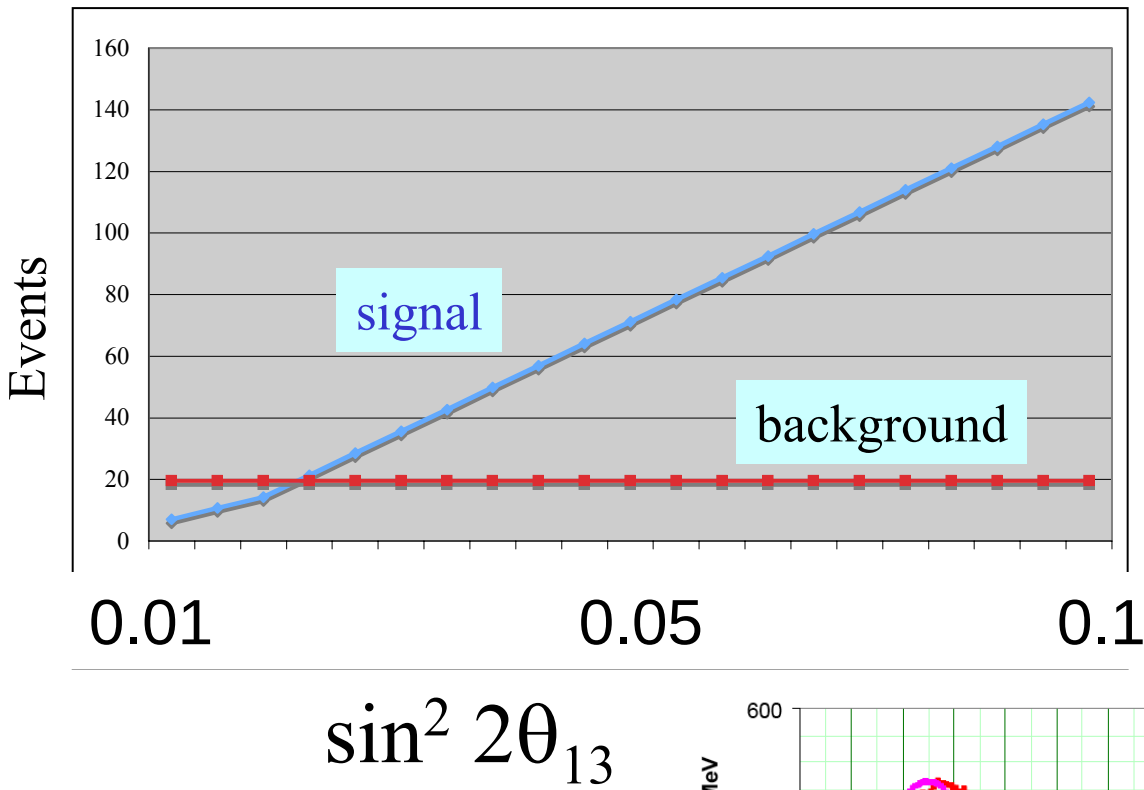
Can move to different locations in underground tunnel to measure off-axis effects and calibrate far spectra



Can also operate early on surface to understand response

Sample ν_e spectrum from "off-axis neutrino test beam"

Measurement is limited by statistics - experiment improves with protons

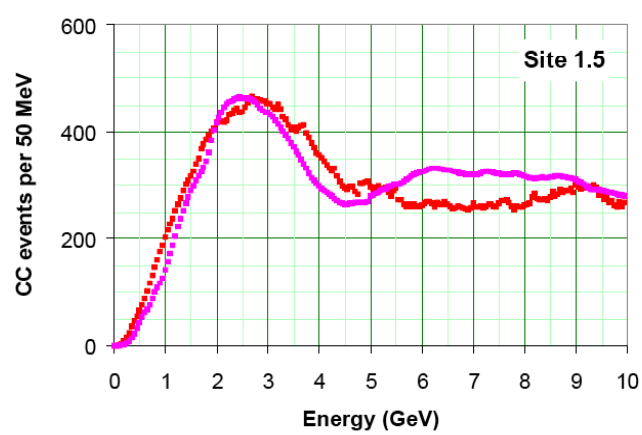


For $\sin^2 2\theta_{13} = 0.1$:

ν: S=142.1, B=19.5

ν: S= 71.8, B=12.1

5 yrs at 6.5E20 pot/yr, efficiencies included



Background ν_e from near detector

Graphic - R. Bernstein

Next Order and CP Violation

- Do not neglect Δ_{12}
- Add back CP phase δ
- Terms group as

$$\left| e^{-i(\delta+\Delta_{32})} A_{atm} + A_{solar} \right|^2$$

(Before we looked only at A_{atm}^2)

