

# NO $\nu$ A NEUTRINO OSCILLATION SEARCHES

---

ANL Scientists Symposium

Feb 16<sup>th</sup> 2016

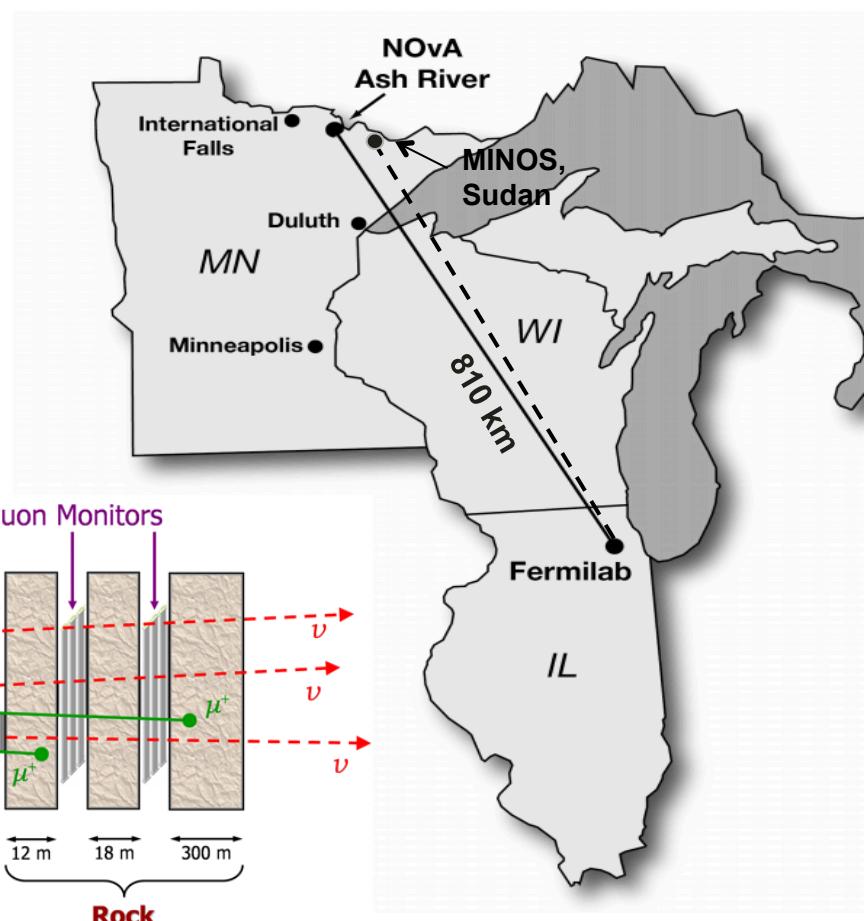
Louise Suter, Argonne National Laboratory



# NOvA physics goals

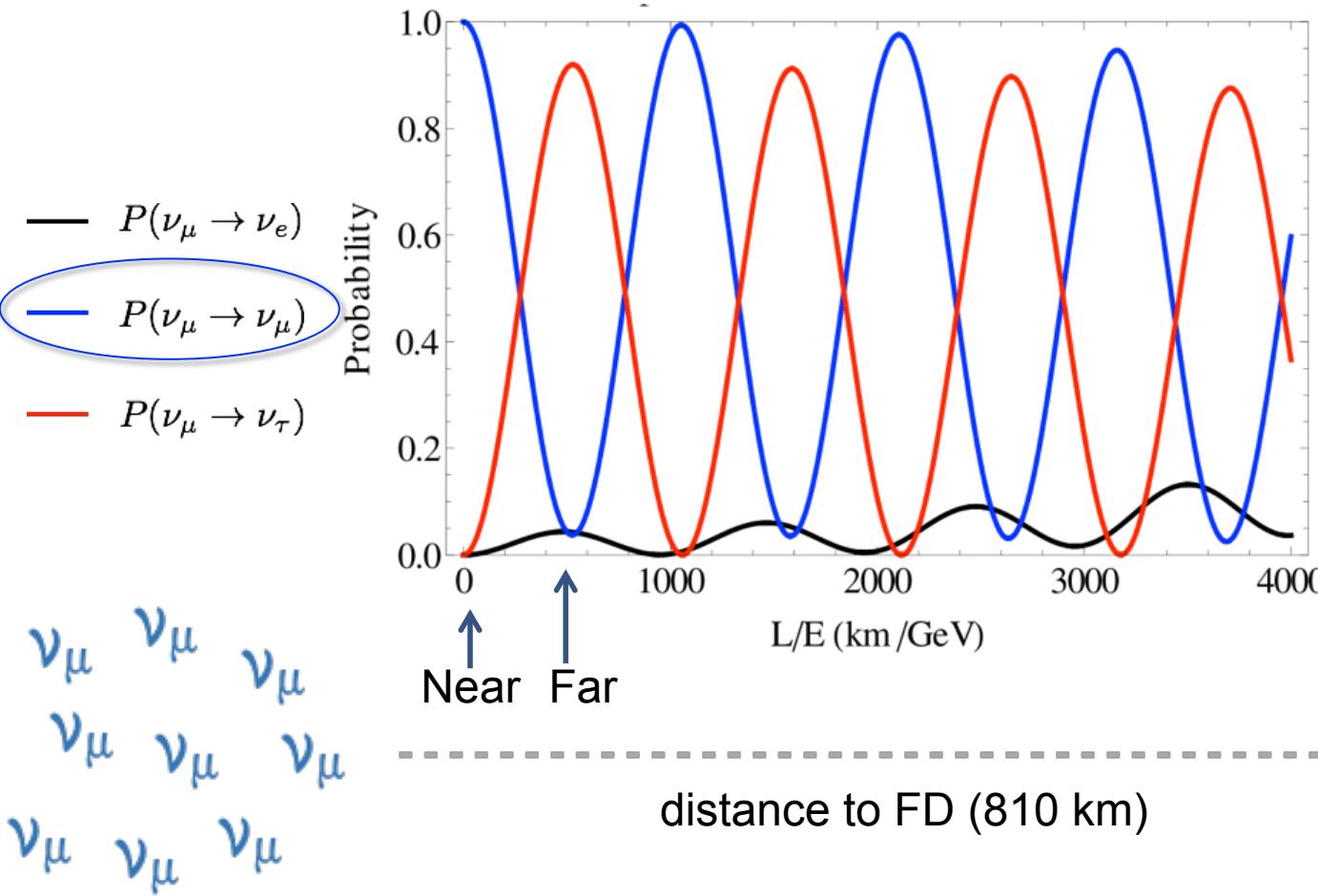
Designed to measure four types of oscillation, using a muon neutrino beam made at FNAL fired through earth 810 km to Northern Minnesota

- $\nu_e$  appearance ( $\nu_\mu \rightarrow \nu_e$ )
- $\bar{\nu}_e$  appearance ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ )
- $\nu_\mu$  disappearance ( $\nu_\mu \rightarrow \nu_\mu$ )
- $\bar{\nu}_\mu$  disappearance ( $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ )

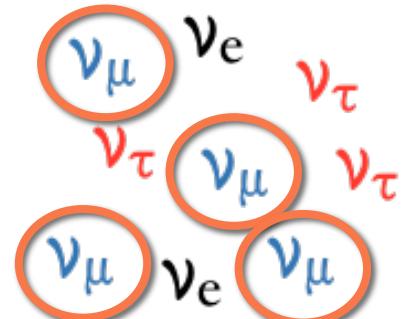
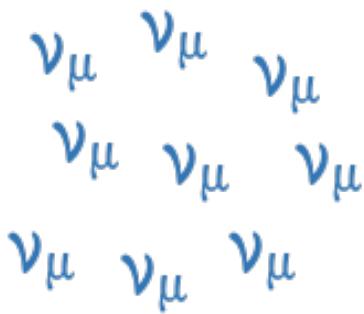


# $\nu_\mu$ disappearance from a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m_{32}^2 [\text{eV}^2] L_\nu [\text{km}]}{E_\nu [\text{GeV}]} \right)$$

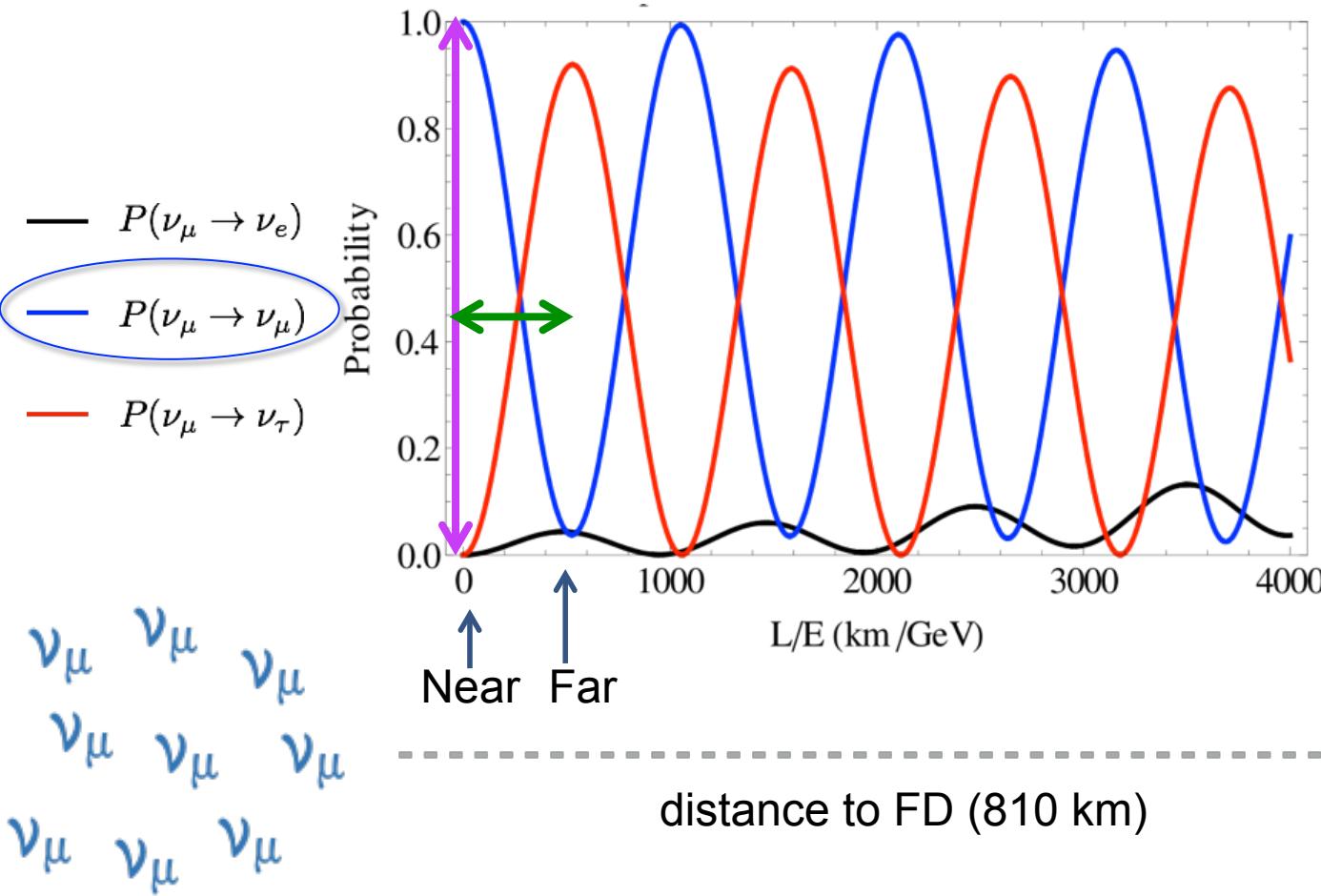


By measuring  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) disappearance, can make precision measurements of  $\sin^2(2\theta)$  and  $\Delta m_{32}^2$



# $\nu_\mu$ disappearance from a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{1.27 \Delta m_{32}^2 [\text{eV}^2] L_\nu [\text{km}]}{E_\nu [\text{GeV}]} \right)$$



By measuring  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) disappearance, can make precision measurements of  $\sin^2(2\theta)$  and  $\Delta m_{32}^2$

# $\nu_e$ appearance from a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2}$$

$$+ \alpha \tilde{J} \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{(1-A)}$$

$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2}$$

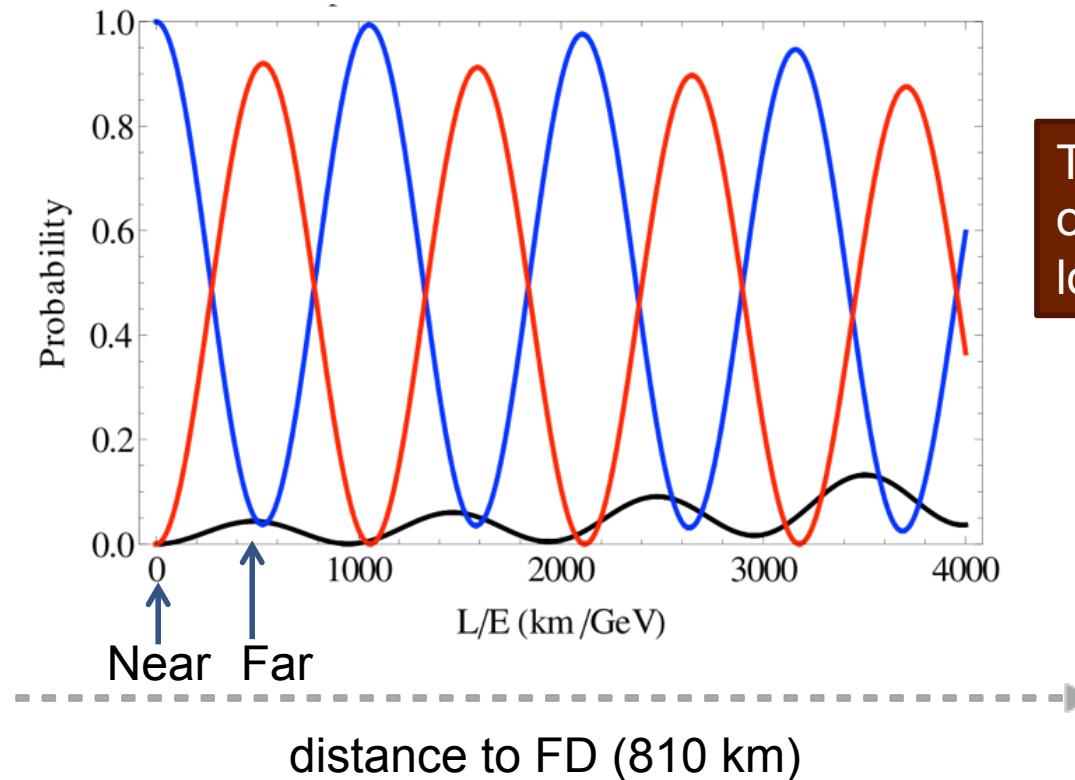
$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$$

$$\tilde{J} = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

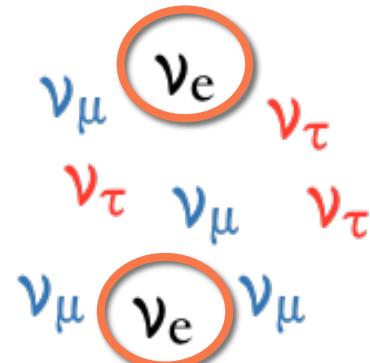
$$\Delta = \Delta m_{31}^2 L_\nu / 4E_\nu$$

- $P(\nu_\mu \rightarrow \nu_e)$
- $P(\nu_\mu \rightarrow \nu_\mu)$
- $P(\nu_\mu \rightarrow \nu_\tau)$

$\nu_\mu$     $\nu_\mu$     $\nu_\mu$   
 $\nu_\mu$     $\nu_\mu$     $\nu_\mu$   
 $\nu_\mu$     $\nu_\mu$     $\nu_\mu$



Two flavor vacuum oscillations no longer applicable



# $\nu_e$ appearance from a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2}$$

$$+ \alpha \tilde{J} \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{(1-A)}$$

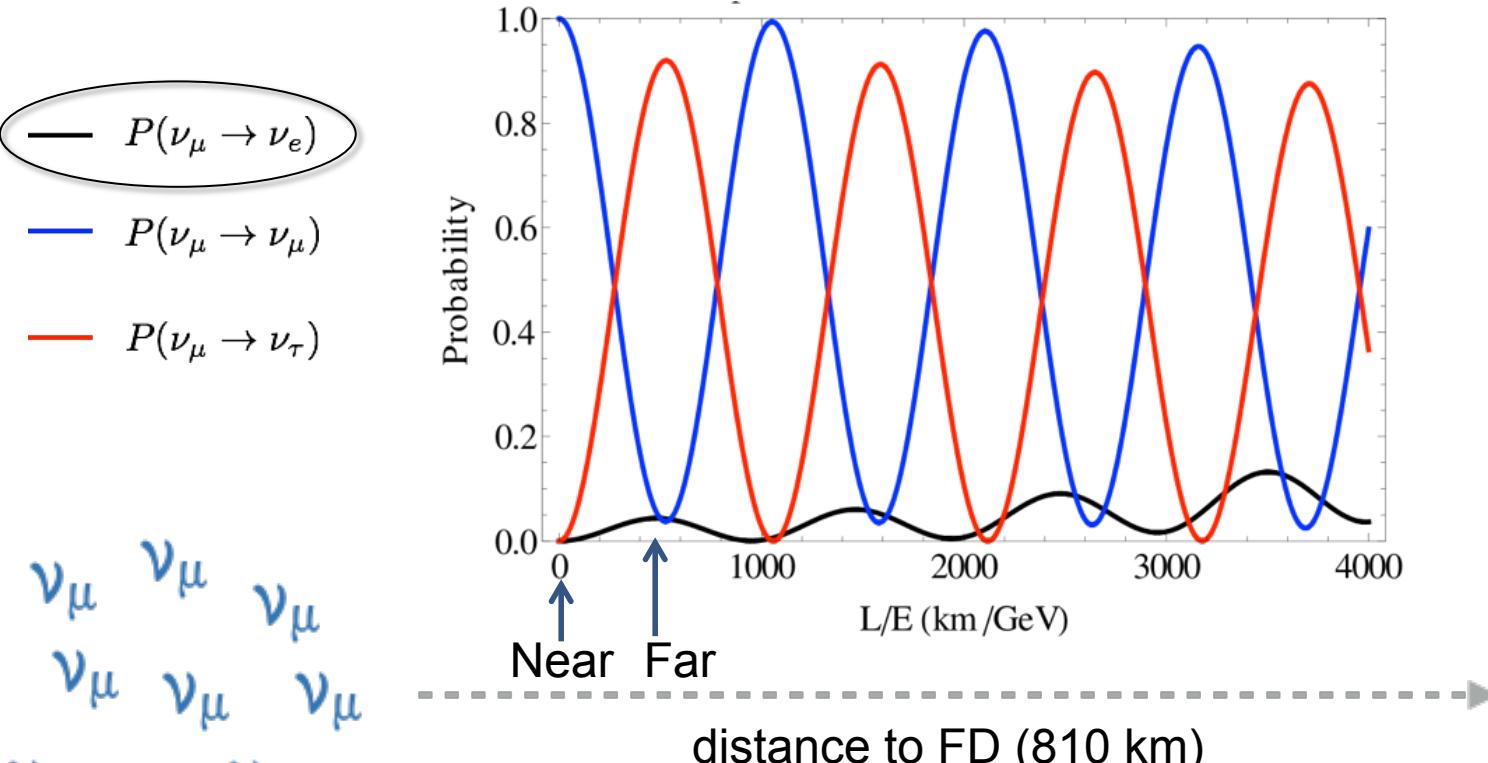
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2}$$

$$\alpha = \Delta m_{21}^2, \Delta m_{31}^2$$

$$\tilde{J} = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

$$\Delta = \Delta m_{31}^2 L_\nu / 4E_\nu$$

- $P(\nu_\mu \rightarrow \nu_e)$
- $P(\nu_\mu \rightarrow \nu_\mu)$
- $P(\nu_\mu \rightarrow \nu_\tau)$



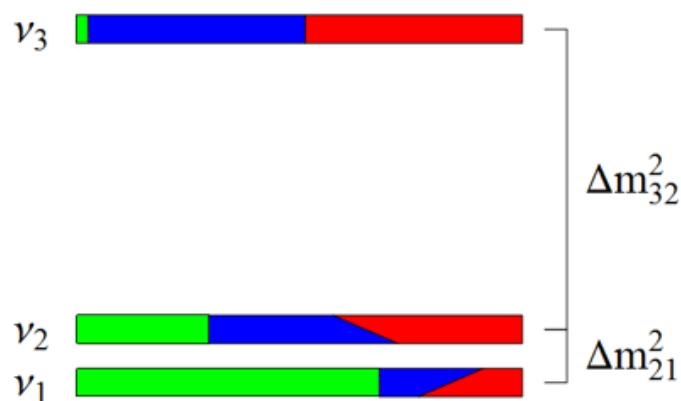
Mass hierarchy through sign of  $\Delta m_{31}^2$

$\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$

$\nu_\mu$   $\nu_e$   $\nu_\tau$   
 $\nu_\tau$   $\nu_\mu$   $\nu_\tau$   
 $\nu_\mu$   $\nu_e$   $\nu_\mu$