Giving

$$P\left(\nu_\mu \to \nu_e\right) =$$

$$\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$ Atmospheric

$$+\cos^2\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$ Solar

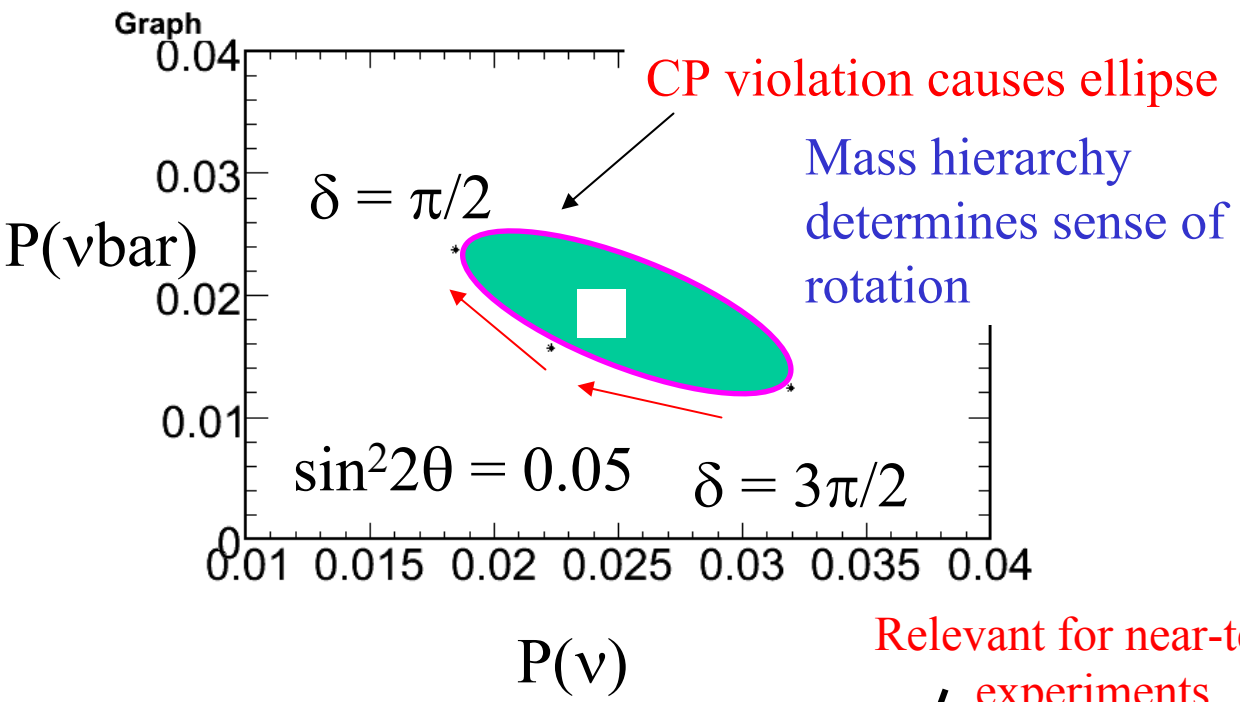
$$+J_r\sin\Delta_{21}\sin\Delta_{31}$$ Interference

$$\left(\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta\right)$$

Note J_r a combination of angles $\cong 0.9\sin^2\theta_{13}$

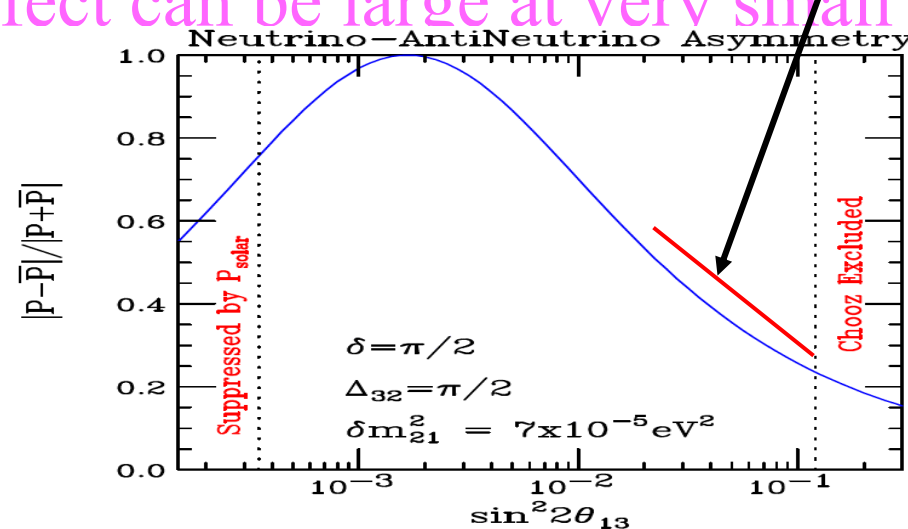
CP and Anti-Neutrinos

- CP δ changes sign between ν and ν–bar.
- As a result $\frac{P_{\bar{\nu}_\mu \to \bar{\nu}_e}}{P_{\nu_\mu \to \nu_e}}$ depends on δ.