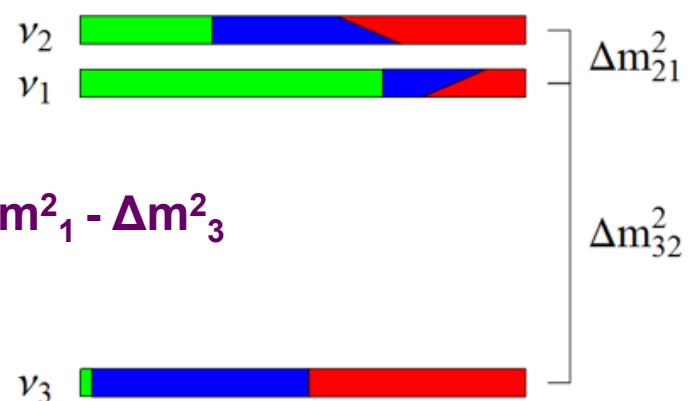
# $\nu_e$ appearance from a $\nu_\mu$ beam

Normal hierarchy



$$\Delta m_{31}^2 = \Delta m_{21}^2 - \Delta m_{32}^2$$

Inverted hierarchy



$\nu_e$        $\nu_\mu$        $\nu_\tau$

Measuring  $\Delta m_{31}^2$  as positive or negative tell us which is heaviest

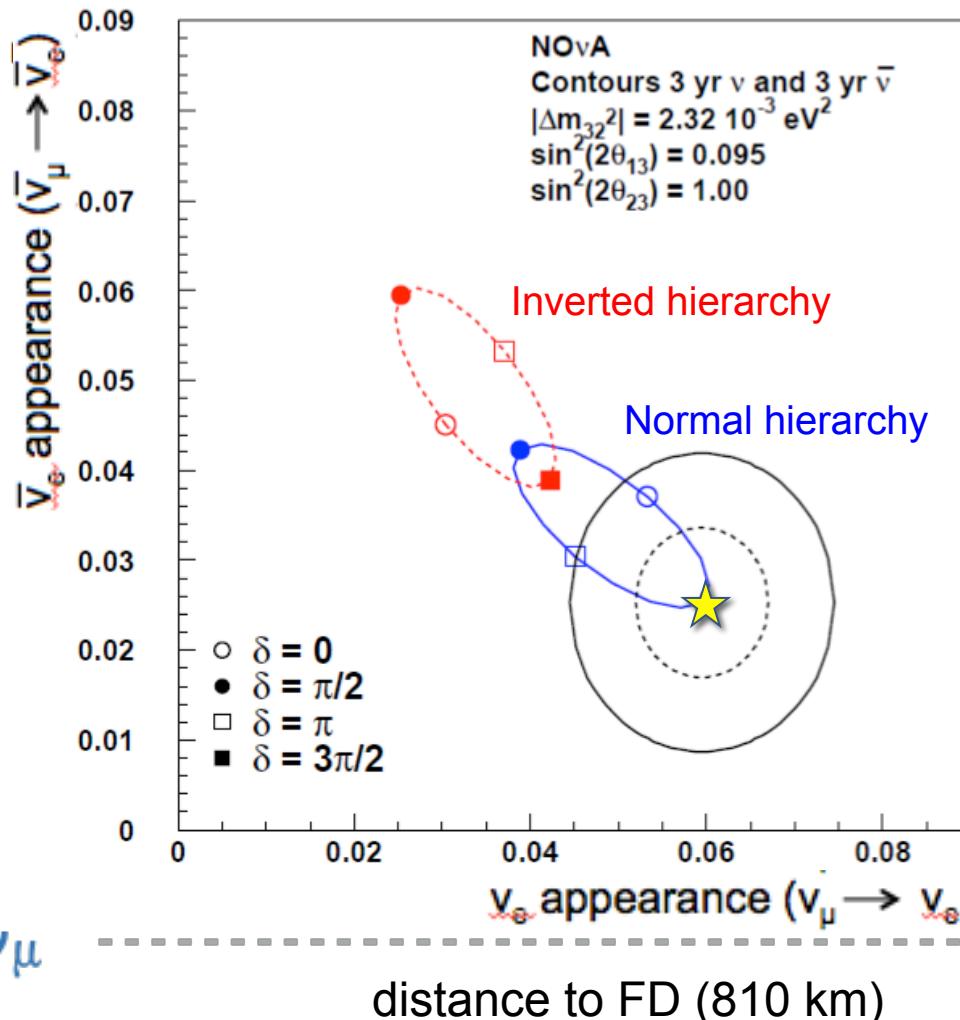
$\nu_\mu$      $\nu_\mu$      $\nu_\mu$   
 $\nu_\mu$      $\nu_\mu$      $\nu_\mu$   
 $\nu_\mu$      $\nu_\mu$      $\nu_\mu$

distance to FD (810 km)

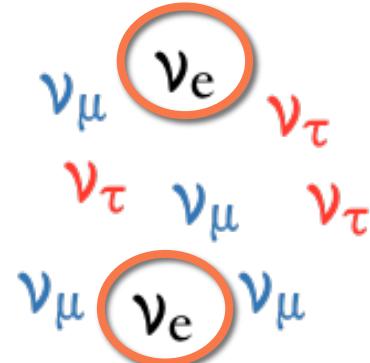
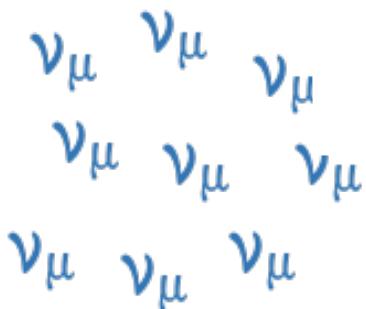
$\nu_\mu$      $\nu_e$      $\nu_\tau$   
 $\nu_\tau$      $\nu_\mu$      $\nu_\tau$   
 $\nu_\mu$      $\nu_e$      $\nu_\mu$

# $\nu_e$ appearance from a $\nu_\mu$ beam

1 and 2  $\sigma$  Contours for Starred Point



Number of electron neutrinos appearing depends on **ordering of mass states**



# $\nu_e$ appearance from a $\nu_\mu$ beam

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2 \Delta(1-A)}{(1-A)^2}$$

$$+ \alpha \tilde{J} \cos(\Delta \pm \delta_{CP}) \frac{\sin \Delta A}{A} \frac{\sin \Delta(1-A)}{(1-A)}$$

$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 \Delta A}{A^2}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2$$

$$\tilde{J} = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}$$

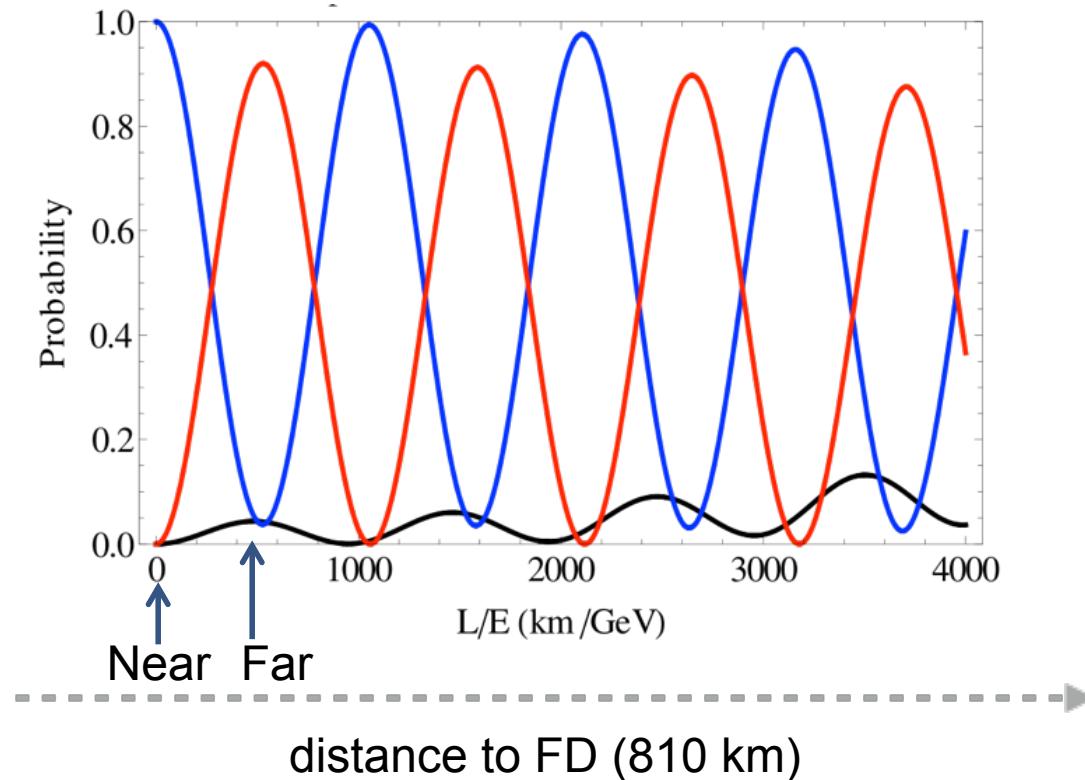
$$\Delta = \Delta m_{31}^2 L_\nu / 4E_\nu$$

—  $P(\nu_\mu \rightarrow \nu_e)$

—  $P(\nu_\mu \rightarrow \nu_\mu)$

—  $P(\nu_\mu \rightarrow \nu_\tau)$

$\nu_\mu$     $\nu_\mu$     $\nu_\mu$   
 $\nu_\mu$     $\nu_\mu$     $\nu_\mu$   
 $\nu_\mu$     $\nu_\mu$     $\nu_\mu$

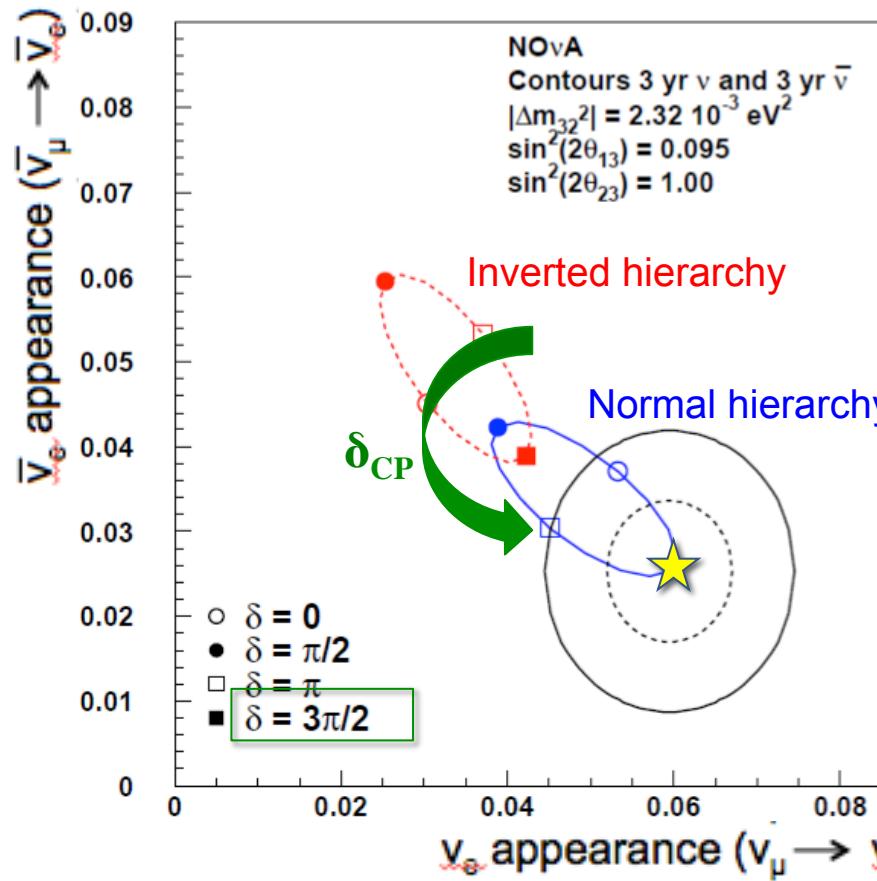


$\nu_\mu$     $\nu_e$     $\nu_\tau$   
 $\nu_\tau$     $\nu_\mu$     $\nu_\tau$   
 $\nu_\mu$     $\nu_e$     $\nu_\mu$

# $\nu_e$ appearance from a $\nu_\mu$ beam

Number of electron neutrinos appearing depends on  
**amount of CP violation in neutrino sector**

1 and 2  $\sigma$  Contours for Starred Point

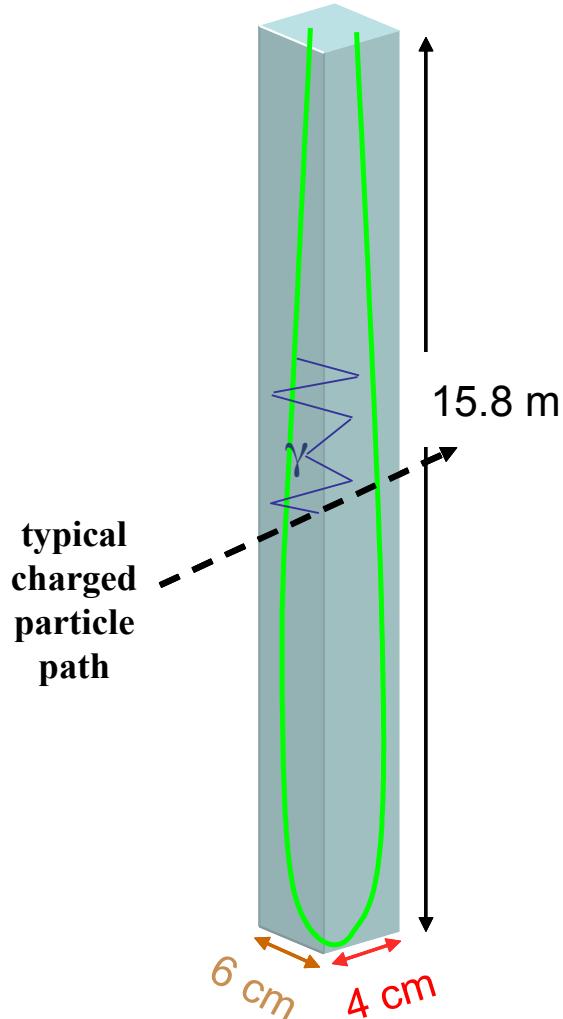


distance to FD (810 km)

$\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$

$\nu_\mu$   $\nu_e$   $\nu_\tau$   
 $\nu_\tau$   $\nu_\mu$   $\nu_\tau$   
 $\nu_\mu$   $\nu_e$   $\nu_\mu$

To 1 APD pixel

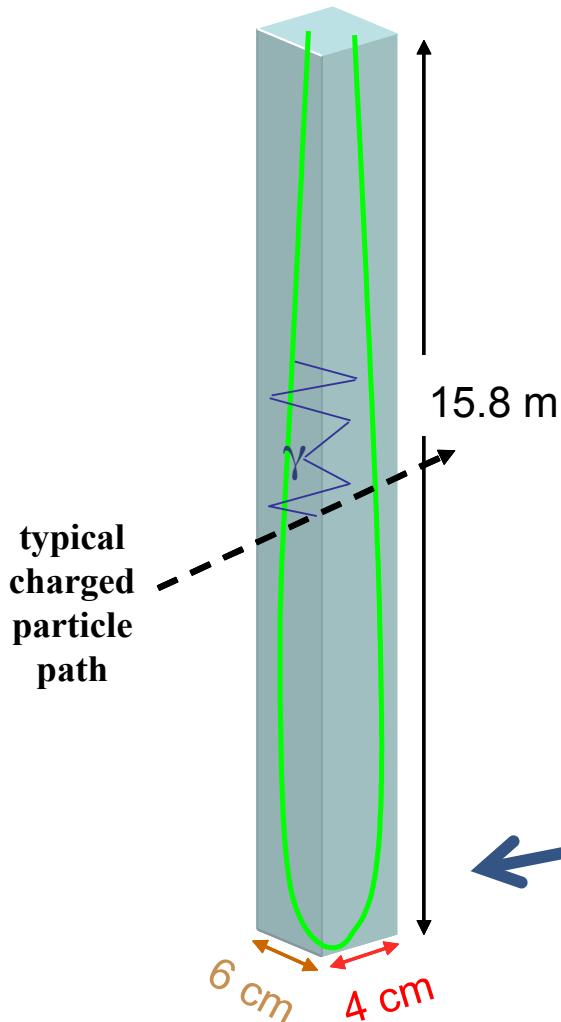


Need to design a detector  
with excellent  $\nu_e$  identification  
and background rejection

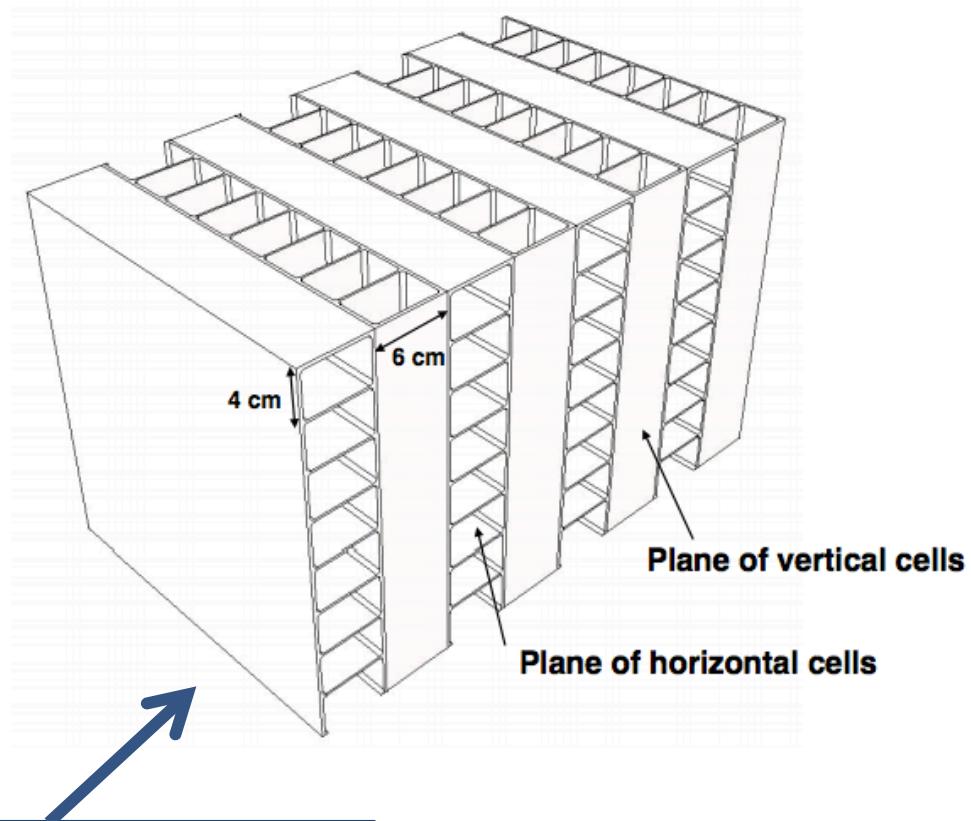
Want a huge, low-Z, totally  
active, tracking calorimeter

PVC cell with 15% TiO<sub>2</sub> for high reflectivity filled with liquid scintillator (mineral oil doped with 5% pseudocumene)

To 1 APD pixel



344,064 identical cells  
constructed into 896  
alternating horizontal and  
vertical planes, each of 384  
cells long