Relevant for near-term experiments

- Effect can be large at very small θ_{13}



$A_{solar}=A_{atm}$

Review of Oscillations in Matter

Recall ν_e + e scattering adds a potential

$$H_{matter} = H_{vac} + V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Leading after some manipulation to

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\Delta_{13}^2}{(\Delta_{13} \mp aL)^2} \sin^2(\Delta_{13} \mp aL)$$

new mixing strength

new effective mass

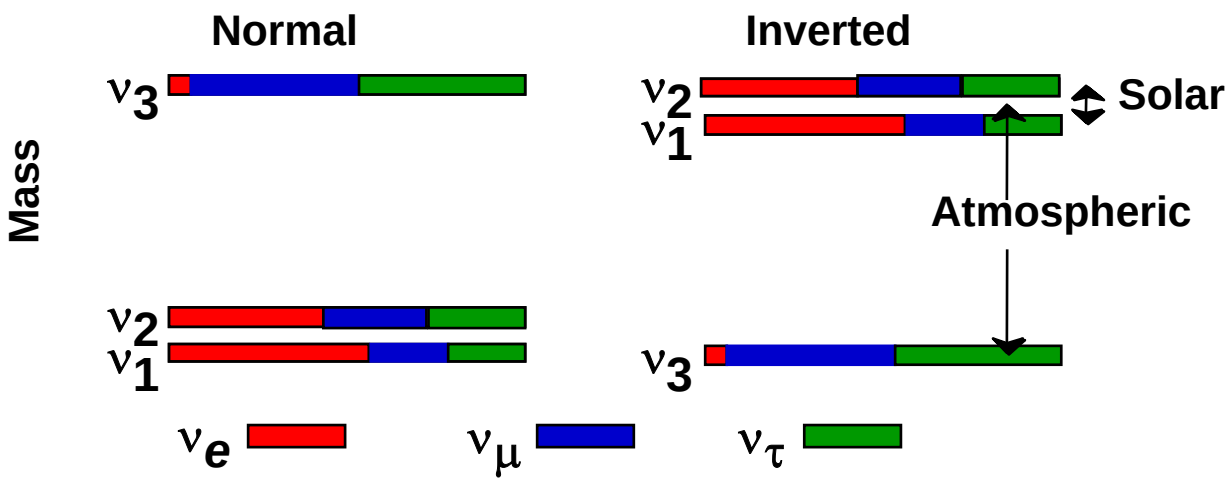
where a is

$$a = \frac{G_F N_e}{\sqrt{2}} \approx (3700 \text{ km})^{-1} \left(\frac{\rho}{2.8 \text{ g cm}^{-3}} \right)$$

and the sign changes between neutrinos and antineutrinos

3-ν's: Change is OK for all orders n of $\sin^n\Delta_{12}$ and $\sin^n\Delta_{13}$

Mass Hierarchy and NOvA



Major unsolved problem

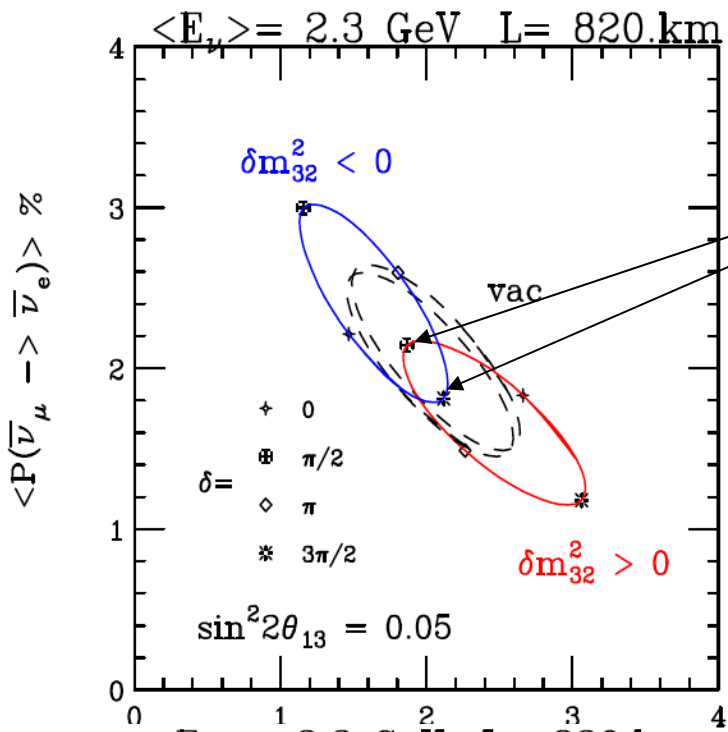
Requires matter effects to observe

Hence a real "target of opportunity" for a long baseline.

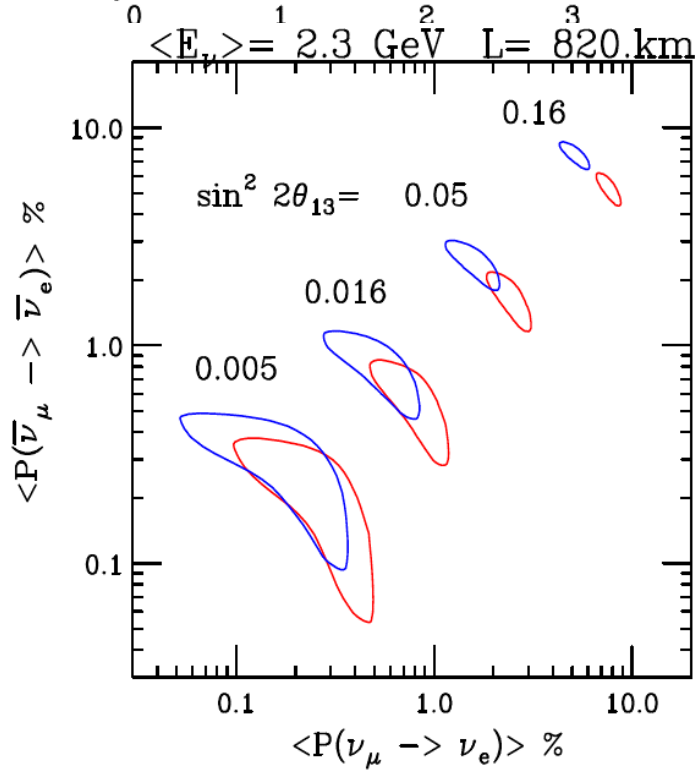
To leading order and zero CP violation, acts as if neutrinos and antineutrinos were interchanged.