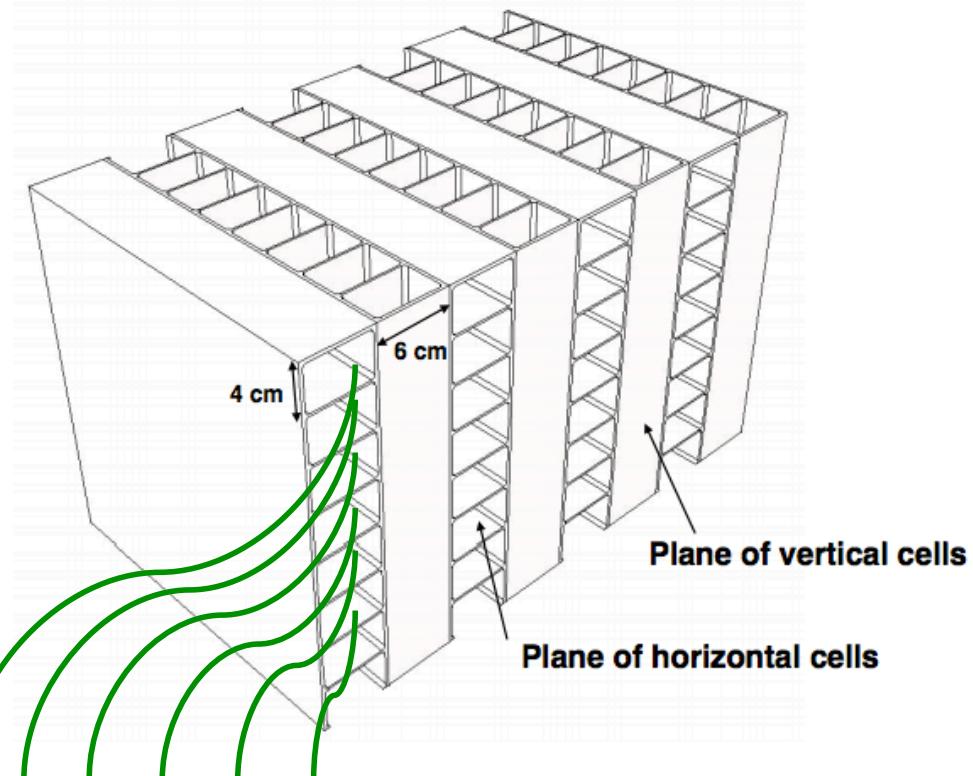


Cells constructed into horizontal and virtual planes for 3D reconstruction

32 pixel APD

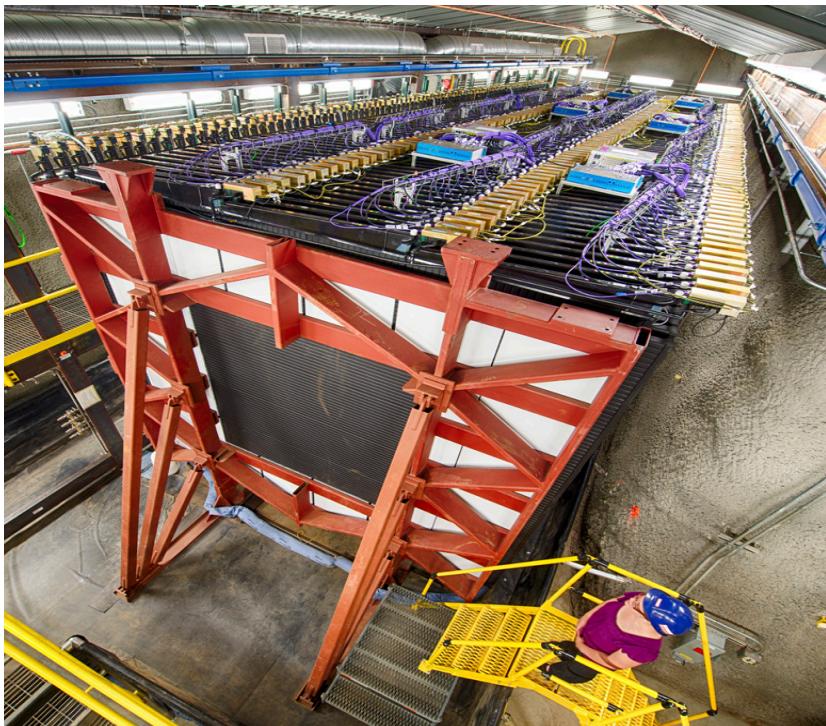


32 WSF loops



Each cell has loop of wavelength shifting fiber read out in groups of 32 by a 32 pixel Avalanche Photodiode

# Near Detector



# Far Detector

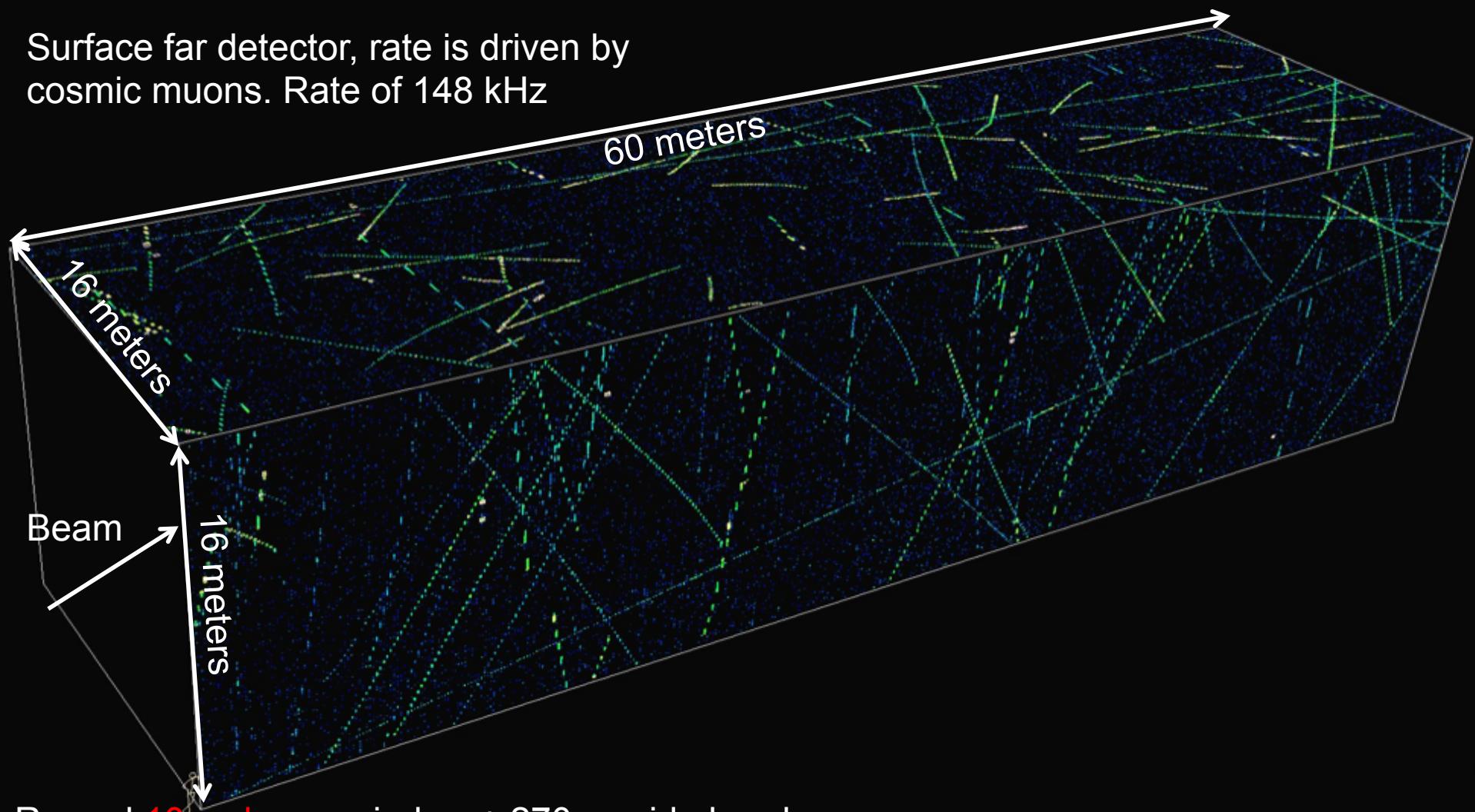


Two identical detectors

- Large flux used to characterize  $\nu$  beam **before oscillation**
- Use data to predict expected rate at FD

- Measure  $\nu$  rates **after oscillation**
- **Use of a ratio measurement allows for cancellation of most systematics**

Surface far detector, rate is driven by cosmic muons. Rate of 148 kHz



Record  $10 \mu\text{s}$  beam window  $\pm 270 \mu\text{s}$  side band

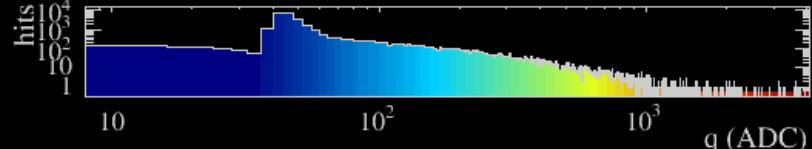
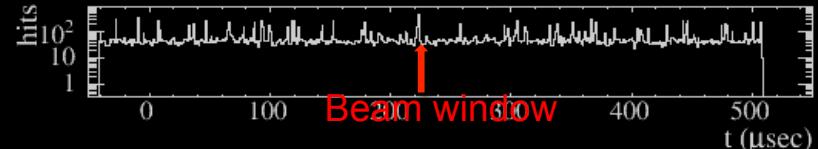
NOvA - FNAL E929

Run: 18620 / 13

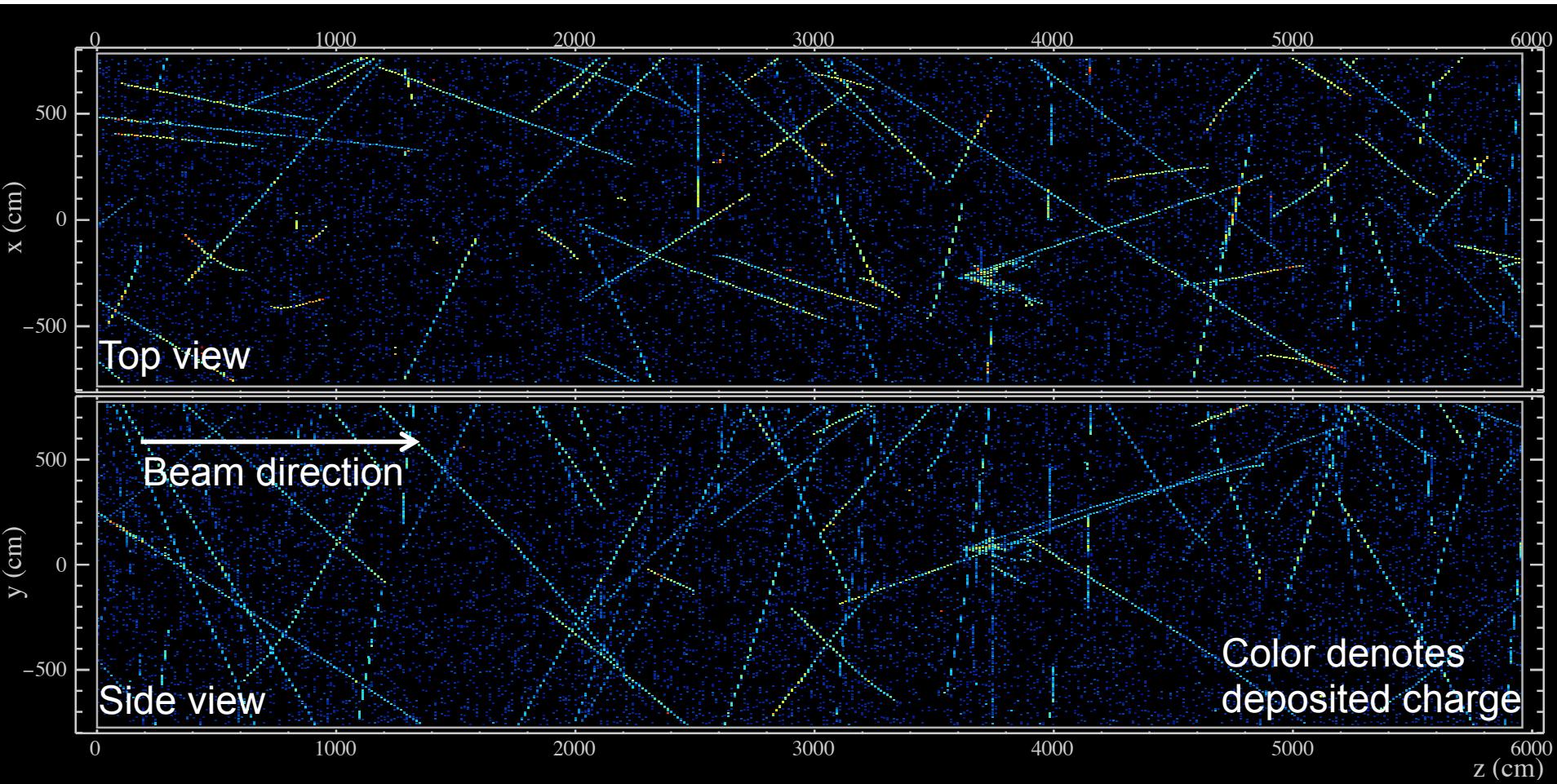
Event: 178402 / --

UTC Fri Jan 9, 2015

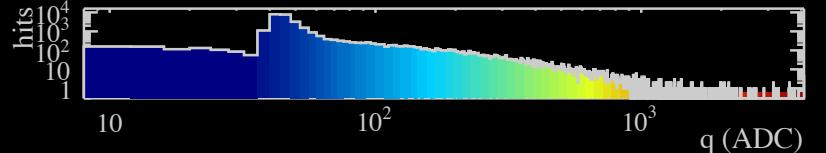
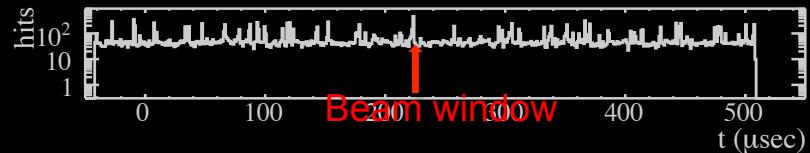
00:13:53.087341608



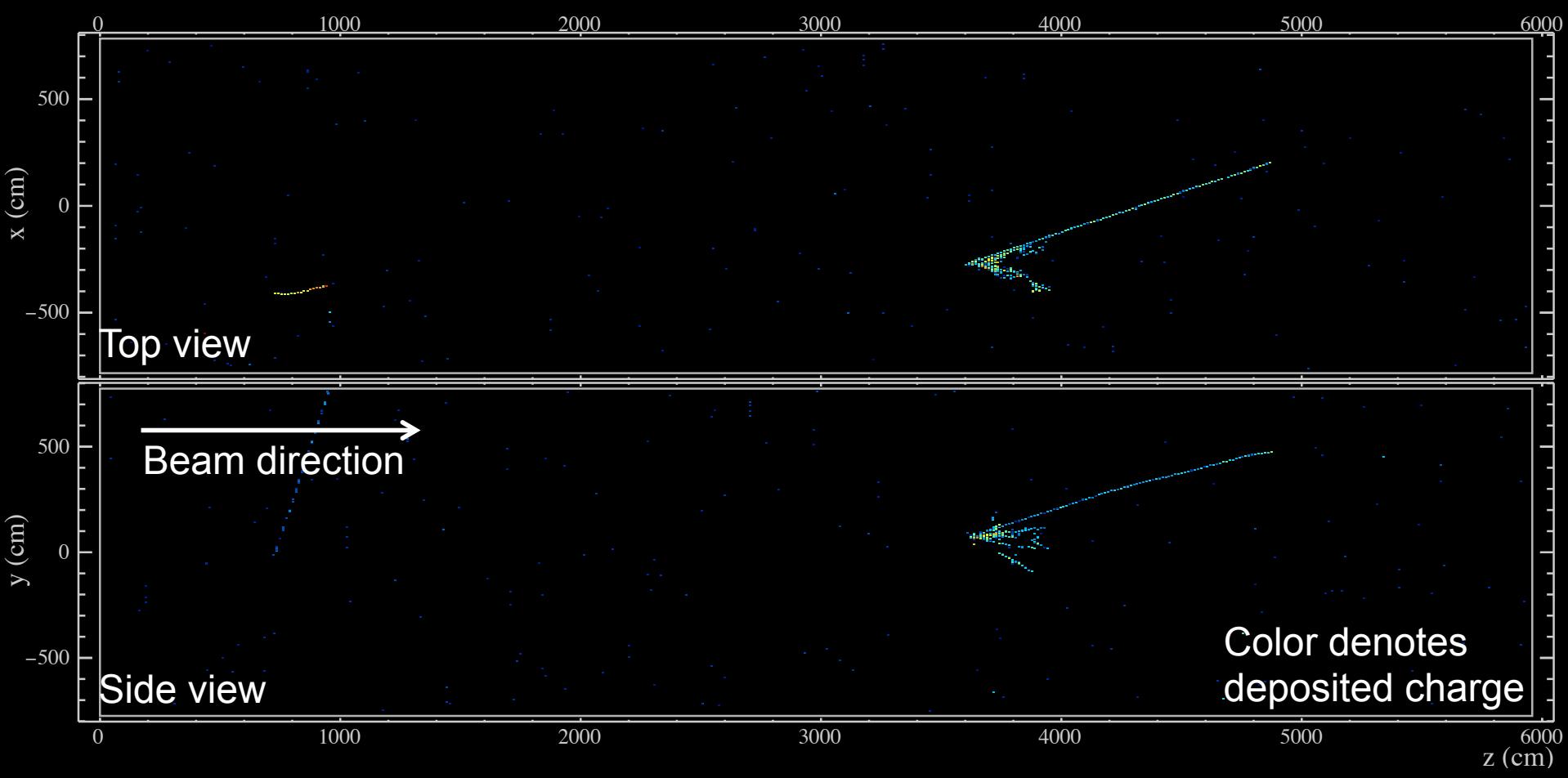
# Far detector 550 $\mu$ s NOvA event



NOvA - FNAL E929  
Run: 18620 / 13  
Event: 178402 / --  
UTC Fri Jan 9, 2015  
00:13:53.087341608

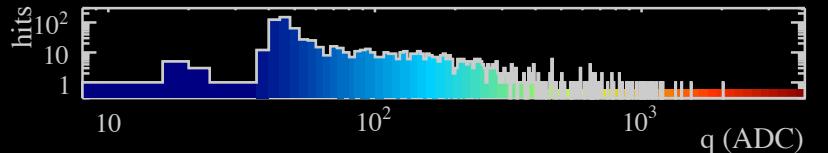


# Zoomed FD 10 $\mu\text{s}$ NOvA event

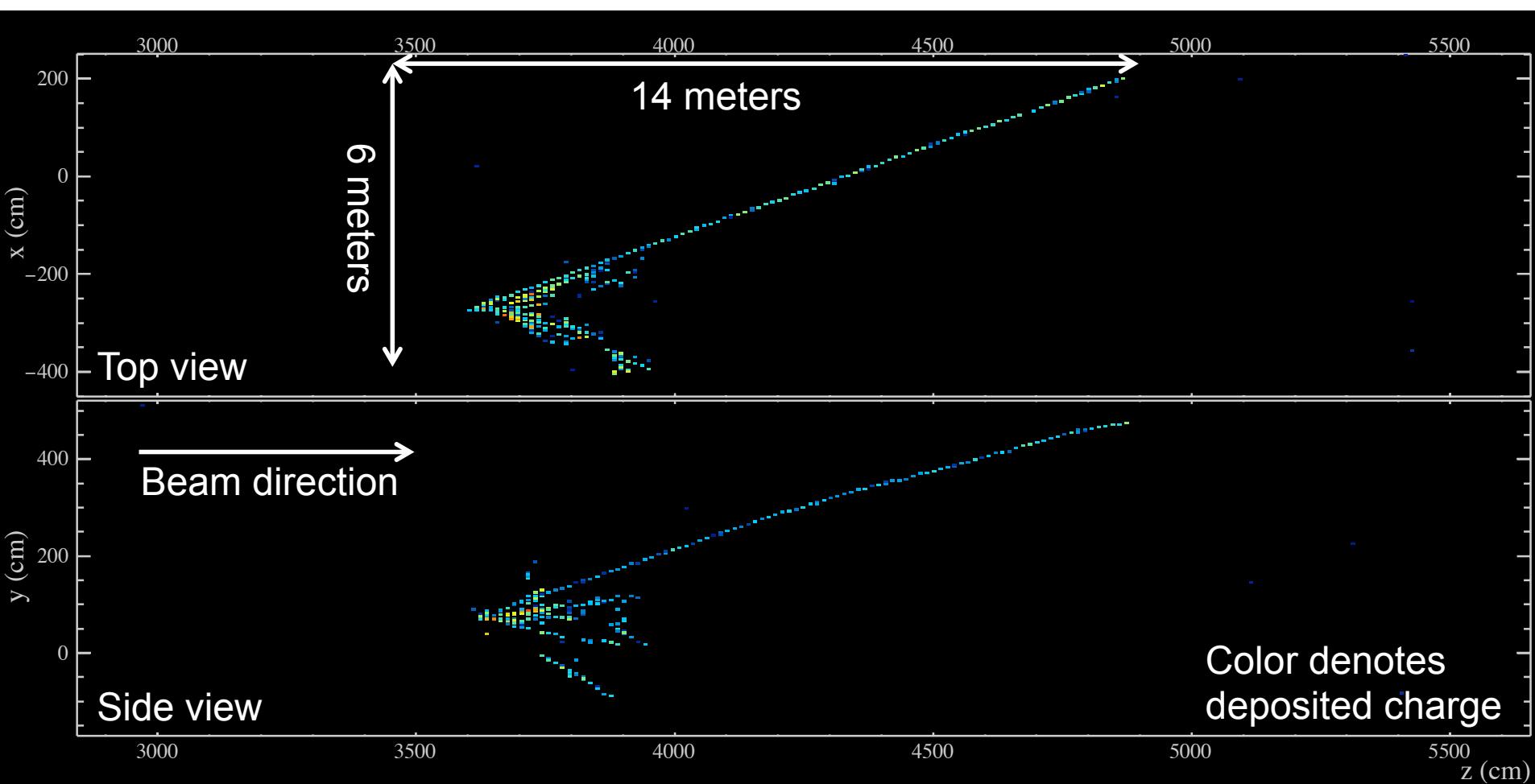


NOvA - FNAL E929

Run: 18620 / 13  
Event: 178402 / --  
UTC Fri Jan 9, 2015  
00:13:53.087341608

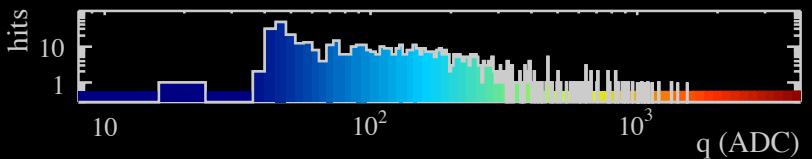


# Zoomed FD 10 $\mu$ s NOvA event

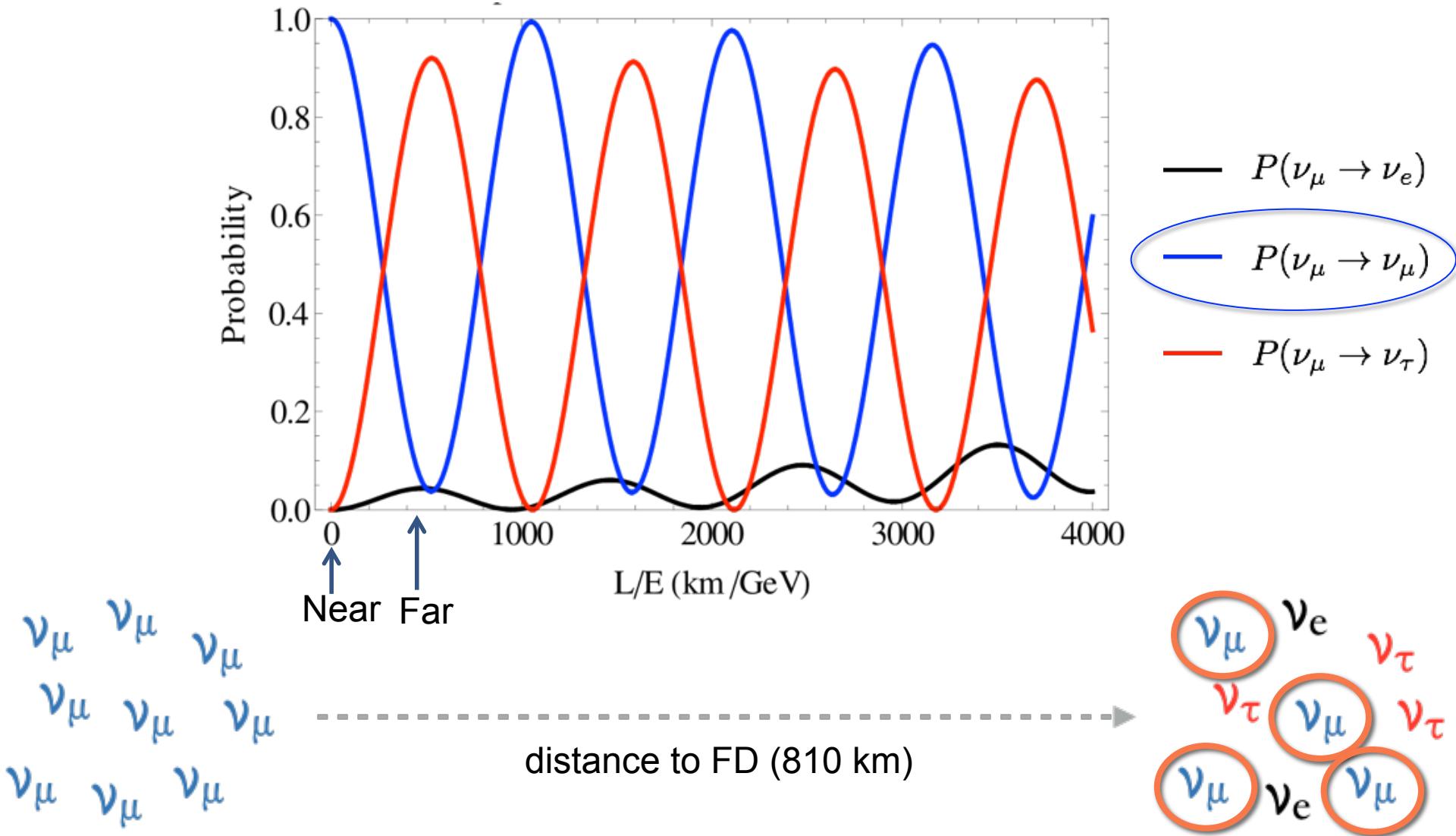


NOvA - FNAL E929

Run: 18620 / 13  
Event: 178402 / --  
UTC Fri Jan 9, 2015  
00:13:53.087341608

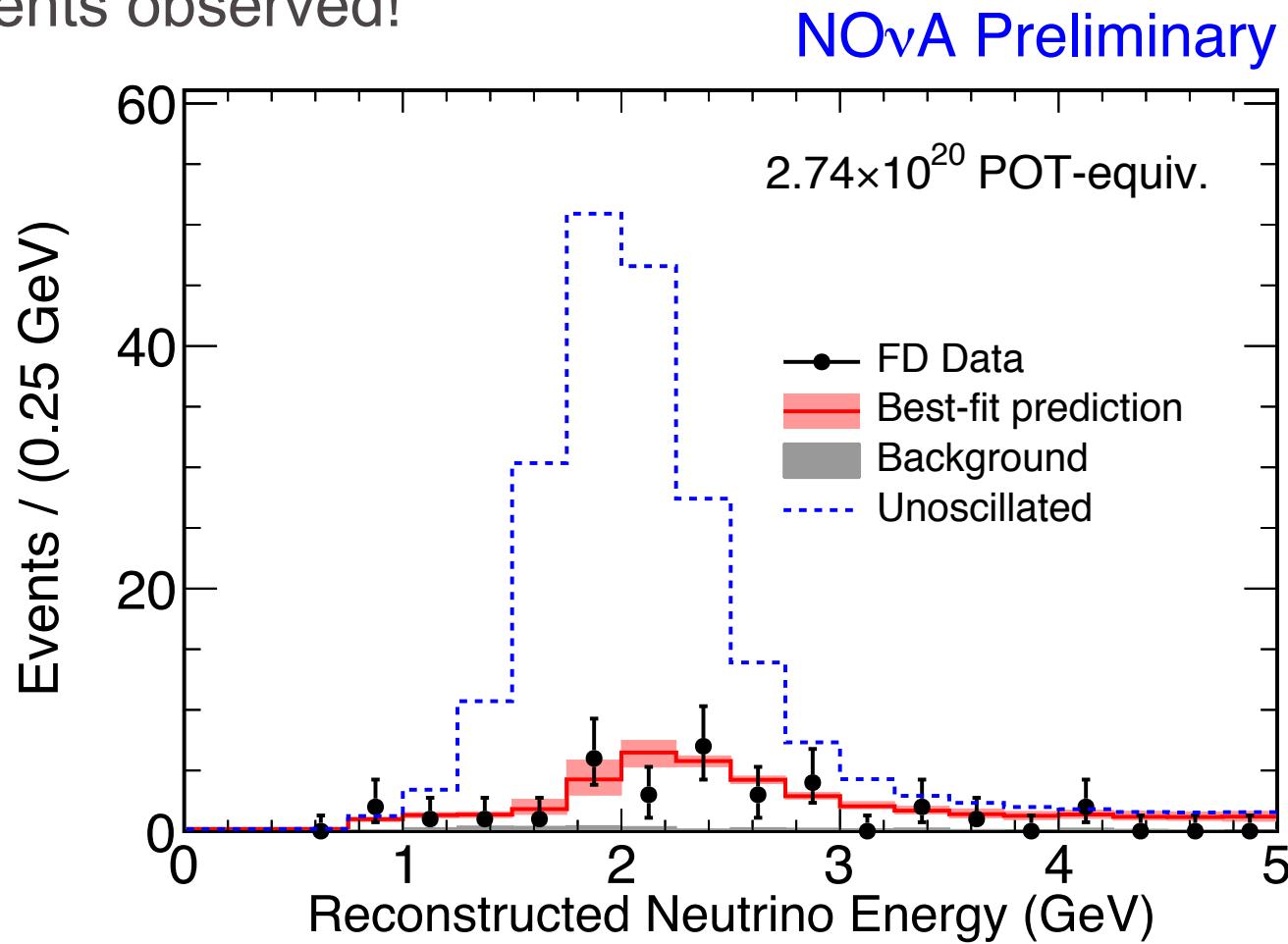


# Muon neutrino disappearance



# $\nu_\mu$ Disappearance Results

- $211.8 \pm 12.5$  events predicted without oscillations
  - Including  $2 \pm 2$  beam background and  $1.4 \pm 0.2$  cosmic events
- 33 events observed!

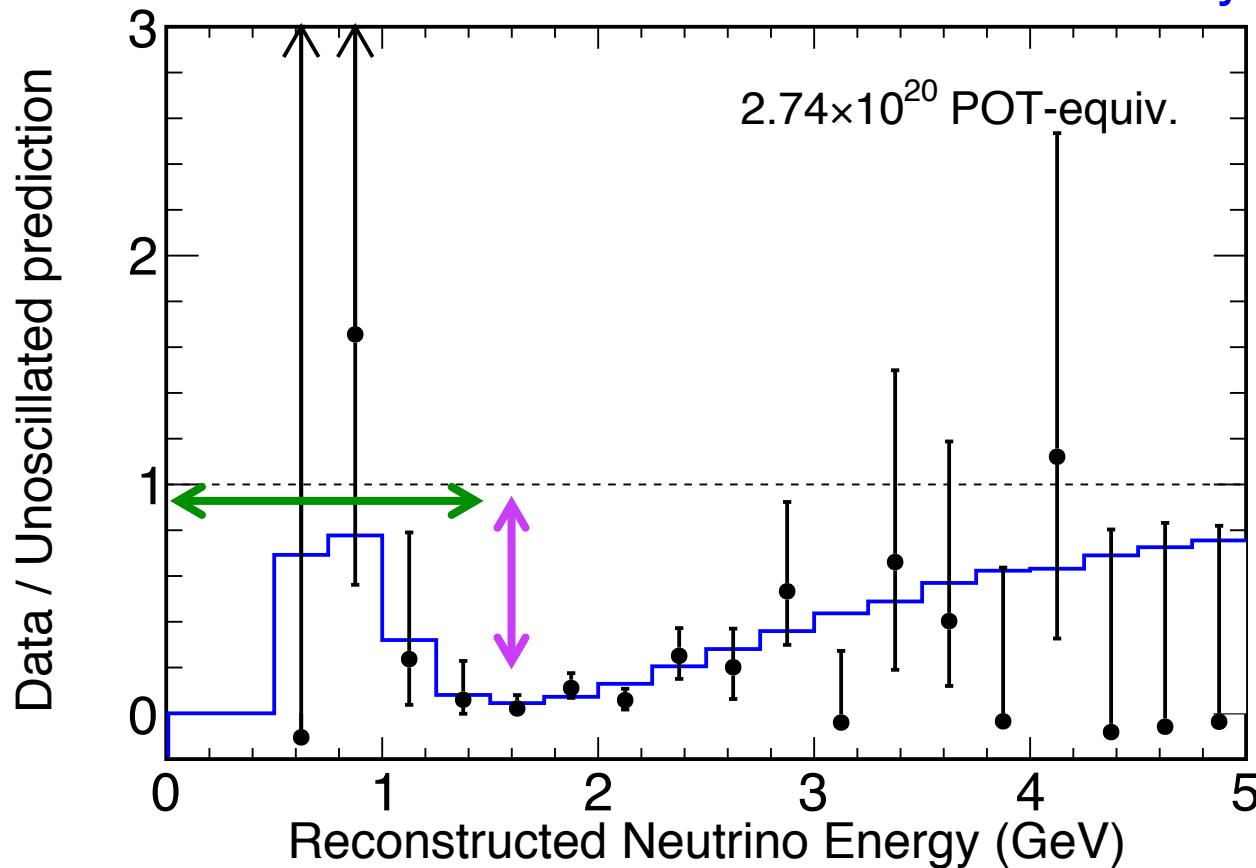


$\nu_\mu$  oscillation probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 (\Delta m_{32}^2 L / 4E)$$

- $211.8 \pm 12.5$  events predicted without oscillations
  - Including  $2 \pm 2$  beam background and  $1.4 \pm 0.2$  cosmic events
- 33 events observed!

NOvA Preliminary

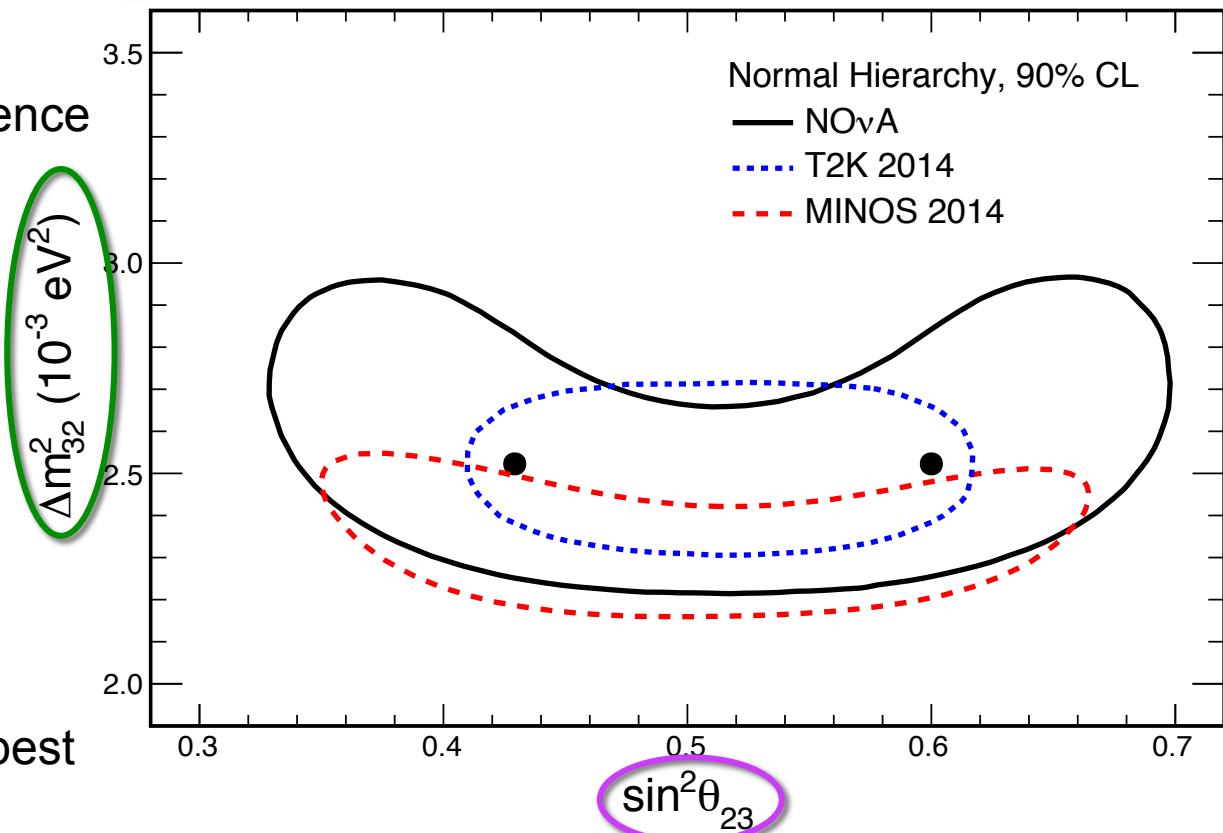


$\nu_\mu$  oscillation probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2(\Delta m_{32}^2 L / 4E)$$

Two solutions due to dependence  
on hierarchy

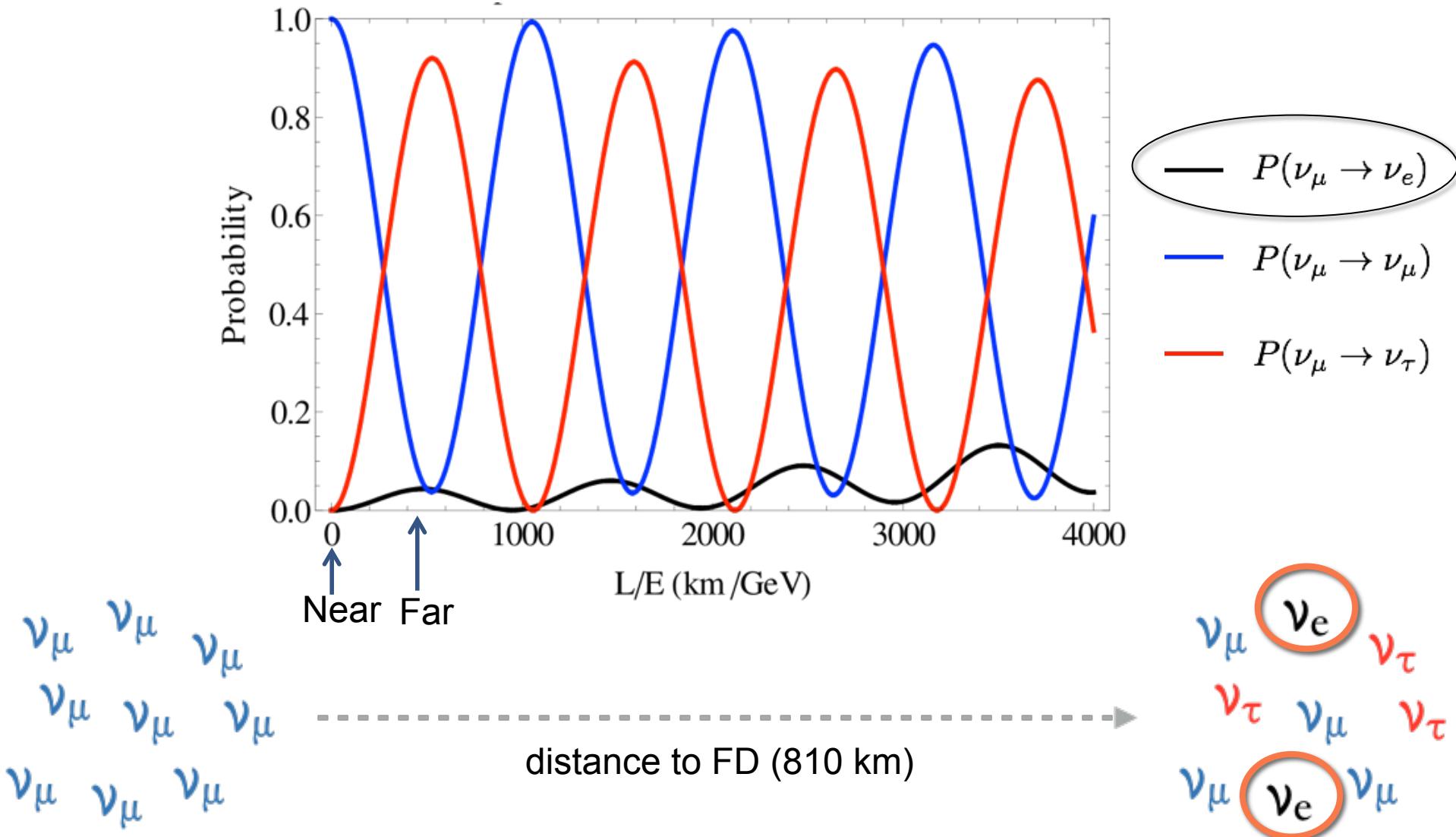
$$\Delta m^2 = \begin{cases} +2.52^{+0.20}_{-0.18} \\ -2.56^{+0.19}_{-0.19} \end{cases} \times 10^{-3} \text{ eV}^2$$



Two statistically-degenerate best  
fit points

- Good compatibility with both MINOS and T2K
- With **less than 10% of the nominal final statistics** NOvA is already competitive with the world limits

# Electron neutrino appearance



# Far Detector Event Prediction

Again use Near Detector data to predict rate in FD  
expect about **1 background event**

	Total Bkg	Beam $\nu_e$	NC	$\nu_\mu$ CC	$\nu_\tau$ CC	Cosmic
LID	$0.94 \pm 0.09$	0.47	0.36	0.05	0.02	0.06
LEM	$1.00 \pm 0.11$	0.46	0.40	0.07	0.02	0.06

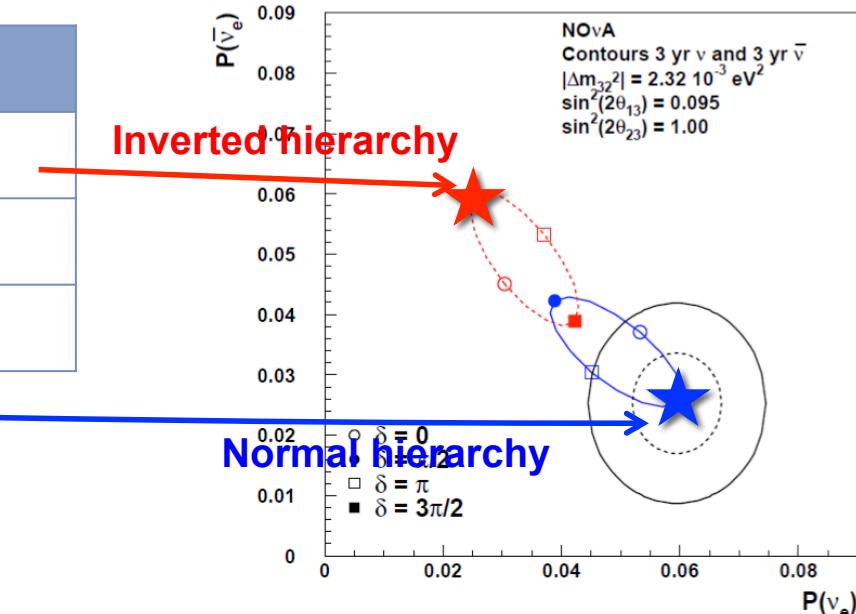
# Far Detector Event Prediction

Again use Near Detector data to predict rate in FD  
expect about 1 background event