CP violation makes it more complicated

Matter effects split the CP ellipses

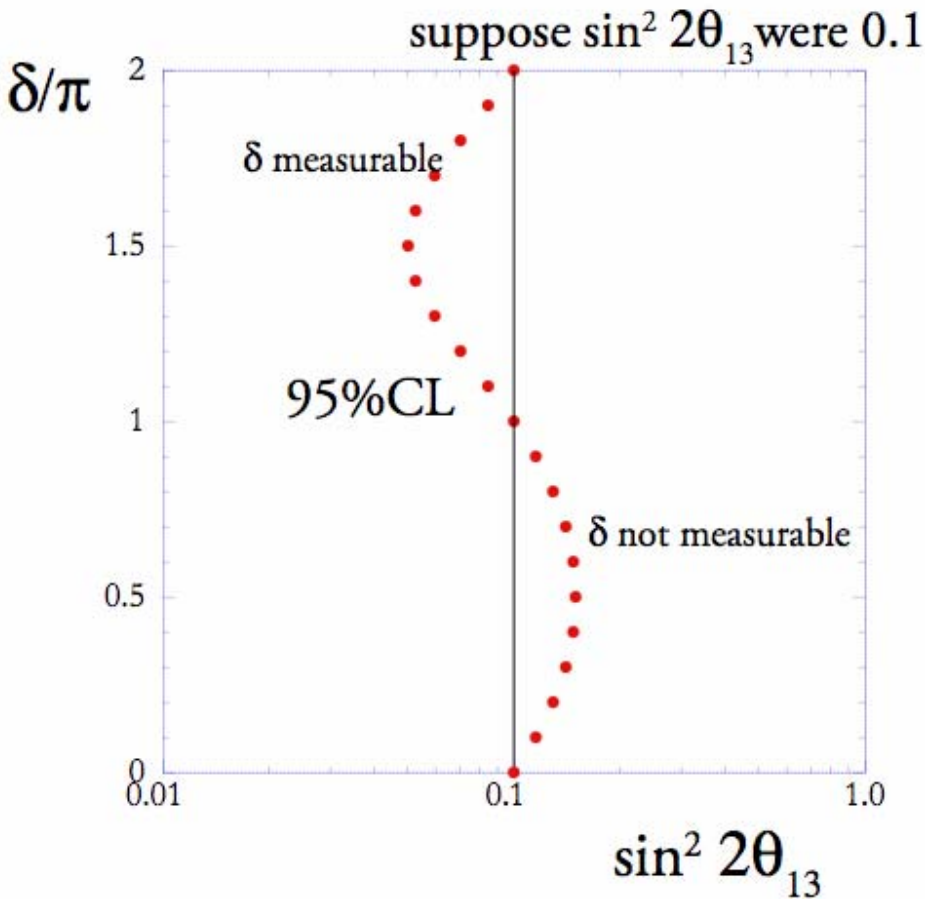


Opposite rotation senses can increase overlap



Ellipse separation is leading order effect, grows with $\sin^2 2\theta$