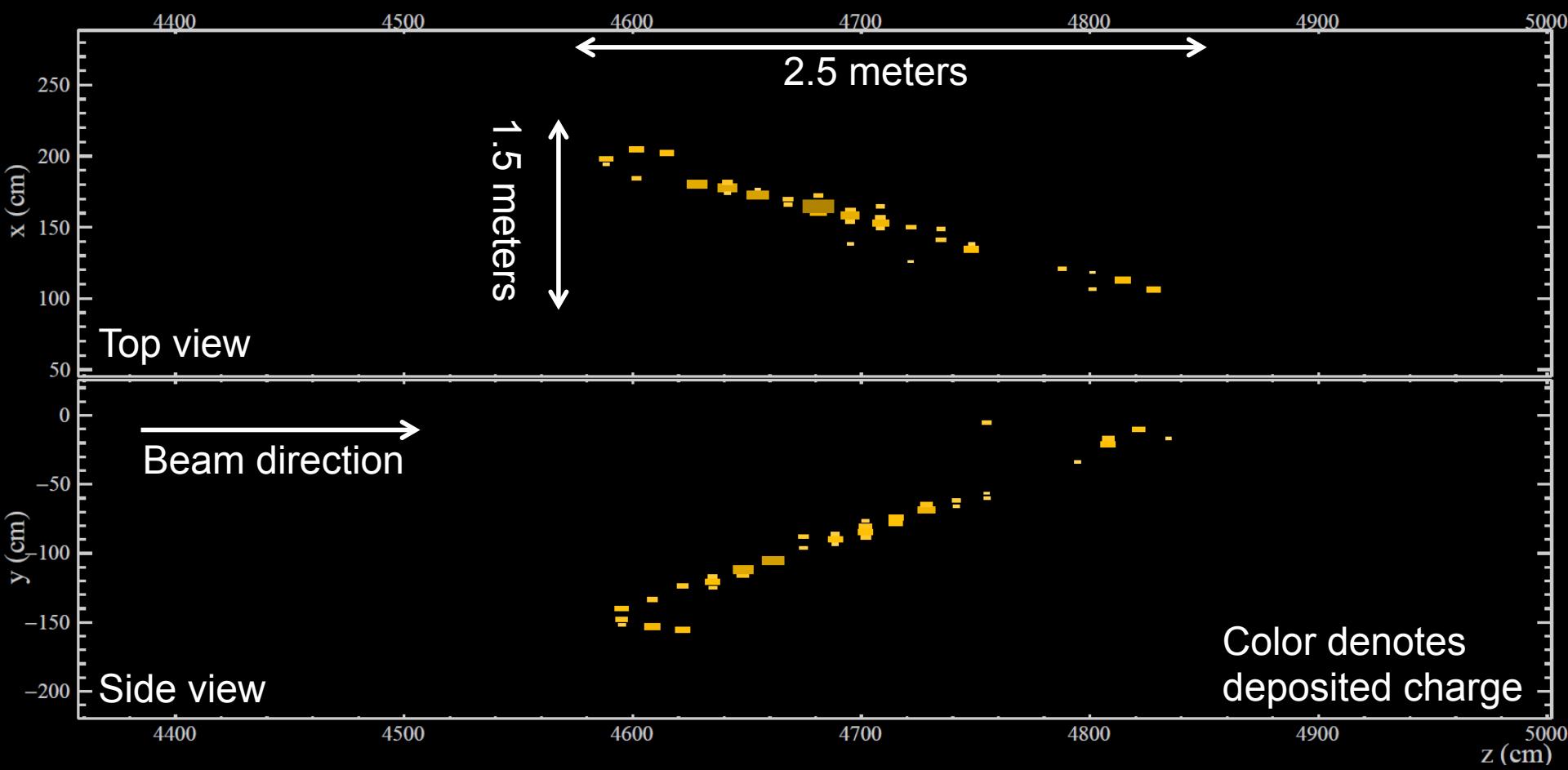
	Total Bkg	Beam $\nu_e$	NC	$\nu_\mu$ CC	$\nu_\tau$ CC	Cosmic
LID	$0.94 \pm 0.09$	0.47	0.36	0.05	0.02	0.06
LEM	$1.00 \pm 0.11$	0.46	0.40	0.07	0.02	0.06

Signal prediction depends on oscillation parameters

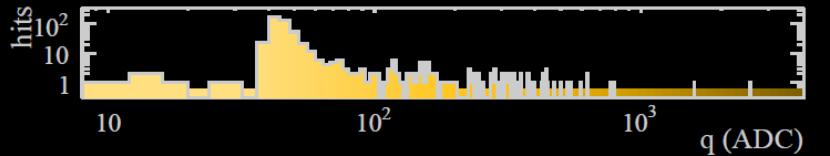
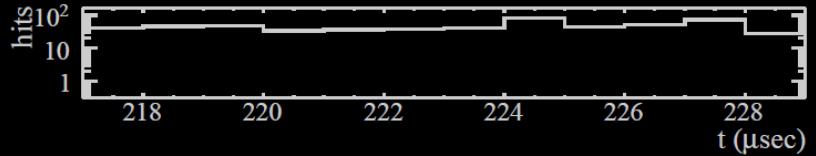
Signal	Most	Least
	$\text{NH } \delta_{\text{CP}} = 3\pi/2$	$\text{IH } \delta_{\text{CP}} = \pi/2$
LID	$5.62 \pm 0.72$	$2.24 \pm 0.29$
LEM	$5.91 \pm 0.59$	$2.34 \pm 0.23$



# Selected $\nu_e$ event

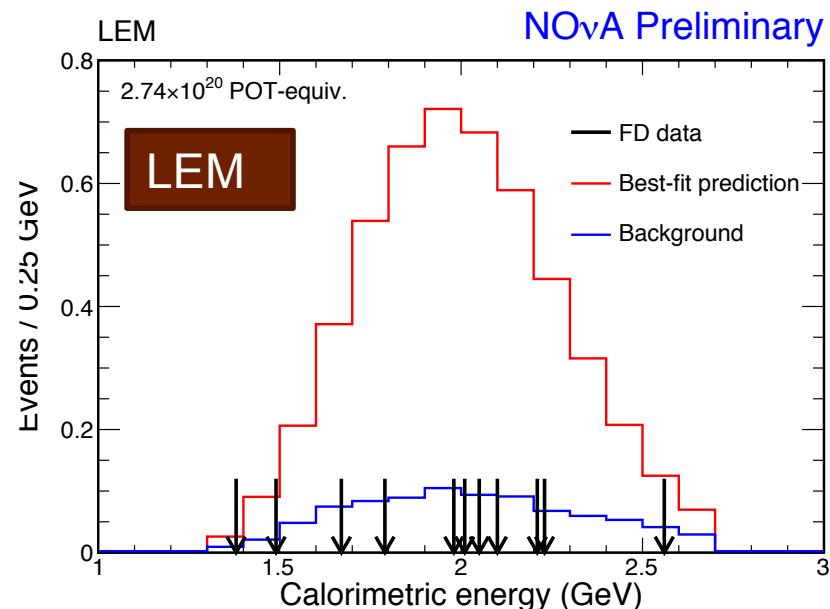
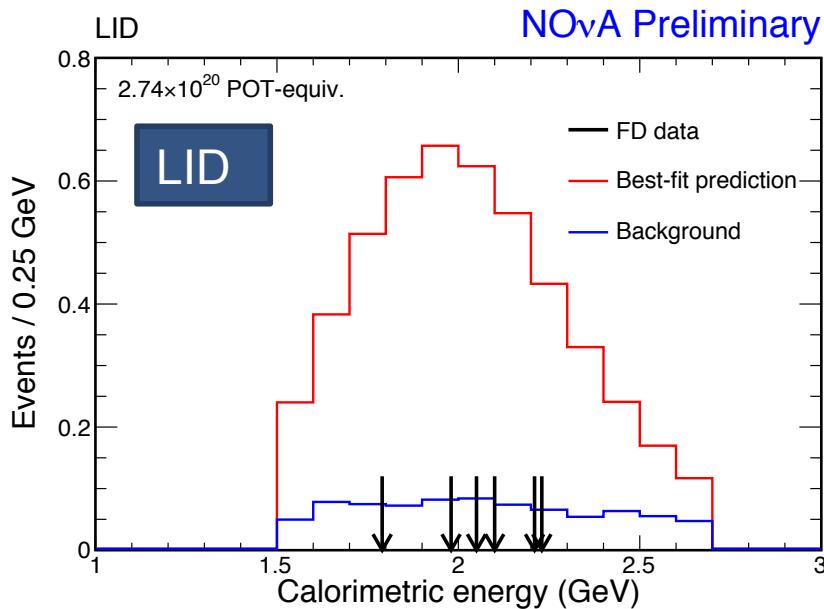


NOvA - FNAL E929  
Run: 19165 / 62  
Event: 920415 / --  
UTC Mon Mar 23, 2015  
11:43:54.311669120



# $\nu_e$ Appearance Results

Two  $\nu_e$  selection algorithms used:



LID: Selected 6 events  
3.3 $\sigma$  significance for  $\nu_e$  appearance

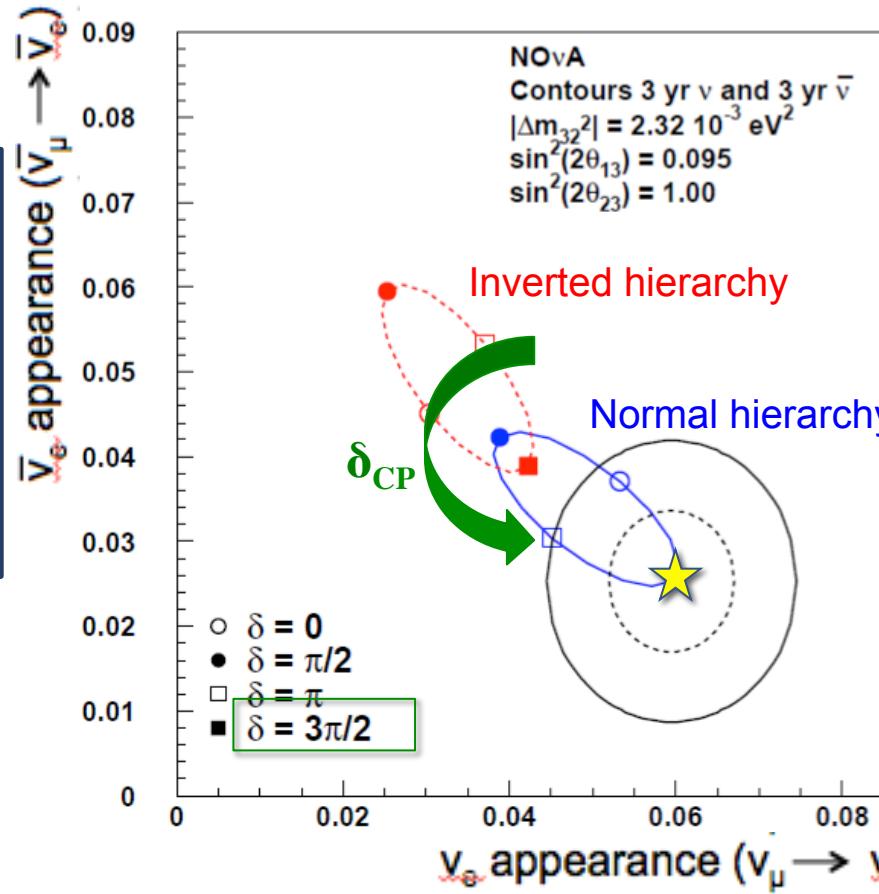
LEM: Select 11 events  
5.5 $\sigma$  significance for  $\nu_e$  appearance

- All 6 LID events selected by LEM
- Trinomial probability of selecting this combination (11:6/5/0) is 9.2%

# $\nu_e$ appearance from a $\nu_\mu$ beam

Number of electron neutrinos appearing depends on **amount of CP violation in neutrino sector and on mass hierarchy**

1 and 2  $\sigma$  Contours for Starred Point



distance to FD (810 km)

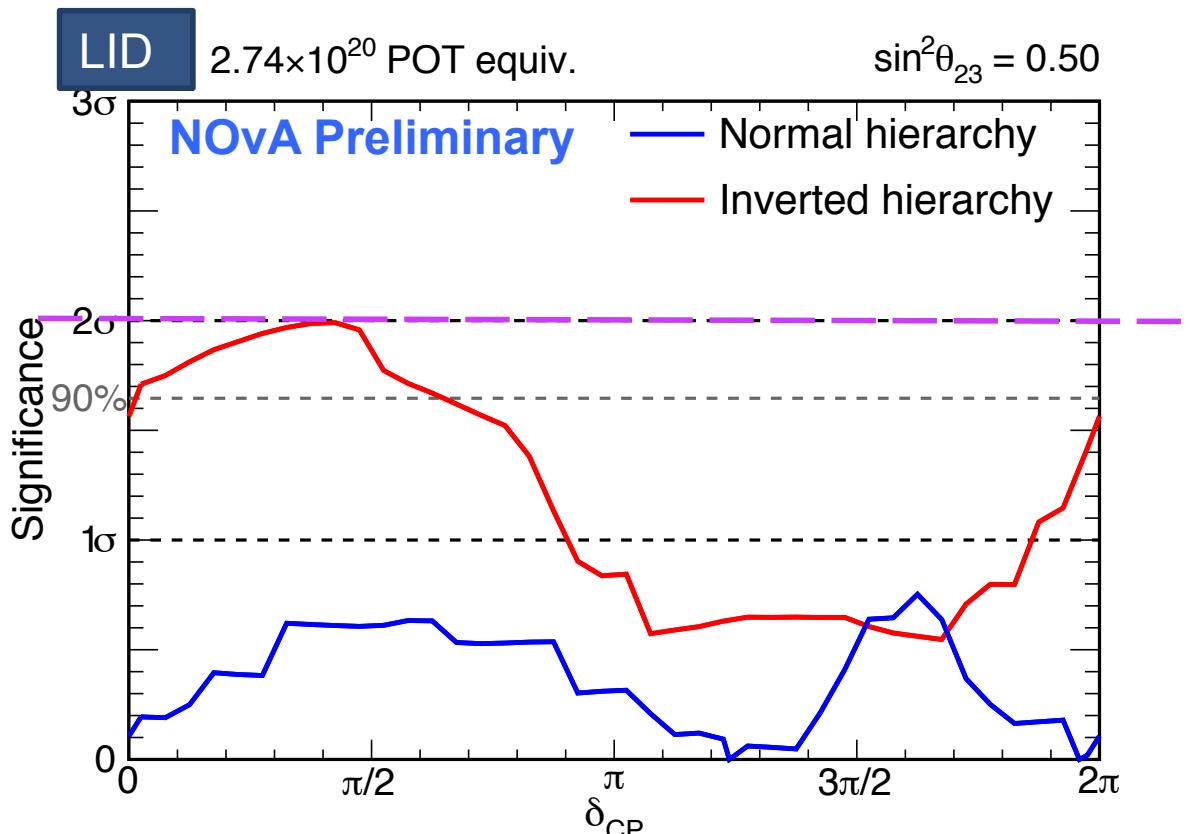
$\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$   
 $\nu_\mu$   $\nu_\mu$   $\nu_\mu$

$\nu_\mu$   $\nu_e$   $\nu_\tau$   
 $\nu_\tau$   $\nu_\mu$   $\nu_\tau$   
 $\nu_\mu$   $\nu_e$   $\nu_\mu$

# $\nu_e$ Appearance Results

Statements holds for  
 $0.4 < \sin^2\theta_{23} < 0.6$

- LID shows mild tension with IH,  $0 < \delta_{CP} < 0.8\pi$
- LEM disfavors IH at greater than  $2\sigma$  for all  $\delta_{CP}$

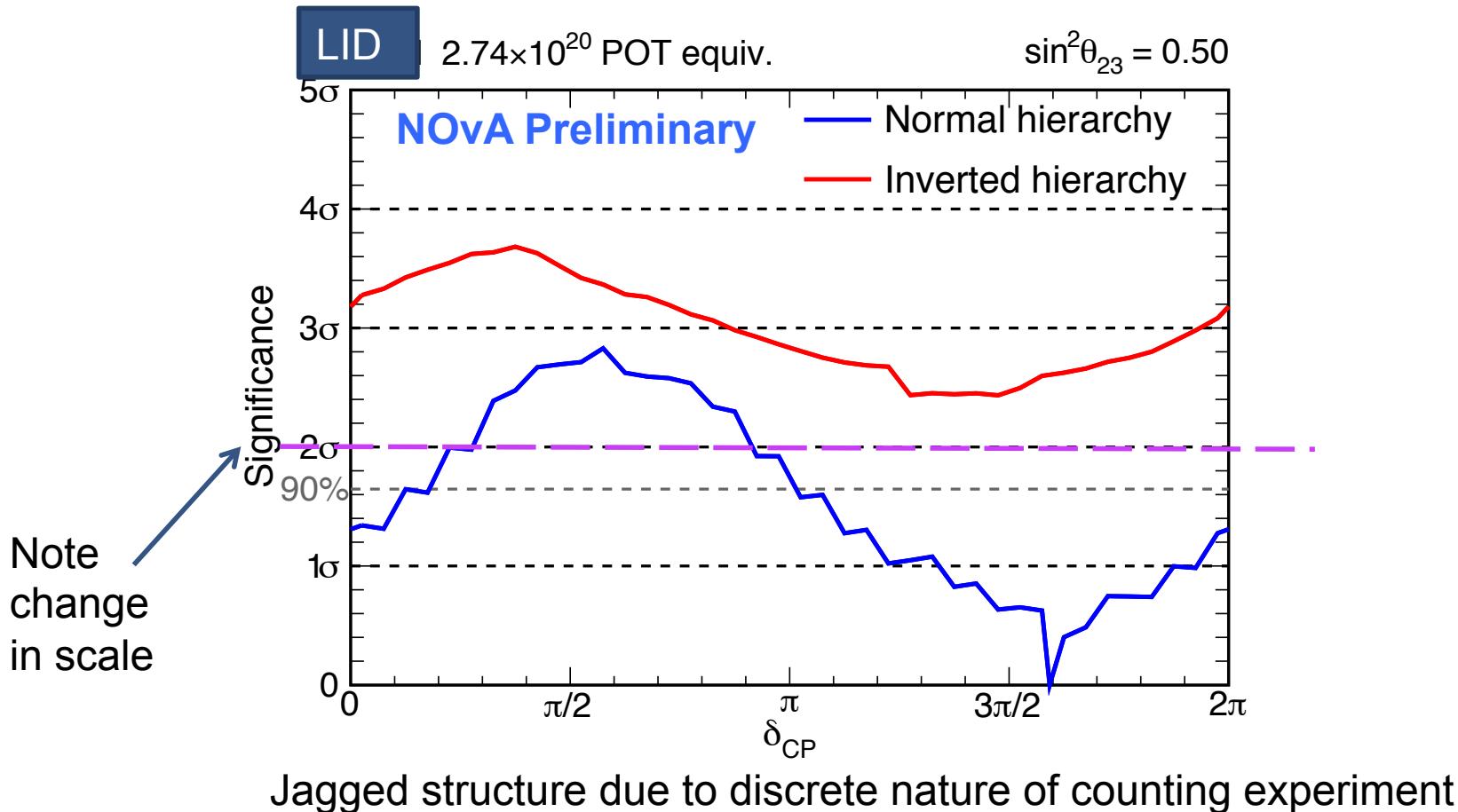


Jagged structure due to discrete nature of counting experiment

Statements holds for  
 $0.4 < \sin^2\theta_{23} < 0.6$

# $\nu_e$ Appearance Results

- LID shows mild tension with IH,  $0 < \delta_{CP} < 0.8\pi$
- LEM disfavors IH at greater than  $2\sigma$  for all  $\delta_{CP}$



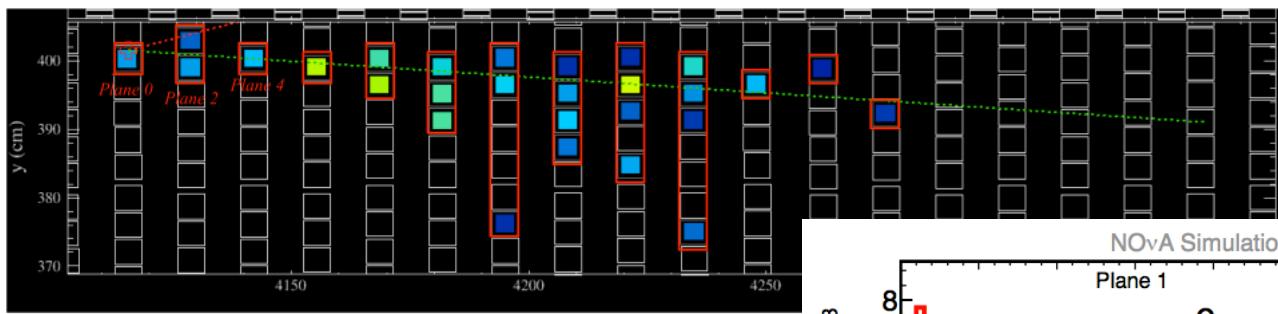
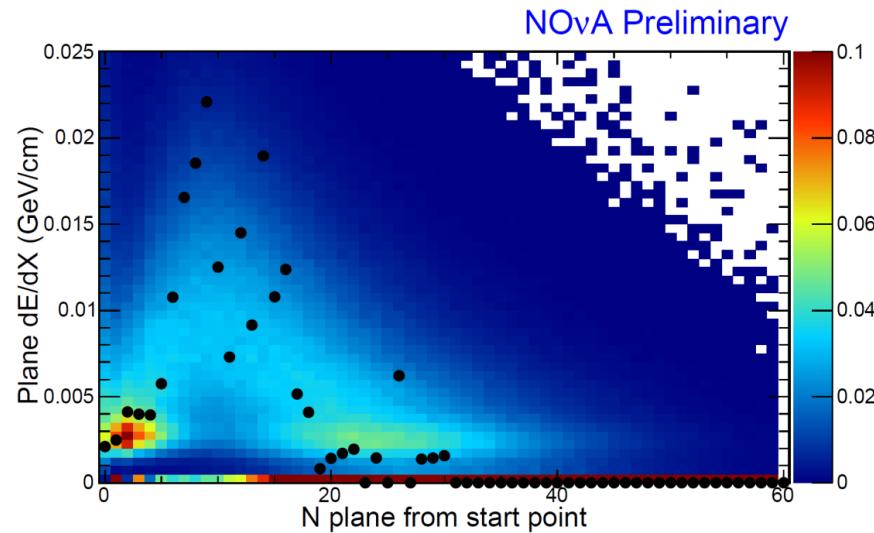
# BACK UP

# Selecting Electron Neutrinos

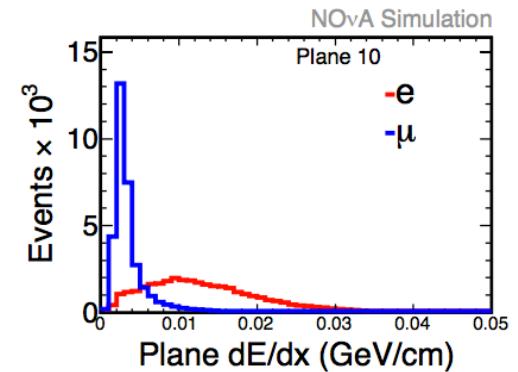
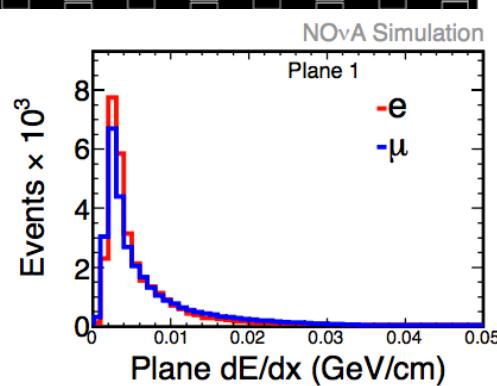
Two complimentary electron identification algorithms

## Likelihood Identification:

Compare  $dE/dx$  in transverse and longitudinal slices to simulated  $e/\mu/\pi/p^+$  distributions

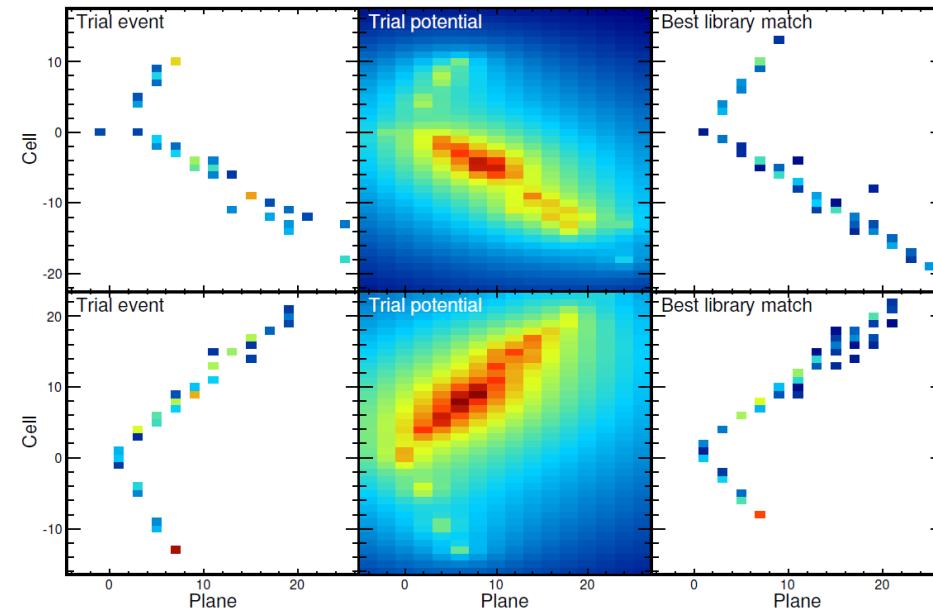


First plane will look MIP like but as move away from vertex  $dE/dx$  for  $e$  and  $\mu$  will differ



# Selecting Electron Neutrinos

Two complimentary electron identification algorithms



**Library Event Matching:**  
Pattern of energy deposition of entire event compared to a simulated event library

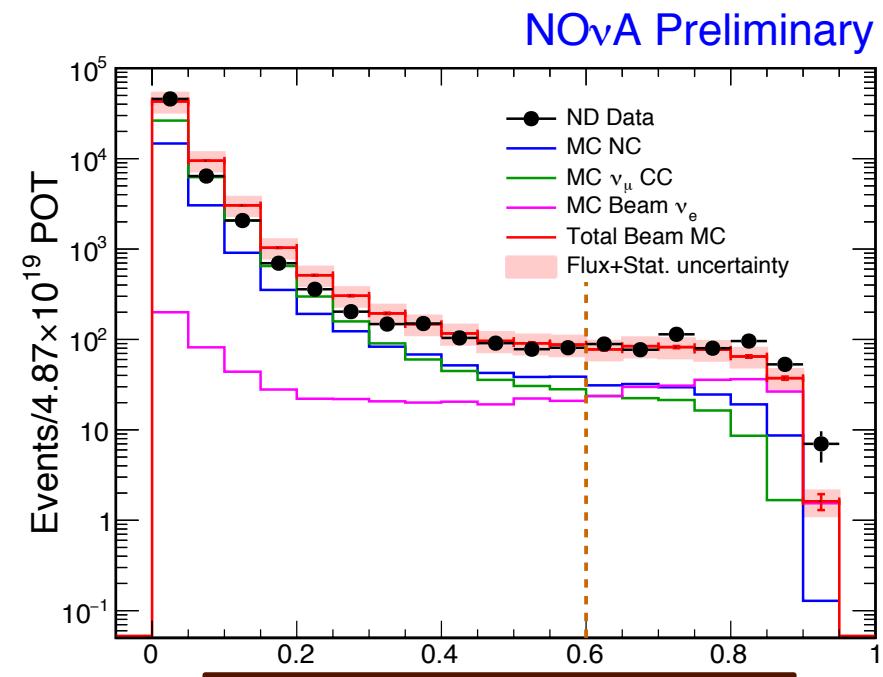
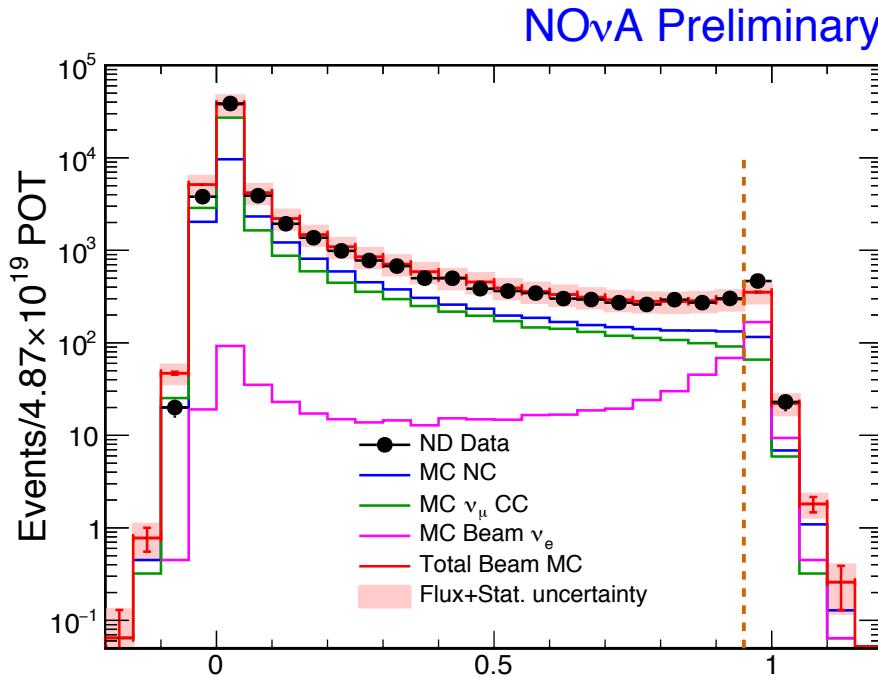
- Compare an trial event to a MC library, using individual cell hits rather than high-level reconstructed variables.
- Extract a pattern function for the trail event cell by cell, including both position and charge information
- Variables based on ‘goodness’ of the match to the best matching events, along with the calorimetric energy of the trial event are trained in a BDT

# Selecting Electron Neutrinos

## Near Detector Data

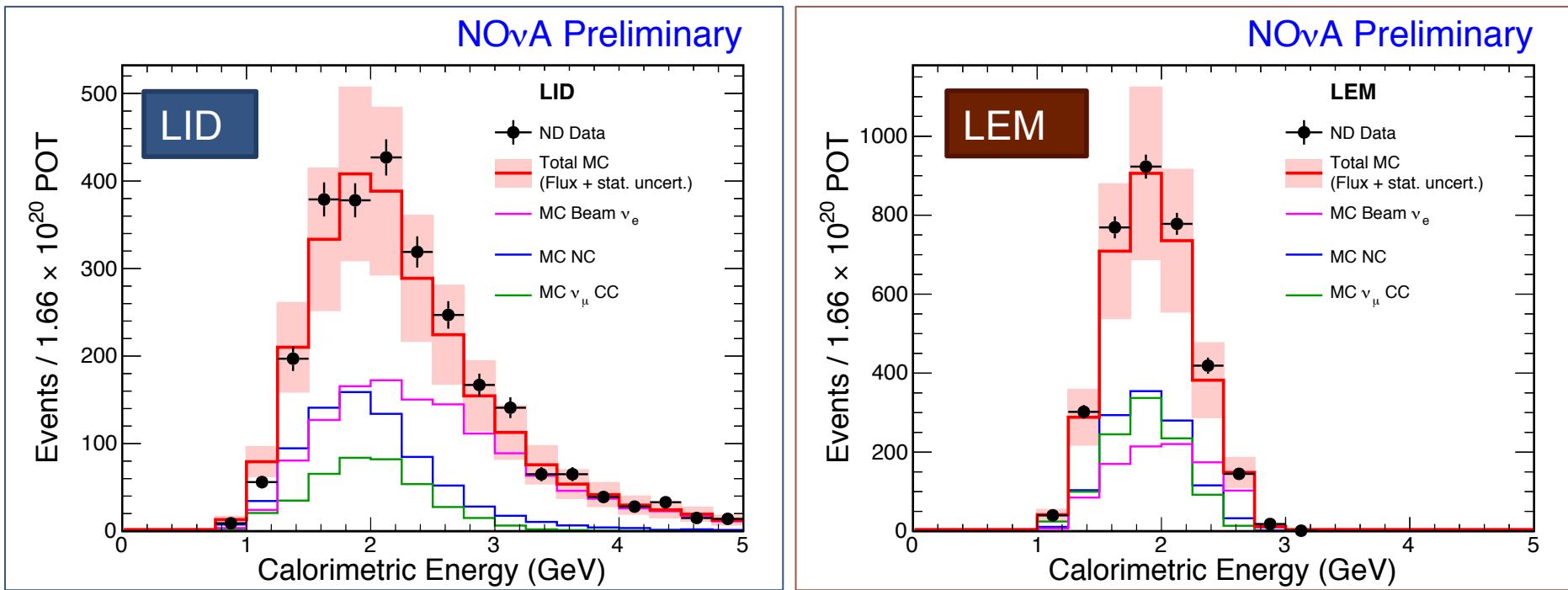
Validate simulation using beam intrinsic  $\nu_e$ 's

Extrapolate beam intrinsic  $\nu_e$ 's in the ND to predict background  $\nu_e$  rate at the FD



# Selecting Electron Neutrinos

## Near Detector Data



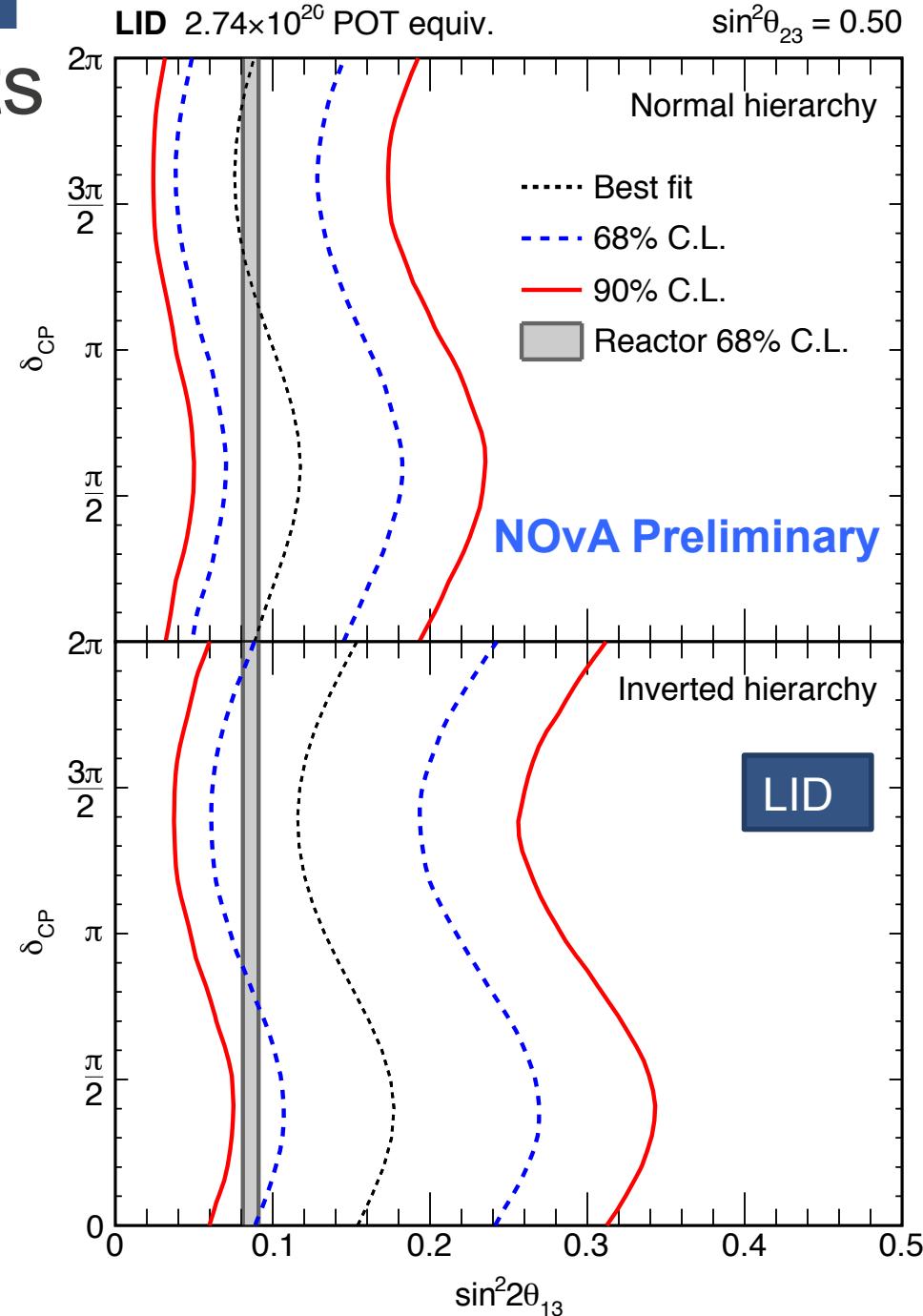
- Good agreement after selection
- Data selects ~5% more events than simulation

# $\nu_e$ Appearance Results

## LID

- Contours determined using Feldman-Cousins procedure
  - Include errors on solar parameters
  - Atmospheric  $\Delta m^2$  varied within new NOvA errors
  - $\sin^2\theta_{23}$  held fixed at 0.5
- LID results in good agreement with reactor measurements

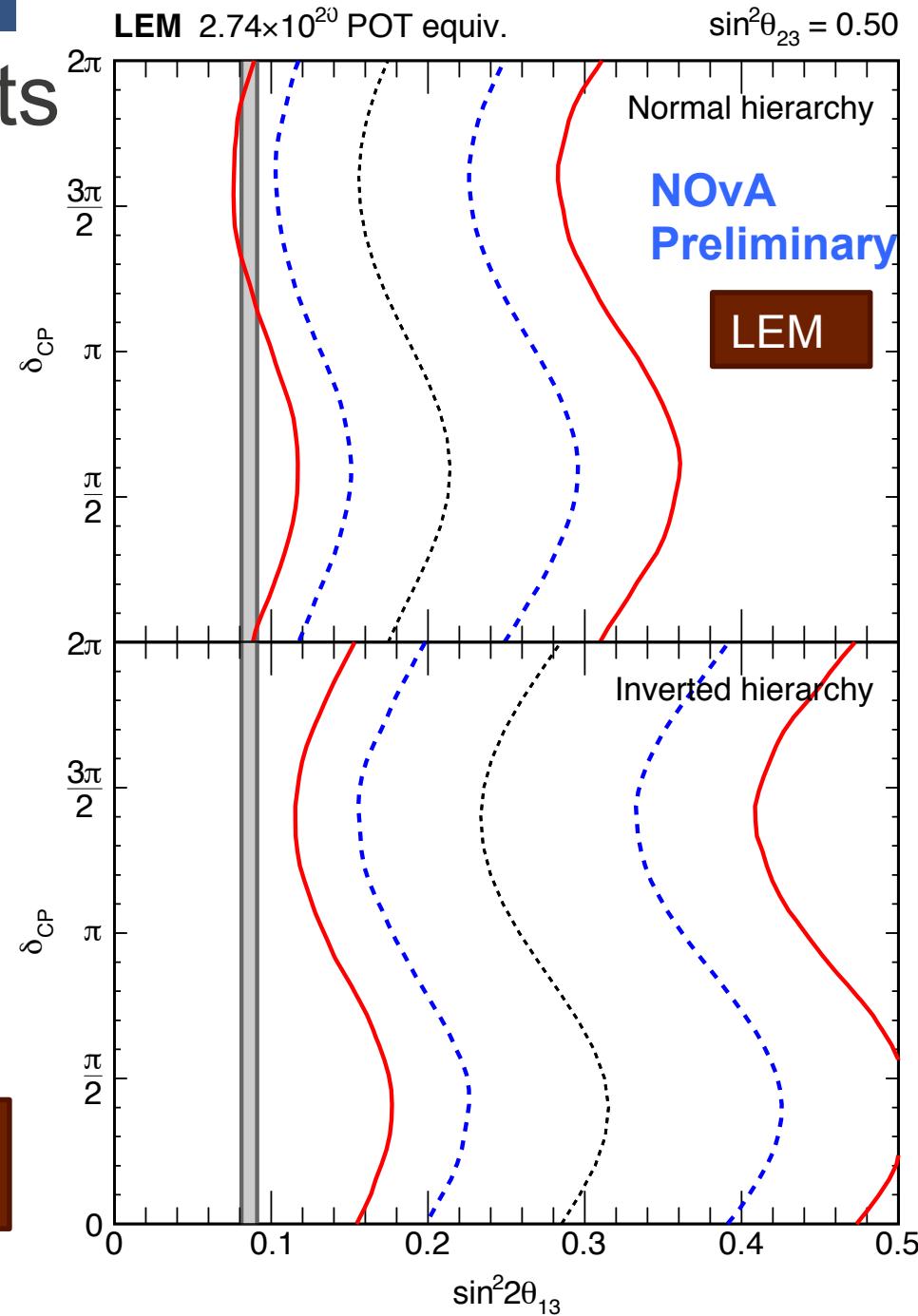
LID: Selected 6 events  
 $3.3\sigma$  significance for  $\nu_e$  appearance