Can discuss measurements of quantities in terms of what fraction of CP-space they can see



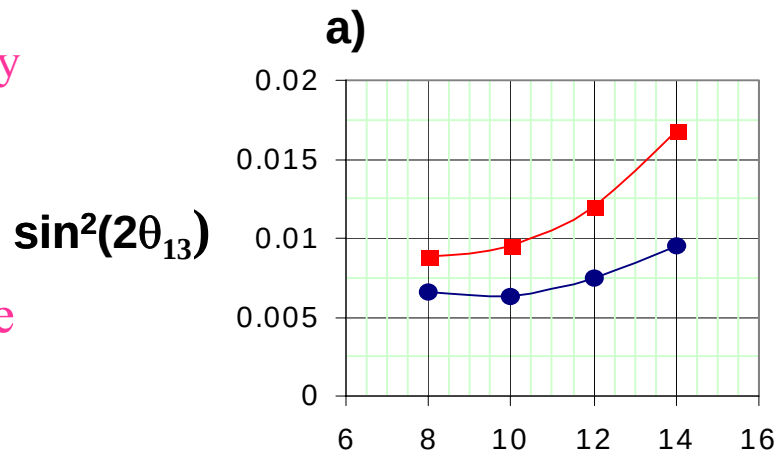
This is just a guide-the-eye example to illustrate the following plots.

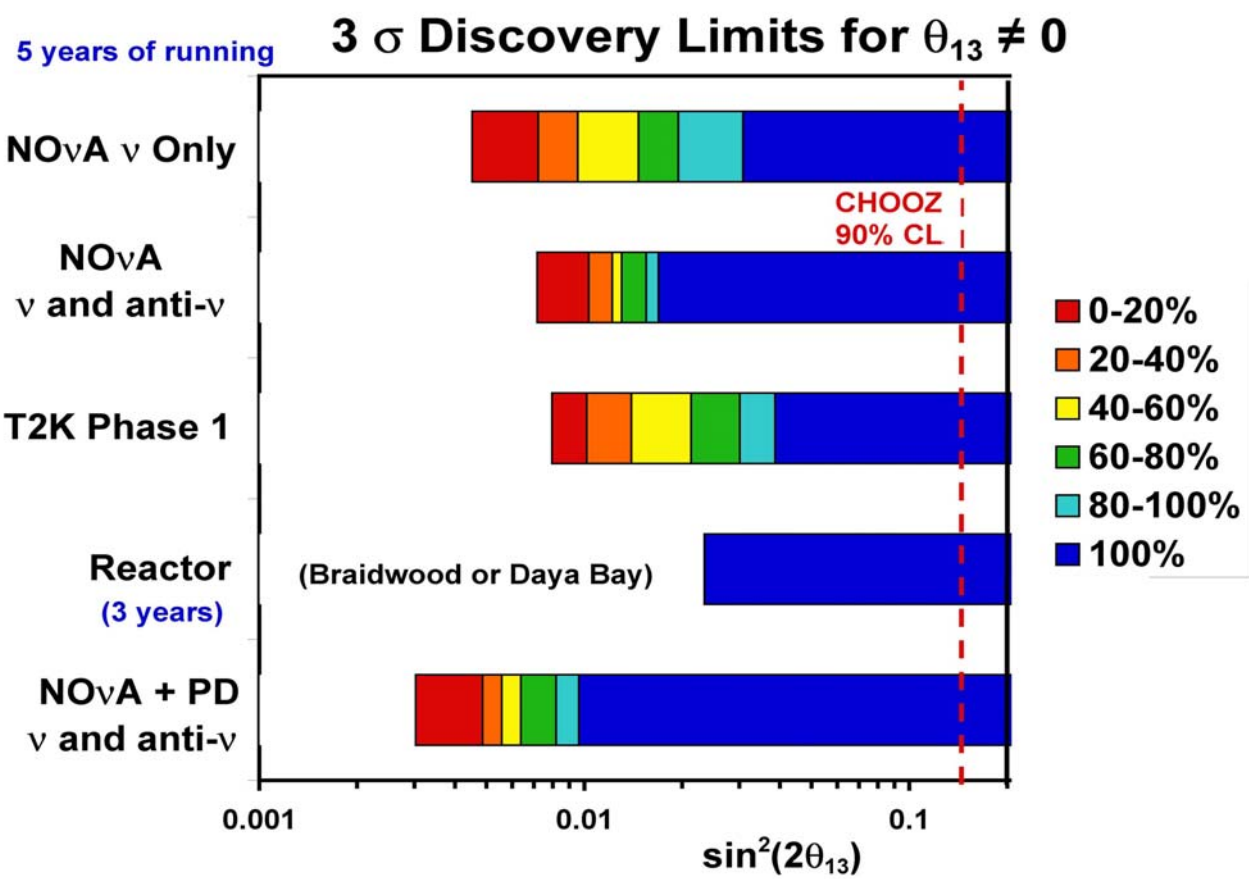
In reality, overlaps, degeneracies can make situation quite complicated.