# $\nu_e$ Appearance Results

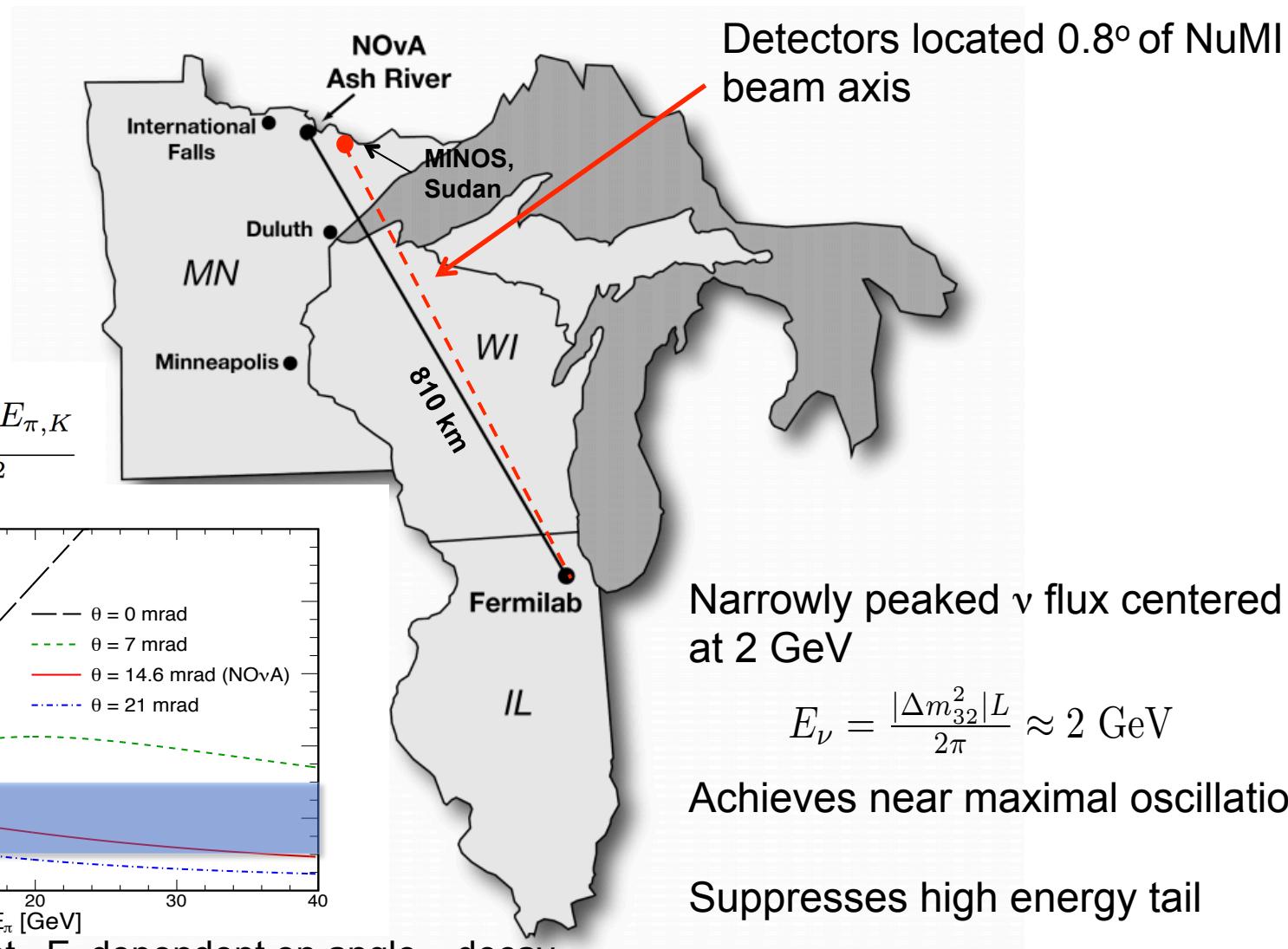
## LEM

- LEM curves shift to the right
- Some tension with reactor results, particularly in IH



LEM: Select 11 events  
5.5 $\sigma$  significance for  $\nu_e$  appearance

# Off-axis long-baseline neutrino oscillation experiment



PNMS matrix factorizes into three regions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{32}^2 \simeq 2 \times 10^{-3} \text{ eV}^2$$

$$L/E = 500 \text{ km/GeV}$$

$$\Delta m_{31}^2 \approx \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

$$L/E = 15,000 \text{ km/GeV}$$

$$P_{\alpha\alpha} \approx 1 - \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 [\text{eV}^2] L_\nu [\text{km}]}{E_\nu [\text{GeV}]} \right)$$

Extending to full three flavors

$$\sin^2(2\theta) = 4 \sin^2 \theta_{23} \cos^2 \theta_{13} (1 - \sin^2 \theta_{23} \cos^2 \theta_{13})$$

$$\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2 \sin^2 \theta_{12} + \Delta m_{21}^2 \cos \delta_{CP} \sin \theta_{13} \tan \theta_{23} \sin 2\theta_{12}$$

PNMS matrix factorizes into three regions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{32}^2 \simeq 2 \times 10^{-3} \text{ eV}^2$$

$$L/E = 500 \text{ km/GeV}$$

$$\Delta m_{31}^2 \approx \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

$$L/E = 15,000 \text{ km/GeV}$$

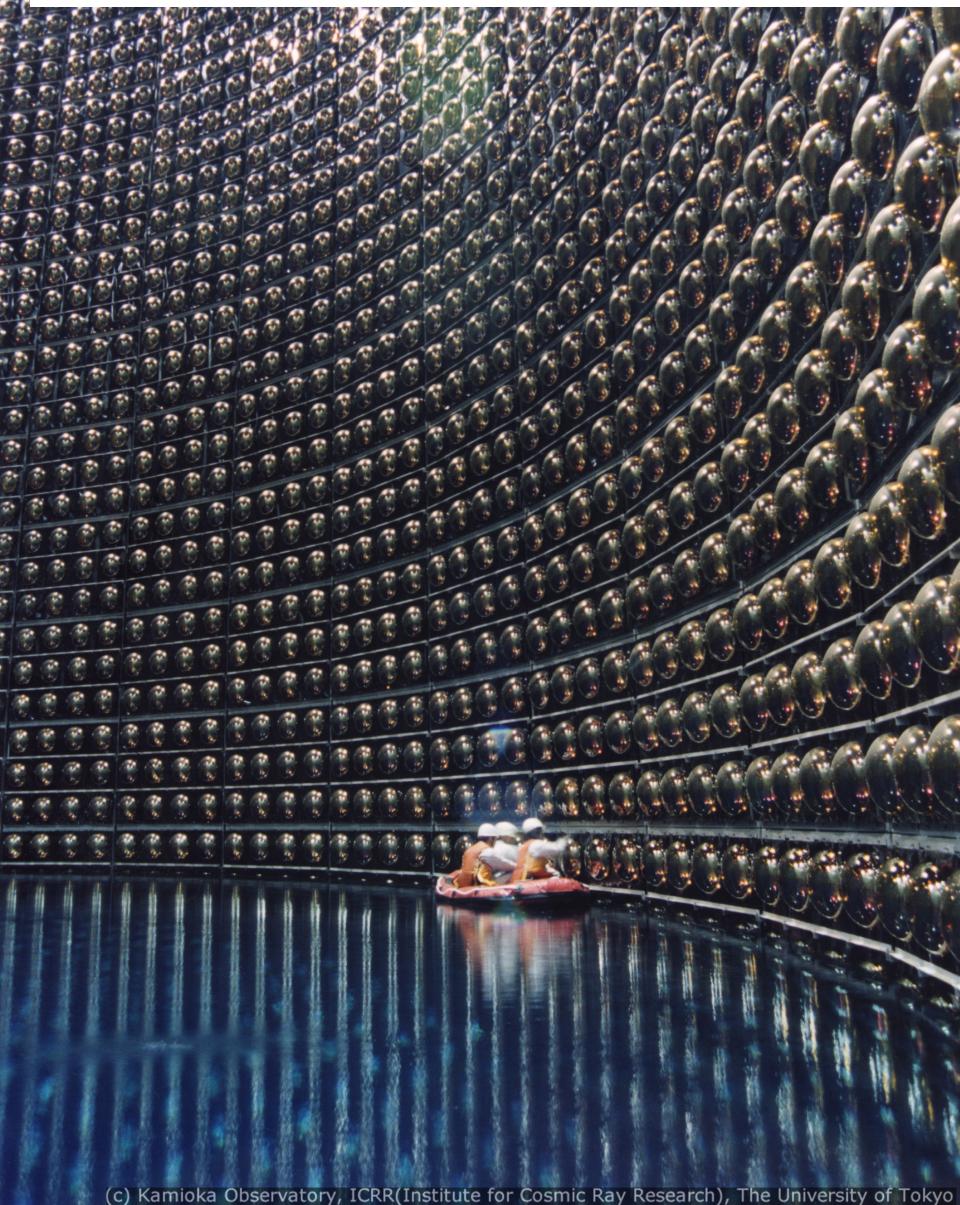
Still not the whole story, this is for oscillations in vacuum. Probability modified as travel through matter. Need to modify  $\theta_{13}$  to  $\theta_M$ , where

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (A - \cos 2\theta_{13})^2}$$

$$A = \pm 2\sqrt{2}G_F n_e E_\nu / \Delta m_{13}^2$$

Sign of  $A$  changes for  $\nu$  and  $\bar{\nu}$   
 Dependence on hierarchy through  
 sign of  $\Delta m_{13}^2$ .

2015 noble prize in physics for “*the discovery of neutrino oscillations, which shows that neutrinos have mass*”



- Takaaki Kajita for the first measurement of  $\nu_{\mu}$  disappearance looking at atmosphere  $\nu$  using Super-Kamiokande
- Arthur McDonald for leading the SNO collaboration who demonstrated that solar  $\nu$  were not disappearing on their way to Earth, instead they arrived at SNO with a different  $\nu$  flavor

### Proved that neutrinos must have mass

New York Times, June 5th 1998

***Mass Found in Elusive Particle; Universe May Never Be the Same***

***Discovery on Neutrino Rattles Basic Theory About All Matter***

By MALCOLM W. BROWNE

#### Detecting Neutrinos



Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water...

Neutrino mass matric factorizes into three regions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{32}^2 \simeq 2 \times 10^{-3} \text{ eV}^2$$

$$L/E = 500 \text{ km/GeV}$$

$$\Delta m_{31}^2 \approx \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

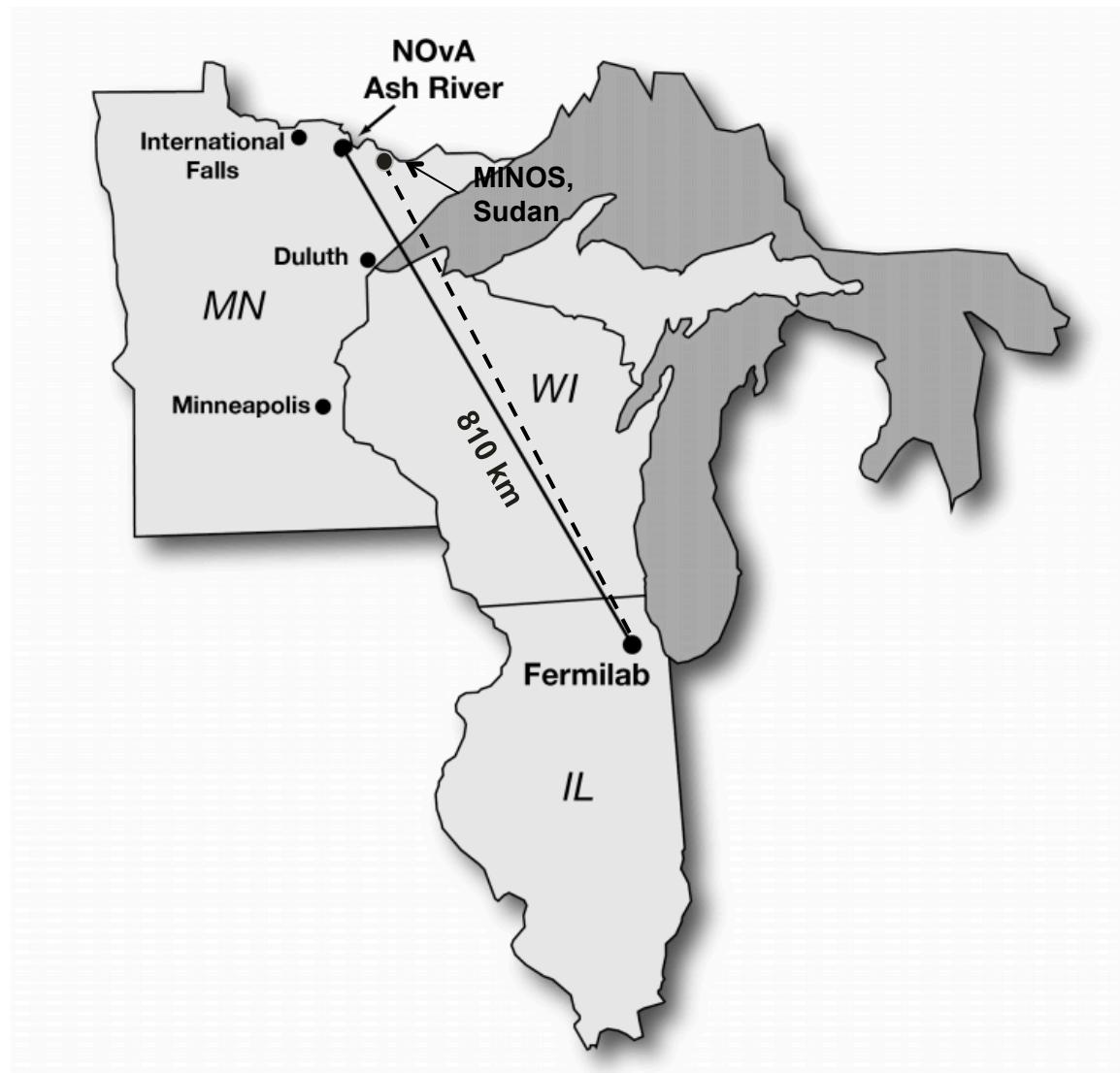
$$L/E = 15,000 \text{ km/GeV}$$

$$P_{\alpha\alpha} \approx 1 - \sin^2(2\theta) \sin^2 \left( \frac{1.27 \Delta m^2 [\text{eV}^2] L_\nu [\text{km}]}{E_\nu [\text{GeV}]} \right)$$

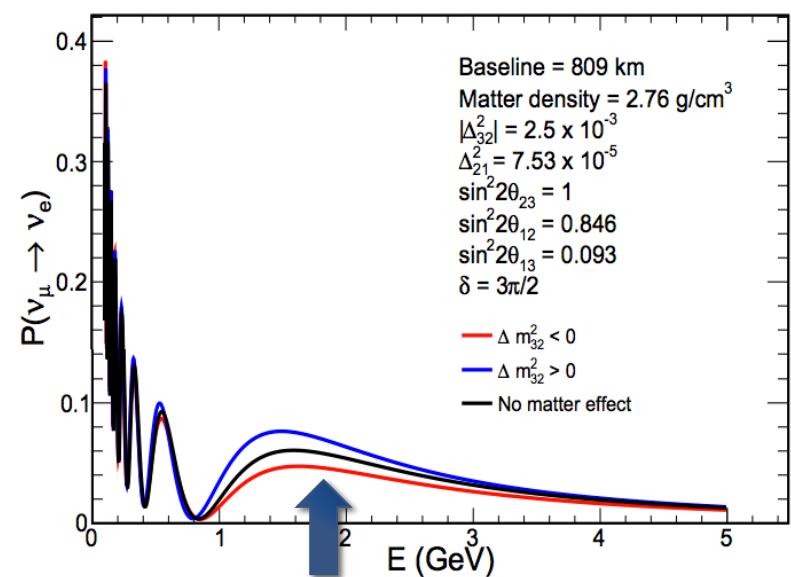
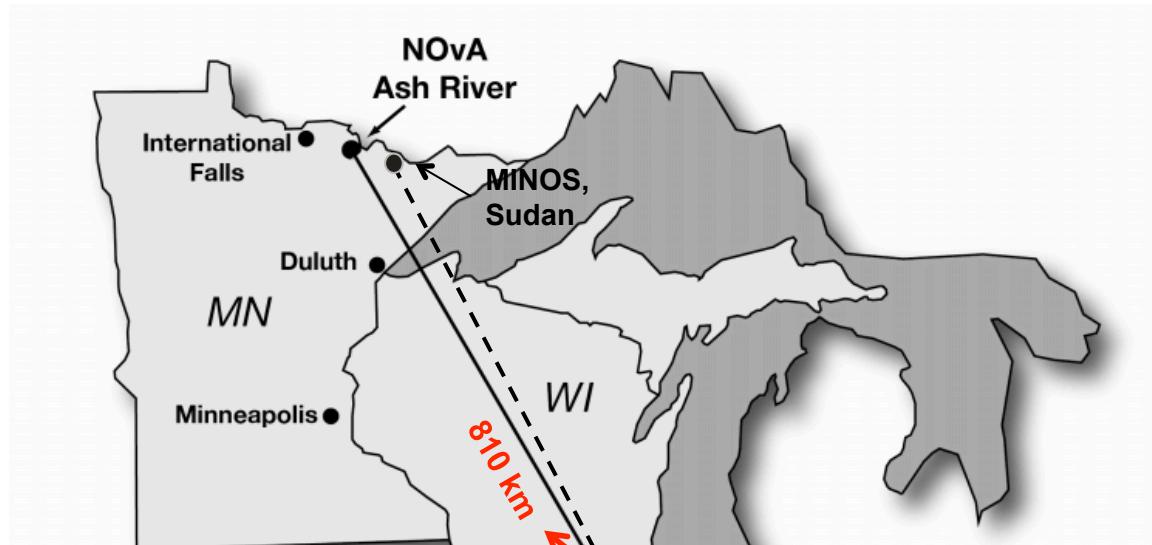
Neutrino flavor oscillation governed by two distinct mass splitting

$$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$$

# Off-axis long-baseline neutrino oscillation experiment

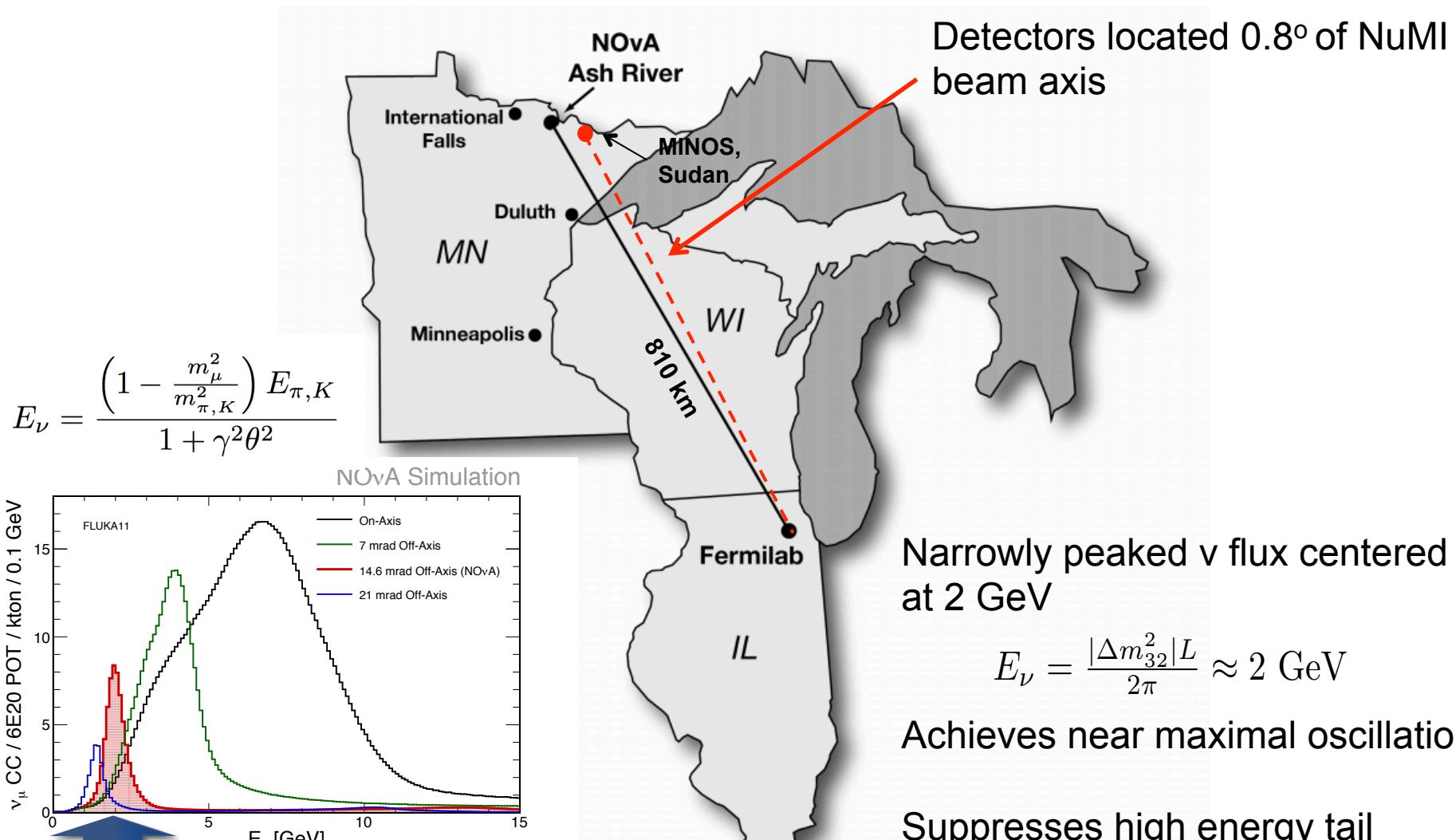


# Off-axis long-baseline neutrino oscillation experiment



- Sensitivity to mass hierarchy comes from **matter effects**
- Longest baseline of any accelerator neutrino experiment at 810km