Graphic - after R. Bernstein

NOνA Sensitivity to θ_{13}

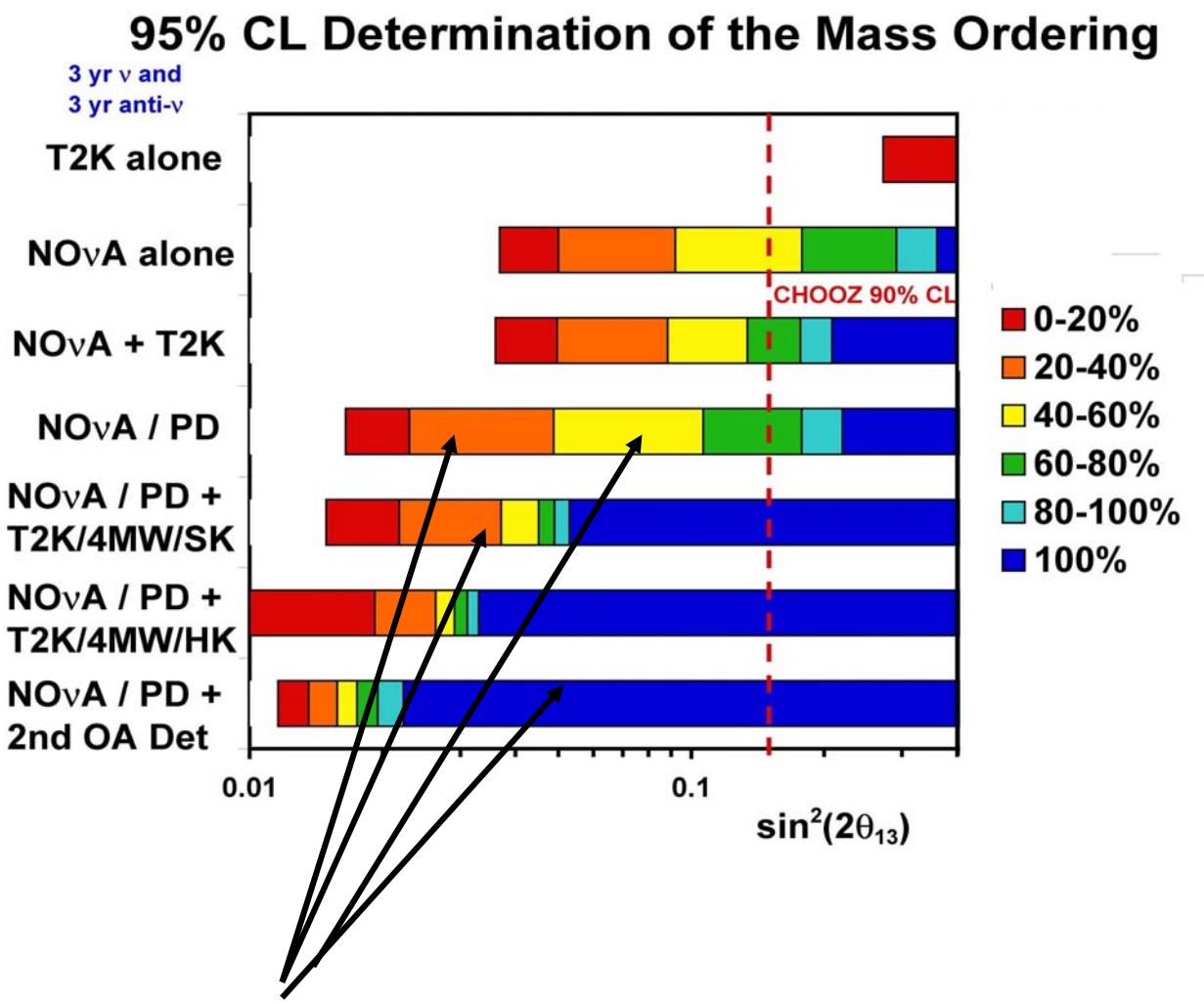
3 standard deviation discovery limit of NOνA for $\nu_\mu \rightarrow \nu_e$ oscillations as a function of $\sin^2(2\theta_{13})$ and the off-axis distance; red inverted, blue normal mass hierarchy