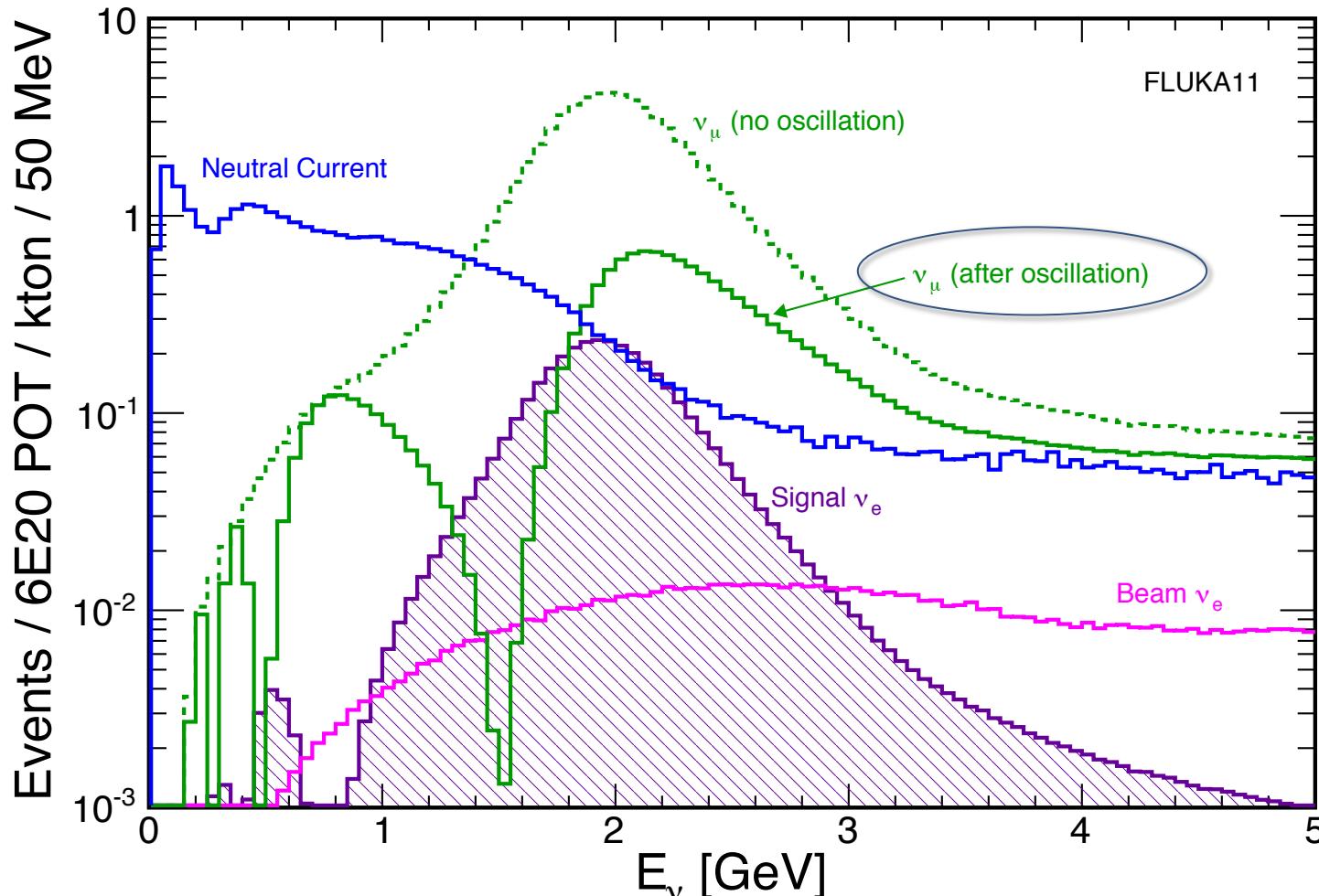
# Off-axis long-baseline neutrino oscillation experiment



For  $\pi$  decay in flight,  $E_\nu$  dependent on angle  $\pi$  decay and  $\nu$  interaction. Off-axis have flat pion dependence.

# $\nu_\mu$ Disappearance at NOvA

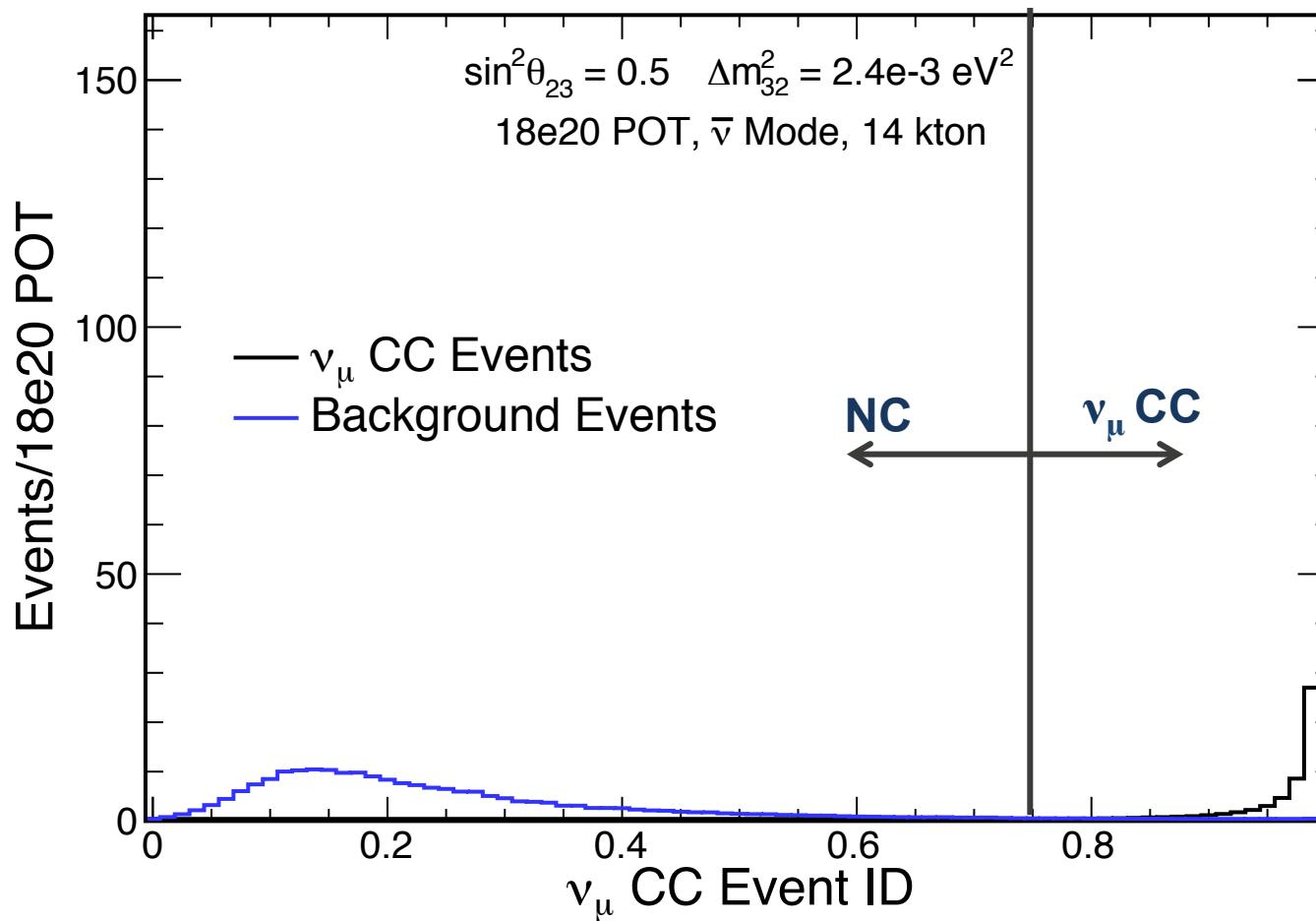
NOvA Simulation



Neutral Current events are suppressed in narrow band beam still the dominant beam background

# Background removal: NC rejection

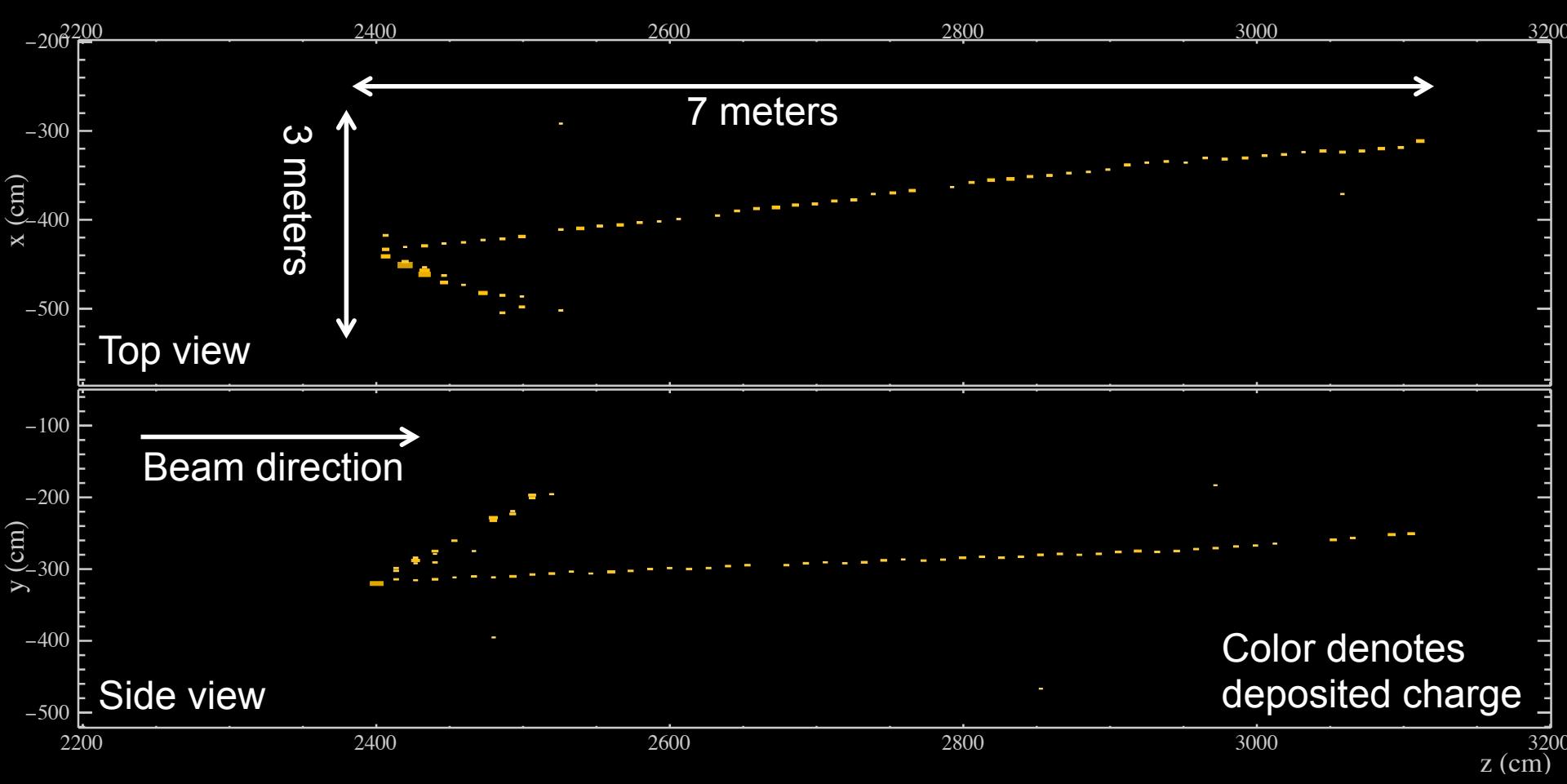
NO $\nu$ A Simulation



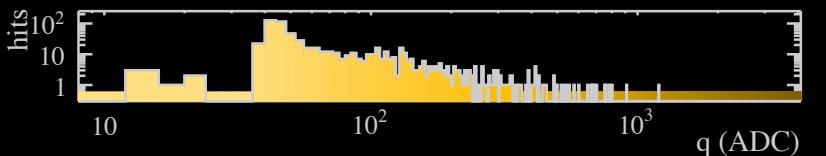
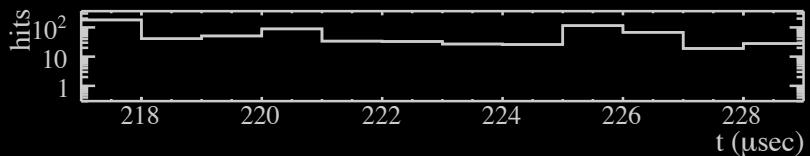
A k-Nearest Neighbour algorithm is used to select  $\nu_\mu$  CC signal from NC background

- 80% efficiency
- 98% purity

# Selected $\nu_\mu$ event

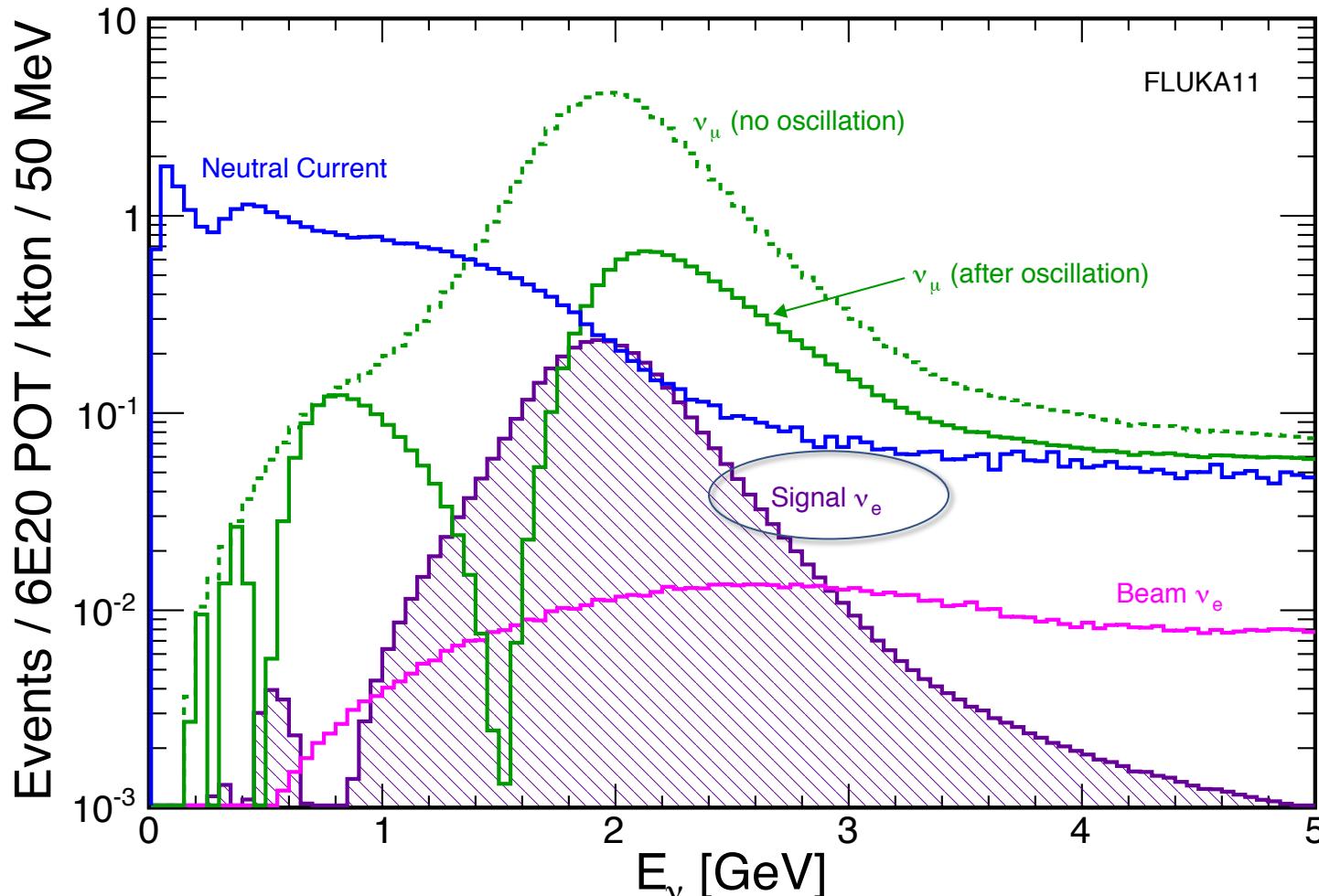


NOvA - FNAL E929  
Run: 14828 / 38  
Event: 192569 / --  
UTC Tue Apr 22, 2014  
21:41:51.422846016



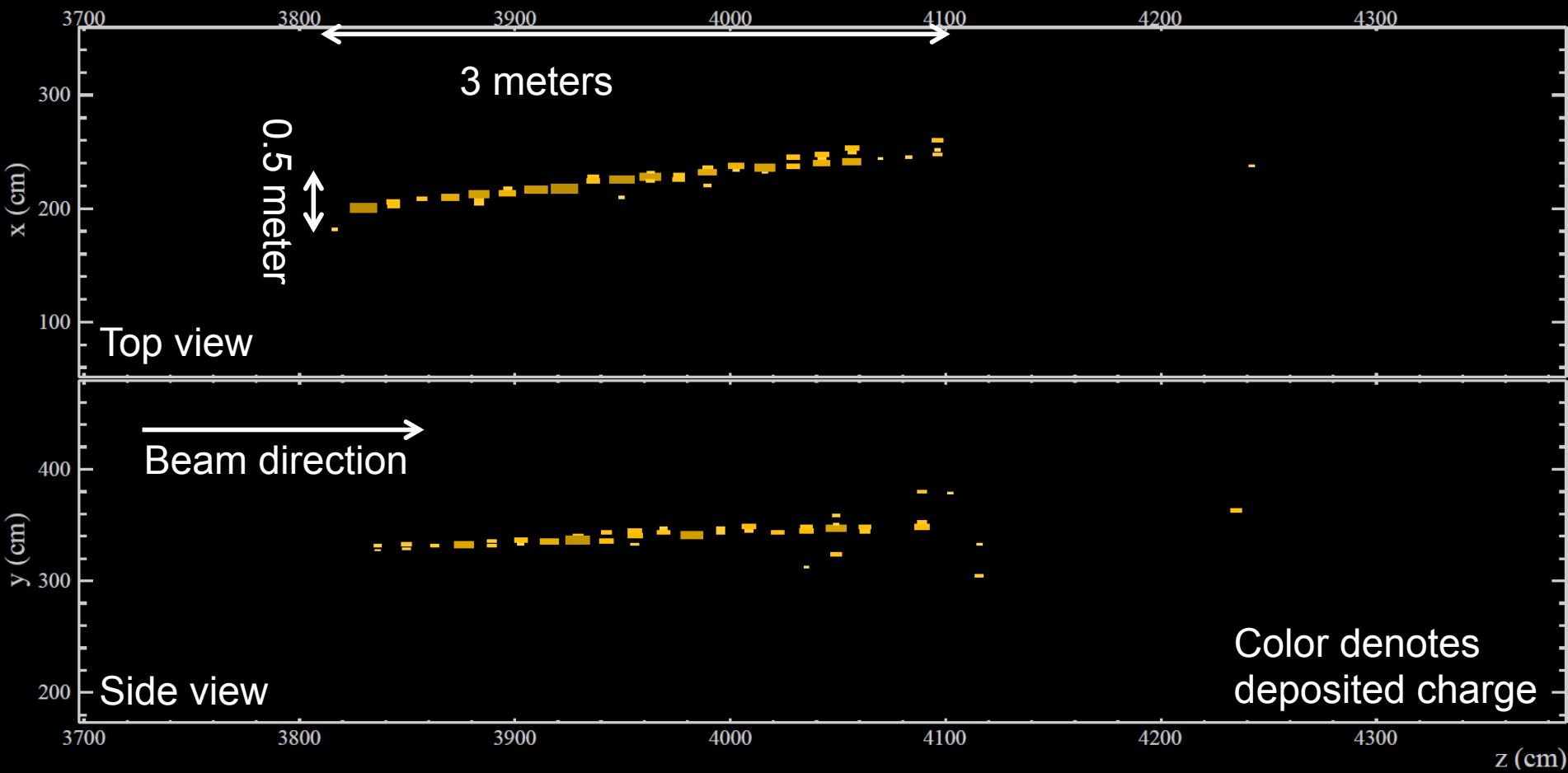
# $\nu_e$ Appearance at NOvA

NOvA Simulation



Neutral Current events are suppressed in narrow band beam still the dominant beam background

# Selected $\nu_e$ event



NOvA - FNAL E929  
Run: 17103 / 7  
Event: 27816 / -  
UTC Wed Sep 3, 2014  
10:04:58.572014784