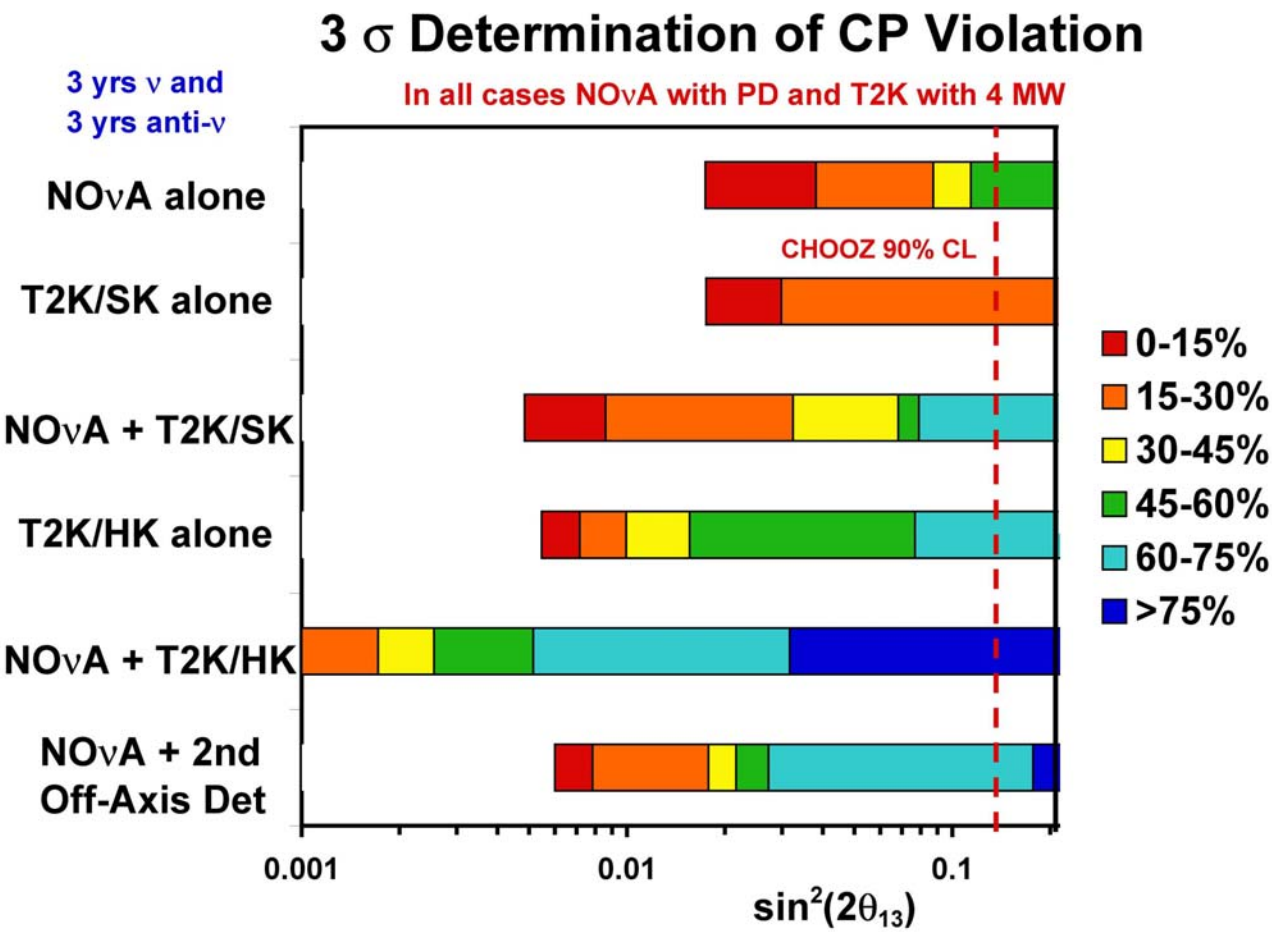
Presented as % coverage in CP phase δ

NOνA Coverage range for mass ordering



Upgraded Fermilab complex could produce more beam, on order 1-2 MW

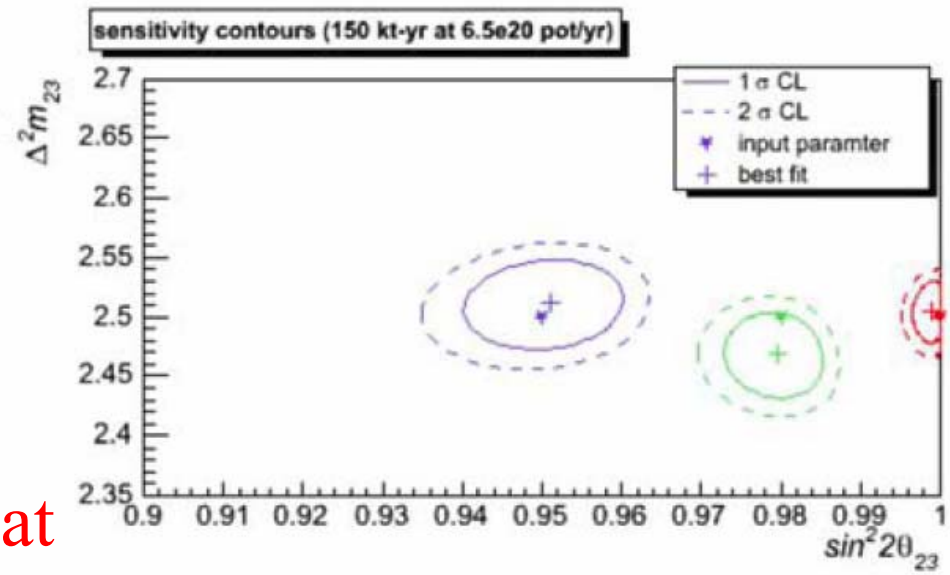
To make progress on CP violation requires all the handles.



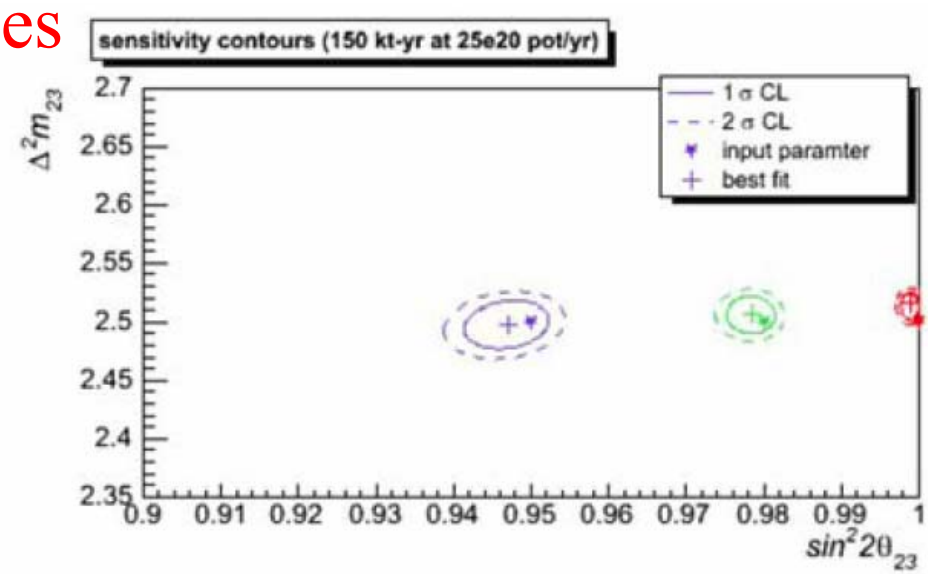
Need lots of protons ==> upgrades of beams

Great help from combining experiments!

Sufficient running of NOvA can make do other precision measurements.



5-year run at two intensities



Excellent results for $\sin^2\theta_{23}$ with expected intensities.